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.”

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 in much the same way 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 experiments. 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 the endpoint forward by more than 2 KeV, thus revising the results and opening the way to a new experiment. 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? Inves-

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**See the box “The Desperate Remedy” on page 6.”**
calculation of the spectrum shape and errors resulting from the energy resolution of the Russian spectrometer.

Members of the ITEP group carefully designed a new instrument specifically for the purpose of measuring the neutrino mass, and this new instrument was the key to their success. The new instrument was a gas-based recoil detector, which was able to measure the energy of the electrons that were produced in the decay of the tritium gas. This allowed them to accurately calculate the neutrino mass, which was previously thought to be too small to measure.

The Los Alamos experiment was a simple and elegant solution to the problem of measuring the neutrino mass. The experiment consisted of circulating tritium gas through a metal tube and measuring the energy of the electrons that were produced in the decay of the tritium gas. The energy of the electrons was measured using a high-precision magnetic spectrometer, which was able to accurately measure the energy of the electrons to within a fraction of an electron volt.

Several months before the ITEP team published their results, the Los Alamos team had already published their results. The Los Alamos team had used a similar technique to measure the neutrino mass, but they had used a different approach. The Los Alamos team had used a gas-based recoil detector, which was able to measure the energy of the electrons that were produced in the decay of the tritium gas. This allowed them to accurately calculate the neutrino mass, which was previously thought to be too small to measure.

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tripping away 90 percent of the electrons from decays in the gas, but successively reduced the number of electrons coming from the walls of the tube by a factor of 100,000 or more, gilding an instrument is one thing; understanding what it does is quite another. Taking data with an acclimated device is like playing an off-tune piano. The result is more noise 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 his response of the apparatus—simply replacing the tritium gas with gaseous rypton-83m (an isotope of krypton that produces monoelectronons). Krypton-83m is another wonderful accident of nature. It produces electrons close in energy (17.8 keV) to tritium endpoint, and so it is perfect for calibrating the spectrometer.

Each of the numerous tritium atoms circulating through the system had, very second, a one-in-a-billion chance of decaying. Roughly, six million electrons of all energies entered the spectrometer every minute, of which nly one, on average, had energy large enough to pass through the fields of the spectrometer. That began as a flood of electrons was reduced to a trickle of nly one every minute. The physicists could 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 spectrum showed no deficit near the end- point. This finding was consistent with electron neutrino mass of zero and the absence of electron antineutrinos. To find a finite neutrino mass via tritium beta decay and solar-neutrino Physics. Letters B 292: 1.

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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 statistics.

Over the years, several other experiments have also ruled out the Russian result and confirmed the strange surplus near the endpoint (Stoeffel 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 upper limit is a factor of about two larger than the 95% confidence level of the Los Alamos result. (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 far each data point is from a particular hypothesis. One can think of plotting the data over the top of the expected spectrum from 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 experimentally determined 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.)

It may be that what began as a search for the 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 that 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 at Los Alamos National Laboratory in 1976. 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-electron line 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 neutrino fluxes and 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 neutrinos at LANSE in order to study fundamental symmetries of nature in neutrino 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.

Further Reading


