

## The Early Days of Experimental Neutrino Physics

Frederick Reines

It is now more than 45 years since Pauli in 1930 (1) and Fermi in 1933 (2) formulated the neutrino hypothesis. In 1953, Clyde Cowan and I and our colleagues at Los Alamos made the first, tentative observation of the free neutrino at the fission reactor at Hanford, Washington, through the inverse beta process

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad (1)$$

where  $\bar{\nu}_e$ ,  $p$ ,  $n$ , and  $e^+$  are an electron antineutrino, proton, neutron, and positron, respectively. Our choice of this reaction was felicitous because of its sim-

spectra and nuclear recoil in K-electron capture) and hence that the neutrino existed. In fact, had any measurements made on the beta decay process been found to be inconsistent with the neutrino hypothesis, then it could have been argued that the neutrino did not exist; the converse is untrue. However attractive the neutrino was as an explanation for beta decay, the proof of its existence had to be derived from an observation at a location other than that at which the decay process occurred—the neutrino had to be observed in its free state to in-

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**Summary.** The neutrino hypothesis, put forward by Pauli to account for the apparent loss of energy and momentum in beta decay, was verified by a series of measurements at a nuclear reactor nearly 25 years ago. An account is given of the first observations of the interaction of neutrinos in a target remote from the fission process that produced them. These experiments completed the observations of the particles involved in beta decay and paved the way for use of the free neutrino to probe the nature of the weak interaction.

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plicity, distinctive products, and the scintillation properties of some liquid hydrocarbons (3). Three years later, in 1956, we completed the job in a definitive way at the Savannah River Plant and experimental neutrino physics was launched (4).

In the summer of 1951 I decided that the detection of the elusive neutrino was a goal worth striving for. At the time, the neutrino hypothesis was already firmly fixed in the lexicon of physics. Physicists generally believed that the neutrino had been demonstrated indirectly and that, in fact, it was not directly observable. It was argued that the neutrino hypothesis explained the apparent lack of energy and momentum conservation in beta decay (for instance, the shapes of decay

vert beta decay or otherwise interact with matter at a remote point.

In effect, observation of a free neutrino would provide incontrovertible proof of the validity of the energy and momentum conservation laws in nuclear beta decay. We tend to regard these principles as universally applicable, yet in the days when the neutrino hypothesis was put forward, agreement on this point was hardly universal. No less an authority than Niels Bohr (5) pointed out in 1930 that no evidence "either empirical or theoretical" existed that supported the conservation of energy in this case. He was, in fact, willing to entertain the possibility that energy conservation must be abandoned in the nuclear realm (6).

### Source of Neutrinos

A few rough estimates indicated to me that a nuclear explosion, which might yield a pulse of particles intense enough to override the background, was the most promising source of neutrinos and that a suitably shielded detector with a mass of about 1 ton might do the job. In any event, the experiment would be vastly more sensitive than any previously imagined. However, I had no idea how such an incredibly large detector could be made and thought it might be helpful to talk with Fermi, who was spending the summer at Los Alamos. As it turned out, although he agreed with the suggestion of an explosion, he also had no idea how to build the detector, and that almost ended the matter.

Some months later, while discussing with Cowan various problems on which it would be interesting to work, I mentioned my thoughts on the neutrino. He immediately felt that there must be a way to make such a detector. Our partnership began at that point, and our ideas flowed together in a mutually reinforcing manner that often made it difficult to decide who thought of what (7). I recall one instance that illustrates the depth of our collaboration. We gave a talk to the Physics Division at Los Alamos in which we described our ideas for a large liquid scintillator that we had constructed (8) for use in the vicinity of a nuclear explosion. We mentioned the delayed coincidence between the positron and neutron pulses as a label for the reaction; it had not yet occurred to us that the label could be used to reduce the background. J. M. B. Kellogg asked whether it might not be possible to use a fission reactor instead of a bomb. We argued that it would not be—and besides, Fermi and Bethe had agreed with us that a bomb was the most promising source. That night I telephoned Cowan and we told each other how the delayed coincidence could be used to reduce the background, which would make the reactor an attractive source. We immediately altered our plans and the next morning met

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The author is a professor in the Department of Physics, University of California, Irvine 92717. This article is an expanded version of a talk given in April 1978 at the Clyde L. Cowan Memorial Symposium, Catholic University, Washington, D.C.

with Kellogg to cancel our bomb preparations and arrange to develop and build a detector suitable for the Hanford reactor. We learned later that others attending the talk had considered Kellogg's question and concluded that the bomb was better suited than the reactor. You can well imagine how embarrassing it would have been had the roles been reversed. A letter to Fermi telling him of our reactor proposal (9) elicited the response shown in Fig. 1.

### The Hanford Experiment

Viewed from the perspective of today's computer-controlled kiloton detectors, sodium iodide crystal palaces, giant accelerators, and 50-man groups, our efforts to detect the neutrino appear quite modest. In the early 1950's, however, our work was thought to be large-scale. The idea of using 90 photomultiplier tubes and detectors large enough to enclose a human was considered to be most unusual. We faced a host of unanswered questions. Was the scintillator sufficiently transparent to transmit its light for the necessary few meters? How

Table 1. Listing of data from the Hanford experiment.

Run	Pile status	Length of run (sec)	Counts per minute*	
			Net delayed pair rate	Accidental background rate
1	On	4000	2.56	0.84
2	On	2000	2.46	3.54
3	On	4000	2.58	3.11
4	Off	3000	2.20	0.45
5	Off	2000	2.02	0.15
6	Off	1000	2.19	0.13

\*Delayed coincidence rates: reactor on (10,000 seconds),  $2.55 \pm 0.15$  count/min; reactor off (6000 seconds),  $2.14 \pm 0.13$  count/min. Reactor-associated delayed coincidence rates,  $0.41 \pm 0.20$  count/min.

reflective was the paint? How could one add a neutron capturer without poisoning the scintillator? Would the tube noise and afterpulses from such a vast number of photomultiplier tubes mask the signal? And besides, were we not monopolizing the market on photomultiplier tubes? (As it turned out we were not; headlight dimmers on Cadillacs consumed far more of them than we did.) In the search for answers to these questions we received

strong support from various scientists at Los Alamos, and Cowan made good use of his undergraduate training as a chemist and his considerable abilities with electronics.

It soon became clear that this new detector designed solely for neutrinos had unusual properties with regard to other particles as well—for instance, neutron and gamma-ray detection efficiencies near 100 percent. We recognized that detectors of this type could be used to study such diverse quantities as neutron multiplicities in fission, muon capture, muon decay lifetimes, and the natural radioactivity of humans. We measured radioactivities of some humans, pointed out other uses, and continued with our neutrino search. (These applications have since been made by other workers.)

Our entourage arrived at Hanford in the spring of 1953 (Figs. 2 and 3). After a few months of operation, during which we made several restackings of hundreds of tons of specially fabricated boron-paraffin boxes and lead bricks, we concluded that we had done all we could in the face of an enormous reactor-independent background. We turned off the equipment and took the train back to Los Alamos, knowing that we had done our best but not knowing that we had actually measured a hint of a signal (Table 1).

Back home we puzzled over the origin of the reactor-independent signal. Was it due to natural neutrinos? Could it be due to fast neutrons from the nuclear capture of cosmic-ray muons? The easiest way to find out was to put the detector underground. We did so and showed that the background was from cosmic rays. While we were engaged in this background test, some theorists were rumored to be constructing a world made predominantly of neutrinos.

### The Savannah River Experiment

Encouraged by the tentative result at Hanford (10), we designed and constructed a detector that would employ the detailed characteristics of the anti-neutrino-proton ( $\bar{\nu}_e + p$ ) reaction and so discriminate more selectively against reactor-independent and reactor-associated backgrounds. The detector was completed in 1955 and, at the suggestion of J. A. Wheeler, was taken to a newly completed reactor at the Savannah River Plant in South Carolina. There a definitive observation of  $\bar{\nu}_e + p$  was made in 1956 (11).

The Savannah River reactor was admirably suited (12) for neutrino studies by

THE UNIVERSITY OF CHICAGO  
CHICAGO 37 · ILLINOIS  
INSTITUTE FOR NUCLEAR STUDIES  
October 8, 1952


Fig. 1. Letter from Fermi on hearing about our plan to use the Hanford reactor to attempt to observe the neutrino.

Dr. Fred Reines  
Los Alamos Scientific Laboratory  
P.O. Box 1663  
Los Alamos, New Mexico

Dear Fred:

Thank you for your letter of October 4th by Clyde Cowan and yourself. I was very much interested in your new plan for the detection of the neutrino. Certainly your new method should be much simpler to carry out and have the great advantage that the measurement can be repeated any number of times. I shall be very interested in seeing how your 10 cubic foot scintillation counter is going to work, but I do not know of any reason why it should not.

Good luck.

Sincerely yours,  
  
Enrico Fermi

EF:vr

virtue of its great power ( $\sim 700$  megawatts at that time) and relatively small physical size, and the availability of a well-shielded location 11 meters from the reactor center and some 12 meters belowground in a massive building. The high  $\bar{\nu}_e$  flux,  $1.2 \times 10^{13}$  per square centimeter per second, and the reduced cosmic-ray background were essential to the success of the experiment, which even under those favorable conditions in-

involved a running time of 100 days over a period of approximately 1 year.

Figure 4 is a schematic of the detection experiment. An antineutrino from fission products in the reactor is incident on a water target containing cadmium chloride. According to the  $\bar{\nu}_e + p$  reaction, a positron and a neutron are produced. The positron slows down and is annihilated with an electron, producing two 0.5-MeV gamma rays, which penetrate

the water target and are detected in coincidence by two large scintillation detectors on opposite sides of the target. The neutron is slowed down by the water and captured by the cadmium, producing multiple gamma rays, which are also observed in coincidence by the two scintillation detectors. The antineutrino signature is therefore a delayed coincidence between the prompt pulses produced by  $e^+$  annihilation and those produced mi-



Fig. 2 (left). First large ( $0.3 \text{ m}^3$ ) liquid scintillation detector in shield. The liquid was viewed by 90 2-inch photomultiplier tubes. Before the development of this detector a  $0.02\text{-m}^3$  volume was considered large. Fig. 3 (right). Shield configuration. The note on the blackboard indicates that we were within a factor of 75 of the required sensitivity. The members of the group for the Hanford phase of the search are listed on the "Project Poltergeist" sign.

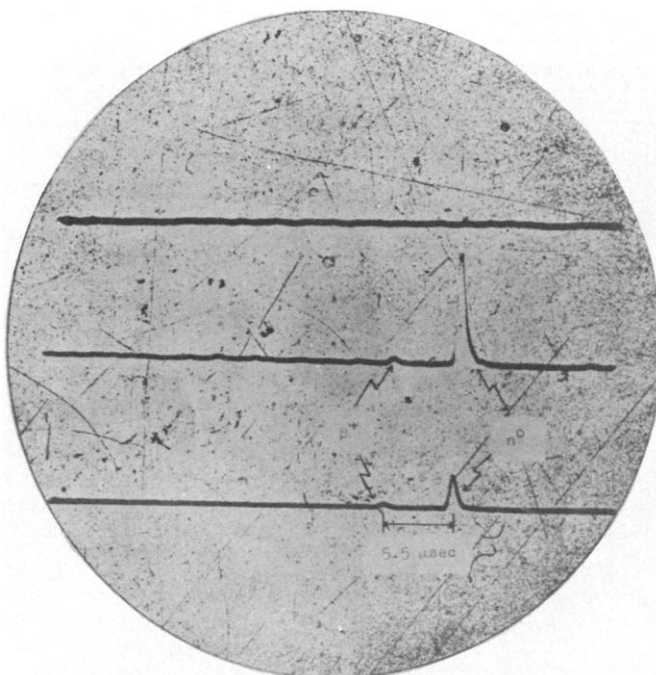
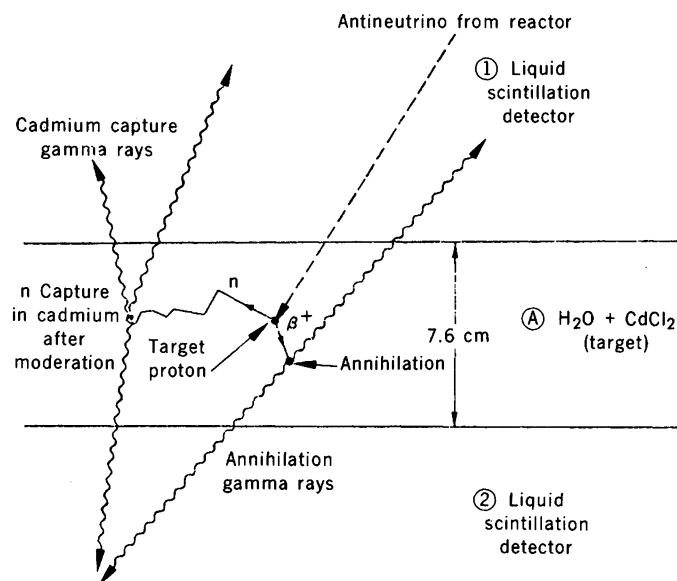


Fig. 4 (left). Schematic of neutrino experiment. Fig. 5 (right). A characteristic record. Each of the three oscilloscope traces corresponds to a detector tank. The event recorded occurred in the bottom triad. First seen in coincidence are the positron annihilation gamma-ray pulses in each tank followed in  $5.5 \mu\text{sec}$  by the larger "neutron" pulses. A second oscilloscope with higher amplification was operated in parallel to enable measurement of the positron pulses. In Figs. 5 and 6 the positron is denoted by  $\beta^+$  and the neutron by  $n^0$ .

croseconds later by the neutron capture in cadmium. A characteristic oscilloscope record is shown in Fig. 5. The experiment was composed of a series of measurements in which the delayed coincidences were studied in detail to show that (i) the reactor-associated signal rate was consistent with theoretical expectations, (ii) the first pulse of the delayed coincidence signal was due to posi-

tron annihilation, (iii) the second pulse of the delayed coincidence signal was due to neutron capture, (iv) the signal was a function of the number of target protons, and (v) radiation from the reactor other than antineutrinos could not be the cause of the signal.

The detection system required for these measurements is shown by the cut-away drawing of the detector assemblage

(Fig. 6). The small interaction cross section ( $\sim 10^{43}$  cm<sup>2</sup> per proton) and the tailed nature of the questions posed were primarily responsible for the size of the detector, which exclusive of the lead shielding weighed about 10 tons.

Translating our ideas into hardware was a formidable task. We calculated that we would need some 8000 liters of scintillator and realized that we would have to find a solvent less dangerous than toluene, which we had used in the smaller detectors at Hanford. A triethylbenzene-based scintillator proved to be suitable, and we set up a small pilot plant to prepare it. Construction of the detectors was complicated by the requirement that they support a 58-cm depth of scintillator over an area of a few square meters and yet be thin enough to transit the positron annihilation radiation. We solved this problem by using a slab that consisted of two thin metal sheets mounted on opposite sides of corrugated cardboard.

It is difficult in these days of sophisticated commercially available solid-state electronics to appreciate the magnitude of the effort required to build the electronics involved in our experiment. Pulse height and time delay analyzers, linear amplifiers, coincidence circuits, gates, and so on were designed and built at Los Alamos. Indeed, the resources of a large laboratory were essential for the task. Figure 7 shows the electronics, which, along with the remainder of the detector and special handling equipment, was built or modified, assembled, and tested at Los Alamos before shipment to Savannah River. Today's electronics would accomplish the same task more expeditiously with less than one-tenth of the space and of the cost.

On the 1500-mile trip to the Savannah River Plant the equipment was transported in three large trucks—one of them, the electronics van, oversized. We were so concerned that the cold weather would cause precipitation of the scintillator solute that we wrapped electrical heaters around our specially constructed insulated storage tanks. Then, to ensure safe passage, we drove at low speed in a convoy preceded by one of us, who stopped and checked each bridge and tunnel. I remember the first turn-on of the detector at Savannah River—no signals were seen. It was a most peculiar feeling: maybe there were no neutrinos, or maybe they existed but were unstable and did not reach our detector. We continued tuning the detector and the signal appeared—but what a heady, if unwarranted, flight of fancy.

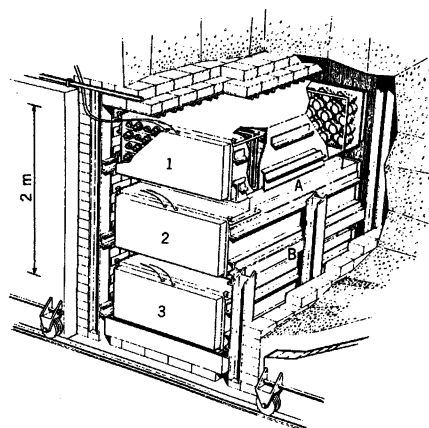


Fig. 6 (left). Sketch of detectors inside their lead shield. The tanks marked 1, 2, and 3 contained 1400 liters of triethylbenzene (TEB) liquid scintillator solution, which was viewed in each tank by 110 5-inch photomultiplier tubes. The TEB was made to scintillate by the addition of *p*-terphenyl (3 grams per liter) and POPOP [1,4-bis-2-(5-phenyloxazoly)benzene] wavelength shifter (0.2 g per liter). The tubes were immersed in pure nonscintillating TEB to make light collection more uniform. Tanks A and B were polystyrene and contained 200 liters of water, which provided the target protons and contained as much as 40 kilograms of dissolved CdCl<sub>2</sub> to capture the product neutrons. Fig. 7 (right). Inside view of electronics van showing equipment required to select and record neutrino signals.

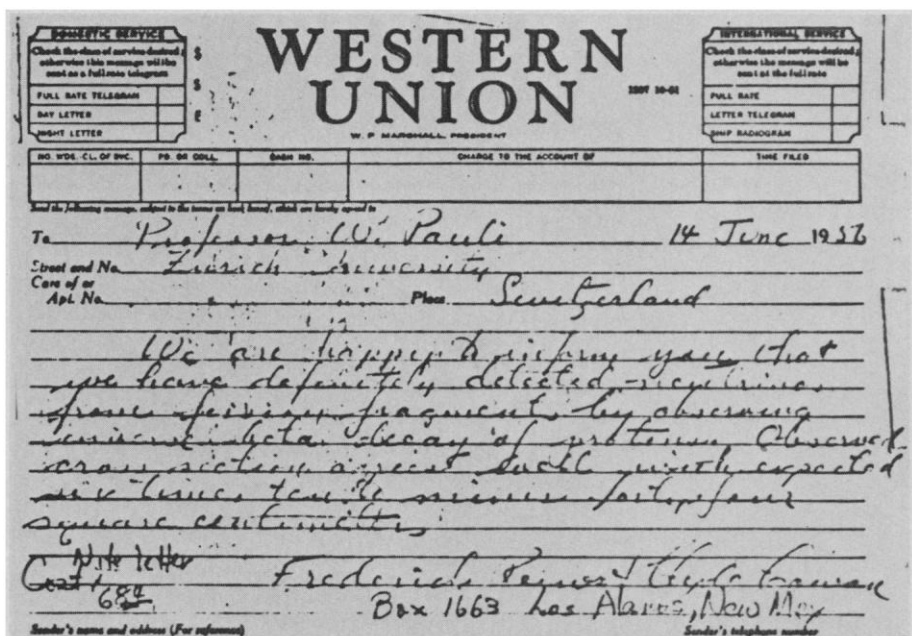
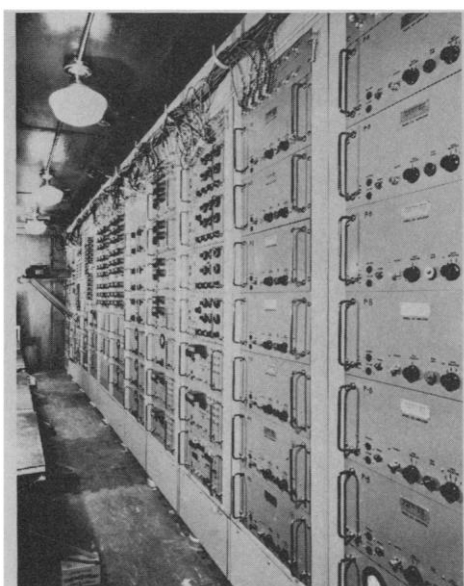


Fig. 8. Telegram to Pauli informing him of our results. The text read: "We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters."

## Observation of the Neutrino

**Signal rate.** A reactor-associated correlated signal rate of  $3.0 \pm 0.2$  events per hour was observed. This represented a ratio of signal to total accidental background of 4:1, a ratio of signal to correlated (as in neutron capture) reactor-independent background of 5:1, and a ratio of signal to reactor-associated accidental background greater than 25:1. Using positron and neutron sources and knowing the reactor flux, we determined that this signal was within a factor of about 2 of the expected value. The measured cross section for fission antineutrinos on protons was

$$\bar{\sigma}_{\text{exp}} = (12^{+7}_{-4}) \times 10^{-44} \text{ cm}^2$$

compared to the theoretically expected value (13)

$$\bar{\sigma}_{\text{th}} = (5 \pm 1) \times 10^{-44} \text{ cm}^2$$

**First and second pulses.** We determined that the first pulse of the delayed coincidence pair was due to a positron by varying the thickness of a lead sheet interposed between the water target and one liquid scintillation detector, so reducing the positron detection efficiency. After we corrected for the small associated drop in the neutron detection efficiency, we observed that the signal diminished as it should if the first pulse were due to positron annihilation radiation. Table 2 shows the expected and observed signal rates as a function of lead thickness. A further check was provided by the spectrum of first pulses, which showed better agreement with that from a positron test source than with the spectrum of the background.

That the second pulse was due to a neutron was clearly demonstrated by a series of experiments in which the cadmium concentration was varied. The most striking measurements were those made with and without cadmium in the water target. As expected for neutrons, removal of the cadmium totally removed the correlated count rate, giving a rate above accidental counts of  $0.2 \pm 0.07$  hour<sup>-1</sup>. In addition, the distribution of time intervals between the first and second pulses was found to be that for neutron capture, and the spectrum of the second pulses was consistent with that expected for neutron-capture gamma rays. Having proved that the second pulse was due to a neutron, we considered it necessary to show that the first pulse was not also caused by a neutron. We showed that such a false pulse sequence was unlikely by experiments

Table 2. Lead absorption test of signal.

Lead thickness (cm)	Signal	
	Predicted	Observed
0	1.00	1.00
0.16	0.40	$0.50 \pm 0.13$
0.48	0.12	$0.32 \pm 0.14$
0.95	0.02	$0.03 \pm 0.06$

with fast neutrons, which caused primarily an increase in the accidental rather than the correlated rate. As pointed out above, the reactor-associated rise in the accidental signal was less than 1/25 of the correlated signal, ruling out neutrons from the reactor as the cause of the delayed coincidence pair.

**Signal as a function of target protons.** In this experiment, the number of target protons was reduced without drastically changing the detection efficiency of the system for events produced by antineutrinos. This was accomplished by mixing light and heavy water and so replacing about half of the protons by deuterons. The ratio of the measured rate for the diluted target to that for 100 percent H<sub>2</sub>O was  $0.4 \pm 0.1$ , compared to an expected ratio of 0.5. This comparison with expectation showed the dependence of the signal on the presence of protons in the target. It was further noted that although the antineutrino signal changed significantly with dilution of the target by deuterons, the detection efficiency for background events was only slightly altered by this dilution, supporting the conclusion that the signal was, in fact, due to antineutrinos.

**Absorption test.** The only known particles, other than antineutrinos, that are produced by the fission process can be heavily discriminated against by means of a gamma-ray and neutron shield. Accordingly, it was possible to test the signal for neutron and gamma-ray contamination by the addition of bulk shielding between the reactor and the detector assembly. It was shown by calculations and separate measurements with neutron and gamma-ray sources that the shield reduced gamma rays and neutrons by at least an order of magnitude. The signal, on the other hand, remained constant; that is, it was  $1.74 \pm 0.12$  hour<sup>-1</sup> with and  $1.69 \pm 0.17$  hour<sup>-1</sup> without the shield.

### Telegram to Pauli,

### Parity, and Accelerators

After convincing ourselves by this redundant series of tests that we were ob-

serving the neutrino, we decided to let Pauli know how correct he was and sent him the telegram shown in Fig. 8. Pauli was at the Eidgenössische Technische Hochschule (not Zurich University, to which the telegram was addressed), but the message was forwarded to him at CERN, where he interrupted the meeting he was attending to read the telegram to the conferees and then made some impromptu remarks regarding the discovery. We learned later that Pauli and some friends consumed a case of champagne in celebration.

Soon after detection of the antineutrino, evidence was found by Wu *et al.*, Garwin *et al.*, and Friedmann and Telegdi (14) for parity nonconservation in beta decay. This was explained by Lee and Yang (15), Landau (16), and Salam (17) as being associated with the two-component character of the neutrino, which, incidentally, predicts the factor of 2 increase in the  $\bar{\nu}_e + p$  cross section over that of the parity-conserving, four-component neutrino (13). It is interesting to speculate on the credibility of this explanation for the violation of parity had it been put forward before proof of the neutrino's existence. It is also interesting to reflect on the fact that evidence for the parity factor would have been obtained in due course (18) independently of the  $\theta$ - $\tau$  puzzle that led Lee and Yang (19) to question the conservation of parity in the weak interaction.

It occurred to us that the free neutrino could be used to probe the weak interaction in energy ranges outside those of ordinary beta decay if sufficiently potent accelerators could be constructed. Also, we puzzled, why should the neutral particle (or "neutretto" as it was first called) produced in the decay of a pion to a muon ( $\pi \rightarrow \mu$ ) be the same as the neutrino of nuclear beta decay—Ockham's razor notwithstanding? We suggested investigating this at the Brookhaven accelerator with a suitable detector, but were unsuccessful in persuading the authorities at Los Alamos to let us continue our search.

The idea of using an accelerator was later conceived independently by Pontecorvo (20) and Schwartz (21). It was demonstrated at Brookhaven by Schwartz and his co-workers (22) that  $\nu_\mu \neq \nu_e$ . Groups at CERN (23), using a meson-focusing magnet, had a neutrino beam of 100 times higher intensity. They detected not only the muonic neutrino, but also electron production by the small admixture in the neutrino beam stemming from beta decays of K mesons, thus verifying the existence of  $\nu_e$ .



## References and Notes

1. W. Pauli, Jr., address to the Group on Radioactivity, Tübingen, Germany, 4 December 1930 (unpublished); *Rapports du Septième conseil physique Solvay, Bruxelles, 1933* (Gautier-Villars, Paris, 1934), chap. 1, p. 324.
2. E. Fermi, *Z. Phys.* **88**, 161 (1934).
3. B. Pontecorvo [*Inverse Beta Decay* (Division of Atomic Energy, National Research Council of Canada, Chalk River; declassified and issued by the Atomic Energy Commission in 1949)] and L. W. Alvarez [*Univ. Calif. Radiat. Lab. Rep. UCRL-328* (1949)] suggested a radiochemical method using a fission reactor based on the reaction  $\nu + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$ . They did not pursue the method. Alvarez was dissuaded by his estimates of the background to be anticipated from cosmic rays; these estimates later proved to be correct for the reactors then available. As we know now, the neutrino produced in fission is  $\bar{\nu}_e$  and the neutrino required for the  ${}^{37}\text{Cl}$  reaction is  $\nu_e$ , so the reactor result would have been negative even though the neutrino exists.
4. It is, of course, not possible to know how the field would have developed if Cowan and I had not met and decided to work together on this "manifestly impossible" search, but in view of the general absence of activity in this direction at the time, I suspect that the observation would have been somewhat delayed. A popular account of these early days was written by Cowan in 1964 ["Anatomy of an experiment: An account of the discovery of the neutrino," *Smithsonian Inst. Annu. Rep.* 4626 (1964), p. 409]. The status of the neutrino in 1936 was reviewed by H. A. Bethe and R. F. Bacher [*Rev. Mod. Phys.* **8**, 82 (1936)]. Attempts to detect the neutrino up to 1948 were summarized by H. R. Crane [*ibid.* **20**, 278 (1948)].
5. N. Bohr, *J. Chem. Soc.* (1932), p. 349.
6. S. Drell [*Am. J. Phys.* **46**, 597 (1978)] suggested that in view of the fact that an isolated quark has not yet been detected, experimental criteria for the existence of elementary particles may require revision. However, he recalled that the neutrino was suggested to preserve conservation of energy, momentum, and spin, whereas no conservation laws require quarks.
7. However, I do remember one conversation regarding detection techniques. "Why not," suggested Cowan, "make a device analogous to a cloud chamber but of liquid to obtain the necessary target mass, and use it in our search." We discussed it at some length but discarded it because it could not be triggered by the event, and random triggers would give a small duty cycle. It was a good idea, as subsequent events have demonstrated, but it did not suit our purpose (to detect the neutrino) and we did not pursue it. (As we now know, the bubble chamber was invented around that time by D. Glaser, and in the hands of L. W. Alvarez and others turned out to be extremely useful for particle physics, eventually including neutrinos at accelerators.)
8. The technique of scintillation counting followed the discovery by W. Crookes and by J. Elster and H. Geitel [*Phys. Z.* **4**, 439 (1903)] of the scintillation properties of zinc sulfide exposed to alpha particles [described by E. Rutherford, J. Chadwick, and C. D. Ellis, *Radiations from Radioactive Substances* (Cambridge Univ. Press, Cambridge, England, 1930)]. It received great impetus from the development of the photomultiplier tube and the crucial observation [H. Kallmann, *Phys. Rev.* **78**, 62 (1950); M. Agena, M. Chiozotto, R. Querzoli, *Atti Acad. Naz. Lincei Cl. Sci. Fis. Mat. Nat. Rend.* **6**, 626 (1949); *Phys. Rev.* **79**, 720 (1950); G. T. Reynolds, F. B. Harrison, G. Salvini, *ibid.* **78**, 488 (1950)] that liquids could be made to scintillate with high efficiency when the scintillating compound was at low concentration. Our contribution was to recognize that with a sufficiently transparent scintillator and enough photocathode area, one should, in principle, be able to make a detector of almost arbitrarily great size—just what was needed for neutrino detection. Our first large detector, nicknamed El Monstro, was a 1-m<sup>3</sup> bipyramidal brass tank containing toluene and viewed on the top and bottom by four 2-inch photomultiplier tubes. Our subsequent detectors employed many more photomultipliers to increase light collection and so obtain the desired energy resolution.
9. F. Reines and C. L. Cowan, Jr., *Phys. Rev.* **90**, 492 (1953); C. L. Cowan, Jr., F. Reines, F. B. Harrison, E. C. Anderson, F. N. Hayes, *ibid.*, p. 493.
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12. At that time R. Davis, Jr., reassessed the  ${}^{37}\text{Cl}$  approach and decided to make an effort to observe the reactor neutrino by using that reaction. We called to his attention the existence of other well-shielded, powerful SRP reactors, and he placed 4000 liters of  $\text{CCl}_4$  near one of them. He obtained a negative result (R. Davis, Jr., paper presented at the American Physical Society Meeting, Washington, D.C., 1956) which, taken together with our observation, proved that although the  $\bar{\nu}_e$  existed it was incapable of inverting  ${}^{37}\text{Ar}$  decay. This suggested that the neutrino emitted by neutron-rich fission fragments ( $e^-$  decay),  $\bar{\nu}_e$ , was different from the  $\nu_e$  emitted in  $e^+$  decay, which at that time was one of the two possibilities to be checked.
13. This prediction incorporated the then held belief that parity is conserved in the weak interaction. In view of the large experimental errors and the poorly known  $\bar{\nu}_e$  spectrum, we considered this crude agreement consistent with the  $\bar{\nu}_e$  origin of the signal and continued our program to make this comparison more precise. (Our initial analysis grossly overestimated the detection efficiency with the result that the measured cross section was at first thought to be in good agreement with prediction.) As commented on later in this account, the effect of parity nonconservation is to increase the predicted cross section by a factor of 2. In the two-component theory the electron neutrino has only two states—one,  $\bar{\nu}_e$ , with its spin angular momentum parallel, and one,  $\nu_e$ , with its spin angular momentum antiparallel to its linear momentum. The old four-component theory allowed each neutrino to have two spin states.
14. C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, R. F. Hudson, *Phys. Rev.* **105**, 1413 (1957); R. L. Garwin, L. M. Lederman, M. W. Weinrich, *ibid.*, p. 1415; J. I. Friedmann and V. L. Telegdi, *ibid.* **106**, 387 (1957).
15. T. D. Lee and C. N. Yang, *ibid.*, p. 1671.
16. L. Landau, *Nucl. Phys.* **3**, 127 (1957).
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18. In the fall of 1956, following the observation experiments, we measured the cross section with equipment built for that purpose in 1954 and 1955, but we did not publish the result until an improved measurement had been made of the  $\bar{\nu}_e$  spectrum from fission (1957), which made possible a more precise comparison with theory [F. Reines and C. L. Cowan, Jr., in *Second United Nations International Conference on the Peaceful Uses of Atomic Energy* (A/Conf. 15/P/1026, United Nations, New York, 1958); R. E. Carter, F. Reines, J. J. Wagner, M. E. Wyman, in *ibid.*; *Phys. Rev.* **113**, 273 (1959); *ibid.*, p. 280].
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24. Supported in part by the Department of Energy. Clyde Cowan left a legacy that will live in the annals of physics. In the search for that poltergeist, the neutrino, he exhibited the courage to tackle a problem that had defied experimentalists for 20 years and the creative imagination to contribute in a fundamental way to its solution.

## Echolocation and Pursuit of Prey by Bats

James A. Simmons, M. Brock Fenton, Michael J. O'Farrell

Of the 700 living species of echolocating bats in the mammalian order Chiroptera (1), about 600 actively pursue prey, probably with partial or complete guidance by sonar. The great majority of these bats are insectivorous and chase airborne insects or glean resting insects

from surfaces when they forage for food. Some are carnivorous and presumably must often actively hunt other bats, small birds, or lizards. A few species have evolved active hunting procedures to the point where they can use echolocation for detecting fish (2). In species

that have been observed hunting, echolocation serves as an important perceptual modality for finding prey (3, 4). In laboratory studies on their pursuit of airborne targets, bats use echolocation for detecting, locating, identifying, and tracking prey to a successful capture (5).

Modern portable electronic equipment for recording and analyzing the ultrasonic orientation signals used by bats (4, 6) has broadened the range of species of bats that have been studied while they hunt. The number of species about which something is known is now large enough for a comparative analysis of some aspects of hunting strategies as they are related to echolocation. In this article we discuss the relationships found among feeding behavior, echolocation, and the acoustic environment within which bats seek their prey.