In 1951, when Fred Reines first contemplated an experiment to detect the neutrino, this particle was still a poltergeist, a fleeting yet haunting ghost in the world of physical reality. All its properties had been deduced but only theoretically. Its role was to carry away the missing energy and angular momentum in nuclear beta decay, the most familiar and widespread manifestation of what is now called the weak force. The neutrino surely had to exist. But someone had to demonstrate its reality. The relentless quest that led to the detection of the neutrino started with an energy crisis in the very young field of nuclear physics.
The Missing Energy and the Neutrino Hypothesis

During the early decades of this century, when radioactivity was first explored and the structure of the atomic nucleus unraveled, nuclear beta decay was observed to cause the transmutation of one element into another without a change in mass. Pauli, in 1930, had proposed that a nucleus undergoing beta decay should emit only a neutron, and that the neutrino (or the "little neutral one") should be found in the reaction products. Fermi, in 1934, confirmed Pauli's hypothesis, and the discovery of the neutrino was one of the great triumphs of 20th-century physics.

The Desperate Remedy

4 December 1930
Gloriastrr.
Zürich

Physical Institute of the Federal Institute of Technology (ETH) Zürich

Dear radioactive ladies and gentlemen,

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the "false" statistics of N=14 and Li=6 nuclei, as well as the continuous $\beta$-spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem. Namely (there is) the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons is the same order of magnitude as the electron mass and, in any case, not larger than 0.51 proton mass. The continuous $\beta$-spectrum would then become understandable by the assumption that in beta decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

Now, the next question is what forces act upon the neutrons. The most likely model for the neutron seems to me to be, on wave mechanical grounds (more details are known by the bearer of these lines), that the neutron at rest is a magnetic dipole of a certain moment $\mu$. Experiment probably required that the ionizing effect of such a neutron should not be larger than that of a $\gamma$-ray, and thus $\mu$ should probably not be larger than $10^{-10}$ cm.

But I don't feel secure enough to publish anything about this idea, so I first turn cordially to you, dear radioactivities, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a $\gamma$-ray. I admit that my remedy may appear to have a small priority probability because neutrons, if they existed, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous $\beta$-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Dubyé, who told me a short while ago in Brussels, "One does best not to think about that at all, like the new taxes." I thus should earnestly discuss every way of salvation. So, dear radioactivities, put it to test and set it right. Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December. With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

"In the 1957 lecture, Pauli explains, "This reads: exclusion principle (Fermi statistics) and half-integer spin for an odd number of particles; Bose statistics and integer spin for an even number of particles.""

Beta Decay and the Missing Energy

In all types of radioactive decay, a radioactive nucleus does not only emit alpha, beta, or gamma radiation, but it also converts mass into energy as it goes from one state of definite energy (or equivalent rest mass $M_1$) to a state of lower energy (or smaller rest mass $M_2$). To satisfy the law of energy conservation, the total energy before and after the reaction must remain constant, so the mass difference must appear as its equivalent energy (kinetic energy plus rest mass energy) among the reaction products.

Early observations of beta decay suggested that a nucleus decays from one state to a state with one additional unit of positive charge by emitting a single electron (a beta ray). The amount of energy released is typically several million electron volts (MeV), much greater than the rest mass energy of the electron (0.51 MeV). Now, if a nucleus at rest decays into two bodies—the final nucleus and the electron—the law of momentum conservation implies that the two must separate with equal and opposite momentum. Thus, conservation of energy and momentum implied that the electron from a given beta-decay process would be emitted with a constant energy.

Moreover, since a nucleus is thousands of times heavier than an electron, its recoil velocity would be negligible compared with that of the electron, and the constant electron energy would carry off just about all the energy released by the decay.

The graph (center) shows the unexpected results obtained from experiment. The electrons from beta decay were not emitted with a constant energy. Instead, they were emitted with a continuous spectrum of energies up to the expected value. In most instances, some of the energy released in the decay appeared to be lost. Scientists of the time wondered whether to abandon the law of energy conservation when considering nuclear processes.

Three-Body Decay and the Neutrino Hypothesis

Pauli’s solution to the energy crisis was to propose that the nucleus underwent beta decay and was transformed into three bodies: the final nucleus, the electron, and a new type of particle that was electrically neutral, at least as light as the electron, and very difficult to detect (see bottom illustration).

Thus, the constant energy expected for the electron alone was really being shared between these two light particles, and the electron was being emitted with the observed spectrum of energies without violating the energy conservation law. Pauli made his hypothesis in 1930, two years before Chadwick discovered the neutron, and he originally called the new particle the neutral one (or neutron). Later, when Fermi proposed his famous theory of beta decay (see the box "Fermi’s Theory of Beta Decay and Neutrino Processes" on the next page), he renamed it the neutrino, which in Italian means the "little neutral one."
in the initial and final states affect the overall reaction rate. Three reactions are illustrated in the lower diagrams.

The fundamental process that takes place in beta decay (see lower diagram) is the change of a neutron into a proton, an electron, and an antineutrino. The neutrino may be a free particle, or it may be bound inside the nucleus.

In analogy with quantum electrodynamics, Fermi represented beta decay as an interaction between two currents, each carrying the weak charge. The weak charge is related to the electric charge. Unlike the electromagnetic force, however, the weak force has a very short range. In Fermi’s theory, the range of the force is zero, and the currents interact directly at a single point. The interaction causes a transfer of electric (weak) charge between the currents so that, for example, the neutron current gains one unit of charge and transforms into a proton current, while the electron current loses one unit of charge and transforms into a neutrino current.*

Because Fermi’s theory is a relativistic quantum field theory, a single current-current interaction describes all weak-interaction processes involving the neutron, proton, electron, and neutrino or their antiparticles. As a result, we can represent all these weak-interaction processes with one basic diagram (on facing page, upper left corner).

Fermi’s Theory of Beta Decay and Neutrino Processes

In 1934, long before the neutrino was detected in an experiment, Fermi gave the neutrino a reality by writing down his simple and brilliant model for the beta decay process. This model has inspired the modern description of all weak-interaction processes. Fermi based his model on Dirac’s quantum field theory of electromagnetism in which two electron currents, or moving electrons, exert force on each other through the exchange of photons (particles of light). The upper diagram represents the interaction between two electrons. The initial state of the system is on the left, and the final state is on the right. The straight arrows represent currents, or moving electrons, and the wiggly line between the currents represents the emission of a photon by one current and its absorption by another. This exchange of a photon causes the electrons to repel each other. Note that the photon has no mass, a fact related to the unlimited range of the electromagnetic force.

In analogy with the electric current, each weak current is depicted as a moving particle (straight arrow) carrying the weak charge. At the point where they interact, the two currents exchange one unit of electric (weak) charge. One can adapt the basic diagram to each reaction by deciding which particles (or antiparticles) are to be viewed as the initial state and which as the final state. (Particles are represented by arrows pointing to the final state, whereas antiparticles point backward, to the initial state.) Since all the reactions described by the diagram stem from the same interaction, they have the same overall strength given by GF, Fermi’s constant. However, kinematic factors involving the amount and distribution of available energy and momentum contribute to the overall reaction rate. Three reactions are illustrated in the lower diagrams.

In the first reaction, neutron beta decay (lower left), the neutron starts out alone, but the interaction of two currents is responsible for the decay. The neutron (current) turns into a proton, and the charge is picked up by the electron/antineutrino (current) that creates a particle (electron) and an antiparticle (antineutrino). Note that the direction of the arrow for the neutrino points backwards, to the initial state, to indicate that an antineutrino has appeared in the final state.

In the second reaction, electron capture (lower center), the initial state is a proton (current) and an electron (current). The weak interaction between the two currents triggers the exchange of one unit of charge so that the proton turns into a neutron while the electron turns into a neutrino. The reverse process is also possible.

In the third case, inverse beta decay (lower right), the initial state is an antineutrino (current) and a proton (current). The weak interaction between the two currents triggers the exchange of one unit of charge so that the antineutrino turns into an antielectron (positron) while the proton turns into a neutron. Again, the arrows pointing backward indicate that an antineutrino in the initial state has transformed into an antielectron in the final state. The reverse process is also possible.

*In the modern theory, the currents interact through the exchange of the W, a very heavy particle analogous to the photon. The W carries one unit of electric charge and one unit of weak isotopic charge between the weak currents.

**For the description of the electron-neutrino reaction, the current and the antiparticle (antineutrino) are to be viewed as the initial state and which as the final state. (Particles are represented by arrows pointing to the final state, whereas antiparticles point backward, to the initial state.) Since all the reactions described by the diagram stem from the same interaction, they have the same overall strength given by GF, Fermi’s constant. However, kinematic factors involving the amount and distribution of available energy and momentum contribute to the overall reaction rate. Three reactions are illustrated in the lower diagrams.

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new subatomic particle that shares the available energy with the electron. To produce the observed energy spectrum, this new particle, later named the neutrino (“little neutral one”), could have a mass no larger than that of the electron.

The Pauli exclusion principle according to which no two identical neutrinos can be in the same state at the same time. Once created, the neutrino would speed away from the site at, or close to, the speed of light. But Pauli was concerned that the neutrinos he had postulated should have already detected.

Shortly thereafter, in a brilliant burst of insight, Enrico Fermi formulated a mathematical theory that involved the neutrino and that has endured with little modification into the present. This theory postulates a force for beta decay and incorporates several brand-new concepts: Pauli’s neutrino hypothesis, Dirac’s ideas about the creation of particles, and Heisenberg’s idea that the neutron and the proton were related to each other. In Fermi’s theory of beta decay, this weak force, so called because it was manifestly much weaker than the electromagnetic force, turns a neutron into a proton and simultaneously creates an electron and an anti-neutrino (see the box on this page). The force can act on a free neutron or on a neutron bound inside a nucleus.

Fermi’s theory is remarkable in that it accounts for all the observed properties of beta decay. It correctly predicts the dependence of the radioactive-nucleus lifetime on the energy released in the decay. It also predicts the correct shape of the energy spectrum of the emitted electrons. Its success was taken as convincing evidence that a neutrino is indeed created simultaneously with an electron every time a nucleus disintegrates through beta decay.

Almost as soon as the theory was formulated, Hans Bethe and Rudolf Peierls understood that Fermi’s theory of the weak force suggested a reaction by which a free neutron would interact with matter and be stopped. As Bethe and Bacher noted (1936), “[I]t seems practically impossible to detect neutrinos in the free state, i.e., after they have been emitted by the radioactive atom. There is only one process which neutrinos can certainly cause. That is the inverse beta process, consisting of the capture of a neutrino by a nucleus together with the emission of an electron (or positron).” Unfortunately, the weak force is so weak that the probability of inverse beta decay was calculated to be close to zero. A target would have to be light-years thick to detect a neutrino in this way.
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figure 2. Liquid Scintillation Counter for Detecting the Positron from Inverse Beta Decay

approached, we would start vacuum umps and evacuate the tank as highly possible. Then, when the countdown reached zero, we would break the suspension with a small explosive, allowing the detector to fall freely in the vacuum. For about 2 seconds, the falling detector would be seeing the antineutrino and the proton causes the proton to turn into a neutron and the antineutrino to turn into a positron ($e^+\bar{\nu}_e$). The neutron wanders about undetected. The positron, however, soon collides with an electron ($e^-$), and the particle-antiparticle pair annihilates into two gamma rays ($\gamma$) that travel in opposite directions. Each gamma ray loses about half its energy each time it scatters from an electron (Compton scattering). The resulting energetic electrons scatter from other electrons and collide with photons to create an ionization cascade (2) that quickly produces large numbers of ultraviolet (uv) photons. The scintillator is a highly transparent liquid (toluene) purposely doped with terphenyl. When it becomes excited by absorbing the uv photons, it scintillates by emitting visible photons as it returns to the ground (lowest-energy) state (3). Because the liquid scintillator is transparent to visible light, about 20 percent of the visible photons are collected by the PMTs lining the walls of the scintillation counter. The rest are absorbed during the many reflections from the counter walls. A visible photon releases an electron from the cathode of a phototube. That electron then initiates the release of further electrons from each dynode of the PMT, a process resulting in a measurable electrical pulse. The pulses from all the tubes are combined, counted, processed, and displayed on an oscilloscope screen.

Before 1952, immediately after Reines and Cowan had presented their plans at a Physics Division seminar, a new idea was born that would dramatically change the course of the experiment. J. M. B. Kellogg, leader of the Physics Division, had urged Reines and Cowan to review once more the possibility of using the neutrinos from a fission reactor rather than those from a nuclear explosion. The neutrino flux from an explosion was the best available approach—unless the background could somehow be further reduced.

Suddenly, Reines and Cowan realized how to do it. The original plan had been to detect the positron emitted in inverse beta decay (see Figure 2), a process in which the weak interaction causes the antineutrino to turn into a proton and the proton to turn into a neutron. Being an antielectron, the positron would quickly collide with an electron, and the two would annihilate each other as they turned into pure energy in the form of two gamma rays traveling in opposite directions. Each gamma ray would have an energy equivalent to the rest mass of the neutrino (1) -- no lengthy proposals or complex review committees. It may have been that the success of Operation Greenhouse, coupled with the blessing given our idea by Fermi and Bethe, eased the path somewhat! 

As soon as Bradbury approved the plan, work started on building and testing El Monstro. This giant liquid-scintillation detector was a pyramidal tank about one cubic meter in volume. Four phototubes were mounted on each of the opposing axes, and the tank was filled with very pure toluene activated with terphenyl so that it would scintillate. Tests with radioactive sources of electrons and gamma rays proved that it was possible to “see” into a detector of almost any size.

Reines and Cowan also began to consider problems associated with scaling up the detector. At the same time, work was proceeding on drilling the hole that would house the experiment at the Nevada Test Site and on designing the large vacuum tank. Current technology limited the size of detectors that could be used, and it’s release mechanism. But one late evening in the fall of 1952, immediately after Reines and Cowan had presented their plans at a Physics Division seminar, a new idea was born that would dramatically change the course of the experiment.

The neutrino flux from an explosion would be thousands of times larger than that from the most powerful reactor. The available shielding, however, would make the background noise from neutrons and gamma rays about the same in both cases. Clearly, the nuclear explosion was the best available approach—unless the background could somehow be further reduced.

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The Reines-Cowan Experiments

Los Alamos Science  Number 25  1997

The Whole-Body Counter

In 1956, Ernest C. Anderson, Robert Schuch, James Peirings, and Wright Langham developed the whole-body counter known as HUMCO I. Its design was a direct spinoff from the development of the first large liquid-scintillation detector used in Reines and Cowan’s neutrino experiments at Hanford. HUMCO I measured low levels of naturally occurring radioactivity in humans. Later, it was used in a worldwide effort to determine the degree to which radioactive fallout from nuclear tests and other nuclear and natural sources was absorbed by the human body. The detector consisted of a cylindrical container filled with 140 gallons of liquid scintillator and surrounded by 108 photomultiplier tubes. The person being measured was placed in a slide and drawn into the detector. Gamma rays emitted by the naturally occurring radioisotope potassium-40 or the fallout isotope cesium-137, for example, would largely penetrate the detector’s inner wall, excite the scintillator, and be detected. HUMCO II, which superseded HUMCO I in 1962, was nearly 10 times more sensitive, and its measurements were much faster and quieter.

The top photo shows Anderson sitting at the controls of HUMCO II. To his right is the slide that would carry Schuch inside the detector for radioactive measurement.

In 1958, the human counter was demonstrated at the Atoms for Peace Conference held in Geneva. Built especially for this conference, the vertical counter was open on one side to allow a participant to step in for measurement. The middle picture shows a conference participant getting ready to enter the detector under Newton Hayes’ supervision. The lower picture and diagram show the first human-radioactivity measurements carried out in the detector that served as the basis for HUMCO I. The original purpose of that detector had been different: to determine the degree to which the natural gamma-ray activity of the materials used to shield the Hanford neutrino detector would add “noise” to the experiments. Schuch suggested that a larger insert into the detector would allow a small person to be placed inside and then be measured for gamma-ray activity. Langham, shown crouched inside the detector, was the only member of the team slim enough to fit in the narrow space.

The Reines-Cowan Experiments

Los Alamos Science  Number 25  1997

The First Large Detector

The group spent that winter building the detectors, developing various liquid-scintillator compositions, and testing the response of the phototubes to gamma rays. Each detector was about 28 inches in diameter and 30 inches high (see photo on this page), and 90 photomultiplier tubes penetrated its curved walls. The phototubes were connected in two interleaved arrays, each of which would produce an electrical pulse in response to a light signal in the detector. The two pulses would then be sent to a prompt-coincidence circuit, which would accept them as a bona fide signal.

The Hanford Neutrino Detector

The background photo is a top view of the neutrino detector used in the Hanford experiments. It shows the interior of the 10-cubic-foot vat for the liquid scintillator and the 90 photomultiplier tubes, each with a 2-inch-diameter face that had a thin, photosensitive surface. The inset is a side view of the detector. Having a 300-liter capacity, “Herr Auge” (German for Mr. Eye, as this detector was named) was the largest detector at the time.

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In 1956, Ernest C. Anderson, Robert Schuch, James Peirings, and Wright Langham developed the whole-body counter known as HUMCO I. Its design was a direct spinoff from the development of the first large liquid-scintillation detector used in Reines and Cowan’s neutrino experiments at Hanford. HUMCO I measured low levels of naturally occurring radioactivity in humans. Later, it was used in a worldwide effort to determine the degree to which radioactive fallout from nuclear tests and other nuclear and natural sources was absorbed by the human body. The detector consisted of a cylindrical container filled with 140 gallons of liquid scintillator and surrounded by 108 photomultiplier tubes. The person being measured was placed in a slide and drawn into the detector. Gamma rays emitted by the naturally occurring radioisotope potassium-40 or the fallout isotope cesium-137, for example, would largely penetrate the detector’s inner wall, excite the scintillator, and be detected. HUMCO II, which superseded HUMCO I in 1962, was nearly 10 times more sensitive, and its measurements were much faster and quieter.

The top photo shows Anderson sitting at the controls of HUMCO II. To his right is the slide that would carry Schuch inside the detector for radioactive measurement.

In 1958, the human counter was demonstrated at the Atoms for Peace Conference held in Geneva. Built especially for this conference, the vertical counter was open on one side to allow a person to step in for measurement. The middle picture shows a conference participant getting ready to enter the detector under Newton Hayes’ supervision.

The lower picture and diagram show the first human-radioactivity measurements carried out in the detector that served as the basis for HUMCO I. The original purpose of that detector had been different: to determine the degree to which the natural gamma-ray activity of the materials used to shield the Hanford neutrino detector would add “noise” to the experiments. Schuch suggested that a larger insert into the detector would allow a small person to be placed inside and then be measured for gamma-ray activity. Langham, shown crouched inside the detector, was the only member of the team slim enough to fit in the narrow space.

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Work was exciting, exhausting, all-consuming. But there was always time for fun. In the menu composed by Hayes and Robert Schuch (c), silica gel, the chemical “jello,” is offered as a tongue-in-cheek dessert together with green men cocktail, a reminder of the green-colored solution left from rinsing the whole system before the experiment could start. The chemicals listed on the menu are some of the actual ingredients used in preparing the liquid scintillators that would fill the detector. The barrels (d) were filled with scintillator solution after the chemicals had carefully been weighed with the scale pictured in (e). Hayes is filling empty barrels (f) with that solution. The barrels would then be hauled onto the storage truck. Schuch is connecting pipes to the storage truck (g) in preparation for transferring the liquid scintillator into the detector. Through these pipes and the supply lines (i), the scintillator solution would flow into the detector.

Amid the jumble of boxes and barrels, Los Alamos researchers were feverishly preparing for the Hanford experiment.

(a) F. Newton Hayes (left) and Clyde Cowan, Jr., discuss the search for the neutrino, while two workers (b) are shielding the face of the reactor to minimize the occurrence of background events. The top of Herr Auge, the neutrino detector, is shown surrounded by an incomplete shield made of boron-paraffin boxes and huge amounts of lead.

These photos are from Robert Schuch’s private collection.
Schuch’s idea gave birth to the Los Alamos total-immersion, or “whole-body,” counter (see box “The Whole-Body Counter” on page 15), which was similar in design to the detector for Project Polgerstein but was built especially to count the radioactive contents of people. Since counting with this new device took only a few minutes, it was a great advance over the standard practice of using multiple Geiger counters or sodium iodide (NaI) crystal scintillators in an underground laboratory. The Los Alamos whole-body counter was used during the 1950s to determine the degree to which radioactive fallout from nuclear tests and other nuclear and natural sources was taken up by the human body.

The Hanford Experiment

In the very early spring of 1953, the Project Polgerstein team packed up Herr Auge, the 300-liter neutrino detector, as well as numerous electronics and hundreds of liters of liquid scintillator, and set out for the new plutonium-producing reactor at the Hanford Engineering Works in Hanford, Washington. It was the country’s latest and largest fission reactor and would therefore produce the largest flux of antineutrinos.

The Savannah River Experiment

The Hanford experience was poignantly summarized by Cowan (1964). “The lesson of the work was clear: It is easy to shield out the noise the scientists make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were not from neutron annihilation and the second from neutron capture. The two pairs would be separated by about 3 to 10 microseconds. Finally, no signal would emanate from detector III because the gamma rays from positron annihilation and neutron capture in tank A are too low in energy to reach detector III.

Thus, the spatial origin of the event could be deduced with certainty, and the signals would be distinguished from false delayed-coincidence signals induced by stray neutrons, gamma rays, and other stray particles from cosmic-ray showers or from the reactor. These spurious signals would most likely trigger detectors I, II, and III in a random combination. The all-important electronics, designed primarily by Kikio Harrison and Austin McGuire. The box entitled “Delayed-Coincidence Signals from Inverse Beta Decay” (page 22) illustrates delayed-coincidence signals from the detector’s top triad (composed of target tank A and scintillation detectors I and II). Once the delayed-coincidence signals had been recorded, the neutrino-induced event is complete. The signals from the positron and neutron circuits, which have to be picked up on delay lines, are presented to the oscilloscopes. Figure 5 shows a few samples of oscilloscope pictures—some are acceptable inverse beta decay while others are not. Austin McGuire was in charge of the design and construction of the “tank farm” that would house and transport the thousands of gallons of liquid scintillator needed for the experiment. Three steel tanks were placed on a flat, tile-covered concrete slab. The outside walls of the tanks were coated with epoxy to preserve the purity of the liquids. Having 110 photomultiplier tubes to collect scintillation light and produce electronic signals.

In this sandwich configuration, a neutrino-induced event in, say, tank A would create two pairs of proton prompt-coincidence pulses from detectors I and II flanking tank A. The first pair of these was from positron annihilation and the second from neutron capture. The two pairs would be separated by about 3 to 10 microseconds. Finally, no signal would emanate from detector III because the gamma rays from proton annihilation and neutron capture in tank A are too low in energy to reach detector III.

Today, the need for purity and cleanliness is becoming legendary as researchers build an enormous tank for the next generation of solar-neutrino experiments (see the article “Exorcising Ghosts” on page 136), but even in the 1950s, possible background contamination was an overriding concern. Since the scintillator had to be kept at a temperature not lower than 60 degrees Fahrenheit, the outside walls of the tanks were wrapped with several layers of fiberglass insulating material, and long strips of electrical heating elements were embedded in the exterior insulation.

During the previous winter, while the equipment was being designed and built, John Wheeler encouraged and supported the team, and he helped pave the way for the next neutrino measurement to be done at the new, very powerful fission reactor at the Savannah River Plant in South Carolina. By November 1955, the Los Alamos group was ready and once again packed up for the long trip to the Savannah River Plant. The only suitable place for the experiment was a small, open area in the basement of the reactor building, barely large enough to house the detector. There, 11 meters of concrete would separate the detector from the reactor core and serve as a shield from reactor-produced neutrons, and 12 meters of overburden would help eliminate the troublesome background neutrons, charged particles, and gamma rays produced by cosmic rays.

The Reines-Cowan Experiments

Figure 4. The Savannah River Neutrino Detector—A New Design

The neutrino detector is illustrated here inside its lead shield. Each of two large, flat plastic tanks (pictured in light blue and labeled A and B) was filled with 200 liters of water. In the water provided the target for inverse beta decay; cadmium chloride dissolved in the water provided the cadmium nuclei that would capture the neutrons. The target tanks were sandwiched between three large scintillator tanks (called I, II, and III), each of which was 200 liters. The neutrino detector is illustrated here inside its lead shield. Each of two large, flat plastic tanks (called I, II, and III) was filled with water. The protons in the water provided the target for inverse beta decay; cadmium chloride dissolved in the water provided the cadmium nuclei that would capture the neutrons.

The box entitled “Delayed-Coincidence Signals from Inverse Beta Decay” (page 22) illustrates delayed-coincidence signals from the detector’s top triad (composed of target tank A and scintillation detectors I and II). Once the delayed-coincidence signals had been recorded, the neutrino-induced event is complete. The signals from the positron and neutron circuits, which have to be picked up on delay lines, are presented to the oscilloscopes. Figure 5 shows a few samples of oscilloscope pictures—some are acceptable inverse beta decay while others are not. Austin McGuire was in charge of the design and construction of the “tank farm” that would house and transport the thousands of gallons of liquid scintillator needed for the experiment. Three steel tanks were placed on a flat, tile-covered concrete slab. The outside walls of the tanks were coated with epoxy to preserve the purity of the liquids. Having 110 photomultiplier tubes to collect scintillation light and produce electronic signals.
After years of intense work, the members of the Los Alamos team were ready for the Savannah River experiment that would fulfill their much expected goal—the definitive detection of the neutrino.

Pictured in (a) is the tank farm, which was composed of three 4,500-liter steel tanks placed on a flat-bed trailer. The liquid scintillator was stored and shipped in those tanks. The outside walls of the tanks were wrapped with fiberglass insulation, and long electrical heating strips were embedded in the insulation to prevent the temperature inside the tanks from falling below 60 degrees Fahrenheit. Had the temperature fallen below this limit, the liquid scintillator would have turned from transparent to cloudy and would have become unusable in the experiment. (b) Fred Reines (left) and Clyde Cowan, Jr., discuss their last-minute plans for the Savannah River experiment. No detail is left uncovered. Resting in a special forklift built to handle the detector sections, one of the two target tanks filled with water and cadmium chloride is shown (c) awaiting its assembly in the detector shield. A completed detector tank (d) is ready to be inserted into the shield. This tank was made of steel plate, but its bottom was a cellular aluminum structure that would provide not only strength against bending but also little obstruction to the entry of gamma rays from below. (e) Pictured here is the additional shielding that surrounded the detector and allowed the team to test whether the signal was coming from background neutrons and gamma rays from the reactor. This makeshift shielding, which was 4 feet thick all around the detector, consisted of bags of sawdust soaked in water for increased density (the mean density was 0.5). Its effect was to decrease the reactor-associated accidental events, whereas the signal remained constant. (f) Los Alamos team members Richard Jones (left) and Martin Warren use a forklift to insert the top target tank into the detector shield. Moving by hydraulic control, heavy lead doors (pictured behind Warren) would enclose the detector when it was on. Preamplifiers placed on a rack (pictured behind Jones) boosted the small-voltage pulses from the photomultiplier tubes and sent them through coaxial cable to the electronics housed in a truck (g) that was parked outside the reactor building.

Photos (c), (d), (e), and (f) were reprinted courtesy of Smithsonian Institution.
he very large detector—over 2 meters high and weighing about 10 tons—had to be installed in those cramped underground quarters. There was just enough room left for several preamplifiers (needed to boost the signal) to be set on a rack near the detector, but the electronics had to be used outside, in a trailer. The tank containing the precious liquid was parked outside. An antimurine (red dashed line) from the reactor has interacted with a proton in tank A through inverse beta decay, creating a positron and a neutron. As a result, two processes occur in tank A: positron annihilation, shown in diagram (a), and neutron capture, shown in diagram (b). In the case illustrated here, the delay between the two processes is 3 microseconds.

In diagram (a), the encounter between a positron and an electron in tank A results in two gamma rays, which go into scintillation detectors I and II, give up their energy, and produce a flash of visible light proportional to that energy. The photomultiplier tubes in each detector convert the light into an electronic signal, which is sent first to the positron signal discriminator and then to the positron prompt-coincidence circuit. The discriminator will accept the signals from detectors I and II if they are within the right energy range (between 0.2 and 0.6 MeV). The prompt-coincidence circuit will accept them if they arrive less than 0.2 microseconds apart. In this case, both conditions are fulfilled. The timer starts to tick and closes the switch to the neutron prompt-coincidence circuit for 30 microseconds, allowing signals from neutron capture to be recorded during that period.

Thus, the accidental background rate could be estimated as the rate of delayed coincidences that occurred with neutron-capture delay times between 11 and 30 microseconds. Using this estimate, the team derived the rate of signal to accidental background events to have been 4 to 1.

Although the delayed-coincidence signal is a telltale signature of inverse beta decay, the Los Alamos team members took nothing for granted. They tested their measured signal extensively to ensure that it was indeed due to the products of neutrino-induced inverse beta decay, in particular that:

- the first and second prompt-coincidence pulses were generated by positron annihilation and neutron capture, respectively, rather than other processes,
- the signal was proportional to the number of target protons, and
- the signal was not due to neutrons and gamma rays from the reactor.

For example, to check the positron signal, the Los Alamos researchers compared the pair of prompt-coincidence pulses making up the positron signal with those produced during a test run by a positron source (copper-64) dissolved in the water. To check the neutron capture signal, they doubled the amount of cadmium in the water to a lower energy state by emitting gamma rays, which once again creates flashes of visible light in detectors I and II. The photomultiplier tubes detect that light and are shown to have produced two electronic signals whose energy is within the acceptable range, that is, the energy is greater than 0.2 MeV in each detector, with a total energy from 3 to 11 MeV (as determined by the discriminator). The signals are less than 0.2 microseconds apart in reaching the neutron prompt-coincidence circuit. Thus, they are accepted as a true signal of neutron capture. At this point, the timer has advanced to 3 microseconds, indicating the delay between the two processes. The delayed-coincidence signals caused by the neutrino-induced inverse beta decay is now complete. A scaler is automatically activated, the recording oscilloscopes are triggered to sweep across the cathode-ray screens, and the signals from the positron and neutron circuits, which have been stored on delay lines, are presented to the oscilloscopes.

Once obtained, a large-scale text file is used to explore various aspects of the delayed-coincidence signal and the instrumentation used to detect it. The text file contains a detailed description of the experiment, the results obtained, and the conclusions drawn. It also includes references to other experiments and research in the field.

This flow diagram traces the generation of a set of delayed-coincidence signals in the top triad of the detector (target tank A and scintillation detectors I and II). An antimurine (red dashed line) from the reactor has interacted with a proton in tank A through inverse beta decay, creating a positron and a neutron. The ne
Figure 5. Oscilloscope Traces from the Savannah River Experiments
In these oscilloscope pictures, traces from detectors I, II, and III are labeled I, II, and III, respectively. The latter two frames of each channel indicate whether the signals were recorded by the scope for positron annihilation or for neutron capture. Acceptable delayed coincidences are shown in (a) and (b), while rejected signals are pictured in (c) through (f).

(a) The delayed-coincidence signal in these two frames has occurred in the top triad of the detector because the pulses appeared in detectors I and II. Positron scope: The pulse energies in detectors I and II were 0.30 MeV and 0.35 MeV, respectively. The pulses reached the positron circuit in prompt coincidence (less than 0.2 microsecond apart) and were accepted as a signal of positron annihilation. Neutron scope: The pulse energies in detectors I and II were 5.8 MeV and 5.3 MeV, respectively. These pulses arrived in prompt coincidence and were accepted as a signal of neutron capture. The neutron and neutron signals were 2.5 microseconds.

(b) The delayed-coincidence signal in these two frames has occurred in the bottom triad because the pulses appeared in detectors II and III. Positron scope: The pulse energies in detectors II and III were 0.25 MeV and 0.30 MeV, respectively. The delay between the positron and neutron signals was 13.5 microseconds. (c) The pulses from the neutron circuit were the result of electrical noise. (d) Three of these signals from the neutron circuit were caused by a cosmic-ray event. (e) These three pulses from the positron circuit were caused by a cosmic-ray event. (f) These pulses may have been caused by a cosmic-ray event. They were rejected as a signal of neutron capture because the extra pulse from detector II. Frames like this one occurred more often than would be expected from chance coincidences. They were, however, not often enough to affect the results considerably. These data appeared in Reines, Cowan, Harrison, et al. 1960.
Frederick Reines is best known for his discovery of the nearly massless elementary particle, the neutrino. For this work, he was awarded the Nobel Prize in physics in 1956. Collaborating with Clyde Cowan, Jr., Reines determined conclusively the existence of the neutrino during experiments conducted at the Savannah River Plant in 1956. Subsequently, Reines devoted his career to investigating the properties and interactions of the neutrino as it relates not only to elementary particle physics but also to astrophysics.

This lifelong research produced a number of fundamental "firsts" credited to Reines. One of the most recent achievements, the codiscovery of neutrinos emitted from supernova 1987A (SN1987A), demonstrated the theoretical role of the neutrino in stellar collapse. Reines captured the difficulty of this work vividly: "It's like listening for a giant's whisper in a hurricane."

Significant other firsts include detecting neutrinos produced in the atmosphere, studying muons induced by neutrino interactions underground, observing the scattering of electron antineutrinos with electrons, detecting weak neutral-current interactions of electron antineutrinos with deuterons, and searching for neutrino oscillations (the possibility of neutrino transformation from one type to another). In addition, Reines and his coworkers have pursued for nearly forty years a program of experiments to test some of the fundamental conservation laws of nature, including conservation of lepton number (which would be violated in the decay of an electron or neutrino or in the change of lepton type) and conservation of baryon number, which would be manifested in the decay of the proton, as predicted by the Gell-Mann Unified Theories of elementary particles.

Reines was born in Paterson, New Jersey, on March 16, 1918. He earned his M.E. in mechanical engineering in 1939 and his M.A. in science in 1941 from Stevens Institute of Technology in Hoboken, New Jersey. He received his Ph.D. in theoretical physics from New York University in 1944. That same year, he joined the Los Alamos Scientific Laboratory as a staff member, later to become group leader in the Theoretical Division, and was tasked to study the blast effects of nuclear weapons. In 1959, Reines became head of the Physics Department at Case Institute of Technology. At the same time, he served as consultant to Los Alamos and the Institute for Defense Analysis, as well as trustee of the Argonne National Laboratory. In 1966, however, Reines accepted a dual appointment as the first dean of physical sciences and physics professor at the University of California, Irvine. Four years later, he was appointed professor of radiological sciences at Irvine's Medical School. When Reines retired in 1988, he was Distinguished Emeritus Professor of Physics at Irvine.

For his outstanding work in elementary particle physics, Reines has received numerous honors and major awards. In 1957, he became fellow of the American Physical Society; in 1959, Guggenheim fellow; in 1959 Alfred P. Sloan fellow; in 1977, fellow of the American Association for the Advancement of Science; and in 1980, member of the National Academy of Sciences. In 1981, Reines received the J. Robert Oppenheimer Memorial Prize. He was the present National Medal of Science by President Ronald Reagan in 1983, the Bruno Rossi Prize in 1989, the Michelson-Morley Award in 1990, the W. K. H. Paneth Prize and the Franklin Medal in 1992. He is a member of the American Academy of Arts and Sciences.

During a 1985 interview with The New York Times, Reines laboroned when he was asked to describe the significance of his discovery of the neutrino: "I don't say that the neutrino is going to be a practical thing, but it has been a time-honored pattern that science leads, and then technology comes along, and then, put together, these things make an enormous difference in how we live." And now, more than forty years after the discovery of the neutrino, Reines' scientific peers believe that this discovery made Reines a giant in his field.

Clyde L. Cowan, Jr., was born in Detroit, Michigan, on December 6, 1919. He earned his B.S. in chemical engineering at the Missouri School of Mines and Metallurgy (later to become part of the University of Missouri) in 1940 and his M.S. and Ph.D. in physics from Washington University in St. Louis, Missouri, in 1947 and 1949, respectively.

During the Second World War, Cowan joined the U.S. Army Chemical Warfare Service as a 2nd lieutenant and shortly thereafter left for England with the 51st Troop Carrier Wing. While he was stationed in England, Cowan was involved in making changes to the newly developed radar. For this significant work, he was later awarded the Bronze Star.

Soon after the war, Cowan returned to the United States where he was accepted as the first physics graduate student to Washington University. His thesis was an in-depth study of the absorption of gamma radiation. Soon after graduate school, Cowan realized that Los Alamos was the logical place for him to work, and in 1949 he joined the Laboratory as a staff member. Only two years later, Cowan became group leader of the Nuclear Weapons Test Division at Los Alamos.

In 1951, Cowan began a historic collaboration with Fred Reines. Its outcome was the successful detection of the neutrino during an experiment conducted at the Savannah River Plant in 1956. After this discovery, neutrino physics became seminal to worldwide studies of the weak force. In 1957, Cowan was awarded a Guggenheim fellowship to study the physics of the neutrino and its interactions with atomic nuclei.

Cowan's creativity has been a mark of his scientific career from the early and fruitful years in Los Alamos to the successful teaching years at the Catholic University of America, where he was a physics professor from 1958 until his untimely death in 1974. Upon his suggestion, the bubble chamber became a tool for studying neutrino interactions. Cowan was one of the first physicists who used large scintillation counters for particle detection, an important technique in elementary particle physics. His collaboration with Reines led to the development of the whole-body counter, which measured low levels of naturally occurring radiation in humans. Having witnessed about thirty nuclear explosions while he was in the Nuclear Weapons Test Division at Los Alamos, Cowan was among the first to have studied the electromagnetic signal produced by a nuclear explosion.

Throughout his career, Cowan served as a consultant to the United States Naval Academy, the U.S. Atomic Energy Commission, the Naval Ordnance, and the Smithsonian Institution, where he helped create the permanent Hall of Nuclear Energy. Cowan was a fellow of the American Physical Society and the American Association for the Advancement of Science. He was a member of numerous scientific and civic organizations. Hailing dedicated his life to scientific investigation, Cowan has been a source of inspiration to generations of young, aspiring scientists.