FOREWORD

DAVID O. CALDWELL

NEUTRINO TIMELINE

1930	Wolfgang Pauli predicts that neutrinos exist.
1956	Frederick Reines and Clyde Cowan discover the electron neutrino.
1961	Muon neutrinos are discovered at the Brookhaven National Laboratory.
1968	Ray Davis and colleagues begin the first solar neutrino experiment.
1989	Experiments at SLAC and CERN prove that there are only three kinds of light neutrinos.
1998	Super-Kamiokande experiment reports conclusive evidence for neutrino oscillations.
2000	DONUT experiment reports direct observation of tau neutrinos.
2001	SNO experiment finds evidence that solar neutrinos indeed oscillate.

THE PAST FEW YEARS have been an exceptionally exciting time for physicists involved in research on neutrinos. We now have two different confirmed (and one unconfirmed) pieces of evidence that neutrinos oscillate from one type into another, which implies that they possess mass. These experiments have provided the first convincing experimental evidence for new physics beyond the Standard Model, today's dominant theory of elementary particles and the interactions among them. For two decades, ever since this theory took firm hold within the community during the late 1970s, particle physicists have been looking in every possible corner and under every accessible rock for this new physics. Now that we have such evidence, neutrino studies will lead the research into what lies beyond the Standard Model.

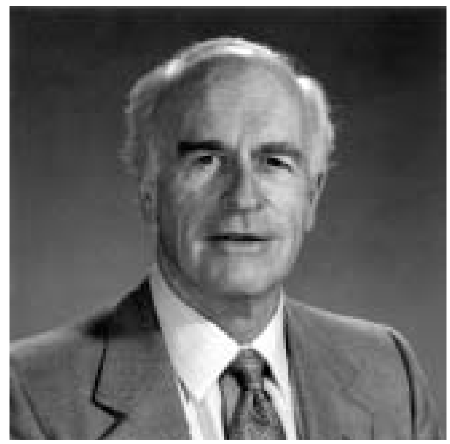
As a probe for new physics, neutrinos are unique among particles. As far as we know today, they are elementary particles, but unlike their fellow leptons and quarks, neutrinos are unencumbered by electrical charge and do not take part in the complicated strong interactions. They seem about as elementary as particles can be—possessing just the tiniest bits of mass and engaging only in weak interactions with other leptons and quarks. Neutrinos' exceptionally small mass may in fact provide a valuable window into the very high-energy scales that are otherwise completely inaccessible at today's particle accelerators. And despite the smallness of their mass, neutrinos may have played an important role in establishing the structure of the Universe during the years immediately after the Big Bang.

This special issue of the *Beam Line* appears at a pivotal moment in the evolution of the neutrino physics, when we take stock of the new advances and try to glimpse what discoveries may lie just over the horizon. A historical article by Michael Riordan helps familiarize readers with Wolfgang Pauli's 1930 conception of the neutrino and its evolution over seven decades of research. Joshua Klein, Paul Nienaber, Koichiro Nishikawa, and Jeffrey Wilkes bring us up to date on recent neutrino experiments as well as others planned for the near future. Theorists Boris Kayser and Joel Primack attempt to interpret the pattern of neutrino masses that seems to be emerging and assess what impact these ghostly particles might have had on the structure of the Universe.

Despite all the recent advances, there appears to be no end of questions about these elusive, fascinating particles and the effects that they may produce. This special *Beam Line* issue on neutrino physics, edited by Michael Riordan, captures the excitement of this field.

UPDATE

AS THIS ISSUE was going to press, we learned about the extensive damage to most of the phototubes in the Super-Kamiokande experiment. This accident is not only devastating for that research group but also for all of physics. Super-Kamiokande has yielded so many insights about neutrinos and into physics beyond the Standard Model that the inevitable delays are a severe blow. We wish them as rapid a recovery as possible.



David O. Caldwell has been doing research on neutrinos since 1980. He earned his Ph.D. in nuclear physics at UCLA in 1953 and since 1965 has been a member of the physics department faculty at the University of California, Santa Bartbara. A Guggenheim Fellow and a Fellow of the American Physical Society, he is editor of the recently published book, Current Aspects of Neutrino Physics.

Pauli's Ghost
A Seventy-Year Saga of the Concep

by MICHAEL RIORDAN

The idea of the neutrino has evolved substantially over the seven decades of its existence.

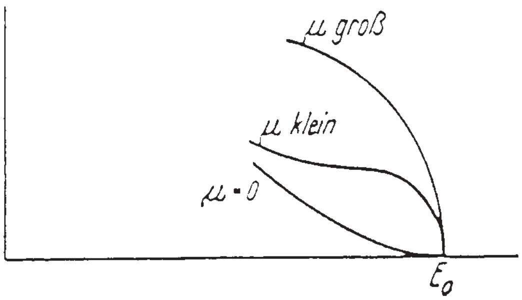
Adapted from "Pauli's Ghost: The Conception and Discovery of Neutrinos," by Michael Riordan, in *Current Aspects of Neutrino Physics*, D. O. Caldwell, Editor (Springer-Verlag Berlin, 2001).

WHEN WOLFGANG PAULI conceived his idea of the neutrino in 1930, it was substantially different from the ghostly particles recognized today. That December he proposed this light, neutral, spin-1/2 particle as a "desperate remedy" for the energy crisis of that time: that electrons emitted in nuclear beta decay had a continuous, rather than discrete, energy spectrum. The crisis had grown so severe by the late 1920s that Niels Bohr began to contemplate abandoning the sacrosanct law of energy conservation in nuclear processes. Pauli could not countenance such radical unorthodoxy. Instead, he suggested that very light poltergeists might inhabit the nucleus along with protons and electrons. They should have a mass "of the same order of magnitude as the electron mass." Normally bound within nuclei, they would have "about 10 times the penetrating capacity of a gamma ray" after their emission. He could account for continuous beta-decay spectra by assuming that this particle "is emitted together with the electron, in such a way that the sum of the energies . . . is constant."

Pauli clearly thought of his ghosts as actual constituents of atomic nuclei, with a small mass and substantial interaction strength. He was trying not only to preserve energy conservation in nuclear processes but also to dodge the severe problems with spin and statistics that cropped up in nuclei—then imagined to consist only of protons and electrons. The nitrogen nucleus, for example, was widely pictured as having 14 protons and 7 electrons, but it did not seem to obey Fermi statistics, as expected of any object containing an odd number of fermions. By adding seven more fermions to the heap,

tion and Discovery of Neutrinos

Wolfgang Pauli, left, Niels Bohr, center, Erwin Schrödinger, and Lise Meitner at the 1933 Solvay Congress (Courtesy Niels Bohr Archives).



Graph from Fermi's paper on the theory of beta decay, showing how the shape of the emitted electron's energy spectrum varies with the possible mass of the neutrino.

Pauli could explain why it behaved like a boson. But nobody could figure out how to cloister such light, speedy particles within the narrow confines of a nucleus.

James Chadwick's 1932 discovery of a heavy fermion he dubbed the neutron resolved most of these problems. Composed of seven protons and seven almost equally massive neutrons, the nitrogen nucleus now had an even number of fermions inside and could easily behave like a boson. Enrico Fermi's famous theory of beta decay put the capstone on the growing edifice. Instead of inhabiting the nucleus as constituents, the electron and "neutrino" (a name coined by Fermi in 1931 to mean "little neutral object") were to be created the moment a neutron transformed into a proton. Fermi even went so far as to indicate how the energy spectrum of beta-decay electrons depends critically on the neutrino's mass. By comparing his theoretical curves with the measured spectra near their high-energy end point, he concluded that "the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron."

Shortly thereafter, Hans Bethe and Rudolf Peierls used Fermi's theory to show that the interaction of neutrinos with matter had to be essentially negligible. In the energy range characteristic of beta-decay neutrinos, they would have a mean free path in water of more than 1000 light years! Bethe and Peierls concluded "there is no practically possible way of observing the neutrino." Pauli himself was dismayed. "I have done a terrible thing," he said. "I have postulated a particle that cannot be detected."

Thus was the idea of the neutrino born, but it remained mostly an intriguing possibility for years. Even after reading Fermi's paper, Bohr was still not convinced of its reality. "In an ordinary way I might say that I do not believe in neutrinos," Sir Arthur Eddington remarked, "Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos?"

WHEN George Gamow wrote "The Reality of Neutrinos" in 1948, however, he could discourse about them with confidence that they indeed existed. Although nobody had yet detected one directly, there were several indirect experimental proofs of their reality. Sensitive measurements of the energy and momentum of beta-decay electrons and their recoiling nuclei in Wilson cloud chambers indicated that substantial quantities of energy and momentum were missing. "This means some other particle must have been ejected at the same time as the electron," he wrote. "These single-process experiments leave little doubt that a third particle must be involved."

Gamow even speculated that neutrinos might be involved in the lethargic disintegration of the recently discovered pi-mesons and their lighter counterparts, then known as mu-mesons. After all, some kind of invisible entity was spiriting energy away from these two-body and three-body decay processes. Why not the same elusive particle involved in beta decays?

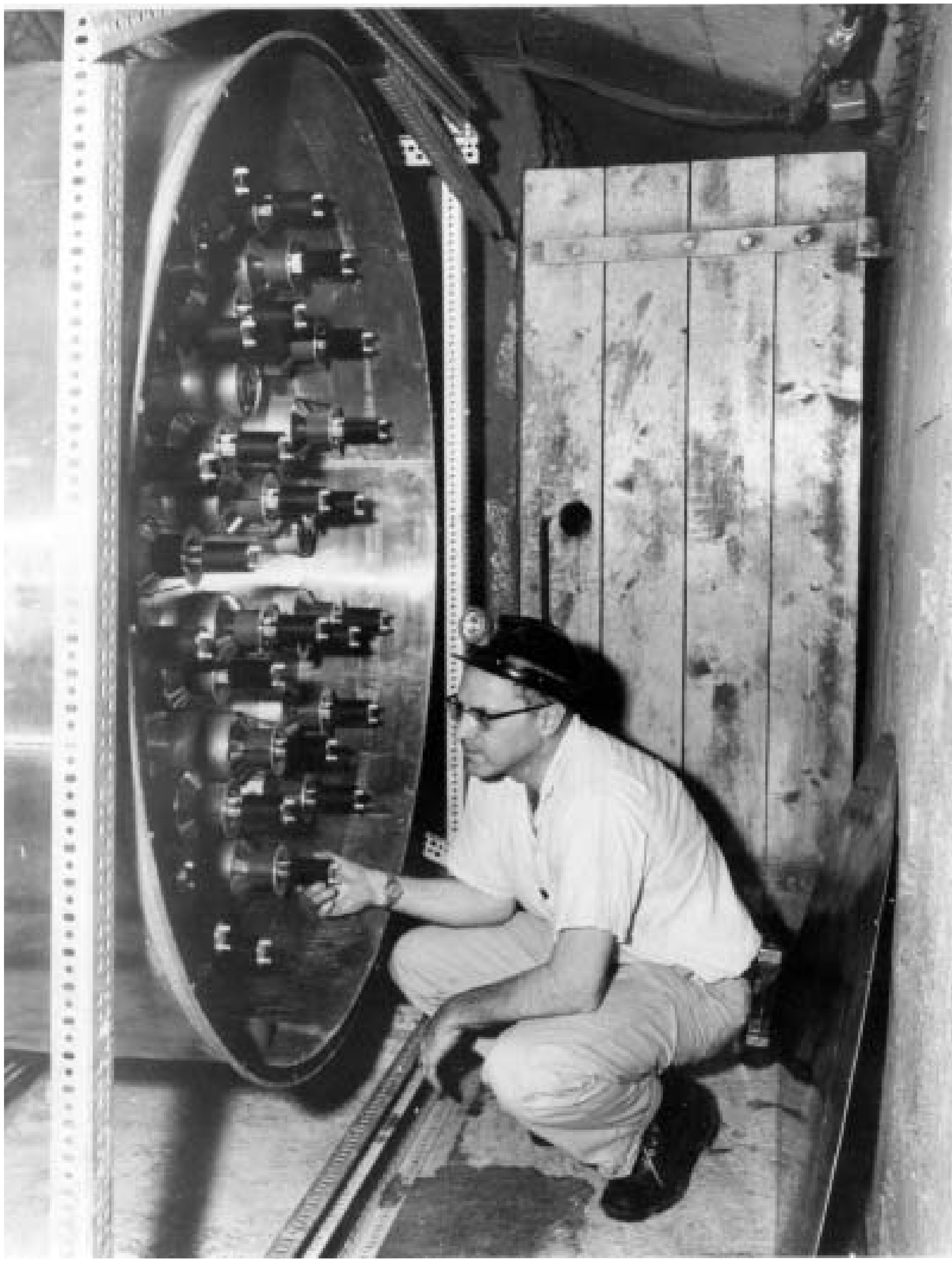
But little could be said conclusively about a particle that had thus far evaded direct detection. Whether its antiparticle was a completely distinct entity or just a different spin state of the same poltergeist could not then be determined. And the best attempts at measuring its mass could only establish an upper limit of about one-twentieth the electron mass. As the 1950s began, however, this situation was about to change dramatically.

In 1951, following atomic-bomb testing at Eniwetok atoll, Los Alamos physicist Frederick Reines began contemplating experiments in fundamental physics he might attempt. The Manhattan Project had provided intense new sources of neutrinos that could be used to ascertain more about them. Reines and Clyde Cowan recognized that the recently developed organic scintillating liquids would allow them to build the massive detector required to observe such ghostly particles. Together with the intense neutrino fluxes generated by atomic blasts or close to a fission reactor, such a large detector might finally overcome the dauntingly miniscule probability of a neutrino interacting.

Reines and Cowan elected to search for evidence of the interaction

$$\nu + p \rightarrow n + e^{+},$$

which should yield a prompt light flash in the organic scintillator due to the positron's annihilation with an atomic electron, followed a few microseconds later by another flash due to neutron capture. (Savvy readers will protest that antineutrinos, not neutrinos, participate in such an "inverse beta-decay" interaction, but this distinction was not clear at the time.) After considering and rejecting the idea of placing a detector within 100 meters of an atomic-bomb explosion, they decided instead to put it close to one of the nuclear reactors then in operation. Their first experiment, placed near one of the Hanford Engineering Works reactors used to breed plutonium for the Manhattan Project, involved a 300-liter tank of liquid scintillator. But the marginal increase in signal they observed with the reactor in operation was



Frederick Reines at work on an underground experiment in a South African mine in 1966. (Courtesy University of California, Irvine)

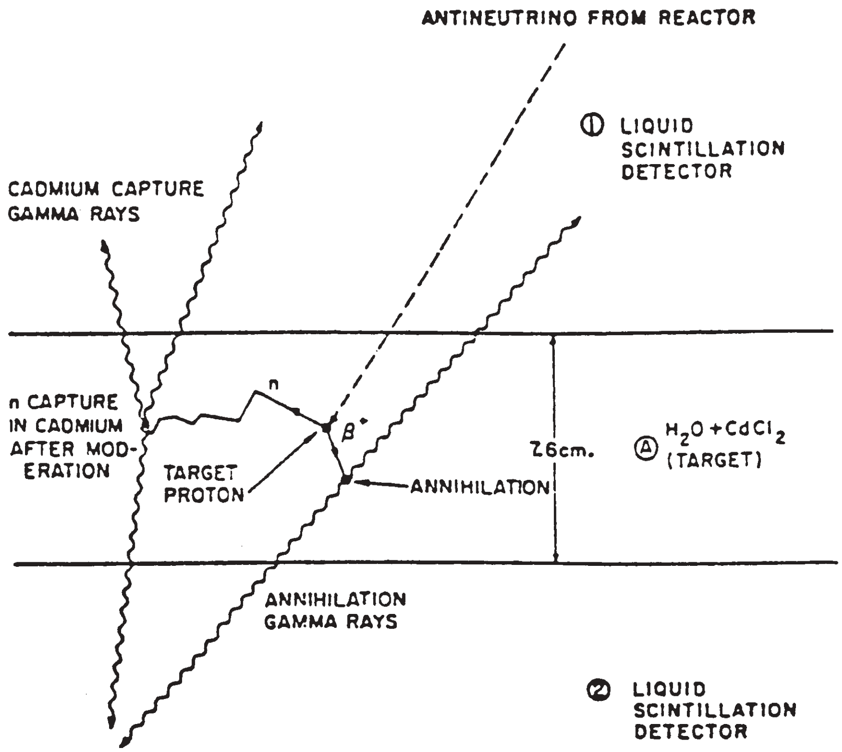


Diagram of the antineutrino-detection scheme used in the Savannah River experiment.

nearly swamped by cosmic-ray backgrounds.

Reines and Cowan then did a second experiment at the Savannah River reactor, which could generate a flux of 10 trillion antineutrinos per square centimeter per second at a position 11 meters away. (By then it was becoming recognized that the neutrino and antineutrino are distinct particles, with the latter being produced in tandem with an electron in beta-decay.) The detector, positioned 12 meters underground to reject cosmic-ray backgrounds, consisted of three tanks of organic scintillator, each viewed by 110 phototubes; between them sat two tanks of water with dissolved cadmium chloride to promote neutron capture (see illustration on next page).

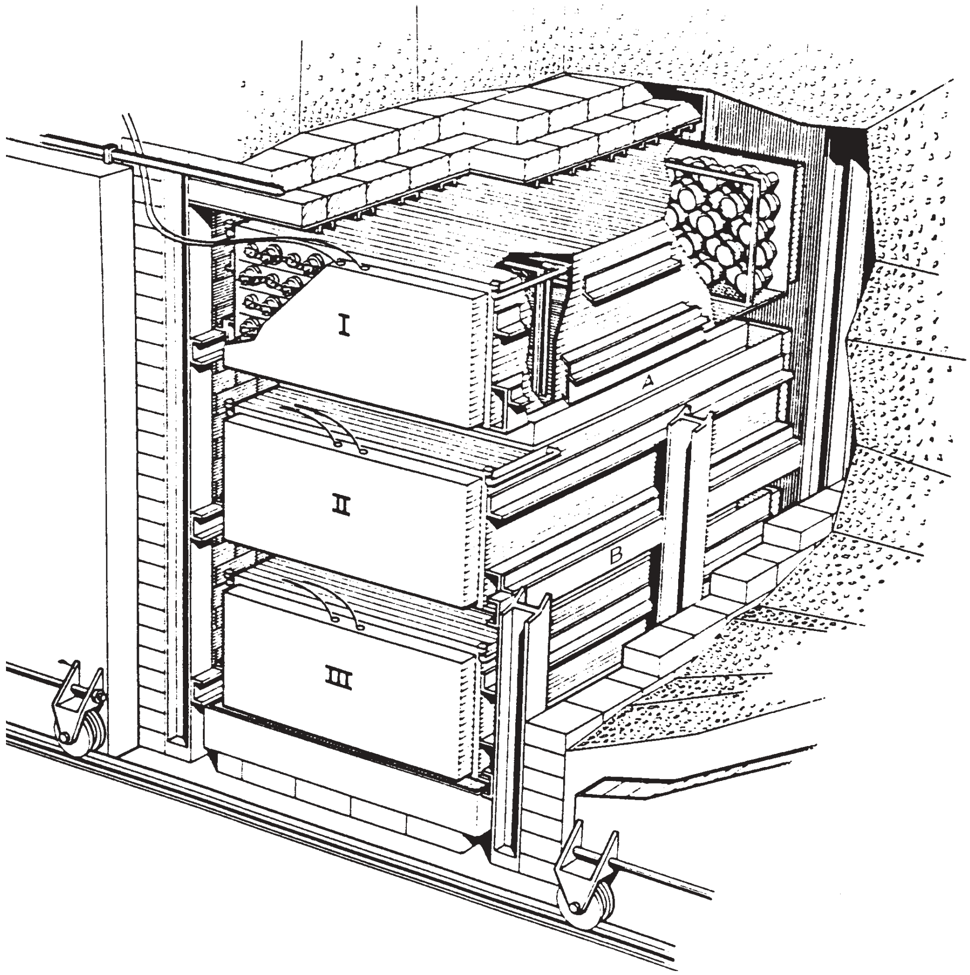
An antineutrino from the reactor occasionally interacted with a proton in the water, producing a positron and a neutron. The positron annihilated almost immediately with an atomic electron, yielding two gamma rays that were detected in the scintillator; about 10 microseconds later, neutron capture by a cadmium nucleus resulted in another burst of gamma rays (see illustration at left). A delayed coincidence between the first and second gamma-ray bursts was taken as the signature of an antineutrino event; Reines and Cowan observed three events per hour with the reactor operating—much greater than backgrounds due to cosmic rays or accidental coincidences.

Elated by their discovery, Reines and Cowan sent Pauli a telegram on June 14, 1956: "We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta-decay of protons." According to Reines, Pauli drank a whole case of champagne with his friends to celebrate the discovery and drunkenly penned a reply. "Thanks for the message," he wrote; "Everything comes to him who knows how to wait."

REVIEWING the status of neutrino physics a year later, Reines and Cowan could cite a variety of major improvements in the understanding of this previously invisible poltergeist. Delicate measurements of the electron spectrum in tritium beta decays had established that the neutrino's mass was less than 1/2000th that of the electron. The lack of evidence for double beta-decay (in which two electrons are emitted) indicated that it was most probably a Dirac particle like the electron, with neutrino and antineutrino distinctly different entities. And the failure of Brookhaven scientist Ray Davis to find any $Cl^{37} \rightarrow Ar^{37}$ conversions in a tank containing a thousand gallons of carbon tetrachloride placed near the Savannah River reactor could also be explained in the same way: antineutrinos could not induce such transitions, while neutrinos should have.

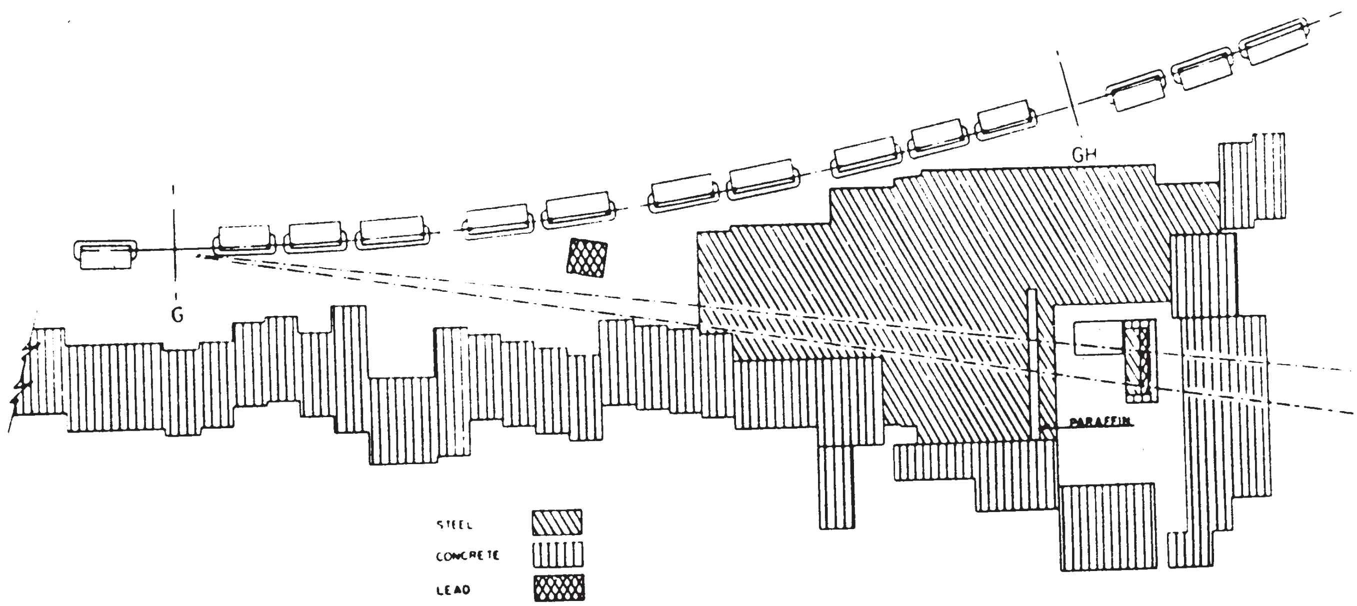
The most striking advance in understanding neutrinos had come the previous year in the wake of the earthshaking discovery of parity violation. Tsung-Dao Lee and Chen-Ning Yang (among others) proposed to rescue the deteriorating situation by invoking a peculiarity of neutrinos. If they were indeed Dirac particles with absolutely no mass, neutrinos themselves would violate parity because their spin vectors would always be aligned along their direction of motion, while the spins of antineutrinos would only point the opposite way. We say neutrinos are "left-handed" and antineutrinos "right-handed." "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," wrote Reines and Cowan.

A further consequence of this hypothesis was that the probability of reactor-produced antineutrinos interacting with protons had to be twice as large—an effect that Reines and Cowan had already begun to observe. But the most convincing proof came from a sensitive experiment at Brookhaven led by Maurice Goldhaber. He determined the spin direction of the recoiling nucleus that emerged after a europium-152 nucleus had captured one of its atomic electrons and emitted a neutrino. From this he concluded that the neutrino is always left-handed, just as Lee and Yang had suggested. Thus the neutrino and antineutrino appeared to be distinctly different, massless entities.



Artist's conception of the detector used by Reines and Cowan in their Savannah River experiment. Tanks I, II, and III contained liquid scintillator viewed on each end by 55 phototubes. Tanks A and B, containing 200 liters of water with dissolved cadmium chloride for neutron capture, served as the target volume.

A MAJOR MYSTERY in the late 1950s was whether the neutral particles emitted in pion and muon decays were the same neutrino and antineutrino as observed in nuclear decays—or something else. Because the strengths of these interactions were similar, and because they also violated parity, it was widely assumed that the very same particles were involved. But if this were the case, then muons should occasionally have been seen decaying into an electron and a photon ($\mu \rightarrow e + \gamma$). If so, the neutrino and antineutrino generated in three-body decays of muons could occasionally annihilate each other, yielding a photon in addition to the departing electron. Theorists calculated that such processes should occur about once in every 10,000 muon decays, but accurate measurements indicated that nothing like this occurred in many millions



Plan view of the two-neutrino experiment at Brookhaven National Laboratory. Pions and kaons produced by protons hitting a beryllium target at far left decayed, yielding neutrinos (and antineutrinos) that traveled from left to right, penetrating the massive steel shielding and striking the detector at the far right.

of events. One way to accommodate this apparent discrepancy was to say that two different kinds of neutrinos were involved in muon decay.

Intrigued by these questions and the possibility of resolving them by making neutrino beams, Melvin Schwartz, Leon Lederman, Jack Steinberger and their colleagues began planning an experiment at Brookhaven. Spurred by his discussions with T. D. Lee, Schwartz recognized that intense, high energy beams of protons soon to be available from its Alternating Gradient Synchrotron would allow them to generate neutrino beams with sufficient intensity (see illustration above).

With energies ranging up to several billion electron volts, these neutrinos had interaction probabilities more than a hundred times greater than reactor-born neutrinos, but a large, massive detector was still required to observe a sufficient number of them. Schwartz and his colleagues elected to build a 10 ton spark chamber from aluminum plates. If neutrinos produced in pion or kaon decays (e.g., $\pi \rightarrow \mu + \nu$) were distinct from those in beta-decays, they expected to see only the long, penetrating tracks of muons generated by neutrinos that interacted in the aluminum. However, Schwartz recalled, "If there had been only one kind of neutrino, there should have been as many electron-type as muon-type events."

In the initial run of this experiment, which began in late 1961, they recorded 34 events in which there appeared a single muon track originating in the aluminum plates. There were another 22 events having a muon and other particles, plus six ambiguous events that might have been interpreted as electrons. But comparisons with actual electron events from a separate run showed little similarity.

Thus the neutrinos produced in tandem with muons in pion and kaon decay are distinct from those