2 September 1966, Volume 153, Number 3740 SCIENCE

Remarks on Nuclear Structure

A. de-Shalit

The history of the discovery of forces in nature is very surprising. Contrary to our expectation, the first fundamental force to be discovered and identified is the weakest of them all—the gravitational force. Other forces, such as those giving rise to elasticity and cohesion, were known almost as early, but the fundamental, unifying force behind them was not traced until many years later. It turned out to be a much stronger force, but still the second-weakest force (*1*)—the electromagnetic force. It was only some 50 years ago that the first indications of the strongest force were recognized. A new force, fundamentally different from both the gravitational and the electromagnetic forces, had to be invoked to explain the accumulating data on the size, mass, and interactions of atomic nuclei.

There is a good reason why these three forces were discovered in that order. Gravitational force, to the best of our knowledge, is associated with any form of matter or radiation. It acts between the sun and a ray of light passing close to it just as much as between the earth and Newton's famous apple. It always pulls the partners together, and nothing can be shielded from its action. Newton himself clearly observed that the gravitational forces exerted by the earth or by the sun were proportional to their total mass. The central part of the earth therefore managed to exert its gravitational pull on the apple without its effects being shielded by the surface of the earth. Nor does the earth change its orbit around the sun when the moon gets exactly in between; the moon shields us from the solar light but in no way affects the solar gravitational pull. The naked, fundamental force is what we feel around us every minute of our lives.

The electromagnetic force is, of course, just as common, if not more so. However, we rarely feel it in nature in its naked fundamental form. All the "mechanical forces" around us are basically electromagnetic, but they all result from many complicated cancellations of electric attractions and repulsions of objects located in different places and shielding each other's effects in different ways. The unraveling of the common element in all these forces naturally took a much longer time. But once this underlying common structure was understood it was possible to perform controlled experiments where the difficulties resulting from complicated systems could be eliminated. Electric forces could be directly compared with gravitational forces, as in the famous Millikan oil-drop experiment, and the basic laws governing the interactions of electrically charged particles could be formulated.

Nuclear forces remained hidden for a different reason. Nothing really shields us from them except the fact that they never reach very far. Unlike the gravitational and the unshielded electrical forces, which reach to very large, even astronomical, distances, the nuclear force disappears completely at a distance from the nucleus of 10 or 20 nuclear diameters. Even in the most dense materials that we have on earth the nucleus of one atom knows nothing whatsoever of the nuclear forces exerted by the nucleus of the atom next to it. The range of nuclear forces—the distance over which they are felt—is measured in units of 10^{-13} centimeter, whereas the distance between the nuclei of neighboring atoms is measured in units of 10^{-8} centimeter—that is, the atom is a hundred thousand times as large as the nucleus! And yet, within their range, nuclear forces are so strong that they leave very little room for the electromagnetic forces to affect basic nuclear properties.

Furthermore, these strongest forces involve only a selected class of particles. The electron, for instance, which presumably responds to the gravitational pull of the earth and to the much stronger electric forces exerted on it by the nucleus, does not react at all to the even stronger nuclear part of the force, even when it comes as close to the nucleus as 10^{-13} centimeter. The dynamics of the electron motion around the nucleus is essentially identical to the dynamics of the electron around another electron, or, better still, around a positively charged electron—the positron.

These circumstances made the study of the nuclear force and its effects on nuclear structure considerably more difficult and complicated than the study of the electromagnetic force and its effect on the chemical structure of matter. For in the realm of nuclei the subject of our study and the tool used are one and the same thing, and in most cases we must use one nucleus to study the nuclear properties of another, trying to build in this way a complete and consistent picture.

The author is the Herbert H. Lehman Professor of Theoretical Nuclear Physics, Weizmann Institute of Science, Rehovoth, Israel.

Size, Shape, and Composition of Nuclei

All known atomic nuclei carry a positive electric charge, otherwise they could not have formed the center around which the negatively charged electrons revolve. The best determination of the distribution of charge in the nucleus can be made by probing it with fast electrons. Since the nucleus is so much more massive than the electrons which surround it in the atom, a fast electron shot through a thin sheet of aluminum, for instance, will be deflected from its straight path only if it happens to pass close to one of the aluminum nuclei. Furthermore, the amount of its deflection depends on the way in which the electric charge is distributed over the aluminum nucleus. If the charge were all concentrated at one point, the electric force, which varies inversely with the square of the distance, could become very strong and cause a big deflection of the electron. If, on the other hand, the charge were all spread on the nuclear surface, an electron passing through the nucleus would feel no electric force whatsoever while traversing the nucleus. The deflection of the electron would then be considerably smaller. Since the electron responds only to the electromagnetic forces exerted by the nucleus and not to the nuclear forces, it is possible to work out just exactly what the deflection of the electron should be for any given charge distribution over the nucleus. Conversely, from the observed deflections of fast electrons shot through thin sheets of different materials it is possible to obtain a reasonably reliable idea of the charge distribution of their respective nuclei. The picture obtained is similar in all nuclei: a nucleus of A mass units (that is, of mass number A) is uniformly charged up to a radius of about $1.2 \times A^{\frac{1}{3}} \times 10^{-13}$ cm, and then, within another 0.5 to 0.7×10^{-13} cm, the charge density falls off rapidly to zero. It looks as if the charge were confined to a spherical box of radius $1.2 A^{\frac{1}{3}} \times 10^{-13}$ cm.

The electrons in the atom also spend a good fraction of their time inside the nucleus, and are therefore influenced by its charge distribution. A detailed analysis of very fine details in the atomic spectrum can reveal the shape of the nuclear charge distribution as well as its dimensions. Thus the nucleus is found very often to be spherical in shape. For some nuclei, especially in the rare-earth region, the nuclear electric charge distribution resembles a prolate ellipsoid whose long axis may be as much as 30 percent longer than its diameter. The electric charge on most nuclei deviates, however, only slightly from spherical shape.

Similar information about the size and shape of the nucleus as a whole, not just about its electric charge distribution, can also be obtained. By and large it can be said that the electric-charge picture of the nucleus gives also a good picture of the mass distribution of the nucleus as a whole. Nuclei are thus found to be spheroidal objects, many of them almost spherical, others showing a marked deviation from a spherical shape and looking more like a thick short cigar.

The composition of nuclei is a somewhat more tricky question. We know that nuclei can be fused to form other nuclei without the addition of any other ingredient. As a matter of fact, nuclei are empire builders, and were it not for the buildup of a positive electric charge in the nucleus as it gets bigger, nuclei would have stuck to each other, forming one big nucleus out of the whole material around us. The observation that two nuclei can stick together and form another nucleus, similar in its properties to another nucleus which is often found in nature, leads to the hypothesis that all nuclei are composed of the smallest known nucleus—the proton. In fact the situation is slightly more complicated, due to the existence of another smallest but chargeless nucleus—the neutron. This particle, which is heavier than the proton by about 0.2 percent, is unstable when free. However, its binding in the nucleus can prevent its decay, as I point out later. All our present information on nuclei is consistent with the assumption that a nucleus with a positive charge that is Z times the (absolute) charge on the electron and a mass number A, is composed of Z protons and $N = A - Z$ neutrons. The mass of such a nucleus is nearly equal to that of Z protons and N neutrons; in fact the difference is quite accurately accounted for by the weight of the energy released in binding the Z protons and N neutrons together. The total charge of the nucleus exactly equals the total charge of Z protons. The total nucleonic charge of the nucleus also equals the sum of the nucleonic charges of Z protons and N neutrons.

Since the concept of a nucleonic charge is perhaps not as familiar as that of an electric charge, I want to devote a few words to it. Of the 80 or more elementary particles known today, all but a very few disintegrate, or decay, sooner or later, into lighter particles. From all the laws of physics known before we had means of studying nuclei we should expect that a given particle will eventually decay into other, lighter particles provided some rather simple rules are obeyed. For instance, the algebraic sum of electric charges cannot change in such decays: electric charge is conserved. A neutron, with no electric charge, can decay into the lighter combination of a positively charged proton, an equally negatively charged electron, and a massless neutral particle known as a neutrino. The stability of the electron against decay into a number of the lighter neutrinos can be understood by the nonexistence of a *charged* particle lighter than the electron; the electron's decay into neutrinos only would have involved the disappearance of electric charge, contrary to our experience that electric charge is conserved.

However, no law that we know can prevent the decay of a proton into two positively charged positrons and one negatively charged electron, and yet there has not been any indication of a single decay of a free proton, and the persistent presence of hydrogen in the universe makes it appear that the proton is as stable as the electron. We cannot escape the conclusion that the proton carries, in addition to its electric charge, another charge, called a nucleonic charge, whose disappearance is as forbidden as that of the electric charge. To explain the failure of the proton to disintegrate into two positrons and an electron, it is then necessary to assume that electrons and positrons carry no nucleonic charge—that is, to assume that, although they are electrically charged, nucleonically they are neutral. The observed disintegration of the neutron into a proton, an electron, and a neutrino now requires the assignment to the electrically neutral neutron of a nucleonic charge equal to that of the proton (other experiments show that this nucleonic charge cannot be carried by the neutrino, which turns out to be also nucleonically neutral).

The statement that a nucleus carries a nucleonic charge which equals the sum of the nucleonic charges of Z protons and N neutrons obtains therefore an operative meaning: No matter how we break or mutilate this nucleus, provided we do not add to it or take away from it neutrons or protons, its fragments will always carry $A = Z + N$ nucleonic charges. A nucleus of uranium-238 may undergo a spontaneous fission—a process in which it suddenly breaks up, releasing much energy, several electrons, neutrinos, and gamma rays; the total number of protons and the total number of neutrons in all the fragments may differ from the totals for protons and neutrons present in uranium-238, but the *sum* of protons and neutrons in all the fragments of the fissioning uranium-238 will always remain 238.

Are the Known Laws of Nature Applicable to Nuclei?

Nuclear dimensions are about 10^5 times smaller than characteristic interatomic distances, and yet nuclei account for all but one part in 4000 of the atomic mass. The number of nucleons per unit volume in the nucleus is therefore 10^{15} times the average number of electrons per unit volume. We naturally wonder whether the physical laws which were found to be valid for the electrons in atoms hold also for nucleons under these extreme conditions inside the nucleus. We recall that the classical laws of physics were actually derived as generalizations of the observable effects of gravitational and "mechanical" forces. Theorems like that of the conservation of energy, the conservation of momentum, Newton's second law—all were formulated in general terms. But they were experimentally verified for just two types of fundamental forces: gravitation and electromagnetism. Furthermore, the classical phenomena involving the electromagnetic forces always involved systems with a very large number of charged particles. Allowance should be made, therefore, for the possibility that some fine aspects of the physics may be averaged out in these large systems.

Indeed, the more profound studies of small systems, like isolated atoms and molecules, containing relatively few charged particles revealed the necessity of revising the laws of physics. While some of the general laws continue to hold on the atomic scale, several fundamentally new laws are required to explain characteristic atomic phenomena. These phenomena are covered by the well-known quantum theory, and the question naturally arises, How about the nucleus? Does its dynamics, involving new forces, require a new theory, or is quantum theory good enough for its description?

Among the new laws and notions introduced by quantum theory, some are particularly important. We know, for instance, that satellites can be put into different orbits around the earth, depending on their velocity, and that there is a continuous set of possible orbits for the motion of a satellite around the earth. On the atomic scale, on the other hand, it was found that the velocity of the electrons moving around the nucleus—or, better still, their energy—could not assume any random value. Energy changes can be effected only in certain definite, finite quantities, or, as we often say in technical language, the energy of the electron is "quantized." The same holds true for many other physical phenomena: their measure is quantized and can assume only a discrete set of prescribed values.

Another innovation introduced by quantum theory had to do with the probabilistic, noncausal interpretation of physical phenomena. This particular development led to many philosophical arguments, and is by now well known.

Two less widely known innovations had to do with the introduction of the concept of "internal degrees of freedom" and with the Pauli principle. The former asserts that the positions and momenta of particles may not always be sufficient for their complete dynamical description. Particles may possess additional, internal dynamics which cannot be described in terms of their positions and momenta, or in terms of the positions and momenta of any "subconstituents" of these particles. In this sense these internal dynamical features require, for their description, the introduction of additional generalized coordinates, or degrees of freedom.

The Pauli principle, which is another important development of quantum theory, gives the absolute identity of two particles an operational meaning. In the world of classical physics, with its continuous range of variation of various physical properties, a precise identity of two systems is extremely hard to establish. The possibility that there are tiny differences, beyond the limits of resolution of our instruments, can never be excluded. But in a quantized world, where a particle's physically measurable quantities can have only a discrete set of values, the notion of two identical situations acquires a qualitatively new meaning. The Pauli principle applies to a certain class of particles, technically known as fermions, which include, among others, the electrons, the proton, and the neutron. It states that two identical fermions (for example, two electrons) can never be found in identical situations at the same time, and it claims a validity irrespective of the nature and strength of the forces between the fermions. It is an extremely deep and powerful principle and is responsible, as is well known, for the periodicities in the periodic table of the elements.

These and other quantum mechanical principles were all derived from the study of atoms and molecules, whose structure is controlled by electromagnetic forces. The amazing thing is that they are all found to hold equally well for the nucleus, with its 10^{15} times as many particles per unit volume and with forces among its particles which are as different from electromagnetic forces as we can only imagine. Moreover, to this day we know of no nuclear phenomenon whose interpretation clearly requires the introduction of a new fundamental physical principle. Nor is there a single known nuclear phenomenon which contradicts the laws of quantum mechanics.

To be sure, not all nuclear phenomena have been completely interpreted, and some are still very obscure largely because of their complexity. But with the development of computational techniques it became possible to calculate the expected spectrum of a number of nuclei, the characteristics of several classes of nuclear reactions, and the electromagnetic properties of some nuclei. The calculations are always made within the framework of standard quantum theory, with approximation methods of various degrees of sophistication. The success of such calculations in reproducing the observed data is sometimes phenomenal, strengthening our feeling that quantum mechanics as we now know it is applicable to nuclei as well as to atoms and molecules.

The Pauli principle, for instance, manifests itself most dramatically in nuclei. Quantum mechanics teaches us that, in a system of finite dimensions, particles can move only in orbits which are energetically separated from each other. Among these there are orbits in which the nucleon moves slowly, being pulled back fast whenever it seems to be going too far from the rest of the nucleons. In other orbits a nucleon may be moving much faster; from time to time it manages to escape somewhat further away from the rest of the nucleons, but eventually it too is pulled back. Orbits of the former type are said to be tightly bound, while those of the latter type may be only slightly bound. The transition of a nucleon from a less tightly bound orbit to a more tightly bound one is accompanied by the emission of radiation which, among other things, balances the energy: a nucleon in a tightly bound orbit requires more energy to be pulled out of the nucleus than does its counterpart in a less tightly bound orbit.

Had it not been for the Pauli principle, all the nucleons in a nucleus would have eventually landed in the most tightly bound orbit. As it is, however, because of the Pauli principle each orbit that characterizes a "situation" for the particle occupying it can accommodate only one nucleon of each type. There are four types of nucleons: a proton and a neutron, each of them with an internal dynamics which makes it spin either clockwise or counterclockwise. Thus the Pauli principle tends to equalize the numbers of protons and neutrons in stable nuclei. If we take, for instance, the common isotope of oxygen, O^{16}, which has 8 protons and 8 neutrons, and let it capture a neutron, this neutron will go into the most tightly bound unoccupied orbit and produce the stable nucleus O^{17}, with 8 protons and 9 neutrons. Another neutron will again go into the same orbit, spinning in a direction opposite to the previous one, and produce the stable nucleus O^{18}, with 8 protons and 10 neutrons. A third neutron cannot be captured into this orbit, and it will necessarily land in a less tightly bound orbit, producing O^{19}, with 8 protons and 11 neutrons. However this nucleus will be unstable, because the 11th neutron will find it energetically advantageous to undergo beta decay, emitting an electron and a neutrino and converting itself into a proton. The proton can now land in the more tightly bound orbit occupied by the 9th and 10th neutrons, and the energy released is carried away by the electron-neutrino pair. The stable nucleus fluorine-19 is thus formed, with 9 protons and 10 neutrons. It is obvious that if we proceed in this way we shall be always producing nuclei with nearly equal numbers of protons and neutrons, $Z \approx N \approx A/2$. (In heavy nuclei the electromagnetic forces can, and do, upset this symmetry between protons and neutrons, but I ignore this here.)

The Pauli principle has another very important effect on nuclear structure, one which makes the orbits we have been talking about meaningful concepts. In view of the strong forces acting among the nucleons and the extremely close packing of the nucleons, we could have expected that nucleons in the nucleus would collide wildly with each other, making any attempt to talk of "a nucleon's orbit inside the nucleus" completely meaningless. However, let us see what happens when two nucleons, each starting in a given orbit, collide in the nucleus. Under normal conditions such a collision would have sent each one of them into a different orbit. But in the nucleus the chances are that one or both of these different orbits are occupied by other nucleons. The Pauli principle forbids the intrusion, into an orbit already occupied by a nucleon, of another, identical nucleon. The collision is thus doomed to be sterile, ending up in no change in the orbits of the two colliding nucleons! Only in rare cases is the collision strong enough to knock the two nucleons all the way out to unoccupied orbits. Thus we conclude that the strong forces between nucleons in a nucleus are drastically quenched by the Pauli exclusion. The nucleon's motion in the nucleus can therefore be described as if the nucleons had nearly no forces acting among them.

This last statement should be properly understood; if there were literally only weak forces acting among the nucleons, no stable nucleus could have existed. Even in the case of the real nuclear forces, strong as they are, the fact that they extend over very short distances makes it barely possible for nucleons to stick together in complex nuclei. However, once we know that a group of nucleons does stick together to form a nucleus, we can consider each one of them as moving in the average field of force created by all the others. This average, "self-imposed" field of force thus serves as a "container" which holds all the nucleons together. Quantum mechanical orbits within this container can be defined and calculated. My statement about the role of the Pauli principle in quenching the effects of the forces among the nucleons in the nucleus should therefore be taken to refer only to what remains of these forces after the average self-imposed force has been subtracted out.

The Pauli principle is, of course, not the only quantum mechanical law which was discovered in atomic physics and found to be so useful in the interpretation of nuclear structure as well. The probabilistic interpretation of phenomena in the micro-world is another such example of great interest. In atomic physics it accounted among other things for the diffraction phenomena observed with electrons, in complete analogy to the well-known diffraction of light. In nuclear physics it has been used in recent years to account most successfully for diffraction-like phenomena in nuclear scattering and nuclear reactions.

The concept of internal degrees of freedom was introduced in atomic physics in order to deal consistently with the spinning motion of the electrons. Internal degrees of freedom were found to be of great use also in nuclear physics, and the concept was extended to include, in addition to the mechanical spin of the nucleon, other internal dynamical features, such as the electric charge on the nucleon.

There is hardly a single new notion or law introduced by quantum theory in atomic physics which did not find its uses in our efforts to understand the physics of the nucleus. Nevertheless we are still lacking a good deal of knowledge in our attempts to understand nuclear phenomena. Let us therefore see what are some of the difficulties still encountered in the study of nuclear structure.

Some Open Problems in Nuclear Physics

The power of physics has always been its ability to explain a wide variety of phenomena with the aid of relatively very few basic laws and "fundamental constants." In nuclear physics such a goal will have been achieved if various nuclear properties can be interpreted in terms of, say, the nucleon's mass, charge, and magnetic moment and the basic force among nucleons. A deeper understanding of nuclear phenomena involves the so-called field theories, in which the nuclear force is replaced by fields of appropriate mesons characterized by their masses, charges, and so on, and their coupling to the nucleons. However, the mathematical difficulties involved in applying any of these theories to actual nuclei are so immense that we are forced to be considerably less ambitious at this stage of our knowledge, paying for it in more than one way.

First of all we limit ourselves in most cases to nuclear phenomena in which only a few particles play an important role. In a nucleus like bismuth-209, with its 83 protons and 126 neutrons, it is conceivable that very complex modes of motion may result when a good fraction of the 209 nucleons change their orbits. However, if the orbits of only one or two particles are changed, the *modification* in the properties of Bi^{209} may still be rather simple and reliably calculable.

Actually we do not have to limit ourselves necessarily to nuclear phenomena dominated by a few particles; it is sufficient that only a few *degrees of freedom* are involved. These may take the form of collective motions in which the nucleus as a whole undergoes changes in shape or orientation, or even undergoes fission into two smaller nuclei.

If we could tackle the most complex nuclear problems, we would have probably considered the nucleus to be "understood" if a couple of hundred phenomena, not obviously related to each other, could have been reproduced by the same theory. Since, however, we have to limit ourselves to specially simple phenomena and use an *approximate* theory for their elucidation, the conclusions which we draw become less certain. We find, for instance, that a whole variety of nuclear forces can explain equally well a limited set of data on energies in selected nuclei, or that different assumptions about the nature of observed excitations in nuclei may lead to the same predictions regarding their de-excitation.

The nuclear physicist, in limiting himself to the simplest manageable nuclei, is therefore forced to pay for it by facing a qualitatively different set of problems. When he compares properties of two similar nuclei he has to distinguish between two classes of nuclear properties. One includes features which are expected to remain the same for a large class of nuclear forces, while the other class of properties includes features which depend crucially on particular properties of the nuclear force. Thus, if the internucleon force is such that it leads to the formation of prolate rather than spherical nuclei, we expect nuclei to show a characteristic rotational spectrum. The excited states of such nuclei are expected to have increasingly larger angular momenta, corresponding to faster rotations, leading to energies which increase quadratically with the angular momentum. Every force which leads to a deformed rather than a spherical equilibrium shape for the nucleus will lead to these conclusions. Therefore the actual observation of rotational spectra in nuclei can teach us only that nuclear forces belong to this general class of forces leading to the formation of deformed nuclei.

I cannot go here into the details of such studies of nuclear structure, but I would like to stress that at present we are still midway between the mere accumulation of data and a profound understanding of these data. We have at most a semiphenomenological theory which has some ingredients of the fundamental theory and replaces others by adjustable parameters. Through systematic studies of nuclear reactions and through nuclear spectroscopy it has become possible to interrelate many nuclear properties and thereby reduce a vast number of data to considerably fewer parameters having some "intuitive" meaning. These include quantities like the moments of inertia of rotating nuclei; "effective charges" carried by neutrons and protons inside complex nuclei; "indices of refraction" characterizing the collision of protons, neutrons, alpha particles, and so on with complex nuclei; and "surface tension" in nuclei.

The ultimate aim is, of course, to explain these "intuitive" parameters, as well as more formal parameters, in terms of the fundamental properties of the nucleons. Relatively little has been achieved so far in this direction. At the present stage it is not even clear which fundamental properties of the nucleus dominate the phenomena observed in complex nuclei; it is still an open question whether the force between two nucleons is modified in any significant way when they are moving inside the nucleus, or whether forces which involve three, rather than two, nucleons at a time play an important role in nuclear structure.

By studying the range of validity of concepts like that of the nuclear moment of inertia and by studying the variations of such parameters from one nucleus to another, we can hope to come closer to the interpretation of those parameters in terms of the fundamental nuclear properties. It is, however, still a long and tedious road which requires much experimental work, as well as the development of additional powerful methods for the handling of systems with many, yet not infinitely many, particles.

Note

1. I disregard here the so-called "weak interactions" which give rise, among other things, to beta decays.