UNDERGRADUATE PHYSICS STUDENTS' UNDERSTANDING AND REPRESENTATIONS OF INTRODUCTORY NUCLEAR PHYSICS CONCEPTS

BY

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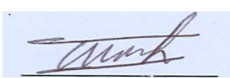

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ABSTRACT

One of the challenges for physics education is to develop the students' conceptual understanding of physics. The developmental phenomenographic research approach, which is a qualitative research approach, can inform effective instructional design that can address such challenges. This study aimed to explore and develop undergraduate physics students' understanding and representations of five basic concepts of nuclear physics. An exploratory case study research design underpinned by the conceptual frameworks of phenomenography and variation theory of learning was carried out. Data were collected using semi-structured interviews after the first group of students (N = 30) were exposed to traditional instruction for six weeks in phase one. Five sets of categories of description were constructed for the five concepts using phenomenography. These categories of description represent the different ways of students' understanding and representations of these concepts. This informed the development of multiple representations (MR's) based instruction with an interactive learning tutorial that was used as an intervention in phase two. The MR's were the combination of text, equation, graph, diagram, simulation, and others. The second group of students (N= 40) was exposed to the intervention for six weeks. Data were collected using an open-ended questionnaire at pre-, post-, and delayed post-intervention. Fifteen sets of categories of description were constructed at these three points for each of the five concepts. In phase three, the results at pre-intervention were used as a baseline and were compared to the results found at post- and delayed post-intervention to explore the efficacy of the intervention. Therefore, the categories of description were used as a basis to identify the critical and irrelevant aspects discerned by students using the variation theory of learning as a lens. Findings suggest that the intervention was effective in developing the students' conceptual understanding and representations of nuclear physics. This could inform effective instructional design for physics curriculum developers on what and how to include materials that facilitate students' conceptual understanding.

Keywords/Terms: Multiple representations, conceptual understanding, interactive learning tutorials, phenomenography, categories of description, and variation theory of learning

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ACRONYMS AND ABBREVIATIONS

α	Alpha Radiation
β	Beta Radiation
γ	Gamma Radiation
λ	The Decay Constant
R_0	The Rate of Radioactive Decay At Time T = 0
A/R	Activity or the Rate of Radioactive Decay At Any Time T
ANOVA	Analysis of Variance
CA	Critical Aspects
CCAM	Constant Comparison Analysis Method
ECTS	European Credit Transfer And Accumulation System
EMOE	Ethiopian Ministry Of Education
EPE	Electric Potential Energy
EtCTS	Ethiopian Credit Transfer And Accumulation System
IA	Irrelevant Aspects
INPLT’s	Interactive Nuclear Physics Learning Tutorials
MANOVA	Multi-Variance Analysis Of Variance
MRI	Magnetic Resonance Imaging
MRs	Multiple Representations
NBD	Negative Beta Decay
NBE	Nuclear Binding Energy
NE	Nuclear Energy
NPCIQ	Nuclear Physics Conceptual Investigation Questionnaire
NPE	Nuclear Potential Energy
NPILT	Nuclear Physics Interactive Learning Tutorials
NRS	Non-Respondent Students
NS	Number Of Students
PDAM	Phenomenographic Data Analysis
PER	Physics Education Research
PET	Positron Emission Tomography
PRDAM	Phenomenographic Research Data Analysis Method
UNISA	University of South Africa
VTL	Variation Theory of Learning

PAPER PRESENTATIONS AND PUBLICATIONS

Tafesse, K., Lemessa, A. & Zeleke, D., (2016). Assessments of the Factors Affecting the Implementation of Practical Based Physics Learning: In the case of some selected schools in the west Shoa zone, Ethiopia. *Paper Presented at 6th Annual International Conference On Education in Ethiopia*. Wolaita Sodo, Ethiopia: Wolaita Sodo University, Unpublished (see the certificate of participation in Appendix X).

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND TO THE STUDY

"One of the grand challenges for science education is to improve students' conceptual development of scientific concepts" (Han & Ellis, 2019, p.1). The introductory nuclear physics course is rich in abstract concepts. This study aimed to explore and enhance undergraduate physics students' understanding and representations of five basic concepts of nuclear physics, namely, nuclear binding energy, radioactivity, radioactive decay law, a half-life, nuclear force, and nuclear dimensions. These concepts were identified as they are interrelated and are used to explain other issues in nuclear physics courses (Makhmudov & Saytjanov, 2020). However, the students encounter challenges in developing their conceptual understanding and representations of these concepts. Kohnle, Mclean, and Aliotta (2011) investigated undergraduate physics students' understanding and representations of the concepts of radioactive decay, nuclear binding energy, the properties of the nuclear force, and nuclear reactions and found that the students encountered conceptual difficulties in learning and understanding these concepts.

In this study, pre-service teachers' understanding and representations of the concepts of radioactive elements, radioactive decay, and half-life were investigated. The investigation was conducted using the modelling constant comparative method, which is a qualitative research approach (Yeşiloğlu, 2019). The investigation revealed the misconceptions of the pre-service teachers. The misconceptions of the surveyed students were also exposed in this study.

In general, findings released in the literature showed that understanding and representing the basic concepts of physics such as that of nuclear physics is one of the most difficult challenges that the students encounter (Aina, 2017; Bilal & Erol, 2012; Engelhard & Beichner, 2003; Entwistle, 1997; Mazur, 2008; McDermott, 2001; Singh, Belloni & Christian, 2006; Trowbridge & McDermott, 1980). Putranta and Supahar (2019) said that understanding and representing a concept should be the most fundamental passion that students must have in learning physics. According to these scholars, students must have an appropriate understanding of the concepts of physics to solve various problems in life. Conceptual understanding and representations are also crucial in teaching physics so that students develop critical thinking skills and do not rely on memorisation (Aina, 2017). Conceptual understanding is the ability of students to construct a verbal and /or visual mental representation of nuclear physics concepts in different ways (Adadan, 2013). According to Larsson (2013) representations are referred to as external representations, internal representations, and metaphorical language are tools that support students' conceptual understanding. According to Larsson, external representations are the students' written explanations, expressed equations, drawn graphs, and drawn diagrams. Internal representations are representations on the student's mind or mental picture. Metaphorical language is represented in a verbal-linguistic form.

The different ways of undergraduate physics students' understanding and representations of the concepts of introductory nuclear physics were not explored and developed in previous studies. So, this is the main focus of this study. Five basic and important concepts of nuclear physics were selected based on the review of literature; the researcher's teaching experiences, and observations for this study. These concepts are the concepts of nuclear binding energy, nuclear force, radioactive decay, negative beta decay, and nuclear energy. This study was conducted in three phases to explore and develop the different ways of students' understanding and representations of these concepts. The first group of students' different ways of understanding and representations was explored in the first phase after they were exposed to traditional instruction for 12 hrs and 50 minutes. And that of the second group of students was explored in the second phase at pre-intervention, in the third phase at post- and delayed post-intervention. The students were exposed to the intervention for 12 hrs and 50 minutes the same as that of the traditional instruction.

Some teaching approaches were used in teaching introductory nuclear physics in previous studies. A laboratory model activity was used focusing on eliminating the students' misconceptions of radioactive substances, radioactive decay, and half-life (Yeşiloğlu, 2019). This was effective as compared to traditional instruction. The "effect of the cooperative learning approach on high school physics students' understanding of the concept of radioactivity" was investigated (Doris & Ndu, 2018, p.36). The findings showed that the cooperative learning strategy was more effective than traditional instruction. Shakya (2015) used guided-inquiry-based instruction to test its effect on gaining knowledge of weak and strong nuclear forces. The findings of the study showed that this instruction was not effective when compared to traditional instruction. Yumuşak, Maraş, and Şahin (2015) examined the "effects of computer-assisted instruction with conceptual change texts in removing the misconceptions of radioactivity" (p.23). Their findings indicated that this instruction was more effective than traditional instruction. These are the instructional strategies used in previous studies to address the students' conceptual difficulties of introductory nuclear physics. A new instructional strategy, which was not used by previous researchers to address the students' conceptual difficulties of introductory nuclear physics, was selected based on the review of related literature.

The new instructional strategy that was selected for this study to enhance the second group of students' different ways of understanding and representations is multiple representations (MR's) based instruction with interactive learning tutorials. It was developed, designed, and implemented in the second phase based on the results found in the first phase and second phase at pre-intervention. In the third phase, the efficacy of this instruction in reducing the students' conceptual difficulties was explored. MRs are useful to visualise and think about the invisible entities at the atomic nuclear level such as the concepts of nuclear binding energy and nuclear force. Aristotle said that thought is impossible without an image (as cited in Stokes, 2002, p.10). The MRs includes simulation, which is an important part of the technology used in teaching physics. According to Holubova (2008), the teaching of physics using technology focus on supporting students to understand the concepts of physics such as that of nuclear physics.

In previous studies, very limited qualitative research approaches were used to explore and enhance the students' different ways of conceptual understanding and representations of nuclear physics. Kohnle (2011) and Rathore (2016)recommended conducting student interviews to gain more insight into students' thinking of nuclear physics. So, an exploratory case study research design underpinned by the conceptual frameworks of developmental phenomenography and variation theory of learning was used in this study. These conceptual frameworks were not used in previous studies to reveal and enhance the students' different ways of understanding and representations of introductory nuclear physics concepts (Doris & Ndu, 2018; Kohnle et al., 2011; Rathore, 2016; Shakya, 2015;

Yeşiloğlu, 2019; Yumuşak, Maraş,&Şahin, 2015). Phenomenographic, semi-structured, face-to-face individual interviews and an open-ended questionnaire were used to collect data.

Developmental phenomenography is a type of qualitative research approach used to reveal the students' different ways of understanding and representations in the first phase, the second phase at pre-, the third phase at post-, and delayed post-intervention. The students' different ways of understanding and representations are represented by categories of description, which are the outcomes of the phenomenographic analysis process. The developmental phenomenographic research approach is used to produce research outcomes that can be subsequently used to address learning or conceptual difficulties (Bowden & Walsh, 2000; Green & Bowden, 2009). The categories of description constructed in the first phase and the second phase at pre-intervention provided a basis to identify the students' conceptual difficulties before intervention. These conceptual difficulties are educational issues that were addressed in the second phase using the new instructional strategy.

The variation theory of learning (VTL) was used as the potential source of information to develop and design the new instructional strategy. In other words, it was used to identify and organise the necessary conditions of learning to develop and design the new instructional strategy in the second phase (Wright & Osman, 2018). According to VTL, critical aspects are the necessary conditions of learning (see Section 2.8). VTL was used to analyse the learning process and its outcomes based on the critical and irrelevant aspects discerned by students after traditional and new instructions. These two aspects were identified based on the categories of description using the VTL as a lens. In the context of this study, the set of critical aspects is regarded as the correct alternative ways of understanding a nuclear physics concept, while the set of irrelevant aspects is regarded as the incorrect alternative ways of understanding a nuclear physics concept. This is adapted from Pang and Ki (2016). From this point of view, the irrelevant aspects can involve misunderstandings, misconceptions, confusion, and learning difficulties, which are not the targeted way of understanding. According to VTL, those students who discerned various critical aspects are said to be learned effectively (Marton & Pang, 2006). Phenomenography and VTL also provided an alternative pedagogical framework that is characterised as the pedagogy of learning (Ference Marton & Tsui, 2004). The instruction designed within this pedagogical framework is considered as phenomenographic instruction (Wright & Osman, 2018). Thus, the new instruction used in this study is phenomenographic instruction, because it was designed based on the VTL. This instruction supported the students to discern more critical aspects of a nuclear physics concept and then to understand it.

The findings of this study indicate that the students discerned a limited number of critical and irrelevant aspects of each of the five concepts of nuclear physics. The categories of description constructed using the phenomenographic analysis process formed the basis to identify these aspects. The categories of description were constructed in the first phase, in the second phase at pre-intervention, in the third phase at post- and delayed post-intervention. The conceptual difficulties identified in the first phase (Chapter 4) of this study support those identified in previous studies (see Section 2.5.2). The irrelevant aspects involve conceptual difficulties. The results found at pre-intervention were used as a baseline in the third phase and were compared to the results found at post- and delayed post-intervention to explore the efficacy of the new instruction. The results found in the third phase (see Chapter 6) show that the new instructional strategy was effective in reducing the irrelevant aspects and supporting students to discern more critical aspects or it was effective in reducing the number of students discerning the irrelevant aspects. In other words, it was effective in addressing the students' conceptual difficulties. The MR's-based instruction with interactive learning tutorials, which is the new instructional strategy, was not considered and used by previous nuclear physics education researchers (see Section 2.5.3). The findings of this study will have implications in developing curriculum, classroom instructions, and transforming higher education.

1.2 THE CONTEXT OF THE STUDY

The nuclear physics school background of Ethiopian university students is almost the same. In the Ethiopian context, before the students join a university, they did not learn nuclear physics in schools like mechanics, electromagnetism, optics, and thermodynamics. However, some concepts of introductory nuclear physics are included in the introduction to atomic physics, which is the topic of the last chapter of the Grade twelve physics textbook. All Ethiopian Grade twelve students use the same physics textbook. The middle and low achiever students were assigned to the physics departments of Ethiopian governmental universities. Top natural science students have been assigned to medicine and engineering.

In the Ethiopian context, an introductory nuclear physics course has been included in higher education. Mainly, it deals with nuclear properties, nuclear structure, nuclear stability, nuclear binding energy, nuclear force, nuclear decay, nuclear radiations, nuclear reactions, nuclear energy, an introduction to elementary particles, and applications of nuclear physics. Taking this course is compulsory for second-year undergraduate physics major students. Ethiopia had one nationally developed undergraduate physics curriculum referred to as knowledge-based and used in all universities of Ethiopia in the same way from 2009 till 2013. This curriculum is referred to as an Ethiopian national harmonised curriculum for the Degree of Bachelor of Science in Physics (EMOE, 2013). This physics curriculum involves compulsory, elective, service, supportive, and general education courses.

By its nature, a curriculum is dynamic. Producing competent physics graduates is the intention of many universities around the world and Ethiopian universities are not an exception. In this light, the new Ethiopian National Modular Curriculum for the Degree of Bachelor of Science in Physics was developed based on competency (EMOE, 2013). A modular curriculum means a curriculum designed in such a way that similar courses are set together based on competency. For instance, the nuclear physics module consists of nuclear physics and experimental nuclear physics courses. This curriculum was developed to address the observed limitations in the previous curriculum. That is, the structure of the curriculum changed from knowledge-based to competency-based. This presents an opportunity for the individual universities to improve 20% of the curriculum. In this study, the data was collected when the competence-based curriculum was in operation.

This study focused on undergraduate introductory nuclear physics. The mode of course delivery is the same throughout the universities in Ethiopia since all of them use the same physics curriculum. The title of the introductory nuclear physics in the physics curriculum of Ethiopian higher education is nuclear physics I. Its course code is Phys.2051. The advanced nuclear physics is titled nuclear physics II. The introductory nuclear physics (Phys.2051) is compulsory and a semester-based course. Its credit hours are three and when these credit hours are converted into EtCTS it becomes five. The acronym EtCTS means the Ethiopian credit transfer and accumulation system (EMOE, 2013). This is not to be confused with ECTS which means the European Credit Transfer and Accumulation System (Adam, 2001).

In the Ethiopian context, one academic semester has 16 weeks. There are five chapters in the introductory nuclear physics. A total of 45 lecture hours and 15 tutorial hours are assigned for the five chapters. An additional 75 hours are assigned to the students to do homework at their homes. The course is delivered to the students through lectures, group discussions, assignments, tutorials, and e-learning resources (EMOE, 2013). The outline of the course is presented in the following table (see Table 1.1).

Table 1.1: The course outline of nuclear physics I

Chapter number	**The topic of a chapter**	**Lecture (hours)**	**Tutor (hours)**	**Home (hours)**	**Total load(hours)**
1	Structure and Static Properties of Nuclei	9	3	15	27
2	Nuclear Decay and Radioactivity	9	3	15	27
3	Nuclear Reactions	9	3	15	27
4	Elementary Particles	6	2	10	18
5	Applications of nuclear physics	12	4	20	36
	Total	45	15	75	135

The concepts of nuclear physics to be studied were selected from the content of this course based on literature review, the researcher’s teaching experiences, and observations.

1.3 STATEMENT OF THE RESEARCH PROBLEM

The repeated generation of information about the threat of nuclear weapons for the world population through mass media could cause the students to consider nuclear physics as if applied only for destructive purposes, and this may affect their interest in learning nuclear physics. Historically, nuclear accidents occurred in developed countries. However, it is not a critical issue for developing countries such as Ethiopia to research the students' beliefs about these nuclear issues. Hence, this nuclear physics research area was not considered in this study.

The second research area, which is the focus of physics education researchers, was to identify the conceptual difficulties that the students encounter in understanding and representing the basic concepts of nuclear physics (Kohnle et al., 2011). In the context of this study, conceptual difficulties denote misconception, confusion, and conceptual learning difficulties of nuclear physics (Kola, 2017). The students' conceptual difficulties with the concepts of nuclear dimensions, nuclear binding energy, the strong nuclear force, weak nuclear force, radioactivity, radioactive decay, a half-life, beta decay, and nuclear fission reaction were identified in previous studies (Burge, 1967; Doris & Ndu, 2018; Kohnle et al., 2011; Rathore, 2016; Shakya, 2015; Yumuşak et al., 2015). The concepts of nuclear binding energy, nuclear force, radioactive decay, negative beta decay, and nuclear energy were selected from these concepts to be studied based on the review of literature, the researcher's teaching experiences, and observations. These are basic concepts are interrelated and used to explain other issues in nuclear physics courses (Basdevant et al., 2005; Heyde, 2004; Makhmudov & Saytjanov, 2020). In previous studies, the different ways of students' understanding and representations of these concepts were not explored and enhanced using the phenomenographic research approach. Kohnle (2011) and Rathore (2016) recommended conducting student interviews to gain more insight into students' thinking of nuclear physics. Therefore, the phenomenographic research approach was selected based on this recommendation and the purpose of this study.

The third research area of physics education is to identify and develop appropriate instructional strategies that can develop students' conceptual understanding and representations of physics or that can address the students' conceptual difficulties. Findings in the literature showed that teaching an introductory nuclear physics course using traditional instruction and teaching materials was not effective (Hartini & Liliasari, 2020). The knowledge of students taught using traditional instruction was only limited to the knowledge contained in the written teaching materials. Different instructional strategies were used in previous studies to address the students' conceptual difficulties of nuclear physics rather than traditional instruction. These are the inquiry-based instruction, computer-assisted instruction with conceptual change text, cooperative learning method, and laboratory activity model that were used to address the students' conceptual difficulties of introductory nuclear physics (Yeşiloğlu, 2019; Doris & Ndu, 2018; Shakya, 2015; Yumuşak et al., 2015). Except for the inquiry-based instruction, the others were more effective in addressing the conceptual difficulties of nuclear physics compared to traditional instruction.

An alternative instructional strategy was identified and developed based on the VTL in the second phase of this study. This instruction was implemented on the second group of students to develop their different ways of conceptual understanding and representations. In other words, the focus of the intervention was to address the conceptual difficulties identified in the first phase and the second phase at pre-intervention. At pre-intervention, the second group of students' different ways of prior understanding and representations of concepts of nuclear physics was explored and categorised. The instructional intervention was developed and designed based on the results found in the first phase and at pre-intervention. The instructional intervention selected and developed for this study was the multiple representations (MR's) based instruction with interactive nuclear physics learning tutorial. The learning environment could be different forms of representation, which can motivate the students and increase their possibilities for learning and understanding complex nuclear physics concepts (Rutten et al., 2012). An interactive learning environment increases the possibilities for learning and understanding the concepts (Mork, 2011).

Based on the above discussions three main research problems were identified. First, the research problem related to the school students' beliefs about radioactivity, nuclear radiation, and nuclear energy was identified. This was not considered and addressed in this study. Second, the research problems related to the students' conceptual difficulties of introductory nuclear physics were identified. Third, the research problem related to identifying, developing, designing, and implementing appropriate instruction to address conceptual difficulties. The second and third research problems were considered and addressed in this study.

1.4 THE RATIONALE FOR THE STUDY

In this section, the reasons for conducting this study are discussed in detail. Understanding the basic and important concepts of nuclear physics can help students to understand and explain a vast range of physics concepts and phenomena (Wieman & Perkins, 2005). For example, Makhmudov and Saytjanov (2020) concluded that consideration of the basic concepts of nuclear physics such as that of nuclear binding energy (NBE) used to explain many of the main issues studied in a course on nuclear physics. NBE is one of the basic and important concepts selected and studied in this study. Furthermore, if students have understood such basic and important concepts correctly, students can solve various problems in physics, nature, and life by applying these concepts (Putranta & Supahar, 2019). For instance, the concept of negative beta decay is applied in carbon dating and that of nuclear energy is applied in generating electricity. Carbon dating is used to determine the age of a sample of the material in archaeology.

However, students encounter difficulties in understanding and representing such types of basic and important nuclear physics concepts. In general, findings released in the literature showed that students encounter difficulties in learning and understanding the basic concepts of physics rather than the manipulation of equations (Trowbridge & McDermott, 1980). That is, developing conceptual understanding and a qualitative way of thinking are more challenging for physics students than dealing with equation manipulations (Singh et al., 2006). In other words, students can solve physics problems by memorising the equations and simply substituting the numerical values without understanding the concept. However, an equation is a tool that represents a concept and supports the students to understand that concept. The reviewing of such related literature, his long teaching experiences, and what he had been observing in different activities of his students, the researcher was motivated to conduct this study. The five concepts studied in this study were also selected from the contents of the introductory nuclear physics course (see Section 1.2) that the researcher had been teaching it for a long time.

The other reason is that most of the findings released in the literature related to nuclear physics focused on school students' beliefs about radioactivity, nuclear radiation, and nuclear energy (Cooper, Yeo, Zadnik, 2003; Maharaj-Sharma, 2011; Millar et al., 1990; Neumann & Hopf, 2012; Rego & Peralta, 2006). For instance, on students' beliefs, the Australian students were frightened and unsure of what to do with radioactivity, nuclear radiation, and nuclear energy production (Cooper et al., 2003). The reason may be the potential for nuclear harm like the nuclear fallout that occurred at Fukushima in Japan or Chernobyl in Russia. The school students considered these nuclear issues as harmful events. Cooper, Yeo, and Zanik, 2003 also suggested that the students obtained this information through communication with their families, friends, the internet, or mass media. The students' beliefs about radioactivity, nuclear radiation, and nuclear energy were not the concern of this study.

Therefore, the researcher decided to explore and develop the undergraduate physics students' different ways of understanding, qualitative ways of thinking, and representations of the introductory nuclear physics concepts. Findings released in the literature indicated that physics students also encounter conceptual difficulties in developing their conceptual understanding and representations of introductory nuclear physics (see Section 2.5.1). The focused exploration of students' conceptual understanding and representations could provide ways to develop appropriate teaching approaches that could address the students' conceptual difficulties (Entwistle, 1997). To achieve this, the researcher selected and used the conceptual frameworks of phenomenography and VTL (see Section 1.1). These conceptual frameworks were appropriate to reveal and address the conceptual difficulties that the students encounter in understanding and representing the basic concepts of physics. Revealing and addressing such difficulties using developmental phenomenographic research approach and VTL was not addressed by previous nuclear physics education researchers (Doris & Ndu, 2018; Kohnle et al., 2011; Rathore, 2016; Shakya, 2015; Yumuşak et al., 2015).

1.5 THE RESEARCH OBJECTIVE

The principal objective of this study is:

To identify and develop the different ways undergraduate physics major students' understand and represent the five introductory nuclear physics concepts, NBE, nuclear force, radioactive decay, negative beta decay, and nuclear energy.

The particular objectives of this developmental phenomenographic study are:

1. To identify the different ways undergraduate physics major students' understand and represent the five concepts in Phase 1 after traditional instruction, Phase 2 at pre-intervention, and Phase 3 at post- and delayed post-intervention
2. To develop and design the MRs-based instruction with interactive learning tutorials using the results found in Phase 1 after traditional instruction and Phase 2 at pre-intervention as a basis
3. To explore the efficacy of MRs-based instruction with interactive learning tutorials in enhancing the different ways undergraduate physics major students understand and represent the five concepts at post- and delayed post-intervention.

The first group of undergraduate physics students was exposed to traditional instruction in the first phase. The second group of students was exposed to the MRs-based instruction with interactive nuclear physics learning tutorials in the second phase, which was used as an intervention.

1.6 RESEARCH QUESTIONS

The main research question of this study is:

What are the different ways undergraduate physics major students' understand and represent the five introductory nuclear physics concepts, NBE, nuclear force, radioactive decay, negative beta decay, and nuclear energy?

The sub-research questions of this developmental phenomenographic study that guided the research process are:

1. What are the different ways undergraduate physics major students' understand and represent the five concepts in Phase 1 after traditional instruction, Phase 2 at pre-intervention, and Phase 3 at post- and delayed post-intervention?

2. How the MRs-based instruction with interactive learning tutorials is developed and designed using the results found in the first phase after traditional intervention and the second phase at pre-intervention as a basis?
3. What is the efficacy of the MRs-based instruction with interactive learning tutorials in enhancing the different ways undergraduate physics major students understand and represent the five introductory nuclear physics concepts at post- and delayed post-intervention?

The different ways of undergraduate physics major students' understanding and representations of the five concepts were explored in the first phase after traditional instruction, in the second phase at pre-intervention, and the third phase at post- and delayed post-intervention. The intervention was developed and designed in the second phase using the results in Phase 1 and at pre-intervention as a basis. Its efficacy in enhancing the different ways of students' understanding and representations was explored in the third phase.

1.7 THE SIGNIFICANCE OF THIS STUDY

Physics education researchers can benefit from the results of this research as most of the previous findings focused on school students' beliefs in radioactivity, nuclear radiations, and nuclear energy (Cooper et al., 2003; Maharaj-Sharma, 2011; Millar et al., 1990; Neumann & Hopf, 2012; Rego & Peralta, 2006). The findings of this study are different as they focused on the students' various ways of understanding and representing introductory nuclear physics concepts, which could reveal the students' conceptual difficulties. Again, this could lead to the development of a specific instructional intervention that addressed the conceptual difficulties. In the second phase of this study, MRs-based instruction with interactive learning tutorials was developed, designed, and implemented based on the conceptual difficulties identified in the first phase. It addressed the students' conceptual difficulties. Developing instructional strategy in such a way plays a great role in enhancing the students' scientific conceptual understanding and representations of physics in a broad sense. Curriculum developers and classroom instructors can benefit from this finding. The students can also benefit from this phenomenographic teaching strategy since it can engage them in interactive learning of a disciplinary concept. In the future, physics education researchers can use the findings of this study as a benchmark.

1.8 THE LIMITATIONS OF THIS STUDY

Three main limitations influenced the journey of this PhD study.

Firstly, the serious and continuous security environment in the country interrupted the teaching-learning process and caused the students to feel insecure. Particularly, this affected the two data collection sessions. Interviewing the students who were unstable because of the security problems according to the interview schedule was challenging. The interruption of the teaching-learning process also affected the students' conceptual learning and understanding capacity as well as the accomplishment of the study according to its work plan.

Secondly, in the context of the country, the majority of the students are not assigned to the physics department based on their interests. This affected the students' conceptual learning interest and capacity. It was challenging to get in-depth qualitative conceptual information from such students through interviews and open-end questionnaires.

Thirdly, it is not possible to generalise the findings due to the small sample size. However, because of the nature of the collected qualitative data, it is possible to obtain in-depth information about the undergraduate physics students' conceptual difficulties and critical aspects of a nuclear physics concept.

Finally, no scholar has used the phenomenographic research paradigm in the researcher's home university, or in the nearby universities to share ideas and experiences.

1.9 DEFINITION OF KEYWORDS/TERMS

This part outlines the keywords/terms relevant to this study.

Categories of description: They are the patterns of variation in students' understanding of a nuclear physics concept (Marton & Booth, 1997). In other words, they are the categories that represent the variation in ways of students' understanding of a nuclear physics concept.

A concept: In this study, a concept is regarded as the mental picture of the nuclear entity, phenomenon, event, and process formed by combining their critical aspects (Concise Oxford Dictionary, 2020). For instance, the mental pictures of the introductory nuclear concepts of NBE, force, and decay were considered.

Conceptual difficulty: When students encounter misconceptions, confusion, and learning difficulties (Kola, 2017).

Conceptual Understanding: Thi**s** is the ability of students to construct a verbal and /or visual mental representation of nuclear physics concepts in different ways (Adadan, 2013).

Critical aspects: They are the various aspects of an object of learning, what the students should learn and understand (Ling Lo, 2012). According to Pang and Ki, 2016, they are the focused aspects highlighted in the teaching-learning process.

Critical features: They are the values of the dimension of various aspects of an object of learning, what the students learn and understand(Ling Lo, 2012). An *example of critical aspects and features of an object of learning:* Ling Lo (2012) considered a dog as an instance of the object of learning. Some of us may discern its critical aspects such as size, colour, and pedigree at the same time. We can discern its critical features such as big, brown, and Alsatian. The dimensions of variation are the size, colour, and pedigree of a dog. The values of the dimensions of variation are big, brown, and Alsatian.

Intervention: It is an instructional intervention used in the second phase to address the students' conceptual difficulties of nuclear physics identified in the first phase of this study.

Irrelevant aspects of an object of learning: According to Pang and Ki, (2016), irrelevant aspects are unfocussed aspects of an object of earning. The irrelevant aspects involve misconceptions or conceptual difficulties.

Multiple Representations-based instructions: It refers to the situation where various representations are used for learning a concept instead of, for instance, using only text, equations, or visual representations (Savinainen et al., 2013). This instruction supports learners to perform interactive learning activities in tutorial sessions using different forms of representations.

Nuclear physics: In the context of this study, this is one of the undergraduate introductory physics courses delivered to Ethiopian second-year physics major students.

Outcome space: Outcome space represents the *possible ways* of students' understanding and representations of a nuclear physics concept (G. S. Åkerlind, 2005). In another way, it is the set of categories of description arranged in a hierarchy from a less to more complicated conceptual understanding.

Phenomenography: It is a qualitative research approach aimed at identifying and describing the different ways of students' understanding and representations of an introductory nuclear physics concept (Wright & Osman, 2018).

Physics students: They are undergraduate second-year physics major students who take the introductory nuclear physics course and are the research participants of this study.

Representations: They depict a nuclear entity, phenomenon, event, process, and transformations (Gilbert, 2010). The depiction can be diagrams, images, pictures, graphs, concept maps, models, simulations, animations, and equations.

The object of learning: The object of learning refers to what the students need to learn and understand to achieve the desired learning objectives(Ling Lo, 2012). A nuclear physics concept is an object of learning considered in this study.

VTL: It is a theory used to identify and organise the necessary conditions for learning a nuclear physics concept (Wright & Osman, 2018). These necessary conditions for learning and understanding are the students' capability to distinguish various critical aspects of a nuclear physics concept (Ling Lo, 2012; Marton & Tsui, 2004; Park et al., 2009).

1.10 CONTRIBUTION OF THE STUDY TO KNOWLEDGE

This study presents how the developmental phenomenographic research approach in combination with the VTL can be used to reveal and address the key challenges that students encounter in developing their conceptual understanding of physics concepts. The different ways of students' conceptual understanding and representations of physics concepts that can be revealed using developmental phenomenographic method can inform appropriate instructional design. In this study, the MR's teaching approach was identified using this methodology and its effectiveness was tested in the classroom. Therefore, physics teachers can use the MRs-based interactive learning activities that were designed in this study to develop the conceptual understanding and representations of their students. The critical and irrelevant aspects of each of the five basic and important concepts of nuclear physics were identified and presented using the VTL. Nuclear physics teachers can use this information to design classroom instruction. The findings of this study could result in an awareness of the scientific research community that the instruction developed and designed based on the VTL can enhance the conceptual understanding and representations of physics students.

1.11 THESIS OVERVIEW

In this section an overview of the remaining chapters is provided:

- A review of related literature is accessible in Chapter 2. A review of literature is the foundation of any study.
- The research methodology is explained in Chapter 3. That is, the relevant research paradigm, the research approach, the research design, and the research methods are discussed in Chapter 3
- The first group of students' conceptual difficulties identified in the first phase after they were exposed to traditional instruction presented in chapter 4
- The second group of students' prior understanding and representations of introductory nuclear physics concepts are explored at pre-intervention in the second phase in Chapter 5. The instructional intervention was developed, designed, and implemented in the second phase based on the results found in the first phase and at pre-intervention.
- In the third phase, the effectiveness of the instructional intervention in addressing the students' conceptual difficulties is explored in Chapter 6.

- The conclusion, implications, and recommendations are discussed in Chapter 7. In general, this study has been organised into three interrelated phases that are in alignment with the three research questions.

1.12 CHAPTER SUMMARY

In this chapter, the background, context, research problem, and rationale of this study were explained. The research problem was identified and defined based on a review of related literature. In any research process, the first and most important step is to identify and then appropriately define a research problem (Kothari, 1985). The rationale of the study justifies the importance of the study. The research objectives and questions used as the compass of the research process formulated based on the defined research problem. The researcher explained the significance of this study and presented the definitions of keywords/terms in this chapter. These are useful to reference before reading and understanding the remaining chapters of this thesis. Finally, the limitation and contributions of this study and the thesis overview were explained. In the next chapter, a review of related literature is presented.

CHAPTER 2: REVIEW OF RELATED LITERATURE

2.1 INTRODUCTION

The literature focused on students' conceptual difficulties of nuclear physics, implemented teaching approaches to address the conceptual difficulties, the research methodologies, and the conceptual and pedagogical frameworks. The origin and development of nuclear physics are explained at the beginning of this literature review (Section 2.2). A short overview of the development of physics education research is also discussed (Section 2.3). The challenges that physics students encounter in acquiring conceptual understanding and representations of physics concepts, in general, are discussed (see Section 2.4). However, this study deals with nuclear physics, which is discussed in detail (Section 2.5.2). The nuclear physics concepts selected for this study were defined and explained based on literature (Section 2.5.1). Some teaching strategies previously used in teaching nuclear physics to address students' conceptual difficulties are also discussed (Sections 2.5.3). The type and importance of the instructional intervention used in this study are discussed (Section 2.6). Phenomenography, developmental phenomenography, and VTL are also discussed in this chapter in detail. Finally, the conceptual frameworks of this study are discussed (Section 2.10). The review of related literature played a crucial role in illustrating the research gap and justifying the research methodology of this study for readers.

2.2 ORIGIN AND DEVELOPMENT OF NUCLEAR PHYSICS

The origin and development of nuclear physics started with the discovery of radioactivity in 1896 by the French physicist Henri Becquerel. Based on his experiment Becquerel reported the discovery of a radioactive nucleus of a Uranium atom. Marie and Pierre Curie also reported the discovery of other more powerfully radioactive nuclei such as radium and polonium in 1898. Radioactivity is a natural nuclear phenomenon in which nuclear radiation is emitted from the core of a radioactive atom. This nuclear phenomenon attracted the attention of scientists to probe the core of an atom. Rutherford was the first scientist who discovered the core of an atom by using the alpha scattering experiment in 1911. He called the core of an atom a nucleus. The discovery of a nucleus of an atom confirmed the establishment of nuclear physics as a subject (Basdevant, Rich, & Spiro, 2005; Krane, 1988; Martin, 2009; Serway, Moses, and Moyer, 2005).

The Becquerel, Curies, Rutherford, and many others, took the observation of radioactivity and constructed the basic ideas that are the subject of nuclear physics. The origin and development of nuclear physics started from the discoveries of these talented scientists. The discovery of radioactivity and the foundation of nuclear physics contribute to the growth of modern physics in the early twentieth century (Basdevant et al.,2005). Deuterium, positrons, and neutrons were identified in 1932. Nuclear fission was discovered in 1938. Liquid-drop, shell, and collective models of the nuclear structure were proposed in 1935, 1949, and 1953 respectively. Moreover, the quark model of hadrons was proposed in 1964 (Krane, 1988). Recently, radiation physics, medical physics, and particle physics developed from nuclear physics. All of these show the development of nuclear physics. Nowadays, nuclear physics is one of the essential study fields in physics.

Nuclear physics is dedicated to studying matter at its most fundamental level (Krane, 1988). The nucleus is the bound state of nucleons. The positively charged protons in the nucleus repel each other and this coulomb repulsive force can cause the nucleons to fly apart. However, the presence of the short-range strong attractive nuclear force counteracts the Coulomb repulsive force among protons (Serway et al., 2005). These scholars said that the nuclear force among nucleons is stronger than the Coulomb force at short range. This maintains the stability of a nucleus, which also plays a prominent role in the stability of an atom. The nucleus of an atom is either stable or unstable based on the domination of the Coulomb repulsive and strong nuclear attractive forces on each other. Radioactivity occurs when the Coulomb repulsive force is more dominant than the strong nuclear attractive force at long range. In this case, the atomic nucleus is said to be unstable.

All physical bodies in our surroundings are composed of atoms (Burcham et al., 1995; Martin, 2009). The nucleus of an atom and its orbital electrons are bound together by an electromagnetic force to form a stable atom. Nucleons are bound together by the attractive nuclear force to form a stable nucleus. Based on this, (Lilley, 2009) stated that a nucleus is the origin of the materials in the world. In more detail, nuclear scattering experiments showed that both proton and neutron are the bound states of the three-point-like charged fundamental particles known as quarks (Paul, 1971). The three point-like charged quarks are bound together by another more basic strong force. The nuclear force is purported to be the consequence of the more fundamental strong force that binds quarks together to form a nucleon (Serway et al., 2005). Possibly, the students confuse the strong nuclear force with this stronger force. Scientists concluded that quarks are the most fundamental particles rather than nucleons in the structure of matter (Krane, 1988; Serway et al., 2005).

Nuclear physics has very useful ubiquitous applications. However, the general population thinks that nuclear physics is applied only in nuclear weapons such as nuclear bombs for destructive purposes. This is a misconception, which is the effect of repeated generation of information about nuclear weapons through mass media around the world (S. Cooper et al., 2003). Some of the useful applications of nuclear physics are generating electricity; seeing inside the body using imaging techniques such as PET and MRI; cancer treatment; dating organic samples using carbon dating; radioactive tracing to track chemicals; food preservation; and identifying elements in a sample of material among many other applications (Martin, 2009; Serway et al., 2005).

The basic concepts of introductory nuclear physics included in this study are the concepts of NBE, nuclear force, radioactive decay, negative beta decay, and nuclear energy. These concepts are defined and explained in Section 2.5.1. Some of these concepts of introductory nuclear physics are applied in technologies mentioned in the previous paragraph. One can use these concepts in understanding advanced nuclear physics and related courses such as radiation physics or medical physics.

2.3 DEVELOPMENT OF PHYSICS EDUCATION RESEARCH

There has been a growing realisation that physics students are not effectively learning and understanding the concepts that they are taught (Bao & Koenig, 2019; McBride et al., 2010; Thornton, 2010). For this reason, a new discipline - physics education research (PER)- arose in the 1970s (Cummings, 2011). From the insight of scholars (Aalst, 2000; Thornton, 2010), it is possible to understand that the origin and development of PER were the problems that appear in the teaching-learning process of physics. These are learning difficulties, misconceptions, and ineffective teaching strategies topics of physics. Physics education researchers intended to identify the learning difficulties and misconceptions that the students encounter when learning physics and to explore the different teaching strategies that could result in effective learning.

Today, PER is acceptable and respected in many countries around the world, including the researcher's home country, Ethiopia. What makes PER different from traditional education research is that PER emphasises students' formal learning and conceptual difficulties of physics, while traditional teaching places more emphasis on learning theories or teaching methods(Lillian Christie McDermott, 2001).

2.4 IMPACT OF PHYSICS EDUCATION RESEARCH ON STUDENTS' CONCEPTUAL UNDERSTANDING OF PHYSICS

Supporting learners to understand the basic and important concepts is one of the main targets of physics studies in schools, colleges, and universities of many countries around the world (Chaimala, 2009). According to Putranta and Supahar, (2019), conceptual understanding should be the main focus of teachers and students in the physics teaching-learning process. Developing the skills of mathematical manipulation of physics equations without the conceptual understanding of physics is meaningless. Discerning the critical aspects of a concept taught in the conceptual learning process can lead to a complete conceptual understanding of physics (Driver et al., 1994). Using mathematical equations and other forms of representations support students to discern various critical aspects of a concept. In another way, conceptual understanding is viewed as the outcome of the process of conceptual change (Aufschnaiter, 2003). Developing a conceptual understanding of physics in such a way is the difficulty that physics students encounter as shown in previous physics education studies (Mazur, 2008; Kim & Pak, 2002; Singh et al., 2006). According to these researchers, compared to that of mathematical manipulations, developing students' understanding of basic concepts and written explanations is more difficult for physics students.

Previous researchers said that developing the students' conceptual understanding of physics is one of the greatest challenges that students face in learning physics

(Mcdermott, 2001; Engelhardt & Beichner, 2004; Bilal & Erol, 2012). Until now, physics education researchers have been exploring students' conceptual understanding of physics in dedication. For example, several studies were undertaken in mechanics (Beichner, 1994; Clark et al., 2011; Coletta et al., 2007; Hake, 1998; Hestenes et al., 1992). Studies were undertaken in electricity and magnetism (Dega, 2012; Ding et al., 2006; Maloney et al., 2001; Stocklmayer, 2010; Thong & Gunstone, 2008; Zavala & Alarcon, 2008). Studies were undertaken in quantum mechanics (Ejigu, 2014; Krijtenburg-Lewerissa et al., 2017; McKagan et al., 2008; Özcan et al., 2009; Wuttiprom et al., 2009). However, limited research has been conducted on students' conceptual understanding of nuclear physics (see Section 2.5). In general, research has played a role in identifying the students' conceptual difficulties and in addressing them by using relevant teaching strategies.

According to this study, conceptual difficulties mean misconceptions and confusion. Alternative conceptions are regarded as the students' descriptions that are accepted by the scientific community of practice but misconceptions are regarded as the students' descriptions that are not accepted (Motlhabane, 2016). The scientific community of practice means the community that does the scientific investigation of something in an organised way repeatedly following the methods and principles of science for a better understanding of that thing (Online Merriam-Webster Dictionary, 2019). From the perspectives of the VTL, the notion of critical aspects and irrelevant aspects are used instead of alternative conceptions and misconceptions respectively in this study (see Section 2.8.2).

2.5 IMPACT OF PHYSICS EDUCATION RESEARCH ON STUDENTS' CONCEPTUAL UNDERSTANDING OF NUCLEAR PHYSICS

The findings of PER supported the researcher to identify the conceptual difficulties of introductory nuclear physics concepts that the students encountered. For example, in Turkey, the undergraduate chemistry students' understanding of the concepts of radioactive elements, nuclear decay law, and half-life was investigated (Yeşiloğlu, 2019). These concepts were chosen from the content of the physical chemistry laboratory course. A qualitative research approach (modelling a constant comparative method) was used to investigate their conceptual understanding. Open-ended questions, students' drawings, interviews, and observation notes were used to obtain the necessary information. The results of the analysis are discussed in Sections 2.5.2 and 2.5.1.

In Spain, "the misconceptions, knowledge, and attitudes of secondary school students towards the phenomenon of radioactivity" were investigated (Morales & Tuzón, 2020, p.1). Sample (N = 191) of students and (N = 29) of trainee teachers participated in this study. A questionnaire with close-ended and open-ended questions was used to collect data. The collected data was analysed using a software program R and the hierarchical clustering technique. The results found by Morales and Tuzón (2020) supported most of the misconceptions that were reported in the scientific literature, which are discussed in Section 2.5.2. The results also provided an effective new teaching strategy that can remove the reported misconceptions.

In India, Rathore (2016, p.7) conducted a study on "Surveying students' misconceptions and understanding in nuclear physics". Undergraduate and postgraduate students (N = 101) from five different institutions took part in the study. The common concepts in nuclear physics at undergraduate and postgraduate levels were selected to develop a nuclear physics conceptual survey for both levels. The purpose of Rathore's study was to assess the students' misconceptions and scientific conceptual understanding of nuclear physics. He used a survey research design to conduct his study. The conceptual multiple-choice questions developed by this researcher on the concepts of NBE, radioactivity, decay law, half-life, nuclear force, and nuclear dimensions were used in the survey. Finally, Rakash recommended conducting student interviews to gain greater insight into students thinking.

In the UK, Kohnle et al. (2011) developed a conceptual diagnostic survey in nuclear physics covering the concept areas of radioactive decay, NBE, properties of the nuclear force, and nuclear reactions. The survey was administered to undergraduate students at two institutions. In the first institution, 49 students were selected and 39 students at the other, in a quasi-experimental design. The pre-test was provided to the students in the two institutions in a free-text entry format. The responses of the students were used to develop a multiple-choice version that was provided as a post-test. The collected data was analysed using statistical tests such as descriptive statistics and a t-test. Finally, “the researcher recommended conducting student interviews to gain more insight into students thinking”(Kohnle et al., 2011, p.61).

In South Africa, school student misconceptions concerning the atomic nucleus were investigated (Pillay & Loonat, 1993). These researchers used a survey research design. The students’ conceptual understanding was examined using written responses to the questionnaire. The findings of the study indicated that the students encountered difficulty in understanding the expression ($n \rightarrow p + e^{-}$), understanding the constituents of a nucleus; understanding the origin of the electron emitted in the reaction ${}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + e^{-}$, and understanding whether the reaction ${}^{1}_{1}H + {}^{7}_{3}Li \rightarrow 2\,{}^{4}_{2}He$ was chemical or nuclear. For example, some students said that the emitted electron came from the thorium nucleus and others said that the electron could arise from the atomic orbital.

As mentioned in the abstract, Sections 1.1 and 1.4, the researcher chose five basic concepts of introductory nuclear physics based on a review of related literature. The reason is that students commonly encounter conceptual difficulties in learning and understanding these five concepts. These concepts are NBE, nuclear force, radioactive decay, negative beta decay, and nuclear energy. Before discussing the conceptual difficulties, the five concepts are defined based on physics reference books in the next section.

2.5.1 Definitions of the Five Basic Concepts of Nuclear Physics

The scientific definitions of the five concepts are presented in the next subsections. They are defined based on physics reference books (Martin, 2009; Basdevant et al., 2005; Serway et al., 2005; Krane, 1988; Beiser, 1963). Krane’s book is commonly used as a textbook in teaching introductory nuclear physics courses. Some modern physics reference books such as Serway et al. (2005), Beiser (1963), and others also define and explain these introductory nuclear physics concepts.

2.5.1.1 Nuclear binding energy (NBE)

It is defined as the sum of the rest energies of the split constituents minus the rest energy of the nuclear mass (Basdevant et al., 2005). In other words, the binding energy of a nucleus can be considered as the total energy needed to break up a nucleus into its constituents. In another way, NBE is defined as the energy produced when the separated nucleons fuse to form a nucleus (Beiser, 1963). The released energy is equivalent to the mass lost in the process of combination. In this process, some of the nuclear rest mass changed into energy. Measurements showed that the nuclear mass is less than the combined masses of its separated constituents. NBE can be expressed using an equation as follows:

$$E_b = \left(Zm_p + Nm_n - m_{nuc}\right)c^2 \quad (2.\ 1)$$

The symbols, E_b m_p Z, N, m_n m_{nuc} and c respectively represent the nuclear binding energy, the atomic number, the proton mass, the number of neutrons, the mass of the neutron, the mass of the nucleus, and the speed of light.

2.5.1.2 Nuclear force

It is the charge-independent and strong force that binds the constituents of the nucleus together to prevent the Coulomb repulsive force among protons causing the nucleus to fly apart (Serway et al., 2005). The coulomb repulsive force acting among protons is more dominant at a large distance than the nuclear force. In other words, nuclear force is more dominant at short distances. The stability of the nuclei of atoms depends on the domination of these forces. The nuclei of atoms in which the nuclear force is more dominant are more stable. The nuclei of atoms in which the Coulomb force is more dominant are unstable nuclei. The nuclear force can be explained based on the exchange field particle model. In other words, the strong interactions of nucleons caused by a nuclear force are mediated by pi-mesons. Some scholars also assumed that nuclear force is the result of the more basic strong force that causes the quarks in a nucleon to interact with each other (Serway et al., 2005). Rather than the strong nuclear interaction, all other strong interactions, which are caused by the more basic strong forces, are mediated by gluons.

2.5.1.3 Radioactive decay

It is the change of radioactive nuclei into other stable nuclei by emitting nuclear radiation. The three common types of nuclear radiation emitted in radioactivity are alpha, beta, and gamma. There are three ways of radioactive decay processes in which these nuclear radiations are emitted. At the end of any decay process, the unstable nuclei eventually decay to a stable state (Serway et al., 2005). There is a general formalism known as radioactive decay law that describes radioactive decay (Paul, 1971). This law states that the number of radioactive nuclei present in a radioactive substance exponentially decreases in time during the decay process. Mathematically, the radioactive decay law is expressed using the equation as follows:

$$N = N_0 e^{-\lambda t} \quad (2.\ 2)$$

The number of radioactive nuclei in a radioactive substance at time $t = 0$ is represented by a symbol (N_0) and at any time t is represented by N. The symbol λrepresents the decay constant of the radioactive nucleus. The number of radioactive nuclei that have decayed at any time t is ($N_0 - N$). The half-life of a radioactive substance is defined as the time necessary for half of the number of radioactive nuclei in the substance to decay (Serway et al., 2005). According to these scholars, the three ways of radioactive decay processes are expressed using Equations 2.3 to 2.6.

Alpha decay process

$${}_{Z}^{A}X \rightarrow {}_{Z-2}^{A-4}Y + {}_{2}^{4}He \quad (2.\ 3)$$

In the alpha decay process, the parent nucleus X loses two protons and two neutrons, and then the alpha particle (${}_{2}^{4}He$) is emitted. The letters A and Z respectively represent the atomic mass number and atomic number.

The negative beta decay process

$${}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + e^{-} + \overline{\nu} \quad (2.\ 4)$$

The positive beta decay process

$$ {}_{Z}^{A}X \rightarrow {}_{Z-1}^{A}Y + e^{+} + \nu \quad (2.5) $$

In the negative beta decay process, electrons e^{-} and antineutrinos $\bar{\nu}$ are emitted and in the positive beta decay process, positron e^{+}s and neutrinos ν are emitted. These particles are emitted in the form of radiation, which we call beta radiation.

Gamma decay process

$$ {}_{Z}^{A}X^{*} \rightarrow {}_{Z}^{A}X + \gamma \quad (2.6) $$

If the nucleus in an excited state comes back to the ground state, it releases energy. This energy is released in the form of gamma radiation. The nuclei (${}_{Z}^{A}X^{*}$) and (${}_{Z}^{A}X$) respectively are the nuclei at excited and ground states. Hence, gamma radiation is produced, when the excited nucleus is de-excited.

2.5.1.4 Negative beta decay

Equation 2.4 expresses the complete negative beta decay process. In this decay process, a nucleus is changed into another nucleus by emitting an electron and antineutrino. The number of protons in the daughter nucleus is increased by one while the number of neutrons in it is decreased by one. The mass number is unchanged in the decay process. The neutron in the parent nucleus is decayed into proton, electron, and antineutrino in the decay process. In the neutral parent atom, the numbers of protons and electrons are equal. But in the daughter atom, they are not equal, because the daughter nucleus has one extra proton. This makes the daughter atom positively charged or an ion since the number of atomic electrons is unchanged. Therefore, the electron and antineutrino emitted in the negative beta decay process come from the decay of a neutron in the parent nucleus (Krane, 1988; Martin, 2009; Serway et al., 2005).

2.5.1.5 Nuclear energy

It is the energy coming out of the nucleus of an atom via nuclear fission and fusion reactions. Nuclear fission is the spontaneous or induced disintegration of a heavy nucleus into light nuclei and nuclear fusion is the combination of two light nuclei into a heavy nucleus by the influence of an attractive nuclear force. In nuclear fission and fusion reactions, nuclear energy is produced in large amounts. Nuclear energy can also come out of the nucleus of an atom via nuclear decay. However, nuclear energy is produced in small amounts in nuclear decay (Martin, 2009; Serway et al., 2005).

The nuclear reaction is either an endothermic or exothermic reaction. In an endothermic reaction, parts of the kinetic energy of the incident particle changed into mass. In exothermic reactions, the mass is converted to energy. This form of energy is called nuclear energy since it is coming out of the nucleus. This implies that the rest mass of a nucleus is the origin of nuclear energy. In a nuclear fission reaction, this nuclear energy exists in the form of the kinetic energies of the fission fragments (Krane, 1988; Serway et al., 2005). The nuclear reaction of an incident particle '*a*' with a target nucleus *X* is expressed using Equation 2.7. *Y* and *b* respectively are known as the product nucleus and particle.

$$a + X \rightarrow Y + b \quad (2.7)$$

The energy released in the nuclear reaction is represented by the Q-value expressed using equation 2.8. The energy released in the nuclear reaction, which we call the reaction energy, comes out of the nucleus of an atom. Since it comes out of the nucleus of an atom, this form of energy is known as nuclear energy (NE).

$$Q = NE = \left(m_a + m_x - m_y - m_b\right)c^2 \quad (2.8)$$

In an exothermic nuclear reaction, the Q-value is positive while in an endothermic nuclear reaction it is negative. The equation of Q-value can be derived from Equation 2.7 using the conservation law of energy and by knowing that NE exists in the form of the kinetic energies of the fission fragments.

2.5.2 Conceptual Difficulties of Introductory Nuclear Physics Concepts

Conceptual difficulties were revealed in previous nuclear physics education studies. For example, the students did not consider the very different short-range properties of a nuclear force; students understood as an electron being emitted in the negative beta decay process is coming from the electron shell (Kohnle et al., 2011). Students also incorrectly understood that "radioactive substances vanish over time and are transformed into energy" (Yeşiloğlu, 2019, p.866). In such a way, the conceptual difficulties of the introductory nuclear physics concepts selected to be studied in this study are discussed in the following subsections.

2.5.2.1 Conceptual difficulties of nuclear binding energy

Rathore (2016)identified the students' common learning difficulties and misconceptions of NBE. The findings of Kohnle et al.(2011) showed that the students had misconceptions in comparing the nuclear mass to the combined masses of its separated nucleons. The students were unable to reason out this nuclear phenomenon. That is the nuclear phenomenon in which mass did not conserve because of conversion of mass to energy. This misconception directly affects the students' conceptual understanding of NBE. Whenever the nucleons bind together to form a nucleus, there is a loss of mass (see Eq. 2.1). The lost mass changes into energy and is then released in the process of combination. We call this released energy NBE.

A considerable number of students incorrectly understood that the nuclear mass is greater than the combined masses of its separated constituents (Kohnle et al., 2011). These students incorrectly reasoned that a nucleus has additional binding energy, which is added to the total mass of the nucleus. According to these students' understanding, the nucleus in the bound state has extra energy between the nucleons. They incorrectly understood that preserving a nucleus in a bound state requires additional energy, which changes into the mass. According to Kohnle et al. (2011), this may be an incorrect comparison to a mechanical system. For instance, making two bodies, which normally repel each other closer, such as bringing two positively charged particles together by hand, requires energy.

2.5.2.2 Conceptual difficulties of nuclear force

Rathore (2016) had also identified the students' common learning difficulties and misconceptions of nuclear force but not discussed particularly. The findings of Kohnle et al. (2011) revealed that the students had misconceptions in learning and understanding nuclear force. That is, the students understood that those nuclei, which have more nucleons, are more tightly bound. The students incorrectly compared the nuclear systems to atomic systems and the long-range Coulomb force. This means the students did not consider the unique short-range properties of a nuclear force. The strong nuclear force acts at the nuclear level, which is more difficult to visualise and understand than that of gravitational and electromagnetic forces (Shakya, 2015).

2.5.2.3 Conceptual difficulties of radioactive decay

Different research instruments gave the researchers an insight into students' learning difficulties and misconceptions of radioactive decay. In the radioactive decay process, the students confused the number of nuclei that had decayed with the number of nuclei remaining in a radioactive substance (Kohnle et al., 2011). These researchers also indicated that students seem understood the concept of a half-life, but they were unable to use the radioactive decay law successively. That is they did not understand what happens at n^{th} half-lives (where n = 1.2.3…) in the decay process. In general, previous findings indicated that students had misconceptions about the radioactive decay law; the half-life of a radioactive substance; and electron capture (Yeşiloğlu, 2019; Morales & Tuzón, 2020; Rathore, 2016). The students use the terms 'radioactivity', 'radiation', and 'radioactive substance interchangeably, which is incorrect (Morales & Tuzón, 2020).

2.5.2.4 Conceptual difficulties of negative beta decay

In the findings of Kohnle et al.(2011) students incorrectly reasoned about negative beta decay in three ways. Firstly, students incorrectly understood that the number of protons was unchanged but the number of atomic electrons in the daughter atom decreased by one. It seems that the students understood that an electron emitted in the negative beta decay process came from the atomic shell.

Secondly, students incorrectly understood that both the number of protons and atomic electrons in the daughter atom decreased by one. It seems that the students incorrectly assumed both of these particles emitted in the beta decay process. Again, these students incorrectly understood that the electron emitted in beta decay is coming from the atomic shell.

Thirdly, other students incorrectly considered that the number of protons and atomic electrons in the daughter atom increased by one. It seems the students correctly understood that a neutron decays into proton, electron, and antineutrino in the parent nucleus ($n \rightarrow p + e^{-} + \overline{\nu_e}$). However, the students incorrectly indicated that this electron is captured by the electron shell of the daughter atom after coming out of the nucleus for the charge to be conserved. That is, they did not consider that the daughter atom is a positive ion. The electron shell of the daughter atom does not capture the electron emitted in the beta decay process. Instead, this electron is created in the nucleus at the moment of decay and is emitted in the beta decay process.

In the findings of Pillay and Loonat (1993), the students incompletely expressed the equation that shows the decay of a neutron into an electron ($n \rightarrow p + e^{-}$). Their reason for using this equation is that a proton is positive, an electron is negative; so that when these particles combine a neutral product; a neutron is formed. They did not consider the third particle antineutrino. Other students correctly understood that the electron emitted in the beta decay process came from the nucleus, but they incorrectly assumed that the electron emitted in the beta decay process exists in the nucleus before decay. Scientifically, this electron is created and emitted at the moment of negative beta decay.

2.5.2.5 Conceptual difficulties of NE

In nuclear decay, the energy is released when a nucleus split into its constituents. Besides, energy is produced in the fission of a heavy nucleus into light nuclei or the fusion of light nuclei into heavy nuclei in a nuclear reaction (Martin, 2009). Since this energy comes out of the nucleus of an atom we call it NE. In reasoning out the induced nuclear fission reaction, the students did not consider the kinetic energy KE_a of the incident particle '*a*' that induces fission (Kohnle et al., 2011). The following equations of Q-value can be derived from Equation 2.7. The equation of Q-value for induced fission (in the presence of incident particle 'a') is given as:

$$Q = KE_y + KE_b - KE_a$$

For spontaneous fission (in the absence of the incident particle 'a'), it is:

$$Q = KE_y + KE_b$$

It seems that the students confused induced fission with spontaneous fission. Induced and spontaneous fissions occur for the heavy nuclei when the fission fragments have greater binding energy per nucleon than that of the initial nucleus (Kohnle et al., 2011). Q is known as Q-value (reaction energy), which is a form of energy known as NE.

The findings of Pillay and Loonat (1993) also indicated that the students confused nuclear reaction with chemical reaction. Their findings clearly showed that the students considered the equation of nuclear reaction as the equation of the chemical reaction. This may cause the students to incorrectly understand that a chemical reaction is a source of NE. Scientifically; NE is released in a nuclear reaction.

2.5.3 Teaching Approaches Used in Nuclear Physics

Different teaching approaches were used to address the conceptual difficulties in introductory nuclear physics in previous studies. These teaching approaches are presented in the next subsections.

2.5.3.1 Traditional instruction

Until now, traditional instruction is the most commonly used method of instruction in schools, colleges, and universities around the world (Lopez, 2004). Mostly, in traditional classes, the blackboard and chalk were used as teaching materials. In traditional instruction, teachers are the main source of knowledge while students are passive learners (Kuzu, 2007). In another way, in this instructional process, knowledge is poured from the teacher into the learners (Scrivener, 2005). Therefore, traditional instruction is a teacher-centered teaching method. It is a passive teaching strategy, which does not keep students engaged in the active-learning process (Scrivener, 2005). Conventionally, the blackboard is considered as the sign of traditional instruction (Gursul & Tozmaz, 2010). Mostly, traditional instruction is used in teaching physics courses in the researcher's country. Large class size, shortage of time, academic resource problems, and insufficient pedagogical training may be the factors that forced the teachers to use traditional instruction.

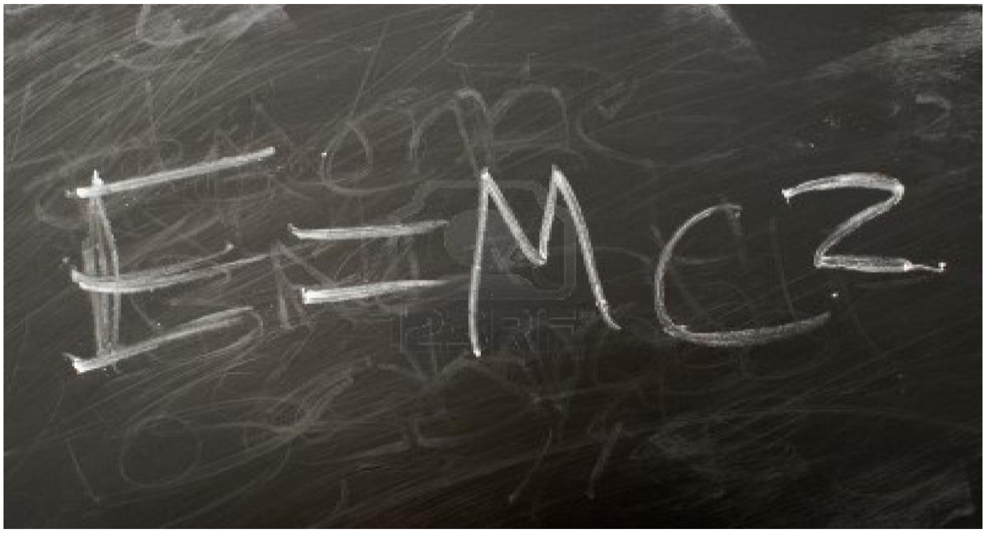


Figure 2.1: Blackboard as a symbol of traditional teaching

2.5.3.2 The laboratory modelling activity

In Turkey, the laboratory modelling activity was used to teach about the radioactive substance, nuclear decay law, and the half-life of a radioactive substance (Yeşiloğlu, 2019). This activity involves constructing, using, evaluating, and revising the model of these concepts in a laboratory. A qualitative research approach (modelling constant comparative method) was used to explore the pre-service chemistry teachers’ conceptual understanding of these concepts after an activity. The laboratory model activity was effective in eliminating the students’ misconceptions of the mentioned concepts.

2.5.3.3 Cooperative learning versus traditional instruction

In Nigeria, the effect of cooperative learning instructional strategy on high school physics students’ conceptual understanding of radioactivity was examined (Doris & Ndu, 2018). A quantitative research approach (quasi-experimental design) was used by these researchers. The researchers used a close-ended radioactivity test to collect data. The collected data was analysed using an independent z-test. The findings of the study showed that this instructional method is more effective than traditional instruction. These researchers recommended using a cooperative learning strategy in teaching physics focusing on conceptual understanding.

2.5.3.4 Jigsaw technique versus traditional instruction

In Spain, the Jigsaw instructional method was used as an intervention in mapping the concept of radioactivity. Finally, its effectiveness compared to the lecture-based teaching approach was investigated (Tobaja, Gil, Solano, &2017). A quasi-experimental research design was used in this study. The research participants were pre-university secondary education students. Close- and open-ended questionnaires were used to collect data. The collected data was analysed by the IBM SPSS 2016 Version Statistics Software. The experimental group of students who were taught using the Jigsaw instructional method achieved significant learning with less individual effort. In other words, using the Jigsaw technique in mapping the concept of radioactivity was more effective than a lecture-based teaching approach.

2.5.3.5 Guided-inquiry based versus traditional instructions

A doctoral dissertation PER was conducted to assess the students' conceptual knowledge of weak and strong nuclear forces"(Shakya, 2015). Traditional and guided-inquiry-based instructions were used to teach the research participants at the University of Southern Mississippi in the USA. The pre and post-tests research were conducted in this study. The principal research question of the study was "what is the impact of active-learning activities on students' knowledge of weak and strong nuclear forces?" The data collected from eighty-six students were analysed quantitatively using descriptive statistics and frequency. In three out of the four courses, the mean post-test scores of the active-learning groups were found to be significantly lower. The overall results of this study indicated that participation in active-learning activities worked for students in one group among the four groups. In another way, the results indicated that the traditional instruction was more effective than the guided-inquiry-based instruction for the three groups in getting the knowledge of weak and strong nuclear forces.

2.5.3.6 Computer-assisted, conceptual change texts and computer-assisted with conceptual change texts versus traditional instruction

In Turkey, research was conducted to examine the efficacy of computer-assisted instruction with conceptual change texts in addressing the students' misconceptions of radioactivity (Yumuşak et al., 2015). Computers are used to present course contents in different ways such as simulations and animations. This is what computer-assisted instruction means. First, students were aware of their misconceptions, and then they were supported to develop a correct conceptual understanding. This ensures conceptual change (Chambers & Andre, 1997). If this used textual explanations, we call it the conceptual change text. A nonequivalent control group quasi-experimental design was used in this study. The effectiveness of the three mentioned teaching methods in removing the three experimental groups of students' misconceptions of radioactivity was explored. A two-tier misconception diagnostic test was used to collect data. The collected data was analysed using MANOVA, dependent paired sample t-test, Post Hoc, and two-way ANOVA analyses. Using the misconception diagnostic test, the researchers determined that the three teaching methods were more effective than the traditional instruction used on one control group. Adolphus and Omeodu (2020) were also examined the effects of computer-assisted instruction on senior secondary schools students' achievement in atomic and nuclear physics. It was effective when compared to the lecture method.

2.5.3.7 Modelling method versus traditional instruction

In Turkey, research was conducted on the teaching of radioactive decay using a modelling method in a high school (Bakaç, Taşoğlu, & Usta, 2015). In the modelling of nuclear decay, 50 coins are used to represent radioactive elements. A descriptive survey method was used in the study. The qualitative data were collected from 41 students and then analysed. The results indicated that the students did not gain sufficient knowledge about radioactivity. The students who were taught using the modelling teaching method performed better than the students who taught using traditional instruction. The researchers recommended that it is better to use the modelling teaching method rather than traditional instruction when it is appropriate.

Again, in Turkey, research was conducted to examine the efficacy of modelling and simulation in teaching the nuclear decay law (Bakaç, Taşoğlu & Uyumaz, 2011). These researchers were used a one-shot case study experimental research design in conducting their research. The research was conducted with students of 4^{th} grade in the University of Turkey in the department of physics. The 200 coins with 200 procreated numbers were used in the simulation to collect data. The coins represent a radioactive element, which was used in the first modelling of nuclear decay. “In the second modelling of nuclear decay, the Microsoft Office Excel programmer is used to simulate the same radioactive element represented by 200 coins”(Bakaç, Taşoğlu, & Uyumaz, 2011, p.2197). The findings of the study revealed that the learners understood the radioactive decay law better by visualising it through modelling methods. That is both modelling instructions supported the students to remove their misconceptions of radioactive decay law.

2.5.3.8 Summary and discussion on previous teaching approaches used in nuclear physics

The laboratory model activity remarkably supported the learners rather than traditional instruction in eliminating the misconceptions of a radioactive element, radioactive decay law, and half-life (Yeşiloğlu, 2019). The cooperative learning strategy was also more successful in eliminating the students’ misconceptions of radioactivity (Doris & Ndu, 2018). The Jigsaw teaching strategy supported the students better than a lecture-based teaching approach in mapping the concept of radioactivity (Tobaja et al., 2017). The traditional teaching method was more successful than the guided-inquiry-based teaching method for the three groups of students out of four groups in gaining the knowledge of weak and strong nuclear forces (Shakya, 2015). Computer-assisted instruction, conceptual change texts, and computer-assisted instruction with conceptual change texts were more effective than traditional instruction in removing the misconception of radioactivity (Yumuşak et al., 2015). The participation of the students taught by the modelling method was better than those taught by the traditional method (Bakaç et al., 2015). Students understood the law of radioactive decay better by reifying it through the modelling method and removing misconceptions (Bakaç et al., 2011).

Most of the previous teaching approaches used in nuclear physics derived from constructivism (Ling Lo, 2012). For example, guided-inquiry-based instruction, cooperative learning strategy, and the Jigsaw technique are derived from constructivism. In recent years, some scholars have started to criticise the teaching approaches derived from constructivism, which depends on the less guided teaching approach (Kirschner, Sweller, & Clark, 2006). Based on the information-processing model, these researchers pointed out that there is a restricted channel for connecting the working memory to long-term memory in the constructivist teaching approach. They also inferred that this teaching approach would cause learners to have a working memory load. This indicates the limitation of the teaching approach derived from constructivism. Hence, physics education researchers initiated a search for an alternative teaching approach to the teaching approaches derived from constructivism.

The researcher decided to explore the effectiveness of using different forms of representations-based instruction with interactive nuclear physics learning tutorials in addressing the students' conceptual difficulties. This teaching strategy was designed within the pedagogical framework of phenomenography and the VTL (see Section 2.10). It could be used to reduce the load of learners' working memory, which made it more advantageous than the teaching approach derived from constructivism. The different forms of representations used in this teaching strategy provided several channels for connecting the working memory to long-term memory. In another way, when different sensory channels are used, learning can become more successful (Kearsley, 1999; Wa, 2007). For example, using a verbal form of representation, a text, an equation, a graph, a diagram, and an interactive simulation in teaching-learning of a certain concept of physics can reduce the load of learners' working memory. That means these different forms of representations can make learning easier. Savolainen, Mäkynen, Nieminen, and Viiri (2013) said that instead of using only verbal or mathematical manipulation or visual representations it is better to use MRs.

2.6 THE MULTIPLE REPRESENTATIONS-BASED TEACHING APPROACH WITH INTERACTIVE LEARNING TUTORIALS

2.6.1 The Meaning of Multiple Representations (MRs)

Representations are entities that convey specific information about something or a process(Gilbert, 2010). A representation is an expression of a concept, quantity, system, phenomenon, or process (De Cock, 2012; Van Heuvelen, 1991; Van Heuvelen & Zou, 2001). Representations transmit information that students can easily understand than other means of instruction do not(Phillips, Norrs, & Macnab, 2010; Risch, 2014). Larsson (2013) referred to representations in physical forms as external representations (in the form of diagrams, images, models, animations, simulations, etc.), representations in an individual's mind as internal representations, and representations in verbal-linguistic forms as metaphorical language.

2.6.2 Representational Competence

"Scientific practice requires the bringing together of a wide range of semiotic resources such as graphs, diagrams, mathematical equations, and specialist language" to facilitate students' conceptual understanding (Volkwyn et al., 2020b, p.89). These researchers stated that the representational capability of such semiotic resources is the skill to suitably constructing and interpret a set of disciplinary-scientific representations of a concept, phenomenon, and process. Teachers should follow up with the students to develop their disciplinary-scientific representational competence to make learning possible. For instance, research was conducted to enhance the students' understanding of representations and the use of rectangular coordinate systems in working out physics problems. Particularly, in working out physics problems using a movable rectangular coordinate system (Volkwyn et al., 2020a). Objects in our environment are either directly visible or indirectly visible. One can represent both of them using different relevant semiotic resources. In the case of indirectly observable objects, mediating physics devices such as microscopes, telescopes, oscilloscopes, and others are required. The mediating devices can be used to accomplish three purposes. These are to intensify, filter, and transducer the meaning potential of an object or a phenomenon in our environment (Volkwyn et al., 2019). These mediating devices are used to represent and interpret the different aspects of scientific concepts associated with the object or phenomenon.

2.6.3 Acceptance and Use of Multiple Representations

There have been continuous discussions about the role of different forms of disciplinary-based representations such as equations, graphs, and diagrams (Volkwyn et al., 2020b). The reasons why we use different forms of representations in physics education or science education have been discussed many times in the literature (Abdurrahman et al., 2019; Eriksson et al., 2020; Hochberg et al., 2020; Johnson, 2020; Opfermann et al., 2017; Svensson et al., 2020). According to these scholars, MRs or social semiotics could be used with VTL to reduce cognitive load, enhance critical thinking skills, and then for conceptual learning and understanding of a disciplinary concept. Particularly, the use of

MRs is highly valued in physics education (Hubber & Tytler, 2017; Kozma, 2003; Van Heuvelen & Zou, 2001), because it is very useful for enhancing students' understanding of basic concepts (Adadan, Trundle, & Karen, 2010). Representations are essential conceptual tools that can support students' conceptual understanding of physics (Larsson, 2013). For example, work at both micro and macro levels has been done on students' use of MRs to enhance their conceptual understanding of physics (Kohl & Finkelstein, 2005, Kohl et al., 2007). Appropriate combinations of representations could provide unique benefits in learning complicated scientific concepts. MRs support the students to engage in effective interactions (Tang, Tan, & Yeo, 2011). This learning environment could be highly motivating for students to learn and to enhance their conceptual understanding of physics.

2.6.4 Multiple Representations-Based Teaching Sequence

The teaching sequence involves several contextual components, in particular its structure, didactic organisation, and activities (Tiberghien, Vince & Gaidioz, 2009). The teaching sequence involves an activity that students do and MRs based instructional strategy designed to make students learning possible (Opfermann et al., 2017; Pang & Marton, 2007). In this pedagogical perspective, the teacher should attempt to structure the lesson based on the appropriate forms of interactive representations to make learning possible. According to Pang and Marton (2007), one cannot see teaching and learning in separation. Preparing the teaching sequence is an important activity of the teacher in designing any instruction.

There are many ways to design the systems of different forms of representations to support the students' conceptual understanding (Ainsworth, 2006). There must be a particular reason to use an individual representation in preparing a certain teaching sequence of representations. Literature shows that effective design of MRs-based instruction includes the following components that apply particularly to the systems of appropriate different forms of representations (Ainsworth, 1999, 2006; de Vries, 2006):

(a) the number of different forms of representation
(b) The way that the information is conveyed via the different forms of representations
(c) The forms of representations in the system (such as text, equations, and graphs)

(d) The sequence of the different forms of representations in the system and

(e) The complement and interpretation of the different forms of representations

For example, in the teaching of radioactive decay law, it is possible to use verbal, text, equation, graph, diagram, and interactive simulation in designing MRs based instruction. These six forms of representation can enhance the students' learning of radioactive decay law. The different forms of representational competence (Volkwyn et al., 2020b) with appropriate teaching sequences can enhance the effective learning of students.

2.6.5 Multiple Representations-based Instruction With Interactive Learning Tutorials

Effective instructional strategies engage, confront, and inspire learners. Active learning is emphasised as a main pedagogic principle by the British Educational Communications and Technology Agency (BECTA, 2004). MRs-based instruction with interactive nuclear physics learning tutorial was designed based on students' conceptual difficulties. This instructional strategy was used as a supplement to lectures and self-study tools (Singh, 2008). An interactive learning environment increases the possibilities for learning (Mork, 2011). The learning environment could introduce different forms of representation, which can motivate the students and increase their possibilities for learning basic and complex scientific concepts (Rutten et al., 2012). These different forms of representations can involve interactive simulations, animations, videos, equations, graphs, diagrams, verbal, and text. When the students interact with well-designed forms of representations, with themselves and with their teacher, learning can become more effective (Jimoyiannis & Komis, 2001). In this study, multiple representations-based teaching approaches were used to develop and retain students' deeper conceptual understanding of introductory nuclear physics (Fayanto & Juni, 2020; Kollmer et al., 2020).

2.7 PHENOMENOGRAPHY

2.7.1 the Meaning of Phenomenography

Literature showed that phenomenography developed from sequential practical educational researches conducted by a Swedish research group in the 1970s(Bussey, Orgill, & Crippen, 2013, p.9; Marton, 1975; Marton & Wenestam, 1978; Pang, 2003).

Phenomenography is understood as experiential research of the various ways in which human beings understand the world. Marton and Booth (1997) claimed that there is only one reality and that reality is constituted as an internal relation between the world and the person. They further argued that as we are all different, we, therefore, experience phenomena differently.

According to Marton (1981), phenomenography describes human beings' understanding of the real object, phenomenon, and process in their environment. In another way, it is a qualitative research approach used to reveal the different ways of human beings' understanding of a particular reality in their surroundings (Wright & Osman, 2018; Han & Ellis, 2019; Hajar, 2020). It aimed to explorer the various ways in which the community experiences the various aspects of phenomena in their surroundings (Bowden et al., 1992). Phenomenography deals with different ways of people's understanding of the world (Marton, 1986). It confirmed that in numerous empirical phenomenographic studies there is a restricted difference of ways of understanding (Dall'Alba & Hasselgren, 1996). The variation in ways of understanding an object includes the "what" and "how" aspects of the object. The "what" aspect indicates what is in the individual's focal point, the "how" aspect explains how learning is possible based on variation in ways of the individual's understanding (Larsson & Holmström, 2007). All of these show that the object of the phenomenographic research approach is the internal relation between the individuals and the aspects of the phenomenon in the world (Bowden, 2005). In this study, the internal relation between the students and aspects of a nuclear physics concept was explored. This internal relation was the object of study of any phenomenographic study. For instance, the internal relation between the students and the aspects of a concept of nuclear force was the objects of this study. To develop their understanding of the concept of nuclear force, the students should discern its various aspects, which is the focus of this study. The object of study of this phenomenographic study is the internal relation between the students and the aspects of nuclear physics concepts (see Figure 2.2). This is illustrated using the diagram below which shows the focus of a phenomenographic study.

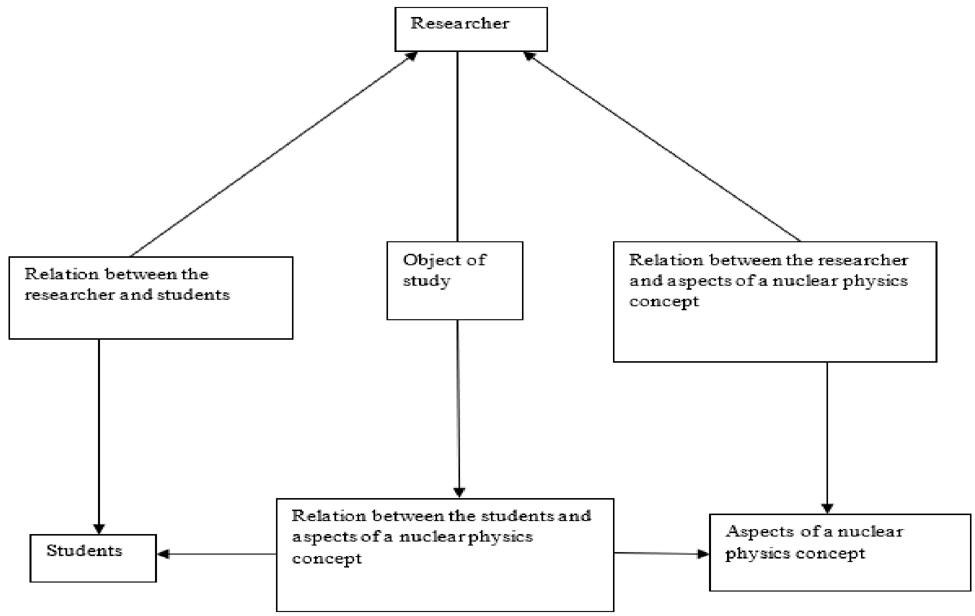


Figure 2.2: Focus of a phenomenographic research

Source: Adapted from Bowden (2005) study.

As indicated by some educational researchers, conceptual confusion of phenomenography and phenomenology has arisen (Stolz, 2020). Even though both are used as a method to study human experiences and uses some concepts or ideas in the same way in educational research, they are not the same. Stolz (2020) had discussed shortly phenomenology and phenomenography in his paper, which also possibly indicated their main difference. According to Stolz (2020, p.10), "phenomenography is generally interested in the study of second-order perspectives, whereas phenomenology is mainly interested in the investigation of first-order or first-person perspectives". In other words, a phenomenographic researcher is responsible for interpreting data collected from a second-order perspective (the lived experiences of students).

2.7.2 Phenomenographic Research in Physics Education

Since the 1970s, phenomenography has played a great role in researching students' conceptual learning and understanding in undergraduate physics programs (Bussey et al., 2013). This qualitative research approach gave an insight into students' conceptual difficulties such as misconceptions and confusions of some physics concepts. Several investigations had been carried out on the students' conceptual understanding of physics using this research approach (Bowden et al., 1992; Ejigu, 2014; Henderson, Stewart, & Traxler, 2019; Linder & Erickson, 1989; Linder, 1993; Sharma et al., 2010; Walsh et al., 1993). For instance, phenomenographic case studies were carried out to explore the alternative conceptions and misconceptions in kinematics and students' mental models in the dynamics of Newtonian mechanics (Motlhabane, 2016; Özcan & Bezen, 2016). And the phenomenographic researchers Park et al. (2009) researched the learning progression in students' conceptualisations of atomic structure.

In the review of related literature, no phenomenographic research was conducted on students' conceptual understanding of nuclear physics found. Therefore, the phenomenographic research approach was selected to explore the students' conceptual understanding of introductory nuclear physics concepts. In particular, the developmental phenomenographic research approach is the interest of the researcher, which is adapted from previous researchers (Bowden et al., 1992; 2000; Ejigu, 2014).

2.7.3 Developmental Phenomenographic Research Approach

This research approach is used to produce research outcomes that can be subsequently used to address learning difficulties (Bowden & Walsh, 2000; Green & Bowden, 2009). In the developmental phenomenographic research approach, the research outcomes of phenomenography are not the final results. Rather, these outcomes are a means of addressing an educational issue. Such research outcomes are known as categories of description. These are not the only objective of a developmental phenomenographic research project. The categories of descriptions can give an insight into students' conceptual difficulties with a disciplinary concept and then can inform effective instructional intervention that can address the difficulties (Han & Ellis, 2019). Thus, developmental phenomenography is a means to identify address an educational issue (Green & Bowden, 2009). For this reason, most of the time developmental phenomenographic research is done in phases.

The "pure" phenomenographic research approach is different from the developmental one. Pure phenomenographic research is aimed at identifying and describing the various ways of students' understanding of a disciplinary concept (Larsson & Holmström, 2007; Marton, 2004). These are commonly represented using categories of description, which are the final results of a pure phenomenographic study. In other words, such type of study ceases on constructing the categories of description without using them afterward to address a given educational issue.

2.8 VARIATION THEORY OF LEARNING

This theory is a development arising out of the traditional phenomenographic research approach (Åkerlind, 2015, 2018; Cheng, 2016; Marton & Tsui, 2004; Runesson, 2005). Marton and Booth (1997) took the first initiative in the development of the VTL. The connection between phenomenography and VTL is "variation"(Orgill, 2012). This "variation" is the variation that Marton and Booth (1997) found and introduced as the VTL. Hence, VTL is a new learning theory that was developed from phenomenography in the 1990s(Orgill, 2012). Phenomenography is used to describe the variation in ways of students' understanding while VTL is used to explain how the variation occurs (Marton& Tsui, 2004; Marton & Booth, 1997; Marton, 1981; Park et al., 2009). These scholars also said that the VTL is used as a lens to explain the learning process and its outcomes. And they also said that it is used to recognise what enables learning achievable. This learning theory assumes that various students understand the same object of learning in different ways.

What makes the VTL exceptional from other learning theories is that it considers the object of learning as its starting point (Ling Lo, 2012). It mainly focuses on how learners discern and understand the various aspects of the object of learning (Runesson, 2005). According to the VTL, the critical aspects distinguished by students are the essential conditions for learning (Marton & Tsui, 2004). Marton and Pang (2006) said that to learn a subject, the student should recognise what they intended to learn. That is, the learners should recognise the various critical aspects of the intended object of learning to learn it. Sun (2011) and Mok (2003) also said that there is one keyword for effective learning in Asian countries, which is "variation". Therefore, learning depends on the discernment of various critical aspects or the dimension of variation (Wright & Osman, 2018).

The object of learning considered in this study is the critical aspects of a concept of introductory nuclear physics. In the context of this study, the VTL focuses on how the students deal with the five concepts of introductory nuclear physics. For students to enhance their understanding of a concept they must discern its various critical aspects (Dull & Shiland, 1995; Tsaparlis, 1997). These critical aspects refer to the critical aspects of conceptual variation. Conceptual variation means variation in ways of understanding a concept. Renström, Andersson, and Marton (1990) said that it is possible to delineate potential conceptual difficulties associated with students' conceptual understanding based on the aspects of conceptual variation. The conceptual difficulties such as misconceptions and confusion refer to irrelevant aspects of the object of learning (see Section 2.8.3). The enhancement of students' conceptual understanding is explained based on the aspects of the conceptual variation. The aspects of conceptual variation provide critical information for developing and designing curriculum, instruction, and assessment focusing on enhancing the students' conceptual understanding.

2.8.1 Object of Learning

It is the first important component of the VTL. According to this learning theory, it is the content that the students can learn or a particular insight or capability that the students can develop (Marton & Booth, 1997). It is impossible to explain completely the nature of learning without understanding what the learners can learn and what the learners are. In the learning process, the learners deal with the object of learning. There should not be confusion between the learning objective and the object of learning. The learning objective is the expected learning outcome while the object of learning is what the students can learn in the learning process (Ling Lo, 2012). So, the object of learning is dynamic, because, in the learning process the learners can discern its various critical aspects. These critical aspects are the necessary conditions for learning.

There are three aspects of the object of learning that are examined by the VTL in a phenomenographic study. These are the intended, enacted, and lived objects of learning (Bussey et al., 2013). According to these scholars, the intended object of learning is what the students are expected to learn. The enacted object of learning is the possibilities offered by the teacher and used by the students in the classroom. The lived object of learning is what the learners have already learned and understood (grasped). The intended object of learning is a first-order description, because, it is described by the researcher himself. "The priorknowledge and the lived object of learning are a second-order description, because, the researcher describes them as understood by the learner" (Marton & Booth, 1997, p.163). In the case of a second-order description, the researcher describes what the learners have understood. But, in the case of the first-order description, the researcher describes what he has observed and understood. The enacted object of learning is "a first-order description", because, the researcher describes what he has observed and understood based on the possibilities offered to the learners (Runesson, 2005, p.70).

The student's prior knowledge is considered to address its consequence on the lived object of learning. Its relationship with the lived objects of learning in the VTL is shown in Figure 2.3. Priorconceptual understanding and representations were used instead of prior knowledge in the context of this study. The students may come to the classroom with misunderstandings/misconceptions. These may affect the lived object of learning.

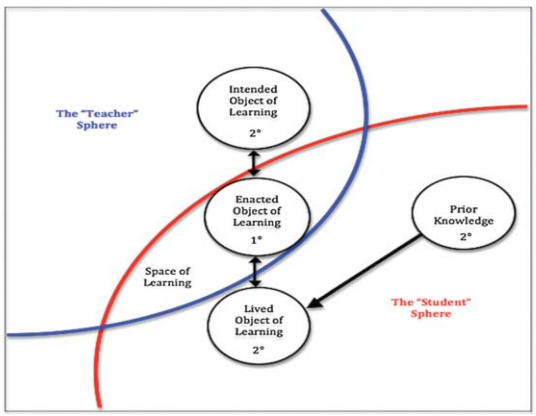


Figure 2.3: The relationship between the prior knowledge and the lived object of learning within variation theory.

Source: Bussey et al. (2013, p.17).

2.8.2 Critical Aspects and Features of the Object of Learning

The critical aspect and features of the object of learning are the second important component of the VTL. The teachers, as well as students, focus on a limited number of critical aspects (Ling Lo, 2012). It is impossible to separate the critical aspects and features of the object of learning. Even though these terms are sometimes used interchangeably, they are not the same. critical aspects refer to the dimension of variation while the critical features refer to its values. To clarify the ideas of these two terms, the following examples are used.

The dog, water, and banana are used as examples of objects of learning (Bussey et al., 2013). According to these scholars, the size, colour, and pedigree of a dog are the three critical aspects of a dog. Big, brown, and Alsatian are the three critical features of the dog. The temperature of the water is its critical aspect. The corresponding critical features of water are its coldness and hotness. According to Orgill (2012), the critical aspect associated with banana ripeness is its colour. Its critical features are a green banana for an under-ripe banana, a yellow banana for a ripe banana, and a brown banana for an over-ripe banana. The taste would be another important critical aspect of the banana that enhances the students' understanding of the concept of the ripeness of the banana. An under-ripe banana has a bitter taste, and a ripe banana has a sweet taste. The learners' experiences of the variation in the critical aspects and features of the dog, water, and banana enhance their understanding of the concepts associated with these objects.

The concept of critical aspects was revisited by Pang and Ki (2016). These scholars said that the concept of critical aspects is explained in various ways in previous studies. There was no agreement in understanding the concept of critical aspects among previous researchers. As noted by Pang and Ki, critical aspects represent the critical differences in students' alternative ways of understanding. The critical aspects discerned by learners are defined as understood by them. Critical aspects are the focused aspects considered to be the necessary conditions of learning (Marton, 2014). According to this scholar, critical aspects are highlighted in the teaching-learning process. The set of critical aspects discerned by learners are their existing alternative ways of understanding.

2.8.3 Irrelevant Aspects of the Object of Learning

The irrelevant aspect of the object of learning is the third important component of the VTL, which was introduced by Pang and Ki (2016). As noted by these scholars, irrelevant aspects are unfocused aspects while critical aspects are focused aspects. The irrelevant aspects are the aspects different from the critical aspects. Or, they are the aspects different from the intended or targeted way of students' understanding. The irrelevant aspects are discerned and attended to by the learners as that of the critical aspects. Irrelevant aspects discerned by the learners can be used in planning a lesson. Because they can be part of any way of understanding separate from the targeted way of understanding. According to Pang and Ki (2016), irrelevant aspects are the aspects that one can take into consideration in the teaching-learning process to enhance the students' understanding.

In the VTL and this study, the irrelevant aspects are seen as the incorrect alternative ways of students' understanding. The incorrect alternative ways of students' understanding are the alternative ways of understanding that are not accepted as seen by the scientific community of practice. From this point of view, the irrelevant aspects can involve the alternative ways of students' misunderstanding, misconceptions, confusion, and learning difficulties. The term conceptual difficulties are also used in this study. They denote any challenges that the students encounter in understanding the introductory nuclear physics concepts. These challenges can be reflected in the form of misunderstandings, misconceptions, and confusion. Thus, in another way, irrelevant aspects involve conceptual difficulties. And the critical aspects are regarded as the correct alternative ways of students' understanding of the object of learning. The correct alternative ways of students' understanding are the alternative ways of understanding that are accepted by the scientific community of practice. The objects of learning in this study are the five concepts of introductory nuclear physics.

The ideas used in the previous paragraph are taken from the study of Motlhabane (2016) and the study of Pang and Ki (2016). According to Motlhabane (2016), "the meanings that are accepted by the scientific community of practice are regarded as alternative conceptions and those that are not accepted are seen as alternative misconceptions" (p.429). This idea was used in a previous phenomenographic study. According to Pang and Ki (2016) and in the VTL, the critical aspects are the critical differences in the intended alternative ways of students' understanding. The notion of critical and irrelevant aspects, which were used in this study is adapted from Pang and Ki (2016). Within the VTL, throughout the thesis, the critical and irrelevant aspects are used as defined in the previous paragraph.

2.9 CONCLUSION OF THE LITERATURE REVIEW

From the above review of related literature, a very useful conclusion was drawn. Research findings released in the literature show that undergraduate physics students encounter conceptual difficulties while learning introductory nuclear physics (see Section 2.5.2). Based on these findings, the concepts of NBE, nuclear force, radioactive decay, negative beta decay, and NE were selected and included in this study. These are the introductory nuclear physics concepts that students commonly encounter conceptual difficulties as indicated in Section 2.5.2. Previous findings indicated that limited qualitative research approaches were used to reveal as well as to address these conceptual difficulties (Yeşiloğlu, 2019). A few studies were conducted to reveal the conceptual difficulties of nuclear physics (see Section 2.5.2). A few teaching approaches were also used to address the conceptual difficulties (see Section 2.5.3). Kohnle et al. (2011) and Rathore (2016) recommended conducting student interviews to gain more insight into students' conceptual understanding (thinking) of introductory nuclear physics.

Therefore, a new qualitative research approach was selected based on these recommendations to gain more insight into students thinking of some concepts of nuclear physics. The developmental phenomenographic research approach was the relevant qualitative research approach that was used to address the research problem of this study (see Section 2.7.3). VTL (see Section 2.8) was used in combination with phenomenography to design the appropriate instructional intervention. The MRs-based instruction with interactive nuclear physics learning tutorials was the appropriate instructional intervention used in this study (see Section 2.6). It was designed based on the students' conceptual difficulties and VTL. This learning theory is a theoretical framework derived from the traditional phenomenographic research approach. Those instructions designed based on the VTL are known as phenomenographic instructions (Marton & Tsui, 2004). Hence, phenomenographic instruction was an alternative instruction to other instructions such as constructivist instruction. In this study, the MRs-based instruction with interactive nuclear physics learning tutorials was a phenomenographic instructional strategy designed based on the VTL.

2.10 THE CONCEPTUAL FRAMEWORKS OF THIS STUDY

In this study, the conceptual frameworks of developmental phenomenography and VTL were used (Imenda, 2014). The researcher understood that the research problem of this study cannot be meaningfully researched using either phenomenography or VTL without using both of them. This is especially true for the developmental phenomenographic research approach, which is conducted in phases (see Section 2.7.3). For this reason, the researcher decided to "synthesise" the views of phenomenography and VTL, which are interrelated (Liehr & Smith, 1999). Recent discussions in literature gave attention to the relationship between phenomenography and VTL(Rovio-Johansson & Ingerman, 2016). The conceptual frameworks of developmental phenomenography and VTL were guided the researcher in the research process.

Phenomenographic physics education studies in undergraduate programs have started to use phenomenography and VTL in combination (Wright & Osman, 2018; Svensson, 2016; Stamouli & Huggard, 2007). Phenomenography and VTL respectively characterised as a theory of awareness and learning (Åkerlind, 2018). Since the VTL developed from the traditional phenomenographic research approach, both of them are interrelated. That is, both of them focus on the different ways students understand a disciplinary concept. To make it clearer, both of them focus on critical aspects of a concept discerned by students. Phenomenographic researchers emphasise the link between phenomenography and VTL to integrate the researches on teaching and learning (Svensson, 2016). That is researches conducted on teaching and learning is not separable.

Even though phenomenography and VTL are interrelated, there is a difference between them. Both of them can be explained in terms of the critical aspects. Phenomenography identifies and describes the critical aspects of an object of learning. The VTL describes the same critical aspects as the necessary conditions for learning in phenomenographic study (Wright & Osman, 2018). The necessary conditions for learning are identified and organised using the VTL(Marton & Tsui, 2004). Pang and Ki (2016) emphasise the "critical aspects" as a "linking thread" between phenomenography and VTL. The VTL is used to analyse the intended, enacted, and lived object of learning based on its critical aspects in an integrated way. It can be used to analyse the students' interaction with the object of learning based on its critical aspects (Park et al., 2009; Bussey et al., 2013). Phenomenography can reveal and describes the critical aspects without considering the nature of learning and what makes learning possible. However, VTL discusses the nature of learning and the conditions that make learning possible.

Historically, there was a paradigm shift in designing instruction, from behaviourism to cognitivism and then to constructivism/interpretivism (Cooper, 1993). The learning theories can be looking from three levels, namely, philosophical, theoretical, and practical or classroom instructional level. Ling Lo (2012) stated that the learning theories developed from philosophical assumptions while the different teaching strategies developed from learning theories. The practicability of the teaching strategies tested in the classrooms is based on educational research. Constructivist researchers think about a dualistic ontology. That is they think about the subjective and objective real world. This reflects the existence of dualistic ontology. Constructivism has been one of the most influential views of learning. Constructivism focuses on the construction of our knowledge based on pre-existing knowledge by reflecting on our experiences. Constructivist learning theory developed from constructivist philosophical assumptions. Furthermore, the learning theory developed into different instructional strategies such as guided inquiry and cooperative learning instructions. Constructivist instruction is designed based on constructivist learning theory.

Phenomenography is underpinned by the interpretivism paradigm, which is the concern of this study. According to interpretivism, reality needs to be interpreted (Denzin & Lincoln, 2005). Phenomenographic researchers think about the non-dualistic ontology. That is they believe that there is only one real world. That real world exists in the linkage between an individual and the external real world (see Section 3.3). Thus, the phenomenographic perspective provides a non-dualistic ontology as an alternative to the dualistic ontology of constructivism. Phenomenography assumes that the world is understood by different people differently. The VTL was developed from this assumption; that is, according to this learning theory, different students focus on various aspects of an object of learning. Phenomenographic instructions are designed based on the VTL. That is the VTL is used as the potential source of information for instruction developers and designers in higher education (Åkerlind, 2015). Hence, this learning theory can be developed into a certain instructional strategy that makes learning possible. In this study, MRs-based instruction with interactive learning tutorials is developed and designed using the VTL to make the learning of introductory nuclear physics possible.

The findings of Åkerlind (2015) indicated that phenomenography and VTL can be used for the pedagogical design of undergraduate programmes. Marton and Tsui (2004) also proposed that phenomenography and VTL give a pedagogical framework, which is characterised as 'pedagogy of learning'. This pedagogical framework takes the object of learning as an initial point to investigate the situation that makes learning achievable. From the phenomenographic perspective, pedagogy is a combination of interrelated acts that are aimed at serving students to learn a certain disciplinary subject (Pang & Marton, 2007). In this pedagogical framework, teaching aims to make students learning possible (Ramsden, 1992; Samuelsson & Pramling, 2016). That is, the phenomenographic pedagogy focuses on learning rather than other pedagogical frameworks. That is why the phenomenographic pedagogy is characterised as the pedagogy of learning. The students must discern various critical aspects of a disciplinary concept for the concept to be learnable (Mason, 2011). Therefore, the phenomenographic pedagogy provides a learning environment that can support students to develop their conceptual understanding of a disciplinary concept by discerning its various critical aspects (Bowden, 2000).

CHAPTER 3: RESEARCH METHODOLOGY

3.1 INTRODUCTION

The undergraduate physics students' conceptual difficulties of introductory nuclear physics are discussed in Section 2.5.1. These conceptual difficulties were identified and described based on the related studies and findings in the literature. To be consistent with the context of this study, the course outline and content of the introductory nuclear physics course were analysed based on the Ethiopian undergraduate physics curriculum (see Section 1.2). The selected concepts of introductory nuclear physics are NBE and force, radioactive decay, negative beta decay, and NE (see Section 2.5.2). To identify and describe the students' conceptual difficulties a quantitative research approach was used in previous studies (see Section 2.5.1).

Kohnle et al. (2011) and Rathore (2016) recommended interviewing learners to get additional insight into their conceptual understanding of introductory nuclear physics. Based on this and analysing the content of introductory nuclear physics, a semi-structured face-to-face individual student interview guide was developed and outlined (Appendix I). The interviews aimed at gaining more insight into students' conceptual understanding and representations of nuclear physics. Such an interview technique is relevant to the developmental phenomenographic research approach. The semi-structured nuclear physics conceptual investigation interview questions were prepared and organised by analysing the contents of introductory nuclear physics and the purpose of this study. This research instrument was used to gather data from the first group of students in the first phase. In the second phase, the open-ended nuclear physics conceptual investigation questionnaire was derived from the semi-structured conceptual investigation interview questions. This research instrument was used to gather data from the second group of students at pre-, post-, and delayed post-intervention. These instruments assisted the researcher to reveal the variation in students' understanding and representations of a nuclear physics concept. The exploratory case study research design was used. This design was underpinned by the conceptual frameworks of developmental phenomenography and VTL. This was used to identify and then to address the conceptual difficulties of nuclear physics. The VTL is used as a lens to identify and organise the necessary conditions for learning. The instructional intervention that was used to address the conceptual difficulties was designed based on these learning conditions and the conceptual difficulties.

3.2 BACKGROUND FOR THE RESEARCH PARADIGM OF THIS STUDY

3.2.1 Definition of the Research Paradigm

Research depends on a certain research paradigm, which originated from the Greek word paradeigma that means pattern. The term paradigm was first used by Kuhn (1962). A research paradigm constitutes the research traditions with a set of ideas, ethics, assumptions, the nature and conduct of research that the research community has in general (Kuhn, 1977). These are very important in identifying the research problems and addressed them. The paradigm concept of Kuhn (1977) and Lee and Hill (1979) is used in social sciences to define the increasing interest in qualitative research. Guba and Lincoln (1994) also said that a research paradigm is a set of basic philosophical ideas that guide the research investigators. These scholars claim that a research paradigm has an impact on visualising the real world and determining our research perspectives. In other words, a research paradigm is a framework for the process of our scientific investigation. Hence, the research paradigm leads and guides the whole process of research within this framework.

3.2.2 Components of the Research Paradigms

Philosophers distinguished the research paradigm based on their components. The main components of a paradigm are ontology, epistemology, and methodology. As Morgan (2007) said, these come from the philosophy of knowledge. According to Guba and Lincoln (1994), ontology is the component of a paradigm that shows how the researcher defines the real existing world. Epistemology is the component of a paradigm that indicates how the researcher comes to know the real existing world. The methodology is the method that can be used in carrying out the study such as data collection and analysis methods. Guba (1990) also said that the methodology is about how a researcher carries out his study on revealing information. The data collection and analysis methods again depend on the quantitative and qualitative research approaches. The ontological and epistemological philosophy perspectives are very important in selecting a research methodology and the methods that are used in a particular study.

3.2.3 Classifications of a Research Paradigm

According to Guba (1990), there are three basic classifications of a research paradigm. They differ in ontology, epistemology, and methodology aspects in social science research. These are the positivist, constructivist and critical paradigms. The post-positivist paradigm is discussed by philosophers as a separate paradigm from positivism. The basic assumptions of post-positivism are not different from those of positivists. This changed the classifications of the research paradigm into the positivist, the post-positivist, the constructivist, and the critical paradigms. The classifications of a research paradigm have changed over time. For instance, Lather (2006) described our research paradigms: positivist, interpretivism, critical, and postmodern.

As discussed in Section 3.2.2, the methodology that can be used in conducting a study is selected based on the kind of research paradigm. On the whole, the quantitative research methodology was selected by researchers based on the positivist paradigm, while the qualitative research methodology was selected based on the constructivist or interpretivist paradigm. Positivist researchers consider that reality is independent of social construction. That is, they believe in the existence of an objective, external real world. Constructivists believe that reality exists in people's personal experiences of the external objective world. Hence, the reality is socially constructed by a human being (Mutch, 2005). Interpretivists hold that reality is recognised through interpretation. The critical paradigm is concerned with historical realism, transactional or value-mediated findings, and dialogic methodology (Lincoln & Guba, 1985, 2005).

3.3 THE RESEARCH PARADIGM OF THIS STUDY

Among the paradigms mentioned in Section 3.2, the research paradigm that was suitable for this study is the interpretivism research paradigm. This paradigm is located within a research paradigm focused on understanding (Lather, 2006). According to this research paradigm, the reality is interpreted and then understood by researchers (Walsham, 2006). The developmental phenomenographic research approach is relevant to this study. Within this research approach, the students' conceptual difficulties of nuclear physics were identified and addressed. Phenomenography is a qualitative research approach, which is linked to the interpretivism research paradigm. Phenomenography aimed at investigating the students' different ways of conceptual understanding and representations of nuclear physics in this study. In the context of this study, non-dualistic ontology, relational epistemology, and phenomenographic research methodology are the components of interpretivist research paradigm. The research paradigm that led and guided the whole process of this research is inherently linked with these components of the interpretivism paradigm. The phenomenographic research methodology supported the researcher in describing how the students in the same situation can understand the same concept differently.

According to the non-dualistic ontology, which is a phenomenographic ontological assumption, there is only one world. Marton and Booth (1997) were accepted the non-dualistic ontology and argued that there is only one world. According to these scholars, that one world exists in the linkage between the human being and the object in the external world. Phenomenographic researchers like Marton and Booth (1997) think that as all of us are different, we experience the world differently. In the context of this study, the object of the study is the linkage of the student (person) and the nuclear physics concept (external world) (see Figure 2.2). However, the person and the world are two distinct entities (dualistic ontology) in the view of traditional positivists. In other words, they consider the subjective world and objective world that oppose the non-dualistic ontology. Relational epistemology is a phenomenographic epistemological assumption. According to relational epistemology, knowledge is assumed as it exists in the linkage between the person and the world (Pang, 2003). The phenomenographic research methodology refers to how a phenomenographic researcher carries out his study. In other words, it refers to how a researcher carries out his study to probe and reveal the information found in the linkage of the person and the world. It is a kind of qualitative research methodology underpinned by exploratory research design. In other words, it is the method used in investigating the phenomenographic study. According to Park et al. (2009), the phenomenographical research method usually describes the different experiences or understanding of people. Phenomenographic data-gathering and analysis methods are used in this study.

In this study, the researcher explored how the students dealt with the concepts of introductory nuclear physics. The object of the study was to determine the various ways of students' understanding of the concept of introductory nuclear physics. Phenomenography was used to reveal the variation in ways of students' understanding of this concept. Variation theory is used to explain how such variation occurs (Park et al., 2009). The VTL is used as a lens to analyse the students' conceptual learning processes and their outcomes based on the critical aspects discerned by them. The research paradigm of this study also involves the VTL as its fourth component in addition to non-dualistic ontology, relational epistemology, phenomenographic research methodology. These are presented in Table 3.1. The first column shows the general components. The second column shows the four components of interpretivism, which is the research paradigm of this study. The third column shows the assumptions of the four components. These four components of the research paradigm guided the researcher throughout the study.

Table 3.1: The research paradigm (philosophy) of this study

Components of research paradigm	**Phenomenographic research paradigm (Interpretivism)**	**Assumptions of the components of the research paradigm of this study**
Ontology	Non-dualistic ontology	There is only one world that exists in the linkage of the person and the world
Epistemology	Relational Epistemology	Knowledge is assumed to be constituted in the linkage of the person and the world
Methodology	Phenomenography	Students in the same situation can understand the same world differently
Theory	Variation theory of learning	For students to learn and understand the world, they must discern its various critical aspects

3.4 PHENOMENOGRAPHIC RESEARCH METHODOLOGY

A phenomenographic research methodology, which is a type of qualitative research methodology, was used. This methodology is underpinned by an interpretive relational epistemology and non-dualistic ontology (Sections 3.3). A phenomenographic research perspective is a belief system within the interpretivist research paradigm. The phenomenographic research perspective does not consider the person and the world separately as the traditional positivism research paradigm does. Instead, it seeks the linkage between the human being and the external world. This is the assumption of non-dualistic ontology that assumes there is only one world (Section3.3). That one world is the internal relation between the person and the aspects of the world. The knowledge is constituted through this internal relationship, which is the assumption of relational epistemology (Pang, 2003). Therefore, the object of the study of phenomenographic research approach is the internal relation between the person and the aspects of the world (see Figure 2.2).

The main objective of this study was to explore the undergraduate physics students' various ways of understanding and representations of the concepts of introductory nuclear physics. The concepts considered for this study were NBE, nuclear force, radioactive decay, negative beta decay, and NE. Hence, the object of this study is the internal relation between the students and these concepts. Phenomenography is selected as an appropriate qualitative research approach for this study based on the literature review (Carbone et al., 2007; Marton, 1981, 1986; Marton & Pong, 2005). These scholars claim that the various ways of students' understanding of a concept are described in terms of the aspects of the concept that students are aware of and those that they are not aware of. The various ways of students' conceptual understanding and representations of nuclear physics are identified and described using phenomenography. This means phenomenography was used as an analytical framework to explore students' various ways of understanding and representations of a nuclear physics concept.

In this study, a developmental phenomenographic research approach was selected and used instead of a 'pure' phenomenographic research approach to reveal and enhance the different ways of students' conceptual understanding and representations. The outcomes of a 'pure' phenomenographic analysis process are presented in terms of categories of description, which are not the only objective of the developmental phenomenographic research approach. These research outcomes were used afterward to address a certain educational issue such as students' conceptual difficulty in developmental phenomenography (Green & Bowden, 2009; Han & Ellis, 2019). In the first phase of this study, the students' conceptual difficulties were identified and described based on the categories of description constructed. This was done using the VTL as a lens to analyse the conceptual learning process and its outcomes. This VTL was used as a source of information to design instruction that was used to address the students' conceptual difficulties during the intervention (see Sections 5.2). Therefore, this study focused on a developmental phenomenographic research approach rather than a pure phenomenographic research approach (see Section 2.7.3).

The developmental phenomenographic research approach that was used in this study had three phases. In the first phase, the first group of students was exposed to traditional instruction for 12 hrs and 50 minutes or six weeks. That is, they were exposed to learning the five concepts of introductory nuclear physics. The conceptual difficulties that students encountered after traditional instruction were identified and described in the first phase. In the second phase, the second group of students' prior conceptual understanding and representations of introductory nuclear physics were explored. In this phase, an instructional intervention was developed, designed, and then implemented for the second group of students. The intervention was developed and designed based on the VTL to address the students' conceptual difficulties identified in the first phase. The students' prior conceptual understanding and representations were considered in designing the intervention. In the third phase, the effectiveness of the intervention in addressing the students' conceptual difficulties was explored. How this study was carried out in each phase is discussed in the following subsections. The overview of the phenomenographic methodological procedures that were used in each phase is represented using a diagram drawn by the researcher (see Figure 3.1 – 3.4).

3.4.1 First Phase

In the first phase, a group of second-year physics major students was exposed to traditional instruction for 12 hrs and 50 minutes to learn the five concepts of introductory nuclear physics. This instruction was implemented between November 2018 and January 2019 based on the course outline presented in Table 1.1 or Section 1.2. After the traditional instruction had been completed, data was collected from the first group of students. Face-to-face semi-structured individual interviews were used to gain in-depth information about the students' conceptual understanding and representations of introductory nuclear physics (Patton, 1991). This interview technique is relevant to the phenomenographic research methodology (see Section 3.5.3.1). The interviews were recorded by an integrated circuit (IC) audio recorder and then transcribed. The transcribed data were analysed using the phenomenographic research analysis method (see Section 3.5.5.1). After the analysis process, the categories of description were constructed in the first phase after traditional instruction (see Chapter 4). These categories of description were the outcomes of the phenomenographic analysis process that represented the first group of students' conceptual understanding and representations of introductory nuclear physics. The VTL was used as a lens to analyse the learning process and its outcomes based on the categories of description. This analysis was done based on the critical aspects discerned by students. The categories of description formed a basis for identifying the conceptual difficulties that the first group of students encountered during traditional instruction. The methodological procedure used in the first phase is represented in Figure 3.1.

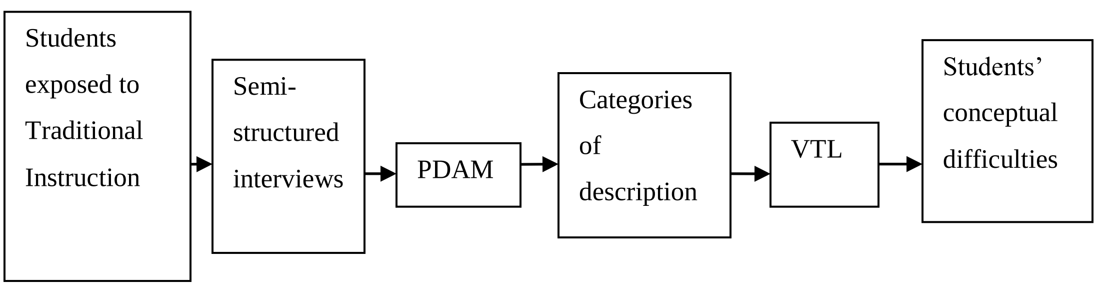


Figure 3.1: Overview of the methodological procedure in the first phase of this study

The abbreviations PDAM and VTL indicated in the diagram represent phenomenographic data analysis method and variation theory of learning respectively.

3.4.2 Second Phase

This group of students was the second-year undergraduate physics major students like that of the first group of students. The second group was equivalent to the first for the reason mentioned in the context of this study (see Section 1.2). Data was collected through an open-ended conceptual investigation questionnaire from the second group of students at pre-, post-, and delayed post-intervention. The results of the analysis at the three points were presented and discussed in the third phase (see Chapter 6).

3.4.3 The Conceptual Understanding and Representations of the Second Group of Students at Pre-Intervention

The students' conceptual understanding and representations of nuclear physics at pre-intervention were explored using an open-ended conceptual investigation questionnaire. The results obtained at pre-intervention and the corresponding discussions were presented in the third phase in a table together with that of post- and delayed post-intervention. This assisted the researcher to understand the baseline of the student's conceptual understanding and representations of introductory nuclear physics at pre-intervention. The information obtained from the results and discussions at pre-intervention was used in developing and designing an instructional intervention.

3.4.4 Development and Design of an Instructional Intervention

To address the students' conceptual difficulties identified in the first phase and at pre-intervention, the instructional intervention was developed and designed based on the VTL. Rathore (2016) recommended using research-based tutorials and peer-instruction tools to reduce the students' conceptual difficulties of nuclear physics. The MRs-based instruction with interactive learning tutorials was selected to address the students' conceptual difficulties and enhance their conceptual understanding and representations. "Students learn more deeply from a multimedia explanation presented in words and pictures than in words alone" (Mayer, 2003, p.131). When developing and designing teaching strategies based on VTL, the students should be provided with the opportunity to discern various critical aspects of a disciplinary concept. According to the VTL, critical aspects are the necessary conditions for learning, which must be taken into consideration in designing instructions (see Section 2.8). If an instruction is designed in this way, the "VTL is compatible with the majority of teaching strategies currently promoted" (Ling Lo, 2012, p.109). Discerning various critical aspects can support the students to enhance their conceptual understanding. The critical aspects discerned by learners were identified using the VTL as a lens. In such a way, the VTL provided critical information for developing and designing the MRs-based instruction with interactive learning tutorials in this study (see Chapter 5).

3.4.5 The Second Group of Students was exposed to the Designed Intervention

The MRs-based instruction with interactive learning tutorials was implemented from November 2019 to February 2020. MRs-based instruction was used to address students' different learning styles in addition to addressing their conceptual difficulties. That is, it was used to address the audio, visual, and kinaesthetic learning styles of the students. The different forms of representations used in this study were verbal, text, equation, symbolic, numerical, graphical, diagram, exchange-force model, liquid-drop model, interactive simulation, animation, educational videos, and concept map forms of representations. MRs literacy are required if instructors are to meet the challenges of students' conceptual learning and understanding the difficulties of abstract concepts (Stokes, 2002). MRs is used to display and present these abstract concepts for learners, which enable them to visualise and think about the concepts.

The students had carried out the designed MRs-based interactive nuclear physics learning activities individually and in small tutorial groups via the facilitation of the researcher (see Section 5.2.2 – 5.2.6). The researcher was on the lookout for students to develop their scientific representational competence of a nuclear physics concept in the classrooms (T. S. Volkwyn et al., 2020). During the MRs-based interactive nuclear physics learning activities, the students were provided with an opportunity to speak, write a text, express equations, draw a graph, draw a diagram, and perform the interactive simulations. All of these allowed students to develop their scientific representational competence; visualisation ability, critical thinking skills, and then in-depth understanding of an introductory nuclear physics concept (see Section2.6).

3.4.6 Third Phase: The Effect of the Instructional Intervention on the Second Group of Students

3.4.6.1 Pre-intervention

The data was collected and analysed at pre-intervention to obtain information that was used to develop and design an instructional intervention in the second phase (see Section

3.4.2.1). However, the data analysis method, results, and discussions were presented in the third phase. The results at pre-intervention for each of the five concepts of introductory nuclear physics are presented together with the results at post- and delayed post-intervention in the same table (see Chapter 6). This way of presentation makes it easy to understand the change in students' conceptual pathways because of the intervention. The methodological procedure used at pre-intervention is represented in the next diagram (Figure 3.2). The categories of description in Figure 3.2 represent the second group of students' different ways of conceptual understanding and representations at pre-intervention.

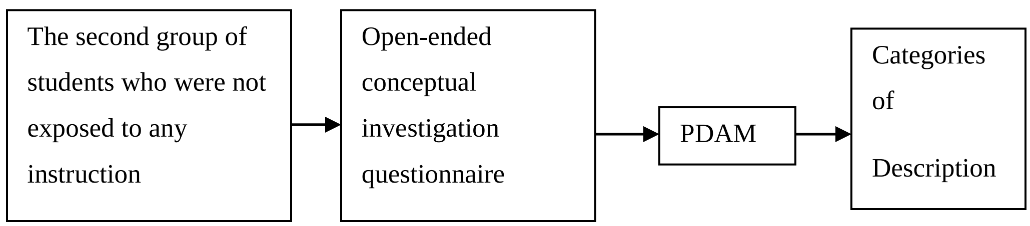


Figure 3.2: Overview of the methodological procedure at pre-intervention in the second phase

3.4.6.2 Post-intervention

After the completion of the instructional intervention, data was collected from the second group of students. The data was collected through an open-ended nuclear physics conceptual investigation questionnaire to gain more insight into students' conceptual understanding and representations of introductory nuclear physics (see Section 3.5.4). The collected data was analysed using the phenomenographic research analysis method (see Section 3.5.7). The VTL was used as a lens to analyse the conceptual learning process and the outcomes achieved because of the intervention. This assisted the researcher to explore the improvement in the students' conceptual understanding and representations of introductory nuclear physics because of the intervention. In other words, the effectiveness of the instructional intervention in enhancing the students' conceptual understanding and representations was explored. The enhancement was explored based on the change in the number of research respondents discerning the critical and irrelevant aspects of each of the five nuclear physics concepts at pre-, post-, and delayed post-intervention (see Tables 6.1 – 6.5). The change in the number of non-respondent students from pre-to-delayed post-intervention was also presented in these tables. The non-respondent students are students who did not respond at all to the open-ended conceptual investigation questionnaire.

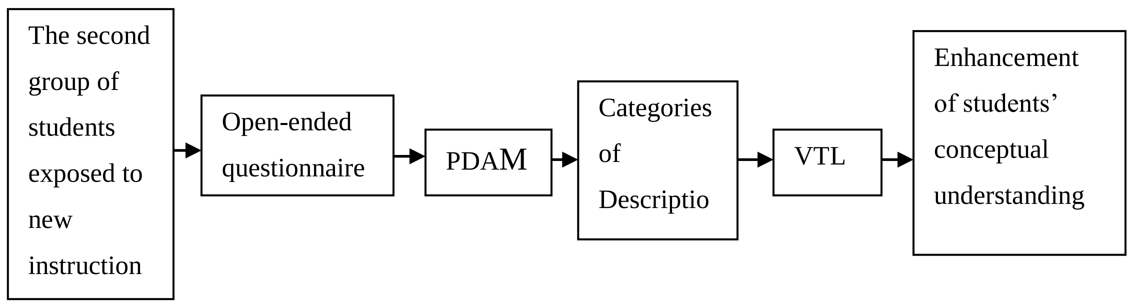


Figure 3.3: Overview of the methodological procedure at post-intervention in the third phase

The methodological procedure followed at post-intervention is presented in Figure 3.3. The categories of description indicated in Figure 3.3 represent the second group of students' different ways of conceptual understanding and representations at post-intervention. The enhancement of students' conceptual understanding and representations was analysed based on the categories of the description using the VTL.

3.4.6.3 Delayed post-intervention

To explore whether the students retained their conceptual understanding and representations of introductory nuclear physics after eight weeks of delayed post-intervention data was collected through the open-ended nuclear physics conceptual investigation questionnaire (see Section 3.5.4).

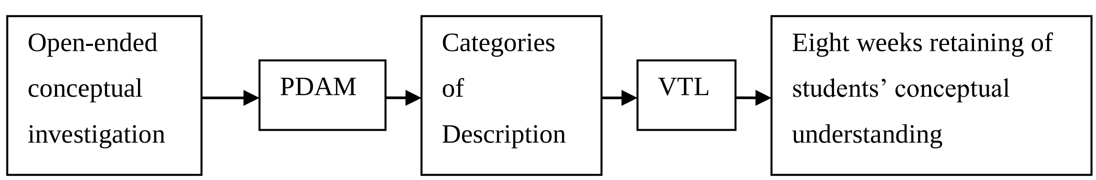


Figure 3.4: Overview of the methodological procedure at eight weeks of delayed post-intervention in the third phase

The collected data was analysed using the phenomenographic research data analysis method (see Section 3.5.7). Based on the results of this analysis process and the pool of data the categories of description were constructed at eight weeks of delayed post-intervention. The VTL is used as a lens to analyse the conceptual learning process and its outcomes based on the categories of description at delayed post-intervention. The results of this analysis process assisted the researcher to understand whether the students retained their conceptual understanding and representations of introductory nuclear physics for eight weeks of delayed post-intervention. See the methodological procedure used at delayed post-intervention in Figure 3.4. The categories of description in Figure 3.4 represent the second group of students' different ways of conceptual understanding and representations after eight weeks of delayed post-intervention.

In summary, the first group of students' conceptual understanding and representations of introductory nuclear physics were explored after they had been exposed to traditional instruction. The second group of students did not take the introductory nuclear physics course before the intervention. This group of students' prior conceptual understanding of introductory nuclear physics was explored. This second group of students was exposed to MRs based instructional intervention with interactive learning tutorials. The students' conceptual understanding and representations of introductory nuclear physics were explored at post- and delayed post-intervention. The results were found at the three points of intervention used to explore the effectiveness of the used instructional intervention in addressing the students' conceptual difficulties.

3.5 EXPLORATORY CASE STUDY RESEARCH DESIGN

According to Kothari (1985), the research design involves the conceptual structure of what the researcher will do starting from identifying and defining the research problem to the final results of the study. This scholar also said that it is the plan of data collection and analysis processes. Other scholars have also said that a research design is an important plan in a research process that directs the ways of data gathering and analysis of a particular research approach (Kinnear & Taylor, 1996). It mainly involves the kind of data to be collected (qualitative or quantitative), its source (population and its sample), and the data collection and analysis procedures (Ejigu, 2014).

The research design selected for this study is an exploratory case study research design. It is a type of qualitative research design intended to explore how undergraduate physics students understand and represent the introductory nuclear physics concepts (Steinert et al., 2016). The exploratory case study research was designed based on a developmental phenomenographic research approach implemented in three phases. An exploratory case study is suitable when researchers think to formulate the research questions to be probed in successive phases of a study (Yin, 2014, 2018). This research design was underpinned by the developmental phenomenographic research approach to explore the various ways of undergraduate physics students' conceptual understanding and representations of nuclear physics. Two groups of students were selected from one of the Ethiopian governmental universities. In-depth exploration was used to reveal the first group of students' conceptual difficulties in the first phase after they had been exposed to traditional instruction. An interventional instruction used on the second group of students was developed and designed in the second phase. The effectiveness of the intervention in reducing the conceptual difficulties explored in the third phase. In other words, an educational issue was identified in the first phase and the issue was treated in the subsequent phases. This is the main principle of the developmental phenomenographic research approach, which is in agreement with an exploratory case study research design (see Section 2.7.3).

3.6 PILOT STUDY

Phenomenographic pilot interviews were conducted on 11 undergraduate physics major second-year students who did not participate in the main interviews. The pilot interviews supported the researcher to correct the wrong ways of wording/phrasing of the prearranged semi-structured interview conceptual questions. From the pilot study, the researcher developed his experiences in carrying out phenomenographic semi-structured interviews, developed the skill of audio recording the verbal responses of the research participants using IC-recorder, and the way of understanding their thinking. The undergraduate physics major second-year students who were participated in the pilot interviews were not included in the main study. The students selected for the pilot and main studies involve the high, medium, and low achievers.

3.7 THE SAMPLE OF THE STUDY

3.7.1 The Sample of Students in the First Phase

The sample of students who were selected in the first phase was a group of undergraduate second-year physics major students, who had taken the introductory nuclear physics course. This course was presented to the students by the researcher using traditional instruction. Phenomenography is a type of qualitative research approach used in this study. Compared to quantitative the qualitative research uses much smaller sample sizes (Strauss & Corbin, 1998). Using a sample size of 15 to 25 students is acceptable in a pure phenomenography as it is manageable. This will reveal the different ways of students' conceptual understanding, which is suitable to make a justifiable interpretation of these results (Trigwell, 2000). Using a sample size of 25 – 30students interviewed in phases is acceptable in doing developmental phenomenography (Bowden & Green, 2005). A sample size (N = 30) was selected from 49 undergraduate physics major second-year students who had taken the introductory nuclear physics course by using a maximum variation sampling strategy based on their academic achievements (Patton, 2002). This means the sample of the first phase comprised 30 students that involve high, medium, and low academic achievers.

The undergraduate physics major students selected for this study were the students enrolled in the researcher's home university in the 2018/2019 academic year. There were six reasons for selecting these students from the researcher's home university. First, qualitative research needs a small sample size compared to that of quantitative research. Second, using the different available academic resources in the researcher's home university during the intervention was more convenient than using the resources of other universities. In addition to this, time and money were saved. Third, it was easier to convince the students enrolled in the researcher's home university to participate voluntarily in the three phases of this qualitative research rather than students in other universities. Fourth, in developmental phenomenography, data was collected and analysed qualitatively in all the phases. Fifth, the physics major students were assigned harmoniously (medium to lower achievers) to the Ethiopian governmental universities. Top achievers are assigned in medicine, engineering, and others. All governmental universities have the same academic resources and curriculum. Sixth, there were serious security problems in the country during the period of data collection. This restricted the researcher to conduct his study at his home university. At that time there was violence against the government throughout the country. So, moving from one place to another was risky.

Therefore, using the students in his home university as the research participants were more convenient to achieve the objectives of the developmental phenomenographic research approach rather than using the students in other universities. Semi-structured face-to-face individual interviews were used to collect data from 30 students in the first phase. The students had responded verbally and using pen and paper. They used pen and paper to express equations, to draw graphs, and to draw diagrams. An open-ended nuclear physics conceptual investigation questionnaire was developed from the validated semi-structured interview questions and the responses of the students to collect data in the second and third phases.

3.7.2 The Sample of Students in the Second Phase

The sample of students in Phase 1 was another group of undergraduate second-year physics major students who were exposed to new instruction. In Phase 2, the sample size (N = 40) of a new second group of students, who were enrolled for the introductory nuclear physics course in the academic year of 2019/2020 was used. These 40 students responded to an open-ended nuclear physics conceptual investigation questionnaire non-verbally using pen and paper. They responded in written explanations, expressing equations, drawing graphs, and drawing diagrams. In the first phase, each of the 30 students responded to the semi-structured interviews while in the second phase, 40 students responded to the open-ended questionnaire non-verbally at pre, post, and delayed post-intervention. Conducting interviews for the 40 students at these three points is more difficult to manage. Hence, the semi-structured interviews were not conducted in the second and third phases.

The data collected from the second group of students at pre-intervention was analysed and the results were used with the conceptual difficulties identified in the first phase to develop the instructional intervention. The results found at pre-intervention presented in the third phase together with the results found at post- and delayed post-intervention, which was convenient to explore the effectiveness of the intervention (see Chapter 6). How the two research instruments were developed and used to collect qualitative data from the two samples of students is discussed in the following sections.

3.8 RESEARCH INSTRUMENTS

They were used to gather qualitative data from the samples mentioned in the previous subsections. A semi-structured face-to-face individual interview technique was used to gather data from the first sample. The open-ended conceptual investigation questionnaire was used to gather data from the second sample. These data collection techniques helped the researcher to gain in-depth information from the qualitative research participants. Gaining in-depth information is the main concern of almost all qualitative research designers. The students' conceptual understanding and representations were explored through the semi-structured interviews in the first phase while in the second phase at pre-intervention and the third phase at post- and delayed post-intervention were explored through the open-ended questionnaire.

3.8.1 Semi-Structured Face-to-face Individual Interviews

3.8.1.1 Development of the semi-structured face-to-face individual interviews

These were developed from the validated conceptual diagnostic survey in nuclear physics that was developed by Kohnle, Mclean, and Aliotta (2011). The researcher communicated with Ms Kohnle, who was the principal investigator of the research team via email. Initially, she was not willing to send the research instrument. However, after repeated email communication, Ms Kohnle sent the validated conceptual diagnostic survey in nuclear physics via email to the researcher's supervisor. The researcher's supervisor sent the research instrument via email to the researcher.

The conceptual diagnostic survey was initially administered with free-text answers, from which the multiple-choice version was developed. The researcher developed semi-structured face-to-face individual interview questions from this multiple-choice version. Particularly, the multiple-choice conceptual questions of NBE, nuclear force, radioactive decay, and negative beta decay were developed into the semi-structured interview questions. These contributed to 80% of the semi-structured interview questions prepared by the researcher. The fifth nuclear physics concept included in this study was the concept of NE. The semi-structured interview conceptual questions of NE were developed by the researcher. Even if, the concept of NE was not included in Kohnle et al.'s (2011) study, the concept of nuclear reactions was included in their study. The concept of NE is linked to the concept of nuclear reactions. Almost, 20% of the semi-structured interview conceptual questions were developed based on the teaching experiences of the researcher and the content of introductory nuclear physics.

3.8.1.2 Phenomenographic interview guidelines

To overcome some potential interview problems, the phenomenographic interview guidelines proposed by skilled phenomenographic researchers (Bowden & Green, 2005; Kvale, 1996) were adopted and used. The proposed phenomenographic interview guidelines are stated as follows:

1. Neutral questions should be asked to encourage the interviewee to say more and then to obtain deeper information
2. Particular questions could be asked by the interviewer to gain more information about the issues raised by the interviewee in previous interviews
3. Specific questions that invite reflection by the interviewee about things they have said could be asked by the interviewer
4. The central purpose of phenomenographic interview is to support the interviewees to expose as much as possible their understanding of a certain phenomenon or a concept
5. All subsequent questions which must be non-directive questions are aimed at finding out what the interviewees thinking
6. The interviewer must take utmost care to avoid adding his ideas to the interview questions

The quality of the instruments used in research is very important, because, the accuracy of the research findings depends on the data obtained through research instruments (Fraenkel et al., 1990). Therefore, the validity and reliability of the research instruments were checked before the beginning of the data gathering. The validity and reliability of the semi-structured interviews are discussed in the following sections.

3.8.1.3 Content and face validity of the semi-structured interview

According to Fraenkel, Wallen, and Hyun (1990) and Gibbs (2007), the validity of the interview refers to the researcher's check for the quality of the qualitative research instrument by using certain procedures to achieve accurate findings. Kohnle et al. (2011) nuclear physics conceptual diagnostic survey validation, an analysis of the initially administered free-text answers, and the particular student difficulties discussed in their article. The contents of introductory nuclear physics were analysed before the preparation of the primary version of the semi-structured interview protocol. The phenomenographic pilot interview was conducted based on the primary version before the preparation of the main semi-structured. This supported the researcher to check the content and face validities of the interview questions (see Section 3.5.1). Face validity means checking whether the questions asked measure what the researcher had been intended (Cannell & Kahn, 1968; Lindzey & Aronson, 1968).

The realistic way of getting more validity of the interview is to reduce the quantity of bias to the lowest level (Cohen, Manion, & Morrison, 2007, 2009). Cohen et al. (2007) said that the causes of bias may be the interviewer, the respondent, and the substantive content of the questions. The amount of bias could be minimised using the pilot interview and developing the confidence of both the interviewer and respondent. The confidence of the interviewer developed based on his subject matter knowledge, reading related literature, his teaching experiences, taking related training, and in the process of the pilot interview. The substantive content questions of the interview were modified using the interviewee's responses to the pilot interview as a basis. The questions were also modified based on the comments given by two nuclear physics instructors and one physics education specialist. The respondents were well informed concerning the essence and objectives of the study before the interviews were started. The final version of the semi-structured interview questions organised by the researcher is available in Appendix I. A number code is assigned to each participant for the sake of confidentiality.

3.8.1.4 Reliability of the semi-structured face-to-face individual interviews

The reliability of qualitative research instruments indicates that the researcher's approach is consistent that could be used by other researchers (Gibbs, 2007). The researcher selected the developmental phenomenographic research approach based on the literature review because it is relevant to the research problem of this study. The phenomenographic researchers confirmed that the semi-structured interviews are relevant to the developmental phenomenographic research approach (Åkerlind, 2005; Booth, 1997; Patton, 2002). The same interview guide was used for all respondents to control the reliability of the interviews.

3.8.2 Open-Ended Conceptual Investigation Questionnaire

The open-ended nuclear physics conceptual investigation questionnaire (NPCIQ) was derived from the validated interview questions that were used to collect data in Phase 1. The open-ended questionnaire was used in the second and third phases. Some questions were directly copied from the semi-structured face-to-face interview questions. The open-ended NPCIQ was developed based on the interview questions, the responses of the students to the interview question, the purpose of this study, and the experiences of the researcher. The validity and reliability check-up of the open-ended conceptual investigation questionnaire are discussed in the following sections. The final version of the open-ended NPCIQ is available in Appendix III.

3.8.2.1 The validity of the open-ended conceptual investigation questionnaire

This research instrument considered is a validated instrument since it is derived from the validated semi-structured interview. The open-ended NPCIQ was modified based on the comments and suggestions given by the two nuclear physics instructors and one physics education specialist. The relevance of the questionnaire to the selected content of introductory nuclear physics and other structural problems was checked, corrected, and then modified based on the comments. These assisted the researcher to establish the content validity, credibility, and applicability of the open-ended nuclear physics conceptual survey questionnaire.

3.8.2.2 Reliability of the open-ended conceptual investigation questionnaire

This research instrument is considered a reliable instrument since it was derived from the validated semi-structured interview. This open-ended NPCIQ was also included in tests and final exams of the introductory nuclear physics course and then modified based on the responses of the students. Because of this, the appropriateness of the questions, wordings, and ambiguity in question-wording checked, corrected, and then modified. This assisted the researcher to set up a reliable research instrument. That is, to set up a reliable open-ended NPCIQ.

3.9 DATA COLLECTION METHOD

3.9.1 Data Collection Method in the First Phase

In the first phase, data were collected using the semi-structured face-to-face individual interview technique from 30 students. In this phase, data were collected after the students were exposed to traditional instruction. The developmental phenomenographic research approach was used to probe the three research questions of this study (Bowden & Green, 2005; Dall'Alba & Hasselgren, 1996; Green & Bowden, 2009; Marton, 1981, 1986). A semi-structured interview is a qualitative data collecting technique relevant to the phenomenographic research perspective (Åkerlind, 2005; Booth, 1997; Patton, 2002). Because the emphasis of the interview technique is to use open-ended questions that motivate the research participants to say more about their understandings. Thus, the participants were given a chance to express their understandings in verbal, text, equation, graph, diagram, and other forms of representations (Edwards, 2007).

In the first part of the semi-structured interviews, the researcher asked the students questions in which they respond verbally to gain in-depth information about the students' conceptual understanding. And in the second part, they were asked to respond by expressing equations, drawing graphs and diagrams, and by using other forms of representations. Based on the willingness of the participants, the researcher recorded the conversations that took place in the process of the interview using the IC audio recorder. The researcher convinced the participants to use audio recorder as he was able to carry on an attentive conversation with them could get all the relevant information from them at the same time.

The face-to-face semi-structured interviews were held from Monday to Friday for two weeks in the physics laboratory. This has been done based on the semi-structured face-to-face individual interview timetable suitable to both the researcher and students. Three students were interviewed per day based on their appropriate time either in the morning or in the afternoon. And the appropriate shift was assigned for each of the research participants based on their willingness. The approximate length of the face-to-face semi-structured individual interview was 50 minutes. The semi-structured face-to-face individual interview schedule format was prepared before the interview started (see Appendix II).

3.9.2 Data Collection Method in the Second and Third Phases

The open-ended NPCIQ was used to collect data from the second group of students. At pre-intervention, the questionnaire was administered two days before the instructional intervention was developed, designed, and used in the second phase (Ejigu, 2014). The purpose of this was to identify the students' pre-existing conceptual understanding and representations and then to use the information obtained in developing, designing, and using the intervention in the second phase.

At pre-intervention, the data was collected and analysed in the second phase. However, the results were presented in the third phase together with the results found at post- and delayed post-intervention in the same table. This was a suitable way to explore the effectiveness of the intervention. In the third phase, the results found at pre-intervention were used as a baseline and compared to the results found at post- and delayed post-intervention to explore the effectiveness of the intervention. In the second phase, the results found in the first phase and at pre-intervention were used as a basis to develop the intervention. The questionnaire was administered five days after the intervention was completed in the third phase (Ejigu, 2014). This aimed at exploring the students' conceptual understanding and representations of nuclear physics at post-intervention. The open-ended questionnaire was also administered at eight weeks' delayed post-intervention in the third phase. This aimed at exploring to what extent the students retained their conceptual understanding and representations of nuclear physics (Ejigu, 2014). In the open-ended NPCIQ, the students were asked to respond by writing a text, expressing equations, by drawing a graph and a diagram. The activities in this questionnaire were designed according to the purpose of this study. That is, the open-ended NPCIQ was used to reveal the in-depth different ways of students' conceptual understanding and representations of introductory nuclear physics at pre-, post-, and delayed post-intervention.

3.10 DATA ANALYSIS METHOD

3.10.1 Steps in the Phenomenographic Data Analysis Process used in Both Phases

Some phenomenographic researchers have reported using a data analysis process involving a greater number of steps until the analysis is complete. For instance, González (2010) used five steps while Sjöström and Dahlgren (2002) used seven steps. Using the seven steps in the phenomenographic data analysis of this study assisted the researcher to reduce the complexity of the data analysis process. Therefore, the following seven steps of phenomenographic research analysis were adopted and used in both phases of this study.

1) Transcription and Familiarisation

The researcher repeatedly read the transcripts to identify the main information within the transcript, which was relevant to the purpose of the study.

2) Compilation

In this step, more attentive reading was done to infer similar and different ideas from the transcripts. The main purpose of this step was to organise the participants' responses to the interview questions. In the compilation process, the most valued responses were identified.

3) Condensation

In this step, the extracts relevant and meaningful for the study were selected. The main objective of this step was to remove the irrelevant and redundant or unnecessary participants’ responses after revising the transcript. Consequently, the main essentials of the participants’ responses were identified.

4) Preliminary Categorisation

Here the main focus was to categorise similar responses into the preliminary categories. These preliminary categories were revisited to verify whether the categories under different headings indicated the same meaning or not. Thus, in this step, the first list of categories of descriptions was presented.

5) Preliminary Comparison of Categories

In this step, the first list of categories of descriptions was reviews compare the preliminary categories. The purpose of this step was to differentiate between the categories. Thus, the first list of categories of the description presented in Step 4 was modified. The transcripts were read once more to confirm whether these modified categories of description represented the different ways of participants’ understanding or not.

6) Naming the Categories

The focus of this step was to name the categories based on their real distinguished meanings and internal relationships.

7) Outcome Space

In the final step, the outcome space was found based on the internal relationships of the categories and variation in ways of participants’ understanding. The outcome space represents the categories in a hierarchy.

The collective categories of description and outcome space are discussed in the next section. These are the most important terms in the phenomenographic study.

3.10.2 Categories of Description

They are the outcomes of the phenomenographic data analysis process obtained following the seven steps of the data analysis process mentioned in section 3.10.1. In the hierarchical arrangement of the categories, the researcher used the students’ complicated conceptual understanding and representations of the concepts of nuclear physics as organising criteria. The categories of description are organised into a hierarchy from less complicated to more complicated students' conceptual understanding and representations of the concepts of nuclear physics. In another way, the categories are organised from less powerful to more powerful different ways of understanding and representations of the concept of nuclear physics (Bowden & Green, 2005). According to these scholars, the categories of description are not arranged in a hierarchy based on judgements from 'worse' to 'better'. Instead, the categories of description are arranged in a hierarchy based on the inclusiveness of one category the other categories. The categories of description organised in a hierarchy are known as the outcome space (Åkerlind, 2008). Thus, outcome space is the combination of reasonably linked and empirically grounded categories of description in a pecking order. In this study, the outcome space represents the different ways that each of the five nuclear physics concepts is understood and represented by physics students (Åkerlind, 2005; Park et al., 2009).

Phenomenography seeks to investigate the collective range of ways of understanding and representations of a concept across a group of individual students (Åkerlind, 2005; Larsson & Holmström, 2007). As a result of this, a researcher can construct the collective categories of description. Phenomenographic study does not seek to investigate the complexity of understanding of any individual student. This study aimed to reveal the various ways of a group of students' understanding and representation of a nuclear physics concept (Bruce, 2000; Khan, 2014; Limberg, 2000). Not all students can have the same ways of understanding and representing a nuclear physics concept. The students who had a similar way of conceptual understanding and representing were assigned to the same group. The similar students' conceptual understandings and representations are categorised into one category (see Chapter 4). The other similar students' conceptual understandings and representations are categorised in the second category. Such categories of description are referred to as collective categories of description. These collective categories of description represent the variation that exists in a certain number of students' conceptual understanding and representations of introductory nuclear physics concepts (Marton & Booth, 1997).

Using phenomenography, the researcher identified the different ways of students' conceptual understanding and representations of nuclear physics in phases one, two, and three. These were represented by the categories of description, which constituted the conceptual learning difficulties that the learners encountered and critical aspects discerned by students. Phase 1 means after the students were exposed to traditional instruction. Phase 2 means at pre-intervention and Phase 3 means at post- and eight weeks delayed post-intervention. Therefore, four sets of categories of description were constructed for each of the five concepts of nuclear physics at these four points. The researcher analysed the students' conceptual learning process and its outcomes based on the categories of the description using the VTL as a lens.

3.10.3 Analysis of Data Collected Through Semi-structured Face-to-face Individual Interviews in the First Phase

The data analysis was begun by transcribing all the interviews verbatim (verbal responses), which were recorded by an audio-IC recorder. The transcripts of the interview were checked several times based on the audio recordings to make sure that they did not contain mistakes made during transcription. The transcriptions as well as the audio-recorded original data were documented. Written explanations, drawn pictures, diagrams, and graphs (nonverbal responses) given by the participants were another focus of the phenomenographic data analysis. The nonverbal responses, which were scanned equations, graphs, and diagrams, were also documented. The transcribed verbal responses were analysed together with the nonverbal responses using phenomenographic research analysis. The transcribed verbal responses together with the nonverbal responses are considered as the pool of data in the first phase.

Following the seven steps of the phenomenographic data analysis process mentioned in Section 3.10.1, the different ways of students' understanding and representations were identified. These outcomes of the phenomenographic analysis process are represented using outcome space (Åkerlind, 2005; Bowden & Green, 2005; Marton & Booth, 1997; Yates et al., 2012). These phenomenographic researchers discussed the method of phenomenographic analysis as it is iterative and comparative rather than in order. The outcome space is the categories of description in a hierarchy, which is constructed after the seven steps of the phenomenographic analysis process are completed (see Section 3.10.2. The categories of descriptions in a hierarchy constructed after the students were exposed to traditional instruction for each of the five concepts of nuclear physics are presented in Tables 4.1 – 4.5. These are collective categories of description as discussed in Section 3.10.2.

3.10.4 Analysis of Data Collected Through the Open-ended NPCIQ at Pre-, Post-, and Delayed Post-intervention

The data collected through the open-ended nuclear physics conceptual investigation questionnaires at pre-, post-, and delayed post-intervention from the second group of students were analysed using the phenomenographic analysis method. The research participants responded to the open-ended questionnaire in the form of written texts, expressed equations, drawn graphs, and drawn diagrams. The steps of the data analysis process mentioned in Section 3.10.1 were used to analyse the data collected at the three points. The categories of description constructed in a hierarchy at pre-, post-, and delayed post-intervention after the seven steps of the phenomenographic analysis process were presented in the third phase (see Chapter 6). The data collected at pre-intervention were analysed in the second phase but the results were presented in the third phase for the sake of convenience. According to Åkerlind (2005), the categories of description at the three points of intervention represent the different ways of students' understanding and representations at the three points.

3.10.5 Analysis of the Change in Students' Conceptual Pathways as a Result of the Intervention

The change in students' conceptual pathways because of the intervention explored using a constant comparative analysis method (see Chapter 6). The constant comparative analysis is the qualitative analysis method. In this study, the collective categorisation of the students' conceptual understanding and representations of nuclear physics were coded and recoded into codes of the dimension of variation. In other words, the Constant Comparative Analysis method (CCAM) is an iterative process of reducing the data through constant coding, recoding, and analysis (Kolb, 2012). The CCAM complement the seven steps of the phenomenographic analysis process. The data were constantly analysed starting from the first coding till it becomes more clear and no new categories were constructed (Adadan et al., 2010). The CCAM was used to construct the final students' categories of description of a particular concept of nuclear physics.

In this study, the VTL is used to identify the critical and irrelevant aspects of a particular nuclear physics concept discerned by the students. The non-respondent students were identified in the analysis process. Non-respondents mean students who did not respond to the open-ended questionnaire or whose responses were omitted. The final students' collective categories of description were coded into the English alphabet letters. This is considered as the standard students' collective categories of description used at pre-, post-, and delayed post-intervention. These standardised collective categories of description involved critical aspects, irrelevant aspects, and non-respondent students (see Chapter 6). The aspects of a nuclear physics concept discerned by learners at pre-, post-, and delayed post-intervention were identified using the VTL (see Chapter 6).

The numbers of research respondents discerning each aspect of a nuclear physics concept in the pre-phase were compared to that of post- and delayed post-intervention. The numbers of non-respondents at these three points of intervention were also compared. This helped the researcher to recognise the conceptual pathways that the students followed from pre-intervention to delayed post-intervention using column charts (see Figures 6.1–6.5). The identified conceptual pathways assisted the researcher to explore the influence of the intervention in addressing the students' conceptual difficulties. In other words, the identified conceptual pathways assisted the researcher to explore the enhancement of the student's conceptual understanding and representations of nuclear physics as a result of the intervention.

After analysing the data in both phases of this study, the researcher did the interpretation very carefully to answer the research questions (Kothari, 1985). According to this scholar, interpretation refers to making conclusions from the analysed empirical data. Or, interpretation is a way of defining and discussing the research findings. Even though the data was correctly gathered and analysed, the incorrect interpretation could result in irrelevant conclusions. To avoid this risk, the researcher took care in the process of interpreting the results of the phenomenographic data analysis. Again, to avoid the risk in the data analysis process, the phenomenographic data analysis guideline outlined in the next paragraph is considered.

The phenomenographic data analysis guideline proposed by Bowden and Green (2005) was adopted for this study. This guideline states that the researcher needs to be careful not to impose his ideas on the students' responses in the transcription, data analysis, and interpretation processes. The transcription, data analysis, and interpretation processes had done focusing only on the empirical data obtained from the research respondents. This important phenomenographic analysis guideline assisted the researcher to reach valid conclusions. This guideline is considered in each of the seven steps of the phenomenographic data analysis process focusing only on the empirical data.

3.11 THE TRUSTWORTHINESS OF THE STUDY

The trustworthiness criteria of research are conventionally presented in terms of validity and reliability. According to Åkerlind (2005), both of them were derived from a positivist method. This is a quantitative method, which is used to research the external objective reality, rather than the subjective reality that is investigated by qualitative researchers. The criterion of trustworthiness of this study was stated and discussed based on the phenomenographic research approach underpinned by the interpretive paradigm. All research paradigms did not have the same criterion for ascertaining the trustworthiness of research since different paradigms have different worldviews (Lincoln & Guba, 1985, 2005). These scholars have given new terms equivalent to validity and reliability that are suitable for qualitative research such as phenomenography. These new terms communicate the same meaning as that of validity and reliability used in quantitative research. These scholars have claimed that interpretive researchers focused on these newly introduced terms. The new terms introduced at that time are transferability, dependability, conformability, and credibility. The transferability of the study findings is equivalent to external validity. The dependability, which means testing for consistency of the findings, is equivalent to reliability. The conformability of the gathered data and the credibility of the results of a study are equivalent to internal validity. These show the similarities between the trustworthiness of interpretive and positivist paradigms.

The criteria of trustworthiness for phenomenographic research are comparable with those of other qualitative research approaches. In essence, trustworthiness means convincing the readers of the research report that they can rely on the work of the researcher in the research process. For the readers to rely on the findings of the researcher whether they are reliable and valid is another way of describing trustworthiness. Trustworthiness helps the readers to rely on the research if it was conducted honestly by the researcher from the beginning to the end. In the following sections, each criterion of trustworthiness is discussed.

3.11.1 Credibility (Internal Validity)

It is a criterion of trustworthiness for helping the readers to be confident in the genuineness of the findings of qualitative research (Guba, 1981). It is also known as communicative validity as claimed by Sandberg (2000), which justifies the researcher's interpretations.

The researcher conducted prolonged and systematic conversations with the research participants in the process of the interviews to obtain valid data (see Section 3.8.1.2). Furthermore, the researcher also took care not to impose his ideas on the student's response in the semi-structured interview, transcriptions, data analysis, and interpretation processes (see Section 3.10.1). The transcription, analysis, and interpretation processes of the data had done focusing only on the empirical data. The empirical data represents the students' various ways of conceptual understanding and representations of nuclear physics. This indicates the dependability of the data on the qualitative research respondents.

3.11.2 Transferability

Transferability is the second criterion of trustworthiness used in this study. According to Sandberg, 2000, it is the degree of applicability of the study findings in a different context. Sandberg also said that in phenomenographic research, validity is tested based on the justification of a researcher. This is also another form of communicative validity criterion used to justify the whole research process and the researcher's interpretations.

The findings of this study such as the identified conceptual difficulties, the intervention used to address them, and the critical aspects of a nuclear physics concept discerned by students disseminated to the stakeholders via publications and conferences. This gives potential information to curriculum and classroom instruction developers and designers. Especially, the findings of this study are highly applicable to undergraduate physics curriculum designers and nuclear physics instructors.

3.11.3 Dependability (Reliability)

This is the third criterion of the trustworthiness of this study. In phenomenographic research perspectives, Sandbergh (1997) suggests reliability as interpretative awareness. This is more appropriate for phenomenographic research than reliability, which is checked based on the replication of a study. The point of the argument is that interpretative awareness is more compatible with the relational aspect of the phenomenographic perspective than inter-judge reliability. As claimed by Sandberg (2000) reliability is used to check the researcher's interpretative awareness. Reliability is also used to evaluate if the interpretation of the results of a study has been well controlled and checked or not (Åkerlind, 2005; Bowden et al., 1992; Kvale, 1996; Sandbergh, 1997). According to these scholars, a better alternative form of reliability, which is appropriate for the phenomenographic study, is to make the interpretative steps clearer to the readers.

The researcher took care in selecting a sample in the first phase. Thirty students were selected from 49 students using a maximum variation sampling strategy based on their academic achievements. Maximum variation sampling is a type of purposive sampling technique used to select the interviewees (Patton, 2002). This means the sample of this study involves the high, medium, and low academic achievers. In the second phase, all 40 students were nominated as a second sample. The data was collected from the two primary sources (the two samples) via validated instruments in a systematic way (see Section 3.8). To have validated research instruments, a pilot study was conducted. And also the research instruments were evaluated by three professionals (see Appendix IX). The responses of the participants to interviews were audio-recorded and documented. The categories of description were constructed focusing on reliable empirical data using a phenomenographic research analysis. Before the construction of categories of description was finalised, the seven steps of the phenomenographic data analysis process followed (see Section 3.10.1).

3.11.4 Conformability

As discussed in Section 3.11.3, reliable data was collected from primary sources. The analysis was done focusing on this reliable data to make the study findings a function of only the qualitative research participants. Based on the ideas of (Guba, 1981), the researcher attempted to apply the appropriate conditions of investigation without any bias. The steps of the phenomenographic data analysis process stated in Section 3.10.1 assisted the researcher to achieve these results. In the data analysis process, the researcher took into consideration, the dependability of the collected data and the data analysis process on the interview and open-ended questionnaire respondents. In the transcription process, the researcher listened to the audio recordings several times in order not to impose any preconceived ideas on the recordings. The transcriptions and the nonverbal sorted were resorted and edited until the refined data were prepared for analysis.

3.11.5 Pragmatic Validity

Pragmatic validity is another special criterion of trustworthiness in the developmental phenomenographic research approach. This is a criterion to justify the researcher's interpretations in phenomenographic research as claimed by Kvale (1996). Kvale said that practical validity is evaluated by checking if the interpretations are associated with an action or lead to future action or lead to the desired results. Based on the ideas and research experiences of Bowden (2005), the researcher developed an interest in conducting a developmental phenomenographic research approach.

The outcomes of a developmental phenomenographic research approach used in this study were used to identify as well as to address the students' conceptual difficulties of nuclear physics. Addressing these conceptual difficulties using a relevant instructional strategy is an action. The conceptual difficulties that were identified in the first phase using the conceptual frameworks of developmental phenomenography and VTL informed effective instructional intervention. This means the interpretation of the results of the phenomenographic study in the first phase led to this action. The instructional intervention was used to address the conceptual difficulties identified in Phase 1. MRs-based instruction with interactive nuclear physics learning tutorials was used as an intervention. This was developed, designed, and implemented in Chapter 5 in the second phase. The results presented in the third phase showed that the students' conceptual difficulties were addressed because of the intervention. The pragmatic validity of this finding is evaluated based on the results found from this teaching and learning context. That is, the pragmatic validity of this finding was evaluated based on the responses of the students to the nuclear physics open-ended conceptual investigation questionnaire after the intervention. In this study, the phenomenographic interpretations of the results found after intervention are accompanied by MRs-based interactive learning activities.

3.12 ETHICAL CONSIDERATIONS

Research involving human participants needs special attention to ethical considerations. The researcher of this study was guided by the UNISA research ethics policy. Accordingly, the researcher obtained ethical clearance from the UNISA Research Ethics Committee (see Appendix VI). The probability of predictable harm or inconvenience that could be experienced by the research participants in this study was not different from that experienced in the common formal classroom teaching-learning activities. Before administering the phenomenographic interviews, the participants in the selected university read and accepted informed students' consent forms (see Appendix V).

3.13 CHAPTER SUMMARY

The research paradigm, approach, methodologies, and learning theory that were used in this study are discussed in this chapter. The interpretive research paradigm that includes a non-dualistic ontology, relational epistemology, phenomenographic research methodology, and VTL is used. These are the four components of the research paradigm of this study. The exploratory case study research design underpinned by the developmental phenomenographic research approach and VTL was used. A sample size of (N = 30) and (N = 40) was selected purposely in the first and second phases respectively. Semi-structured face-to-face individual interviews and an open-ended questionnaire were used respectively to gather data from the two samples of students. The open-ended questionnaire was developed based on the validated semi-structured interview questions. The interviews and the open-ended questionnaire were aimed at gaining more insight into students' conceptual understanding and representations. These data-gathering instruments are relevant to the phenomenographic study. The data gathered in both phases were analysed using the phenomenographic analysis method. The VTL was used to analyse the learning process and its outcomes based on the categories of description. Finally, the trustworthiness and ethical consideration of this study are discussed.

Developmental phenomenography was used to construct the students' categories of description in Phase 1, Phase 1 at pre-, and Phase 3 at post- and delayed post-intervention. The VTL was used to identify the critical and irrelevant aspects of a nuclear physics concept discerned by students, which were then used to analyse the learning process and its outcomes. These aspects are the constituents of the categories of description. Thus, the critical and irrelevant aspects were identified based on the categories of description. These critical aspects are the necessary conditions for learning the nuclear physics concept. Based on the content of the introductory nuclear physics, the researcher also attempted to identify the critical aspects of a nuclear physics concept. The irrelevant aspects involve conceptual difficulties such as misconceptions and confusion. The VTL was used to develop and design an instructional intervention in the second phase. The main purpose of the intervention was to address conceptual difficulties identified in Phase 1 and 2 at pre-intervention. The VTL was used to identify and organise the necessary conditions of learning before developing and designing the instructional intervention. The critical aspects are the necessary conditions of learning. The students should attend to the critical aspects to learn and understand. The intervention could reduce the irrelevant aspects and then enhanced the students' conceptual understanding and representations of nuclear physics.

CHAPTER 4: RESULTS AND DISCUSSIONS OF THE FIRST PHASE

4.1 INTRODUCTION

Chapter four deals with the results of the analysis of the data gathered from the students who were exposed to traditional instruction in the first phase. In this phase, the data was gathered using the semi-structured face-to-face individual interviews (see Section 3.8.1) in which the participant students were given a chance to respond in verbal and nonverbal responses. The categorisation of the students' conceptual understanding and representations of each of the five nuclear physics concepts are presented in terms of categories of description in a hierarchy in tables (Tables 4.1-4.5). The five concepts are the concepts of NBE and force, radioactive decay, negative beta decay, and NE (see Sections 2.5.1 & 2.5.2). The transcription and analysis of the data were done based on Sections 3.10.1 to 3.10.3 to categorise the students' conceptual understanding and representations of the five concepts of nuclear physics (see Sections 4.2-4.6).

The researcher interviewed 30 undergraduate physics major students. The transcription was done based on the verbal responses of each participant student to the interviews, which were recorded on an audio-IC-recorder. The semi-structured face-to-face individual interview guide and questions to which the students responded in the first phase are available in Appendix I. The students' verbal responses recorded on the audio-IC-recorder were listened to several times not to miss the most valued different ways of students' conceptual understanding in the transcription process. Finally, the relevant interviews transcribed verbatim of the 30 students were captured in a Microsoft Word document. Each student was also asked to respond in nonverbal responses such as written explanations, equations, graphs, and diagrams. The relevant written explanations, expressed equations, images of the graphs, and diagrams of each of the 30 students were also included in the Microsoft Word document. The verbatim transcriptions and nonverbal responses of the individual participant students are presented under their coded names from S_{01}-S_{30}. The verbatim transcriptions and the nonverbal responses formed the pool of data to be analysed using the phenomenographic data analysis process in the first phase. The pool of data represents the responses of the 30 students to the interview questions on the five concepts of introductory nuclear physics.

The pool of data was analysed, following the seven steps of the phenomenographic research analysis process mentioned in Section 3.10.1 and using the ideas discussed in Sections 3.10.2 and 3.10.3. The data analysis of the pool of data was done for each of the five concepts of introductory nuclear physics in Sections 4.2-4.6. Using Steps 1 to 3, the pool of data was sorted resorted, and edited. This was done based on focused reading and rereading of the transcriptions and written explanations. It was also done based on the context and purpose of this study. The equations, graphs, and diagrams were also sorted, resorted, and edited repeatedly based on the purpose of this study. These three steps of the phenomenographic analysis process helped the researcher to correct any mistakes, identify the most valued elements, and understand the central elements of the participants' responses within the pool of data.

Using Steps 4 to 7, the categories of description were constructed based on the sorted and edited data using categorisation and coding. In the categorising process, similar responses of the participants were assigned to the same category for each concept of nuclear physics. We call such a type of categorisation process collective categorisation (see Section 3.10.2). In Step4, the preliminary list of categories of description was constructed for each concept. In Step 5, the preliminary listed categories were compared to each other until the critical differences amongst them were distinguished. Whether the constructed categories of description represent the participants' conceptual understanding and representations of a nuclear physics concept were also checked based on the pool of data. In Step 6, names were allocated to each of the lists of categories. In Step7, the categories of description were arranged in a hierarchical arrangement based on the students' complicated conceptual understanding and representations of each concept of nuclear physics. That is, the categories were organised into a hierarchy from less complicated to more complicated students' conceptual understanding and representations of nuclear physics.

Phenomenography revealed the various ways of students' understanding and representations of the five concepts of nuclear physics. How the variations were occurred explained using the VTL (see Sections 4.2.4, 4.3.4, 4.4.4, 4.5.4 &4.6.4). This learning theory also gave an insight into the conceptual difficulties of each of the five concepts that the students encountered after they were exposed to traditional instruction (see

Section 4.7). The students' conceptual difficulties of each of the five concepts were exposed in terms of learning difficulty, misunderstanding, and confusion. The misunderstandings and confusion were considered to be irrelevant aspects (unfocussed aspects) from the perspective of the VTL. The alternative ways of students' scientific understanding were considered to be critical aspects, which are also known as focused aspects (see Section 2.8.2).

The illustrative examples of the verbatim transcriptions and nonverbal responses of the three selected students and the data analysis process are presented in Appendix VII. These support the categories of description constructed and presented in Tables 4.1 – 4.5.

4.2 CATEGORISATION OF STUDENTS' CONCEPTUAL UNDERSTANDING AND REPRESENTATIONS OF NBE

4.2.1 Categorisation

Based on the phenomenographic data analysis process elaborated in Section 4.1, the following four qualitatively different ways of students' conceptual understanding and representations of NBE were identified. This means four collective categories of description were identified. An example of how the data collected from three students through semi-structured interviews were analysed and categorised for NBE is presented in Appendix VII.

A. NBE is equivalent to the mass lost when the separated nucleons combine to form a nucleus
B. NBE equals the amount of energy that must be added to a nucleus to separate it into its constituent nucleons
C. NBE binds the nucleons in the nucleus of an atom
D. NBE generates a strong nuclear force

The illustrative excerpts of the interview dialogue of three students associated with NBE are presented as follows to support these categories of description.

Researcher: Define NBE

Student S_{02} *:* “The NBE of a nucleus as the energy that equals the negative of the difference of the mass of a nucleus and the sum of the masses of its split constituents times the square of the speed of light”. “NBE is the energy that binds protons and neutrons together” (Categories A and C).

Student S_{20} *:* “NBE is the energy added to the nucleus to disintegrated or split into protons and neutrons” (Category B).

Student S_{21} *:* “NBE is the energy that binds protons and neutrons”. “It is the negative of the difference between the nuclear mass and the sum of the masses of its constituent’s protons and neutrons times the square of the speed of light” (Category C and A).

Researcher: Compare the energy that must be added to a nucleus to separate it into its constituent nucleons with its binding energy

Student S_{02} *:* She was not able to compare

Student S_{20} *:* “The binding energy of a nucleus should be less than the energy added to it to split it into its constituents” (Category B).

Student S_{21} *:* “The NBE of a nucleus should be equal to the energy added to it to split it into its constituents” (Category B).

Researcher: Compare the mass of the nucleus inbound state and the combined masses of its separated constituent nucleons

Student S_{02} *:* “The mass of a nucleus inbound state and the sum of the masses of its split constituents are equal” (Category A).

Student S_{20} *:* “The mass of a nucleus inbound state is greater than the sum of the masses of its split constituents” (Category A).

Student S_{21} *:* “The mass of a nucleus inbound state is less than the sum of the masses of its split constituents” (Category A).

Researcher: Relate the binding energy of a nucleus to the mass lost using an equation when the separated nucleons combine to form a nucleus

Student S_{02} *:* She expressed it using Equation 4.2 (Category A)

Student S_{20} *:* He expressed it using Equation 4.1 and 4.2 (Category A)

Student S_{21} *:* He expressed it using Equation 4.1 and 4.2 (Category A)

$$E_B = -\left(m_{nuc} - Zm_p - Nm_n\right)c^2 \quad (4.\ 1)$$

$$E_B = \left(m_p + m_n - m_{nuc}\right)c^2 \quad (4.\ 2)$$

Other students used Equations 4.3 and 4.4.

$$E_B = \left(\Delta m\right)c^2 \quad (4.\ 3)$$

Equations 4.1–4.3 are relevant to Category A, because, they express the equivalence of NBE to the mass lost. Equation 4.4 is not relevant to Category A or in general to NBE but it is relevant to the energy released in a nuclear reaction. This energy is referred to as the reaction energy or Q-value. Since this energy comes out of the nucleus of an atom it is also known as NE.

$$E_B = Q = \left(m_a + m_x - m_y - m_b\right)c^2 \quad (4.\ 4)$$

Even if, the critical aspects E and F of NBE were the intended critical aspects in this study all students did not discern them.

E. NBE is the energy released when the separated nucleons combine to form a nucleus (the missing mass changed into the released energy)
F. NBE is the energy missed when a nucleus is separated into its constituent nucleons (the energy that must be added to a nucleus is changed into mass after separation)

4.2.2 Naming the Categories of NBE and How They Evolved

In Figures 4.1(a), (b), and (c), the name was given for the previous categories based on the aspects of the NBE described by students in each category. How these categories evolved is also illustrated in these figures. In Category D students understood NBE as nuclear force-generating energy. Thus, the name given for this category was ‘a nuclear force-generating energy’. How this category evolved was not illustrated using a diagram like other categories. Category A represents similar ways of students’ understanding and representations of NBE. These students understood that NBE is equivalent to the missing mass.

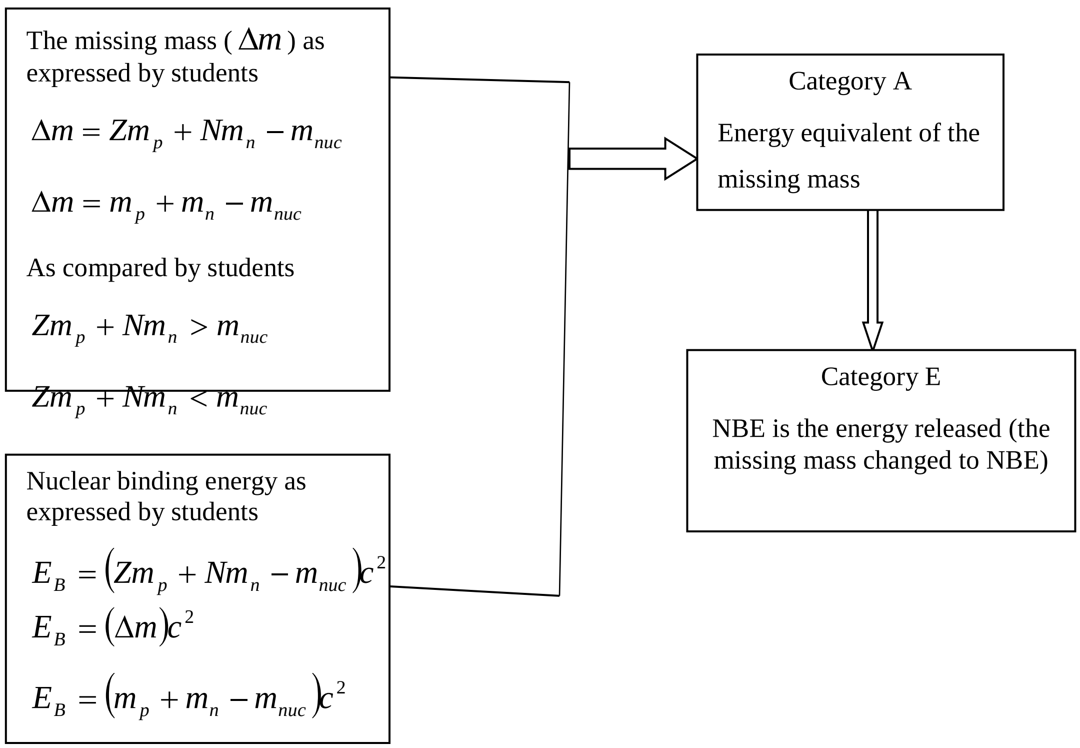


Figure 4.1 (a) How Categories A and E evolved

As indicated in Figure 4.1 (a), the students attempted to represent and describe this aspect of NE using an equation. Some students were not able to compare the nuclear mass with the combined masses of the separated nucleons of a nucleus.

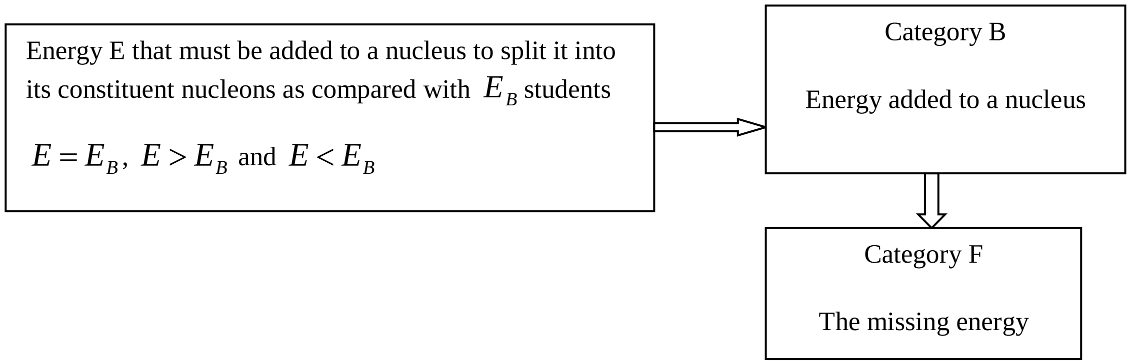


Figure 4.1 (b) How categories B and F evolved

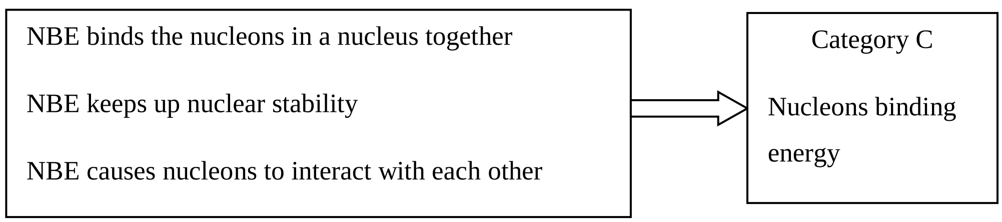


Figure 4.1: How the categories of description representing the students' different ways of conceptual understanding and representations of NBE evolved

Figures 4.1 (a), (b), and (c) illustrate how the categorisation of students' conceptual understanding and representations of NBE was reduced to create boundaries between the categories. The six reduced categories show the students' different ways of conceptual understanding and representations.

4.2.3 Categories of the Description of NBE in a Hierarchy

Outcome space is the set of reasonably linked and empirically grounded categories of description in a pecking order (see Section 3.10.2). The previous categories are arranged in a hierarchy from less complicated (Category I at the top) to more complicated conceptual understanding (Category VI at the bottom) as illustrated in Figure 4.2. These six phenomenographic categories are the identified different ways of students' conceptual understanding of NBE. Without understanding the concept of the missing mass based on the experiment, it may be difficult to understand NBE as the energy equivalent of the mass lost, when separated nucleons combine to form a nucleus (Category III).

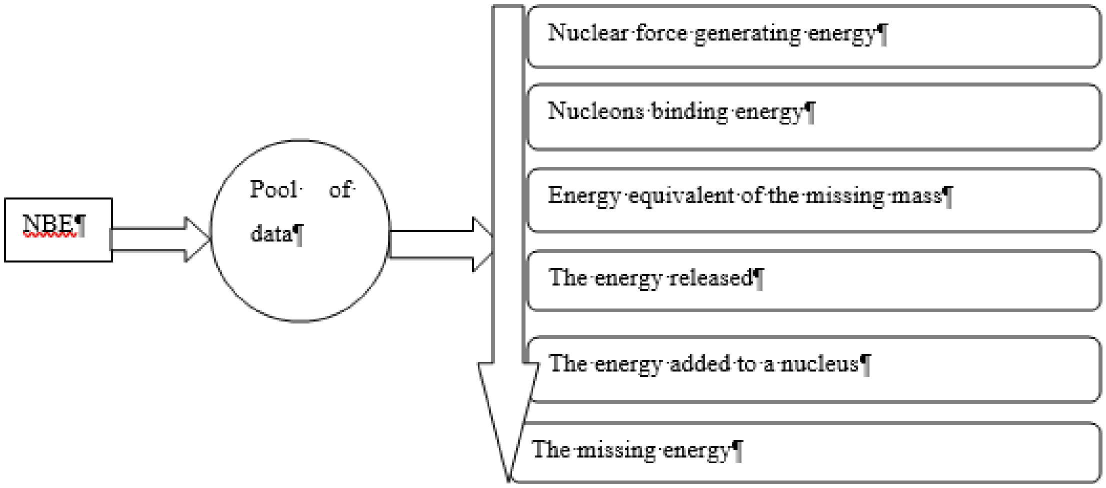


Figure 4.2: The categories of description in a hierarchy that represent the students' different ways of conceptual understanding of NBE

The lost mass is changed into the energy released in the combination process (Category IV). Again, without understanding this released energy, it may be difficult to understand the quantity of energy that must be used to break up a nucleus into its constituent nucleons (Category V). Experiments show that this quantity of energy must be equals to or greater than NBE. Without understanding the energy that must be used to break up a nucleus into its constituents, it is difficult to understand the energy missed in the recombination process (Category VI). Hence, the aspect of NBE described in Category VI is more difficult to understand than other categories. This hierarchical arrangement shows the internal relationships amongst Category III to Category VI. But Categories I and II are different from other categories as well as from each other. In these categories, the students used simple ideas to describe NBE. In Category I, it seems that the students considered NBE as nuclear potential energy and the strong nuclear force as the conservative force. In Category II, the students described NBE simply based on its name binding energy'.

The phenomenographic analysis process of the pool of data of NBE and its results are summarised in Table 4.1. In the last columns of this table, the students' categories of description are further coded into the number of research respondents (NRR), critical aspects (CA), and irrelevant aspects (IA). An (X) is used to mark the appropriate column to indicate where a group of research respondents' categories of descriptions belong. The concepts of critical and IA were adapted from the phenomenographic study of Pang and Ki (2016) (see Section 2.8.2).

Table 4.1:Students'categories of the description of NBE

Category Name	**Categories of description**	**NRR (N=30)**	**NRR In %**	**CA**	**IA**
Category I Nuclear force-generating energy	NBE generates the strong nuclear force	1	3.3		X
Category II Nucleons binding energy	NBE is the energy that binds the nucleons in a nucleus together not to be disintegrated	9	30		X
	NBE is the energy that keeps the stability of a nucleus	1	3.3		X
	NBE causes nucleons to interact with each other	1	3.3		X
Category III The energy equivalent of the missing mass	The mass of the nucleus in the bound state is less than the combined mass of the separated nucleons	5	16.7	X	
	The mass of the nucleus in the bound state is greater than the combined masses of the separated nucleons	8	26.7		X
	The mass of the nucleus in a bound state equals the combined masses of the separated nucleons	1	3.3		X
	NBE equals the difference between the combined masses of the separated nucleons and the mass of the nucleus in the bound state times the square of the speed of light	4	13.3	X	
	$\boldsymbol{E_B = (Zm_p + Nm_n - M_{nuc})c^2}$	11	36.7	X	
	$\boldsymbol{E_B = (m_p + m_n - M_{nuc})c^2}$	6	20	X	
	$\boldsymbol{E_B} = (\boldsymbol{m_x} + \mathrm{m_a} - \boldsymbol{m_y} - \boldsymbol{m}_\mathrm{b})\boldsymbol{c^2}$	1	3.3		X
Category IV Energy released	NBE is the energy released when nucleons combine to form a nucleus (not discerned by students)	0	0	X	

Category Name	Categories of description	NRR (N=30)	NRR In %	CA	IA
Category V Energy Added to nucleus	NBE equals an amount to the energy that must be added to a nucleus to separate it into its constituents	7	23.3	X	
	The energy that must be added to a nucleus to separate it into its constituents can be greater than NBE	3	10	X	
	The energy that must be added to a nucleus to separate it into its constituents can be less than NBE	2	6.7		X
Category VI The missing energy	NBE is the missing energy that changed into mass when a nucleus is separated into its constituent nucleons (not discerned by students)	0	0	X	
Category VII Non-respondent students	Students who did not respond to the semi-structured interviews	4	13.3		

The seventh category was added to indicate the students that did not respond or those students who did not discern any aspect of the concept.

4.2.4 Discussion on the Categories of Description of NBE

Category I: Nuclear Force-Generating Energy

Findings from Table 4.1 indicate that one student understood that NBE is the energy that generates a strong nuclear force. This student's conceptual understanding of NBE is not a scientific understanding. In other words, this is an irrelevant aspect of NBE discerned by students. It seems that the student thought of the strong nuclear force as a conservative force and NBE as nuclear potential energy. Scientifically, a conservative force equals the negative of the gradient of the potential energy $\left(\vec{F} = -\vec{\nabla}U\right)$ in three dimensions (Serway & Jewett, 2004). This is classical physics thinking about conservative forces. The strong nuclear force cannot be described using classical thinking, because, it has a non-central component, which is not a conservative force. Furthermore, NBE is not nuclear potential energy. It seems that the student possibly confused NBE with nuclear potential energy.

All of these imply that NBE cannot generate a strong nuclear force or it cannot be the negative of the gradient of the NBE.

Category II: Nucleons binding energy

The results in Table 4.1 show that nine students understood that NBE is the energy that binds the nucleons together in the nucleus of an atom. One student understood that NBE is the energy that keeps the stability of a nucleus. And another student understood that NBE causes nucleons to interact with each other. These findings show that the students possibly confused NBE with the strong nuclear force. In scientific understanding, it is the strong nuclear force that causes nucleons to interact with each other, which binds them together to form a nucleus and keeps its stability (Serway et al., 2005). These scholars said that the NBE per nucleon for stable nuclei is approximately constant for mass number $A>20$. And also they said that the nuclear forces between a particular nucleon and all the other nearest neighbour nucleons in the nucleus for $A>20$ are saturated. That is, a particular nucleon forms nuclear attractive bonds with only a limited number of other nucleons since nuclear force is a short-range force. But this does not mean nuclear force and NBE are the same.

Category III: The energy equivalent of the missing mass

Understanding the Einstein mass-energy equivalence relationship in modern physics is very important to understand and represent the concept of NBE (Serway et al., 2005). The findings in table 4.1 indicate that the students compared differently the mass of a nucleus in the bound state with the combined masses of its separated constituent nucleons. Five of the 30 students' correctly understood that the mass of a nucleus in the bound state is less than the combined masses of its separated nucleons. The scientific measurements support this response of the students (Beiser, 1963). It seems that the students correctly understood that the energy added to a nucleus is used to separate it into its constituents and the remaining changed into the mass. However, eight students understood that the mass of a nucleus in the bound state is greater than the combined masses of the separated nucleons, which violates the results of scientific measurements. It seems that the students incorrectly understood as if the mass is lost when a nucleus in the bound state is separated into its constituent nucleons. Scientific measurements showed that mass is lost when the separated nucleons combine to form a nucleus (Beiser, 1963). The lost mass is changed into energy in the combination process of the nucleons. We call this energy NBE ($E_B = (\Delta m)c^2$). Another student incorrectly indicated that the mass of a nucleus in a bound state equals the combined masses of the separated nucleons. That is, the students understood that the mass is conserved in both the combination of nucleons and the separation of a nucleus in the bound state into nucleons. It seems that the students tried to describe this nuclear phenomenon using the classical physics approach.

Students compared in different ways the mass of a nucleus in a bound state with the combined masses of its separated constituent nucleons. This claim was supported by Kohnle et al. (2011) when they indicated that at St Andrew's 60% of the participants at the post-test responded correctly and certainly that the mass of a nucleus in the bound state is less than the combined masses of its separated nucleons. At Edinburgh, about 25% of the participants at the post-test incorrectly responded that the mass of a nucleus in the bound state is greater than the combined masses of its separated constituent nucleons. At St Andrew's about 10% of the participants at the pre-test incorrectly responded that both masses are equal. The comparison of these masses affects the NBE of a nucleus since it is equivalent to the mass lost. For instance, if both masses are equal the binding energy of a nucleus in the bound state equals zero, which is incorrect.

The findings in Table 4.1 also correctly indicate that four students understood NBE equals the difference between the combined masses of the separated nucleons and the mass of a nucleus in the bound state times the square of the speed of light. It seems that the students correctly understood the equivalence of NBE to mass loss. Eleven students expressed this using an equation, $E_B = (Zm_p + Nm_n - m_{nuc})c^2$ which is the correct general equation of NBE. Six students expressed it using an equation $E_B = (m_p + m_n - m_{nuc})c^2$, which is correct but not general. This equation is valid only to calculate the binding energy of the nucleus of a deuterium atom. Another student incorrectly expressed it using an equation $E_\mathrm{B} = (m_x + \mathrm{m_a} - m_y - m_\mathrm{b})c^2$. This is the expression of reaction energy, not that of NBE. The reaction energy is the energy released when a particle collides with a nucleus, which is considered to be NE. This student may be possibly confused with NBE with NE.

NBE can also be defined as the energy released when the separated free nucleons are combined to form a nucleus. In this case, the mass lost in the combination process is changed into energy, which is referred to as NBE (Beiser, 1963). But the students did not define NBE in this way. This aspect of NBE is illustrated in Figure 5.2, which was not understood by the students after traditional instruction.

Category IV: The Energy Added to a Nucleus

The findings in Table 4.1 indicate that seven students had the correct understanding that NBE equals the amount of energy that must be added to a nucleus to separate it into its free nucleons. It seems that the students understood the amount of energy that must be added to a nucleus must be equals to the energy released when the free nucleons combine to form a nucleus. As discussed in the previous category, the energy released equals NBE. Three students understood that the energy that must be added to a nucleus can be greater than the NBE. This is a scientific understanding. This could be because the students understood that the part of the amount of energy added, which is greater than NBE is existing in the form of the kinetic energies of the separated nucleons. Two students understood that the amount of energy that must be added to a nucleus to separate it into its separated free nucleons can be less than its NBE. This is a misunderstanding, because, for a nucleus to be separated into its constituent nucleons the amount of energy added to it must be equals to or greater than its NBE. NBE can also be defined as the energy missed when a nucleus is separated into its constituent nucleons (Beiser, 1963). The missing energy is the part of the amount of energy added to a nucleus to separate it into its constituent nucleons that changed into mass after separation. This aspect of NBE wasn’t discerned explicitly by the students. This is illustrated using Figure 5.3, which was not understood and represented by all students after traditional instruction.

4.3 CATEGORISATION OF STUDENTS’ CONCEPTUAL UNDERSTANDING AND REPRESENTATIONS OF NUCLEAR FORCE

4.3.1 Categorisation

Following the phenomenographic data analysis process elaborated in Section 4.1, the following five qualitatively different ways of students’ conceptual understanding and representations of nuclear force were identified. This means five collective categories of description were identified. An example of how the data collected from three students through semi-structured interviews were analysed and categorised for nuclear force is presented in Appendix VII.

A. Nuclear force binds nucleons together to form a nucleus
B. The nuclear force is a short-range, attractive (0.4-3fm), charge-independent, strong force, nucleons' relative spin orientation-dependent force, and the students also understood that nuclear force has a non-central component and a repulsive term (0fm – 0.4fm)
C. The nuclear force is unique as compared to electromagnetic and gravitational forces because it is a short-range and strong force
D. Nuclear force can be described based on the exchange-force model in which the students considered gluons as the exchange field particles of the strong nuclear force
E. Nuclear force binds the nucleus of an atom and its orbiting electrons

The illustrative excerpts of the interview dialogue of three students associated with nuclear force are presented as follows to support these categories of description.

Researcher: Define nuclear force

Student S_{02}*:* "The nuclear force is the force that binds protons and neutrons together" (Category A).

Student S_{20}*:* "The nuclear force is the force that binds nucleons together not to be disintegrated" (Category A).

Student S_{21}*:* "The nuclear force is a force that binds the nucleus not to be disintegrated or split" (Category A).

Researcher: State and describe the properties of the strong nuclear force

Student S_{02}*:* "A nuclear force is a short-range (0.4-3fm), attractive, repulsive, and strong force" (Category B).

Student S_{20}*:* “It is attractive, short-range (0.4-3fm), charge-independent and strong force” (Category B).

Student S_{21}*:* “The properties of the nuclear force are: it is a strong, attractive, charge-independent, and short-range force” (Category B).

Researcher: Describe the nuclear force based on the field particle exchange model

Student S_{02}*:* “Gluons are the exchange field particles of nuclear interaction via nuclear force” (Category D).

Student S_{20}*:* “Gluons are the exchange field particle of the nuclear interaction via the nuclear force” (Category D).

Student S_{21}*:* “Gluons are the exchange field particle of the strong nuclear interaction via the nuclear force” (Category D).

Researcher: What makes the nuclear force unique when compared to that of the electromagnetic and gravitational forces?

Student S_{02}*:* “The Coulomb force is the force that separates the nucleons (makes a nucleus unstable), the gravitational force is the force that depends on the mass, and nuclear force is the force that binds protons and neutrons together to form a stable nucleus” (Category A).

Student S_{20}*:* “What makes nuclear force unique when it is compared with that of coulomb and gravitational forces is that it is the strongest force” (Category C).

Student S_{21}*:* “What makes nuclear force unique, when it is compared with that of coulomb and gravitational forces is that it is a short-range (0.4-3fm) force” (Category C).

Researcher: Relate the strong nuclear force to the more basic strong force that binds quarks together.

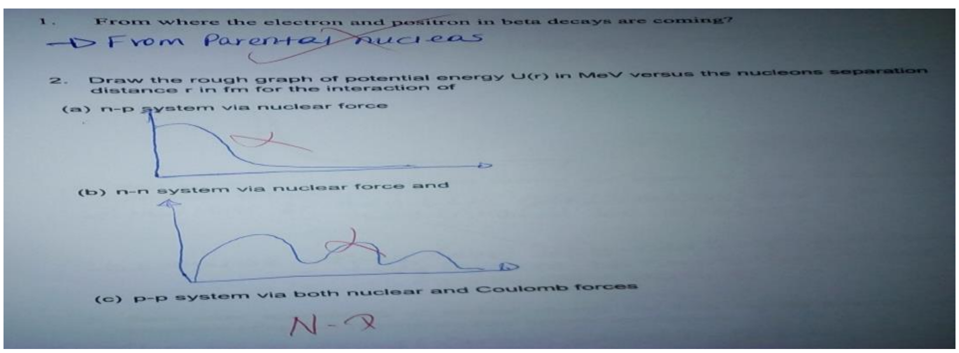
Student S_{02} *:* "Strong nuclear force is the force that binds nucleons together to form the nucleus and the more basic strong force is the force that binds the quarks together to form nucleons. The more basic strong force is greater than the strong nuclear force".

Student S_{20} *:* "The strong nuclear force that binds nucleons together to form a nucleus and the more basic strong force that binds the quarks together to form nucleons are the same".

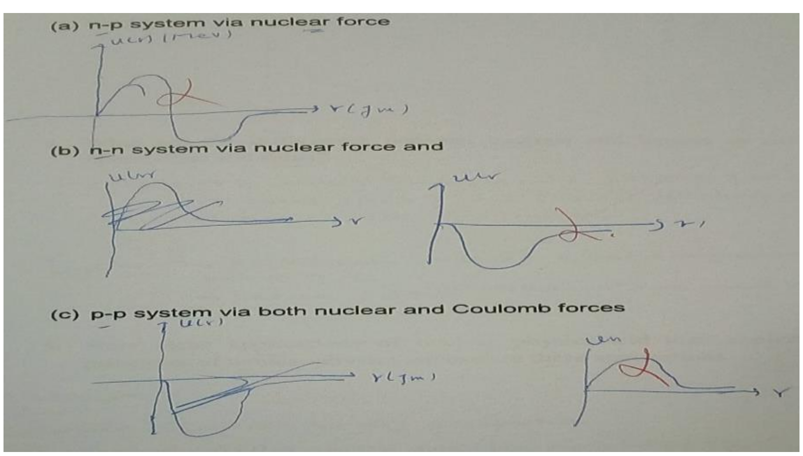
Student S_{21} *:* "The strong nuclear force that binds nucleons together to form a nucleus and the more basic strong force that binds the quarks together to form nucleons are the same".

Researcher: Draw the graph of potential energy U(r) versus the nucleons separation distance r for the interaction of n-p and p-p systems and then indicates the nuclear force and the Coulomb force in the graph.

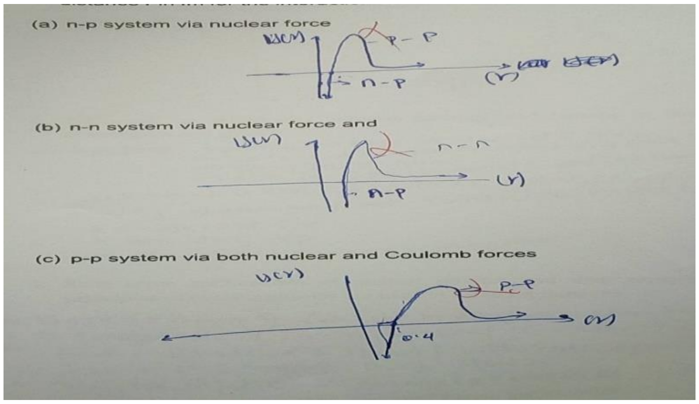
Student S_{02} *:* She drew and used the graph shown below (Category B)



Student S_{20} *:* She drew and used the graph shown below (Category B)



Student S_{21} *:* She drew and used the graph shown below (Category B)



The other two students drew and used Figure 4.7 to describe the strong nuclear force (see Page 117).

One student used Equation 4.5 to describe the strong nuclear force, which is not relevant to it (Category E).

$$F = k\frac{q_1 q_2}{r^2} \quad (4.5)$$

Equation 4.5 corresponds to Category E. The students confused nuclear force with Coulomb force.

4.3.2 Naming the Categories of Nuclear Force and How They Evolved

How the previous categories evolved and the names are given for each category are illustrated in Figures 4.3 (a), (b), (c), and (d). The name was given based on the similar aspects of a nuclear force discerned by a group of students in each category. How each category evolved is indicated in the following figures.

Category A represents the different ways of students' understandings of the concept of the strong nuclear force. This category can be considered as one of the critical aspects of the strong nuclear force discerned by a group of students in this study. In this aspect, the students understood that this force is the force that binds nucleons together to form the nucleus of an atom. That is, the students understood that the strong nuclear force keeps nuclear stability. Other students understood that the nucleons interact with each other via a strong nuclear force. Some students incorrectly understood that the strong nuclear force is the force that binds quarks together to form a nucleon. This is an irrelevant aspect of the strong nuclear force. It seems that the students confused the more basic strong force that binds quarks with the strong nuclear force that binds nucleons.

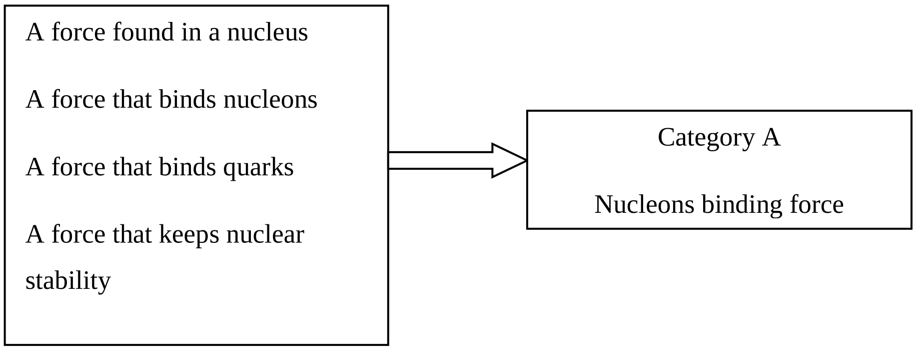


Figure 4.3(a): How Category A has evolved

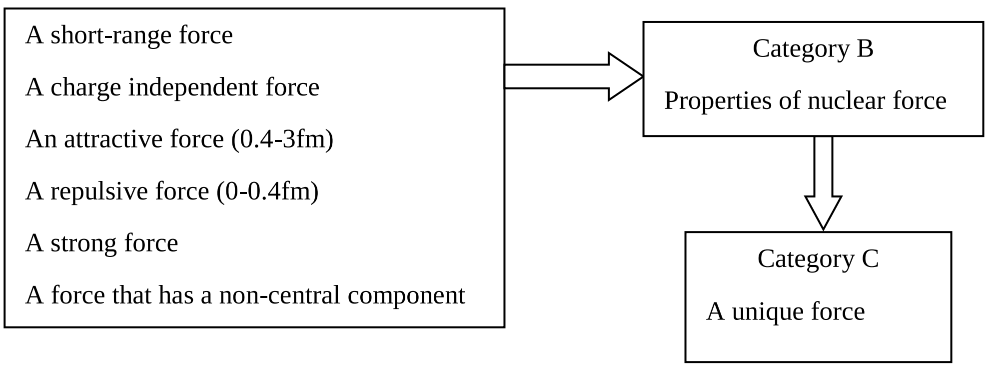


Figure 4.3(b): How categories B and C have evolved

Category B represents the second critical aspect of the strong nuclear force discerned by a group of students. That is the properties of the nuclear force, which includes its unique properties

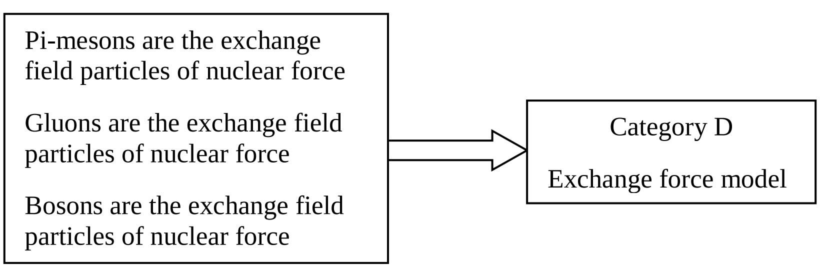


Figure 4.3(c): How Category D has evolved

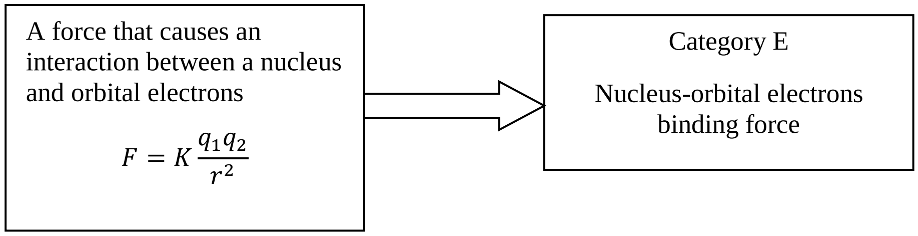


Figure 4.3(d): How Category E has evolved

Figure 4.3: How the categories of description representing the students' different ways of conceptual understanding and representations of nuclear force have evolved

Category D represents the third critical aspect of the strong nuclear force discerned by students. The strong nuclear interactions caused by the nuclear force are mediated by the exchange field particles known as pi-mesons. This is a scientific understanding, but most of the students incorrectly understood that gluons are the exchange field particles that mediate these interactions.

Category E represents the fourth aspect of the strong nuclear force, which was incorrectly discerned by students. It is an irrelevant aspect of the strong nuclear force, which was discerned by students.

Figures 4.3 (a), (b), (c), and (d) illustrates how the categorisation of students' conceptual understanding and representations of nuclear force was reduced to set up boundaries between the categories in the coding and recoding process. These figures show the students' different ways of conceptual understanding and representations of nuclear physics.

4.3.3 The Categories of Description of Nuclear Force in a Hierarchy

The previous categories are arranged in a hierarchy from less (Category I at the top) to a more complicated conceptual understanding of nuclear force (Category V at the bottom) (see Figure 4.4). The five phenomenographic categories are the students' different ways of conceptual understanding and representations of nuclear force. In another way, these are the five aspects of a strong nuclear force. The properties that make the strong nuclear force unique are that it is a short-range and strong force.

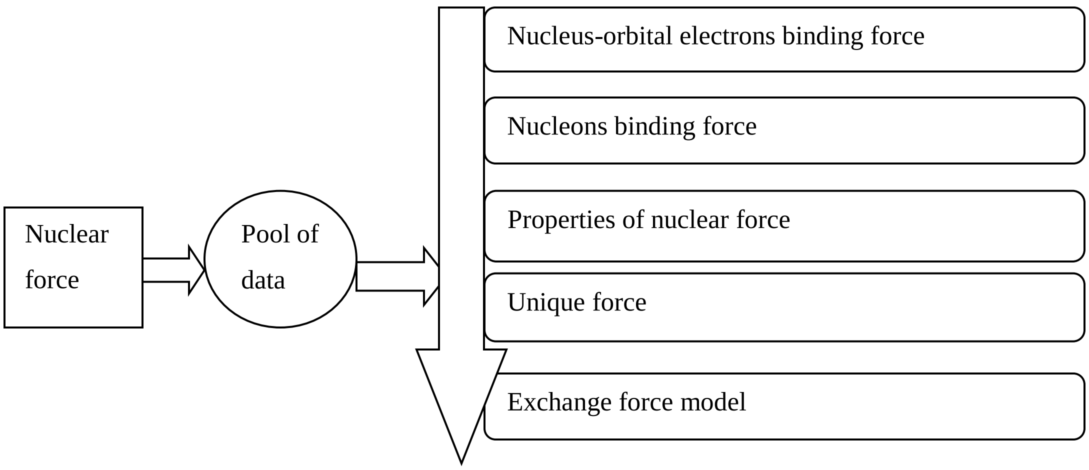


Figure 4.4: The categories of description in a hierarchy that represent the students' different ways of conceptual understanding of nuclear force

The students incorrectly understood that a nuclear force is a force that binds the nucleus of an atom and its orbital electrons. This means that the students incorrectly understood a nuclear force as a long-range force, which is classical thinking. However, a nuclear force is a short-range force that binds nucleons together within a nucleus. The force that binds the nucleus of an atom and its orbital electrons is Coulomb's attractive electric force. The concept of a nuclear force is more complicated to understand than that of an electric force because the long-range electromagnetic force is more familiar to the students than the short-range nuclear force.

Understanding the properties of the nuclear force is also more difficult than understanding nuclear force as a force that binds nucleons together to form a nucleus. Without understanding the properties of nuclear force, it may be difficult to understand its uniqueness compared to electromagnetic and gravitational forces. Understanding and describing nuclear force based on the exchange-force model is the most difficult one among the aspects of nuclear force discerned by students in this study. This may be due to the conceptual difficulty of the exchange field particles that mediate any interaction.

The phenomenographic analysis process of the pool of data of nuclear force and its results are summarised in Table 4.2. In the last columns of this table, the students' categories of description are further coded into the NRR, CA, and IA. An (X) is used to mark the appropriate column to indicate where a group of research respondents' categories of descriptions belong.

Table 4.2: Students' categories of description of nuclear force

Category Name	**Students' description of nuclear force**	**NRR (N=30)**	**NRR in %**	**CA**	**IA**
Category I Nucleus-orbital electrons binding force	The force that causes an interaction between the nucleus and the electrons orbiting it	1	3.3		X
	$F = K\frac{q_1 q_2}{r^2}$	1	3.3		X
Category II Nucleons binding force	The force that is found in a nucleus	1	3.3	X	
	The force that binds the nucleons together to form a nucleus	18	60	X	
	The force that binds nucleons together to form a nucleus and the force that binds quarks together to form nucleons are the strong forces	5	16.7	X	
	A force that keeps nuclear stability	3	10	X	
	The force that causes the nucleons to interact	2	6.7	X	
	The force that causes the nucleons to collide	1	3.3	X	
	The students described n-p and p-p strong interaction via nuclear force using a graph	22	73.3		X
Category III Properties of nuclear force	A short-range force that falls to zero more than 3fm	14	46.7	X	
	A long-range force	2	6.7		X
	The nuclear force is strong	17	56.7	X	

Category Name	Students' description of nuclear force	NRR (N=30)	NRR in %	CA	IA
	An attractive force (0.4fm-3fm)	20	66.7	X	
	Nuclear force has a repulsive term from 0-0.4fm that prevents the nucleons from approaching each other	7	23.3	X	
	The nucleons' relative spin orientation-dependent force	2	6.7	X	
	A charge-independent force	16	53.3	X	
	A force that has a non-central component	4	13.3	X	
Category IV Unique force	As compared with electromagnetic and gravitational forces nuclear force is unique, because it is a short-range strong force	12	40	X	
Category V Exchange-force model	Gluons are the exchange field particles of nuclear force	8	26.7		X
	Bosons are the exchange field particles of nuclear force	4	13.3		X
	Pi-mesons are the exchange field particles of nuclear force	0	0	X	
Category VI Non-respondent students	Students who did not respond to the semi-structured interviews	3	10		

The sixth category was added to indicate the participant students that did not respond. To understand how the data collected from the 30 participant students were analysed for nuclear force see Appendix VII, which is illustrated using three students as an example.

4.3.4 Discussion on the Categories of Description of Nuclear Force

Category I: The nucleus –atomic orbital electrons binding force

Findings from Table 4.2 indicate that one student incorrectly assumed that the strong nuclear force causes an interaction between a nucleus of an atom and its orbital electrons. That is, the student incorrectly understood nuclear force as responsible for binding the nucleus of an atom and its orbital electrons. This student also incorrectly indicated the formula for nuclear force as that of Coulomb force. It seems that the student did not clearly understand the short-range property of nuclear force and the long-range property of electromagnetic force. The long-range electromagnetic force is responsible for binding the nucleus of an atom and its orbital electrons and it is not the short-range strong nuclear force.

For 15 to 18 years old school students, electric forces of attraction between a nucleus and its atomic electrons were not well understood (Taber, 2013). This indicates that the students encountered a conceptual difficulty in understanding the force responsible for binding the nucleus of an atom and its orbital electrons. Undergraduate physics students incorrectly understood that those nuclei which have more nucleons are more closely bound. It seems that the students drew a false analogy with the atomic system and the long-range coulomb force, and not considering the very different short-range interaction via the strong nuclear force Kohnle et al. (2011). The real operation of the strong nuclear force occurs at the nuclear level, which makes it difficult to observe directly or to visualise (Shakya, 2015).

Category II: The nucleon binding force

The results in Table 4.2 indicate that 18 students understood that nuclear force is a force that binds nucleons together to form a nucleus. Three students understood that nuclear force is the force that keeps the stability of a nucleus while two understood that nuclear force is the force that causes the nucleons to interact with each other. One student indicated that nuclear force is the force that causes nucleons to collide with each other while another student understood that nuclear force is a force found in a nucleus. All of these explanations are scientifically correct. It seems that these students clearly understood the nucleons interact via the short-range attractive strong nuclear force. The strong nuclear interactions via nuclear force involve the n-p, p-p, and n-n interactions (see Figures 4.5 & 4.6).

Five students understood that a nuclear force binds nucleons together to form a nucleus and the more basic strong force binds quarks together to form a nucleon. But these students were not able to explain the difference and similarities between the nuclear force and the more basic strong force, which is very difficult even for experts. It is believed that the nuclear force that binds nucleons to form a nucleus is a residual effect of the more basic strong force that binds quarks to form a nucleon (Serway et al., 2005). This means the nuclear force originates from the interactions of quarks via the attractive more basic strong force between the nucleons found in a nucleus. As a result of this, the nuclear force that binds nucleons is also considered to be a strong force.

Category III: Properties of nuclear force

The results in Table 4.2 show that most of the students focused on the attractive (N=20), strong (N=17), charge independence (N=16), and short-range (N=14) properties of nuclear force. Except for the long-range (N=2) property, these properties of the strong nuclear force, which were understood by students are accepted by the scientific community of practice. N = 2 students understood the strong nuclear force as a long-range force. Kohnle et al. (2011) also indicated that the students did not consider the very different short-range properties of the strong nuclear force. Scientifically, nuclear force is a short-range force, not a long-range force.

Category IV: A unique force

Twelve students understood the unique properties of nuclear force, which makes it unique when compared to electromagnetic and gravitational forces. These are the strong and short-range properties of a nuclear force, which are acceptable by the scientific community of practice. Electromagnetic and gravitational forces have attractive and repulsive properties like nuclear force. But they are long-range and weaker forces than the strong nuclear force.

Category V: The exchange-force model

The findings in Table 4.2 indicate that eight and four students respectively incorrectly understood that gluons and bosons are the exchange field particles of the strong nuclear force. In scientific thinking, gluons are the exchange field particles of the more basic strong force that binds quarks together to form a nucleon. Bosons represent the group of the exchange field particles gluons, photons, W and Z_0 bosons, and gravitons. These are respectively the exchange field particles of the more basic strong force, electromagnetic force, weak force, and gravitational force. The correct exchange field particles of the strong nuclear force are pi-mesons, which were not understood by all students. Pi-mesons are not bosons. The exchange-force model is a model used to explain the four fundamental forces in nature. The four fundamental interactions caused by these fundamental forces are mediated by the mentioned exchange field particles. The indirect graphical representation of the strong nuclear force is discussed in the next paragraph

Twenty-two students (see Category II, Table 4.2) tried to describe n-p and p-p strong interactions using a graph (see Figure 4.7). These graphs are incorrect when compared to the graphs drawn in Figure 4.5 and Figure 4.6, which are accepted by the scientific community of practice. Figure 4.5 represents the interaction of p-p in a nucleus of an atom via both the strong nuclear and Coulomb repulsive forces while Figure 4.6 represents the interaction p-n via only the strong nuclear force. In the p-p interaction, both nuclear and electrical potential energies exist while in p-n or n-n interaction only nuclear potential energy exists. In Figures 4.5 to 4.7, the vertical and horizontal axes represent the potential energy (U) and the nucleons' separation distance r respectively. Conventionally, the potential energy produced due to attractive interactions is considered to be negative while the potential energy produced due to repulsive interactions is considered to be positive (see Figures 4.5 & Figures 4.6).

In Figure 4.5, at short ranges (0-0.4fm) and (0.4-3fm) there are strong repulsive and attractive nuclear forces respectively. And at long-range (>3fm) there is a coulomb repulsive electric force. The repulsive nuclear force prevents nucleons from approaching each other and the attractive strong nuclear force binds nucleons together to form the nucleus of an atom. The coulomb repulsive electric force among protons tends to disintegrate the nucleus of an atom against the attractive strong nuclear force that binds nucleons together to form a nucleus. Based on this discussion and the students' graphs (Figure 4.7), it is possible to conclude that the students had difficulty in describing nuclear force using a graph. For instance, in Figure 4.7 (a), the graph drawn by a student for n-n interaction is similar to the p-p graph in Figure 4.5. It seems that the student confused the graph of n-n interaction with the graph of p-p interaction. No student described correctly the strong nuclear force using a graph. In general, the deeper study of the strong nuclear force is not finalised (Serway et al., 2005).

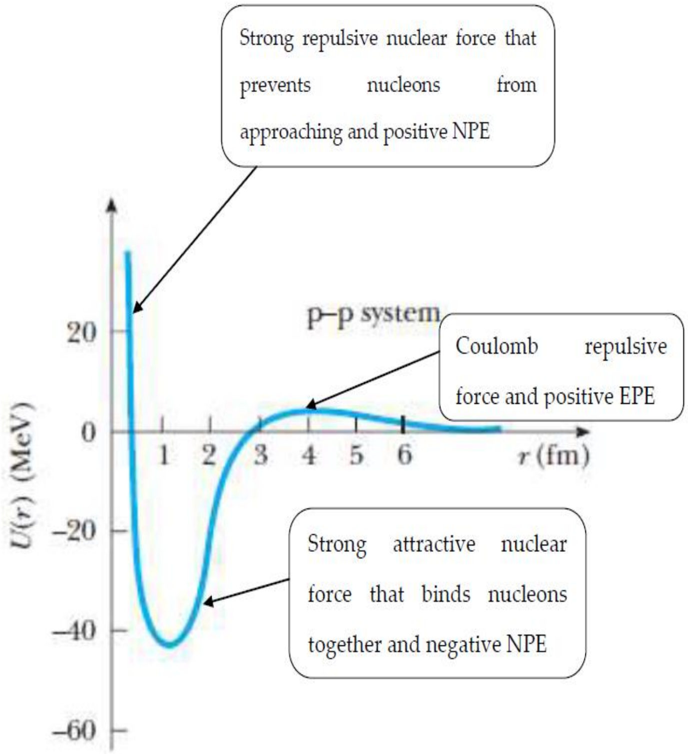


Figure 4.5: Potential Energy U(r) versus p-p separation distance r

Source: Adapted from Serway (2005, p. 474)

EPE = Electrical potential energy and NPE = Nuclear potential energy

U(r) represents either nuclear potential energy or electrical potential energy as a function of the separation distance r between two nucleons. In Figure 4.5, r represents the separation distance between two protons in a nucleus and U is the sum of the two potential energies. Coulomb's repulsive force between the two protons is dominated by the strong nuclear force at short distances and vice versa.

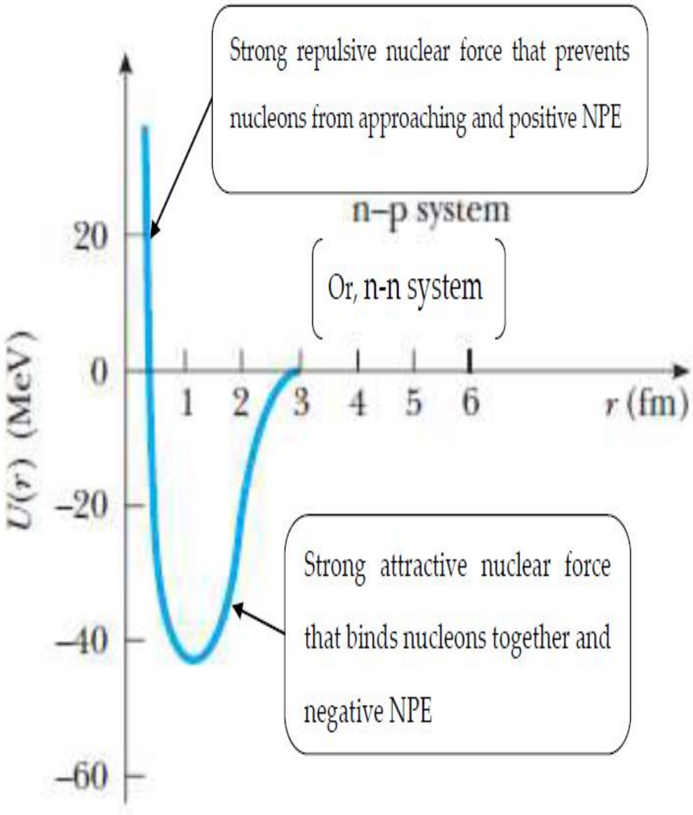
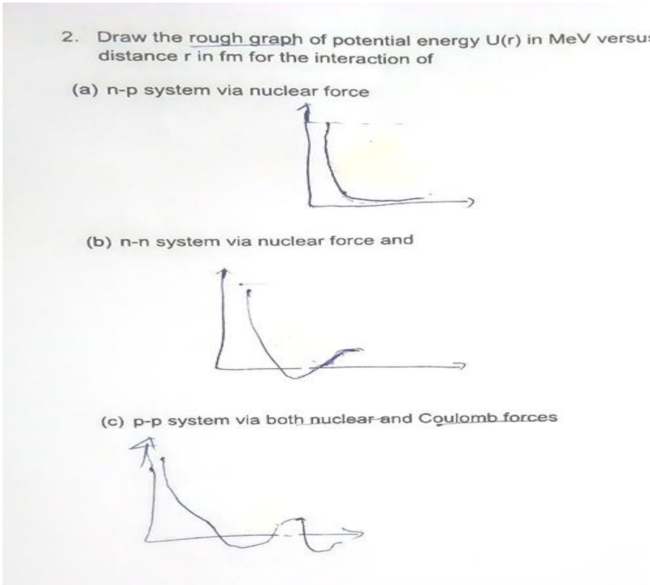


Figure 4.6: Potential Energy U(r) versus n-p separation distance r

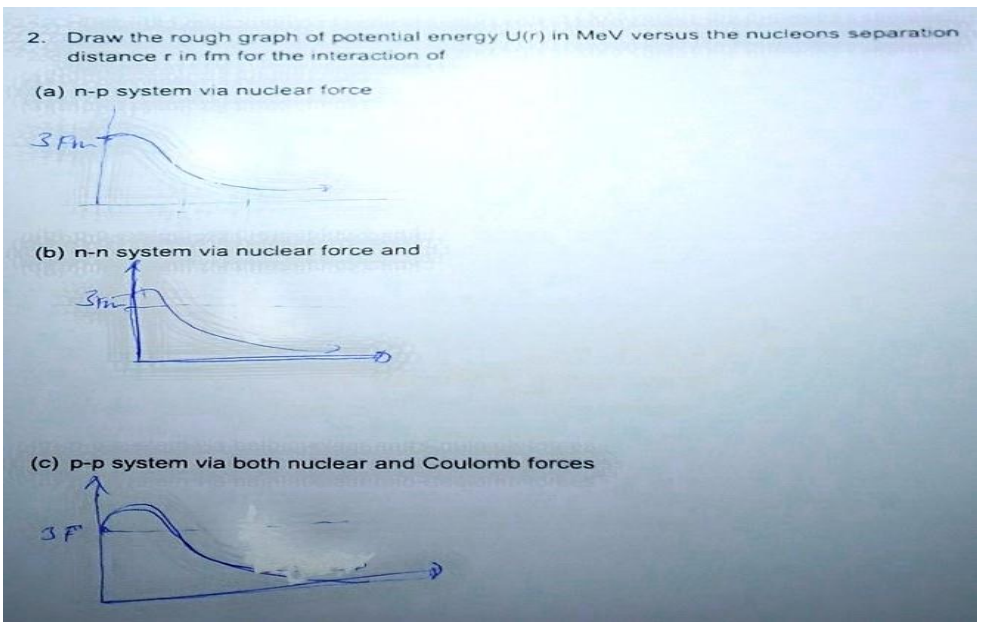
Source: Adapted from Serway et al. (2005, p.474)

In Figure 4.6, U represents the nuclear potential energy due to n-p and n-n interactions.

All students were asked to draw Figures 4.5 and 4.6. The following U-r graphs were the graphs that were drawn by some of the research participants, which are not the same as the scientific graphs that were drawn in Figures 4.5 and 4.6. No research participants drew the correct U-r graph.



(a) Students' U-r graph



(b) Students' U-r graph

Figure 4.7: Students' graph of potential energy U versus nucleons separation distance r

4.4 CATEGORISATION OF STUDENTS' CONCEPTUAL UNDERSTANDING AND REPRESENTATIONS OF RADIOACTIVE DECAY

4.4.1 Categorisation

Using the phenomenographic data analysis process elaborated in Section 4.1, the following six qualitatively different ways of students' conceptual understanding and representations of radioactive decay were identified. This means six categories of description were identified. An example of how the data collected from three students through semi-structured interviews were analysed and categorised for radioactive decay is presented in Appendix VII.

A. the number of radioactive nuclei remaining in a radioactive substance exponentially decreases in time
B. the number of nuclei that have decayed in a radioactive substance increases in time
C. the activity of a radioactive substance is the number of decays per unit of time
D. the half-life of a radioactive substance is the time taken for a half number of nuclei in a radioactive substance to decay
E. the half-life of a radioactive substance is its half time (half age)
F. the half-life of a radioactive substance is the time used to determine the age of material using carbon dating

The illustrative excerpts of the interview dialogue of three students associated with radioactive decay are presented as follows to support these categories of description.

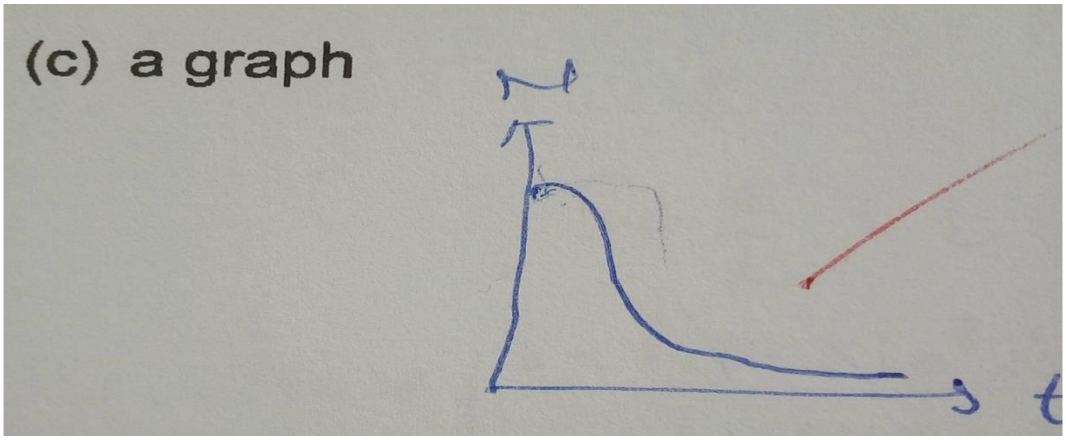
Researcher: State the radioactive decay law

Student S_{21}*:* "The radioactive decay law states that the number of nuclei in a sample decreases exponentially during the decay process" (Category A).

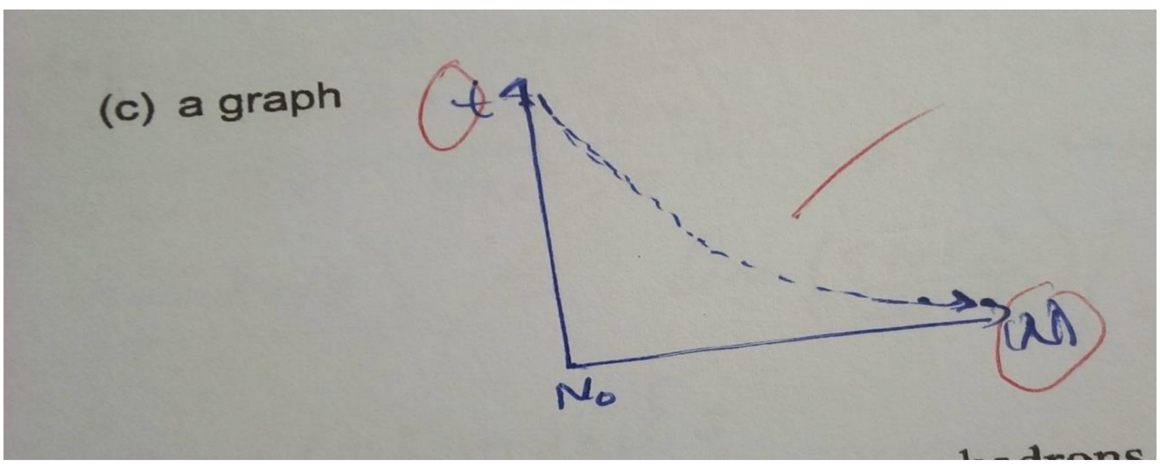
Researcher: Illustrate the radioactive decay law using a graph

Student S_{02}*:* She expressed the radioactive decay law using an equation and illustrated it using a graph as shown in Figure 4.9 (a) (Category A).

Student S_{20}*:* He illustrated it using a graph without expressing it using an equation (Category A):



Student S_{21}*:* He illustrated it using a graph without expressing it using an equation as follows (Category A)



The other three students drew and used the graphs represented in Figure 4.9.

Researcher: Define the half-life of a radioactive substance

Student S_{02}*:* “The half-life of a radioactive substance is the time needed for its half of the number of radioactive nuclei to decay” (Category E).

Student S_{20}*:* “The half-life of a radioactive substance is a carbon dating that can be used to determine the age of a material” (Category F).

Student S_{21}*:* "The half-life of a radioactive substance is the time used to determine the age of a sample of material" (Category F).

Researcher: Express the half-life of a radioactive substance using an equation.

Student S_{02}*:* She expressed it using Equation 4.8 (Category D).

In general, other students described radioactive decay using Equations 4.6, 4.7, and 4.9.

$$N = N_0\left(1 - e^{-\lambda t}\right) \qquad \text{(Eq. 4. 6)}$$

$$R = R_0 e^{-\lambda t} \qquad \text{(Eq. 4. 7)}$$

$$T_{1/2} = \frac{0.693}{\lambda} \qquad \text{(Eq. 4. 8)}$$

$$R = -\frac{dN}{dt} \qquad \text{(Eq. 4. 9)}$$

Eq. 2.2 is the students' representation of Category A while Eq. 4.6 is the representation of Category B. Eqs.4.9 and 4.7 are the students' representation of Category C while Eq. 4.8 is the representation of Category D.

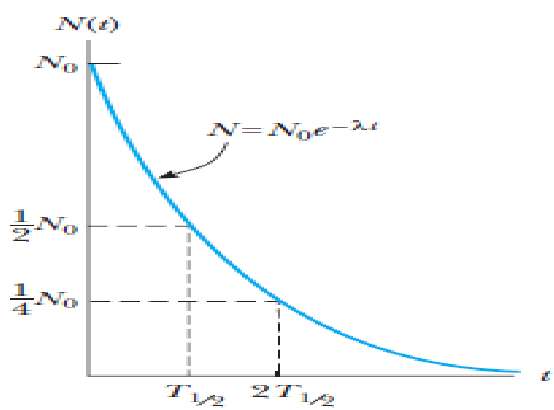
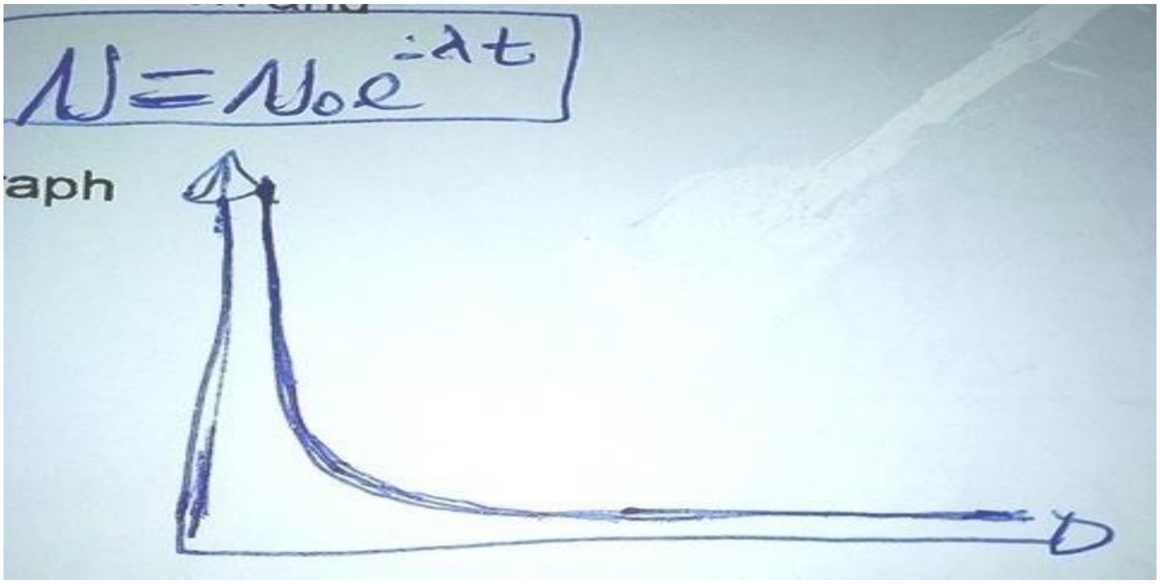


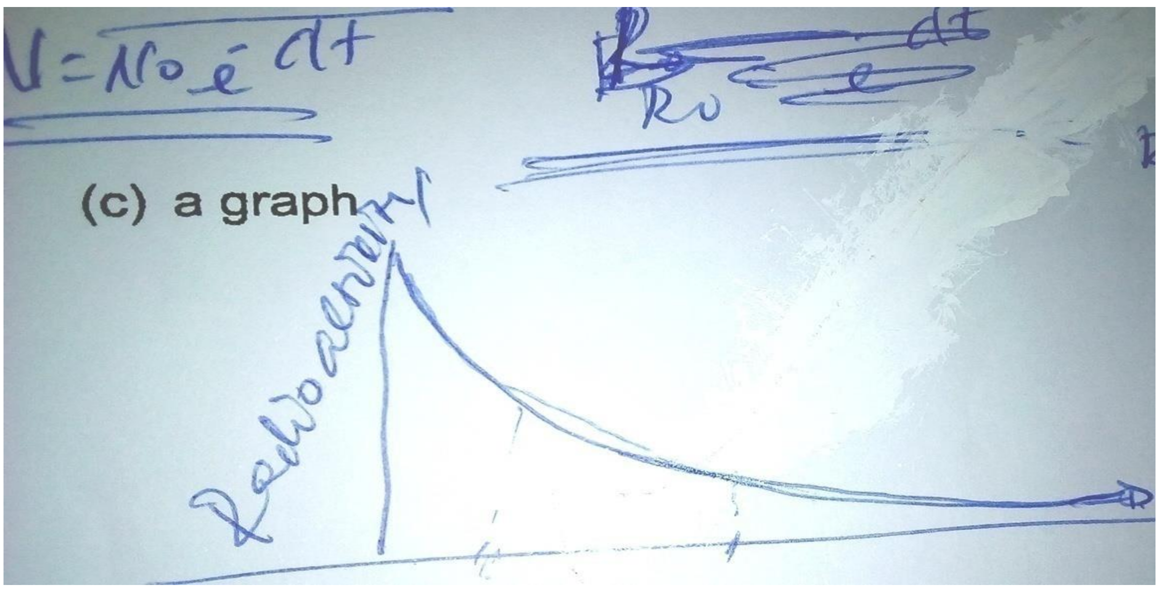
Figure 4.8: The scientific graph of radioactive decay law

Source: Adapted from Serway et al.(2005, p.482)

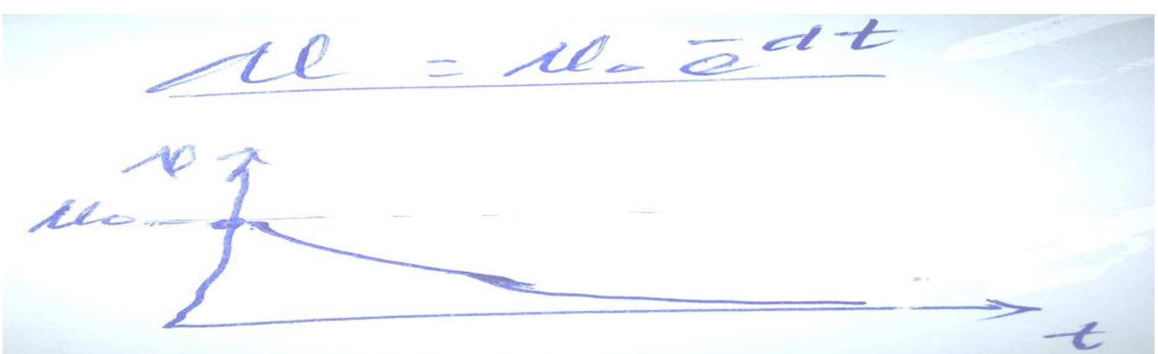
All students were allowed to illustrate a radioactive decay law using a graph. The following graphs are the graphs that were drawn by some students.



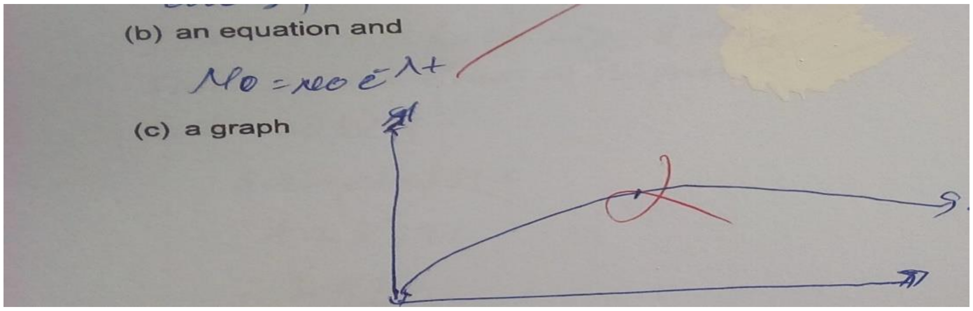
(a) First graph



(b) Second graph



(c) Third graph



(d) Fourth graph

Figure 4.9: Students' graphs of radioactive decay law

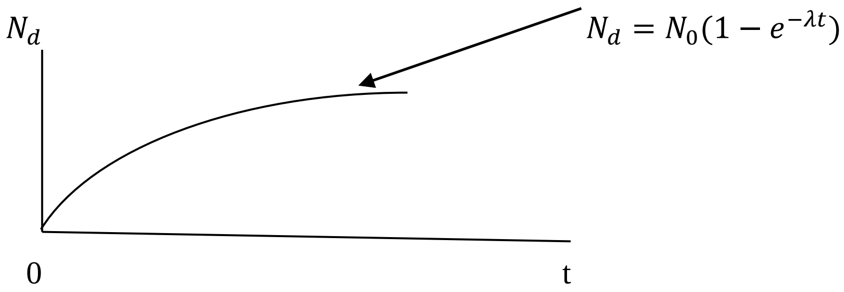


Figure 4.10: The scientific graph of the number of nuclei that have decayed versus time

Figures 4.9 (a), (b), (c) are the students' graphical representations of Category A. These graphs are similar to the scientific graph in Figure 4.8. Figure 4.9 (d) is a student's incorrect graphical representation of Category A. This graph is similar to the graph in Figure 4.10 not to Figure 4.9. Eq. 4.10 is the scientific graphical representation of Category B, which was not drawn by students for Category B.

4.4.2 Naming the Categories of Radioactive Decay and How They Have Evolved

The names are given for each of the previous categories and how they have evolved is illustrated in Figures 4.11 (a), (b), (c), and (d). The name was given based on the aspects of radioactive decay described by students in each category. Category A represents the first aspect of radioactive decay. The students understood that the number of radioactive nuclei remaining in a radioactive substance exponentially decreases in time.

Exponentially decreases in time Exponential decay Radioactive decay law Represented by equation 2.2	⇒	Category A Number of nuclei remaining	Figure 4.11(a): How Category A has evolved
Logarithmically increases in time Represented by equation 4.6 Represented by the graph in	⇒	Category B Number of nuclei that have decayed	Figure 4.11(b): How Category B has evolved
Decay rate The number of decays per unit time Exponentially decreases in time Activity law Represented by equations 4.9 and 4.7	⇒	Category C The activity	Figure 4.11(c): How Category C has evolved
The time taken for half number of nuclei to decay At one half-life, $N = \frac{N_o}{2}$ Represented by equation 4.8 Indicated in graph 4.8 The half-life of a radioactive substance	⇒	Category D The half-life	Figure 4.11(d): How Category D has evolved

Figure 4.11: How the categories of description representing the students' different ways of conceptual understanding and representations of radioactive decay have evolved

Figures 4.11 (a), (b), (c), and (d) illustrates how the categorisation of students' conceptual understanding and representations of radioactive decay was reduced to set up boundaries among the categories in the coding and recoding process. These figures show the students' different ways of conceptual understanding and representations.

4.4.3 The Categories of Description of Radioactive Decay in a Hierarchy

The previous categories are arranged in a hierarchy from less (Category I at the top) to a more complicated conceptual understanding of radioactive decay (Category V at the bottom) (see Figure 4.12). These four phenomenographic categories are the students' different ways of conceptual understanding radioactive decay.

In Category I, the students described how the number of radioactive nuclei remaining in a radioactive substance changes over time. Particularly, the students described this easily using an equation and a graph. At one half-life, the numbers of nuclei that have remained and that have decayed are the same. That is, it is half of the number of radioactive nuclei present at time t = 0. Hence, the students may have greater difficulty in understanding the second category than the first one.

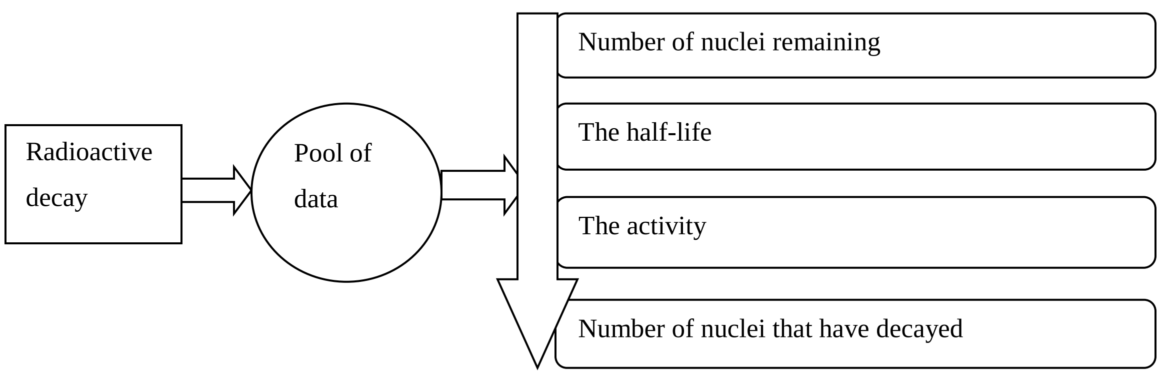


Figure 4.12: The categories of description in a hierarchy that represent the students' different ways of conceptual understanding radioactive decay

The activity is defined based on the number of nuclei remaining. So, without understanding the first category, it may be difficult for students to understand the activity, which is the third category. The number of nuclei that have decayed can be found by subtracting the number of nuclei remaining from the number of radioactive nuclei present at time t = 0.

Therefore, it may be difficult for the students to understand how the number of nuclei that have decayed changes over time without understanding the first category. These are the reasons for arranging the categories in this hierarchy.

The phenomenographic analysis process of the pool of data of radioactive decay and its results are summarised in Table 4.3. In the last columns of this table, the students' categories of description are further coded into the NRR, CA, and IA. An (X) is used to mark the appropriate column to indicate where a group of research respondents' categories of descriptions belong.

Table 4.3: Students' categories of description of radioactive decay

Category name	**Categories of description**	**NRR (N=30)**	**NRR In %**	**CA**	**IA**
Category I Number of nuclei remaining	The number of radioactive nuclei remaining in a radioactive substance exponentially decreases in time	10	33.3	X	
	The number of particles of a radioactive substance exponentially decreases in time	2	6.7		X
	$N = N_0 e^{-\lambda t}$	20	66.7	X	
	Graphical representation-Figure 4.9	17	56.7	X	
	$N = N_0(1 - e^{-\lambda t})$	1	3.3		X
	Graphical representation–Figure 4.10	2	6.7		X
Category II The half-life	The half-life of a radioactive substance is the time taken for its half number of nuclei to decay	1	3.3	X	
	$T_{1/2} = \frac{0.693}{\lambda}$	3	10	X	
	The half-life of a radioactive substance is its half time	1	3.3		X
	The half-life of a radioactive substance is the time used to determine the age of material using carbon dating	2	6.7		X

Category III The activity	$R = R_0 e^{-\lambda t}$	1	3.3	X	
Category IV Number of nuclei that have decayed	The number of nuclei that have decayed logarithmically increases in time	0	0	X	
	$N = N_0(1 - e^{-\lambda t})$	0	0	X	
	Graphical representation-Figure 4.10	0	0	X	
Category V Non-respondent students	Students who did not respond to the semi-structured interviews	3	10		

The fifth category was added to indicate the students that did not respond or those students who did not discern any aspect of the concept. To understand how the data collected from the 30 students were analysed for radioactive decay see Appendix VII, which is illustrated using three students as an example.

4.4.4 Discussion on Students' Categories of Description of Radioactive Decay

Category I: Number of radioactive nuclei remaining in a substance

Findings in Table 4.3 indicate that 10 students understood the number of radioactive nuclei remaining in a substance exponentially decreases over time. This is commonly known as the radioactive decay law. 20 students correctly expressed this law using an equation similar to Eq. 2.2 while 17 students correctly represented his law using the graphs drawn in Figure 4.9, which are similar to Figure 4.8. Another student incorrectly expressed radioactive decay law using an equation $N = N_0(1 - e^{-\lambda t})$ and two students incorrectly represented this law using the graph in Figure 4.10. Scientifically, these equations and the corresponding graph represent how the number of nuclei that have decayed changes in time. It seems that the student confused the number of nuclei remaining in a radioactive substance with the number of nuclei that have decayed. The students had difficulty in stating the radioactive decay law verbally and in writing as opposed to representing the law using an equation and a graph.

The findings of Kohnle et al. (2011)also indicated that the students confused the number of nuclei that have decayed with the number of nuclei remaining in a radioactive substance. Other researchers' findings also indicated that the students had a misconception about radioactive decay (Rathore, 2016; Yeşiloğlu, 2019). Particularly, the findings of Yeşiloğlu (2019, p.866) indicated that the students incorrectly understood that "the radioactive substances vanish over time and are transformed into energy". Experimental measurements indicate that the number of radioactive nuclei in the radioactive substances exponentially decreases over time, but the radioactive substances do not vanish. Instead, these radioactive substances can be changed into other substances after the decay is complete.

Category II: The half-life of a radioactive substance

The results in Table 4.3 indicate that only one student correctly defined the half-life of a radioactive substance in words while three students expressed it using the correct equation similar to the graph in Figure 4.8. Scientifically, the half-life is defined as the time taken for the half number of the radioactive nuclei in a radioactive substance to decay. 3 students incorrectly defined the half-life. One student incorrectly defined that the half-life is the half time or half of the age of a radioactive substance while the other two students defined incorrectly the half-life of a radioactive substance is the time used to determine the age of a substance. It seems that the students confused the half-life with carbon dating. It is possible to measure the age of a substance using the concept of the beta decay of carbon-14, which commonly we call carbon dating, not using half-life.

The previous findings indicated that the students' encountered the conceptual difficulty of the half-life of a radioactive substance (Kohnle et al., 2011; Rathore, 2016; Yeşiloğlu, 2019). Kohnle et al. (2011) found that some students correctly defined the half-life of a radioactive substance but were unclear how to use the decay law successively at one half-life, two half-lives, three half-lives, and so on.

Category III: The activity of a radioactive substance

As the results in Table 4.3 show, one student correctly expressed the activity of a radioactive substance using Eq. 4.7. The student incorrectly expressed this equation as an equation of radioactive decay law. Eq. 4.7 is the equation of activity law and not that of radioactive decay law. Even if the graphs of both radioactive decay law and activity law are the same (see Figure 4.8), their equations are different in content but the same in form (see Eqs.2.2& 4.7). It seems that the student confused the equation of radioactive decay law with that of the activity law. The time derivative of the equation of radioactive law gives the equation of activity law.

Category IV: Number of nuclei that have decayed

Findings in Table 4.3 indicate that the students were not able to describe how the number of radioactive nuclei that have decayed changes over time verbally, in text, using the equation, and a graph. This indicates that the fourth category is more difficult to understand than the previous categories. As discussed in Category I, the students confused the number of nuclei that had decayed with the number of nuclei remaining in a radioactive substance. How the number of nuclei remaining in a radioactive substance changes over time was described by 67% of the students using an equation, 57% of them using a graph, and 33% of them using text. But no student described how the number of nuclei that have decayed changes over time.

The change in the number of nuclei remaining in a radioactive substance in time (Eq. 4.8) is the inverse of the change in the number of nuclei that have decayed in time (Eq. 4.10) as illustrated in the next figure (Figure 4.13), which makes their differences clear.

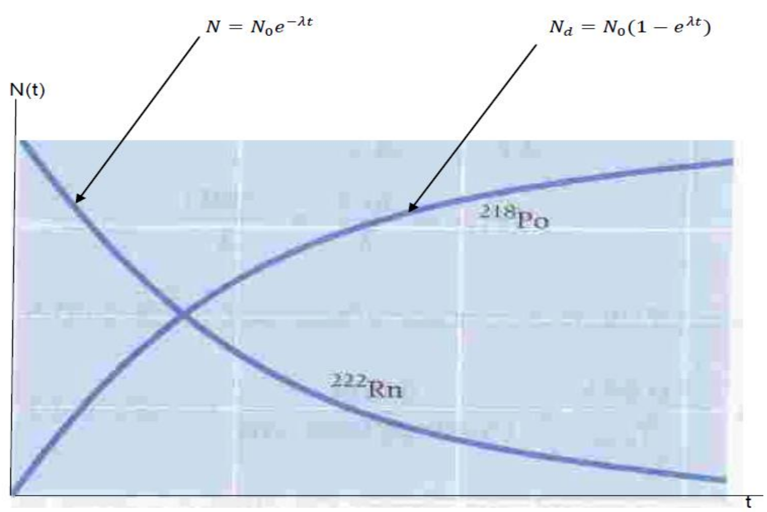


Figure 4.13: The alpha decay of radioactive Rn-222 to Po-218

Source: Adapted from Beiser(1963)

Where N and N_d respectively are the number of nuclei remaining and that have decayed in a radioactive substance at time t. No students drew the two graphs in the same plane as that of Figure 4.13 to understand their differences clearly.

4.5 CATEGORISATION OF STUDENTS' CONCEPTUAL UNDERSTANDING AND REPRESENTATIONS OF NEGATIVE BETA DECAY

4.5.1 Categorisation

By using the phenomenographical data analysis process elaborated in Section 4.1, the following seven qualitatively different ways of students' conceptual understanding and representations of the negative beta decay (NBD) were identified. An example of how the data collected from three students through semi-structured interviews were analysed and categorised for NBD is presented in Appendix VII.

A. the origin of the electron emitted in the NBD process is the electron that exists in the parent nucleus
B. the origin of the electron emitted in the NBD process is the neutron that exists in the parent nucleus
C. the origin of the electron emitted in the NBD process is the proton that exists in the parent nucleus
D. the origin of the electron emitted in the NBD process is the rest energy of the decaying parent nucleus
E. the origin of the electron emitted in the NBD process is the atomic orbital electrons
F. the origin of the electron emitted in the NBD process is the nuclear reaction
G. the origin of the electron emitted in the NBD process is the daughter nucleus

The illustrative excerpts of the interview dialogue of three students associated with radioactive decay are presented as follows to support these categories of description.

Researcher: What is the origin of an electron emitted in the beta decay process?

Student S_{02} *:* "The electron is produced during the beta decay process" (Category B).

Student S_{20} *:* "The electron emitted in the beta decay process is coming from a proton in a nucleus" (Category C).

Student S_{21} *:* "The electron emitted in the beta decay process is coming from a neutron in a nucleus of an atom" (Category B).

Researcher: Does the electron emitted in the beta decay process exist in the nucleus before beta decay? Explain the reason for your answer.

Student S_{02} *:* "An electron does not exist within the nucleus" (Category A).

Student S_{20} *:* "The electron does not exist in the nucleus, because the nucleus is positively charged" (Category A).

Student S_{21} *:* "The electron does not exist in the nucleus; instead, it is orbiting the nucleus" (Category A).

Researcher: Express the NBD process using an equation

Student S_{02} *:* She expressed it as follows (Equation 2.4)

$$^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e^{-} + \bar{v}$$

Student S_{20} *:* He expressed it as follows (Equation 2.4)

$$^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e^{-}+\bar{v}$$

Student S_{21} *:* He expressed it as shown below (Equation 2.4)

$^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + e^{-}+\bar{v}$

Other students expressed the NBD process using Equations 4.10 - 4.15.

The incomplete positive beta decay process

(Irrelevant to NBD)

$${}_{Z}^{A}X \rightarrow {}_{Z-1}^{A}Y + e^{+} \quad (4.\ 10)$$

Electron capture

(Relevant to atomic electron)

$${}_{Z}^{A}X + e^{-} \rightarrow {}_{Z-1}^{A}Y + \nu \quad (4.\ 11)$$

The incomplete NBD process

(Relevant to NBD)

$${}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + e^{-} \quad (4.\ 12)$$

The incomplete neutron decay process

(Relevant to NBD)

$$n \rightarrow p + e^{-} \quad (4.\ 13)$$

Irrelevant equation

$${}_{Z}^{A}X \rightarrow {}_{Z-1}^{A}Y + e^{-} + \overline{\nu} \quad (4.\ 14)$$

Irrelevant equation

$${}_{Z}^{A}X \rightarrow {}_{Z-1}^{A}Y + e^{-} \quad (4.\ 15)$$

The correct complete NBD process is expressed using Eq. 2.4. Eqs.4.12, 4.13, and 2.4 were assumed by students to be relevant to Category B. Eq. 4.14 and 4.15 were also considered by students as relevant to Category B but they are not. Eq. 4.10 is relevant to Category C but irrelevant to NBD. Eq.4.11 is assumed by students to be relevant to Category E.

4.5.2 Naming the Categories of the Possible Origin of the Electron Emitted in NBD

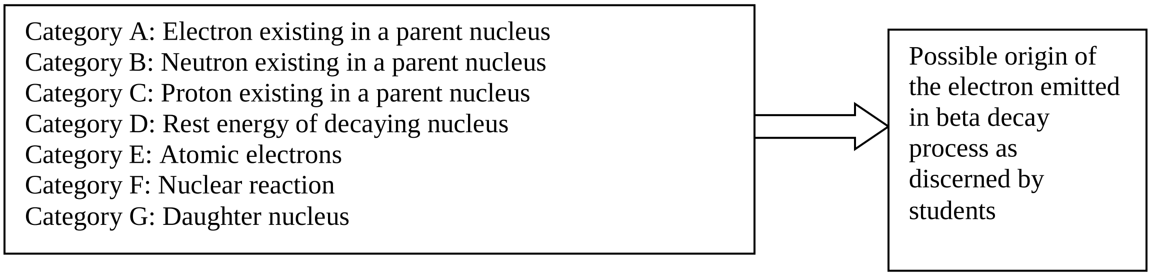


Figure 4.14: Possible origins of the electron emitted in beta decay process as understood by students

The names are given for each of the previous categories and the possible origins of the electron emitted in the beta decay process as understood by students are illustrated in Figure 4.14. The name was given based on the possible origins of the electron emitted in the NBD process identified by students. Some of the categorised possible origins of the electron emitted in the beta decay process as understood by students are scientific. These are discussed in Section 4.5.4 on the discussion part of the categories of the description of NBD.

4.5.3 Categories of the Description of NBD in a Hierarchy

The categories are arranged in a hierarchy from less complicated (Category I at the top) to a more complicated conceptual understanding of NBD (Category VII at the bottom) as illustrated in Figure 4.15. These seven phenomenographic categories are the students' different ways of conceptual understanding of NBD. The categories are arranged in a hierarchy from the atomic level to the nuclear level of students' understanding. The entities at the nuclear level are more complicated to understand than those at the atomic level.

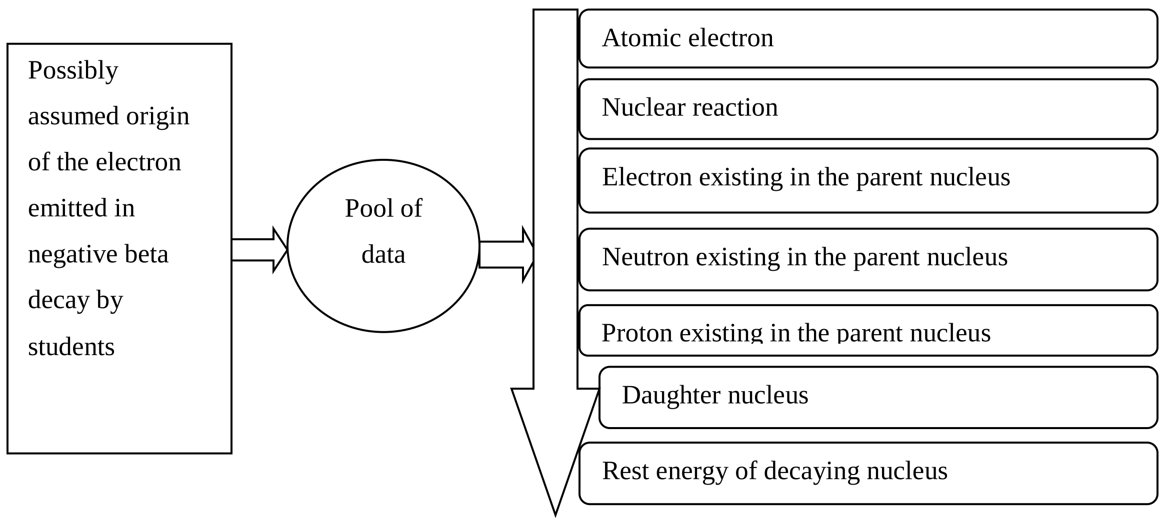


Figure 4.15: The categories of description in a hierarchy that represent the students' different ways of conceptual understanding of NBD

Since the electron emitted in beta decay comes out of the nucleus, the students assumed that an electron exists in a nucleus, which is direct thinking. However, assuming that the electron emitted in beta decay comes out of the entity in a nucleus such as a neutron and a proton is more complicated. Thinking of the daughter nucleus as the origin of the electron emitted in beta decay is more complicated than the previous categories, because it may not be possible to understand the daughter nucleus without understanding the decay of the parent nucleus. Finally, understanding the rest energy of the decaying parent nucleus as the origin of the electron emitted in the beta decay process is difficult since it needs an understanding of relativity.

The phenomenographical analysis process of the pool of data of NBD and its results are summarised in Table 4.4. In the last columns of this table, the students' categories of description are further coded into the NRR, CA, and IA. An (X) is used to mark the appropriate column to indicate where a group of research respondents' categories of descriptions belong. The students' categories of description of the NBD process are presented in the next table.

Table 4.4: Students' categories of description of NBD

Category name	Students' description	NRR (N=30)	NRR In %	CA	IA
Category I Atomic electrons	The origin of the electron emitted in the beta decay process is the electrons orbiting the nucleus	5	16.7		X
	The electron capture is the origin of the electron emitted in the beta decay process	2	6.7		X
Category II Nuclear reaction	A nuclear reaction is the origin of the electron emitted in the beta decay process	1	3.3		X
	The disintegration of a parent nucleus is the origin of the electron emitted in the beta decay process	1	3.3		X
Category III Electron existing in the parent nucleus	The electron that exists within the parent nucleus before the beta decay process is emitted at the moment of beta decay	6	20		X
	The unstable parent nucleus is the origin of the electron emitted in the beta decay process	7	23.3	X	
Category IV The neutron in the parent nucleus	The neutron in the unstable parent nucleus is the origin of the electron emitted in the beta decay process	12	40	X	
	$n \rightarrow p + e^{-} + \bar{\nu}$	0	0	X	
	$n \rightarrow p + e^{-}$	4	13.3		X
	${}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + e^{-} + \bar{\upsilon}$	9		X	
	${}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + e^{-}$	4		X	
	The change of the atomic number of a parent nucleus by one is the origin of the electron emitted in the beta decay process	2			X
Category V The proton in the parent nucleus	The proton in the parent nucleus is the origin of the electron emitted in the beta decay process	2			X
	${}_{Z}^{A}X \rightarrow {}_{Z-1}^{A}Y + e^{-} + \bar{\upsilon}$	5			X
	${}_{Z}^{A}X \rightarrow {}_{Z-1}^{A}Y + e^{-}$	1	3.3		X
Category VI The	The daughter nucleus is the origin of the electron emitted in the beta decay process	1	3.3		X

Category name	Students’ description	NRR (N=30)	NRR In %	CA	IA
daughter nucleus					
Category VII The rest energy of the parent nucleus	The electron emitted in the beta decay process is created out of the rest energy of the decaying parent nucleus at the moment of beta decay	0	0	X	
	The electron does not exist within the nucleus before the beta decay process, but it is created at the moment of decay	10		X	
Category VIII Non-respondent students	Students who did not respond to the semi-structured interviews	4	13.3		

The eighth category was added to indicate the students who did not respond or those students who did not discern any aspect of the NBD. How the data collected from 3 students was analysed for NBD is shown in Appendix VII.

4.5.4 Discussion on the Students’ Categories of Description of the NBD

Category I: Atomic electrons

As the findings in Table 4.4 indicate, five students incorrectly understood that the origin of the electron emitted in the beta decay process is atomic electrons while two students understood electron capture as the origin of the electron. Electron capture is the third kind of beta decay process next to negative and positive beta decay processes. In electron capture, the nucleus of an atom captures an electron from its innermost atomic shells such as K-shell, and emits neutrino, not electron (see Eq. 4.11). This is the result of the internal coulomb attractive force between the positively charged nucleus and the negatively charged atomic electron say in K-shell. But it seems the students assumed that the electron emitted in the beta decay process was the atomic electron captured by the nucleus. The students did not consider the neutrino emitted in electron capture.

Kohnle et al. (2011) found that the students incorrectly assumed that the electron in the NBD process is emitted from the atomic electron shell of the parent nucleus. This led the students to assume incorrectly that the number of atomic electrons in the daughter atom is decreased by one and that the number of protons in the daughter nucleus is unchanged.

However, in scientific thinking, the number of protons of the daughter nucleus is increased by one while the number of atomic electrons is unchanged. Other students incorrectly indicated that both the number of protons and atomic electrons of the daughter nucleus decreased by one. They incorrectly assumed that both of them were emitted in the beta decay process. In both cases, the students wrongly assumed that the origin of the electron emitted in beta decay was atomic electrons.

Category II: Nuclear reaction

One student understood that nuclear reaction is the origin of the electron emitted in the beta decay process. This is not correct. A nuclear reaction is a reaction in which a particle and a nucleus collide to be changed into another nucleus and emit a particle. The emitted particle is not necessarily an electron. Other students confused nuclear decay with nuclear reaction. NBD is a kind of nuclear decay, not a nuclear reaction. Another student understood that the disintegration of a parent nucleus is the origin of the electron emitted in the beta decay process. This is ambiguous because a parent nucleus can be disintegrated in negative as well as in positive beta decay and also in a nuclear reaction. Hence, the student's description in this category is irrelevant to NBD.

Category III: Electron existing in the parent nucleus

As the results in Table 4.4 indicate, six students understood that the electrons existing in the parent nucleus are the origin of the electron emitted in the beta decay process. This led the students incorrectly to assume that electrons exist in the parent nucleus before decay. Scientifically, the electron does not exist in the parent nucleus before decay. However, the electron is created at the moment of beta decay and then is emitted.

In a previous study, students correctly understood that the electron emitted in the beta decay process comes out from the parent nucleus. However, students incorrectly understood that electrons are one of the constituents of the nucleus. It seems that since this electron comes out from the nucleus of an atom, the students wrongly assumed as if this electron exists in the nucleus before beta decay (Pillay & Loonat, 1993).

Category IV: Neutron existing in the parent nucleus

As the findings in Table 4.4 indicate, 12 students understood that the decay of a neutron in the parent nucleus is the origin of the electron emitted in the beta decay process. This description is acceptable to the scientific community of practice. At the moment of beta decay, a neutron in the parent nucleus decays into a proton, electron, and antineutrino. This is expressed using Equation 4.16.

$$n \rightarrow p + e^{-} + \bar{\nu} \quad (4.\ 16)$$

The electron indicated in Eq. 4.16 is the electron emitted in the NBD process. No students expressed the complete Eq. 4.16 of the decay process of the neutron in the parent nucleus. Four students expressed Eq. 4.13 ($n \rightarrow p + e^{-}$), which is an incomplete equation of the decay of a neutron in a parent nucleus. The third particle antineutrino ($\bar{\nu}$) was not considered by students. In previous studies, the students expressed the decay of neutrons similarly (Pillay & Loonat, 1993). The students tried to give a reason why they expressed the decay of a neutron in this form. Their reason was that the neutron is the combination of a positively charged proton and a negatively charged electron in which they did not consider the third particle antineutrino indicated in Eq. 4.16.

Nine students expressed the correct complete Eq. 2.4 of the NBD process. However, four students expressed Eq. 4.12, which is an incomplete equation of the NBD process in which the students did not consider the third particle antineutrino. Two students understood that the change of the atomic number by one is the origin of the electron emitted in the beta decay process. This is incorrect because the change is the result of decay not the origin of the electron. In the NBD process, the atomic number of the daughter nucleus is increased by one, which is correct. Seven students understood that the unstable parent nucleus is the origin of the electron emitted in the beta decay process. This understanding of students is not clear, because the decay of a neutron in the unstable parent nucleus is the origin of the electron emitted in NBD.

Category V: Proton existing in the parent nucleus

Two students incorrectly understood that the proton existing in the parent nucleus is the origin of the electron emitted in the beta decay process. However, the proton existing in the parent nucleus is the origin of the positron emitted in the positive beta decay process. This is shown in Equation 4.17.

$$p \rightarrow n + e^{+} + \nu \quad (4.\ 17)$$

The students confused the NBD with positive beta decay. In a positive beta decay process, the atomic number of the daughter nucleus is decreased by one. Eqs.4.14 and 4.15 expressed by students indicate this but the emitted particles are electron and antineutrino, which is incorrect. In other words, it seems that the students confused the origin of an electron with the origin of the positron emitted in the beta decay process. The complete equation of the positive beta decay process is expressed in Eq. 2.5. It seems also that the students confused the equation of the NBD process with that of the positive beta decay process (see Eqs.2.4 & 2.5).

Category VI: Daughter nucleus

One student incorrectly understood that the daughter nucleus is the origin of the electron emitted in the beta decay process. It seems that this student didn't understand the concept of the NBD. In NBD process, the daughter nucleus is a positive ion, because there is one extra proton in it, and the number of atomic electrons stays unchanged. This extra proton comes from the decay of neutrons existing in the parent nucleus (see Eq. 4.16). So, an electron cannot be emitted by the daughter nucleus. In a previous study, the students wrongly understood that the electron emitted in the beta decay process comes from the daughter nucleus (Pillay & Loonat, 1993). That is, the students incorrectly assumed that the origin of the electron emitted in the NBD process is the orbital electrons in the daughter atomic shells.

Category VII: Rest energy of the decaying nucleus

Scientifically, the electron emitted in the beta decay process is created out of the rest energy of the decaying parent nucleus at the moment of beta decay. No students understood the origin of an electron in this way. This indicates that this category is the most difficult compared to other categories. Ten students understood that the electron does not exist in the parent nucleus before beta decay, but they did not reason this out. The reason is that the electron emitted in the beta decay process is created out of the rest energy of the decaying parent nucleus at the moment of beta decay. Scientifically, the origin of the electron emitted in the beta decay process is the decay of neutron that exists in the parent nucleus into a proton, electron, and antineutrino.

4.6 CATEGORISATION OF STUDENTS' CONCEPTUAL UNDERSTANDING AND REPRESENTATIONS OF NE

4.6.1 Categorisation

Using the phenomenographic data analysis process mentioned in Section 4.1, the following six qualitatively different ways of students' conceptual understanding and representations of NE were identified. This means six categories of description were identified. An example of how the data collected from three students through semi-structured interviews were analysed and categorised for NE is presented in Appendix VII.

A. NE is released in a nuclear reaction
B. NE is coming out of the nucleus of an atom
C. NE is created out of the nuclear rest mass
D. NE is released in nuclear decay
E. NE is released in a chemical reaction
F. NE is the energy that must be added to a nucleus to separate it into its constituent nucleons

The illustrative excerpts of the interview dialogue of three students associated with radioactive decay are presented as follows to support these categories of description.

Researcher: Define NE

Student S_{02}*:* "The NE is the energy gained or lost during a nuclear reaction, that is, during nuclear fission and fusion reaction" (Category A).

Student S_{20}*:* "NE is the energy of the nucleus which is produced by nuclear fission and fusion reactions" (Category A and B)

Student S_{21}*:* "NE is the energy that causes the particles of a nucleus to attract or repel or causes them to react to each other". "NE is produced by nuclear fission and fusion reaction" (Category A).

Researcher: Describe the difference between NBE and NE

Student S_{20}*:* "NBE is the energy lost when the nucleons bind together while NE is the energy lost during the disintegration of a nucleus" (Category A).

Student S_{21}*:* "Both NBE and NE are related to the nucleus" (Category B).

Researcher: Express NE using an equation

Student S_{20}*:* He called NE as Q-value and expressed it using Equation 2.8

$NE = Q \; = \left(m_a + m_x - m_y - m_b\right)c^2$(Category C)

4.6.2 Naming the Categories of Possible Sources of NE

The names are given for each of the previous categories and the possible sources of NE understood by students are illustrated in Figure 4.16. The name was given based on the possible sources of NE identified by students.

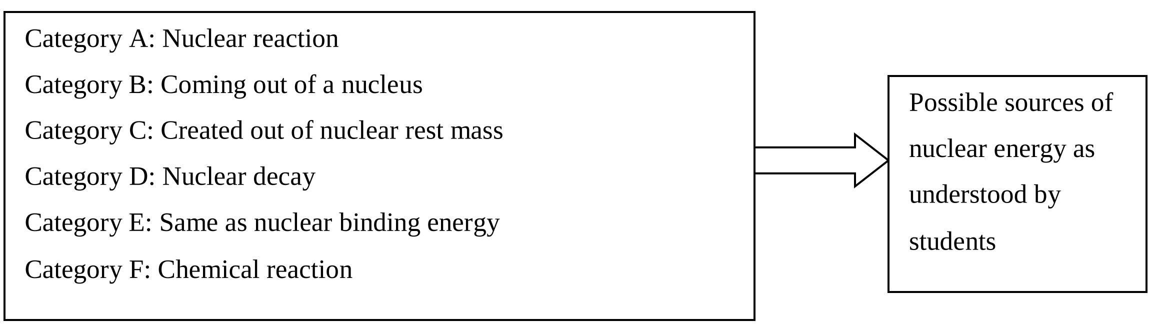


Figure 4.16: Possible sources of NE as understood by students

4.6.3 Categories of the Description of NE in a Hierarchy

The previous categories are arranged in a hierarchy from less complicated (Category I at the top) to a more complicated conceptual understanding of NE (Category VI at the bottom) as illustrated in Figure 4.17. The categories of the description presented in Table 4.5 indicated one student incorrectly understood that NE is produced in a chemical reaction. It seems that this student confused a nuclear reaction with a chemical reaction. Scientifically, NE is released in nuclear reactions and nuclear decay. A nuclear reaction occurs at an atomic nuclei scale, but a chemical reaction occurs at an atomic scale. As Figure 4.17 indicates, the students discerned six possible sources of NE, which are arranged in a hierarchy.

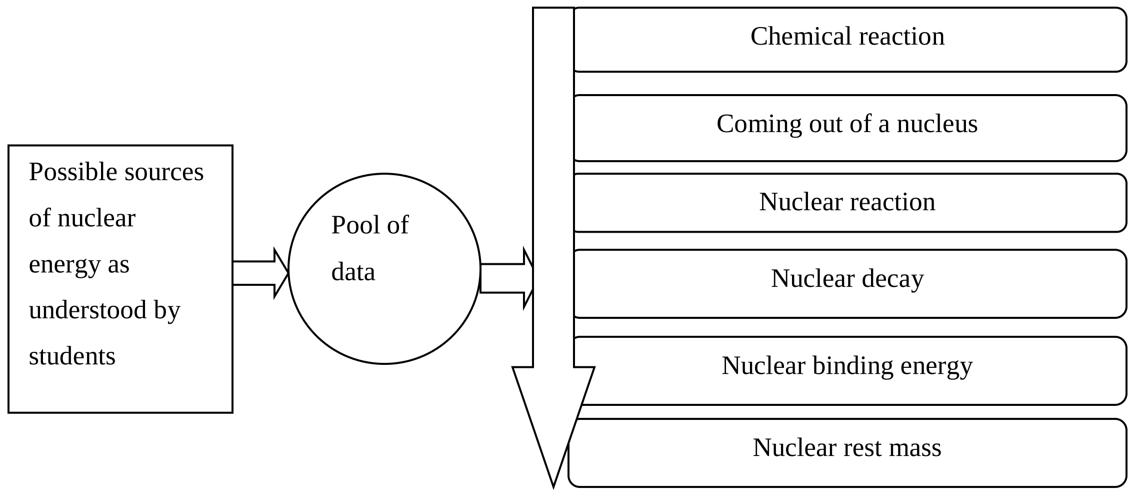


Figure 4.17: The categories of description in a hierarchy that represent the students' different ways of conceptual understanding of NE

As indicated in Table 4.5, 20 students understood that NE is released in large amounts in nuclear fission and fusion reactions. As compared to nuclear reactions, NE is released in small amounts in nuclear decay. These are discussed in detail in Section 4.6.4.

A chemical reaction occurs at the atomic level while a nuclear reaction occurs at the nuclear level. This implies that a nuclear reaction is more complicated than a chemical reaction to understand. In a nuclear reaction, a particle collides with a nucleus, and then the nucleus changes to another nucleus and particle while in nuclear decay a nucleus decays into another nucleus and particle by itself. The students also have an idea of collision from mechanics. So, the conceptual understanding of nuclear decay may be more difficult than that of nuclear reaction. In both nuclear reactions and decay, energy is coming out of a nucleus. This energy is NE. Understanding NE in this way is not difficult. However, understanding how NE comes out of a nucleus is more difficult. Four students defined NE the same as that of NBE. It seems that these students confused NE with NBE. The last category in which NE is described as the energy created out of the nuclear rest mass is the most difficult one among the six categories. It needs an understanding of the concept of energy-mass equivalence.

Table 4.5: Students' categories of description of NE (Results)

Category name	**Students' description**	**NRR (N=30)**	**NRR In %**	**CA**	**IA**
Category I: chemical reaction	NE is the energy found in a nucleus that can be produced by a chemical reaction	1	3.3		X
Category II: Nuclear reaction	NE is the energy produced by nuclear fission and fusion reactions	25	83.3	X	
	NE is the energy produced by a nuclear chain reaction	2	6.7	X	
	NE is the energy absorbed or released in a nuclear reaction	2	6.7	X	
	NE is the energy gained or lost in nuclear reactions	1	3.3	X	
	NE is the energy produced by nuclear reaction	6	20	X	
	NE is the energy released when a particle collides with a nucleus	3	10	X	
	NE is the energy produced by exothermic and endothermic nuclear reaction	4	13.3	X	
	NE is the energy released when a thermal neutron collides with $^{235}_{92}U$	1	3.3	X	
	E = $Q = (m_a + m_x - m_y - m_b)c^2$	3	10	X	
	NE is the energy released or absorbed in the form of kinetic energy in a nuclear reaction	3	10	X	
Category III: Nuclear decay	Students understood that NE is the energy produced by nuclear decay	1	3.3	X	
	NE is the energy released during the disintegration of a nucleus	2	6.7	X	
Category IV: The nucleus of an atom	NE is the energy coming out of a nucleus	5	16.7	X	
Category V: Nuclear binding energy	NE is the energy that should be added to a nucleus to disintegrate it into its separate constituents. Or it is the energy that binds	4	13.3		X

Category name	Students' description	NRR (N=30)	NRR In %	CA	IA
	nucleons together				
	$E = (Zm_p + Nm_n - M_N)c^2$	2	6.7		X
Category VI: Nuclear rest mass	NE is the energy formed as a result of the conversion of nuclear rest mass into energy in a nuclear reaction	1	3.3	X	
Category VII Non-respondent students	Students who did not respond to the semi-structured interviews	7	23.3		

The seventh category was added to indicate the students who did not respond. To show how the data collected from the 30 students analysed in the case of NE, the verbal and nonverbal responses of three students were analysed (see Appendix VII)

4.6.4 Discussion on the Categories of Description of NE

Category I: Chemical reaction

Findings in Table 4.5 indicate that one student understood that NE is produced by chemical reactions. This is not a scientific understanding. It seems that the students confused nuclear reactions with chemical reactions. This supports the findings of Pillay and Loonat (1993). The particles that participate in the nuclear reaction are protons and neutrons while the particles that participate in a chemical reaction are electrons. This may not be clearly understood by students.

Category II: Nuclear reaction

As the results in Table 4.5 show, 25 students understood that NE is produced by nuclear fission and fusion reactions. Six students understood that NE is produced by nuclear reactions. Five students understood that NE is the energy absorbed or released in the form of kinetic energy in a nuclear reaction. Four students understood that NE is produced by exothermic and endothermic nuclear reactions. Three students understood that NE is released when a particle collides with a nucleus and they expressed it using an equation $Q = (m_a + m_x - m_y - m_b)c^2$. Two students understood that NE is produced by a nuclear chain reaction while one student understood that NE is the energy gained or lost in a nuclear reaction. Another student understood that NE is released when a thermal neutron collides with a $^{235}_{92}U$ nucleus, which we call induced fission.

These different ways of students' understanding and representations of nuclear reaction as a source of NE are acceptable by the scientific community of practice. The energy released in a nuclear reaction is known as reaction energy or Q-value. Since this energy comes out of a nucleus we call it NE. In a nuclear reactor, NE is produced in large amounts in fission nuclear reactions to be converted to electrical energy. Kohnle et al. (2011) found that the students neglected to consider the kinetic energy of the particle 'a' that induces fission in an induced fission nuclear reaction. Scientifically, NE exists in the form of the kinetic energies of the fission fragments, which is expressed as $Q = KE_y + KE_b - KE_a$. Hence, neglecting the kinetic energy of the particle that induces fission affects the NE that exists in the form of kinetic energies.

Category III: Nuclear decay

Three students understood that NE is produced by nuclear decay while two understood that it is released in the disintegration of a nucleus. These ways of students' understanding are correct. According to the findings of Kohnle et al. (2011), students understood that NE is released in nuclear decay. That is, when a nucleus is split into its constituents in the nuclear decay process NE is released. The released energy is known as disintegration energy or Q-value. Since this energy comes out of the nucleus of an atom, commonly, it is regarded as NE.

Category IV: The nucleus of an atom

Five students understood that NE comes out of a nucleus. This way of understanding is also correct, because, in reality, this energy comes out of the core of an atom called a nucleus. But these students did not describe how NE came out of the nucleus, which is more difficult to understand.

Category V: NBE

As the findings in Table 4.5 indicate, four students defined NE as NBE. That is, they defined NE as the energy that binds nucleons together to form a nucleus or the energy that must be added to separate a nucleus into its constituents. Two students expressed NE using the equation $E = (Zm_p + Nm_n - M_N)c^2$, which is the formula of NBE. In general, this way of understanding is not correct. It seems that the students confused NE with NBE. Scientifically, NBE is defined as the energy released when the separated nucleons bind together to form a nucleus (Beiser, 1963). This definition may cause the students to confuse NE with NBE since the released energy comes out of a nucleus. NBE is also defined as the energy that must be added to a nucleus to split it into its constituent nucleons (Serway et al., 2005). However, NE is one of the forms of energy in nature that comes out of a nucleus at the moment of nuclear reaction and radioactive decay processes. Nuclear fission reaction produces NE in large amounts. According to Kohnle et al. (2011), fission only occurs for heavy nuclei when the fission fragments have greater binding energy per nucleon than that of the initial nucleus in the bound state.

Category VI: Nuclear rest mass

As the results in Table 4.5 show, one student understood that NE is created out of the nuclear rest mass and released at the moment of nuclear reaction. That is, NE is formed as a result of the conversion of nuclear rest mass into energy and then released at the moment of nuclear reaction. In a fission nuclear reaction, NE exists in the form of the kinetic energies of the fission fragments. That is, NE is the form of energy that can be transformed into other forms of energy. This indicates the origin of NE, how it comes out of a nucleus, and how it is transformed into kinetic energy. This is a correct way of understanding NE because it is acceptable by the scientific community of practice. It seems that the students understood the energy-mass equivalence ($E = (\Delta m)c^2$). This relationship between energy and mass was discovered for the first time by the famous physicist Albert Einstein. This is the most difficult category to understand among the six categories that the students encountered.

In the traditional teaching-learning process of the concept of energy, some basic ideas of energy were considered. These are forms of energy, the transformation of energy, transfer of energy, loss of energy, the gain of energy, and conservation of energy. NE is one of the forms of energy in nature that can be transformed into other forms of energy such as electrical energy. In the teaching-learning process of the concept of NE, some basic ideas of NE were considered. NE is the energy that comes out of the nucleus of an atom. It is produced in large amounts in nuclear fission and fusion reactions. In nuclear reactions, the nuclear rest mass is not conserved. This means the nuclear rest mass is lost in a nuclear reaction. This mass is changed into NE, which can be expressed as $E = (\Delta m)c^2$. This shows the mass-energy equivalence. From this, it is possible to understand that the nuclear rest mass is the origin of NE released in nuclear reactions. This NE exists in the form of the kinetic energies of the fission fragments in a fission nuclear reaction. In a nuclear reactor, this heats water and changes it into steam. The steam rotates the turbine-generator system. In this process, NE is converted to electrical energy. These are the basic ideas to be considered in the teaching and learning of the concept of NE.

4.7 THE CONCEPTUAL DIFFICULTIES IDENTIFIED IN THE FIRST PHASE

These are the conceptual difficulties identified based on the categories of description in the first phase after the students were exposed to traditional instruction. Renström et al. (1990) said that it is possible to delineate the potential conceptual difficulties associated with students' understanding and representations of a concept. This can be done based on the aspects of conceptual variation discerned by learners. The VTL provided insight into the conceptual difficulties that the students encountered after they were exposed to traditional instruction. In Sections 4.2.4, 4.3.4, 4.4.4, 4.5.4, and 4.6.4, the phenomenographic categories of description of each concept of nuclear physics were identified and discussed. These categories of description represent the various ways of students' understanding and representations of a nuclear physics concept. The categories of description arranged in a hierarchy are the aspects of the students' conceptual variation of a nuclear physics concept discerned by students. In the context of this study, these aspects are considered as either critical or IA (see Section 2.8.3). Those conceptual difficulties identified and discussed in the next sections are constituted in the IA in Tables 4.1 to 4.5. The conceptual difficulties revealed in this study were also identified by previous studies (see Section 2.5.2). The conceptual difficulties of NBE, nuclear force, radioactive decay, NBD, and NE identified in this study are clarified in the following subsections.

4.7.1 Conceptual Difficulties of NBE

In Section 4.2.4, four aspects of conceptual variation of NBE discerned by the students were discussed. In the discussion, the following conceptual difficulties associated with the students' understanding and representations of NBE were revealed.

- **Students understood NBE as the strong nuclear force-generating energy**

Students indicated incorrectly that NBE is generating an attractive strong nuclear force. This conceptual difficulty is discussed in Section 4.2.4 in Category I. On the NBE per nucleon versus atomic mass number graph of stable nuclei, the NBE per nucleon is approximately constant for mass number, A > 20. In this case, the attractive strong nuclear force between a particular nucleon and all the other nucleons in the nucleus is said to be saturated (Serway et al., 2005). This shows how the binding energy per nucleon of a nucleus and the attractive strong nuclear force exerted by a particular nucleon on other nucleons in this nucleus changes with mass number, A. But this does not indicate that NBE generates an attractive strong nuclear force. This was not identified in previous studies (see Section 2.5.2).

- **The students confused NBE with the attractive strong nuclear force**

Students incorrectly indicated that NBE binds nucleons together to form a nucleus. Or, putting it differently, they indicated incorrectly that NBE keeps a nucleus stable. This conceptual difficulty is discussed in Section 4.2.4 in Category II. It is the short-range attractive strong nuclear force that binds nucleons together to form a stable nucleus, not NBE. NBE is the energy released when the separated nucleons combine to form a nucleus. Or it is the energy that must be added to a nucleus to separate it into its constituent nucleons. This was not identified in previous studies (see Section 2.5.2).

- **The students were unable to compare the mass of a nucleus in the bound state with the combined masses of its separated nucleons**

This supports the findings of Kohnle et al. (2011). As the findings of these researchers indicate the students were unable to compare the mass of a nucleus in a bound state and the combined masses of its separated constituent nucleons. In this study, students incorrectly understood that mass is unchanged after separation, which is a classical physics approach. Other students incorrectly understood that the nuclear mass is greater than the combined masses. This understanding affects the students' conceptual understanding and representations of NBE. The reason for this is that NBE is related to the nuclear masses using the following equation.

$$E_B = (Zm_p + Nm_n - m_{nuc})C^2$$

If the nuclear mass and combined masses are equal or mass is constant, the NBE is equal to zero, which is unacceptable by the scientific community of practice. Other students expressed NBE using the following equations.

$$E_B = (m_p + m_n - m_{nuc})C^2$$

This is not the general equation of NBE. It is valid only for a deuteron. It seems that the students did not have a clear understanding of the energy-mass equivalence. That is, mass can be changed into energy and vice versa in the modern physics approach. In this case, mass cannot be conserved.

In another way, the students incorrectly expressed NBE using the following equation.

$$\boldsymbol{E_B} = \left(\boldsymbol{m_x} + m_a - \boldsymbol{m_y} - \boldsymbol{m}_b\right)\boldsymbol{c^2}$$

This is an incorrect equation of NBE, but it is the correct equation of reaction energy. The reaction energy is the energy is released in a nuclear reaction. Since this energy comes out of the nucleus we call it NE. It seems that the students confused the equation of NBE with NE. This conceptual difficulty is discussed in Section 4.2.4 in Category III. This equation representation problem was not identified in previous studies (see Section 2.5.2).

- **Students were unable to compare the amount of energy that must be added to a nucleus to separate it into its constituent nucleons with its binding energy**

In scientific understanding, the amount of energy that must be added to a nucleus to separate it into its constituent nucleons is equal to or greater than the binding energy of the nucleus (Beiser, 1963). If the energy added to a nucleus is greater than its binding energy, the extra energy goes into the kinetic energies of the separated nucleons as they fly apart, but the students did not understand this. Students understood that the amount of energy that must be added to a nucleus is less than its binding energy, which is incorrect. This conceptual difficulty is discussed in Section 4.2.4 in Category IV. This particular difficulty was not identified in previous studies. In general, Rathore (2016)identified the students' learning difficulties and misconceptions of NBE, which is supported by this study.

4.7.2 Conceptual Difficulties of Nuclear Force

In Section 4.3.4, five aspects of conceptual variation of nuclear force were discerned by the group of students and discussed from Category I to Category V. Based on the discussion; the following conceptual difficulties associated with the students' conceptual understanding of nuclear force were identified.

- **The students understood that nuclear force is a force that binds the nucleus of an atom and its orbiting electrons together in an atomic system**

It seems that the students confused the long-range electromagnetic force with a short-range strong nuclear force in the atomic system. The force that binds the nucleus of an atom and its orbiting electrons in the atomic system is Coulomb's attractive electrostatic force. The attractive strong nuclear force binds the nucleons together to form a nucleus. This conceptual difficulty is discussed in Section 4.3.4 in Category I. Such a type of conceptual difficulty was not identified in previous studies (see Section 2.5.2).

- **The students were confused about the strong nuclear force with the more basic strong force that binds quarks together to form a nucleon**

There were no students who described the difference and similarity between the strong nuclear force and the more basic strong force that binds quarks together. Relating the concepts of these two forces is difficult even for experts. There were no students who described the strong nuclear force using an equation and a diagram. Where students tried to describe nuclear force using graphs, the graphs were not relevant to the scientific graphs. This conceptual difficulty is discussed in Section 4.3.4 in Category II. Such a type of conceptual difficulty was not identified in previous studies (see Section 2.5.2).

- **Students understood that the strong nuclear force is a long-range force**

This incorrect description of the students indicates that the students did not clearly understand the short-range properties of the strong nuclear force. This supports the findings of Kohnle et al. (2011). The findings of these researchers showed that students understood that nuclei that have more nucleons are more tightly bound. This shows that the students did not understand the short-range property of the strong nuclear force. In scientific understanding, the strong nuclear force is a short-range force. The short-range property of a nuclear force is one of its unique properties. This conceptual difficulty is discussed in Section 4.2.4 in Categories III and IV.

- **Students were unable to describe a strong nuclear force based on the exchange-force model**

The four fundamental interactions in nature are mediated by certain field particles. These interactions are caused by certain attractive or repulsive forces. Scientifically, the exchange field particles of the interaction caused by the strong nuclear force are pi-mesons. But students indicated incorrectly that the exchange field particles of the interaction caused by the strong nuclear force are gluons. Gluons are the exchange field particles of the interaction caused by the more basic strong force that binds quarks together to form a nucleon, which is accepted by the scientific community of practice. It seems that the students confused pi-mesons with gluons. This conceptual difficulty is discussed in Section 4.3.4 in Category V. This particular difficulty was not identified in previous studies. But in general, the learning difficulties and misconceptions of nuclear force were identified in previous studies (Kohnle et al., 2011; Rathore, 2016; Shakya, 2015), which is supported by this study.

4.7.3 Conceptual Difficulties of Radioactive Decay

In Section 4.4.4, four aspects of conceptual variation of radioactive decay discerned by the group of students are discussed from Category I to Category IV. The half-life of a radioactive substance, radioactive decay law, and activity law are commonly taught under the title of radioactive decay. Based on this discussion, the following conceptual difficulties associated with the students' conceptual understanding and representations of radioactive decay were revealed.

- **Students were unable to describe the half-life of a radioactive substance, using text, a graph, and a diagram**

Students expressed the half-life of a radioactive substance correctly using an equation, but there were no students who described it correctly in verbal, in text, in a graph, or in a diagram. One student indicated incorrectly that the half-life of a radioactive substance is half of the age of a radioactive substance. Other students defined incorrectly that the half-life of a radioactive substance is the time needed to determine the age of a sample of material. The students' conceptual difficulty of the half-life of a radioactive substance was also identified by Kohnle et al. (2011). This conceptual difficulty is discussed in Section 4.4.4 in Category II.

- **Students confused the number of nuclei remaining in a radioactive substance with the number of nuclei that have decayed**

This supports the finding of Kohnle et al. (2011). Students were unable to describe how the number of nuclei that have decayed changes over time in the decay process using a text, an equation, or graph. Students were also unable to describe how the number of radioactive nuclei that are present in radioactive substances changes over time using an equation and a graph. That is, students were unable to understand the difference between them. This indicates that the students were confused in describing the number of nuclei remaining with the number of nuclei that had decayed. This is discussed in Categories I and IV.

- **The students confused the radioactive decay law with the activity law**

The students incorrectly expressed the radioactive decay law using the equation of activity law. The scientific equation of radioactive decay law is$\mathrm{N} = \mathrm{N}_0 \mathrm{e}^{-\lambda t}$ while that of activity law is$\mathrm{R} = \mathrm{R}_0 \mathrm{e}^{-\lambda t}$. These equations and their corresponding graphs are the same in form, but they are different in content. The equation of the activity law is the time derivative of the equation of radioactive decay law. This conceptual difficulty is discussed in Section 4.4.4 in Categories I and III. This was not identified in previous studies (see Section 2.5.2).

4.7.4 Conceptual Difficulties of the NBD Process

In Section 4.5.4, seven aspects of conceptual variation of origin of the electron emitted in the NBD process discerned by the group of students are discussed from Category I to Category VII. Based on the discussion, the following conceptual difficulties associated with the students' conceptual understanding and representations of the origin of the electron emitted in the NBD process were identified.

- **Students understood that the origin of the electron emitted in the beta decay process is the atomic electrons**

This supports the finding of Kohnle et al. (2011). The findings of these researchers showed that the electron emitted in the beta decay process comes from the electron shell of an atom. Students indicated incorrectly that the origin of the electron emitted in the beta decay process is the electron captured from an atomic electron shell. Electron capture is the capture of the negatively charged electron by the positively charged nucleus from the innermost shell of the atom such as the K-shell as a result of Coulomb's attractive force. In this case, the negatively charged atomic electron attracted by the positively charged nucleus combines with a proton in the nucleus and then changed into a neutron and neutrino. So, the emitted particle is the neutrino, not the electron. It seems that the students confused the NBD with the electron capture. An electron and antineutrino are emitted in the NBD process, but only the neutrino is emitted in the electron capture. This conceptual difficulty is discussed in Section 4.5.4 in Category I.

- **Students understood that nuclear reaction is the origin of the electron emitted in the NBD process**

Students understood that nuclear reaction or the disintegration of a nucleus is the origin of the electron emitted in the NBD process. In a nuclear reaction, when a particle with sufficient energy collides with a nucleus it will be disintegrated. Scientifically, an electron is emitted as a result of nuclear decay not as a result of nuclear reaction. It seems that students were confused about nuclear decay with nuclear reactions. This conceptual difficulty is discussed in Section 4.5.4 in Category II. This was not revealed in previous studies (see Section 2.5.2).

- **Students understood that the electrons that already existing in the parent nucleus are the origin of the electron emitted in the NBD process**

This supports the finding of Pillay and Loonat (1993). The findings of these researchers showed that the school students considered the electron emitted in the beta decay process as the constituent of the parent nucleus. They also showed that students were not able to write the complete equation of the beta decay process. This difficulty is also revealed in this study. Since the electron emitted in the NBD process comes out of the parent nucleus the students assumed incorrectly that the electron exists in a nucleus. They considered this electron as the origin of the electron emitted in the beta decay process, which is not acceptable by the scientific community of practice. Scientifically, the electron does not exist in a nucleus before beta decay, but it is created at the moment of beta decay. This conceptual difficulty is discussed in Section 4.5.4 in Category III.

- **Students understood that the daughter nucleus is the origin of the electron emitted in the beta decay process**

Students incorrectly indicated that the daughter nucleus is the origin of the electron emitted in the NBD process. Scientifically, the number of orbital atomic electrons is not changed in the NBD process. However, in this decay process, the atomic number in the daughter nucleus is increased by one and the number of neutrons in the daughter nucleus is decreased by one. This implies that the daughter atom is a positive ion. So, there is no means by which an electron could be emitted by the daughter nucleus. It seems that the students did not clearly understand the concept of this nuclear phenomenon. This conceptual difficulty is discussed in Section 4.5.4 in Category VI. This type of difficulty was not identified in previous studies (see Section 2.5.2).

- **Students understood that the proton existing in the parent nucleus is the origin of the electron emitted in the beta decay process**

Students indicated incorrectly that the decay of a proton existing in the parent nucleus is the origin of the electron emitted in the NBD process, but, this electron is emitted by the decay of neutron existing in the parent nucleus, which is accepted by the scientific community of practice. Scientifically, the positron is emitted in the decay of proton existing in the parent nucleus, which we call the positive beta decay process. It seems that the students confused the NBD process with the positive beta decay process. This conceptual difficulty is discussed in Section 4.5.4 in Categories V and IV. Such a type of conceptual difficulty was not identified in previous studies (see Section 2.5.2).

- **Students did not understand that the electron emitted in the NBD process is created out of the rest energy of the decaying parent nucleus at the moment of decay**

The origin of the electron emitted in the NBD process is the rest energy of the decaying parent nucleus, which is accepted by the scientific community of practice. That is, this electron is created out of the rest energy of the decaying parent nucleus at the moment of beta decay. This indicates that the electron does not exist in the parent nucleus before beta decay. The students were unable to understand this complicated concept of the beta decay process. This conceptual difficulty is discussed in Section 4.5.4 in Category VII. Such a type of difficulty was not also identified in previous studies (see Section 2.5.2).

4.7.5 Conceptual Difficulties of NE

In Section 4.6.4, six aspects of conceptual variation of NE discerned by the group of students were discussed from Category I to Category VI. Based on the discussion, the following conceptual difficulties associated with the students' conceptual understanding and representations of NE were exposed.

- **Students understood that NE is produced by a chemical reaction**

This supports the finding of Pillay and Loonat (1993). According to the findings of these researchers, the school students confused nuclear reaction with chemical reaction. In scientific practice, NE is produced by a nuclear reaction, not by a chemical reaction. It seems that the students confused nuclear reactions with chemical reactions. The nuclear reaction takes place at a nuclear level while the chemical reaction takes place at the atomic level. The particles that participate in nuclear reactions are nucleons while the particles that participate in chemical reactions are atomic electrons. This conceptual difficulty is discussed in Section 4.6.4 in Category I.

- **Students considered NE as NBE**

Students incorrectly defined that NE as the amount of energy that must be added to a nucleus to separate it into its constituent nucleons, but this is the scientific definition of NBE not that of NE. It seems that the students confused NE with NBE. This conceptual difficulty is discussed in Section 4.6.4 in Category IV. This was not identified in previous studies (see Section 2.5.2).

- **Most of the students did not understand that NE is created out of the nuclear rest mass at the moment of nuclear reaction**

A few students understood that NE is created out of the nuclear rest mass at the moment of nuclear reaction, which is acceptable by the scientific community of practice. It seems that the students encountered difficulty in understanding this aspect of NE. This conceptual difficulty is discussed in Section 4.6.4 in Category VI. In general, there is limited information about the conceptual difficulty of NE in previous studies (see Section 2.5.2).

In conclusion, the conceptual difficulties of introductory nuclear physics were not explored to large extent and in detail in previous studies (see Section 2.5.2). Most of the researchers used the quantitative research approach to investigate these difficulties. The phenomenographic research approach used in this study supported the researcher to gain more insights into students' conceptual understanding and representations of nuclear physics.

4.8 CHAPTER SUMMARY

In this chapter, various ways of the first group of students' understanding and representations of the five concepts were identified after traditional instruction. These are presented in Tables 4.1 to 4.5. They are discussed in Sections 4.2.4 to 4.6.4. Based on this, the conceptual difficulties of each of the five concepts of introductory nuclear physics were identified and summarised in Section 4.7. The findings from the first phase of this study provided insights into how to develop and design an instructional intervention in Chapter 5 to address the conceptual difficulties of students.

CHAPTER 5: THE INSTRUCTIONAL INTERVENTION

5.1 GENERAL INTRODUCTION

The second phase aimed at developing, designing, and employing an instructional intervention to address the students' conceptual difficulties identified in the first phase. The MRs-based instruction with interactive learning tutorials was the instructional intervention developed, designed, and used. This instructional intervention was used to teach a newly identified second group of students. The VTL provided critical information to develop and design the instructional intervention. The MRs-based instruction with interactive nuclear physics learning tutorials provided conceptual tools that supported the students' conceptual understanding and representations(Larsson, 2013). Abdurrahman et al. (2011) also found that the teacher and students were enabled to display and present the physics concepts via oral, textual, numerical, equation, table, graph, diagram, interactive simulations, and other forms of representations simultaneously. This allowed the learners to visualise and think about the nuclear entities, phenomena, processes, events, and abstract concepts associated with them.

The MRs based instruction was used via the interactive nuclear physics learning tutorials and MRs-based student worksheet. The MRs-based student worksheet consists of the interactive learning activities to be performed using small tutorial groups. The MRs-based worksheet was provided to each student before the interactive learning tutorials were attempted individually. These were used to help students build their intuition about nuclear physics concepts and keeps students engaged in the conceptual learning process. Abdurrahman et al. (2019) found that the MRs-based student worksheet has a remarkable effect on the delivery of content. That is, it actively engages students in the interactive MRs and enhanced their conceptual learning capacities. The interactive nuclear physics learning tutorials were facilitated by the researcher himself.

In general, about 10 major different forms of representations were selected to develop the MRs based instruction (see Section 3.4.2.2). The representations were appropriate to display and present each of the five concepts of nuclear physics. These representations provided an opportunity for learners to discern the critical aspect of a nuclear physics concept. These critical aspects are the necessary conditions for conceptual learning, and then to have a deeper understanding. The students were asked to link and translate among the different forms of representations of a single concept of introductory nuclear physics. How these forms of representation were appropriate to display and present each of the five concepts of nuclear physics is explained in Sections 5.2.1 – 5.2.5.

In Section 5.1.1, the students' prior conceptual understanding and representations of nuclear physics were explored. From the perspective of the VTL, this is considered as the students' "pre-lived objects of learning" (Bussey et al., 2013, p.18) that may affect the lived object of learning. The objects of learning in this study are the critical aspect of each of the five concepts of introductory nuclear physics. These are the critical aspect of each of the concepts of NBE, nuclear force, nuclear decay, NBD, and NE.

5.1.1 The Students' Pre-lived Objects of Learning

The students' prior conceptual understanding and representations of nuclear physics were considered to address its effect on the lived objects of learning. The relationship between the prior conceptual knowledge and the lived object of learning within the VTL was illustrated using a figure (see Figure 2.3). To assess the students' "pre-lived objects of learning", the nuclear physics conceptual investigation open-ended questionnaire was used to collect data. The collected data were analysed and categorised using the phenomenographic data analysis method. The results obtained from the analysis of pre-lived objects of learning provided insight into how to develop and design the MRs-based instruction in addition to the conceptual difficulties identified in the first phase. The data analysis process and the results obtained in this phase are presented in the third phase (see Chapter 6).

5.1.2 The Intended Objects of Learning

The intended object of learning is what the students should learn about a particular object of learning (Marton & Booth, 1997). In this study, the intended objects of learning were the critical aspect of each of the five concepts of nuclear physics mentioned in this section. The intended object of learning involves how the teacher deals with each of the five important concepts of nuclear physics and identifies what the students should learn about them (See Figure 2.3). According to the VTL, the students learn about these concepts by discerning their CAs. That is, the critical aspects of each concept of nuclear physics are the necessary conditions for learning each concept. In this sense, the role of the teacher is to support students to discern more critical aspects of each nuclear physics concept, which are the intended objects of learning. “The intended objects of learning are bound by the teacher’s sphere of knowledge and experience” (Bussey et al., 2013, p.12-13).

The MRs-based instruction was also developed and designed to achieve the intended objects of learning. The teacher (researcher) supported students to discern more critical aspects of a nuclear physics concept via the appropriate forms of representations selected, organised, and presented for learners (see Section 5.2). The critical aspects are the main components of the intended objects of learning within the VTL. Next, the act of learning in the classroom, which we call the enacted object of learning within the VTL, is discussed.

5.1.3 The Enacted Object of Learning

Referring to Section 2.8.1 and Figure 2.3, the enacted object of learning is the act of learning in the classroom or the learning event that happens in the classroom. The enacted object of learning is the possibility of the students to learn the intended object of learning in the classroom (Marton & Tsui, 2004). According to these researchers, the opportunity of learning created by the enacted object of learning constitutes a space of learning for students. In this study, the conceptual learning and understanding in the tutorial classroom were made possible using appropriate forms of multiple representations (MRs).

The learning environment created in this study was the different forms of representations that could be used to display and present the abstract concepts of nuclear physics. This could support the learners to discern more critical aspects of a nuclear physics concept for learning. According to the VTL, discerning more critical aspects of a concept could lead the learners to have a deeper understanding of that concept. These critical aspects are the necessary conditions for learning, which provide an opportunity for learning in the classroom. VTL was used to identify and organise what makes the learning of the content of introductory nuclear physics possible and how the students learn. The appropriate different forms of representations selected and used during the interactive nuclear physics learning tutorials were made possible for students to learn and understand the concepts of introductory nuclear physics. The students' effective conceptual learning and understanding could be achieved via the interaction of students with the different forms of representations and the interactions of students among themselves. The instructional intervention that was intended to be used in this study was designed in the next ways.

5.1.4 The Design of MRs-based Instruction with Interactive Learning Tutorials

To facilitate the students' understanding and representations of the five important concepts of introductory nuclear physics; the following interventional instruction was designed (Table 5.1). The second group of students was exposed to the instructional intervention for 12 hrs and 50 minutes at the same time as that of the first group of students who were exposed to traditional instruction. This time was assigned for the five concepts based on the course outline presented in Table 1.1 or Section 1.2.

Table 5.1: The design of MRs-based instruction with interactive learning tutorials

S. No	**Forms of MRs**	**Intended objects of learning**				
		Concepts of NBE	**Concepts of NF**	**Concepts of RD**	**Concepts of BD**	**Concepts of NE**
1	Verbal	X	X	X	X	X
2	Text	X	X	X	X	X
3	Numeric	X		X	X	X
4	Symbolic	X	X	X	X	X
5	Equation	X		X	X	X
6	Graph	X	X	X		
7	Diagram	X		X	X	X
8	Liquid-drop model	X	-	-	-	X
9	Exchange-force model	-	X	-	-	-
10	Atomic structure model	-	X	-	-	-
11	Nuclear structure model	-	X	-	-	-

S. No	Forms of MRs	Intended objects of learning				
		Concepts of NBE	**Concepts of NF**	**Concepts of RD**	**Concepts of BD**	**Concepts of NE**
12	Nucleon structure model	-	X	-	-	-
13	Interactive simulations	-	-	X	X	X
Academic Year		2019	2019	2019	2019	2020
Month of tutorial		December	December	December	December	January
Week of tutorial		1^{st}	2^{nd}	3^{rd}	4^{th}	1^{st}
Tutorial time/ week		2:30 hrs.	2:30 hrs.	2:30 hrs.	2:30 hrs.	2:30 hrs.
Interactive learning tutorial activities and the use of MRs		Table 5.2	Table 5.3	Table 5.4	Table 5.5	Table 5.6
Tutorial Facilitator		Researcher				
Tutorial classroom		Physics computer laboratory				

This was the instructional intervention designed to be implemented in the tutorial classroom to address the students' conceptual difficulties in introductory nuclear physics. It was designed based on the students' conceptual difficulties and VTL. An X is used to mark the appropriate forms of MRs used to display and present each concept of nuclear physics. The abbreviations NBE, NF, RD, BD, and NE represent nuclear binding energy, nuclear force, radioactive decay, beta decay, and nuclear energy respectively. The tasks that the students performed in the classroom were described as interactive nuclear physics tutorial activities. These activities were designed and facilitated by the researcher.

Multiple representations (MRs) mean the combined appropriate different forms of representations used for instructional purposes of each of the five concepts of introductory nuclear physics. Using them offered a variety of possibilities to the researcher to create a suitable learning environment in the classroom. The MRs used in this study involved using technology, because, the teaching of physics in the twenty-first century aimed at 'how to teach physics for understanding' (Holubova, 2008). For instance, the interactive simulations of NBD and nuclear fission were used in designing the intervention. The content and structure of the introductory nuclear physics in the

Ethiopian undergraduate physics curriculum (see Section 1.2) were analysed and considered during the selection of the appropriate different forms of representations.

During the interactive learning tutorials, the students learned by their interaction with the representations generated by experts or by making their representations. The interactive learning tutorial activities were performed in a small group of students aimed at discerning more critical aspects of a nuclear physics concept. Eight small tutorial groups were formed based on the availability of desktop computers in the physics laboratory. In addition, the laptops of the researcher and some students were used. Each small tutorial group of students had a maximum of five members. The interactive learning tutorials, as well as self-study tools, were used as a supplement to lectures (Singh, 2008). The use of MRs in facilitating the students' conceptual understanding of nuclear physics is discussed in detail in the next section (Section 5.2).

5.2 THE USE OF MRS IN UNDERSTANDING INTRODUCTORY NUCLEAR PHYSICS

Aristotle once said that 'without image thinking is impossible'(cited in Stokes, 2002). And without critical thinking, a deeper understanding of a concept is impossible. Hence, the main reason for using MRs was to display and present the concepts of introductory nuclear physics to learners to enable them to discern more critical aspects and then to develop their understanding and representations of an introductory nuclear physics concept. The multiple representations (MRs) were used as a learning environment to facilitate students' understanding of nuclear physics concepts. How using the MRs facilitated the students' understanding and representations of each of the five concepts via interactive learning activities are presented in Sections 5.2.1-5.2.5).

5.2.1 Understanding the Concept of NBE using MRs

The students' conceptual difficulties associated with understanding NBE were identified and discussed in Section 4.7.1. To address the conceptual difficulties, some appropriate representations of the concept of NBE were selected. These are verbal, textual, symbolic, numeric, equation, liquid-drop model, graphic, diagram, and concept maps forms of representations. These forms of representations, the interactive learning tutorial activities associated with them, and the use of each representation in facilitating students' conceptual understanding are presented in Table 5.2. The equations, graphs, diagrams, and concept maps were indicated in Table 5.2.

Table5.2: MRs-based interactive NBE learning tutorial activities

Form of representation or model	**Interactive learning tutorial activities**	**Using MRs or models to facilitate students' conceptual understanding of NBE**
Students can use any form of representation during the warm-up activity	Warm-up activity (5 min) What are the three common nuclear structure models? State and describe them. What do you mean by mass defect?	The students would have used the verbal-linguistic forms of representations to describe nuclear structure models. Measurements show that the mass of a nucleus in the bound state is less than the combined masses of its separated nucleons. The students would have used Figure 5.2 to describe this nuclear phenomenon.
Verbal-linguistic	Describe the different aspects of NBE in words. (15 min)	A verbal-linguistic form of representation was used when students describe the different aspects of NBE and share their various ways of conceptual understanding with each other via verbal discussion. The conversations gave a chance for students to enhance their conceptual understanding of NBE via critical thinking and discussion.
Text	Describe the different aspects of NBE in the text. (20 min)	Writing texts using pen and paper allowed students to enhance their conceptual understanding of NBE via exchanging their texts and critical thinking.
Symbolic and numeric	When do you use symbolic and numeric representations in learning NBE? What can they represent? (15 min)	Symbolic and numeric representations were used when students describe NBE using an equation and a graph. They can represent speed, mass, atomic number, mass number, particles, etc. This gave them a chance to express equations and to draw graphs using appropriate symbols and numerical values.
Equation	Express NBE using an equation and then interpret it. (10 min)	The students expressed the equation of NBE using a pen and paper. The scientific Eq. 2.1 was displayed for them to compare and contrast with their expressions. This provided an opportunity for students to relate it to the lost mass and to calculate the binding energy of any nucleus.
Liquid-drop model	What are the three major	This representation was used when students described NBE

Form of representation or model	Interactive learning tutorial activities	Using MRs or models to facilitate students' conceptual understanding of NBE
of nuclear structure	effects that influence the binding energy of a nucleus in the liquid-drop model? (20 min)	based on the liquid-drop model of nuclear structure. This model accounts for NBE as discussed during the warm-up activity. In this model, a nucleus is treated as though it is a drop of liquid while nucleons are treated as though they are molecules. This gave a chance for students to understand the major effects that influence the binding energy of a nucleus and to express these effects to NBE using Eq. 5.1.
Graph	How does the NBE per nucleon change with the atomic mass number of stable nuclei? Illustrate it using a graph. (20 min)	This representation was used when students describe how the NBE per nucleon changes with the mass number of stable nuclei. They described this change by drawing their NBE per nucleon versus mass number rough graph. The scientific graph indicated in Figure 5.1 displayed for students to compare and contrast with their graph. This provided an opportunity for students to predict the nuclei that can have the greatest stability based on the mass number in the graph.
Diagram-1	Describe the binding energy of a deuteron using a diagram while it is formed by the combination of proton and neutron. (15 min)	This representation was used when students described the binding energy of a deuteron as the energy released when proton and neutron combine to form a deuteron. They were asked to draw a diagram that represents this nuclear phenomenon. The scientific diagram in Figure 5.2 was displayed for them to compare and contrast with their diagram. This gave a chance for students to understand the binding energy of a nucleus as it is the energy released when its separated nucleons combine to form it. They would have also an opportunity to develop their understanding of the concept of the mass defect.
Diagram-2	Describe the binding energy of a deuteron using a diagram while it is separated into its constituent proton and neutron. (15 min)	This representation was used when students describe the binding energy of a deuteron as it is the energy required to break up it into its constituent particles proton and neutron. They were asked to draw their diagram. The scientific diagram in Figure 5.3 was displayed for students to compare and contrast with their diagram. This provided an opportunity for them to understand the NBE of a nucleus as it is the energy that must be added to it to separate it into its constituent nucleons. Or, to understand NBE as it is the energy missed after

Form of representation or model	**Interactive learning tutorial activities**	**Using MRs or models to facilitate students' conceptual understanding of NBE**
		separation. If the energy E added to a nucleus is greater than the binding energy of the nucleus, the extra energy is released in the form of the kinetic energy of the separated nucleons.
Concept map	Construct a concept map that indicates the different aspects of NBE discerned in the previous MRs-based activities. (15 min)	This representation was used when students summarised what they understood about NBE from the previous different forms of representation. They constructed their concept map. There is no fixed concept map. The concept map constructed by the researcher, which is indicated in Figure 5.4 was displayed for them to compare and contrast with their concept map. This provided an opportunity for students to recap what they have learned and understood about NBE from the previous MRs-based activities.

Additional information for representations is indicated in Table 5.2

In Eq. 2.1, NBE is expressed as

$$E_B = \left(Zm_p + Nm_n - m_{nuc}\right)c^2$$

The semi-empirical NBE formula, which is formulated based on the liquid-drop model of nuclear structure, is given in Eq. 5.1. This formula fits with experimental data for the nuclei whose atomic mass number, A $\geq$15.

$$E_B = c_1 A - c_2 A^{2/3} - c_3 \frac{Z(Z-1)}{A^{1/3}} - c_4 \frac{(N-Z)^2}{A} \quad (5.\ 1)$$

The NBE per nucleon versus the atomic mass number graph for stable nuclei is indicated in Figure 5.1shown below.

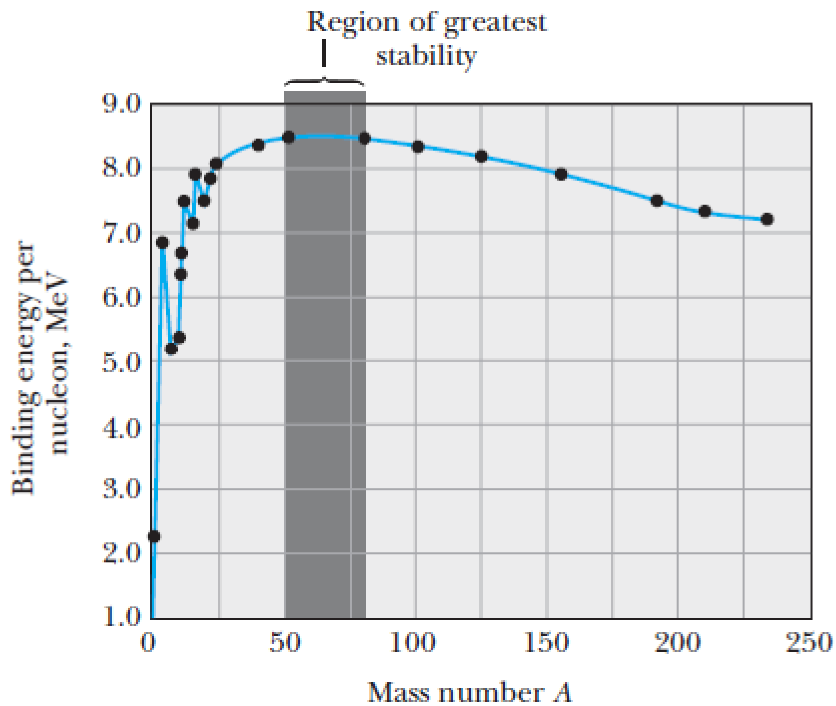


Figure 5.1: The binding energy per nucleon versus mass number A

Source: Serway et al. (2005, p. 473)

Figure 5.2 illustrates the combination of proton and neutron to form a deuteron.

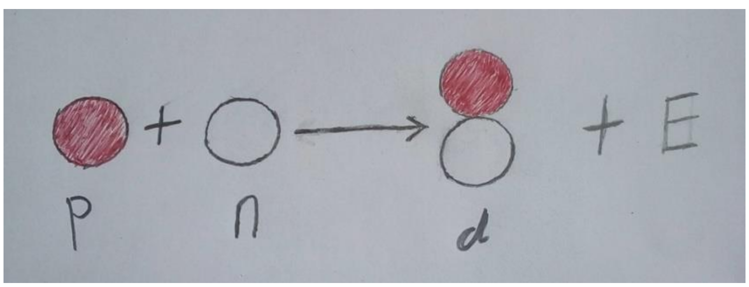


Figure 5.2: The combination of a proton p and a neutron n to form a deuteron *d*

Source: Adapted from Beiser (1963, p. 401)

Figure 5.3 illustrates the separation of a deuteron into its constituent proton and neutron.

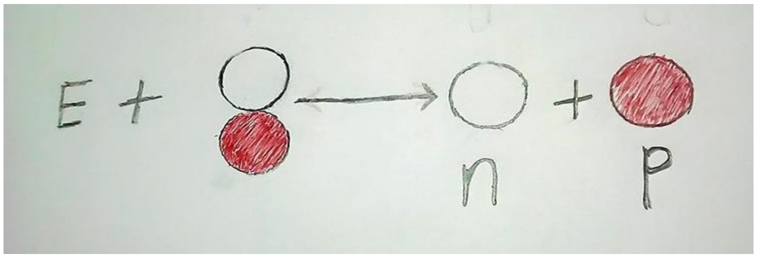


Figure 5.3: The separation of a deuteron into a neutron n and a proton p

Source: Adapted from Beiser (1963, p.401)

The findings in the first phase of this study (Section 4.7.1) indicated that students confused NBE with nucleon binding force (nuclear force). The word binding could have caused them to be confused. As indicated in Figure 5.2, NBE is the energy released when separated nucleons combine to form a nucleus. This combination process occurs at the atomic nuclei scale, which is visualised using the diagram. The short-range, attractive, and strong nuclear force is responsible for this combination (fusion). The NBE per nucleon of stable nuclei is roughly constant for atomic mass number A greater than 20 (see Figure 5.1). In this case, the nuclear forces between a nucleon and all other nucleons in the nucleus are said to be saturated (see Table 5.2).

"Concept mapping was used to organise, and illustrate the different aspects of a nuclear physics concept" (Dhull & Verma, 2020, p.2484). These scholars classify concept mapping into spider, hierarchy, and flowchart concept mappings. According to these scholars, a spider map has the main concept in the centre of the diagram. Each sub-concept is linked with the main concept. Hierarchy concept mapping shows the concept ranging from simple to complex. The flowchart concept mapping organises the information in a linear form. The spider concept mapping of NBE was constructed to organise, summarise, and illustrate its different aspects (see Figure 5.4). The concept of NBE is the main concept placed in the centre of the diagram. The spider concept mapping was also used to organise and illustrate the different aspects of the other four concepts of introductory nuclear physics.

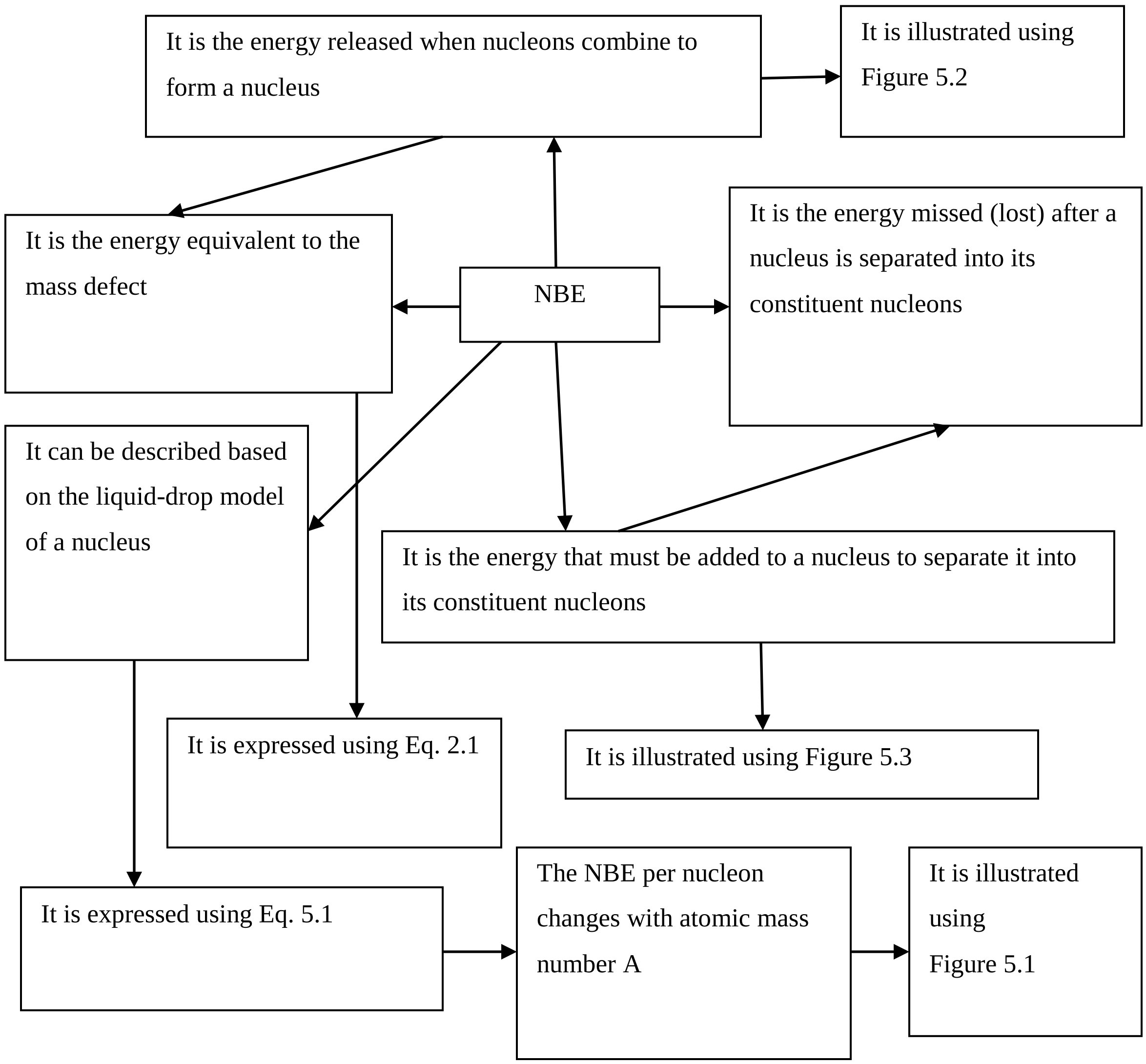


Figure 5.4: The concept map of nuclear binding energy (NBE)

The different forms of representations of the concept of NBE provided an opportunity for students to discern its different aspects and then to have a complete conceptual understanding. Furthermore, the different forms of representations could be seen to enhance the possibilities of students' conceptual understanding and representations of NBE (Bussey et al., 2013). This allowed students to confront their conceptual difficulties and misconceptions of NBE.

As discussed earlier, the students confused NBE with nuclear force which is completely a different concept. Those stable nuclei which are highly bound together by the short-range, attractive, and strong nuclear force have high binding energies. That is, high energy is released when the separated nucleons are combined and bound together by the attractive strong nuclear force. In other words, a high amount of energy must be added to those highly stable nuclei to break them apart into their constituent nucleons. The energy that must be added to those stable nuclei is equal to or greater than their binding energy. Thus, NBE can be thought of as the energy that must be added to a nucleus to break it apart into its constituent nucleons. Those highly stable nuclei are the nuclei such as iron and cobalt found in the region of greatest nuclear stability indicated in Figure 5.1 as shown above. After learning and understanding nuclear force using MRs in the next section, the students would have been given the opportunity to clearly understanding the difference between nuclear binding energy and nuclear force.

5.2.2 Understanding the Concept of Nuclear Force Using MRs

The students' conceptual difficulties associated with the understanding of nuclear force are identified and discussed in Sections 4.3.4 and 4.7.2. To address the students' conceptual difficulties and to enhance their conceptual understanding of nuclear force, some appropriate forms of representations were selected and used. These are: verbal, text, symbolic and numeric, graph, atomic structure model, nuclear structure model, nucleon structure model, field particle exchange model, and concept map. These forms of representations, the interactive learning tutorial activities associated with them, and the use of each representation in facilitating students' conceptual understanding are presented in Table 5.3 below. The equation, graph, model, picture, diagram, and concept map referred to in the table are shown next to the table. However, Figures 4.5 and 4.6, which are related to nuclear force, are found in Chapter 4 in Section 4.3.5.

Table 5.3: MRs-based interactive nuclear force learning tutorial activities

Form of representation or model	**Interactive learning tutorial activities**	**Using MRs or models to facilitate students' conceptual understanding of nuclear force (NF)**
Students can use any form of representation during the warm-up	Warm-up activity (5 min) There is a coulomb repulsive force between protons in a	The students would have used Figure 5.5b and verbal-linguistic forms of representation to perform the warm-up activity. The warm-up activity provided an opportunity for students to think about

Form of representation or model	Interactive learning tutorial activities	Using MRs or models to facilitate students' conceptual understanding of nuclear force (NF)
activity	nucleus. Why not the nucleons in the nucleus fly apart? How can stable atomic nuclei exist in nature?	the force that binds the nucleons in a nucleus not to fly apart. This force must be more powerful than the Coulomb repulsive force that exists in a nucleus. Again, it is the presence of the force that binds nucleons together that keeps up nuclear stability or a nucleus in the bound state. This prepared the students to learn and understand the concept of nuclear force via the next activities
Verbal-linguistic	Describe the different aspects of nuclear force in words. (25 min)	Students describe the different aspects of nuclear force and share their various ways of conceptual understanding with each other via verbal discussion. The conversations gave a chance for students to develop their understanding of the concept of nuclear force via critical thinking
Text	Describe the different aspects of nuclear force in words. (20 min)	Text representation was used when students described the different aspects of nuclear force using pen and paper. This allowed them to develop their understanding of the concept of nuclear force via writing a text, exchanging their texts, and critical thinking
Symbolic and numeric	When do you use symbolic and numeric representations in learning nuclear force? What can they represent? (10 min)	Students were used symbolic and numeric representations when they describing nuclear force using an equation and a graph. This gave them a chance to draw a graph based on an equation using appropriate symbols and numerical values. They can represent potential energy, particles, distance, etc. using symbols
Graph	How do the graphs of nuclear and Coulomb potential energies U(r) versus nucleons separation distance, r, change? Describe the ranges of nuclear repulsive and attractive force and	The students draw a graph when they describing how the graph of nuclear and Coulomb potential energies U(r) in a nucleus versus nucleons separation distance r changes (see Figure 4.5 & 4.6). They were asked to draw their rough graphs. The scientific graphs indicated in Figures4.5 and 4.6 were displayed for them to compare and contrast. This provided an opportunity for students

Form of representation or model	**Interactive learning tutorial activities**	**Using MRs or models to facilitate students' conceptual understanding of nuclear force (NF)**
	Coulomb repulsive force based on the graph. Describe the saturation property of nuclear force using a graph. (20 min)	to understand the ranges of nuclear repulsive and attractive force as well as that of coulomb repulsive force in the nucleus. And to understand the evidence for the limited range of nuclear forces indicated in the graph that was coming from nuclear scattering experiments. Again, a graphical representation was used when students described the saturation property of nuclear force(see Figure 5.1). This graph was displaced to them, which facilitated the students' understanding of the saturation property of nuclear force. "The nuclear forces between a particular nucleon and all other nucleons in the nucleus are said to be saturated" (Beiser, 1963, p.474). This is another evidence for the limited range of nuclear force (Serway et al., 2005).
Atomic and nuclear structure models	What force binds the nucleus and orbital electrons of an atom together? What force binds the nucleons in the atomic nucleus together not to fly apart by the action of the Coulomb repulsive force between protons in the nucleus? Which force is dominant in the short range? The force that binds the nucleus together or the Coulomb repulsive force? (20 min)	The students draw these models when they attempt to describe the force that binds the nucleus and orbital electrons of an atom together as well as the force that binds the nucleons in the atomic nucleus together. As the findings in the first phase of this study indicated, the students incorrectly understood that the force that binds the nucleus and orbital electrons of an atom is the attractive nuclear force (see Section 4.7.2). The atomic and nuclear structure models shown in Figure 5.5 were displayed for the students. These make the invisible nuclear entities visible to them. These models provided an opportunity for students to visualise and think about the nuclear force that binds the nucleons together in the atomic nucleus. This attractive nuclear force binds the nucleons together not to fly apart by the action of Coulomb repulsive force between protons in a nucleus. The effect of interaction via the nuclear force is not

Form of representation or model	**Interactive learning tutorial activities**	**Using MRs or models to facilitate students' conceptual understanding of nuclear force (NF)**
		directly observable as that of electromagnetic and gravitational forces. So, these models may reduce the abstractness of the concept of nuclear force
Nucleon structure model (Proton and Neutron structure models)	What are the constituents of a nucleon? What is the difference and similarity between the force that binds the nucleons in the atomic nucleus and the force that binds the quarks in a nucleon together? (15 min)	The students draw the diagram of the nucleon structure model when describing the difference and similarity between the nuclear force and the more basic force that binds the quarks in a nucleon together. The nucleon structure model indicated in Figure 5.6 was displayed to students. As the findings in the first phase of this study indicated the students confused the nuclear force with the more basic force that binds the quarks in a nucleon together (see Section 4.7.2). Currently, quarks are considered as the more basic particles in the structure of matter as illustrated in Figure 5.6. Understanding the difference and similarities between the two forces is even difficult for experts. This model provides an opportunity for learners to develop an understanding of the differences and similarities between the two mentioned abstract forces.
Exchange-force model or field particle exchange model	What exchange field particles are responsible for the interaction of nucleons via a strong nuclear force? What exchange field particles are responsible for the interaction of quarks via the more basic strong force? What is the relationship between the nuclear force and the more basic strong force? (20 min)	The students draw a diagram of the field particle exchange model when they describe the mechanism that accounts for the powerful nuclear force. As the findings in the first phase indicate, no student correctly described nuclear force based on the exchange-force model (see Section 4.7.2). And the students were also confused about the exchange field particle 'pi-meson'; responsible for the interactions of nucleons via nuclear force with the exchange field particle 'gluon' responsible for the interaction of quarks via the more basic strong force. The picture and diagram in Figure 5.8 were displayed to students. This figure helped the students to understand the

Form of representation or model	**Interactive learning tutorial activities**	**Using MRs or models to facilitate students' conceptual understanding of nuclear force (NF)**
		concept of the field particle exchange model and then to develop a deeper understanding of the nuclear force. Particularly, it was helped them to understand the exchange field particle that is responsible for the interaction of nucleons via the strong nuclear force. The students were assisted to understand nuclear force as it is believed to be the residual effect of the more basic strong force (Serway et al., 2005, p.548). Every field interaction is either attractive or repulsive. The exchange-force model can be described as the "field particle exchange that can produce either attractive or repulsive interaction via a certain force" (Beiser, 1963, p.412). The strong nuclear force is repulsive at a very short range of 0 – 0.4fm) and attractive at a greater nucleon-nucleon separation distance of 0.4fm – 3fm (Serway et al., 2005, p.548).
Concept map	Construct a concept map that indicates the different aspects of a nuclear force discerned by students in the previous MRs-based activities. (15 min)	A concept map was used when students summarise what they understood about nuclear force from the suggested MRs-based activities. The concept map constructed by the researcher, which is indicated in Figure 5.9 was displayed to them to compare and contrast with their concept map. This provided an opportunity for students to learn and develop their understanding of nuclear force from the previous different forms of representation

<u>Additional information for representations is indicated in Table 5.3</u>

As indicated in Figure 5.1, for the atomic mass number A>20, the NBE per nucleon is approximately constant. In this case, "the nuclear forces between a particular nucleon and all other nucleons in the nucleus are said to be saturated"(Beiser, 1963, p.474). A particular nucleon forms attractive bonds with only a limited number of other nearest neighbour nucleons, because of the short-range property of the strong nuclear force. When the NBE per nucleon is greatest, the nuclear force between that particular nucleon and the other nearest neighbour nucleons is also greatest. But it does not mean NBE and nuclear force are the same.

The atomic and nuclear structure models showed in Figure 5.5make the invisible nuclear entities visible for students.

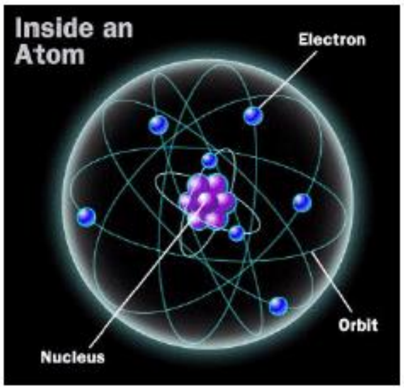
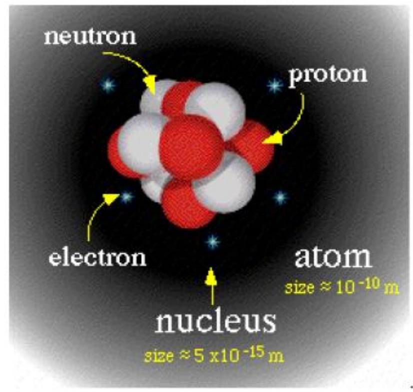
	

Figure 5.5 (a): Atomic structure model	Figure 5.5 (b): Atomic and nuclear structure models
Source for Figure 5.5 (a): Atomic and Nuclear Physics–Advanced Placement (AP) Physics B	Source for Figure 5.5 (b): URL: http://www.lbl.gov/abc/Basic.html (2008)

Figure 5.5: The atomic and nuclear structure models

The nuclear force is a strong force of attraction that operates over very short distances between nucleons (n-p, n-n, & p-p) as indicated in Figure 5.5. This force overcomes the Coulomb repulsive force between protons in a nucleus and binds the nucleons together to form this nucleus.

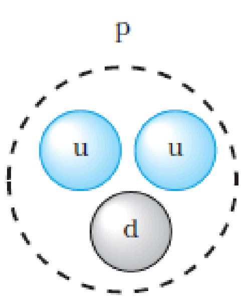
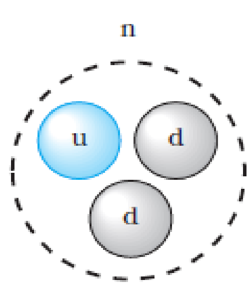
	
5.6(a) Structure of proton	5.6(b) Structure of neutron

Figure 5.6: The quark compositions of proton and neutron

Source: (Serway et al., 2005, p.575)

As indicated in Figure 5.6, the attractive force that binds quarks together to form a nucleon is another basic strong force that operates over very short distances like that of the attractive nuclear force.

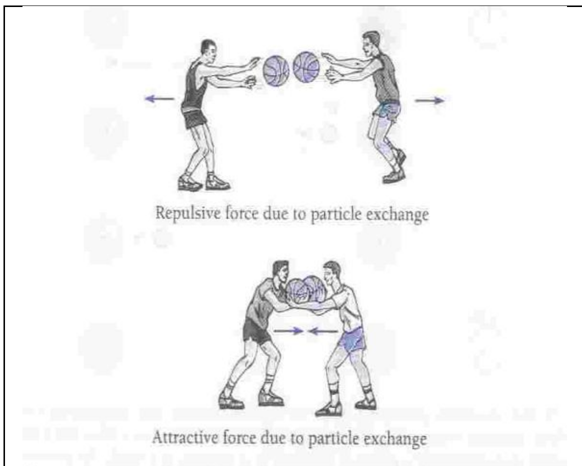
Currently, quarks are considered as the more basic particles in the structure of matter as illustrated in the following figure.

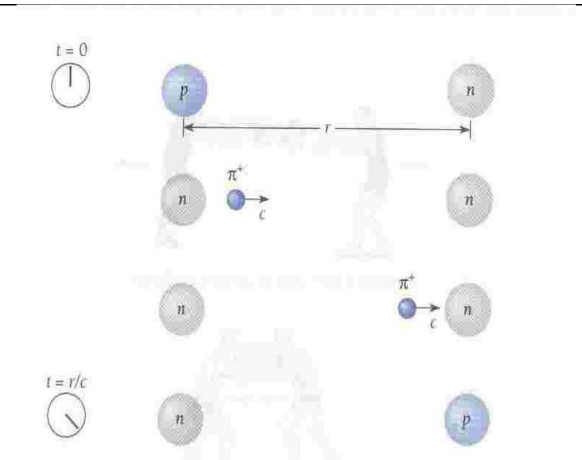
Matter ⇨ Atom ⇨ Nucleus ⇨ Nucleon ⇨ Quark

Figure 5.7: The general structure of matter

Source: The researcher's own

The following rough analogy may make the Yukawa meson theory of the strong nuclear force less mysterious for learners (Beiser, 1963). The strong nuclear interactions caused by the nuclear force are mediated by the exchange field particles known as pi-mesons. The ball exchanged by the two persons is analogous to the exchange field particle that mediates any interaction. In the case of the strong nuclear interaction via nuclear force, the pi-meson is exchanged between the two interacting nucleons.





5.8(a) Attractive and repulsive forces can both arise from field particle exchange	5.8(b) A positive pi-meson (π^+) emitted by a proton is absorbed by a neutron

Figure 5.8: Field particle exchange model

Source: Adapted from (Beiser, 1963, p.4013-414)

Figure 5.8 (b) shows the attractive nuclear force that arises from the exchange field particle of a positive pi-meson (π^+ - meson). As a result of this, a proton becomes a neutron, and a neutron becomes a proton. Hence, the positive pi-meson is the exchange field particle responsible for the attractive interaction of proton and neutron via the attractive nuclear force.

Concept mapping of the concept of nuclear force:

The following concept mapping of nuclear force was constructed to organise and illustrate the different aspects of the concept of nuclear force. Four critical aspects of the concept of strong nuclear force are indicated in the concept map. Some of these critical aspects were discerned by students (see Table 4.2). However, no student correctly described the strong nuclear force based on the exchange-force model. The concept of the strong nuclear force is the main concept placed in the centre of the diagram.

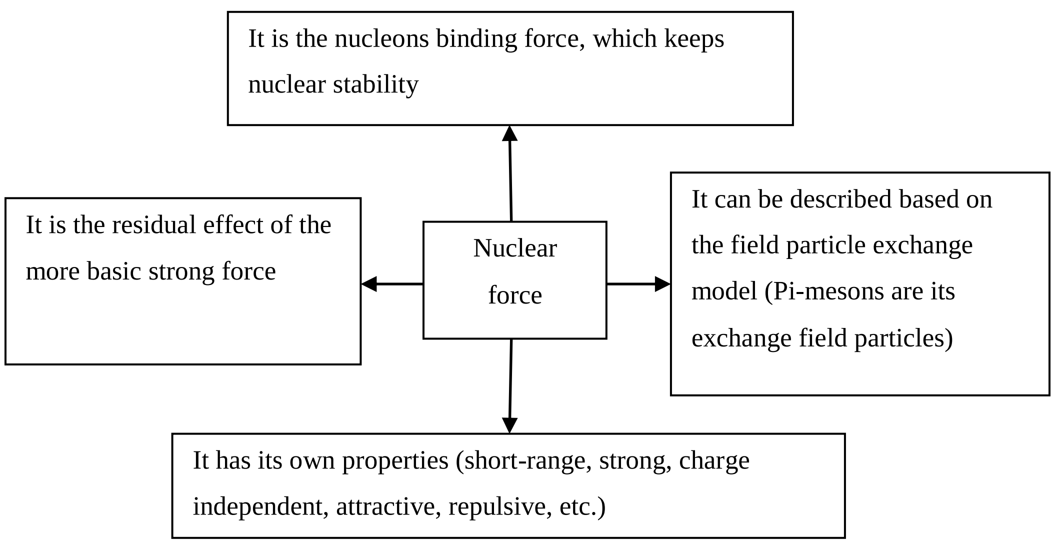


Figure 5.9: The concept map of nuclear force

The different forms of representations (see Table 5.3) provided an opportunity for students to discern the different aspects of the concept of nuclear force. This may support them to develop their conceptual understanding of the nuclear force. Furthermore, the different forms of representations could enact the possibilities of students' conceptual understanding and representations of nuclear force (Bussey et al., 2013). This allowed students to confront their conceptual difficulties and misconceptions about nuclear force.

Those nuclei in which the attractive nuclear force is more dominant than Coulomb's repulsive force are said to be stable. In the reverse case, the nuclei are said to be unstable. These nuclei are also known as radioactive nuclei. In the next section, the students learn and understand using MRs how the number of radioactive nuclei in a radioactive substance changes due to radioactive decay.

5.2.3 Understanding of the Concept of Radioactive Decay Using MRs

The students' conceptual difficulties associated with radioactive decay were identified and described in Section 4.7.3. To develop the MRs-based instruction with interactive learning tutorials, some forms of representations were selected. These are verbal, text, equation, symbolic, graph, diagram, interactive simulations, and concept map. These forms of representations, the interactive learning tutorial activities associated with them, and the use of each representation in facilitating students' conceptual understanding are presented in Table 5.4. The equation, graph, diagram, and concept map referred to in the table as a figure are shown next to the table.

Table 5.4: MRs-based interactive radioactive decay learning tutorial activities

Form of representation	**Interactive learning tutorial activities**	**Using MRs to facilitate students' conceptual understanding of radioactive decay (RD)**
Students can use any form of representation during the warm-up activity	Warm-up activity (10 min) What do you mean by radioactivity? How was it discovered? By whom it was discovered? How are the three types of nuclear radiations emitted in radioactivity produced and distinguished by scientists?	The students would have used verbal-linguistic and diagram forms of representations to perform the warm-up activity. The warm-up activity provided an opportunity for students to discuss the famous historical nuclear phenomenon radioactivity. In this activity, the students discussed how scientists discovered radioactivity, and how the three types of nuclear radiations are emitted and distinguished. They were also asked to describe how the three types of nuclear radiations were distinguished using a diagram. Radioactivity is the result of the decay or disintegration of unstable nuclei. This helped the students to get themselves ready to learn and understand the concept of radioactive decay in the next activities.
Verbal-linguistic	In verbal-linguistic form,	A verbal-linguistic form of representation was used when

Form of representation	Interactive learning tutorial activities	Using MRs to facilitate students' conceptual understanding of radioactive decay (RD)
	Describe the different aspects of radioactive decay. State radioactive decay law. Define the half-life and activity of a radioactive substance. (15 min)	students describe the different aspects of radioactive decay and share their various ways of conceptual understanding with each other via discussion. It was used when they define radioactive decay, the half-life and activity of a radioactive substance, and stating the radioactive decay law and activity law in a verbal-linguistic form. This allowed students to learn and understand the different aspects of the concept of radioactive decay via discussion and critical thinking. The students may understand the concept in different ways and share it.
Text	Using a text, Describe the different aspects of radioactive decay State radioactive decay law Define the radioactive decay, half-life, and activity of a radioactive substance (20 min)	Text representation was used when students described the different aspects of radioactive decay. That is, to define radioactive decay, half-life, and activity of a radioactive substance and to state radioactive decay law using a pen and paper. This allowed students to learn and understand the concept of radioactive decay via writing a text, exchanging their texts, and critical thinking.
Symbolic and numeric	When do you use symbolic and numeric representations in learning radioactive decay? What can they represent? (10 min)	Symbolic and numeric representations were used when students describe radioactive decay using an equation, a graph, a diagram, and interactive simulations. This gave them a chance to express equations, draw graphs and diagrams, and perform interactive simulations using appropriate symbols and numerical values. The students used these forms of representations to represent nuclei, atomic number, mass number, particles, half-life, decay constant, number of radioactive nuclei, number of nuclei that have decayed, etc.
Equation	Express radioactive decay law, activity law, half-life, and the number of nuclei that have decayed using an equation and then interpret it? (25 min)	This representation was used when students describe different aspects of radioactive decay using equations. They expressed their equations using a pen and paper. The scientific Eq. 2.2, 5.2, 5.3, and 5.4 were displayed to them to compare and contrast with their expressions. This provided an opportunity for students to discern different aspects of radioactive decay and develop their understanding.

Form of representation	**Interactive learning tutorial activities**	**Using MRs to facilitate students' conceptual understanding of radioactive decay (RD)**
Graph	Illustrate how the number of radioactive nuclei remaining in a radioactive substance changes in time (radioactive decay law) and activity law using a graph? Illustrate how the number of nuclei that have decayed changes in time using a graph? (20 min)	This representation was used when students describe how the number of radioactive nuclei remaining and the number of nuclei that have decayed change in time in a radioactive substance. And also it was used when they describe the activity law using a graph. In the activity, the students were asked to draw their rough graphs. The scientific graphs indicated in Figures 4.8, 4.10, and 4.13 were displayed to compare and contrast with their rough graphs. In Figure 4.13 the graphs in Figure 4.8 and 4.10 are drawn in the same plane for the decay of Radon-222 to polonium-2018 by emitting alpha radiation to make their difference clearer. This provided an opportunity for students to learn and understand the different aspects of the concept of radioactive decay. For instance, radioactive decay and activity laws are some of the aspects of radioactive decay.
Diagram	If the original number of radioactive nuclei in a sample is sixteen, indicate the number of nuclei remaining and the number of nuclei that have decayed at one half-life, two half-lives, three half-lives, and four half-lives using a diagram? (10min)	This representation was used when students described the number of nuclei remaining and the number of nuclei that have decayed in a radioactive sample at one half-life, two half-lives, three half-lives, and four half-lives. The students were asked to draw their diagrams. The diagram drawn by the researcher, Figure 5.10 was displayed for students to compare and contrast. This provided an opportunity for students to learn and understand the concept of half-life, which is one of the important aspects of radioactive decay.
Interactive simulations radioactive decay	Perform the simulations of alpha and NBD processes using the nuclear physics interactive simulations guide. (25 min)	This representation was used when students described the number of nuclei remaining and the number of nuclei that have decayed in a sample in time as well as the half-life of a radioactive substance. The interactive simulations performed by the students are indicated in Figures5.11 and 5.12. They are freely available and can be downloaded from http://phet.colrado.edu This provided an opportunity for students to learn and understand how the number of nuclei remaining and the number of nuclei that have a decayed change in time (Figure 5.11 & 5.12) as well as to learn and understand the concept of

Form of representation	Interactive learning tutorial activities	Using MRs to facilitate students' conceptual understanding of radioactive decay (RD)
		half-life (Figure 5.11).
Concept map	Construct a concept map that indicates the different aspects of radioactive decay discerned in the previous MRs-based activities. (15 min)	This representation was used when students summarise what they understood about radioactive decay from the previous MRs-based activities. They constructed their concept map. There is no fixed concept map. The concept map constructed by the researcher, which is indicated in Figure 5.13 was displayed for them to compare and contrast with their concept map. This provided an opportunity for students to recap what they have learned and understood about radioactive decay from the previous different forms of representation.

Additional information for representations is indicated in Table 5.4

The number of radioactive nuclei (N_r) remaining in a radioactive substance exponentially decreases in time, which is expressed using Eq. 2.2 in Chapter 2. This is known as the radioactive decay law, which is expressed as

$$N_r = N_0 e^{-\lambda t}$$

How the number of radioactive nuclei (N_d) that have decayed changes in time is expressed using the next Eq. 5.2.

$$N_d = N_0 (1 - e^{-\lambda t}) \quad (5.2)$$

A half-life of a radioactive substance, which is the time required for half of the original number of radioactive nuclei in the substance to decay is expressed using Equation 5.3 as shown below.

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \quad (5.3)$$

The activity (A) of a radioactive substance, which is defined as the number of decays per unit time, is expressed using Eq. 5.4 as shown below.

$$A = -\frac{dN_r}{dt} = A_0 e^{-\lambda t} \quad (5.\,4)$$

In some reference books, Eq. 5.4 is considered as the activity law. The activity law is stated as the activity of a radioactive substance exponentially decreases over time. How the number of radioactive nuclei remaining in a radioactive substance and the number of nuclei that have decayed change in time is respectively illustrated using the graphs indicated in Figures 4.8 and 4.10 in Chapter 4. Both graphs have been drawn in the same plane in Figure 4.13. The graphs in Figure 4.7 show the decay of Rn-222 to Po-2018 by emitting alpha radiation.

If the original number is 16, the number of nuclei remaining and the number of nuclei that have decayed at one half-life, two half-lives, three half-lives, and four half-lives is described using the following diagram (Figure 5.10).

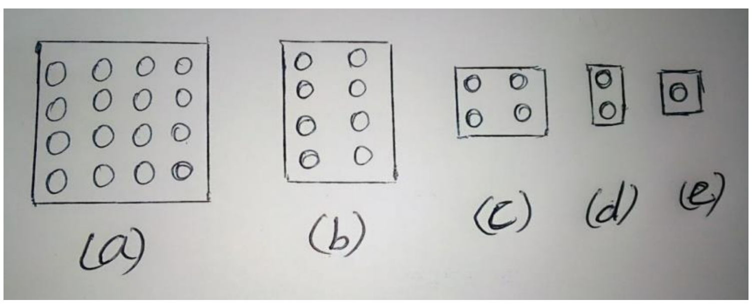


Figure 5.10: The number of radioactive nuclei remaining at one half-life, at two half-lives, three half-lives, and four half-lives

Source: Researcher's own

In Figure 5.10 (a), at time t = 0, N_r = 16 and N_d = 0. In Figure 5.10 (b), at time t = one half-life, N_r = 8 and N_d = 8. In Figure 5.10 (c), at time t = two half-lives, N_r = 4 and N_d = 4. In Figure 5.10 (d), at time t = three half-lives, N_r = 2 and N_d = 2. In Figure 5.10 (e), at time t = four half-lives, N_r = 1 and N_d = 1. What happens to the radioactive nuclei that have decayed? They have changed into new stable nuclei after decay. The interactive simulations indicated in Figures5.11 and 5.12, illustrate how the number of radioactive nuclei remaining and the number of nuclei that have delayed change in time.

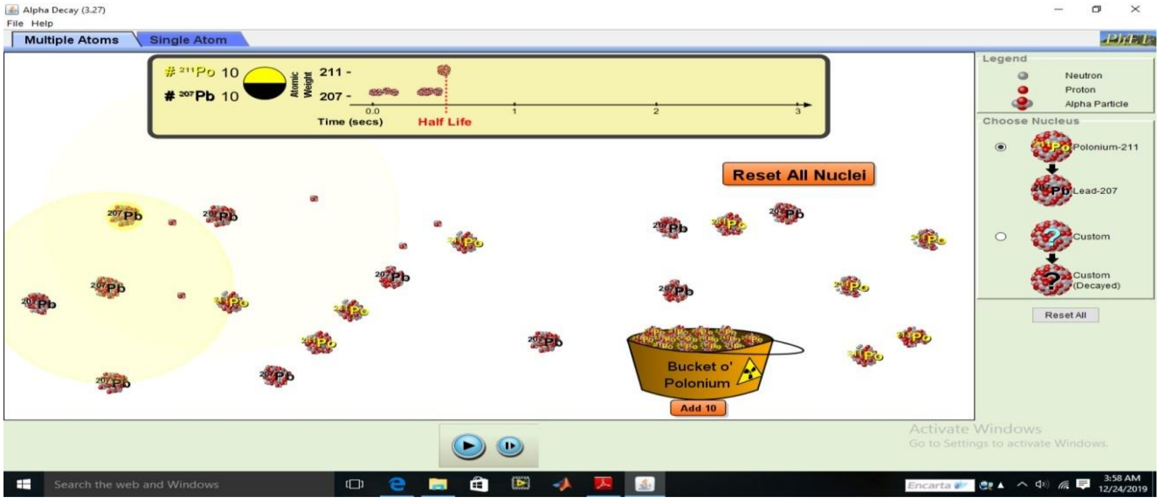


Figure 5.11: The alpha decay process from Polonium-211 to Lead-207

In Figure 5.11, the yellow and black colours indicate the number of radioactive nuclei remaining and the number of nuclei that have decayed respectively. At time t = 0, the number radioactive polonium nuclei $N_0 = 20$. At time t = one half-life, $N_r = 10$ and $N_d = 10$. This illustrates the concept of the half-life of a radioactive substance. The next figure indicates the interactive simulation of NBD.

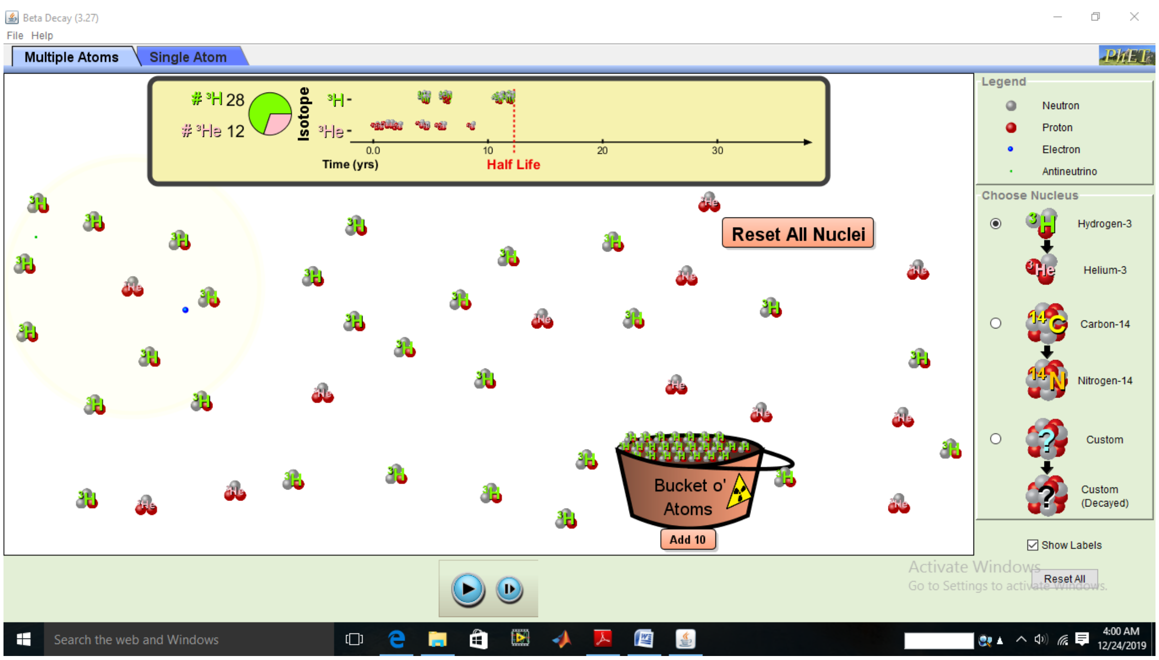


Figure 5.12: The NBD process from Tritium to Helium-3

In Figure 5.12, the green and pink colours indicate the number of radioactive nuclei remaining and the number of radioactive nuclei that have decayed respectively. At time t = 0, the number of radioactive nuclei $N_0 = 40$. In this figure, the number of radioactive nuclei remaining is 28 and the number of radioactive nuclei that have decayed is 12 at a certain time t. This indicates that as the number of radioactive nuclei remaining N_r decreases, the number of nuclei that have decayed N_d increases.

Concept map of radioactive decay

The following concept map was constructed by the researcher to organise and illustrate the different aspects of the concept of radioactive decay. The concept map indicates that the concept of radioactive decay is the main concept placed in the centre of the diagram. The number of radioactive nuclei remaining in a radioactive substance exponentially decreases in time. In another way, this is known as the radioactive decay law. The change in the number of nuclei that have decayed in time is the inverse of the change in the number of radioactive nuclei remaining in time. The half-life of a radioactive substance is the time at which half of the original number of radioactive nuclei that are present in it at time t = 0 decays. The activity of a radioactive substance is the number of decays per unit of time. There are three types of common decay processes as indicated in the concept mapping. Only some of them are included in this study.

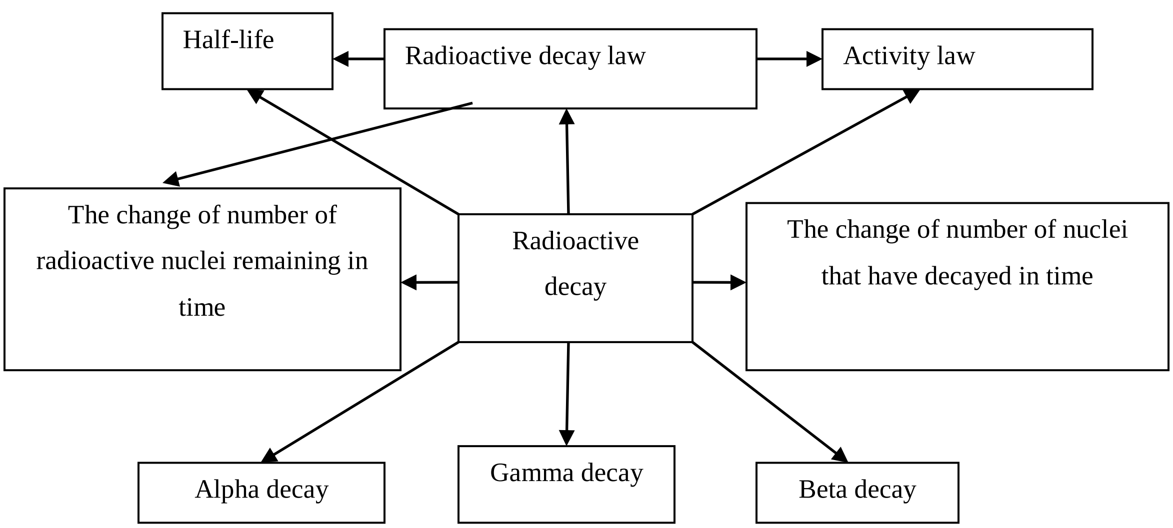


Figure 5.13: The concept map of a radioactive decay

The different forms of representations provided an opportunity for students to discern the different aspects of the concept of radioactive decay. This may support them in developing a conceptual understanding of radioactive decay. Furthermore, the different forms of representations could be seen to enhance the possibilities of students' conceptual understanding and representations of radioactive decay (Bussey et al., 2013). This allowed students to confront their conceptual difficulties and misconceptions about radioactive decay.

Radioactive decay is the natural spontaneous disintegration of unstable nuclei. In the process of disintegration, the unstable nuclei change into more stable nuclei by releasing particles and /or energy. The most common forms of radioactive decay are alpha decay, beta decay, and gamma decay. In the gamma decay process, only energy is released without a change in the identity of the parent unstable nucleus. Particularly, the student's learning and understanding of NBD were facilitated using MRs as discussed in the next section.

5.2.4 Learning and Understanding of the Concept of NBD Using MRs

The students' conceptual difficulties associated with NBD were identified and described in Section 4.7.4. Particularly, the conceptual difficulty associated with the origin of the electron emitted in the beta decay process was described. Verbal, text, symbolic and numeric, equation, interactive simulations, diagram, and concept map were the forms of representations selected to address the students' conceptual difficulties. These forms of representations, the interactive learning tutorial activities associated with them, and the use of each representation in facilitating students' conceptual understanding are presented in Table 5.5. The equation, diagram, picture of interactive simulation, etc. used to represent radioactive decay are shown next to this table.

Table 5.5: MRs-based interactive NBD learning tutorial activities

Form of representation	**Interactive learning tutorial activities**	**Using MRs to facilitate students' conceptual understanding of NBD**
Students can use any form of representation	Warm-up activity (10 min) What are the three types	The students can use verbal-linguistic and equation forms of representations to perform the warm-up activity. The warm-up activity provided an opportunity for students to recall the three

Form of representation	Interactive learning tutorial activities	Using MRs to facilitate students' conceptual understanding of NBD
during the warm-up activity	of beta decay processes? What forces are responsible for the three types of beta decay process? What makes a unique NBD process as compared with other types? What are the possible sources of an electron in nature?	types of beta decay processes and the force responsible for these beta decay processes. The three types of NBD processes are NBD, positive beta decay, and electron capture. The weak nuclear force is responsible for beta decay and the electromagnetic force is responsible for electron capture. Atomic electron, NBD, and pair production are the possible sources of an electron. The warm-up activity helped the students to prepare themselves to learn and understand the concept of NBD via the following interactive activities:
Verbal-linguistic	What is the difference between negative and positive beta decay? What is the origin of the electron emitted in the beta decay process? What is the origin of the positron emitted in the positive beta decay process? Do electrons and positrons emitted in beta decay exist in a nucleus before decay? (15 min)	A verbal-linguistic form of representation was used when students describe the difference between negative and positive beta decay and then share their various ways of conceptual understanding with each other via discussion. This representation was also used when they discussed the origin of electrons and a positron emitted in the beta decay process. The students also discussed whether electrons and a positron exist or not in a nucleus before decay. This helped students to learn and understand the different aspects of the concept of NBD via discussion and critical thinking.
Text	What is the difference between negative and positive beta decay? What is the origin of the electron emitted in the beta decay process? What is the origin of the positron emitted in the positive beta decay	Text representation was used when students described the difference between negative and positive beta decay using a pen and paper. This representation was also used when they described the origin of electrons and positrons emitted in the beta decay process. The students described if electrons and a positron exist or not in a nucleus before decay using text. This allowed students to learn and understand the different aspects of the concept of NBD via exchanging their text and critical thinking.

Form of representation	Interactive learning tutorial activities	Using MRs to facilitate students' conceptual understanding of NBD
	process? Do electrons and positrons emitted in beta decay exist in a nucleus before decay? (20 min)	
Symbolic and numeric	When do you use symbolic and numeric representations in learning NBD? What can they represent? (10 min)	Symbolic and numeric representations were used when students described NBD using an equation, a diagram, and interactive simulations. This gave them a chance to express equations, draw a diagram, and perform interactive simulations using appropriate symbols and numerical values. They can represent nuclei, atomic numbers, and particles.
Equations of negative beta decay	Express negative and positive beta decay using equations and then interpret Describe the decay of neutron and proton in unstable nuclei using an equation and then interpret (25 min)	This representation was used when students describe negative and positive beta decay using an equation. They expressed their equations using a pen and paper. The scientific Eq. 2.4, 2.5, and 4.16 were displayed to them to compare and contrast with their expressions. These equations provided an opportunity for students to understand the difference between negative and positive beta decay. Eq. 4.16 provided an opportunity for students to understand the origin of the electron emitted in the beta decay process. This equation also facilitated the students' understanding of conservation laws.
Graph	Look at the typical beta decay curve in Figure 5.14. Why do the emitted beta particles have different kinetic energies? (15 min)	This representation was used when students describe the number of beta particles versus the kinetic energy graph drawn before the discovery of the neutrino. The graph was displayed for students. This provided an opportunity for students to understand the existence of the third particle emitted in NBD processes and to develop an awareness of the complete equation of the NBD process. As the findings in the first phase indicated, students missed the third particle while writing the equations of negative and positive beta decay processes.
Interactive simulations of negative beta decay	Perform the interactive simulation of the NBD of tritium to helium-3 based on its guide. What is the origin of	This representation was used when students described the simulation of NBD of tritium to helium-3. The picture of this interactive simulation is indicated in Figure 5.12. It is freely available and can be downloaded from http://phet.colrado.edu.This provided an opportunity for

Form of representation	Interactive learning tutorial activities	Using MRs to facilitate students' conceptual understanding of NBD
	electron and antineutrino emitted in this simulation? (25 min)	students to visualise and understand the concept of NBD. Simply by observing the simulation the students had the opportunity to understand that the neutron existing in the nucleus of tritium is the origin of the emitted electron and antineutrino.
Diagram	Draw the diagram that indicates the decay of tritium to helium-3 by observing the interactive simulation of the NBD process. Among the three nucleons in tritium, which one is changed in the decay process? How is it changed? (15min)	This representation was used when students described the NBD of tritium to helium-3. The students were asked to draw their diagram based on the nuclear models of the two nuclei indicated in the interactive simulation. The diagram drawn by the researcher and indicated in Figure 5.15 was displayed for students to compare and contrast. The diagrammatical representation provided an opportunity for students to visualise and understand the decay of neutron in tritium to proton, electron, and antineutrino. This is the fundamental decay process in the NBD process. This may be helped the students to understand the concept of NBD. This representation (Figure 5.15) complements the interactive simulation (Figure 5.12).
Concept map	Construct a concept map that indicates the origin of the electron emitted in the NBD process. (15 min)	This representation was used when students summarise what they understood about NBD from the previous MRs-based activities. They constructed their concept map. The concept map constructed by the researcher, which is indicated in Figure 5.16 was displayed for them to compare and contrast with their concept map. This provided an opportunity for students to recap what they have learned and understood about NBD from the previous different forms of representations.

Additional information for representations is indicated in Table 5.5

The complete equation of the NBD process is expressed in Eq. 2.4. Figure 5.14 showed that the emitted beta particles have different kinetic energies. This graph was drawn before the discovery of the neutrino. This indicated for scientists the existence of the third particle neutrino in the beta decay process (see Eq. 4.16).Since a particle has antiparticle, antineutrino is the antiparticle of neutrino. The third particle emitted in the NBD process is antineutrino. However, the particle that is emitted in the positive beta decay process neutrino is not considered in this study. In the first phase, the students confused the NBD process with the positive beta decay process (see Table 4.4).

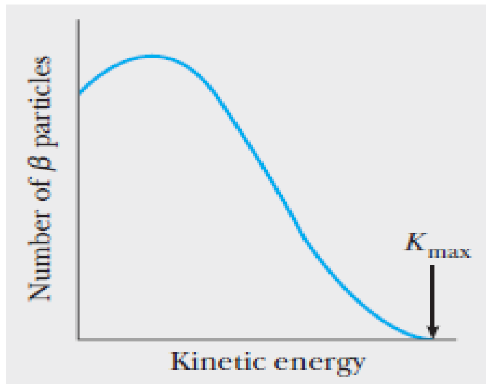


Figure 5.14: A typical beta decay curve

Source: Serway et al. (2005, p.488)

The picture of an interactive simulation of the NBD of tritium to helium-3 is shown in Figure 5.12. Simply, by looking at this simulation, the students were given the task of understanding the decay of a neutron in the parent nucleus into proton, electron, and antineutrino, which is expressed in Eq. 2.4.

The rest mass of a neutron is greater than the rest mass of a proton by 1.29 $MeV/_{c^2}$.The electron emitted in beta decay is created out of the nuclear rest mass, which can be described based on the concept of mass-energy equivalence. This can be considered as the origin of the electron emitted in the beta decay process.

Based on the interactive simulation of the NBD of tritium into helium-3 (see Figure5.12) and Eq. 4.16, it is possible to draw the following diagram (Figure 5.15) of NBD. The number of protons in the daughter nucleus of the helium-3 atom is greater than the number of the electron in helium-3 atom by one. This implies that the daughter atom (He-3 atom) is positively charged.

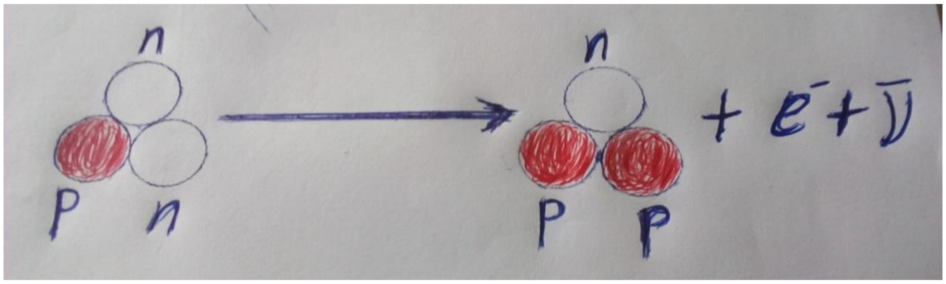


Figure 5.15: The change of Tritium into Helium-3 as a result of NBD

Source: Researcher’s own

The next concept map of NBD was constructed by the researcher. Four critical aspects of NBD are indicated in the concept map. Some of these aspects were discerned by students (see Table 4.4).

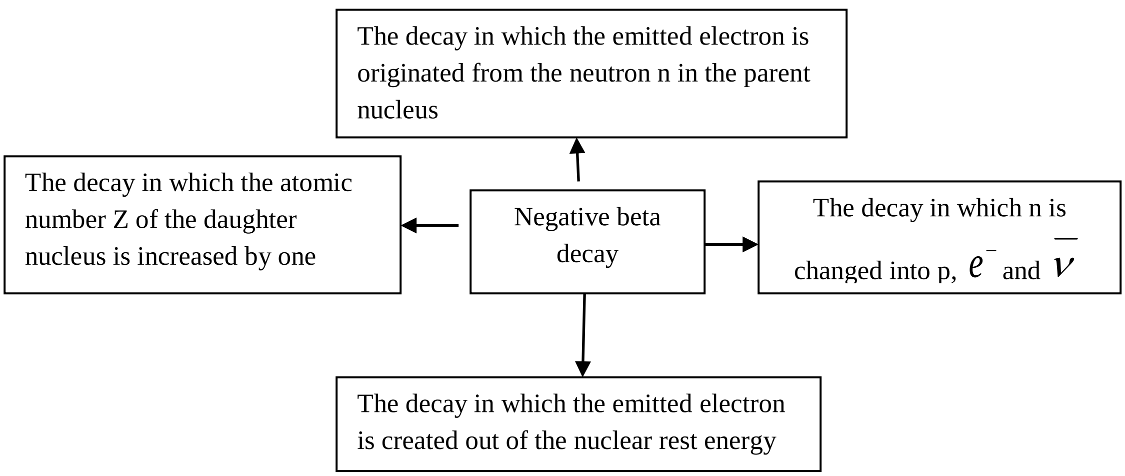


Figure 5.16: The concept map of NBD

Figure 5.12, Eq. 4.16, and Figure 5.15 complement each other. The representations facilitated the students’ understanding of the different aspects of the NBD process. This provided an opportunity for students to confront their conceptual difficulties and misconceptions of NBD.

5.2.5 Learning and Understanding of the Concept of NEUsing MRs

The students’ conceptual difficulties associated with NE were identified and described in Section 4.7.5. Verbal, text, symbolic, equation, liquid-drop model, interactive simulation, animation, diagram, and concept map were the forms of representations selected to address the conceptual difficulties of NE. These forms of representation, the interactive learning tutorial activities associated with them, and the use of each representation in facilitating students' conceptual understanding are presented in Table 5.6 as shown below. The equation, graph, diagram, and concept map referred to in the table are shown next to the table.

Table 5.6: MRs-based interactive NE learning tutorial activities

Form of representation or model	**Interactive learning tutorial activities**	**Using MRs or models to facilitate students' conceptual understanding of NE**
Students can use any form of representation during the warm-up activity	Warm-up activity (10 min) What are the basic ideas of energy that could be considered in general? What forms of energy exist in nature? What forms of energy are released in radioactive decay and nuclear reaction?	The students would have used the verbal-linguistic form and equation form of representations to perform the warm-up activity. The warm-up activity provided an opportunity for students to discuss the different forms of energy in nature. Some basic ideas of energy had previously been considered. These are forms of energy, the transformation of energy, transfer of energy, loss of energy, the gain of energy, and conservation of energy. Again, this activity also provided an opportunity for students to understand the form of energy released in radioactive decay and nuclear reaction. This helped the students to get themselves ready to learn and understand the concept of NE via the next MR 's-based activities.
Verbal-linguistic	What do you mean by NE? What are the two main ways in which NE is produced in large amounts? How is NE transformed into electricity in a nuclear reactor? (15 min)	A verbal-linguistic form of representation was used when students define and describe the different aspects of NE and share their various ways of conceptual understanding with each other via discussion. This form of representation was used when they state and describe how NE is produced in large amounts and how it is transformed into another form of energy. This allowed students to learn and understand the concept of NE via discussion and critical thinking.
Text	What do you mean by NE? What are the two main	Text representation was used when students defined and described the different aspects of NE using pen and paper. Again, it was used when students described the two main ways

Form of representation or model	Interactive learning tutorial activities	Using MRs or models to facilitate students' conceptual understanding of NE
	ways in which NE is produced in large amounts? 20 min)	in which NE is produced in large amounts. This allowed students to learn and understand the concept of NE via writing a text, discussion on the text, and critical thinking.
Symbolic and numeric	When do you use symbolic and numeric representations in learning NE? What can they represent? (10 min)	Symbolic and numeric representations were used when students described NE using an equation, a diagram, and interactive simulations (animation). This allowed them to express equations, draw diagrams, and perform interactive simulations using appropriate symbols and numerical values. They could represent nuclear mass and energy, speed of light, nuclei, kinetic energy, particle, and others.
Equation	Express nuclear reaction, conservation of energy related to it, and its Q-value (NE) using an equation. Express the equation of Q-value (NE) in terms of the kinetic energies of the fission fragments and nuclear masses. (25 min)	This representation was used when students describe the nuclear reaction, energy conservation law applied to it and the energy released in this reaction (NE) using an equation. The released energy (NE) is created out of the nuclear rest mass. For this reason, the released energy E (NE) is related to nuclear masses by equation 4.4. This representation was also used when the thermal neutron is colliding with U-235. They expressed their equations using a pen and paper. The scientific Eq. 2.7, 2.8, 5.6, 5.7, and 5.8 were displayed for them to compare and contrast with their expressions. This provided an opportunity for students to discern the different aspects of NE and then to have a complete understanding of it.
Interactive simulations	Perform the interactive simulation of the fission of Uranium-235 by thermal neutron In what form the NE exists in this simulation? (25 min)	This representation was used when students perform the simulation of nuclear fission of Uranium-235 by a thermal neutron. The picture of this interactive simulation is indicated in Figure 5.18. It is freely available and can be downloaded from http://phet.colrado.edu This provided an opportunity for students to visualise the concept of nuclear fission reactions and NE. This enabled the students to have a better conceptual understanding of NE. That is, they understood that NE exists in the form of the kinetic energies of the fission fragments observed in the simulation.
Liquid-drop nuclear structure model	Illustrate the fission of Uranium-235 by thermal	This representation complements the interactive simulation performed by the students (see Figure 5.18). Figure 5.17

Form of representation or model	Interactive learning tutorial activities	Using MRs or models to facilitate students' conceptual understanding of NE
	neutron using the liquid-drop model of a nucleus? (15 min)	displaced students after they attempted for themselves to describe the fission of Uranium-235 using the liquid-drop model of a nucleus. This provided an opportunity for students to understand the concepts of nuclear fission reactions and how NE is released in this process.
The diagram of a pressurised-water nuclear reactor and its animation	Illustrate how NE is transformed into electrical energy in a pressurised-water nuclear reactor (15 min)	This representation was used by students to illustrate how NE is transformed into electrical energy in a nuclear reactor. This provided an opportunity for students to visualise and understand how NE is transformed into electrical energy. Figure 5.19 was displaced for students after they attempted for themselves.
Concept map	Construct a concept map that indicates the different aspects of NE (15 min)	This representation was used when students summarise what they understood about NE from the previous MRs-based activities. They constructed their concept map. The concept map constructed by the researcher, which is indicated in Figure 5.20 was displayed for them to compare and contrast with their concept map. This provided an opportunity for students to recap what they have learned and understood about NE from the previous different forms of representation.

<u>Additional information for representations is indicated in Table 5.6</u>

A nuclear reaction is expressed using Eq. 2.7 in Chapter 2. In this equation, the symbols a, X, Y, and b represent the incident particle, the target nucleus, the product nucleus, and the product particle respectively.

By applying the law of conservation of energy to the nuclear reaction represented by Eq. 2.7, it is possible to get Eq. 5.5.

$$M_a c^2 + K..E_a + M_x c^2 = M_y c^2 + K.E_y + M_b c^2 + K.E_b \quad (5.5)$$

NE, which is represented by the Q-value that exists in the form of kinetic energies, is equivalent to the lost mass as it can be derived from Equation 5.5 and shown next.

$$K.E_y + K.E_b - K.E_a = (M_a + M_x - M_y - M_b)c^2$$

This equation implies that the Q-value or NE can be expressed using Eq. 5.6, 2.8.

$$Q = NE = K.E_y + K.E_b - K.E_a \quad (5.6)$$

And

$$Q = NE = (M_a + M_x - M_y - M_b)c^2 \quad \text{(From Equation 2.8)}$$

Equation 2.8 indicates that NE is created out of nuclear rest mass. So, nuclear rest mass can be considered as the origin of NE. The energy released in an exothermic nuclear reaction, Q> 0. This implies that the sum of the masses of the incident particle and the target nucleus is greater than the sum of the masses of the product nucleus and the product particle. The lost nuclear rest mass is converted to the kinetic energies of the product nucleus Y and the product particle b. For instance, about 200MeV of NE is released in the fission of $^{235}_{92}U$ by incident thermal neutron into barium and krypton as shown in Eq. 5.7 (Serway et al., 2005). This energy is very large as compared to the energy released in a chemical reaction. Three neutrons are also emitted in this nuclear reaction process.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n \quad (5.7)$$

In this nuclear fission reaction, there are two product nuclei and three product particles. Most of the 200MeVgoes into the kinetic energies of the heavy fission fragments barium and krypton. There are other possible product nuclei (say X and Y) rather than barium and krypton in this nuclear fission reaction. The general equation for the fission of U-235 by thermal neutron is expressed as follows.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U^{*} \rightarrow X + Y + 3neutrons \quad (5.8)$$

NE can also be defined as the energy released when two light nuclei combine as a result of the strong attractive nuclear force (see Figure 5.2). Such a nuclear reaction is known as a nuclear fusion reaction. The thermonuclear fusion reaction is the reaction by which NE is generated in the sun and other stars that have an abundance of hydrogen.

The nuclear fission reaction is described using a liquid-drop nuclear structure model as shown below. Three neutrons are emitted in the process of the nuclear fission reaction.

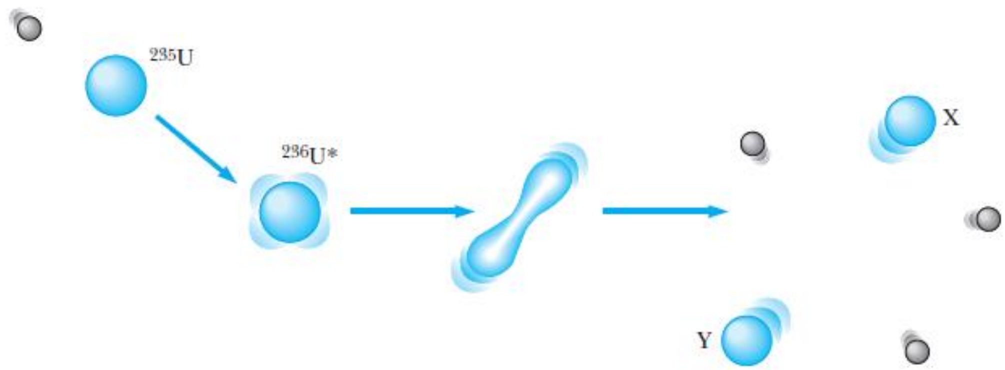
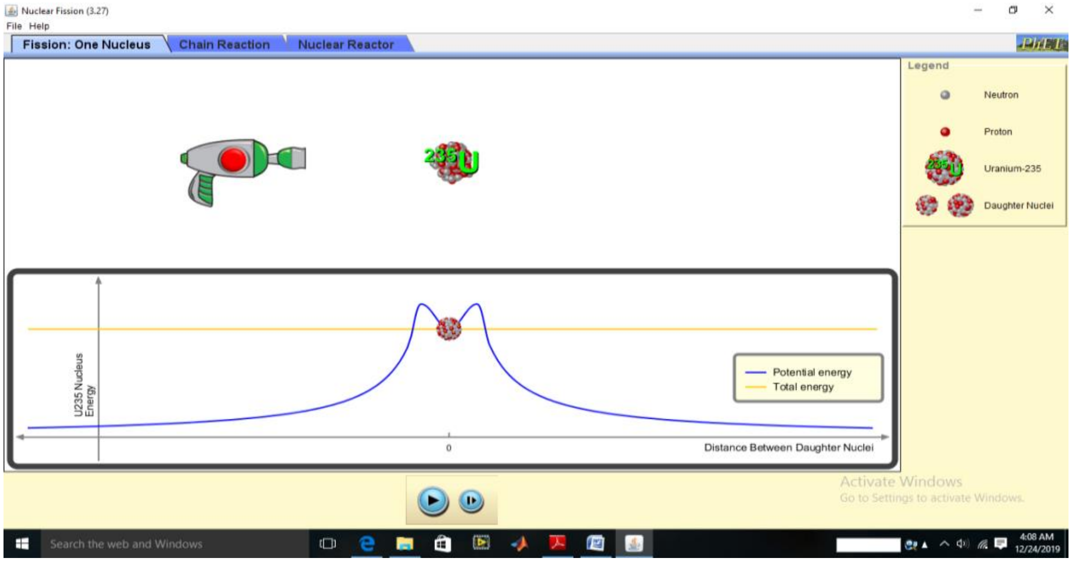


Figure 5.17: The fission of ${}^{235}_{92}U$ by the incident thermal neutron as described by liquid-drop nuclear structure model

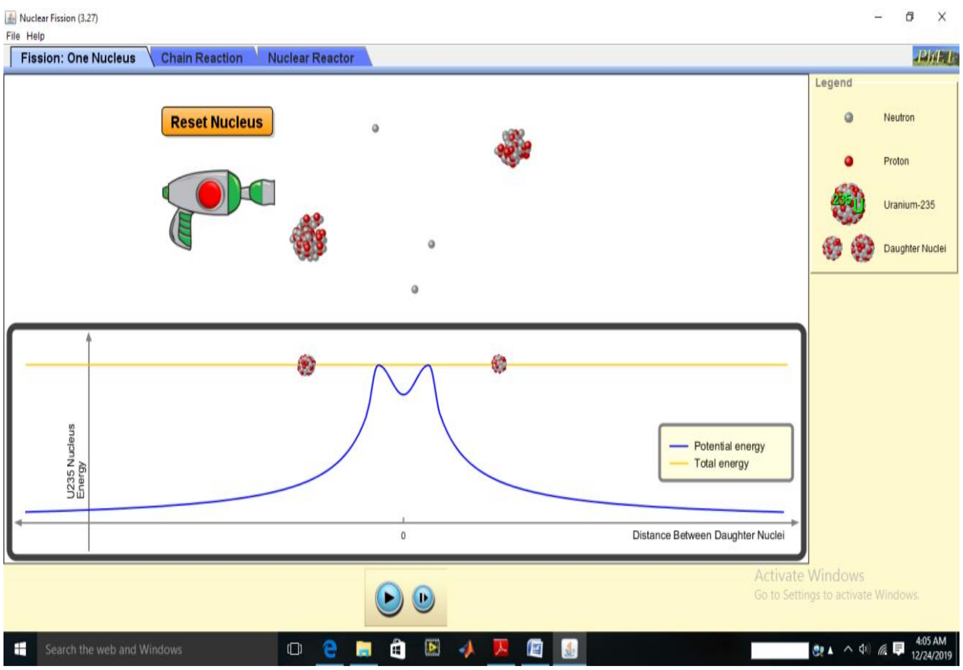
Source: (Serway et al., 2005, p.5012)

About 85% of the NE produced by this fission reaction exists in the form of the kinetic energies of the fission fragments X and Y. The emitted thermal neutrons cause other fission ${}^{235}_{92}U$ reactions in a controlled way, which we call a chain reaction.

The interactive simulation (Figure 5.18) has the same way of illustration as that of the above liquid-drop nuclear structure model (Figure 5.17). That is Figures 5.17 and 5.18complement each other. Both forms of representations illustrate the fission of U-235 by the incident thermal neutron. These are the liquid-drop nuclear structure model and the interactive simulation. These representations also supported the students to understand the existence of NE in the form of the kinetic energies of the fission fragments. These representations also indicate that three neutrons are emitted in the nuclear fission of U-235, which causes the fission of other U-235s. As a result of this, the chain nuclear fission of U-235s occurs, in which an enormous amount of NE is released. The release of this NE is controlled and transformed into electrical energy in a nuclear reactor.



(a) Before fission of $^{235}_{92}U$ by thermal neutron



(b) After fission of $^{235}_{92}U$ by thermal neutron into two fission fragments

Figure 5.18: The interactive simulation of fission $^{235}_{92}U$ by thermal neutron

An enormous amount of NE is produced by the nuclear fission chain reaction. The students also performed the interactive simulation of the nuclear fission chain reaction of U-235.

The students also performed an activity based on the static and animated pressurised-water nuclear reactor. These supported the students to understand how NE is produced and converted into electrical energy in a nuclear reactor. The following diagram of a pressurised-water nuclear reactor was used to describe the transformation of NE into electrical energy (see Figure 5.19). In this nuclear reactor, there are two closed loops, which contain water. The water contained in the first and second loops was maintained at high and low pressures respectively. Hence, the boiling point of water in the first loop is greater than that of the second loop.

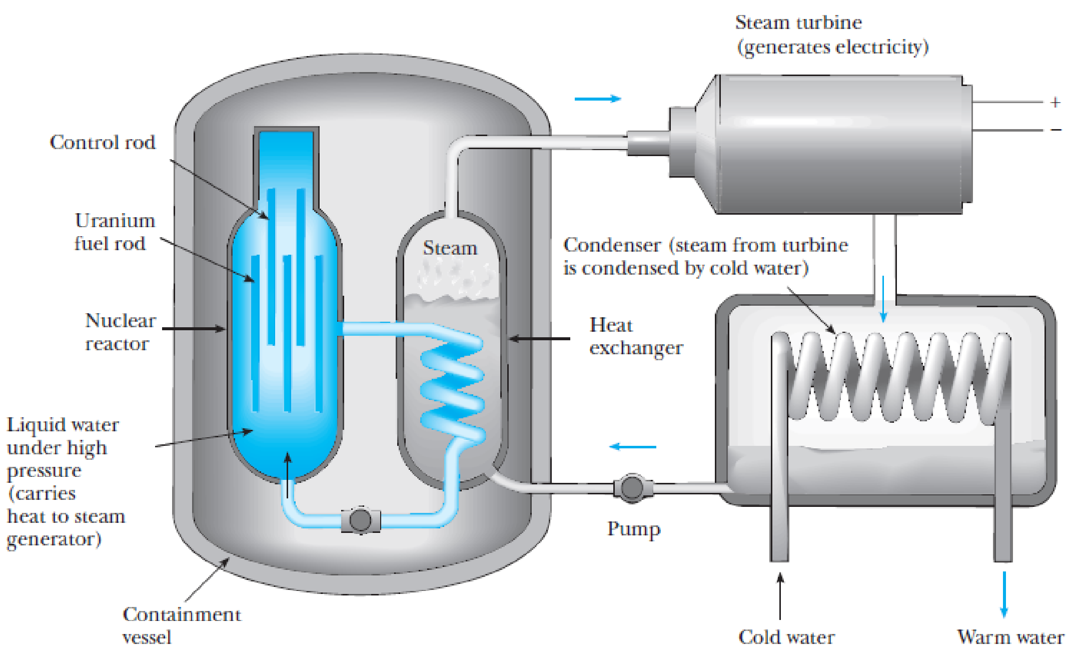


Figure 5.19: Main components of a pressurized-water nuclear reactor

Source: Serway et al. (2005, p.516)

The kinetic energies of fission fragments are produced as a result of the fission of U-235 by incident thermal neutron supply heat to the water in the first loop. That is, the kinetic energy of the fission fragments (NE) is transformed into the heat energy of the water contained in the first loop. The heat energy of the water in the first loop is transferred to the water contained in the second loop by a pipe. As a result of this, the water in the second loop is heated and then changed into steam. Then, the fast-moving steam drives a turbine-generator system. In this process, the heat energy carried by the steam is converted into mechanical energy. In the generator, the mechanical energy converts into electrical energy. In a generator, a huge coil of wire rotates in a strong magnetic field with the turbine. This induces an electromotive force in the coil of the wire due to the time rate of change of magnetic flux through the coil of wire. The electromotive force also induces an electric current in the closed coil of wire. In the overall process, the kinetic energy of the fission fragments (NE) is converted into electrical energy, which creates electric power.

The students also used the animation of the transformation of NE into electrical energy using the pressurised-water nuclear reactor shown in Figure 5.19. This provided an opportunity for students to develop their understanding of the concept of NE.

Concept map of NE

The following concept map of NE had constructed by the researcher of this study to organise and illustrate the different aspects of NE. Some of these aspects of NE had discerned by students in the first phase (see Table 4.5).

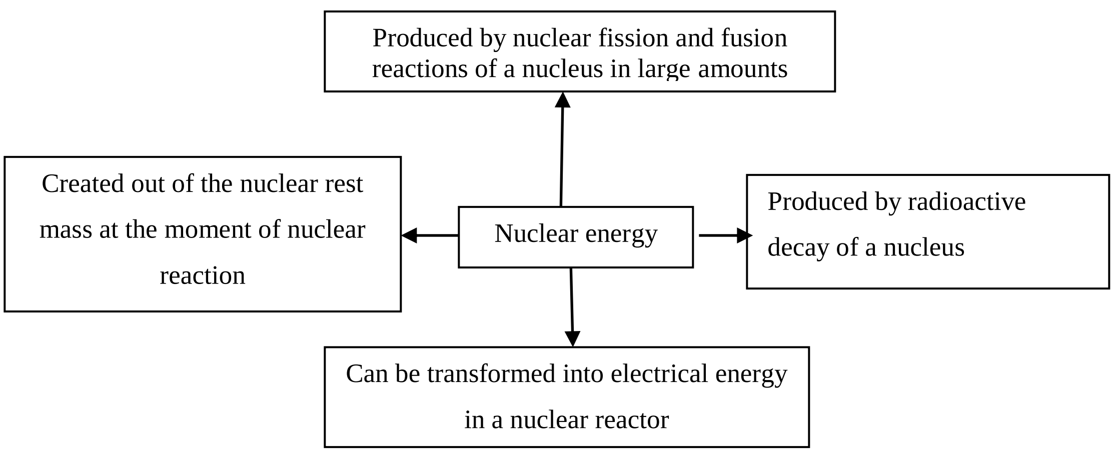


Figure 5.20: The concept map of NE

The above different forms of representations provided an opportunity for students to discern the different aspects of NE. This could have allowed students to confront their conceptual difficulties and misconceptions about NE.

5.3 CHAPTER SUMMARY

The MRs-based instruction with interactive learning tutorials was developed, designed, and implemented in the second phase in Chapter 5 to address the students' conceptual difficulties. Information obtained from the results found in Phase 1 after traditional instruction and Phase 2 at pre-intervention was used for developing and designing this instructional intervention. The VTL was used as a potential source of information to develop the intervention. To explore the second group of students' prior understanding and representations of each of the five concepts of introductory nuclear physics, data was collected via the open-ended questionnaire at pre-intervention. The results obtained at pre-intervention were presented in Tables 6.1 to 6.5 together with the results obtained at post- and delayed post-intervention in the third phase. The results obtained at pre-intervention were used as a baseline in the third phase to explore the effectiveness of the intervention in addressing the students' conceptual difficulties.

The second group of students (N = 40) identified in the second phase were divided into eight small tutorial groups. The eight small tutorial groups of students interacted with the appropriate different forms of representations selected and used to represent each of the five concepts. In other words, the students performed the MRs-based interactive learning activities designed in the second phase in small groups. At the moment of performing the interactive learning activities, the students used the experts' and their representations. The MRs-based interactive learning activities provided an opportunity for students to discern the different aspects of each of the five concepts. In another way, the MRs-based interactive learning activities provided an opportunity for the students to confront their conceptual difficulties. These MRs-based interactive learning activities were presented in Tables 5.2 to 5.6. The different forms of representations used to represent the different aspects of each of the five concepts of introductory nuclear physics were indicated in these tables and presented after each table.

CHAPTER 6: EFFECTIVENESS OF THE INSTRUCTIONAL INTERVENTION IN ADDRESSING THE STUDENTS' CONCEPTUAL DIFFICULTIES

6.1 INTRODUCTION

The third phase aimed at exploring the effectiveness of the intervention in addressing the students' conceptual difficulties identified in the first phase and at pre-intervention. Pre-intervention means before the intervention was developed, designed, and implemented on the second group of students in the second phase. The instructional intervention used on the second group of students was the MRs-based instruction with interactive nuclear physics learning tutorials. The data was collected using the open-ended NPCIQ from the second group of students (N=40) at pre-, post-, and delayed post-intervention. The open-ended NPCIQ is available in Appendix III. In the first phase, data was collected using the validated semi-structured interviews from the first group of students (N = 30) who were exposed to traditional instruction. The open-ended NPCIQ was developed from the validated semi-structured interview questions and the responses of the students to the interviews.

The data collected at pre-, post-, and delayed post-intervention were analysed using the phenomenographic data analysis method (see Section 6.2 - 6.6). The seven steps of the phenomenographic analysis process (see Section 3.10.1) were used in this analysis process in addition to the constant comparison analysis method (see Section 3.10.5) which was used in association with the seven steps of the phenomenographic data analysis process. In the analysis process, the data collected at the three points of intervention coded, recoded, and then categorised in a hierarchy. The categories of description in a hierarchy represent the students' different ways of understanding and representations of each of the five concepts of nuclear physics (see Section 3.10.2). The categories of description involve CAs, IAs, and non-respondent students (see Table 6.1 – 6.5). These three main constituents of the categories of description are identified based on the VTL (see Section 2.8.2). The critical aspects discerned by the students represent the critical differences between the correct various ways of students' conceptual understanding of each of the five nuclear concepts. The set of IAs discerned by the students represent the incorrect alternative ways of students' existing understanding of each of the five nuclear physics concepts. The non-respondent students represent students who did not respond at all to the open-ended NPCIQ.

The data collected at pre-intervention was analysed in the second phase. However, the results obtained from this analysis were presented in the third phase together with the results obtained at post- and delayed post-intervention (see Table 6.1 – 6.5). In the second phase, the information obtained from the results of the data analysis at pre-intervention was used to develop and design the intervention. The results found at pre-intervention were used as the baseline in the third phase. That is these results were used as the baseline and compared to the results found at post- and delayed post-intervention to explore the effectiveness of the intervention (see Figure 6.1 – 6.5). The critical and IA of each of the five nuclear concepts discerned by students were coded into English alphabet capital letters (see Section 6.2 – 6.6). The number of students who discerned each critical and irrelevant aspect and the number of non-respondent students at pre-, post-and delayed post-intervention are presented in Tables 6.1 – 6.5). According to the VTL, critical aspects are the necessary conditions for learning (see Section 2.8). To learn and understand a disciplinary concept, the students have to discern its various critical aspect (Marton, 2014).

The effectiveness of the intervention in addressing the students' conceptual difficulties of each of the five nuclear physics concepts was explored. Its effectiveness was explored using the next five criteria outlined based on the results of this study presented in Tables 6.1 – 6.5.

1) If the number of students, who were discerning the critical aspect of each of the five concepts of nuclear physics increases from pre- to post-intervention, then the intervention is effective.
2) If the number of students discerning the critical aspect at post- and delayed post-intervention is nearly equal, then the intervention is effective in retaining the students' conceptual understanding and representations.
3) If the number of students who discerned the IA decreased from pre- to post-intervention, then the intervention was effective.

4) If the number of non-respondent students decreases from pre- to post-intervention, then the intervention is effective.
5) If the number of students using MRs correctly at post-intervention increased compared to that of pre-intervention, then the intervention is effective.

These five criteria were used in the discussion of the results to determine the effectiveness of the intervention in addressing the students' conceptual difficulties. The abbreviation NS in Tables 6.1 to 6.5 represents the number of students who discerned each critical and irrelevant aspect, the number of non-respondent students, and the number of students who used an equation, a graph, and a diagram. These are the different forms of representations used by the students to represent the various aspects of each of the five concepts of nuclear physics.

The illustrative example of the responses of three students to the open-ended questionnaire and the analysis process is presented in Appendix VIII. These support the categories of description constructed and presented in Tables 6.1 – 6.5.

6.2 CATEGORISATION OF STUDENTS' CONCEPTUAL UNDERSTANDING AND REPRESENTATIONS OF NBE AT PRE, POST - AND DELAYED POST-INTERVENTION

6.2.1 The Categories of Description of NBE

The seven steps of the phenomenographic analysis process were used to analyse the students' conceptual understanding and representations of each of the five concepts of introductory nuclear physics (see Section 3.10.1). In addition to this, the VTL was used to identify the critical and IA discerned by students (see Section 2.8). The responses of 40 students to the open-ended questionnaire about NBE at pre-, post-, and delayed post-intervention were analysed. Based on the analysis process, the different ways of students' conceptual understanding of NBE were identified in the following section. An example of the analysis process of the three students' responses to the open-ended questionnaire about NBE is available in Appendix VIII.

I. The critical aspect of NBE discerned by students

A. The energy equivalent to the mass lost when the free nucleons combine to form a nucleus

B. The energy is released when the free nucleons combine to form a nucleus

C. The amount of energy that must be added to a nucleus to separate it into its constituent nucleons

D. The energy missed, after a nucleus is separated into its constituent nucleons

E. The NBE per nucleon of the stable nuclei changes with their mass numbers

F. Three major effects are influencing the binding energy of a nucleus in a liquid-drop nuclear structure model

II. The IA of NBE discerned by students

G. It is the energy that binds nucleons together to form a nucleus

H. It is the energy needed to eject an electron from the outermost shell of a given atom

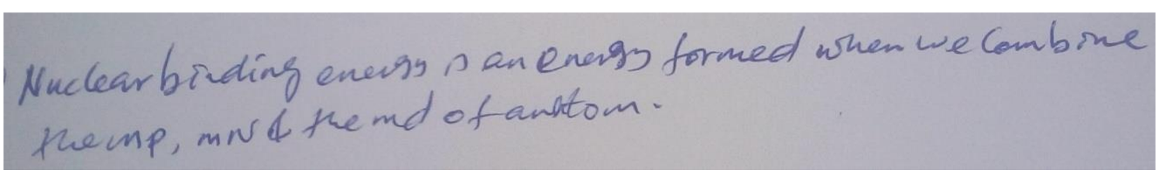
III. Non-respondent students: The students, who did not respond at all to the open-ended NPCIQ

The illustrative excerpts of the responses of a student to the open-ended questionnaire associated with NBE are presented as follows to support these categories of description.

At pre-intervention:

Question: Define NBE in text

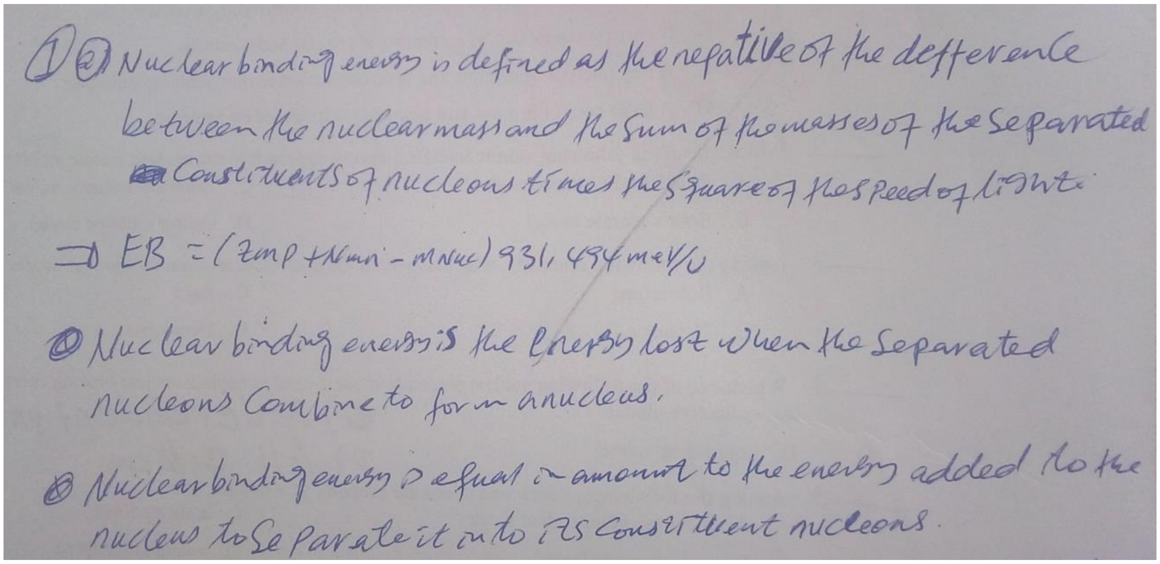
Student S_{18}*:* The student responded as follows to the question (Category B)


Nuclear binding energy is an energy formed when we combine the mp, mn & the md of an atom.

At post-intervention:

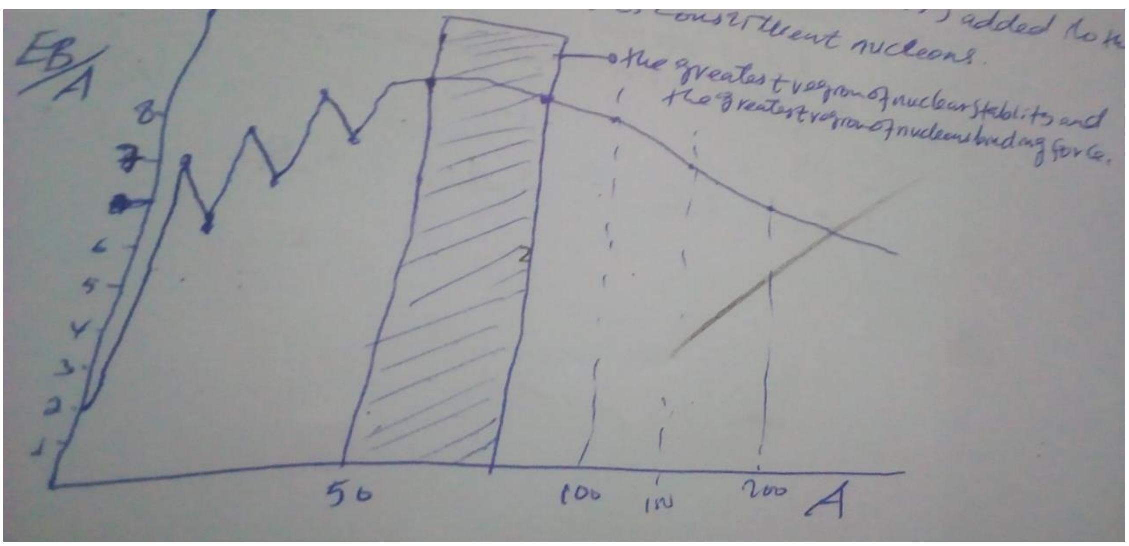
Question: Define NBE in text and express it using equation

Student S_{18}*:* The student responded as follows to the question (Categories A, B, and C)



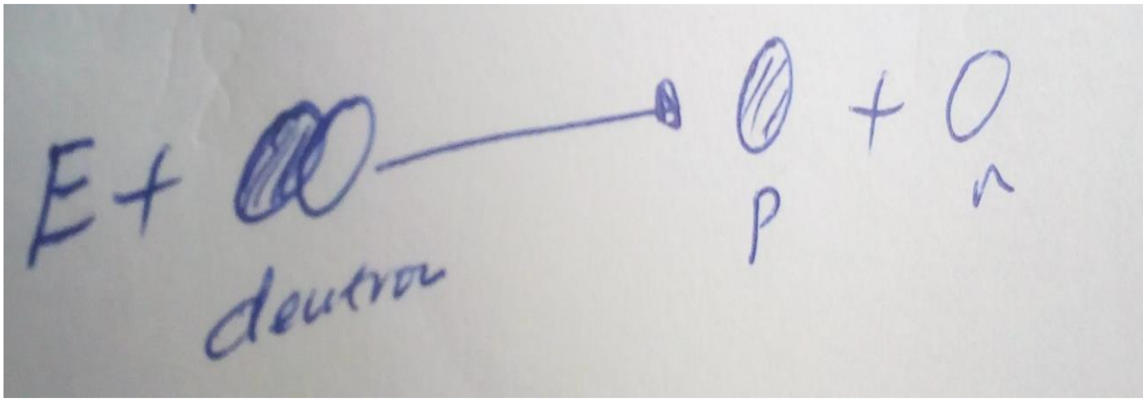
Question: Draw a rough graph of NBE per nucleon versus the mass number. Indicate on the graph the greatest region of NBE per nucleon, nuclear stability, and nucleon binding force.

Student S_{18} *:* The student drew and used it as follows (Category E)



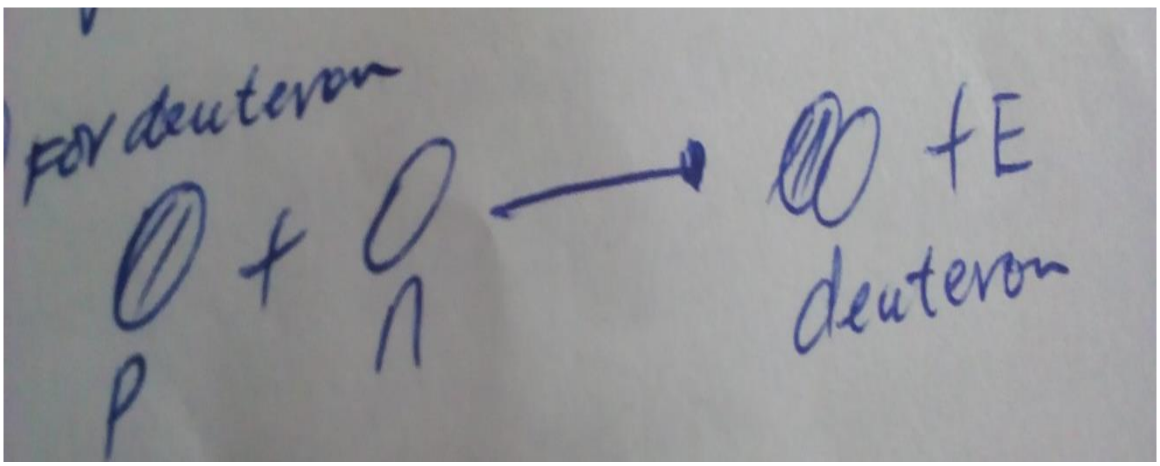
Question: Draw a diagram that shows the process of the separation of a deuteron into proton and neutron. And then describe NBE based on this diagram.

Student S_{18} *:* The student drew and used it as follows (Category C)



Question: Draw a diagram that shows the process of the combination of proton and neutron to form a deuteron. And then describe NBE based on this diagram

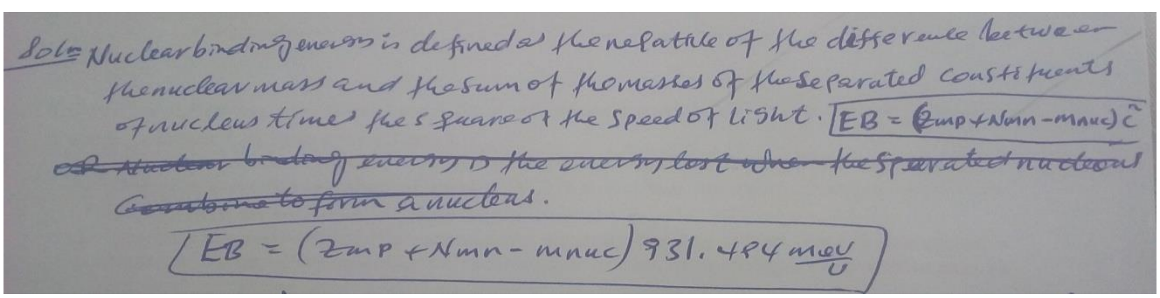
Student S_{18}*:* The student drew and used it as follows (Category B)



At delayed post-intervention:

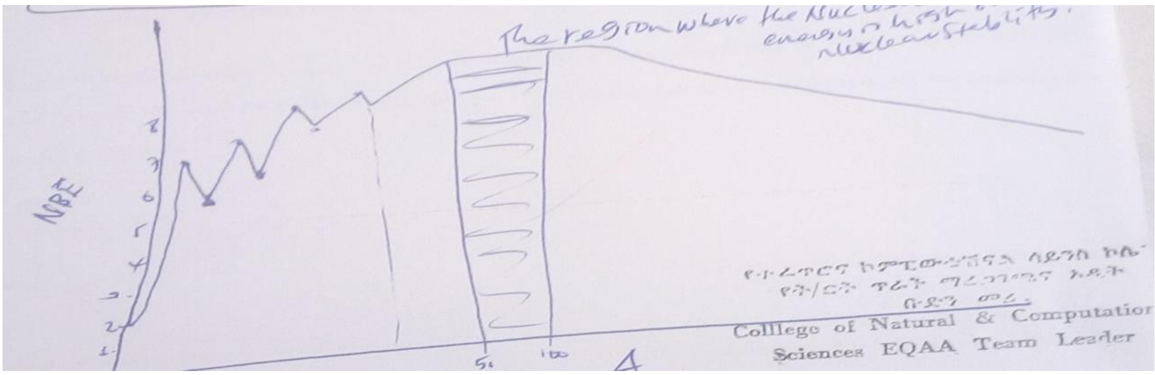
Question: Define NBE in text and then express it using equation

Student S_{18}*:* The student responded as follows to the question (Category A)



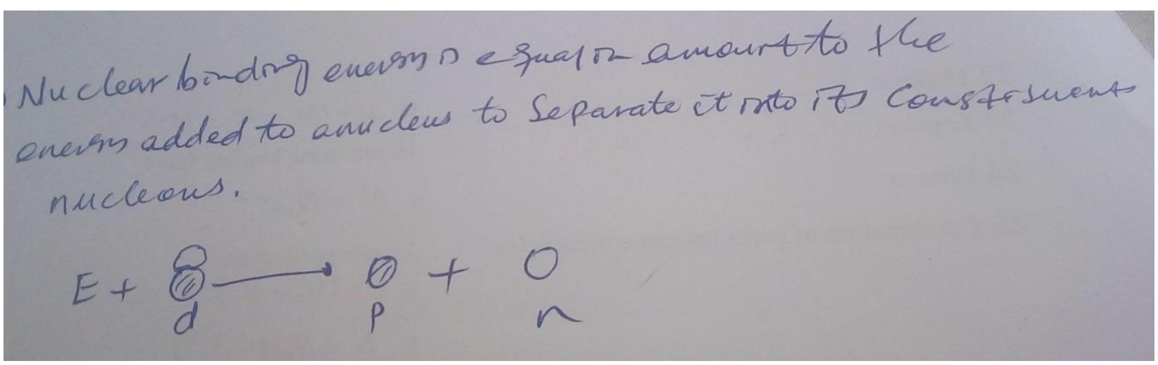
Question: Draw a rough graph of NBE per nucleon versus the mass number. Indicate on the graph the greatest region of NBE per nucleon, nuclear stability, and nucleon binding force.

Student S_{18}*:* The student drew and used it as follows (Category E)



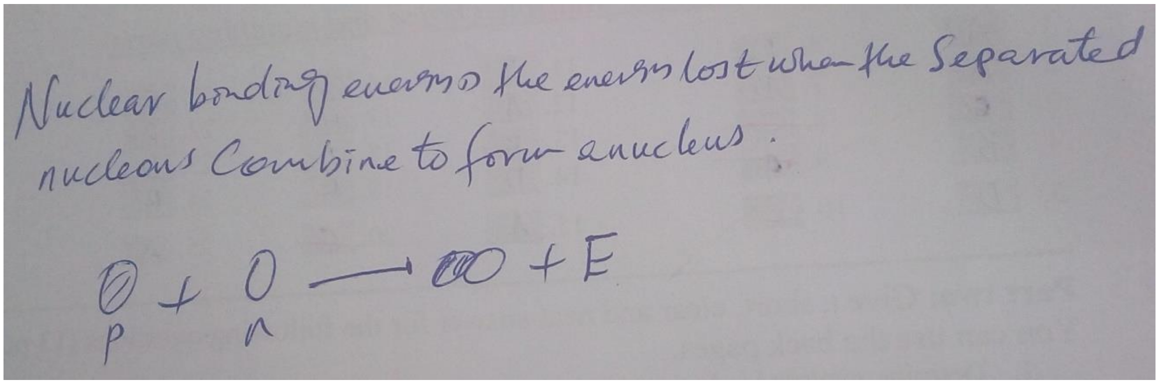
Question: Draw a diagram that shows the process of the separation of a deuteron into proton and neutron and then describe NBE based on this diagram.

Student S_{18}*:* The student drew and used it as follows (Category C)



Question: Draw a diagram that shows the process of the combination of proton and neutron to form a deuteron. And then describe NBE based on this diagram

Student S_{18}*:* The student responded as follows to the question (Category B)



As shown in Table 6.1, the NS who discerned each of the critical and IA of NBE and the number of non-respondent students at the three points of intervention is not the same. For instance, more critical aspects were discerned by the students at post-intervention than at the pre-intervention. The irrelevant aspect is discerned by less NS at post-intervention compared to that of pre-intervention. The number of non-respondent students at post-intervention is less than that of pre-intervention. The NS who used MRs correctly at post-intervention is greater than that of pre-intervention.

Table 6.1: Students' categories of description of NBE at pre-, post-, and delayed post-intervention

Categories of description	**Pre-Intervention N = 40**		**Post-Intervention N = 40**		**Delayed Post-intervention N = 40**	
I. CA in codes	NS	NS in %	NS	NS in %	NS	NS in %
A	5	12.5	22	55	24	60
B	1	2.5	16	40	14	35
C	6	15	21	52.5	19	47.5
D	1	2.5	4	10	8	20
E	2	5	21	52.5	17	42.5
F	0	0	4	10	0	0
II. IA in codes						
G	1	2.5	3	7.5	1	2.5
H	1	2.5	0	0	0	0
III. Non- respondent students	26	65	7	17.5	8	20
MRs used by students						
Eq. 2.1 for A	4	10	15	37.5	18	45

Categories of description	Pre-Intervention N = 40		Post-Intervention N = 40		Delayed Post-intervention N = 40	
Eq.4.2 for A	1	2.5	2	2.5	5	21
Eq.5.1 for F	0	0	4	10	0	0
Figure 5.1 for E	2	5	21	52.5	17	42.5
Figure 5.3 for C	0	0	13	32.5	11	27.5
Figure 5.3 for D	0	0	4	10	8	20
Figure 5.2 for B	0	0	8	20	6	15

First, the results presented in Table 6.1 indicate the critical aspect of NBE discerned by a particular NS at pre-, post-, and delayed post-intervention. For instance, critical aspect A is one of the critical aspects of NBE discerned by 5, 22, and 24 students respectively at pre-, post-, and delayed post-intervention. Critical aspect A could be written in text form as follows.

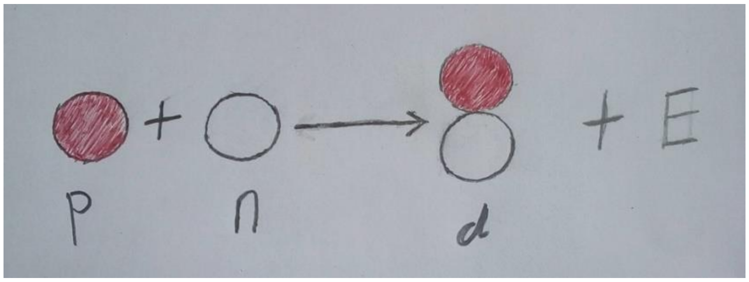
> *The students correctly understood that NBE is the energy equivalent to the mass lost when the free nucleons combine to form a nucleus.*

Second, the results presented in Table 6.1 indicate the IA of NBE discerned by a particular NS at pre-, post-, and delayed post-intervention. For instance, irrelevant aspect H, which is one of the IA of NBE discerned by 1, 0, and 0 students respectively at pre-, post-, and delayed post-intervention. Irrelevant aspect H can be written in text form as follows.

> *The students incorrectly understood that NBE is the energy needed to eject an electron from the outermost shell of a given atom*.

Third, the results presented in Table 6.1 indicate the NS who did not respond to the open-ended NPCIQ about NBE. The results in Table 6.1 indicate that 26, 7, and eight students respectively at pre-, post-, and delayed post-intervention did not respond to the open-ended NPCIQ.

Fourth, the results in Table 6.1 indicate the NS who used a particular form of representation to illustrate a certain aspect of NBE. For instance, 0, 8, and six students respectively at pre-, post-, and delayed post-intervention attempted to illustrate critical aspect B using the diagram indicated in Figure 5.2 in the previous chapter, namely:



Category B is the critical aspect of NBE discerned by 1, 16, and 14 students respectively at pre-, post-, and delayed post-intervention. Critical aspect B could be represented in text form as follows:

> *The students understood that NBE is the energy E released when the free nucleons combine to form a nucleus.*

It is also possible to represent the other critical and IA of NBE discerned by students in the text form. These are helpful to understand the results presented in Tables 6.2 – 6.5 in the same way.

6.2.2 Discussion on the Categories of Description of NBE

As indicated in the following sections, the effectiveness of the instructional intervention in addressing the students' conceptual difficulties of each of the five concepts of nuclear physics was illustrated and discussed based on the bar charts. The bar charts were drawn using Microsoft Excel. To draw the bar charts, the results presented in Tables 6.1-6.5 for the concept areas of NBE, nuclear force, radioactive decay law, NBD, and NE were used. The bar charts make it easier to understand how the NS discerning the critical and IA and the number of non-respondents changes from pre- to post-intervention. These charts are also helpful to determine the effectiveness of the instructional intervention in enhancing the students' conceptual understanding. The conceptual pathways that the group of students pursued from pre- to delayed post-intervention for each of the five concept areas is illustrated and discussed as follows based on the bar charts (see Figures 6.1-6.5).

The bar chart in Figure 6.1 illustrates the results presented in Table 6.1. The effectiveness of the intervention was determined based on the results illustrated in the bar chart and the five criteria mentioned at the end of Section 6.1. The overall results indicated that the intervention was effective in addressing the students' conceptual difficulties of NBE. For instance, critical aspect A discerned by 5, 22, and 24 students respectively at pre-, post-, and delayed post-intervention. Table 6.1 indicated that 4, 15, and 18 students respectively at pre-, post-, and delayed post-intervention used the relevant Equation 2.1 to express the critical aspect A. Table 6.1 also indicated that other relevant equations and figures were used by more NS at post- and delayed post-intervention than at pre-intervention. The NS discerning the irrelevant aspect H reduced from pre- to post-intervention. The irrelevant aspects involve misconceptions. The number of non-respondent students decreased from pre- to post-intervention. All of these indicate the effectiveness of the instructional intervention.

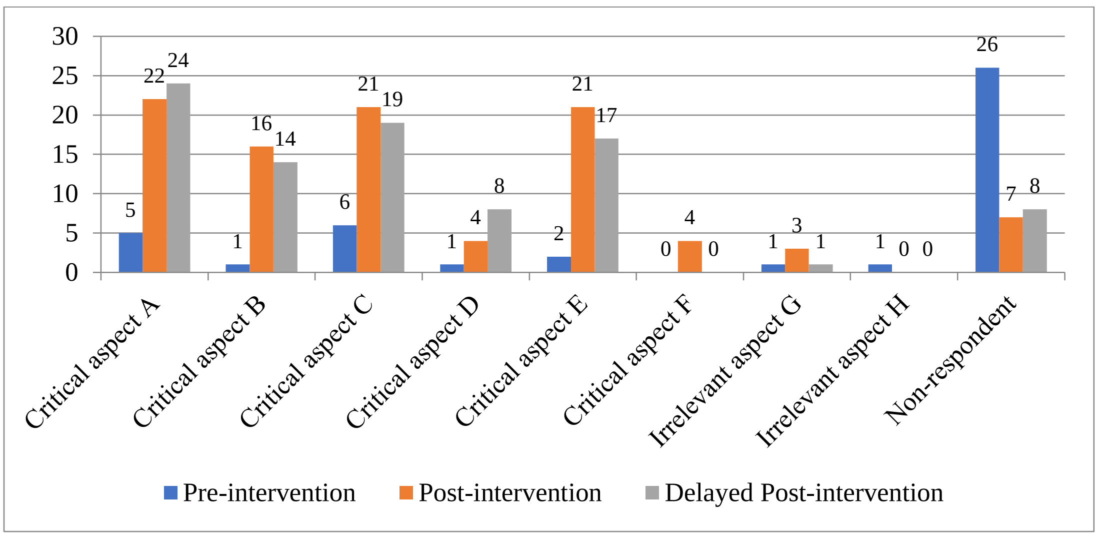


Figure 6.1: Critical and IA of NBE and non-respondent students at pre-, post-, and delayed post-intervention

The figures used by students in Table 6.1 supported them to discern the different CAs, which are the necessary conditions for learning and understanding the concept of NBE. No student discerned the irrelevant aspect H at post- and delayed post-intervention. This indicates the effectiveness of the intervention. Figure 6.1 also indicates that 26, 7, and eight were the non-respondent students respectively at pre-, post-, and delayed post-intervention. Again, this indicated the effectiveness of the intervention. Eighteen students were used Equation 2.1 to describe critical aspect A at delayed post-intervention. This equation supported the students to understand that NBE is equivalent to the mass lost when the free nucleons combine to form a nucleus. Twenty-one students correctly used Figure 5.1 to illustrate the critical aspect E of NBE at post-intervention.

Eight students correctly used the diagram in Figure 5.2 for describing critical aspect B at post-intervention. This diagram supported the students to understand that the binding energy of a nucleus is equal to the energy released in the combination of the separated nucleons. In the process of combination, the nuclear mass changed into NBE. In this process, mass is lost, and energy is gained. The released energy (the NBE) is equivalent to the lost mass. Figure 5.2 and Equation 2.1 complement each other, which supported the students to discern critical aspect B.

Seventeen students used the diagram in Figure 5.3 for describing critical aspects C and D at post-intervention. This diagram supported the students to understand NBE is equal to the amount of energy that must add to a nucleus to separate it into its constituents, which is critical aspect C. This diagram also supported the students to understand that NBE is equal to the energy missed after a nucleus separated into its constituent nucleons, which is Critical aspect D. In the separation process, energy has missed, and mass has gained. The missed energy has changed into the mass. Four students used the liquid-drop nuclear structure model for describing the binding energy of a nucleus at post-intervention, which is a Critical aspect F. Table 6.1 indicates some NS retained the use of equations, graphs, and diagrams in the delayed post-intervention to illustrate the critical aspect of NBE.

The conceptual difficulties of NBE identified in the first phase in Section 4.7.1 were addressed by using the intervention. Only a few students discerned IA after the intervention. This means the intervention was effective in eliminating the students' misconceptions of NBE. The MRs-based instruction with interactive learning tutorials, which was used for the instructional intervention, enhanced the students' conceptual understanding of NBE; i.e., the different forms of representations used by students supported them to discern and represent the critical aspect of NBE. The instructional intervention also played a role in developing the students' representational competence of NBE. The results of this study showed that only one student could not discern all critical aspects of the concept of NBE. The summary was given to the students using the concept map (Figure 5.4) constructed by the researcher that supported the students to develop their understanding of the concept of NBE. The instructional intervention used in this study was not used by previous nuclear physics education researchers. Moreover, no evidence was of research that addressed the conceptual difficulties of NBE even using other instructional methods.

6.3 CATEGORISATION OF STUDENTS' CONCEPTUAL UNDERSTANDING AND REPRESENTATIONS OF NUCLEAR FORCE AT PRE-, POST-, AND DELAYED POST-INTERVENTION

6.3.1 Categories of the Description of Nuclear Force

The responses of 40 students to the open-ended questionnaire about nuclear force at pre-, post-, and delayed post-intervention were analysed. Based on the results, various ways of students' conceptual understanding of nuclear force were identified. An example of the analysis process of the three students' responses to the open-ended questionnaire about nuclear force is available in Appendix VIII.

I. The critical aspect of a nuclear force discerned by students
   - A. The force that binds nucleons to form a nucleus
   - B. The force that has particular properties such as short-rang, strong, charge-independent, attractive, has a repulsive term, has a non-central component and it depends on the orientation of the nucleons' spins
   - C. A force that causes a strong nuclear interaction mediated by the exchange field particles known as pi-mesons
   - D. A force that believed to be the residual effect of the more basic strong force that binds quarks together to form a nucleon

II. The IA of a nuclear force discerned by students
   - E. A force that binds the nucleus of an atom and its orbiting electrons
   - F. A force the same as NBE in binding nucleons together to form a nucleus
   - G. A force that causes a strong nuclear interaction mediated by the exchange field particles gluons
   - H. A force that binds quarks together to form a nucleon

III. Non-respondent students: They are students who did not respond at all to the open-ended NPCIQ

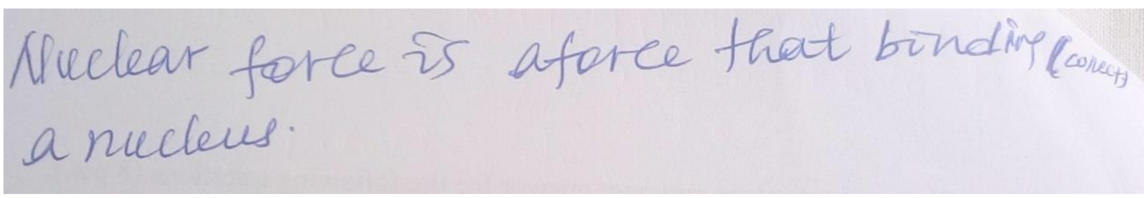
The illustrative excerpts of the responses of a student to the open-ended questionnaire associated with nuclear force are presented as follows to support these categories of description.

At pre-intervention: No response

At post-intervention:

Question: Define and describe the strong nuclear force using text

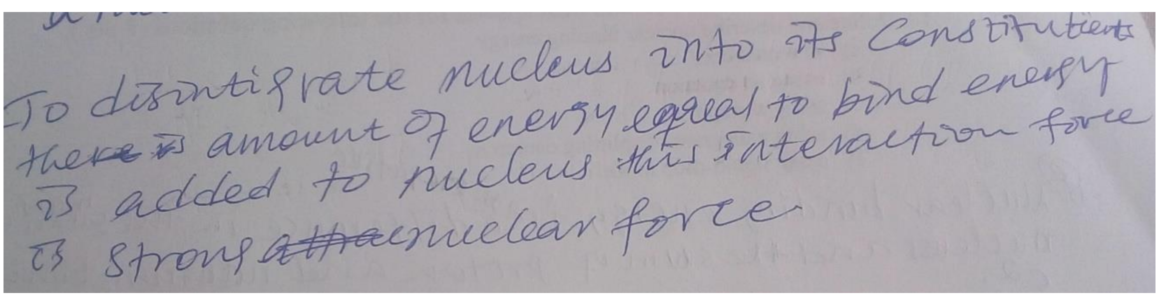
Student S_{28}*:* The student responded as follows to the question:



Nuclear force is aforce that binding (correct)
a nucleus.

Question: State and describe the properties of nuclear force

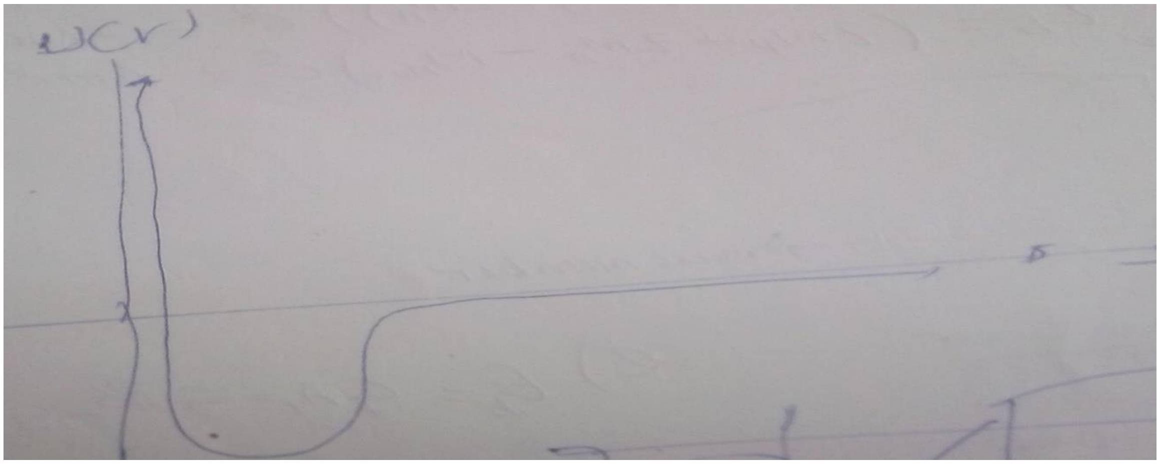
Student S_{28}*:* The student responded as follows to the question:



To disintigrate nucleus into its Constituents
there is amount of energy equal to bind energy
is added to nucleus this interaction force
is strong ~~attrac~~ nuclear force

Question: Draw a rough graph of potential energy U(r) versus the nucleons' separation distance r for p-p and n-p interactions. Indicate on the graph the nuclear attractive force, nuclear repulsive force, and Coulomb repulsive forces

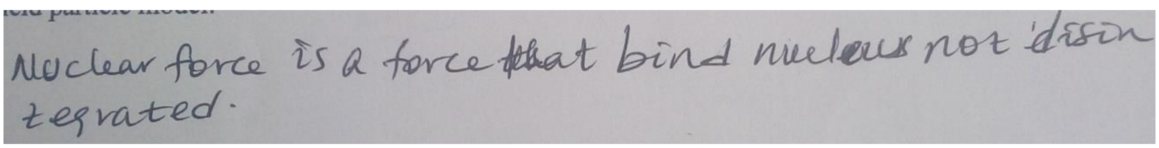
Student S_{28}*:* The student responded as follows to the question:



At delayed post-intervention:

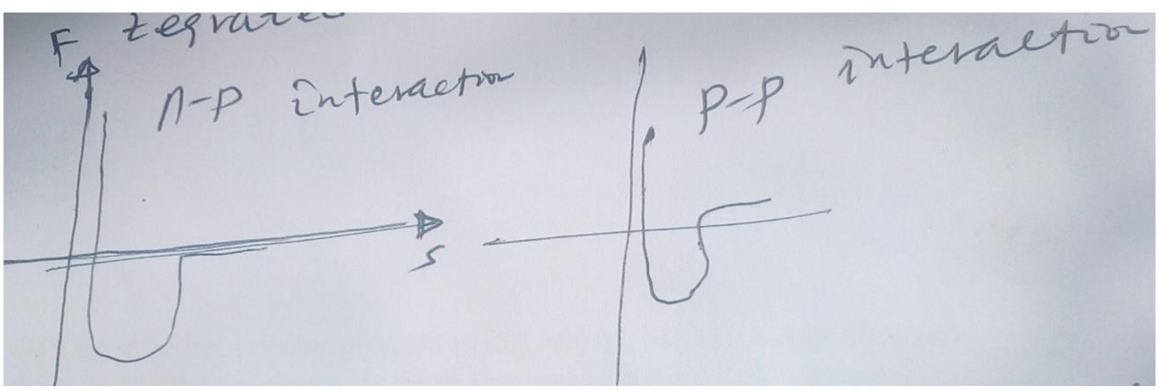
Question: Define and describe the strong nuclear force using text

Student S_{28}*:* The student responded as follows to the question:


Nuclear force is a force that bind nuclous not disin tegrated.

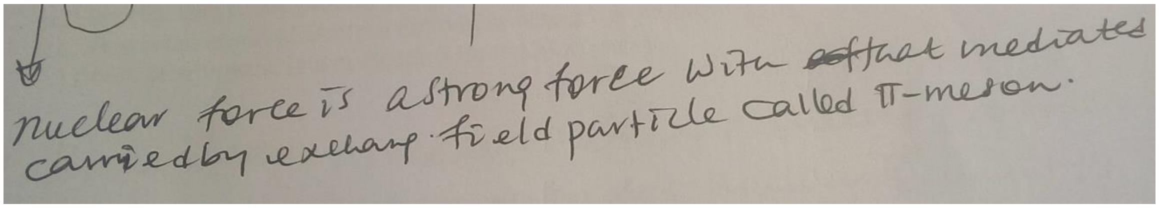
Question: Draw a rough graph of potential energy U(r) versus the nucleons' separation distance r for p-p and n-p interactions. Indicate on the graph the nuclear attractive force, nuclear repulsive force, and Coulomb repulsive forces

Student S_{28}*:* The student responded as follows to the question:



Question: Describe the strong nuclear force based on the exchange-force model (field particle exchange model)

Student S_{28} *:* The student responded as follows to the question:



nuclear force is astrong force With ~~of~~ that mediates carriedby exchang. field particle called π-meson.

Table 6.2: Students' categories of description of nuclear force at pre-, post-, and delayed post-intervention

Categories of description	**Pre-Intervention N = 40**		**Post-Intervention N = 40**		**Delayed Post-intervention N = 40**	
I. CA in codes	NS	Ns in %	NS	NS in %	NS	NS in %
A	6	15	23	57.5	18	45
B	7	17.5	22	55	18	45
C	0	0	16	40	12	30
D	0	0	1	2.5	4	10
II. IA in codes						
E	1	2.5	0	0	0	0
F	1	2.5	3	7.5	0	0
G	0	0	0	0	3	7.5
H	0	0	1	2.5	0	0
III. Non-respondent students	27	67.5	5	12.5	7	17.5
MRs used by students						
Figure 4.5, 4.6 for B	0	0	19	47.5	16	40

The results presented in Table 6.2 are illustrated in the bar chart (Figure 6.2) in the next Section. Critical aspect A was discerned by 6, 23, and 18 students respectively at pre-, post-, and delayed post-intervention. Critical aspect A represents the students' conceptual understanding of the nuclear force, namely:

> *The strong nuclear force is the force that binds nucleons to form the nucleus of an atom.*

This is one of the critical aspects of the strong nuclear force discerned by students. It is possible to state the other critical and IA in the same way.

6.3.2 Discussion on the Categories of Description of Nuclear Force

The bar chart in Figure 6.2 illustrates the results presented in Table 6.2. The overall results indicated that the intervention was effective in addressing the students' conceptual difficulties of nuclear force. This was determined based on Figure 6.2 and the criteria outlined in Section 6.1. For instance, critical aspect A discerned by 6, 23, and 18 students respectively at pre-, post-, and delayed post-intervention. This indicated the effectiveness of the intervention based on the first criteria. Table 6.2 indicated that 0, 19, and 16 students respectively at pre-, post-, and delayed post-intervention used Figure 4.5, 46 to visualise and understand the short-range property of nuclear force, which is critical aspect B. This also indicated the effectiveness of the intervention based on the fifth criteria.

The results presented in Table 6.2 indicated that 16 students at post-intervention described nuclear force based on the exchange-force model, which is critical aspect C. The students at post- and delayed post-intervention did not discern the irrelevant aspect E. However, a very small NS discerned the other IA. This indicated the effectiveness of the intervention. Figure 6.2 also indicated that there were 27, 5, and 7 non-respondent students at pre-, post-, and delayed post-intervention. Again, this indicated the effectiveness of the intervention. In general, based on the fifth criteria, most of the students did retain their conceptual understanding and representational competence of nuclear force at eight weeks delayed post-intervention (see Table 6.3).

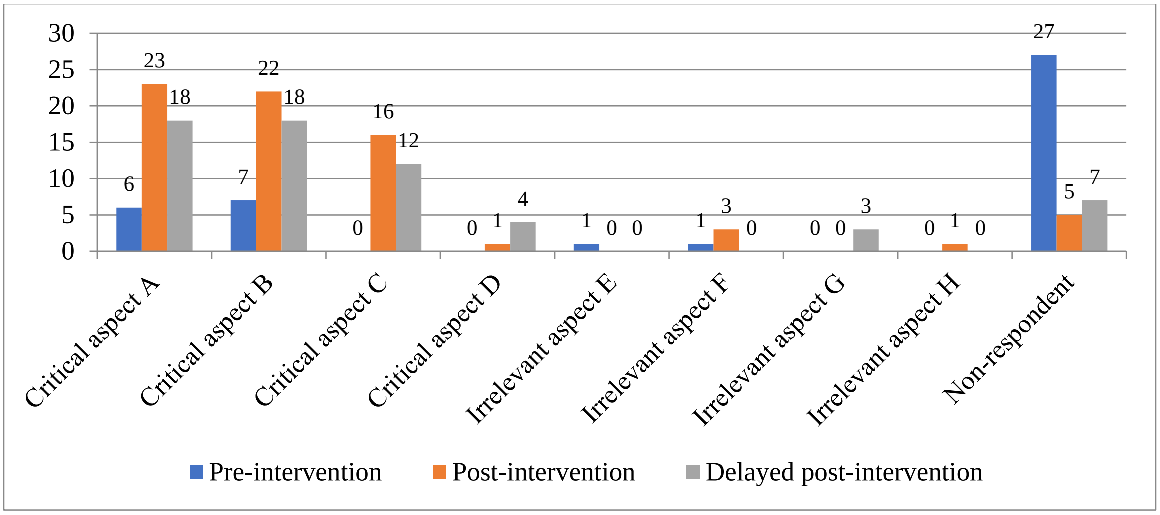


Figure 6.2: Critical and IA of nuclear force and non-respondent students at pre-, post-, and delayed post-intervention

The conceptual difficulties of nuclear force identified in the first phase in Section 4.7.2 were addressed by using the intervention. Only a few students discerned IA after the intervention. This means the intervention played a role in eliminating the students' misconceptions of nuclear force. In the case of nuclear force, the students used Figures 4.5, 4.6, and the exchange-force model in addition to written text to represent its critical aspects. The summary was given to the students using the concept map (Figure 5.9) constructed by the researcher also supported the students to have a complete conceptual understanding of the nuclear force.

The MRs supported the students to discern the different aspects of a nuclear force. The MRs-based instruction with interactive learning tutorials designed based on the VTL to make the learning of nuclear force possible. This phenomenographic instruction (see Section 2.10) was not used by previous researchers to address the conceptual difficulties of nuclear force. The findings shown in the literature review showed that guided-inquiry-based instruction was used in supporting students to gain knowledge of weak and strong nuclear forces (Shakya, 2015). This instruction was based on constructivist learning theory. It was not effective in supporting the undergraduate students in gaining knowledge of the weak and strong nuclear forces.

6.4 CATEGORISATION AND CODING OF STUDENTS' UNDERSTANDING AND REPRESENTATIONS OF THE CONCEPT OF RADIOACTIVE DECAY AT PRE-, POST-, AND DELAYED POST-INTERVENTION

6.4.1 Categories of Description of the Radioactive Decay

The responses of 40 students to the open-ended questionnaire about radioactive decay at pre-, post-, and delayed post-intervention were analysed. Based on the results, the following different ways of students' conceptual understanding of radioactive decay were identified. An example of the analysis process of the three students' responses to the open-ended questionnaire about radioactive is available in Appendix VIII.

I. The critical aspect of radioactive decay law discerned by students

   A. The number of radioactive nuclei remaining in a decaying radioactive substance exponentially decreases in time
   B. The half-life of a radioactive substance is the time required for half of the original number of radioactive nuclei in it to decay
   C. The number of nuclei that have decayed in a decaying radioactive substance logarithmically increases in time

II. No IA of radioactive decay law discerned by students

III. Non-respondent students: They are students who did not respond at all to the open-ended NPCIQ

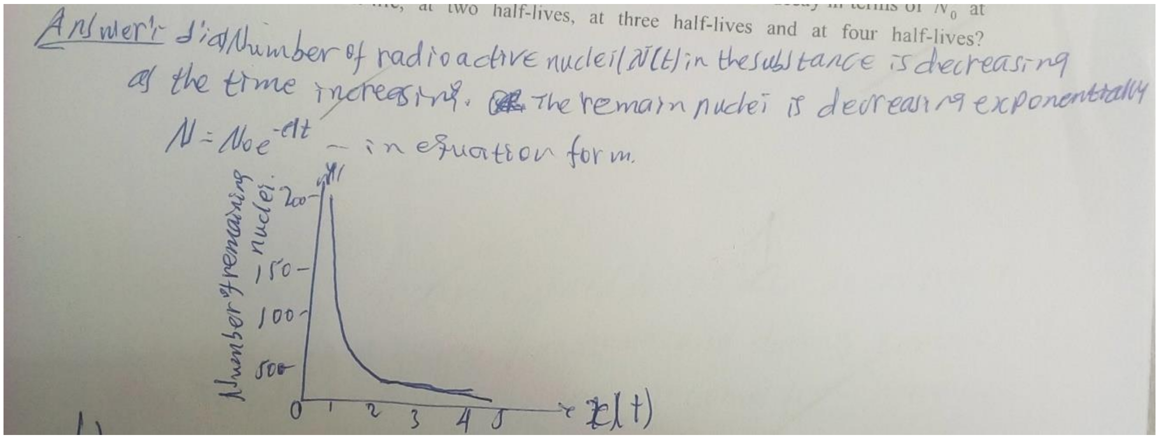
The illustrative excerpts of the responses of a student to the open-ended questionnaire associated with radioactive decay are presented as follows to support these categories of description.

At pre-intervention: No response

At post-intervention:

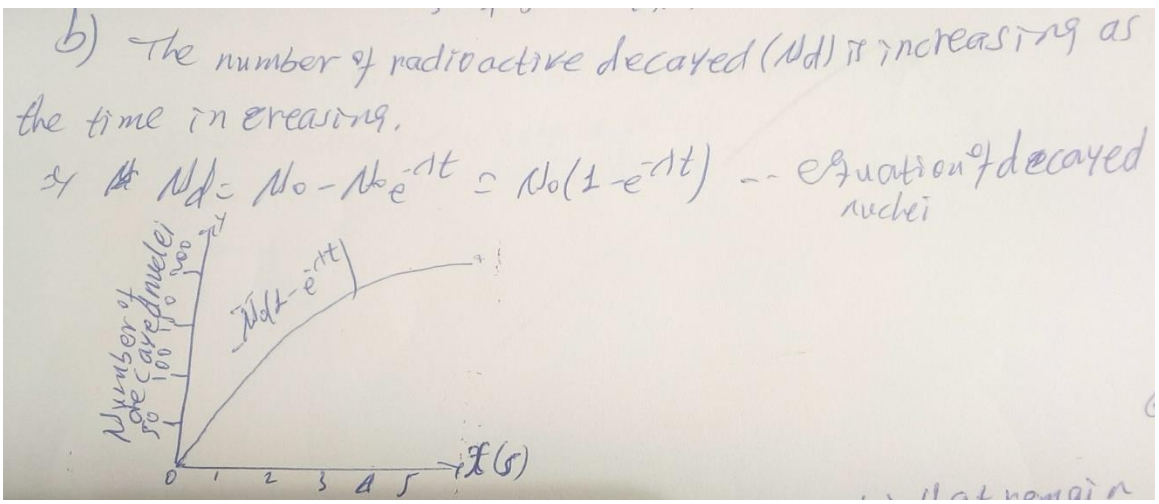
Question: How does the number of radioactive nuclei present in a radioactive substance change in time? Describe your answer using text, an equation, a graph, and a diagram

Student S_{32} *:* The student responded as follows to the question (Category A):



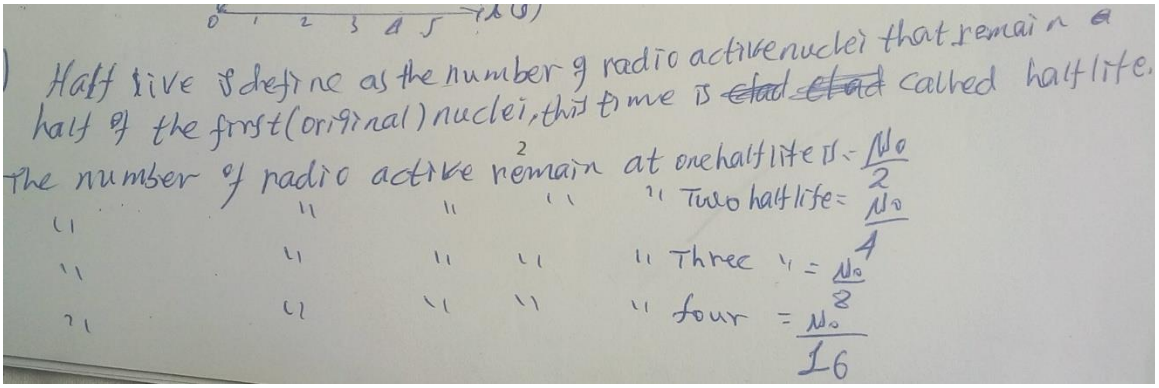
Question: How does the number of nuclei that have decayed in a radioactive substance change in time? Describe your answer using text, an equation, a graph, and a diagram

Student S_{32} *:* The student responded as follows to the question (Category C):



Question: Describe the half-life of the radioactive substance; using text, an equation, and a diagram. What is the number of radioactive nuclei remaining in a radioactive substance in terms of the original number at two and three half-lives?

Student S_{32} *:* The student responded as follows to the question (Category B):

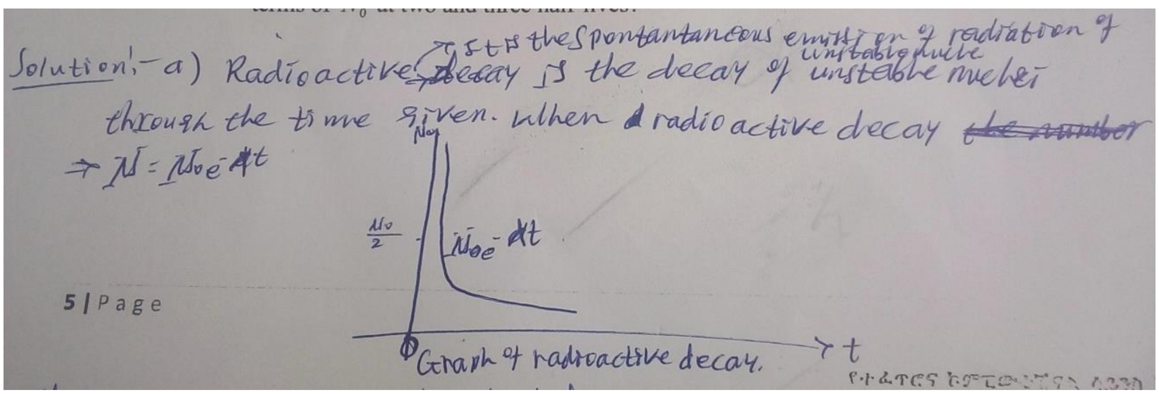


Half live is define as the number of radio active nuclei that remain a half of the first (original) nuclei, this time is called half life.
the number of radio active remain at one half life is = No/2
" " " " " Two half life = No/4
" " " " " Three " = No/8
" " " " " four = No/16

At delayed post-intervention:

Question: How does the number of radioactive nuclei present in a radioactive substance change in time? Describe your answer using text, an equation, a graph, and a diagram.

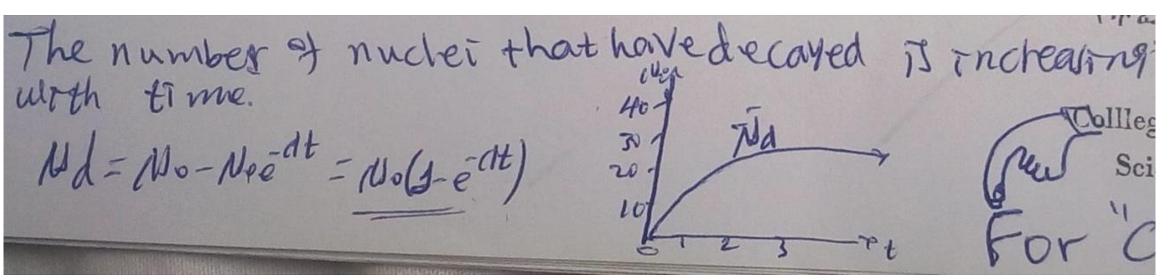
Student S_{32} *:* The student responded as follows to the question (Category A):



Solution:- a) Radioactive decay is the decay of unstable nuclei through the time given. when radio active decay → it is the spontaneous emission of radiation of unstable nuclei
→ N = Noe^-λt

Question: How does the number of nuclei that have decayed in a radioactive substance change in time? Describe your answer using text, an equation, a graph, and a diagram

Student S_{32} *:* The student responded as follows to the question (Category C):



The number of nuclei that have decayed is increasing with time.
Nd = No − Noe^-λt = No(1 − e^-λt)

Question: Describe the half-life of the radioactive substance; using text, an equation, and a diagram.

Student S_{32} *:* The student responded as follows to the question (Category B):

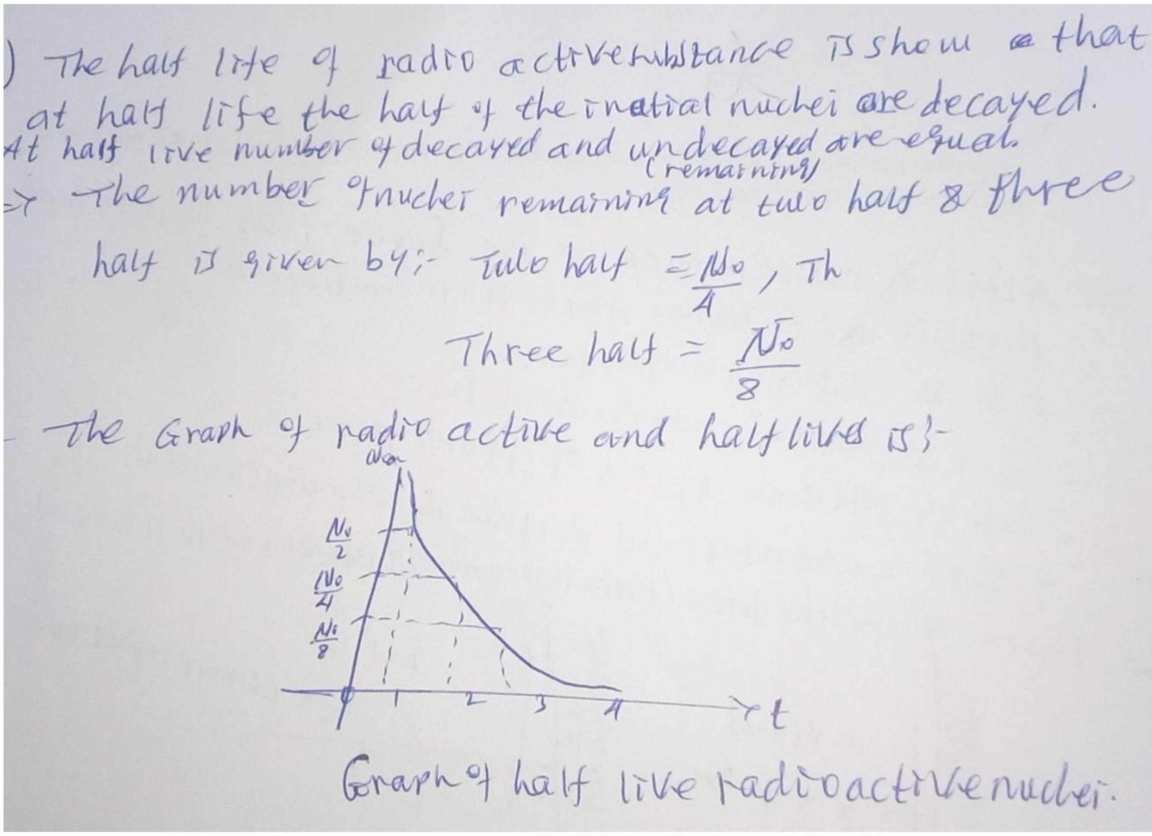


Table 6.3: Students' categories of description of radioactive decay law at pre-, post-, and delayed post-intervention

Codes of categories of description	**Pre-Intervention N = 40**		**Post-Intervention N = 40**		**Delayed Post-intervention N = 40**	
I. CA in codes	NS	NS in %	NS	NS in %	NS	NS in %
A	9	22.5	27	67.5	19	47.5
B	5	12.5	22	55	9	22.5
C	0	0	18	45	12	30
II. IA codes	0	0	0	0	0	0
III. Non-respondent students	24	60	6	15	8	20

Codes of categories of description	Pre-Intervention N = 40		Post-Intervention N = 40		Delayed Post-intervention N = 40	
IV. MRs used by students						
Eq.2.2 for A	5	12.5	21	52.5	8	20
Figure 4.4 for A	1	2.5	27	67.5	10	25
Eq.4.8 for B	3	7.5	14	35	3	7.5
Figure 5.10 for B	0	0	4	10	5	12.5
Eq.4.6 for C	0	0	17	42.5	11	27.5
Figure 4.6 for C	0	0	16	40	10	25

6.4.2 Discussion on Categories of Description of Radioactive Decay

The bar chart in Figure 6.3 illustrates the results presented in Table 6.3. The overall results indicated that the intervention was effective in addressing the students' conceptual difficulties of radioactive decay. This was determined based on Figure 6.3 and the criteria outlined in Section 6.1. For instance, critical aspect A discerned by 9, 27, and 19 students respectively at pre-, post-, and delayed post-intervention. This indicated the effectiveness of the intervention. Students used different forms of representations in addition to written text to describe the concept of radioactive decay. Table 6.3 indicated that1, 27, and 10 students respectively at pre-, post-, and delayed post-intervention used Figure 4.8 to visualise and understand the radioactive decay law (critical aspect A). This also indicated the effectiveness of the intervention even though all 27 students did not retain their representational competence. However, all students who used Figure 5.10 retained this in the delayed post-intervention as indicated in Table 6.3.

> *The NS who discerned critical aspect B decreased from 22 at post-to nine at eight weeks delayed post-intervention. This means the NS retaining discerning critical aspect B of radioactive decay in the delayed post-intervention decreased.*

Table 6.3 indicated that more students used equations and figures to represent critical aspects of radioactive decay at post-intervention than at pre-intervention. The figures and equations used by students supported them to discern the different critical aspects of radioactive decay. No student discerned the IA of radioactive decay after the intervention, which indicates the effectiveness of the intervention. Figure 6.3 also indicated that the number of non-respondent students was 24, 6, and 8 respectively at pre-, post-, and delayed post-intervention. Again, this indicated the effectiveness of the intervention. The MRs-based instruction with interactive nuclear physics learning tutorial was the instructional strategy used for intervention in this study.

The conceptual difficulties of radioactive decay identified in the first phase in Section 4.7.3 were addressed using the instructional intervention. That is a small NS discerned IA of radioactive decay after the intervention. The intervention played a role in eliminating the students' misconceptions of radioactive decay. In other words, the intervention supported the students to develop their conceptual understanding of radioactive decay. Especially, the different forms of representations used by the students supported them to understand the concept of radioactive decay. The students performed the interactive simulations of radioactive decay indicated in Figures 5.11 and 5.12. This supported the students in visualising and understanding how the number of radioactive nuclei remaining in a radioactive substance and the number of nuclei that have decayed change in time (critical aspect A and C). The students illustrated the difference between these two critical aspects of radioactive decay using Figures4.8 and 4.10. One cannot separate critical aspects A and C in the discussion, as one is the inverse of the other. The summary and given to the students using the concept map (Figure 5.13) constructed by the researcher also supported the students to develop their conceptual understanding of radioactive decay.

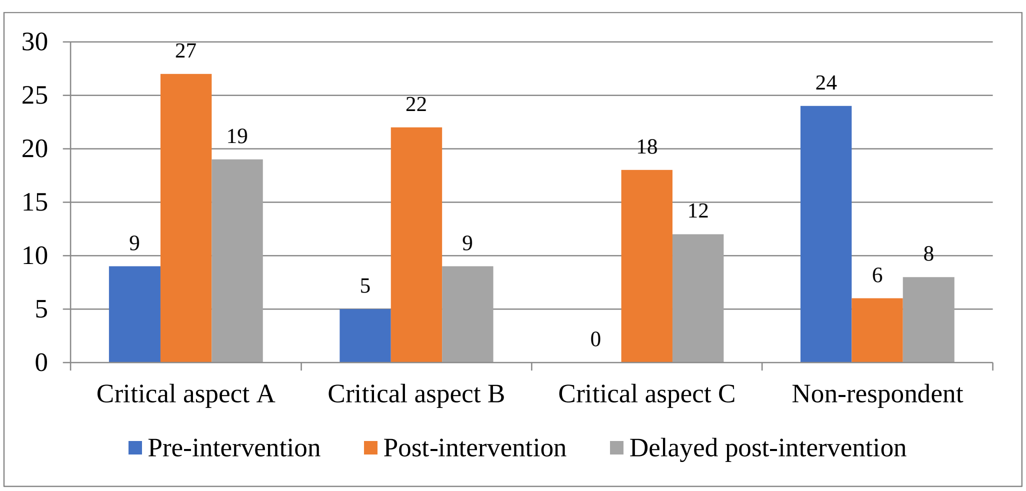


Figure 6.3: Critical and IA of radioactive decay and non-respondent students at pre-, post-, and delayed post-intervention

In the case of radioactive decay, the written text, the equations, graphs, and the interactive simulations complemented each other. The MRs-based instruction with interactive nuclear physics learning tutorials was based on the VTL. This is commonly known as a phenomenographic instruction (see Section 2.10). This instructional strategy was not used by previous nuclear physics education researchers to address the conceptual difficulties of radioactive decay. The findings released in the literature showed that the laboratory modelling activity (Yeşiloğlu, 2019) and modelling instruction (Bakaç et al., 2011) were used to address the conceptual difficulties of radioactive decay. The laboratory modelling activity played a great role in eliminating the pre-service teachers' misconceptions of radioactive decay. The school students were enabled to better understand the concept of radioactive decay by reifying it through modelling instruction. These instructions were based on constructivist learning theory. Therefore, the phenomenographic instruction used in this study is considered an effective alternative instruction method to address the conceptual difficulties of radioactive decay.

6.5 COLLECTIVE CATEGORISATION AND CODING OF STUDENTS' UNDERSTANDING AND REPRESENTATIONS OF THE CONCEPT OF NBD AT PRE-, POST-, AND DELAYED POST-INTERVENTION

6.5.1 Categories of Description of the NBD

The responses of 40 students to the open-ended questionnaire about the concept of NBD at pre-, post-, and delayed post-intervention were analysed. Based on the results, the following different ways of students' conceptual understanding of NBD were identified. An example of the analysis process of the three students' responses to the open-ended questionnaire about NBD is available in Appendix VIII.

I. The critical aspect of the NBD discerned by students: The students understood that the NBD is the decay process in which:
   A. an electron and electron-antineutrino are emitted
   B. the atomic number increases by one and the mass number remain the same
   C. the origin of the emitted electron and electron-antineutrino is the neutron in the parent nucleus

D. the emitted electron and electron-antineutrino do not exist in the nucleus before decay but are created at the moment of decay

E. the emitted electron is created out of the nuclear rest energy

II. The IA of NBD discerned by students

F. Atomic electron is the origin of the electron emitted in the beta decay process

G. The proton in the parent nucleus is the origin of the electron emitted in the NBD process

H. The electron emitted in the beta decay process exists in the nucleus before the beta decay process

III. Non-respondent students: They are students who did not respond at all to the open-ended NPCIQ about NBD.

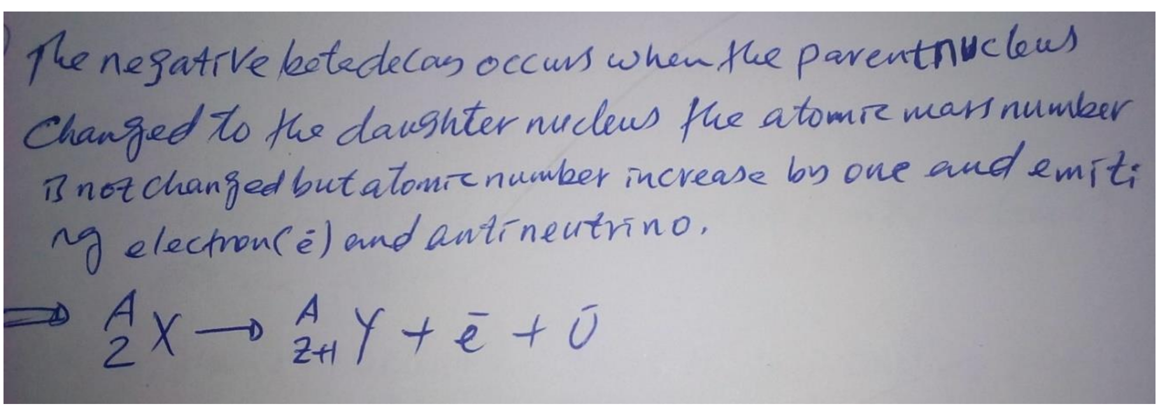
The illustrative excerpts of the responses of a student to the open-ended questionnaire associated with NBD are presented as follows to support these categories of description.

At pre-intervention: No response

At post-intervention:

Question: Describe the NBD process using text and an equation.

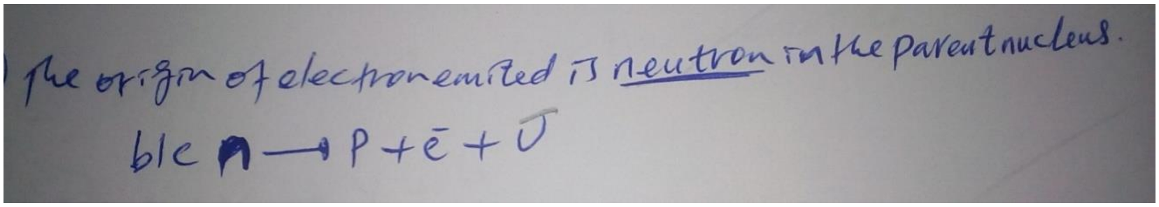
Student S_{18}*:* The student responded as follows to the question (Categories A and B):


The negative betedecay occurs when the parent nucleus Changed to the daughter nucleus the atomic mass number is not changed but atomic number increase by one and emiting electron(ē) and antineutrino.

$$\Rightarrow {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \bar{e} + \bar{\upsilon}$$

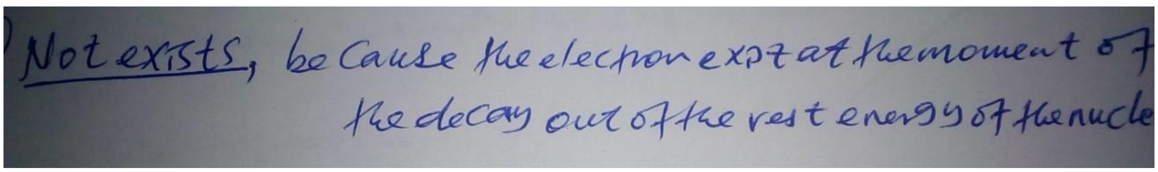
Question: What is the origin of the electron emitted in the beta decay process?

Student S_{18}*:* The student responded as follows to the question (Category C):



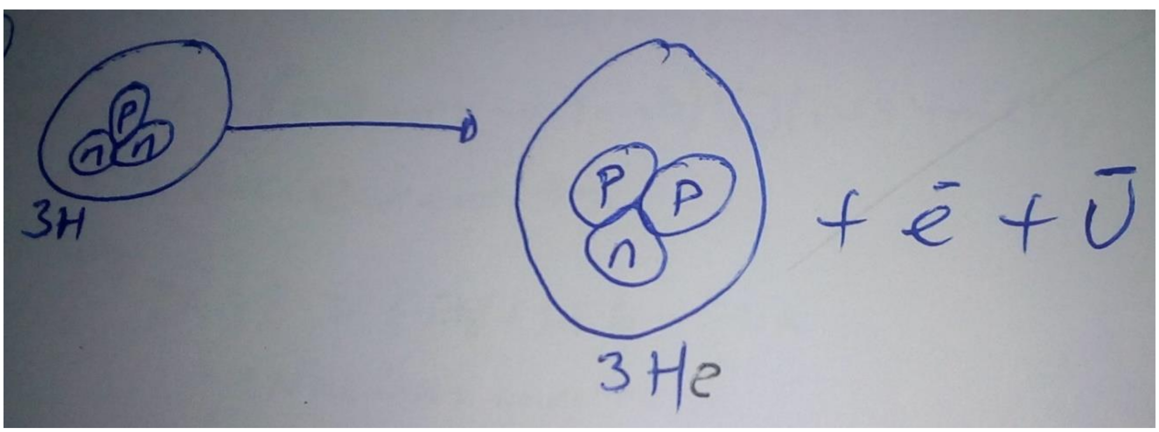
Question: Does the electron emitted in the beta decay process exist in the nucleus before decay? Explain the reason for your answer.

Student S_{18}*:* The student responded as follows to the question (Categories D and E):



Question: Describe the NBD process based on the decay of hydrogen-3 into helium-3 using a diagram.

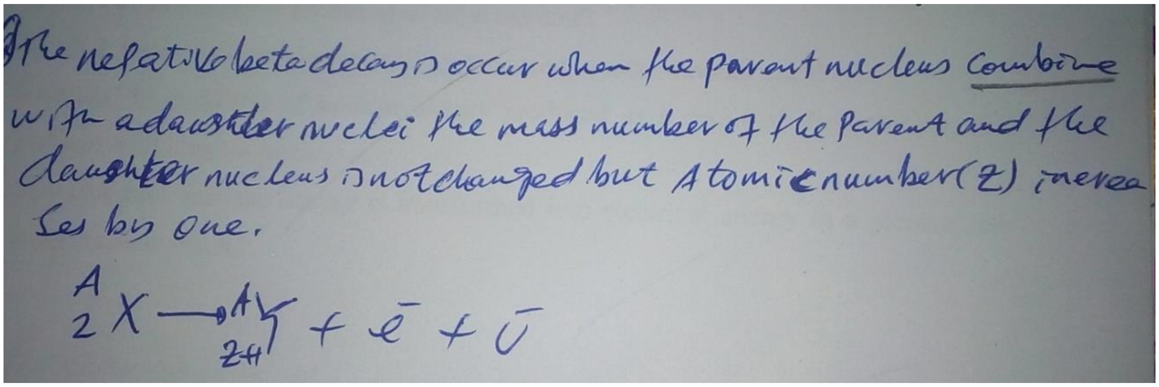
Student S_{18}*:* The student responded as follows to the question (Categories A and C):



At delayed post-intervention:

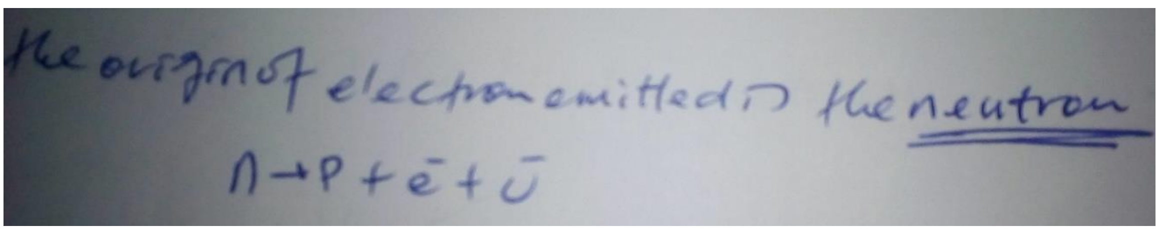
Question: Describe the NBD process using text and an equation.

Student S_{18}*:* The student responded as follows to the question belongs to (Categories A and B):



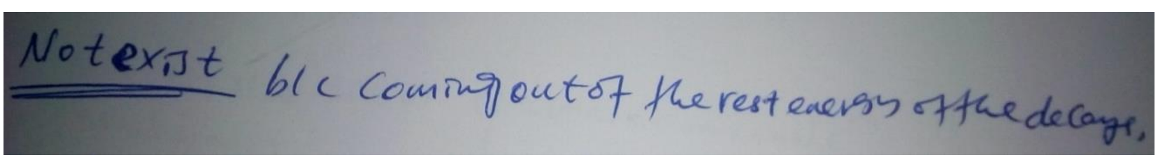
Question: What is the origin of the electron emitted in the beta decay process?

Student S_{18}*:* The student responded as follows to the question (Category C):



Question: Does the electron emitted in the beta decay process exist in the nucleus before decay? Explain the reason for your answer.

Student S_{18}*:* The student responded as follows to the question (Categories D and E):



Question: Describe the NBD process based on the decay of hydrogen-3 into helium-3 using a diagram.

Student S_{18}*:* The student responded as follows to the question (Categories A and C):

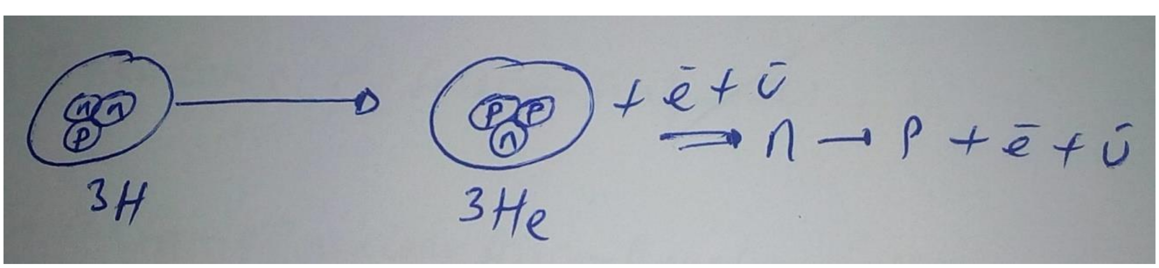


Table 6.4: Students' categories of description of NBD at pre-, post-, and delayed post-intervention

Categories of description	Pre-Intervention N = 40		Post-Intervention N = 40		Delayed Post-intervention N = 40	
I. CA in codes	NS	NS in %	NS	NS in %	NS	NS in %
A	5	12.5	18	45	18	45
B	1	2.5	9	22.5	7	17.5
C	0	0	18	45	20	50
D	3	7.5	16	40	22	55
E	2	5	3	7.5	1	2.5
II. IA in codes						
F	2	5	0	0	0	0
G	0	0	2	5	4	10
H	1	2.5	4	10	1	2.5
III. Non-respondent students	26	65	6	15	11	27.5
IV. MRs used by students						
Eq.2.4 for A	1	2.5	18	45	19	47.5
Eq.4.12 for A	3	7.5	2	5	4	10
Eq.4.16 for A & C	0	0	6	15	5	12.5
Figure 5.15 for A & C	0	0	12	30	5	12.5

6.5.2 Discussion on Categories of Description of NBD

The bar chart in Figure 6.4 illustrates the results presented in Table 6.4. The overall results indicated that the intervention was effective in addressing the students' conceptual difficulties of NBD. This was determined based on Figure 6.4 and the criteria outlined in Section 6.1. For instance, critical aspect A discerned by 5, 18, and 18 students respectively at pre-, post-, and delayed post-intervention. This indicated the effectiveness of the intervention based on the first criteria. Students used different forms of representations in addition to written text to describe NBD. Table 6.4 indicated that1, 18, and 19 students respectively at pre-, post-, and delayed post-intervention used Equation

2.4 to express critical aspect A. This also indicated the effectiveness of the intervention based on the fifth criteria.

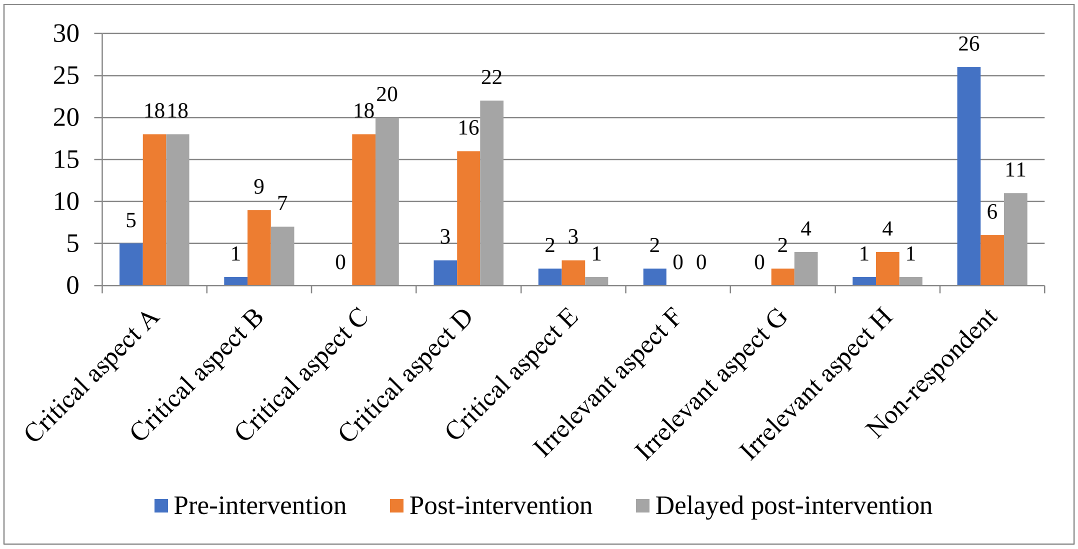


Figure 6.4: Critical and IA of NBD and non-respondent students at pre-, post-, and delayed post-intervention

Table 6.4 indicated that the NS who used Figure 5.15 to represent critical aspects A and C decreased from 12 at post-intervention to 5 at eight weeks delayed post-intervention. This showed that12 students did not retain their representational competence of using Figure 5.15.

Except for Figure 5.15, the equations and figures presented in Table 6.4 effectively supported the students to visualise and understand the concept of NBD by discerning its different CAs. The students at post- and delayed post-intervention did not discern the irrelevant aspect F. The other IA's were discerned by very few NS at post- and delayed post-intervention. Figure 6.4 also indicated that 26, 6, and 11 were the non-respondent students at pre-, post-, and delayed post-intervention. Again, this indicated the effectiveness of the intervention.

The results of this study indicated that the conceptual difficulties of NBD identified in Section 4.7.4 were addressed by using the intervention; i.e., a small NS discerned IA after the intervention. This means, the intervention played a role in eliminating the students' misconceptions of NBD and then supporting them to develop their scientific understanding. The students used equations and figures indicated in Table 6.4 in addition to written text to represent the concept of NBD. The students also performed interactive simulations of negative decay indicated in Figure 5.12 and this supported the students to visualise and understand how hydrogen-3 decayed into helium-3, electron, and an antineutrino. From this simulation, the students understood that the neutron in the parent nucleus decayed into protons, electrons, and antineutrinos. Table 6.4 indicated that 12 students at post-intervention and five students at delayed post-intervention used the diagram shown in Figure 5.15 to visualise and understand the NBD process. This diagram and the interactive simulation complement each other in visualising critical aspects A and C. Seven students did not retain their representational competence in this way. The summary was given to the students using the concept map (Figure 5.16) constructed by the researcher also supported the students to develop their conceptual understanding of NBD.

The MRs supported the students to discern the various critical aspect of the concept of NBD. The MRs-based instruction with interactive learning tutorials designed based on the VTL could make the learning of NBD possible. This effective phenomenographic instruction (see Section 2.10.) had not been used in previous studies to address the conceptual difficulties of NBD. Besides, no evidence had been found concerning the conduction of research to address the conceptual difficulties of NBD using any other instructions.

6.6 COLLECTIVE CATEGORISATION AND CODING OF STUDENTS' UNDERSTANDING AND REPRESENTATIONS OF THE CONCEPT OF NE AT PRE-, POST-, AND DELAYED POST-INTERVENTION

6.6.1 Categories of the Description of NE

The responses of 40 students to the open-ended questionnaire about the concept of NE at pre-, post-, and delayed post-intervention were analysed. Based on the analysis, the following different ways of students' conceptual understanding of NE were identified. An example of the analysis process of the three students' responses to the open-ended questionnaire about NE is available in Appendix VIII.

I. The critical aspect of NE discerned by participants

A. The energy reserved in the nucleus of an atom

B. The energy released from the nucleus of an atom at the moment of nuclear reaction

C. The energy created out of the nuclear rest mass at the moment of nuclear reaction

D. The energy that exists in the form of the kinetic energies of the fission fragments

E. The form of energy that can be transformed into electrical energy in a nuclear reactor

II. The IA of NE discerned by participants

F. The energy that binds the nucleons in the nucleus

G. The energy released in a chemical reaction

III. Non-respondent students: They are students who did not respond at all to the open-ended NPCIQ

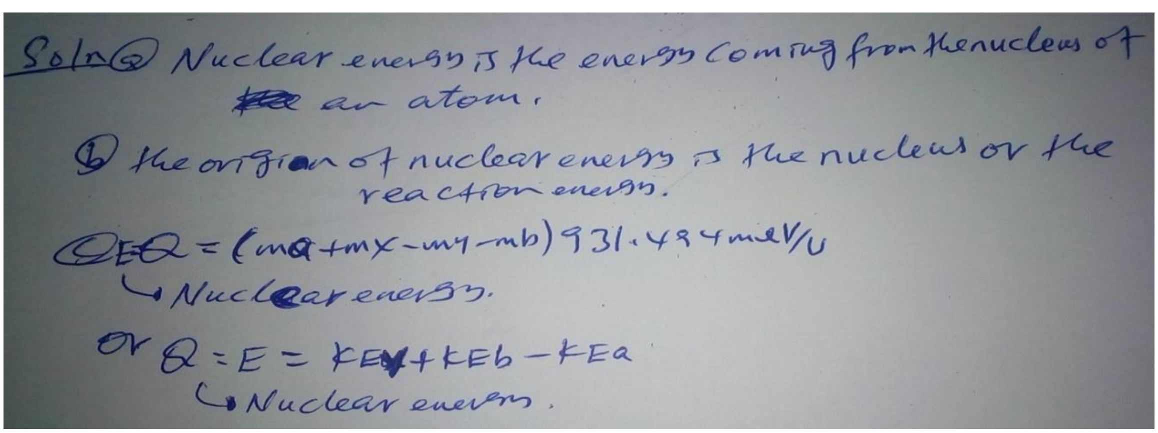
The illustrative excerpts of the responses of a student to the open-ended questionnaire associated with NE are presented as follows to support these categories of description.

At pre-intervention: No response

At post-intervention:

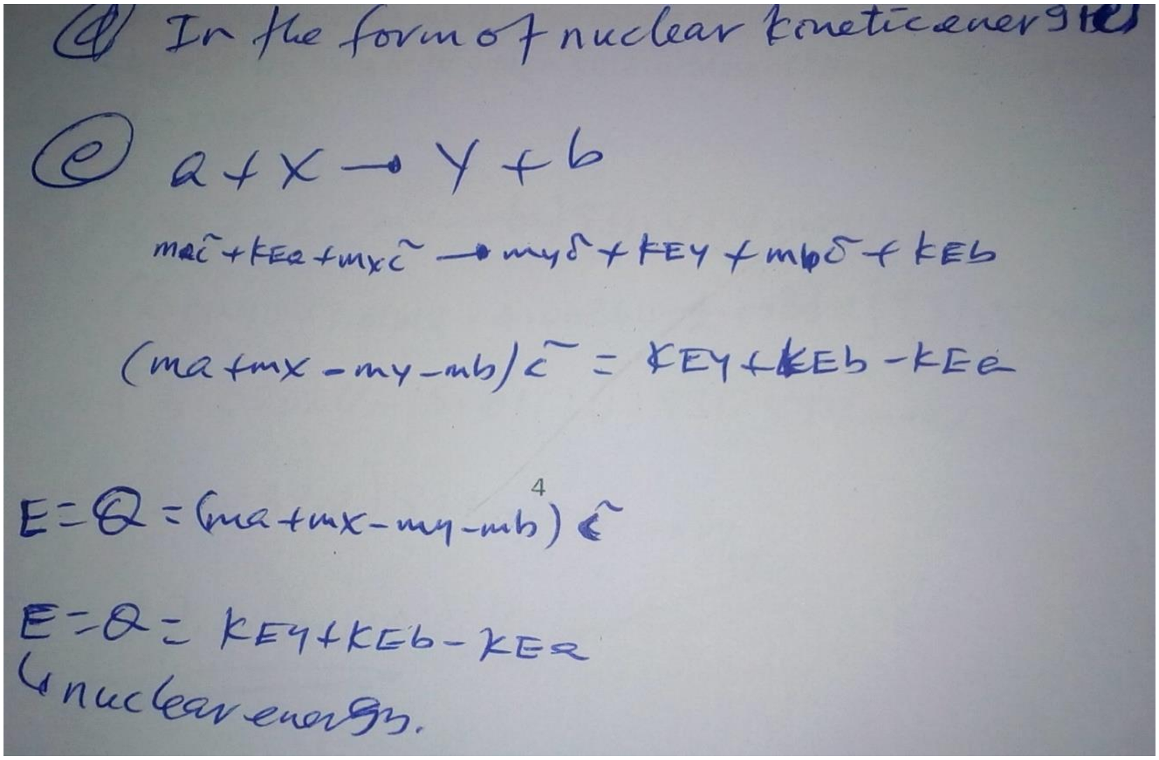
Question: Define NE.

Student S_{18}: The student responded as follows to the question (Categories A, C, and D):


Soln (a) Nuclear energy is the energy coming from the nucleus of an atom.
(b) the origin of nuclear energy is the nucleus or the reaction energy.
(c) $E_Q = (m_a + m_x - m_y - m_b)\,931.494\ \text{meV/u}$
↳ Nuclear energy.
or $Q = E = KE_y + KE_b - KE_a$
↳ Nuclear energy.

Question: In what form does the NE release in the fission of a nucleus exist?

Student S_{18}*:* The student responded as follows to the question (Category D):



(d) In the form of nuclear kinetic energies

(e) $a + X \rightarrow Y + b$

$m_a c^2 + KE_a + m_X c^2 \rightarrow m_Y c^2 + KE_Y + m_b c^2 + KE_b$

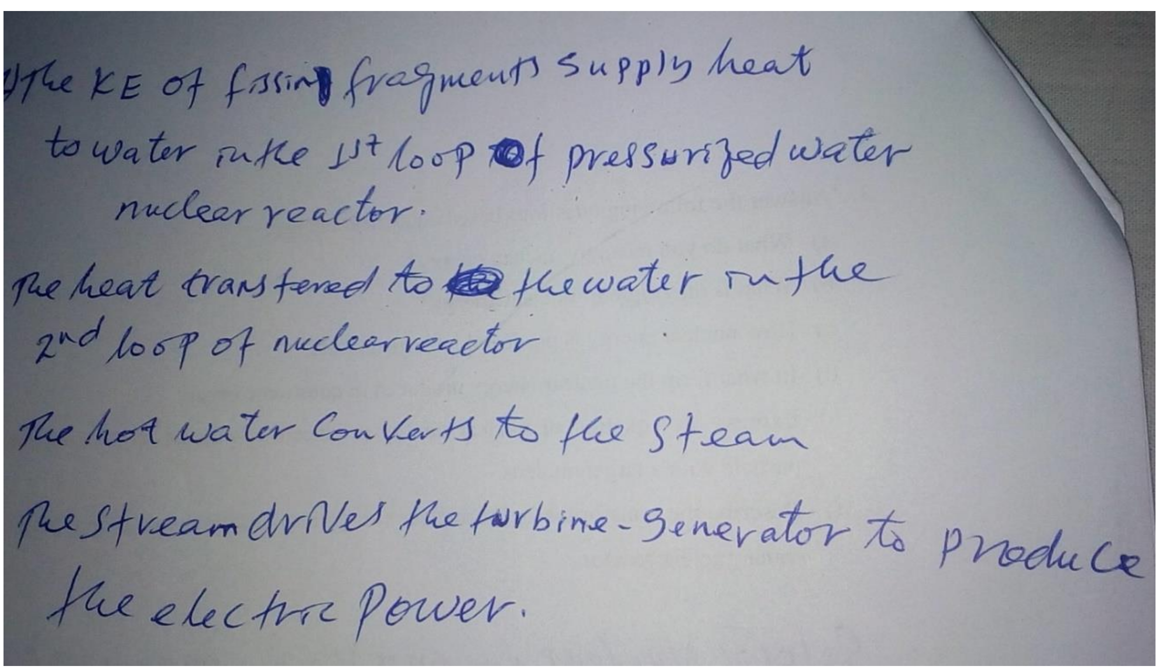
$(m_a + m_X - m_Y - m_b)c^2 = KE_Y + KE_b - KE_a$

$E = Q = (m_a + m_X - m_Y - m_b)c^2$

$E = Q = KE_Y + KE_b - KE_a$

↳ nuclear energy.

In addition, this student attempted to describe how NE is converted to electricity. This belongs to Category E.



1) The KE of fissing fragments supply heat to water in the 1st loop of pressurized water nuclear reactor.

The heat transfered to the water in the 2nd loop of nuclear reactor

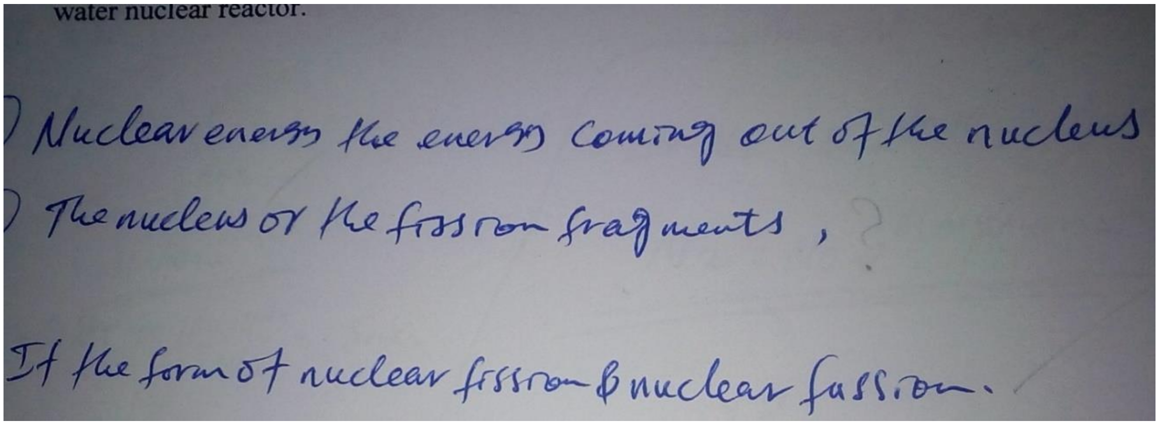
The hot water converts to the steam

The stream drives the turbine-generator to produce the electric power.

At delayed post-intervention:

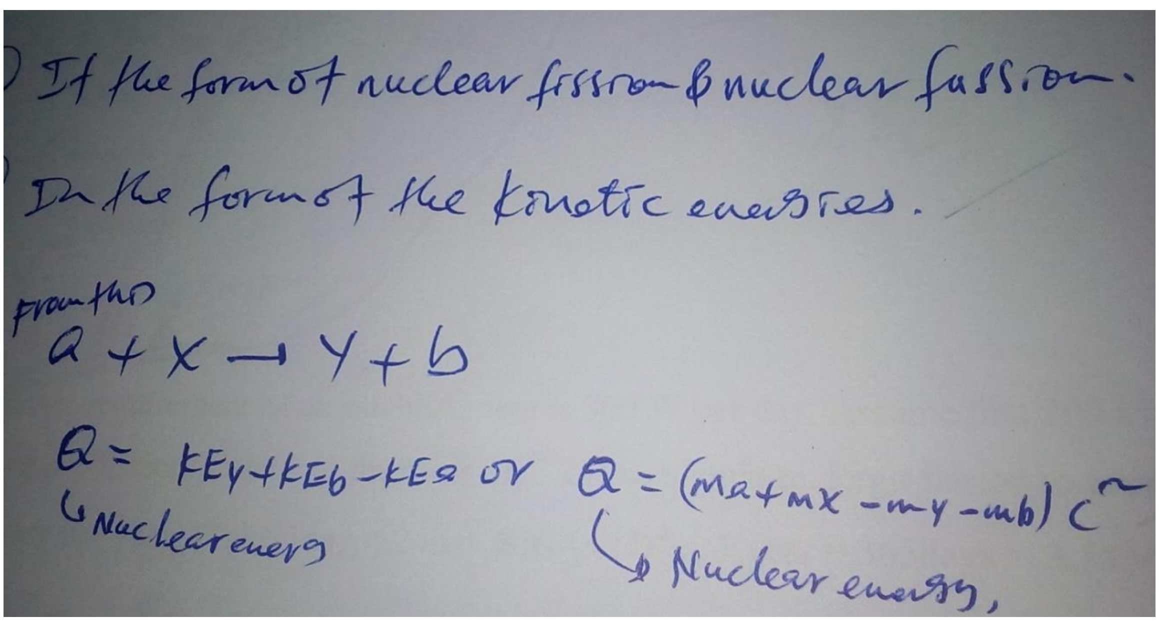
Question: Define NE.

Student S_{18}*:* The student responded as follows to the question (Categories A and B):



Question: In what form, does the NE released in the fission of a nucleus exist?

Student S_{18}*:* The student responded as follows to the question (Category D):



At delayed post-intervention also this student was attempted to describe how NE is converted to electricity. It belongs to Category E.

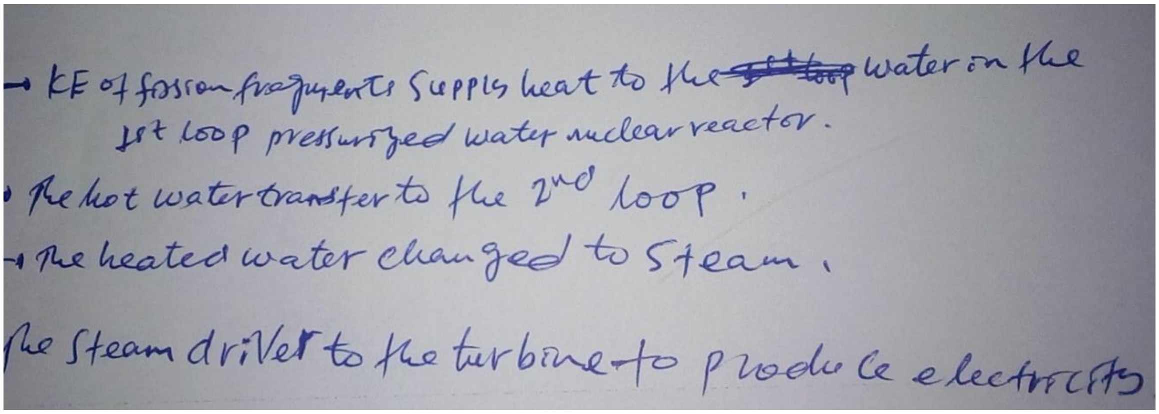

→ KE of fission fragments supply heat to the water on the 1st loop pressurized water nuclear reactor.
• The hot water transfer to the 2nd loop.
→ The heated water changed to steam.
The steam driven to the turbine to produce electricity

Table 6.5: Students' categories of description of NE at pre-, post-, and delayed post-intervention

I. Codes of categories of description	Pre-Intervention N = 40		Post-Intervention N = 40		Delayed Post-intervention N = 40	
Critical aspects in codes	NS	NS in %	NS	NS in %	NS	NS in %
A	4	10	11	27.5	9	22.5
B	9	22.5	15	37.5	12	30
C	0	0	7	17.5	5	12.5
D	0	0	16	40	12	30
E	1	2.5	6	15	7	17.5
Irrelevant aspects in codes						
F	2	5	0	0	2	5
G	1	2.5	0	0	0	0
II. Non-respondent students	24	60	9	22.5	18	45
III. MRs used by students						
Equa.4.4 for B & C	0	0	11	27.5	9	22.5
Equa.5.6 for D	0	0	7	17.5	4	10
Figure 5.17 for D	0	0	2	5	1	2.5
Figure 5.19 for E	0	0	6	15	7	17.5

The results presented in Table 6.5 are illustrated and discussed using the bar chart indicated in Figure 6.5 in the next Section.

6.6.2 Discussion on Categories of Description of the NE

The bar chart in Figure 6.5 illustrates the results presented in Table 6.5. The overall results indicated that the intervention was effective in addressing the students' conceptual difficulties of NE. This was determined based on Figure 6.5 and the criteria outlined in Section 6.1. For instance, critical aspect A discerned by 9, 15, and 12 students at pre-, post-, and delayed post-intervention, respectively. This indicated the effectiveness of the intervention based on the first criteria. Students used other forms of representations in addition to written text to describe NE. Table 6.5 indicated that 0, 11, and 9 students at pre-, post-, and delayed post-intervention respectively used Equation 4.4 to express critical aspects B and C. This also indicated the effectiveness of the intervention based on the fifth criteria. The NS using Figure 5.19 to represent critical aspect E at pre-, post-, and delayed post-intervention respectively is zero, six, and seven. That is, the students described NE as the form of energy that can transform into electrical energy in a nuclear reactor using Figure 5.19.

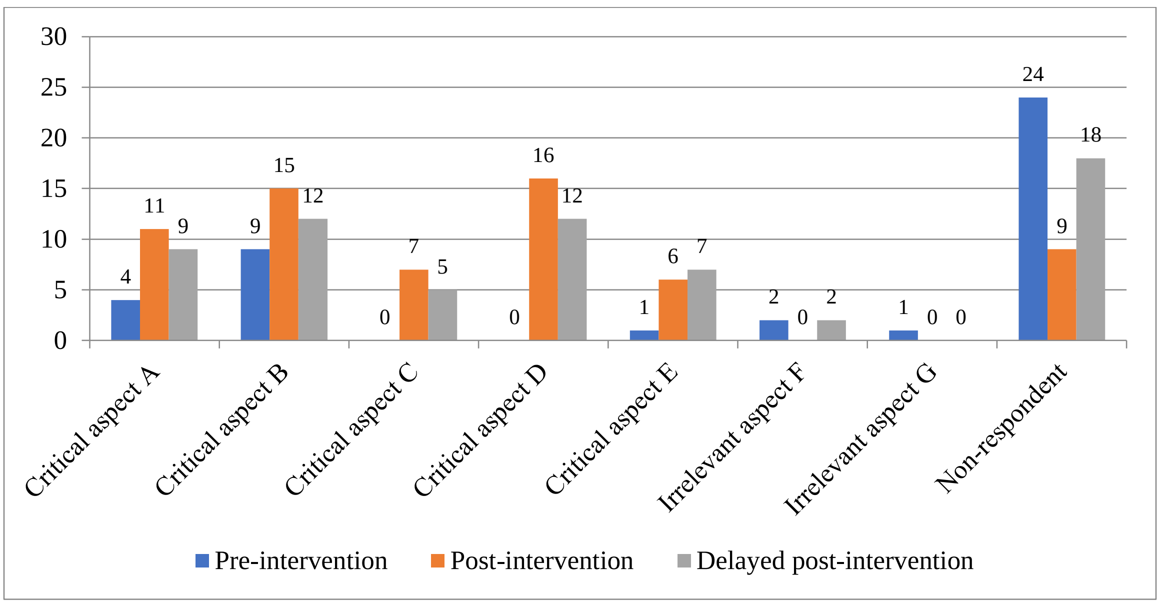


Figure 6.5: Critical and IA of NE and non-respondent students at pre-, post-, and delayed post-intervention

The small NS using the equations and figures presented in Table 6.5 not remarkably changed from post-to-eight weeks delayed post-intervention. This indicates that almost all the small NS retain their representational competency of NE for eight weeks delayed post-intervention. The equations and figures indicate in Table 6.5 supported a small NS to visualise and develop their understanding of the concept of NE by discerning its different CAs. The interactive simulation of the fission of U-235 by a thermal neutron (Figure 5.18) and the liquid-drop model of a nucleus (Figure 5.17) used to describe it supported the students to visualise the existence of NE in the form of kinetic energies of the fission fragments (critical aspect D). The irrelevant aspect F was not discerned by the students at post- and delayed post-intervention. The other IA were also discerned by a very small NS at post- and delayed post-intervention. Figure 6.5 indicated that 24, 9, and 18 were the non-respondent students at pre-, post-, and delayed post-intervention. In this case, the effectiveness of the intervention is not satisfactory, because the number of non-respondent students at eight weeks delayed post-intervention is greater compared to that of post-intervention. The other cases indicated that the intervention is effective.

The results of this study indicated that the conceptual difficulties of NE identified in Section 4.7.5 were addressed to a large extent by using the intervention. That is a small NS had discerned IA after the intervention. This means, the intervention played a role in eliminating the students' misconceptions of NE and then supporting them to develop their scientific understanding. The students used equations and figures presented in Table 6.5 in addition to written text to represent the different aspects of NE. The students also performed interactive simulations of the fission of Uranium-235 by a thermal neutron (see Figure 5.18). This supported the students to develop their understanding of NE. Two students at post- and one at eight weeks delayed post-intervention had used the liquid-drop model (see Figure 17) to illustrate the fission of Uranium-235 by a thermal neutron in which it releases NE. This NE exists in the form of the kinetic energy of the fission fragments. Seven students at post- and four at eight weeks delayed post-intervention expressed the existence of NE in the form of kinetic energies using Equation 5.6. This equation represented critical aspect D. The interactive simulation (Figure 5.18), the liquid-drop model (Figure 5.17), and Equation 5.6 complemented each other. Eleven students at post- and nine at eight weeks delayed post-intervention had used Equation 4.4 to represent critical aspects B and C. The summary was given to the students using the concept map constructed by the researcher (Figure 5.20) also supported the students to develop their understanding of the concept of NE.

The MRs supported the students to discern the various critical aspect of NE. The MRs-based instruction with interactive learning tutorials was based on the VTL to make the learning of NE possible. This phenomenographic instruction (see Section 2.10.) was not used by previous nuclear physics education researchers to address the conceptual difficulties of NE. Moreover, no evidence was found of research to address the conceptual difficulties of NE even using any other research-based instructions.

6.7 THE EFFECTIVENESS OF THE MRS-BASED INSTRUCTION WITH INTERACTIVE LEARNING TUTORIALS

The overall discussions on the students' categories of the description presented in Sections 6.2.2 to 6.6.2 indicate that the MRs-based instruction with interactive nuclear physics learning tutorials was effective. This is determined based on the criteria set in Section 6.1 and using Tables 6.1 – 6.5.

- It was effective in increasing the NS discerning the CAs. Discerning the critical aspect supported the students to enhance their conceptual understanding.
- It was effective in reducing the NS discerning the IA. In other words, it was effective in addressing the students' conceptual difficulties.
- It was fairly effective in retaining the students' conceptual understanding and representations for eight weeks delayed post-intervention.
- It was effective in reducing the number of non-respondent students.
- It was effective in developing the students' skills of using MRs to represent each of the five concepts.

The MRs-based instruction with interactive nuclear physics learning tutorial was effective because that it was designed within the phenomenographic pedagogical framework. This means it was designed based on the VTL. In phenomenographic perspectives, "variation" is the keyword for learning (Ling Lo, 2012) That is to learn and understand a concept, the students must discern its various CAs. Phenomenography and VTL provided a phenomenographic pedagogical framework (Wright & Osman, 2018). These scholars claimed that this pedagogical framework supports the students to discern the various critical aspect of a disciplinary concept. This phenomenographic pedagogy is aimed at helping students to develop their possibility of learning by exploring the conditions that make learning possible(Pang & Marton, 2007). For this reason, this pedagogy is referred to as the pedagogy of learning rather than the pedagogy of teaching (Wright & Osman, 2018). According to these researchers, a phenomenographic pedagogical framework has the potential to transform higher education.

The nuclear physics teaching approaches used in previous studies were developed and designed based on a constructivist pedagogical framework (see Section 2.5.3). The constructivist paradigm emphasises the individual's acts of an active and constructive process. Nevertheless, the phenomenographic paradigm emphasises various critical aspects of a disciplinary concept discerned and focused on by different students (Wright & Osman, 2018). The instructional methods derived from constructivism were based on the minimum guided teaching approach (Kirschner et al., 2006). These scholars pointed out that there is a limited channel for linking the working memory to the long-term memory in the constructivist teaching approach, which would overburden learners' working memory load. Previous researchers have used MRs in teaching nuclear physics (Bakaç, Taşoğlu, & Usta, 2015; Bakaç, Taşoğlu, & Uyumaz., 2011; Tobaja, Gil, & Solano, 2017; Yeşiloğlu, 2019; Yumuşak et al., 2015). These researchers used laboratory modelling to eliminate the students' misconceptions of radioactive elements, radioactive decay law, and a half-life of a radioactive substance. Mapping the concept of radioactivity was used to help individual students to learn with less effort. Simulations and animations were used to remove the misconception of radioactivity. A modelling method was used in teaching radioactive decay. All of these teaching methods, which were designed within the constructivist pedagogical framework, were effective compared to traditional instruction (see Section 2.5.2). However, the MRs teaching approach, which is designed based on VTL in this study, could give a better channel to reduce the overburden on learners' working memory load. The result found in Chapter 6 indicates that this teaching approach supported the learners to discern the various critical aspect of a nuclear physics concept. Discerning the various critical aspects facilitated the students' in-depth conceptual understanding. The MRs-based interactive learning tutorial activities (see Tables 5.2 – 5.6) used in this study could give a better channel in linking the working memory to long-term memory. The results found in this study indicated that this

MRs teaching approach retained the students' conceptual understanding and representations of a nuclear physics concept.

The appropriate different forms of representations used to represent each of the five concepts of nuclear physics in this study were created a suitable learning environment. The findings of this study indicated that the MRs supported the students to develop their possibility of learning. The results presented in Sections 6.2 – 6.6 indicate that the MRs supported the students to discern the various critical aspect of each of the five concepts of nuclear physics. According to Marton (2014), these critical aspects are the necessary conditions for learning and understanding each concept of nuclear physics. The bar charts in Figures 6.1 – 6.5 show that the NS discerning the critical aspect at post- and eight weeks delayed post-intervention is almost the same except for a few special cases. This indicates that the students retained their conceptual understanding and representations for eight weeks delayed post-intervention. This supports the findings of Aldrich (2000) and Aldrich and Sheppard (2001). These scholars said that the appropriate use of the different forms of representations could retain the students' conceptual understanding and representations of a disciplinary concept. The overall results of the third phase indicate that the MRs-based instruction with interactive learning tutorials was effective in enhancing the students' conceptual understanding and representations. These support the findings of previous studies (Dermott, 2004; Ejigu, 2014; Kozma, 2003; Larsson, 2013; Mayer, 2003; Opfermann et al., 2017; Van Heuvelen & Zou, 2001). Mayer (2003) claimed that "students learn more deeply from a multimedia explanation presented in words and pictures than in words alone" (p.131). The other physics education researchers also said that the use of MRs is highly valued in physics education. Their reason is that using multi-representational instruction is critical for developing students' conceptual understanding and representations.

The MRs used in this study involved visual representations such as diagrams, graphs, concept maps, and interactive simulations. Shabiralyani et al. (2015) found that learning using visual representations stimulated the students' critical thinking and improved their learning environment in a classroom. For instance, Figure 4.13 supported the students to understand how the number of radioactive nuclei remaining in a radioactive substance and the number of nuclei that have decayed change over time. The interactive NBD simulation indicated in Figure 5.12 also complements the graphs in Figure 4.13. These two visual representations supported the students to develop their understanding of radioactive decay. The interactive simulation also indicated that the number of radioactive nuclei presents in the sample decreases while the number of nuclei that have decayed increases over time. The findings of Kohnle et al. (2011) showed that the students confused the number of nuclei remaining with the number of nuclei that have decayed in a radioactive substance. The findings of this study support this and also addressed the confusion problem using MRs. Equations 4.16, Figure 5.12, and Figure 5.15, which complement each other, supported the students to understand the origin of the electron emitted in the NBD process. Scientifically, the origin of the electron emitted in the beta decay process is the decay of a neutron into an electron in the parent nucleus (Equation 4.17). Eighteen students at post- and 20 at the delayed post-intervention understood this as indicated in Table 6.4 (critical aspect C). The findings released in the literature indicated that the students incorrectly understood that the electron emitted in beta decay is coming out of the electron shell of the parent nucleus (Kohnle et al., 2011). Five students understood this in this way in this study after traditional instruction in the first phase (see Table 4.4). And two students understood in the same way at pre-intervention (see Table 5.5). But no student understood in this way at post- and eight weeks delayed post-intervention. This indicates the effectiveness of the intervention.

Irrelevant aspect G of NBE presented in Table 6.1 was discerned by one, three, and one student respectively at pre-, post-, and eight weeks delayed post-intervention. Irrelevant aspect H presented in Table 6.1 was discerned by one student at pre-intervention but was not discerned after the intervention. Irrelevant aspect H of nuclear force presented in Table 6.2 discerned by one student only at post-intervention. Irrelevant aspect E in Table 6.2 was discerned by one student only at pre-intervention. Irrelevant aspect F in Table 6.2 was discerned by one and three students respectively at pre and post-intervention but not at eight weeks delayed post-intervention. Irrelevant aspect G in Table 6.2 was not discerned at pre-and-post-intervention but was discerned at delayed post-intervention. In Table 6.3, the irrelevant aspect of radioactive decay was not discerned at pre, post-, and delayed post-intervention. In Table 6.4, the irrelevant aspect F of NBD was discerned by two students only at pre-intervention. The irrelevant aspect G in Table 6.4 was discerned by two and four students respectively at post- and delayed post-intervention. The irrelevant aspect H in Table 6.4 was discerned by one, four, and one student respectively at pre-, post-, and delayed post-intervention. In Table 6.5, the irrelevant aspect F of NE was discerned by two and two students respectively at pre and delayed post-intervention. The irrelevant aspect G was discerned only at pre-intervention. All of these indicate that there are a few IA of each concept except that of radioactive decay discerned by a very small number of students after the intervention. As mentioned, irrelevant aspects of a concept are regarded as the incorrect alternative ways of students' understanding of a concept (see Section 2.8).

The number of non-respondent students considerably increased from pre- to post-intervention. This indicates the effectiveness of the intervention. However, the change of the number of non-respondent students in the first phase compared to that at post-intervention in the third phase the change is not considerable. These results indicate that there are very low achievers students in both groups of students. These results are presented in Table 6.6.

Table 6.6: Number of non-respondent students, CA, and IA discerned by students

	First phase		**Second phase**		**Third phase**			
	After traditional instruction (N = 30)		**At pre-intervention (N = 40)**		**At post-intervention (N = 40)**		**At delayed post-intervention (N = 40))**	
Concept area	No of non-respondent student		No of non-respondent student		No of non-respondent student		No of non-respondent student	
NBE	4		26		7		8	
Nuclear force	3		27		5		7	
Nuclear decay	3		24		6		8	
NBD	4		26		6		11	
NE	7		24		9		18	
	No of CA	No of IA	No of CA	No of IA	No of CA	No of IA	No of CA	No of IA
NBE	2	2	5	2	6	1	5	1
Nuclear force	3	2	2	2	4	2	4	1
Nuclear decay	2	1	2	0	3	0	3	0

NBD	2	5	4	2	5	2	5	2
NE	4	2	3	2	5	0	5	1

Non-respondent means students who did not respond to the semi-structured interviews or the open-ended questionnaire. The analysis of the profiles of these non-respondent students indicated that these students were the lowest achievers. Table 6.6 indicates that more critical aspects and less IA were discerned at post- and delayed post-intervention compared to that of pre-intervention. Even though five critical aspects of NBE were discerned at pre-intervention, they were discerned by a very small number of students compared to that of post and delayed post-intervention (see Table 5.1)

6.8 CHAPTER SUMMARY

The sources of the information conveyed by the tables and bar charts that are shown in Sections 6.2 - 6.6 were the collected empirical data. That is the empirical data that were collected through the open-ended questionnaire. The data collected at pre-, post-, and the eight weeks delayed post-intervention was analysed using the phenomenographic analysis method. The outcomes of the phenomenographic analysis process were referred to as the categories of description constructed at the three points. The categories of description represent the students' different ways of conceptual understanding and representations at the three points. These categories of description involved the critical and irrelevant aspects discerned by students and non-respondent students. These are identified using the VTL as a lens. The critical aspects (focused aspects) are regarded as the correct alternative ways of students' conceptual understanding. However, the irrelevant aspects (IA's) (unfocused aspects) are regarded as the incorrect alternative ways of students' conceptual understanding (see Section 2.8.3). The IA's involve the students' conceptual difficulties of each of the five nuclear physics concepts.

The overall results found in Chapter 6 indicate that the MRs-based instruction with interactive learning tutorials was effective in enhancing the different ways of students' conceptual understanding and representations. Five criteria were set up to determine its effectiveness in Section 6.1. This teaching strategy was designed within the pedagogical framework of phenomenography and VTL. This was not considered and used by previous nuclear physics education researchers (see Section 2.5.3). These researchers used a constructivist teaching approach but this study has been used a phenomenographic teaching approach. In this study, the MRs-based interactive nuclear physics learning activities supported the students to retain their conceptual understanding and representations of a nuclear physics concept for eight weeks delayed post-intervention. This supports the findings of Aldrich and Sheppard (2001). Nevertheless, a few students could not retain their understanding and representations of a nuclear physics concept. For instance, the number of students (NS) that discerned critical aspect B of a radioactive decay decreased from twenty-two at post-to nine at eight weeks delayed post-intervention as indicated in Table 6.5. As indicated in Tables 6.1– 6.6, the number of non-respondent students considerably decreased from pre- to post-intervention. In the next chapter, the conclusion, implications, and recommendations of this study are discussed.

CHAPTER 7: CONCLUSION, IMPLICATIONS, AND RECOMMENDATIONS

7.1 THE CONCLUSION OF THE STUDY

An exploratory case study research design underpinned by developmental phenomenography and VTL was used in this study. This design was used to explore and enhance the different ways of students' conceptual understanding and representations of the introductory nuclear physics concepts. These concepts are the concepts of NBE, nuclear force, radioactive decay, NBD, and NE. The conceptual frameworks of developmental phenomenography and the VTL were used to probe the following interrelated research questions in three phases.

1. What are the different ways undergraduate physics major students' understand and represent the five concepts in Phase 1 after traditional instruction, Phase 2 at pre-intervention, and Phase 3 at post- and delayed post-intervention?
2. How the MRs-based instruction with interactive learning tutorials is developed and designed using the results found in the first phase after traditional intervention and the second phase at pre-intervention as a basis?
3. What is the efficacy of the MRs-based instruction with interactive learning tutorials in enhancing the different ways undergraduate physics major students understand and represent the five introductory nuclear physics concepts at post- and delayed post-intervention?

To probe the first research question, data were collected and analysed in the first phase, in the second phase at pre-, and the third phase at post- and delayed post-intervention. The first phase took place after the first group of students was exposed to traditional instruction. At the pre- and post-intervention mean before and after the students were exposed to MRs-based instruction with interactive learning tutorials. At delayed post-intervention mean eight weeks after the student was exposed to this new teaching strategy. Twenty sets of students' categories of description were constructed at these four points for each of the five concepts (see Tables 4.1 – 4.5 & 6.1 – 6.5) after the developmental phenomenographic analysis process. These represent the different ways of students' understanding and representations of each of the five concepts revealed at the four points. The categories of description at pre-intervention mean the different ways of students' prior conceptual understanding and representations in the second phase (see Figure 2.3). The categories of description were arranged in a hierarchy. A hierarchy means the students' different ways of understanding and representations of each concept were arranged from less to more complex conceptual understanding. These were used as a basis to identify a limited number of critical and irrelevant aspects (see Table 6.6) of each concept discerned by students using the VTL as a lens. As mentioned repeatedly in this thesis the IAs involve conceptual difficulties such as misunderstandings, misconceptions, confusions, and conceptual learning difficulties. In this study, the set of irrelevant aspects (IAs) are regarded as the incorrect alternative ways of students' understanding of each concept. And the set of critical aspects are regarded as the correct alternative ways of students' understanding of each concept. A certain number of non-respondent students were also identified for each concept of nuclear physics at the four points. The NS who discerned the critical aspect of each concept increased after the intervention (see Table 6.6). And the NS who discerned the IAs of each concept after the intervention is decreased (see Table 6.6). The IA's discerned in the first phase involve the students' conceptual difficulties of nuclear physics that were summarised and presented in Section 4.7. These were the important results found in the first phase after the students were exposed to traditional instruction for six weeks. Some of the conceptual difficulties identified in this study were also identified in previous studies (Morales & Tuzón, 2020; Kohnle et al., 2011; Pillay & Loonat, 1993; Rathore, 2016; Yeşiloğlu, 2019).

To probe the second research question, the multiple representations (MRs) based instruction with interactive learning tutorials was developed and designed based on the results found in the first and second phases at pre-intervention. This means it was developed and designed based on the critical and irrelevant aspects (IA's) identified in the first phase and at pre-intervention using the VTL as a lens. Critical aspects are what the students must learn and IA's involve the conceptual difficulties that should be addressed. Before the interactive learning tutorial class, the students were given an MRs-based student worksheet to attempt individually at their homes (Hidayati et al., 2019). The different forms of representations used in designing are verbal, written explanations, equations, graphs, diagrams, simulations, and others which are referred to as semiotic resources by some scholars (Volkwyn et al., 2020b). These scholars said that there has been extensive work in the area of PER into “multimodality”. By this, they mean how different forms of representations can function together to make learning possible. The MRs provided an opportunity for students to confront their conceptual difficulties. The MRs-based interactive nuclear physics learning activities that were performed by students were presented in Tables 5.2 to 5.6. The students performed the MRs-based interactive learning activities in the tutorial classes in small groups. The VTL was used as a lens to identify and organise the necessary conditions of learning for each concept of introductory nuclear physics concepts before intervention (Marton& Tsui, 2004; Marton & Pang, 2006; Marton, 2014; Wright & Osman, 2018). According to these scholars, discerning the various critical aspect of a concept is the necessary condition for learning that concept. That is, the interactive learning activities were developed and designed based on the concept of “variation”(Wright & Osman, 2018). According to Ott (2017), to learn and understand a disciplinary concept “variation” is required. This is the basic theorem of the VTL. In other words, the VTL postulates that different learners understand the same object of learning in different ways (Marton & Booth, 1997). According to this theory, for learners to have a complete understanding of a disciplinary concept, they must discern its various critical aspect (Marton & Tsui, 2004). This MRs teaching approach was developed and designed focusing on enhancing the different ways of students’ conceptual understanding and representations.

To probe the third research question, the results found at pre-intervention were used as a baseline and compared to the results found at post- and delayed post-intervention to explore the efficacy of the intervention. That is to explore the efficacy of MRs-based instruction with interactive learning tutorials, which was used as an intervention. The students were exposed to the MRs teaching approach for six weeks (see Table 5.1 & Section 5.2) the same as the time assigned for the traditional instruction in the first phase. The five criteria presented in Section 6.1, which are set by the researcher, and Tables 6.1 – 6.6 were used to determine the effectiveness of this teaching strategy. For instance, less number of IAs by a small number and a greater number of critical aspects by a greater number of students were discerned after intervention (see Table 6.1 – 6.6). Thus, this MRs-based instruction supported the students to discern various critical aspects and to reduce the IA discerned by them. The results in these tables indicate that except for a few special cases, the students retained their conceptual understanding and representations for the eight-week delayed post-intervention. This supports the previous findings (Aldrich, 2000; Aldrich and Sheppard; 2001). The number of non-respondent students at post-intervention was also considerably reduced compared to that of pre-intervention. The overall results indicate that the intervention was effective in developing students' conceptual understanding and representations of each of the five concepts.

This MRs teaching approach was designed based on the VTL. But most of the teaching methods used to teach nuclear physics in previous studies were designed based on the constructivist learning theory (see Section 2.5.3). Some of these teaching methods are cooperative learning, Jigsaw, computer-assisted instruction, and others. A laboratory modelling, simulations, animations, and concept mapping are the MRs used by these previous researchers (Adolphus & Omeodu, 2020; Bakaç, Taşoğlu, & Usta, 2015; Bakaç, Taşoğlu, & Uyumaz., 2011; Tobaja, Gil, & Solano, 2017; Yeşiloğlu, 2019; Yumuşak et al., 2015). Laboratory modelling activity was used to eliminate the students' misconceptions of a radioactive element, radioactive decay law, and a half-life of a radioactive substance. Mapping the concept of radioactivity was used in serving individual students to learn with less effort. Simulations and animations were used to remove the misconception of radioactivity. The modelling method was also used in teaching radioactive decay effectively. Modelling and simulations were used together to remove the students' misconceptions of a radioactive decay law.

Most of these previous researchers used quantitative research approaches, particularly; the quasi-experimental design. Most of them used this research design to investigate the effectiveness of these teaching methods in teaching school students as compared to traditional instruction. But the researcher of this study used a qualitative research approach, particularly; developmental phenomenographic research approach. This research approach informed effective instructional design, which is the MRs-based instruction with interactive learning tutorials. Consequently, this MRs teaching approach supported the undergraduate physics students to acquire an in-depth understanding of each of the introductory nuclear physics concepts. They were enabled to acquire this by integrating information from the different forms of representations that represent a single concept. The studies conducted in other fields of physics and sciences in previous studies also confirmed the effectiveness of the MRs teaching approach in developing students conceptual understanding (Ejigu, 2014; Eriksson et al., 2020; Gunawan et al., 2018; Hidayati et al., 2019; Opfermann et al., 2017; Vegisari et al., 2020).

7.2 THE IMPLICATIONS OF THE STUDY

The findings of this study indicate that the MRs-based instruction with interactive learning tutorials (see Tables 5.2 - 5.6) is effective in enhancing the different ways of students' conceptual understanding and representations of nuclear physics. The interactive nuclear physics learning tutorials activities designed and implemented based on the different forms of representations are presented in these tables. These supported the students to discern more critical aspects of a nuclear physics concept. Consequently, these supported the students to acquire an in-depth conceptual understanding of nuclear physics. This is possible when learners can integrate information from the different forms of representations that represent a single concept, which is hard to gain from one representation alone (Ainsworth, 2006). For instance, to acquire an in-depth understanding of the concept of radioactive decay law, the students should be able to represent it verbally, in written text, to express it using an equation, to illustrate it using a graph, and to perform it using interactive simulation rather than using one form of representation (see Table 5.4). The radioactive decay law indicates how the number of radioactive nuclei remaining in a radioactive substance changes. This is the first critical aspect of radioactive decay. How the number of radioactive nuclei that have decayed changes in time is also represented by different forms of representations. This is the second aspect of radioactive decay. The findings of this and previous studies indicated that the students are confused with the first aspect with the second aspect. The MRs teaching approach used in this study supported the students to confront their confusion.

If physics instructors use MRs teaching approach, they can enhance the different ways of their students' conceptual understanding and representations of physics. This will be more effective if it is developed and designed within the pedagogical framework of phenomenography and VTL. Developmental phenomenography can inform effective instructional design that makes physics learning possible. Or, this phenomenographic pedagogical framework can support the instructors to develop their students' possibility of learning. The MRs that can represent the critical aspect of each of the five concepts of nuclear physics are identified (see Sections 6.2 - 6.6 & 5.2). They are identified using the VTL as a lens. Nuclear physics instructors can use these MRs-based interactive learning activities to develop and design their classroom instructions. According to Marton (2014), critical aspect are the necessary conditions for learning. Additional critical aspect can be identified and organised based on the contents they teach using the VTL as a lens to make learning possible (Wright & Osman, 2018). The instructors can also identify and organise the conceptual difficulties of their students using this learning theory based on the responses of the students to the assignments, tests, and final exams. In such a way, nuclear physics instructors can develop and design effective classroom instruction based on the VTL. Currently used instructional methods may be designed based on the VTL to have a deeper level of conceptual understanding. According to Ling Lo (2012, p.109)"VTL is compatible with the majority of teaching strategies currently promoted". However, when developing, designing, and implementing these teaching strategies, the students must be provided with an opportunity to discern various critical aspects of a disciplinary concept. In general, phenomenographic instruction is helpful for physics instructors who are focusing on the concept of phenomenographic "variation" that enhances the students' deeper conceptual understanding of physics.

The findings of this study can also provide critical information for physics curriculum developers. The physics curriculum developed within the phenomenographic pedagogical framework creates the appropriate learning environment, which makes learning possible. The curriculum developed within this framework aims at supporting students to develop their possibility of learning (Marton & Pang, 2006). Such a phenomenographic curriculum has implications for transforming higher education. The critical aspects of a nuclear physics concept that are identified and organised in this study can provide information for physics curriculum developers particularly to nuclear physics. If the stakeholders can establish, equip, and organise a virtual physics laboratory based on this curriculum, the MRs teaching approach will be more facilitated and effective. These create a suitable learning environment that makes the students learning possible and enhance their possibility of learning. This can also provide an opportunity for students to develop their competence in interpreting and using the experts' as well as their representations. In the physics virtual laboratory, the students and instructors can use interactive simulations, models, animations, equations, graphs, and diagrams, which are the different forms of representations.

7.3 RECOMMENDATIONS FOR FUTURE RESEARCH

Future researchers can use the conceptual frameworks of developmental phenomenography and VTL to reveal the different ways of students' conceptual understanding of physics that can inform and develop an effective instructional design (Green & Bowden, 2009; Han & Ellis, 2019; Wright & Osman, 2018). The critical and IA of a physics concept discerned by students can be identified using the VTL. And this can be used as a potential source to design effective instruction. Using this research methodology, future researchers can explore and enhance the different ways of students' conceptual understanding and representations of alpha decay, positive beta decay, electron capture, and gamma decay, which are not included in this study. Even though these are integrated into a radioactive decay, which is included in this study, like the NBD, to reduce the complexity of the thesis, they were not included in this study.

This study did not explore if the students can integrate the concepts of nuclear physics using concept mapping. This is a limitation of this study that should be addressed by future researchers. However, the spider concept mapping was used in this study to summarise the different ways of students' understanding and representations of each of the five concepts. Students can acquire a deeper understanding of a concept of physics by integrating the information obtained from different forms of representations that represent this single concept. This is a MRs-based teaching approach used in this study. The competence of students in interpreting and using the experts' and their representations of physics concepts in the classroom was not explored. This also needs video recordings. According to the VTL, we call this enacted object of learning. This may also be another limitation of this study that could be addressed by future researchers.

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APPENDIX I: THE SEMI-STRUCTURED FACE-TO-FACE INDIVIDUAL INTERVIEWS USED IN THE FIRST PHASE

The Interview Guide

Thank you for coming on time. In the first phase, the purpose of these in-depth interviews is to reveal the students' conceptual difficulties of introductory nuclear physics after they had been exposed to traditional instruction. In the second phase, the purpose of this Ph.D. research project is to develop and design an instructional intervention to address the conceptual difficulties identified in the first phase. And in the third phase, the purpose of the study is to explore the effectiveness of the instructional intervention in addressing the conceptual difficulties.

This scripture involves two parts. These are the semi-structured face-to-face individual interview to be responded to verbally and the second part to be responded to by expressing equations and drawing graphs and diagrams. The second part is a pen-and-paper task. There are no right and wrong answers to the questions. The researcher would like you to feel comfortable with saying and in responding in written in verbal and non-verbal what you think about the concepts in introductory nuclear physics.

This interview will be used to get in-depth information about the students' various ways of conceptual understanding and representations of nuclear physics. Based on your voluntary, the researcher will record our conversations using an audio-recorder. The reason for this is that the researcher can get all the information and at the same time be able to carry on an attentive conversation with you. The researcher assures you that all your verbal and nonverbal responses will remain confidential. The researcher will be compiling a research report which will contain all participants' responses without any reference to individual participants.

Thank you for your participation in this doctoral research project. Please be as honest as you can be in helping the researcher to investigate the various ways of undergraduate physics students' conceptual understanding and representations of introductory nuclear physics. I hope that your genuine responses to these interview questions are valuable to the findings of this research project. Confidentiality of your responses is guaranteed. The information you provide to the researcher is used only for the research purpose. The approximate length of the questions of the semi-structured face-to-face individual interviews to be responded to verbally and using a pen and paper task is 50 min.

The Nuclear Physics Conceptual Investigation Semi-Structured Face-To-Face Individual Interview Questions

1. Nuclear Binding Energy

1.1. Define nuclear binding energy

1.2. Compare the energy that must be added to a nucleus to separate it into its constituent nucleons with its binding energy

1.3. Compare the mass of the nucleus inbound state and the combined masses of its separated constituent nucleons

1.4. Relate the binding energy of a nucleus to the mass lost using an equation when the separated nucleons combine to form a nucleus

1.5. Illustrate the combination of proton and neutron to form a deuteron using a diagram. Describe nuclear binding energy based on this diagram.

1.6. Illustrate the separation of deuteron into its constituent proton and neutron when energy is added to it using a diagram. Describe NBE based on this diagram.

1.7. Compare the energy missed after a nucleus is separated into its constituent nucleons to its binding energy

1.8. Draw and interpret the graph of NBE per nucleon versus atomic mass number

1.9. Describe nuclear binding energy (NBE) using the liquid-drop nuclear structure model

2. Nuclear force

2.1. Define nuclear force?

2.2. State and describe the properties of the strong nuclear force

2.3. What makes the nuclear force unique when compared to that of the electromagnetic and gravitational forces?

2.4. Describe the role of nuclear force in nuclear stability?

2.5. What is the relationship if any between nuclear binding energy and nuclear force?

2.6. Describe the nuclear force based on the field particle exchange model

2.7. Relate the nuclear force to the more basic strong force that binds quarks together

2.8. Draw the graph of potential energy U(r) *versus* the nucleons separation distance r for the interaction of n-p and p-p systems concerning nuclear and Coulomb forces and then interpret it

3. Radioactive decay

3.1. Describe radioactive decay law verbally and then using text, an equation, and a graph

3.2. Describe how the number of radioactive nuclei presents in a radioactive substance change in time using text, an equation, and a graph

3.3. Describe how the number of nuclei that have decayed in a radioactive substance change in time verbally and then using text, an equation, and a graph

3.4. Define the half-life of a radioactive substance verbally and then using an equation and a diagram?

3.5. Define the activity of the radioactive substance verbally and then using an equation and a graph?

4. Negative beta decay

4.1. Describe the negative beta decay verbally and then using text and an equation

4.2. Draw the historical beta decay curve that had drawn before the discovery of neutrino and then interpret it

4.3. What is the origin of an electron emitted in the beta decay process?

4.4. Is the electron emitted in the beta decay process the same as that of an atomic electron? Explain the reason for your answer.

4.5. Does the electron emitted in the beta decay process exist in the nucleus before beta decay? Explain the reason for your answer.

4.6. Describe the negative beta decay process using the diagram that illustrates the decay of hydrogen-3 to helium-3?

5. Nuclear energy

5.1. Define nuclear energy verbally and then using text and an equation?

5.2. What is the origin of nuclear energy?

5.3. How can nuclear energy be produced by a nucleus in large amounts?

5.4. What is the initiator of the nuclear fission chain reaction of Uranium-235 in a nuclear reactor?

5.5. How can nuclear energy be converted into electricity in a controlled way in a pressurized-water nuclear reactor?

APPENDIX II: THE INTERVIEW TIME SCHEDULE FORMAT

The interview schedule was designed based on the agreement of the researcher and the research participants. This is part of the data collection method employed in this study. The interview schedule created the appropriate condition, time, and place for the interview process. The interviews were performed in an appropriate classroom to prevent noise disturbance.

Day					Monday		Tuesday		Wednesday		Tuesday	
S.No	ID.No	Sex	100%	Date, time, place	morning	afternoon	morning	afternoon	morning	afternoon	morning	afternoon
1				Date								
				Time								
				Place								
2				Date								
				Time								
				Place								
3				Date								
				Time								
				Place								

APPENDIX III: THE OPEN-ENDED NUCLEAR PHYSICS CONCEPTUAL INVESTIGATION QUESTIONNAIRE TO BE USED IN THE SECOND AND THIRD PHASES

1. Answer the following questions based on nuclear binding energy
    a) Define nuclear binding energy using text
    b) Express nuclear binding energy using an equation and then interpret it
    c) Draw a rough graph of nuclear binding energy per nucleon versus the mass number. Indicate on the graph the greatest region of nuclear binding energy per nucleon, nuclear stability, and nucleon binding force.
    d) Draw a diagram that shows the process of the separation of a deuteron into proton and neutron. And then describe nuclear binding energy based on this diagram.
    e) Draw a diagram that shows the process of the combination of proton and neutron to form a deuteron. And then describe nuclear binding energy based on this diagram
2. Answer the following questions based on the strong nuclear force
    a) Define and describe the strong nuclear force using text
    b) State and describe the properties of nuclear force
    c) Among the properties of strong nuclear force, which of them make it unique when compared to that of electromagnetic and gravitational forces
    d) Draw a rough graph of potential energy U(r) versus the nucleons' separation distance r for p-p and n-p interactions. Indicate on the graph the nuclear attractive force, nuclear repulsive force, and Coulomb repulsive forces
    e) Describe the strong nuclear force based on the exchange force model (field particle exchange model)
    f) Relate the nuclear force to the more basic strong force that binds quarks together to form a nucleon
3. Answer the following questions based on radioactive decay
    a) How the number of radioactive nuclei presents in a radioactive substance changes in time. Describe your answer using text, an equation, a graph, and a diagram
    b) How the number of nuclei that have decayed in a radioactive substance changes in time. Describe your answer using text, an equation, a graph, and a diagram

c) Describe the half-life of the radioactive substance; using text, an equation, and a diagram.

d) What is the number of radioactive nuclei remaining in a radioactive substance in terms of the original number at two and three half-lives?

e) Describe the activity of a radioactive substance using text, an equation, and a graph.

4. Answer the following questions based on the negative beta decay process.

a) Describe the negative beta decay process using text and an equation

b) What is the origin of the electron emitted in the beta decay process?

c) Does the electron emitted in the beta decay process exist in the nucleus before decay? Explain the reason for your answer

d) Describe the electron emitted in the beta decay process based on the nuclear rest energy

e) Describe the negative beta decay process based on the decay of hydrogen-3 into helium-3 using a diagram

5. Answer the following questions based on nuclear energy.

a) Define nuclear energy?

b) What is the origin of nuclear energy?

c) How can nuclear energy be produced in large amounts?

d) Express the equation of nuclear energy released in the reaction of a particle with a target nucleus in terms of the nuclear rest mass.

e) In what form, does the nuclear energy released in the fission of a nucleus exist?

f) How can nuclear energy be produced in large amounts andthen transformed into electrical energy in a pressurized-water nuclear reactor?

APPENDIX IV: RESEARCH CONSENT LETTER

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The Federal Democratic Republic
of Ethiopia
Ambo University

Ref.No AU/T371/1/8/2016

Date 19 JAN 2016

To: Institute for Science and Technology Education, University of South Africa (UNISA)

Subject: Giving the letter of research consent

Mr. *Tafesse Kabtihymer Atlabachew* requested Ambo University, Ethiopia, to get letter of research consent for the participant in his research work. The researcher is looking for all those second year physics major student participants who are taking the introductory nuclear physics course (nuclear physics I). The department entertaining this course is physics. He also points out in detail the research proposal topic, purpose, nature, methods, scope, and intent of the research study in the student research consent form.

Therefore, we would like to inform your institution that Mr. *Tafesse Kabtihymer Atlabachew* is allowed to conduct his PH.D project in our University to give all the necessary data and facilities he need in the study.

With best regards

Lakew Wondimu Abachiri (PhD)
Academic & Research Vice President

The Federal Democratic Republic of Ethiopia
Ambo University

APPENDIX V: RESEARCH CONSENT FORM

Research Consent Form

(To be completed by student participant aged 18 years and above)

1. Research Proposal Topic:- Conceptual Understanding of Nuclear Physics: ***An investigation into students' representations of basic concepts in nuclear physics***
2. Purpose of the research:-
   - To investigate into 2^{nd} year undergraduate physics major students' conceptual understanding of the basic concepts of nuclear physics
   - To investigate into Ethiopian undergraduate physics major students' beliefs about nuclear physics that influence students' conceptual understanding
   - to investigate if there is a change in students' beliefs and conceptual understanding by using the *traditional instruction* and the *multiple representations*
3. Nature of the study: - It is solely to develop research thesis on physics in accordance with the requirements for the degree of Doctor of philosophy in Mathematics, Science and Technology Education in the subject *physics education* at the University of South Africa.
4. Researcher's Details:-
   Name: Tafesse Kabtihymer Atlabachew
   Address: Ambo University, P.O.Box 19, Ethiopia
   Telephone: +251913350930 (mobile)
5. Research site:- Ambo University and Wolega University

You should be enrolled in physics department for the second year study in first semester to participate in this research study. It is hoped that you have read and familiarized with the purpose, nature, scope, and intent of the research study mentioned above. If you agree to participate you will be required to sit for the conceptual diagnostic test, open-ended conceptual questions/focus groups discussions and the 5-point Likert Rating Scale statement (questionnaire) in the pre-and post-tests. The researcher kindly requests you to bear in mind the information you are provided is very essential to obtain the expected result. Your cooperation will contribute more for the completion of the study. The findings in turn may help to improve future students' learning of basic concepts of nuclear physics. In doing so, you are advised not to hesitate as something may occur that makes you get risk. Equivalently, this is to say that confidentiality will be ensured at every step of the study. During and after data are collected you will be identified by a code to guarantee anonymity. After all, if you have any reservation, your decision to carry on or quit is respected.

Date: - __________

I ______________________________consent to participating in this research. I understand that the researcher will ensure confidentially as is explained above. Furthermore, I understand that may quit my participation in this study at any time or refuse to respond to any questions to which I choose not to respond. I am voluntary participant and have no liability or responsibility for the implementation, methodology, claims, substance, or outcomes resulting in any adverse consequences or disparate treatment due to that decision. I fully understand that this research is being conducted for constructive educational purposes. Finally, I would like to give my permission to the researcher to use the data collected for the solely purpose of this study through my signature here under.

Participant's Name: - ________________________________

Postion: - ____________________

Address: - ____

Telephone: - ____________________

Participant's Signature: - ______________

Date: - ______________

APPENDIX VI: ETHICAL CLEARANCE

UNISA | college of science, engineering and technology

Dear Mr Tafesse Kabtihymer Atlabachew (student number 57653801)

Date: 2016-06-06

Application number: 2016_CGS/ISTE_002

REQUEST FOR ETHICAL CLEARANCE: (Topic: An investigation into Ethiopian 2nd year physics students' conceptual understanding and beliefs of basic concepts in nuclear physics: A case study of Ambo University)

The College of Science, Engineering and Technology's (CSET) Research and Ethics Committee has considered the relevant parts of the studies relating to the abovementioned research project and research methodology and is pleased to inform you that ethical clearance is granted for your research study as set out in your proposal and application for ethical clearance.

Therefore, involved parties may also consider ethics approval as granted. However, the permission granted must not be misconstrued as constituting an instruction from the CSET Executive or the CSET CRIC that sampled interviewees (if applicable) are compelled to take part in the research project. All interviewees retain their individual right to decide whether to participate or not.

We trust that the research will be undertaken in a manner that is respectful of the rights and integrity of those who volunteer to participate, as stipulated in the UNISA Research Ethics policy. The policy can be found at the following URL:
http://cm.unisa.ac.za/contents/departments/res_policies/docs/ResearchEthicsPolicy_apprvCounc_21Sept07.pdf

Please note that the ethical clearance is granted for the duration of this project and if you subsequently do a follow-up study that requires the use of a different research instrument, you will have to submit an addendum to this application, explaining the purpose of the follow-up study and attach the new instrument along with a comprehensive information document and consent form.

Yours sincerely

Dr CE Ochonogor
Chair: Ethics Sub-Committee (STRI/ISTE) CSET

Prof MN Feza
Director/Head: ISTE

Prof I Alderton
Executive Dean (Acting): College of Science, Engineering and Technology

University of South Africa
College of Science, Engineering and Technology
The Science Campus
C/o Christiaan de Wet Road and Pioneer Avenue,
Florida Park, Roodepoort
Private Bag X6, Florida, 1710
www.unisa.ac.za/cset

APPENDIX VII: EXAMPLE OF ANALYSIS OF THE DATA COLLECTED USING THE SEMI-STRUCTURED FACE-TO-FACE INDIVIDUAL INTERVIEWS IN THE FIRST PHASE OF THIS STUDY

1. Transcription

In the first phase of this study, the data was collected using semi-structured face-to-face individual interviews. The collected data was analyzed using phenomenographic data analysis method. The three students were selected from the word document consists of the interview transcribed verbatim and nonverbal responses of 30 students. Their verbal responses to the semi-structured face-to-face individual interviews were recorded in the audio IC-recorder from 121222-004 up to 121222-005 for S_{02}, on Z0000025 for S_{20}, and Z0000026 for S_{21}. The transcription was done by the researcher listening again and again to the verbal responses of each student recorded in audio IC-recorder. The semi-structured interview questions to which the students responded are available in appendix I. The transcription was written in Microsoft office word.

The written explanations, expressed equations, the images of the graph, and diagrams that had been drawn by these three students also included in the word document next to the transcriptions as shown from sections 2 to 4. Scientific graphs and diagrams are indicated using a sign $\surd$ and nonscientific ones indicated using sign X. And N.D represents not done. The phenomenographic data analysis process of the three students' conceptual understanding and representations of the five concepts of nuclear physics is illustrated as an example from Sections 5 to 7 in this appendix.

2. The transcriptions and nonverbal responses of the student S_{02}

Transcription of the Verbal Response of S_{02}

Researcher: Define nuclear binding energy

Participant: "The nuclear binding energy of a nucleus is the energy that equals the negative of the difference of the mass of a nucleus and the sum of the masses of its split constituents times the square of the speed of light"."Nuclear binding energy is the energy that binds protons and neutrons together".

Researcher: Compare the energy that must be added to a nucleus to separate it into its constituent nucleons with its binding energy

Participant: The participant wasn't able to compare the binding energy of a nucleus and the energy added to it to split it into its constituents.

Researcher: Compare the mass of the nucleus inbound state and the combined masses of its separated constituent nucleons

Participant: "The mass of a nucleus inbound state and the sum of the masses of its split constituents are equal".

Researcher: Define nuclear force

Participant: "The nuclear force is the force that binds protons and neutrons together".

Researcher: State and describe the properties of the strong nuclear force

Participant: "A nuclear force is a short-range (0.4-3fm), attractive, repulsive, and strong force".

Researcher: Describe the nuclear force based on the field particle exchange model

Participant: "Gluons are the exchange field particles of nuclear interaction via nuclear force.

Researcher: What makes the nuclear force unique when compared to that of the electromagnetic and gravitational forces?

Participant: "The Coulomb force is the force that separates the nucleons (makes a nucleus unstable), gravitational force is the force that depends on the mass, and nuclear force is the force that binds protons and neutrons together to form a stable nucleus".

Researcher: Relate the nuclear force to the more basic strong force that binds quarks together

Participant: "Nuclear force is the force that binds nucleons together to form the nucleus and the strong force is the force that binds the quarks together to form nucleons". "The strong force is greater than the nuclear force".

Researcher: Define radioactivity

Participant: “Radioactivity is the spontaneous emission of radiation by unstable nuclei”.

Researcher: Describe how the three forms of nuclear radiation emitted by a radioactive substance during radioactivity were distinguished by scientists

Participant: “Scientists were able to distinguish the three types of nuclear radiation using the magnetic field and their ionizing power”.

Researcher: Define the half-life of a radioactive substance

Participant: “The half-life of a radioactive substance is the time needed for half of the number of radioactive nuclei to decay”.

Researcher: What is the origin of an electron emitted in the beta decay process?

Participant: “The electron is produced during the beta decay process”.

Researcher: Does the electron emitted in the beta decay process exist in the nucleus before beta decay? Explain the reason for your answer.

Participant: “An electron does not exist within the nucleus”.

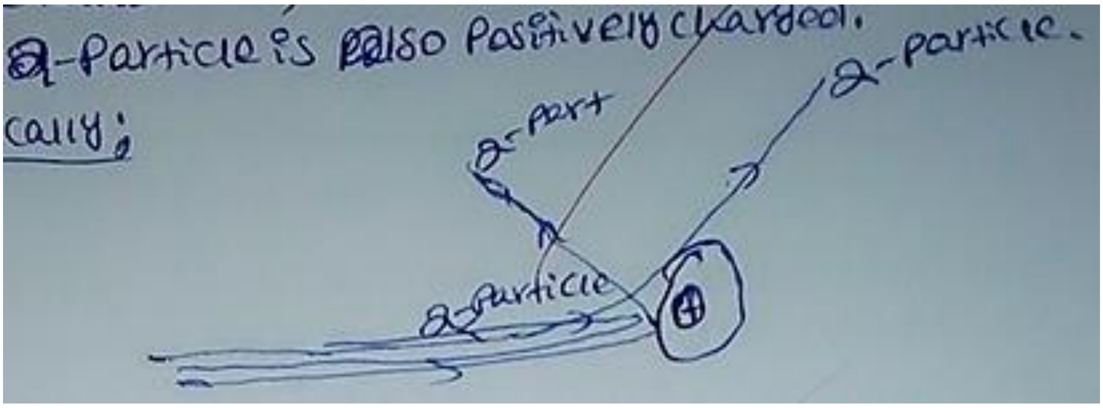
Researcher: Define nuclear energy

Participant: “Nuclear energy is the energy gained or lost during a nuclear reaction, that is, during nuclear fission and fusion reaction”.

Nonverbal Response of the student S_{02}

Researcher: Illustrate using an alpha scattering experiment and a diagram of how Rutherford was discovered the nucleus of an atom

Participant: This participant illustrated it as follows



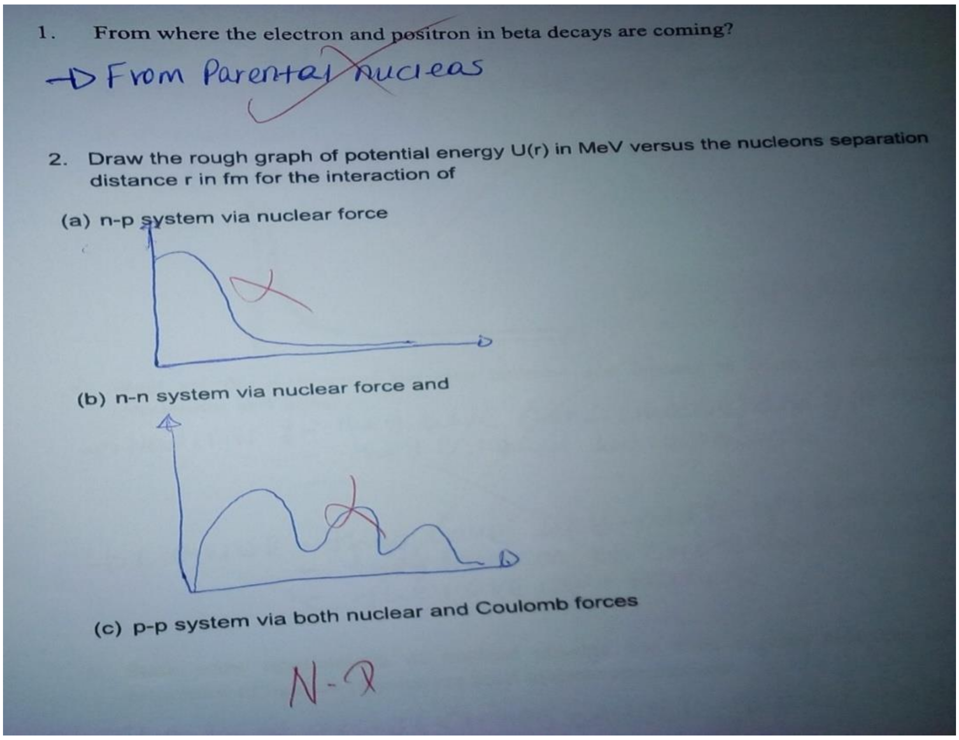
Researcher: Relate the binding energy of a nucleus to the mass lost using an equation when the separated nucleons combine to form a nucleus

Participant: She expressed it using an equation as follows:

$$E_B = \left(m_p + m_n - m(A,Z)\right)c^2$$

Researcher: Draw the graph of potential energy U(r) versus the nucleons separation distance r for the interaction of n-p and p-p systems and then indicates the nuclear force and the Coulomb force in the graph.

Participant: She tried to describe the n-p and p-p interactions via nuclear force using a graph as shown below:



Researcher: Express the half-life of a radioactive substance using an equation.

Participant: She expressed half-life in terms of the equation, $T_{1/2} = \frac{0.693}{\lambda}$.

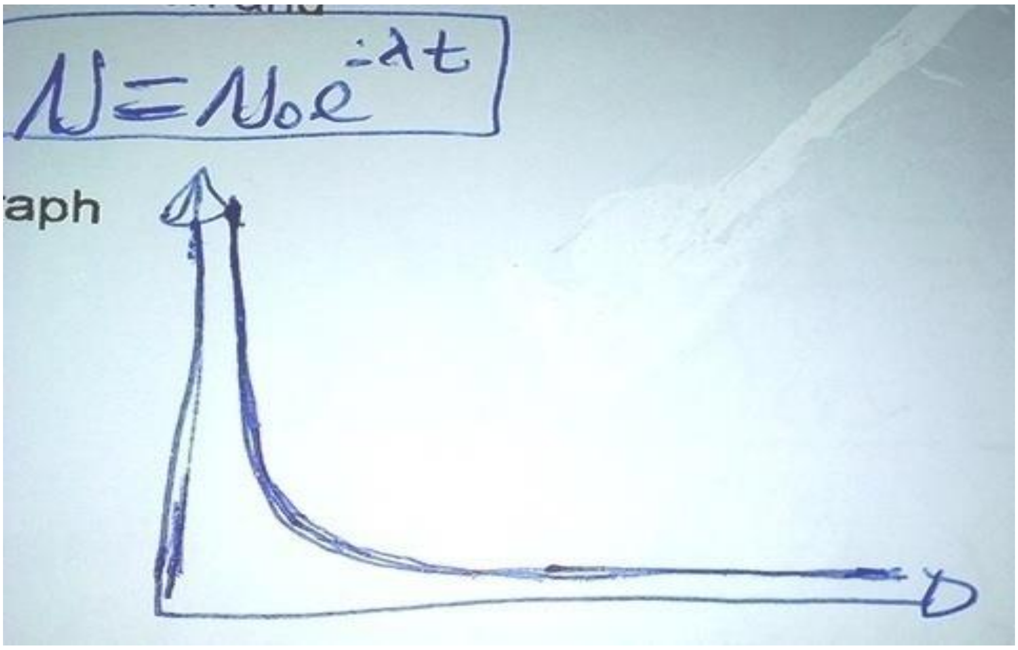
Researcher: Express the negative beta decay process using an equation

Participant: She expressed the negative beta decay process using the following equation.

$$ {}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + e^{-} + \bar{\upsilon} $$

Researcher: Express the radioactive decay law using an equation and a graph

Participant: She expressed the radioactive decay law using an equation and illustrated it using a graph as shown below.



3. The transcriptions and nonverbal responses of the student S_{20}

Transcription of the Verbal Response of S_{20}

Researcher: Define nuclear binding energy

Participant: "Nuclear binding energy is the energy added to the nucleus to disintegrated or split into protons and neutrons".

Researcher: Compare the energy that must be added to a nucleus to separate it into its constituent nucleons with its binding energy

Participant:"The binding energy of a nucleus should be less than the energy added to it to split it into its constituents".

Researcher: Compare the mass of the nucleus inbound state and the combined masses of its separated constituent nucleons

Participant: "The mass of a nucleus inbound state is greater than the sum of the masses of its split constituents".

Researcher: Define nuclear force

Participant: "The nuclear force is the force that binds nucleons together not to be disintegrated".

Researcher: State and describe the properties of the strong nuclear force

Participant: "Nuclear force is attractive, short-range (0.4-3fm), charge independent and strong force".

Researcher: Describe the nuclear force based on the field particle exchange model

Participant: "Gluons are the exchange field particle of the nuclear interaction via nuclear force.

Researcher: What makes the nuclear force unique when compared to that of the electromagnetic and gravitational forces?

Participant: "What makes nuclear force unique when it is compared with that of coulomb and gravitational forces is that it is the strongest attractive force".

Researcher: Relate the nuclear force to the more basic strong force that binds quarks together

Participant: "The force that binds nucleons together to form a nucleus and the force that binds the quarks together to form nucleons are the same".

Researcher: Define radioactivity

Participant: "Radioactivity is the spontaneous emission of radiation by unstable nuclei".

Researcher: Describe how the three forms of nuclear radiation emitted by a radioactive substance during radioactivity were distinguished by scientists

Participant: "Scientists can distinguish the three types of nuclear radiation using ionizing and penetrating power".

Researcher: Define the half-life of a radioactive substance

Participant: "The half-life of a radioactive substance is a carbon dating that can be used to determine the age of a material".

Researcher: What is the origin of an electron emitted in the beta decay process?

Participant: "The electron emitted in the beta decay process is coming from a proton in a nucleus".

Researcher: Does the electron emitted in the beta decay process exist in the nucleus before beta decay? Explain the reason for your answer.

Participant: "The electron does not exist in the nucleus, because, the nucleus is positively charged".

Researcher: Define nuclear energy

Participant: "Nuclear energy is the energy of the nucleus which is produced by nuclear fission and fusion reactions"

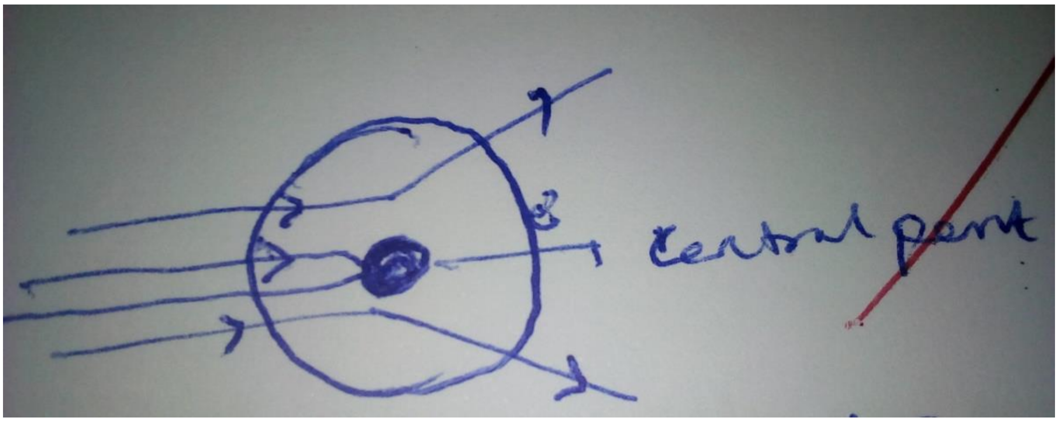
Researcher: Describe the difference between nuclear binding energy and nuclear energy

Participant: "Nuclear binding energy (NBE) is the energy lost when the nucleons bind together and nuclear energy (NE) is the energy lost during the disintegration of a nucleus".

Nonverbal Response of the student S_{20}

Researcher: Illustrate using an alpha scattering experiment and a diagram of how Rutherford was discovered the nucleus of an atom

Participant: This participant illustrated it as follows



Researcher: Relate the binding energy of a nucleus to the mass lost using an equation when the separated nucleons combine to form a nucleus

Participant: The participant expressed it using the following equation

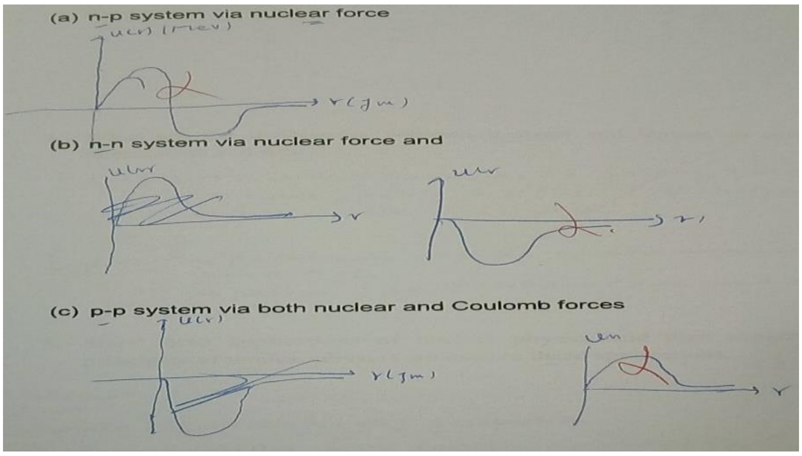
$$E_B = -(M_N - Zm_p - Nm_n)c^2$$

He also expressed it using an equation as shown below.

$$E_B = (m_p + m_n - m(A, Z))c^2$$

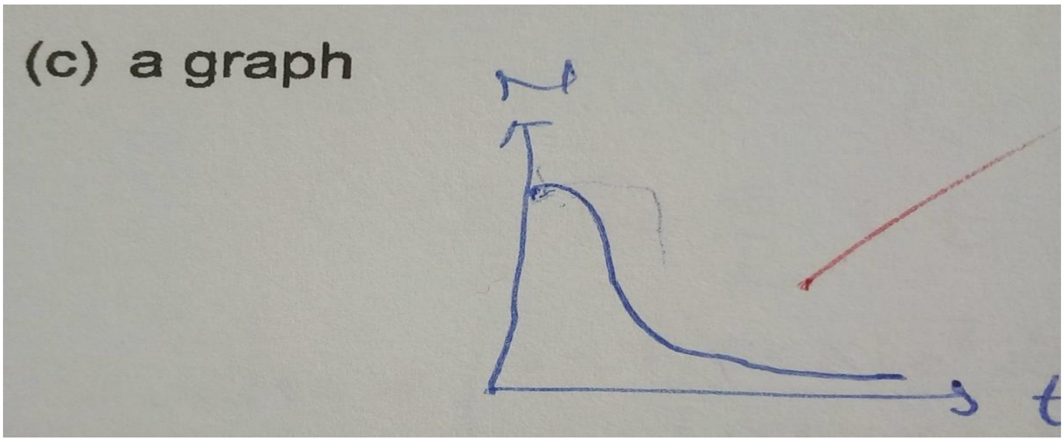
Researcher: Draw the graph of potential energy U(r) versus the nucleons separation distance r for the interaction of n-p and p-p systems and then indicates the nuclear force and the Coulomb force in the graph.

Participant: The participant had drawn it as follows



Researcher: Express the radioactive decay law using an equation and a graph

Participant: He illustrated it using a graph without expressing it using an equation



Researcher: Express the negative beta decay process using an equation

Participant: He expressed it as follows

${}^{A}_{Z}X \rightarrow {}_{Z+1}{}^{A}Y + e^{-} + \bar{\nu}$

Researcher: Express nuclear energy using an equation

Participant: He called nuclear energy a Q-value and expressed it using

$$Q = (m_a + m_x - m_y - m_b)c^2$$

4. The transcriptions and nonverbal responses of the student S_{21}

Transcription of the Verbal Response of S_{21}

Researcher: Define nuclear binding energy

Participant: "Nuclear binding energy (NBE) is the energy that binds protons and neutrons". "NBE is the negative of the difference between the nuclear mass and the sum of the masses of its constituent's protons and neutrons times the square of the speed of light"

Researcher: Compare the energy that must be added to a nucleus to separate it into its constituent nucleons with its binding energy

Participant:"The nuclear binding energy of a nucleus should be equal to the energy added to it to split it into its constituents".

Researcher: Compare the mass of the nucleus inbound state and the combined masses of its separated constituent nucleons

Participant: "The mass of a nucleus inbound state is less than the sum of the masses of its split constituents".

Researcher: Define nuclear force

Participant: "The nuclear force is a force that binds the nucleus not to be disintegrated or split".

Researcher: State and describe the properties of the strong nuclear force

Participant: "The properties of the nuclear force are: it is a strong, attractive, charge-independent, and short-range force".

Researcher: Describe the nuclear force based on the field particle exchange model

Participant: "Gluons are the exchange field particle of the nuclear interaction via nuclear force".

Researcher: What makes the nuclear force unique when compared to that of the electromagnetic and gravitational forces?

Participant: "What makes nuclear force unique, when it is compared to that of the coulomb and gravitational forces, is that it is a short-range (0.4-3fm) force".

Researcher: Relate the nuclear force to the more basic strong force that binds quarks together

Participant: "The force that binds nucleons together to form a nucleus and the force that binds the quarks together to form nucleons are the same".

Researcher: Define radioactivity

Participant: "Radioactivity is the spontaneous emission of radiation by unstable nuclei".

Researcher: Describe how the three forms of nuclear radiation emitted by a radioactive substance during radioactivity were distinguished by scientists

Participant: "Scientists can distinguish the three types of nuclear radiation using a magnetic field".

Researcher: State the radioactive decay law

Participant: "Radioactive decay law is the number of nuclei in a sample decreases exponentially during the decay process".

Researcher: Define the half-life of a radioactive substance

*Participant: "*The half-life of a radioactive substance is a time used to determine the age of a sample of material".

Researcher: What is the origin of an electron emitted in the beta decay process?

Participant: "The electron emitted in the beta decay process is coming from a neutron in a nucleus of an atom".

Researcher: Does the electron emitted in the beta decay process exist in the nucleus before beta decay? Explain the reason for your answer.

Participant: "The electron does not exist in the nucleus instead it is orbiting the nucleus".

Researcher: Define nuclear energy

Participant: "Nuclear energy is produced by nuclear fission and fusion reaction".

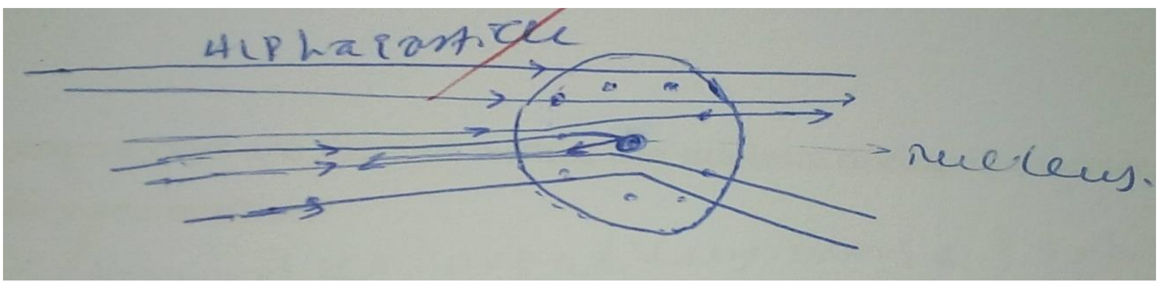
Researcher: Describe the difference between nuclear binding energy and nuclear energy

Participant: "Nuclear binding energy and nuclear energy are related to the nucleus".

Nonverbal Response of the student S_{21}

Researcher: Illustrate using an alpha scattering experiment and a diagram of how Rutherford was discovered the nucleus of an atom

Participant: This participant illustrated it as follows



Researcher: Relate the binding energy of a nucleus to the mass lost using an equation when the separated nucleons combine to form a nucleus

Participant: The participant expressed it using the equation

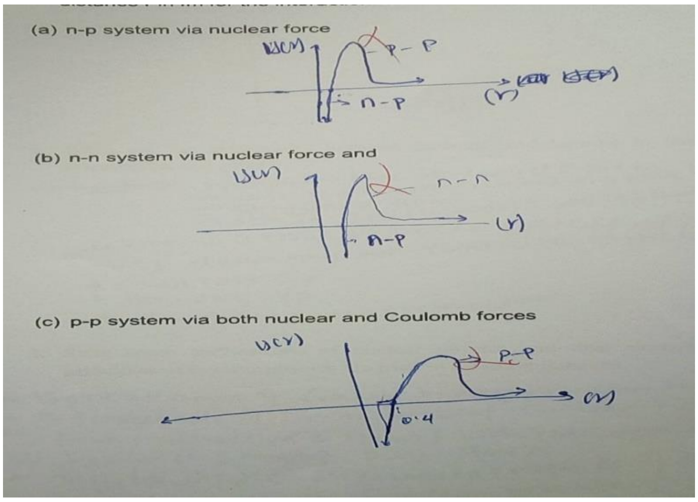
$$E_B = -\left(M_N - Zm_p - Nm_n\right)c^2$$

He also expressed it using an equation as shown below.

$$E_B = \left(m_p + m_n - m(A,Z)\right)c^2$$

Researcher: Draw the graph of potential energy U(r) versus the nucleons separation distance r for the interaction of n-p and p-p systems and then indicates the nuclear force and the Coulomb force in the graph.

Participant: He had drawn it as follows



Researcher: Express the negative beta decay process using an equation

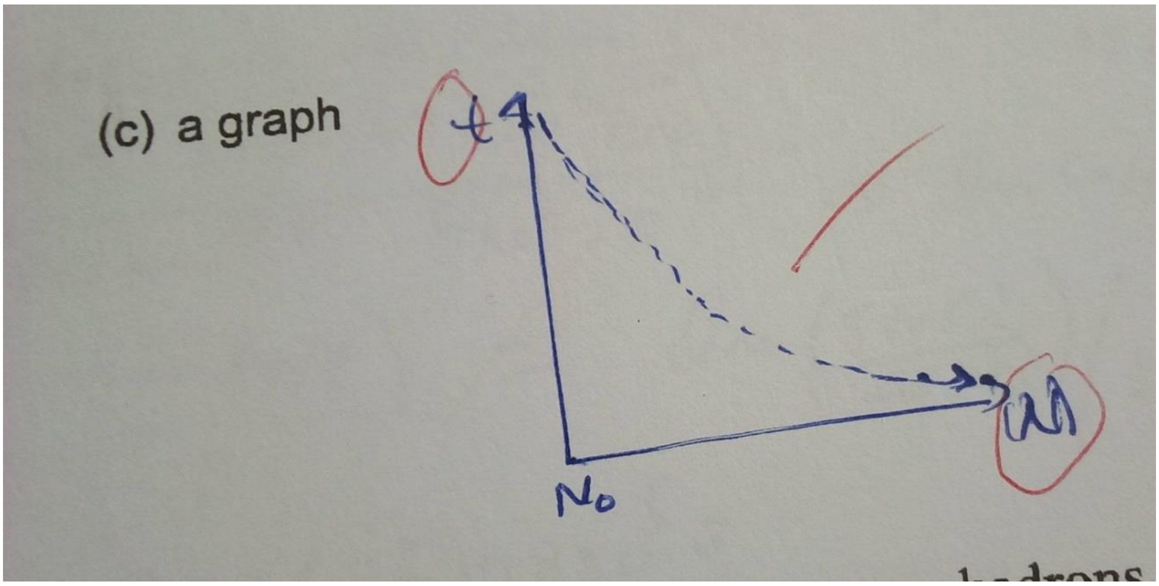
Participant: He expressed it as shown below.

${}^{A}_{Z}X \rightarrow {}_{Z+1}^{\;\;A}Y + e^{-} + \bar{\nu}$

$$n \rightarrow p + e^{-}$$

Researcher: Illustrate the radioactive decay law using a graph

Participant: He illustrated it using a graph without expressing it using an equation as follows



I) Collective categorization of the three students' conceptual understanding and representations of nuclear binding energy

The transcriptions and the nonverbal responses of the three students together form the pool of data to be analyzed as an example using phenomenographic research data analysis process. The seven steps of phenomenographic data analysis process (see Section 3.10.1) were used to analyze and categorize the pool of data. The pool of data represents the students' conceptual understanding and representations of nuclear binding energy (NBE). The phenomenographic data analysis process is outlined as follows. The data were analyzed by the researcher of this study.

In the first step, the transcriptions and the written explanations were read repeatedly to become familiar with their contents. The equations, graphs, and diagrams were also analyzed again and again. This step could help the researcher to correct any mistakes within the pool of data.

In the second step, the researcher made a more focused reading and analysis to deduce similarities and differences from the pool of data. Through this analysis process, the researcher identified the most valued elements in the verbal and nonverbal responses of the students to the interview questions.

In the third step, the extracts relevant and meaningful for this study were selected and stated based on the second step as follows.

a) Student S-20incorrectly understood that the mass of a nucleus inbound state is greater than the combined masses of its split constituent nucleons
b) Student S-02 incorrectly understood that the mass of a nucleus in a bound state equals the combined masses of its split constituent nucleons
c) Student S-21correctly understood that the mass of a nucleus in a bound state is less than the combined masses of its split constituent nucleons
d) Students S-02 and S-21 correctly understood that the binding energy of a nucleus equals the difference between the combined masses of its split constituents and the mass of a nucleus inbound state times the square of the speed of light
e) The students S-02 and S-21 also expressed nuclear binding energy using the next equations. The first equation is correct only for deuteron and the second equation is correct for all nuclei.

$$E_B = \left(m_p + m_n - m_{nuc}\right)c^2$$

$$E_B = \left(Zm_p + Nm_n - m_{nuc}\right)c^2$$

f) Students S-02 and S-21incorrectly understood that nuclear binding energy is the energy that binds protons and neutrons together
g) Student S-02 isn't able to compare the binding energy of a nucleus and the amount of energy that must be added to it to split into its constituent nucleons.
h) Student S-20correctly understood that the binding energy of a nucleus in a bound state is less than the amount of energy that must be added to it to split into its constituent nucleons
i) Students S-20 and 21 correctly understood that the binding energy of a nucleus in a bound state equals the amount of energy that must be added to it to split into its constituent nucleons

Fourth step, the researcher focused on locating and classifying similar responses to the preliminary categories. In this step, an initial list of categories of descriptions was constructed.

Fifth step, the researcher revised the list of categories of description constructed in step four to bring forth a comparison among the categories and to set up boundaries among them. The pool of data was seen again by the researcher to check whether the constructed categories of description represent the accurate conceptual understanding and representations of the participants. The analysis in this step presents the revised list of categories of descriptions as follows.

Category A: The students understood that nuclear binding energy is equivalent to the mass defect when the separated nucleons combine to form a nucleus. This category includes the extracts relevant and meaningful for this study stated under a, b, c, d, and e in the third step.

Category B: The students understood that nuclear binding energy is related to the amount of energy that must be added to a nucleus to separate it into its constituent nucleons. This category includes the extracts relevant and meaningful for this study stated under g, h, and in the third step.

Category C: The students understood that nuclear binding energy binds the nucleons in the nucleus of an atom (it includes f)

In the sixth step, the name was given to the categories A, B, and C to emphasize their essence based on the groups' internal attributes and distinguishes features between them.

Category A: Energy equivalent of the mass defect

Category B: Energy added to a nucleus

Category C: Nucleons binding energy

Seventh step, the researcher discovered the outcome space based on their internal relationships and qualitatively different ways of conceptual understanding and representations of nuclear binding energy. It would then represent the categories in a hierarchy. The categories A, B, and C are arranged in a hierarchy from less complicated (category I) to more complicated students' conceptual understanding and representations of nuclear binding energy (Category III) as follows.

Category I: Nucleons binding energy
Category II: Energy equivalent of the missing mass

Category III: Energy added to a nucleus

II) Collective categorization of the three students' conceptual understanding and representations of nuclear force

No student described correctly nuclear force using an equation and a graph. Following the first, second, and third steps used in A, the extracts relevant and meaningful for this study were selected and stated as follows.

i. Students S-02 and S-20 correctly understood that nuclear force is the force that binds the protons and neutrons together to form the nucleus of an atom
ii. Student S-02 correctly understood that nuclear force has a repulsive term
iii. Students S-02, S-20, and S-21 correctly understood that a nuclear force is a short-range, strong, attractive, and charge independent force
iv. Students S-20 and S-21 correctly understood that nuclear force is a unique force as compared with electromagnetic and gravitational forces. That is, they said its short-range and strong properties make it unique.
v. Students S-02, S-20, and S-21 incorrectly understood that gluons are the exchange field particles of nuclear interaction via nuclear force
vi. Students S-02understood that the basic strong force binds quarks together to form a nucleon
vii. Student S-20 and S-21understood that the force that binds nucleons together and the force that binds quarks together is the same

Following the fourth, fifth, and sixth steps used in A, the following categories of descriptions were constructed. The students understood that

Category A: nuclear force is the force that binds nucleons together to form a nucleus. This category includes i, ii, vi, and vii. The name given for this category is *nucleon binding force*.

Category B: nuclear force is a short-range, strong, charge-independent, and attractive force (includes iii). The name given for this category is *properties of nuclear force*.

Category C: gluons are the exchange field particles of the strong nuclear force (includes v). The name given for this category is the *exchange force model*.

Category D: nuclear force is a unique force as compared with electromagnetic and gravitational forces (includes IV). The name given for this category is *a unique force*.

Following the seventh step, the categories are arranged in a hierarchy from less complicated understanding (Category I) to more complicated (Category IV) as follows.

Category I: Nucleons binding force

Category II: Unique force

Category III: Properties of nuclear force

Category IV: Exchange force model

III) Collective categorization of the three students' different ways of conceptual understanding and representations of radioactive decay

IV) Collective categorization of the three students' different ways of conceptual understanding and representations of negative beta decay

V) Collective categorization of the three students' different ways of conceptual understanding and representations of nuclear energy

The students' categories of description of radioactive decay, negative beta decay, and nuclear energy were constructed following the seven steps of phenomenographic data analysis process the same as that of nuclear binding energy. The categories of description of the thirty students for each of the five nuclear physics concepts are available in chapter four.

The categories of description were constructed after traditional instruction in the first phase of this study. In each category, there are similar different ways of students' conceptual understanding and representations of nuclear physics. These were revealed by the phenomenographic data analysis process. The revealed students' different ways of conceptual understanding and representations were classified into critical and irrelevant aspects by variation theory of learning. This theory was used to analyze the students' conceptual learning process and understanding based on critical and irrelevant aspects. That is, the variation theory of learning was used to explain the nature of learning based on critical and irrelevant aspects discerned by students. The non-respondent or unlearnt students, who didn't discern both of the critical and irrelevant aspects, were also revealed. In this case, the students didn't respond at all or their responses were omitted.

The example of critical and irrelevant aspects of nuclear binding energy discerned by students is given as follows.

Critical aspects:

Students S-02 and S-21 correctly understood that the binding energy of a nucleus is equivalent to the mass lost when its separated nucleons combine to form a nucleus.

The students S-02 and S-21 also correctly expressed nuclear binding energy using the next equations.

$$E_B = \left(Zm_p + Nm_n - m_{nuc}\right)c^2$$

Irrelevant aspects:

Students S-02 and S-21incorrectly understood that nuclear binding energy is the energy that binds protons and neutrons together.

Student S-20 incorrectly understood that the mass of a nucleus in a bound state is greater than the combined masses of its split constituent nucleons.

In this study, the variation theory of learning was used to explain the learning process based on critical and irrelevant aspects. Students who discerned more critical aspects were learned more or could have a complete understanding. And students who discerned more irrelevant aspects were learned less or could have a misunderstanding. The critical aspects represent the correct various ways of students' conceptual understanding and representations of nuclear physics. And the irrelevant aspects represent the incorrect various ways of students' conceptual understanding and representations of nuclear physics. The irrelevant aspects involve conceptual difficulties such as misconceptions, confusion, and learning difficulties. After traditional instruction, considerable irrelevant aspects of each concept were discerned. To address the conceptual difficulties constituted in the irrelevant aspects; variation theory of learning was used to identify and organize what made conceptual learning and understanding possible. This was done in the second phase of this study.

APPENDIX VIII: EXAMPLE OF ANALYSIS OF THE DATA COLLECTED USING THE OPEN-ENDED NUCLEAR PHYSICS CONCEPTUAL INVESTIGATION QUESTIONNAIRE IN THE SECOND PHASE OF THIS STUDY

Three students were selected from 40 students who responded to the open-ended nuclear physics conceptual investigation questionnaire. This questionnaire is available in Appendix III. The collected data was analyzed using phenomenographic data analysis method. This data analysis was aimed at identifying and describing the students' different ways of conceptual understanding and representations of nuclear physics. The responses of the three students to the conceptual investigation questionnaire at pre-, post-, and delayed post-intervention are presented as follows. The codes of the three students selected from the 40 students are S_{18}, S_{28} and S_{32}.

1. The responses of a student S_{18} to the open-ended questionnaire about nuclear binding energy, nuclear force, radioactive decay, negative beta decay, and nuclear energy at pre-, post- and delayed post-intervention were presented as follows.
    1.1. Nuclear binding energy

At pre-intervention

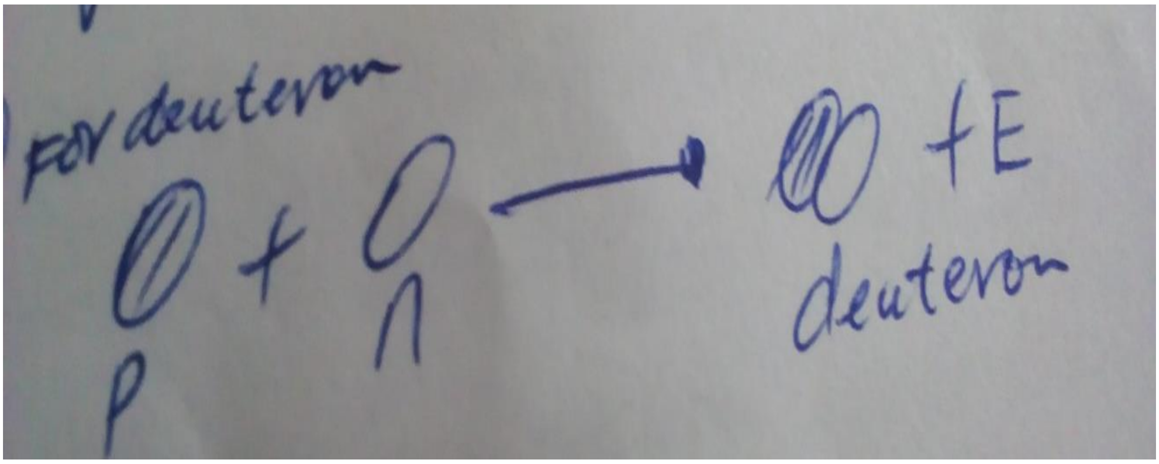
At pre-intervention, this student responded that nuclear binding energy is the energy formed when proton and neutron combine. This is correct, but instead of formed the word released should be used.

At post-intervention

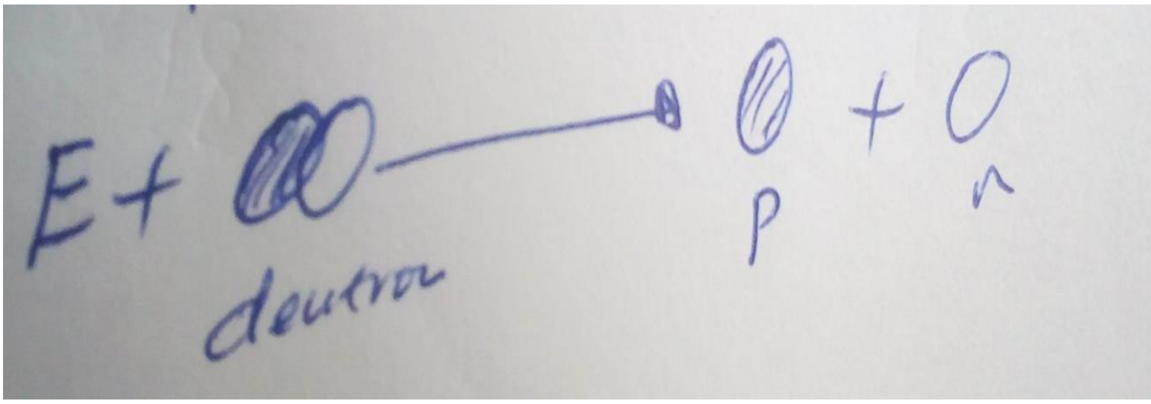
The student correctly responded that the binding energy of a nucleus is the difference between the combined masses of the separated nucleons and the mass of the nucleus times the square of the speed of light. In equation form, the student correctly expressed it as follows. This is assigned to Critical aspect A. This student correctly expressed nuclear binding energy using the next equation.

$$E_b = \left(Zm_p + Nm_n - m_{nuc}\right)x931.494\, {}^{MeV}\!/_{u}$$

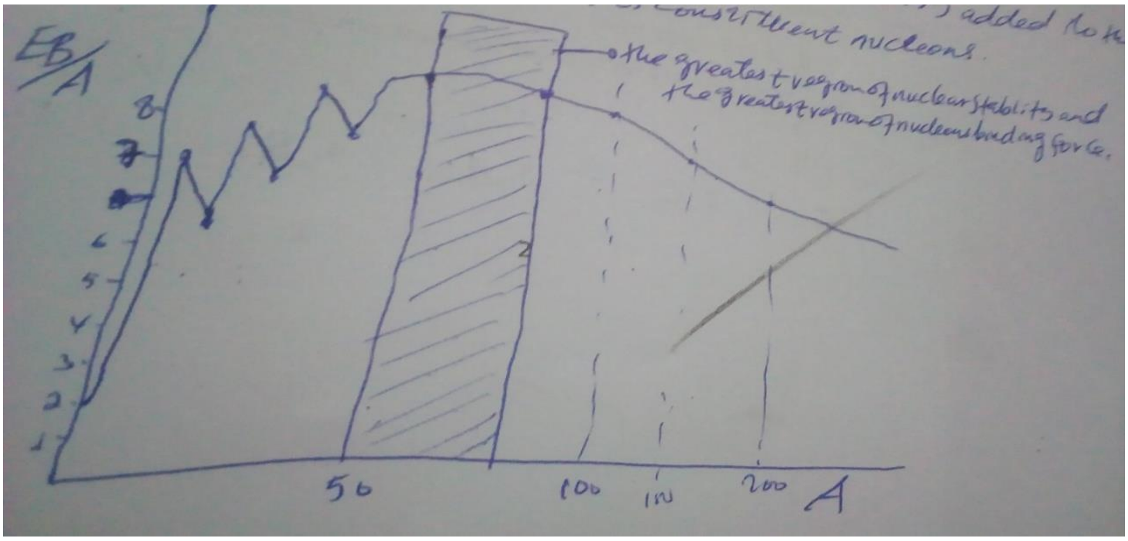
In another way, the student correctly responded that the binding energy of a nucleus is the amount of energy E released when its separated nucleons combine. The student correctly illustrated this aspect of the concept of nuclear binding energy using the next diagram. This is assigned to Critical aspect B.



This student also correctly responded that the binding energy of a nucleus is equal to the amount of energy E added to the nucleus to separate it into its constituents. The student also correctly illustrated this aspect of the concept of nuclear binding energy using the next diagram. This is assigned to Critical aspect C.



This student correctly illustrated how the binding energy of the stable nuclei per nucleon changes with a mass number using the next graph. This assigned to Critical aspect E.



At delayed post-intervention

The student had been retained his understanding and representations of the concept of nuclear binding energy at delayed post-intervention.

1.2. Nuclear force

At pre-intervention

At pre-intervention, the student incorrectly responded that the nuclear force is a force that binds the nucleus of an atom and its orbiting electrons. This is incorrect because nuclear force is a short-range force that binds the nucleons together to form the nucleus of an atom. The student also incorrectly expressed nuclear force in equation form as follows.

$$F_N = \frac{mv^2}{r}$$

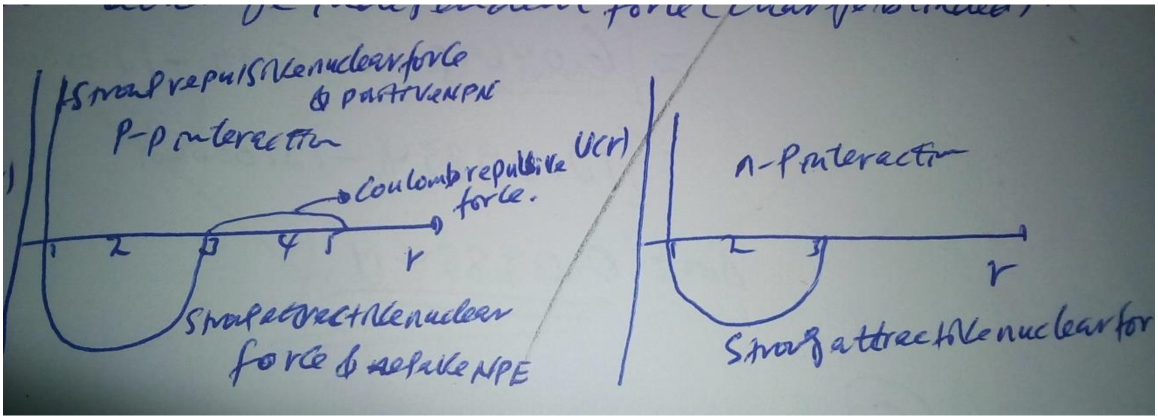
At post-intervention

The student correctly responded that the nuclear force is the force that binding the nucleus not to be disintegrated.

In another way, the student correctly described the nuclear force based on the exchange force model. That is, he described that pi-meson is the exchange field particle of the strong interaction caused by the strong nuclear force.

Again, in another way, the student correctly described that the nuclear force is the residual effect of the basic strong force that binds quarks together to form a nucleon.

The student stated the short-range, strong, and charge-independent properties of a nuclear force. To illustrate the short-range property of a nuclear force the student used the graph of the potential energy U(r) versus the nucleons separation distance r for p-p and n-p interactions.



At delayed post-intervention

At delayed post-intervention, the student almost had been retained his different ways of conceptual understanding and representations of nuclear force

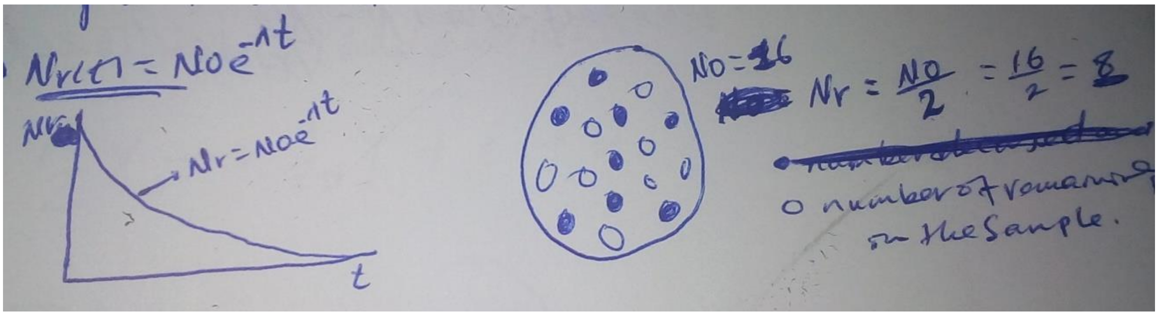
1.3. Radioactive decay

At pre-intervention

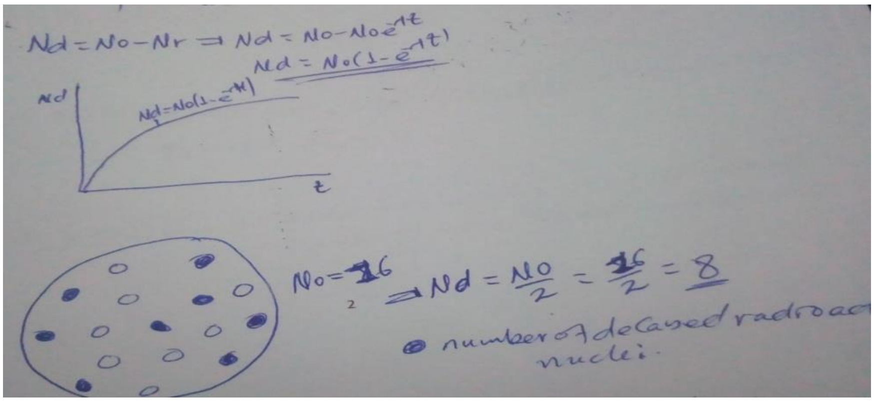
At pre-intervention, the student didn’t respond to the open-ended questionnaire about radioactive decay.

At post-intervention

The student correctly described that the number of radioactive nuclei present in a radioactive substance exponentially decreases in time. The student illustrated this aspect of radioactive decay using the next graph and diagram.



In another way, the student correctly responded that the number of radioactive nuclei that have decayed in a radioactive substance increases in time. The student correctly illustrated this aspect of radioactive decay using the next graph and diagram.



The student correctly responded that the half-life of the radioactive substance is the time at which half of the given radioactive nuclei decay. The student correctly expressed this using the following equation.

$$T_{1/2} = \frac{0693}{\lambda}$$

At delayed post-intervention

The student almost had been retained his understanding and representations of the concept of radioactive decay at delayed post-intervention.

1.4. negative beta decay

At pre-intervention

The student didn't respond to the open-ended questionnaire about negative beta decay at pre-intervention.

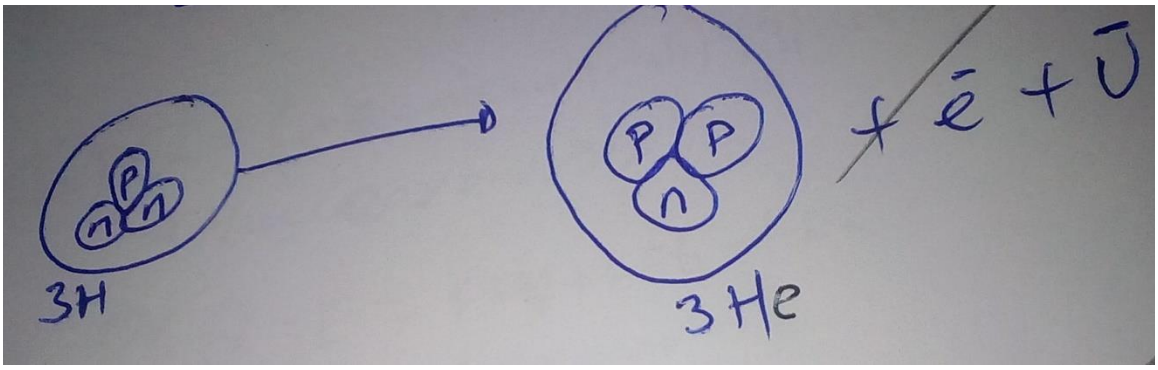
At post-intervention

The student responded that in the negative beta decay process the parent nucleus changes into another nucleus (the daughter nucleus). The student understood that the mass number is unchanged but the atomic number increased by one in the decay process. And, in this decay process, an electron and antineutrino are emitted. The student correctly expressed this decay process using the next equation.

$${}_{Z}^{A}X \longrightarrow {}_{Z+1}^{A}Y + e^{-} + \overline{\nu}$$

The student understood that the origin of the electron emitted in the negative beta decay process is the neutron in the parent nucleus. The student expressed this using the next equation and diagram.

$$n \rightarrow p + e^{-} + \overline{\nu}$$



The student also understood that the electron doesn't exist in the nucleus before decay but is created at the moment of decay.

At delayed post-intervention

The student had been retained his understanding and representations of the concept of negative beta decay at delayed post-intervention.

1.5. Nuclear energy

At pre-intervention

The student didn't respond to the open-ended questionnaire about nuclear energy at pre-intervention.

At post-intervention

The student correctly understood that nuclear energy is the energy coming out of the nucleus of an atom. The student considered nuclear energy as reaction energy that is released in the nuclear reaction. The student also correctly expressed it using the next equation.

$$Q = (m_a + m_x - m_y - m_b)x931.494 \, {MeV}/{u}$$

The student considered the Q-value as nuclear energy. He correctly expressed the equation of nuclear reaction as

$$a + x \rightarrow Y + b$$

The student also expressed Q in terms of the kinetic energies of the product nucleus, the product particle, and the incident particle in the induced fission reaction as shown below.

$$Q = K.E_y + K.E_b - K.E_a$$

The student attempted to describe how nuclear energy is transformed into electrical energy in a pressurized-water nuclear reactor.

At delayed post-intervention

The student had been retained his understanding and representations of the concept of nuclear energy.

2. The responses of a student S_{28} to the open-ended questionnaire about nuclear binding energy, nuclear force, radioactive decay, negative beta decay, and nuclear energy at pre-, post- and delayed post-intervention were presented as follows.

2.1. Nuclear binding energy

At pre-intervention

At pre-intervention, the student understood that the binding energy is the energy that separates an atom. The energy that must be added to a nucleus to separate it into its constituent nucleons is equal to or greater than its binding energy. It seems that the student is thinking about this idea. Instead of a nucleus, he used an atom.

At post-intervention

The student correctly understood that nuclear binding energy is equal to the negative of the difference between the mass of a nucleus inbound state and the combined masses of its separated nucleons times the square of the speed of light. The student also correctly expressed it in equation form as follows. This is assigned in critical aspect A.

$$E_b = -(m_{nuc} - Zm_p - Nm_n)c^2$$

In another way, the student correctly described how the nuclear binding energy per nucleon of the stable nuclei changes with their mass number using a graph. This graph is the same as that of the previous student. This is assigned in Critical aspect D.

The student also correctly expressed the binding energy of a nucleus using the semi-empirical binding energy formula. This equation indicates the three major effects influencing the binding energy of a nucleus in the liquid-drop nuclear structure model. This is assigned in Critical aspect E.

At delayed post-intervention

The student had been retained his understanding and representations of nuclear binding energy at delayed post-intervention. But he didn't describe it based on the liquid-drop nuclear structure model at delayed post-intervention.

2.2. Nuclear force

At pre-intervention

The student didn't respond to the open-ended questionnaire about nuclear force at pre-intervention.

At post-intervention

At post-intervention, the student correctly understood that nuclear force is the force that binding a nucleus.

The student described the short-range property of nuclear force using the nuclear potential energy U(r) versus the nucleons separation distance r graph. This is the same as the graph of the previous student.

At delayed post-intervention

The student had been retained his understanding and representations of nuclear force. At delayed post-intervention, the student described nuclear force based on the force exchange model, which was not considered by the student at post-intervention.

2.3. Radioactive decay

At pre-intervention

The response of the student to the open-ended questionnaire about radioactive decay was inconsiderable.

At post-intervention

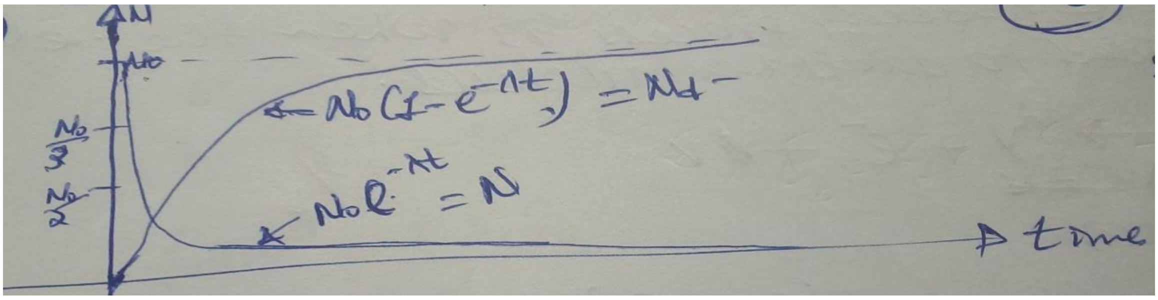
The student incorrectly responded that radioactive decay is the way of expressing the number of nuclei present as a function of exponential form. It seems that the student was trying to state the radioactive decay law. Mathematically, the student correctly expressed the radioactive decay law as follows.

$$N = N_0 e^{-\lambda t}$$

The student also correctly expressed the number of nuclei that have decayed using the next equation.

$$N_d = N_0 \left(1 - e^{-\lambda t}\right)$$

To indicate how the number of nuclei presents in a radioactive substance and the number of nuclei that have decayed change in time; the student had drawn both graphs on the same plane as shown in the next graph.



The student understood that the half-life of a radioactive substance is the half number of nuclei present in a radioactive decay process. He correctly expressed it in equation form as follows.

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

At delayed post-intervention

At delayed post-intervention, the student described how the number of radioactive nuclei that were present in a radioactive substance changes in time using an equation and a graph. Again, he correctly expressed the half-life using an equation.

2.4. Negative beta decay

At pre-intervention

The student understood that the origin of the electron emitted by a radioactive nucleus in the beta decay process is the nucleon. This is incorrect because nucleon means either proton or neutron. Scientifically, the neutron in a parent nucleus is the origin of the electron emitted in the negative beta decay process. This student also expressed negative beta decay using the following incomplete equation.

$${}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + e^{-}$$

At post-intervention

The student correctly understood that negative beta decay is the decay in which an electron is emitted. He expressed the complete equation of the beta decay process by adding the third particle neutrino. But the correct third particle is antineutrino. Neutrino is the third particle emitted in the positive beta decay process. This student also understood that an electron doesn't exist in a nucleus before decay.

At delayed post-intervention

The student correctly understood that negative beta decay is the decay process in which the number of protons in the daughter nucleus increases by one. At delayed post-intervention, the student correctly expressed the complete equation of the negative beta decay process. The student also correctly understood that the origin of the electron emitted in the beta decay process is the decay of a neutron into an electron at the moment of decay in the parent nucleus. He correctly understood that the electron doesn't exist in a nucleus before decay.

2.5. Nuclear energy

At pre-intervention

The student didn't respond to the open-ended questionnaire about nuclear energy.

At post-intervention

The student understood that nuclear energy comes from the splitting of an atom.

At delayed post-intervention

The student incorrectly understood that nuclear energy is the energy added to a nucleus to disintegrate it into its constituents. It seems that the student confused nuclear energy with nuclear binding energy.

3. The responses of a student S_{32} to the open-ended questionnaire about nuclear binding energy, nuclear force, radioactive decay, negative beta decay, and nuclear energy at pre-, post-, and delayed post-intervention were presented as follows.

3.1. Nuclear binding energy

At pre-intervention

The student understood that nuclear binding energy is equal to the difference between the nuclear mass and the combined masses of its separated nucleons. This is incorrect because the difference must be multiplied by the square of the speed of light. In equation form, the student expressed it as follows.

$$E_b = \left(m_p + m_n - m_{nuc}\right) x 931.494 \, {MeV}/{u}$$

This equation is valid only for a deuteron. That is, this equation can't be used to calculate the binding energy of other nuclei.

At post-intervention

At post-intervention, this student understood and represented nuclear binding energy using text, equation, a graph, and diagrams the same as the first student (S_{18}). This is assigned to Critical aspects A, B, C, and E.

At delayed post-intervention

The student had been retained his conceptual understanding and representations of nuclear binding energy except for the graphical representation of nuclear binding energy per nucleon.

3.2. Nuclear force

At pre-intervention

The student didn't respond to the open-ended questionnaire about nuclear force at pre-intervention.

At post-intervention

The student correctly understood that the nuclear force is a force that binds the nucleons in the nucleus not to fly apart. The student also stated the short-range, strong, non-central, and unique properties of a nuclear force. Particularly, he illustrated the short-range property of a nuclear force using the potential energy U(r) versus the nucleons separation distance r for n-p and p-p interactions. The graph that had drawn by this student is the same as that of the previous students.

In another way, the student correctly described nuclear force based on the force exchange model. That is, he understood that pi-meson is the exchange field particle of the strong nuclear force. The student incorrectly considered as the nuclear force and the more basic strong force that binds quarks together are the same. In scientific thinking, it is believed that the nuclear force that binds nucleons together is the residual effect of the more basic strong force that binds quarks together.

At delayed post-intervention

The student had been retained his conceptual understanding and representations of nuclear force.

3.3. Radioactive decay

At pre-intervention

The student didn't respond to the open-ended questionnaire about radioactive decay at pre-intervention.

At post-intervention

The student correctly understood how the number of radioactive nuclei that were present in a radioactive substance and the number of nuclei that have decayed change in time. He correctly described how both of them change in time using equations and graphs. The equations expressed and the graphs drawn by this student are the same as that of the previous students. This student also correctly described the half-life of a radioactive substance by using text and an equation.

At delayed post-intervention

The student had been retained his conceptual understanding and representations of radioactive decay.

3.4. Negative beta decay

At pre-intervention

The response of the student to the open-ended questionnaire about negative beta decay was inconsiderable.

At post-intervention

The student correctly understood that negative beta decay is the decay in which its mass number unchanged and the atomic mass number of the daughter nucleus increased by one. He correctly understood that the origin of the electron emitted in the beta decay process is the decay of a neutron into an electron in the parent nucleus. The student also correctly understood that the electron doesn't exist in a nucleus before decay. The correct complete equation of the negative beta decay process is expressed by the student as the previous students.

At delayed post-intervention

The student had been retained his conceptual understanding and representation of negative beta decay.

3.5. Nuclear energy

At pre-intervention

The response of the student to the open-ended questionnaire about nuclear energy is inconsiderable.

At post-intervention

The student correctly understood that nuclear energy is the energy released in nuclear reactions and radioactive decay. The student also correctly understood that nuclear energy exists in the form of the kinetic energies of fission fragments. He correctly understood that its origin is the nuclear rest mass. He also attempted to describe how nuclear energy is transformed into electrical energy in a pressurized-water nuclear reactor.

At delayed post-intervention

The student had been retained his conceptual understanding of nuclear energy. At delayed post-intervention, the student expressed nuclear energy using the next equation, which wasn't expressed by him at post-intervention. He considered the Q-value or the energy released in a nuclear reaction as nuclear energy.

$$Q = \left(m_a + m_x - m_y - m_b\right)c^2$$

The responses of each of the 40 students at pre-, post-, and delayed post-intervention to the five concepts of nuclear physics were considered the same as that of the above three students.

I. Categorization and coding of the three students' conceptual understanding and representations of nuclear binding energy

The three students' conceptual understanding and representations of nuclear binding energy were analyzed following the seven steps of the phenomenographic data analysis process (see Section 3.10.1).Following step one to step three in the phenomenographic analysis process, the mistakes in the content of the responses of the three students were corrected. And the redundant or unnecessary responses of the students were omitted from the content of the students' responses. Finally, the most valued responses of the three students were identified at pre-, post-, and delayed post-intervention. Following steps, four to seven in the analysis process, the students' different ways of conceptual understanding and representations were categorized and coded at pre-, post-, and delayed post-intervention.

The different ways of students' conceptual understanding and representations of nuclear binding energy revealed using phenomenographic data analysis process were classified into critical and irrelevant aspects. Those students who didn't discern both aspects were considered non-respondent students. These non-respondent students are either didn't respond at all to the open-ended questionnaire or their responses were omitted. These classifications were done based on the variation theory of learning. The number of students who discerned the critical and irrelevant aspects of nuclear binding energy and the number of non-respondent students at pre-, post-, and delayed post-intervention is presented in the next table. The MRs used by three students at the three points are also presented in the table.

The number of students (NS) who discerned the critical and irrelevant aspects and the number of non-respondent students (NS) determined based on the responses of the above three students.

Students' categories of description	Pre-intervention N = 40	Post-intervention N = 40	Delayed post-intervention N = 40
Critical aspects	NS	NS	NS
A. The energy equivalent to the mass lost, when the free nucleons combine to form a nucleus	0	3	3
B. The energy released, when the free nucleons	0	2	2

combine to form a nucleus			
C. The energy that must be added to a nucleus to separate it into its constituent nucleons	2	2	2
D. The nuclear binding energy per nucleon of the stable nuclei changes with their mass numbers	0	2	2
E. The energy that can be affected by the volume, surface area, and Coulomb repulsive force of a nucleus according to a liquid-drop model	0	1	1
Irrelevant aspects	0	0	0
Non-respondent students	0	0	0
MRs used by students			
Equation (for critical aspect A)	0	3	3
Graph (for critical aspect D)	0	3	3
Diagram (for critical aspects B & C)	0	2 (B), 2 (C)	2 (B), 2 (C)

The categorization, coding, and presentations of the three students' conceptual understanding and representations of the other four concepts of nuclear physics were done the same as that of nuclear binding energy. These were also done based on the responses of the three students to the open-ended questionnaire about the four concepts.

II. Categorization and coding of the three students' conceptual understanding and representations of nuclear force

After categorized and coded the same as that of nuclear binding energy, the different ways of the three students' conceptual understanding and representations of the nuclear force are presented in the next table. The number of students (NS) at pre-, post-, and delayed post-intervention was determined based on the responses of the three students mentioned above.

Students' categories of description	Pre-intervention N = 40	Post-intervention N = 40	Delayed post-intervention N = 40
Critical aspects	NS	NS	NS
A. The force that binds nucleons to form a nucleus	0	3	3
B. The force that has particular properties. For instance, a short-rang, strong, charge independent, attractive, and repulsive properties	0	3	3
C. A force that causes a strong nuclear interaction mediated by the exchange field particles known	0	2	3

as pi-mesons			
D. A force that believed to be the residual effect of the more basic strong force that binds quarks together to form a nucleon	0	1	1
Irrelevant aspects			
E. A force that binds the nucleus of an atom and its orbiting electrons			
F. A force that binds quarks together to form a nucleon	0	1	1
Non-respondent students	2	0	0
MRs used by students			
Equation (for irrelevant aspect E)	1	0	0
Graph (for critical aspect B)	0	3	3

The categorization and coding of the three students' conceptual understanding and representations of radioactive decay, negative beta decay, and nuclear binding energy can be done the same as that of nuclear binding energy. This was done based on the above responses of the three students to the open-ended questionnaire about these three concepts of nuclear physics.

The different ways of the forty students' conceptual understanding and representations of the five concepts of nuclear force were categorized, coded, and presented in tables 6.1 to 6.5 the same as that of nuclear binding energy. The number of students (NS) at pre-, post-, and delayed post-intervention was determined based on the responses of forty students the same as the above two examples. To determine the number of students who discerned each of the critical and irrelevant aspects and the number of students who didn't respond or whose responses were omitted, a systematic counting technique was used.

As mentioned above the different ways of the students' conceptual understanding and representations of each of the five concepts of nuclear physics were revealed using phenomenographic data analysis process. And the nature of the students' conceptual learning and understanding was explained using the variation theory of learning. This theory explains the nature of conceptual learning and understanding based on the critical and irrelevant aspects of a nuclear physics concept discerned by students. Students who discerned more critical aspects of a nuclear physics concept could have a complete understanding and representation of the nuclear physics concept. Students who discerned more irrelevant aspects of a concept or who encountered more conceptual difficulties were less learned and understood the concept. Therefore, in this developmental phenomenographic study, the necessary conditions of learning for nuclear physics were identified and organized using the variation theory of learning. These necessary conditions of learning are the critical aspects of a nuclear physics concept discerned by students.

In this developmental phenomenographic study, there are two phases of the study. In the first phase of this study, the conceptual difficulties that the students encountered after traditional instruction were identified using phenomenography and variation theory of learning. In the second phase, these conceptual difficulties were addressed using the MRs based instruction with interactive learning tutorials designed based on the variation theory of learning. The findings of this study indicated that this instructional strategy is effective. Thus, the developmental phenomenography was intended to produce research outcomes that can subsequently be used to address a given educational issue (students' conceptual difficulties)(Green & Bowden, 2009).

APPENDIX IX: CERTIFICATE OF PARTICIPATION IN PAPER PRESENTATION

WOLAITA SODO UNIVERSITY

CERTIFICATE OF PARTICIPATION

This is to certify that Mr/Ms. Tafesse Kabtihymer has presented a research paper on the title "**Assessment of the Factors Affecting the Implementation of Practical Based Physics Learning: The Case of Some Selected Senior Secondary and Preparatory Schools in West Shoa Zone, Ethiopia.**" on the 6th Annual International Conference on Education in Ethiopia held at Wolaita Sodo University from April 02-03, 2016 with a theme`` Education in Ethiopia: Critical Issues Worth Considering with Regard to Access, Quality and Human Capital Development in GTP II Period ".

Therefore, Wolaita Sodo University has given this certificate of participation to acknowledge his/her contribution for the quality of Education.

Signature_____________

Dr. Mesfin Bibiso

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Institutional Quality Enhancement & Assurance Directorate Director

Signature_____________

Senbetie Toma Lachore (PhD)
President

APPENDIX X: EVIDENCE FOR THE PROFESSIONAL EVALUATION OF THE RESEARCH INSTRUMENTS

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DEPARTMENT OF PHYSIC

Ref. No: Dep/Phy/040/10
Date: 26/02/2018 G.C

To: Dr. Bekele Gashe (bekelega@yhaoo.com)
Mr. Dinberu Faji (dinbfg@gmail.com)
Mr. Abebe Gucho (abegucho12@gmail.com)
Ambo University

Subject: The content and face validity evaluation of the

(i) semi-structured face-to-face individual interview conceptual investigation questions and

(ii) open-ended conceptual investigation questionnaire of the concepts of Introductory Nuclear Physics

The Department of Physics, Ambo University, kindly requests you to cooperate with Mr. Tafesse Kabtihymer, a staff member of the Department who is currently conducting his PhD research on the title "Undergraduate Physics Students' understanding and representations of concepts in Introductory Nuclear Physics". You, therefore, cooperate with him in evaluating the content and face validity of the after mentioned research instruments of his PhD research study. In doing so, you will consider the following main points in your evaluation process.

1. Evaluating the protocol of the semi-structured face-to-face individual interviews.
2. Evaluating the adequacy of the open-ended questions in probing the students' conceptual understanding and representations of Introductory Nuclear Physics (level of difficulty) based on the syllabus.
3. Evaluating whether it fulfills the proposed objectives of the study or not.
4. Evaluating the clarity of the conceptual investigation questions and the appropriateness of the words and phrases used in the context of nuclear physics. Thank you for your cooperation!

With best regards!

Tolasa Adugna, PhD
Head, Department of Physics

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UNDERGRADUATE PHYSICS STUDENTS' UNDERSTANDING AND REPRESENTATIONS OF INTRODUCTORY NUCLEAR PHYSICS CONCEPTS

by

Tafesse Kabtihymer Atlabachew

I declare that I have edited and proofread the this thesis. My involvement was restricted to language usage and spelling, completeness and consistency and referencing style. I did no structural re-writing of the content.

I am qualified to have done such editing, being in possession of a Bachelor's degree with a major in English, having taught English to matriculation, and having a Certificate in Copy Editing from the University of Cape Town. I have edited more than 200 Masters and Doctoral theses, as well as articles, books and reports.

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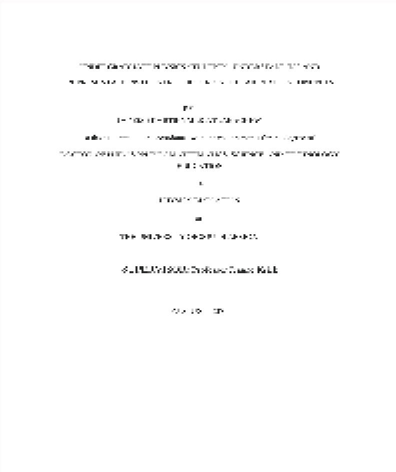

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UNDERGRADUATE PHYSICS STUDENTS' UNDERSTANDING...
By Tk Atlabachew

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APPENDIX XIII: CURRICULUM VITAE OF THE RESEARCHER

THE RESEARCHER'S CURRICULUM VITAE

I. Language Proficiency

Language	Reading	Writing	Speaking
Amharic	Excellent	Excellent	Excellent
English	Very good	Very good	Very good
Affanoromo	good	good	good

II. Educational qualifications

Educational Qualification	Year of study	Study schools/University
MSc degree in physic	2008 - 2010	Addis Ababa University, Ethipia
BSc degree in physics	1984 - 1987	Addis Abba University, Ethiopia
Grade 9 - 12	1980 - 1983	Arbegnoach High School, Ethiopia
Grade 7 - 8	1978 - 1979	Guna Junior School, Ethiopia
Grade 1 - 6	1972 - 1977	Mine Elementary School, Ethiopia

III. Trainings

Type of training	Time of training	Pace of training
Training on School of Nuclear Security	7 May – 18 May 2012	Trieste Italy
Training on Higher Diploma Program	2011/2012 (for 1 year)	Ambo University, Ethiopia
Training on Student Centered Teaching Methods and Continuous Assessment	October, 2010 (for five days)	Ambo university, Ethiopia
Training on leadership course	4 – 6 June 2007	Arsi Negelle, Ethiopia
Training on instructional language for physics teachers	7August – 7 September 2006	Haramaya University, Ethiopia
Training on English language improvement program	2 – 17 February 2001, 7 – 22 July 2001	Shashemene, Ethiopia
Training on basic computer course	7 November – 22 April 2002	Arsi Negelle High School, Ethiopia

IV. Work Experience

Work experience	Working time	Work place
Lecturer in physics	2010 – 2021	Ambo University, Ethiopia
College academic commission member	2014 - 2021	Ambo University, Ethiopia
High School Physics teacher	2002 – 2007	Arsi Negale, Ethiopia
High School Physics Department Head	1998 – 2006	Arsi Negelle, Ethiopia
High School Unit Leader	1996 – 1997	Arsi Negelle, Ethiopia
Academic vice director	1992 – 1994	Arsi Negelle, Ethiopia