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Quantum Theory and the Roots of Atomic Science

THE concept of the atom goes back much further than the beginning of modern science in the seventeenth century; it has its origin in ancient Greek philosophy and was in that early period the central concept of materialism taught by Leucippus and Democritus. On the other hand, the modern interpretation of atomic events has very little resemblance to genuine materialistic philosophy; in fact, one may say that atomic physics has turned science away from the materialistic trend it had during the nineteenth century. It is therefore interesting to compare the development of Greek philosophy toward the concept of the atom with the present position of this concept in modern physics.

The idea of the smallest, indivisible ultimate building blocks of matter first came up in connection with the elaboration of the concepts of Matter, Being and Becoming which characterized the first epoch of Greek philosophy. This period started in the sixth century B.C. with Thales, the founder of the Milesian school, to whom Aristotle ascribes the statement: "Water is the material cause of all things." This statement, strange as it looks to us, expresses, as Nietzsche has pointed out, three fundamental

ideas of philosophy. First, the question as to the material cause of all things; second, the demand that this question be answered in conformity with reason, without resort to myths or mysticism; third, the postulate that ultimately it must be possible to reduce everything to one principle. Thales' statement was the first expression of the idea of a fundamental substance, of which all other things were transient forms. The word "substance" in this connection was certainly in that age not interpreted in the purely material sense which we frequently ascribe to it today. Life was connected with or inherent in this "substance" and Aristotle ascribes to Thales also the statement: All things are full of gods. Still the question was put as to the material cause of all things and it is not difficult to imagine that Thales took his view primarily from meteorological considerations. Of all things we know water can take the most various shapes; it can in the winter take the form of ice and snow, it can change into vapor, and it can form the clouds. It seems to turn into earth where the rivers form their delta, and it can spring from the earth. Water is the condition for life. Therefore, if there was such a fundamental substance, it was natural to think of water first.

The idea of the fundamental substance was then carried further by Anaximander, who was a pupil of Thales and lived in the same town. Anaximander denied the fundamental substance to be water or any of the known substances. He taught that the primary substance was infinite, eternal and ageless and that it encompassed the world. This primary substance is transformed into the various substances with which we are familiar. Theophrastus quotes from Anaximander: "Into that from which things take their rise they pass away once more, as is ordained, for they make reparation and satisfaction to one another for their injustice according to the ordering of time." In this

philosophy the antithesis of Being and Becoming plays the fundamental role. The primary substance, infinite and ageless, the undifferentiated Being, degenerates into the various forms which lead to endless struggles. The process of Becoming is considered as a sort of debasement of the infinite Being—a disintegration into the struggle ultimately expiated by a return into that which is without shape or character. The struggle which is meant here is the opposition between hot and cold, fire and water, wet and dry, etc. The temporary victory of the one over the other is the injustice for which they finally make reparation in the ordering of time. According to Anaximander, there is "eternal motion," the creation and passing away of worlds from infinity to infinity.

It may be interesting to notice at this point that the problem—whether the primary substance can be one of the known substances or must be something essentially different—occurs in a somewhat different form in the most modern part of atomic physics. The physicists today try to find a fundamental law of motion for matter from which all elementary particles and their properties can be derived mathematically. This fundamental equation of motion may refer either to waves of a known type, to proton and meson waves, or to waves of an essentially different character which have nothing to do with any of the known waves or elementary particles. In the first case it would mean that all other elementary particles can be reduced in some way to a few sorts of "fundamental" elementary particles; actually theoretical physics has during the past two decades mostly followed this line of research. In the second case all different elementary particles could be reduced to some universal substance which we may call energy or matter, but none of the different particles could be preferred to the others as being more

fundamental. The latter view of course corresponds to the doctrine of Anaximander, and I am convinced that in modern physics this view is the correct one. But let us return to Greek philosophy.

The third of the Milesian philosophers, Anaximenes, an associate of Anaximander, taught that air was the primary substance. "Just as our soul, being air, holds us together, so do breath and air encompass the whole world." Anaximenes introduced into the Milesian philosophy the idea that the process of condensation or rarefaction causes the change of the primary substance into the other substances. The condensation of water vapor into clouds was an obvious example, and of course the difference between water vapor and air was not known at that time.

In the philosophy of Heraclitus of Ephesus the concept of Becoming occupies the foremost place. He regarded that which moves, the fire, as the basic element. The difficulty, to reconcile the idea of one fundamental principle with the infinite variety of phenomena, is solved for him by recognizing that the strife of the opposites is really a kind of harmony. For Heraclitus the world is at once one and many, it is just "the opposite tension" of the opposites that constitutes the unity of the One. He says: "We must know that war is common to all and strife is justice, and that all things come into being and pass away through strife."

Looking back to the development of Greek philosophy up to this point one realizes that it has been borne from the beginning to this stage by the tension between the One and the Many. For our senses the world consists of an infinite variety of things and events, colors and sounds. But in order to understand it we have to introduce some kind of order, and order means to recognize

what is equal, it means some sort of unity. From this springs the belief that there is one fundamental principle, and at the same time the difficulty to derive from it the infinite variety of things. That there should be a material cause for all things was a natural starting point since the world consists of matter. But when one carried the idea of fundamental unity to the extreme one came to that infinite and eternal undifferentiated Being which, whether material or not, cannot in itself explain the infinite variety of things. This leads to the antithesis of Being and Becoming and finally to the solution of Heraclitus, that the change itself is the fundamental principle; the "imperishable change, that renovates the world," as the poets have called it. But the change in itself is not a material cause and therefore is represented in the philosophy of Heraclitus by the fire as the basic element, which is both matter and a moving force.

We may remark at this point that modern physics is in some way extremely near to the doctrines of Heraclitus. If we replace the word "fire" by the word "energy" we can almost repeat his statements word for word from our modern point of view. Energy is in fact the substance from which all elementary particles, all atoms and therefore all things are made, and energy is that which moves. Energy is a substance, since its total amount does not change, and the elementary particles can actually be made from this substance as is seen in many experiments on the creation of elementary particles. Energy can be changed into motion, into heat, into light and into tension. Energy may be called the fundamental cause for all change in the world. But this comparison of Greek philosophy with the ideas of modern science will be discussed later.

Greek philosophy returned for some time to the concept of the One in the teachings of Parmenides, who lived in Elea in the

south of Italy. His most important contribution to Greek thinking was, perhaps, that he introduced a purely logical argument into metaphysics. "One cannot know what is not—that is impossible—nor utter it; for it is the same thing that can be thought and that can be." Therefore, only the One is, and there is no becoming or passing away. Parmenides denied the existence of empty space for logical reasons. Since all change requires empty space, as he assumed, he dismissed change as an illusion.

But philosophy could not rest for long on this paradox. Empedocles, from the south coast of Sicily, changed for the first time from monism to a kind of pluralism. To avoid the difficulty that one primary substance cannot explain the variety of things and events, he assumed four basic elements, earth, water, air and fire. The elements are mixed together and separated by the action of Love and Strife. Therefore, these latter two, which are in many ways treated as corporeal like the other four elements, are responsible for the imperishable change. Empedocles describes the formation of the world in the following picture: First, there is the infinite Sphere of the One, as in the philosophy of Parmenides. But in the primary substance all the four "roots" are mixed together by Love. Then, when Love is passing out and Strife coming in, the elements are partially separated and partially combined. After that the elements are completely separated and Love is outside the World. Finally, Love is bringing the elements together again and Strife is passing out, so that we return to the original Sphere.

This doctrine of Empedocles represents a very definite turning toward a more materialistic view in Greek philosophy. The four elements are not so much fundamental principles as real material substances. Here for the first time the idea is expressed that the mixture and separation of a few substances, which are funda-

mentally different, explains the infinite variety of things and events. Pluralism never appeals to those who are wont to think in fundamental principles. But it is a reasonable kind of compromise, which avoids the difficulty of monism and allows the establishment of some order.

The next step toward the concept of the atom was made by Anaxagoras, who was a contemporary of Empedocles. He lived in Athens about thirty years, probably in the first half of the fifth century B.C. Anaxagoras stresses the idea of the mixture, the assumption that all change is caused by mixture and separation. He assumes an infinite variety of infinitely small "seeds," of which all things are composed. The seeds do not refer to the four elements of Empedocles, there are innumerable many different seeds. But the seeds are mixed together and separated again and in this way all change is brought about. The doctrine of Anaxagoras allows for the first time a geometrical interpretation of the term "mixture": Since he speaks of the infinitely small seeds, their mixture can be pictured as the mixture between two kinds of sand of different colors. The seeds may change in number and in relative position. Anaxagoras assumes that all seeds are in everything, only the proportion may change from one thing to another. He says: "All things will be in everything; nor is it possible for them to be apart, but all things have a portion of everything." The universe of Anaxagoras is set in motion not by Love and Strife, like that of Empedocles, but by "Nous," which we may translate as "Mind."

From this philosophy it was only one step to the concept of the atom, and this step occurred with Leucippus and Democritus of Abdera. The antithesis of Being and Not-being in the philosophy of Parmenides is here secularized into the antithesis of the "Full" and the "Void." Being is not only One, it can be repeated an

infinite number of times. This is the atom, the indivisible smallest unit of matter. The atom is eternal and indestructible, but it has a finite size. Motion is made possible through the empty space between the atoms. Thus for the first time in history there was voiced the idea of the existence of smallest ultimate particles—we would say of elementary particles, as the fundamental building blocks of matter.

According to this new concept of the atom, matter did not consist only of the "Full," but also of the "Void," of the empty space in which the atoms move. The logical objection of Parmenides against the Void, that not-being cannot exist, was simply ignored to comply with experience. From our modern point of view we would say that the empty space between the atoms in the philosophy of Democritus was not nothing; it was the carrier for geometry and kinematics, making possible the various arrangements and movements of atoms. But the possibility of empty space has always been a controversial problem in philosophy. In the theory of general relativity the answer is given that geometry is produced by matter or matter by geometry. This answer corresponds more closely to the view held by many philosophers that space is defined by the extension of matter. But Democritus clearly departs from this view, to make change and motion possible.

The atoms of Democritus were all of the same substance, which had the property of being, but had different sizes and different shapes. They were pictured therefore as divisible in a mathematical but not in a physical sense. The atoms could move and could occupy different positions in space. But they had no other physical properties. They had neither color nor smell nor taste. The properties of matter which we perceive by our senses were supposed to be produced by the movements and positions

of the atoms in space. Just as both tragedy and comedy can be written by using the same letters of the alphabet, the vast variety of events in this world can be realized by the same atoms through their different arrangements and movements. Geometry and kinematics, which were made possible by the void, proved to be still more important in some way than pure being. Democritus is quoted to have said: "A thing merely appears to have color, it merely appears to be sweet or bitter. Only atoms and empty space have a real existence."

The atoms in the philosophy of Leucippus do not move merely by chance. Leucippus seems to have believed in complete determinism, since he is known to have said: "Naught happens for nothing, but everything from a ground and of necessity." The atomists did not give any reason for the original motion of the atoms, which just shows that they thought of a causal description of the atomic motion; causality can only explain later events by earlier events, but it can never explain the beginning.

The basic ideas of atomic theory were taken over and modified, in part, by later Greek philosophers. For the sake of comparison with modern atomic physics it is important to mention the explanation of matter given by Plato in his dialogue *Timaeus*. Plato was not an atomist; on the contrary, Diogenes Laertius reported that Plato disliked Democritus so much that he wished all his books to be burned. But Plato combined ideas that were near to atomism with the doctrines of the Pythagorean school and the teachings of Empedocles.

The Pythagorean school was an offshoot of Orphism, which goes back to the worship of Dionysus. Here has been established the connection between religion and mathematics which ever since has exerted the strongest influence on human thought. The Pythagoreans seem to have been the first to realize the creative

force inherent in mathematical formulations. Their discovery that two strings sound in harmony if their lengths are in a simple ratio demonstrated how much mathematics can mean for the understanding of natural phenomena. For the Pythagoreans it was not so much a question of understanding. For them the simple mathematical ratio between the length of the strings *created* the harmony in sound. There was also much mysticism in the doctrines of the Pythagorean school which for us is difficult to understand. But by making mathematics a part of their religion they touched an essential point in the development of human thought. I may quote a statement by Bertrand Russell about Pythagoras: "I do not know of any other man who has been as influential as he was in the sphere of thought."

Plato knew of the discovery of the regular solids made by the Pythagoreans and of the possibility of combining them with the elements of Empedocles. He compared the smallest parts of the element earth with the cube, of air with the octahedron, of fire with the tetrahedron, and of water with the icosahedron. There is no element that corresponds to the dodecahedron; here Plato only says "there was yet a fifth combination which God used in the delineation of the universe."

If the regular solids, which represent the four elements, can be compared with the atoms at all, it is made clear by Plato that they are not indivisible. Plato constructs the regular solids from two basic triangles, the equilateral and the isosceles triangles, which are put together to form the surface of the solids. Therefore, the elements can (at least partly) be transformed into each other. The regular solids can be taken apart into their triangles and new regular solids can be formed of them. For instance, one tetrahedron and two octahedra can be taken apart into twenty equilateral triangles, which can be recombined to

give one icosahedron. That means: one atom of fire and two atoms of air can be combined to give one atom of water. But the fundamental triangles cannot be considered as matter, since they have no extension in space. It is only when the triangles are put together to form a regular solid that a unit of matter is created. The smallest parts of matter are not the fundamental Beings, as in the philosophy of Democritus, but are mathematical forms. Here it is quite evident that the form is more important than the substance of which it is the form.

After this short survey of Greek philosophy up to the formation of the concept of the atom we may come back to modern physics and ask how our modern views on the atom and on quantum theory compare with this ancient development. Historically the word "atom" in modern physics and chemistry was referred to the wrong object, during the revival of science in the seventeenth century, since the smallest particles belonging to what is called a chemical element are still rather complicated systems of smaller units. These smaller units are nowadays called elementary particles, and it is obvious that if anything in modern physics should be compared with the atoms of Democritus it should be the elementary particles like proton, neutron, electron, meson.

Democritus was well aware of the fact that if the atoms should, by their motion and arrangement, *explain* the properties of matter—color, smell, taste—they cannot themselves have these properties. Therefore, he has deprived the atom of these qualities and his atom is thus a rather abstract piece of matter. But Democritus has left to the atom the quality of "being," of extension in space, of shape and motion. He has left these qualities because it would have been difficult to speak about the atom at all if such qualities had been taken away from

it. On the other hand, this implies that his concept of the atom cannot explain geometry, extension in space or existence, because it cannot reduce them to something more fundamental. The modern view of the elementary particle with regard to this point seems more consistent and more radical. Let us discuss the question: What is an elementary particle? We say, for instance, simply "a neutron" but we can give no well-defined picture and what we mean by the word. We can use several pictures and describe it once as a particle, once as a wave or as a wave packet. But we know that none of these descriptions is accurate. Certainly the neutron has no color, no smell, no taste. In this respect it resembles the atom of Greek philosophy. But even the other qualities are taken from the elementary particle, at least to some extent; the concepts of geometry and kinematics, like shape or motion in space, cannot be applied to it consistently. If one wants to give an accurate description of the elementary particle—and here the emphasis is on the word "accurate"—the only thing which can be written down as description is a probability function. But then one sees that not even the quality of being (if that may be called a "quality") belongs to what is described. It is a possibility for being or a tendency for being. Therefore, the elementary particle of modern physics is still far more abstract than the atom of the Greeks, and it is by this very property more consistent as a clue for explaining the behavior of matter.

In the philosophy of Democritus all atoms consist of the same substance if the word "substance" is to be applied here at all. The elementary particles in modern physics carry a mass in the same limited sense in which they have other properties. Since mass and energy are, according to the theory of relativity, essentially the same concepts, we may say that all elementary particles consist of energy. This could be interpreted as defining energy as

the primary substance of the world. It has indeed the essential property belonging to the term "substance," that it is conserved. Therefore, it has been mentioned before that the views of modern physics are in this respect very close to those of Heraclitus if one interprets his element fire as meaning energy. Energy is in fact that which moves; it may be called the primary cause of all change, and energy can be transformed into matter or heat or light. The strife between opposites in the philosophy of Heraclitus can be found in the strife between two different forms of energy.

In the philosophy of Democritus the atoms are eternal and indestructible units of matter, they can never be transformed into each other. With regard to this question modern physics takes a definite stand against the materialism of Democritus and for Plato and the Pythagoreans. The elementary particles are certainly not eternal and indestructible units of matter, they can actually be transformed into each other. As a matter of fact, if two such particles, moving through space with a very high kinetic energy, collide, then many new elementary particles may be created from the available energy and the old particles may have disappeared in the collision. Such events have been frequently observed and offer the best proof that all particles are made of the same substance: energy. But the resemblance of the modern views to those of Plato and the Pythagoreans can be carried somewhat further. The elementary particles in Plato's *Timaeus* are finally not substance but mathematical forms. "All things are numbers" is a sentence attributed to Pythagoras. The only mathematical forms available at that time were such geometric forms as the regular solids or the triangles which form their surface. In modern quantum theory there can be no doubt that the elementary particles will finally also be mathematical

forms, but of a much more complicated nature. The Greek philosophers thought of static forms and found them in the regular solids. Modern science, however, has from its beginning in the sixteenth and seventeenth centuries started from the dynamic problem. The constant element in physics since Newton is not a configuration or a geometrical form, but a dynamic law. The equation of motion holds at all times, it is in this sense eternal, whereas the geometrical forms, like the orbits, are changing. Therefore, the mathematical forms that represent the elementary particles will be solutions of some eternal law of motion for matter. Actually this is a problem which has not yet been solved. The fundamental law of motion for matter is not yet known and therefore it is not yet possible to derive mathematically the properties of the elementary particles from such a law. But theoretical physics in its present state seems to be not very far from this goal and we can at least say what kind of law we have to expect. The final equation of motion for matter will probably be some quantized nonlinear wave equation for a wave field of operators that simply represents matter, not any specified kind of waves or particles. This wave equation will probably be equivalent to rather complicated sets of integral equations, which have "Eigenvalues" and "Eigensolutions," as the physicists call it. These Eigensolutions will finally represent the elementary particles; they are the mathematical forms which shall replace the regular solids of the Pythagoreans. We might mention here that these "Eigensolutions" will follow from the fundamental equation for matter by much the same mathematical process by which the harmonic vibrations of the Pythagorean string follow from the differential equation of the string. But, as has been said, these problems are not yet solved.

If we follow the Pythagorean line of thought we may hope

that the fundamental law of motion will turn out as a mathematically simple law, even if its evaluation with respect to the Eigenstates may be very complicated. It is difficult to give any good argument for this hope for simplicity—except the fact that it has hitherto always been possible to write the fundamental equations in physics in simple mathematical forms. This fact fits in with the Pythagorean religion, and many physicists share their belief in this respect, but no convincing argument has yet been given to show that it must be so.

We may add an argument at this point concerning a question which is frequently asked by laymen with respect to the concept of the elementary particle in modern physics: Why do the physicists claim that their elementary particles cannot be divided into smaller bits? The answer to this question clearly shows how much more abstract modern science is as compared to Greek philosophy. The argument runs like this: How could one divide an elementary particle? Certainly only by using extreme forces and very sharp tools. The only tools available are other elementary particles. Therefore, collisions between two elementary particles of extremely high energy would be the only processes by which the particles could eventually be divided. Actually they *can* be divided in such processes, sometimes into very many fragments; but the fragments are again elementary particles, not any smaller pieces of them, the masses of these fragments resulting from the very large kinetic energy of the two colliding particles. In other words, the transmutation of energy into matter makes it possible that the fragments of elementary particles are again the same elementary particles.

After this comparison of the modern views in atomic physics with Greek philosophy we have to add a warning, that this comparison should not be misunderstood. It may seem at first

sight that the Greek philosophers have by some kind of ingenious intuition come to the same or very similar conclusions as we have in modern times only after several centuries of hard labor with experiments and mathematics. This interpretation of our comparison would, however, be a complete misunderstanding. There is an enormous difference between modern science and Greek philosophy, and that is just the empiristic attitude of modern science. Since the time of Galileo and Newton, modern science has been based upon a detailed study of nature and upon the postulate that only such statements should be made, as have been verified or at least can be verified by experiment. The idea that one could single out some events from nature by an experiment, in order to study the details and to find out what is the constant law in the continuous change, did not occur to the Greek philosophers. Therefore, modern science has from its beginning stood upon a much more modest, but at the same time much firmer, basis than ancient philosophy. Therefore, the statements of modern physics are in some way meant much more seriously than the statements of Greek philosophy. When Plato says, for instance, that the smallest particles of fire are tetrahedrons, it is not quite easy to see what he really means. Is the form of the tetrahedron only symbolically attached to the element fire, or do the smallest particles of fire mechanically act as rigid tetrahedrons or as elastic tetrahedrons, and by what force could they be separated into the equilateral triangles, etc.? Modern science would finally always ask: How can one decide experimentally that the atoms of fire are tetrahedrons and not perhaps cubes? Therefore, when modern science states that the proton is a certain solution of a fundamental equation of matter it means that we can from this solution deduce mathematically all possible properties of the proton and can check the

correctness of the solution by experiments in every detail. This possibility of checking the correctness of a statement experimentally with very high precision and in any number of details gives an enormous weight to the statement that could not be attached to the statements of early Greek philosophy.

All the same, some statements of ancient philosophy are rather near to those of modern science. This simply shows how far one can get by combining the ordinary experience of nature that we have without doing experiments with the untiring effort to get some logical order into this experience to understand it from general principles.

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