ELEMENTARY PARTICLES

~~Lecture delivered at the University of São Paulo on July 21, Monday, 1958.~~

1. There are a number of questions which philosophers and scientists have been asking to themselves for many years and to which we cannot give the final answers as yet. One of the oldest and the most important among such questions is that of the ultimate constituents of matter .
If you open any of the books on the history of science, you would find the two important concepts of"element"and "atom" at the very beginning. According to the first Greek philosopher Thales, water was the unique element of matter, but the philosophers who came later increased the number of elements from one to four.
Thus, water, fire, air and earth have been for many years believed to be the four elements from which every form of matter could be constructed. The concept of atom was also conceived by early Greek philosophers. According to Democritos, matter was an assembly of a great number of small and invisible atoms.

2. Since the advent of modern science in seventeenth century, the two rather philosophical concepts of elements and atoms evolved ~~to the~~ into more scientific notions of "chemical elements" and "chemical atoms". Thus, hydrogen, oxygen, silver,gold,etc., were considered to be chemical elements in that they could not be decomposed into simpler elements by any chemical means. Each of the chemical elements was considered to consist of invisible atoms which were characteristic to the element in question. In this way, we had to accept the existence of as many kinds of atoms as there were chemical elements. By the end of nineteenth century, the number of chemical elements increased so much that we were compeled to accept more than ninety different atoms.

3. Obviously, this was a very unsatisfactory situation. Scientists have been making efforts to understand the world in which we live with the believe that it is fundamentally simple in spite of its apparent complications. Thus, the scientists have begun to doubt that the chemical atoms were the ultimate constituents of matter. As a matter of fact, the existence of the electron was confirmed toward the end of the nineteenth century and turned out to be more elementary than atoms in many respects.
On the other hand, the discovery of radioactivity at about the same time lead us to the concept of the atomic nucleus. Namely, it was revealed by Rutherford in 1911 that each atom consists of a number of electrons surrounding the atomic nucleus.
Each of the chemical elements has its own nucleus, so that there are as many different kinds of nuclei as there are chemical elements. This is again unsatisfactory. The situation became even worse because of the discovery of isotopes. Namely, a chemically pure element, such as hydrogen turned out to be a mixture of isotopes such as the ordinary hydrogen and heavy hydrogen. The isotopes differ from each other because of the difference of nuclei which they contain. Thus, there are even more kinds of atomic nuclei than the number of chemical elements.
A very simple solution of this problem was obtained when the neutron was discovered by Chadwick in 1932. Namely, physicists came to the conclusion that each nucleus consists of a number of neutrons and protons, the latter being nothing other than the nuclei of the ordinary hydrogen atoms.
Thus, we arrived at an apparently satisfactory answer to the original question:

"What are the ultimate constituents of matter?"

The answer was:

"They are only three kinds of elementary particles, i. e., the electrons, protons and neutrons".

Is this the final answer ? Not at all. This is not the end of the story, but the beginning of the new story.

4. In order to make clear the situation, we have to go back to the beginning of the twentieth century, when two revolutionary ideas in physics came out.

The first one is the idea of quantum of energy due to Max Planck. Until the end of nineteenth century, matter and energy have been regarded as two entities which are not only completely separated from each other, but are entirely different in nature. Namely, whereas matter consists of discrete atoms, energy can change only continuously. The preocupation that nature does not make jump was so firm that nobody could accept the concept of atomistic structure of energy, until quantum theory was proposed by Planck.

Now, there are different forms of energy such as kinetic energy, potential energy, heat and light. It has been believed by physicists that not only the total amount of energy does not change, but also the change is always continuous. According to quantum theory, we had to accept on the contrary, that a finite amount of energy is emitted or absorbed by an atom all at once in the form of light quantum or photon. This means that the energy of light has corpuscular nature similar to the atom of matter. On the other hand, we can not deny that light is a wave and, in fact, a kind of electromagnetic wave which propagates in space continuosly.

This dilemma of duality of wave and corpuscle in the case of light was enhanced by the prediction by de Broglie in 1924 of the wave nature of matter. According to de Broglie, the motion of material particle such as an electron is associated always with the material wave, which propagates in the direction of motion of the particle. Thus, the duality of wave and corpuscle is something universal and common to matter and energy.

Thus, the distinction between matter and energy became obscure due to the discovery of light quantum and the discovery of material wave.

5. The second revolutionary idea was the principle of relativity due to Albert Einstein. One of the most important conclusions of the special theory of relativity which was proposed by Einstein in 1905 was the equivalence of mass and energy. Wherever there is a mass m , there is a corresponding energy of an amount mc^2 , and vice-versa, where c is the velocity of light in vacuum. Thus, the mass and the energy cannot be separated from each other, but they are the two aspects of the same entity. The wellknown principles of conservation of matter and conservation of energy are to be unified into the principle of conservation of energy by regarding the mass to be a particular form of energy.

This means, together with quantum theory, the complete change of our situation in relation to the old question; "What are the ultimate constituent of matter?"

We have to change the question itself into a new form: "What are the ultimate constituent of matter and energy?", because we know now matter and energy cannot be separated from each other. In order to answer this new question, we have, at least, to include the photon into our family of elementary particles.

Is this the final answer? Certainly not, because we know that there are other forms of energy which cannot be ascribed to the above four kinds of elementary particles.

6. First of all, we have to add to the list of elementary particles the particle called "neutrino". When a radioactive nucleus disintegrates by emitting a β-ray, the latter is always accompanied by a neutral particle of zero rest mass, i.e., a neutrino. Otherwise, the principle of conservation of energy breaks down.

Secondly, we have to accept the existence of the so-called "anti-particle" in addition to the particle. For instance, there exists in Nature the positron which has the same mass as the electron but the opposite electric charge. The positron is the anti-particle of the electron. Each of the proton, neutron and neutrino has its own anti-particle. Thus, there are 9 different kinds of elementary particles.

7. Even this is not the end of the story. There is a very important and new form of energy which is related to the strueture of atomic nucleus. The protons and neutrons in the nucleus are bound together by forces which cannot be reduced to other known forces such as electromagnetic and gravitational forces. Thus, we have to accept the existence of specific nuclear forces to which a new form of energy is to be associated. Here again, the duality of wave and corpuscle prevails. The corpuscular aspect of the nuclear forces was confirmed by the discovery of the π-mesons, which have masses about 270 times as the electron mass, in 1947, by Prof. Powell, Prof. Lattes and their colaborators.

There are three kinds of π-mesons with positive, zero and negative charges respectivelly. We have altogether 12 different kinds of elementary particles, but the situation may not be too bad, if this were the end of our story, because each of these particles has its reason of existence in that, each of them, is connected with a known form of matter or energy.

8. It turned out, however, that Nature is richer in content and more complicated than we suspected. First of all, ten years before the discovery of the π-mesons, another type of meson which is now called μ-meson had been discovered, but, up to now, this μ-meson remains to be one of the particles which puzzle us.

Furthermore, new strange particles have been discovered in cosmic rays one after another in these ten years. They are called K-mesons, Λ-particles, Σ-particles and Ξ-particles. If we include them into our list of elementary particles, we have altogether 30 different species. (14 + 4 + 2 + 6 + 4 = 30).

We do not know whether there are other particles which would eventually be discovered, because we do not understand the reason of existence of all these new particles.

9. History seems to repeat in the sense that we have again to worry very seriously about the increase number of ultimate constituents of matter and energy, just as the scientist in the last century had to worry about the increase in the number of chemical elements.

What have we to do in order to get away from this situation ?

Many of the physicists are inclined to think that most of the socalled elementary particles are not really elementary, but are composite particles consisting of very few kinds of really elementary particles. One example of such a way of thinking is Sakata model, according to which π-mesons, K-mesons, Σ, Ξ -particles are considered to be composite particles consisting of neutrons, protons and Λ-particles. However, a simple-minded composite particle model seems to be only one-sided picture, because of a number of serious difficulties which we encounter in developing such an idea. Recent attempt by Heisenberg at a unified theory of elementary particles is on this main line of thought, but differs essentially from the simple-minded composite particles model in that he started from the ultimate matter or urmaterie which is not identical with any of the known elementary particles, but is something more fundamental. Right now, we cannot say anything very definite about his theory, because of a number of uncertainties and difficulties in it.

10. In this connection, I would like to point out that the complete understanding of elementary particles can be reached only when we take into account an equally important problem of space and time, because space-time cannot be completely separeted from matter-energy. Matter and energy are contents of our physical world, whereas space and time are the framework. In other words, matter and energy are put into the vessel of space and time.

We used to think that the space-time framework was predetermined entirely independent of the matter and energy in it, until Einstein established the general theory of relativity in 1915. The general theory of relativity changed our way of thinking decisively in that it revealed for the first time the mutual dependence of space-time framework and matter-energy content on each other. The universal gravitation, which is a form of energy of interaction between material particles, is related, at the same time, to the shape of our space-time world according to general theory of relativity. Thus, the curvature of the four-dimensional space-time world is defined in terms of the gravitational potentials and their derivaties. The gravitation is not simply a content of the physical world, but is related to both the shape of the vessel and its content.

11. This ~~new and~~ important point of view which underlies general theory of relativity has been almost completely ignored by most of the physicists in dealing with problems of elementary particles, for the obvious reason that the gravitational force between elementary particles remains to be very small compared with other forces unless the distance between them becomes very small compared with ~~nuclear~~ dimensions.

I do not deny that the gravitational force as such has practically nothing to do with the elementary particles. However, I am inclined to think that the spirit of general theory of relativity should be reminded even when we are dealing with the small scale world of elementary particles. The recognition of the mutual dependence of framework and content on each other in the world of elementary particles may well be ~~key~~ the key point of the real understanding of elementary particles themselves. I would like to emphasize that the way of thinking which lead us to quantum mechanics and that which underlies general theory of relativity are, in many aspects, complementary to each other.

I already mentioned that the old question about the ultimate constituents of matter changed into a new question about the ultimate constituents of matter and energy. Now, I think we have to add another question:

"what would be the mutual dependence of space-time and matter energy on each other in the world of elementary particles ?"

Perhaps, this question cannot entirely be separeted from the original question, but an answer to one of these two question may well come out ~~simultaneously~~ simultaneously ~~with~~ with an answer to the other.