Borexino experiment detects neutrinos from the Sun's carbon-nitrogen-oxygen cycle

The cycle's catalytic reactions account for just 1% of the Sun's energy, but they are the dominant energy producers in heavier stars.

FIGURE 1. THE BOREXINO NEUTRINO DETECTOR, after being wrapped in an aluminum-reinforced wool blanket in 2014 and after the installation of a temperature control system in 2019. Solar neutrinos are detected in its inner 8.5-meter-wide balloon filled with 280 tons of petroleum-based scintillator liquid. The scintillator emits flashes of light when the neutrinos scatter from its electrons.[2]

In 1920, Arthur Eddington proposed that the Sun shines from the fusion of four protons into helium nuclei. The proposal was inspired by Francis Aston's measurement earlier that year of the mass difference between the four protons and a helium nucleus and by Albert Einstein's revolutionary thesis on the equivalence of mass and energy. Despite those foundations, Eddington's idea faced what was then a reasonable objection: The Sun isn't hot enough to sustain nuclear fusion.

Quantum mechanics was in its infancy at the time. It took eight more years for George Gamow to realize that two protons could overcome their Coulombic repulsion and get close enough to fuse through quantum tunneling. In the late 1930s, Hans Bethe and Carl Friedrich von Weizsäcker, independently, finally deduced the detailed nuclear reactions in which hydrogen in stars is converted into helium: the proton–proton (pp) chain and the carbon-nitrogen-oxygen (CNO) cycle.[1]

The relative importance of those two mechanisms depends mostly on stellar mass and the metallicity—the abundance of elements in the core that are heavier than helium. Hydrogen-burning stars like the Sun sustain themselves by converting four protons into a helium nucleus, with the release of two electron neutrinos and 26.73 MeV. In our Sun, a relatively low-mass star, 99% of helium synthesis occurs through the pp chain. The remaining 1% is made through the CNO cycle, in which the heavier elements carbon, nitrogen, and oxygen (known by astrophysicists as "metals") act as catalysts for hydrogen burning. It depends sensitively on a star's core temperature. Heavier stars have hotter cores, and the CNO cycle is the dominant mechanism in stars significantly heavier than the Sun. Like the pp chain, it releases two neutrinos for each ^{4}He nucleus.

Both sets of neutrinos emerge from the Sun's core and reach Earth in just eight minutes. In their flux—about 60 billion neutrinos per square centimeter per second—and energy distribution they carry a detailed account of the fusion reactions. But with a mean free path of roughly a light-year through rocky matter, neutrinos are exceedingly difficult to detect. Even so, for more than 50 years physicists have been catching glimpses via their weak interactions inside underground detectors made of tons of material. (See the article by John Bahcall, Frank Calaprice, Arthur McDonald, and Yoji Totsuka, PHYSICS TODAY, July 1996, page 30, and PHYSICS TODAY, December 2015, page 16.)

The most energetic solar neutrinos are born from the decay of boron-8. Although scarce, their high energy makes them relatively easy to identify by Cherenkov radiation or inverse beta decay. Others from the pp chain are lowest in energy but most abundant. By contrast, neutrinos from the CNO cycle occupy an elusive middle ground that, for observers, combines the worst of both worlds: They are both scarce and too low in energy to rise above background radioactivity.

But now, the Borexino detector at Italy's Gran Sasso National Laboratory has identified CNO neutrinos for the first time, and a collaboration of nearly 100 scientists have measured their interaction rate at just a handful of counts per day per 100 tons of scintillator.[2] "The measurement is heroic," says Wick Haxton from the University of California, Berkeley. "No one anticipated that Borexino would be able to pull out the CNO signal from the background." The achievement completes the spectroscopy of solar neutrino fluxes and isolates the mechanism that governs the evolution of stars more massive than our Sun.

Purification

Five years ago, the Borexino collaboration began its hunt for CNO neutrinos on the heels of its 2014 measurement of the spectral flux of pp neutrinos (see PHYSICS TODAY, November 2014, page 12). Like the pp neutrinos, the CNO neutrinos register when they scatter from electrons in the scintillator, whose light emission is picked up by photomultiplier tubes surrounding the scintillator tank. From the number of photons and their arrival times, researchers reconstruct the electron recoil energy and interaction point in the detector.

In operation since 2007, the neutrino detector was built with an onionlike structure to achieve the utmost radiopurity at its core. The inner sanctum, an 8.5-meter-diameter nylon balloon containing 280 tons of petroleum-based scintillator, resides inside another balloon filled with a buffer solution—both within a stainless-steel sphere studded with 2212 photomultiplier tubes. That sphere, in turn, is surrounded by a tank filled with 2400 tons of ultrapure water.

Shown in figure 1, the detector lies under 1.4 km of the Apennine Mountains, 120 km east of Rome. The overlying rock and surrounding water shield the detector from cosmic rays. The nylon barriers and buffer solution protect the innermost vessel from external sources of radioactivity and from gammas in the photomultiplier tubes. Besides those measures, the collaboration adapted distillation and filtration methods from petroleum engineering to purify the liquid scintillator.

Unfortunately, the very nature of the scintillation emission makes it impossible to distinguish a signal emitted by neutrino-scattered electrons from one emitted in nuclear beta decays or Compton scattered by γ rays. That means the radioactive background had to be kept at or below the level of the expected signal rate—a few tens of events per ton of scintillator per day. In contrast, materials such as air, water, and metals are usually contaminated with radioactive impurities at levels up to 100 000 decays per ton per second.

The CNO experiment ran from July 2016 to February 2020, with 1072 days of live time. The collaboration filtered the number of events in the detector's 100-ton fiducial volume by applying selection criteria that removed contributions due to impurities, cosmogenic isotopes, and instrumental noise. Figure 2 shows the surviving count rate as a function of energy. The central task for the Borexino collaboration was to disentangle the signals of the CNO-neutrino recoil electron from those of cosmogenic ^{11}C and beta decays in bismuth-210. The collaboration was able to reduce the ^{11}C contributions by looking for their time correlation with cosmic rays, but ^{210}Bi, as part of the decay chain of the pervasive contaminant radon-222, was more insidious.

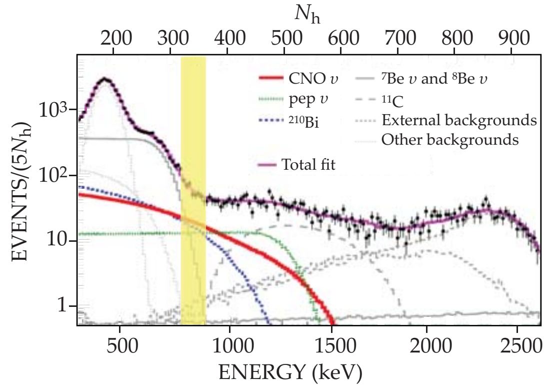

FIGURE 2. THE SPECTRAL FLUX (red) of carbon-nitrogen-oxygen neutrinos from the Sun is the distribution of recoil energies of scattered electrons. That signal is obtained by subtracting background contributions from other solar neutrinos such as proton-electron-proton (pep) neutrinos (dotted green), naturally occurring radionuclides such as bismuth-210 (dashed blue), and other sources of noise (gray). The black dots represent the total signal as a function of energy. N_h represents the number of photoelectrons detected by photomultipliers. The CNO signal is completely hidden in the background; the yellow band represents the region with the largest signal-to-background ratio for CNO neutrinos. (Adapted from ref. 2.)

Temperature stabilization

The energy spectrum of the beta decay from ^{210}Bi is located in nearly the same energy window where the CNO neutrino–electron recoil signal is expected. Fortunately, another isotope, polonium-210, is a daughter of ^{210}Bi and in the same lead decay sequence. Being an alpha emitter, ^{210}Po is much easier to identify, so the collaboration used it as a proxy to study the behavior of ^{210}Bi. The ^{210}Po turns out to contaminate the scintillator by detaching from the wall of the inner nylon balloon. The upshot: The ^{210}Po (and hence ^{210}Bi) couldn't be filtered away as part of the purification campaign.

Nevertheless, the researchers realized that they could effectively ignore the isotopes' presence on the balloon and instead focus on protecting the purity of the fiducial volume inside it, from which signals are selected. That focus required them to eliminate any temperature fluctuations, which might induce convection currents in the scintillator and drive detached ^{210}Bi toward the center. To that end, they wrapped the detector in a wool blanket, shown in figure 1, to insulate it from room air.

The detector also sits on a floor in thermal contact with mountain rock that acts as a deep thermal sink. To stabilize the vertical convection, the researchers attached horizontal heating circuits to the detector. As a final measure, they installed a feedback-control loop in the experiment hall to stabilize the room's temperature against variability from changes in the seasons. The effort paid off: From their observations of ^{210}Po, the researchers inferred the diffusion distance of ^{210}Bi (with a half-life of five days) as less than the separation between the balloon wall and the fiducial volume.

Metallicity

After accounting for other neutrinos and subtracting the background radioactivity caught in the detector, the collaboration converted the handful of observed CNO neutrino interactions per day to derive a total flux of CNO neutrinos on Earth of $7.0^{+3}_{-2} \times 10^8$ cm^{-2} s^{-1}. That result quantifies the relative contribution of CNO fusion in the Sun at about 1%, as predicted by theorists. And because the CNO fusion cycle is catalyzed by reactions with C, N, and O, the neutrino flux depends directly on the abundance of those elements in the solar core.

Two long-established methods for determining the solar metallicity have given discordant results. Helioseismic data suggest that the Sun's interior is metal-rich, whereas photoabsorption measurements of solar surface abundances reveal an environment about 30% lower in metals. According to Frank Calaprice, one of the members of the Borexino collaboration, the newly published value for the flux is not precise enough to resolve the discrepancy, "but newer data taken in the few months since the paper was written lean toward a more metal-rich solar core."

According to Haxton, one explanation for the discrepancy may come from the effect of planetary formation on the early Sun. Jupiter and Saturn are both enriched in C and N by factors of 4 to 7 relative to the Sun's surface. Late in the evolution of the solar system, those planets are likely to have stripped as much as 90 Earth masses of metal from the remaining gas in the planetary disk. The late accretion of metal-depleted gas onto the Sun's chemically isolated convective zone could dilute the outer portion of the Sun.[3] Indeed, volatile elements such as C appear depleted in the accreting gas streams of very young, planet-forming systems.[4]

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References

1. H. A. Bethe, *Phys. Rev.* **55**, 434 (1939); C. F. von Weizsäcker, *Phys. Z.* **38**, 176 (1937).
2. Borexino collaboration, *Nature* **587**, 577 (2020).
3. W. C. Haxton, A. M. Serenelli, *Astrophys. J.* **687**, 678 (2008).
4. M. K. McClure, *Astron. Astrophys.* **632**, A32 (2019).

Stretchy molecules rupture far from the crack

Newly observed molecular consequences of fracturing in an elastic sheet reveal some surprises.

FIGURE 1. IN THE BLINK OF AN EYE, a single pinprick can prompt an inflated balloon (shown here filled with water) to tear itself to shreds: The energy stored in the stretched latex is more than enough to power the rapidly propagating cracks. When less energy is available, damage in an elastic solid develops more slowly. The molecular details of material failure are key to how the process plays out. (Image by Jose Luis Stephens/Shutterstock.com.)

Anyone who's ever stuck a pin into a balloon knows well what happens next: The tiny puncture swiftly grows into one or more fractures that propagate across the balloon's surface. Captured by high-speed photography, as shown in figure 1, the phenomenon is spectacular.

Inflated balloons store so much energy in their stretched latex that they invariably burst when pierced. But elastic material failure isn't always so certain. Car tires, soft medical implants, and O-ring seals all routinely experience stresses and strains that may or may not be enough to cause them to rupture. The safe use of elastic materials depends on understanding just how much deformation they can withstand before they break. In other words, how much energy does it take to propagate a crack in a stretchy substance?

That complicated problem involves physics on multiple size scales, from the macroscopic bulk down to individual molecules. For decades, models that seek to span those scales have been stymied by a dearth of information. After all, it's not possible to just zoom in with a microscope to see what the molecules are doing.

Or is it? Costantino Creton of ESPCI Paris, his recently graduated PhD student Juliette Slootman, and their colleagues have now reported an unprecedented look at the molecular-scale damage in a fractured elastic material.[1] Their experiment relies on new molecules, recently developed by coauthor Robert Göstl, that become fluorescent when ripped apart. The researchers find that many more molecular bonds are broken than anticipated—not just on the newly torn edge but tens of microns away.

Rubber theory

The leading model of fracture in elastic materials stems from a 1967 theory by Graham Lake and Alan Thomas,[2] two scientists from the UK-based Natural Rubber Producers' Research Association. The organization was founded in 1938 to better understand a major cash crop of what were then the British colonies of Southeast Asia. Today it's wholly owned by the Malaysian Rubber Board and has been renamed the Tun Abdul Razak Research Centre after Malaysia's second prime minister.

Rubber, as Lake and Thomas knew, is made of a random tangle of polymer chains. What makes it a stretchy solid rather than a goopy liquid are the chemical cross-links that bind the chains together where they touch. To break a solid piece of rubber in two, all the covalent bonds that connect atoms on opposite sides of the fracture plane must be severed.

But simply adding up the dissociation energies of all those bonds gives a value far smaller than the experimentally measured energy required to propagate a crack in the material. Lake and Thomas's in-