

Scintillator yields glimpse of elusive solar neutrinos

The low-energy neutrinos are byproducts of the first reaction in a chain that generates 99% of the Sun's energy.

Virtually everything we know about the Sun has been gleaned from the light it emits. Images collected at various wavelengths provide clues to its composition, magnetic field dynamics, subsurface flows, and more. (See the articles in *PHYSICS TODAY* by Eugene Parker, June 2000, page 26, and by Gordon Holman, April 2012, page 56.)

To glimpse directly into the Sun's opaque core, however, one needs to look not for photons but for neutrinos. Both are products of the fusion of protons into helium-4, the multistep process that powers our parent star. But photons scatter in the Sun's core for tens of thousands of years before escaping. By the time we see them, they retain little history of their origins. Because neutrinos interact weakly with matter, they escape almost immediately. From their flux and energy, one can deduce rates of reactions occurring in the core.

The most energetic neutrinos emanating from the solar core are born of boron-8 decays. With energies of up to 14 MeV, those neutrinos can be identified by the Cherenkov radiation that's emitted as they scatter off electrons in a water tank or by the inverse beta decays they instigate in radiochemical detectors. (See *PHYSICS TODAY*, August 2001, page 13.) All told, however, ^8B neutrinos make up just a fraction of a percent of all solar neutrinos. Detecting the rest has proved a formidable task; the lower a neutrino's energy, the more easily it is drowned out by background noise from naturally occurring radioactivity.

For the past two decades, researchers at the Borexino detector at Italy's Gran Sasso National Laboratory have been meticulously engineering a low-background environment in which low-energy breeds of solar neutrinos might be detected. In recent years they've detected the roughly 1-MeV neutrinos generated during the decay of beryllium-7 and during rare proton-electron-proton (pep) reactions.¹ Now they've measured the spectral flux of the Sun's least energetic neutrinos:² so-called pp neutrinos, which are emitted when two protons combine to form deuterium and have an upper energy limit of around

400 keV. The measurements fill in one of the last and by far biggest pieces of the solar-neutrino puzzle—pp neutrinos account for about 90% of the Sun's total neutrino flux.

Noise reduction

About 99% of the fusion in the solar core occurs by way of the proton-proton chain of reactions; the rest occurs via the CNO chain, a secondary pathway mediated by carbon, nitrogen, and oxygen. More than 99% of the time, the proton-proton chain is instigated by the reaction that begets pp neutrinos. In essence, that reaction sets the rate of solar energy generation.

Technically, pp neutrinos have been detected before. In the 1990s, two groups—one working at the SAGE detector in the Russian Caucasus and another at the Gallex detector, Borexino's predecessor at Gran Sasso—detected the elusive neutrinos in vats of liquid gallium. In those experiments, incoming neutrinos having energy greater than about 230 keV can signal their

presence by converting gallium atoms to germanium ones; the flux is then inferred by tallying the Ge atoms that accumulate during an experimental run. (See the article by John Bahcall, Frank Calaprice, Arthur McDonald, and Yoji Totsuka, *PHYSICS TODAY*, July 1996, page 30.)

"But the gallium measurements are like long-exposure, black-and-white photographs," explains Josh Klein (University of Pennsylvania), who wasn't affiliated with the Borexino study. "They don't provide spectral information." And without that information, one can't readily distinguish pp neutrinos from their more energetic cousins.

By contrast, the Borexino group detects neutrinos in real time using the scintillator detector pictured in figure 1. An incoming neutrino that scatters off one of the scintillator's electrons is heralded by a burst of light, which is detected by photomultiplier tubes. The brightness of the burst gives the neutrino's energy.

The researchers used a suite of measures to protect their detector from ambient radioactivity: The underground detector is shielded from cosmic rays by more than 1 km of overlying rock; the

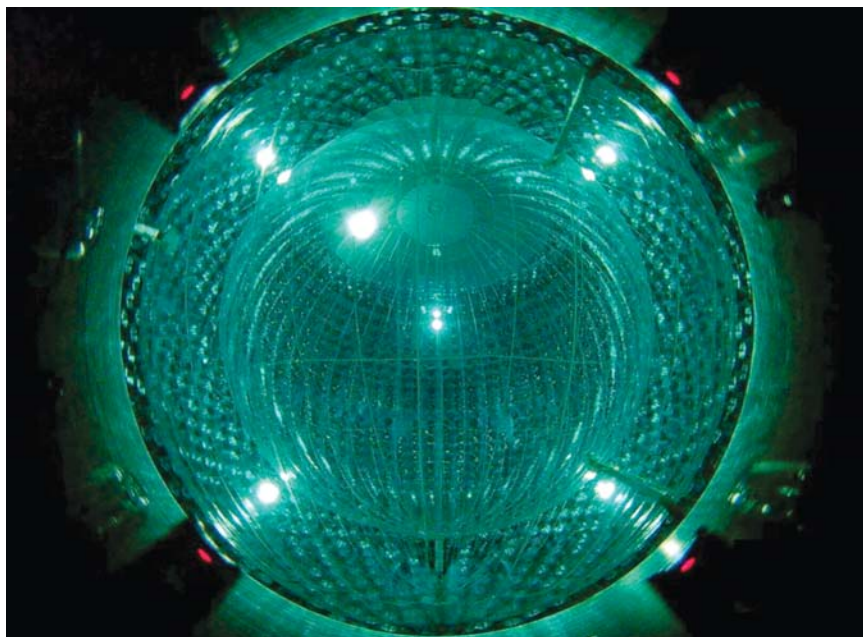


Figure 1. At the Borexino detector, pictured here, solar neutrinos are detected in a 14-m-tall sphere filled with 278 tons of liquid scintillator. Incident neutrinos are heralded by bursts of light emitted as they scatter off the scintillator's electrons. (Photo courtesy of the Borexino collaboration.)

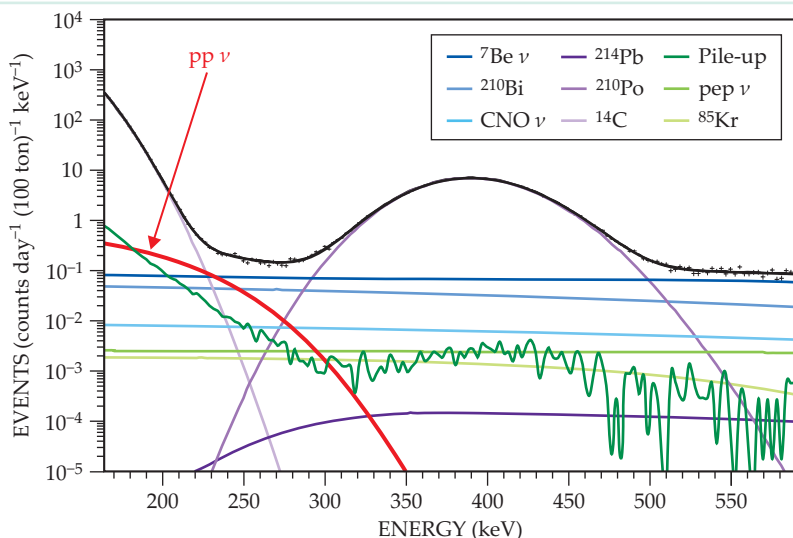


Figure 2. The signal and the noise. The spectral flux of pp solar neutrinos (pp ν), byproducts of proton-proton fusion in the Sun's core, is obtained from the total neutrino flux (black crosses) by subtracting background contributions from naturally occurring radionuclides (lead-214, polonium-210, carbon-14, bismuth-210, and krypton-85), other solar neutrino breeds (from beryllium-7 decay, proton-electron-proton fusion, and the carbon-nitrogen-oxygen cycle), and pile-up—instances where two successive events, usually from ^{14}C , are detected as a single count. The black curve is a fit to the data. (Adapted from ref. 2.)

scintillator itself is immersed in a water buffer, to protect it from radioactive elements in the surrounding metal tank and equipment.

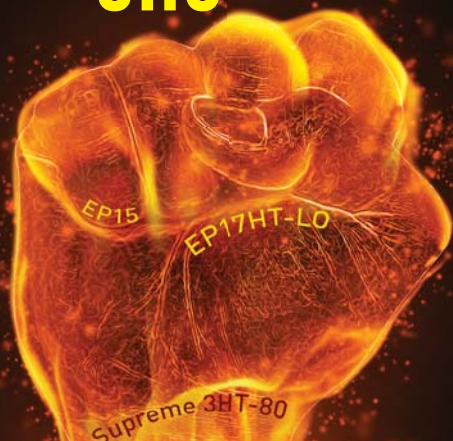
At the low energies of pp neutrinos, however, even trace amounts of radionuclides in the liquid scintillator itself can be ruinous. To sufficiently purify the

oil-based scintillator, the group used distillation, extraction, and filtration methods borrowed from petroleum engineering.³ “We essentially built a plant that could take fluid out of the detector and recirculate it, and we kept purifying it as we went,” says Frank Calaprice (Princeton University), of the Borexino collaboration. “We’re still pushing the background down.”

Between January 2012 and May 2013, Borexino registered more than 300 000 neutrino scattering events in the 150–600 keV range, as shown in figure 2. A significant share was attributable to naturally occurring radionuclides, but those background contributions could be tightly constrained using statistical models. Likewise, contributions from low-energy ^7Be and pep neutrinos could be inferred from those neutrinos' spectral line shapes, determined in the previous measurements at higher energies. Only the contribution from CNO neutrinos had to be assumed theoretically. But because that flux is relatively small and spectrally flat, the assumption doesn't introduce much systematic error.

The pp neutrino spectrum that remains after correcting for the background falls off sharply near 300 keV, as expected. The total integrated flux,

the power of
one



Benefits of One Component Epoxy Adhesive Systems:

- No mix compounds
- Fast cures with heat
- High bond strength
- Easy application

MASTERBOND

Hackensack, NJ 07601 USA • +1.201.343.8983 • main@masterbond.com
www.masterbond.com

Download
white paper on
One Part Epoxies



**Connect, Move,
Illuminate... in
Vacuum**

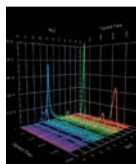
Subminiature-D
Thermocouple
Fiber Optic
In-Vacuum Wiring
Motion & Manipulation

Accu-Glass Products, Inc.



818-365-4215 www.accuglassproducts.com

QGA



Mass Spectrometers for Gas Analysis

- ▶ Fast data acquisition > 500 measurements/sec
- ▶ Fast response time to 150 ms
- ▶ Species molecular weight range to 200, 300 or 500 amu. Up to 1000 amu for specialist applications
- ▶ Multiple gases & vapors



NEW

COMPACT SIMS

New affordable Compact SIMS instrument

for depth profile & interface analysis.

- ▶ Small footprint
- ▶ Positive SIMS and SNMS
- ▶ Depth Profiling
- ▶ 3D characterisation and imaging
- ▶ Isotopic analysis
- ▶ Analysis on the nanometre scale

Designed for:

- ▶ Solar cells
- ▶ Glass coatings
- ▶ Metallic thin films



for further details of Hiden Analytical products contact:

HidenAnalytical.com

E info@hideninc.com

T +1 734 542 6666

Meet us at AVS—Baltimore—Booth 311

$(6.6 \pm 0.7) \times 10^{14} \text{ m}^{-2} \text{ s}^{-1}$, agrees with the value obtained when the standard solar model is constrained by observed solar luminosities.

The composition question

With its latest measurements, the Borexino group has now characterized the spectral fluxes of every breed of neutrino generated in the proton-proton chain. The ultimate promise of the Borexino detector, however, may lie in what it can tell us about the CNO chain. At present, the heavy elements that mediate that pathway are a source of controversy: Optical measurements of their concentrations find values roughly 30% smaller than those obtained from helioseismology.

One tantalizing possibility is that neither technique is in error. Since optical measurements probe the Sun's surface, and helioseismology probes its interior, "the discrepancy might be telling us that a fundamental assumption of

the standard solar model—that the star has a uniform composition—is just wrong," Calaprice says.

Forthcoming high-precision measurements at Borexino, at the SNO+ detector in Canada, and at the proposed CLEAN and LENS experiments may help settle the debate. Each experiment aims to tally the flux of CNO neutrinos, from which one could infer the abundance of heavy elements in the core. If the Borexino group is to see those neutrinos, however, they'll need to reduce their background levels by at least a factor of four. Says Calaprice, "That's our next goal."

Ashley G. Smart

References

1. G. Bellini et al. (Borexino collaboration), *Phys. Rev. Lett.* **107**, 141302 (2011); *Phys. Rev. Lett.* **108**, 051302 (2012).
2. G. Bellini et al. (Borexino collaboration), *Nature* **512**, 383 (2014).
3. J. Benziger et al., *Nucl. Instrum. Methods Phys. Res. A* **587**, 277 (2008).

Europa may host a system of tectonic plates

Investigating Jupiter's enigmatic moon requires revisiting images more than a decade old. A new result suggests they haven't yet given up all their secrets.

In the 11 years since the *Galileo* spacecraft transmitted its last pictures of Jupiter and its satellites, those who study the icy Jovian moon Europa have been left with a puzzle. Pieces of the European crust appear to have cracked and drifted apart over time, with new regions of pristine water-ice crust forming in the gaps. Those so-called dilational bands make up tens of percent of the total surface area. And the paucity of craters on Europa's nearly unblemished face suggests that the whole surface has been recycled over the past 40 million to 90 million years, just 1–2% of the moon's age.

And yet there was no clear sign of any process capable of consuming surface area at the same rate as it's produced. Europa as a whole is not getting any bigger. So where is the extra surface going?

Simon Kattenhorn (formerly of the University of Idaho) and Louise Prockter (of the Johns Hopkins University's Applied Physics Laboratory) think they might have the answer.¹ By reanalyzing an old *Galileo* image of a 134 000-km² region, slightly less than 0.5% of the total surface, they make the case that Europa's crust, at least in that region, is made up

of tectonic plates similar to those on Earth. To satisfy the definition of a plate-tectonic system, the researchers found that not only do the plates drift apart and slide alongside each other, they also subduct, or move underneath one another. If subduction turns out to occur across its surface, Europa would be the first body other than Earth known to have tectonic plates.

Dilation without contraction

The idea of European plate tectonics pre-dates *Galileo* by more than a decade. In 1979 the two *Voyager* spacecraft sped by Jupiter and offered the first good look at the Jovian satellites. The *Voyager* images of Europa, taken from a distance of a few hundred thousand kilometers, showed the moon's surface to be crisscrossed by dark lines and bands. The following year Paul Schenk, then an undergraduate student working with Carl Seyfert Jr at Buffalo State College, spotted a curious property of the images. When narrow linear features passed across certain dark bands, they didn't perfectly line up. Features on one side of a band were shifted with respect to those on the other. But when the area of