The Atomic Nucleus, A New World to Conquer

I. I. Rabi
Department of Physics, Columbia University

THE ELECTRICAL CONSTITUTION OF MATTER—that is, the fact that matter is made of constituents which are electrically charged positive and negative—was clearly understood only at the turn of the last century. The fundamental fact of atomic structure, that the atom was made up of a central positive core, the nucleus of the atom, which was positively charged and surrounded by electrons charged negatively, was realized only after 1911 from the great work of Rutherford.

However, it was not until after the work of Bohr, Einstein, Schrodinger, Heisenberg, Pauli, and Dirac that we had adequate intellectual tools to understand atomic structure. By the end of 1928 the job was complete. The fundamentals had been understood, and the structure of the atom was a problem which, in principle, had been solved. The atom had been conquered, but conquest and consolidation are two very different things.

Newton, almost 300 years ago, gave the fundamental theory of the solar system and celestial mechanics, yet there are astronomers and mathematicians working on these very problems even today. One hundred years from now there will be physicists, chemists, and engineers working on important problems of atomic and molecular structure.

Long before the fundamental principles of atomic structure had been understood, very important advances had been made both in theory and application, because practical results do not depend on detailed knowledge of the basic laws.

The subject to be discussed here, however, is not the structure of the atom but the atomic nucleus. In assessing our present position on this problem and forecasting the future, however, there is much we can learn from the development of our attempts to understand the atom. Let me sketch very briefly the fundamentals of the problem.

If an atom of uranium were magnified 1,000,000,000 times, it would be the size of a basketball, and if its weight were increased correspondingly, it would weigh about a ton. If one were to examine it carefully, one would at first sight see nothing at all, but on very close inspection one would find 92 tiny particles, each much smaller than the point of a very fine needle, moving with enormous speed, approximately inside the confines of the basketball. These are the electrons. Altogether these electrons, small as they would appear, would weigh one-half pound.

In the center one would discover a speck of dust about 1/1,000 of an inch in diameter. This is the nucleus of the atom. Its weight or mass would be a ton, less one-half pound, of course, for all the electrons put together. If we take, with Einstein, the famous relations $E = Mc^2$—that is, energy is proportional to mass—we see that almost 99.99% of the energy of matter is locked up in the nucleus.

The useful energy we have had available up to the present from fuels such as oil, coal, or food has been chemical energy and generally less than one billionth of the total conceivable energy which is locked in the atom and more particularly in the nucleus. These numbers stir the imagination. They are inspiring and frightening, especially if we remember Hiroshima.

I am not, however, predicting the release of these stupendous powers. We have a long way to go before we can even begin to assess the validity of such speculations. Let us examine further this speck of dust we called the nucleus of the uranium atom.

Looked at more closely, it would turn out to be comprised of 238 objects, 92 protons all positively charged and 146 neutrons. I did not pick uranium 235 because that is fissionable material and is classified secret. The protons are all positively charged and have the same charge as the electrons. The neutrons have no charge at all.

We now come to the fundamental question: What forces keep this conglomeration of protons and neutrons together against the mighty repulsions of the protons for one another? What force keeps these nuclear particles which move at tremendous speeds from flying apart in less than one billion billionth of a second? I do not know, nor does anyone else in the whole world.

There are some charming speculations which may contain some grains of truth. I will tell you something about them, but first I must say that our ignorance is not entire. Although the why of nuclear forces is not known, we have a very definite notion about the magnitude of these forces. Otherwise, the atomic bomb could not have been made and we could not be seriously discussing the use of nuclear energy for the production of power. Application of scientific

This paper is based upon material presented in an address at the dedication of the Laboratory of Nuclear Studies at Cornell University, October 7, 1948.

discovery does not have to wait on complete understanding of the whys and wherefores.

The utilization of atomic energy, whether for warfare or the greater arts of peace and healing, does not await a great basic discovery. The fundamental science is at hand, and it is a question for the engineer, the chemist, the metallurgist, and applied science in general.

At this dedication of the Institute for Nuclear Physics we are concerned with much more fundamental questions which look beyond the immediate practical problems of today but which may bring the headaches of the future. We will now proceed from what may be considered the more or less well-known to what is known only partially and on into the unknown.

The real reason for basic research is to expand the boundaries of knowledge pure and simple. It is an expression of the human spirit. This passion for new knowledge, for the exploration of nature, is strong in some, easily controllable in others, and in many people completely absent. Various societies have differed in this respect. The Athenians were passionately devoted to the search of abstract knowledge, but the Spartans were quite indifferent.

Fortunately, we are living in a time in our country when the interest in scientific research and discovery is mounting very rapidly. This new Institute for Nuclear Science is one of the many expressions of this interest. The great telescope on Mount Palomar is another. All over the country great new laboratories are arising in all fields. Schools of art and music are multiplying. The country is growing up, and some of the energy which went into the conquest of this continent is turning toward intellectual and artistic endeavor. We may see the dawn of a Golden Age. Perhaps it has already come and we are no more aware of it than the Athenians in the time of Pericles.

Let us return to the examination of the atomic nucleus just for the sheer pleasure and interest of it. To study an object as small as the atomic nucleus is even more difficult than it sounds. In the first place, you know that one can see smaller objects with the ultraviolet-ray microscope than with an ordinary microscope using visible light, the reason being that the wave length is shorter in the ultraviolet. More recently you have heard of the electron microscope, with which one sees things even smaller, because electron waves can be utilized which are very much shorter. The large synchrotron which is now nearing completion will produce electron wave lengths and gamma rays which are a sort of supershort ultraviolet, of approximately the size of the nucleus. In a certain broad sense the plan is to take a "look-see" at the atomic nucleus with these extraordinarily powerful instruments.

What will Prof. Wilson and his colleagues see? If he knew, he would not have built the instrument, but we can conjecture some of the strange things he might see and study. In the first place, the energy of the radiation, although compressed in volume, comes in such enormous packets (about 300,000,000 v, compared with 3 v of ordinary light) that mostly chips in the form of protons and neutrons will come out of the nucleus. These chips will interest them enormously but will probably not be the main show.

The chief phenomenon will be in the class which has already been observed in cosmic rays and in the large synchrocyclotron at Berkeley. When these ultra-high-energy particles strike a nucleus, new particles come out which were not supposed to be there in the first place. They cannot be within the nucleus for reasons which would be too lengthy to set forth here. Yet they come out of the nucleus under the extreme condition of high-energy impact. The only possibility is that they are created then and there, on the instant, out of the energy of the collision.

This fascinating phenomenon was first observed about 15 years ago by Carl Anderson in Pasadena. When gamma rays of over 1,000,000 v of energy strike an atomic nucleus, a pair of electrons comes out once in so often, one positive and one negative. Vice versa, a positive electron and a negative electron can combine, leaving nothing but gamma radiation, which is pure light energy.

In the big Berkeley cyclotron it was observed only a few months ago by Lattes and Gardner that when a 400-Mev nucleus of helium struck a carbon nucleus, a new particle appeared, perhaps identical with one previously observed in cosmic rays by Powell and his group in Bristol, England, about a year ago. This new particle has been called a pi meson. It is about 300 times as heavy as an electron and can have either positive or negative charge. The pi meson does not last very long, only about one hundred millionth of a second, and then it turns into two other things. One of these is another kind of meson of about 200 electron mass units; the other partner is at present unknown.

This phenomenon was first observed in cosmic rays by the Bristol group about 18 months ago, although we have no real assurance that the Berkeley and Bristol phenomena are identical. The Cornell synchrotron is therefore coming into existence at a very exciting time and is bound to play an important role of discovery. The mu meson, which may be identical with a particle which Anderson in Pasadena and Street of Harvard found in cosmic rays about 13 years ago, does not linger with us very long either. After about a millionth of a second it turns into an electron and something else which is also unknown.

What do these phenomena mean? It is far too early to tell. No one knows how many more particles will be found in the next few years, after the new machines are in operation, or perhaps in the next few months or days.

Strangely enough, some of these discoveries were foreshadowed in 1935 by the Japanese theoretical physicist, Yukawa, who was then about 27 years old. He reasoned from the fact that nuclear forces were short range like the cohesive force of a glue which is very strong on close contact but disappears on a small separation, that the forces could not be electrical in nature, since these are long-range forces like gravitational forces. On the other hand, if one postulated that a proton or neutron in a nucleus could spontaneously emit a massive particle which could be absorbed by another proton or neutron, and vice versa, such short-range forces could be explained. Shortly afterward, following this same lead, Anderson and Street independently discovered the mu meson, which could be such a particle but isn't. Perhaps the pi meson is this Yukawa particle. It has been suggested with justice that they be called Yukons.

We see that somehow there may be a connection between these new particles and nuclear forces. Why there are so many, why they should disintegrate so quickly and spontaneously, we do not know. We do not know how many there are, or just how they behave in the neighborhood of a nucleus, or anything solid about them really. The young men and women here who expect to be physicists will have plenty of problems to study.

In conclusion I wish to tell you of the most charming new particle of all, the neutrino. This particle has never been observed, but, like the God of the philosopher, if it did not exist, it would have to be invented. It comes about in this way: Some nuclei, like rubidium or potassium, spontaneously emit electrons and change into another kind of nucleus. Yet there cannot be any electrons within the nucleus itself. They are just created and come out. On the other hand, they do not all come out with the same energy, even though there is a definite energy difference between the energy of the original and final nucleus. This is more than tragedy, because the law of the conservation of energy, without which we would not know how to turn around in physics, says that any energy lost must appear in some other place. That is where the neutrino comes in; it is a particle invented to carry off the missing energy in order to keep the books straight. There is a similar law about spin, and the neutrino takes care of that, too. It is a most convenient little gadget.

After it had been invented, consequences as to its properties could be drawn fairly easily. The most striking property is that it has no mass whatever. It interacts with matter so slightly that it could pass right through the earth in its thickest part without hindrance. For this reason there is no known way of detecting it. It is merely the subject of the verbs "to be" and "to spin."

I hoped in this talk to show you that we physicists do not know everything, that this is not a depressing subject, hopelessly involved in atomic warfare, but a great and exciting, civilized, intellectual adventure. The new Institute of Nuclear Physics puts Cornell right in the center of this wonderful life.