A Brief History of Neutrino Experiments at LAMPF

Gerry Garvey

Frederick Reines and Clyde Cowan Jr.'s observation of neutrino interactions in the late 950s went largely unnoticed. It was vershadowed by the then recent, startling observation of parity violation in he weak interaction, an observation hat flew in the face of cherished eliefs. Parity violation meant that the weak force had a handedness, a bias oward whether particles would spin ight or left. In the case of the neutrino, ature always chose left. In 1932, when Wolfgang Pauli made the brilliant peculation that a nearly massless, eutrally charged particle must exist to xplain perplexing features in nuclear eta decay, no physicists in their right mind would have suggested that such a article also have the audacity to break eft-right symmetry.

Parity violation evoked what is perhaps the most fundamental principle in science: the requirement to test, with ever more exacting experiments, the limits of prevailing theories and explanations. This arduous, challenging, and sometimes personally unrewarding search for the truth lies at the heart of the story of neutrino research. And nowhere is that story better exemplified than in the history of neutrino experiments at LAMPF (the Los Alamos Meson Physics Facility, now renamed the Los Alamos Neutron Science Center, or LANSCE).

The LAMPF accelerator came into operation in 1972 (see aerial photograph above and Figure 1). It was designed primarily to accelerate a high-intensity beam of protons to energies high enough to produce unbound pions. Pions are short-lived, subatomic particles that are created when an energetic proton collides with a nucleus.

Neutrinos are a natural by-product of pion decay, and even before the accelerator was operational, physicists proposed exploiting that fact. Directing the unused portion of the beam into a large block of copper (called the beam stop) would produce pions that would come to rest within the beam stop. The positive pions, π^+, would decay into positive muons, μ^+, and muon neutrinos, ν_μ. (The negative pions would be reabsorbed by the copper nuclei before they decayed.) The positive muons would then decay into a positron, e^+, an electron neutrino, ν_e, and a muon antineutrino, $\bar{\nu}_\mu$. In all, three types of neutrinos would be produced—ν_e, ν_μ, and $\bar{\nu}_\mu$—that would radiate from the beam stop in all directions.

(a) (b) (c) (d)

The neutrinos produced would have energies between 10 and 55 million electron volts (MeV). In the early 1970s, neutrino interactions had been observed at only "low" energies (a few million electron volts) or "high" energies (roughly 1,000 MeV). Thus, LAMPF would enable the study of interactions at intermediate energies.

LAMPF had several unique properties that made it an almost ideal neutrino source. First, it had the highest instantaneous beam intensity of any of the existing, or proposed, meson factories (even though one never has "sufficient" intensity for neutrino experiments). In comparison with other high-energy accelerator sources, the intense LAMPF proton beam produced more neutrinos per second, so that one could anticipate more neutrino events in the detectors. Second, the average energy of the neutrinos was below the threshold for producing muons from muon neutrinos or muon antineutrinos.

(e)

Figure 1. A Brief Photo History of LAMPF

(a) Early photo of the trench dug into the mesa to accommodate the proton accelerator. (b) Happy faces around the control console when the proton beam was first accelerated to design specifications (800 MeV). (c) LAMPF's first stage—an Alvarez linear accelerator—which brings the beam to an energy of 100 MeV. (d) Keyhole view of the accelerator's second stage, which brings the beam from 100 MeV to its final energy of 800 MeV. (e) LAMPF's end station, where experiments are carried out. The detector for the LSND experiment sits in the tunnel in the lower right-hand corner of the photo.

able I. Neutrino Experiments at LAMPF

Experiment	Years	Reactions Observed	Principal Scientific Goals
E-31	1975–1980	$\bar{\nu}_e + p \rightarrow e^+ + n$ $\nu_e + \mathrm{D} \rightarrow e^- + p + p$	Deduce the form of the muon-family-number conservation law
E-225	1975–1993	$\nu_e + e^- \rightarrow e^- + \nu_e$ $\nu_e + {}^{12}\mathrm{C} \rightarrow e^- + \mathrm{X}$	Measure the scattering cross section between electrons and electron neutrinos Measure the electron neutrino cross section on ^{12}C (X is another atom, typically ^{12}N)
E-645	1980–1993	$\bar{\nu}_e + p \rightarrow e^+ + n$	Search for $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations
E-764	1982–1992	$\nu_e + {}^{12}\mathrm{C} \rightarrow \mu^- + \mathrm{X}$ $\nu_\mu + {}^{12}\mathrm{C} \rightarrow \mu^- + \mathrm{X}$	Search for $\nu_\mu \leftrightarrow \nu_e$ oscillations Measure the muon neutrino cross section on ^{12}C
E-1173	1989–present	$\bar{\nu}_e + p \rightarrow e^+ + n$ $\nu_e + {}^{12}\mathrm{C} \rightarrow \mu^- + \mathrm{X}$	Search for $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations Search for $\nu_\mu \leftrightarrow \nu_e$ oscillations
E-1213	1990–present	$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$ $\nu_e + {}^{127}\mathrm{I} \rightarrow e^- + {}^{127}\mathrm{Xe}$	Measure the cross section for electron neutrino capture on ^{37}Cl and ^{127}I to calibrate solar-neutrino detectors

his meant that electron neutrino interctions could be studied without nterference from the muon neutrino rocesses that dominate experiments at igher energies. Third, because the roton beam was bunched in time, the eutrinos were only created during hort intervals. An experimenter knew recisely when a neutrino produced y LAMPF could enter the detector. vents that occurred outside of those me windows would be the result of ackground processes.

There was one other feature of AMPF that was favorable to neutrino xperiments. Neutrinos were produced rimarily from positive pion and muon ecay. Aside from knowing very well he flux and energy spectrum of each eutrino type that was produced, expermenters also knew that electron antieutrinos were *not* produced. Therefore, n excess flux of electron antineutrinos n their experiment could be interpreted s evidence for neutrino oscillations.

All these advantages were outlined in proposal that was written before LAMPF began operation (Lande and Reines 1971). The proposal was prophetic insofar as it anticipated what was to be the LAMPF neutrino program for the next 20 years. It called for several specific experiments to be carried out when the proton beam neared its design intensity of 1 milliampere (equal to 6×10^{15} protons per second). Four experimental goals were outlined: (1) to deduce the form of the lepton-family-number laws, in particular, the electron- and muon-family-number conservation laws; (2) to measure the scattering cross section between electrons and electron neutrinos; (3) to measure the neutrino interaction cross sections that were relevant to solar-neutrino experiments; and (4) to search for neutrino oscillations.

Ken Lande and Fred Reines wrote the proposal, but they had input from many of the outstanding scientists of the day, including Clyde Cowan, Vernon Hughes, Hans Frauenfelder, Darragh Nagle, and Ray Davis. Also contributing were some of the younger researchers who were later to provide much of the technical innovation and drive necessary to make the LAMPF neutrino program a success: Bob Burman, Herb Chen, Don Cochran, and Peter Nemethy. The proposed neutrino source was built, and Don Cochran and Lou Agnew assumed primary responsibility for its operation.

All told, six experiments have been conducted using the LAMPF neutrino source. A brief summary of them is given in Table I. The remainder of this article discusses these experiments, although the focus is on the three experiments that have had the most-far-reaching consequences. Each of the experiments was a sizable undertaking involving several institutions plus the resources and technical personnel at LAMPF. But it is equally important to note that each experiment, while executed to achieve its own goals, was also a precursor for the next. Experience gained from one experiment, like stepping stones, helped researchers to cross uncharted waters.

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Experiment E-31

Headed by Vernon Hughes and Peter Nemethy, this experiment examined the manner in which the muon-family-number is conserved. It had been established in the early 1960s that a positive muon decayed by transforming into a positron and two neutrinos. With our current understanding of lepton families and the weak interactions, we would write the decay as

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+ . \qquad (1)$$

Muon decay is entirely analogous to the beta decay of the neutron. As written, Reaction (1) also obeys separate, additive lepton-family-number conservation laws.

A conservation law simply means that whatever is present at the start of a reaction is also present—in the same amount—at the end of the reaction. Separate additive conservation laws meant that for each lepton family (either the electron family or the muon family), the *sum* of the family numbers before and after a reaction would be the same. Table II lists the first two lepton families with their family numbers and demonstrates both additive and multiplicative conservation laws. (See the primer, "The Oscillating Neutrino," on page 28 for a more detailed discussion of muon decay and the lepton-family-number conservation laws.)

In the early 1970s, many of the conservation laws, especially those involving the muon, still needed to be confirmed. Most physicists viewed the muon as a mysterious particle. It appeared to be simply a heavy version of the electron, and no one could understand why nature would summon up such a beast. The mathematical structure of the weak interactions was not well established, and there were no unbreakable laws governing muon decay.

Indeed, when E-31 was proposed in the early 1970s, all the available data were consistent with the four possible lepton-family-number conservation laws listed in Table II. However, the *multiplicative* conservation law allowed a second muon decay channel:

$$\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu . \qquad (2)$$

Reaction (2) had never been observed. It was strictly forbidden by the much more theoretically appealing additive law. (The sum of the electron-family numbers is −2 after the reaction, instead of 0, so that the conservation law is violated. The sum of the muon-family numbers is also not conserved. Therefore, the reaction should not occur.) If the muon did decay by this mode, some of the guiding principles about the weak interactions would have to be reevaluated. It was of interest to see if muons decayed by this channel at all, and if so, to make an accurate measurement of the relative rates between Reactions (1) and (2).

LAMPF was ideally suited to perform such an experiment because the facility relied on positive muon

Table II. Lepton-Family Numbers and Possible Conservation Laws

Lepton	Electron-Family Number, L_e	Muon-Family Number, L_μ
e^-	+1	0
ν_e	+1	0
e^+	−1	0
$\bar{\nu}_e$	−1	0
μ^-	0	+1
ν_μ	0	+1
μ^+	0	−1
$\bar{\nu}_\mu$	0	−1

Possible conservation laws:
1. Additive: ΣL_e and ΣL_μ separately conserved
2. Multiplicative: $\Sigma (L_e + L_\mu)$ and $(-1)^{\Sigma L_e} (-1)^{\Sigma L_\mu}$ separately conserved
3. $\Sigma (L_e + 2L_\mu)$ conserved
4. $\Sigma (L_e - L_\mu)$ conserved

Reaction (1) in the text obeys separate additive conservation laws:

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$

$0 = 0 + 1 + (-1)$ Sum of electron-family numbers is conserved.
$-1 = -1 + 0 + 0$ Sum of muon-family numbers is conserved.

Reaction (1) also obeys the multiplicative law:

$[0 + (-1)] = [0 + 1 + (-1)] + [(-1) + 0 + 0]$ $\Sigma (L_e + L_\mu)$ is conserved.
$(-1)^0 (-1)^{-1} = (-1)^0 (-1)^{-1}$ $(-1)^{\Sigma L_e} (-1)^{\Sigma L_\mu}$ is conserved.

The reaction also obeys the third and fourth conservation laws.

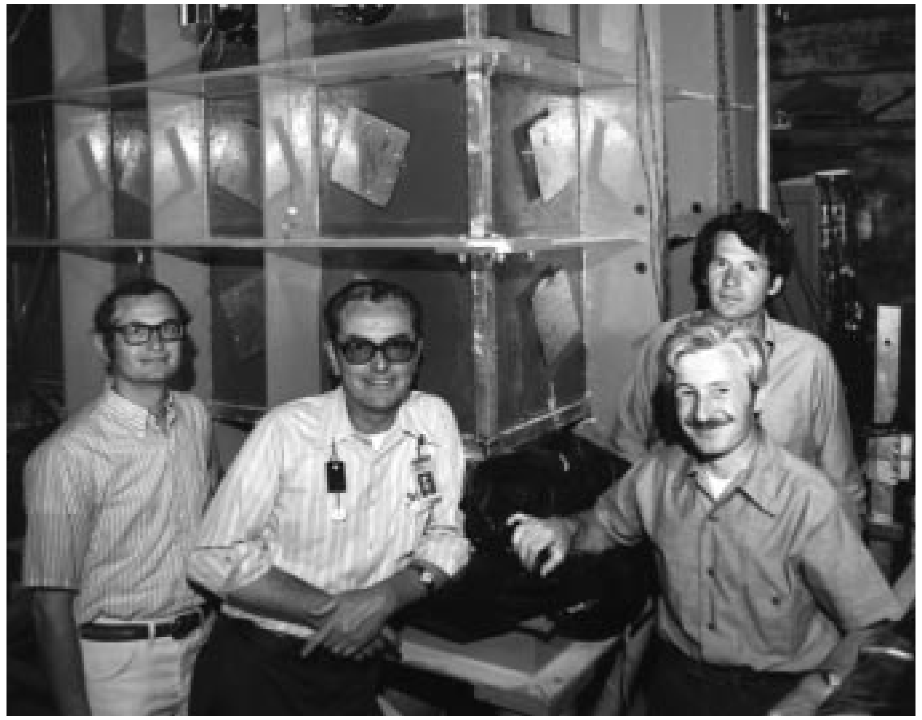

Figure 2. E-31 Collaborators and Detector
rom left to right, Robert Burman, Donald Cochran, Jean Duclos, and Peter Nemethy tand in front of the E-31 detector, the first water-filled Cerenkov detector used to earch for neutrinos.

ecay to produce its neutrinos. An xperiment could verify the forbidden ecay mode simply by observing lectron *antineutrinos* in a suitably uilt detector.

Hughes, Nemethy, and their collabo-ators used a water-filled Cerenkov etector to search for electron nti-neutrinos (see Figure 2). They ooked for the signature of a positron merging from the reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n \ , \qquad (3)$$

which is the same inverse-beta-decay eaction exploited by Reines and owan to observe the first neutrino nteractions. But E-31 detected no lectron antineutrino events coming om positive muon decay. Thus, the robability for Reaction (2) to occur ad to be very small, below the sensi-vity limits of the experiment. It ppeared that the additive conservation aw was correct to a very high level of ccuracy and that family number was eparately conserved by each lepton family. (The later observance of a few electron antineutrinos in experiment E-1173 is now interpreted as evidence for oscillations of muon antineutrinos into electron antineutrinos. The possibility that Reaction (2) might still occur is described in the article "The Nature of Neutrinos in Muon Decay and Physics Beyond the Standard Model" on page 128.)

E-31 also carried out the only measurement of the cross section for electron neutrinos on deuterium, D. In order to calibrate the detector, the experimenters filled it with heavy water (D_2O) and observed the reaction

$$\nu_e + \mathrm{D} \rightarrow e^- + p + p \ . \qquad (4)$$

Comparing the frequency of events to the known electron neutrino flux yields the cross section. Reaction (4) is directly related to the primary energy-generating reaction in our sun:

$$p + p \rightarrow \mathrm{D} + e^+ + \nu_e \ . \qquad (5)$$

This is the *pp* reaction that has figured so prominently in the solar neutrino problem (see the article "Exorcising Ghosts" on page 136.)

Experiment E-225

Parity violation in nuclear beta decay was discovered in 1956 by Chien-Shiung Wu and her collaborators at the National Bureau of Standards. Shortly thereafter, Richard Feynman and Murray Gell-Mann formulated the $\boldsymbol{V-A}$ theory (a "left-handed" theory that violated parity) for what is now called the charged-current weak interaction. The theory was immediately confirmed in a flurry of experimental and theoretical activity.

During the sixties and early seventies, powerful new theoretical insights by Sheldon Glashow, Abdus Salam, Steven Weinberg, George Zweig, and Gell-Mann, supplemented by numerous experimental observations at high-energy accelerators in the United States and Europe, led to a partial unification of the weak and electromagnetic interactions. The hallmark of the new electroweak theory was the inclusion of neutral-current interactions, which were mediated by the exchange of a neutral boson (Z^0). These neutral interactions were in addition to the well-studied charged-current interactions, which in the new electroweak theory were mediated by the exchange of a W^+ boson.

E-225 was proposed before neutral currents were discovered. Its original intent was to observe the charged-current scattering of electron neutrinos from electrons and to measure the cross section. In that reaction, the incoming electron neutrino transforms into an electron, and the target electron is transformed into an electron neutrino:

$$\nu_e + e^- \rightarrow e^- + \nu_e \ . \qquad (6)$$

With the introduction of the electroweak theory, the objective of E-225 was quickly changed. In addition to the charged-current interaction, the new

theory predicted that Reaction (6) could also proceed through neutral-current scattering, in which both the electron neutrino and the electron maintained their identities as they scattered from one another. The two distinct modes of interaction meant that two terms entered into the calculation of the cross section and could potentially "interfere" with each other. The electroweak theory of Glashow, Salam, and Weinberg predicted a destructive interference, meaning that the cross section would be less than what was expected for just the charged-current scattering. The new objective of E-225 became to confirm or disprove that prediction. The experiment was headed by Herb Chen, a very talented young man who was in many ways the leader of the neutrino physics community at Los Alamos during this time. Unfortunately, Chen died of leukemia in 1987.

The experiment used a detector that was built like a 40-layer sandwich, with each layer made of plastic scintillator and flash-chamber module. A single module (see Figure 3) contained 10 flash-tube panels, with each panel containing 520 flash tubes. A flash tube is a long, narrow tube of gas that outputs a current pulse when a charged particle passes through it. A panel of 520 flash tubes could provide one-dimensional position information for a particle with very good resolution. Within a flash-chamber module, panels were alternately arranged either horizontally or vertically, so that each module could track a charged particle in two dimensions.

The stack of 40 modules (containing a total of 208,000 flash tubes) enabled the detector to provide a three-dimensional trajectory of an electron with very good position resolution. Experimenters knew that the scattered electron emerging from Reaction (6) would follow a trajectory that was confined to a narrow cone surrounding the neutrino's direction. Trajectory information, combined with energy information provided by the plastic scintillators, allowed the experimenters

Figure 3. A Flash-Chamber Module
Bobby Rechtor (center) prepares to lift a flash-chamber module (silver plane.) Forty modules made up the neutrino detector for the E-225 experiment. At left are Minh Van Duong and Robert Burman; at the back are Peter Doe and K. C. Wang. The man at the right is unidentified.

to identify those electrons that came from neutrino-scattering events.

E-225 found that the scattering cross section ruled out constructive interference between neutral- and charged-current interactions, and thus the experiment was altogether consistent with the predictions of the electroweak theory. It also confirmed the widely held belief that, when passing through electron-rich matter, electron neutrinos have a different scattering cross section than do muon or tau neutrinos. (The latter neutrino types can only interact with electrons through neutral-current scattering.) The different cross section was also applicable to the solar-neutrino problem. If neutrino oscillations do occur, then electron neutrinos born in the core of the Sun would scatter differently than would the neutrinos into which they oscillate. This is the fundamental assumption underlying the MSW effect, which is the most-favored solution to the solar neutrino problem. (See the article "MSW" on page 156.)

Experiments E-645, E-764, and E-1173

The Standard Model assumes that neutrinos are massless. Consequently, there can be no mixing between the three lepton families, and hence lepton-family numbers are separately conserved in every interaction. However, there appears to be no fundamental reason for a massless neutrino. Furthermore, any extension of the Standard Model that leads to neutrinos with mass also leads to mixing between the lepton families. Therefore, a neutrino that has mass will likely be a mixture of the three neutrino types and will have some probability to oscillate between them.

E-645 was undertaken in the early 1980s with the specific goal of searching for the oscillation of muon antineutrinos into electron antineutrinos. The experiment was headed by Tom Romanoski. Although it did not find any evidence for oscillations, for a time it established the upper limit on the

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Figure 4. E-645 and the Cosmic-Ray Veto Shield
a) E-645 began with the excavation of a unnel to house the experiment. The tructure in the lower left is the cosmic-ay veto shield in an early stage of con-truction. (b) An inside view of the black, rchlike veto shield. The shield was mov-ble and was rolled into the completed unnel to check clearances. The inner set f railroad tracks allowed the E-645 etector to be rolled under the shield. c) With the detector in place beneath he shield, the electronics "caboose" was oined to the end. The veto shield and etector were then pushed the remaining ew meters into the tunnel.

(a)

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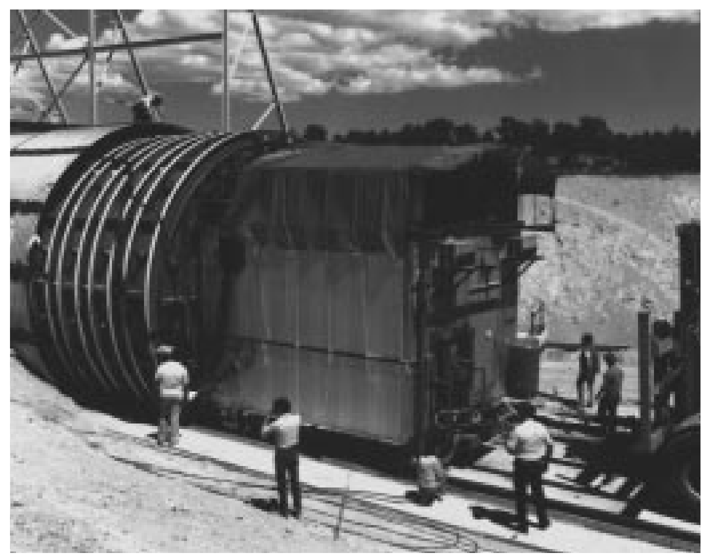


(c)

robability of oscillations taking place. he experiment also had long-term onsequences in that it produced a iece of equipment known as the cos-mic-ray veto shield. The double-walled hield weighed over a thousand tons nd surrounded the bulk of the detector. was filled with liquid scintillator and would send out a signal when a cosmic ay passed through, thus allowing the xperimenters to reject a huge number f background events. The veto shield was a marvelous piece of equipment hat was gratefully used by later neutri-o experimenters (see Figure 4).

E-764 was to be a follow-up to E-645. Headed by Tom Dombeck, it in-vestigated the use of the proton storage ring (PSR) as a low-duty-factor, decay-in-flight muon neutrino source. Unfortu-nately, the experiment was plagued with many difficulties, most notably a high background rate and a low initial neutri-no flux (because the PSR was still being commissioned). As a result, E-764 was administratively terminated. Researchers were able to obtain a new upper limit for the oscillations, but mostly they gained a heightened awareness for how difficult it is to do neutrino experiments.

The oscillation experiment that is currently running, E-1173, also known as LSND for its liquid scintillator neu-trino detector, represents a giant step forward in the neutrino program at LAMPF (see Figure 5). The detector is nearly 10 times larger than the ones used in E-225 and E-645. (The detector was designed to be as large as possible, constrained only by the need to fit inside the E-645 veto shield.) The detector has a trigger that is 5 times more efficient than any used by earlier experiments, and data is gath-ered 50 times faster. A new proton beam target was even built with the purpose of providing higher-energy muon neutrinos that would enable a search for muon neutrino to electron neutrino oscillations.

The neutrino source and detector improvements have allowed LSND to detect a surplus of events ascribable to electron antineutrinos, which the experimenters believe provides evi-dence of oscillations. If this result is confirmed, the experiment will prove that neutrinos have mass and will pro-vide the first experimental evidence for physics beyond the Standard Model. (See the article "A Thousand Eyes" on page 92 for more information on this experiment.)

Figure 5. Members of Experiment E-1173 (the LSND Collaboration)
The large tank in the background is the LSND detector, which is filled with mineral oil and scintillator.

Experiment E-1213

This ongoing experiment is trying to measure the capture cross sections for electron neutrinos on ^{37}Cl and ^{127}I. These elements are used as targets in detectors that are looking at solar neu-trinos, such as Ray Davis' chlorine experiment in the Homestake Mine in South Dakota and a new radiochemi-cal experiment (IODINE), also installed in the Homestake Mine.

To extract the ^{127}I cross section, the E-1213 detector is filled with 1.5 tons ($\approx 7 \times 10^{27}$ atoms) of ^{127}I in the form of sodium iodide dissolved in water. "Interaction of the iodine nucleus with electron neutrinos creates ^{127}Xe, which is periodically extracted from the "detector. The analysis for the ^{127}I experiment is continuing.

The Legacy

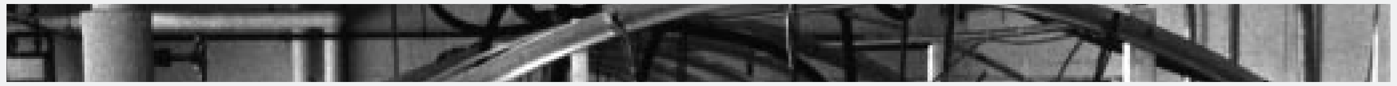
Beginning with Reines and Cowan's experiments that were followed by more than 20 years of neutrino experi-ments at LAMPF, Los Alamos has a history of neutrino physics for which it can be truly proud. In many ways, the success of the neutrino physics program here at Los Alamos and at other nation-al laboratories is a tribute to the creative vitality of these institutions, often maintained in the face of bureau-cratic conservatism. The research begins with a burst of enthusiasm, high hopes, and optimistic schedules. Unfortunately, the reality is that the experiments take a great deal of time, taxing both the resources and the patience of the experimenters, and the rewards, if any, often come only after the initial researchers have left.

But the human intellect is compelled to understand, rather than simply describe, nature's phenomena, and neu-trino experiments have provided unique and crucial insights into the structure and processes of our physical universe. It is somewhat ironic that the nearly undetectable neutrino has had such an impact on scientific knowledge. ■

Further Reading

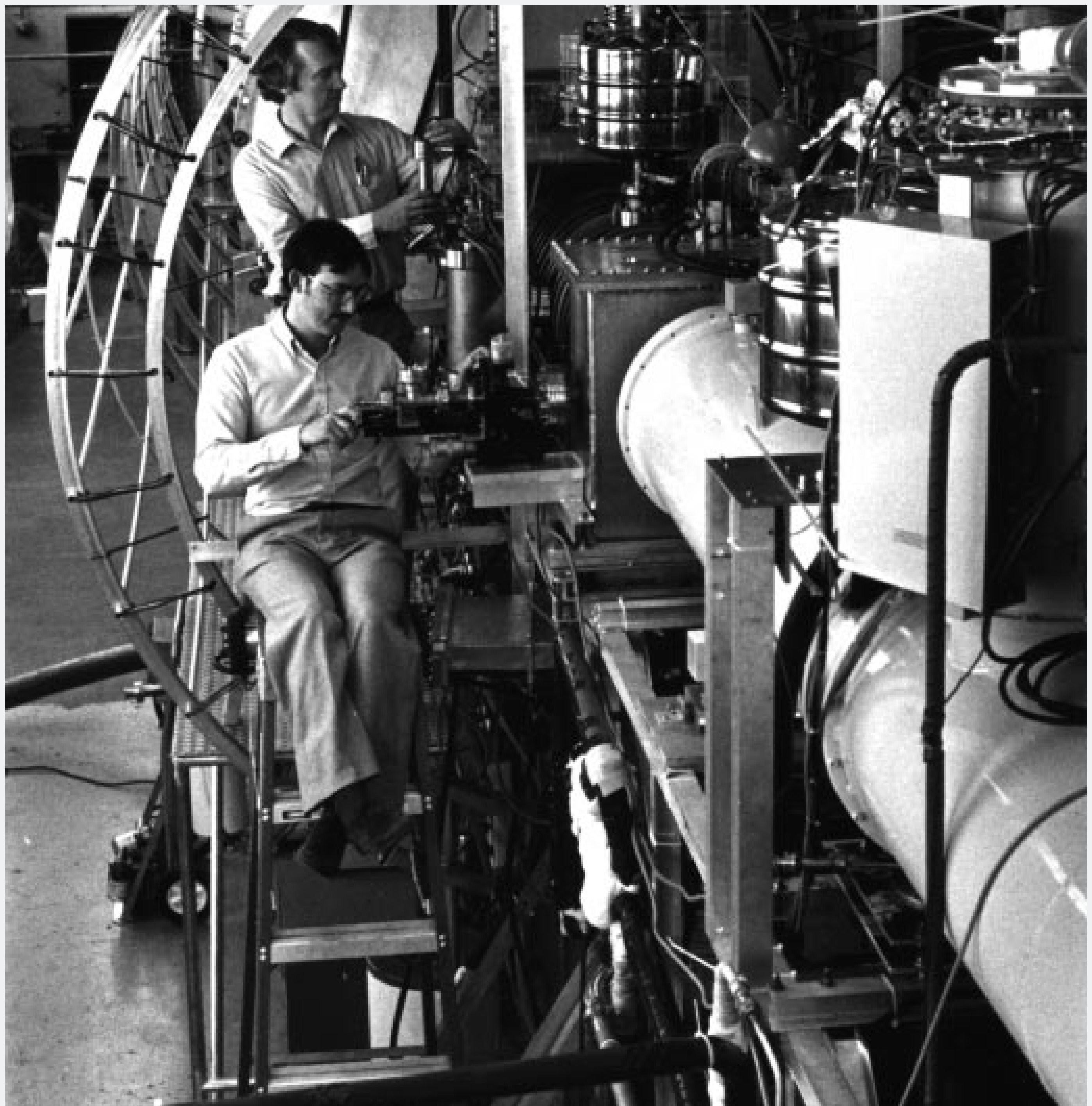
Lande, K., and F. Reines. 1971. LAMPF Neu-trino Facility Proposal. Los Alamos Scientific Laboratory report LA-4842-MS. (Online at http://lib-www.lanl.gov/la-pubs/00362846.pdf)

Gerry Garvey is the former director of LAMPF. His biography appears on page 63.



Tritium Beta Decay and the Search for Neutrino Mass

Thomas J. Bowles and R. G. Hamish Robertson as told to David Kestenbaum



Neutrinos have been around, literally, since the beginning of time. In the sweltering moments following the Big Bang, neutrinos were among the first particles to emerge from the primordial sea. A minute later, the universe had cooled enough for protons and neutrons to bind together and form atomic nuclei. Ten or twenty billion years later—today—the universe still teems with these ancient neutrinos, which outnumber protons and neutrons by roughly a billion to one. Stars such as the sun churn out more; Wolfgang Pauli himself was unknowingly awash in trillions of solar neutrinos while he was drafting his “desperate remedy.”[1]

We tend to think of neutrinos as transients, interacting only through the weak force and gravity and tracing long, lonely trajectories across the universe. But what they lack in strength they make up in number. Even if neutrinos were to have a mass as small as one billionth of that of a proton or neutron, their cumulative tug would be enormous, affecting the gravitational evolution of the universe as much as the normal matter we observe every day. It is believed that a neutrino mass of 22 electron volts would cause our universe to contract and eventually collapse because of gravitational forces.

Ironically, all who attempted to measure the mass of the neutrino directly used the very process that compelled Pauli to postulate its existence more than sixty years ago—the curious phenomenon of beta decay. Early experiments determined that certain radioactive atoms produced beta particles (high-energy electrons) when they decayed. The law of energy conservation dictates that the electron should emerge with a specific energy, identical every time, as it recoils against the atom. The electrons, however, appeared with a variety of energies, and Pauli correctly inferred that the decay also produced a second unseen particle, now called the electron neutrino. The neutrino would share the energy released in the decay with the daughter atom and the electron. The electrons would emerge with a spectrum of energies.

In 1934, Enrico Fermi pointed out that, if the neutrino had mass, it would subtly distort the tail of this spectrum. When an atom undergoes beta decay, it produces a specific amount of available energy that is carried away by the electron, the neutrino, and the daughter atom. Typically, the bulky atom remains relatively still, while the electron and neutrino split the available energy. Sometimes, the electron takes more than half, sometimes less. On extremely rare occasions, it can carry off nearly all the energy.

This maximum amount of energy the electron can carry off is called the endpoint energy and marks the tail end of the spectrum of electron energy released in the decay. If the neutrino has no mass, the endpoint energy is very nearly equal to the energy released in the decay. On the other hand, Fermi pointed out, a finite neutrino mass would make the endpoint energy slightly lower and shorten the tail of the spectrum.

If some of the energy released in the decay were “locked up” in the mass of the neutrino, it would be unavailable to the electron, and the mass of the neutrino could be determined from a careful measurement of the spectrum near the endpoint. Unfortunately, the converse (a massless neutrino) can never be proved; it is always possible that the neutrino has a small mass that lies just beyond the reach of the latest experiment. A Zen-like axiom underlies this quandary: you cannot weigh something that has no mass.

The ideal beta-decay source has a short lifetime and releases only a small amount of energy in the decay. A small energy release means that more decays fall near the endpoint, where the shape of the electron energy spectrum is sensitive to a small neutrino mass. A short lifetime means atoms decay more rapidly, making more data available.

A wonderful accident of nature, tritium (a hydrogen atom with two extra neutrons) is a perfect source by both of these measures: it has a reasonably short lifetime (12.4 years) and releases only 18.6 kilo-electron-volts (keV) as it decays into helium-3. Additionally, its molecular structure is simple enough that the energy spectrum of the decay electrons can be calculated with confidence.

The predicted spectrum (shown in Figure 1) peaks at around 4 keV and extends up to the endpoint energy, around 18.6 keV. Only one out of every 10 million decays emits an electron in the last 100 electron volts before the endpoint, where the shape is sensitive to neutrino masses in the range of 30 electron volts (see close-up of the endpoint), so testing the tail requires precision as well as patience.

ITEP Weighs in with Neutrino Mass

Was the neutrino mass holding back some energy from the electron? In 1980, the answer seemed to be a startling “yes.” Over the years, numerous experiments had probed the endpoint with increasing precision and concluded that the neutrino could have a mass no more than a few tens of electron volts. But in 1980, Russian scientists at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow announced that they had pushed even further and discovered a shortfall near the endpoint corresponding to a neutrino mass of around 35 electron volts. The consequences of such a hefty mass would be enormous. The Standard Model would have to be revised, and the universe would eventually collapse, albeit not for another 40 billion years or so.

But were the results correct? Investigations uncovered problems in the

[1] See the box “The Desperate Remedy” on page 6.

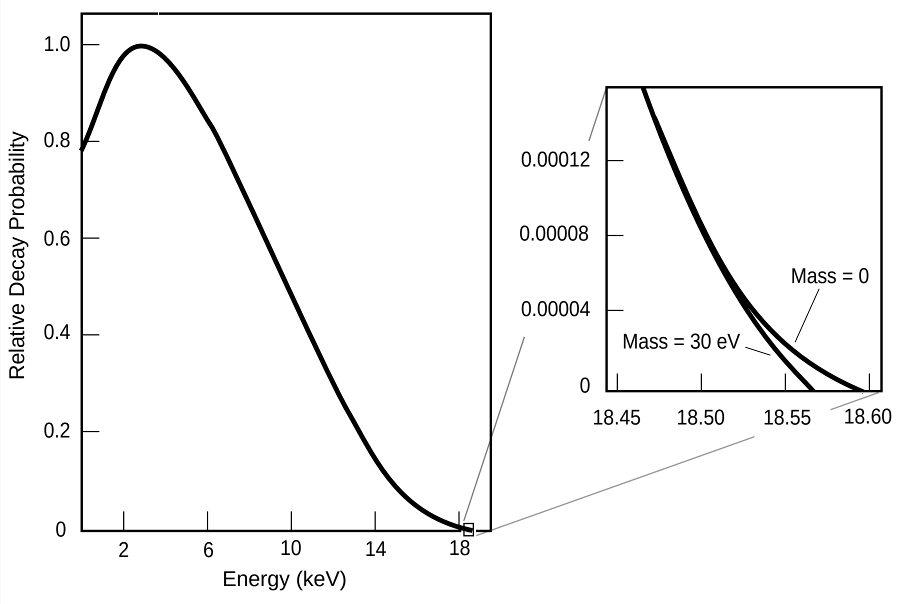


Figure 1. The Beta Decay Spectrum for Molecular Tritium

The plot on the left shows the probability that the emerging electron has a particular energy. If the electron were neutral, the spectrum would peak at higher energy and would be centered roughly on that peak. But because the electron is negatively charged, the positively charged nucleus exerts a drag on it, pulling the peak to a lower energy and generating a lopsided spectrum. A close-up of the endpoint (plot on the right) shows the subtle difference between the expected spectra for a massless neutrino and for a neutrino with a mass of 30 electron volts.

alculation of the spectrum shape and rrors resulting from the energy reso- ution of the Russian spectrometer. Members of the ITEP group carefully nd methodically conducted a new ound of experiments checking for hese and other systematic errors and roviding new data. Although they educed their prediction of the electron eutrino mass to 26 electron volts, heir original conclusion that the eutrino has mass remained the same.

Still, there were many ways to enerate a slump at the end of the spec- um and mimic a finite neutrino mass: he electrons could be losing energy om scattering off other atoms in the ource, the spectrometer resolution ould be off, or some energy could be ed up in an unanticipated excited state f the daughter atom. In particular, the ommunity voiced concern over ITEP's se of a solid source, an amino acid alled valine in which some of the ydrogen atoms had been replaced with tritium. Valine was convenient because it was readily available, but its complex molecular structure meant that the atoms were left in a myriad of excited states following the decay. The excitations could rob the electron of energy and, if not properly taken into account, could induce an apparent ero- sion of the spectrum near the endpoint. Moreover, the excitation energies were quite similar to the observed neutrino mass, and a difficult and uncertain theoretical calculation was needed to correct for the effect. Thus, the ITEP claim left room for considerable doubt.

The Los Alamos Experiment: Simple in Theory, Tough in Practice

Several months before the ITEP announcement, over gelati at the Erice conference in Italy, Los Alamos physicists Thomas Bowles and Hamish Robertson (now at the University of Washington) had decided they would also join the hunt for a neutrino mass. With the salvo that the ITEP measurement drew, there was no better time to enter the fray.

In 1980, armed with innovative methods designed to circumvent the uncertainties that had cast doubt on the earlier work, a team at Los Alamos led by Robertson and Bowles began an exhaustive search for the electron neu- trino mass. Instead of a solid source, pure, gaseous, molecular tritium was used (see Figure 2). Molecular tritium (a bound state of two tritium atoms) was simple enough that theoretical physicists could accurately calculate the atomic excitation energies, taking into account all the interactions between the two elec- trons and nuclei. Even with this seem- ingly simple system, the calculations were involved, requiring many days of computation on a Cray computer. By contrast, the ITEP source, valine, contained 19 atoms and 64 electrons, making such a calculation intractable.

The use of a gas also reduced energy loss in the material and eliminated "backscattering" where the electron could hit the backing (used to support the solid source) and do an energy- sapping U-turn, which could produce a dip in the spectrum near the endpoint. But this theoretical simplicity came at the expense of experimental complexity. Handling a kilocurie of tritium gas posed many challenges. The complex arrangement of magnets, pumps, and other equipment for the experiment filled a room 30 feet by 70 feet.

But the grand contraption had a rela- tively simple task: To capture electrons from the beta decay of the tritium gas and carefully transport them to a high- precision magnetic spectrometer. Only those electrons that enter with a certain fixed energy can traverse the magnetic fields set up in the spectrometer. A sili- con detector sits at the end of the spec- trometer and counts the electrons that make it through.

The tritium gas that begins the whole process is circulated and

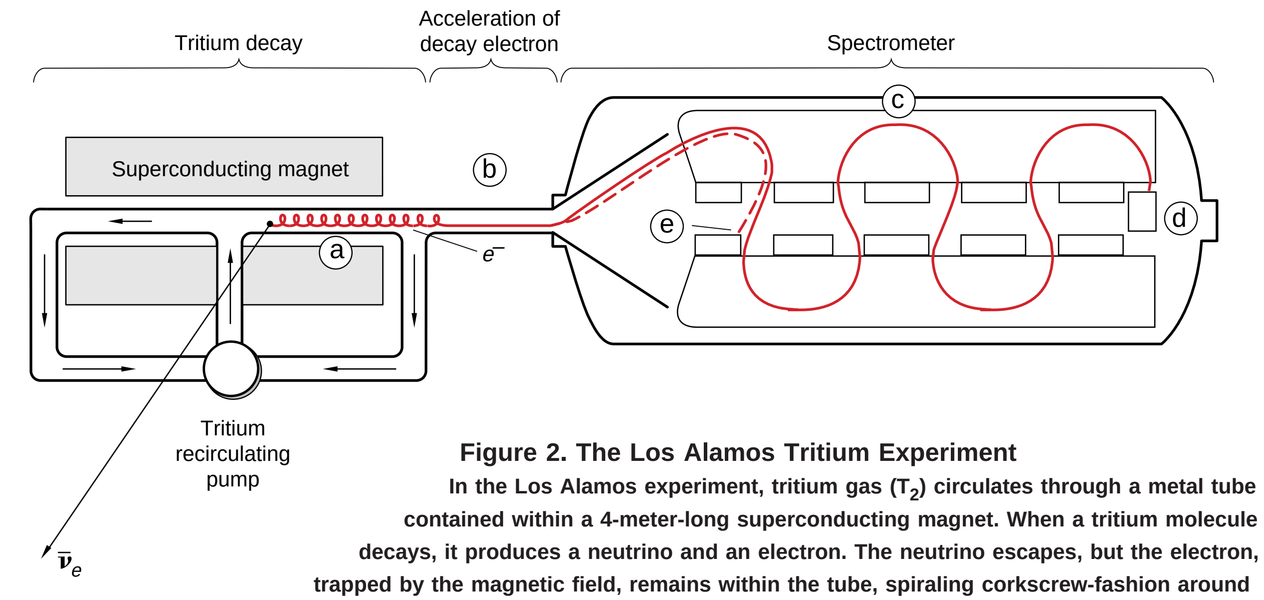


Figure 2. The Los Alamos Tritium Experiment

In the Los Alamos experiment, tritium gas (T_2) circulates through a metal tube contained within a 4-meter-long superconducting magnet. When a tritium molecule decays, it produces a neutrino and an electron. The neutrino escapes, but the electron, trapped by the magnetic field, remains within the tube, spiraling corkscrew-fashion around the field lines (a). The electron emerges from the magnet and receives a kick in energy (b) before it is passed to the spectrometer (c). Magnetic fields in the spectrometer guide the electron through several S-turns and focus them onto the detector (d). The magnetic fields are chosen so that only the electrons with energies near the endpoint reach the detector. Electrons with too little energy quickly get off course and run aground in the walls of the spectrometer (e).

recirculated through a long metal tube, 4 centimeters in diameter, which itself is contained in a larger-diameter solenoidal superconducting magnet. The magnetic field points along the axis of the tube, and it contains and guides the decay electrons without altering their energy. The electron neutrino, of course, leaves the tube, the room, and eventually the solar system, but the electrons remain, spiraling corkscrew-fashion in very tight, millimeter-radius circles along the field lines. The field strength varies along the tube so that the electrons are corralled toward one end of the 4-meter magnet. Electrons that head off toward the wrong end are bounced back by an increasing field gradient. When the electrons exit the magnet, a second magnetic field separates them from the gas before they are finally injected into the large toroidal spectrometer. Electrons near the endpoint energy have a velocity roughly one million meters per second, and their dizzying journey takes only a fraction of a second.

One concern was that tritium would accumulate inside the spectrometer. Electrons resulting from its decay could bypass the difficult obstacle course and pollute the data with spurious "background" counts. The Los Alamos group solved this problem by setting the spectrometer to count elec- trons of 23 or 24 keV (above the end- point) and placing the tritium source at a higher voltage than the spectrometer's. The added voltage gave the electrons that entered the spectrometer an extra "kick" in energy. The silicon detector, in addition to counting the arriving electrons, was also designed to provide a rough measurement of the electron energy (accurate to about 3.5 keV) and, so, could be used to discriminate between the electrons coming from the source and the lower-energy ones coming from the tritium lodged in the spectrometer.

Transporting and measuring the electrons were delicate affairs, and care also had to be taken to eliminate any stray magnetic fields that could derail the electrons. An additional coil outside the spectrometer eliminated the earth's magnetic field. Steel girders in the building had to be demagnetized by hand.

Another concern was that contaminants such as oxygen and nitrogen, which inevitably leak into the system, could build up. These atoms, which are relatively bulky compared with tritium, could skim off energy from the electron through inadvertent collisions. Forcing gas through a palladium filter removed the larger atoms and cleaned the system.

The tritium itself also presented a few sticky problems. Because tritium and hydrogen are effectively siblings (both contain one proton), the two often trade places, and the tritium ends up affixed to all manner of surfaces. Over time, for instance, tritium accu- mulates in the walls of the tube, taking the place of hydrogen atoms that used to be there. To ensure that the electrons reaching the spectrometer originated from the gas and not the tube walls, the physicists tuned the spectrometer to accept only electrons that came from the very center of the tube. This had the unfortunate consequence of tripping away 90 percent of the lectrons from decays in the gas, but uccessfully reduced the number of lectrons coming from the walls of the ube by a factor of 100,000 or more.

uilding an instrument is one thing; nderstanding what it does it quite nother. Taking data with an ncalibrated device is like playing an ut-of-tune piano. The result is more oise than music. In this case, the uning had to be very precise: the nergy measurements good to nearly ne part per thousand. Fortunately, here was an elegant way to test he response of the apparatus—simply eplacing the tritium gas with gaseous rypton-83m (an isotope of krypton hat produces monoenergetic electrons). Krypton-83m is another wonderful ccident of nature. It produces elec- ons close in energy (17.8 keV) to he tritium endpoint, and so it is per- ect for calibrating the spectrometer.

Each of the numerous tritium atoms irculating through the system had, very second, a one-in-a-billion chance f decaying. Roughly, sixty-million lectrons of all energies entered the pectrometer every minute, of which nly one, on average, had an energy ear the endpoint that would carry it hrough the selective fields of the pectrometer. What began as a flood f electrons was reduced to a trickle of nly one every minute. The physicists ould only drum their fingers and wait or the drops to accumulate.

Seven Years Later: A Verdict and a New Mystery

In 1987, the Los Alamos scientists ad finished an initial measurement and, y 1991, they had a clear verdict: the measurement of the tritium beta-decay pectrum showed no deficit near the end- oint. This finding was consistent with n electron neutrino mass of zero and otably inconsistent with ITEP's results. A very tiny mass might have escaped etection, but it could not have been arger than 9.4 electron volts, which is far smaller than the 22 electron volts needed to cause the universe to contract. Figure 3 shows the data compared with the expected shape for a neutrino mass of 30 electron volts and for a neutrino mass of zero.

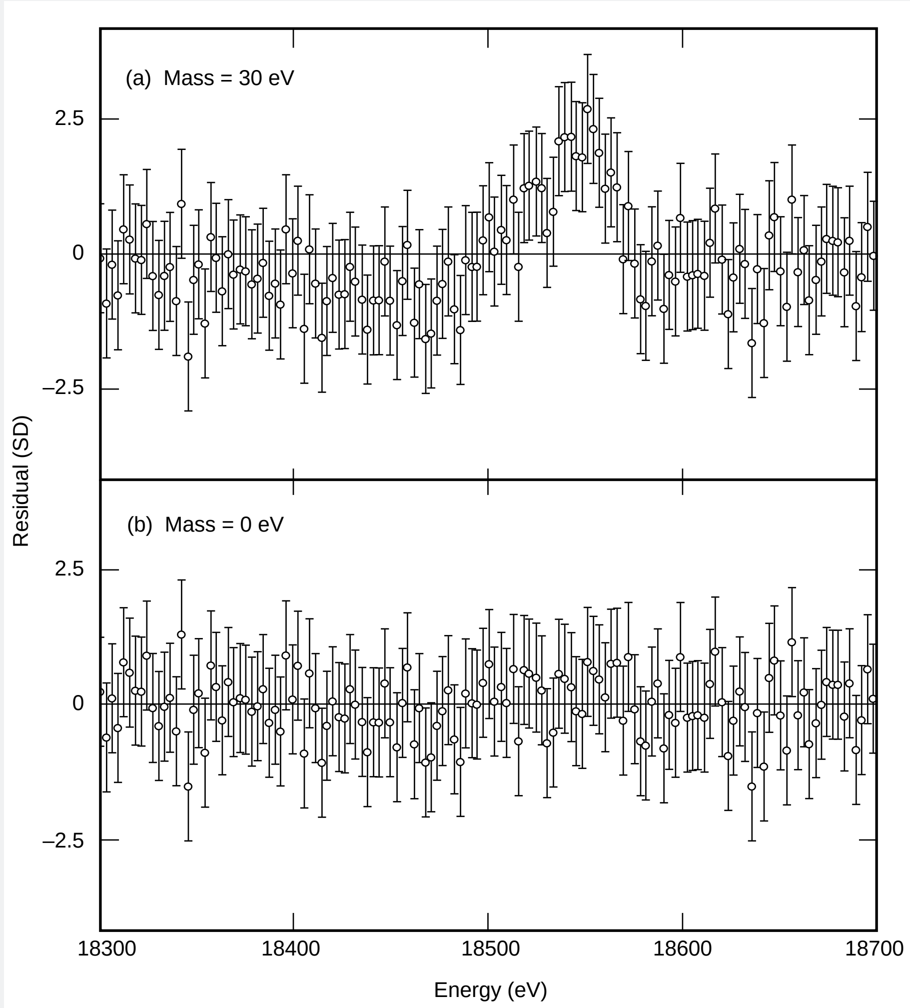


Figure 3. Did the Neutrino Weigh 30 Electron Volts?

Not according to the Los Alamos data. The top figure shows the data points from the tail of the spectrum compared with the expected values (the straight line) for an electron neutrino with a mass of 30 electron volts. The data wander from the line, ruling out the possibility of a 30-electron-volt neutrino. On the other hand, the bottom figure shows the same data points compared with the expectation for a neutrino mass of zero. While the data clearly favor a neutrino mass of zero (the points lie close to the line) over a mass of 30 electron volts, the best fit is actually for a slightly *negative* neutrino mass. (Note that in the bottom plot, the data points lie, on average, slightly above the line, so this is not a perfect fit.) Both plots display "residuals," which indicate how many standard deviations each data point is from a particular hypothesis. One can think of plotting the data over the top of the predicted spectra shapes of Figure 1, pulling the tail out so that it lies horizontal, and adjusting each data point so that its distance to the line is represented in standard deviations. (Each point has an experimental uncertainty associated with it. Two-thirds of the time, the true value is expected to lie within plus or minus one "sigma" or standard deviation from the point.)

But from the ashes of the Russian result arose a new mystery. Careful inspection of the Los Alamos data revealed a small, curious surplus near the endpoint. A deficit would have meant that neutrinos had mass (see Figure 1), but a surplus did not make any sense. Although unlikely (the odds were roughly 1 in 30), the result could have simply been a statistical fluctuation.

Over the years, several other experiments have also ruled out the Russian result and confirmed the strange surplus near the endpoint (Stoeffl and Decman 1995 and Weinheimer et al. 1993). The surplus can no longer be explained away as a statistical fluctuation, and it prevents experimenters from establishing a tight upper limit on the neutrino mass. As stated in the Review of Particle Physics, the accepted encyclopedia of particle properties, "Given the status of the tritium results, we find no clear way to set a meaningful limit on m_{ν_e}."

Today, the tritium quandary has spawned a small cottage industry of professional speculators. There are, possibly, as many theories to explain the surplus as there are groups investigating it. The exotic possibilities run from tachyonic (traveling faster than the speed of light) neutrinos, to a new force that would cause clumping of neutrinos around our galaxy. More mundane explanations include unanticipated molecular or atomic effects in the tritium decay. Still, the simple structure of molecular tritium is thought to be well understood, and the calculations that yield the shape of the spectrum rest solidly on the time-proven laws of quantum mechanics.

It may be that what began as a search for neutrino mass has unearthed something far stranger. Experiments designed to ferret out whatever is hiding in the tail are on the drawing boards, but given the enormous technical challenges involved, headway will be hard won. Neutrinos had been around for billions of years before Pauli noticed them, and it may be a few more before their true character is revealed. ■

Thomas J. Bowles received his Ph.D. degree in 1978 from Princeton University. After a postdoctoral appointment at Argonne National Laboratory, he joined the Physics Division of the Laboratory in 1979. Bowles initiated a program in weak-interaction physics in the Physics Division, working on problems in beta decay, neutrino studies at LAMPF, and nuclear astrophysics. This program was initially centered on measurements of the tritium beta-decay spectrum as a sensitive means of searching for a finite mass of the electron antineutrino. The Los Alamos experiment was the first to employ a windowless free-molecular-tritium source. The results from this experiment refuted the claims of a Russian group who claimed to have measured a finite neutrino mass. They also ruled out electron antineutrinos as a possible candidate for most of the dark matter of the universe. Subsequently, Bowles became involved in studies of solar neutrinos as a means to extend the experimental sensitivity to a finite mass of the neutrino. In 1986, Bowles became the U.S. principal investigator on the Russian-American Gallium Experiment and a member of the Sudbury Neutrino Observatory project. Most recently, he initiated a program to develop a source of ultracold neutrons at LANSCE in order to study fundamental symmetries of nature in neutron beta decay. Bowles was elected Fellow of the American Physical Society in 1992, Los Alamos National Laboratory Fellow in 1994, and was appointed as an affiliate professor at the University of Washington in 1995.

R. G. Hamish Robertson was born in Ottawa, Canada, and was educated in Canada and England. He earned his undergraduate degree at Oxford University and his Ph.D. degree in atomic-beam and nuclear-structure physics at McMaster University in 1971. Robertson went to Michigan State University as a postdoctoral fellow and remained on the faculty, becoming professor of physics in 1981. In 1976, he received an Alfred P. Sloan Fellowship, and his research resulted in the first observation of an isobaric quintet of states in nuclei. Additionally, he carried out experiments on parity violation, nuclear astrophysics, and nuclear reactions. In 1981, he joined Los Alamos National Laboratory, becoming a Fellow in 1988, and was responsible for investigating neutrino mass via tritium beta decay and solar-neutrino physics. In 1994, Robertson took a professorship at the University of Washington, where he continued his work in neutrino physics. In 1997, he received the American Physical Society (APS) Tom W. Bonner Prize. He is a member of the Canadian Association of Physicists, an associate member of the Institute of Physics (London), and a Fellow of the APS. Robertson has chaired the Nuclear Science Advisory Committee and served on its Instrumentation Subcommittee. He is a member of the Board of Physics and Astronomy of the National Research Council (NRC) and has served on the NRC's Nuclear Physics and Neutrino Astrophysics Panels and the APS Division of Nuclear Physics Executive and Program Committees. Robertson has served on review committees for the Lawrence Berkeley National Laboratory's Nuclear Science Division and Caltech's Physics, Mathematics, and Astronomy Division, the Editorial Board of Physical Review D, and review panels for the National Science Foundation and the Department of Energy.

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