The Two-Neutrino Experiment

An account of the heroic experiment, involving a 30-billion-volt accelerator, a 10-ton spark chamber and 45 feet of armor plate, that demonstrated that there is not one kind of neutrino but two

by Leon M. Lederman

These days the discovery of a new elementary particle is scarcely news. Physics has been plagued by what seems to be a surfeit of particles for some time. Within the past year, however, a particle has been discovered that may have solved more problems than it has created. An experiment carried out with the 30-billion-electron-volt accelerator at the Brookhaven National Laboratory has demonstrated that there is not, as had been assumed, one variety of the particle known as the neutrino but two. When the Brookhaven accelerator was being designed 10 years ago, many uses were conceived for it, but no one dreamed that it would ever be employed to make neutrinos for experimental observation. Indeed, 10 years ago many investigators were still concerned with the verification of the neutrino's existence. The proof was ultimately supplied by a long series of detailed experiments, climaxed by the direct observation of neutrino-induced reactions in 1956.

Neutrinos are the most impalpable of particles. They have no electric charge, no mass (or none that has yet been measured) and (if it is assumed that they are massless) they travel with the speed of light. They are produced in huge numbers by nuclear processes inside the sun and other stars. Those that encounter the earth pass right through it with ease. Only about one neutrino in every 10 billion (10^{10}) passing through the center of the earth is likely to react with another particle. Obviously a particle that reacted with nothing whatever could never be detected. It would be a fiction. The neutrino is just barely a fact.

Elementary particles reveal their presence by interacting in various ways. Physicists speak of four fundamental kinds of interaction (the modern term for force), which differ markedly in strength. The weakest is gravitation, which is so weak that it becomes manifest only when vast numbers of particles are bound together to form a ponderable body. In the atomic domain, therefore, it can be ignored. In studying the behavior of elementary particles only three forces need to be considered: "strong," electromagnetic and "weak." The relative strengths of the three are roughly in the ratio of 10^{12} to 10^{10} to 1. The strong force is that which holds the particles in the nucleus of the atom together and which is released in nuclear fission and fusion. It has the further property of generating reactions among strongly interacting particles. These are cataclysmic: no sooner are two such particles within "reach" of the strong force than the reaction takes place. The electromagnetic force is that which binds electrons to the atomic nucleus and which underlies all chemical and electric phenomena. For our purposes it is important to note that fast-moving electrically charged particles are slowed down in matter by their continuous interaction with atomic electrons. Weak forces are responsible for the spontaneous decay of unstable—radioactive—nuclei and of elementary particles. Here again to the force or interaction must be attributed the property of inducing transformations among particles. It is believed that all elementary particles are subject to weak-force interactions, although the effects are often obscured by the strong and electromagnetic forces.

All this can be expressed another way by classifying particles according to the interactions in which they can take part. In the present discussion we shall be concerned only with six particles: the proton, pion, neutron, electron, muon and neutrino [*see illustration on page 62*]. Proton and pion take part in all three interactions: strong, electromagnetic and weak. The neutron, being electrically neutral, has only very subtle electromagnetic properties, but it is involved in both strong and weak interactions. Physicists often refer to the three particles—proton, pion and neutron—as "stronglies." The other three—electron, muon and neutrino—are "weaklies." The neutrino, alone among particles, has only weak force. Each of the six particles has a corresponding antiparticle, with an identical set of forces.

One of the earliest forms of nuclear instability to be investigated was that known as beta decay. This is the spontaneous emission of an electron (or its antiparticle, a positron) from an unstable atomic nucleus. When the energies of the emitted electrons were first measured in the 1920's, the results were baffling. It was expected that all the electrons emitted from one kind of nucleus would have the same energy. Instead they had a wide spectrum of energies, ranging downward from some maximum value. How to account for the missing energy?

With deep insight and considerable daring Wolfgang Pauli of Austria suggested in 1931 that the missing energy was being carried off by an undetected particle. The name "neutrino" was soon supplied by Enrico Fermi. Perceiving that the rate of beta decay was enormously slow compared with the rate of other nuclear reactions, Fermi postulated that it represented a new force and developed a theory to describe it. The simplest beta-decay reaction involves the free neutron. Upon ejection from an atomic nucleus the neutron decays spontaneously, yielding a proton and an electron. Again there was missing energy to be accounted for and it was also assigned to the neutrino, or, to be precise, the antineutrino.

Fermi's theory predicted that it should

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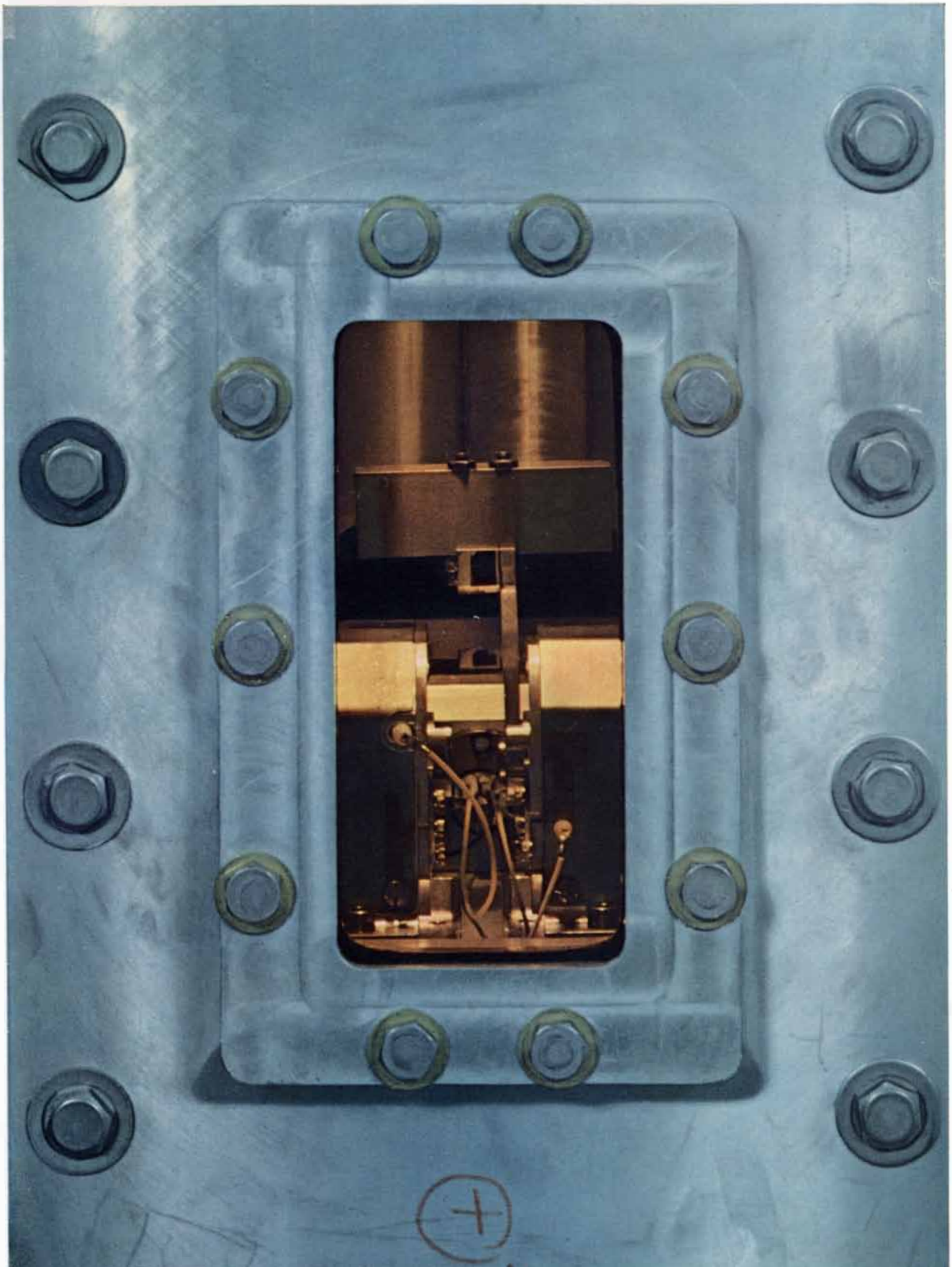

TARGET OF BEAM OF PROTONS that gave rise to one of two kinds of neutrino is the horizontal block above the bright yellow metal parts in the vacuum chamber of the alternating-gradient synchrotron at the Brookhaven National Laboratory. The collision of the protons with atoms in the target results in the production of pions, which decay into the neutrinos required for the experiment described in the text. In this experiment the synchrotron accelerated the protons to 15 billion electron volts, one-half of its energy range.

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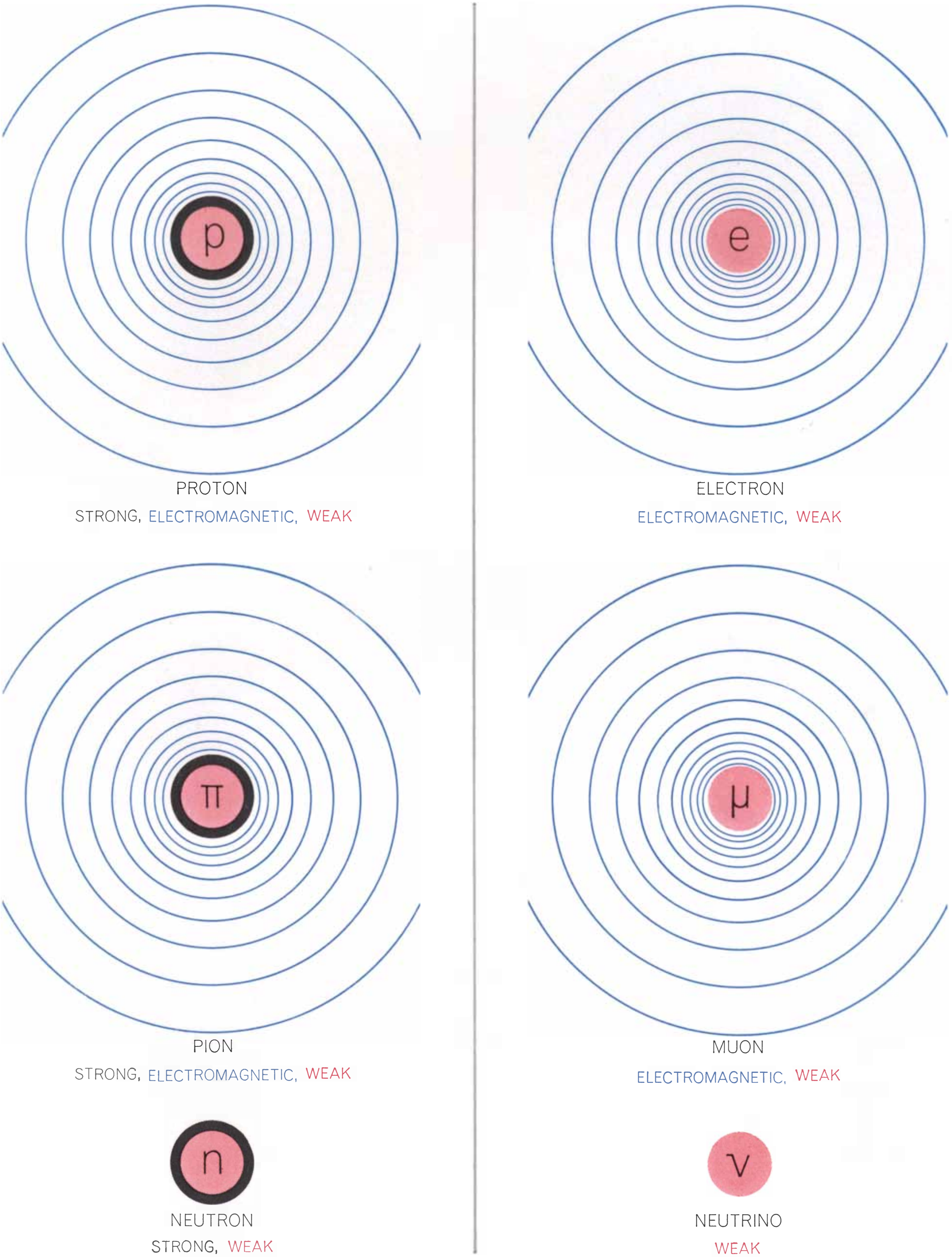

SIX PARTICLES discussed in the text are characterized by three types of "interaction" (the modern term for "force"): strong (*black*), electromagnetic (*blue*) and weak (*pink*). The proton and pion enter into all three types of interaction; the neutron displays only strong and weak forces. The electron and muon have identical properties. Of all the particles, the neutrino alone enters into weak interactions only. In general the three particles at left can be regarded as strong interactors; the three at right, as weak interactors.

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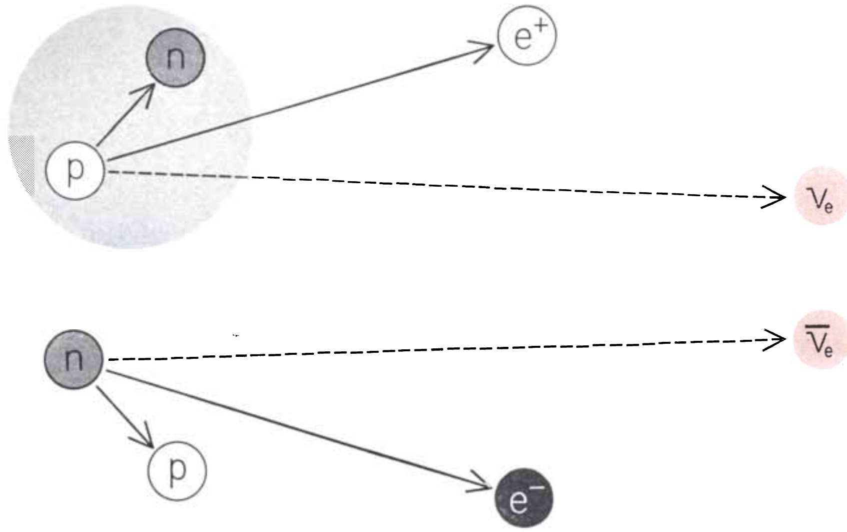
be possible for the reaction to go in reverse; that is, that an antineutrino should occasionally react with a proton to produce a neutron and (to balance charges) a positron. This is the reaction that was sought and found in 1956 by Frederick Reines and Clyde L. Cowan, Jr.

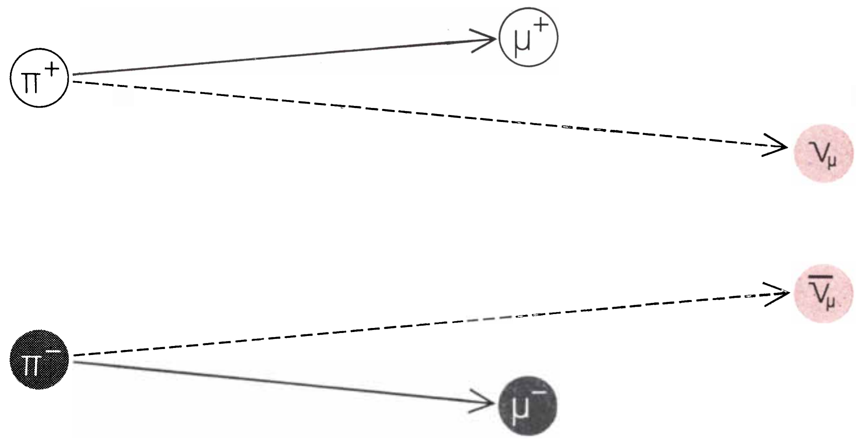
By the time the neutrino was finally observed, physics was deep in new troubles, brought on by the discovery of new particles. They were many, they were unstable and their lifetimes indicated that almost all decayed through weak interactions. A weak-interaction decay is characterized by a lifetime ranging roughly from 10^{3} seconds to 10^{-10} second. If strong forces were involved, the decay rate would be 10^{-23} second.

Among the many new particles was one destined to play a central role in the two-neutrino experiment. The particle is the pion, which was discovered in 1947 at Bristol University by C. F. Powell, C. M. G. Lattes and G. P. S. Occhialini. The pion appeared in cosmic ray tracks recorded in photographic emulsions exposed at high altitudes. The pion had been expected by physics since 1935, when the Japanese physicist Hideki Yukawa predicted its existence on theoretical grounds. According to quantum field theory, every force in nature is accompanied by a particle whose assignment is to transmit that force between interacting particles. For example, the electromagnetic force is borne by the photon. Yukawa postulated that a particle with 200 or 300 times the mass of the electron would be needed to conduct the nuclear force field—the strong force—between nuclear particles. The mu meson, or muon, was discovered in 1936 and had about the right mass, but subsequent observations proved that the muon was a weakly. It did not transmit the strong force. In fact, it was the first of the elementary particles for which physical theory was unable to provide a role. The pi meson, or pion, met Yukawa's specifications. The very first emulsion photographs showed that pions reacted violently with atomic nuclei.

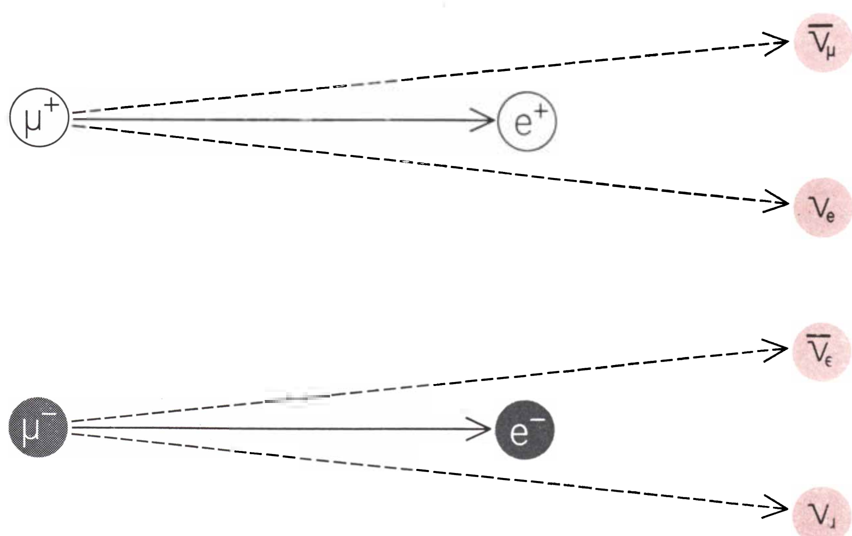
In 2.55×10^{-8} second the positive pion decays into a positive muon and a neutrino. As in beta decay, the neutrino is needed to account for missing energy (and momentum). The first paper analyzing the pion-decay reaction, however, assigned a mass of about 100 electron masses to the invisible particle produced in the decay and dubbed it the "neutretto," to distinguish it from the presumably massless neutrino. Before long the estimated mass was reduced by a



BETA DECAY is a weak interaction involving a proton or neutron. Inside an atomic nucleus, a proton (*top*) can decay into a neutron, positron and neutrino of the electron type. Free neutron (*bottom*) decays into proton, electron and electron-type antineutrino.



PION DECAY, another weak interaction, yields positive muon and muon-type neutrino (*top*) or negative muon and muon-type antineutrino (*bottom*), according to pion's charge.



MUON DECAY, also weak, yields a positron (*top*) or an electron (*bottom*). Both decays yield a neutrino and an antineutrino, one "belonging" to the muon, the other to the electron.

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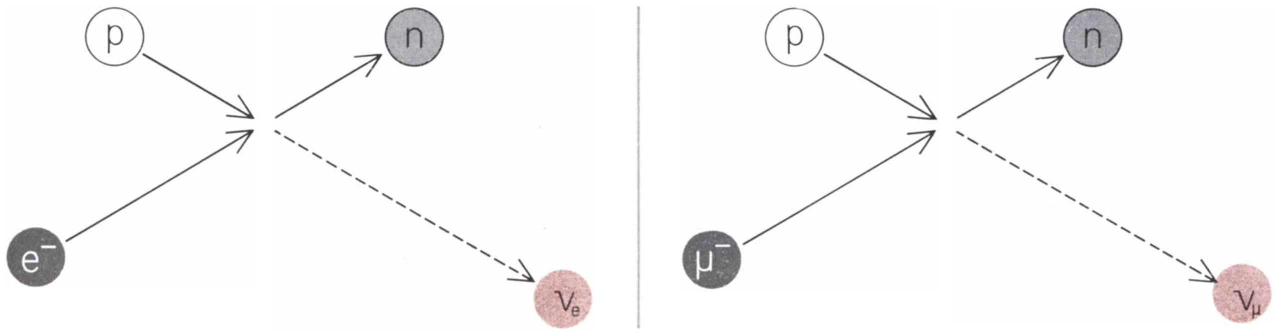


ELECTRON AND MUON appear to be identical in every respect except mass (and lifetime), the muon having a mass some 200 times greater. This identity extends to the reactions in which they take part. For every reaction involving an electron there is a corresponding reaction involving a muon; for example, the reaction of either particle with a proton produces a neutron and a neutrino.

factor of 10 and the distinction was dropped. The simplest conclusion was that pions decay into muons and neutrinos—the same kind of neutrinos, presumably, as those produced in beta decay. Furthermore, the conservation law known as charge conjugation led to the conclusion that if positive pions produce positive muons and neutrinos, negative pions must produce negative muons and antineutrinos.

The assignment of the neutrino to the positive pion and the antineutrino to the negative pion follows from the idea that "leptons" are conserved. The leptons are the electron, the negative muon and the neutrino; the antileptons are the positron, the positive muon and the antineutrino. The conservation of leptons requires that in any reaction the total number of leptons minus the number of the antileptons is constant.

By 1958 the theory of weak interactions, originally due to Fermi, had been developed in a highly successful manner by a number of workers, most notably by T. D. Lee at Columbia University and C. N. Yang at the Institute for Advanced Study and by Richard P. Feynman and Murray Gell-Mann of the California Institute of Technology. Nevertheless, problems remained.

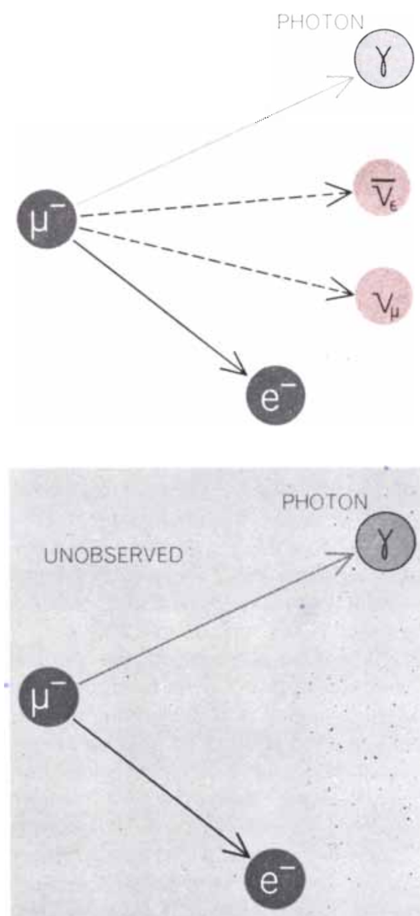
First, there was (and still is) the muon-electron problem. For every reaction known to involve an electron there is a corresponding reaction involving a muon [*see illustration above*]. The similarity of muons and electrons extends also to their intrinsic properties: they have the same quantum characteristic known as spin, and their magnetic and electric properties have been compared to an accuracy of a few per million and found to be the same. Indeed, apart from the fact that the muon is some 200 times heavier than the electron, the two particles seem identical.

The problem of mass is central to the entire subject of elementary particles. The fact that the large difference in the masses of the muon and the electron does not seem to induce other differences in their properties is one of the most fascinating in contemporary physics. These differences must be sought, however subtle. How can the neutrino help? In beta decay the electron is produced with a neutrino. In pion decay the muon is produced with a neutrino. In neutrino-nuclear collisions electrons and muons should be generated. At high energies this type of experiment would constitute a sensitive probe of muon-electron differences. No one, however, had ever shown that the neutrino born with an electron in beta decay and the neutrino born with a muon in pion decay were identical. If they were different, the difference must obviously be connected with the muon-electron difference. This, then, was one motive for considering a high-energy neutrino experiment.

The fruitfulness of such an experiment was analyzed in detail in late 1959 by Lee and Yang. All knowledge of weak reactions up to the spring of 1962 had been gained from observations at low energies. In no case did the energy transfer exceed 100 million electron volts. Physicists were most anxious to see how the weak force behaved when the energy exchange was increased toward a billion electron volts, and beyond. The traditional result of observing interactions at higher and higher energies is to "see" finer and finer details of structure. Obviously what was needed was a high-energy collision experiment involving a weak interaction. The only collision that would tell anything about the weak force, and that would not be "drowned out" by electromagnetic and strong forces, was a collision in which one of the particles was a neutrino.

The desire for a high-energy weak-interaction experiment was sharpened by a widely recognized defect of weak-interaction theory. In the summer of 1960 Lee and Yang analyzed this problem at length. Although the theory yielded excellent predictions for low-energy reactions, it led to absurd results for high energies. As a general rule an increase in energy provides an increasing number of ways for a reaction to occur.

In the case of the Fermi theory for weak interactions this led to the prediction that above a certain energy there would be more reactions than particles available to take part in them. Something, therefore, must intervene to damp the reaction rate. What was it?



ANNIHILATION of neutrino and antineutrino (*top*) should yield bottom reaction if there were only one kind of neutrino.

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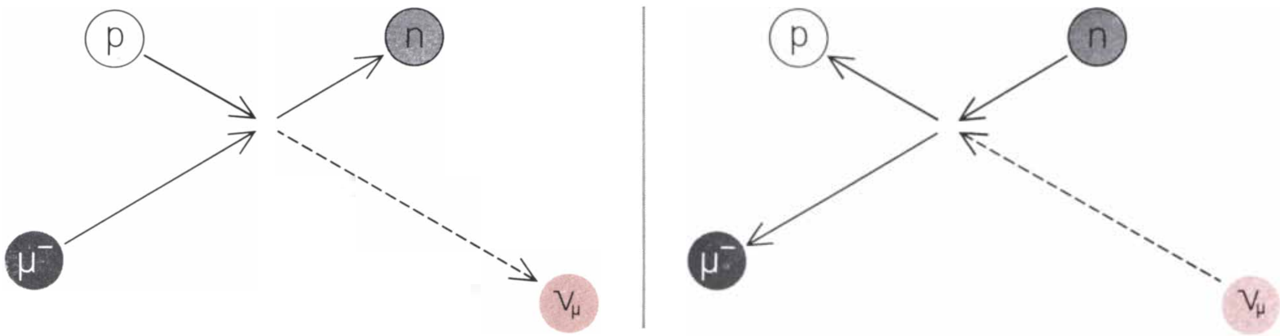


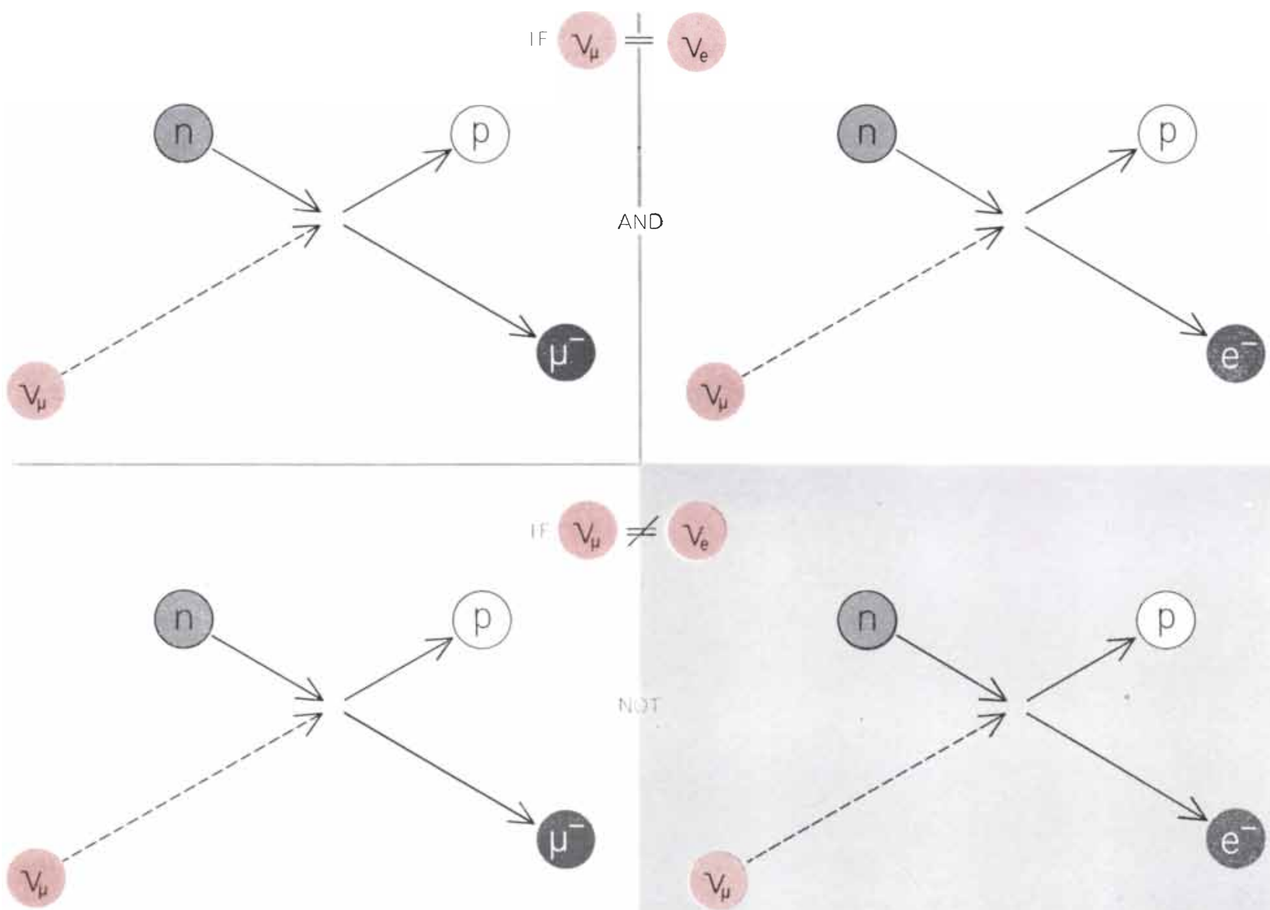
DETECTION OF NEUTRINOS depends on the reversal of a reaction already known to occur. The neutrino leaves no visible tracks in a spark chamber and can only be detected through its interaction with other particles. Since a muon-proton reaction (*left*) produces a neutron and a neutrino, a visible muon (*right*) should occasionally appear when a neutron and a neutrino collide.

One mechanism for damping the weak-reaction rate was the possible existence of an undiscovered particle, about which there had been wide discussion ever since Yukawa's theory of the meson. It had been given the name "intermediate boson" and the symbol "*w*."

It would serve to carry the weak force in the same way that the photon carries the electromagnetic force and the pion the strong force. It would be the "unglue" that makes a particle break up when it decays. It could not be directly recorded by photographic emulsions, bubble chambers, spark chambers or other devices for making particle tracks visible because its predicted lifetime—about 10^{-17} second—is too short. In this length of time a particle moving at almost the speed of light would travel less than a millionth of a centimeter.

A likely reaction for generating the particle is the collision of a high-energy neutrino with a proton. Out of the collision should come the intermediate boson (if it exists), a proton and a negative muon. Immediately the boson should decay, yielding, some of the time, a positron and a neutrino [*see illustration on page 70*]. With the aid of a suitable detecting device one should be able to see the negative muon and the positron as if they originated at a common point. This would be the boson's "signature." The big advantage of using neutrinos to hunt the boson was that they would produce relatively few background events to obscure its signature.

The most compelling motive for wish-



LOGIC OF TWO-NEUTRINO EXPERIMENT depends on the identity (*top*) or nonidentity (*bottom*) of electron-type and muon-type neutrinos. If they are identical, the reaction of muon-type neutrinos (from pion decay) and neutrons should produce muons and electrons in equal numbers. If the two types of neutrino are different, the same reaction should produce muons but not electrons.

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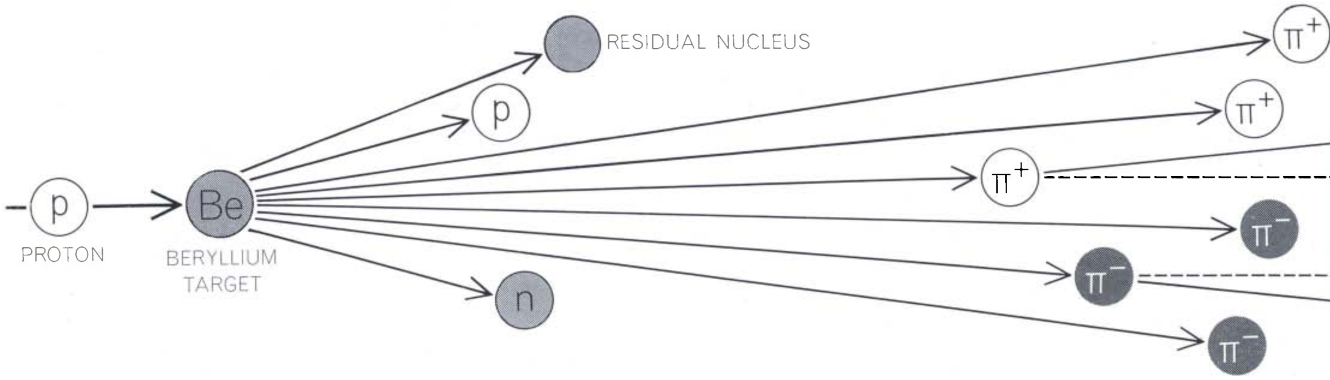
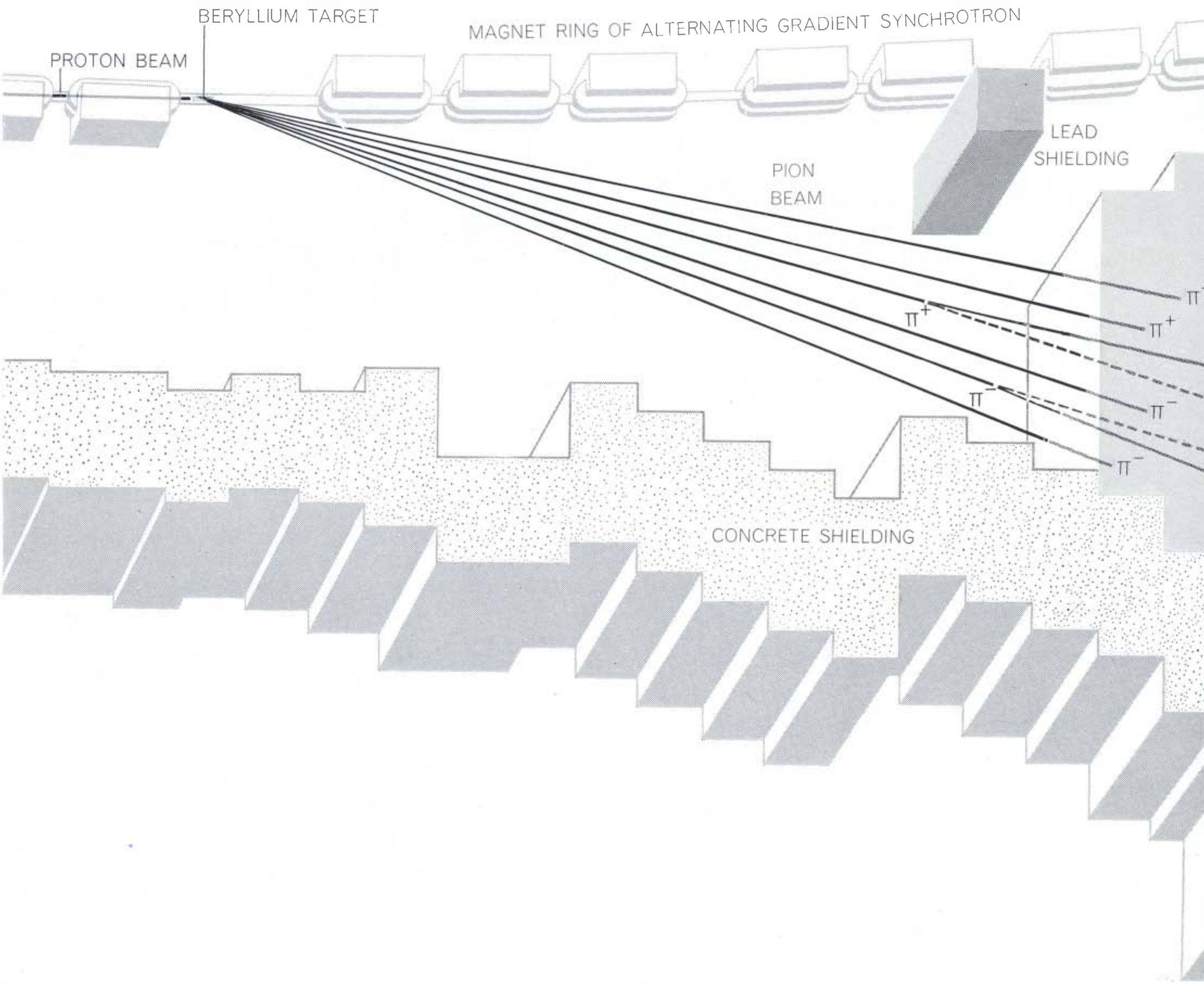


PRODUCTION OF NEUTRINOS for the two-neutrino experiment was achieved by directing a beam of accelerated protons at a target of beryllium atoms (*Be*). The interaction of these protons with the neutrons and protons of the target produces positive and negative



TWO-NEUTRINO EXPERIMENT used the 600-foot-diameter alternating-gradient synchrotron at Brookhaven, only part of which appears in this drawing. A beam of 15-billion-electron-volt protons was allowed to strike a beryllium target, producing an intense beam of pions. About 10 per cent of the pions decayed into muons and neutrinos before smashing into a 13.5-meter wall of armor plate.

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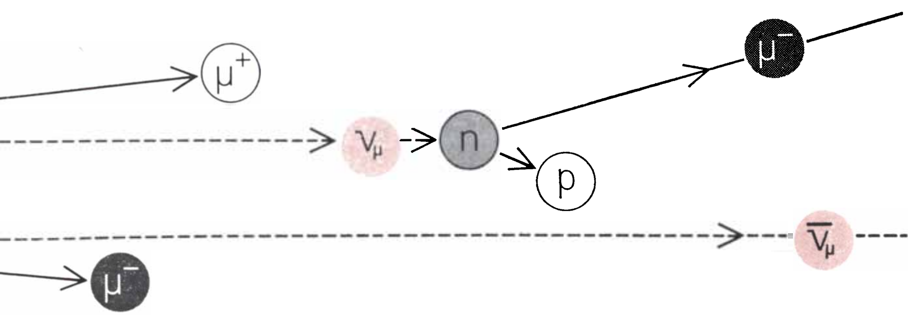
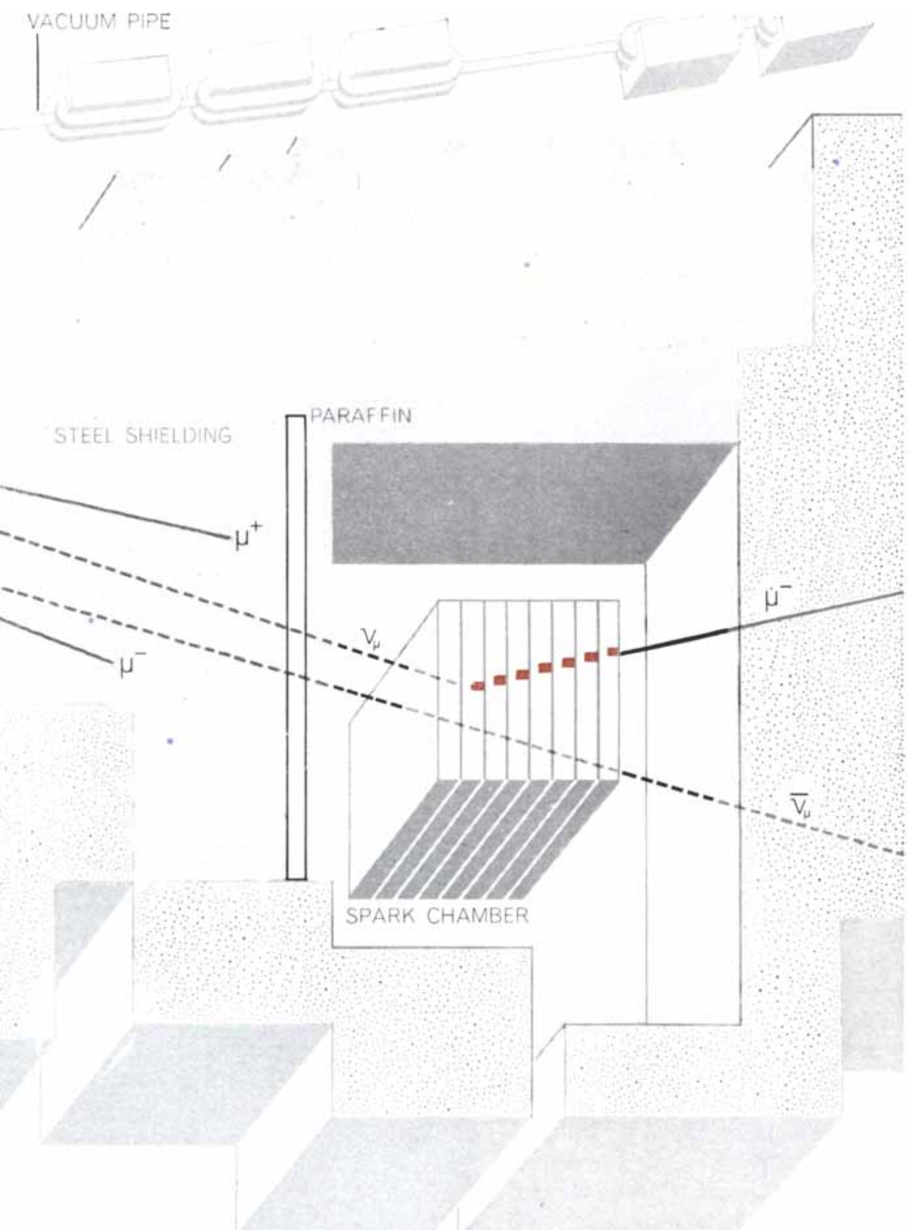


pions, which decay into muons and neutrinos and antineutrinos of the muon type. Occasionally a neutrino (or antineutrino) will react with a neutron (or proton), producing a muon.



The pions and muons were stopped by the wall; the neutrinos penetrated easily and passed through a spark-chamber detector. At rare intervals the chamber was "triggered" by appearance of a muon (*colored track*) produced by interaction of a neutrino or antineutrino.

ing to examine weak interactions at high energies was the puzzle presented by certain nonobserved reactions. Whenever an electron or a muon appears in a reaction, it is always accompanied by a neutrino. It is possible, however, to write down perfectly good weak reactions for the muon and electron that satisfy all the conservation laws and in which neutrinos do *not* appear. Yet no such reactions had ever been observed. When reactions that could take place are not seen, one must conclude that a basic prohibition law is at work.

One in particular of these evidently prohibited reactions had been sought in many laboratories, with very sensitive techniques. This was the decay of a muon into an electron and a photon. It is well known that a muon sometimes decays into an electron, a photon, a neutrino and an antineutrino [*see bottom illustration on page 64*]. Moreover, particles and their antiparticles annihilate each other when they are in suitable proximity. One can think of the muon's decay into four particles and the annihilation of two of them as being two steps in a "virtual" reaction, virtual meaning that the reaction meets theoretical requirements but cannot be observed. This particular virtual reaction would be stimulated by the presence of the intermediate boson. Under such circumstances the electron and photon would carry off all the energy and momentum of the muon decay. It was this that had never been observed.

Gell-Mann and Gerald Feinberg of Columbia University had independently pointed out that if the intermediate boson, w, existed, the unobserved reaction should "go" at a rate thousands of times faster than the minimum rate experimentally detectable. In fact, the absence of the reaction was often taken as evidence against w. To our experimental group at Columbia the puzzle was converted to a crisis by the further point emphasized to us by Lee (and also contained in the 1960 Lee-Yang paper). *Any* mechanism that would serve to damp the weak-interaction rate at high energies would stimulate the very reaction that no one had been able to observe.

One way to resolve the paradox is to assume that the neutrino and antineutrino of the muon decay cannot annihilate each other because they are of different species. Conceivably one species "belongs" to the disappearing muon and the other to the newly created electron. This hypothesis had the great virtue of preserving all successful features of the existing theory. Clearly a decisive experiment was needed, and this was an-

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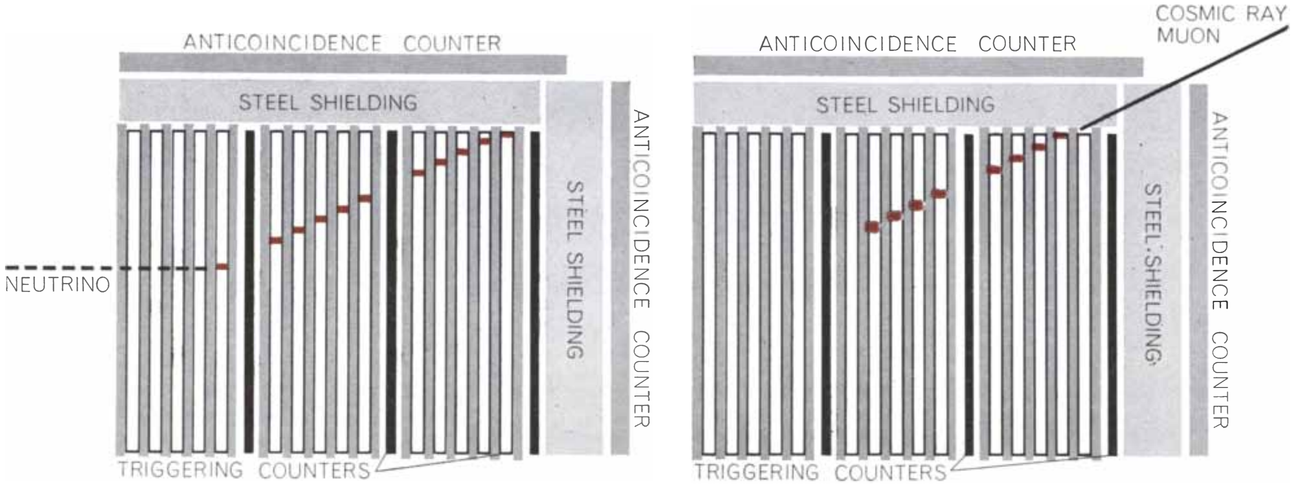


REAL AND SPURIOUS EVENTS detected by the spark chamber are sometimes indistinguishable. The spurious event (*right*) is produced by a cosmic ray muon, which has slipped into the chamber without triggering "anticoincidence" counters. Ordinarily they would prevent other counters inside the chamber from recording the event. In the actual experiment several hundred cosmic ray events were recorded, but they were identified by the angle of passage. It is estimated, however, that of the 56 events attributed to neutrinos, about five represented cosmic ray muons entering at an angle that made them indistinguishable from a genuine event.

other motive for the Brookhaven neutrino experiment.

Thus there were three urgent reasons for wanting to study weak interactions at high energies: to learn more about the muon and the electron, to observe reaction rates at high energies and to look for a second kind of neutrino. In each case the key to an experiment lay in observing high-energy neutrinos. How could they be obtained?

Late in 1959 Bruno Pontecorvo, working at the high-energy physics laboratory at Dubna, north of Moscow, and Melvin Schwartz of Columbia University independently put forward the feasibility of using accelerators to provide neutrinos of the desired energy. The neutrinos would arise primarily from the decay of pions produced when high-energy protons from an accelerator were allowed to strike a suitable target.

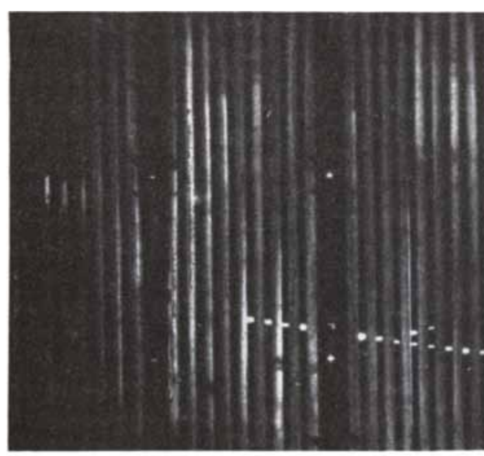
In 1960 Schwartz, Jack Steinberger and I at Columbia calculated that the alternating-gradient synchrotron (AGS) recently completed at Brookhaven might possibly provide high-energy neutrinos in the quantity needed to carry out a search for the second neutrino and to observe the rates of weak interactions at high energies. If the experiment provided evidence for the intermediate boson, so much the better. The proposal was received enthusiastically by the Brookhaven staff and in collaboration our two groups began setting up the experiment with the support of the Atomic Energy Commission. Associated with Schwartz, Steinberger and me in the experiment were Gordon T. Danby of the Brookhaven accelerator department, two Columbia graduate assistants, Konstantin Goulianos and Nariman Mistry, and Jean-Marc Gaillard, a visitor from the French high-energy physics laboratory at Saclay.

The search for the second neutrino was based on the following reasoning. The AGS at Brookhaven produces large numbers of high-energy pions. The neutrinos arising from pion decay would be born with muons; therefore they would be of the muon type, if there were really two types. Only a negligible number of neutrinos of the electron type could be produced. (These would arise from a tiny fraction of pions and K mesons that decay into neutrinos and electrons.) The neutrinos would collide with neutrons (and protons), with two possible consequences. If neutrinos were of only one type, they should react with neutrons to produce *equal numbers* of electrons and negative muons. If there were two kinds of neutrinos, the kind generated in our experiment should be unable to produce electrons and we should observe only muons.

Although the experiment was straightforward, considerable effort was required to obtain a suitable pion beam, to provide shielding that would reduce spurious events to an acceptable level and to design and construct a detector for neutrino collisions. Some 18 months elapsed between the initial planning of the experiment and the first runs with all the apparatus in place.

The great Brookhaven synchrotron is 600 feet in diameter. Protons injected into it require several seconds to reach the full energy of 30 billion electron volts (Bev). At full energy the muons produced in pion decay would be so energetic that they would penetrate more shielding than we could provide and spoil our results. Accordingly we selected for the experiment a beam energy of 15 Bev. When protons of this energy are deflected into a target made of beryllium, they produce pions with a broad distribution of energies peaked at about three Bev. A fraction of these pions fall within a 14-degree cone aimed in the direction of our detecting apparatus.

A three-Bev pion will decay, on the average, after traveling 150 meters. The neutrino arising from the decay will continue in the same general direction as its parent. A simple calculation showed that if we provided a full 150 meters for the pions to decay in, the beam would continue to diverge and we would get fewer neutrinos through our detector than if we placed the detector closer to the target. It turned out, in view of the required shielding, that a flight path of about 20 meters was optimum. In



SINGLE MUON TRACKS were photographed in the 10-ton spark chamber at

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this distance about 10 per cent of the pions decay, sending their muons and neutrinos forward. The last, together with the remaining pions, crash into the main shielding wall: 13.5 meters of steel armor plate from an old battleship. The steel wall stops all the particles except the neutrinos, which penetrate the wall as if it were not there. The pions and other strongly interacting particles penetrate only about a foot before being stopped. The muons, which "feel" only the electric force of the electrons in the iron atoms, penetrate farther before all of their energy is removed. The thickness of the shield was actually dictated by the necessity of stopping these highly penetrating particles.

In its early stages the experiment was plagued by leaks, mostly of particles that would pass under or over the steel wall and then be deflected into the detector. Thanks, however, to the zeal of the AGS staff under Kenneth Green, the sources of the background were eventually located and suppressed. This involved stacking hundreds of tons of rusty armor plate within inches of one of the world's most delicately aligned mechanisms.

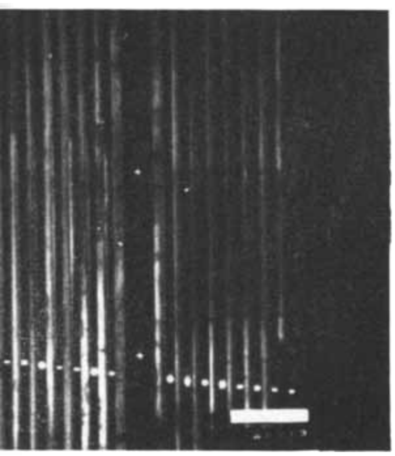
The detector used in our experiment is called a spark chamber, which is quite new to particle physics [see "The Spark Chamber," by Gerard K. O'Neill; SCIENTIFIC AMERICAN, August, 1962]. It is the only detector yet developed that could supply the 10 tons of protons and neutrons required to induce a reasonable number of neutrinos to react. In other words, the number of neutrino events we could hope to observe depended on the number of protons and neutrons that could be packed within the detector itself. Our spark chamber consisted of 90 aluminum plates, each an inch thick and four feet square, arranged in 10 modules of nine plates each. The plates were held three-eighths of an inch apart by spacers made of transparent plastic. The space between the plates was filled with neon gas.

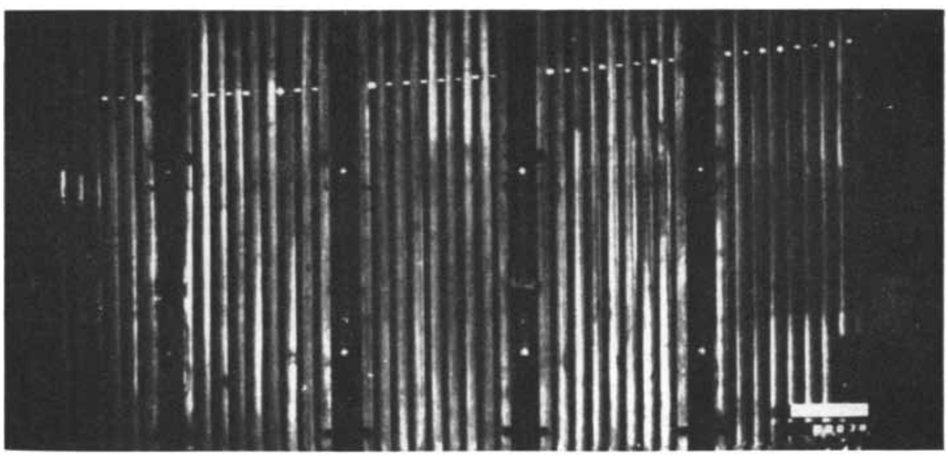
When a charged particle passes through the spark chamber, it leaves in the gas a wake of free electrons, which stay put for many millionths of a second. This period, although brief, is crucial because it allows one to record only selected events. Scintillation counters located both inside and outside the chamber detect the passage of the charged particles. The output of these counters provides information about the events taking place within the chamber. Only if the event is "interesting" is the recording process set in motion. This is done by placing a high voltage on the plates of the chamber. Where particles have left a wake of free electrons, a spark jumps through the neon gas. Cameras photograph the spark tracks through the clear plastic walls, thereby providing a stereoscopic view of the paths taken by charged particles less than a millionth of a second earlier.

In our experiment we were interested in events produced by charged particles that had more than 100 million electron volts (Mev) of energy and that were created *within* the chamber. It was impractical to provide enough shielding to block all cosmic ray muons entering the chamber from the outside. These, of course, were able to activate the triggering counters, arranged as vertical slabs between the 10 modules of the chamber. We established that several hundred cosmic ray muons entered the chamber every second. To avoid photographing so many useless events we placed "anticoincidence" counters on the front, back and roof of the chamber. If any of these counters recorded the passage of a particle immediately before it was sensed by the triggering counters inside the chamber, the command to fire was canceled. Since the bottom and side faces of the chamber could not be monitored in this way, however, the cosmic ray muon count still came to about 80 per second.

The problem was managed by making the durations of the synchrotron-produced radiation as short as possible. The Brookhaven experts were able to generate pulses of radiation that were only three-millionths of a second long. Pulses were repeated at intervals of 1.2 seconds. Most of the cosmic ray background could therefore be eliminated simply by requiring that the synchrotron be "on" when a particle was detected. The entire experiment, which stretched over eight months, consisted of just under two million pulses. This meant the machine was on for only six seconds all told. At a rate of 80 counts per second only about 480 cosmic ray events were recorded in this period, and it was usually easy to establish from the position of the tracks in the photographs which of them had been produced by cosmic rays. Nevertheless, we estimated that about five cosmic rays entered the chamber at such an angle that they were indistinguishable from genuine events. The number of such events that could simulate neutrino collisions was carefully determined by long runs on weekends when the synchrotron was in fact off.

The experiment was run intermittently from September, 1961, until June, 1962. When the synchrotron was well behaved, 10 million neutrinos passed through the spark chamber on each pulse. In a good hour the machine delivered 3,000 pulses, and a good day had 20 good hours. The experiment ran for 25 good days, during which time nearly 10^{14}, or 100 trillion, high-energy neutrinos traveled through the spark cham-





Brookhaven during the two-neutrino experiment. They provide visible evidence of the occurrence of reactions between individual neutrinos and neutrons (or antineutrinos and protons). Electron tracks (*see text*) would have a distinctly different appearance.

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ber. This is about the number of low-energy neutrinos from the sun that pass through our bodies every second, producing, perhaps, one reaction in a human lifetime. We had estimated that 10^{14} high-energy neutrinos would yield about 25 reactions.

The counters triggered the chamber about 10 times an hour—about five times the rate anticipated—providing us with some 5,000 photographs. More than half of the pictures were blank; we have never figured out why. We found the expected number of cosmic ray tracks (about 480) and a surprising number of tracks made by muons from the accelerator beam, which had slipped past the anticoincidence guard to trigger the system. When all such nonsignificant events were thrown out, we were left with 51 events that we could attribute to neutrino collisions. Of these, 29 showed the tracks of single muons and 22 showed the tracks of a muon together with one or more tracks produced by a pion or something else.

How could we be sure that the tracks had been produced by muons and not half by muons and half by electrons? Certainty on this point was essential to a decision whether there are two neutrinos or only one. Fortunately electron tracks are readily distinguished from muon tracks. We established the character of electron tracks by exposing two modules of our spark chamber to an electron beam produced by another accelerator. A muon almost always produces a strong track that follows a straight path. An electron track is usually erratic, wandering slightly from side to side. Often the path is marked by several weak sparks, and frequently there are gaps in the track. The neutrino experiment produced only six photographs that might be interpreted as electron showers. All were obtained in the first part of the run, when some neutrons were almost certainly leaking into the spark chamber. It is probable that some of the six events are small "stars" produced by neutrons. One or two could, in fact, be muons. Finally, a few electron events could be expected from electron-type neutrinos created in the decay of K mesons known to be in the pion beam. In short, there was nothing approximating equal production of muons and electrons, as predicted by the "one neutrino" theory.

The conclusion, we think, is quite clear. There are two kinds of neutrino. Those produced by the decay of pions in our experiment are of the muon type and cannot produce electrons by interacting with neutrons. To produce electrons by this reaction one would need neutrinos of the electron type.

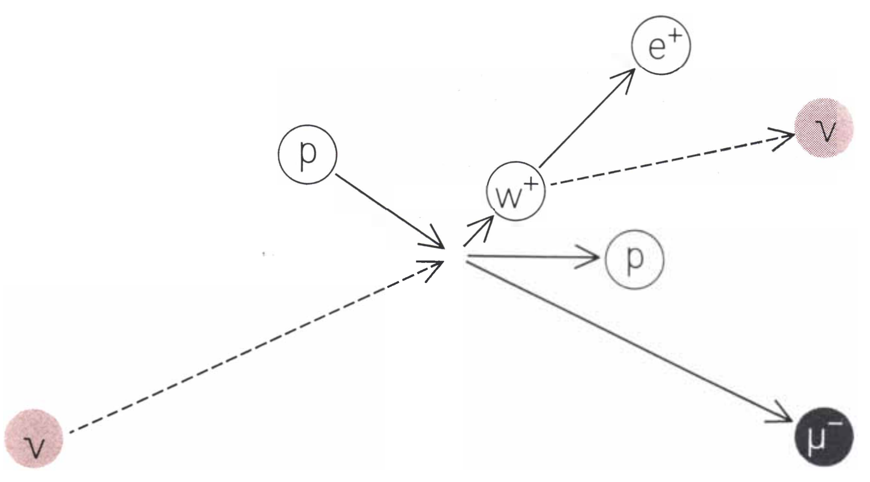
Over and above this particular finding, the Brookhaven experiment proved the feasibility of high-energy neutrino experiments using accelerators of 15 Bev or more. The only accelerators now capable of such experiments are the Brookhaven synchrotron and the similar machine at the European Organization for Nuclear Research (CERN) in Geneva. Investigators at both laboratories (as well as at the Argonne National Laboratory, where a 12-Bev machine is nearing completion) are preparing experiments in which the proton beam will be extracted from the machines to obtain intense pion beams.

The Brookhaven experiment failed to indicate any deviation from the weak-interaction rate predicted by theory. This is probably because our average neutrino energy was still well below that at which the theory predicts a steep rise. The next experiments should be done with particles of considerably higher energy. My associates and I are preparing a new experiment that may reveal whether or not the intermediate boson exists. We plan to look for its signature this fall.

Meanwhile theorists have two neutrinos to play with. The first clear gain of this finding is that a long list of prohibited reactions can now be understood. Neutrinos born with muons are in some way different from neutrinos born with electrons. This difference can be labeled with a new "quantum number"—say M, for muon-ness—which must be conserved. For the positive muon and its neutrino M equals 1. For the negative muon and the antineutrino M equals −1. For all other particles M equals 0. The new quantum number must be conserved in reactions, and this is nothing but a standard way of "explaining" why the unobserved reactions do not occur. The electron and its neutrino have a corresponding quantum number, say N, which must also be conserved.

Until recently physicists asked the question: Why does nature need two particles, the muon and the electron, that are alike in everything but mass? One must now add: Why does nature need a muon-neutrino and an electron-neutrino that may not even have a mass difference? The electron-neutrino's mass is now known to be less than a thousandth the mass of the electron, and it is generally assumed to be zero. Less is known about the muon-neutrino's mass. The best measurements indicate a mass less than seven times the mass of the electron. Should it turn out to be different from zero, the original name "neutretto" would be most appropriate for it.

The puzzle of the two particles may be resolved in two quite different ways. It may turn out that muon-ness conceals a complex inner structure to which present-day experiments are not sensitive. Another possibility, suggested by Lee, is that muon-ness and electron-ness are analogous to the situation presented by electric and magnetic fields. In the 19th century the two fields were regarded as similar but not identical. Albert Einstein's special theory of relativity, presented in 1905, revealed the intimate relation of the two and explained how electric and magnetic fields can be transformed into each other. The theory that will explain how muon-ness transforms into electron-ness may provide another deep clarification of physical thought



"INTERMEDIATE BOSON," if it exists, should be created by the collision of a high-energy neutrino and a proton. Almost instantly it should decay into a positron and a neutrino, although other decay modes are possible. The decay is so rapid that in a spark-chamber photograph the positron should seem to arise at the same point as the negative muon.

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Kodak reports on:

movies without entertainment . . . the value of a dollar . . . a big one with a low threshold

Brig. Gen. Webb's assignment

You sway in the Sea Beach Express under Manhattan and note how deeply engrossed is the young woman across the aisle in reading about movie stars. You walk down a side street in a Kansas town in the evening and note how every family in every house sits transfixed before the blue bottle. The motion picture camera has held the people in thrall for a long time now. You have your opinions and impressions of how most professional motion picture cameras are employed. You could be wrong.

Not long ago we announced a new 16mm professional motion picture camera, the KODAK Reflex Special. Embodies 10 years' research and design, we told the movie-makers. They bought. Then we took a look at exactly who they might be. Not entirely the crowd that the careless observer might have guessed—

Cineangioradiographers who make clinical x-ray movies of the great vessels and valves of the heart.

Psychiatrists.

Petroleum engineers.

Sociologists, professional ones.

Surgeons.

Aerospace medical people.

A biologist who shoots 5,000 feet per month of time-lapse motion pictures of tissue cultures, mostly through the oil-immersion microscope objective, and who has opened up dynamic morphology by photographing the mechanism of neoplasia, the functioning of organoids within the living cell, and the structural changes by which it answers physical and chemical changes in its environment.

A physicist, a mathematician, and a few others talked one night at Woods Hole till dawn about the motion picture as a research tool and means of communication between scientists, quite apart from science teaching. They moved the National Academy of Sciences, the National Research Council, and the National Science Foundation. These imposing bodies have correlated their complex functions to seek out the scholar bending a movie camera to his will in some ignored nook of the campus. Their survey has turned up two or three hundred of him.

NSF has granted funds to the National Academy of Sciences to start the American Science Film Association. Brig. Gen. Willard Webb has left the Library of Congress to become administrative director of ASFA. The isolated researcher with a movie camera and the scientifically dead-serious businessman with priceless studies of whales copulating can look to ASFA. It will be able to tell one how others have solved problems he is still struggling with and to help him make contact with colleagues in various parts of the world who want to see *his* footage. He ought to make sure that his name and his interests are on file with American Science Film Association, 704 Seventeenth St. N. W., Washington 6, D. C.

Neither ASFA, NSF, NRC, nor NAS endorses any particular brand name, but we do. In doing so we can answer many pertinent questions about cameras, projectors, film, processing services, and auxiliary equipment for anybody who asks them of Eastman Kodak Company, Motion Picture Film Department, Rochester 4, N. Y.

An interest in silver

To avoid crippling confusion in motivation, one stoutly reaffirms the belief of ages past that one is in business for the money. Today, however, other motivators exhibit their power, and though we still pursue the almighty dollar fiercely, once we have caught it we give little thought to the promise printed on it under President Washington's portrait. It promises silver.

Our house is founded on this truly unique gem of the periodic table. The marvelous behavior of the crystal lattice that it forms with bromine, when properly studded with impurities, makes photography possible; the importance of photography in both the serious and the gay is a major component of the force that attracted over 10^9 almighty dollars into the till last year. (Figuratively. Physically they are only a configuration of magnetized domains on a strip of iron oxide in some vault. Wonderful is the mind of man.)

Silver is drawn from the vault (a different vault) and made into pure $AgNO_3$. The vast bulk of this gets converted to silver halides and moves out on photographic goods. A very few parts per million find their way into bottles carrying the EASTMAN Organic Chemicals label.

Silver Nitrate itself, a fixture of the chemical laboratory since long before the invention of the test tube, still makes news. Only last spring it was revealed that silica impregnated with $AgNO_3$ displays highly selective adsorption with respect to the geometry and number of $C=C$'s in related unsaturated lipids, as detailed for chromatographic practice in *Chemistry and Industry*, June 16 and July 7, 1962. Last year also $AgNO_3$-Dichromate spray reagent was proposed for mercapturic acids and S-phenylcysteines (*J.C.S., 1962*, 608). $AgNO_3$ paper detects and fixes volatile As and Sb hydrides (*Chim. Anal.*, 43, 441). $AgNO_3$ is needed in the complexometric titration of K, Li, and Rb (*Mikrochim. Acta, 1961*, 644, 729, 732).

We also offer Silver Nitrite, Silver Arsenate, Silver Carbonate, Acetic Acid Silver Salt (*aren't we silly in our nomenclature!*), Silver Cyanate, p-Toluenesulfonic Acid Silver Salt, *numerous reagents* for *silver*, *and an invitation to all chemists interested in silver to keep in touch with* EASTMAN *Organic Chemicals Department, Distillation Products Industries, Rochester 3, N. Y. (Division of Eastman Kodak Company).*

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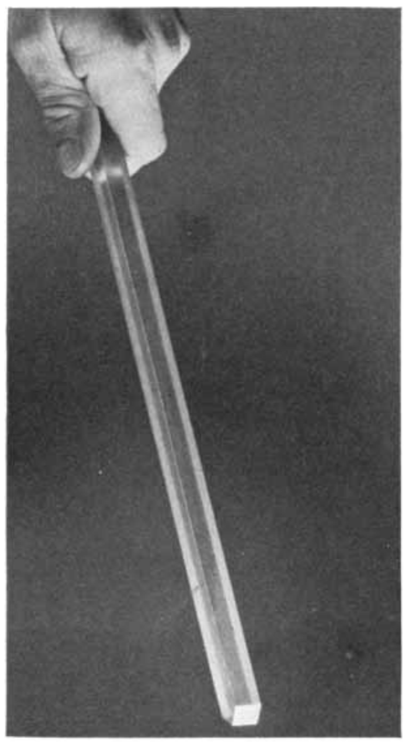

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This is another advertisement where Eastman Kodak Company probes at random for mutual interests and occasionally a little revenue from those whose work has something to do with science

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