What Holds the Nucleus Together?

Electrical forces bind the electron to the atom, but they cause nuclear particles to fly apart. The powerful cohesion of protons and neutrons must be explained by a wholly different phenomenon

by Hans A. Bethe

In the preceding article Erwin Schrödinger deals with the basic nature of matter (does it consist of particles or waves?) and touches on some of the questions about its construction. My assignment is to discuss what is by all odds the most mystifying of these questions: What holds the nucleus of the atom together? In the past quarter century physicists have devoted a huge amount of experimentation and mental labor to this problem—probably more man-hours than have been given to any other scientific question in the history of mankind. The problem is not only fundamental but alien to our experience. By all the laws of known forces, the particles in an atom's nucleus should flee from one another, instead of clinging together so strongly that we must build enormously energetic machines to pry them apart. The glue that holds the nucleus together must be a kind of force utterly different from any we yet know.

Let us first look briefly at the general features of the atom, which is much too small to be seen under the most powerful microscope but about which we nonetheless have a great deal of information. It is constructed of a heavy, positively charged nucleus surrounded by a "planetary system" of light, negatively charged electrons. The forces that govern the behavior of the electrons are thoroughly familiar: they are the forces of electric attraction and repulsion. To describe the motions of the electrons physicists had to invent a new mechanics known as quantum mechanics. Once this was worked out, it became possible to understand all the properties of atoms as a whole—their sizes, their chemical behavior, the light they emit, and so on—in terms of the motions of the electrons around the nucleus.

The nucleus itself is a very different problem. Its building blocks are the positively charged particles called protons and the electrically neutral particles known as neutrons. The nucleus, containing about 99.95 per cent of the total mass of the atom, is far more densely packed than the electrons in the atom's outer regions; if you were to imagine the atom as a whole to be as big as a house, the nucleus would be the size of a pinhead. Now detailed investigations of the nucleus early turned up a remarkable fact: whereas the density of the fluffy outer structure of atoms varies greatly from one kind of atom to another, all nuclei have a uniform density (about 100 trillion times that of water). Thus the total volume of an atom, insofar as its volume can be defined at all, is not necessarily proportional to its weight, a circumstance which makes some substances denser than others. But the volume of a nucleus is very nearly proportional to its weight, just as a piece of iron 10 times as heavy as another is also 10 times as large in volume.

This resemblance of nuclei to the matter of everyday experience suggested that the forces holding the nucleus together might be something like those that bind atoms together. We know that gross matter is held together by forces between neighboring atoms, and that there are no important interactions between atoms distant from one another. It is therefore assumed that the forces in the nucleus likewise act mainly between neighboring particles, rather than from one end of the nucleus to the other.

But what can these forces be? Clearly electric forces are out of the question.

Nuclear events caused by the cyclotron at the Nevis Laboratory of Columbia University are revealed by thin white tracks

In the first place, the electric force between two protons is repulsive, not attractive. And even if the sign were changed so that they attracted one another, the electric force of attraction would be too small by a factor of 40 to account for the binding energy with which protons are held together in the nucleus. Besides all this, what about the uncharged neutrons, which cannot exert any electric force, attractive or otherwise—how could the nucleus hold them?

As for gravitation, the other important force with which we are acquainted, that is completely hopeless. The gravitational force between two particles in a nucleus is too small to explain their attraction by a factor of 10^{37}!

We are confronted with a problem which is just the opposite of the one physicists had when they began to study the atom as a whole. They were completely familiar with the forces (electric) at play, but had to discover the laws (quantum mechanics) that governed the operation of these forces. In the case of the nucleus, we are fairly confident about the governing laws (again quantum mechanics), but must discover the force.

One might picture the situation in this way. You are walking in the park and come upon a group of men playing baseball. After watching for a few minutes you decide that it is a match between lunatics. The batters seem to run to any base that pleases them; the fielders throw the ball at random; the object of the game is utterly obscure, and the score, impossible to compute. But by long, intense observation you finally figure out the strange rules of the game. That is where atomic physics had arrived 20 years ago. We have now moved along to another place in the park and discovered a second game more insane than the first. The rules seem to be the same, but the players are playing without a ball! Something—we do not know just what—is passing back and forth among the players, and to understand the game we must find out what that something is. The invisible ball shuttling among the players corresponds to the force between particles in the nucleus.

Our problem is twofold: (1) to measure the force and determine its other properties, and (2) to probe into the "cause" of the nuclear force, as it were, by studying its connections with other physical phenomena.

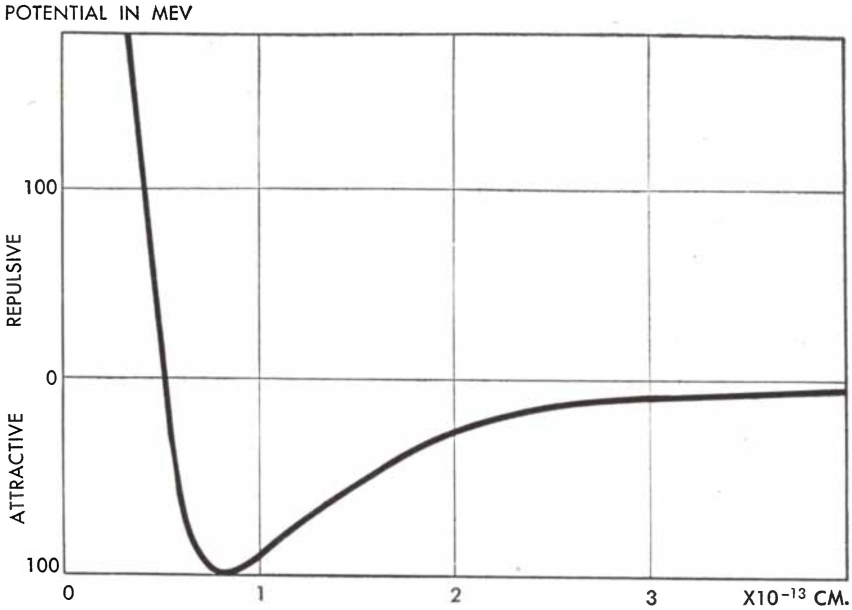
We can get an approximate measurement of the strength of the nuclear forces by determining the binding energy with which the nucleus is held together. This can be done in two ways: by measuring the energy set free or consumed in various nuclear reactions, or by using Einstein's relation $E=Mc^2$, which says that the binding energy is equal to the mass defect in the nucleus times the square of the velocity of light. The "mass defect," of course, refers to the fact that the mass of the nucleus is slightly smaller than the sum of the masses of the particles combined in it; the difference is the "defect."

By these two methods it has been determined that the binding energy holding each particle in a heavy nucleus is between six and eight million electron volts (roughly a million times the energy that holds atoms together in a molecule). But this is still far from telling us much about the force between two individual particles—to say nothing of the complex set of interacting forces operating among the whole group of particles. We can try to use the measured energies with which particles are bound to the nucleus as a basis for calculating the nuclear force. If we tried this with any complex nucleus, however, we would be in very deep water; the mathematical problem of computing from the binding energy the forces among the 16 particles of the oxygen nucleus, for instance, is so formidable that no one would dream of attempting it. We are forced to concentrate, as the atomic physicists did in studying the atom, on the simplest possible system. The atomic physicists obtained most of their information about atoms from the two-particle hydrogen atom—one proton and one electron. As a subject for investigating nuclear forces, the simplest nucleus we can find is the deuteron (the nucleus of heavy hydrogen), which consists of one proton and one neutron.

Unfortunately the deuteron is far less helpful than the hydrogen atom was. The hydrogen atom's various energy states, normal and excited, all provide means of testing the laws governing the forces between its proton and electron. But the deuteron has no excited state. The only measurement it can give us is the binding energy in its fixed ground state, and this alone is not sufficient to determine with precision the force between its two particles and—what the nuclear physicist particularly wants to know—how that force varies with distance. We have therefore had to study the matter indirectly by investigating the interaction between free protons and free neutrons. A beam of neutrons is directed at a piece of matter containing hydrogen. Neutrons colliding with the protons in the hydrogen are scattered in various directions. By observing how many neutrons are scattered in each direction, and by using neutron beams of varying speeds, we are able to deduce the force between the proton and the neutron.

The most conspicuous feature of nuclear forces turns out to be their short range. At a distance of about 10^{-13} centimeter (which is a hundred-thousandth of the radius of an atom) the nuclear force of attraction between two protons is about 40 times as strong as the electric force of repulsion between them. At four times that distance the nuclear force has dropped off to the same strength as the electric force; at 25 times the distance the electric force is a million times stronger. On the other hand, there is some evidence that at extremely short distances (perhaps less than half of 10^{-13} cm.) the nuclear force changes from a

in a diffusion cloud chamber. A 35-millimeter camera automatically photographs the chamber once every 10 seconds



NUCLEAR FORCE (measured in millions of electron volts) is plotted against the distance between particles. When the distance is less than half of 10^{-13} centimeter, the nucleons repel one another. They most strongly attract one another at just under 10^{-13} cm.

strong attractive force to an even stronger force of repulsion.

The nuclear forces are far more complicated than electric or any other known forces. The force between two nuclear particles apparently depends not only on the distance but also on the particles' relative velocity and on the relative orientation of their spins. Moreover, there are forces which act among three, four or more particles simultaneously. Again, there is the remarkable fact that the force between particles is independent of the particles' charge. Proton and proton, neutron and neutron, proton and neutron—all have about the same attractive force toward each other. This finding is especially hard to explain because it is so contrary to the behavior of charged particles in common experience.

Another remarkable feature of the nuclear force is the kind of exchange that occurs between one particle and another. In the gross material world, and in the world of atoms, when two bodies of equal weight collide usually the faster moving body retains the greater speed or the two bodies share their energy about equally. But in the world of protons and neutrons something quite different commonly happens. When a very fast neutron hits a proton, very often the proton jumps forward with almost as much speed as the neutron had, while the neutron is stopped almost to a standstill. The simplest way to explain this is that the neutron snatches the positive charge from the proton and keeps on going, without transferring much of its momentum to the proton. In other words, the proton that suddenly jumps forward is really the original neutron transformed into a proton.

Having explored the properties of nuclear forces, we may now try to "explain" them. At this point it is appropriate to point out that for a physicist the word "explanation" has a rather different meaning from that in everyday usage. People generally explain something in terms of concepts more familiar than what they are explaining. But physicists very often "explain" a rather familiar phenomenon in terms of far less familiar concepts. For them an explanation consists in connecting different physical phenomena, building a logical structure and deriving the simplest possible mathematical formula to describe all the connected phenomena.

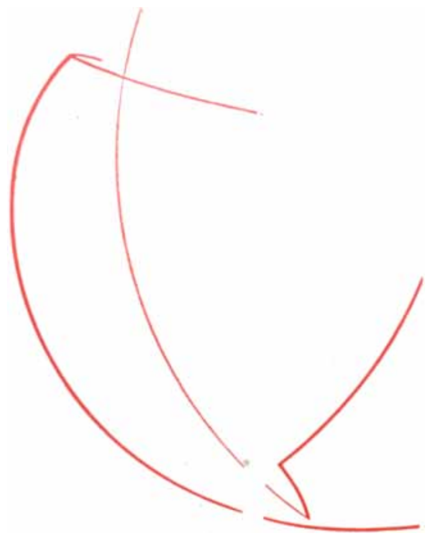
It must be clear from what has already been said that the nuclear forces cannot be explained in terms of forces with which physicists were familiar before 1930. Analogies with those forces can, however, be a starting point for a theory of the new force.

The force about which we know the most is electromagnetic force. We know that the interaction between electrically charged bodies moves with the speed of light. Further, this interaction can be described essentially by saying that quanta of light are emitted by one electric particle and absorbed by another. In the process, the light quanta transmit energy and momentum from the first to the second particle; in other words, they transmit an electric force, though they themselves have no electric charge.

It was natural to assume that nuclear forces behave like electromagnetic ones, and this suggestion was made by the Japanese physicist Hideki Yukawa as early as 1935. In Yukawa's theory, in the nucleus the role of the light quantum is taken by a new particle, whose emission and absorption is supposed to transmit the nuclear forces. This particle, when Yukawa invented it, was of course purely hypothetical. Today it is known as the meson.

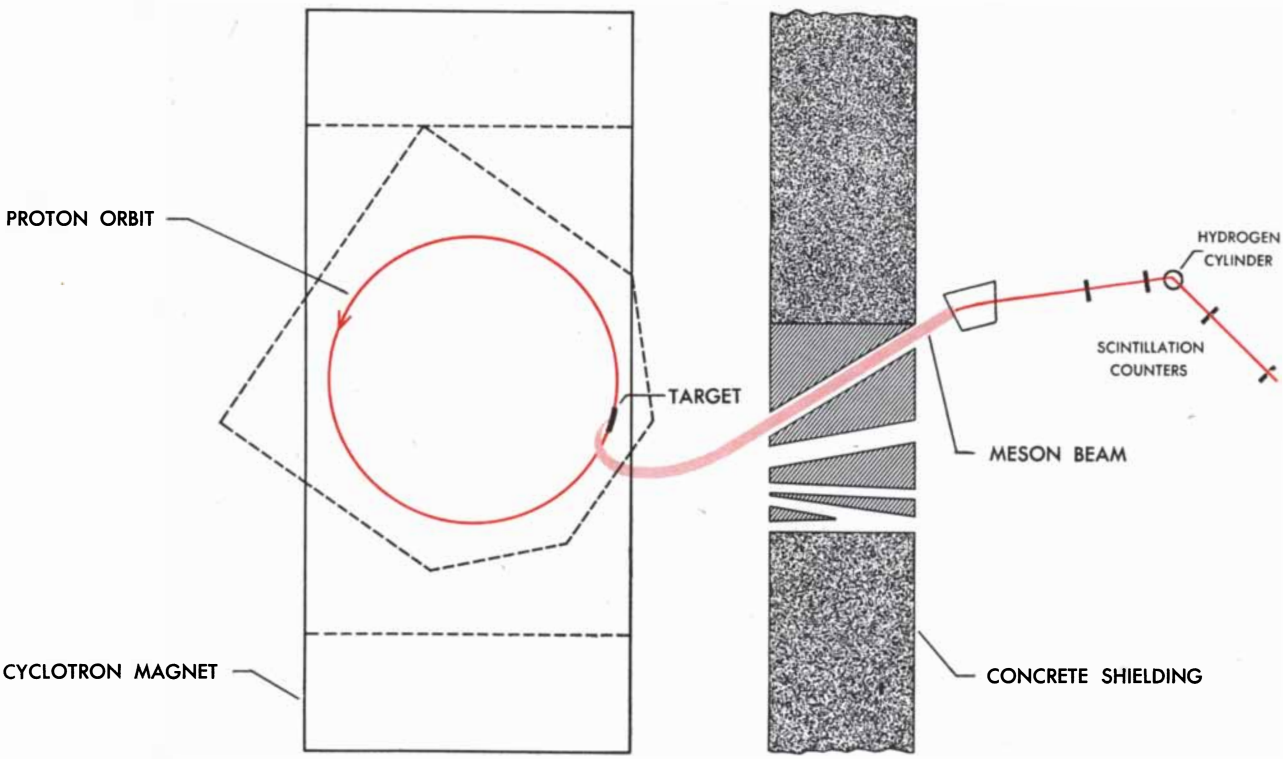
Yukawa next tried to figure out what properties his hypothetical particle should have. First of all, he noted that the short range of nuclear forces would be explained if the mesons were supposed to have a mass—in contrast to light quanta which have none. In fact, he worked out the range of the nuclear forces mathematically in terms of Planck's constant, the velocity of light and the mass of the meson. He estimated that the meson mass should be between 100 and 200 times the mass of the electron. (Today we know that 300 is a better figure.)

Secondly, Yukawa suggested that to explain exchange forces the mesons must be charged. When a proton and a neutron interact, he postulated, the proton may emit a positive meson which is absorbed by the neutron. In this process the



TWO MESON "EVENTS," which are diagrammed above, can be seen in a cloud chamber photograph from the Nevis Cyclotron Laboratory of Columbia University. A negative pi meson entering at bottom right splits into a high-energy pair of electrons, positive and negative, at top left. Another negative pi meson entering at right center decays into a mu meson (first jog) and then into a high-speed electron (second jog). The object running from top to bottom of the picture is not in the path of the particles.

CYCLOTRON at Nevis Laboratory operates at 385 million electron volts and can produce mesons. In this picture the six-foot-thick concrete shielding blocks have been removed to the pile at right, exposing the circular magnetic pole pieces (*center*). Between the magnets can be seen the vacuum chamber, which connects with the pumping system through the system of pipes to the right.



MESON SCATTERING experiment is shown in outline. Accelerated protons (*red circle*) hit metal target to form mesons (*red line*) which are deflected by magnet through a port in iron block (*cross-hatched*). Second magnet to right of port steers them to hydrogen sample which scatters them. Counters placed ahead of sample and behind it insure that only scattered mesons are detected.

proton loses its positive charge and becomes a neutron, while the neutron gains a unit of positive charge and turns into a proton. The same result is obtained, of course, if the neutron emits a negative meson which is absorbed by the proton. Yukawa suggested the existence of both positive and negative mesons, in conformity with a general principle of physics: that for every positively charged particle there is a negatively charged counterpart. The best known examples are the negative and positive electrons.

Three years after Yukawa proposed the meson, physicists found in cosmic radiation a particle which seemed to have just the properties he had predicted. It had a mass about 200 times that of the electron and was found in both positive and negative forms. But this particle turned out to be the wrong answer—it did not interact strongly with nucleons and therefore could not transmit nuclear forces. At length in 1947 C. F. Powell, G. P. S. Occhialini and C. M. G. Lattes—an Englishman, an Italian and a Brazilian working together—discovered another particle which *did* interact strongly with nucleons and had a mass of 276 electron masses. There is every indication that this is Yukawa's meson. It is known as the pi meson, or "pion." (If kept away from nucleons it will decay after a moderately short time into one of the earlier discovered mesons, now called mu mesons.) Since the discovery of the pion, heavier mesons have been found, but probably they are less important for nuclear forces.

The next step in the theory was taken by the English physicist N. Kemmer. He reasoned that there should be a neutral meson, in order to explain the interaction between proton and proton (or neutron and neutron). A proton cannot absorb a positive meson, for it cannot acquire a second positive charge. Therefore no single charged meson could transmit a force between protons (though the simultaneous exchange of two mesons of opposite charge migh do so). Kemmer consequently suggested that a neutral meson might carry the forces between proton and proton, or, for that matter, between unlike nucleons. His theory accounted for the nuclear forces' independence of charge.

Soon after the pions were discovered in cosmic radiation, it became possible to produce them artificially with large new cyclotrons. Physicists now could obtain mesons in large quantities and explore their properties and interactions with nucleons. They soon confirmed the existence of Kemmer's neutral mesons. As for the interaction of mesons and nucleons, exact calculations will probably remain very difficult for a long time—incomparably more difficult than the calculation of electric and atomic phenomena. The main reason is that the interaction between a meson and a proton or neutron is exceedingly strong—about 1,000 times stronger than that between an electron and the electric field. The mathematical methods of quantum theory are all adapted to the weak interactions of electrodynamics.

SCATTERING EXPERIMENT setup is photographed above. At left is port through which mesons emerge. Large apparatus topped by funnel supplies liquid hydrogen to aluminum chamber, where scattering occurs. The rectangular objects at right are two of the counters.

Once the interaction between mesons and nucleons has been worked out, one can then try to derive that between two nucleons. As we have seen, the mass and charge of mesons are sufficient in themselves to explain the nuclear forces' short range, their exchange property and their independence of charge. Other aspects of meson theory can account for the dependence of nuclear forces on the direction of the spins of the nucleons and of the line joining their positions, for the strong repulsion between nucleons at extremely small distances and for the simultaneous interaction between more than two nucleons.

In short, the meson theory already accounts for all the qualitative features of nuclear forces. It looks as if we have found the ball with which the nuclear game is played. But we cannot be sure until we have figured out whether our theory can explain the behavior of the participants in quantitative terms, that is, whether the range of forces, the strength of interactions and other quantities derived from the theory by calculation are of the right magnitude.

A promising start has been made by the French physicist Maurice Lévy, working at the Institute for Advanced Study in Princeton. He has shown that calculations based on the observed mass of the meson do indeed yield the correct figure for the range of the nuclear forces. His work, in combination with the theoretical work of others, also shows that the strength of interaction between nucleon and meson required to explain nuclear forces is about the same as that required to explain the scattering of mesons by protons. *About* the same—actually, the two numbers differ by approximately 50 per cent, but probably this difference is simply a measure of our mathematical ineptness in dealing with large forces. Thus the indications are that physicists are on the right track in explaining nuclear forces by transfer of mesons. But it will be a long time before our mathematical tools are developed sufficiently to determine whether the meson theory *really* explains the forces in all details.