# Electronic Battle Over Solar Neutrinos

**An elusive measurement of a key solar reaction has prompted a fierce dispute, with attacks and counterattacks circulating electronically well before the measurement was published**

One of the problems facing physics in these days of electronic communication is keeping up with the back-and-forth, as results and theories are kicked around even before they are formally published. Witness the 14 November issue of *Physical Review Letters*, which includes a new and unique experimental determination of what has been called by astrophysicists "the most important nuclear measurement there is"—the rate at which beryllium-7 in the sun will fuse with a proton to become boron-8, which will later emit a high-energy neutrino.

The experiment that produced these results was done at Japan's Institute of Physical and Chemical Research (RIKEN) by a group led by Tohru Motobayashi of Rikkyo University in Tokyo and Moshe Gai of the University of Connecticut. The measurement is crucial to understanding the long-standing "solar neutrino problem," which is the discrepancy between the flux of solar neutrinos as predicted by theoretical models of the sun and the flux detected by four Earth-bound experiments.

So rapid is communication in physics these days that by the time the work made it into print, it was practically irrelevant. The data had already been published by another group (albeit incorrectly) in a perceptive analysis in a rapid communication in another journal. It had been cited in a theoretical paper distributed over the Internet as evidence that there was no solar neutrino problem. And that theoretical analysis, in turn, had been dismissed as most likely wrong in yet another electronically distributed theory paper, this one authored by 15 of the most prominent researchers in the field. The uproar attending these rapid-fire publications has left physicists wondering about the utility of the experiment, the true extent of the solar neutrino problem, and the significance, if any, of journal publications in a community that has come to rely almost entirely on electronic publication for information exchange (*Science*, 11 November, p. 967).

At the heart of the controversy are the ephemeral neutrinos themselves. These elementary particles interact so infrequently with matter that, of the 10 billion that pass each second through every square centimeter of Earth, only one will be recorded every few days in any of the four solar neutrino detectors that have been set up around the world. The oldest detector, dating back to the 1960s, was erected in the Homestake gold mine in South Dakota by Ray Davis, who was then at Brookhaven National Laboratory on Long Island. That detector has spotted only a third of the solar neutrinos it was predicted to find. The Kamiokande detector in Japan, which came on line in 1987, has detected only half the predicted flux. The two newest detectors, both using gallium as the target for the neutrinos, recently reported seeing only two thirds of the expected number of neutrinos.

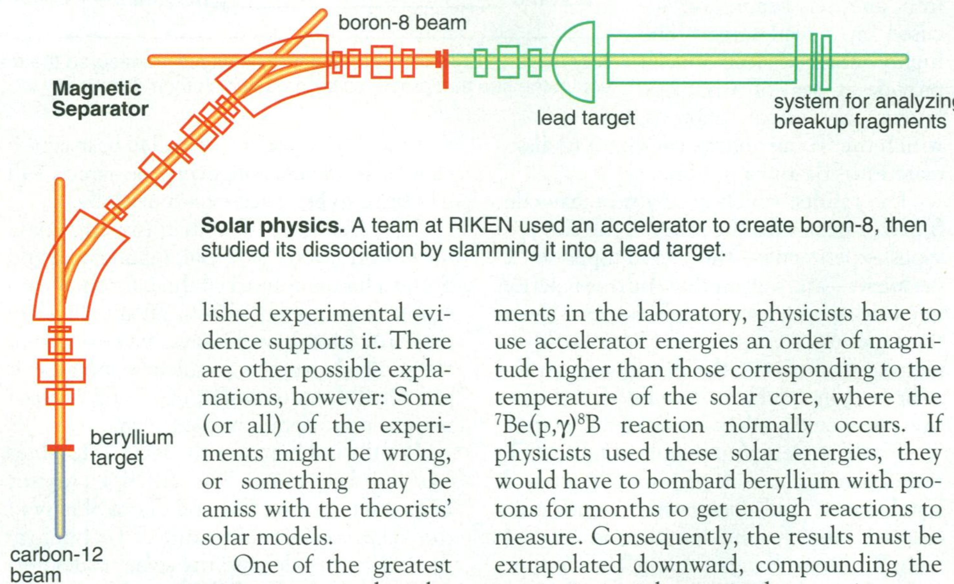
The most exciting explanation proposed so far for the discrepancy between experiment and theory is that neutrinos "oscillate" into a neutrino species that the experiments cannot detect. If it's true, it would be a Nobel-caliber revelation, but so far no published experimental evidence supports it. There are other possible explanations, however: Some (or all) of the experiments might be wrong, or something may be amiss with the theorists' solar models.

One of the greatest uncertainties in the solar models is in the measurement of the rates of nuclear reactions that generate neutrinos. Several reactions emit neutrinos with different energies, but the key uncertainty, says John Bahcall, a physicist at the Institute for Advanced Study in Princeton, New Jersey, who has been a driving force in solar neutrino research, has been the rate at which $^{7}$Be fuses with a proton to become $^{8}$B and a gamma ray, which is a high-energy photon. [The reaction is written as the $^{7}$Be(p,$\gamma$)$^{8}$B reaction]. It's the $^{8}$B that then decays radioactively, emitting a high-energy neutrino. (Most of the neutrinos detected by the Homestake experiment and all those seen by Kamiokande are these $^{8}$B neutrinos; the two gallium experiments can also see the much more plentiful low-energy neutrinos from the fusion of protons into deuterium.)

A handful of attempts have been made to measure this reaction rate in the laboratory by bombarding a target of $^{7}$Be with a beam of protons. The two best measurements have come from physicists now at the California Institute of Technology—Ralph Kavanagh in 1969 and Brad Filippone in 1983—but Filippone's experiment came up with a reaction rate 25% lower than Kavanagh's. "John Bahcall has been beating on people's heads for 20 years to get a better measurement of [the reaction rate]," says Yale University nuclear physicist Peter Parker.

One difficulty, says Moshe Gai, is that to create enough $^{8}$B to get meaningful measurements in the laboratory, physicists have to use accelerator energies an order of magnitude higher than those corresponding to the temperature of the solar core, where the $^{7}$Be(p,$\gamma$)$^{8}$B reaction normally occurs. If physicists used these solar energies, they would have to bombard beryllium with protons for months to get enough reactions to measure. Consequently, the results must be extrapolated downward, compounding the uncertainties inherent in the experiments.

In 1991, however, a Belgian group and a Japanese team led by Motobayashi independently reported an experiment that circumvents this kind of problem—essentially by doing the experiments in reverse. They calculated the fusion rate of nitrogen-13 and a proton to make oxygen-14, a reaction that is of interest in stars heavier than the sun, and they did it by first creating $^{14}$O, which they could do relatively copiously, and then studying its dissociation into $^{13}$N and a proton. By examining this backward reaction, they were able to fill in the parameters in the theory that allowed them to calculate the rate of the real proton-$^{13}$N fusion. Gai heard the work presented at a conference in Tokyo




**Solar physics.** A team at RIKEN used an accelerator to create boron-8, then studied its dissociation by slamming it into a lead target.

and discussed the possibility that the same technique might work for $^{8}$B with Fred Barker, a theorist at the Australian National University, and Motobayashi.

Indeed, the rate of the reaction in which $^{8}$B absorbs a photon and decays into $^{7}$Be and a proton, says Gai, is a million times higher than its inverse. "What nature has provided is an amplifier," says Gai. Carlos Bertulani of the Federal University of Rio de Janiero demonstrated theoretically that a measurement of the dissociation of $^{8}$B would provide them with an accurate guide to calculate the rate of the reaction in which it is created. "All you need is an accelerator which provides you with ion beams at medium energies," says Bertulani. "Anybody could do it. It's just that nobody believed such a thing could be useful."

The experiment was done in March 1992 using the accelerator at RIKEN. Gai, Motobayashi and his student Naohito Iwasa, and their colleagues bombarded a target of beryllium with a beam of carbon-12 atoms and then used a magnetic field to sift out $^{8}$B from the various isotopes created. The $^{8}$B was channeled into another beam and focused on a lead target. The highly charged lead nuclei provide a sea of what are known as virtual photons, which the $^{8}$B can absorb, causing it to dissociate into $^{7}$Be and a proton.

The results, which are by no means definitive, agree with the lower of the two previous experiments—the 1983 Filippone experiment—and suggest that the true reaction rate may be even lower still. This means that if the experiment is right, says Gai, it could explain a good part of the discrepancy in the solar neutrino problem, because a lower reaction rate would produce a lower neutrino flux.

If only it were that simple. The RIKEN researchers circulated a preprint of their work last January, and controversy immediately erupted. First, two nuclear theorists at Caltech, Karlheinz Langanke and Tim Shoppa, realized that the RIKEN researchers had neglected a factor known as the E2 component of the interaction between the photon and $^{8}$B. (The photons can carry angular momentums of one or two units—known as electric dipole, E1, and electric quadrupole, E2.) They scanned the data from the RIKEN preprint into their computer and calculated the potential effect of this component. They then submitted their work to *Physical Review* C and sent it to an electronic distribution system (the electronic archives) run out of Los Alamos.

According to Langanke and Shoppa, the E2 component might have a sizable effect, and Motobayashi and his colleagues should not have ignored it without measuring it first. They also calculated that if the E2 component is indeed sizable, the experiment would have indicated a reaction rate so low as to either dramatically change the solar neutrino problem or, as some physicists took it, to imply that the RIKEN method simply didn't work.

Shoppa and Langanke's paper appeared in April and represented the first journal publication of the RIKEN data. As it turned out, however, the RIKEN preprint had incorrect error bars, and that problem was compounded when the two Caltech theorists misscaled the data in their article—"our stupidity," concedes Langanke. When Bertulani and Gai later realized that the Caltech paper not only had errors in the data but did not take into account what they considered the relevant parameters of the RIKEN experimental setup, they now redid it and concluded that the E2 component seemed to be insignificant. That conclusion, everyone agrees, will still have to be tested experimentally.

**NEUTRINO-PRODUCING REACTIONS IN THE SUN**

**proton + proton → deuterium + positron + neutrino**

**proton + electron + proton → deuterium + neutrino**

**beryllium-7 + electron → lithium-7 + neutrino**

**boron-8 → beryllium-8 + positron + neutrino**

**Key uncertainty.** RIKEN researchers indirectly measured the rate of the reaction in the sun that produces boron-8, which then decays.

"A great deal of embarrassment could have been saved," says Gai, if Langanke and Shoppa had simply asked them for their data rather than taking it from an unpublished preprint. Motobayashi says, however, that the Caltech work was valuable because it prompted them to work out the E2 component in more detail on their own.

But the hubbub over the RIKEN findings was just beginning. The RIKEN preprint helped spur Arnon Dar and Giora Shaviv of the Technion-Israel Institute of Technology in Haifa to recalculate the solar model predictions using the RIKEN value for the $^{7}$Be(p,$\gamma$)$^{8}$B rate. They also plugged in a handful of other corrections they believed had not been properly taken into account by other modelers. They submitted their paper—entitled "A Standard Model Solution to the Solar Neutrino Problem?"—to *Physical Review Letters* in January and sent it to the Los Alamos electronic archives. The abstract claimed that their recalculated model of reactions in the sun is consistent with the solar neutrino flux observed on Earth.

"The Dar and Shaviv paper had a sexy title and sexy conclusions," says Filippone, "and it was getting a lot of play even though it was only a preprint. Everybody was talking about it, and a lot of people who didn't know the details thought it might be taken seriously." Perhaps more irksome to those in the field, says Marc Pinsonneault, an Ohio State University astronomer, was the "subtext of the Dar and Shaviv paper, which was that everybody else was wrong."

Within days, Bahcall had marshaled 14 experimentalists, nuclear theorists, and solar modelers to test and critique the Dar and Shaviv model. The result was an electronic preprint entitled, rhetorically, "Has a Standard Model Solution to the Solar Neutrino Problem Been Found?" The answer, they strongly concluded, was no. The gang of 15 argued that Dar and Shaviv, among other scientific sins, used ad hoc assumptions in their model, selectively chose their data to support their theory, and incorrectly extrapolated rates of nuclear reactions. The debate continued at Neutrino '94, which was held in Israel at the beginning of June and organized by Dar. The session on solar neutrinos was described by one participant as "everybody yelling at each other."

How the solar neutrino problem will shake out, of course, remains to be seen. Dar and Shaviv have posted their own electronic response to the 15-author critique but have not yet managed to get their original paper accepted by *Physical Review Letters*. Meanwhile, Motobayashi and Gai repeated the $^{7}$Be(p,$\gamma$)$^{8}$B experiment last July hoping to improve their data, come up with a believable value for the reaction rate, and put the E2 controversy to rest. The analysis, says Gai, is not complete.

And Gai and others are hoping to try yet another tack to measure the $^{7}$Be(p,$\gamma$)$^{8}$B rate—by bombarding a hydrogen target with a radioactive $^{7}$Be beam. Gai has submitted a proposal to do so at the Louvain-la-Neuve laboratory in Belgium, while similar experiments are being discussed at the University of Washington and the TRIUMF Laboratory in Vancouver, British Columbia, as well as at the Oak Ridge National Laboratory in Tennessee and at the University of Naples.

By the time a definitive value is agreed upon, two new solar neutrino detectors—one in Canada and the other an upgraded version of the Kamiokande detector—will have come on line, and they should nail down the flux, at least, of the solar neutrinos once and for all. If the flux is still low, these new detectors will also be able to measure and compare the rates from different species of neutrinos, addressing the question of whether neutrino oscillations can really explain those missing neutrinos. As Dar suggests, the solar neutrino problem "will be resolved experimentally, so the fights can go on theoretically for only a few more years."

–**Gary Taubes**