Epicurus On Swerving Atoms: A Modern Scientific Appraisal

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Abstract

In an effort to distance himself from the Democritan conception of the atomic particle, Epicurus posited three essential characteristics to explain the movement of atoms in the void — mass, velocity and something that has puzzled ancient and modern thinkers, called the klinamen*. This occurrence was an hypothesized shift in the linear trajectory of an atom at an entirely unexpected and random point in time, and explains how compounds came to be formed in the Epicurean universe, where atoms fall unhindered in parallel to one another. I argue that the* klinamen *is not an entirely random occurrence but is instead a phenomenon predicated upon the laws of modern physics, the Newtonian laws of motion and gravitation in particular. I further posit that the* klinamen *is an entirely necessary aspect of the development of the universe from its initial origins of 'atoms and void' (Epicur. Phys. 1.13,14; Ep. Hdt. 39).*

In developing the early Greek knowledge of atoms, and in shifting away from its earlier Democritan conception,[1] Epicurus put forward the idea that atoms moved through the 'void' because of three essential factors—their specific mass, their individual velocity, and the *klinamen*,[2] an unpredictable swerve that brought atoms crashing into one another and thereby allowed for the formation of compounds.[3] This concept of the *klinamen* has long troubled readers of philosophy. However, through the application of modern particle physics an explanation of this strange concept can be crafted in a manner that has been impossible until recently. It may then be plausible to vindicate the entirely intuitive reasoning of Epicurus through modern scientific thinking and thus prove that something as apparently outlandish as randomly swerving atoms does indeed occur. I intend to pursue this argument primarily through the use of a modern understanding of gravitational field effects and will in this way attempt to reconcile the ancient theories of Epicureanism, as propounded by Epicurus, the movement's founder, and Lucretius, the movement's Latin poet, with a modern discussion of atomic motion.

The ancients never truly had a concept akin to our understanding of the Universe, with its galaxies, nebulae, black holes and exotic particles. While modern science offers the Big Bang as the starting point for all things, the Greek philosopher Epicurus suggested something a little different. Central to his theory is the doctrine of the *klinamen* or 'swerve', which explains how atoms freefalling in parallel are suddenly able to combine to form the basic elements of the universe. There is no explicit mention of the *klinamen* in the surviving work of Epicurus, but it is always apparent in his approach to atomic motion. The idea was later amplified to its fullest extent by Lucretius. Epicurus does however staunchly defend the notion of free will, the corollary to which the concept of the *klinamen* has been extensively applied. This psychological interpretation of the swerve is characterized by Russell as obviating 'the greatest charge of psychological determinism against the atomist, namely that the rigid necessity of atomist physical systems implies that genuine agency is impossible.'[4] However, when it is viewed from a purely physical perspective, the *klinamen* becomes a vital element of Epicurus' atomic processes. This is especially true if one takes into consideration that Epicurus most likely designed his system while keeping Artistotle's critique of early Atomism[5] foremost in his mind.[6] It is thus probable that 'Epicurus posited the swerve as a third kind of motion, and had already done so when he wrote the works that survive to us. But he did not advertise his endorsement of this positive doctrine'.[7] This is confirmed by the Roman poet and Epicurean, Lucretius (*DRN* 2.284-287),[8] who writes:

> Quare in seminibus quoque idem fateare necessest, (284)
>
> Esse aliam praeter plagas et pondera causam
>
> Motibus, unde haec est nobis innata potestas,
>
> De nilo quoniam fieri nil posse videmus. (287)
>
> 'Wherefore in the seeds too you must needs allow likewise that there is another cause of motion besides blows and weights, whence comes this power born in us, since we see that nothing can come to pass from nothing.' (tr. Bailey 1947)

In stark contrast to the modern Big Bang, Epicureanism paints the picture of a perfectly ordered beginning to the universe with all atoms falling in neat parallel lines, never making contact with one another (Epicur. *Ep. Hdt.* 43-44, see pg. 47-49 when I deal with this specific extract in more detail). Therefore, without the essential process of the *klinamen* the universe, from an Epicurean perspective, could not exist at all, as this atomic swerve is required to induce physical contact between atoms that would otherwise travel unobstructed through the void. Finally, the *klinamen* could perhaps be viewed as a foreshadowing of the entropic theories of modern

thermodynamics, whereby the entropy contained within a given system is always believed to increase, thus explaining the shift from an ordered Epicurean beginning to the current state of our ever-expanding universe.

The Way Things Move

Epicurus (Sext. Emp. *Adv. Dogm.* 3.333; Plut. *Adv. Col.* 1112e10) describes the elemental beginning of the universe as being composed of both 'bodies' (σώματα) and 'void' (κενόν) or rather, atoms and void. The Epicurean universe started off its life as a vast nothingness—the 'void'—populated exclusively by elements called 'atoms' that simply fall indefinitely through space. In distancing himself from the earlier atomic theories of Democritus, Epicurus made several important distinctions, explaining that atoms have three essential qualities—'weight, shape, and size'. This was an expansion of the two qualities that Democritus had posited.[9] Democritus had not suggested 'weight' as an essential element of the atom, stating instead that atoms were moved through the void by the collisions that took place between them (Simp. *in Ph.* 42.10).[10] The Epicurean counter to this idea was to assert that 'weight' is, in reality, a characteristic inherent in all atoms, something that endows them with their own capacity for motion without the need to rely solely upon the possibility of random collisions.

According to the laws of physics, in an environment in which there is frictional resistance to the passage of an object (i.e. not in vacuum), all three qualities of weight, size and shape, contribute to the flight characteristics of an object as it falls. The overall size and shape create a profile against which resistance operates, while the object's inherent mass is acted upon by the constant force of gravity which in turn imparts a certain velocity to the object. However, the significant term to be noted in the Epicurean description of the situation is κενός or 'void', a space in which there can be no friction, because there is nothing within the void except the atoms themselves. Logically, then, only the characteristic of mass truly has any effect on the motion of an Epicurean atom, as it is the only quality that remains constant, regardless of whether or not there is any frictional resistance involved. Size and shape can obviously be removed from any calculations because of the fact that they would only influence the object's flight in an environment in which friction occurred. Lucretius describes the void by saying that it is in essence quite similar to the water through which fish swim everyday of their lives (*DRN* 1.370-383). Water, like void, has a specific function, in that it provides the medium through which fish, and atoms, may move. As Epicurus (*Ep. Hdt.* 40) put it, if there were no void, atoms would have 'nowhere to exist and nothing through which to move…'. Lucretius (*DRN* 2. 83-85) then discusses the motion of the atoms through void:

nam quoniam per inane vagantur, cuncta necessest (83)

aut gravitate sua ferri primordia rerum

aut ictu forte alterius. (85)

'For since they wander through the void, it must needs be that all the first beginnings of things move on either by their own weight or sometimes by the blow of another.' (tr. Bailey 1947)

Lucretius' choice of the verb *vagari* (*DRN* 2.83) for describing the way in which the atoms move, is significant. Fowler tells us that Lucretius makes use of this term because he is attempting to emphasize the fact that atoms can travel in any direction, as they find themselves to be surrounded by an infinite nothingness.[11] Additionally, while *gravitas* (i.e. the individual mass of an atom), mentioned above in *DRN* 2.84, is always a component of any motion that the atoms are involved in, there is only a probability that the atoms may strike one another. This is revealed in the Lucretian use of the word *forte* (*DRN* 2.85) to describe the random nature of one atom striking another. However, later on in *DRN* 2.225-229, Lucretius explains that it is not solely the atom's individual mass that causes the collisions of which he speaks:

Quod si forte aliquis credit graviora potesse (225)

corpora, quo citius rectum per inane feruntur,

incidere ex supero levioribus atque ita plagas

gignere, quae possint genitalis reddere motus,

avius a vera longe ratione recedit. (229)

'But if perchance anyone believes that heavier bodies, because they are carried more quickly straight through the void, can fall from above on the lighter, and so bring about the blows which can give creative motions, he wanders[12] far away from true reason.' (tr. Bailey 1947)

Clearly, the contention is that mass, although sufficient to propel atoms through the vast void, is insufficient to cause any of them to strike one another without the aid of an outside force, given that the atoms (1) are all falling in straight lines to begin with, and must therefore be parallel to one another and (2) are not accelerating or decelerating, but moving under the influence of the constant force of gravity.[13] This is a particularly interesting element in Epicurean physics, as the Epicureans are probably amongst the first philosophers before Galileo to suggest that an object in freefall descends at a rate of speed that is invariant with respect to the object's mass or, more simply, that objects in freefall move solely under the influence of gravity (any frictional resistance aside).[14] Furthermore, if both the size (which

includes the relative mass) and shape of atoms are insufficient to motivate the required shift from an apparently ordered parallel descent through the void to the chaos of atoms crashing into one another for the production of compounds (the process of accretion), what else, then, is necessary?

Explaining the Swerve

At this point, the *klinamen* enters into the equation, as the hypothesized and entirely unexpected swerve of an atom previously in a state of uniform motion. Lucretius notes the components that are essential for forming an understanding of this concept as being that the *klinamen* occurs during an atom's downward[15] trajectory, a path that is assumed to be caused due to the mass of the atom, that the *klinamen* is an extremely small movement,[16] and that this motion can take place at any time. Several ancient philosophers like Plotinus (*Enn.* 3.1.1.15) argued against this idea, refusing to believe that an event with no apparent cause could motivate atoms to swerve so suddenly:

> οὔτε παρεγκλίσεσι κεναῖς χώραν διδόντα οὔτε κινήσει σωμάτων τῇ ἐξαίφνης, ἣ οὐδενὸς προηγησαμένου ὑπέστη…
>
> '…we must leave no room for vain "slants" or the sudden movement which happens without any preceding causation'. (tr. Armstrong 1967)[17]

Original evidence stemming directly from Epicurus himself is impossible to find, but evidence can be inferred from his various statements on atomic motion, discussions that were clarified and expanded by later adherents like Lucretius. In this vain, Bailey suggests the following reconstruction of a severely fragmented section of the work of Epicurus[18]:

> Κινοῦνται τε συνεχῶς αἱ ἄτομοι τὸν αἰῶνα καὶ αἱ μὲν <κατὰ στάθμην, αἱ δὲ κατὰ παρέγκλισιν, αἱ δὲ κατὰ παλμόν. τούτων δὲ αἱ μὲν φέρονται> εἰς μακρὰν ἀπ᾽ ἀλλήλων διιστάμενοι, αἱ δὲ αὐτοῦ τὸν παλμὸν ἴσχυσιν, ὅταν τύχωσι τῇ περιπλοκῇ κεκλειμέναι ἢ στεγαζόμεναι παρὰ τῶν πλεκτικῶν.
>
> 'And the atoms move continuously for all time, some of them <falling straight down, others swerving, and others recoiling from their collisions. And of the latter, some are borne on> separating to a long distance from one another, while others again recoil and recoil, whenever they chance <to be checked by the interlacing with others,> or else shut in by atoms interlaced around them.' (*Ep. Hdt.* 43-44, tr. Bailey 1970)

It is unfortunately in the lacunae that Bailey must conjecture Epicurus' description of the *klinamen*. By contrast, Lucretius seems to be relating

something that was indeed previously extant in Epicurean philosophy at the time of his writing the *De Rerum Natura*, as he does indeed directly describe the *klinamen* (*DRN* 2.243-250):

> quare etiam atque etiam paulum inclinare necessest
>
> corpora; nec plus quam minimum, ne fingere motus
>
> obliquos videamur et id res vera refutet. (245)
>
> namque hoc in promptu manifestumque esse videmus,
>
> pondera, quantum in sest, non posse obliqua meare,
>
> ex supero cum praecipitant, quod cernere possis.
>
> sed nil omnino <recta> regione viai
>
> declinare quis est qui possit cernere sese? (250)
>
> 'Wherefore, again and again, it must needs be that the first-bodies swerve a little; yet not more than the very least [a minimum], lest we seem to be imagining a sideways movement, and the truth refute it. For this we see plain and evident, that bodies, as far as in them lies, cannot travel sideways, since they fall headlong from above, as far as you can descry. But that nothing at all makes itself swerve from the straight direction of its path, who is there who can descry?' (tr. Bailey 1947)

Here it appears that the Epicureans foreshadow the thesis of Newton by suggesting that even on the atomic level an unbalanced force is required to alter the existing trajectory of an object in motion. Moreover, Epicurus does tell us that something like the *klinamen* must be inherent to his postulated atoms—not a force external to them, but part of their very nature, because there is nothing outside of the universe that is capable of inducing changes within it. As he writes to Herodotus (*Ep. Hdt.* 39. 3-6):

> Καὶ μὴν καὶ τὸ πᾶν ἀεὶ τοιοῦτον ἦν οἷον νῦν ἐστι, καὶ ἀεὶ τοιοῦτον ἔσται. οὐθὲν γάρ ἐστιν εἰς ὃ μεταβαλεῖ. παρὰ γὰρ τὸ πᾶν οὐθέν ἐστιν, ὃ ἂν εἰσελθὸν εἰς αὐτὸ τὴν μεταβολὴν ποιήσαιτο.
>
> 'Furthermore, the universe always was such as it is now, and always will be the same. For there is nothing into which it changes: for outside the universe there is nothing which could come into it and bring about the change.' (tr. Bailey 1970)

However, it is evident from the above passages that Epicurus did have a cause in mind to provoke the *klinamen*, and thus we can now set down a more accurate Epicurean conception of atomic motion: (1) Epicurean atoms

have mass and, (2) they are moving at a particular velocity that is constant for all postulated atoms everywhere and at all times in the universe. Lucretius paints a poetic image of the speed at which atoms travel (*DRN* 2. 161-164):

> debent nimirum praecellere mobilitate (161)
>
> et multo citius ferri quam lumina solis
>
> multiplexque loci spatium transcurrere eodem
>
> tempore quo solis pervolgant fulgura caelum. (164)
>
> 'they… must needs, we may be sure, surpass in speed of motion, and be carried far more quickly than the light of the sun, and rush through many times the distance of space in the same time in which the flashing light of the sun crowds the sky.' (tr. Bailey 1947)

This passage, when coupled with the extract from Lucretius (*DRN* 2. 225-229) discussed above, quite clearly states that all atoms share one common but incredibly swift velocity.[19]

Atoms and Gravitational Energy

Having analyzed the Epicurean understanding of atomic motion, we now move to reinterpret it in the light of modern theoretical physics. Consider the Newtonian equation for gravitation, $F = G(m1.m2/r^2)$, wherein the gravitational force that is evident between two solid objects (even between two tiny atomic particles) is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers, all in relation to the Universal Gravitational Constant. Similarly, standard relativity posits that 'just as a moving charge generates a magnetic field, so a moving mass should generate a gravitational field.'[20] The fact that the Epicurean concept of atomic motion states that atoms have mass and are traveling at a predetermined (albeit extremely high) velocity, necessarily indicates that even entities as minute as Epicurean atoms would, according to the standards of modern physics, generate some level of gravitational attraction by virtue of their possessing both the mass and velocity required. Furthermore, according to Heisenberg's Uncertainty Principle, it is impossible to simultaneously measure both the velocity and position of a particle at any given time. If, by extension, this is also true of Epicurean atoms, generating their minute gravitational field, then even through the application of modern methods, it would still be impossible to accurately predict the occurrence of the *klinamen*, because we can never conclusively and continuously measure both the velocity and position of an

Epicurean atom. We can, however, following the *reductio ad absurdum* of Lucretius, observe the effects of the movement of these atoms. As Englert summarizes, because we can see that compounds exist, and given that the Epicurean universe originated in ever-falling atoms that never make contact with one another, we can be quite certain that either some event took place or some process exists in order to bridge the gap from atoms drifting without purpose in the void to fully assembled forms of life. This is the *klinamen*.[21]

The nature of this gravitational force is still, however, quite weak. As each atom is generating an attractive force, it is ultimately capable of drawing another atom toward it when they are in proximity to one another—hence the *klinamen* occurs and atoms shift very slightly in their trajectories. A more visual representation of the *klinamen* can be found in the occurrence of laminar fluid flow. Essentially laminar flow is indicative of a situation of perfectly ordered liquid flow (or the beginning of the Epicurean universe) over a particular surface in a totally uniform and unimpeded manner (atoms falling perfectly in parallel to one another). However, as time passes entropy builds up within the system to such an extent that the laminar flow disintegrates into random swirls of liquid. The *klinamen* can thus be perceived as a means of explaining why this phenomenon occurs.[22] The disintegration of laminar flow can also be said to be a visible representation of the Second Law of Thermodynamics, which states that 'the entropy of an isolated system always increases.'[23] To explain why this is useful in the Epicurean context, the *klinamen* must be conceived as a very early expression of this same scientific principle. The Universe is certainly an isolated system, and therefore within its boundaries there will tend to be a greater state of chaos and disorder after any given event than there was before it, and ultimately, everything in the universe is proceeding towards greater chaos and disharmony, and the eventual breakdown of the system as a whole. So it is with the *klinamen*.

The Epicurean universe began with perfectly harmonious falling atoms travelling in parallel to one another. The continuing proximity of these atoms to each other, with each bearing its own minute gravitational field and thus a force of attraction, eventually disrupted the orderly linear motion of the atoms, leading to a pronounced swerve—a shift in trajectory—for some, and the occurrence of the first compounds as the atoms crashed into one another and combined.[24] Logically, the *klinamen* must therefore be occurring continuously as the force of gravity is ever present.

This explicitly contradicts the position held by Furley[25], who would argue that these atomic swerves can only occur with extreme rarity. As it stands, one atom that swerves in a barely perceptible manner from its previous course would necessarily result in an increasing cascade effect that would spread larger and larger deviations throughout the void in which the

atoms are traveling, ultimately resulting in deviations on a grand scale that are sufficient to at last cause compounds to be formed.[26]

However, while it has generally been assumed that the *klinamen* represents an oblique shift in trajectory from the parallel path of all atoms, this is not actually the case according to the Epicureans.[27] Epicurus in his *Letter to Herodotus* (56-59) addresses the notion of *minima* in atomic motion in order to counter certain criticisms posed by Aristotle. Following these arguments, Lucretius notes that the size of this atomic movement is no more than one *minimum* or ἐλάχιστον (*DRN* 1.609-614), 'a measure that is equal to the size not of an atom, but one of its parts.'[28] This makes it impossible for the *klinamen* to represent a slight and continuous shift in trajectory, with the logical explanation then being that, due to the influence of an atom's weight (i.e. mass influenced by gravitational acceleration) it shifts trajectory in a stepwise pattern, essentially shifting at right angles before resuming a downward path.[29] Unfortunately, this analysis runs counter to Newtonian principles of motion, which state that an object in motion will not change its trajectory unless acted upon by an external force. In order for an Epicurean atom to resume its previous path following the occurrence of the *klinamen*, it must therefore either strike another atom at precisely the angle and velocity necessary to return it to its original course, or there must be two consecutive occurrences of the *klinamen*! This is almost certainly impossible. Therefore, as long as the mass of an atom remains constant, the basic equation for motion, $F = ma$, in essence defines the weight of an atom. $F = ma$ represents the force an object exerts (for example, one atom striking another in the void) as being the product of its mass and its acceleration. Acceleration is the tricky part of this equation, as it is in some sense dependent on an atom's position relative to other atoms, because they all exert a gravitational force upon one another, based in some part on their proximity. Thus the fact that mass remains constant for an atom regardless of whether it is passing through void or earth's atmosphere is important, not only because this characteristic determines how much energy is imparted in any given collision between atoms, but also because the relative mass of an object in space (e.g. an atom) determines it capacity for warping surrounding space-time with its gravitational field and thereby hindering the motion of other objects.

Up or Down?

Stocker makes an interesting point in connection with the falling of Epicurean atoms. He states that while Epicurus views the atoms as proceeding in a downward direction due to their inherent mass, an entirely logical inference since the Epicureans could only generalize from their own

experience of earthbound gravitational effects, he 'does not seem to have stopped to consider that in infinite space (i.e. within the κενός) there could be no "up" or "down".'[30] Does directionality then make any difference to the path of multiple objects as they pass through nothingness?

I do not believe that the direction in which an atom falls has any impact at all, especially if one considers that we are describing a limitless and utterly vacant three-dimensional space in which these atoms are moving. As the atoms have nothing, save themselves, to interact with, there can be no justification for their falling downwards (or shooting upwards for that matter) as having any impact upon the actual physics of their movement.[31] Furthermore, directionality is in no way a component of the Newtonian equation for gravitation and can therefore have no discernible effect on the atoms.

In fact, Deutsch notes that the rectilinear atomic motion propounded by Epicurus, along with his postulated *klinamen*, are both indicative of modern scientific principles—Newton's laws of motion and Einstein's general relativity theory.[32] This is because, as Newton's First Law states, motion tends to continue uniformly unless an external force intervenes, something that is evident in macrocosm in astrophysics, which demonstrates that objects passing by large masses in space (e.g. stars and planets), necessarily follow curved trajectories, as the gravitational field around these massive objects is so enormous that it bends them away from their normal path of linear motion. In microcosm this behaviour is evidenced in the gravitational effect that is visible in the motion of postulated Epicurean atomic particles.

Thus it is demonstrable, through the use of modern scientific principles, that the notion of swerving atomic motion postulated by Epicurus and chronicled by his follower, Lucretius, is a viable description of the reality of particle motion, as we understand it today. Using purely intuitive reasoning Epicurus was able to suggest an idea—the *klinamen*—that could be validated only after science had advanced almost two and a half thousand years beyond his own time and capabilities. Because of its inherent properties, the Epicurean atom is capable of shifting its trajectory (i.e. swerving) in an effort to begin the processes that eventually resulted in the formation of the very first compounds. This procedure is governed by the laws of modern particle physics and predicted by the Newtonian laws of motion. However, and precisely as Epicurus stated, the *klinamen* itself can never be accurately predicted (c.f. Heisenberg's Uncertainty Principle), adding an element of chaos and unpredictability into the mix that was even extended from the realm of physics into the universe of psychology.

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1. Because even ancient opinion was divided on what Democritus described as properties of his atoms, there are three scholarly perspectives on atomic weight and motion that need to be considered: (1) Atoms possess the property of 'weight' but it is non-relational and is responsible for imparting motion to the atom; (2) Atoms possess the property of 'weight' but it is more akin to the notion of mass, and thus influences velocity but in no way imparts a particular directionality to motion; (3) Atoms do not have the inherent property of 'weight'. Rather this is something that is generated in relation to other atoms as they combine and results instead from size and shape (Englert 1987: 30-31).

2. In common parlance 'weight' and 'mass' often appear to be interchangeable, although for scientific purposes 'mass' is invariant, whereas 'weight' depends upon relative velocity. For the purposes of this paper I shall maintain the scientific usage of these terms as far as is possible.

3. See Lucretius (*DRN* 2.218-219, 2.293) wherein he states that it is impossible to predict the occurrence of the swerve either temporally or spatially.

4. 2000: 227.

5. For the early Atomists only collisions between atoms were important for the purpose of motion:

οὗτοι γὰρ (sc. Λεύκιππος καὶ Δημόκριτος) λέγουσιν ἀλληλοτυπούσας καὶ κρουομένος πρὸς ἀλλήλας κινεῖσθαι τὰς ἀτόμους.

'For they (sc. Leucippus and Democritus) say that atoms move by mutual collisions and blows.'

6. Englert 1987: 35-62.

7. Purinton 1999: 295.

8. I shall henceforth make use of the addreviation *DRN* in order to designate Lucretius' *De Rerum Natura*.

9. Farrington 1969: 112-113.

10. Δημόκριτος φύσει ἀκίνητα λέγων τὰ ἄτομα πληγῇ κινεῖσθαί φησιν.

'Democritus, saying that all the atoms are naturally motionless, asserts that they are moved by a blow.'

11. Fowler 2002: 168.

12. In this particular context, Bailey's rendering of avius (*DRN* 2.229) can perhaps be intensified to 'led astray' as opposed to simply 'wander from'. The implication is then one of the philosopher actively being led from the true path by a false assumption.

13. Note that this force of gravity is constant throughout the universe, and is not the standard 10m.s.s gravitational acceleration experienced by people and objects on earth, an acceleration that is based upon Newton's equation for gravitation, $F = G(m1.m2 / r^2)$.

14. Because of the fact that the force exerted by gravity upon different objects is constant, they are therefore accelerated at the same speed regardless of their mass, as Galileo determined in his experiments from atop the tower of Pisa.

15. In the nothingness of the void, the notions of up and down are for the sake of argument more than directionality (see pages 51-52).

16. As Lucretius has it, *spatio depellere paulum* (*DRN* 2.219), 'they push a little from their path'.

17. See also Cicero's *De Fato* 18, 22-25, 46-48; *De Natura Deorum* 1.69 and *De Finibus* 1.19 for other similar criticisms of the *klinamen*.

18. 1970: 24-25, 186-187.

19. It must be remembered that Lucretius is not advocating that something can move faster than the speed of light. He is utilizing his poetic ability to depict something that the Graeco-Roman mind could not possibly fathom.

20. Richmond 2000: 158.

21. 1987: 15.

22. Prigogine & Stengers 1985: 141.

23. Hawking 1989: 108.

24. Richmond (2000: 227) makes use of the process of crystallization as a means of

explaining the formation of compounds, stating that 'once a durable arrangement of molecules in solution arises, it will bring its neighboring, undifferentiated molecules into alignment with it.' There is therefore a natural tendency of atoms toward combining into compounds, creating order from chaos as it were. It is also interesting that the electromagnetic bonds between atoms that are being described here are extremely weak, and without other forces (e.g. electrochemical bonds) the atoms would have a tendency to break apart, illustrating the Epicurean belief that all substances eventually disintegrate into their original particle state (*Ep. Hdt.* 41).

25. 1967: 161-237.

26. The best illustration of this fact is the example of the particle dispersion that takes place in a fission reaction. Portions of an atom that have been 'split' off fly out in random directions and collide into other nearby atoms, creating the explosive energy of the nuclear reaction.

27. Englert 1987: 17-25.

28. Englert 1987: 22.

29. Englert 1987: 23-24.

30. 1948: 398.

31. Epicurus (*Ep. Hdt.* 41.9-10) notes the boundless nature of this void: Καὶ μὴν καὶ τῷ πλήθει τῶν σωμάτων ἄπειρόν ἐστι τὸ πᾶν καὶ τῷ μεγέθει τοῦ κενοῦ. 'Furthermore, the infinite is boundless both in the number of the bodies and in the extent of the void.'

32. 1945: 100.