

SEARCH AND DISCOVERY

Novel Heavy-Water Detector Unveils the Missing Solar Neutrinos

For 30 years, the evidence of a shortfall of solar neutrinos has been growing ever stronger. The robust standard solar model (SSM) predicts a flux of electron neutrinos (ν_e) emanating from the core of the Sun that's more than twice as great as what has been observed by a variety of detectors on Earth, all of them sensitive only, or primarily, to electron neutrinos.

The prevalent opinion nowadays blames the shortfall on exotic neutrino physics rather than on possible imperfections in the astrophysics of the SSM. Neutrinos come in three different flavors— ν_e , ν_μ , and ν_τ —associated with the electron and its heavier cousins, the muon and the tau lepton.

The fusion reactions in the solar core produce only ν_e . It is widely supposed that a significant fraction of these electron neutrinos suffer a flavor change somewhere on their journey to the detector. The details of this putative “neutrino oscillation,” together with evidence for similar oscillatory neutrino metamorphoses in other observational realms, are of crucial interest to the search for a more encompassing theory beyond the present standard model of particle physics. Neutrino oscillation would be a first step beyond the standard model. One really wants to know, for example, what the vanishing solar neutrinos are turning into.

Finding the missing neutrinos

To address that crucial question, the Sudbury Neutrino Observatory (SNO), a detector with novel capabilities, began observing solar neutrinos at the end of 1999 from deep inside a Canadian nickel mine north of Lake Huron. SNO is an international collaboration headed by Art McDonald of Queen's University in Kingston, Ontario. Now, at last, we have the much anticipated first report of results from SNO's first year of observations.¹

Like the 50-kiloton Super Kamiokande detector that has been operating under a mountain in Japan since 1996, SNO is an imaging water Čerenkov detector whose thousands of photomultiplier tubes can measure the energies and directions of electrons scattered by neutrinos bom-

Two thirds of the solar neutrinos confidently predicted by models of how the Sun works come to Earth disguised in altered flavors.

barding the water. But the kiloton of heavy water (D_2O) at the heart of the new 8-kiloton detector gives SNO a unique ability to determine what has actually become of the missing solar electron neutrinos. (See the article by McDonald, John Bahcall, Frank Calaprice, and Yoji Totsuka in *PHYSICS TODAY*, July 1996, page 30.)

In brief, the first SNO results tell us that about $2/3$ of the most energetic electron neutrinos produced in the solar core have indeed metamorphosed into ν_μ or ν_τ , and that the total flux of neutrinos of all three flavors is in excellent agreement with the ν_e flux predicted by the SSM in the absence of any neutrino oscillation.²

Not only do these results confirm the conviction that the astrophysics of the power plant at the core of the Sun is well understood. They also leave very little room for “sterile neutrinos.” There had been serious speculation that solar neutrinos were metamorphosing into some putative sterile neutrino species that does not participate in the standard weak interactions. The apparent absence of sterile neutrinos, in turn, calls into question the controversial 1995 report of flavor oscillations over short distances in an

accelerator-based neutrino beam at Los Alamos (see *PHYSICS TODAY*, January 2001, page 16).

Why heavy water?

What's so special about D_2O , aside from the fact that Canada has lots of it left over from its heavy-water nuclear reactor program? Solar neutrino energies do not extend much above 14 MeV. At these modest energies, the only way a neutrino can signal its presence in a traditional H_2O Čerenkov detector is by elastic scattering off an electron. And, indeed, one only gets sufficient Čerenkov light above background if the recoil energy of the struck electron exceeds a threshold of about 5 MeV.

The cross section for such elastic scattering by ν_e is notoriously small. But it's even smaller, by about a factor of 7, for ν_μ and ν_τ . That's because a ν_e can scatter off an electron by two different weak-interaction mechanisms: “neutral current” exchange (figure 1a) and “charged current” exchange (figure 1b). The ν_μ and ν_τ , by contrast, can only scatter off electrons by neutral-current exchange. In any case, if one has only elastic scattering data, one cannot disentangle the incident ν_e flux from that of the other neutrino flavors.

That's where the deuteron, the heavy hydrogen nucleus, comes to the rescue. Because it contains a weakly bound neutron, the deuteron can respond to solar neutrinos by breaking

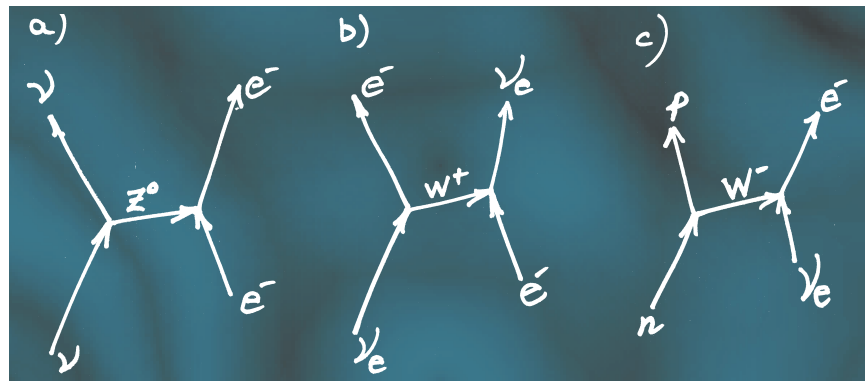
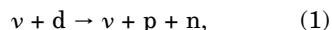
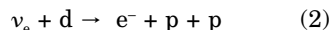


FIGURE 1. FUNDAMENTAL PROCESSES contributing to interactions of solar neutrinos. Elastic ν - e scattering involves the virtual exchange of both (a) neutral and (b) charged heavy bosons. Inverse β decay off a neutron (c) involves only charged boson exchange. All three neutrino flavors contribute equally to the “neutral current” Z exchange, but only ν_e can produce electrons by “charged current” W exchange.

up in one of two useful ways: A neutrino of any flavor can break up the deuteron quasi-elastically,



leaving a free neutron whose subsequent capture can be recorded by the release of a telltale γ . Alternatively, a ν_e can turn a deuteron's neutron into a second proton, while turning itself into an electron detectable by its Čerenkov radiation. This kind of inverse- β -decay reaction



is a charged-current interaction (figure 1c) unavailable to the other neutrino flavors. Because both of these deuteron-breakup reactions have much larger cross sections than neutrino-electron elastic scattering, SNO can make do with a much smaller fiducial volume of water than Super Kamiokande.

The most obvious way of using SNO to find out what becomes of the missing solar neutrinos would be to compare the surviving ν_e flux implied by the observed rate of reaction 2 with the total neutrino flux implied by the observed rate for reaction 1. (All the reaction cross sections necessary for turning observed rates into incident neutrino fluxes can be calculated from standard particle theory.) Because quasi-elastic deuteron breakup is a neutral-current reaction to which all three neutrino flavors contribute equally, it becomes a direct measure of all the neutrinos arriving from the Sun, irrespective of any flavor oscillation en route—provided, of course, that none of the solar neutrinos have been rendered sterile.

That straightforward comparison, however, will have to wait until later this year. Measuring reaction 1 requires a reliable way of detecting the capture of the neutrons freed in the reaction. To that end, highly purified NaCl has recently been added to the heavy water so that liberated neutrons will be captured by the chlorine nuclei, each such capture releasing an easily detected 8-MeV gamma.

But the data that have now been reported were taken *before* the salt was added, the philosophy being that one should start out as simply as possible. Any added ingredient is another potential source of background radioactivity. SNO is much more sensitive to radioactive backgrounds than Super Kamiokande. First of all, it only takes a 2.2-MeV γ to produce a spurious deuteron breakup. Furthermore, reaction 2 produces a fairly isotropic electron distribution not unlike the radioactive background. By

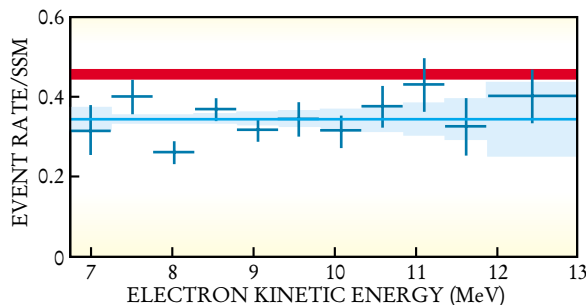


FIGURE 2. SHORTFALLS of solar-neutrino-induced ν -e elastic scattering at Super Kamiokande (red) and inverse β decay (reaction 2) at SNO (blue) are shown by plotting the observed rates, divided by the standard-solar-model predictions, against recoil electron energy.¹ Their difference implies that ν_μ or ν_τ contribute to the elastic scattering. The light blue background indicates systematic experimental uncertainties.

contrast, the neutrino-electron elastic scattering that Super Kamiokande relies on produces a strongly peaked angular distribution of electrons. One can separate the elastic scattering events from radioactive backgrounds or other reactions simply by requiring that the electron be scattered within a few degrees of the direction from the Sun. Extraordinary measures are taken to keep SNO free of radioactive contamination. For example, everyone entering the cavernous underground laboratory must first shower and put on a clean-room garment.

Symbiosis

So how is it that SNO can tell us so much about the missing solar neutrinos even before it acquires its full

capacity to detect neutrons? Until there's adequate data on reaction 1, the SNO collaboration can make do with Super Kamiokande's enormous harvest of neutrino-electron elastic scattering events.³ Because ν_μ and ν_τ can participate only via neutral-current interaction, the total rate for ν -e elastic scattering is proportional to the flux ϕ_e of electron neutrinos plus about one-seventh of $\phi_{\mu\tau}$, the combined flux of ν_μ and ν_τ .

This admixture is not very informative about the flavor of the missing solar neutrinos until one compares it to the SNO rate for reaction 2, which, by itself, tells us only about ϕ_e . If the incident neutrino flux implied by the rate of elastic scattering at Super Kamiokande turns out to exceed that implied by the rate for reaction 2 observed at SNO, the excess can be attributed to the other neutrino flavors, presumably produced by flavor oscillation during the journey from the solar core to the detector.

Figure 2 shows just such an excess for recoil electron energies above the provisional SNO threshold of 6.75 MeV. Each observed reaction rate, plotted against electron energy, is shown as a fraction of the rate predicted by the SSM in the absence of any

flavor oscillation. As measured by Super Kamiokande, the elastic scattering rate is about 47% of the solar-model prediction, with the shortfall showing no discernible energy dependence. By contrast, the SNO data for reaction 2 come to only about 35% of the SSM prediction, also without any obvious energy dependence. (The electron energy approximates the incident neutrino energy after one corrects for the small deuteron binding energy and mass changes in reaction 2.)

If the missing solar neutrinos had somehow disappeared entirely or become sterile, the rates for both processes would fall short of the

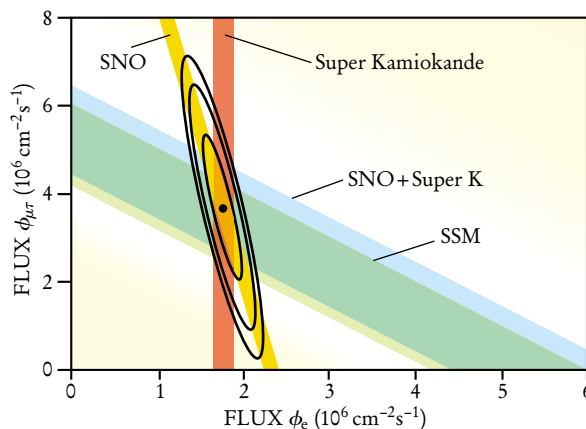


FIGURE 3. SOLAR NEUTRINO FLUXES of different flavors implied by the SNO data (orange) for inverse β decay (reaction 2) and the Super Kamiokande ν -e elastic-scattering data (red). The point where they cross, yielding the best estimates of the flavor-specific fluxes ϕ_e and $\phi_{\mu\tau}$, is surrounded by contours for confidence levels from 68% to 99%. The overlapping diagonal swaths show how well the total flux $\phi_e + \phi_{\mu\tau}$ implied by the combined data (blue) agrees with that predicted by the standard solar model (green). (Adapted from ref. 1.)

SSM prediction by the same fraction. But, in fact, the two shortfalls turn out to differ by 3.3 standard deviations.

A direct comparison of the SNO and Super Kamiokande data, quite independent of any SSM predictions, translates this discrepancy into the separate flavor fluxes ϕ_e and $\phi_{\mu\tau}$. In figure 3, the orange and red bands represent the SNO and Super Kamiokande results in terms of these neutrino fluxes. Where they cross, one has a consistent pair of integrated fluxes above the threshold energy. The best fit to the combined data yields a value of 68% for the fraction of electron neutrinos leaving the solar core that arrive at the detectors with their flavors changed either to ν_μ or ν_τ . The data do not distinguish

between ν_μ and ν_τ .

The blue diagonal swath represents the total flux $\phi_e + \phi_{\mu\tau}$ one gets by combining the SNO and Super Kamiokande data. It overlaps, almost perfectly, the total ν_e flux predicted by the SSM for neutrino energies above the SNO threshold, vindicating the solar model that Bahcall and others have been refining and testing since the mid-1960s, when pioneer Ray Davis was planning to build the first radiochemical solar neutrino detector.

Irrespective of solar models, the new SNO result is the first direct evidence for a large component of active non-electron neutrinos at the high-energy end of the solar neutrino spectrum.

Neutrino oscillation implies neu-

trino mass. If, as it now seems, only the three active neutrino flavors are involved in the oscillation of solar neutrinos and of atmospheric neutrinos produced by cosmic rays, then one can deduce a lower limit for the neutrino mass density of the universe. That lower limit, the SNO paper tells us, is about 2% of the cosmic density of ordinary baryonic matter.

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Atoms Hop between Islands of Regular Motion in a Sea of Chaos

We've long since grown used to the idea that atoms in a double potential well can go back and forth between wells, even though classically an atom with insufficient energy is precluded from surmounting the energy barrier between the two compartments. We should not be too surprised then to learn that an atom executing one type of regular motion can suddenly be found to be moving 180° out of phase with its initial motion: At a point in the motion when the atom should be moving to the right, it's seen to be moving to the left. That's the idea behind dynamical tunneling, or the hopping between separate, stable regions in phase space. Although there's been some evidence for dynamical tunneling in molecular systems, it has now been seen very directly in two new experiments on ultracold atoms.^{1,2}

Eric Heller of Harvard University says that the two experiments highlight the dramatic quantum manipulation of ultracold gases that is now possible, and raise new issues in quantum dynamics. Ultracold atomic systems have been used for a number of years to explore the quantum behavior of nonlinear dynamical systems (see the news story in *PHYSICS TODAY*, June 1995, page 18, and the article by Mark Raizen, Christophe Salomon, and Quan Niu in *PHYSICS TODAY*, July 1997, page 30). Whereas many studies are done on systems that are totally chaotic, the two new experiments enter less well-charted territory: a mixed region where both stable motion and chaos are present. One of the new experiments² claims evidence that the chaos has actually

► Collections of ultracold atoms are continuing to prove their worth as systems for studying the interface between quantum behavior and nonlinear dynamics.

facilitated the dynamical tunneling.

Dynamical tunneling was demonstrated in a Bose-Einstein condensate (BEC) by William Phillips and his coworkers at NIST in Gaithersburg, Maryland, in collaboration with Halina Rubinsztein-Dunlop, Gerard Milburn, and their colleagues at the University of Queensland in Brisbane, Australia.¹ It was also seen in a

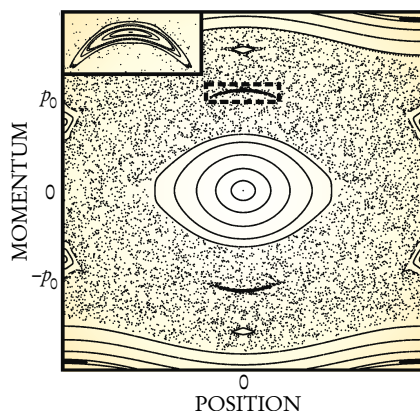


FIGURE 1. PHASE-SPACE DIAGRAM of momentum p versus position q shows islands of stable motion (elliptical curves) in a sea of chaos (dots). Diagram is a stroboscopic sampling of atoms in a periodic, modulated system. Dynamic tunneling takes a system from the island near $+p_0$ (enlarged in the inset) to the bottom island near $-p_0$. (Figure adapted from ref. 1.)

system of ultracold atoms by Raizen and his group at the University of Texas at Austin.² (Tunneling of a BEC through an energy barrier was already seen several years ago.³)

Symmetric modes

In each of the new experiments, the ultracold atoms, all having nearly identical momenta, were placed in a one-dimensional optical lattice; such a lattice essentially provides a washboardlike energy potential. The heights of the potential walls were temporally modulated in a periodic way. In the NIST-Queensland experiment, the height was varied between finite values so that atoms in the BEC sloshed back and forth within each well. In the Texas experiment, the walls were periodically driven to zero, so that the atoms could skim over them, moving like a traveling wave consistently either to the right or to the left.

The two research groups always sampled the momenta of the atoms at the same point in their periodic motion. That way, the atoms were expected to be always moving with the same velocity. The NIST-Queensland experimenters, for example, sampled the momenta when the atoms were in the lowest part of their swing. Even when the atoms started out moving, say, from left to right, the researchers found that, after a certain number of modulation periods, the atoms were found to be going from right to left, signaling a 180° shift in the motion. The atoms shifted from right-going to left-going motions at regular intervals.

Both left-moving and right-moving