Electron neutrino survival probability in the energy range 200 keV–15 MeV

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The Borexino experiment, located at the Laboratori Nazionali del Gran Sasso in Italy, has been the first and so far unique experiment capable to measure the interaction rate of all solar neutrino components produced by the Sun through the so called *pp*-chain and CNO-cycle fusion mechanisms. Particularly, Borexino has measured the rate of *pp*, ^{7}Be, *pep* and ^{8}B neutrinos, which span a wide energy range from a few hundreds keV up to almost 15 MeV. This capability offered Borexino the unique opportunity to experimentally test the expected electron neutrino survival probability predicted by the theory. The paper briefly summarises this important achievement and discusses possible future developments.

Keywords: Solar neutrinos; electron neutrino survival probability; neutrino oscillations; LMA-MSW effect

1. Introduction

The Sun is a powerful source of low energy neutrinos that are a unique tool to test the solar theory and to probe neutrino physics. A remarkable set of discoveries have been made by means of solar neutrinos, among which the most important is the discovery electron neutrino oscillations into muon and tau neutrinos made by the SNO[1,2] experiment, which led to the Nobel prize of Art McDonald in 2015.[3]

It is quite well known that the stellar theory has long predicted two mechanisms for hydrogen fusion into helium in the Sun, known as the *pp*-chain and the

CNO cycle.[4] Both mechanism are based on a sequence of nuclear reactions, some of which produce electron neutrinos. The *pp*-chain is initiated by the fusion of two protons and produce neutrinos through four detectable mechanisms[a]. The CNO cycle bears this name because carbon, nitrogen and oxygen act as catalysers and produce neutrinos as well.[4] Fig. 1 shows the electron neutrino spectrum predicted by[4] without any neutrino oscillation effect.

The two fusion reactions occur in the Sun's core, and because of the relatively low solar temperature, they contribute very unequally to energy production: about 99% of the solar luminosity is due to the *pp*-chain, while the rest is due to the CNO cycle. The CNO cycle is dominant for more massive stars.

Borexino is the first experiment that was able to measure directly all individual solar neutrino components emitted by the *pp*-chain reactions[5] and by the CNO cycle in the Sun.[6] This fact is by itself a remarkable experimental achievement, which was obtained thanks to almost 30 years of activity.[7] It has also the consequence that the

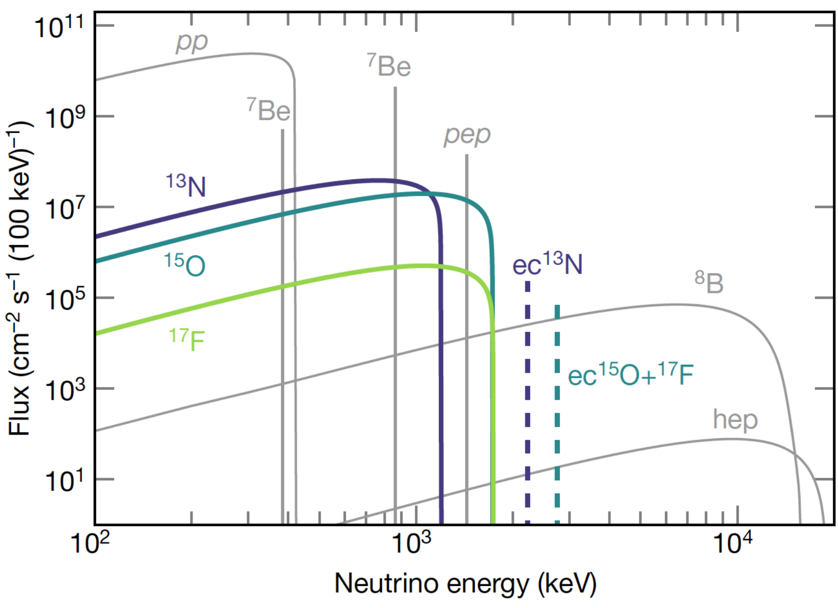

Fig. 1. The spectrum of solar neutrinos as predicted by Vinyoles et al. Hep neutrinos, while at high energy, have a flux that is too low to be detected by current generation experiments. All other components have been measured directly by Borexino through spectral analysis, exploiting the very low radioactive background, the low energy threshold and the good energy resolution of the liquid scintillator detector. Borexino has been so far the only experiment being able to perform such a comprehensive spectral measurement.

[a]A fifth mechanism due to the fusion of ^{3}He with a proton (hep neutrinos) is too small to be detected.

experiment was able to measure the survival probability of neutrinos as a function of the energy and to test directly the LMA-MSW[8] theory of neutrino oscillations. LMA refers to Large Mixing Angle solution, while MSW to the Mikheyev-Smirnov-Wolfenstein mechanism.[9–11]

According to MSW theory, at energy above a few MeV the different refractive index affecting the propagation of electron neutrinos with respect to that affecting the muon and tau neutrinos propagation introduce an additional phase shift that can change the survival probability of electron neutrinos from the central core to the Earth. At some energies the effect can be very large because of a resonance.[10,11] As a consequence, the LMA-MSW theory predicts that solar neutrino oscillations are strongly energy dependent and particularly are dominated by the matter effects above above a few MeV. Vacuum oscillations are dominant at lower energies.

When the LMA-MSW theory is taken into account, the neutrino fluxes predicted by the Standard Solar Model[4] are translated into a well defined prediction of the neutrino interaction rate in Borexino, which depends both on the total electron neutrino flux and on the fraction of electron neutrinos and other neutrino types reaching the Earth.

In this paper we show how the precision measurement pp, ^{7}Be, pep and ^{8}B neutrino rate made by Borexino translates into the first direct measurement of the electron neutrino survival probability as a function of the neutrino energy.

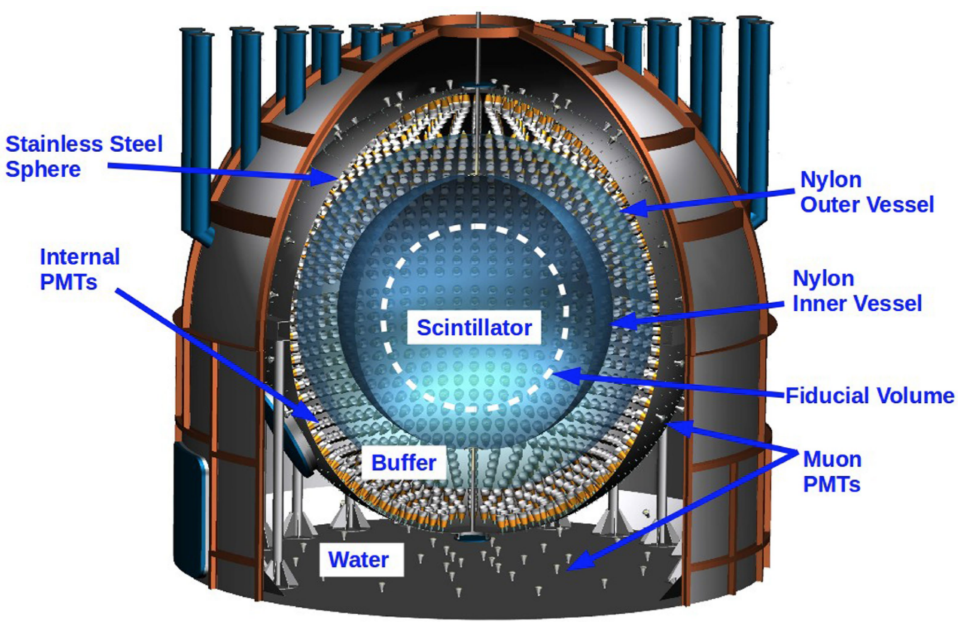

Fig. 2. Drawing of the Borexino detector. The various components are labelled in the picture. To give a feeling of the size, we quote the diameter of the Stainless Steel Sphere, which is 13.7 m.

2. The Borexino experimental setup

Borexino is a very pure liquid scintillator detector[12–15] designed for the real–time observation of low energy solar neutrinos. It is located in Italy deep underground (≃3800 meters of water equivalent, m w.e.) in the Hall C of the Laboratori Nazionali del Gran Sasso, where the muon flux is suppressed by a factor of $\approx 10^6$ with respect to sea level.

The detector is schematically depicted in Fig. 2. The inner part is an unsegmented stainless steel sphere (SSS) that is both the container of the scintillator and the mechanical support of the photomultipliers. Within this sphere, two nylon vessels separate the scintillator volume in three shells of radii 4.25 m, 5.50 m and 6.85 m, the latter being the radius of the SSS itself. The inner nylon vessel (IV) contains the liquid scintillator solution, namely PC (pseudocumene, 1,2,4-trimethylbenzene $C_6H_3(CH_3)_3$) as a solvent and the fluor PPO (2,5-diphenyloxazole, $C_{15}H_{11}NO$) as a solute at a concentration of approximately 1.5 g/l (0.17 % by weight). The second and the third shell contain PC with a small amount (few g/l) of DMP (dimethylphthalate, $C_6H_4(COOCH_3)_2$) that is added as a light quencher in order to further reduce the scintillation yield of pure PC.[12]

The Inner Vessel is made of 125 μm thick Nylon-6 carefully selected and handled in order to achieve maximum radio–purity. Since the PC/PPO solution is slightly lighter (about 0.4 %) than the PC/DMP solution, the Inner Vessel is anchored to the bottom (south pole of the SSS) with a set of nylon strings. The outer nylon vessel (OV) has a diameter of 11 m and is built with the same material as the inner one. The OV is a barrier that prevents ^{222}Rn emanated from the external materials (steel, glass, photomultiplier materials) to di?use into the fiducial volume.

The buffer fluid between the Inner Nylon Vessel and the SSS (PC/DMP solution) is the last shielding against external backgrounds. The use of PC as a buffer is convenient because it matches both the density and the refractive index of the scintillator, thus reducing the buoyancy force for the nylon vessel and avoiding optics aberrations that would spoil the spatial resolution.

The addition of the DMP quenches the scintillation yield of the buffer fluid by a factor of 20. This is important in order to avoid the unacceptable trigger rate due to the radioactivity of the photomultipliers.

The scintillation light is collected by nominally 2212 photomutipliers (PMTs) that are uniformly attached to the inner surface of the SSS. All but 384 photomultipliers are equipped with light concentrators that are designed to reject photons not coming from the active scintillator volume, thus reducing the background due to radioactive decays originating in the buffer liquid or γ's from the PMTs. The PMTs without concentrators are used to measure this background, and to help identify muons that cross the buffer, but not the Inner Vessel.

The number of active PMTs has changed over time during the almost 15 years of data taking, so that collection efficiency is a function of time and run–dependent.

The SSS is supported by 20 steel legs and enclosed within a large tank that is filled with ultra-pure water. The tank has a cylindrical base with a diameter of 18 m and a hemispherical top with a maximum height of 16.9 m. The Water Tank (WT) is a powerful shielding against external background (γ rays and neutrons from the rock) and is also used as a Cherenkov muon counter and muon tracker. The muon flux, although reduced by a factor of 10^6 by the 3800 m w.e. depth of the Gran Sasso Laboratory, is of the order of 1 m^{-2} h^{-1}, corresponding to about 4000 muons per day crossing the detector. This flux is well above Borexino requirements and a strong additional reduction factor (about 10^4) is necessary and was indeed achieved[13] by the combined use of WT signal and inner detector signal. More details on the detector can be found in.[12,13]

3. Neutrino detection

Low energy neutrinos of all flavours are detected by means of their elas- tic scattering off electrons or, in the case of electron anti–neutrinos, by means of their inverse beta decay on protons or carbon nuclei. The electron (positron) recoil energy is converted into scintillation light, which is then collected by a set of pho- tomultipliers. Neutron detection is often possible as well, through its capture on proton and emission of energetic gamma. A tiny amount of Cherenkov light is also produced, though it is mostly absorbed and re–emitted.

Scintillation light offers several advantages with respect to both the water Cherenkov detectors and the older radiochemical detectors used before Borexino in solar neutrino experiments. Water Cherenkov detectors, in fact, can not effectively detect solar neutrinos whose energy is below approximately 3.5 MeV, both because the Cherenkov light yield is low and because the intrinsic radioactive background cannot be pushed down to suffciently low levels. On the other hand, radiochemical experiments cannot intrinsically perform spectral measurements and do not detect events in real time. Cherenkov detector, however, can effciently detect the direction of the scattered electron and therefore of the incoming neutrino, which is not possible yet in liquid scintillators.

A liquid scintillator, on the other hand, solves these problems: the detection of low energy neutrino becomes possible possible because the light yield is high, offering an energy threshold as low as a few tens ofkeV[b]; the organic nature of the scintillator, and its liquid form at ambient temperature, provide very low solubility of ions and metal impurities, and yield the technical possibility to purify the material as required. However, no measurement of the direction of the incoming neutrino is possible[c] and, even more importantly, the neutrino induced events are intrinsically

[b]However, the unavoidable contamination of ^{14}C that is present in any organic liquid practically limits the "neutrino window" above ?200 keV

[c]Very recently Borexino has shown that some of this prompt Cherenkov light can be detected and identified. Future detector might be able to make useful use of this additional information.

indistinguishable from β and γ radioactivity, posing formidable requirements in terms of radio–purity of the scintillator and of the detector materials.

The total number of detected photons and their arrival times are used to reconstruct the electron recoil energy and the interaction point in the detector, respectively. The energy and spatial resolution of Borexino is not constant because it has slowly deteriorated over time owing to the steady loss of photomultiplier tubes (on average 1238 channels were active during the recent CNO analysis, with larger numbers available at the time of *pp*-chain analysis), with current values of $\sigma_E/E \approx 6\%$ and $\sigma_{x;y;z} \approx 11$ cm for 1 MeV events at the centre of the detector. The time profile of the scintillation light provides also a powerful way to distinguish between different particle types α, β and β^+ via pulse-shape discrimination methods.[16,17]

The final radio–purity levels achieved by Borexino on ^{238}U and ^{232}Th chains, and on several other radioactive contaminants, are many orders of magnitude lower than those either set as design goals or achieved by any other low–background experiment. In this short paper it is simply not possible to give an account of the amount of work done, nor a detailed description of the final numbers obtained. We invite the interested reader to look at the bibliography and particularly to[16,17] and references therein.

The total cross section of electron neutrinos on electrons depends on both charged and neutral currents weak interactions, while that of muon and tau neutrinos is induced by neutral currents only. The interaction rate depends therefore on the neutrino type at the target, a fact that makes the experiment sensitive to neutrino oscillations occurring along the path from the production site in the Sun's up to the detector. This is the key element that allows the direct measurement of the energy dependence of the flavour conversion probability through the Sun induced by the LMA-MSW effect.

The extraction of the survival probability can be obtained from the measured rate using the total fluxes predicted by the Standard Solar Model through the formula:

$$R_x(E) = \Phi_x \left[P_{ee}(E)\sigma_e + (1 - P_{ee}(E))\, \sigma_\mu \right] \tag{1}$$

where R_x is the measured rate of the x neutrino component with average energy E (x can be *pp*, ^{7}Be, *pep*, ^{8}B), Φ_x is the predicted electron neutrino flux of the x component at the Sun's core, P_{ee} is the electron neutrino survival probability, and σ_e and σ_μ are the neutrino-electron total cross sections for electron and muon neutrinos respectively. It is clear from the equation above that for any given measured rate the corresponding value of P_{ee} can be directly measured using as inputs the very well known standard model cross sections (which introduce a negligible uncertainty) and the solar model predictions, which drive most of the uncertainty beside experimental errors.

At the time of the proposal, the main goal of Borexino was the precise measurement of the rate induced by the monochromatic electron neutrinos (0.862 keV)

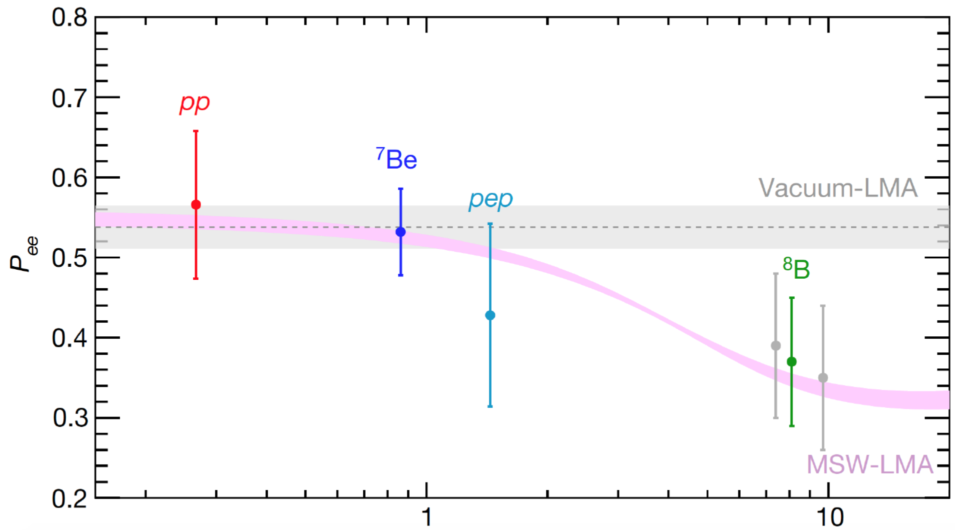

Fig. 3. The measured survival probability for the four neutrino components of the *pp*-chain. The pink band is the theoretical prediction of the P_{ee} with its uncertainty. The error on each value of P_{ee} depends on both theoretical errors and experimental error. See text for more details.

produced by the electron capture decay of ^{7}Be in the Sun. However, the very high radio purity of the scintillator offered new unexpected results, such as a clear evidence of the *pep* solar neutrinos,[18] a low energy threshold (3 MeV) detection of ^{8}B neutrinos,[19] the first direct measurement of *pp* neutrinos,[20] an unambiguous detection of geo-neutrinos,[21–23] and, last but definitely not least, the first prove of the existence of the CNO cycle in the Sun.[6]

After a careful detector calibration with internal sources[15] and an extensive purification campaign performed in 2010-2011, the complete *pp*-chain has been studied. This chain includes four reactions that emit four electron neutrino components of quite different energies: the *pp* neutrinos, whose average energy is around 200 keV, the ^{7}Be neutrinos, which offer a monochromatic line at 0.862 keV, the *pep* neutrinos, which offer another monochromatic line at 1.44 MeV, and ^{8}B neutrinos, which have a broad β^+ energy spectrum reaching about 15 MeV. These four neutrino components have very different survival probabilities in the Sun matter because of MSW effect, as we will see in the next section.

Although not relevant for LMA-MSW measurement, it is worth recalling that Borexino, after a substantial effort devoted to the thermal stabilisation of the detector developed in 2016-2018, has been able to measure the small and diffcult CNO neutrino signal.

In next section we focus on the complete measurement of the *pp*-chain neutrinos and on the consequence of these measurements to the knowledge of LMA-MSW effect in the Sun.

4. Electron neutrino survival probability measurement

The neutrinos produced in the *pp*-chain fusion reactions are all electron neutrinos because they originate from reactions with either an electron in the initial state (^{7}Be and *pep*) or with a positron in the final state (^{8}B and *pp*). However, neutrinos may undergo flavour transitions through the propagation inside solar matter, in the vacuum between the Sun and the Earth and, in the case of ^{8}B neutrinos, also while propagating at night through the Earth itself.

Without matter effects the conversion probability would be just a constant that depends on the vacuum mixing angle θ_{12}, with very little dependence on the other mixing angles and no dependence at all on mass splittings, because for solar neutrinos quantum coherence is completely lost. Indeed, coherence is washed out by the fact that the core of the Sun (diameter approximately 200.000 km) is comparable to the wavelength induced by mass-splitting at solar energies $(2\pi\ E/(1.27 \cdot \delta m^2_{12}) \simeq (2\pi\ 1\ MeV)/(1.27 \cdot 7.\ 10^{-5}\ eV^2) \simeq 70.000$ km) and also because the relative high temperature inside the Sun induce full decoherence of the neutrino beam ($k_B T \gg \delta m_{12}$).

However, since the late '80s and early '90s it was noticed that neutrino flavour oscillations may explain the solar neutrino problem only by assuming that the survival probability is energy dependent, chiefly because the neutrino deficit observed by Gallex[24] and SAGE[25] was different from that observed by Homestake[26] and also from that observed by the SuperKamiokande experiment.[27] The LMA-MSW effect provides an elegant mechanism to recover the energy dependence of the survival probability and Borexino is the first experiment which has been able to test it directly by measuring the survival probability of several neutrino components of various energies.

The LMA-MSW theory predicts a very well defined value of P_{ee} which is shown in Fig. 3 as a pink band whose thickness corresponds to the theoretical error. The same figure also shows the result of the P_{ee} computed using Borexino data using the measurements of *pp*, ^{7}Be, *pep* and ^{8}B neutrinos by means of formula (2). Neutrinos from *pp* initial fusion into deuteron are very low energy and their flavour conversion is dominated by vacuum oscillations. The grey band labelled as Vacuum-LMA corresponds to:

$$P^{vac}_{ee} = 1 - \frac{1}{2}\sin^2 2\theta_{12}\,, \tag{2}$$

which is the expected value for vacuum oscillations in case of completely incoherent propagation.

The neutrinos produced by ^{7}Be electron capture and *pep* three body fusion are mono–chromatic, so they bear no uncertainty in horizontal axis. *pep* is well within the transition region and shows a hint of that, with a large statistical uncertainty. ^{7}Be energy is still in the vacuum regime region and its corresponding P_{ee} is well consistent with that. Finally, ^{8}B neutrinos, on the other side, are well within the matter dominated LMA-MSW regime. Being a broad β^+ spectrum it is possible

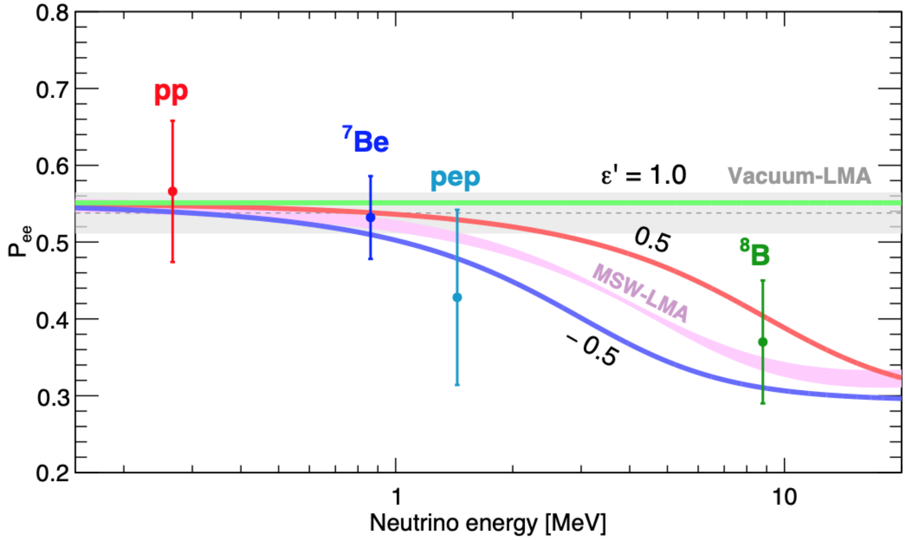

Fig. 4. Electron neutrino survival probability P_{ee} as a function of neutrino energy in LMA-MSW solution with uncertainties of oscillation parameters taken into account (pink band), and LMA-MSW + NSI solutions for ϵ'= -0.5, 0.5, 1.0 and average values of oscillation parameters. Vacuum oscillations scenario with LMA-MSW parameters is also shown (grey band). The definition of the non–standard interaction parameter is that of reference.[28]

to bin in energy, offering the data points shown in grey, while the green one is the average value. The error are too large, however, to show any hint of the expected rise of P_{ee} at lower energies (the slight uprise of the points has no real statistical significance, though consistent).

Globally, Borexino data clearly are well consistent with the theoretical expectation, confirming LMA-MSW effect, though the error are still large. Unfortunately, there is no room for Borexino to improve further.

In order to improve the result significantly two elements are important, depending on the energy. The ^{7}Be point has an error dominated by the theoretical uncertainty on the expected flux, while other points have also a relevant error coming from the rate measurement. Therefore, a better test of LMA-MSW theory requires an improvement in the Standard Solar Model predictions. For a discussion of the main sources of uncertainties see.[5]

The result obtained on the P_{ee} can be used to test the existence of low energy non–standard neutrino interactions beyond those predicted by the Standard Model. We have carefully studied this opportunity, parametrising the effect of non–standard interactions in terms of a single parameter ϵ'.[28] Fig. 4 shows that with the current theoretical and experimental uncertainties there is still quite a lot of room for new physics and that the future better measurement of this curve might be worth pursuing.

5. Conclusions

Borexino is the first and sole experiment able to measure all neutrino components from *pp*-chain reactions in the Sun and probe the electron neutrino survival probability as a function of energy.

The results confirm the LMA-MSW scenario with nice agreement with Standard Model physics. The precision is still low and room for new physics exists.

Borexino has opened the era of precise solar neutrino spectroscopy, but even better experiments are desirable to complete the job.

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