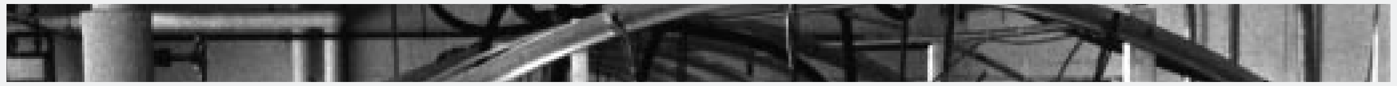
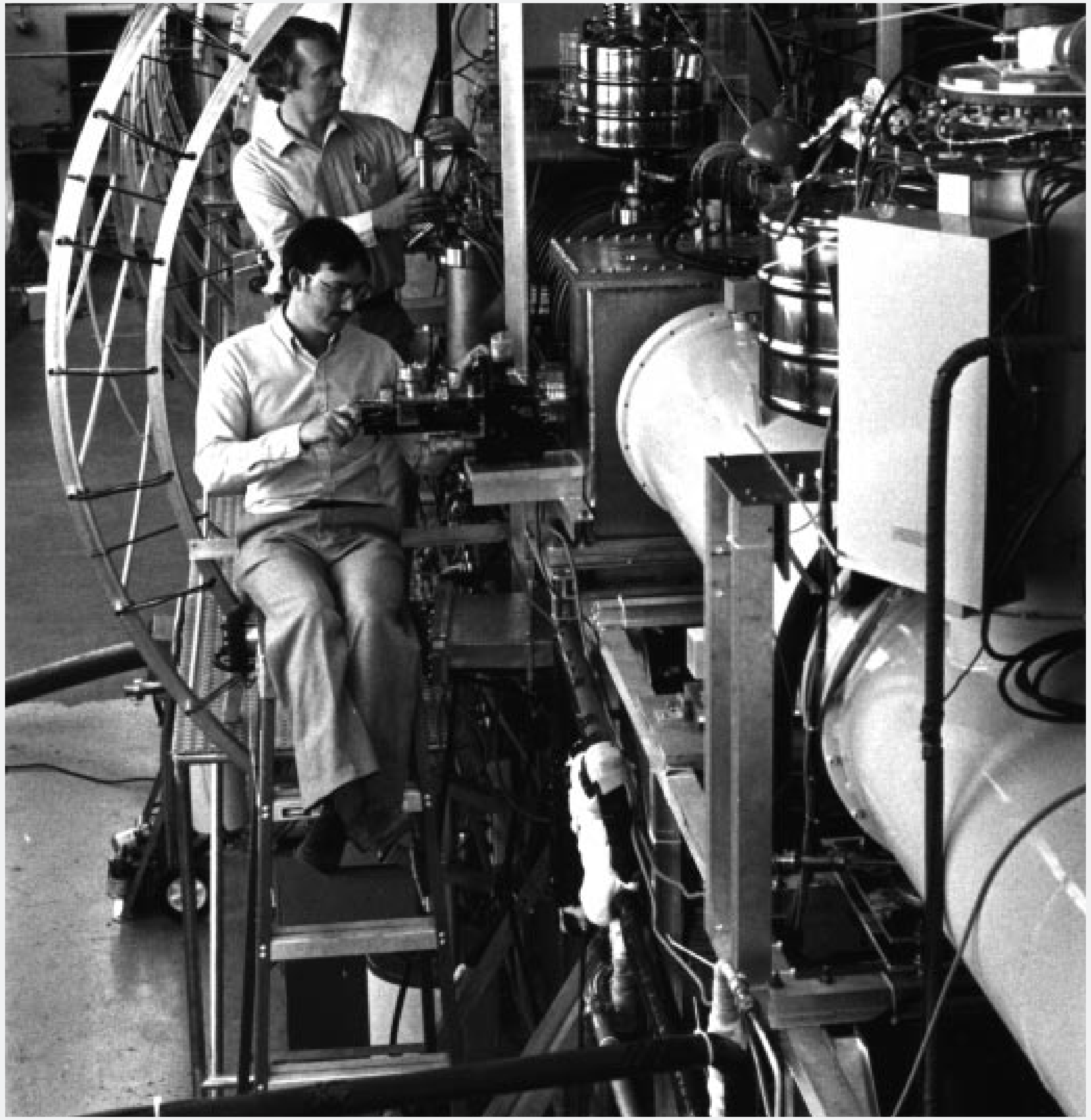


Tritium Beta Decay and the Search for Neutrino Mass

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.

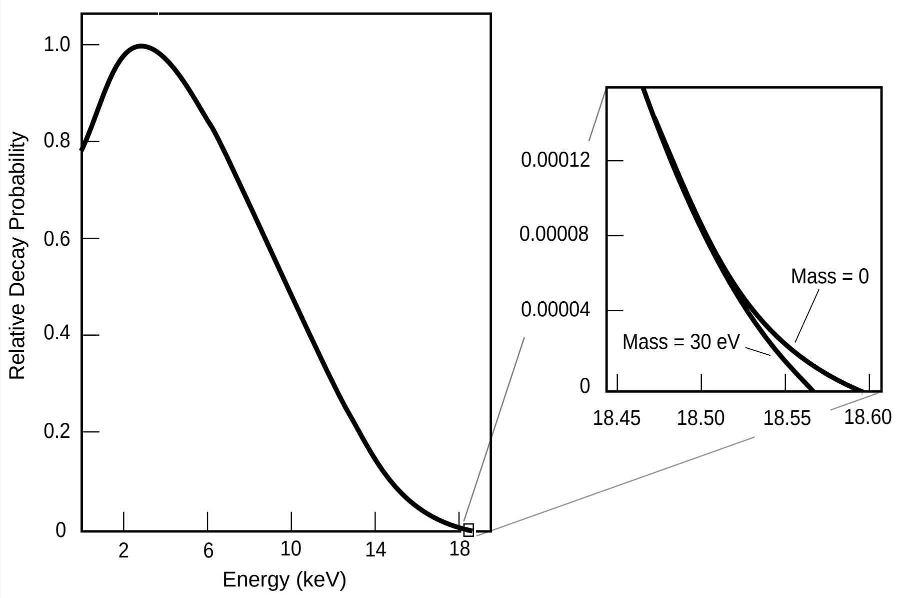


Figure 1. The Beta Decay Spectrum for Molecular Tritium

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 erosion 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 neutrino 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 electrons and nuclei. Even with this seemingly 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 relatively 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 silicon detector sits at the end of the spectrometer and counts the electrons that make it through.

The tritium gas that begins the whole process is circulated and

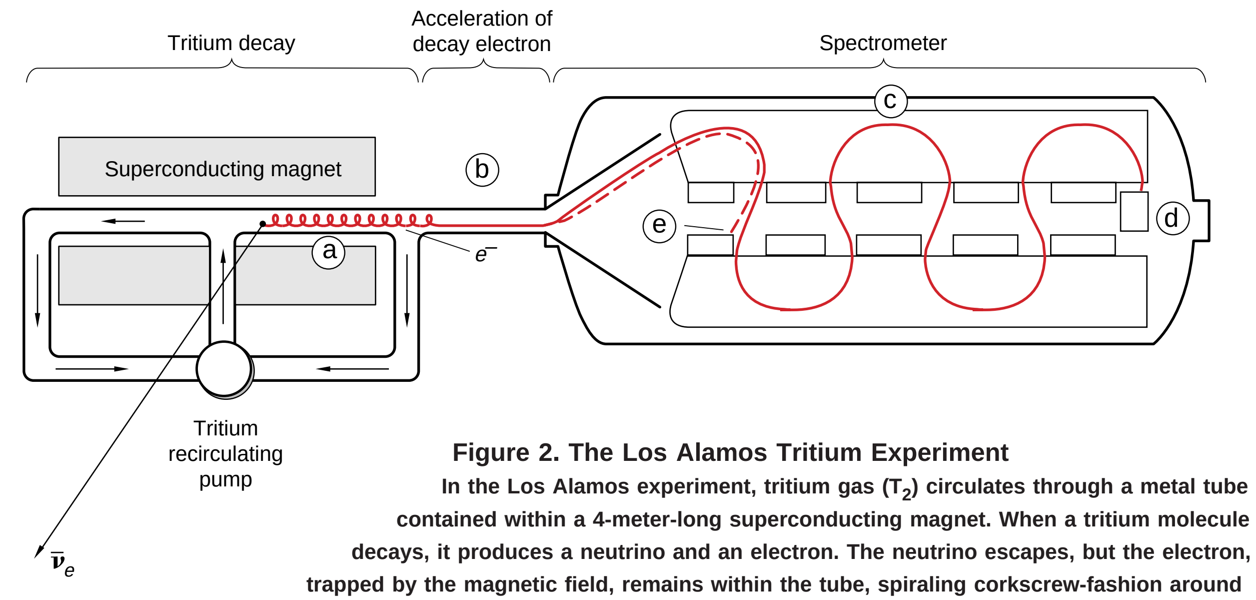


Figure 2. The Los Alamos Tritium Experiment

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 electrons of 23 or 24 keV (above the endpoint) 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 accumulates 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.

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.

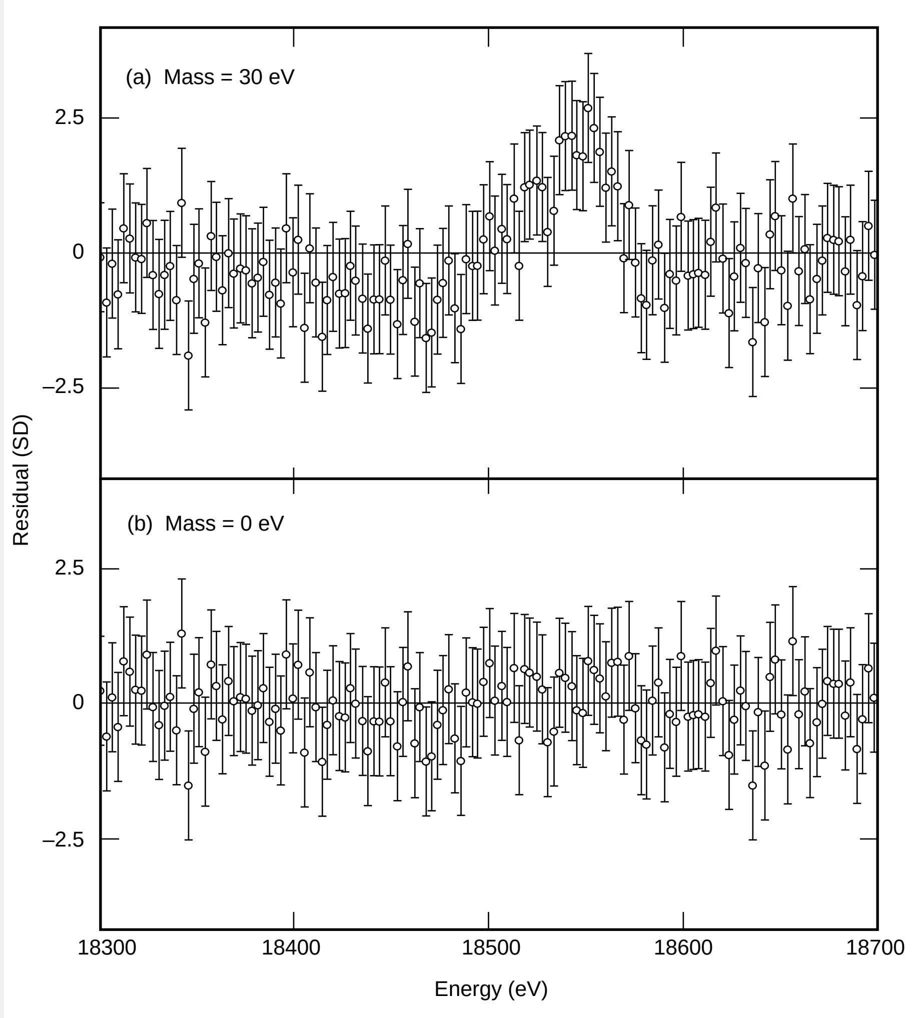


Figure 3. Did the Neutrino Weigh 30 Electron Volts?

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.)

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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