PIONS

These particles, also known as pi mesons, are an important atomic structural material. They appear to be the cement which holds protons and neutrons together in the nucleus

by Robert E. Marshak

The cement that holds the universe together is the force of gravity. The glue holding the atom together is electromagnetic attraction. But the glue that holds the nucleus of the atom together is a mystery that defies all our experience and knowledge of the physical world. It is a force so unlike any we know that we can hardly find words to describe it. We do have a clue, however, to which we can give a name. It is the pi meson, or pion. In some way, not yet understood, pions are certainly involved in the nuclear binding force. Now that these particles can be generated at will by high-energy bombardment of matter, their properties are being industriously explored. What have we learned about them?

Before entering this strange realm, let us retrace very quickly the steps by which the physicists got there, along the now familiar path of electromagnetic forces. Considering the operation of these forces in the macroscopic world—as electricity, magnetism, light and so on—Michael Faraday and James Clerk Maxwell developed the concept of fields of force, pervading all space. When physicists began to examine the microscopic world of the atom, they assumed that the same field concept applied there as well: that the force between one electron and another, or between an electron and the positive nucleus, obeyed the laws of the classical electromagnetic field. But eventually it became clear that much of the behavior of atoms and electrons could be explained only on the assumption that the field in the atom is quantized. In other words, in the light of the quantum theory physicists concluded that electromagnetic forces are exerted by an exchange of quanta or packets of energy between charged bodies. These quanta are photons—massless units of energy. The field around an electron, say, consists of photons which the electron is continually emitting and absorbing. When one electron repels another, photons are interchanged; the photons are emitted by one particle and absorbed by the other. Thus the quantum theory, which is often said to do away with physical models, actually gives a more concrete picture of electromagnetic interaction than the classical theory did. Two charged bodies influence each other not through an intangible field but by tossing little pellets back and forth.

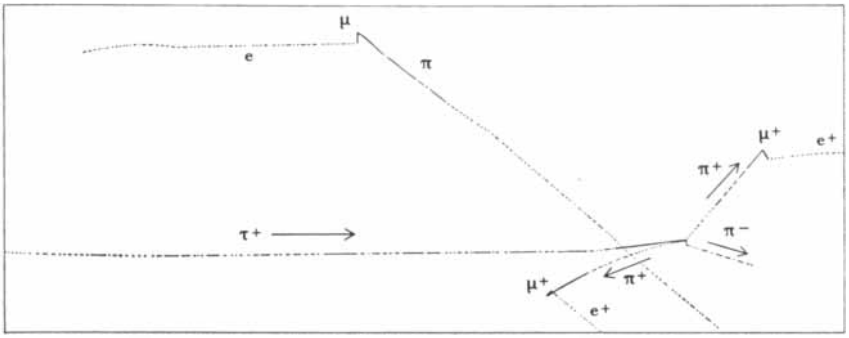
PION TRACKS are made visible as strings of tiny bubbles in a chamber of liquid propane. This photograph was made while the chamber was exposed to a beam of heavy mesons from the Brookhaven Cosmotron. As indicated in the drawing, one series of tracks shows

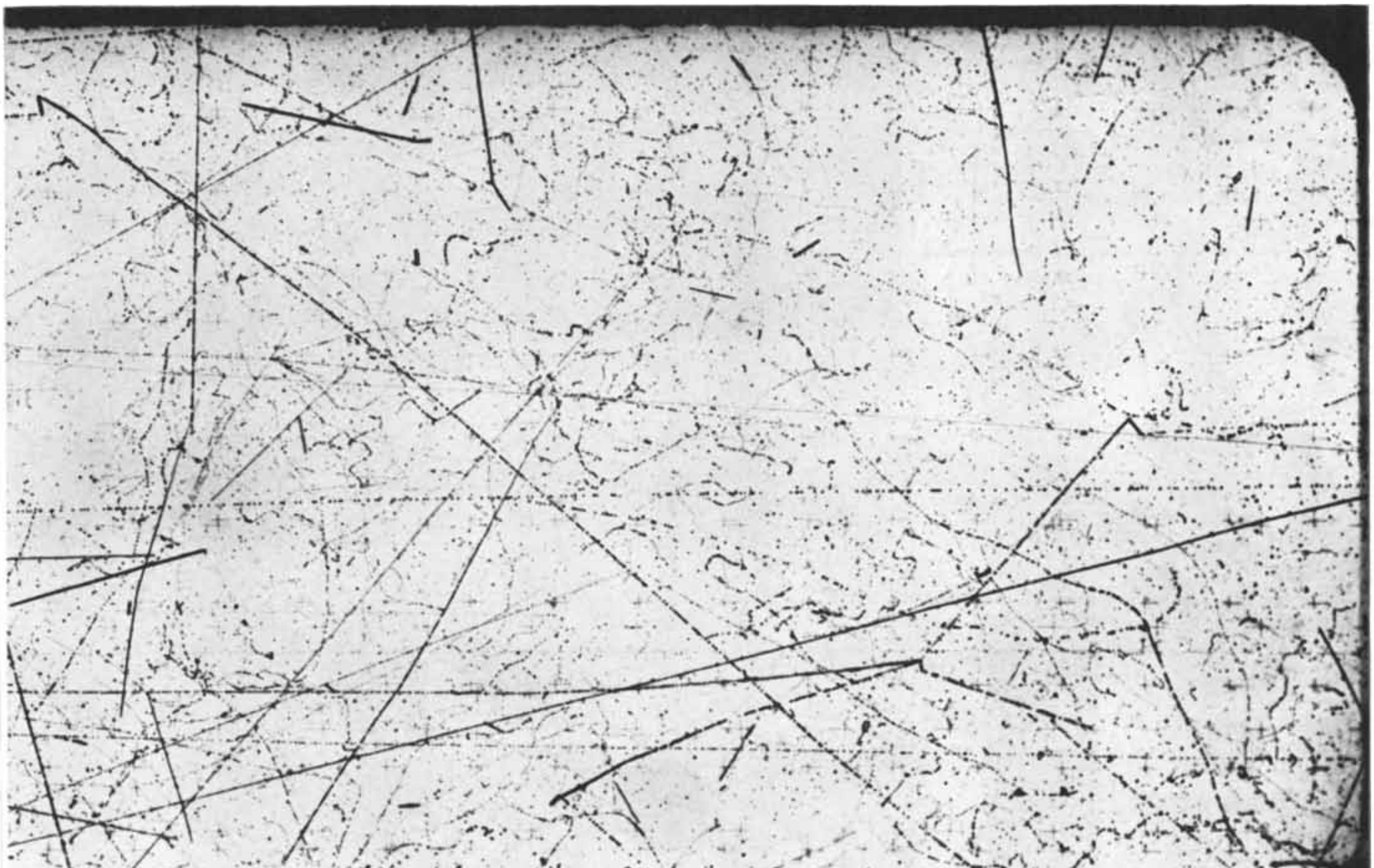
This conception was so successful in accounting for the forces on the atomic scale that the Japanese physicist Hideki Yukawa adopted it to attack the problem of the mysterious forces in the nucleus. He assumed that the force field in the nucleus, like that in the outer atom, is quantized. The attraction holding together protons and neutrons (nucleons) would thus be accounted for by a continual exchange of quanta of energy. But whereas the quantum of electromagnetic energy (the photon) is massless, Yukawa found that to explain the force of attraction in the nucleus, particularly its very short range, it had to be supposed that the nuclear quantum had an appreciable mass, which he calculated to be between 200 and 300 times that of an electron. To account for the great strength of the nuclear force, he assumed that the quanta were exchanged at a very rapid rate.

Yukawa's brilliant intuition was rewarded 12 years later (in 1947) by the discovery of the quanta, or particles, that he had proposed [see "The Multiplicity of Particles," by Robert E. Marshak; SCIENTIFIC AMERICAN, January, 1952]. The pi meson, or pion, has just the properties he predicted for it. Its mass is about 270 times that of the electron.

The notion that pions are exchanged between nucleons immediately raises some basic questions. To begin with, if a nucleon continually emits pions, what happens to the conservation of mass? The emission of a pion, with its appreciable mass, should reduce the mass of the nucleon, and yet in all our experiments the mass of a nucleon remains constant. The answer is that the emission and reabsorption of pions takes place so rapidly that we cannot detect it. Since any phenomenon that is undetectable cannot be regarded as "real," in the physical sense, we must speak of "virtual" emission and exchange of pions.

To understand a little more clearly what this means, and to see approximately how brief the appearance of a pion must be, we must recall the famous



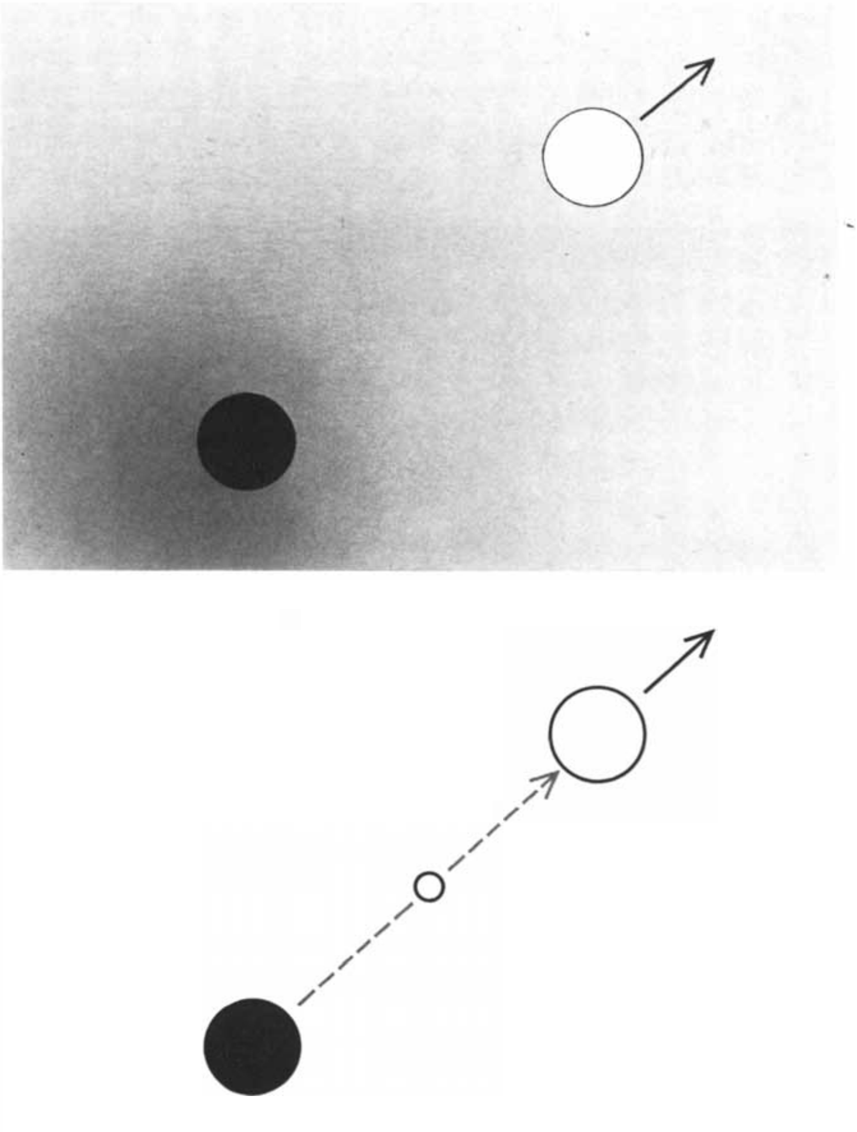


a tau meson (τ^+) entering from the left and decaying into two positive pions (π^+) and a negative pion (π^-). The positive pion decays into a mu meson (μ^+), which decays into an electron (e^+). Another pion enters the chamber from the lower right and decays into a mu meson at upper left. The experiment was performed by D. A. Glaser and his colleagues of the University of Michigan.

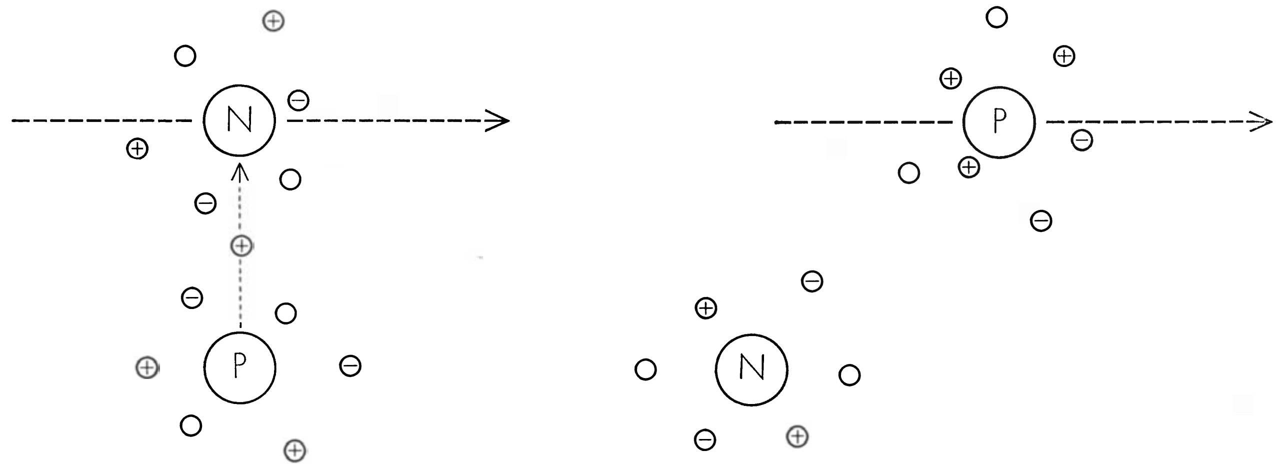
uncertainty principle. This principle sets a definite limit to our knowledge of very small-scale phenomena. It says, for example, that if we measure an electron's *position* exactly, we thereby destroy our ability to make any measurement whatever of its *momentum* and *vice versa.* If we want figures for position and momentum at the same time, we must settle for inexact measurements of both. The uncertainty principle of quantum theory tells us the maximum accuracy we can hope to attain: the uncertainty in position multiplied by the uncertainty in momentum must be at least as great as the value of Planck's constant, h.

Another pair of quantities which fall under the principle are energy and time. Any experiment for measuring the energy of a system requires a certain time to perform. Any such experiment also tends to alter the energy. Now it turns out that the shorter the time of measurement, the greater the effect on the energy. In other words, the more certain we are about the time at which the energy is determined, the less certain we can be about its amount. Again, the product of the two uncertainties can never be less than h.

The energy equivalent of the mass of a pion is 135 million electron volts. The calculation based on h tells us that the margin of uncertainty for the energy content of a nucleon will be at least 135 Mev when the time of measurement is 5×10^{-24} of a second. Hence if a pion is emitted and reabsorbed within this time,



ELECTROMAGNETIC FIELD around a charged particle such as an electron (***black circle***) is shown schematically according to classical theory (***above***) and quantum theory (***below***). The gray shading in the upper diagram represents the continuous classical field through which the particle was thought to exert its force on a second electron (***white circle***). The circle in lower diagram shows the field quantum or photon now thought to transfer the force.



NUCLEAR FORCE FIELD consists of clouds of virtual pions (*small open circles*) which surround each nucleon. At left a moving neutron (*above*) passes close to a stationary proton (*below*) and picks up a positive pion. The moving particle is now a proton and the stationary one a neutron. By transferring neutral pions, nucleons are also able to interact without this exchange of charge.

it will be undetectable, *i.e.*, "virtual." In that time a pion, moving at practically the speed of light, could travel to about 1.4×10^{-13} of a centimeter from the center of a nucleon. This distance is just about the observed range of nuclear forces! The agreement seems a striking support for the theory that pions act as agents of these forces.

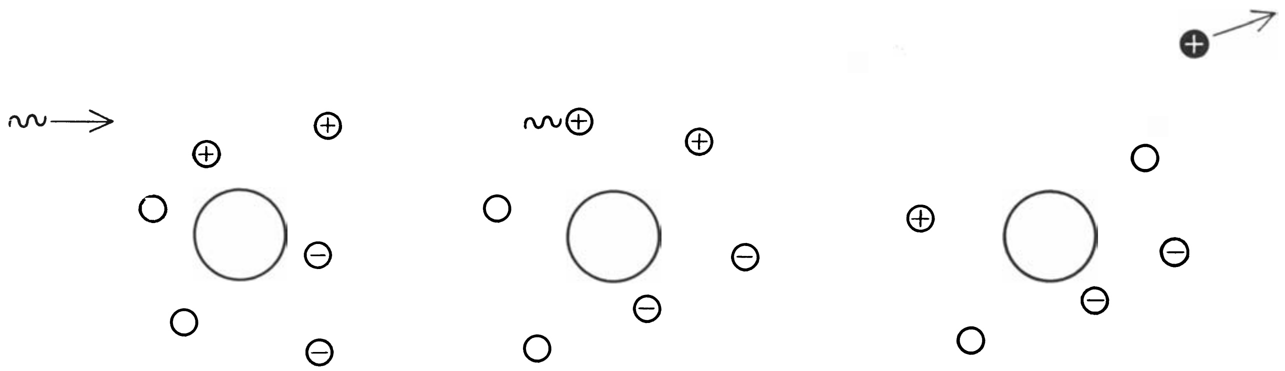
This conception of the pion accounts for another phenomenon observed in experiments. When hydrogen is bombarded by a beam of fast neutrons, many protons (hydrogen nuclei) shoot out in the forward direction at about the speed of the impinging neutrons, while a corresponding number of neutrons is found almost stationary within the target. It is altogether improbable that so many neutrons would hit protons dead center and transfer all their momentum to the protons. A much more plausible interpretation is that the emerging protons represent neutrons which were converted into protons during passage through the target. Such a conversion could occur if a neutron seized a positively charged pion: the neutron would thus become a proton, and the proton that lost the positive charge would become a neutron. Thus a neutron dashing through a proton target grabs a pion from a proton and leaves a neutron behind.

The attraction between nucleons in the nucleus of an atom (other than ordinary hydrogen, which has only one nucleon) may be exerted through such exchanges of pions. There should be positive, negative and neutral pions, to bind together protons with protons, protons with neutrons and neutrons with neutrons.

How is it that the ghostly "virtual" pions are in fact detectable as real particles? If we consider pions as packets of energy, it is not difficult to describe the circumstances under which we should be able to detect them. Suppose the energy equivalent of a pion is supplied to a nucleon, replacing the pion energy. A pion may then be released and detected before it is captured by another nucleon. Pions were first identified in the debris from cosmic ray collisions and then manufactured in high-energy accelerators by bombardment of nuclei.

All three forms of the pions have been found—positive, negative and neutral. The neutral pion has 264 times the mass of the electron. The charged pion, which gains a little mass from its interaction with the electromagnetic field, has a mass of 273. Pions are readily absorbed by nuclei. They are unstable. The charged pion decays into a lighter particle (called the mu meson) and a neutrino with a half-life of a few hundred-millionths of a second. The neutral pion decays much faster (half-life about 10^{-15} of a second) into two gamma rays.

Pions, produced in large quantities by bombarding targets such as carbon, are now formed into beams for probing nuclei. The way in which a beam of real pions is deflected or scattered by the target nuclei shows how the pions interact with the nuclear force field. The sim-



VIRTUAL PION MATERIALIZES if the system is provided with an amount of energy at least equivalent to the pion's rest mass. In these diagrams a high-energy gamma ray (*wavy line*) enters a meson cloud and strikes a virtual positive pion (*open circle*). The energy of the gamma ray is absorbed and the virtual pion turns into a real pion (*solid circle*). It can now escape from the nucleon.

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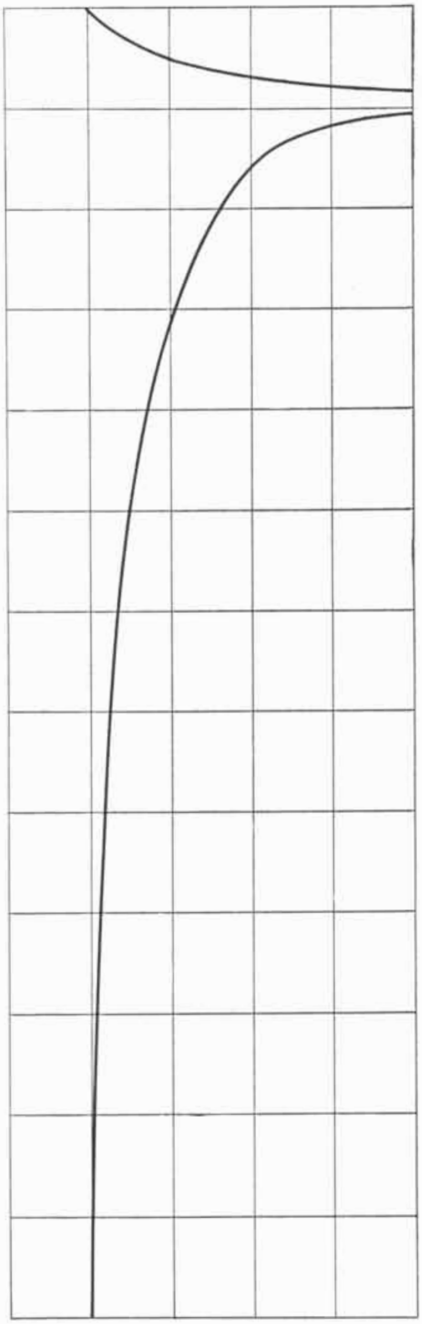
plest and most informative experiments are those on individual nucleons. Protons can be studied directly by bombarding a target of hydrogen. Neutrons are examined by bombarding heavy hydrogen, or deuterium, whose nucleus contains one proton and one neutron. When the proton's effect is subtracted out, the remaining pattern gives the neutron's interaction with the pion.



FIELD STRENGTHS due to electromagnetic and nuclear forces are indicated by these curves. Upper curve represents the electromagnetic field around a proton (which repels another proton). Lower curve is proton's nuclear field (which attracts another proton). Horizontal axis gives distance from proton in units of 1.4×10^{-13} centimeters. Vertical scale is arbitrary.

These experiments support a picture which, if rather obscure, at least fits together well as far as it goes. For instance, investigators of the nuclear forces have been interested in the fact that the force of attraction between nucleons seems to be exactly the same whether they are charged or uncharged (*i.e.*, protons or neutrons). This of course is entirely foreign to our experience in the world outside the atomic nucleus. Considering the hypothetical roles of charged and neutral pions in these several attractions, the investigators have calculated that nucleons must emit and absorb charged pions twice as frequently as neutral pions. To put it another way, the nucleon interacts twice as strongly with a charged pion field as with a neutral pion field. Scattering experiments with real pions have confirmed this assumption.

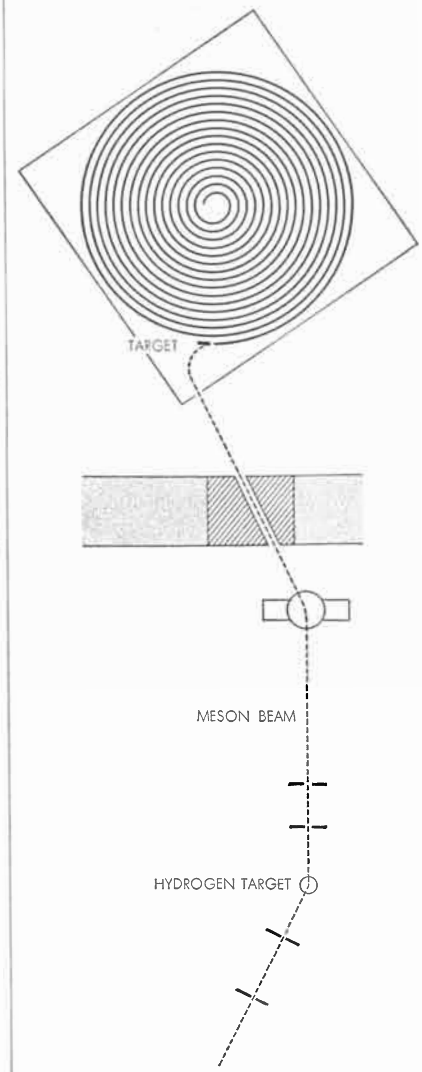
The nuclear force of attraction is very strong—so strong that, if the pion is its agent, a nucleon must emit virtual pions at a high rate, and must be surrounded at close quarters by a veritable cloud of them. This suggests that if enough energy could be supplied, it should be possible to materialize more than one real pion from a nucleon. This has indeed turned out to be true. The three-Bev Cosmotron at the Brookhaven National Laboratory produces an average of two pions per collision. The six-Bev Bevatron at Berkeley gives an average of more than three. In primary cosmic radiations, where there are energies as high as 10,000 Bev, as many as 20 real pions have been observed to emerge from a single collision.

Thus the proton and the neutron, once supposed to be the ultimate building blocks of matter, become less monolithic than they seemed. Each consists of a core surrounded by a fluctuating cloud of pions—an arrangement somewhat reminiscent of the atom with its nucleus and planetary electrons. Pion scattering experiments now indicate that nucleons may even have excited states, as the atom does. The excitation, produced when a pion hits a nucleon violently, takes the form of a temporary increase in the nucleon's charge. Presumably this state involves some rearrangement of the meson cloud, but the details are not yet known.

The inner region near the core of the nucleon, where the meson cloud is most dense, remains an area of mystery. We can probe it with very fast particles: the faster the projectiles, the deeper they penetrate. But our knowledge and theo-

ries about the meson field are still too vague to yield equations which might account for the scattering patterns observed or predict how many pions will be produced at a given bombarding energy.

The chief difficulty is the fact that we must deal with a swarm of pions. Our mathematical techniques cannot effectively handle more than one pion at a time. Beyond this things become much too complicated. The problem appears to be a basic one, and it seems that only some radically new idea will enable us to solve it. And so the pion, while providing a tantalizing glimpse into the nuclear forces, serves also to deepen our ignorance.



PION SCATTERING experiment is diagrammed above. Meson beam from a cyclotron (*top*) is steered by a magnet to strike a sample of hydrogen. Counters in front and back of target record the numbers of particles that are deflected at various angles.

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