Solar neutrinos are copiously produced by hydrogen fusion reactions in the Sun’s core. Therefore, they are the direct evidence that the Sun is powered by nuclear reactions. Measurements of solar neutrinos have provided information about the temperature and density of the solar interior, but uncertainties remain about the chemical ingredients. Now the Borexino Collaboration reports a new measurement of the neutrino flux produced by the so-called CNO hydrogen burning cycle in the Sun [1]. This cycle—which requires the presence of carbon (C), nitrogen (N), and oxygen (O)—produces neutrinos that carry enormous diagnostic power relating to the properties of the solar interior. By measuring these neutrinos, the collaboration provides a precious piece of information about the elemental makeup of the Sun, bringing us closer to resolving a controversy that has plagued solar physics for over 20 years [2].

Stars spend about 90% of their lifetimes fusing hydrogen into helium, producing two neutrinos in the process. The pp chain—or proton–proton chain—and CNO cycle are the two fundamental modes by which stellar fusion occurs. Whether a star is dominated by the pp chain or the CNO cycle depends on its core temperature, which is primarily determined by the mass of the star. In the Sun and similar low-mass stars, the pp chain generates almost all the nuclear energy; the CNO cycle is the main power source for more massive stars. The pp chain is a series of nuclear reactions that require no additional nuclei besides hydrogen as fuel. By contrast, the CNO cycle relies on the presence of C, N, and O nuclei as catalysts in the production of helium (Fig. 1). In the Sun, this catalytic process introduces a linear dependence between the amount of C, N, and O and the flux of CNO neutrinos. Thus, CNO neutrinos are a powerful tool for probing the chemical composition in the Sun’s core.

Knowing the Sun’s chemical composition is important not just...
for solar physics but for all of astronomy, as the solar
abundances for different elements provide a “chemical ruler”
for measuring the elemental abundances in other stars and gas
clouds [3]. There has, however, been a long-standing
controversy surrounding the solar abundances. The main
technique for measuring the Sun’s chemical composition is
observing absorption lines in the solar spectrum. Early
spectroscopic studies found relatively high levels of key
elements such as C, N, and O, but in the early 2000s advanced
techniques began to measure abundances that were 30 to 40%
lower than the preliminary estimates. When these lower
abundance values are used as inputs for the standard solar
model (SSM)—the physical framework for calculating the Sun’s
structure and evolution—the predictions strongly disagree with
helioseismology measurements of the Sun’s interior structure
[4]. On the other hand, the older solar abundances—which are
based on simplistic and outdated modeling—lead to SSM
predictions that are remarkably in-line with helioseismology
data [5].

This 20-year-old paradox, dubbed the solar abundance
problem, has defied a satisfactory solution. The most recent
spectroscopic measurements seem to be moving toward better
agreement with the helioseismology observations [6].
Nevertheless, the solar physics community has long been on
the lookout for an independent way to measure the chemical
abundance of the Sun. And it is here where neutrinos and the
new Borexino results come into play.

Located deep underground in Italy’s Gran Sasso National
Laboratory, the Borexino Collaboration measures the energy
spectrum of the solar neutrino flux down to very low energies
(around 100 keV) and separates the individual contributions
originating from different nuclear reactions in the Sun’s core.
From its analysis of data from the experiment’s final phase III
(January 2017 to October 2021), the collaboration estimated
4.8 counts per day of CNO neutrinos in the detector’s volume of
71.3 tons. The collaboration previously reported a detection of
CNO neutrinos in 2020 [7] but have now reduced the
measurement errors by a factor of 2, allowing the team to make
inferences about solar abundances.

The CNO flux measurement can be turned into a measurement
of C plus N abundances by including measurements of another
neutrino flux: that from boron-8 decay, which strongly depends
on temperature [8]. The collaboration used this flux to constrain
the Sun’s core temperature to a precision of about 0.1%. The
team applied this temperature to the relation between the CNO
flux and the C, N, and O abundances, arriving at the first-ever
measurement of chemical abundances in the Sun’s core.
Relying only on neutrino measurements, this methodology
offers a truly independent determination of the solar
composition against which spectroscopic determinations, new
and old, can be checked. The results strongly favor the Sun
having high C, N, and O abundances, contrary to the estimates
from modern, state-of-the-art spectroscopic studies (with the
exception of E. Magg et al. [6]).

The discrepancy between the core abundances estimated by
Borexino and the surface abundances measured by
spectroscopic studies may imply that the Sun’s chemical
composition varies with depth. Such a nonuniform distribution
elements could be explained, for example, by the Sun having
formed in an inhomogeneous environment, or by the Sun’s
outer layers having been enriched in certain elements by
accretion of planetary material [9, 10].

Testing these hypotheses will require more refined
CNO-neutrino measurements. Sadly, Borexino shut down in
2021, and there is currently no experiment that can observe
solar neutrinos at low enough energies. Borexino has, however,
left us with an impressive legacy, as its measurements of the
CNO flux and other solar neutrino signals represent landmarks
for future neutrino experiments. The Borexino team developed
technologies, particularly in radioactive purification, that are
and will be of great benefit for other experiments, such as the
SNO+ neutrino experiment in Canada. The collaboration also
developed data-analysis techniques for background subtraction
that will certainly find future applications in neutrino studies as
well as dark matter searches. There are no plans yet for a
dedicated solar neutrino experiment, but if one were to be built
using the expertise acquired by Borexino, it would have a bright
future and would provide invaluable information about the Sun.

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REFERENCES
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