Massive underground instrument finds final secret of our sun's fusion

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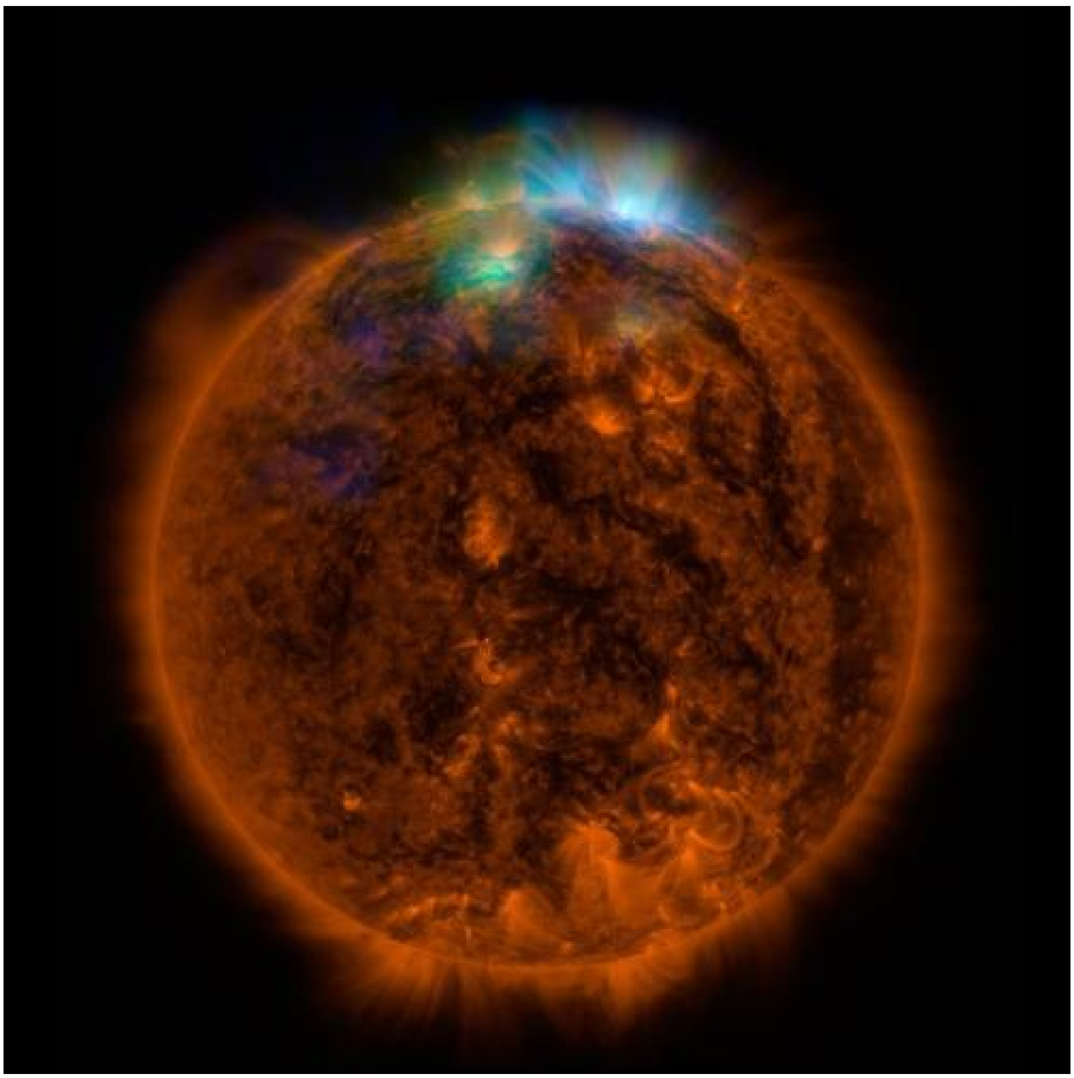

X-rays stream off the sun in this image showing observations from by NASA's Nuclear Spectroscopic Telescope Array, or NuSTAR, overlaid on a picture taken by NASA's Solar Dynamics Observatory (SDO). Credit: NASA

A hyper-sensitive instrument, deep underground in Italy, has finally succeeded at the nearly impossible task of detecting CNO neutrinos (tiny particles pointing to the presence of carbon, nitrogen and oxygen) from our sun's core. These little-known particles reveal the last missing detail of the fusion cycle powering our sun and other stars.

In results published Nov. 26 in the journal *Nature* (and featured on the cover), investigators of the Borexino collaboration report the first detections of this rare type of neutrinos, called "ghost particles" because they pass through most matter without leaving a trace.

The neutrinos were detected by the Borexino detector, an enormous underground experiment in central Italy. The multinational project is supported in the United States by the National Science Foundation under a shared grant overseen by Frank Calaprice, professor of physics emeritus at Princeton; Andrea Pocar, a 2003 graduate alumna of Princeton and professor of physics at the University of Massachusetts-Amherst; and Bruce Vogelaar, professor of physics at the Virginia Polytechnical Institute and State University (Virginia Tech).

The "ghost particle" detection confirms predictions from the 1930s that some of our sun's energy is generated by a chain of reactions involving carbon, nitrogen and oxygen (CNO). This reaction produces less than 1% of the sun's energy, but it is thought to be the primary energy source in larger stars. This process releases two neutrinos—the lightest known elementary particles of matter—as well as other subatomic particles and energy. The more abundant process for hydrogen-to-helium fusion also releases neutrinos, but their spectral signatures are different, allowing scientists to distinguish between them.

"Confirmation of CNO burning in our sun, where it operates at only a 1% level, reinforces our confidence that we understand how stars work," said Calaprice, one of the originators of and principal investigators for

Borexino.

CNO neutrinos: Windows into the sun

For much of their life, stars get energy by fusing hydrogen into helium. In stars like our sun, this predominantly happens through proton-proton chains. However, in heavier and hotter stars, carbon and nitrogen catalyze hydrogen burning and release CNO neutrinos. Finding any neutrinos helps us peer into the workings deep inside the sun's interior; when the Borexino detector discovered proton-proton neutrinos, the news lit up the scientific world.

But CNO neutrinos not only confirm that the CNO process is at work within the sun, they can also help resolve an important open question in stellar physics: how much of the sun's interior is made up of "metals," which astrophysicists define as any elements heavier than hydrogen or helium, and whether the "metallicity" of the core matches that of the sun's surface or outer layers.

Unfortunately, neutrinos are exceedingly difficult to measure. More than 400 billion of them hit every square inch of the Earth's surface every second, yet virtually all of these "ghost particles" pass through the entire planet without interacting with anything, forcing scientists to utilize very large and very carefully protected instruments to detect them.

The Borexino detector lies half a mile beneath the Apennine Mountains in central Italy, at the Laboratori Nazionali del Gran Sasso (LNGS) of Italy's National Institute for Nuclear Physics, where a giant nylon balloon—some 30 feet across—filled with 300 tons of ultra-pure liquid hydrocarbons is held in a multi-layer spherical chamber that is immersed in water. A tiny fraction of the neutrinos that pass through the planet will bounce off electrons in these hydrocarbons, producing flashes of light that can be detected by photon sensors lining the water tank. The great depth, size and purity makes Borexino a truly unique detector for this type of science.

The Borexino project was initiated in the early 1990s by a group of physicists led by Calaprice, Gianpaolo Bellini at the University of Milan, and the late Raju Raghavan (then at Bell Labs). Over the past 30 years, researchers around the world have contributed to finding the proton-proton chain of neutrinos and, about five years ago, the team started the hunt for the CNO neutrinos.

Suppressing the background

"The past 30 years have been about suppressing the radioactive background," Calaprice said.

Most of the neutrinos detected by Borexino are proton-proton neutrinos, but a few are recognizably CNO neutrinos. Unfortunately, CNO neutrinos resemble particles produced by the radioactive decay of polonium-210, an isotope leaking from the gigantic nylon balloon. Separating the sun's neutrinos from the polonium contamination required a painstaking effort, led by Princeton scientists, that began in 2014. Since the radiation couldn't be prevented from leaking out of the balloon, the scientists found another solution: ignore signals from the contaminated outer edge of the sphere and protect the deep interior of the balloon. That required them to dramatically slow the rate of fluid movement within the balloon. Most fluid flow is driven by heat differences, so the U.S. team worked to achieve a very stable temperature profile for the tank and hydrocarbons, to make the fluid as still as possible. The temperature was precisely mapped by an array of temperature probes installed by the Virginia Tech group, led by Vogelaar.

"If this motion could be reduced enough, we could then observe the expected five or so low-energy recoils per day that are due to CNO neutrinos," Calaprice said. "For reference, a cubic foot of 'fresh air'—which is a thousand times less dense than the hydrocarbon fluid—experiences about 100,000 radioactive decays per day, mostly from radon gas."

To ensure stillness within the fluid, Princeton and Virginia Tech scientists and engineers developed hardware to insulate the detector—essentially a giant blanket to wrap around it—in 2014 and 2015, then they added three heating circuits that maintain a perfectly stable temperature. Those succeeded in controlling the temperature of the detector, but seasonal temperature changes in Hall C, where Borexino is located, still caused tiny fluid currents to persist, obscuring the CNO signal.

So two Princeton engineers, Antonio Di Ludovico and Lidio Pietrofaccia, worked with LNGS staff engineer Graziano Panella to create a special air handling system that maintains a stable air temperature in Hall C. The Active Temperature Control System (ATCS), developed at the end of 2019, finally produced enough thermal stability outside and inside the balloon to quiet the currents inside the detector, finally keeping the contaminating isotopes from being carried from the balloon walls into the detector's core.

The effort paid off.

"The elimination of this radioactive background created a low background region of Borexino that made the measurement of CNO neutrinos possible," Calaprice said.

"The data is getting better and better"

Before the CNO neutrino discovery, the lab had planned to end Borexino operations at the close of 2020. Now, it appears that data gathering could extend into 2021.

The volume of still hydrocarbons at the heart of the Borexino detector has continued to grow in size since February 2020, when the data for the *Nature* paper was collected. That means that, beyond revealing the CNO neutrinos that are the subject of this week's *Nature* article, there is now a potential to help resolve the "metallicity" problem as well—the question of whether the core, outer layers and surface of the sun all have the same concentration of elements heavier than helium or hydrogen.

"We have continued collecting data, as the central purity has continued to improve, making a new result focused on the metallicity a real possibility," Calaprice said. "Not only are we still collecting data, but the data is getting better and better."

More information: , Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun, *Nature* (2020). DOI: 10.1038/s41586-020-2934-0

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