PARTICLE PHYSICS

Are Neutrino Mass Hunters Pursuing a Chimera?

There's been a new sighting in no man's land. Last December, Anthony Turkevich of the University of Chicago and his collaborators published the result of a study of rare radioactive decays in *Physical Review Letters*, and chemist Turkevich told *The New York Times* that the data represented "another, independent line of evidence pointing toward neutrinos' having mass"—12 electron volts (ev), to be exact. If Turkevich's measurements of the ephemeral particles (which are copiously emitted by radioactive decays, nuclear reactions within the sun, and exploding stars) were confirmed, the result would have revolutionary implications for physics. But critics quickly wrote off Turkevich's sighting of a massive neutrino as yet another will-o'-the-wisp.

Along with their reservations about the theoretical and experimental uncertainties underlying the conclusion, the doubters noted that precedent did not bode well for it—or for the half-dozen other claims of a nonzero neutrino mass. Wick Haxton, a nuclear theorist at the University of Washington, observes that the history of neutrino mass experiments is checkered with earlier claims, and they have one thing in common: All have been retracted or contradicted by now. "I would hope that one or more experiments going on right now would really show evidence for new physics," says Haxton. "But I would bet that when we understand all these experiments better the evidence will all go away."

For Haxton and other physicists, it's a disappointing prospect. The mass—or masslessness—of the neutrino stands as the single most crucial question in both cosmology and high-energy physics. If the neutrino has sufficient mass, then it offers a solution to the enigmas of dark matter and missing mass in the universe. And if the neutrino has any mass at all, then there is physics, finally, beyond the standard model—the edifice of theory built in the 1970s, which specifies a massless neutrino. The standard model has so far managed to fit every observation except what Harvard Nobel laureate Sheldon Glashow calls the "hullabaloo over neutrinos."

But neutrinos are a treacherous testing ground for physics and cosmology. Weighing the neutrino—a particle so ethereal, as the author John Updike put it, that it can pass through the entire Earth "like photons through a sheet of glass"—has required pushing experimental techniques to the limits of their resolution. This is "no man's land," in the words of University of Chicago cosmologist Michael Turner. It's physics at the limit, agrees Haxton. "One has to have some sympathy for the poor experimentalists," he says. "Lots of people do very safe experiments. These guys are all out there trying to push realms that have never been explored before."

It is the nature of research in no man's land that any unknown background or instrumental artifact can lead to spurious data. Add to this a theoretical predisposition to find a nonzero mass, together with the allure of being first in such a quest, and the requisite skepticism of good research becomes hard to maintain. "Everybody would love to discover the mass of the neutrino," says Michael Moe of the University of California at Irvine, who has been doing neutrino physics for 20 years. "So you're always walking a tightrope between jumping the gun and being too late if somebody else discovers it." That, say researchers, is the danger of doing science in a realm where data are almost hidden in the noise, and the theoretical stakes are high.

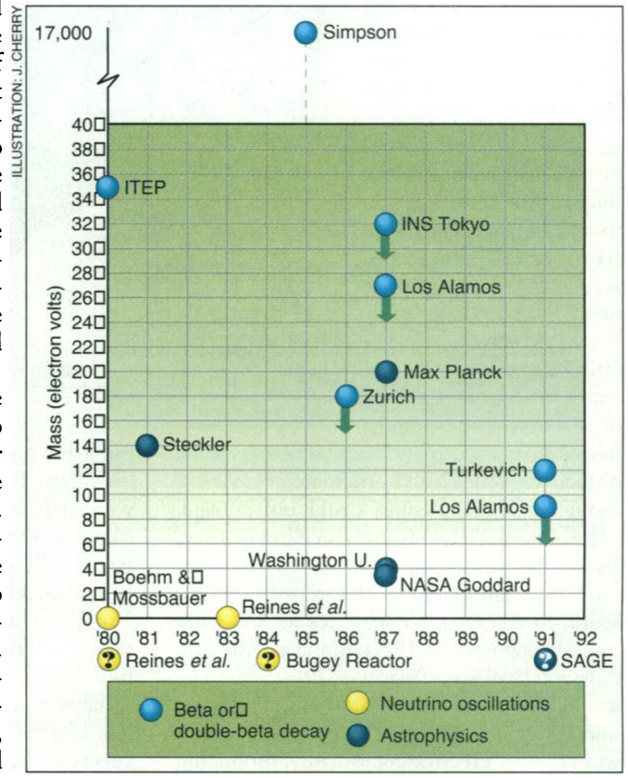
Putting on weight. That the neutrino might have a nonzero mass only became an issue after the confirmation of particle physics' standard model in 1973. The standard model, which unified electromagnetism with the weak force, defined the neutrino as having zero mass without offering any persuasive rationale. Meanwhile, theoretical attempts to improve on the standard model—in particular, Grand Unified Theories and supersymmetry—predicted a nonzero mass. That prediction naturally prompted experimentalists to begin tackling the problem. Felix Boehm of Caltech, a central figure in the quest for neutrino mass, recalls that in 1975 his Caltech colleagues Murray Gell-Mann and Harold Fritsch "strongly encouraged" him to take up the search for just this reason.

True, neutrino mass was only one of three major predictions of Grand Unified Theories. The other two were magnetic monopoles—particles carrying an isolated north or south magnetic pole—and the decay of the proton. But the hopes for a proton decay signal within immediate experimental reach were put to rest by the mid-1980s, with reports from two definitive experiments: the Kamioka detector in Japan, and the Irvine-Michigan-Brookhaven (IMB) detector, in a salt mine in Ohio. As for monopoles, hopes were dampened by several compelling cosmological arguments, notably the inflationary theory of the universe, which holds that the cosmos underwent a drastic growth spurt when it was just a fraction of a second old. The theory predicts that all monopoles created in the Big Bang were "inflated" away from the observable universe.

Although inflation pushed monopoles out of reach, at the same time it gave massive neutrinos an added theoretical rationale. Inflation requires a universe containing much more mass than is visible: enough mass for gravity to "close" the universe—halt its expansion. Neutrinos became the leading candidate for the missing mass. In 1980 David Schramm of the University of Chicago and Gary Steigman of Ohio State University observed that given a plausible density of neutrinos, a mass of 33 ev, give or take a factor of 2, would serve very nicely to close the universe.

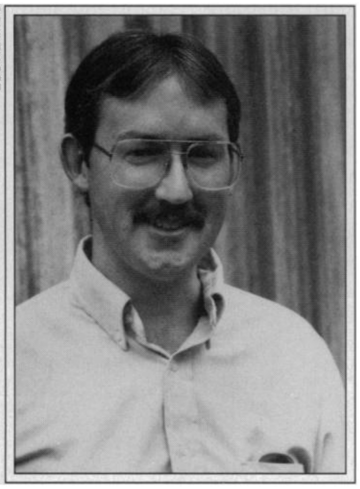
All of which is to say that by 1980, there was a strong theoretical prejudice from both cosmology and particle physics that neutrinos had a mass in the ev range. And physicists quickly began to report the discovery of exactly what they sought.

First off, in April 1980, were Valentin Lyubimov and his colleagues at the Institute of Theoretical and Experimental Physics (ITEP) in Moscow. The ITEP group had ana-



Now you see it, now you don't. Some of the results from the neutrino mass hunt; arrows indicate upper limits.

lyzed the decay of tritium into helium-3, an electron, and a neutrino. The energy released by the reaction—18,600 ev—is shared by the electron and the neutrino, and the cases of interest are those in which the electron takes virtually all the available energy. What it can't carry off, if the neutrino has mass, is a tiny residue of energy corresponding to that mass. Subtract the measured energy of the electron from the total energy of the reaction, and you're left with the neutrino rest mass. The catch is that if the neutrino mass is only a few tens of ev, the electron will carry off the maximum allowable energy only one time in 10^{10}, which makes the experiment excruciatingly difficult. Nonetheless, Lyubimov and company claimed that the technique had revealed a neutrino mass of between 14 and 46 ev, with a best fit of 35 ev.


LOS ALAMOS

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–Tom Bowles

Shifty neutrinos. Just as rumors of the ITEP results were circulating through the physics community, evidence of neutrino mass came from another quarter. Physicist Fred Reines of the University of California at Irvine announced that his experiment at the Savannah River nuclear reactor had yielded signs that neutrinos can change identity as they travel, "oscillating" from electron neutrinos to one of the two other neutrino species, muon and tau neutrinos. Such oscillations were de facto evidence for a nonzero neutrino mass, though how much mass could not be said. "The universe," Reines announced at the time, "is not the way we thought."

Those tantalizing results were enough to spark dozens of other searches for neutrino mass throughout the 1980s, along with a flurry of theoretical speculation.

■ Glashow and Alvaro de Rujula of Harvard immediately proposed that heavy neutrinos would decay electromagnetically, producing signals in the cosmic ultraviolet background radiation. Astrophysicist Floyd Steckler of NASA speculated that a signal indicating a 14 ev neutrino mass was already apparent in existing French and American satellite data. But if the signal existed, Steckler discovered, it could not be dug out of the background radiation. "It was a mess," he told *Science*. "There's been a lot of conflicting data."

■ In 1984, a French collaboration working at the Bugey Reactor near Grenoble announced strong evidence of neutrino oscillations. The French later retracted their claim, recalls Boehm, explaining that they had "overlooked the effect of the enormous gamma ray background associated with the reactor."

■ The next year, J.J. Simpson of the University of Guelph in Canada, searching tritium decays for evidence of a neutrino weighing a few ev, instead found what he interpreted as the signature of a far more massive neutrino, too massive at 17,000 ev to fit into any theoretical framework. A handful of experimenters promptly went searching for Simpson's elephantine neutrino and came up empty-handed.

All the while, the evidence that had sparked this flurry of activity—the tritium-decay and neutrino-oscillation results—was crumbling. Even before Reines and his collaborators went public, he had met with Richard Feynman and Peter Vogel of Caltech, who suggested that, among other things, Reines' data were inconsistent with his own earlier experiments, and that his statistical analysis was less than sound. "We understood what their point was," said Irvine's Henry Sobel, who collaborated with Reines. "But we had this experiment. What are you supposed to do? You publish what you have."

When Reines and his collaborators reworked their statistical calculation, the significance of the effect dropped from 3 sigma—statistically speaking, only a .27% change of being a freak background fluctuation—to about 1 or 1.5. The latter, observes Reines, "almost says you don't see anything, you don't have a hint." The result was also contradicted by a collaboration from Caltech, the Laue-Langevin Institute in Grenoble, and the Technical University of Munich led by Boehm and Nobel laureate Rudolph Mossbauer. Boehm and Mossbauer *et al.* had been searching for neutrino oscillations since 1978 and had a null result. Finally, after doing an improved neutrino oscillation experiment at Savannah River, Reines published new results revealing no evidence at all of neutrino oscillations,

Meanwhile, groups at the University of Zurich, Los Alamos, and the Institute for Nuclear Studies (INS) in Tokyo had all been diligently working to duplicate and, if possible, improve on the ITEP tritium-decay experiment. And since 1980 the upper limit for neutrino mass allowed by this kind of experiment has crept downward. By now, with the limit down to 8 or 9 ev, the ITEP group seems to have conceded. "For many years," says Hamish Robertson of the Los Alamos collaboration, "they would appear at a conference and quote their latest results. But the last time they did so was 4 or 5 years ago. Their silence is taken as indication that they don't have anything more to say."

In 1987, the great supernova Shelton SN1987a provided yet another method of weighing the neutrino, and yet another opportunity to speculate on a neutrino mass. The Kamioka experiment of proton-decay fame (now called Kamiokande) had been upgraded in 1984 to detect neutrino interactions, and it saw 11 such events coinciding with the appearance of the supernova. The IMB experiment in Ohio detected eight. These few neutrinos were traces of the neutrino pulse emitted by the supernova, and after traveling several hundred thousand light-years to Earth, they had arrived virtually all at once, spread out by less than 13 seconds. That meant that all of them had traveled within a hair's breadth of the speed of light—which meant, in turn, that they had to be massless, or very close to massless. Although several groups asserted they could calculate a positive rest mass from the data, to many physicists the results looked most like zero. "It was very small statistics," says Haxton. "Lots of little glitches in the data, but not every glitch has to have an explanation. The [neutrino mass] value that's consistent is roughly an upper limit of 20 ev. There's no minimum value."

And so it went. As early as 1987, little direct evidence remained for a massive neutrino. But by then, another line of reasoning was already encouraging some physicists to look for new evidence.

The case of the missing neutrinos. The new argument for neutrino mass was built on the work of physicist Ray Davis of the University of Pennsylvania, who for two decades had been capturing neutrinos from the sun in a tank of carbon tetrachloride deep in the Homestake gold mine in South Dakota. Solar physicists' standard picture of the sun implies that nuclear reactions in its core should be generating a specific number of neutrinos. But Davis' experiment was detecting only one-third the predicted number. That could indicate either some problem with the standard picture of the sun or some unexpected behavior on the part of neutrinos—perhaps because they have mass.

A link between the solar neutrino problem and neutrino mass was proposed in 1985, in a theoretical paper published by Stanislaw Mikeyev and Alexei Smirnov of the Soviet Academy of Sciences. Mikeyev and Smirnov, working off an earlier suggestion of Carnegie-Mellon University's Lincoln Wolfenstein, argued that the dearth of neutrinos resulted from neutrino oscillations in the sun's interior. The idea—called the MSW model—was that the core of the sun was generating the expected number of neutrinos; they were simply oscillating to a form to which the detector was blind as they streamed outward. The implication, again, was that neutrinos have mass.

The solar neutrino problem soon grew more acute, raising the stock of the MSW mechanism. In 1988, a second experiment, the Kamiokande collaboration, reported only half the predicted flux of solar neutrinos. But even then, the problem couldn't be confidently ascribed to neutrino mass rather than some gap in the understanding of the sun. Both the Kamiokande and Homestake experiments are sensitive only to the high-energy neutrinos produced by the decay of boron-8, which is created by a tertiary nuclear reaction in the sun. "Its rate," says Michael Turner, "is very temperature dependent, and if one had miscalculated the temperature of the sun by 6%, that would explain why they see a deficit." In that case, the missing neutrinos might be coming out of the sun at lower energies. But if there were also a scarcity of low-energy neutrinos from proton-proton fusion—the key reaction powering the sun—the MSW theory would be riding high, and the standard model of physics would be in trouble.

Thus, since 1985, a Soviet-American collaboration had been building a gallium-arsenide detector, designed to observe these low-energy neutrinos. And in the summer of 1990, the Soviet-American Gallium Experiment, SAGE, reported that it had detected only three solar neutrinos in 4 months of running. Calculations based on the standard solar model suggested that the collaboration should have seen 17 such events. Because of experimental uncertainties, not every neutrino "event" is necessarily an actual neutrino, so the observation of only three events could mean that SAGE observed no low-energy neutrinos at all.

Can SAGE see? This null result appeared to be a smoking gun for neutrino oscillations, and hence neutrino mass—"perhaps the first experimental evidence for grand unification," as astrophysicist John Bahcall of the Institute for Advanced Study, an outspoken proponent of the MSW model, put it in *The New York Times*. But the dearth of neutrinos could also betray a serious problem with the detector. "The $64,000 question," as Turner put it, was whether SAGE could detect neutrinos at all. An unpublicized attempt by the SAGE collaboration to calibrate their detector using a powerful neutrino source failed; the detector didn't register any of the neutrinos. According to SAGE member Tom Bowles of Los Alamos, the collaborators hope to repeat the calibration carefully with a stronger neutrino source in the fall of this year.

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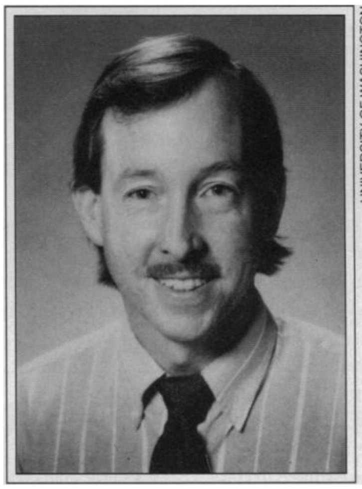

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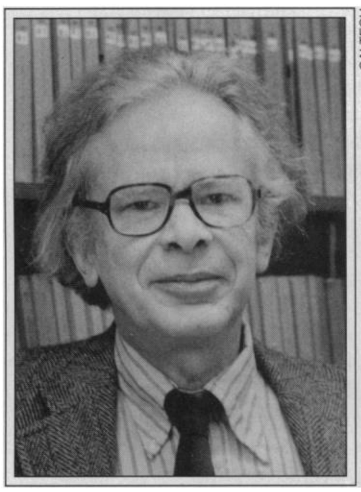
For Steven Koonin, a nuclear physicist at Caltech, those uncertainties make any conclusion about neutrino mass premature. "SAGE is a very complicated experiment at a low signal level. I'm reluctant to believe anything in the first few years of the experiment. It takes that long just to shake the bugs out." Bowles admits he is uneasy. "The first time I saw this data," he says, "my heart skipped a beat. I was saying, What could be going on? I couldn't believe myself that Mother Nature was telling us anything this clearly. There has to be something wrong. We spent the last 2 years trying to find anything that's wrong. So far we can't find anything." But he acknowledges, "I'll feel a whole lot better once we do the calibration."



CALTECH

Stalking the massive neutrino. Felix Boehm was one of the first to take up the quest.

Until SAGE proves it can observe neutrinos or a second gallium experiment, GALLEX in the Gran Sasso Laboratory in Italy, reproduces the SAGE results, says Douglas Morrison, a physicist at CERN, "there is no good evidence for a solar neutrino problem." The verdict from GALLEX is due soon. According to a spokesman for the experiment, Till Kirsten of the Max Planck Institute for Nuclear Physics in Heidelberg, the collaboration hopes to release its results by the end of May. "We have to be patient," Kirsten told *Science*. "When we say something, it should be defendable and it should stand up."

The latest neutrino results have done nothing to dispel this background of uncertainty. Simpson's supermassive neutrino remains in the picture, with a trio of results supporting it and a dozen or more refuting it (*Science*, 29 November 1991, p. 1298). And then, last December, Turkevich and his colleagues reported their neutrino mass measurements—either the latest spurious result in the search for neutrino mass or a real clue to new physics.

Turkevich had chemically analyzed a sample of uranium salt that had been sealed against nuclear fallout since 1956. His quarry was plutonium 238—an isotope that can be generated by nuclear explosions and cosmic rays, and also by the double beta decay of uranium 238. Such decays, in which two neutrons simultaneously change into two protons, emitting two electrons and two neutrinos in the process, are mind-bogglingly rare. Turkevich calculated that a mere 10,000 atoms of plutonium 238 existed in his 17-pound sample of uranium, and thus the half-life of this decay was 2 billion trillion years. But sluggish as it is, that rate is also 100 times faster than the only existing theoretical prediction for the decay, based on a massless neutrino. The difference could be reconciled, according to Turkevich, if "the standard model is wrong and neutrinos have mass."

But critics suggested that his results might be explained by measurement difficulties and the possibility that fallout or cosmic rays had contaminated the sample. They also pointed out that the predicted rate of double beta decay for uranium was rife with uncertainties and that Turkevich's conclusion disagreed with existing double beta decay measurements in other elements. Turkevich acknowledges the uncertainties and says he would like to repeat the experiment with a large lump of uranium in Vienna—a relic of the German war effort sealed since 1945. "We'll try to get some of this uranium, if it's decided that the experiment is worth repeating," he says. The massive neutrino hunt is not over.

But after 12 years of eager searching for this key to new physics, many physicists are tempted to conclude that, as one veteran of the hunt puts it: "It's very difficult to measure zero." Given the evidence, says Glashow, "I would believe the standard model, as advertised, until I was forced to some other conclusion."

–Gary Taubes

Gary Taubes is a free-lance writer in Santa Monica, California.