Neutrino physics

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THE neutrino * is one of nature's strangest exhibits in the showcase of nuclear physics. Produced in the process of nuclear beta decay and very likely in the decay of certain members of the meson family, the neutrino lives on toward infinity with negligible probability of further interaction with matter, unaffected by anything except the gravitational field of the universe. It might be imagined that this peculiar behavior is sufficient for one particle, but as recent experimental developments stimulated by the theorists Lee and Yang have indicated, the neutrino may be near the heart of the parity puzzle: a given neutrino would seem to know right from left and to communicate this information via the law of conservation of angular momentum to particles with which it is associated in decay processes.

The neutrino concept was born because of the necessity for explaining the apparent unbalance in the energy associated with nuclear beta decay. In addition, if the total angular momentum of nuclear systems undergoing beta decay was to be conserved, it was necessary to postulate some particle or mechanism to permit this. The pioneer work on beta decay which brought these difficulties into view was done at Rutherford's laboratory in the twenty-year period from about 1914 to 1934, and prominent members of the group at the Cavendish were Chadwick (1914), who discovered the continuous nature of the beta spectrum, and Ellis and Wooster (1927), who observed apparent nonconservation of energy in calorimetric experiments using beta emitters. Specifically, the energy paradox was this: in nuclear beta decay the initial and final states of the beta-emitting nucleus were known to have definite energies, and all associated nuclear gamma rays were monochromatic in the decay, but the energy of the beta particle was not a single line spectrum representing the remaining available energy. The nuclear spin angular momentum difficulty was complicated at the time by the fact that the neutron was not yet known. In any event, two of the basic tenets of physics, the energy and momentum conservation laws, were at stake, and one had either to relax them in the case of nuclear systems or invent a new hypothesis. This was a most trying situation for physicists of the late 20's and early 30's, but the correct way out, the strikingly successful neutrino hypothesis, was indicated by W. Pauli, Jr. in 1930. As a measure of the desperate situation it is interesting to recall that there was a brief period of speculation during which some physicists were willing to relinquish the conservation laws for atomic processes, suggesting that these laws applied in some manner on the average but not in detail for each process. Brilliant though Pauli's neutrino hypothesis was, it remained to build a formalism so that quantitative statements could be made about the phenomenon of beta decay.

Following the discovery of the neutron by Chadwick (1932), E. Fermi (1934) constructed his famous beta decay theory in which he assumed that a new interaction existed which gave rise to a free negative electron (β) and a free neutrino (ν) whenever a neutron (n) in the nucleus changed into a proton (p). A similar statement was made for the conversion of a nuclear proton into a neutron. These reactions are summarized in the formulae

$$n^0 \rightarrow p^+ + \beta^- + \nu_-$$
$$p^+ \rightarrow n^0 + \beta^+ + \nu_+.$$

The first reaction is exoergic for a *free* neutron, and the free neutron is accordingly unstable. It follows that the *free* proton should be stable against β^+ decay. Internucleon forces in complex nuclei may, however, reinforce, cancel, or reverse this stability condition.

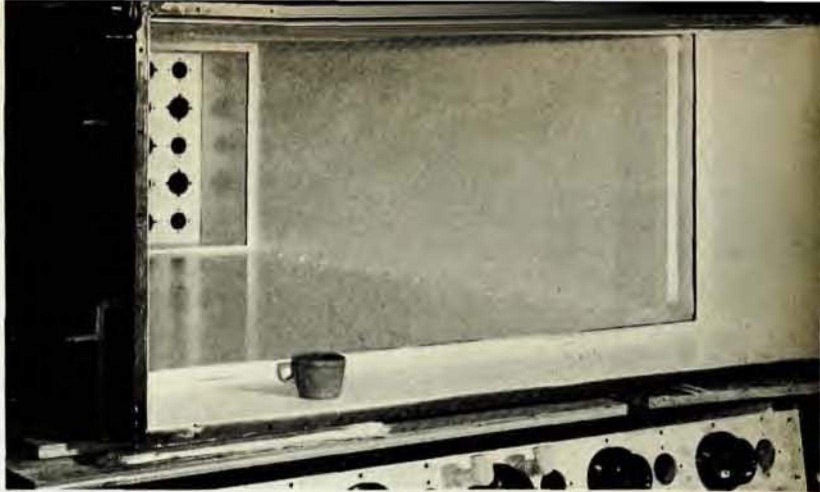
* We use the word neutrino in its generic sense although occasionally we find it necessary to make a distinction between two kinds of neutrino, i.e. neutrino and antineutrino.

Pauli described the neutrino, calling it a neutron, but Fermi, recognizing that the name had been preempted for the neutron of Chadwick, renamed the Pauli particle very appropriately as the "little neutron" or "neutrino". Fermi's theory explained the shape of the beta spectrum as essentially due to the sharing of the available momentum and energy by the electron and the neutrino. Spin conservation difficulties were removed by the assignment of spin $\frac{1}{2}$ $(h/2\pi)$ to the neutrino. The form of the interaction was taken to be restricted by the generally accepted requirement for invariance under the proper Lorentz transformations (relativistic invariance) but was otherwise unspecified. Furthermore, he assumed that the relativistically invariant quantum mechanical Dirac equations applied to the neutrino. By consideration of the shape of the beta spectrum near its high-energy end point, a region in which the neutrino carries off little more than its rest-mass energy and hence a region which is most sensitive to the value of the neutrino rest mass, Fermi demonstrated that the neutrino must have either zero mass or one which is very small compared to the mass of the electron. With sure instinct he chose to assume a zero mass as "simplest". In one masterful stroke Fermi described the kind of interaction known today as a "weak interaction" and constructed the theoretical framework which provided a basis for subsequent investigations of the neutrino. Much has been said of late about "weak" and "strong" interactions. The strength of an interaction is related to the rate at which it proceeds under favorable circumstances. So nuclear beta decays, for example, which take from tens of milliseconds to perhaps days to occur, proceed at a rate which is $< 10^{-20}$ of that characteristic of the strong nucleon-nucleon interactions.

Shortly after the publication of Fermi's theory, estimates were made by Bethe and Peierls (1934) relative to the possibility of direct detection of the neutrino by inverting the process of beta decay. For example, the inverse of free neutron decay is to change a free proton into a neutron by either absorption of a negative electron or emission of a positron upon submitting the proton to bombardment by neutrinos. They concluded that the problem was extremely difficult, if not insoluble, because of the tiny interaction cross section, about 10^{-43} cm^2, for a neutrino with a few million electron volts energy. The smallness of this cross section, 10^{-20} times the more familiar nuclear values, is illustrated by the extreme penetrability of matter by neutrinos—a 3-Mev neutrino can with good probability penetrate a layer of liquid hydrogen a hundred light years thick. This cross section is small, but at least it has the virtue of being a necessary consequence of the Pauli-Fermi neutrino theory. The possibility of other interactions, viz., via a small magnetic moment or electrical charge, was not required by the Fermi formalism, nor was any restriction placed on the neutrino rest mass other than that it be small so as not to distort the beta spectrum. Undaunted by the lack of an estimate, Nahmias (1935) looked experimentally for a direct interaction of neutrinos with electrons which would result in electron recoils in a Geiger counter. Bethe (1935) estimated from the Nahmias data that, if the neutrino had a magnetic moment, it was $< 2 \times 10^{-4}$ electron Bohr magnetons. As pointed out in an order-of-magnitude estimate by Wightman (1951), similar experiments by Barrett (1950) also showed that if the neutrino carried an electric charge it was also extremely small, $< 2 \times 10^{-6}$ times the electronic charge.

SOME ten years elapsed during which a large amount of theoretical and experimental work was done on the process of beta decay, but there was no significant change in the status of the neutrino. Sporadic attempts were made to construct theories involving the neutrino, such as a neutrino theory of light, but with little success. The motivation for such attempts, however, is clear. After all, if the neutrino is assumed to have zero rest mass and zero electrical charge—facts not inconsistent with experiment—then does it not resemble that other particle of zero rest mass and zero charge, the photon? Perhaps a light quantum (with "spin" 1) was a combination of two neutrinos (each with "spin" $\frac{1}{2}$). A difficulty with such a theory was indicated by Pryce (1938) to be due to the transverse nature of photon polarization as compared with the longitudinal nature of neutrino polarization. An additional trouble with such a theory of light is the conflict between the requirement that two neutrinos (or antineutrinos) be in the same bound state and the Pauli exclusion principle which forbids such a configuration. An alternative suggestion that the photon is composed of a neutrino-antineutrino pair is in conflict with the recent two-component neutrino theory (see below) which does not allow a neutrino-antineutrino pair traveling together to have a spin angular momentum greater than zero. Other conjectures by Gamow (1948) sought a connection between neutrinos and gravitons, the quanta of the gravitational field. The theoretical possibility that large assemblages of neutrinos might be held together by their mutual gravitational field has been considered by Wheeler (1955) in his treatment of these assemblages which he names geons.

Since World War II the neutrino has been studied in a variety of experiments. Most of these experiments were indirect in that they concentrated on the other particles in the reactions studied and inferred the neutrino characteristics from the motions of these particles. For example, application of the Fermi approach by Langer and Moffat (1952) and others to the carefully measured beta decay spectrum of tritium made it possible to limit the neutrino rest mass to $< 1/2000$ of the rest mass of the electron. The virtue in using tritium is that it has a small available energy (18 kev) for beta decay and hence gives rise to a beta spectrum which should be more easily distorted by a neutrino rest mass. In addition, the availability of hitherto undreamed of neutron fluxes from fission chain reactors made possible a direct measurement by Snell and his collaborators (1948) and by Robson (1950) of the beta decay period and spectrum of the free neutron, with a resultant im-



Interior of one of the partly assembled detector tanks. End plates for mounting the tubes are seen, with the rear one in place. Two clear plastic windows, edges of which are marked by the vertical black lines on the far wall of the detector, divided the detector into a central scintillating chamber and two end chambers filled with non-scintillating liquid. This helped make the response of the detector reasonably independent of the location of the origin of the light pulses. The floor of the detector is constructed of a glued sandwich of corrugated cardboard between two thin sheets of stainless steel. This construction was thin to gamma radiation but was adequate support for the load of liquid scintillator. The roof of the detector was made of a thin sheet of stainless steel, creased for stiffness. Gaskets and O rings were made of Dow-Corning Silastic silicone rubber.

provement in our knowledge of the beta coupling-constant. Another question which was studied was whether the neutrino was truly a Dirac particle in the same sense as in an electron. The formalism for "single" beta decay is indifferent to the answer, but in the case of "double" beta decay in which the simultaneous emission of *two* electrons occurs the situation was somewhat altered. Here the requirement that the neutrino must obey the Dirac electron equations as for "electrons" but with zero charge, and that there exist particle (ν_+)-antiparticle (ν_-) pairs, resulted in very long half lives for double beta decay, whereas if the neutrinos emitted in positron decay and negative electron decay are identical, the lifetimes should be short and observable. The original work of Firemen (1948) on double beta decay stimulated many subsequent searches with the conclusion based on the presently unobservably great lifetimes that the neutrino can best be described as a "true" Dirac particle, i.e., by the Dirac equation, and that the neutrino is distinct from the antineutrino.

Completing the list of indirect neutrino studies is a most striking series of experiments in which the linear momentum carried off by the neutrino was inferred by observing the linear momentum unbalance in beta decaying systems. That such an unbalance should occur is required by the original Fermi theory, because any particle carrying energy out of a system must necessarily carry linear momentum. However, when one calculates the recoil energy of a nucleus caused by the departure of a neutrino it turns out to be very small, and even in the unusually favorable case of the decay of He^6 it is only 1.4 kev. K. C. Wang (1942) suggested the use of a nucleus such as Be^7, which beta decays by capture of an orbital electron, would result in the emission of a neutrino alone which causes a recoil of the nucleus. J. Allen (1942) successfully observed this nuclear recoil in a specially constructed electron multiplier tube with no windows so that it could detect almost all the recoil (58 ev) energy of the resultant nucleus. Since Allen's pioneer experiments, he and others have succeeded in making accurate measurements on nuclear recoils using other isotopes and have even correlated them with the direction of emission of the electrons. Such angular correlation experiments have made it possible to restrict the forms of the beta interaction, and hopefully this approach may eventually make possible a decision as to the precise form of the interaction.

It has been argued that these recoil experiments are a confirmation of the neutrino hypothesis, and in a sense this is so. If it had been demonstrated that the expected recoils did not occur then the hypothesis would have received a fatal blow. The successful observation of the recoils, however, is again an observation not of the neutrino but of the particles with which it was associated at the time of production, and it was for precisely this situation that the neutrino was hypothesized in the first place. A convincing argument that the neutrino exists in the free state, and that it is not an ingenious dodge invoked to describe a peculiarity of nature manifested at the location of the beta decay process and nowhere else, can be based only on the observation of the neutrino in the free state. So for example the observation of inverse beta decay in the vicinity of a neutrino source would settle the question of the "reality" of neutrinos conclusively. The miniscule cross section for this event, however, made such a direct observation of even the most favorable reaction, $\nu_- + p^+ \rightarrow \beta^+ + n^0$, a questionable undertaking at best.

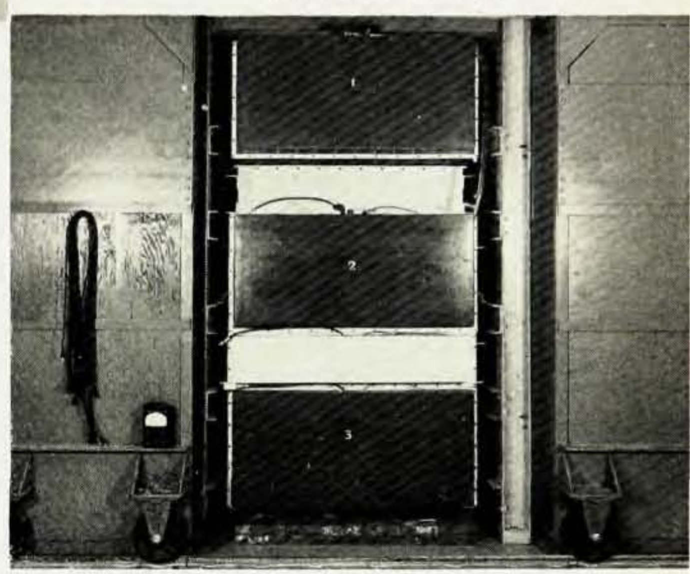
WITH the success of chain-reacting fission piles, Fermi, Wheeler, Wigner, and others quickly realized (1943) that the newly available and enormous fluxes of energetic neutrinos probably associated with fission reactors ($\sim 10^{12}$ to 10^{13}/cm^2 sec) made the problem worth reinvestigating. Before the advent of fission reactors, radioactive sources were measured in terms of curies, or 3.7×10^{10} disintegrations per second, representing a neutrino flux at one meter of 3×10^5/cm^2 sec. This increase of about 10^7 times in neutrino flux does not by itself make the detection problem soluble, but since the cross sections for the reactions have an energy threshold and are energy dependent (increasing approximately as the square of the remaining neutrino energy above the threshold) the high energy of many neutrinos from fission fragment decay is also a significant factor. Despite these many favorable conditions, the absolute counting rate to be expected per gram of target material is so small that the target mass must be measured in hundreds of kilograms to obtain a signal of several events per hour.

Pontecorvo (1946) suggested studying the inverse *K* capture,

$\nu_+ + Cl^{37} \rightarrow A^{37} + \beta^-$ (cross section about 10^{-45} cm^2),

View of a tube bank of 55 photomultipliers on one end of a large detector. Tubes were staggered in order to obtain tighter packing.

The assembled neutrino detector in its lead shield. The detector tanks marked 1, 2, and 3 contained liquid scintillator solution which was viewed in each tank by 110 five-inch photomultiplier tubes. The white tanks contained the water-cadmium target, and in this picture are some eleven inches deep, though these were later replaced by three-inch thick polystyrene tanks, and the detectors 1 and 2 lowered correspondingly. The movable doors visible were also constructed of lead.



by irradiating a large tank of carbon tetrachloride with neutrinos from a fission reactor and then removing and counting the tiny amounts of radioactive A^{37} that would be formed. Alvarez (1949) considered this proposal in some detail, and the experiment using a thousand gallons of CCl_4 was performed by R. Davis, Jr. (1956) at the Savannah River Plant of the Atomic Energy Commission with the result that he has been able to place an upper limit on the cross section of one-third the predicted value. The reason for Davis' negative result can be explained either by the assumption that there are two "kinds" of neutrino, i.e., neutrino and antineutrino, and that the fission process gives rise to the wrong "kind" for the Cl^{37} reaction, or by the nonexistence of the free neutrino.

The point is that if there are two sorts of neutrino, under the above assumption a given reaction can be reversed only by the kind of neutrino emitted in the forward reaction itself; a ν_+ is emitted in A^{37} decay, whereas fission fragments are neutron-rich and should emit ν_- (or antineutrinos) only.

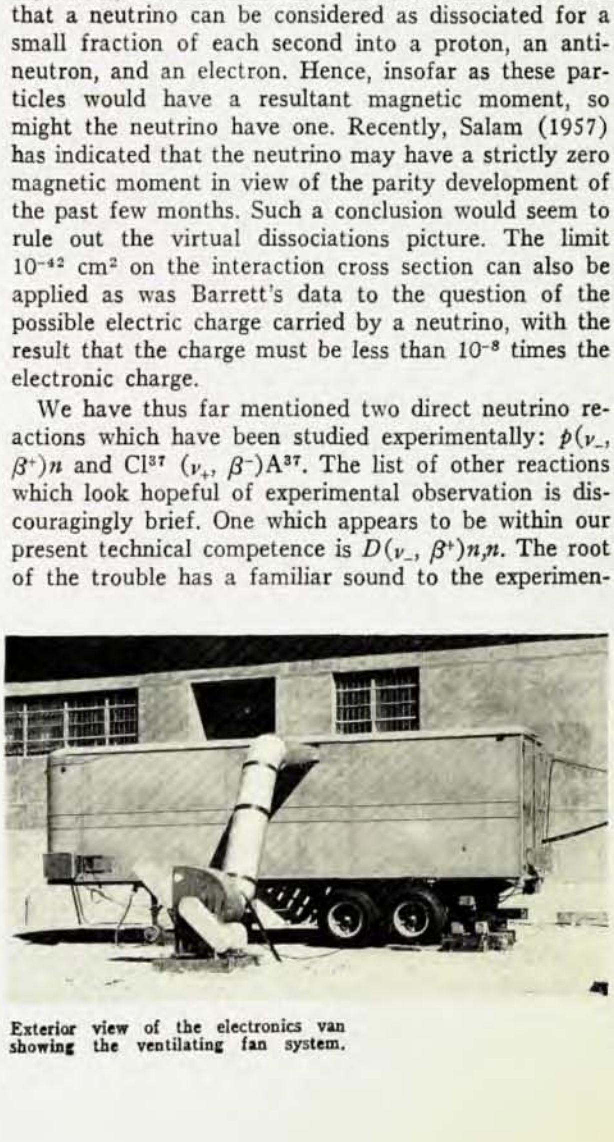
Returning to the proton-antineutrino reaction, on the other hand, we recognize many attractive features, foremost among which is the fact that this reaction gives rise to two of the most easily recognized particles in nuclear physics, the neutron and the positron. Furthermore, it involves the kind of neutrino (ν_-) most reasonably assumed to be emitted by the neutron-rich fission fragments. In addition one can incorporate protons directly into a large detector by the use of hydrogenous liquid scintillators. The smallness of the cross section (about 10^{-43} cm^2) together with a geometry providing efficient neutron and positron detection results, however, in the requirement for design of a rather massive detector weighing several tons. In 1953 a liquid scintillation detector of some 300 liters volume and containing dissolved cadmium was placed by our Los Alamos group near a Hanford reactor, and a power-associated delayed coincidence counting rate was observed which was consistent with that expected from the detection of positrons and neutrons due to the neutrino, proton reaction. Large statistical uncertainties associated with the Hanford measurement made further work desirable, and so a more elaborate system was constructed and taken to the Savannah River Plant (1956). In the Savannah River experiment a water target provided the protons and contained Cd to capture the neutrons produced. This was viewed by two large liquid scintillation detectors which were set above and below the water target in a sandwich arrangement.

The sequence of observed events following a neutrino capture in the target was as follows: (1) the emitted positron slowed down in the water target and annihilated with an atomic electron, producing two 0.5-Mev gamma rays which were promptly detected in coincidence by the scintillation counters; (2) the neutron produced in the neutrino reaction was moderated by the target water and was captured in a few microseconds by the dissolved cadmium, giving rise to a few capture gamma rays which were detected in coincidence by the scintillation counters. This sequence of events was displayed on oscilloscopes and photographed. In this arrangement it was possible to obtain a signal to background ratio of three to one and to apply various detailed checks to make certain that the signal, about three counts per hour, was due to reactor neutrinos. It was demonstrated that the signal was reactor-power dependent, that the first pulse was due to a positron and the second due to a neutron. A bulk shielding experiment demonstrated that the signal was not due to gamma rays or neutrons from the reactor.

A second independent experiment, in principle like that performed at Hanford but with various technical improvements, was also carried out. Because of the reduction in requirements imposed on the signal in the second Savannah River experiment, the detection efficiency was much greater, and the signal rate correspondingly higher (44 counts/hr). The second experiment, designed with a view to a more accurate measurement of the cross section, has an added significance which will be discussed later. These direct experiments remove the logical objection to the neutrino's "reality" and may be considered as a verification of the neutrino hypothesis as it applies to nuclear beta decay.

In addition to the above measurements an experimental upper limit was placed on the possible magnitude of a neutrino interaction with electrons ($< 10^{-42}$ cm^2) and hence on its possible magnetic moment ($< 10^{-9}$ Bohr electron magnetons), so removing grounds for conjecture as to other larger interactions to which the neutrino might be subjected. A theoretical estimate of Houtermans and Thirring (1954) would ascribe a magnetic moment to the neutrino of some 10^{-10} Bohr magnetons, but present techniques are not capable of reaching this figure. The estimate is based on the observation that a neutrino can be considered as dissociated for a small fraction of each second into a proton, an antineutron, and an electron. Hence, insofar as these particles would have a resultant magnetic moment, so might the neutrino have one. Recently, Salam (1957) has indicated that the neutrino may have a strictly zero magnetic moment in view of the parity development of the past few months. Such a conclusion would seem to rule out the virtual dissociations picture. The limit 10^{-42} cm^2 on the interaction cross section can also be applied as was Barrett's data to the question of the possible electric charge carried by a neutrino, with the result that the charge must be less than 10^{-8} times the electronic charge.

We have thus far mentioned two direct neutrino reactions which have been studied experimentally: $p(\nu_-, \beta^+)n$ and Cl^{37} $(\nu_+, \beta^-)A^{37}$. The list of other reactions which look hopeful of experimental observation is discouragingly brief. One which appears to be within our present technical competence is $D(\nu_-, \beta^+)n,n$. The root of the trouble has a familiar sound to the experimentalist: it lies in the need for a distinctive event which can be sorted out of a welter of backgrounds. Again, the small cross section of 10^{-45} cm^2 for neutrinos on deuterium indicates the distinctive nature required of the reaction, happily provided in this case by the resultant positron and two neutrons.



Exterior view of the electronics van showing the ventilating fan system.

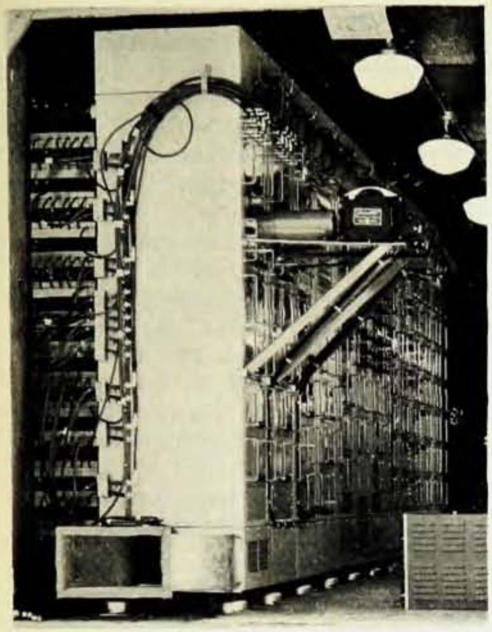
Copious production of neutrinos in the nuclear reactions presumed responsible for stellar energy generation and in the various theories of the evolution of the elements, coupled with the supra-astronomical absorption lengths for neutrinos, makes this particle an object of some importance in cosmological considerations. So, for example, our sun possibly puts forth a few percent of its energy in the form of neutrinos which arrive at earth at the rate of about 10^{11}/cm^2 sec, penetrate it with 99.999....% probability, and travel on through space with negligible probability of absorption in the next 10^{10} years!

Gamow and Schoenberg (1940) have made use of the extreme penetrability of matter by neutrinos in their theory of the mechanism of supernovae in which they describe the generation of energy as an "Urca" process. They liken the steady disappearance of energy from the star due to neutrino emission, which is responsible for the final stellar collapse and enormously enhanced energy generation, to the traceless loss of money by a gambler at the Casino da Urca.

This substantially irreversible and as yet directly unobservable energy sink is fascinating to contemplate since, uncoupled from the rest of the universe except through its interaction with the gravitational field, it carries with it the "story" of its origin. It is interesting that the calculated initial rate of expansion of the universe on an explosive model depends sensitively on the fact that there are two kinds of neutrinos (Alpher, Follin, and Herman (1953)). We note that a cosmic neutrino flux of, say, 10^{12}/cm^2 sec 3-Mev antineutrinos would be barely detectable with our equipment although such a flux would imply that the energy of the universe would then reside largely in neutrinos. If ever physics had an example of the disembodied spirit, it is the cosmic neutrino.

This, then in outline form, is the present status of the neutrino—except for the startling developments of the past few months.

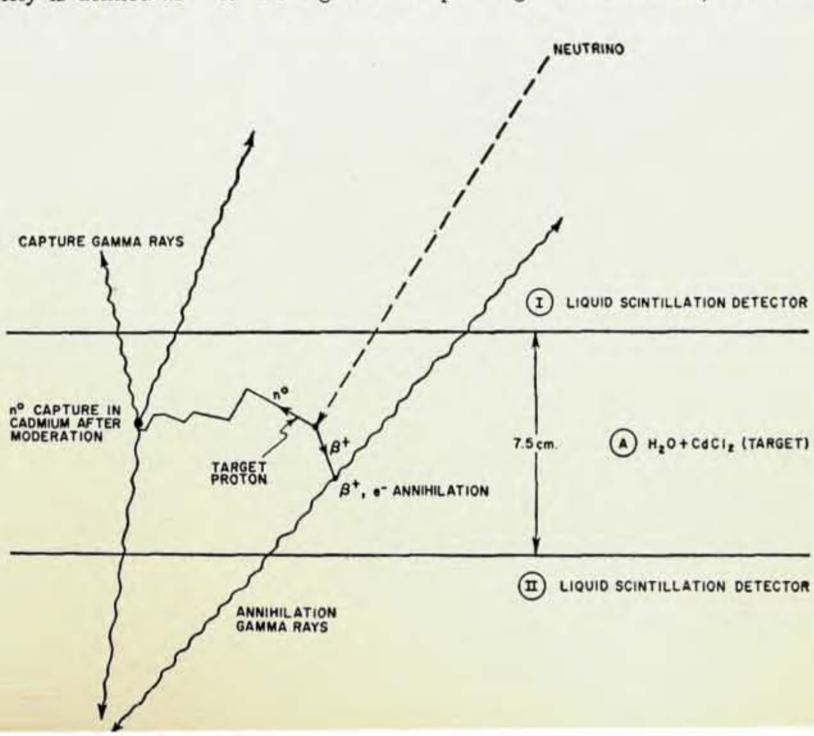
THE concept of the neutrino was born of a grave difficulty and *saved* the energy and momentum conservation laws in their application to nuclear phenomena. A few months ago Lee and Yang (1957) invoked the neutrino to explain another puzzle, this time the *failure* of a conservation law, that of parity conservation as it has been applied until now. This historic renunciation followed experiments suggested by Lee and Yang (1956) dealing with weak interactions, the class first introduced by Fermi to explain beta decay. The concept of parity, or the expected symmetry of phenomena with respect to reflection of coordinates through an origin, held until recently that *any* real phenomenon



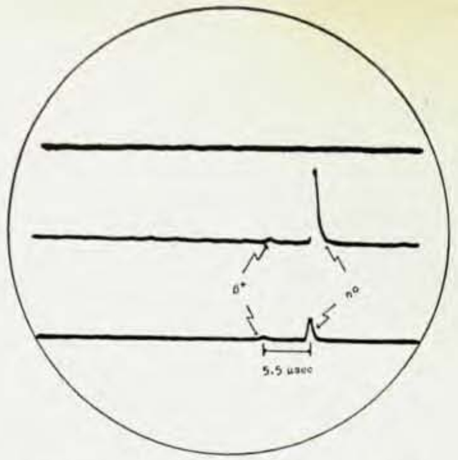
An interior view of the electronics van used to analyze and record the output of the detector. The two triple-beam oscilloscopes and their cameras are in the foreground, and delay lines may be seen behind the racks. Plenum chambers may be seen below and above the racks to provide forced air ventilation. Adequate shock mounting protected the equipment while traveling from all but negligible damage.

in nature has a *real physical counterpart* which could appear as the mirror reflection of that phenomenon, no matter where the mirror may be held, or how many mirrors may be used. In quantum mechanics such questions as the parity of the wave functions which describe angular distributions of particles emitted in decay processes, for example, arise constantly. Up to the present these questions were always considered answered by preserving the parity or symmetry property of the wave function under reflection in the same manner as for observable phenomena. Since it will be recalled that we observe not the wave function, ψ, but quantities given by functions of $\psi^*\psi$, a wave function can change sign under the parity operation without destroying the symmetry of the observable quantities. But the wave function must have an even or odd parity where if ψ does not change sign upon reflection, its parity is defined as even, whereas if it changed sign on reflection it is odd. It is this evenness or oddness which must be preserved if parity is to be conserved.

According to the parity conservation argument electrons emitted from a system of oriented nuclei should in all cases be emitted symmetrically in the solid angle about the nuclei. Wu, Ambler, Hayward, Hoppes, and Hudson (1957), who studied the angular distribution of decay electrons from Co^{60}, found that they were emitted instead in a preferred direction relative to the nuclear spin direction. In addition, a remarkable experiment was performed, using a cyclotron, by Garwin, Lederman, and Weinrich (1957) in which the decay sequence $\pi \rightarrow \mu + \nu$ followed by $\mu \rightarrow \beta + \nu + \nu$ was observed to produce an asymmetrical angular distribution of the electrons from the decay of the muons. To explain these cases of parity nonconservation Lee and Yang (1957) resurrected a suggestion by H. Weyl (1929), a suggestion duly noted and discarded as physically inadmissable by Pauli in an article in the *Handbuch der Physik* written some twenty-five years ago. This stated that if the neutrino has strictly zero mass then the Dirac equations, assumed to apply to the neutrino by Fermi, can be simplified with the remarkable result that the parity principle is not obeyed by the neutrino. Explicitly, the Weyl equation gives the neutrino (ν_+) a spin which is always parallel to its linear momentum vector and the antineutrino (ν_-) a spin which is always antiparallel to its linear momentum vector. That such a neutrino would not obey the parity principle may be seen by performing the reflection operation on a neutrino traveling, say to the right. The spin angular momentum, an axial



Schematic diagram of neutrino detector.



A characteristic record. Each of the three oscilloscope traces shown corresponds to a detector tank. The event recorded occurred in the bottom triad. First seen in coincidence are the "positron" annihilation gamma-ray pulses in each tank followed in 5.5 μsec by the larger "neutron" pulses. The amplification was chosen in this case to enable measurement of the neutron pulses. A second oscilloscope with higher amplification was operated in parallel to enable measurement of the positron pulses.

vector which can be represented by a cross product of two vectors perpendicular to the direction of motion, will not change sign on reflection through the origin, whereas the neutrino on reflection now travels to the left. The image neutrino now has its spin antiparallel to its direction of motion—a conclusion in contradiction with the two component simplification of Dirac's theory, unless reflection also changes the neutrino into an antineutrino. Since this new model for the neutrino does not obey the simple parity principle, no reaction involving such a neutrino can be expected to conserve parity in its restricted sense, i.e., that reflection of space coordinates alone always results in a physically admissable situation. These considerations were independently, and almost simultaneously, suggested by Landau (1957) and Salam (1957).

A subsequent experiment in which the angular correlation in the $\pi \rightarrow \mu \rightarrow \beta$ sequence was studied using cosmic-ray mesons was performed by Fowler, Freier, Lattes, Ney, and St. Lorant (1957) with the result that no angular correlation or asymmetries were observed. These investigators, noting the fact that their pions are produced in a much higher energy process than are the accelerator-produced pions, suggest the possibility that the pions themselves are different in the two cases.

One of the consequences of the postulated spin characteristics of the neutrino is that the cross section for the interaction of reactor-born neutrinos with free protons is expected to be twice as great as was believed to be the case with the "old" neutrino. For a given neutrino in the new theory only one spin state is possible instead of two, and hence the beta coupling constant which is obtained from experimental data on the decay of the free neutron must be twice as strong as before to compensate for the reduction in the number of possible final states in neutron decay. Thus, a cross section for this reaction obtained experimentally in a measurement at the Savannah River Plant can be used in a comparison with a predicted cross section from this calculated coupling constant to ask the parity question again, this time addressing it to the neutrino directly. An examination of the data obtained at the Savannah River Plant and of the experimental parameters involved is now being undertaken to improve the value obtained there in the hope that a predicted cross section will soon be available with which to make the comparison. A prime source of uncertainty in the predicted figure to date is the uncertainty in the energy spectrum of beta particles (and hence, of neutrinos) from an equilibrium mixture of fission fragments.

A problem basic to neutrino physics is the question of the identity of the neutrino from nuclear beta decay with those produced in the decay of various mesons. To date we have only indirect arguments on this point, but in the experimental results of Garwin, Lederman, and Weinrich which demonstrate that meson decay neutrinos also probably fail the parity test we may have an additional reason for assuming this identity. Until now, the main argument has stemmed from the apparent equality of the coupling constant in the beta decay of the mu meson with that of nuclear beta decay and from the rule of parsimony as applied to the invention of new particles.

In closing this brief summary of the field of neutrino physics it is interesting to contemplate the history of the neutrino concept which began as an apology for an apparent discrepancy and has come to occupy such a central role in modern physics.

REFERENCES

J. Allen, Phys. Rev. **61**, 692 (1942).
R. A. Alpher, J. W. Follin, Jr., and R. C. Herman, Phys. Rev. **92**, 1347 (1953).
L. W. Alvarez, UCRL-328 (1949) (Unpublished).
J. H. Barrett, Phys. Rev. **79**, 907 (1950).
H. A. Bethe and R. Peierls, Nature **133**, 532 (1934).
H. A. Bethe, Proc. Cambridge Phil. Soc. **31**, 108 (1935).
J. Chadwick, Verhandl. deut. physik. Ges. **16**, 383 (1914).
J. Chadwick, Proc. Roy. Soc. (London) **136**, 692 (1932).
C. L. Cowan, F. Reines, F. B. Harrison, H. Kruse, and A. D. McGuire, Science **124**, 103 (1956).
C. L. Cowan and F. Reines, Phys. Rev., describing the second Savannah River Experiment (to be published).
R. Davis, Jr., Contributed paper, Am. Phys. Soc. meeting, Washington, D. C. (1956).
C. D. Ellis and W. A. Wooster, Proc. Roy. Soc. (London) **A117**, 109 (1927).
E. Fermi, Z. Physik **88**, 161 (1934).
E. L. Fireman, Phys. Rev. **74**, 1238 (1948).
P. H. Fowler, P. S. Freier, C. M. G. Lattes, E. P. Ney, S. J. St. Lorant, Amer. Phys. Soc. meeting, paper M-10, Washington, D. C. (1957).
G. Gamow and M. Schoenberg, Phys. Rev. **58**, 1117 (1940).
G. Gamow, Phys. Today **1**, No. 3, 4 (July 1948).
R. L. Garwin, L. M. Lederman, and M. Weinrich, Phys. Rev. **105**, 1415 (1957).
L. Landau, Nuclear Phys. **3**, 127 (1957).
L. M. Langer and R. J. D. Moffat, Phys. Rev. **88**, 689 (1952).
T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).
T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).
M. E. Nahmias, Proc. Cambridge Phil. Soc. **31**, 99 (1935).
W. Pauli, Jr., Address to Group on Radioactivity of Tübingen, December 4, 1930; *Rapports du Septiems Conseil de Physique Solvay, Brussels, 1933;* (Gautier-Villars, Paris, 1934).
W. Pauli, *Handbuch der Physik* (Published by Julius Springer, Berlin, 1933), Vol. **24**, p. **83**.
B. Pontecorvo, National Research Council of Canada, P. D.-205 (November 20, 1946) (Unpublished).
M. H. L. Pryce, Proc. Roy. Soc. (London) **A165**, 247 (1938).
F. Reines and C. L. Cowan, Phys. Rev. **92**, 830 (1953).
J. M. Robson, Phys. Rev. **78**, 311 (1950); Phys. Rev. **83**, 349 (1951).
A. Salam, Nuovo cimento **5**, 299 (1957).
A. H. Snell and L. C. Miller, Phys. Rev. **74**, 1714A (1948).
K. C. Wang, Phys. Rev. **61**, 97 (1942).
H. Weyl, Z. Physik **56**, 330 (1929).
J. A. Wheeler, Phys. Rev. **97**, 511 (1955).
A. Wightman, Princeton University Notes (1951) (Unpublished).
E. Wigner. Metallurgical Project Report CP-720, June 2, 1943 (Unpublished).
C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. **105**, 1413 (1957).