GALLEX DATA CAN'T QUITE LAY THE SOLAR NEUTRINO PROBLEM TO REST

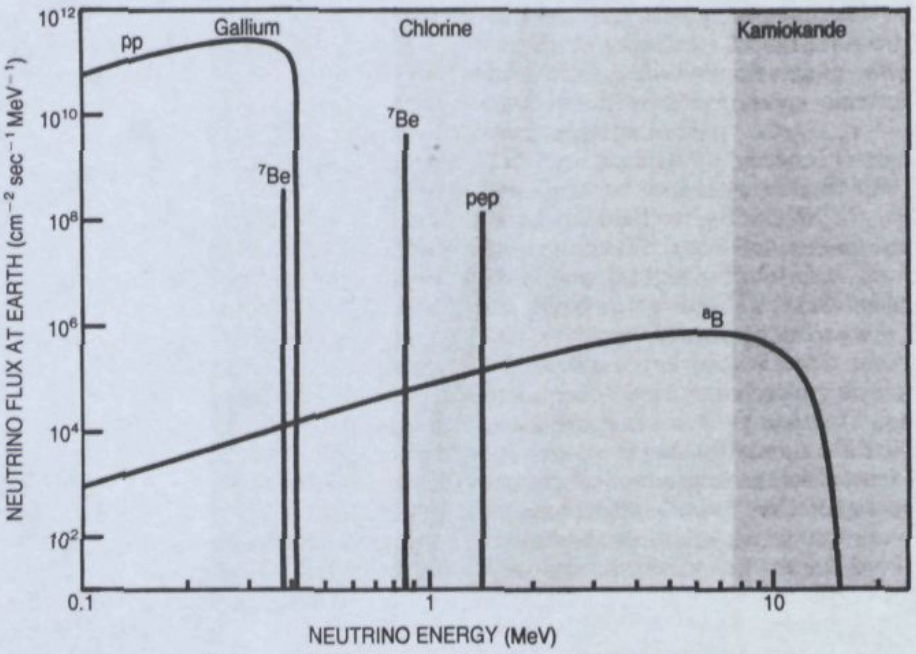
The 16 July issue of *Physics Letters* brings us the eagerly awaited report of the first results from the Gallex solar neutrino experiment.[1,2] The Gallex detector, with its 30 tons of gallium, sits in a laboratory underneath the Gran Sasso d'Italia, a 2900-meter peak in the Apennines northeast of Rome. The suspense was heightened last fall when the SAGE collaboration, which operates the only other gallium detector, reported that it had seen no clear evidence of any solar neutrinos in its first seven months of running.[3] The name Soviet–American Gallium Experiment may now seem out of date, but the experiment, located under a mountain in the Caucasus, goes on. SAGE is now operating with 57 tons of gallium.

A null result from a gallium detector is particularly worrying, though some might call it stimulating. Pioneer Ray Davis's chlorine detector, which has been holding the fort deep inside South Dakota's Homestake gold mine for 20 years, can't detect solar neutrinos with energies below its 814-keV threshold. (See PHYSICS TODAY, October 1990, page 17.) Thus it is blind to all the neutrinos produced in the proton–proton fusion reaction

$$p + p \rightarrow {}^2H + e^+ + \nu_e$$

which is confidently presumed to dominate the Sun's energy production. The standard solar model tells us that these "pp neutrinos" account for more than 90% of the neutrino flux emanating from the Sun. Unfortunately the pp neutrino spectrum cuts off at 420 keV. (See the figure above.) Japan's Kamiokande water Čerenkov detector can't see the pp neutrinos either; its detection threshold is 7.3 MeV.

Kamiokande and the Homestake chlorine detector have indeed seen solar neutrinos, but only the more energetic ones produced in peripheral branches of the solar energy mechanism. And they're seeing too few of these high-energy neutrinos. That's the essence of the "solar neutrino problem," which has been with us for a long time—ever since it became clear that the chlorine detector was seeing less than a third of the neutrino signal predicted for it by the standard solar model.



Solar neutrino spectra that contribute significantly to the signals predicted for the extant detectors, as calculated from the standard solar model. For the monoenergetic ^{7}Be and pep lines, the flux is given in cm^{-2} sec^{-1}. Shadings indicate detector thresholds: Kamiokande sees only the ^{8}B decay spectrum. Chlorine detectors can also see ^{7}Be neutrinos. The gallium detectors, with a 233-keV threshold, are the only ones that can see the pp spectrum.

What makes gallium detectors so attractive, despite the enormous cost of gallium by the ton, is their 233-keV threshold. Gallex and SAGE should see the bulk of the pp neutrinos. And if they don't, the standard solar model provides very little wiggle room. If they discovered a severe dearth of solar neutrinos, that would be telling something quite new about the Sun—or about neutrinos.

First Gallex result

It turns out we needn't have worried about a null signal. But on the other hand, Gallex has not yet yielded up the unambiguous result one might have hoped for. After 295 days of exposure, the Gallex collaboration reports a neutrino capture rate $63 \pm 16\%$ of that predicted by the standard solar model. The quoted error, which is at present dominated by statistics, should be cut in half by the end of the four-year anticipated life of the experiment.

The gallium and chlorine detectors are radiochemical systems in which one looks for a particular nuclear transmutation induced by neutrino capture. In the gallium detectors, for example, one measures the incident neutrino flux by monitoring the accumulation of radioactive germanium-71 produced by the reaction

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

where ν_e denotes the electron neutrino, the only kind of neutrino produced by the nuclear reactions in the solar core. For such radiochemical experiments it is traditional to give predictions and results in solar neutrino units; 1 SNU equals one neutrino capture per second for every 10^{36} atoms of the relevant target isotopic species in the detector.

The standard solar model predicts that gallium detectors should see solar neutrinos at the rate of 132 ± 7 SNU. For a detector with 30 tons of gallium (about 40% of which is the relevant isotope ^{71}Ga) that translates into only 1.2 atoms of germanium produced per day in the whole detector. Of that predicted total, the standard solar model attributes 74 SNU, a little more than half, to the pp neutrino spectrum (plus the related monoenergetic "pep" neutrinos from electron-assisted pp fusion).

The total rate observed by Gallex is 83 ± 21 SNU. Radiochemical detectors can say nothing about the energy of an individual captured neutrino, except that it was above threshold. So the experiment cannot distribute the observed total capture rate among the various processes in the solar core, each of which produces a distinctive, calculable neutrino energy spectrum. Nonetheless the experimental paper[1] concludes that "the Gallex experiment can truly claim to have observed, for the first time, the primary pp neutrinos."

The higher energy neutrinos seen by the Homestake deteector come primarily from the decay of boron-8 and electron capture by beryllium-7. Both of these processes are quite rare in the solar core. But the ^8B decay neutrinos, in particular, play a significant role in the solar neutrino detection business because the ^8B neutrino spectrum goes all the way up to 15 MeV. Kamiokande, with the highest threshold of all the detectors, can see nothing but the ^8B decay neutrinos.

Fiddling with the model

The standard solar model's prediction for the pp neutrinos is rather inflexible. By contrast, the ^8B prediction is particularly sensitive to the temperature one takes for the solar core. What is the minimum signal the gallium detectors must see if we are to avoid radical departures from conventional astrophysics or neutrino physics? Taking a cue from the observation that Kamiokande and especially the chlorine detector found drastic shortages of higher-energy neutrinos, one might ask what Gallex would see if all these rare high-energy channels, which play very little role in generating the Sun's energy, were turned off. John Bahcall (Institute for Advanced Study, Princeton) has done that exercise.[4] Bahcall has been calculating SNUs since the days when Homestake was only a gleam in Davis's eye. Given the constraint of the observed total luminosity of the Sun, he calculates, the gallium detectors would have to see 80 SNU, even if pp (and pep) fusion were the only source of solar neutrinos. That represents an absolute minimum, Bahcall told us. If Gallex had unambiguously seen less, he argues, one would be forced to invoke some "new physics" mechanism that renders neutrinos invisible on their way from the solar core to the waiting detector.

But Gallex did not see less than 80 SNU. In fact this first Gallex result, with its capacious statistical uncertainty, is only two standard deviations below the undoctored prediction of the standard solar model. "By itself, if you forget about Homestake and Kamiokande for the moment, our result poses no 'solar neutrino problem,'" says theorist Joseph Weneser, a member of the Gallex collaboration's Brookhaven contingent.

But of course one can't simply forget about Homestake and Kamiokande. The long-term average capture rate observed by the chlorine experiment is 2.1 ± 0.3 SNU. The standard solar solar model prediction for chlorine is 7.9 ± 0.9 SNU. Kamiokande, unlike the Homestake detector, measures neutrino flux by looking for scattered electrons rather than transmuted nuclei. It even records a rough spectrum of neutrino energies. Kamiokande has kept the solar neutrino problem very much alive in recent years by finding ^8B neutrinos at only $46 \pm 8\%$ of the rate predicted by the standard solar model.

Can one simultaneously reconcile the Gallex, Kamiokande and Homestake results with conventional solar physics by modestly varying the accepted parameters of the solar core? In the interpretational paper[2] that accompanies its experimental report, the Gallex group has tried to fit the Sun's central temperature to all the solar neutrino data in what it describes as a "phenomenological mock-up" rather than a consistent calculation that takes full account of the coupling between all the nuclear reactions going on in the core. A small decrease in temperature has little effect on pp fusion, but it greatly reduces the production rate of boron-8.

The best fit with this phenomenological mock-up reduces the central temperature by about 5% from the accepted standard-model value (15.6×10^6 K). But even this cooler Sun puts out a neutrino flux two standard deviations higher than what the chlorine detector sees. The group concludes that "the confidence levels associated with such a fit (less than 5%) make it a very poor bet." And besides, a 5% core-temperature reduction is actually a lot for the astrophysicists to swallow. A similar calculation by Sidney Bludman and colleagues at the University of Pennsylvania concludes that an even more drastic 15% cooling of the solar core would be required to explain the Gallex data.[5]

Changing neutrino flavors

The resolution of the solar neutrino problem may well come from particle physics rather than astrophysics. We know of three kinds of neutrinos, associated respectively with the electron, the muon and the much heavier tau lepton. In the absence of convincing evidence to the contrary, standard particle theory conveniently presumes all three neutrino species to be massless. But the standard theory can easily accommodate small neutrino masses, and indeed evidence of such masses would be a welcome beacon pointing the way toward a "grand unification" of the disjoint sectors of the theory.

If the three neutrinos have different masses it is quite likely that the three mass eigenstates do not coincide precisely with the three "weak flavor" eigenstates associated with the three charged leptons. That would permit metamorphosis of neutrinos from one flavor to another. The radiochemical solar-neutrino detectors can see only electron neutrinos, and Kamiokande has reduced sensitivity to the other neutrino flavors. Nuclear reactions in the solar core generate only electron neutrinos. But if enough of them were to change flavor on the way out, we might have an explanation for our missing solar neutrinos.

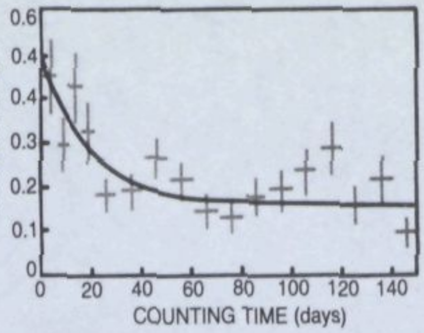
In 1985 S. P. Mikheyev and A. Yu. Smirnov at the Institute for Nuclear Research in Moscow, exploiting the formalism developed by Lincoln Wolfenstein of Carnegie–Mellon University, pointed out that neutrinos produced in the solar core can experience resonant enhancement of flavor metamorphosis as they traverse the outer precincts of the Sun, if the mass differences and mixing angles between the different neutrino states are big enough. This "MSW mechanism" took what had been thought to be a marginal phenomenon at best and turned it into what many now regard as the best hope for solving the solar neutrino problem.

The Gallex interpretational paper describes the group's fit of its data plus those of Homestake and Kamiokande to the MSW mechanism. This time they leave the parameters of the standard solar model unaltered, varying only the two parameters that determine the MSW effect: the mixing angle and Δm^2, the difference between the squared masses of the electron neutrino and the other state (presumably, but not necessarily, the muon neutrino) into which it does its disappearing act. The paper reports good fits in three nicely localized regions of the MSW parameter space. The most attractive of these three solutions, from the viewpoint of particle physics, has a mixing angle of about 3° and Δm^2 around 5×10^{-6} eV^2.

The threshold energy for a neutrino to experience a resonant MSW metamorphosis on its way out of the Sun is proportional to the parameter Δm^2. The Gallex group's fit puts this threshold at about 500 keV, too high to have much effect on the pp neutrinos that make up the bulk of the gallium signal. Last year, when the early SAGE data were suggesting that the pp neutrinos were the most severely depleted, a Δm^2 of a few times 10^{-7} eV^2 seemed more likely. That would have put the MSW threshold below 50 keV, thus optimizing the disappearance of pp neutrinos.

Two years ago Bahcall and Hans Bethe (Cornell) made the point[6] that the discrepancy between Kamiokande and the chlorine data already required MSW or some other new particle physics to the same effect, *irrespective* of how the gallium experiments might turn out. The shape of the boron-8 decay spectrum is known from laboratory nuclear physics, they argued, and the Kamiokande data provide the normalization that lets one extrapolate down to the chlorine detector. Thus they concluded that a chlorine detector would have to see at least 2.9 SNU of ^{8}B neutrinos. Add to that an irreducible minimum of other neutrinos that can't be fudged away by tinkering with the solar model and you are left with an absolute minimum of 4 SNU, unless something is killing the neutrinos on their way to the chlorine detector. "If you believe Davis's 2.1 ± 0.3 SNU and the Kamiokande data," Bahcall told us, "you are forced to invoke MSW or some other new physics, quite apart from the gallium results. I, for one, find the Mikheyev–Smirnov–Wolfenstein theory very beautiful."

At this juncture, Bahcall argues, the solar neutrino problem is of greater interest for the particle physics we can learn than for the astrophysics. "The fact that we've been able to predict the right order of magnitude for such obscure branches as boron-8 and beryllium-7, which play almost no role in stellar evolution, shows that we understand quite well what's going on in the cores of main-sequence stars. As the gallium error bars shrink over the next few years, and especially when the new generation of water Čerenkov detectors [SuperKamiokande in Japan and the Sudbury heavy-water detector in Ontario] begin operation in mid-decade, we should be able to pin down the details of the new physics."



Counting Ge^{71} decays for months after the germanium is extracted from Gallex following a three-week exposure. The curve is a fit to the fast ^{71}Ge decay (halflife 11.4 days) plus constant background and the 288-day decay of ^{68}Ge contaminant. The initial peak represents only about five ^{71}Ge counts above background. The peak at 115 days is not significant. The data are an average over 14 Gallex exposures.

The gallium experiments

The Gallex results were announced in June at the Neutrino-92 conference in Granada, Spain, by spokesman Till Kirsten, from the Max Planck Institute for Nuclear Physics in Heidelberg. Other groups in the collaboration come from the Institute for Hot Chemistry in Karlsruhe, the Technical University of Munich, Italy's Gran Sasso National Laboratories, the Universities of Milan and Rome, the Nice Observatory, Saclay, the Weizmann Institute and Brookhaven. The Munich group is led by Rudolf Mössbauer.

Also at the Granada conference, Thomas Bowles, leader of SAGE's Los Alamos contingent, gave an update of the SAGE experiment. Other Americans in the collaboration come from the University of Pennsylvania, Louisiana State University and Princeton. The (former) Soviet contingent, headed by Vladimir Gavrin, is from the Institute for Nuclear Research in Moscow. Bowles told his audience that the group was not yet ready to quote a new overall neutrino capture rate. He did show data from recent exposures indicating that SAGE now has a distinctly nonzero solar neutrino signal; but it's still somewhat lower than the published Gallex rate.

Gallex's 30 tons of gallium atoms reside in 100 tons of an aqueous solution of gallium chloride and hydrochloric acid. SAGE has chosen the more compact option: pure liquid gallium metal. (Gallium melts at 30 °C.) "We also figured that keeping hydrogen out of the detector would keep background reaction rates down," Bowles told us. The designers of Gallex opted for the bulkier and more corrosive alternative because they felt that the chemistry of extracting a dozen or so germanium atoms from a massive detector posed fewer headaches in ionic solution than in liquid metal.

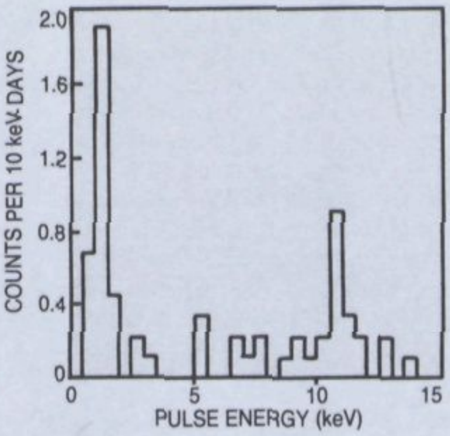
Taking the 83-SNU result at face value one concludes that solar neutrinos are producing only five atoms of germanium-71 *per week* in Gallex's 50 000 liters of gallium chloride solution. The trick is to extract this meager harvest of germanium about once every three weeks with high efficiency, concentrate it into a small cupful of liquid and then look for ^{71}Ge decays in one of the miniaturized proportional counters specially developed at Heidelberg for painfully low counting rates. ^{71}Ge decays by electron capture with a convenient halflife of 11.4 days.

The germanium is extracted from the Gallex detector by bubbling nitrogen through the liquid. The acidity and high chloride concentration of the solution ensure that the germanium will form the volatile compound $GeCl_4$. The efficiency of this extraction, monitored by adding a milligram of a stable germanium isotope to the tank at the beginning of each three-week "exposure," is typically 99%. After chemical purification and concentration in tritium-free water, the $GeCl_4$ is converted into germane (GeH_4), a methane-like gas which then serves both as the radioactive source and as part of the ionizing medium in the tiny proportional counting chamber.

The germanium from each three-week exposure is monitored in one of these ultralow-level proportional counters for about six months. That's more than 15 times the halflife of ^{71}Ge, but the Gallex group feels it needs to count that long to get a good determination of background. In fact counting is still in progress for some of the 14 three-week exposure samples on which the Gallex paper is based.

The figure above shows how the daily counting rate settles down to background after the ^{71}Ge atoms have all decayed in the first month or two after extraction. These data are an average over all 14 runs. The curve is a fit to the decay of ^{71}Ge plus two kinds of background: the decay of a stubborn ^{68}Ge contaminant with a halflife of 288 days, and a time-independent background counting rate.

The area under the initial peak, after background subtraction, shows that the entire solar-neutrino signal gleaned from 100 tons of liquid after three weeks of exposure comes to only about 5 observed Ge^{71} decays. Because the efficiency of the proportional counter is about 65%, this implies something like 7 or 8 Ge^{71} atoms actually make it to the counter after each extraction. About 40% of the Ge^{71} atoms generated during a three-week exposure decay while waiting to be extracted.



Energy spectrum of fast pulses in a proportional counter during the first 16 days after germanium extraction from the Gallex tank. The peaks near 1 and 10 keV clearly signal ^{71}Ge decay by L and K capture, respectively.

Fighting the background

Extracting so delicate a signal requires heroic measures to reduce obscuring background. Everything involved in the extraction and counting procedures must be made of ultrapure nonradioactive materials. The counting area is rigorously quarantined from outside air with its threat of radon contamination. A whole mountain is required to shield Gallex from cosmic rays. The few honest ^{71}Ge decay counts must be distinguished from the many impostors.

The electron captured by the decaying ^{71}Ge nucleus comes from either the atom's K shell or its L shell. In either case the decay releases some combination of Auger electrons and x-ray photons the sum of whose energies, as measured by the proportional counter's ionization pulse, equals the binding energy of the captured electron. K capture is easier to see because the K electron's binding energy (10.4 keV) is 9 times that of the L electron. SAGE has only recently begun counting L captures. For fast pulses the energy spectra recorded by the Gallex counters (see figure above) show clear ^{71}Ge L- and K-capture peaks. One can almost always distinguish a legitimate Ge^{71} decay from a spurious ionization pulse by requiring that the measured energy be appropriate for either K or L capture and that the rise time and shape of the pulse meet strict criteria.

In one important case, however, that doesn't work. Germanium-68 also decays by electron capture, producing pulses that look just like ^{71}Ge decays. But ^{68}Ge makes its presence known in two ways: Its halflife is nine months and it has a daughter that occasionally decays by β^+ emission. It turns out that ^{68}Ge contamination unexpectedly delayed the start of Gallex data-taking by about half a year: During the weeks that the gallium chloride solution sat unprotected on the surface before being admitted to the shielded precincts of the Gran Sasso tunnel, cosmic rays generated some 10 million atoms of ^{68}Ge in the liquid. But this was not thought to be a problem. The plan was to purge the liquid of ^{68}Ge before starting the experiment by precisely the same chemical extraction procedures to be used for harvesting the ^{71}Ge. And indeed this scheme worked well, but not well enough. Repeated purging removed 99.9% of the ^{68}Ge, as determined from the residual β^+ activity. But 0.1% of 10 million ^{68}Ge atoms is still an intolerable contamination when one is trying to count a dozen atoms of the all too similar ^{71}Ge.

Something unforeseen was obviously trapping a tiny fraction of the germanium in the detector lining or in some contaminant. The problem was that the trapped ^{68}Ge was then leaking into the detector liquid at a slow rate that would nonetheless mask the production of ^{71}Ge by solar neutrinos. Finally it was decided to heat the liquid in the detector in hopes of speeding up the release of the trapped contaminant. That did the trick. When the background ^{68}Ge activity was finally down to about 0.1 counts per day at the beginning of last year, Gallex could finally start looking for solar neutrinos.

One important calibration test remains to be done next year. The detector will be exposed to a megacurie chromium-51 source of monoenergetic 746-keV neutrinos, in effect an artificial Sun. "It's an essential overall test of the whole experiment," Kirsten told us. "We have painstakingly tested all the steps individually. Such a complicated experiment, however, requires an overall performance test." There's always the outside possibility, for example, that the unusually energetic germanium atoms born in radioactive decays might get bound up in aberrant "hot chemistry."

Irradiating and enriching natural chromium to get a megacurie of ^{51}Cr is, however, a demanding and expensive business. The test was to have been done before data-taking began. But unforeseen funding problems, which have since been resolved, caused the delay. The chromium test would, of course, have been even more pressing if Gallex were seeing a null result.

SAGE also is planning to do a chromium calibration. Before SAGE started seeing a significant solar neutrino rate, there was some talk that its liquid metal was the problem. Much of SAGE's chemistry is quite similar to Gallex's. But in extracting the germanium from pure liquid gallium, SAGE confronts issues of surface chemistry at boundaries between liquid metal and aqueous phases.

It may just be that last year's result was simply a statistical fluke. The report[3] was based on the first five SAGE exposures, three of which gave null readings. The average Gallex exposure, after all, produces only five counts above background, and three of Gallex's 14 reported exposures also gave null results. At their 90% confidence limits the two reports are not in conflict: At that level SAGE quoted an upper limit of 79 SNU and the Gallex paper gives a lower limit of 49 SNU. The SAGE group plans to report its new results in the fall.

—Bertram Schwarzschild

References

1. P. Anselmann *et al.* (Gallex collaboration), Phys. Lett. B **285**, 376 (1992).
2. P. Anselmann *et al.* (Gallex collaboration), Phys. Lett. B **285**, 390 (1992).
3. A. I. Abazov *et al.* (SAGE collaboration), Phys. Rev. Lett. **67**, 3332 (1991).
4. J. Bahcall, *Neutrino Astrophysics*, Cambridge U. P., New York (1989) p. 356.
5. S. Bludman, N. Hata, D. Kennedy, P. Langacker, submitted to Phys. Rev. D (1992).
6. J. Bahcall, H. Bethe, Phys. Rev. Lett. **65**, 2233 (1990).

Stalking Solar Neutrinos

In caverns deep under the ground
They hunt SNUs like hungry
bloodhounds.
But maybe the prey
Can change 'long the way
And sneak by without being found.

—Barbara Goss Levi