In the core of the Sun, energy is released through sequences of nuclear reactions that convert hydrogen into helium. The primary reaction is thought to be the fusion of two protons with the emission of a low-energy neutrino. These so-called \( pp \) neutrinos constitute nearly the entirety of the solar neutrino flux, vastly outnumbering those emitted in the reactions that follow. Although solar neutrinos from secondary processes have been observed, proving the nuclear origin of the Sun’s energy and contributing to the discovery of neutrino oscillations, those from proton–proton fusion have hitherto eluded direct detection. Here we report spectral observations of \( pp \) neutrinos, demonstrating that about 99 per cent of the power of the Sun, \( 3.84 \times 10^{33} \text{ ergs per second,} \) is generated by the proton–proton fusion process.

We have known for 75 years that the energy generated by stars comes from the fusion of light nuclei into heavier ones. In the Sun, hydrogen is transformed into helium predominantly via the \( pp \) cycle, a chain of reactions releasing 26.73 MeV and electron neutrinos \( \nu_e \), and summarized as

\[
4p \rightarrow ^{4}\text{He} + 2e^+ + 2\nu_e
\]

The cycle begins with the fusion of two protons into a deuteron, which occurs 99.76% of the time by means of the primary reaction

\[
p + p \rightarrow ^2\text{H} + e^+ + \nu_e
\]

Neutrinos produced in this step are referred to as \( pp \) neutrinos. Some of the nuclear reactions that follow also produce neutrinos of various energies. \(^4\text{He}\) may also be formed through the CNO (carbon–nitrogen–oxygen) cycle, which is thought to be predominant in heavy stars, but to produce at most 1% of the Sun’s energy. Present models of the Sun precisely predict the flux and energy distribution of emitted neutrinos (Fig. 1). So far, only the radiochemical gallium experiments (after the first observation by GALLEX and, later, by SAGE) have been sensitive to \( pp \) solar neutrinos \((0 < E < 420 \text{ keV})\). However, by measuring only an integrated flux of all solar electron neutrinos above an energy threshold \((233 \text{ keV})\), the \( pp \) neutrino flux could be extracted only indirectly, by combining the GALLEX and SAGE measurements with those of other experiments.

The Borexino experiment came online in 2007 with high sensitivity to all solar neutrino components, particularly those below 2 MeV (Fig. 1). Borexino has made the first measurement of \(^7\text{Be}\) neutrinos and proton–electron–proton \((pep)\) neutrinos, measured \(^8\text{B}\) neutrinos at a lower energy threshold than other experiments, and set the best available limit on the solar CNO neutrino component. The detection of \( pep \) neutrinos itself indirectly indicates the existence of \( pp \) neutrinos, because the \( p + e^+ + p \rightarrow ^{2}\text{H} + \nu_e \) reaction is a rare \((0.24\%\text{; ref. 6})\) alternative first step of the \( pp \) cycle. Attempts to measure \( pp \) neutrinos directly over the past 30 years (see ref. 20 for a recent review) have been hindered by the inability to sufficiently suppress radioactive backgrounds in this low-energy region. The Borexino detector, which is designed to minimize backgrounds from radioactive isotopes both within, and external to, the liquid scintillator target, made it possible to search for the very low-energy \( pp \) neutrinos. The measured solar \( pp \) neutrino flux is \((6.6 \pm 0.7) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \), in good agreement with the prediction of the standard solar model \((5.98 \times (1 \pm 0.006) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1})\).

The observation of \( pp \) neutrinos provides us with a direct glimpse at the keystone fusion process that keeps the Sun shining and strongly reinforces our theories on the origin of almost the entirety of the Sun’s energy. Their measured flux can also be used to infer the total energy radiated by the Sun, \( 3.84 \times 10^{33} \text{ erg s}^{-1} \). However, because photons produced in the Sun’s core take a very long time (at least a hundred thousand years; ref. 21) to reach the surface, neutrino and optical observations in combination provide experimental confirmation that the Sun has been in thermodynamic equilibrium over such a timescale.

**Searching for \( pp \) neutrinos with Borexino**

The Borexino experiment (Methods) detects solar neutrinos by measuring the energy deposited in the liquid scintillator target by recoiling electrons undergoing neutrino–electron elastic scattering:

\[
v_x + e \rightarrow v_x + e
\]

where \( x \) denotes one of the three neutrino flavours \((e, \mu, \tau)\). The detector is fully described in ref. 22.

The solar neutrino flux reaching the Earth is composed not only of electron neutrinos produced in the nuclear reactions in the Sun, but, owing to the process of flavour oscillations (Methods), also of muon and tau neutrinos. The \( pp \) neutrino energy spectrum extends up to 420 keV, yielding a maximum electron recoil energy of \( E_{\text{max}} = 264 \text{ keV} \) (ref. 23). The expected flux of \( pp \) neutrinos is calculated in the framework of the SSM (Methods). The most recent calculations are those of ref. 9 (other models, such as the one described in ref. 24, give similar results). The predictions for the total flux of \( pp \) neutrinos at Earth\(^7\) range between \( 5.98 \times (1 \pm 0.006) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \), for the high-metallicity model, and \( 6.03 \times (1 \pm 0.006) \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \), for the low-metallicity model. The latest values of the neutrino oscillation parameters\(^25\) are needed to calculate the relative proportions of the three flavours within the solar neutrino flux at Earth. For reference, when combining them with the high-metallicity SSM prediction (assumed throughout this paper unless otherwise specified) and using neutrino–electron scattering cross-sections derived from refs 25, 26 (also P. Langacker and J. Erler, personal communication), we expect the \( pp \) neutrino interaction.
The signal (thick red line), as well as of the other solar neutrino components (the 'fiducial volume': $86\ \text{m}^3$, $75.5\ \text{t}$) are used in the analysis. The fit is done with a software tool developed for previous Borexino measurements and is constructed as follows. Real triggered events without any position reconstruction of pile-up events, are automatically taken into account. The synthetic pile-up is mainly due to the overlap of two $^{14}\text{C}$ events, but includes all possible event combinations, for example $^{14}\text{C}$ with the external background, PMT dark noise or $^{210}\text{Po}$. $^{14}\text{C}$–$^{14}\text{C}$ events dominate the synthetic pile-up spectrum between approximately 160 and 265 keV. The fit to the $^{14}\text{C}$–$^{14}\text{C}$ pile-up analytical shape in this energy region gives a total rate for $^{14}\text{C}$–$^{14}\text{C}$ pile-up events of $154 \pm 10\ \text{c.p.d. per 100 t}$ in the whole spectrum, without threshold.

**Measurement of the $pp$ neutrino flux**

The data used for this analysis were acquired from January 2012 to May 2013 (408 days of data; Borexino Phase 2). This is the purest data set available, and was obtained after an extensive purification campaign that was performed in 2010 and 2011 and reduced, in particular, the content of $^{85}\text{Kr}$ and $^{210}\text{Bi}$ isotopes, which are important backgrounds in the low-energy region.

The $pp$ neutrino flux determination is based on fitting the measured energy spectrum of the selected events in the 165–590 keV energy window with the expected spectra of the signal and background components. The energy scale in units of kiloelectronvolts is determined from the energy spectrum of synthetic pile-up events, automatically taken into account. The synthetic pile-up is mainly due to the overlap of two $^{14}\text{C}$ events, but includes all possible event combinations, for example $^{14}\text{C}$ with the external background, PMT dark noise or $^{210}\text{Po}$. $^{14}\text{C}$–$^{14}\text{C}$ events dominate the synthetic pile-up spectrum between approximately 160 and 265 keV. The fit to the $^{14}\text{C}$–$^{14}\text{C}$ pile-up analytical shape in this energy region gives a total rate for $^{14}\text{C}$–$^{14}\text{C}$ pile-up events of $154 \pm 10\ \text{c.p.d. per 100 t}$ in the whole spectrum, without threshold.

**Figure 1 | Solar neutrino energy spectrum.** The flux (vertical scale) is given in cm$^{-2}$ s$^{-1}$ MeV$^{-1}$ for continuum sources and in cm$^{-2}$ s$^{-1}$ for mono-energetic ones. The quoted uncertainties are from the SSM$^9$.

The solar neutrino signal (red line) is considered, as well as the other solar neutrino components ($^{7}\text{Be}$, pep and CNO), and of the relevant backgrounds ($^{14}\text{C}$, intrinsic to the organic liquid scintillator; its pile-up (see definition below); $^{210}\text{Bi}$, $^{210}\text{Po}$, $^{85}\text{Kr}$ and $^{214}\text{Pb}$), all approximately at the observed rates in the data. The $pp$ neutrino spectral component is clearly distinguished from those of $^{85}\text{Kr}$, $^{210}\text{Bi}$, CNO and $^{7}\text{Be}$, all of which have flat spectral shapes in the energy region of the fit. Most of the $pp$ neutrino events are buried under the vastly more abundant $^{14}\text{C}$, which is a $\beta$-emitter with a Q value of 156 keV. In spite of its tiny isotopic fraction in the Borexino scintillator ($^{14}\text{C}/^{12}\text{C} \approx 2.7 \times 10^{-18}$), $^{14}\text{C}$ $\beta$-decay is responsible for most of the detector triggering rate ($\lesssim 30$ counts s$^{-1}$ at our chosen trigger threshold). The $^{14}\text{C}$ and $pp$ neutrino energy spectra are, however, distinguishable in the energy interval of interest.

The $^{14}\text{C}$ rate was determined independently from the main analysis, by looking at a sample of data in which the event causing the trigger is followed by a second event within the acquisition time window of 16 μs. This second event, which is predominantly due to $^{14}\text{C}$, does not suffer from hardware trigger-threshold effects and can thus be used to study the rate and the spectral shape of this contaminant. We measure a $^{14}\text{C}$ rate of $40 \pm 1\ \text{Bq per 100 t}$. The error accounts for systematic effects due to detector response stability in time, uncertainty in the $^{14}\text{C}$ spectral shape, and fit conditions (Methods).

An important consideration in this analysis were the pile-up events: occurrences of two uncorrelated events so closely in time that they cannot be separated and are measured as a single event. Figure 2 shows the expected pile-up spectral shape, which is similar to that of the $pp$ neutrinos. Fortunately, the pile-up component can be determined independently, using a data-driven method, which we call 'synthetic pile-up' (Methods). This method provides the spectral shape and the rate of the pile-up component, and is constructed as follows. Real triggered events without any selection cuts are artificially overlapped with random data samples. The combined synthetic events are selected and reconstructed using the same procedure applied to the regular data. Thus, some systematic effects, such as the position reconstruction of pile-up events, are automatically taken into account. The synthetic pile-up is mainly due to the overlap of two $^{14}\text{C}$ events, but includes all possible event combinations, for example $^{14}\text{C}$ with the external background, PMT dark noise or $^{210}\text{Po}$. $^{14}\text{C}$–$^{14}\text{C}$ events dominate the synthetic pile-up spectrum between approximately 160 and 265 keV. The fit to the $^{14}\text{C}$–$^{14}\text{C}$ pile-up analytical shape in this energy region gives a total rate for $^{14}\text{C}$–$^{14}\text{C}$ pile-up events of $154 \pm 10\ \text{c.p.d. per 100 t}$ in the whole spectrum, without threshold.

**Figure 2 | Energy spectra for all the solar neutrino and radioactive background components.** All components are obtained from analytical expressions, validated by Monte Carlo simulations, with the exception of the synthetic pile-up, which is constructed from data (see text for details).
and independently fixed in the fit, allowing for a variation consistent with their measured uncertainty. The $^{214}$Pb rate is fixed by the measured rate of fast, time-correlated $^{214}$Bi($\beta$, $^{210}$Po($\gamma$)) coincidences. The scintillator light yield and two energy resolution parameters are left free in the fit. The energy spectrum with the best-fit components is shown in Fig. 3. The corresponding values of the fitted parameters are given in Table 1.

Many fits have been performed with slightly different conditions to estimate the robustness of the analysis procedure. In particular, we varied the energy estimator, the fit energy range, the data selection criteria and the pile-up evaluation method (Methods). The root mean square of the distribution of all the fits is our best estimate of the systematic error (7%). In addition, a systematic uncertainty (2%) due to the nominal fiducial mass determination is added in quadrature; this was obtained from calibration data by comparing the reconstructed and nominal positions of a ($^{222}$Rn–$^{14}$C) radioactive source located near the border of the fiducial volume. Other possible sources of systematic errors, like the dependence of the result on the details of the energy scale definition and on the uncertainties in the $^{14}$C and $^{210}$Bi $\beta$-decay shape factors, were investigated and found to be negligible (Methods). We also verified that varying the pep and CNO neutrino rates within the measured or theoretical uncertainties changed the $pp$ neutrino rate by less than 1%. We finally confirmed that the fit performed without constraining the $^{14}$C rate returns an $^{14}$C value consistent with the one previously measured independently (see above) and does not affect the $pp$ neutrino result. The systematic errors are given in Table 1 for all fitted species.

![Figure 3](image)

Figure 3 | Fit of the energy spectrum between 165 and 590 keV. a. The best-fit $pp$ neutrino component is shown in red, the $^{14}$C background in dark purple and the synthetic pile-up in light purple. The large green peak is $^{210}$Po $\alpha$-decays. $^7$Be (dark blue), pep and CNO (light blue) solar neutrinos, and $^{210}$Bi (orange) are almost flat in this energy region. The values of the parameters (in c.p.d. per 100 t) are in the inset above the figure. b. Residuals. Error bars, 1 $\sigma$.

Table 1 | Results from the fit to the energy spectrum

| Parameter | Rate & statistical error (c.p.d. per 100 t) | Systematic error (c.p.d. per 100 t) |
|-----------|------------------------------------------|-----------------------------------|
| $pp$ neutrino | 144 ± 13 | ±10 |
| $^{87}$Kr | 1 ± 9 | ±3 |
| $^{210}$Bi | 27 ± 8 | ±3 |
| $^{210}$Po | 583 ± 2 | ±12 |

The best-fit value and statistical uncertainty for each component are listed together with its systematic error. The $\chi^2$ per degree of freedom of the fit is $\chi^2$/d.o.f. = 172.3/147.

We note that the very low $^{87}$Kr rate (Table 1) is consistent with the independent limit (< 7 c.p.d. per 100 t, 95% confidence level) obtained by searching for the $\beta$–$\gamma$ delayed coincidence $^{86}$Kr$\rightarrow^{86}$Rb (lifetime of the intermediate metastable isotope, $\tau = 1.46$ μs; branching ratio, 0.43%). We have checked for possible residual backgrounds generated by nuclear spallation processes produced by cosmic ray muons that interact in the detector. We detect these muons with > 99.9% efficiency. We increased the time window for the muon veto from 300 ms to 5 s and observed no difference in the results. Furthermore, we searched for other possible background due to radioisotopes with sizeable natural abundances and sufficiently long half-lives to survive inside the detector over the timescale of this measurement. These include low-energy $\alpha$-emitters such as $^{222}$Rn and $^{218}$Po (both belonging to the radon decay chain), $^{147}$Sm and $^{148}$Sm, and $\beta$-emitters ($^7$Be), which are all estimated to be negligible and are excluded from the final fit. One $\beta$-emitter, $^{87}$Rb (half-life, $t_{1/2} = 4.7 \times 10^{10}$ yr; 28% isotopic abundance; $Q = 283.3$ keV), is of particular concern because of the relatively high abundance of Rb in the Earth’s crust. Rubidium is an alkali chemically close to potassium but typically 2,000–4,000 times less abundant in the crust. Under these assumptions, and using the measured $^{40}$K ($t_{1/2} = 0.125 \times 10^{10}$ yr; 0.0117% isotopic abundance) activity in the fiducial volume, that is, < 0.4 c.p.d. per 100 t at the 95% confidence level, the $^{87}$Rb activity in the Borexino scintillator can be constrained to be much less than 0.1 c.p.d. per 100 t, which is negligible for this analysis. A deviation from the crustal isotopic ratio by a factor of 100 would still keep this background at ~ 1 c.p.d. per 100 t.

The solar $pp$ neutrino interaction rate measured by Borexino is 144 ± 13 (stat.) ± 10 (syst.) c.p.d. per 100 t. The stability and robustness of the measured $pp$ neutrino interaction rate was verified by performing fits with a wide range of different initial conditions. The absence of $pp$ solar neutrinos is excluded with a statistical significance of 10σ (Methods). Once statistical and systematic errors are added in quadrature and the latest values of the neutrino oscillation parameters are taken into account, the measured solar $pp$ neutrino flux is $1.1 \times 10^{10}$ cm$^{-2}$ s$^{-1}$ cm$^{-2}$ s$^{-1}$. This value is in good agreement with the SSM prediction (5.98 ± 0.006) $\times 10^{10}$ cm$^{-2}$ s$^{-1}$ cm$^{-2}$ s$^{-1}$. It is also consistent with the flux calculated by performing a global analysis of all existing solar neutrino data, including the $^7$B, $^{8}$B and $^{10}$Be fluxes and solar neutrino capture rates. Finally, the probability that $pp$ neutrinos produced in the core of the Sun are not transformed into muon or tau neutrinos by the neutrino oscillation mechanism is found to be $P(V_{\tau}\rightarrow V_{\mu}) = 0.64 ± 0.12$, providing a constraint on the Mikheev–Smirnov–Wolfenstein large-mixing-angle (MSW-LMA) solution in the low-energy vacuum regime (Methods).

**Outlook**

The proton–proton fusion reaction in the core of the Sun is the keystone process for energy production in the Sun and in Sun-like stars. The observation of the low-energy ($0–420$ keV) $pp$ neutrinos produced in this reaction was possible because of the unprecedentedly low level of radioactivity reached inside the Borexino detector. The measured value is in very good agreement with the predictions of both the high-metallicity and the low-metallicity SSMs. Although the experimental uncertainty does not yet allow the details of these models to be distinguished, this measurement strongly confirms our understanding of the Sun. Future Borexino-inspired experiments might be able to measure solar $pp$ neutrinos with the level of precision (~ 1%) needed to cross-compare photon
and neutrino solar luminosities, while providing insight into solar dynamics over 10^7 yr timescales. At the same time, such a precise measurement of pp neutrinos would yield the ultimate test for the MSW-LMA neutrino oscillation model and allow precision tests for exotic neutrino properties.

Online Content Methods, along with any additional Extended Data display items and Source Data are available in the online version of the paper; references unique to these sections appear only in the online paper.

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METHODS

The Borexino detector. The detector (Extended Data Fig. 1) is located deep underground (3,800 m of water equivalent) at the Gran Sasso laboratory, in central Italy.22 The active neutrino target, 278 t of ultrapure liquid scintillator (pseudocumene (1,2,4-trimethylbenzene) solvent with 1.5 gL⁻¹ 2,5-diphenyloxazole (PPO) wavelength-shifting fluor), is contained inside a thin transparent nylon spherical vessel of 8.5 m diameter. Borexino detects solar neutrinos by measuring the energy deposited by recoiling electrons following neutrino–electron elastic scattering. The scintillator promptly converts the kinetic energy of electrons into photons, detected and converted into electronic signals (photoelectrons) by 2,212 PMTs mounted on a double-scintillator layer. The liquid scintillator promptly converts the kinetic energy of electrons into photons, detected and converted into electronic signals (photoelectrons) by 2,212 PMTs mounted on a double-scintillator layer, and acts as radiation shield for radioactivity emitted by the PMTs. A second, larger (11.5 m diameter) nylon sphere prevents radon and other radio-active contaminants from the PMTs and SSS from diffusing into the inner part of the detector. The sphere is immersed in a 2,100 t water Cherenkov detector for residual cosmic muons, which can induce background via spallation processes with the scintillator.

Solar electron neutrino neutrino probability. After the SNO experiment in 2001, the deficit of solar $\nu_e$ observed on Earth has been explained by the neutrino oscillation mechanism: these $\nu_e$ undergo lepton flavour transformation into $\nu_x$ or $\nu_\tau$ in a quantum mechanical process requiring neutrinos to have a finite mass difference. This explains why the Sun, when viewed from Earth, appears white, not yellow, as its relative efficiency for neutrino and background events could not be reliably measured, and so the energy content of the Sun could not be measured. Hence, the basic event selection and analysis can be found in ref. 28, with some conditions relaxed specifically for this analysis. In particular, the energy threshold for acceptance of events used in this analysis was lowered with respect to previous analyses looking for higher-energy neutrino interactions. Also by contrast with what was done in previous measurements, no $\beta$-like selection condition (based on the different scintillation time profile of $\alpha$- and $\beta$-particles) was used, as its relative efficiency for neutrino and background events could not be reliably evaluated at the lower energies characteristic of solar $pp$ neutrino interactions.

The standard solar model and the $pp$ neutrino flux. The predictions for the solar neutrino fluxes come from solar models developed by astrophysicists since the 1960s. The SSM uses the simplest physical hypotheses and the best available physics input. It is assumed that energy is generated by nuclear reactions in the core of the star (see Extended Data Fig. 3 for the $pp$ cycle) and is transported by radiation in the central part and by convection in the outer part. The basic evolution equation is the hydrostatic equilibrium between the outward radiative pressure force and the inward gravitational force. One ingredient of the model, the metallicity Z/X (content of heavy elements relative to hydrogen), is under discussion at present (see, for example, ref. 9): the most recent determination of Z/X (AGS09) gives a lower value than the previous one (GS98), but the corresponding predictions significantly disagree with the helioseismology observations. The measurement of all solar neutrino components, which differ between solar models in these two metallicity scenarios, could help resolve the issue. The most recent calculations are those of ref. 9 (other models, such as the one described in ref. 24, give similar results). We use the solar neutrino fluxes for high metallicity throughout this paper. When combined with the latest values of the neutrino oscillation parameters25, the SSM predicts 131 ± 2 c.p.d. per 1001 ppm neutrinos in Borexino. Neutrino oscillation parameters are key for translating the interaction rate measured in Borexino into a solar neutrino flux, as they provide the relative ratio between electron neutrinos and muon and tau neutrinos, which have different elastic scattering cross-section with electrons.

Event selection, position and energy reconstruction. The basic event selection cuts for solar neutrino analysis are (1) no coincidence with muon events26 (a 300 ms veto is applied following muons crossing the scintillator and buffer volumes, and a 2 ms veto following muons crossing only the water tank) and (2) position reconstruction within the innermost volume of the detector (the fiducial volume). The second cut is necessary to eliminate background from radioactivity in the nylon vessel, the SSS and the PMTs; for this analysis, R < 3.021 m, z < 1.67 m (the geometrical centre of the sphere defines the origin of the coordinates x and y in the horizontal plane) and z, as well as the origin from where, R, is measured. A signal is recorded when more than a preset number of PMTs (25 until February 2013, 20 thereafter) detect light within a 100 ns time window. Dedicated software then decides whether to classify this as a physics event or archive it as electronic noise or other instrumental effect. A ray-tracing algorithm triangulates photon arrival times at each struck PMT to determine the position of the event, which is assumed to be point-like.

The procedure to assign the correct energy to each event starts from the number of photoelectrons recorded by the PMTs. For $\beta$- and $\gamma$-events, the energy of an event is roughly proportional to the number of collected photoelectrons26. Notably, $\alpha$-events display sizeable quenching of scintillation light, description of which is beyond the scope of this Article. The number of photons detected for a given type of event depends on its position, being maximal at the centre of the detector. We correct for this position dependence using a parameterized response obtained by simulating the detector with known radioactive sources deployed at different positions. Source calibration data (mostly $\gamma$-ray emitters) are then used to tune Monte Carlo simulation software26, allowing us to model the detector response correctly. These are in turn used to determine the energy response of the detector.

We detect approximately 500 photoelectrons for a 1 MeV electron; this number progressively reduces as ageing, malfunctioning PMTs are taken offline.

A complete description of the data selection and analysis can be found in ref. 28, with some conditions relaxed specifically for this analysis. In particular, the energy threshold for acceptance of events used in this analysis was lowered with respect to previous analyses looking for higher-energy neutrino interactions. Also by contrast with what was done in previous measurements, no $\beta$-like selection condition (based on the different scintillation time profile of $\alpha$- and $\beta$-particles) was used, as its relative efficiency for neutrino and background events could not be reliably evaluated at the lower energies characteristic of solar $pp$ neutrino interactions.

Fit of the $^{14}$C. The $^{14}$C rate has been determined by looking at a sample of data in which the event causing the trigger is followed by a second event within the time acquisition window of 16 ms. This particular second-event selection bypasses threshold effects intrinsic to any self-triggering approach, clearly visible in Extended Data Fig. 4. The energy spectrum and its fit, using the theoretical $^{14}$C $\beta$-emission shape,23,24 are shown in Extended Data Fig. 2 for the data. This fit yields a $^{14}$C rate of 40 ± 1 Bq per 1001. The uncertainty accounts for systematic effects due to the stability of the detector response in time, knowledge of the $^{14}$C spectral shape and fit conditions, including the fit energy range. We note that the relatively poorly known shape factor of the $^{14}$C $\beta$-emission spectrum has a <2% effect on the $pp$ neutrino result. The measured $^{14}$C rate translates into a $^{14}$C/$^{12}$C isotopic ratio of (2.7 ± 0.1) × 10⁻⁶. The typical value for this ratio for atmospheric (that is, biologic) carbon is $\sim$ 10⁻¹². The $^{14}$C is mainly produced by the nuclear reaction $^{14}$N(p,$\gamma$)C supported by cosmic rays in the upper atmosphere. The underground petroleum liquid scintillator explains its much smaller $^{14}$C abundance.

Study of pile-up events. The pile-up component is determined using a data-driven method as follows. The real triggered events without any selection cuts are artifically overlapped with random data samples. The combined synthetic events are selected and reconstructed using the procedure applied to the regular data. By construction, the synthetic pile-up method accounts for all possible event pile-up
combinations. The corresponding spectrum includes events that vary in energy with respect to the original event (that is, before being artificially overlapped with the random sample) by more than a given number of photoelectrons \( (N_{\text{min}}) \). In addition, the same event selection criteria as in the real data set are applied after the overlap. Thus, some systematic effects, for example the position reconstruction of pile-up events, are automatically taken into account. To increase the statistical precision, every real event is overlapped four times, each time with a different random data sample, and the final pile-up spectrum is divided by a factor of 4. An expanded view of the synthetic pile-up spectral probability density function (visible in Figs 2 and 3) is presented in Extended Data Fig. 6.

The final fit was performed using this synthetic pile-up with \( N_{\text{min}} = 5 \) photoelectrons. This component is dominated but not exclusively composed of \(^{14}\text{C}\) pile-up with itself. Some of the events are from dark noise of the PMTs. The robustness of the method was confirmed by checking that the fit results were not dependent on the choice of \( N_{\text{min}} \).

We compared the synthetic pile-up method with an alternative one. Regularly solicited trigger events with a 16 \( \mu \)s acquisition time window (acquired at 0.5 Hz) are collected and sliced into fixed-time windows of the same duration as the signal window (230 and 400 ns). The hits in these windows produce the energy distribution shown in Extended Data Fig. 7, which represents a randomly sampled signal from the detector, including contributions from dark noise of the PMTs, \(^{14}\text{C}\) and other radioactive contaminants. Pile-up can be thought of as the combination of events belonging to any spectral component combined with such a spectrum. The final fit can then be performed without a separate pile-up probability density function (as in the synthetic approach), by using 'smeared' spectral species in the final fit. The smearing is the convolution of ideal spectral components with the solicited trigger spectrum. Solar \( pp \) neutrino interaction rates measured using this method are in full agreement with those obtained with the synthetic pile-up method.

**Stability of the result.** The stability and robustness of the measured \( pp \) neutrino interaction rate was verified by performing fits with a wide range of different initial conditions, including fit energy range, synthetic-versus-convolution pile-up spectral shape, and energy estimator. The distribution of \( pp \) neutrino interaction rates obtained for all these fit conditions is summarized in Extended Data Fig. 8. The possibility of some remaining external background in the fiducial volume has been carefully studied in all Borexino solar neutrino analyses (see, for example, refs 17, 28). From these, we are confident that such a background at energies relevant for the \( pp \) neutrino study is negligible. In the particular case of the very low-energy part of the spectrum, we have tested this confidence by repeating the fit in five smaller fiducial volumes (with smaller radial and/or \( z \)-cut), which yields very similar results. Finally, the goodness (\( \chi^2 \)) of the spectral fit was computed using different values of the \( pp \) interaction rate, as shown in Extended Data Fig. 9. The absence of \( pp \) solar neutrinos is excluded with a statistical significance of 10\( \sigma \).

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Extended Data Figure 1 | The Borexino detector. The characteristic onion-like structure of the detector is displayed, with fluid volumes of increasing radiological purity towards the centre of the detector. Although solar neutrino measurements are made using events whose positions fall inside the innermost volume of scintillator (the fiducial volume, shown as spherical for illustrative purposes only), the large mass surrounding it is necessary to shield against environmental radioactivity. The water tank (17 m high) contains about 2,100 t of ultraclean water. The diameter of the stainless steel sphere is 13.7 m, and that of the thin nylon inner vessel containing the scintillator is 8.5 m. The buffer and target scintillator masses are 889 and 278 t, respectively.
Extended Data Figure 2 | Survival probability of electron-neutrinos produced by the different nuclear reactions in the Sun. All the numbers are from Borexino (this paper for \( pp \), ref. 17 for \( ^7 \)Be, ref. 18 for \( pep \) and ref. 19 for \( ^8 \)B with two different thresholds at 3 and 5 MeV). \(^7\)Be and \( pep \) neutrinos are mono-energetic. \( pp \) and \( ^8\)B are emitted with a continuum of energy, and the reported \( P(\nu_e \rightarrow \nu_e) \) value refers to the energy range contributing to the measurement. The violet band corresponds to the \( \pm 1\sigma \) prediction of the MSW-LMA solution\(^{25} \). It is calculated for the \( ^8\)B solar neutrinos, considering their production region in the Sun which represents the other components well. The vertical error bars of each data point represent the \( \pm 1\sigma \) interval; the horizontal uncertainty shows the neutrino energy range used in the measurement.
Extended Data Figure 3 | The sequence of nuclear fusion reactions defining the *pp* chain in the Sun. The *pp* neutrinos start the sequence 99.76% of the time.
Extended Data Figure 4 | Study of the low energy part of the spectrum.
Comparison of the spectrum obtained with the main trigger (black) and by selecting events falling in the late part of the acquisition window triggered by preceding events (red). Above 45 struck PMTs, the spectral shapes coincide.

The threshold effect for self-triggered events (black) is clear. The residual threshold effect at lower energy in the red curve is due to the finite efficiency for identifying very low-energy events within a triggered data window.
Extended Data Figure 5 14C spectrum, and residuals, obtained from events triggered by a preceding event. a, Spectrum. b, Relative residuals of a fit with the 14C β-emission spectrum (in units of standard deviations). The error bars thus represent ±1σ intervals.
Extended Data Figure 6 | Energy spectrum of the pile-up data for the standard cuts. The small bump around 150 struck PMTs (~400 keV in Figs 2 and 3) is due to the pile-up of $^{14}$C with $^{210}$Po; at lower energies, pile-up is dominated by $^{14}$C+$^{14}$C, and by $^{14}$C+ dark noise.
Extended Data Figure 7 | Energy distribution of events collected with no threshold applied. The events correspond to regular, solicited triggers (sliced into 230 ns windows). This represents what the detector measures when randomly sampled. In an alternative treatment of pile-up, this spectrum is used to smear each spectral component used in the fit (see text for details).
Extended Data Figure 8 | Distribution of best-fit values for the pp neutrino interaction rate. Values are obtained by varying the fit conditions, including the fit energy range, synthetic-versus-analytic pile-up spectral shape, and energy estimator. The distribution shown is peaked around our reported value of 144 c.p.d. per 100 t.
Extended Data Figure 9 | Goodness of fit versus pp neutrino interaction rate. The $\chi^2$ minimum is at our reported value of 144 c.p.d. per 100 t.