Is There a Massive Neutrino?

Three far-flung labs say yes, triggering an avalanche of speculation about how theories from the Standard Model to the Big Bang might need to be revised

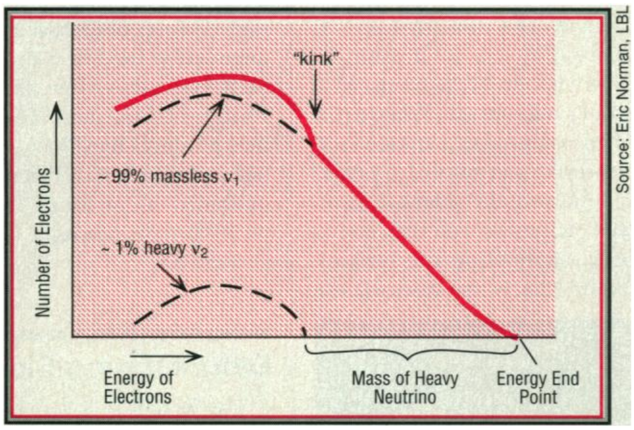
EVEN BY THE STANDARDS OF PARTICLE physics, the subatomic particle called the neutrino is a shadowy commodity. It can pass through the entire Earth without leaving a trace, and it's immune to many of the forces that bind matter together, including the electromagnetic force. Until recently, it was even thought to be without mass—or at least without much. But now, dramatic evidence has begun to emerge from laboratories in Oxford, Czechoslovakia, and Berkeley that the neutrino does have mass—and lots of it, thousands of times more than predicted by current theories. Sheldon Glashow, Nobel Prize–winning physicist at Harvard, who's seen the recent results (which are speeding around the physics community in preprint form) calls them "quite spectacular." In fact, he says "it's the kind of thing Nobel Prizes are awarded for."

If the results hold up, and there is a Nobel Prize for the "massive neutrino," the award would likely go to John Simpson, a physicist not in one of the three labs that have claimed recent successes but at the University of Guelph in Ontario. It was Simpson who, in 1985, first presented evidence for a neutrino with a mass as heavy as 17,000 electron-volts (keV, the units of energy that are interchangeable with mass). If Simpson is correct, his discovery will send shock waves through not merely the high-energy physics community but through astrophysics and cosmology as well—indeed it would fundamentally alter physicists' views of the universe.

A massive neutrino would "violate every theoretical prejudice we have in particle physics, astrophysics, and cosmology," says Michael Turner, a University of Chicago expert on cosmology. Adds astrophysicist John Bahcall of the Institute for Advanced Study at Princeton: "It's a true surprise. If it's true, then it's pointing us in a different direction than previous physics suggested."

That new direction would actually include a number of major course corrections. Elegant theories purporting to explain why neutrinos are so light would crumble. Overarching conceptions, like the "Standard Model" of particle physics—which unifies the so-called weak force and the electromagnetic force and for which Glashow received his Nobel Prize—would need embellishing. (Glashow has already rushed into print with what he calls "various crazy models" in an attempt to patch his notions up.) And there might be a profound impact even on the Big Bang theory.

All this assumes that the latest discovery isn't just an experimental artifact—something difficult to be sure of in an area where experimental results can be deceptive and prey to perturbations. Although the recent work from the far-flung labs is suggestive, many feel it won't hold up. "My attitude toward this 17keV neutrino," says Bahcall, "is, if you're thinking of skating on a lake which you're not sure is frozen and you see a sign posted on the lake [reading] 'There is suggestive evidence that the ice is safely thick,' I wouldn't skate on that ice, and I wouldn't invest much of my reputation on the likelihood that this 17keV neutrino is real."



Kinky stuff. *A "kink" 17KeV below the endpoint of the emitted electron's energy spectrum in beta-decay was the first clue to a possible massive neutrino.*

Felix Boehm, a respected experimentalist at the California Institute of Technology who has tried and failed to find evidence for a massive neutrino, acknowledges being "a little biased." But Boehm, who has seen the new results, argues that "there is nothing"—the massive neutrino doesn't exist. Even he admits, however, that the case isn't closed: He's still looking for conclusive evidence one way or the other.

The reason for the current excitement is that it is the first time results confirming Simpson's hypothesis have come from outside his own laboratory. In 1985, Simpson, already a world-renowned neutrino physicist, began table-top experiments aimed at measuring the energy of electrons emitted from tritium (heavy hydrogen) in the radioactive process called beta-decay. Although Simpson's interest was in the nearly invisible neutrino (which is spit out alongside the electron), he couldn't observe the neutrino directly. Instead, he measured the effect of the neutrino on the electron.

Ordinarily in beta-decay the electron and the neutrino share the energy of the reaction. Under those conditions, the energy of the emitted electrons appears as a spectrum varying smoothly from zero to a maximum called the "endpoint" energy. But in Simpson's mid-'80s work, he observed a small "kink," or disturbance, of the smooth spectrum corresponding to an energy 17keV below the endpoint.

Published in *Physical Review Letters*, this result startled physicists, who have studied beta-decay for decades without seeing the 17keV anomaly. The kink, Simpson argued, came from the occasional emission of a massive neutrino, which was "stealing" energy from the electron and changing its energetic spectrum. But the kink was small: 97% of the time, the electron associated with the ordinary, massless neutrino was found, and only 3% of the time did the electron paired with the massive newcomer show up.

Those early results triggered a feverish hunt aimed at confirming them—or proving that they weren't valid. If the kink was real and was caused by a massive neutrino, experimentalists reasoned, it should appear not just in tritium but also in other nuclei that undergo beta-decay. Moreover, although the endpoint of the electron's spectrum varies from nucleus to nucleus, if there is indeed a 17keV neutrino, the kink should appear 17keV below the endpoint in each case. Eight different groups, including two led by such notables as Caltech's Boehm and Princeton's Frank Calaprice, attempted to find that kink in a variety of nuclei: Sulfur-35, Iron-55, Nickel-63, and Iodine-125. All of them failed.

Meanwhile, Simpson's experimental technique and data analysis was raked over the coals by heavyweights such as Wick Haxton of the University of Washington. In order to ensure that all electrons were captured with their full energy, Simpson had implanted tritium inside his detector, and the critics argued that the implantation process could have damaged the detector. A further blow to confidence in his results was delivered in 1986. In that year Simpson lowered his estimate of the percentage of beta-decay episodes in which a massive neutrino was seen—from 3% to 1%. Says Eric Norman of the Lawrence Berkeley Laboratory (one of those who have come up with data confirming Simpson's), "if it could go from 3% to 1%, people figured maybe it could go to 0%."

But instead of throwing in the towel, Simpson launched a counteroffensive. In 1989, he and his student Andrew Hime published back-to-back papers in *Physical Review D* that presented new data on the 17keV neutrino, this time from nuclei of both tritium and Sulfur-35. The size of the kink indicated that the massive neutrino appeared between 0.6% and 1.6% of the time. In addition to including data from two types of nuclei, the new experiments addressed technical problems raised by critics. Simpson and Hime also delivered their own critique of the experiments that had failed to find the massive neutrino. Chicago's Turner, who calls Simpson "just a very good experimentalist," says "he carefully went through the experiments [of others] and found they had flaws."

Simpson's care helped persuade other researchers that the hunt was still worth the effort. Experimentalists around the world again tried to repeat the work—and this time key results are turning up positive. The most impressive evidence comes from Oxford, where Simpson's former student Hime is working with Nick Jelley. They carried out an improved Sulfur-35 experiment and found evidence for a 17.0keV neutrino, detected 0.84% of the time. Hime and Jelley, whose work has been accepted for publication in *Physics Letters B*, report that theirs is an "eight-sigma" effect. Hime says this means there is only one chance in a million that the results stem from a statistical fluke.


University of Guelph

Heavy dude. *John Simpson of the University of Guelph.*

At Lawrence Berkeley, Norman, with Bhaksar Sur, Kevin Lesko, and other coworkers, using Carbon-14, also see evidence for a 17.2keV neutrino, found 1.4% of the time. They quote a confidence level of three-sigma, meaning there is a 1% chance that the effect is a statistical fluke. (The same group has also carried out work with Iron-55 that yields a 21keV particle, but that experiment produced worse statistics and more systematic problems, and Norman told *Science* that in view of those difficulties, the difference between 17keV and 21keV is not significant.) Finally, Igor Zlimen and his colleagues at the Ruder Boskovic Institute in Zagreb, Czechoslovakia, using Iron-55 and Germanium-71 have found evidence for a 17.2keV neutrino, appearing 1.6% of the time.

"Suddenly," says Glashow, "there was someone not in the same family advocating the data." Which is why Glashow believes "it has to be taken seriously." He and his colleagues have already published one paper—and circulated more in preprint form—trying to explain the massive neutrino.

Several aspects of the new findings make them impressive enough for people like Sheldon Glashow to sit up and take notice. The data come from a range of nuclei—tritium, sulfur, carbon, iron, and germanium. The "kink" in the energy spectrum always appears about 17keV below the endpoint. And what's more, the kink is about the same size in all the experiments, corresponding to roughly a 1% probability that a massive neutrino will be emitted in a decay event. The data now seem so strong that Simpson thinks the critics are in a weakened position. "I think these people are grasping at straws."

Dreaming Up New Flavors

All neutrinos, including the massive 17keV particle that John Simpson of the University of Guelph may have discovered, come in what particle physicists call "flavors." Just what flavor is this newcomer that threatens to overturn—or at least shake up—many of physicists' prized theories?

There are three known neutrino flavors, each associated with either the electron or an electron-like particle. The electron-neutrino is the most common on Earth, almost certainly accounting for the massless (or nearly massless) neutrino emitted approximately 99% of the time during the beta-decay of radioactive nuclei. (Beta-decay is the phenomenon Simpson observed in detecting his 17keV anomaly.) Experiments at accelerators around the world have determined that the mass of the electron-neutrino is less than 10eV, so this flavor can't account for the new, massive specimen.

The other two known flavors are the muon-neutrino and the tau-neutrino (the muon and tau being short-lived cousins of the electron). Like the electron-neutrino, the muon-neutrino is probably also ruled out, but for a different reason. As long ago as 1958, Bruno Pontecorvo of the Dubna Joint Nuclear Research Institute in the USSR proposed that neutrinos might be quantum-mechanical mixtures of several different states having different masses.

It is now known that different flavors of neutrinos can indeed mix together—even oscillating from one state to another. And the 1% probability of finding the 17keV neutrino in the beta-decay work indicates that the electron-neutrino is mixing with some other type of neutrino. But experiments in accelerators set up to look for oscillations between the electron and muon neutrinos show that the mixing can't be more than 0.3%, ruling out the muon flavor.

That leaves the tau neutrino. And limits placed on the tau-neutrino mass and mixing probability by accelerator experiments do not rule out the tau flavor, which makes it the leading current candidate—if the 17keV results hold up.

The final possibility is that the 17keV find is none of the three known varieties but represents a new fourth flavor. If so, it must be a bizarre flavor. For example, all three ordinary flavors can "feel" the weak force, the fourth neutrino would not. The reason: a fourth flavor that does feel the weak force is rigorously excluded by measurements made at LEP in Geneva, Switzerland, on the Z_0, carrier of the weak force. Because the fourth flavor represents such a departure from the established menu, most theorists discount it as a very remote possibility.

■ P. S.

Naturally, the critics don't see it quite that way. Felix Boehm cites a variety of problems with the recent results. First and foremost, the kink has been seen only in solid-state detectors (using silicon or germanium as the detection material)—and not in magnetic spectrometers, despite many tries. This doesn't bother Simpson much; he claims magnetic spectrometers need large, poorly understood correction factors that could obscure the kink.

But critic Boehm doesn't stop there. Just as Simpson critiqued his critics, Boehm has reviewed the positive results and finds fault with all of them: the iron and germanium studies rely on fitting data to a theoretical curve that is poorly understood, the carbon study has a problem with the proper background subtraction, Hime and Jelley's sulfur results could suffer from scattering.

For the moment, most physicists agree that if the kink is real, it indicates a massive neutrino does exist, although what type of neutrino remains open to speculation (see sidebar on page 1427). There are three "flavors" of neutrinos—the electron-neutrino, the muon-neutrino, and the tau-neutrino—each associated with an electron or one of its kin. (The muon and tau are heavy, short-lived cousins of the electron). Other experiments rule out the electron-neutrino and the muon-neutrino, so the likeliest possibility is the tau-neutrino—or even an unknown fourth type, although most experts think that's a long shot.

Whatever its flavor, if the new discovery holds up, it is going to do some potent rearranging of accepted notions in physics. Take the Solar Neutrino Problem. That long-standing puzzle stems from the fact that detectors on Earth measure only a third to a quarter the number of neutrinos from the sun that theory would predict. Either theory is wrong, or somehow neutrinos "get lost" on their way to Earth. One way out of the quandary would be to propose that solar neutrinos sometimes transform themselves into neutrinos of a different flavor that the detectors aren't sensitive to.

That's just what would be predicted in the so-called Mikheyev-Smirnov-Wolfenstein (MSW) effect—but only if one of the neutrinos in the transaction has mass. But that neutrino with mass isn't likely to be the new find with its 17keV mass, since the MSW effect requires a neutrino with a mass of between 0.01 and 0.001 electron-volts. But all isn't lost, says Bahcall: If it's confirmed, the massive neutrino "demonstrates at least one neutrino has finite mass and presumably others could also."

Also on the agenda: "dark matter," the puzzling, invisible stuff that may constitute 99% of the mass of the universe and whose identity is a big problem for cosmology. Could a 17keV neutrino be the dark matter? Maybe, says Chicago's cosmological expert Turner. It's not the ideal candidate for dark matter, he explains: that would be a much smaller particle, with a mass of say, 30ev. A particle 500 times larger (as the 17keV would be) would have caused the universe to collapse on itself long ago, according to Big Bang theory. To get around that problem, says Turner, the neutrino would have to be unstable, with a lifetime shorter than 200,000 years and probably shorter than one year. But that leads to "whole new realms of speculation," says Bahcall, centering on new, unknown particles into which the neutrino might decay.

First Hominid Finds From Ethiopia in a Decade

In 1983 foreign researchers were banned from excavating sites in Ethiopia—a fossil-rich country that holds the remains of many early human ancestors. Last fall, American researchers were allowed back. Now, after an unusually productive field season, three teams have returned to the United States with some remarkable finds. Those finds may push back the date for the existence of the earliest known hominid, shed light on the split between apes and human ancestors, and show that some early hominids still spent time in trees.

The first set of results was made public last week when a team from the Institute of Human Origins in Berkeley, headed by Donald C. Johanson, announced they had found bones from no less than 15 different individuals at Hadar. Hadar is the site where, 16 years ago, Johanson found "Lucy," the remains of a small female from the species *Australopithecus afarensis*, the first known hominid. The newly discovered fossils appear to be from the same species but show a surprising diversity in size and build.

The most notable remains included a large humerus (upper arm bone), which showed signs it was attached to powerful shoulder muscles. "It doesn't lead us to believe [the early hominid] was going to a workout gym, but it leads us to believe this individual was capable of powerful movements of the shoulder that would have been useful for hoisting the body up," says Johanson. "It doesn't mean they were spending a lot of time in trees, but the option was certainly there." This contrasts with Lucy, who stood no more than 3½ feet tall and was not well muscled. The difference could be attributable to differences between the sexes: The humerus probably belonged to a male. Furthermore, that male lived about 500,000 years before Lucy came on the scene.

Another surprise was a 3-million-year-old jaw and facial bones showing some features similar to those seen in a species called *Australopithecus africanus*, which may have been ancestral to *A. afarensis*. Although the bones bear both *africanus* features and *afarensis* features, Johanson and his colleague, William Kimbel, think they more closely resemble *afarensis*. There is also a remote possibility that the jaw could be from yet another, intermediate species.

Another team, led by John Fleagle and Solomon Yirga of the State University of New York at Stony Brook (SUNY)—and partially funded by the National Geographic Society—reports finding a collection of hominid teeth at Fejej, a site in southern Ethiopia. One surprise was that the teeth date back at least 3.7 million years and possibly as much as 4.4 million, making them some of the oldest unequivocal remains of *A. afarensis*. "What makes it really exciting is that the Fejej remains are more complete than other remains of that antiquity, providing some of the most solid evidence of what hominids of that time were like," says SUNY professor Bill Jungers, coeditor of the *Journal of Human Evolution*, where the Fejej data are in press. That could have implications for the dating of the split of early hominids from the great apes—a controversial breakpoint now thought to have occurred between 4 million and 6 million years ago.

A third team from the University of California at Berkeley, led by anthropologists Tim White and Desmond Clark, has yet to release its findings, although the team reportedly also has found hominid fossils in the Middle Awash valley, south of Hadar. All three teams collaborated with Ethiopian researchers, partly as an effort to restore good relations with Ethiopia. All three are also seeking to renew their permits to return for another field season later this year.

■ ANN GIBBONS

But that's just the beginning, because, as Turner notes, "for astrophysics and cosmology, this guy is a disaster." Even the supernova of 1987 gets into the act. Unless unknown interactions trap massive neutrinos in the supernova, they would come streaming out and—according to astrophysical theory—cool the supernova faster than was actually observed. Yet endowing the neutrino with new interactions creates problems for cosmology. Big Bang theory says the universe expanded very rapidly during the first seconds of its existence, until it had cooled enough for disparate particles to join into elements such as hydrogen, lithium, and helium. The postulated neutrino interaction would alter the universe's expansion rate, ultimately causing these elements to form in ratios different from what is now observed.

"It's not easy to get around this dilemma," Turner concedes. One way would be to postulate a lifetime for the heavy neutrino of only a millionth of a second, so that by the time elements started to form almost all the neutrinos would have been gone. A more remote possibility: the Big Bang model of how the elements formed is off the mark.

And if the Big Bang might have to be retooled to accommodate this new player among subatomic particles, it's not the only theory that will. The Standard Model would also need work. In pristine form, the Standard Model assumes neutrinos have zero mass; simple extensions of the theory postulate masses still too small for the recent results—by factors ranging from ten thousand to ten billion. Says Glashow: "There have been suggestions—over a dozen over the last few months—of how to accommodate something like this, but it's not obvious.... It's possible to add junk to the Standard Model to save the phenomenon, but none are particularly attractive."

But all of this assumes that the 17keV neutrino is for real. And a lot of people, including some harsh critics like Felix Boehm, say that idea is a lot to swallow. As usual in experimental physics, the answer is going to be more, and more definitive, results. As Glashow says: "More and better experiments can still be done. And they will."

Indeed, some of those presenting the new findings say it's too soon to become true believers. When Norman presented his results to the Berkeley physics department in February he said, "I believe the result is positive, but I'm not trying to sell you a bill of goods. We should be closer to an answer in about 6 months." The physics community will be waiting attentively.

■ PAUL SELVIN

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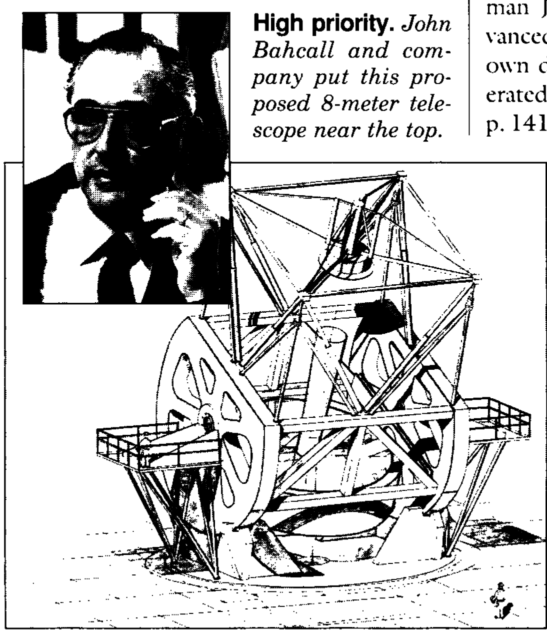
Astronomers Forge a Consensus for the 1990s

The Bahcall committee is getting high marks for making tough choices about astronomy research priorities.

ASK ANY GROUP OF SCIENTISTS WHAT Washington should give them in the coming decade, and 99 times out 100 their answer will be utterly predictable: "Every project is top priority—send more money!" The U.S. budget deficits being what they are, nobody wants to admit that his or her pet project is less deserving of funding than someone else's.

But now comes one of the rare exceptions. In a 200-page report* released on 19 March, the 15 members of the National Research Council's Astronomy and Astrophysics Survey Committee have explicitly listed their research recommendations for the coming decade in order of priority—the third time that astronomers have done so since 1972. And even more remarkable, considering the ample potential for conflict, they have agreed to those priority rankings unanimously.

In Washington, where scientific advisory reports come and go by the dozens, officials are impressed. "This is one of the most effective decision-making processes in science," declares NASA space science chief Lennard Fisk. It is especially effective, he says, because the astronomers have produced one unified list for two very different agencies: The National Aeronautics and Space Agency (NASA), which funds space-based astronomical facilities, and the National Science Foundation (NSF), which supports the ground-based facilities. "That means they've looked at the entire discipline of astronomy and asked how the scientific issues can most effectively be dealt with," says Fisk. "In that sense, it's a very far-reaching strategy."



High priority. *John Bahcall and company put this proposed 8-meter telescope near the top.*

NOAO

Take, for example, the committee's list of recommended "large" projects—"large" being defined relative to what is typical at each agency. The top billing goes to a $1.3 billion NASA project known as the Space Infrared Telescope Facility, a liquid helium-cooled observatory designed to make ultrasensitive infrared observations of star-forming regions and newborn galaxies. But right behind it comes a ground-based facility costing about one sixteenth as much: An 8-meter infrared telescope to be built by the NSF on Mauna Kea in Hawaii.

And on a separate list of "medium"-sized projects, a host of ambitious space-based and ground-based missions were beaten out for the top spot by a relatively modest, $35-million program of laboratory research in adaptive optics: A set of innovative techniques that promise to reduce greatly the distorting effects of atmospheric turbulence and allow ground-based telescopes to achieve much of the clarity originally advertised for the Hubble Space Telescope.

From all accounts, much of the credit for the committee's achievement goes to chairman John Bahcall of the Institute for Advanced Study at Princeton, who records his own description of how the committee operated in his accompanying Policy Forum on p. 1412. As a scientist with long experience in Washington—in the mid-1970s, for example, he was a leader in lobbying for the Space Telescope—Bahcall knew it was important that the committee's final report be accepted by the funding agencies and the political powers-that-be, as well as by the astronomical community. So in 1989, before the committee even started its deliberations, he made the rounds of top officials at NASA, NSF, the White House, and Congress, asking them what con-

* "A Decade of Discovery in Astronomy and Astrophysics," National Academy Press, Washington, D.C., 1991.