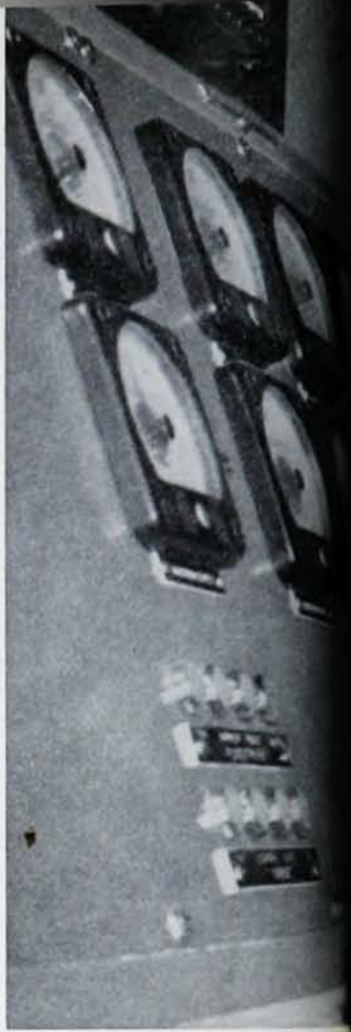
The NUCLEUS



By Enrico Fermi

The following article is based on the first of six invited papers presented during the symposium on contemporary physics which keynoted the Twentieth Anniversary Meeting of the Institute of Physics in Chicago last October. An audience of three thousand assembled in the Chicago Civic Opera House to hear the addresses, four of which have appeared in recent issues of this journal.

IN THE TWENTY-YEAR PERIOD since the founding of the American Institute of Physics, nuclear physics has been advancing perhaps as rapidly as any other branch of our science. Twenty years ago the neutron had not yet been discovered, and a favored hypothesis as to the structure of the atomic nucleus was that it consisted of protons and electrons. This very fact may give some idea of the exponential rate of our progress.

Perhaps, to think of another reference mark, consider that it was just about forty years ago when the discovery of the nucleus was announced by Rutherford.

In nuclear physics, as in many other branches of physics, the past four decades have seen advances in very many directions. These advances have occurred both in techniques and in fundamental knowledge. During the period with which we are concerned, voltages achieved in accelerating machines have been going up in steps roughly of $10—10^6$, 10^7, 10^8, and very soon, we hope, 10^9 electron volts. The Cosmos is of course still far ahead, and provides a formidable challenge to the constructors of high energy accelerating machines.

Neutron sources have gone up in steps which are more nearly (in round numbers) of the order of one million each—from the small radium or radium-beryllium sources, to cyclotrons, to atomic reactors.

Of course quite sizeable steps have been taken in the amount of money used for research. Large steps have also been taken in the population growth of physicists, and in the audiences that come to listen to a symposium in physics—if I should judge from this audience.

Technical advances that have been less spectacular than those mentioned previously, but I believe no less significant, have taken place in the development of detecting devices. Counters, ionization chambers, and the more recent and very important discovery of the scintillation counter should be mentioned. The latter does automatically what Rutherford and his pupils did so laboriously in watching the minute scintillations that result when an alpha particle hits a crystal. The refined electronic techniques used in the scintillation counter have shortened the time of counting to the range of 10^{-9} seconds and less. One can thus measure directly the time taken by particles traveling close to the velocity of light to cross a distance of a few feet, and consequently obtain the velocity of the particle.

The Wilson cloud chamber has led to the development of the diffusion chamber, which promises to be one of the fundamental tools in investigating elementary particle reactions. Photographic plates have been

Enrico Fermi, Nobel Laureate and professor of physics at the University of Chicago, came to the United States from Italy in 1938. Professor Fermi's contributions to the present knowledge of nuclear physics have been both numerous and important. He played a prominent part in the development of the atomic energy program in this country, having been in charge of the work which resulted in the first self-sustaining nuclear chain reaction produced in the Chicago pile in 1942, and later having served as a member of the wartime staff of the Los Alamos Laboratory in New Mexico. Professor Fermi is vice president of the American Physical Society.
Wide World photo

developed to a very high degree of perfection as recorders of tracks of particles.

Now these technical developments have resulted in part in, and in good part have promoted, a very considerable advance in the knowledge of the nucleus and of its constituents. We have by now what seems to be the final understanding at least of the generalities of the nuclear structure—the nucleus built of neutrons and protons. We have some understanding of the features of the beta spectrum. We have discovered hundreds of nuclear reactions and hundreds of new radioactive isotopes, with the result that a new branch of the art of nuclear science has emerged which includes radiochemistry and all of the complex techniques in chemistry and biology for the use of tracers.

The discovery of fission has led to the realization of the possibility of chain reactions, soon followed by the actual construction of nuclear reactors. This has provided the starting point for the new science of nuclear engineering. The spectroscopy of the nucleus is approaching in complexity, although by no means in understanding, that of the atom. Charts of nuclear energy levels with corresponding gamma-ray and other transitions between them are beginning to acquire a complexity that may remind one of the early atlases of atomic levels that were in use in the early Twenties. Measurement of nuclear masses and moments, primarily with the technique of mass spectroscopy and radiofrequency resonances, has become an extremely precise art. We have learned a great deal about elementary particles and, with the help of the cosmic radiation, have discovered many new ones. Great progress has been made in the determination of beta spectra and recently even the beta disintegration of the neutron has been investigated quite thoroughly.

The mass of data resulting from these many discoveries presents a challenge for the understanding, and unfortunately the business of understanding is not as well in hand as one might wish. The present state might be illustrated by choosing, for purposes of discussion, two of the many topics in nuclear physics that are of current interest.

IN DISENTANGLING the problems of the atom, one of the major steps has been the recognition that it is useful to speak of individual orbits of the electrons in the atom. This, to be sure, is only an approximation, in fact a crude approximation, but still it provides a quite invaluable starting point for the study of complex atoms containing large numbers of electrons.

When physicists became reasonably certain that the nucleus was constructed of protons and neutrons, questions were raised concerning the orbital behavior of these particles. Could nuclear structure be interpreted on the general pattern of atomic structure by attributing to the various neutrons and to the various protons within the nucleus something like individual orbits and individual states? If so, an understanding of the nuclear levels and the nuclear structure could possibly emerge from the much simpler pattern of the individual states.

No definite answer has ever been given to this question, although nuclear science has for a long time "officially" frowned on such attempts. Strong arguments were quoted for saying that the constituents of the nucleus are mixed so thoroughly and interact so rapidly that there is little basis for hoping that individual orbit considerations can lead to an understanding of nuclear structure.

Consider one nucleon in the nucleus travelling along its orbit among the other nucleons. If the collision mean free path is λ this nucleon would collide with the other neutrons and protons in the nucleus and its orbit would be lost after it had gone the distance of its free path. A criterion that one might adopt in deciding whether or not it is a sensible approach to talk of individual orbits is to compare the mean free path with the size of the expected orbit. If the mean free path is long, then we may take the orbital behavior seriously. But if the mean free path is much less than the size of the orbit, one expects the idea of orbit to become rather unusable. Now it is a very difficult problem to decide the length of the mean free path, but if one takes somewhat literally the strength of the interactions between the neutron and other components of the nucleus, one is led to a value that seems discouragingly short.

In spite of this argument, evidence has been accumulating for the last few years, both in this country and in Germany, to the effect that orbits do exist. The best-known feature of this evidence has been the discovery of the so-called "magic numbers." They are the numbers 2, 8, 20, 50, 82, 126. When a nucleus contains a number of either neutrons or protons equal to one of the magic numbers, it is particularly stable, as if a shell of either neutrons or protons had been closed.

This and other evidence to be discussed later indicate that the orbit approximation is much better than the discussion above may have suggested. It would appear that for some reason the mean free path must be longer than is given by a somewhat crude estimate of its length. One possible reason for this may be the Pauli principle, according to which collisions between two particles may be forbidden when, after the collision, one of the two particles would go to an occupied state.

Another possible explanation of the long mean free path may have to do with the saturation property of the nuclear forces. It has been suggested, for example, that the meson field responsible for these forces may have a non-linear character and reach a saturation level in nuclear matter due to the high density of the nucleons present. In spite of the fact that neither of the two above possibilities has been worked out to the point that it can be considered a satisfactory theory, it is now rather generally believed that many features of the single particle model will ultimately prove correct.

Strong additional evidence for this model is the detailed explanation of the magic numbers in terms of the assumption of a very strong spin orbit coupling. Maria Mayer here in Chicago, and the investigators in Germany who developed independently similar ideas, have been able to point out very many features of the isomeric nuclear levels which lend strong support to these views.

There is at present no understanding of the origin of the strong spin orbit coupling that is suggested by the empirical evidence. Such understanding perhaps will come only when a satisfactory theory of the nuclear forces will have been developed. At present we must take the existence of this coupling as an empirical fact.

In spite of our only partial understanding of the situation, the orbit theory of nuclear structure offers a hopeful model for at least a qualitative understanding of nuclear structure, and already it has been possible to fit into this picture a very great number of details.

IT IS OF COURSE IMPOSSIBLE to hope for any deep understanding of the structure of the nucleus without knowing a lot about the forces acting between the elementary constituents of the nucleus—between neutron and proton and between proton and proton and between neutron and neutron.

The classical experimental approach to investigations of nuclear forces has been the study of scattering. One hurls a neutron at a proton and sees how they are deflected. From the features of the deflection, the angular distribution, the energy dependence, and so on, one hopes to deduce the force responsible for the deflection. Early experiments by Tuve, Herb, and others, interpreted by Breit, gave the first knowledge of a short range interaction between nuclear nucleons that is responsible for the fact that particles stay together. Then came the Yukawa theory to give a great help to our understanding of the problem by offering for the first time a model for us to consider. The model is quite similar in many ways to that of the electromagnetic forces: one particle produces a field and the field acts on another particle. In this case, however, Yukawa was faced with the additional problem of designing a theory that would automatically account for the short-range character of the nuclear forces. Yukawa recognized that a field whose quanta have zero mass (like the photons) would have a long range, while a field whose quanta have a finite and relatively large mass would have a short range.

According to the Yukawa theory, a neutron will occasionally convert into a proton plus a pi-meson, which will then be reabsorbed and thrown out again and reabsorbed and so on. The nuclear field involved in this oscillation will extend as far from the original neutron as the continually emitted pi-mesons can reach. And how far can they reach? The argument runs as follows:

A meson has considerable mass, and to fabricate a meson with which to play this odd ball game requires an amount of energy equal to the mass of the meson, μ, multiplied by the square of the velocity of light, c. Who pays for this amount of energy? Well, nobody; so if nobody pays one has to borrow. Now in the bank of energy there is a very special rule that should perhaps occasionally be adopted by commercial banks—namely, the larger the loan, the shorter the term. Quantitatively, this banking practice is represented by one of the forms of the Heisenberg uncertainty relation. One can borrow an amount of energy W for a time of the order of Planck's constant h divided by W; therefore the time t of the loan shall be $h/\mu c^2$. The meson will be capable of moving away from its source a distance equal at most to the time t multiplied by the velocity of light c; therefore the range of the nuclear forces according to this mechanism is essentially $h/\mu c$ and is inversely proportional to the mass. For short-range action, the quanta of the field that transmits the nuclear forces must be very massive; in fact, the early estimates of Yukawa indicated that the mass would have to be comparable to 300 times the electron mass.

Almost on the heels of the announcement of the Yukawa theory came the discovery of the meson in cosmic radiation, thus giving the theory a tremendous boost. The particle first found in the cosmic radiation, as is well known now but was not known at the time, is not the Yukawa meson, but is a son of the Yukawa meson. This was discovered recently when Powell found tracks in photographic plates that had been exposed at high altitudes, showing the existence of two different mesons. One of these, the so-called pi-meson, is the one responsible for nuclear forces; the other, the mu-meson, is a rather uninteresting offspring of the first—at least it seems uninteresting at present.

Then, of course, came another fundamental experimental result that was determined at least in part by the Yukawa theory: if two nucleons, each of which is surrounded by a meson field, collide with sufficient energy, some mesons are likely to be shaken loose. There was evidence from cosmic-ray studies of the actual existence of this process, but the most spectacular experimental result in this direction was obtained at Berkeley where Lattes and Gardner discovered that these mesons are actually produced in the high energy collisions in the synchrocyclotron. The discovery of an artificial means for the production of pi-mesons has put at the disposal of the physicists a source of this particle that is easily controllable and extremely more intensive than any cosmic-ray source. This is an ideal situation for investigating the properties of these new particles and research is going on actively in this direction in many laboratories. But again, what about the understanding?

PERHAPS, in outlining the Yukawa theory (which in my opinion certainly has a considerable amount of qualitative correctness), I should have included the warning that there is not just one theory, but that there are several theories, and that none of them seems to be really the correct one. It is sometimes difficult to say what is wrong with any particular theory because the mathematics involved is almost prohibitively complicated. But one can seldom manage to make a calculation that is really right because the theory is so complicated, and if one tries, more as a rule than as an exception, one encounters divergent infinite terms which one usually attempts to eliminate by not perfectly orthodox procedures. Perhaps at the root of the trouble is the fact that the theory attempts to oversimplify a situation which may in fact be quite complicated. When the Yukawa theory first was proposed there was a legitimate hope that the particles involved, protons, neutrons and pi-mesons, could be legitimately considered as elementary particles. This hope loses more and more its foundation as new elementary particles are rapidly being discovered.

Perhaps the situation might be compared (although comparisons are always dangerous) to that of the early quantum theory, which provided a large amount of qualitative insight in the atomic structure, but nevertheless failed from the quantitative point of view. Perhaps the situation is similar; perhaps brilliant solutions of the same type will be forthcoming.

It is difficult to say what will be the future path. One can go back to the books on method (I doubt whether many physicists actually do this) where it will be learned that one must take experimental data, collect experimental data, organize experimental data, begin to make working hypotheses, try to correlate, and so on, until eventually a pattern springs to life and one has only to pick out the results. Perhaps the traditional scientific method of the textbooks may be the best guide, in the lack of anything better.

At present, rapid progress is being made in collecting data on nuclear forces, both by direct observation from scattering experiments and by indirect study of the mesons. Results are accumulating quite rapidly, and while they have not yet fallen into a satisfying pattern, perhaps they will before too long.

Some of the many Yukawa theories seem to be excluded by these experiments, and the favored one at present is the "pseudoscalar theory with pseudovector coupling," which in slightly plainer words means that the meson has spin zero and behaves like a pseudoscalar, a symmetry property that is certainly familiar to most physicists.

Of course, it may be that someone will come up soon with a solution to the problem of the meson, and that experimental results will confirm so many detailed features of the theory that it will be clear to everybody that it is the correct one. Such things have happened in the past. They may happen again. However, I do not believe that we can count on it, and I believe that we must be prepared for a long hard pull if we want to make sure that at the next anniversary celebration of the American Institute of Physics we shall have the solution to this problem.