not those of a pawl moving along the asymmetric teeth of a physical rachet but those of a particle in an uneven, sawtooth potential.

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Chromium Surrogate Sun Confirms That Solar Neutrinos Really Are Missing

> As we hear early reports of neutrino oscillation in an accelerator beam, an experiment with a surrogate Sun lends credence and clarity to the solar neutrino puzzle, the oldest of the anomalies that point to exotic neutrino metamorphosis.

There may still be some who doubt that the missing-solar-neutrino problem is real. But an impressive experiment with a radioactive solar surrogate recently completed at the Gallex solar neutrino detector in Italy makes it difficult to sustain such skepsis.[1] The new experiment supports the reports over the last several years that Gallex and Russia's SAGE, the other large gallium detector, see only about 60% of the solar neutrino signal confidently predicted by astrophysical models. (See PHYSICS TODAY, August 1992, page 17.) Thus it does much to bring the observational features of the solar neutrino puzzle into clearer focus.

Neutrino oscillation

Keen interest in solar neutrinos extends far beyond the astrophysics community. If the discrepancy between what the detectors see and what the solar models predict is real, the best explanation at the moment is "neutrino oscillation," an exotic but quite plausible speculation of the elementary-particle theorists. The neutrinos we know about come in three "flavors." What the solar core puts out, and what the detectors are designed to see, are the *electron* neutrinos (ν_e) created in beta decay and hydrogen fusion. If at least one of the three neutrino varieties has a nonvanishing mass, it is possible that solar neutrinos defy detection by oscillating between different flavors.

Tentative evidence for neutrino oscillation also comes from an apparent shortage of muon neutrinos (ν_μ) in atmospheric cosmic-ray showers, reported by various groups since 1988. (See PHYSICS TODAY October, page 22.)

Very recently Hywel White and colleagues at Los Alamos created considerable stir with informal reports that their experiment with a neutrino beam at Los Alamos gives evidence of $\nu_\mu \to \nu_e$ oscillation, with a ν_μ mass of a few electron volts. As of this writing the jury is still out, pending the appearance of a preprint.

But even if all these tantalizing hints of neutrino oscillation turn out to be right, they appear to require different sets of oscillation parameters (mass-squared difference and mixing angle). That's no problem if each of these phenomena involves a different pair of oscillation partners: Perhaps the atmospheric muon neutrinos are oscillating with tau neutrinos (ν_τ), the third known variety, while the solar neutrinos oscillate with a speculative species of "sterile" neutrinos that are impervious to the standard weak interaction.[2] The accumulating evidence of neutrino oscillation would of course be more compelling if the different observational regimes were converging on the same parameters.

Trusting the radiochemical detectors

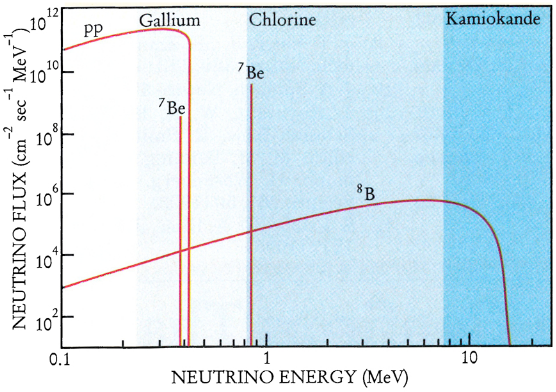
At this juncture it becomes all the more important to determine once and for all whether the solar-neutrino deficit, the oldest of the reported anomalies, is real. Like Ray Davis's pioneering chlorine detector in South Dakota, which gave the first evidence of a solar neutrino shortfall in the early 1970s, Gallex and SAGE are radiochemical detectors that attempt to extract something like a dozen alien, neutrino-generated atoms every few weeks from many tons of detector material. In Gallex, for example, solar neutrinos raining down on 30 tons of gallium transmute less than one gallium nucleus per day into a radioactive germanium nucleus. To believe that such experiments are really showing a significant deficit of solar neutrinos, one must have confidence that the experimenters can, with sufficient reliability, chemically extricate one atom from among 10^{28} others and then detect its decay.

The radiochemical groups have taken exquisite pains over the years to examine and avoid the many imaginable pitfalls. They carefully studied, for example, "hot-atom chemistry" issues: whether the unusually energetic atoms created by neutrino collisions might not form unusually stubborn bonds. "We had tested all the individual steps of our solar neutrino detection," says Gallex spokesman Till Kirsten (Max Planck Institute for Nuclear Physics, Heidelberg). "But it was essential to have an overall performance test. In such a complex experiment there could always be systematic error we hadn't thought of. And besides, we had to address the hand-waving skepticism that clouded all the radiochemical results."

A surrogate Sun

It was fairly obvious how such a comprehensive test should be done, but it would be an expensive, demanding task. The idea was to insert into the Gallex detector a calibrated radioactive neutrino source so powerful that it would subject the detector to a flux an order of magnitude greater than that coming from the Sun. Its energy spectrum had to be appropriate. Neutrinos of about 800 keV are particularly desirable for addressing what has become the most urgent issue—the almost complete disappearance, or so it seems, of the neutrinos from the decay of beryllium-7 in the solar core. (See the figure on page 20.)

Several years before Gallex began running in 1991, the group had already concluded that the radioisotope ^{51}Cr, produced by activating chromium in a reactor, would make the best surrogate Sun. With a convenient halflife of 28 days, ^{51}Cr decays to vanadium-51 by electron capture, usually emitting a neutrino of 0.75 MeV. One time in ten it decays to an excited ^{51}V state, emitting a neutrino of only 0.43 MeV.



SOLAR NEUTRINO spectra at the Earth, predicted by the standard solar model.[3] Monoenergetic beryllium-7 decay fluxes are in cm^{-2} sec^{-1}. Shadings indicate threshold energies for extant detectors. Only the gallium detectors can see neutrinos from the principal proton–proton fusion reaction that powers the Sun.

These energies are particularly well suited to mimic the two decay modes of the ^{7}Be that is almost certainly produced in the solar fusion cycle.

That's the good news. The bad news is that naturally occurring chromium has only 4% ^{50}Cr, the stable isotope that can be turned into the desired ^{51}Cr by neutron bombardment in a reactor. That's not nearly enough to make the 1.5-*mega*curie source the Gallex group needed for an adequate test. To produce a neutrino source of such unprecedented strength by irradiation, they would first have to get someone to undertake a prodigious and costly task of isotope enrichment: They needed about 40 kg of chromium with the ^{50}Cr fraction enriched to at least 20%. Then they would have to find a high-flux reactor whose irradiation chamber could accommodate such an extraordinarily large sample. Finally they would have to quickly transport this highly radioactive mass to the tunnel where Gallex sits, underneath the 2900-meter-high Gran Sasso in the Apennines, and insert it into the detector before too much of the activity had decayed away.

Once the activated chromium source was ensconced in a "thimble" protruding into Gallex's 100 tons of gallium chloride solution, the plan was to test the validity of the solar neutrino experiments by using essentially the identical radiochemical procedures to deduce the known activity level of the chromium source. This was no mean undertaking. It would require the most powerful radioactive neutrino source ever made. And incidentally, it would be the first ever detection of sub-MeV neutrinos from a terrestrial source. The lower the energy of a neutrino, the harder it is to detect.

'What makes you think . . . ?'

When Richard Hahn and his Brookhaven colleagues joined the largely European Gallex collaboration, the 40 kilograms of isotope-enriched chromium for the performance test was to be their dowry, as it were. Oak Ridge, with its long history of uranium isotope enrichment, was the obvious place to do the enrichment. Oak Ridge did a feasibility test and concluded that it could produce the requisite quantity of enriched chromium by gas centrifugation for about a million dollars. So in 1988 the Brookhaven group applied to the Department of Energy to fund this contribution to Gallex.

That's when the troubles started. To enrich the ^{50}Cr fraction by gas centrifugation requires that the chromium metal be converted to chromyl fluoride, a corrosive and hazardous gas. DOE and local authorities began piling on so many safety requirements that the prospective cost began to skyrocket. When the exasperated Hahn complained that Oak Ridge had been doing isotope enrichment with the equally dangerous uranium hexafluoride for almost half a century, the response was, "What makes you think that, in today's regulatory climate, we'd approve UF_6 if it were being proposed for the first time now?"

When the estimated cost of doing the gas centrifugation at Oak Ridge had risen to about \$3 million, DOE turned down the Brookhaven group's funding request. "That left us, very late in the game, suddenly without the enriched chromium and without European funding for it," recalls Kirsten. "We had been counting on the Americans." Finally a group at the Kurchatov Institute in Moscow offered to do the isotope enrichment at bargain-basement prices.

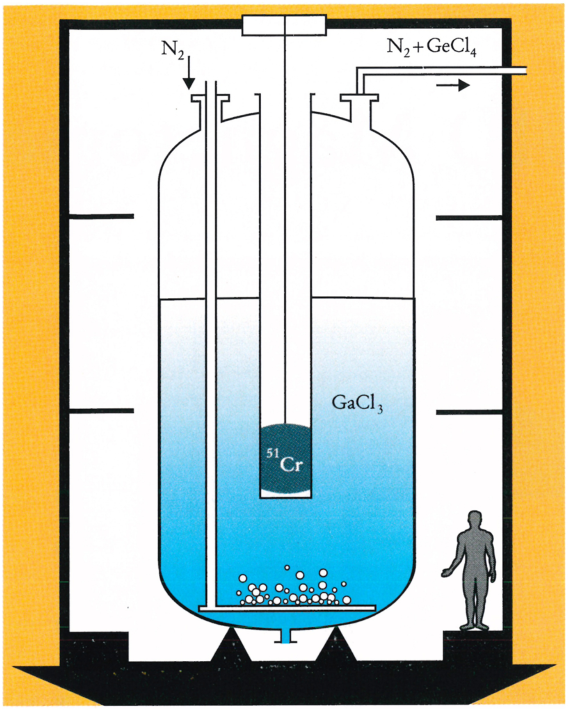
In the spring of 1994, when the Russians had enriched 36 kg to 39% ^{50}Cr by gas centrifugation, the chromium was shipped to the French contingent of Gallex. They prepared it for irradiation in the Siloé reactor at the Center for Nuclear Studies in Grenoble. In a dedicated core chamber of the reactor, the 36 kg of chromium, now in the form of purified metal chips, was irradiated continuously for 24 days, ending on 20 June last year. The resulting radioactivity was then carefully calibrated by four independent methods.

On the morning of 23 June the megacurie source set out on its 400-mile truck ride from Grenoble to the Gran Sasso laboratory on the Adriatic slope of the Apennines. Timing was crucial. The 28-day halflife of the ^{51}Cr would brook no delays. That night the chromium source was safely in place inside the Gallex tank, having radiated away only 9% of the activity with which it had emerged from the reactor. For the next three months, at growing intervals as the source waned, nitrogen was bubbled through the gallium solution to extract any radioactive germanium atoms produced by neutrinos from the chromium source and, of course, from the Sun. (The gallium solution is always spiked with a bit of nonradioactive germanium to make macroscopic chemistry possible.) The germanium extracted from each run was then monitored in a miniature counter designed to detect Auger electrons and x-ray photons from the decay of ^{71}Ge.

After 15 weeks of chromium-neutrino exposure and germanium extraction, and several more months of counting germanium decays, the Gallex group obtained a value of 64.1 ± 8 petabecquerels for the initial source strength. (100 PBq = 2.7 megacuries.) Comparing that value, measured in precisely the same way Gallex measures the *solar* neutrino flux, with 61.9 ± 1.2 PBq, the calibrated strength of the chromium source measured at Siloé, the group concludes that any systematic errors in its solar neutrino results do not exceed 11% at the level of one standard deviation. In other words, the missing 40% of the solar neutrino signal predicted for gallium detectors cannot be explained away as an experimental artifact.

The missing beryllium neutrinos

How do we know it's particularly the ^{7}Be neutrinos that are missing? It's because different sorts of solar neutrino detectors, with different neutrino-energy thresholds, report different shortfalls. The Kamiokande water Čerenkov detector in Japan, whose threshold is so high (7 MeV) that it can see nothing from the Sun except boron-decay neutrinos, records about half the signal predicted for it by the standard solar model. Davis's chlorine detector, with a threshold (814 keV) low enough to detect most of the boron and beryllium neutrinos but none of the low-energy proton–proton fusion neutrinos that dominate the solar flux, sees only about a third of the



Chromium surrogate Sun spews 10^{17} neutrinos per second into the surrounding gallium chloride solution in the Gallex solar neutrino detector. Nitrogen is bubbled through the solution at intervals to carry off the handful of germanium atoms engendered by neutrinos hitting gallium nuclei.

signal predicted for chlorine detectors.

The great virtue of the gallium detectors is that their threshold (233 keV) is low enough to see much of the pp neutrino spectrum. And indeed, the 60% of the predicted solar neutrino signal that the gallium detectors report seeing is just about what they would see if all the other processes in the solar core were shut down *except* the principal fusion reaction $p + p \rightarrow {}^2H + e^+ + \nu_e$. The neutrino flux from the pp reaction is predicted within 1 or 2% by the solar models. Unlike the ^7Be and ^8B neutrino fluxes, it's hard to tinker with.

Now that the chromium experiment has lifted the shadow of exaggerated skepticism from the gallium experiments, it's tempting to make the simple assumption that the solar-cycle byways leading to beryllium and boron production are somehow cut off. But that way lies a paradox: All the boron in the solar cycle comes from beryllium absorbing a proton. Kamiokande sees fully half the predicted boron signal, and unless the gallium *and* chlorine results are severely wrong, there's room in the data for only a small fraction of the predicted beryllium-decay neutrinos. But there's no way you can produce so much boron in the core of the Sun from so little beryllium. That's why astrophysicists are beginning to call the solar neutrino problem "the missing-beryllium paradox."[3]

Right now the Mikheyev–Smirnov–Wolfenstein hypothesis of resonant neutrino oscillation in the outer reaches of the Sun offers the most convincing way out of the paradox. That theory, now in circulation for almost a decade, leaves the standard solar model intact except to point out that neutrino oscillation *in vacuo* could be greatly amplified by resonant interaction between solar matter and neutrinos on their way out. Because the probability of resonant oscillation is strongly energy dependent in the MSW theory, different kinds of detectors can see different shortfalls.

The new Los Alamos neutrino-oscillation data suggests a ν_μ mass that's attractive to cosmologists worrying about dark matter.[2] But it's much too large for the MSW fits to the solar neutrino data. And the Los Alamos $\nu_\mu - \nu_e$ mixing angle is much too small to account for a significant disappearance of solar neutrinos. So if the Los Alamos result survives, solar electron neutrinos would appear to be metamorphosing into something other than mu neutrinos.

The next generation of solar neutrino detectors should do much to unravel this tangled web. Unlike the radiochemical detectors, the new Čerenkov and scintillator systems will be sensitive to all three neutrino flavors. And they will have enough energy resolution to tell us what parts of the solar-neutrino spectrum are most severely depleted.

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Horseradish can clean industrial wastewater

Horseradish is so potent that it clears clogged sinuses, tickles tastebuds when dabbed on gefilte fish or roast beef . . . and now, it can clean up industrial wastewater. Jean-Marc Bollag, codirector of Penn State's Center for Bioremediation and Detoxification, and Jerzy Dec, a research associate there, report[1] that minced horseradish root can clean wastewater containing phenols a lot more cheaply than other chemical and physical treatments.

Fifteen years ago Alexander M. Klibanov at MIT and his collaborators had pointed out that the enzyme horseradish peroxidase, when added to wastewater with hydrogen peroxide, causes pollutants such as phenols, anilines and other aromatic compounds to form insoluble polymers that can then be filtered off. Phenols are found in wastewater from steel and iron manufacturing, ore mining, paper bleaching, coal conversion, and manufacture of dyes, resins, plastics, pesticides, textiles and detergents.

Bollag and Dec used wastewater from the production of the herbicide 2,4-D. They minced ordinary horseradish root to maximize the enzyme's contact with the water, and found that the minced root cleaned up phenol as well as purified horseradish peroxidase does. Better results occurred as the root was chopped finer; mashed worked best. The horseradish remained effective for as many as 30 treatments.

The Penn State horseradish treatment takes 30 minutes, compared to the weeks or even months required by microbial degradation, according to Bollag and Dec. They say the major reason that enzymatic treatment hasn't been applied on an industrial scale is the huge size of polluted environments needing bioremediation and the cost of treating them. Bollag told us minced horseradish costs half as much as standard chemical methods.

Although minced horseradish works best, minced white radish and minced potato also remove phenols. So if you're all out of horseradish, try potato latkes.

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