NEWS & VIEWS

SOLAR PHYSICS

# A window onto the Sun's core

**An experiment has measured the energy spectrum of solar neutrinos associated with 99% of the nuclear reactions that power the Sun. The results provide a glimpse into the depths of the solar core.** SEE ARTICLE P.505

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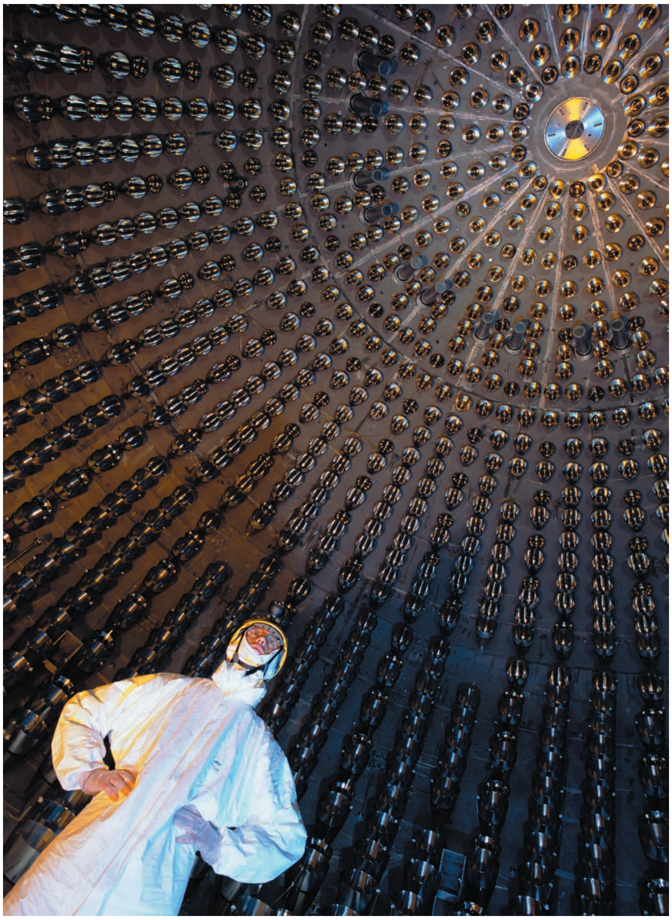
Energy is generated in the interior of the Sun through sequences of nuclear reactions in which four protons fuse together to form a helium-4 nucleus. These sequences are accompanied by the release of two particles known as electron neutrinos. Models suggest that 99% of the nuclear energy released by the Sun originates from three reaction sequences — collectively known as the proton–proton (*pp*) chain — that are initiated by the fusion of two protons. On page 505, the Borexino Collaboration[1] reports the first complete measurement of neutrino fluxes that originate from these three sequences, based on an analysis of more than 2,000 days of data collection. The results help us to understand the details of how and why the Sun shines.



VOLKER STEGER/SPL

**Figure 1 | The Borexino experiment, Gran Sasso, Italy.** A researcher stands in a spherical vessel that forms part of the Borexino neutrino detector. The Borexino Collaboration[1] has used the detector to produce the first simultaneous measurement of the neutrino fluxes associated with the nuclear reactions that account for 99% of the Sun's energy.

Neutrinos interact weakly with matter, and therefore escape almost unhindered from the Sun's interior, to reach Earth about eight minutes later. Solar neutrinos therefore provide a direct view into the nuclear furnace in the Sun's core. The Borexino experiment (Fig. 1) detects such neutrinos and determines how much energy they have by measuring the amount of light produced when the particles interact with the detecting agent (an organic liquid, called the scintillator, which is kept underground to minimize the amount of background radiation that can interfere with the neutrino signals). In contrast to all other solar-neutrino experiments, Borexino can measure the energies of both high- and low-energy neutrinos, which makes it possible to study the structure of the solar core using a technique known as neutrino spectroscopy.

Electron neutrinos can change into two other types (or flavours) of neutrino, known as tau and muon neutrinos, as they travel to Earth, a phenomenon known as flavour oscillation. The Borexino experiment is more sensitive to electron neutrinos than to tau or muon neutrinos, and so flavour oscillation needs to be accounted for when the measured neutrino fluxes are used to calculate the fluxes produced in the Sun. Taking this into consideration, the Borexino collaborators used the measured neutrino flux to work out the total power generated by nuclear reactions in the Sun's core, with an uncertainty of about 10%, and found that this is the same as the measured photon output — thus showing that nuclear fusion is indeed the source of energy in the Sun. This value, calculated for the amount of energy produced through nuclear reactions, is comparable with previous[2] results obtained by combining data from several neutrino-detection experiments, and places the most robust and model-independent constraints on the source of solar energy.

The findings also have interesting ramifications for neutrino physics. By combining their data with predictions from standard solar models, the collaborators determine a quantity known as the electron neutrino survival probability (which describes the probability that an electron neutrino created in the Sun will also be detected as an electron neutrino at the detector) for neutrinos produced in four reactions of the *pp* chain. The calculated survival probabilities include the best available value for low-energy neutrinos, which correspond to an energy regime in which flavour oscillation is expected to occur mostly in vacuum conditions. Combined with the survival probabilities determined for higher-energy neutrinos, the findings give strong support to our current understanding[3,4] of neutrino oscillations — that is, the idea that low-energy neutrinos change flavour as they propagate through a vacuum, and that the oscillations of high-energy neutrinos are enhanced by their interactions with electrons.

The new results also shed light on a long-standing paradox in solar physics, which arises because the chemical composition of the Sun is not well established. The most-recent complete spectroscopic determinations of the Sun's metallicity[5] (the abundance of all solar elements heavier than helium) yielded a value that is 35% lower than older spectroscopic results[6]. Intriguingly, when numerical models of the solar interior are constructed using the lower value of metallicity as a constraint, the simulated properties are at odds with our knowledge of the Sun's interior structure (which is well characterized by helioseismological studies[7] that analyse oscillations produced by waves that propagate through the Sun's interior). But when the older (higher) metallicity values are used, the simulations reproduce solar properties very well. This is known as the solar abundance problem, and calls into question the validity of the present models of stellar evolution, or of spectroscopic methods for determining the Sun's composition, or both.

However, the relative contributions of the three different reaction sequences in the *pp*-chain, determined from the Borexino experiment, can be used to infer the temperature in the solar core — a region that is poorly mapped by helioseismological studies. The Borexino findings hint at a core temperature that is consistent with predictions from models that assume high solar metallicity. That said, the results are not yet precise enough to provide a definite answer to the solar abundance problem, because neutrino fluxes predicted by both the high- and low-metallicity solar models are compatible with the new results.

Nevertheless, the Borexino experiment might provide a definite answer in the future. About 1% of the Sun's nuclear energy is produced through chains of nuclear reactions known as CNO cycles[8]. These cycles are catalysed by the presence of carbon, nitrogen and oxygen, and so their efficiency depends linearly on solar metallicity. If the neutrino fluxes associated with CNO cycles could be measured, then the abundances of these elements in the solar core could be determined.

Such measurements have proved difficult at Borexino so far, because of background radiation produced by the radioactive decay of bismuth-210 (which forms from the decay of uranium-238, an isotope present in tiny quantities in all matter in the Solar System). Modifications to the vessel that holds the liquid scintillator have now been made[9] that should address this issue. The detection of CNO neutrinos would not only allow the Sun's metallicity to be determined, but would also provide direct evidence that CNO cycles occur in nature. This is important, because CNO cycles are thought to be the main mechanism by which stars more massive than the Sun generate energy[8].

Another major issue in astrophysics is the proposed existence of non-standard mechanisms for the production or loss of energy in stars[10]. If such a mechanism exists, there will be an imbalance between the solar production rate of nuclear energy and luminosity (the total amount of energy radiated as photons from the Sun's surface). The precision with which the power generated by nuclear reactions in the Sun can be measured would need to be increased tenfold to 1% to allow tests of such non-standard particle physics. Such precision may be out of reach for Borexino, but it might be possible in future large-scale neutrino and dark-matter detectors. ■

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1. The Borexino Collaboration. *Nature* **562**, 505–510 (2018).
2. Bergström, J. *et al. J. High Energ. Phys.* **3**, 132 (2016).
3. Mikheyev, S. P. & Smirnov, A. Y. *Yadernaya Fiz.* **42**, 1441–1448 (1985).
4. Wolfenstein, L. *Phys. Rev. D* **17**, 2369 (1978).
5. Asplund, M., Grevesse, N., Sauval, A. J. & Scott, P. *Annu. Rev. Astron. Astrophys.* **47**, 481–522 (2009).
6. Grevesse, N. & Sauval, A. J. *Space Sci. Rev.* **85**, 161–174 (1998).
7. Basu, S. & Antia, H. M. *Phys. Rep.* **457**, 217–283 (2008).
8. Haxton, W. C., Hamish Robertson, R. G. & Serenelli, A. M. *Annu. Rev. Astron. Astrophys.* **51**, 21–61 (2013).
9. Smirnov, O. Data available at https://doi.org/10.5281/zenodo.1286860 (2018).
10. Raffelt, G. G. *Annu. Rev. Nucl. Particle Sci.* **49**, 163–216 (1999).

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DEVELOPMENTAL BIOLOGY

# How to lose your inheritance

**In developing embryos, molecular and physical differences divide the cells that will form eggs or sperm and those that will form the body. The mouse protein OTX2 directs this decision by blocking reproductive-cell fate.**

DIANA J. LAIRD

In an ultimate act of family planning, the cells destined to contribute to the next generation of an organism are set aside early in embryonic development. It is unclear why primordial germ cells (PGCs), the precursors of eggs and sperm, are established so early in the development of many multicellular organisms. This process of establishing the germ line involves both preventing a non-reproductive-cell (somatic-cell) fate and activating a cellular state known as pluripotency — the ability to give rise to the many different cell types in the body. Understanding how the germ line forms is a key requirement for the goal of generating healthy eggs and sperm *in vitro* for fertility treatment in the clinic. Work in this area has focused mainly on identifying proteins that specify germline fate, but comparatively little is known about why somatic cells do not acquire such a fate. Writing in *Nature*, Zhang *et al.*[1] reveal that the formation of PGCs in mice can be blocked by a protein called OTX2.

In many animals, specification of the germ line operates like a hereditary monarchy in which, like the direct transmission of the crown jewels from one generation to the next, the passage of molecular components in the cytoplasm down the generations determines the cells that will form PGCs. However, some animals, including salamanders, crickets, mice and possibly humans, take a different approach. In the early mouse embryo, designation of the germ line occurs as a result of cells being in the right place at the right time, rather than inheriting the species' crown jewels. In this inductive fate-determination scenario, cells of a cylindrically shaped region of pluripotent cells known as the epiblast are coaxed into adopting a PGC fate by signals from supporting extraembryonic tissues adjacent to the embryo.

In this mode of germline formation, the instructive cues that travel between cells include proteins of the Wnt and BMP families[2]. PGCs normally form at a predictable location in the epiblast (Fig. 1). However, *in vivo* grafting experiments in mouse embryos revealed that cells from elsewhere in the epiblast have the capacity to become PGCs if they are transplanted to that location[3]. The search for the components that drive germline fate in epiblast cells in response to the 'kingmaker' BMP proteins identified the transcription-factor proteins BLIMP1, PRDM14 and AP2γ (refs 4, 5). This trio of proteins not only drives the expression of genes required to make the germ line, but also blocks the expression of genes associated with a somatic-cell fate[4,5].

The process of PGC development can be recapitulated *in vitro,* starting from mouse embryonic stem (ES) cells that can be induced to form epiblast-like cells. If these epiblast-like cells are exposed to BMPs and certain other factors, then as many as 13.5% of the cells form PGCs[6]. However, if such epiblast-like cells are engineered to express BLIMP1, PRDM14 and AP2γ, more than 30% form PGCs without the requirement[4] for BMPs. Yet knowing that a particular pathway can drive the formation of PGCs doesn't answer the questions of whether the default pathway of cellular differentiation in embryonic development is to form germline or somatic cells, or whether all of the cells in the epiblast are equally capable of becoming germline cells. Both matters have implications for our understanding of the evolution of multicellularity, as well as for our ability to generate healthy eggs or sperm from stem cells for clinical applications.