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17. My colleagues Claude Ronne and Professor Herbert Riehl made this study feasible. Professor Riehl provided the initial inspiration, collated and analyzed the meteorological data, and drew on his vast experience in tropical meteorology at all stages. Mr. Ronne made all the flights, took all the pictures, and spent endless hours in the labors of reduction and mapping. We are all grateful to the Pacific Division of the Military Air Transport Service, whose officers and men often went far beyond the call of duty in making the research both possible and pleasurable. The work was supported by the Office of Naval Research, whose cooperation in all phases we deeply appreciate. We also thank the Woods Hole Oceanographic Institution for the use of their facilities during the long period of data reduction. This article is University of California (Los Angeles) Department of Meteorology paper No. 89.

Neutrinos, Old and New

The neutrino, discovered several years ago, is a curious particle now believed to exist in four states.

Frederick Reines

Thirty years have passed since Pauli (*1*) suggested the neutrino hypothesis in order to extend the validity of the principles of conservation of energy and momentum to include the process of beta decay. Nuclear beta decay is a process in which a nucleus spontaneously changes to another which differs by one unit in electric charge, simultaneously emitting a positive or a negative electron. It was noticed that, despite the existence of well-defined nuclear energy states—that is, a definite amount of energy available for the process—the emitted electrons only rarely carried off all the energy. Pauli hypothesized that the missing energy was in fact embodied in an unobserved particle which interacted weakly with matter. This particle was concluded to be electrically neutral because of the equality of the charge on the initial nucleus and on the final nucleus-plus-electron. In the years since this conjecture was made, the particle (named the neutrino by Fermi) has, primarily on the basis of Fermi's brilliant theory of beta decay (*2*), become an indispensable, if peculiar, member of the family of elementary particles. Symbolically we can describe nuclear beta decay by the equation

$$[A, Z] \rightarrow [A, Z \pm 1] + \beta^{\mp} + \nu_{\beta\mp} \quad (1)$$

where A is the number of neutrons plus protons in the nucleus, Z is the number of protons in the original nucleus, and $\beta^{\mp}$ and $\nu_{\beta\mp}$ refer, respectively, to the emitted electrons and neutrinos. The upper signs on the exponents go together, and the two subscripts on the neutrino indicate the two neutrinos associated with nuclear beta decay ($\nu_{\beta-}$ is the antineutrino, $\nu_{\beta+}$ is the neutrino).

Until 1956 the evidence for the existence of the neutrino was based on observations made on the other particles which participated in the act of beta decay—that is, the electron and the residual nucleus. This indirect evidence, though impressive and consistent with the neutrino hypothesis, was not logically conclusive because it represented no more than a restatement of the original premise that energy and momentum are conserved in beta decay.

However, in 1956, after a series of experiments carried out over a period of 5 years, a Los Alamos group (*3*) observed the free neutrino—that is, the occurrence of a reaction induced by a neutrino at a location other than its point of origin. This direct observation removed any doubts as to the existence of the neutrino, and it became as "real" as any other elementary particle. In 1962 a significant advance was made in neutrino physics when it was discovered, by a group of Columbia University and Brookhaven physicists working at the Brookhaven National Laboratory (*4*), that there is a second class of neutrinos, those associated with particle decays involving mu mesons. An example of a process in which neutrinos of this class are emitted is the decay of a pi meson to a mu meson

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu\pm} \quad (2)$$

Pi mesons, predicted by Yukawa and first discovered in the cosmic radiation by Powell and his collaborators (*5*), are produced in processes involving the bombardment of nuclei by high-energy protons. The decay process shown has a mean life of 2.5×10^{-8} second, and the masses of the meson are 270 and 207 times the mass of the electron.

Studies of the interactions of free neutrinos, though difficult because of the extreme rarity of the interactions, are aimed at the elucidation of fundamental questions about the nature of the weak interaction, which, along with interactions of the other three types—that is, strong (the type responsible for nuclear forces), electromagnetic, and gravitational—is considered to be responsible for the universe as we know it.

A further field of neutrino research, still in a very speculative stage, has to do with the neutrino's cosmic and astrophysical role. What makes the neutrino a subject of special fascination for physi-

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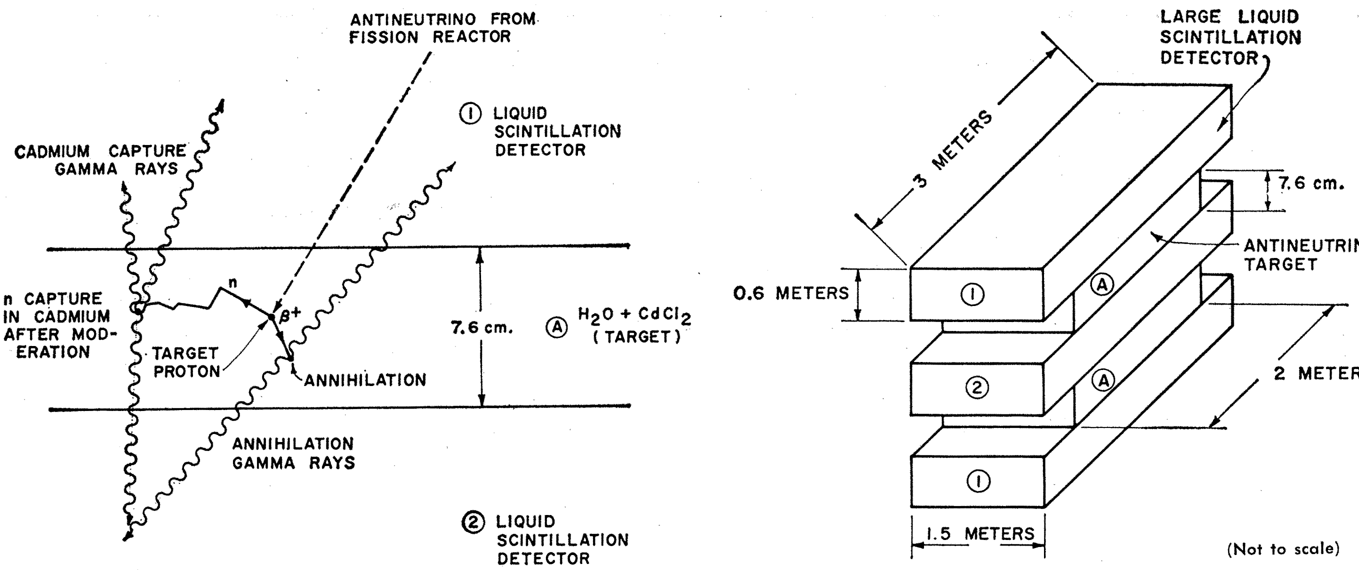

Fig. 1. Schematic diagram of detector for low-energy $\nu_{\beta-}$ particles. (Left) An antineutrino from a fission chain reactor strikes a target proton (p), producing a positron (β^+) and a neutron (n). The positron is annihilated, emitting two oppositely directed gamma rays which are detected by the liquid scintillation detectors on both sides of the target. The neutron diffuses in the target for $\sim$ 10 microseconds and is then captured by cadmium dissolved in the target. The gamma rays resulting from capture of a neutron are detected by the side counters. Capture of an antineutrino is therefore signified by a distinctive sequence of coincidences known as a delayed coincidence. (Right) In the actual array, 5 tons (4536 kg) of liquid scintillator were viewed by 330 5-inch (12.7 cm) photomultiplier tubes. The target, 400 liters of a water-cadmium chloride solution, was contained in two slabs, each 7.5 centimeters thick and 1.5 by 2 meters in width and length.

cists is its weak interaction with matter. Once it has been produced, the likelihood of its ever again interacting with an individual nucleus is (unlike the chance of interaction for nuclear and electromagnetic particles) extremely small. For example, a 3-million-volt antineutrino ($\nu_{\beta-}$) can penetrate 100 light-years of liquid hydrogen, on the average, before being absorbed: a neutrino signal carries unaltered the characteristic energy, momentum, and direction imprinted on it at its moment of birth. We therefore see that the very property which makes neutrinos difficult to observe makes observing them interesting.

Old Neutrinos

The first fundamental question which arose in connection with the neutrino was, Does it exist? The second question concerned the nature of its interaction with matter. By the first was meant, did the neutrino possess the properties predicted by the Fermi theory and, most specifically, the property that a neutrino produced by the beta decay of one nucleus could cause the reverse process to occur in a second nucleus. The simplest case of beta decay is decay of the neutron, n, to the proton, p.

$$n \rightarrow p + \beta^- + \nu_{\beta-} \qquad (3)$$

Its reverse is, according to the Fermi theory,

$$\nu_{\beta-} + p \rightarrow \beta^+ + n, \qquad (4)$$

with the reaction threshold at 1.8 Mev. The cross section for this reaction for a 3-Mev neutrino, as calculated from the Fermi theory and the observed characteristics of neutron decay is 10^{-43} cm^2 per proton. In view of this miniscule probability of interaction, for a few events to occur per hour we must have both an enormous flux of sufficiently energetic neutrinos and a large number of target protons. These were impossible requirements until the discovery of fission, the development of high-power fission reactors, and the development of appropriately large and sensitive scintillation detectors.

The fission process produces $\nu_{\beta-}$ particles because the fragments resulting from fission are rich in neutrons, a situation which results occasionally in the emission of the neutrons that perpetuate the chain of fissions in a reactor but results more often in the process of negative beta decay. Fluxes of 10^{13} $\nu_{\beta-}$ per square centimeter per second are used in these neutrino studies. The detector volumes vary, depending on the technique employed, ranging from $\sim$70 kilograms, in an approach currently under study, to several tons.

In the first free neutrino experiments the idea was to observe a signal, characteristic of reaction 4, in which two pulses were required, the first one due to the slowing down and annihilation of the positron with an orbital electron and the second due to the capture of the neutron by a nucleus added to the target for that purpose. This delayed rate of coincidences (of about three per hour) was observed as a function of reactor power, and various tests were performed to make certain that the reactor-associated signal could not be attributed to particles other than neutrinos. Figure 1 (left) shows schematically the sequence of events, and Fig. 1 (right) is a block sketch of the detector used in these identification experiments.

Once the signal had been identified, the problem of a direct, accurate determination of the details of the neutrino interaction became of interest; this is currently being pursued at Case Institute of Technology. Perhaps the most esthetically pleasing of the several neutrino experiments under study by the Case group is the so-called "table top" approach, in which only the positron produced in reaction 4 is detected. As of this writing it appears that a relatively simple positron detector, such as that shown schematically in Fig. 2, will be capable of reducing the background to acceptable limits and of determining the positron spectrum (and hence, from the principles of conservation of energy and momentum and certain well-founded statistical considerations involving phase space, the neutrino spectrum) with the accuracy characteristic of conventional nuclear physics. In brief, each antineutrino event in the plastic scintillator target produces a positron which slows down in the plastic and is then annihilated, producing two 0.51-Mev gamma rays which are detected by the side crystals. The rates expected in this experiment are one interaction every hour or so. In the event that additional background reduction is required, the product neutron can also be detected without much complication.

This reaction, the inversion of beta decay, is required by the Fermi theory. We might ask what other reactions can be expected of the neutrino. Marshak and Sudarshan (*6*) and Feynman and Gell-Mann (*7*) have suggested that the neutrino can also interact directly with an electron, scattering elastically in much the same way that billiard balls bounce off each other. In reaction 5

$$\nu_{\beta-} + \beta^- \rightarrow \nu_{\beta-} + \beta^- \qquad (5)$$

we have the interaction of two elementary particles, which should be a most revealing test of this more general theory. Unlike the reactions typified by reaction 4, in 5 the weak interaction is unsullied by the presence of nucleons. Also, as I discuss later, reactions of the type of 5 may be of great importance in stellar explosions, such as supernovae.

A brief consideration of this problem of neutrino-electron elastic scattering will suffice to indicate the formidable challenge it presents to the enterprising experimentalist. The cross section for fission antineutrinos is $\sim 5 \times 10^{-45}$ cm^2 per electron, and the signal is that of an electron merely nudged by a neutrino. The problem is one of distinguishing such electrons from those kicked by the much more copious gamma rays. Despite the apparently nondescript signal, the situation is under study, and some progress is being made in the difficult matter of reducing the background.

Thus far, an experimental search for other interactions of fission-produced neutrinos with matter has revealed no features beyond those of the picture proposed by Fermi, Marshak and Sudarshan, and Feynman and Gell-Mann. Existence of the particles $\nu_{\beta\pm}$ is consistent with our experimental data; they are chargeless, massless, and of spin ½. In attempting to picture the neutrino we must try to visualize a "disembodied" packet of energy traveling at the speed of light (since it has no rest mass) and possessing an angular momentum due to its spin. The revolution in our ideas of symmetry that has resulted from the work of Lee and Yang (*8*) and their concept of the so-called nonconservation of parity in weak interactions has led to the conclusion that neutrinos have spins parallel (in the case of $\nu_{\beta-}$) or antiparallel (in the case of $\nu_{\beta+}$) to their direction of motion. In some strange way this dual relationship between intrinsic angular momentum (spin) and linear momentum causes the $\nu_{\beta-}$ particles to invert β^- decays and the $\nu_{\beta+}$ particles to invert β^+ decays, thus lowering or raising the nuclear charge by one unit. A second consequence of this characterization of the neutrino is that the mirror image of $\nu_{\beta-}$ is not $\nu_{\beta-}$ but its antiparticle $\nu_{\beta+}$. This conclusion is surprising in view of the fact that the mirror image of a negative electron, for example, is a negative electron, not its antiparticle, the positron. A further consequence of the Lee and Yang ideas which result in this "handedness" of neutrinos is the asymmetric beta decay of oriented nuclei, as first revealed by the famous cobalt-60 experiment of C. S. Wu and her collaborators (*9*). Another interesting result of this limited relationship between neutrino spin and linear momentum is that the magnitude of the cross section for reaction 4 should be twice what one would expect from the Fermi theory. The experiments do not yet have the accuracy required for definitely checking this conclusion, but it appears to be favored by the data. The theoretical argument is based on the fact that the rate of neutron decay from which the cross section for reaction 4 is deduced is fixed by experiment, and that the smaller number of decay possibilities allowed by the newer ideas must be compensated for by attributing an increased strength to the weak interaction responsible for the decay. Since the number of decay possibilities turns out to be reduced by two, the interaction strength, and hence the cross section, goes up by two.

New Neutrinos

With the emergence of high-energy physics after World War II, a large variety of unstable elementary particles were discovered and studied. In many instances these particles decayed in such a manner that it was necessary to invoke the presence of a neutral particle of a mass which was small as compared to that of a neutron. As the reactions which involved these new neutral particles were studied further it became evident that the interaction strength for these decay processes—for example, reaction 2—was the same as the interaction strength for nuclear beta decay. Consequently, it appeared reasonable to identify these neutral particles with the Pauli-Fermi nuclear beta neutrino. In the absence of further information this assumption was attractive because of its parsimonious nature. The observation that the muon, which was assumed to decay by the route

$$\mu^{\mp} \rightarrow \beta^{\mp} + \nu_{\beta-} + \nu_{\beta+}, \qquad (6)$$

never appeared to decay by way of the route

$$\mu^{\mp} \rightarrow \beta^{\mp} + \gamma, \qquad (7)$$

despite the possibility that annihilation of the two neutrinos could give rise to a γ ray, was the first hint that the neutrinos might not be related as indicated in reaction 6. A solution to the difficulty was proposed by Onsda and Pati and by Feinberg (*10*), who suggested that the two neutrinos in reaction 6 were not related as particles and antiparticles and hence could not be annihilated, yielding reaction 7. The introduction of two types of neutrinos would require that muon decay be expressed as follows:

$$\mu^{\mp} \rightarrow \beta^{\mp} + \nu_{\beta\mp} + \nu_{\mu}\pm \qquad (8)$$

This relationship implies that muons and electrons are associated with their own distinctly different neutrinos.

At about this time it was suggested independently by Pontecorvo and by Schwartz (*11*) that the multibillion-electron-volt electronuclear machines just becoming available at the Brookhaven National Laboratory and the European Organization for Nuclear Research (CERN) in Geneva might be capable of producing a sufficiently large flux of neutrinos by way of pion decay (reaction 2) to make it possible to study high-energy neutrino interactions and check this idea directly. If the two classes of neutrinos are indeed distinct, only the reaction

$$\nu_{\mu+} + p \rightarrow n + \mu^+ \qquad (9)$$

should occur. If the two neutrinos are the same, the reaction should sometimes produce a β^* particle, as in reaction 4.

The most remarkable experiment by Danby and his collaborators at Brookhaven (*4*) showed that only muons resulted. Hence we must conclude that there are not two but four neutrinos, $\nu_{\mu\pm}$, $\nu_{\beta\mp}$, and that in all reactions involving only muons and neutrinos, these neutrinos must be of the $\nu_{\mu\pm}$ type. A reaction involving both electrons and muons must, if neutrinos are present, have neutrinos of both types.

Columbia-Brookhaven Experiment

The idea of the Columbia-Brookhaven experiment is shown schematically in Fig. 3. The figure shows, at left, the high-energy proton beam (15 Gev) from the Brookhaven alternating-gradient synchrotron striking a target and producing a shower of pions. Because of the principle of conservation of momentum, the pions are generally ejected in the direction of the incident protons. As they travel toward the massive shield housing the neutrino detector, some pions decay, producing a roughly collimated beam of neutrinos which, unlike the muons, penetrate the shield and enter the neutrino detector. Figure 3 shows, at right, the detector used in this experiment. It consisted of a well-shielded 10-ton (9100-kg) spark chamber, a device which revealed the path of products of the rare neutrino interactions by means of a series of electrical spark discharges in the gas between adjacent plates (see Fig. 4). The series of sparks produced by a high-energy electron differs distinctly from that produced by muons, since electrons are much lighter than muons and hence scatter more easily, giving rise to processes producing secondary electrons. The experimenters observed 51 events which they thought were due to neutrinos. They concluded that electrons were not produced.

Structure of Weak Interaction

The existence of four neutrinos does not of itself make it easier to understand the neutrino in terms of a model. What other degrees of freedom are available which will enable us to encompass two more particles in our scheme? Two suggestions have been made, but they are incomplete. These are (i) that, unlike the electron neutrino, the muon neutrino has some rest mass, and (ii) that a new quantum number is required to differentiate between the old and new neutrinos.

As to suggestion i, because of the relatively high energies (~ 50 Mev) of decay processes involving muon neutrinos, the effect of a rest mass is much more difficult to observe for muon decays than for the less energetic electron beta decays in which energies are as low as 10 Kev for H^3. Suggestion ii has, at least at present, an empty sound, since it merely renames the puzzle. Something new is needed.

It is to be hoped that the situation will improve as we learn about the structure of the weak interaction. The results of current experiments can be accounted for by the assumption that the weak interaction has no spatial extension—that it is a "point" interaction and can be described in terms of constants which give the strength of the interaction and introduce only those relativistically invariant combinations of wave functions which the experiment allows. A difficulty, in principle, with a "point" interaction is the unlimited cross section for interaction to which this assumption leads as the neutrino energy increases. This "point" description is therefore believed to be incomplete, and various theoretical models of

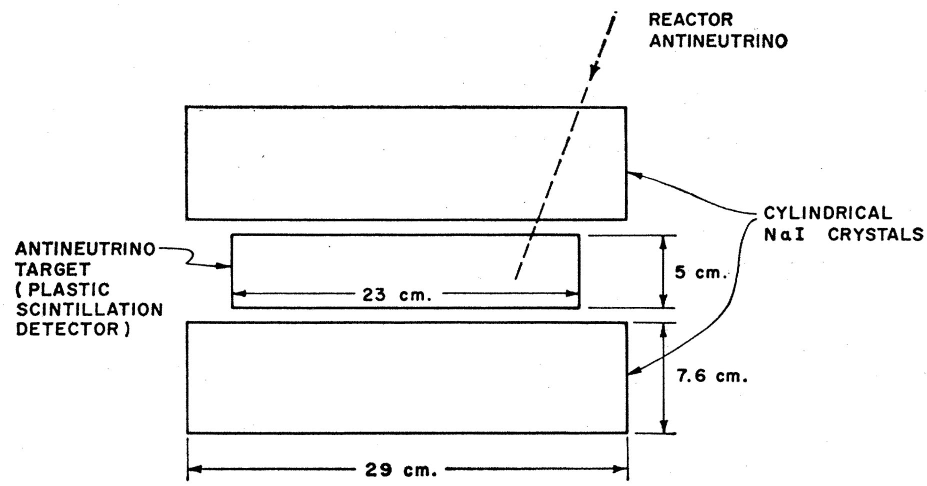

Fig. 2. Schematic drawing of the "table top" neutrino detector. The reactor antineutrinos (ν_{β^-}) interact with a proton (p), producing a positron (β^+), which slows down in the plastic and is annihilated, producing two oppositely directed 0.51-Mev gamma rays which are detected in coincidence by the sodium iodide crystals. It may not be necessary to observe the product neutron (n) in this experiment. As in the identification experiment, the detector is enclosed in a massive lead shield.

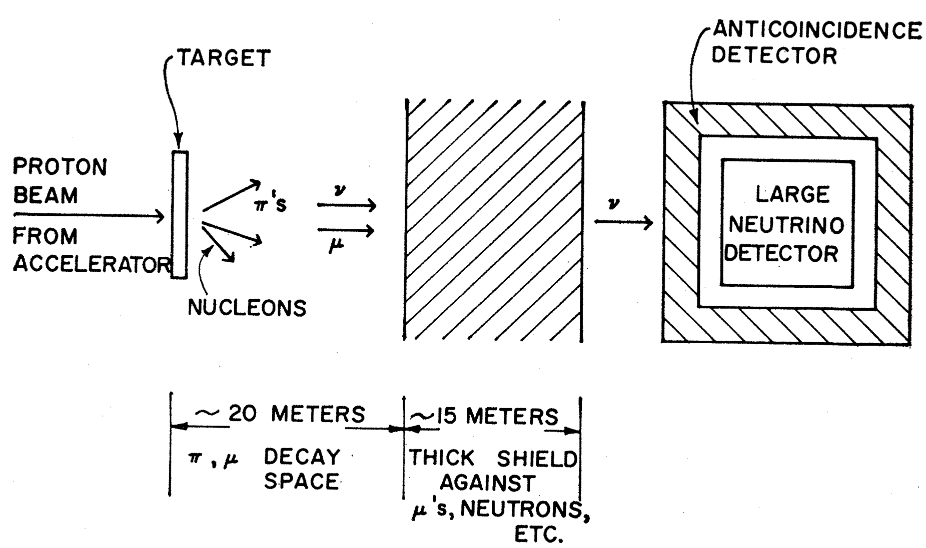

Fig. 3. Schematic representation of the high-energy neutrino experiment. The proton beam from the accelerator strikes a target, producing a shower of pions and nucleons. Since the pions must be allowed to decay, and to produce neutrinos, before they interact with matter and become absorbed, an air gap is provided. The thick shield prevents the penetrating neutrons and muons produced in these high-energy collisions from reaching the neutrino detector. In some designs an anticoincidence detector is provided, to shield the neutrino detector from cosmic rays.

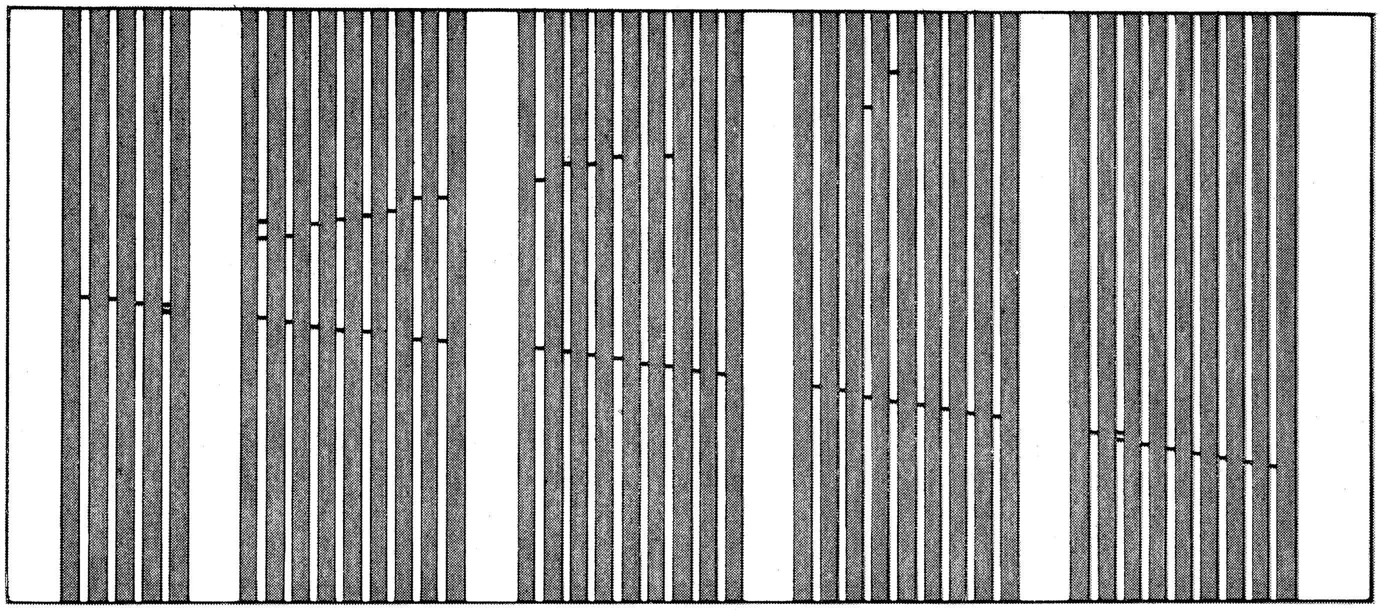

Fig. 4. Sketch of a neutrino collision in an aluminum spark chamber. The long straight track is attributed to the product muon; the incomplete track, to a gamma ray. The neutrinos strike the chamber from the left. [After a picture in the AEC report "Fundamental Nuclear Energy Research" (Government Printing Office, Washington, D.C., 1962)]

the weak interaction have been proposed which assume that, as with the other fundamental interactions, the weak interaction is mediated by a special particle. In the case of the nuclear field, the pi meson of Yukawa is responsible, by way of its exchange by two nucleons, for the nuclear force and its finite range; the electromagnetic field is carried by the photon. Once we assume that the mechanism involves the exchange of a particle associated with a field, the impossibility of localization in a manner consistent with the Heisenberg uncertainty principle implies that the range is finite and hence that the weak interaction, if so constructed, cannot be represented as acting at a point. A mediator of the weak interaction can be introduced, as in reaction 10.

$$\nu_{\mu+} + p \rightarrow W^{+} + p + \mu^{-} \qquad (10)$$

Consideration of the conservation of angular momentum leads to the conclusion that such a mediator must have an integral intrinsic spin, hence that it is one of the class of particles known as bosons. In the event that the energy of the neutrino is insufficient to produce the mediator, reaction 10 is replaced by reaction 9.

These and other theoretical ideas lead to various predictions about the distribution of the weak interaction in a nucleon (neutron or proton) and the variation of the weak interaction with energy. Marked differences between experimental results and the "structureless" Fermi prediction can be expected only at high energies, at which the neutrinos have sufficiently short wavelengths for these details to be seen (*12*). Consequently, the neutrino has become an object of great interest to physicists working at the very highest energies, and we can expect to hear a great deal about neutrinos from the groups at Brookhaven and at CERN, and eventually from those working with the new accelerator at the Argonne National Laboratory.

Neutrinos, Cosmic Rays, Astronomy

Nuclear reactions responsible for the production of sunlight (starlight) and the comparable amounts of energy embodied in high-energy particles called cosmic rays all have, as products, neutrinos which carry off several percent and more of the reaction energy. Since these neutrinos, once produced, have such a low probability of interacting again, they constitute a sink from which the energy cannot be recovered. Although no such nuclear and cosmic-ray "ashes" have as yet been detected, the possibility that they may be has intrigued physicists and, in some instances, has even stimulated the eloquent to flights of poetic fancy (*13*): "the message is there, bearing information on the cores of the stars and perhaps on the very bounds of space and time." Indeed, the neutrino message can, in principle, tell us many things. For instance, if certain theoretical conjectures are correct, we might conceivably learn of the occurrence of supernovae before they become visible to the optical or radio astronomer (*14*). According to these ideas, as the temperature inside a supernova rises, its interior is filled with high-temperature thermal radiation which materializes into β^{+}, β^{-} pairs. If the temperature becomes high enough ($\sim 10^{12}$ degrees Kelvin), μ^{+}, μ^{-} pairs result. These proposals are not surprising to physicists, but the possibility that the particle-antiparticle pairs can be annihilated, producing $\nu_{\beta-}$, $\nu_{\beta+}$ and $\nu_{\mu-}$, $\nu_{\mu+}$ pairs, was only recently suggested as a means by which the star rapidly loses energy. These reactions are related to reaction 5, which can be rewritten as

$$\beta^{+} + \beta^{-} \rightarrow \nu_{\beta-} + \nu_{\beta+} \qquad (11)$$

Also theoretically possible is the analogous reaction

$$\mu^{+} + \mu^{-} \rightarrow \nu_{\mu+} + \nu_{\mu-} \qquad (12)$$

Unlike the charged particles which produce them, the product neutrinos interact weakly and are able to leave the star without further collisions, carrying off energy extremely rapidly and allowing the star to collapse further and thus to generate more energy, and the process ends in a catastrophic stellar explosion—a supernova. The flood of neutrinos from a supernova, though impressive, is not overwhelming at the distances from the solar-system-bound observer at which these events are likely to occur. Chiu (*14*) concludes that a detector of some 10,000 tons ($\sim 9.1 \times 10^{6}$ kg) might give 10 counts in 100 to 1000 seconds for a supernova

1000 light-years away. On the average, supernovae that could be observed by such a detector occur at a rate of something like one in 100 years. The first signal from a supernova, according to this picture, is a neutrino signal, because the optical radiation takes a long time to diffuse to the stellar surface from the dense stellar core. On learning this, a graduate student at Case Institute of Technology labeled a modest 18-ton underground detector array "SNEWS," an acronym for "*s*uper*n*ova *e*arly *w*arning *s*ystem." The missing factor of 1000 troubled him not at all!

Other sources of high-energy neutrinos are the collisions of cosmic rays with matter, either stellar, galactic, or intergalactic. The process of neutrino production is as pictured in Fig. 3, except that the accelerator is the cosmos, the proton target is extraterrestrial matter, and the background shield is the earth. Estimates of these fluxes and the appropriate cross sections by Greisen and others (*15*) indicate that a detector of the order of 10^6 tons ($\sim 9.1 \times 10^8$ kg) would be required to give a counting rate of the order of 10 counts per year!

If the interaction cross section at these energies is 10^{-38} square centimeter, a much more readily detectable source of high-energy neutrinos is that provided by the bombardment of the earth's atmosphere by cosmic-ray protons (*16*). A rough estimate, based on the decay of the pi mesons produced in our atmosphere by such collisions, leads to the conclusion that a detector of about 10^3 tons ($\sim 9.1 \times 10^5$ kg) might be expected to detect neutrino-produced muons at the rate of ten to 100 per year. A group at Case Institute, consisting of T. L. Jenkins, M. F. Crouch, and myself, is engaged in the detailed design of a detector with an effective mass of about 10^3 tons. We propose to locate this detector in a very deep mine so as to minimize the ordinary background signal from cosmic-ray muons, which at sea level is about 10^{10} to 10^{11} times the expected neutrino signal. Since the rate of the expected signal would be a function of the cross section for high-energy weak interactions, it is possible that new information on the weak interaction may be obtained from this experiment. The real goal, however, is to detect and study the high-energy neutrinos of extraterrestrial origin, not the neutrinos produced in the atmosphere. It is hoped that this first small step will show the way.

With the possible exception of neutrinos from our own sun, the low-energy neutrinos produced in the nuclear fusion processes characteristic of the generation of stellar energy are not detectable by any known means. The neutrinos from the sun produce at the earth a total flux of about 10^{11} neutrinos in the million-electron-volt range per square centimeter per second (*17*). A most ingenious radiochemical technique developed by R. Davis of the Brookhaven National Laboratory (*18*) may possibly provide a means of detecting solar neutrinos and thus of obtaining direct evidence concerning conditions in the interior of the sun. Davis's technique consists of searching for the conversion, by neutrinos, of the chlorine-37 isotope in carbon tetrachloride to argon-37. The radioactive argon-37, a noble gas, is flushed from the carbon tetrachloride and placed inside a small counter in which background radiation is low. With some 100,000 gallons ($\sim 3.8 \times 10^5$ liters) of carbon tetrachloride, a perceptible counting rate of 1 to 2 counts per day may result.

There is always the intriguing possibility that unknown processes have produced a much larger but as yet undetected flux of neutrinos. A recent, relatively modest, experiment (*19*) shows that the total flux of high-energy neutrinos is something less than 1000 times that expected from the neutrinos produced in the atmosphere. Poor though this limit may be, the flux of low-energy neutrinos is even less well limited by experiment, and we must acknowledge that thus far we have not been able to exclude by direct experiment the possibility of an energy content in the neutrinos of the universe which is much greater than all other forms of energy combined. Current experiments (*20*) may reduce these limits, and we must await the results with an open mind (*21*).

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15. K. Greisen, in *Proceedings of the International Conference of Instrumentation for High Energy Physics* (Interscience, New York, 1960), pp. 209–211; V. A. Kuzmin, M. A. Markov, G. T. Zatsepin, I. M. Zheleznykh, *J. Phys. Soc. Japan* **17**, suppl. 3A, 353 (1962).
16. The Russians (notably Pontecorvo, Markov, and their collaborators), several Americans, and physicists from other countries are considering various approaches to the problem of detecting these neutrinos. One recurring suggestion is that a directional detector be used so that only muons from upward-traveling neutrinos will be detected, unwanted cosmic-ray muons thus being eliminated. However, when the first detection of cosmic-ray neutrinos is accomplished, detailed observations will require a neutrino target surrounded and defined by an anticoincidence shield. It is conceivable that such a detector will consist of 1000 tons ($\sim 9.1 \times 10^5$ kg) of spark chambers triggered by vast assemblages of scintillation counters.
17. J. N. Bahcall, W. A. Fowler, I. Iben, Jr., and R. L. Sears [*Astrophys. J.* **137**, 344 (1963)] predict a flux of 4×10^7 and 4×10^{10} ν_{β^+} per square centimeter per second from the decay of boron-8 and beryllium-7, respectively.
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20. I thank my colleagues Professors T. L. Jenkins and M. F. Crouch for discussions of these questions.
21. This study was supported in part by the U.S. Atomic Energy Commission.