The neutrino: from poltergeist to particle*

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The Second World War had a great influence on the lives and careers of very many of us for whom those were formative years. I was involved during, and then subsequent to, the war in the testing of nuclear bombs, and several of us wondered whether this man-made star could be used to advance our knowledge of physics. For one thing this unusual object certainly had lots of fissions in it, and hence, was a very intense neutrino source. I mulled this over somewhat but took no action.

Then in 1951, following the tests at Eniwetok Atoll in the Pacific, I decided I really would like to do some fundamental physics. Accordingly, I approached my boss, Los Alamos Theoretical Division Leader, J. Carson Mark, and asked him for a leave in residence so that I could ponder. He agreed, and I moved to a stark empty office, staring at a blank pad for several months searching for a meaningful question worthy of a life's work. It was a very difficult time. The months passed and all I could dredge up out of the subconscious was the possible utility of a bomb for the direct detection of neutrinos. After all, such a device produced an extraordinarily intense pulse of neutrinos and thus the signals produced by neutrinos might be distinguishable from background. Some handwaving and rough calculations led me to conclude that the bomb was the best source. All that was needed was a detector measuring a cubic meter or so. I thought, well, I must check this with a real expert.

It happened during the summer of 1951 that Enrico Fermi was at Los Alamos, and so I went down the hall, knocked timidly on the door and said, "I'd like to talk to you a few minutes about the possibility of neutrino detection." He was very pleasant, and said, "Well, tell me what's on your mind?" I said, "First off as to the source, I think that the bomb is best." After a moment's thought he said, "Yes, the bomb is the best source." So far, so good! Then I said, "But one needs a detector which is so big. I don't know how to make such a detector." He thought about it some and said he didn't either. Coming from the Master that was very crushing. I put it on the back burner until a chance conversation with Clyde Cowan. We were on our way to Princeton to talk with Lyman Spitzer about controlled fusion when the airplane was grounded in Kansas city because of engine trouble. At loose ends, we wandered around the place, and started to discuss what to do that's interesting in physics. "Let's do a real challenging problem," I said. He said, "Let's work on positronium." I said, "No, positronium is a very good thing but Martin Deutsch has that sewed up. So let's not work on positronium." Then I said, "Clyde let's work on the neutrino." His immediate response was "GREAT IDEA." He knew as little about the neutrino as I did, but he was a good experimentalist with a sense of derring-do. So we shook hands and got off to working on neutrinos.

NEED FOR DIRECT DETECTION

Before continuing with this narrative, it is perhaps appropriate to recall the evidence for the existence of the neutrino at the time Clyde and I started on our quest. The neutrino of Wolfgang Pauli (1930, 1934) was postulated in order to account for an apparent loss of energy-momentum in the process of nuclear beta decay. In his famous 1930 letter (Pauli, 1930) to the Tübingen congress, he stated: "I admit that my expedient may seem rather improbable from the first, because if neutrons[1] existed they would have been discovered long since. Nevertheless, nothing ventured nothing gained . . . We should therefore be seriously discussing every path to salvation."

All the evidence up to 1951 was obtained "at the scene of the crime" so to speak, since the neutrino, once produced, was not observed to interact further. No less an authority than Niels Bohr pointed out in 1930 that no evidence "either empirical or theoretical" existed that supported the conservation of energy in this case (Bohr, 1932). He was, in fact, willing to entertain the possibility that energy conservation must be abandoned in the nuclear realm.

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 interact with matter at a remote point.

It must be recognized, however, that, independently of the observation of a free neutrino interaction with matter, the theory was so attractive in its explanation of beta decay that belief in the neutrino as a "real" entity was general. Despite this widespread belief, the free neutrino's apparent undetectability led it to be described as "elusive, a poltergeist."

So why did we want to detect the free neutrino? Because everybody said you couldn't do it. Not very sen-

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*The 1995 Nobel Prize in Physics was shared by Frederick Reines and Martin L. Perl. This paper is the text of Professor Reines's address on the occasion of the award.

[1] When the neutron was discovered by Chadwick, Fermi renamed Pauli's particle the "neutrino."

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sible, but we were attracted by the challenge. After all, we had a bomb which constituted an excellent intense neutrino source. So, maybe we had an edge on others. Well, once again being brash, but nevertheless having a certain respect for certain authorities, I commented in this vein to Fermi, who agreed. A formal way to make some of these comments is to say that, if you demonstrate the existence of the neutrino in the free state, i.e., by an observation at a remote location, you extend the range of applicability of these fundamental conservation laws to the nuclear realm. On the other hand, if you didn't see this particle in the predicted range then you have a very real problem.

As Bohr is reputed to have said, "A deep question is one where either a yes or no answer is interesting." So I guess this question of the existence of the "free" neutrino might be construed to be deep. Alright, what about the problem of detection? We fumbled around a great deal before we go to it. Finally, we chose to look for the reaction $\bar{\nu}_e + p \rightarrow n + e^+$. If the free neutrino exists, this inverse beta decay reaction has to be there, as Hans Bethe and Rudolf Peierls recognized, and as I'm sure did Fermi, but they had no occasion to write it down in the early days. Further, it was not known at the time whether $\tilde{\nu}_e$ and ν_e were different. We chose to consider this reaction because if you believe in what we today call "crossing symmetry" and use the measured value of the neutron half-life then you know what the cross section has to be—a nice clean result. (In fact, as we learned some years later from Lee and Yang, the cross section is a factor of two greater because of parity nonconservation and the handedness of the neutrino.) Well, we set about to assess the problem of neutrino detection. How big a detector is required? How many counts do we expect? What features of the interaction do we use for signals? Bethe and Peierls (1934), almost immediately after the Fermi paper on beta decay (Fermi, 1934), estimated that if you are in the few MeV range, the cross section with which you have to deal would be $\sim 10^{-44}$ cm^2. To appreciate how minuscule this interaction is, we note that the mean-free path is $\sim$1000 light years of liquid hydrogen. Pauli put his concern succinctly during a visit to Caltech when he remarked: "I have done a terrible thing. I have postulated a particle that cannot be detected." No wonder that Bethe and Peierls concluded in 1934 "there is no practically possible way of observing the neutrino." I confronted Bethe with this pronouncement some 20 years later and with his characteristic good humor he said, "Well, you shouldn't believe everything you read in the papers."

DETECTION TECHNIQUE

According to the Paul-Fermi theory (Pauli, 1930; Fermi, 1934), the neutrino should be able to invert the process of beta decay as shown in Eq. (1):

$$\nu + A^z \leftrightarrow A^{z-1} + e^+ \quad \text{or} \quad A^{z+1} + e^- . \tag{1}$$

We chose to focus on the particular reaction

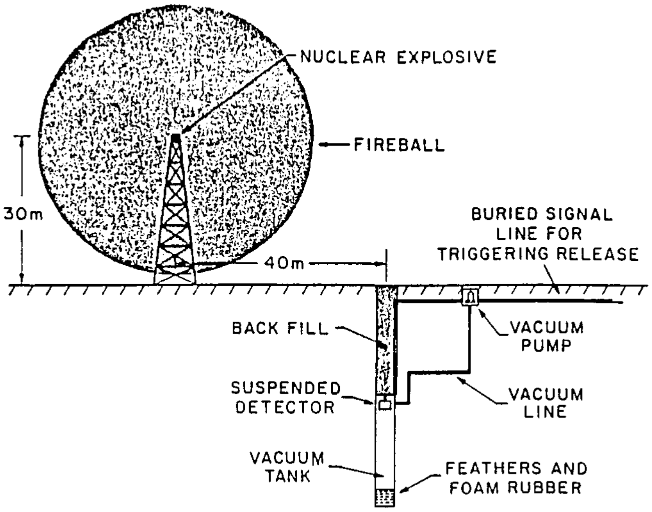


FIG. 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superseded by the approach that used a fission reactor.

$$\nu + p \rightarrow n + e^+ \tag{2}$$

because of its simplicity and our recognition of the possibility that the scintillation of organic liquids, newly discovered by Kallmann *et al.* (Ageno *et al.*, 1949; Kallman, 1950; Reynolds *et al.*, 1950) might be employed on the large ($\sim$1 m^3) scale appropriate to our needs. [At the time Cowan and I got into the act, a "big" detector was only a liter or so in volume. Despite the large (>3 orders of magnitude) extrapolation in detector size we were envisioning, it seemed to us an interesting approach worth pursuing.] The initial idea was to view a large pot of liquid scintillator with many photomultiplier tubes located on its boundary. The neutrinos would then produce positrons, which would ionize causing light flashes which could be sensed by the photomultipliers and converted to electrical pulses for display and analysis.

The idea that such a sensitive detector could be operated in the close proximity (within a hundred meters) of the most violent explosion produced by man was somewhat bizarre, but we had worked with bombs and felt we could design an appropriate system. In our bomb proposal a detector would be suspended in a vertical vacuum tank in the near vicinity of a nuclear explosion and allowed to fall freely for a few seconds until the shock wave had passed (Fig. 1). It would then gather data until the fireball carrying the fission-fragment neutrino source ascended skyward. We anticipated a signal consisting of a few counts assuming the predicted ($\sim 10^{-43}$ cm^2/proton) cross section, but background estimates suggested that our sensitivity could not be guaranteed for cross sections $<10^{-39}$ cm^2/proton, four orders of magnitude short! It is a tribute to the wisdom of Los Alamos Director, Norris Bradbury, that he approved the attempt on the grounds that it would nevertheless be $\sim$1000 times as sensitive as the then existing limits.

I recall a conversation with Bethe in which he asked how we proposed to distinguish a neutrino event from other bomb associated signals. I described how, in addition to the use of bulk shielding which would screen out gamma rays and neutrons, we could use the delayed coincidence between the product positron and neutron to identify the neutrino interaction. It was not until some months later that Clyde and I recognized that this signature would drastically reduce other backgrounds, so that we were able to use a steady fission reactor as a source instead of a bomb. I have wondered since why it took so long for us to come to this now obvious conclusion and how it escaped others, despite what amounted to a description of its essence as we talked to those around us. But of one thing I am certain: the open, free communication of our ideas was most stimulating to us and played a significant role in our eventual success. We were not inhibited in our communication by the concern that someone would scoop us. Neutrino detection was not a popular activity in 1952.

We sent the following letter to Fermi relating our plan to use a nuclear pile.

October 4, 1952

Dear Enrico,

We thought that you might be interested in the latest version of our experiment to detect the free neutrino, hence this letter. As you recall, we planned to use a nuclear explosion for the source because of background difficulties. Only last week it occurred to us that background problems could be reduced to the point where a Hanford pile would suffice by counting only delayed coincidences between the positron pulse and neutron capture pulse. You will remember that the reaction we plan to use is $p+\bar{\nu}\rightarrow n+\beta^+$. Boron loading a liquid scintillator makes it possible to adjust the mean time T between these two events and we are considering $T\sim 10\ \mu$sec. Our detector is a 10 cubic foot fluor-filled cylinder surrounded by about 90 5819's operating as two large tubes of 45 5819's each. These two banks of ganged tubes isotropically distributed about the curved cylindrical wall are in coincidence to cut tube noise. The inner wall of the chamber will be coated with a diffuse reflector and in all we expect the system to be energy sensitive, and not particularly sensitive to the position of the event in the fluor. This energy sensitivity will be used to discriminate further against background. Cosmic ray anticoincidence will be used in addition to mercury and low background lead for shielding against natural radioactivity. We plan to immerse the entire detector in a large borax water solution for further necessary reduction of pile background below that provided by the Hanford shield.

Fortunately, the fast reactor here at Los Alamos provides the same leakage flux as Hanford so that we can check our gear before going to Hanford. Further, if we allow enough fast neutrons from the fast reactor to leak into our detector we can simulate double pulses because of the proton recoil pulse followed by the neutron capture which occurs in this case. We expect a counting rate at Hanford in our detector about six feet from the pile face of $\sim\frac{1}{5}$/min. with a background somewhat lower than this.

As you can imagine, we are quite excited about the whole business, have canceled preparations for use of a bomb, and are working like mad to carry out the ideas sketched above. Because of the enormous simplification in the experiment, we have already made rapid progress with the electronic gear and associated equipment and expect that in the next few months we shall be at Hanford reaching for the slippery particle.

We would of course appreciate any comments you might care to made.

Sincerely,

Fred Reines, Clyde Cowan

That letter elicited the response from Fermi dated Oct. 8, 1952 (Fig. 2):

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,

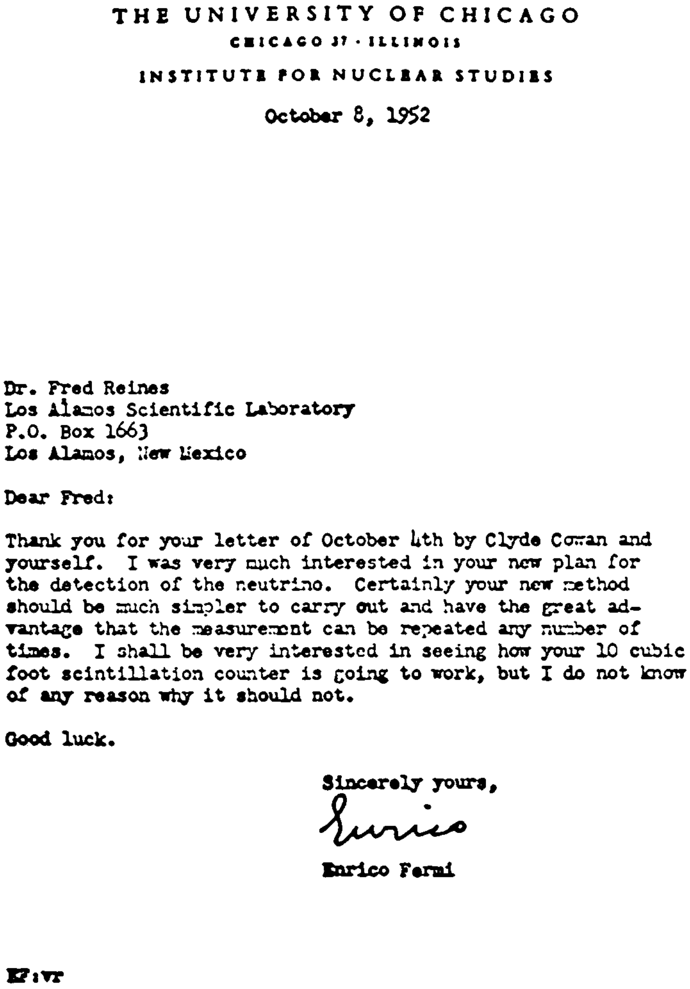
Enrico Fermi

Reflecting on the trail that took us from bomb to reactor, it is evident that it was our persistence which led us from a virtually impossible experiment to one that showed considerable promise. The stage had been set for the detection of neutrinos by the discovery of fission and organic scintillators—the most important barrier was the generally held belief that the neutrino was undetectable.

THE HANFORD EXPERIMENT

Our first attempt was made at one of the Hanford Engineering Works reactors in Hanford, Washington, built during the Second World War to produce plutonium for the atomic bomb.

Viewed from the perspective of today's computer-controlled kiloton detectors, sodium iodide crystal palaces, giant accelerators, and several hundred-person groups, our efforts to detect the neutrino appear quite modest. In the early 1950s, however, our work was thought to be large scale. The idea of using 90 photomultiplier tube 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



THE UNIVERSITY OF CHICAGO
CHICAGO 37 · ILLINOIS
INSTITUTE FOR NUCLEAR STUDIES

October 8, 1952

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
Enrico Fermi

EF:vr

FIG. 2. Letter from Fermi in response to our Oct. 4th letter to him describing our intention to use a nuclear pile rather than a bomb for the experiment.

few meters? How reflective was the paint? 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?

It soon became clear that this new detector designed 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. Incidentally, the detector we designed turned out to be big enough so that a person, bent up, could fit in an insert placed in it. Intrigued, we proceeded to measure the total K^{40} radioactivity in a couple of humans. Prior to this detector development, if you wanted to measure the K^{40} in a human being you had to ash the specimen or reduce backgrounds by putting geiger counters deep underground. Incidentally, even though it was an excellent neutron as well as gamma-ray detector, we resisted the temptation to be sidetracked and harvest these characteristics for anything other than the neutrino search.

Our entourage arrived at Hanford in the spring of 1953. Figure 3 shows Clyde and me sitting in front of some of our equipment. What results did we get from this particular reactor experiment? We had a 300-liter liquid scintillator viewed by 90 2-inch photomultiplier tubes. Backgrounds were very troublesome and we found it necessary to pile and unpile hundreds of tons of lead to optimize the shielding. We worked around the clock as we struggled with dirty scintillator pipes, white reflecting paint that fell from the walls under the action of toluene-based scintillator and cadmium propionate neutron capturer, etc., etc. We took the data with reactor on and off and labored until we were absolutely exhausted.

But despite our efforts, background rates due to cosmic rays and electrical noise during reactor off periods frustrated our attempts to achieve the required sensitivity.

After a few months of operation, 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.

On he way home we analyzed the data. We had checked by means of neutron sources and shielding tests that the trace of a signal, 0.4±0.2 events/min., wasn't

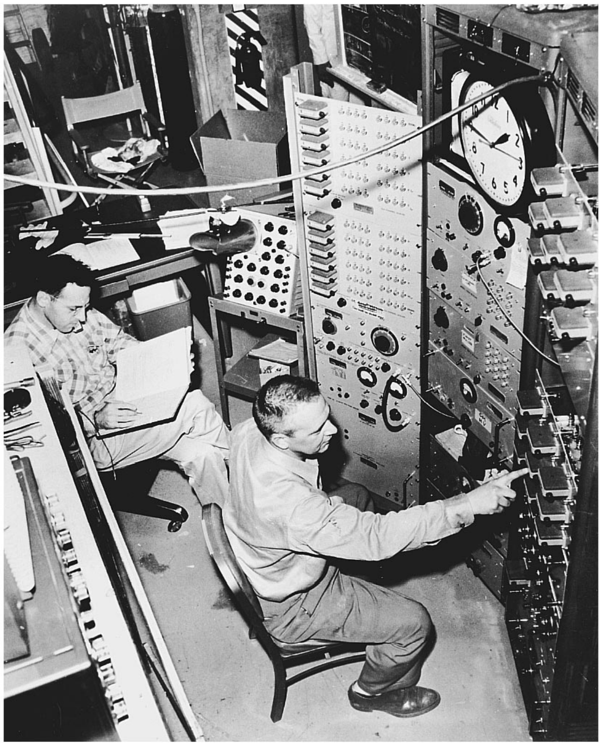


FIG. 3. Photograph of Clyde Cowan (right) and me (left) with some of the equipment we used in the Hanford experiment.

just due to reactor neutrons leaking into the detector. These marginal results merely served to whet our appetites—we figured that we had to do better than that.

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. So back at Los Alamos we performed an underground test that showed that the background was in fact 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 Hanford results, we considered how it might be possible to build a detector that would be even more discriminating in its rejection of background. We were guided by the fact that neutrons and positrons were highly distinctive particles and that we could make better use of their characteristics.

Figure 4 is a schematic of the detection technique used in the new experiment. An antineutrino from fission products in the reactor is incident on a water target containing cadmium chloride. As previously noted, the $\bar{\nu}_e+p$ reaction produces a positron and a neutron. 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 microseconds later by the neutron capture in cadmium.

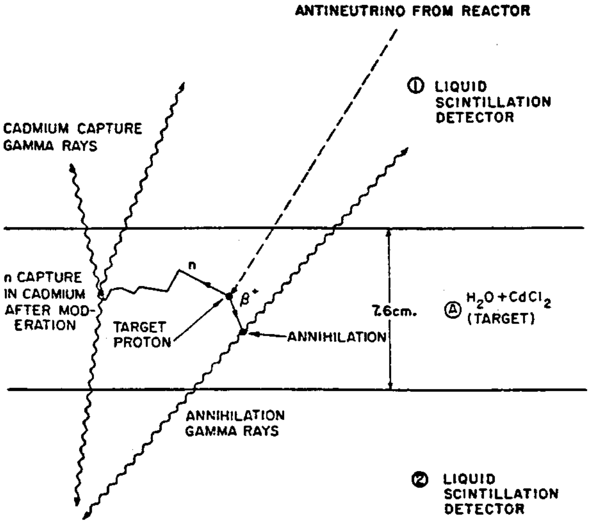


FIG. 4. Schematic of the detection scheme used in the Savannah River experiment. An antineutrino from the reactor interacts with a proton in the target, creating a positron and a neutron. The positron annihilates on an electron in the target and creates two gamma rays, which are detected by the liquid scintillators. The neutron slows down (in about ten microseconds) and is captured by a cadmium nucleus in the target; the resulting gamma rays are detected in the liquid scintillators.

These ideas were translated into hardware and associated electronics with the help of various support groups at Los Alamos. Figure 5 is a sketch of the equipment. It shows the target chamber in the center, sandwiched between the two scintillation chambers. Figure 6 shows one of the banks of 55 photomultiplier tubes that was used to view the scintillation chambers. Then, in the fall of 1955, at the suggestion and with the moral support of John A. Wheeler, the detector was taken to a new, powerful (700 MW at that time), compact heavy-water moderated reactor at the Savannah River Plant in Aiken, South Carolina.

The Savannah River reactor was well suited for neutrino studies because of the availability of a well shielded location 11 meters from the reactor center and some 12 meters underground in a massive building. The high $\bar{\nu}_e$ flux, $1.2\times10^{13}/\mathrm{cm}^2/\mathrm{sec}$, and reduced cosmic-ray background were essential to the success of the experiment which, even under those favorable conditions, involved a running time of 100 days over the period of approximately one year.

Observation of the neutrino

At Savannah River we carried out a series of measurements (Reines *et al.*, 1950) to show that:

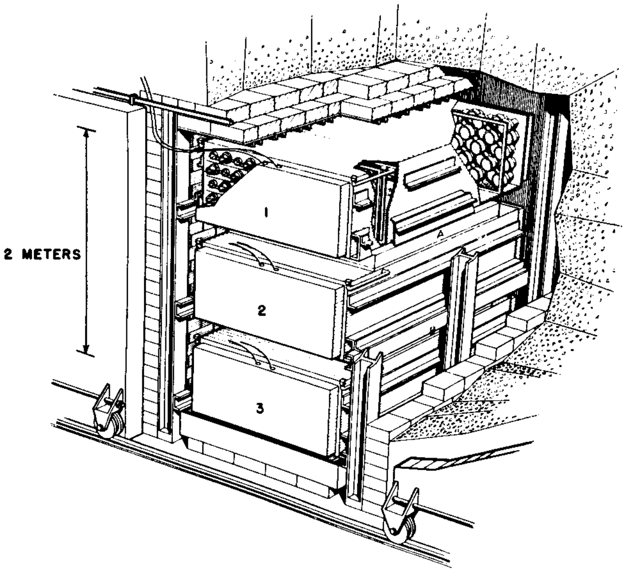


FIG. 5. A sketch of the equipment used at Savannah River. The tanks marked 1, 2, and 3 contained 1400 liters of liquid scintillator solution and were viewed on each end by 55 photomultiplier tubes. The thin tanks marked A and B were polystyrene and contained 200 liters of water, which provided the target protons and contained as much as 40 kilograms of dissolved $CdCl_2$ to capture the product neutrons.

(a) The reactor-associated delayed-coincidence signal was consistent with theoretical expectation.

(b) The first pulse of the delayed-coincidence signal was due to positron annihilation.

(c) The second pulse of the delayed coincidence signal was due to neutron capture.

(d) The signal was a function of the number of target protons.

(e) Radiation other than neutrinos was ruled out as the cause of the signal by means of an absorption experiment.

Our standard of proof was that every test must yield the anticipated result for us to conclude that we were observing the Pauli-Fermi neutrino. An unanticipated result would imply either experimental error or the need to modify our view of the neutrino.

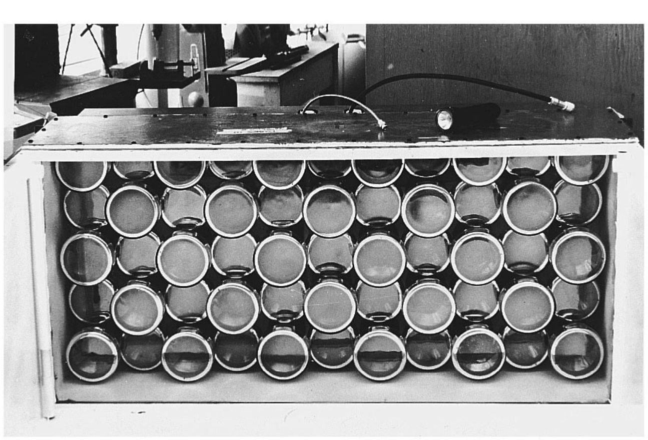


FIG. 6. A photograph of one of the banks of phototubes which viewed a liquid scintillator box (see Fig. 5).

Signal rate

A reactor-associated correlated signal rate of 3.0 ± 0.2 events per hour was observed. This represented a very favorable set of signal-to-background ratios: signal-to-total accidental background of 4:1, signal-to-correlated (as in neutron capture) reactor-independent background 5:1, and signal-to-reactor-associated accidental background $>25:1$. Determining the positron and the neutron detection efficiencies with radioactive sources and using the crudely known $\bar{\nu}_e$ flux, we found the cross section for fission $\bar{\nu}_e$ on protons to be

$$\bar{\sigma}_{\mathrm{exp}}=(12^{+7}_{-4})\times10^{-44}\ \mathrm{cm}^2$$

compared to the expected[2]

$$\bar{\sigma}_{\mathrm{th}}=(5\pm1)\times10^{-44}\ \mathrm{cm}^2.$$

First and second pulses

The first pulse of the delayed-coincidence pair was shown to be due to a positron by varying the thickness of a lead sheet interposed between the water target and one of the liquid scintillators, so reducing the positron detection efficiency in one of the detector triads but not in the others. The signal diminished as expected in the leaded triad but remained unchanged in the triad without lead. A further check provided by the spectrum of first pulses showed better agreement with that from a positron test source than with the background.

The second pulse was shown to be due to a neutron by varying the cadmium concentration in the target water. As expected for neutrinos, removal of the cadmium totally removed the correlated count rate, giving a rate above accidentals of 0.2±0.7/h. The spectrum of time intervals between the first and second pulses agreed with that expected for neutron-capture gamma rays. A false pulse sequence in which neutrons also produced the first pulse was ruled out by use of a neutron source which showed that fast neutrons cause primarily an increase in accidental rather than correlated rates, a fact incompatible with the observed reactor-associated rates noted above.

Signal as a function of target protons

The number of target protons was changed without drastically altering the detection efficiency of the system for both background and for $\bar{\nu}_e$ events. This was accomplished by mixing light and heavy water in approximately equal parts. The measured rate for the diluted target was 0.4 ± 0.1 of that for 100% H_2O, a number to be compared with the expected value of 0.5.

Absorption test

The only known particles, other than $\bar{\nu}_e$ produced by the fission process, were discriminated against by means

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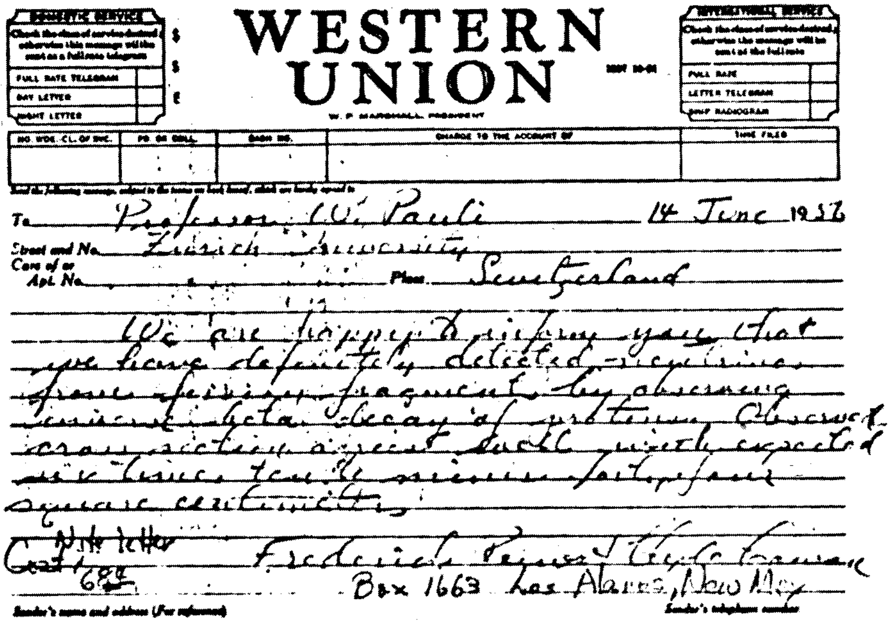
[2] This was the preparity prediction.



DOMESTIC SERVICE

FULL RATE TELEGRAM

DAY LETTER

NIGHT LETTER

WESTERN UNION

W. P. MARSHALL, PRESIDENT

INTERNATIONAL SERVICE

FULL RATE

LETTER TELEGRAM

SHIP RADIOGRAM

NO. WDS.-CL. OF SVC.	PD. OR COLL.	CASH NO.	CHARGE TO THE ACCOUNT OF	TIME FILED

To Professor W. Pauli 14 June 1956

Street and No. Zurich University

Care of or Apt. No. Place Switzerland

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.

Night letter

Cost 68¢

Frederick Reines & Clyde Cowan

Box 1663 Los Alamos, New Mex

Sender's name and address (For reference)

Sender's telephone number

FIG. 7. The telegram to Pauli which told of our detection of the neutrino at Savannah River. The contents of this message are quoted in the text.

of a gamma-ray and neutron shield. When a bulk shield measured to attenuate gamma rays and neutrons by at least an order of magnitude was added, the signal was observed to remain constant; that is, the reactor-associated signal was 1.74±0.12/h with the shield and 1.69±0.17/h without the shield.

TELEGRAM TO PAULI

The tests were completed and we were convinced (Cowan *et al.*, 1956). It was a glorious feeling to have participated so intimately in learning a new thing, and in June of 1956 we thought it was time to tell the man who had started it all when, as a young fellow, he wrote his famous letter in which he postulated the neutrino, saying something to the effect that he couldn't come to a meeting and tell them about it in person because he had to go out to a dance!

The message, Fig. 7, 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. That message reads, "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." We learned later that Pauli and some friends consumed a case of champagne in celebration!

Many years later (~1986) C. P. Enz, a student of Pauli's, sent us a copy of a night letter Pauli wrote us in 1956, but which never arrived. It is shown in Fig. 8 and says, "Thanks for the message. Everything comes to him who knows how to wait. Pauli"

The quest was completed, the challenge met. There was, however, something missing—independent verification by other workers. As it turned out we were, in fact, correct but it took some eight years for this check to occur as a by-product of neutrino experiments at accelerators (Block *et al.*, 1964). I suspect that the unseemly delay was largely due to the fact that our result was not unexpected.

Some twenty years later, stimulated by the possibility of neutrino oscillations, other groups also observed $\bar{\nu}_e + p$ at reactors (Boehm *et al.*, 1980; Reines *et al.*, 1980).

WHAT NEXT?

Once we had detected the neutrino the question arose, what next? What, as Luis Alvarez wrote me at the time, did we propose to do as an encore? A survey of the old notebooks indicated a variety of possibilities ranging from a study of the neutrino itself to its use as a tool in probing the weak interaction.

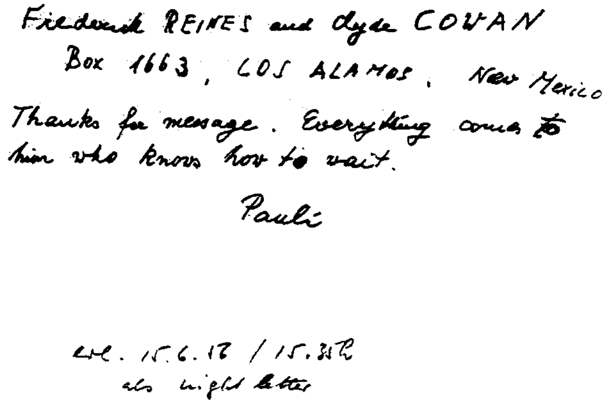
Neutrino-electron elastic scattering

One question I found particularly fascinating was: Did the neutrino possess a direct elastic-scattering interaction with electrons

$$\bar{\nu}_e + e^- \overset{?}{\rightarrow} \bar{\nu}_e + e^- \tag{3}$$

say, via a magnetic moment? This question had great appeal for a variety of reasons which were not entirely sensible. First, there was no theoretical guide to suggest that such a reaction between two of nature's "simplest" particles occurred and second, reminiscent of the earlier conversation with Fermi regarding bomb neutrinos, I had no idea how to construct a suitable detector. Despite these excellent reasons for choosing a more sensible problem I decided to work on it.

The essence of the detection problem was to distinguish an electron produced by the imagined elastic-scattering process from an electron produced by gamma



Friedrich REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.

Pauli

[illegible] 15.6.[illegible] / 15.[illegible]
als night letter

FIG. 8. The night letter Pauli sent in response to our message shown in Fig. 7.

rays or beta emitters. This sorting out of such a nondescript process occupied me, and a succession of colleagues, for some twenty years (Reines, 1960). The key to the solution was the recognition (1959) that if one chose a low-Z medium, most of the gamma-ray background would arise from Compton recoil electrons, whereas a $\bar{\nu}_e$ scattering would occur only once. It was therefore possible, in principle, to construct a detector in which spatial anticoincidences of the sequential Compton electrons would be discriminated against, thus reducing this source of background. While this idea was being translated to experimental reality and then eventual detection, various theoretical developments took place in weak-interaction physics. As the theorists labored they made predictions ranging from vague qualitative guesses about magnetic moments (Bethe and Peierls, 1934) to statements that the interaction was zero (Salam, 1957), that it was given by $V-A$ (Feynman and Gell-Mann, 1958) and that it is undefined. The situation had finally settled down by 1976 to a specific prediction with the advent of the Weinberg (1967), Salam (1969), Glashow (1970) theory.

That same year marked the end of our intense 20 year effort (Reines *et al.*, 1976). The neutrino-electron elastic-scattering process has the smallest cross section of any process ever measured. The measurement also provided one of the earliest determinations of the weak mixing, or Weinberg, angle; it was only 1.2 standard deviations from the current world average.

Once again, as in the case of the inverse beta-decay process, even prior to experimental verification of the elastic-scattering reaction, theorists, in particular astrophysicists, assumed its existence and used it in building stellar models.

I find it interesting to contemplate the possible consequences of a closer coupling between theory and experiment in this case. If I had required a theory in the first place I would not have started to consider the scattering experiment when I did. If I had followed the theorists peregrinations I would have sacrificed the steadfastness of purpose which eventually led to the solution. This is not to say that experimentalists should proceed independently of theory, but it does suggest that the coupling should not be too tight.

Neutrino interactions with deuterons

In 1956 we also began another lengthy search; this one was for the interactions of reactor neutrinos with deuterons. In 1969 we finally observed (Jenkins *et al.*, 1969) the so-called "charged-current" reaction [$\bar{\nu}_e + d \rightarrow n + n + e^+$] and in 1979 the "neutral-current" reaction [$\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$] (Pasierb *et al.*, 1979). The neutral-current reaction had been previously discovered at an accelerator at CERN in 1973 with muon neutrinos, but it was nevertheless most gratifying to see that $\bar{\nu}_e$ exhibited the expected behavior.

Detection of atmospheric neutrinos

In the early 1960's, many authors (Greisen, 1960; Markov and Zheleznykh, 1961; Zatsepin and Kuzmin, 1961) had calculated the flux of high-energy neutrinos expected to arise from the decay of K and π mesons and muons produced in the earth's atmosphere by the interaction of primary cosmic rays. A major experimental question was, how does one detect these atmospheric neutrinos? The only practical method seemed to be to detect the muons produced by the neutrinos in one of their rare interactions with matter. But this meant that one would have to place a detector deep underground to reduce the major background, the flux of muons produced directly in the atmosphere.

So in 1963 we started construction of a detector some two miles underground in the East Rand Proprietary gold mine near Johannesburg, South Africa. The design and construction of what was then the world's largest particle detector—a 180 ft long, 20 ton segmented scintillation detector array—took a surprisingly short time, about one year. This experiment was a collaboration between Case Institute of Technology, Cleveland, Ohio (now Case-Western Reserve University) and the University of the Witwatersrand, Johannesburg.

On February 23, 1965, the first "natural" (meaning it did not arise from a man-made nuclear reactor) neutrino was discovered. In all, 167 such events were recorded.

Neutrino stability and oscillations

When we first turned on our detector at Savannah River in the Fall of 1955, no signals were observed. As we checked our apparatus, a desperate thought crossed our minds: the neutrino might be emitted from fission but did not survive the 11-meter journey from the reactor to our detector. Perhaps the neutrino was unstable! A moment of excitement ensued until we made some adjustments in our apparatus and neutrino-like signals began to appear. The consequence of these errors resulted in a notebook entry which suggested making a check of the inverse-square law dependence of the neutrino signals on the distance from reactor to detector. But in any event we had no theoretical basis at that time for questioning the stability of the neutrino and were reminded once again that experiment was the final arbiter in these matters.

I found the idea of neutrino instability to be a "repulsive" thought, but nevertheless proceeded to imagine what sorts of decay products there might be if the neutrino was, in fact, unstable. In 1974 we measured a $\bar{\nu}_e$ lifetime limit (Reines *et al.*, 1974). That experiment looked for the radiative decay of the neutrino at a nuclear reactor.

Early on it had been suggested by Pontecorvo (1967) and by Nakagawa *et al.* (1963) that the neutrino may oscillate from one flavor to another as it travels from its place of origin. A graphic analogy is the change of character from dog to cat: Imagine at time zero a dog leaving his house to walk down the street to another dog house at the end of the block. As he progresses down the street a transformation takes place—his appearance gradually changes (à la Escher) from that of a dog to that of a cat! Halfway down the block the transformation is complete and the erstwhile dog—now a cat—continues on its feline journey. But the transformation goes on and, *mirabile dictu*, upon arrival at the dog house the erstwhile dog turned cat is once again a dog. If such bizarre behavior is observed to occur in neutrinos it would provide evidence of the neutrino's structure. Neutrinos of all types would be construed to be built out of common building blocks whose rearrangements en route would give rise to observably different combinations.

There have been many searches for neutrino oscillations. The first experiment to report on neutrino oscillations was performed in 1979, but it was in no sense definitive; it was the same experiment in which we reported the first measurement of the neutrino-deuteron neutral-current cross section (Pasierb *et al.*, 1979). Since the neutral-current reaction may be initiated by neutrinos of any flavor, whereas the charged-current reaction may be initiated only by $\bar{\nu}_e$'s, taking the ratio of the charged- to neutral-current cross sections is a sensitive test for neutrino oscillations where the oscillations occur with a wavelength short enough that the oscillation process has reached equilibrium before reaching the detector location. The results of that 1979 experiment suggested that such oscillations might occur.

OTHER NEUTRINO PHYSICS EXPERIMENTS

It must be emphasized that this grand endeavor, which we now call Neutrino Physics, is being carried out by many groups. Even in 1970 there were several such groups around the world, some using nuclear reactors, some high-energy accelerators, and others cosmic rays. We list here only a few of the salient results that they have obtained:

In 1961 the muon-neutrino was identified in an experiment at the Brookhaven AGS (Danby *et al.*, 1961) and this marked the beginning of the fruitful use of high-energy neutrino beams at accelerators.

In 1973, at CERN, $\bar{\nu}_\mu$-e elastic scattering was observed (Hasert *et al.*, 1973) and with it the landmark discovery of weak neutral currents.

Since the late 70's great progress has been made in studying nucleon structure functions by looking at the deep-inelastic scattering of neutrinos and antineutrinos on nucleons. These studies are complementary to the deep-inelastic electron and muon studies because the neutrinos couple to the nuclear constituents in a different manner and, due to parity nonconservation, they can distinguish quarks from antiquarks.

Searches for vacuum oscillations have been performed at reactors and accelerators, and since the mid 80's matter oscillations have been looked for in solar neutrinos and atmospheric neutrinos. To date there is no definitive evidence for neutrino oscillations.

Supernova 1987A was a windfall for neutrino physics (Kielczewska, 1994). Conventional supernova theory predicts that a supernova such as 1987A yields 3×10^{53} ergs (99% of its gravitational binding energy) in a burst of $\sim10^{58}$ neutrinos in a few seconds. On earth 19 low-energy neutrino events were observed in two large Čerenkov detectors each containing several kilotons of water. All of the events were recorded within about 10 seconds; the background event rate was only a few *per day* (Bionta *et al.*, 1987; Hirata *et al.*, 1987).

Many determinations of neutrino properties were extracted from the supernova data. These include neutrino mass, charge, lifetime, magnetic moment, number of flavors, etc. In addition, some of the most basic elements of supernova dynamics were studied and found to be in surprisingly good agreement with predictions. One interesting consequence was the testing of the Einstein Equivalence Principle. The fact that the fermions (neutrinos) and bosons (photons) reached the Earth within 3 hours of each other provides a unique test of the equivalence principle of general relativity. The observation proved that the neutrinos and the first recorded photons are affected by the same gravitationally induced time delay within 0.5% (Krauss and Tremaine, 1988; Longo, 1988).

And while describing neutrinos arriving at the earth from the cosmos, we want to recall the intriguing history of the study of solar neutrinos. After 20 years of observation by Ray Davis and others, and now with four detectors reporting, it appears that the number of neutrinos arriving at the earth from the sun is significantly less than that expected from the standard solar model (Bahcall *et al.*, 1995). We are not yet sure whether this is telling us something about the sun or something about the properties of the neutrino.

During the latter part of the 1980's several determinations of the number of light neutrino flavors were made. The values were derived from many sources including cosmological limits, supernova 1987A neutrinos, $p\bar{p}$ colliders, and e^+e^- colliders. By the end of the decade it was clear that there are only three families of light neutrinos—see, for example, Denegri and Martinelli (1991).

Surely the longest series of experiments in neutrino physics concerns the attempt to measure the mass of the neutrino. These studies started in 1930 with Pauli's initial estimate that: "The mass of the neutron [neutrino] should be of the same order of magnitude as that of the electron and in any event no greater than 0.01 of the proton mass." Since then many techniques have been used: nuclear beta decay (especially tritium), Supernova 1987A, cosmological constraints, radiative nucleon capture of electrons and, for the mu- and tau neutrinos, particle decays.

THE FUTURE OF NEUTRINO PHYSICS

The formative years of neutrino physics have been extraordinarily fruitful. But with all of the important accomplishments, are there any things left for the future? Most definitely yes.

We will continue to see more precise measurements of all of the neutrino's intrinsic properties, of course. In addition, from searches for neutrinoless double beta decay (Moe and Vogel, 1994) we may soon have an answer to a most fundamental question: is the neutrino Majorana or Dirac?

Also we are all anxiously awaiting the discovery of the tau neutrino, as signaled by its detection at a point remote from is origin.

There are also several outstanding issues having to do with astrophysics and cosmology. For instance: Are neutrinos an important component of the dark matter? And wouldn't it be exciting if someone could figure out how to observe the relic neutrinos left over from the big bang!

As large neutrino telescopes are constructed over the next few years, we may finally see neutrinos coming from cosmic sources such as other stars and active galactic nuclei.

I don't think it is too much to hope that we will see a resolution to the solar neutrino puzzle in the next few years. And, if we are lucky, those same detectors which will be looking for solar neutrinos may see a supernova or two.

I am confident that the future of neutrino physics will be as exciting and fruitful as the past has been.

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