What Goes Around Comes Around: Elements and Elementary Particles

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To understand motion and change we must understand its causes. The modern science of chemistry began with the search for the material causes of natural substances. The first of these causes are the elements. To understand how the elements function as causes of motion and change, one must also discover their essential powers or active qualities. According to Aristotle, Plato and the medieval tradition, there were four elements (earth, water, air, fire) and two pairs of contraries which served as their active qualities (hot and cold, moist and dry). But with the development of modern chemistry, the number of elements was increased to more than one hundred, and ideas about their active powers remained vague for a long time. The power associated with chemical change went by the name of "affinity," and eventually by the name "valence," but it was not at first clear whether affinity could be reduced to measure, or whether it could in any way explain chemical change. As for the properties exhibited by the

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various elements, one was mostly at a loss as to how to explain them. In the proliferation of elements with inexplicable properties, and with the failure to see within them the active principles by which they could act upon each other so as to become something new, the theory was in some respects less satisfactory than the four element theory of old.

The overcoming of these deficiencies came about principally through two discoveries. The first involved the discovery of the role of positive and negative electricity in chemical change, and the second in the discovery that the chemical elements are not irreducibly simple. The discovery of the prior material causes and their electrical properties was the key to understanding chemical action, and this led to the conversion of chemistry from a mere science of phenomena to a science based upon causes. Tonight I will give you an outline of the history of the discovery of the material causes of the chemical elements. I will compare them both to the elements proposed by Aristotle and to the elemental atoms of the early modern chemists and the Newtonian physicists. I will argue that they resemble Aristotle's elements in certain important respects, and that they are very unlike the atoms of Dalton and Newton.

Let us begin with the definition of "element." The meaning of element is set out by Saint Thomas, who quotes Aristotle then comments in his usual clear fashion on the definition. "Whence Aristotle, in the fifth book of the *Metaphysics*, says that an element is 'that from which a thing is first composed, and is in it, and is not divisible according to form.' "[1]

The elements compose the thing, therefore they are material causes. Moreover, they are the first material causes, that is, first with respect to nature. The fact that the element is the first material component is closely related to the fact that

[1] Saint Thomas Aquinas, *On the Principles of Nature*, c. 3, n. 21, quoted from the translation by Christopher DeCaen in *Sophomore Laboratory Manual: An Introduction to the Atomic Theory*, Thomas Aquinas College, 2005–2006 edition, p. 10.

it is not divisible according to form. This phrase means that its form is simple, and the form belongs to the element in its entirety. If gold is an element, then every part of a lump of gold is gold. Saint Thomas explains that this qualification is added to rule out some false suppositions, for example, that hands are elements. Someone might think that they are among the first components of the human body. But hands are made of flesh and bones—so they clearly are divisible in respect to form. Flesh and bones, or whatever like that is not divisible in respect to form, will be the elements. It might be worth noting in this context that it makes sense to speak of elements in a relative way. The living body has elements of its own, which are first in the science of biology, and these are not the same as the elements of natural body as such.

By saying that the elements are "in" the thing, Aristotle means that they are not corrupted when the thing is generated—rather, they remain in it, albeit in a virtual way, not actually. For example, when oxygen and hydrogen are put in a container and are made to combine by means of an electrical spark, producing water, these are present in the water in a different way than when they were simply mixed. This is evident from the new properties of water, which is neither breathable like oxygen, nor flammable like hydrogen. But neither have they been entirely destroyed, because they may be recovered from the water, in the same proportion in which they were combined. Thus Saint Thomas says that they are virtually present.

Saint Thomas points out that, although the elements are not divided according to form, being indivisible in quantity is not part of their definition. That is, it is not part of the nature of an element to be an atom. But is it possible that the elements are atoms? A related question is, are the elements indestructible? Since atoms are indivisible, it seems that they are also immutable in every respect. But if the elements are not atomic in nature, one still may ask whether or not they come to be and pass away.

Aristotle and Saint Thomas give compelling arguments against the atomic composition of the elements, especially by showing that this leads to a denial of substantial change. Powerful arguments are also given against the void, which seems to be an essential part of the doctrine of atoms. On the other hand, the chemists following Dalton show the usefulness of the notion of atoms for explaining chemical change. The physicists also find the atomic hypothesis useful for explaining heat, change of state, and the physical properties of substances. The supposed immutability of the atoms exercises a strong appeal as well for those who seek to understand the constancy of natural law and the conservation of mass and electrical charge. The idea that everything in the universe is made up of a constant number of atoms with immutable properties thus has an almost irresistible appeal to the chemist or physicist.

Atomism as a characteristic idea of modern science may be summed up in two texts. Isaac Newton writes in the *Opticks*:

> All these things being considered, it seems probable to me that God, in the beginning, formed matter in solid, massy, hard, impenetrable and moveable particles, of such sizes and figures, and with such other properties, and in such proportions to space, as most conduced to the end for which He formed them; and that these primitive particles, being solids, are incomparably harder than any porous body compounded of them, even so very hard as never to wear or break in pieces; no ordinary power being able to divide what God has made one in the first creation. . . . And therefore that nature may be lasting, the changes of corporeal things are to be placed only in the various separations and new combinations of these permanent particles. . . .[2]

Dalton speaks for the chemists in *A New System of Chemical Philosophy*:

[2] Isaac Newton, *Opticks*, Query 31, in *Great Books of the Western World*, (Chicago: 1952), vol. 34, p. 541.

> Chemical analysis and synthesis go no farther than to the separation of particles one from another, and to their reunion. No new creation or destruction of matter is within the reach of chemical agency. We might as well attempt to introduce a new planet into the solar system, or to annihilate one already in existence, as to create or destroy a particle of hydrogen. All the changes which we can produce consist in separating particles that are in a state of cohesion or combination, and joining those that previously were at a distance.[3]

These texts express quite well the most problematic assumptions of atomic theory: that all change consists merely in the rearrangement of discrete parts, which parts themselves are incapable of change. These parts, moreover, are separated from each other and act upon each other in some mysterious way through the void. This action is understood to come about through force, whether gravitational force, the force of chemical affinity, or electrical attraction.

According to the doctrine of Newton and Dalton, the atoms are immutable. But even if the elementary substances are not atomic in nature, will they not still be changeless in their form? Not so, according to Aristotle. Because they themselves have as their principles both form and matter, they are capable of generation and corruption. Concerning the principles of perceptible bodies, Aristotle writes in Book II of *De Generatione* that "as principles we have *firstly* that which is potentially perceptible body, *secondly* the contrarieties (I mean, e.g., heat and cold), and *thirdly* Fire, Water and the like. For these bodies change into one another (they are not immutable as Empedocles and other thinkers assert, since alteration would then have been impossible), whereas the contrarieties do not change."[4]

[3] John Dalton, *A New System of Chemical Philosophy*, (Manchester, England: 1808), Part I, Chapter 3, as quoted in *Sophomore Laboratory Manual: An Introduction to the Atomic Theory*, Thomas Aquinas College, 2005–2006 edition, p. 134.

[4] Aristotle, *On Generation and Corruption*, II, 1, 329a31, trans. H.H.

Here we see that there *are* unchanging principles—the contraries—but the elements must be able to change. Plato also supposes that the elements are able to transform into each other. In the *Timaeus*, he associates a regular solid with each element: earth with the cube, water with the icosahedron, air with the octahedron and fire with the pyramid. These solids are themselves constructed of two types of right triangle, an isosceles and a scalene.[5] These correspond to the contraries of Aristotle, in the sense that they are formal and unchangeable principles. The notable difference is that Aristotle looks to active powers to define the elements, while Plato looks to symmetrical mathematical forms. I believe that both these ideas have a role to play in our understanding of the modern theory.

My claim here is that Newton and Dalton are fundamentally in error in the texts recently quoted, not only from the point of view of sound philosophy, but even from within the very science which they helped to found. I will argue that their opinion is false by examining the nature of the most fundamental constituents of material substance, as they have become known through experiment and theory in the twentieth century. Moreover, I will argue that classical atomism is incorrect, even if there exist particles more fundamental than those which have been discovered. Finally, I will suggest some ways in which the Perennial Philosophy can be helpful for interpreting the modern theory of elementary particles.

The time has come for me to explain what is meant by the phrase "elementary particle." Since there is no agreed-upon formulation,[6] I will propose my own definition: "an elementary particle is a sub-atomic thing which not composed of other things simpler in nature." No doubt this definition can be improved, but it will do for now. I do want to explain it to you, in some detail. First, I call them "sub-atomic" to give the definition a context. "Sub-atomic" means they are less complex than the chemical atom, that is, the supposed least part of a chemical element. I call them "*things*", since they are something, but they are primitive and imperfect relative to matter in the bulk, and maybe even in comparison to the chemical atoms. The name "particle" has connotations which do not fit very well with their nature. I will call them particles, but that word does not belong in the definition. A better, less determinate name for these things is "quantum."

Next I add: "not composed of other things simpler in nature" to show that the elementary particle is primary and formally simple: *non dividitur secundum formam*. Notice that I do *not* claim that it is a material cause of more complex things. This might apply to some of the elementary particles, but not to all of them. Let me explain this briefly. The first division of the genus "elementary particle" is two-fold. The first division contains the "fermions"; these are the ones which can go into the composition of bodies. The "bosons", on the other hand, are carriers of force. They do not have mass; they can combine with each other, but in the way that waves combine, that is, by superposition. They do not compose bodies. For example, it is proposed that there are least parts of light, which are called photons. In the theory, photons are the mediators of electric and magnetic forces. They are *not* material causes of other things. These particles are sometimes called "force field quanta," which seems like a better name than "elementary particle." It is not clear to me that such things are substances, although they may well be irreducibly simple

Joachim, in *The Complete Works of Aristotle* (Princeton: 1984), edited by Jonathan Barnes, vol. I, p. 539.

[5] Plato discusses the elements in *Timaeus* [53]ff.

[6] As I looked at various sources to find a concise definition, I found as many variations as there were sources. Some had merit, but none seemed perfectly satisfying, either because they were lists rather than definitions, or because they used language which might be misleading if taken literally. The interested reader can find some of these definitions by going online and doing a search on the phrase "elementary particle."

aspects of reality. It seems reasonable to call them "sub-atomic things." Even among the more "particle-like" particles, the fermions, only three enter into the composition of the chemical elements. According to most theorists, the three elements are the electron, the up quark and the down quark. For a long time, the triad of elements was held to be the electron, proton and neutron.[7] Whichever triad one might prefer, the idea of being a constituent of more complex things is best left out of the definition of elementary particle, even if it does apply to a few of them.

To argue for the existence of the many species of elementary particle would be far too great a task for this lecture. Let us take on the less ambitious task of considering why scientists started to think that the chemical elements are not the most simple substances. The first sign that the elements might not be elementary was the discovery in the late 1900s that some elements spontaneously change into others. Although this would not be a surprise to students of Aristotle, it is antithetical to the thinking of the classical atomists, among whom we must number nearly all of the physicists and chemists of the nineteenth century. They concluded therefore that the atoms of the chemical elements must be composed of prior elements. This was an appealing idea, since the number of

[7] In the 1960s, some physicists began to consider the possibility that neutrons and protons are composite particles. The evidence for the existence of quarks is indirect, that is, they are inferred as causes of certain observed effects. Up and down quarks were first "discovered" in 1968 in an electron-proton scattering experiment at the Stanford Linear Accelerator Center. Evidence for the charm quark was discovered in 1974 (SLAC and Brookhaven), for the bottom quark in 1977 (Fermilab) and for the top quark in 1995 (Fermilab).

Unlike protons, neutrons and electrons, quarks have never been observed in isolation, and most physicists think they do not exist outside their compounds. There is now speculation among certain astrophysicists that neutron stars may give rise to "quark stars" made of "strange matter" formed of uncombined quarks. If so, it is possible for them to exist in act and not just virtually, albeit under very extreme circumstances.

substances in the Periodic Table was much greater than one would expect if they were the ultimate elements.

To prove that the chemical atoms are composed, it will be sufficient to show that they break down into smaller parts, the weights of which add up to the weight of the originals. After all, that is how it was verified that the chemical elements make up the various compounds. Lavoisier, for example, used this method to demonstrate that a calx is composed of a metal combined with oxygen. It was fortunate that no effort is required to produce the desired decomposition, for it happens naturally and spontaneously.

The transmutations that were first observed fall into two classes. The first involves a process called alpha decay. In this process, an element is transformed into a lighter element two numbers lower on the Periodic Table. To understand how this works, it needs to be understood that the elements can come in versions having slightly different weights. These are called isotopes. Everybody, I suppose, has heard of Carbon 14, since it is famous for its use in dating artifacts and fossils. Normal carbon has an atomic weight of 12, but this carbon has a weight of 14, the same as that of normal nitrogen.

Consider radium, number 88 on the Periodic Table. This substance was first studied by Marie and Pierre Curie. Although they were not the first to notice radioactivity, as this phenomenon is called, they were the first to study it in detail and give a good account of it. The most common of the isotopes of radium has an atomic weight of 226. It is found in nature as a component of pitchblende, an ore of uranium. The radium in the ore is produced from the uranium by a chain of radioactive decay. The rate of decay is described by the half-life, a statistical notion. The half-life is the amount of time, on the average, for half of a given sample to turn into something else. The half-life of this isotope of radium is 1620 years. That seems like a long time, but it is short enough for a detectible amount of decay to occur in a laboratory specimen during the course of a day.

Now radium is one of the alkaline metals; it is in the same column of the Periodic Table as calcium, magnesium and barium. As such, it oxidizes easily and reacts strongly with water. But if you put some in a container and examine the sample after some time has gone by, you will find that some of it has changed into radon, one of the noble gases. Radon's atomic number is 86, and its weight is less than the weight of radium by about 4 units, where hydrogen is 1. Like the other noble gases and unlike the alkaline metals, radon is inert. There is no doubt that a new substance has been generated from the old.

One need not wait to see that something is happening to the radium, because the sample will be giving off radiation even as he observes it. This radiation is in the form of gamma rays. These rays are something like light, but of much smaller wavelength and greater energy. This is the hazardous part of the radiation from the radioactive element, but it cannot account for the loss of mass. Recall that the bosons have no mass. The other radiation given off by the radium is called alpha radiation. This consists of particles with practically the same mass as a helium atom. They are not electrically neutral, however, like a normal atom; they carry a positive charge. The fact that they carry this charge made them easy to detect and identify. As they move, they constitute an electrical current, and sensitive devices to measure electric currents are readily available.

Since the alpha particles have a positive charge, it is clear that the radium has in it a negative component as well, to maintain electrical neutrality. The nature of this negative component was not clear until Robert Millikan established that there is a natural unit of electric charge. By measuring the total charge on many individual instances of charged ions, he found that these were all multiples of the same small charge. Some were positive and some negative, but all were multiples of the same amount. Millikan was also able to measure the ratio of the charge to the mass of these ions. The carrier of

the negative unit charge is known as the electron, and it was the first of the fermions to be identified. Since positive charge is also numerable, it is plausible to suppose that each element has a characteristic number of positive and negative charges. This quantity is the atomic number, the number according to which the Periodic Table is organized.

From the beginning, electrons were understood to be unmeasurably small. The atom's positive charge was at first thought to be uniformly spread throughout its bulk, in association with most of the mass. Thompson compared the atom to a plum pudding, with the electrons being the plums. This turned out to be an incorrect picture. By looking at the way alpha particles scattered off a piece of gold foil, Rutherford determined that the positive charge and most of the mass is concentrated into a small nucleus. By small, I mean that the nucleus is only about one one-hundred thousandth of the radius of the atom.

It has now been established that the atom consists of a tiny positively charged and relatively massive nucleus, and electrons somehow surrounding it. It was soon established that the chemical properties of the elements could be accounted for by the electrical forces arising from the electrons, especially the outermost ones. The only role of the nucleus, as far as chemistry is concerned, is to provide the positive charge needed to attract the electrons and keep them in order.

One further thing could be noted about the positively charged nucleus. It had been discovered that, to a good approximation, all the atomic nuclear masses were multiples of the mass of the hydrogen nucleus. In accordance with the idea of atomism, it was concluded that each nucleus consists of a number of hydrogen nuclei, and these were given the name "protons." Each proton has one unit of positive charge.

Our picture of the atom, as it was conceived at the beginning of the twentieth century, is nearly complete. Only one piece is missing. Rutherford suggested that another kind of particle could be made by joining a proton and an electron.

Such a particle could explain why there are isotopes. Recall that there are, for example, two versions of carbon, one having a mass of 12 units and the other a mass of 14. Both have 6 protons and 6 electrons. It seems that one might posit a second component of the nucleus, one which was electrically neutral and which has a mass similar to the proton. Carbon 12 would have 6 of these, and Carbon 14 would have 8. Yet it was hard to be sure this was the right idea until it became possible to produce a beam consisting of these hypothetical particles. This was accomplished by James Chadwick in 1932, who shot alpha particles at a sample of beryllium and proved that the product of the bombardment contained a component with a mass approximately equal to that of the proton but carrying no electric charge. Chadwick called this particle the neutron. We now have all the ingredients for a chemical atom: protons and neutrons, carrying almost all the mass, in the nucleus, and electrons located at a relatively great distance from the nucleus.[8]

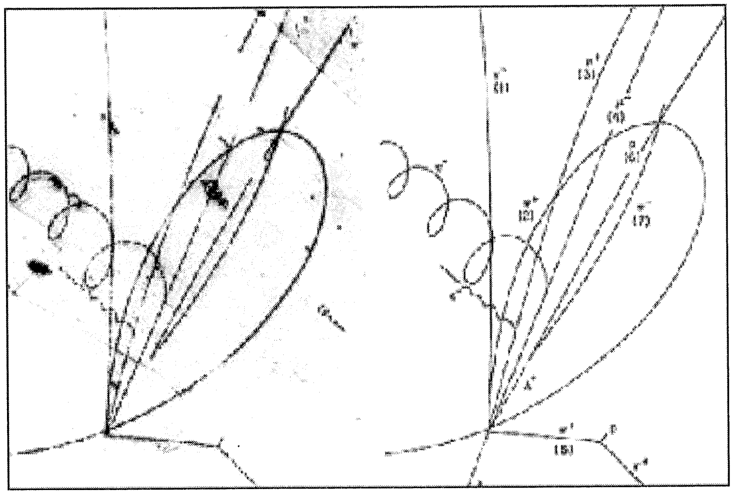
I have already indicated that there are many kinds of elementary particle. Some have mass, like other material substances, while others are massless mediators of force. I will now indicate briefly how these are detected and measured. The first to be discovered, of course, was light, and after that radiations comparable to light. These can be detected by photographic emulsions; all one needs is the right kind of film. This is how Roentgen discovered x-rays, for example. If you have been to the dentist, you have seen pictures made by x-rays. Nowadays, researchers are more likely to use CCD imagers, similar to the ones in your digital camera. I have already indicated how charged particles such as the electron and the proton

[8] If this lecture was about these chemical atoms, I would need to say more about how the various components are put together. Here I am concerned with them only in so far as they relate to the elementary particles. I will say that, in my opinion, the protons, neutrons and electrons are virtually present in the atoms that they compose, much in the way that the chemical substances are virtually in their compounds.

may be detected and in some way measured, since in their motion they constitute electric currents. It is even possible to detect them as discrete entities, and so to count them. If you have a traditional type television set, you have a device for detecting electrons. A cathode ray tube is the device which produces the picture. "Cathode rays" is just an old name for electrons. The little elements—the pixels—respond by lighting up when electrons hit them. A sufficiently sensitive CRT can detect single electrons. The neutron, since it has no electric charge, must be detected in some other manner.

Various kinds of detectors exist which are capable of revealing even uncharged particles. One such device is the bubble chamber. The bubble chamber allows us to examine the tracks made by minute particles as they travel through its interior, much as we could study the wakes of boats from an airplane flying high above the ocean. Although we cannot see the particles, the wakes are easy to see. What I am calling the wake is a trail of bubbles in the liquid through which the particle moves. The liquid is kept just below the boiling point and at a low pressure, so that only a small input of energy is required to cause bubbles to form. The kinetic energy of the particles passing through the chamber supplies this energy. An example of a bubble chamber photograph is shown below (p. 66).

There are distinctive signatures by which we can identify the various particles from their wakes. For example, an alpha particle has a fatter wake than an electron, since it is more massive, and it is more steady. By applying a magnetic field, the particles will be made to follow curved paths, if they have an electric charge. By looking at the tracks, one can determine whether the charge is positive or negative, and what the ratio of the charge to the mass of the particle is. The track of a neutron will resemble that of a proton, except for keeping to a straight track despite the magnetic field. Other types of detectors have been made to allow the researchers to measure the velocities of the particles.



One particle which is not seen in the picture,[9] but which is inferred to have been present from its effects, is the neutrino. It is represented by the dotted line in the lower half of the interpretive sketch. Neutrinos hardly interact with matter, and so they are rarely detected in a direct manner. The story of the neutrino is an interesting one. Since it is elusive, it was not discovered until after its existence was predicted. This prediction came from the attempt to understand the second type of radioactivity, beta decay. Recall that in alpha decay, as when radium becomes radon, one element changes into another two steps lower on the Periodic Table, and four mass units lighter, by giving off a helium nucleus. In beta decay, an element turns into the next element *higher* on the chart, but with very little change of mass. The increase of atomic number implies that there is now an extra proton, while the negligible change in mass suggests that an additional neutron has appeared. Soon it was determined that the particles emitted from the original element—the "beta particles"—were

[9] Photo credit: Brookhaven National Laboratories, 1975. See "Discovery of the Charmed Baryon" (http://www.bnl.gov/bnlweb/history/charmed.asp).

electrons. It makes sense, then, to say that when one of these atoms changes form, the electron comes from a neutron, and that the leftover part of the neutron is the extra proton. That is, the process of beta decay may be thought of as arising from: $n \rightarrow p^{+}e^{-}$.

What makes a nucleus unstable? The problem with these unstable isotopes seems to be that the atoms have an unsuitable number of neutrons for the number of protons. As in the moral life, so in the atomic nucleus, there is a virtuous mean. Beta decay happens when there is an excess of neutrons. By eliminating a neutron, the nucleus becomes more stable. On the other hand, alpha decay happens when there is an excess of protons. By jettisoning two of them, it achieves greater stability.

Eventually, it was found that another particle had to be produced to preserve the conservation of angular momentum. This conservation law deals with the momentum associated with rotations; in elementary particles, angular momentum can come from something called spin. (An electron going around a nucleus will also have orbital angular momentum.) There is evidence that the fermions have an intrinsic angular momentum, as if they were spinning on an axis. It is not clear that this should be taken literally; it is enough to say that they show signs of behaving as if they were spinning. This spin cannot take on just any value. It is always a multiple of a least amount (which we may take as ½) and it will be measured as either up or down (but not in between.) Strangely enough, up may be defined as any arbitrary direction! According to the theory, the total amount of angular momentum, including the spin, must be conserved when particles change into others. The beta-decay process which I have just described does not conserve angular momentum. It was also found to fail to observe the conservation of energy and ordinary momentum. The neutrino—technically a similar particle called the antineutrino—was predicted to supply the missing quantities. As I have said, it is difficult to find neutrinos, but eventually they were detected. The neutrino has no charge, as its name suggests, and it is thought to have a tiny mass compared even to the electron. To my knowledge, its mass has not been measured.

Let's see where we are now, with all this: The electron and the neutrino look as if they might be elementary particles, and likewise the proton. Perhaps we have found some atoms? Are these examples of the small indestructible bodies posited by Newton, Dalton and the rest? As it turns out, the answer is no. Werner Heisenberg, one of the founders of Quantum Mechanics, and one of its greatest interpreters, argues forcefully that the elementary particles are not atoms in the traditional sense.

I will read some passages from his essay "Tradition in Science," pausing to comment on what he says as I read. In this text, he expresses the physicists' sense of puzzlement about what on earth is going on at the sub-atomic level.

> In our time the fundamental structure of matter is one of the central problems, and the concept of the elementary particle has dominated this problem since the time of Democritus. This can be clearly recognized in our pictures and our questions. A lump of matter consists of molecules; a molecule consists of atoms; an atom consists of nucleus and electrons; a nucleus consists of protons and neutrons. A proton —well, that could be an elementary particle. But we would term it "elementary" only if it could not be divided again; we would then wish it to be a point of mass and of charge. But a proton has a finite size and can be divided."[10]

Consider his disappointment that the proton has a finite size and can be divided. He wants the elementary particle to be indivisible, to be an atom. Most physicists would prefer their atoms to be points. This is not as absurd as it sounds, for they are well aware that their theories deal with mathematical

[10] Werner Heisenberg "Tradition in Science" in *Encounters with Einstein*, (Princeton, New Jersey: 1983), pp. 15–16.

idealizations. No doubt a real particle would have a size, but if it is truly indivisible, its size should be irrelevant to the theory. The physicist wants to consider it just as a center of force. Heisenberg is saying that the proton is not able to be thought of or treated mathematically as if it were a point. For example, in some experiments, it manifests itself in the guise of a wave. All the elementary particles present themselves to the observer in this dual way, sometimes looking like a particle, sometimes like a wave. It is only prejudice which leads us to call them elementary particles rather than elementary wavicles. This is why I think the neutral name "quantum," is better, for it does not suggest that we know the innermost essence.

He goes on to say: "From a collision between two energetic protons many pieces may emerge. But these pieces are not smaller than the proton, they are just particles like the protons; particular objects out of a whole spectrum of particles, whose charge—if it is not zero—is not smaller than that of the proton."[11]

Consider the fact that the pieces which emerge from a collision of two protons are not smaller than the protons. This goes counter to the notion of composing parts since a whole must be greater than any one of its parts. In fact, no determinate size can be given to these things. They are not extended in the way ordinary material things are, and so it makes no sense to say that one is larger or smaller than the other. Arthur Eddington remarks that giving a size to a single quantum is like trying to read the Riot Act to one man.[12] Because size is

[11] Ibid., p. 16.

[12] Arthur Eddington, *The Nature of the Physical World*, (Ann Arbor, Michigan: 1958), p. 201. Eddington explains that the diffraction pattern of the light from a single star, as observed by the Mt. Wilson telescope, implies that a single quantum of light must be large enough to cover the 100 inch mirror. The same quantum must also be small enough to enter an atom of the photographic emulsion which records the image, causing the release of a single electron.

not a meaningful concept for elementary particles, their collisions and interactions with each other in experiments are described by the notion of a "cross-section". The cross section is measured by the probability that an interaction will occur between a projected particle and a target particle. This is analogous to the area which a target presents to a bullet, and so has some relation to our ordinary notion of size. But the cross-section is not a constant property of the particle; it depends upon the energy of the particles as well as on what particles they are. So, we can say that a particle has something comparable to a size, but not a definite size, and nothing like a sharp edge. Heisenberg also indicates that the charge of the particles produced from the destruction of the proton will not be less than that of the proton, unless they have no charge at all. This is obvious, since the proton has the least possible charge. Thus, its charge is not made up of the charges of its so-called components.

We see from this that it is not correct to say that the protons are divided when they collide. Rather, they change into other things. Heisenberg also indicates that there are various possible outcomes. He gives some examples of this in his essay, "What Is an Elementary Particle?":

"A proton, for example, could be made up of neutron and pion, or Λ-hyperon and kaon, or out of two nucleons and an anti-nucleon; it would be simplest of all to say that a proton just consists of continuous matter, and all these statements are equally correct or equally false."[13] They all are correct in the sense that the proton can become any of these sets of other particles; they all are false in asserting that the proton is composed of them.

According to Heisenberg, it makes as much—or as little—sense to say that protons are components of neutrons as to say that neutrons are components of protons. These considerations lead him to deconstruct the very notion of an elementary particle: "What actually happens in a very energetic collision of two particles is the creation of new particles out of the kinetic energy. Energy becomes matter by assuming the form of elementary particles. But again the distinction between 'elementary particle' and 'compound system' has no well defined meaning. Particles are stationary states of the physical system 'matter.'"[14]

Before we consider the meaning of Heisenberg's words, we should consider the evidence for the claim that the elementary particles are not unchangeable and least particles of matter. The idea that elementary particles can be destroyed, and moreover that there are many possible outcomes from the destruction of an elementary particle, may seem strange and implausible. It is necessary therefore to consider the evidence, at least briefly. After that, we should consider what kind of theoretical account physics can give for this.

Here is an example of what might happen. Consider a beam of free neutrons, free in the sense that they are not bound to the nucleus of atoms. Free neutrons are not stable but have a half-life of about 15 minutes. Recall that this means that half

[13] Heisenberg, "What Is an Elementary Particle?" in *Encounters with Einstein*, p. 73.

[14] Heisenberg, "Cosmic Radiation and Physics," in *Encounters with Einstein*, p. 59. Heisenberg credits Niels Bohr with the introduction of the notion of discrete stationary states into physics. ("Development of Concepts in the History of Quantum Mechanics," in *Encounters with Einstein*, p. 19.) Bohr meant by "discrete stationary state" a stable configuration or disposition of an atom with respect to the orbital energies of its electrons. In Bohr's quantum theory, these states are discrete, since electrons bound to the nucleus can be stable only with certain definite energies. Heisenberg extends the notion here and elsewhere to refer to any stationary—i.e. stable—disposition of a physical "system."

In the passage quoted here, Heisenberg contrasts elementary particle formation, which happens in high energy collisions, with the situation where the energy involved in disintegrating a compound into two or more parts is very small in comparison with the masses of the components. An example of the latter would be a chemical reaction. In the latter case, he says, it does make sense to speak of composition and division.

of any given sample of neutrons, on the average, will corrupt in 15 minutes. I have already mentioned that when a neutron corrupts, three particles are generated: a proton, an electron, and an antineutrino. This is normally what happens, but there are other possibilities.

The possible results are governed by conservation laws. Two of these are important for our purpose. The first is the conservation of electrical charge. This means that the algebraic sum of the charges of the products must equal the charge that one starts with. The second is the conservation of energy, which includes the mass. Neither energy nor mass is conserved separately, but together they are. Nuclear physicists use an energy unit called the "electron volt" to measure mass. Masses of elementary particles are generally measured in millions of electron-volts (MeV.) To give you an idea of the scale: an electron's mass may be expressed as either about one half of a MeV or as $9.10938188 \times 10^{-31}$ kilograms.

Here is how these conservation laws apply to our example.[15] The proton has a charge of +1 and mass of 938.28 MeV. The electron has charge of -1 and mass of 0.51 MeV. The antineutrino has no charge and either no mass or a currently unmeasured amount much less than the electron. The neutron is electrically neutral and has a mass of 939.57 MeV. As you can see, the charges add up as they should. In addition, there is sufficient mass to account for the masses of the components: $939.57 = 938.28 + 0.51 + 0.78$ left to account for the kinetic energy of the products and the possible undetectable mass of the antineutrino.

Here is another possibility: the neutron can change into a proton, a negative muon, and an antineutrino. This is interesting, because the only difference from the normal decay is that we get this muon rather than the electron. The muon is

[15] The details of my example are taken from *The Forces of Nature* by P.C.W. Davies, (Cambridge, England: 1986), Chapter Three, "Inside the Nucleus."

basically the same thing as an electron, except that it has a considerably greater mass. This process has been observed to occur, so it is not just a theoretical possibility.

Can the change go the other way? Can we, for example, produce a neutron from a proton, an electron and an antineutrino? The answer is no, for practical reasons. It is extremely unlikely that the three of them could be made to collide all at once, either by nature or by art. A simpler scenario, in which only the proton and the electron collide, brings about an interesting result. Together they produce a neutron and a neutrino. So we have at least a partial converse of our original process.

Let us look more closely at these two processes:

neutron → proton + electron + antineutrino
proton + electron → neutron + neutrino

Compare this to chemical decomposition and composition:

water → hydrogen + oxygen
hydrogen + oxygen → water

If the antineutrino and the neutrino are different particles, these processes are not the same as chemical composition and decomposition.

The following processes are also possible:

proton → neutron + positron (i.e. antielectron) + neutrino
(This is a version of beta decay.)
proton + antineutrino → neutron + positron

It seems that these are not instances of composition from prior particles or of virtual presence of some particles in other particles. Particles corrupt, and others are generated, not by breaking down into prior elements, but just by changing their forms. From the point of view of the physicist, the key to understanding these mutations lies in two things, the equivalence of mass to energy and the existence of antimatter.

First, let us consider mass, what it is and how it is related to matter. In the *Opticks*, Newton says that God formed matter into "solid, massy . . . particles." Mass is therefore seen as a property of matter and is multiplied as matter is multiplied, in accordance with the idea of atomism. Thus Newton defines mass in the *Principia* as the "quantity of matter." The other possible candidate for "quantity of matter" would be volume, but Newton wants to quantify matter according to a principle of motion and rest. This seems most appropriate to the physicist. Mass is a principle of motion and rest in Newtonian physics in that it is the source of inertia. Newton also discovered that mass is much more than the source of inertia: it is the measure of a body's power of gravitational attraction for other bodies. This raises the question of whether mass is correctly defined as the quantity of matter. How can a quantity give rise to an attraction? Looked at under this aspect, mass seems rather to be a quality or power of matter.

Mass is of course capable of being quantified, but it is not a quantity. This becomes clear when we consider Einstein's theoretically and practically spectacular discovery that mass may be converted into energy. This discovery is the key to understanding the inter-convertibility of elementary particles. Before Einstein, physicists admitted two separate conservation laws, of mass and of energy. Einstein united them through his famous equation, "$e = mc^2$" into one law. The meaning of his equation is that mass is just another form of energy. So what I said a moment ago, that mass may be converted into energy, was not well-put. I should have said that mass may be converted into other forms of energy, and various forms of energy may be converted into mass.

In 1928, Paul Dirac, the English theoretical physicist, made a startling prediction. He said that all the elementary particles should come in two versions, in which all their properties would be the same except that their charge (if not zero) would be of opposite sign and that they would be mirror images of each other. The latter refers to those properties which are spatially asymmetric, properties analogous to being right- or

left-handed. For example, the spin of particles looked at from the direction of their motion can be either clock-wise or anti-clockwise. He called these particles antimatter. I have made use of two of these particles in my examples, the antineutrino and the positron, or antielectron. It will not be possible to explain why he predicted these particles, but it is sufficient for us to know that many of them have been discovered, using the same techniques by which the regular particles were discovered. The first to be discovered was the positron, found in 1932 by Carl Anderson. Negative protons were artificially produced in 1955 by a particle accelerator at University of California, Berkeley, and other anti-particles have been observed since then.

What is relevant to our explanation of the mutation of elementary particles is that when a particle meets its corresponding anti-particle, both are destroyed and all their mass and kinetic energy are converted into radiation. Because this is always possible, there is no fundamental particle which cannot be destroyed. Moreover, radiation—photons—can change into particles. The energy of the photon can be converted into the mass of twin anti-particles. This has been observed to happen. So there is always the possibility of converting the mass of any elementary particle to energy, and this energy can take the form of the mass of other particles, as well as the energy of their motion. The transformation of the elementary particles into each other is not by a rearrangement of elements, but by the corruption of certain forms and the generation of others. In this theory, the natures of the corrupted and generated forms are related to each other through the conservation laws.

As time went on, more and more of these fundamental particles were found. This seemed dissatisfying, to think that there should be so many, as many as the elements of the Periodic Table. Moreover, it seemed strange that most of them are ephemeral. Heisenberg addresses this dissatisfaction in the following text:

> Besides the three fundamental building stones of matter—electron, proton and neutron—new elementary particles have been found which can be created in these processes of highest energy and disappear again after a short time. The new particles have similar properties as the old ones except for their instability. . . . These results seem at first sight to lead away from the idea of the unity of matter, since the number of fundamental units of matter seem to have again increased to values comparable to the number of chemical elements. But this would not be a proper interpretation. The experiments have at the same time shown that the particles can be created from other particles or simply from the kinetic energy of such particles, and they can disintegrate into other particles. Actually, the experiments have shown the complete mutability of matter. All the elementary particles are made of the same substance, which we may call energy or universal matter; they are just different forms in which energy can appear. If we compare this situation with the Aristotelian concepts of matter and form, we can say that the matter of Aristotle, which is mere "potentia," should be compared to our concept of energy, which gets into "actuality" by means of the form, when the elementary particle is created.[16]

In this interesting text, Heisenberg rejects the idea of the atomists that the underlying matter is many, either in quantity or in form. He understood what Aristotle taught long ago, that underneath all change lies a primary matter, which is merely a potency for form. Recall that in a text quoted earlier Heisenberg said that particles are "stationary states" of the physical system "matter." This seems to mean that the underlying *prima materia* (which he identifies with energy) can take on more or less stable forms, which are the elementary particles. I think he means that the particles themselves are accidents of the underlying "substance."

[16] "Quantum Theory and the Structure of Matter," *Physics and Philosophy* (New York: 1958), pp. 159–60.

The mutability of the elements does indeed show that primary matter underlies all change, but I think it is incorrect to identify primary matter with energy. I see that it is tempting to do so, because energy plays a primary role in modern physical theory, more fundamental than either mass or force. The problem is that energy is not without actuality of its own, and this rules it out as a candidate for prime matter. The fact that it can be measured is sufficient proof that it is not without form. Energy, then, is a formal rather than a material principle; perhaps it is the first and most primitive form which accrues to prime matter.

Although I must disagree with Heisenberg in his interpretation of energy, his point remains valid that the first matter is one rather than many, and that the first substances in which this matter is brought into act will not be small and indestructible versions of the solid physical bodies familiar to ordinary experience. It does not seem unreasonable to think that they are measurable states or conditions of the underlying spatial (or perhaps space-time) continuum. If this is the correct interpretation, they are not substances. They may be causes or principles, but they are not elements. The chemists, then, would be right to see hydrogen, carbon and so forth as the true elements of natural bodies. But if this interpretation is incorrect, and they are substances in their own right, they are very imperfect in their lack of characteristics which characterize the material substances with which we are familiar, such as size, shape, color, temperature.

An amazing thing about the elementary particles is that they can be brought into a mathematical scheme that is simple and beautiful, in an abstract way. This is called the Standard Model, and a number of popular accounts of it may be found, by those who are interested. What the Periodic Table did for the chemical elements, reducing them to a system in which their properties take on some kind of intelligible order, the Standard Theory does for the elementary particles. But this would be a subject for another lecture. I will only mention that this simplification is brought about in part by the introduction of quarks.

Now the possible existence of quarks does not alter the way in which we must understand elementary particles. The quarks will be subjected to the same laws of change as the others. The account of what happens when a neutron corrupts will not be radically different, even if the neutron somehow contains within it three quarks. It does not change into a proton by swapping some of its quarks for others. Rather, the quarks themselves change in the way already described. Again, when protons and anti-protons annihilate each other, it will be quarks and anti-quarks annihilating, so again they can become any other particles consistent with the conservation laws. These laws, expressed in the form of fundamental symmetries, are proposed as a way of making the elementary particles intelligible to us.

> What is really needed is a change in the fundamental concepts. We will have to abandon the philosophy of Democritus and the concept of fundamental elementary particles. And we should accept instead the concept of fundamental symmetries, which is a concept derived from the philosophy of Plato. Just as Copernicus and Galileo, in their method, abandoned the descriptive science of Aristotle and turned to the structural science of Plato, so we are probably forced, in our concepts, to abandon the atomic materialism of Democritus and to turn to the ideas of symmetry in the philosophy of Plato.[17]

I believe that Aristotle's philosophy gives a true account of the mutation of the elementary particles in terms of the very general principles of matter and form, potency and act. Nonetheless, it is the Platonic contemplation of the mathematical forms which provides the inspiration for our modern-

[17] "Tradition in Science," *Encounters with Einstein*, p. 17.

day physicists, as they try to bring order to the many phenomena which they have discovered in their study of the elementary particles, and so "to save the phenomena."[18]

[18] The symmetries of which Heisenberg writes are expressions of geometrical, or at least quasi-geometrical, patterns or regularities in the fundamental measures of things. In accordance with a famous theorem, proved by Emma Noether, to every conservation law there corresponds a symmetry, and vice versa. One of the simplest examples is symmetry of translation in space. This means that if any self-contained physical system is moved elsewhere, nothing else having changed, it will behave exactly as it did before. This symmetry is shown to be equivalent to the law of conservation of momentum.

It would be a mistake to suppose that these conservation laws are comparable to what are usually thought of as the laws of physics. They are not mere summaries of empirical data, as in the case of the ideal gas law, nor do they propose to give some measurable relation between agent causes and their effects, as in the case of Newton's second law. Rather, they express the consequence of a deep, underlying pattern. These patterns are proposed as the object of knowledge in elementary particle physics. Thus we see the Platonic frame of mind of Heisenberg and the others.