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Physics in Perspective

Detecting the Neutrino

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In 1930 Wolfgang Pauli suggested that a new particle might be required to make sense of the radioactive-disintegration mode known as beta decay. This conjecture initially seemed impossible to verify since the new particle, which became known as the neutrino, was uncharged, had zero or small mass, and interacted only insignificantly with other matter. In 1951 Frederick Reines and Clyde L. Cowan, Jr., of the Los Alamos Scientific Laboratory undertook the difficult task of detecting the free neutrino by observing its inverse beta-decay interaction with matter. They succeeded in 1956. The neutrino was accepted rapidly as a fundamental particle despite discrepancies in reported details of the experiments and despite the absence of independent verification of the result. This paper describes the experiments, examines the nature of the discrepancies, and discusses the circumstances of the acceptance of the neutrino's detection by the physics community.

Key words: History of Science; neutrino; nuclear physics; particle physics; beta decay; Frederick Reines; Clyde L. Cowan, Jr.

Introduction

At the end of the nineteenth and beginning of the twentieth century, when radioactivity was first being studied, the decay mode of the atomic nucleus known as beta decay was found to be accompanied by the transmutation of one element into another. In analogy to the unique energies of alpha particles emitted in the alpha decay of a particular nuclear species, physicists expected that a well-defined amount of energy would be released in the beta-decay process, that is, that the beta particle or electron should carry off the same amount of kinetic energy in every decay of nuclei of the same radioactive species. Beta particles proved to be difficult to study, however, and it was not until the late 1920s that it became clear that something was wrong – that the energies of electrons emitted by a particular nuclear species formed a continuous energy spectrum.[1] This suggested either that energy was not conserved or that the beta-decay process was more complicated than the simple emission of an electron, specifically that some of the decay energy was dissipated in a form other than the electron's kinetic energy.

There were other troubles as well. During the 1920s, the combination of quantum theory and experimental optical spectroscopy was immensely productive and much physics and chemistry research was aimed at a consistent description of various properties of the atom and its nucleus. At that time there were only three known

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"particles" in nature: the proton (the nucleus of the hydrogen atom), the electron, and the photon. The prevailing model of the atom was a combination of A protons (A = atomic mass number) in the nucleus of the atom and a total of A electrons: A–Z of them inside the nucleus, and Z (Z = atomic number) of them as orbital electrons outside the nucleus. This gave the right mass for the nucleus, a positive charge of Z for the nucleus, and an electrically neutral atom. But several difficulties emerged, mostly from spectroscopic studies, as more became known about the atom.[2] By 1929, Niels Bohr was fully prepared to give up both energy conservation and the applicability of quantum mechanics to the nucleus to accommodate these problems. He opined that the behavior of nuclear electrons lay outside of "existing quantum mechanics" and that it would require the development of a "new physics."[3]

In December 1930, Wolfgang Pauli suggested very tentatively that neutral particles might exist within atomic nuclei and carry away some of the beta-decay energy and that this "desperate remedy," as he put it, might save the day.[4] Bohr and Pauli differed until 1936, with Bohr unwilling to countenance a new particle and Pauli unwilling to give up conservation of energy. Neither Bohr nor Pauli realized initially that the various ailments that had been identified demanded two distinct remedies. Pauli's conjecture, which he had called a "neutron," had some properties in common with what we now call the neutron and some in common with what we now call the electron neutrino.*

Even the 1932 discovery of what we now call the neutron[5] – the neutral particle, constituent of the nucleus, with a mass slightly larger than that of a proton – did not lead to immediate simplification of the dilemma. The discoverer of the neutron, James Chadwick, described it as consisting "of a proton and an electron in close combination" that made it possible "to avoid the presence of uncombined electrons in a nucleus." While he admitted that it is "possible to suppose the neutron is an elementary particle," he stated that "this view has little to recommend it at present." The disputation over whether Chadwick's neutron was a fundamental particle of nature or a proton-electron composite went on for two years. There was a genuine reluctance to postulate the existence of additional fundamental particles.

Finally, the satisfying nature of Enrico Fermi's 1934 theory of beta decay began to lift the veil.[6] In this theory the weak interaction, so-called because it is much weaker than the electromagnetic force, turns a neutron in the nucleus into a proton and simultaneously creates an electron and a neutrino. In Fermi's scheme, the neutrino is uncharged and has a small mass and carries away some of the decay energy as kinetic energy, thus giving rise to the continuous beta spectrum. Energy, and other critical properties such as linear momentum and angular momentum, are all conserved.

With Fermi's weak force it was also possible to consider inverse beta-decay reactions by which a free neutrino would interact with matter and be stopped. In the simpler language that was appropriate before particle-antiparticle distinctions were clearly established, a neutrino interacting with a neutron would yield a proton

* The neutrino of ordinary beta decay became known as the electron neutrino (or, more correctly, the electron antineutrino) to distinguish it from the mu and tau neutrinos that were discovered later.

and an electron. A neutrino interacting with a proton would give a neutron and a positron, a positively-charged electron. The positron* also had been discovered in 1932.[7] Unfortunately, Fermi's weak force is so weak that the probability of inverse beta decay was predicted to be close to zero. Hans Bethe and Rudolf Peierls calculated the interaction cross section to be less than "10^{-44} cm^2 (corresponding to a penetrating power of 10^{16} km in solid matter)" and stated that, "It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations."[8] It seemed as if the neutrino might ever remain a ghost particle if detection meant observation of the inverse reaction. In this paper, which is based on the published literature, on archival materials, and on interviews, I describe the detection and acceptance of the free neutrino more than a quarter century after Pauli's suggestion.

Wanted: An Intense Source of Neutrinos

As time passed, philosophical opposition to new particles began to fade. The reluctance was overwhelmed by: (1) inescapable evidence that the sub-atomic world could not be described solely in terms of the known constituents of atoms; this evidence emerged as cosmic rays were investigated and as particle accelerators reached higher and higher energies; (2) the tidiness provided by Fermi's beta-decay theory and Pauli's neutrino hypothesis; (3) the continuing success of quantum mechanics; and (4) the strengthening of belief in the broad applicability of fundamental conservation laws, such as conservation of energy. The neutrino concept became more acceptable. Many experiments were carried out in attempts to measure some neutrino property, such as mass, or to check on the role of the neutrino in conserving linear momentum by studying recoils in beta-decay experiments. The recoil experiments lent plausibility to the existence of the neutrino, but did no more than demonstrate repeatedly that the dynamics of the decays under study were consistent with the neutrino hypothesis. Charles Atchley's study of the acceptance of the neutrino hypothesis has covered this background thoroughly.[9] In addition, as more and more experimental evidence regarding beta decay was amassed, the Fermi theory continued to enjoy success. However, as H. Richard Crane noted in a 1948 summary of experimental evidence for the neutrino:

> Not everyone would be willing to say that he believes in the existence of the neutrino, but it is safe to say that there is hardly one of us who is not served by the neutrino hypothesis as an aid to thinking about the beta-decay process … .While the hypothesis has had great usefulness, it should be kept in the back of one's mind that it has not cleared up the basic mystery, and that such

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* The positron is the antiparticle of the negative electron of ordinary matter and of beta decay following nuclear fission. Unless qualified, the word neutrino, as used in this paper, stands for either the electron neutrino (ν) or its antiparticle, the electron antineutrino ($\bar{\nu}$). Beta decay following fission produces an electron antineutrino and this, interacting weakly with a proton, yields a positron and a neutron. Solar energy processes and the accelerator-based neutrino experiment described later in this paper produce electron neutrinos that interact weakly with neutrons to yield protons and negative electrons.

will continue to be the case until the neutrino is somehow caught at a distance from the emitting nucleus.[10]

The experiments of Frederick Reines and Clyde L. Cowan, Jr. (figures 1 and 2), who were both at Los Alamos Scientific Laboratory, sought to take the next step, to observe inverse beta decay away from the site of the neutrino's origin by exploiting two new developments: (1) the availability of high-flux sources of neutrinos, in the form of nuclear fission bombs and reactors, and (2) the power, zest, and resources of "Big Science" that had emerged during World War II.[11]

Fred Reines was a theoretical physicist who had received his Ph.D. degree from New York University in 1944. He then joined Los Alamos Scientific Laboratory (LASL) and the nuclear weapons' testing program. Norris Bradbury, the Director who succeeded J. Robert Oppenheimer as head of LASL, gave his approval in 1951 when Reines suggested using the intense burst of neutrinos from the detonation of a nuclear weapon, specifically from beta decays following the splitting of ^{235}U in a fission bomb, as a source for a detection experiment. Reines estimated that a sensitive target volume of about one ton would be needed to stop a few neutrinos

Fig. 1. Frederick Reines in the 1950s. Courtesy of the Regents of the University of California, operators of the Los Alamos National Laboratory for the Department of Energy.

Fig. 2. Clyde L. Cowan, Jr., in the 1950s. Courtesy of the Regents of the University of California, operators of the Los Alamos National Laboratory.

in inverse beta-decay reactions, and that the products of these reactions would signal the presence of the neutrinos *if* the reaction products could be detected.

Shortly thereafter, Reines found himself stranded in the Kansas City airport with Clyde Cowan, who had joined the Los Alamos weapons' testing program in 1949. Reines told Cowan about his notion for detecting neutrinos. They became a team. Cowan had studied chemical engineering as an undergraduate and served in the army in World War II where he worked on radar. After the war he entered graduate studies in physics at Washington University, St. Louis, and received his Ph.D. degree in 1949. His thesis – he was an experimentalist – involved the absorption of gamma rays.

Reines and Cowan decided to exploit a new detection technology, a liquid scintillation counter, to detect the products of the inverse beta-decay reaction.[12] The experiment called for the detonation of a 20-kiloton fission bomb on a 30-meter high tower, with the base of the tower approximately 40 meters from the mouth of a vertical hole at the bottom of which a vacuum tank was placed beneath several meters of backfill to shield the detector from neutrons and gamma rays from the bomb. The detector was to fall freely in the vacuum tank for two seconds following the instant of detonation and come to a soft landing while detecting positrons and neutrons from the interaction of neutrinos with protons in the scintillation liquid.

Reines and Cowan planned to return to the site a few days later, after the surface radioactivity had died down, to dig up the record. Work began on the hole (150 feet deep), on the vacuum tank (10 feet in diameter and 75 feet tall), and on the detector. In the fall of 1952, they realized that a nuclear reactor would also work as a source of neutrinos if they could reduce the background from other events, which they could do if they could detect the flashes from both the positron and the neutron as separate but related signals. There also were other advantages in the use of a reactor as the source, such as ease in repeating a measurement and the opportunity to extend the observation time to reduce statistical uncertainty. They abandoned the idea of detonating a bomb and turned their attention in this new direction.

The Hanford Neutrino Experiment of 1953

Reines and Cowan's first detector had a volume of 300 liters of liquid scintillator in a cylindrical tank 28 inches in diameter and 30 inches high and incorporated ninety 2-inch-diameter photomultiplier tubes (figure 3). The detector was set up and heavily shielded near the wall of C Reactor, a new plutonium-producing reactor at the Hanford Engineering Works near Richland, Washington. The shielding was intended to stop reactor neutrons and gamma rays not induced by neutrinos from entering the detector and producing unwanted background.

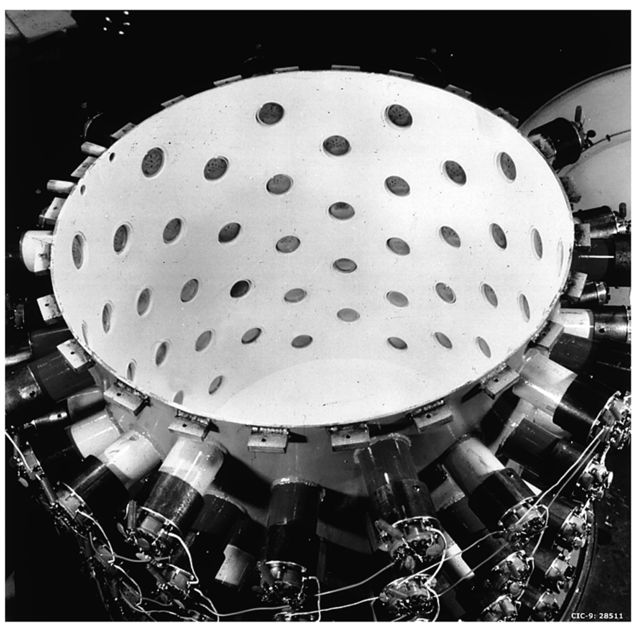

Fig. 3. The scintillation detector for the 1953 neutrino detection experiment at Hanford. Courtesy of the Regents of the University of California, operators of Los Alamos National Laboratory.

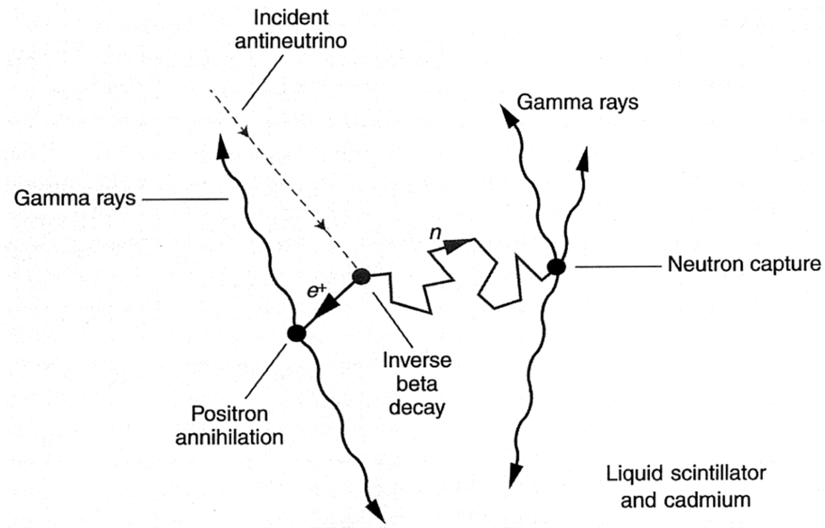

Fig. 4. The signature of the inverse beta-decay reaction has two parts. Two oppositely-directed 0.511-MeV gamma rays resulting from positron (e^+) annihilation are the first signal of the reaction. The first signal is followed a few microseconds later by a second signal due to energetic gamma rays from neutron capture in cadmium. Courtesy of the Regents of the University of California, operators of Los Alamos National Laboratory.

The scintillation liquid, a mixture of organic compounds that emitted a flash of light when excited by radiation, contained protons and served both as target and detector. Fission antineutrinos interacting with protons give rise to energetic positrons of significant intensities in the range of 1–5 MeV (million electron volts) and to neutrons with typical energies of 10 keV (thousand electron volts). The positrons slow down quickly and annihilate, giving rise to two oppositely-directed 0.511-MeV gamma rays. The scintillation liquid also contained a small amount of dissolved cadmium salts to capture the neutrons, giving rise to energetic capture gamma rays. The neutrons slow down less rapidly, through elastic collisions, until they reach energies, typically below 0.2 eV, at which cadmium has a large neutron-capture cross section (figure 4). Two independent electronic gates were set, one to accept pulses characteristic of the prompt positron signal (2–5 MeV in the final set of runs), the other set to accept the neutron-capture signal (energy range 2–7 MeV) which appeared later. If a pulse appeared in the neutron channel within a fixed time (1–9 microseconds) after a pulse in the positron channel, a delayed coincidence (presumably a neutrino-capture event) was counted. Counts were recorded with the reactor on and when it was off.

The background turned out to be larger than expected, mostly owing to cosmic rays that mimicked the neutrino events. This gave rise to a very poor signal-to-noise ratio (about 1 to 20) even after a Geiger-Müller anticoincidence blanket and additional shielding had been added. Reines, Cowan, and their co-workers also had serious problems with the detector electronics, with intermittent electrical noise, and with varying reactor background.

In describing their 1953 experiment, as in reports of their later 1956 experiments, Reines and Cowan cited both the signature of the event and the measured cross section as evidence of the neutrino. Luis Alvarez had pointed out in 1949* the important role ascribed to the cross section:

> Although it would be important to know that the cross section is less than 10^{-41} cm^2, nothing could be concluded about the existence of the neutrino from such information. However, if it could be shown that the cross section were less than 10^{-45} cm^2, the whole neutrino theory would have to be re-examined critically, and it is quite possible that the theory would have to be discarded. If, on the other hand, a cross section of this magnitude were observed, it would prove conclusively that neutrinos had a real existence … . [Every] effort should be made to increase the sensitivity to the point where the theoretical cross section would yield an effect many times the expected background … .[13]

During their 1953 experiment, Reines and Cowan used their observed counting rate from time-to-time to calculate the experimental cross section and to compare it with the theoretical value – to determine whether the events they were seeing were actually due to neutrinos.[14] The results of these checks, based on arbitrary assumptions about the signal-to-noise ratio, were not convincing.

A net counting rate of 0.41 ± 0.20 counts per minute (*i.e.*, 25 ± 12 events per hour) was the difference between a reactor-on counting rate of 2.55 ± 0.15 counts per minute and a reactor-off rate of 2.14 ± 0.13 counts per minute. These results, reported in a Letter to the Editor in *The Physical Review*, were based on less than three hours of useful reactor-on time and less than two hours of useful reactor-off time. They reported that this net counting rate (0.41 ± 0.20 events per minute) "is to be compared with the predicted $\sim 1/5$ count/min due to neutrinos, using an effective [theoretical] cross section of $\sim 6 \times 10^{-20}$ barn [$\sim 6 \times 10^{-44}$ cm^2] for the process." They stated that "it appears probable that this aim [to detect the free neutrino] has been accomplished although further confirmatory work is in progress."[15]

Reports of these results also appeared in *The New York Times*, *Scientific American*, and *Time*.[16] Reporting on a paper presented at the 1954 winter meeting of the American Physical Society at Columbia University, a press release by *Science Service* stated that "the physicists [Reines and Cowan] are confident that … they have 'seen' the elusive neutrino … [The] textbooks that now say that the neutrino has never been detected will have to be revised … . [The] poltergeist of modern physics … has been caught."[17]

* Although Alvarez's paper described the experimental method that later became the basis for the detection of solar neutrinos, it was not known in 1953, when it was cited by Reines and Cowan (n. 5 in the report of their 1953 experiment), that reactor neutrinos (*i.e.*, electron antineutrinos) could not be detected by the method proposed by Alvarez. It is interesting to note that Alvarez concluded that shielding equivalent to 60 feet of water would be needed to reduce the cosmic-ray background to the level needed to make a useful cross section measurement. A subsequent Hanford report by C. W. J. Wende ("Neutrino Test," HW-13466, May 23, 1949) pointed out that this was not possible at any existing or planned Hanford reactor without digging an underground tunnel to enclose the detector.

In contrast to the optimistic reports in the popular press, Cowan made the following entry in one of their laboratory notebooks in August 1953:

> Although we cannot explain the change in counting rate when the pile went down except as due to the neutrino, we realize that we have not proved anything. As the observed counting rate due to the pile was very close to the predicted rate, if the signal was spurious then the actual cross section lies below the theoretically predicted one. Quite certainly, the "non-pile" counting rate was due to cosmic rays which penetrated our shielding and escaped the G.M. [Geiger-Müller] blankets.
>
> Our thoughts up to this point have been in the direction of making a larger detector and using it *beneath* a pile, where we would hope to find adequate shielding from cosmic radiation … .[18]

As Reines would later say on many occasions, the results were "inconclusive." Indeed, they realized at an early stage that there were serious problems in the experiment; they already had begun in March – two months before they saw what Reines later described as a "hint" of the neutrino – to plan a new and bigger detector.[19] The hint was sufficiently subtle that it was not recognized until after they had left Hanford and therefore were unable to take more data using the same experimental conditions.

Reines, Cowan, and their co-workers published three additional papers in 1954 based on work related to the Hanford experiment. These involved: (1) a measurement of a lower limit for the lifetime of the proton, performed at an underground location near Los Alamos after returning from Hanford; (2) detection of neutrons with the Hanford liquid-scintillation counter, using the general cosmic-ray background as the source of neutrons; and (3) measurement of the upper limit of the neutrino magnetic moment as deduced from the Hanford results.[20]

The First Savannah River Experiment of 1956

Reines and Cowan redesigned their inverse beta-decay experiment from top to bottom. Their new detector is shown in figure 5. It had five components in a multi-layered ("club-sandwich") arrangement. Each of two target tanks, the "meat" layers shown as A and B, was filled with 200 liters of water. The protons in the A and B tanks provided the target for inverse beta decay; cadmium chloride dissolved in the water provided the cadmium nuclei that would capture the neutrons. The two target tanks were placed between three "bread" layers, scintillation detector tanks (I, II, and III). Each detector (2 feet by 6 feet 3 inches by 4 feet 6 inches) contained 1400 liters of organic liquid scintillator that was viewed by 110 5-inch-diameter photomultiplier tubes.

In this configuration, a neutrino event in target tank A, for example, would give rise to two sets of pulses from detectors I and II flanking target tank A. The first set (in time of appearance) would be from positron annihilation (two oppositely-directed gamma rays each of 0.511 MeV) and the second set, appearing 3–10 microseconds later, would be from neutron capture (three or more photons totaling about 9 MeV in energy). Coincidence signals triggered three-beam oscilloscopes showing the pulses in I, II, and III; the signals were recorded photographically. The photographs were examined to reject spurious events, such as simultaneous appearance of signals in all three detector tanks signifying the passage of a cosmic ray.

Late in 1955 Reines and Cowan moved their new detector to an underground location adjacent to a new tritium-production reactor at the Savannah River (South Carolina) Plant of the U.S. Atomic Energy Commission. Eleven meters of concrete separated the detector from the reactor core, and therefore from reactor-produced neutrons and twelve meters of shielding from above helped eliminate cosmic rays. They completed the installation of the detector and target tanks and shielding by the end of February 1956. The coincidence electronics was operated in a tractor trailer (figure 6) parked adjacent to the reactor building. By mid-April the detection system had been tested and a reactor-power-dependent signal had been observed. Various measurements were undertaken to demonstrate that this signal was indeed due to neutrino-induced inverse beta decay. These entailed, for example, demonstrating that the signal rate was proportional to the total number of target protons, which was checked by remeasuring the signal rate after diluting the light water in the target with heavy water. They also showed that the first prompt-coincidence pulse was due to positron annihilation, which required, in part, comparison of the pulse-height spectrum of the first pulse to that obtained from a positron-emitting radioactive source; and that the second prompt-coincidence signal was due to neutron capture in cadmium, which they showed by observing the decrease in the mean time delay between the first (positron-annihilation) and second (neutron-capture) pulses after the cadmium concentration in the target was increased. Finally, to

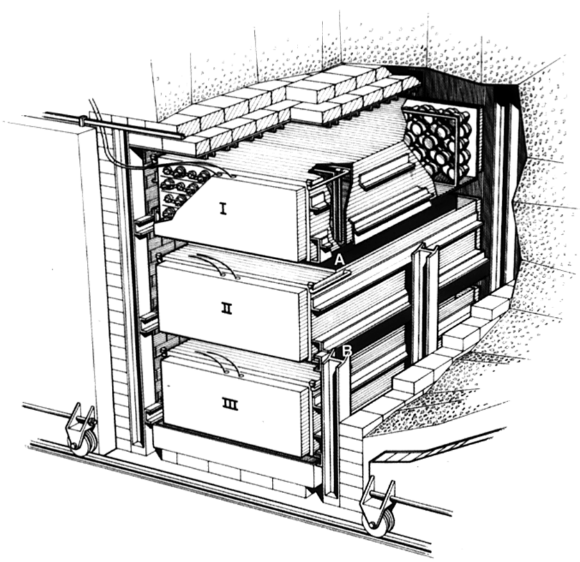

Fig. 5. The Savannah River neutrino detector. *Source:* Reines, *et al.*, "Detection of the Free Neutrino" (ref. 24), Figure 2; copyright 1960 by the American Physical Society.

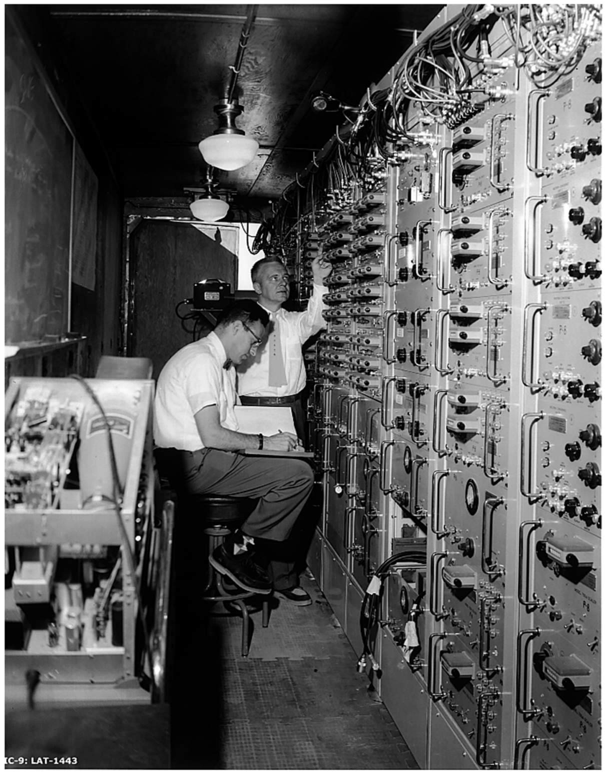

Fig. 6. Reines (seated) and Cowan in the electronics trailer for the 1956 Savannah River neutrino-detection experiments. Courtesy of the Regents of the University of California, operators of Los Alamos National Laboratory.

show that the signal was not due to neutrons and gamma rays from the reactor, they surrounded the detector with extra shielding and found that the signal rate remained constant while reactor-induced accidental coincidences decreased.

Reines and Cowan's monthly report of June 20, 1956, stated that the "experiment to detect the free neutrino has been completed with a positive result and has been reported on at the American Physical Society meeting at Yale."[21] Six days earlier, on June 14, 1956, Reines and Cowan had sent a telegram to Wolfgang Pauli in Zurich that read:

> We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.[22]

Reports also appeared in *Science* (July 20, 1956, with Cowan as first author) and *Nature* (September 1, 1956, with Reines as first author).[23] The *Science* article reported that the total running time, including reactor-down time, was 1371 hours (about 900 hours with the reactor on) and that, "A reactor-power-dependent signal was observed which was (within 5 percent) in agreement with a [theoretical] cross section for [the] reaction … of 6.3×10^{-44} cm^2. The predicted cross section … , however, is uncertain by ± 25 percent." The article in *Nature* reported that the experiment had "a signal-to-reactor associated accidental background in excess of 20/1. The signal-to-reactor independent background ratio was 3/1."

Both of these 1956 articles described the tests that were undertaken to prove that the events detected were indeed characteristic of inverse beta decay. These articles and the telegram to Pauli also offered the match between the experimental and theoretical cross sections as evidence for the neutrino. Comparison of the theoretical and measured cross sections also played an important role in Reines and Cowan's 1953 experiment at Hanford; they calculated the experimental cross section to check whether the neutrino was being seen. But such a comparison does not appear to have figured in their first 1956 experiment at Savannah River. An examination of their 1956 laboratory notebooks indicates that demonstrating the uniqueness of the signature of the event was the focus of attention. Detection of the neutrino was shown unequivocally on that basis.* Offering the cross section comparisons in their 1956 publications may have been an unfortunate afterthought, because they then did not yet have enough information about the neutrino flux and about detector efficiencies to make such strong statements about the measured cross section. As I will describe below, their need to backtrack later may have raised doubts in the minds of some scientists about the legitimacy of their work.

Reines and Cowan did not publish a second and more detailed analysis of their first 1956 measurements until 1960.[24] Based on a net rate of 2.88 ± 0.22 events per hour with a ratio of reactor-on to reactor-off rates of better than three to one, their 1960 paper reported a value for the measured cross section of $12^{+7}_{-4} \times 10^{-44}$ cm^2,** which differed from their 1956 value. However, their 1960 report of the experimental cross section, from the 1960 analysis of their first 1956 experiment, remained consistent with the new theoretical cross section as reported in 1959 to be $10.0 \pm 1.7 \times 10^{-44}$ cm^2. This value of the theoretical cross section had increased by a factor of two from the 1956 value, following the discovery of parity non-conservation in 1957, and also had been adjusted because of a better knowledge of the neutrino energy spectrum.[25]

The Second Savannah River Experiment of 1956

Reines and Cowan and their co-workers undertook another measurement of the inverse beta-decay cross section beginning in late September 1956 using a different arrangement of the Savannah River detector.[26] In their new arrangement, tank III, formerly used only as a scintillation detector, became both target and detector. The 110 photomultiplier tubes of tank III were wired in two interleaved banks of 55

* This point is demonstrated by the elegant laboratory notebooks kept by Herald W. Kruse, who was responsible for interpreting the oscilloscope photographs, and by interviews of surviving group members.

** That is, as high as 19×10^{-44} cm^2 or as low as 8×10^{-44} cm^2.

each to reduce the effect of electronic noise; they provided a prompt coincidence trigger signal when annihilation radiation from the decay of a positron was seen in the tank. This trigger signal then initiated the same kind of data gathering and interpretation sequence as was used in their first 1956 experiment. Tank II served as a detector in a cosmic-ray anticoincidence arrangement: simultaneous signals in tanks II and III vetoed the output of tank III.

They reported the results of this second 1956 measurement in 1959,[27] one year prior to their 1960 definitive report of their first 1956 measurement. Because of the larger target volume, a counting rate of 36 ± 4 events per hour was recorded. In conjunction with the new measurement of the fission neutrino spectrum mentioned above,[28] their second 1956 experiment yielded a cross section for the inverse beta-decay process of $11 \pm 2.6 \times 10^{-44}$ cm^2. This, too, was consistent with the 1959 theoretical cross section.

During the period between their two 1956 experiments and their final publication of the results of these experiments in 1959 and 1960, Reines and Cowan published the results of several related investigations: (1) a lower limit for the double beta-decay lifetime of ^{150}Nd, which was seen as a test of neutrino-antineutrino identity; (2) a new value for the upper limit of the magnetic moment of the neutrino; (3) results of a measurement of the upper limit of the cross section for antineutrino interaction with deuterons, based on data from Savannah River; and (4) an improved value for the lower limit of the lifetime of the proton.[29] Both physicists also left Los Alamos during this period to take up academic positions: Cowan went to Washington, D.C., first to George Washington University in 1957 and then to Catholic University the following year as professor of physics; Reines became professor of physics and head of the physics department at Case Institute of Technology in Cleveland, Ohio, in 1959.

The Savannah River Experiment of 1964

In 1964 one of Reines's graduate students, Frank A. Nezrick, and Reines undertook another neutrino-detection experiment at Savannah River. Its purpose was twofold, (1) to obtain a more precise experimental value for the cross section for the interaction of neutrinos with protons to test the two-component theory of the neutrino; and (2) to measure the positron energy spectrum to determine the fission neutrino spectrum from it. The measurement featured a novel "table top" detector, a 3.2-liter gadolinium-loaded liquid-scintillator target (and detector) placed between two cylindrical NaI(Tl) crystals, each 29 centimeters in diameter and 7.6 centimeters thick, acting as independent scintillation detectors. The latter detectors were set to select the oppositely-directed 0.511-MeV gamma rays from positron annihilation. The signature of the inverse beta-decay reaction consisted of a prompt coincidence of all three detectors, due to the positron quickly slowing down and annihilating, followed by a delayed coincidence with the gamma-ray signals from neutron capture.

The 1964 experiment incorporated several improvements over Reines and Cowan's 1956 experiments. First, the energy resolution was much improved by the use of NaI(Tl) detectors. Second, the signal-to-background ratios were more favorable. Third, and critical for the improvement of the cross section results, the detection efficiency, both for positrons and for neutrons, was much more carefully determined.

Nezrick and Reines obtained their data from 2484 hours of reactor-on time and 357 hours of reactor-off time with a signal-to-background ratio of approximately 3 to1. The net counting rate of 0.187 ± 0.021 events per hour corresponded to an experimental value for the interaction cross section of $9.4 \pm 1.3 \times 10^{-44}$ cm^2 as compared to the then-current theoretical value of $10.7 \pm 0.7 \times 10^{-44}$ cm^2. The measured neutrino spectrum from the fission of ^{235}U showed a larger number of energetic neutrinos – and hence more energetic beta decays – than had been observed previously.[30]

Changing Numbers

Several of the co-workers of Reines and Cowan whom I interviewed noted particularly that the detection of the neutrino was not recognized by the award of a Nobel Prize in Physics until 1995, when Reines was cited "for the detection of the neutrino," and when he shared the prize with Martin L. Perl, who was cited for "the discovery of the tau lepton."[31] (Cowan died in 1974 and thus could not share in the prize.) This long delay was all the more striking because the 1988 Nobel Prize in Physics was awarded to Leon M. Lederman, Melvin Schwartz, and Jack Steinberger "for the first use of a neutrino beam and the discovery of the muon neutrino."[32]

One of the people I interviewed offered the observation that "the numbers kept changing" as part of the reason for this delay, the "numbers" being the counting rates and the experimentally-determined cross sections as reported at different times. For example, from the publications alone it is difficult to understand the counting rate Reines and Cowan reported in 1953 (25 ± 12 events per hour) when compared to that they reported in their first 1956 experiment (2.88 ± 0.22 events per hour), which utilized both a larger target and a larger detector. This comparison of these two experiments is invited, however, by the title of their 1956 *Science* article, "Detection of the Free Neutrino: A Confirmation," and by their statement in the text of that paper that, "This work confirms the results obtained at Hanford … ."*

Another source of puzzlement in their 1956 *Science* article is their description of the results of their first Savannah River detection experiment: "In one set of runs, the neutrino signal rate was 0.56 ± 0.06 count per hour, and with *changed requirements* [my emphasis] it was 2.88 ± 0.22 counts per hour." In their *Nature* article six weeks later, they identified the second number as the counting rate that gave agreement with the theoretically-predicted cross section. The fivefold difference

* Comparing the counting rates alone is not definitive. The two rates would be consistent, for example, *if* the detection efficiencies of the 1953 detector were assumed to be significantly higher than those of the 1956 detector because of less stringent requirements on pulse height and timing in the 1953 measurements.

between these two counting rates might suggest that the criteria for deciding which events were due to neutrinos were difficult to establish, perhaps even somewhat arbitrary. In fact, the two counting rates were not comparable for two reasons: (1) an error was made in picking numbers out of a data book; and (2) the two rates corresponded to different experimental settings* with different neutron-detection efficiencies.[33]

The doubling of the reported experimental cross section between Reines and Cowan's two 1956 papers reporting on their first 1956 experiment and their 1960 paper reporting on the same experiment – during a period in which the theoretical cross section also had increased by roughly a factor of two owing to the discovery of parity non-conservation in 1957 and the formulation of the two-component neutrino theory – was cited more frequently as a troubling episode.[34] It appears that Reines and Cowan submitted their 1956 *Science* and *Nature* articles for publication and then busied themselves with new experiments without obtaining sufficient information about the detector efficiencies, which were needed to calculate the experimental cross section. Nor did they have this information fully in hand at the time of their 1960 publication; the uncertainty in their neutron-detection efficiency was the largest contributor to the uncertainty in the measured cross section. At Savannah River in 1956 they had used a plutonium-beryllium neutron source to test neutron efficiency. Such a source emits much more energetic neutrons, with energies up to 11 MeV, compared to neutrino-produced neutrons at 10 keV, so that the experimental value of 0.14 they obtained for neutron-detection efficiency provided only a lower limit. In their 1960 paper, after a series of other arguments regarding various contributions to the neutron-detection efficiency, they stated: "… we obtain as a rough estimate for the over-all detection efficiency of the system for [antineutrino] $\bar{\nu}$-produced neutrons … = 0.24. It seems reasonable to state the efficiency as $\varepsilon_n = 0.17 \pm 0.06$ where 0.06 represents a guess as to the uncertainty of ε_n."[35] In April 1956, when the crucial data in the first 1956 experiment were being taken, Reines believed this (same) neutron-detection efficiency to be "about 30%."[36]

Other people I interviewed did not believe that the changing numbers were particularly relevant. They offered other conjectures regarding the delay in Reines's Nobel Prize, such as that Reines and Cowan were not "members of the club," that is, in the leadership circle of particle physics; and that they had been involved in the weapons'-testing program at a time when many physicists were becoming increasingly uneasy about the proliferation of nuclear weapons. Be this as it may, Reines and Cowan's changing numbers, because they were noticed at least by some physicists, are significant from another point of view: they make it all the more

* The 0.56 ± 0.06 count per hour was the *average* counting rate (of the two triads) on a set of runs that were not used because the gate settings eliminated some of the neutron signals by requiring that at least 1.5 MeV be seen in each of the two detectors of a triad (*i.e.*, these runs had neutron side gates set at 1.5–7.0 MeV each). The 2.88 ± 0.22 counts per hour was the *total* counting rate (of both triads) for a later set of runs in which each of the two detectors was required to see a neutron signal of at least 0.2 MeV and the sum of two signals was required to be at least 3.0 MeV (*i.e.*, neutron side gates set at > 0.2 MeV; an additional sum gate set at 3.0–11.0 MeV).

surprising that an experiment to detect the neutrino was not undertaken independently by another group or groups.

Bases for Belief

Between 1930, when Pauli tentatively suggested what became known as the neutrino as a "desperate remedy," and 1952 when Reines and Cowan arrived in Hanford with their co-workers to try to detect it, the neutrino had become a desperate necessity. It had fulfilled its assigned task of accounting for the missing energy, momentum, and spin in beta decay, and there were many elegant recoil experiments, especially those involving the K-capture mode of beta decay, that required the emission of a neutral and nearly massless particle to account for the missing momentum.[37] The Fermi theory of beta decay also had become well established, and the 1950s were an especially active and successful time for theoretical and experimental investigations involving beta decay.[38] Especially notable in this regard were: (1) T. D. Lee and C. N. Yang's suggestion that parity (reflection symmetry) might not be conserved in the weak interaction and its experimental verification, in the case of beta-decay, by C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes and R. P. Hudson;[39] (2) the determination of the mathematical form of the beta-decay interaction (as a linear combination of vector and axial vector terms) that emerged from a long series of theoretical and experimental investigations;[40] and (3) the measurement of the helicity (handedness) of the neutrino by Maurice Goldhaber, Lee Grodzins, and A. W. Sunyar.[41] These hard-won victories of theory and experiment, all of which assumed the existence of the neutrino, were reported between 1956 and 1958.

Against this background of overwhelming evidence for the neutrino in beta decay, Reines and Cowan undertook the task of showing that it existed as an independent particle. The reaction that they were seeking, inverse beta decay, had a probability of occurring that was several orders of magnitude smaller than any interaction that had been observed previously. Their first attempt, using neutrinos from the Hanford reactor in 1953, was not successful. They were plagued by a variety of problems, including a high cosmic-ray background that produced events that looked like neutrinos and did so at a rate several times larger than the effect they were seeking. Although they reported seeing a two-standard-deviation neutrino signal based on a brief (six-hour) period of data taking in which everything seemed to be working, they did not attempt to reproduce the data.

In this first 1953 effort Reines and Cowan attempted repeatedly to check the cross section derived from their counting rate to verify that they were identifying neutrino events correctly. The theoretical cross section against which they checked their counting rate was independent of their measurement, an assumption that guided their experiment.[42] In this first effort they also seemed to be struggling with "experimenters' regress," the circularity described by Harry Collins that may arise in seeking to verify a new phenomenon, here to detect a previously unseen particle, because "we won't know if we have built a good detector until we have tried it and obtained the correct outcome! But we don't know what the correct outcome is until … [we have built a good detector].'' As noted by Collins, ''Experimental work can only be used as a *test* if some way is found to break into the circle.''[43]

The circle was broken at Savannah River in Reines and Cowan's first 1956 experiment. Although they asserted at the time that their experimentally measured cross section matched the theoretical value, and presented this as part of the evidence that the neutrino had been detected, the signature of the inverse beta-decay event, and the experimental checks that they undertook to rule out alternative explanations, appear to have been sufficient to support their claim of having detected the neutrino. Indeed, cross section checks do not appear to have entered their experiment at all. They published preliminary reports of their results in 1956 and a full analysis in 1960. The physics community did not wait until 1960. As Atchley has noted, acceptance of the 1956 news that the neutrino had been detected was widespread and nearly universal.[44]

The fourth experiment, that of Nezrick and Reines carried out at Savannah River in 1964, had an even stronger set of signature characteristics and resulted in a more precise measurement of the experimental cross section that was fully independent of the signature. The detectors and detection electronics available to nuclear and particle physicists expanded significantly during the 1950s: single-event (Geiger-Müller and ionization-chamber) counters, cloud chambers, and photographic emulsions were superceded by solid and liquid scintillation counters, fast-coincidence circuits, bubble chambers and spark chambers. Not only was detection efficiency greatly improved; it also became standard practice to design experiments to recognize a distinctive signature and to rely on that signature as evidence that a particular particle had been detected. The evolution of the neutrino-detection experiments from a proposal of Luis Alvarez in 1949, which placed great weight on cross section comparisons as a test of detection,[45] through the Nezrick and Reines work of 1964, which used a clean signature as the basis for a definitive cross section determination, reflected this pattern of changing technique.

In 1980, neutrinos from fission reactors were detected again in inverse beta-decay experiments, in connection with the investigation of neutrino oscillations.[46] In the meantime, no other group attempted to detect neutrinos from fission reactions. This is surprising because of the irregularities in the reported results, as described above, and because the physics community has depended traditionally on independent experiments to lend credence to earlier results.[47] Although Reines himself pointed out that neutrinos were seen as by-products in a 1964 accelerator-based experiment, that experiment does not appear to have provided the quality of evidence for the ''ghost particle'' that had been developed in the experiments of Reines, Cowan, and their co-workers in 1956. The 1964 accelerator experiment dealt mostly with elastic muon production and reported only 39 events in which the appearance of an outgoing (negative) electron and an outgoing proton was interpreted as signaling the agency of a neutrino interacting with a neutron. The signature was not as distinctive as that developed in the reactor experiments.[48]

There are several plausible reasons why other experiments were not undertaken quickly to detect the electron antineutrino. First, the Savannah River reactor was a unique source of neutrinos in terms of neutrino flux, in terms of the availability of an adjacent underground space in which the detectors could be operated with little background from cosmic-ray muons, and because it was off limits to people who lacked the appropriate level of security clearance. Few scientists would have had access to a neutrino source of this quality. Second, the experiments were very expensive; Reines, Cowan, and their co-workers enjoyed excellent funding. Third, and probably most important, the neutrino, which had begun as an artifice, had become a necessity. As James Allen stated in 1958, "The Fermi theory was so successful in explaining most of the important features of beta-decay that most physicists accepted the neutrino as one of the 'particles' of modern physics."[49] The acceptance by the physics community was strong despite any perceived irregularities in the way in which the evidence of detection was handled and presented; indeed it probably would have been strong even if the neutrino-detection experiment had not been carried out. The announcement that the neutrino finally had been detected may have brought a sense of psychological release to some, but for many others it was just icing on the cake.

As Lincoln Wolfenstein has observed, the neutrino concept marked the "beginning of elementary-particle physics … . The neutrino was the first particle proposed that was not a constituent of normal matter, and Fermi's weak interaction was the first proposed interaction that had no classical analog."[50] Reines and Cowan took on the seemingly impossible task of detecting the free neutrino and got the institutional and financial backing to carry it out. They went well beyond the current technology in developing new instrumentation and new detectors. They struggled with new experimental challenges at every turn. They persevered and eventually were successful. The physics community was relieved by their 1956 announcement that the neutrino had been detected, but hardly surprised. Indeed, if their result had been negative, their experiment probably would have been considered a failure. Despite the fits and starts, the pioneering efforts of Reines and Cowan affirmed belief in the neutrino. Their work also led the way to the wide range of experiments involving neutrino detection that characterize particle physics and astrophysics nearly fifty years later.

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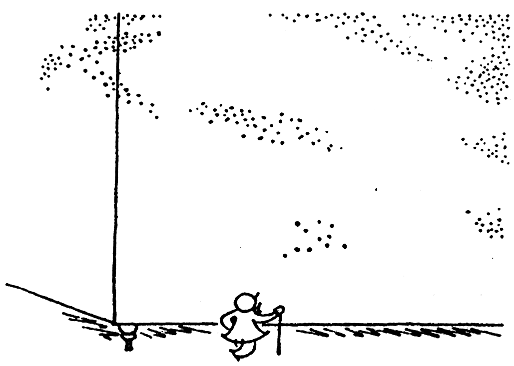

ATOMYRIADES

Nature, it seems, is the popular name
for milliards and milliards and milliards
of particles playing their infinite game
of billiards and billiards and billiards.

Piet Hein