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200 days of Borexino data

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Borexino is a large-volume liquid scintillator detector placed in the underground halls of the Laboratori Nazionali del Gran Sasso in Italy. After several years of construction, data taking started in May 2007, providing immediately incontrovertible evidence of the unprecedented radiopurity of the target mass. Here we report on the newest Borexino results obtained with about 200 days of data. Borexino provides the first direct measurement of the solar neutrino survival probability in both vacuum-dominated and matter-enhanced regions provided by a single experiment. The interaction rate of the 0.862 MeV ^{7}Be solar neutrinos is found to be $49 \pm 3_{\rm stat} \pm 4_{\rm sys}$ counts/(day·100 tons), in agreement with the oscillation hypothesis in the MSW Large Mixing Angle scenario. The first real-time measurement of the ^{8}B solar neutrinos above 2.8 MeV provides interaction rate of $0.26 \pm 0.04_{\rm stat} \pm 0.02_{\rm sys}$ counts/(day·100 tons). These measurements improve the experimental determination of the flux of the *pp* and CNO solar neutrinos, and the limit on the effective magnetic moment using solar neutrinos.

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1. Introduction

Solar neutrinos (ν) have been studied for 30 years by means of radiochemical and water-Cherenkov detectors and brought to the discovery of ν–oscillations. Moreover, combined with the reactor anti-ν data, lead to the determination of the ν–oscillation parameters $\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5} eV^2$ and $\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$ [1]. However, investigation of the solar–ν spectrum is far from being complete. In the past, the most stringent limitations were due to the fact that radiochemical experiments cannot measure ν energies, and that water-Cherenkov detectors have to work with a high energy threshold of ∼4.5 MeV. The Borexino experiment has opened a new chapter in the experimental history of solar ν by making feasible the solar–ν spectroscopy in real–time down to 250 keV [2,3]. This was possible by employing a liquid scintillator technique which has several advantages. Namely, it allows the real–time detection (unlike the radiochemical technique) and decreasing the energy threshold. The latter one is due to a light yield (LY) ∼50 times higher than the Cherenkov one and a very low solubility to ions and metal impurities making it possible to reach unprecedented levels of radiopurity. The main drawback of this technique is a loss of the directionality information, since the produced scintillation light is homogeneous. As a consequence, it is not possible to distinguish ν–scattered electrons from electrons due to the natural radioactivity. Thus, the key requirement in the Borexino technology is an extremely low radioactive contamination, possible, but extremely challenging and never obtained before.

The present work reports the first direct measurement of the solar ν survival probability (P_{ee}) in both vacuum-dominated and matter-enhanced regions provided by a single experiment. The P_{ee} determination is based on the real-time measurement of the interaction rate of the 0.862 MeV ^{7}Be–ν (vacuum-dominated region) and of the ^{8}B–ν above 2.8 MeV (matter-enhanced region). The results are presented after a short description of the detector and of the low background levels achieved. We conclude with the Borexino future perspectives not only in the field of solar ν.

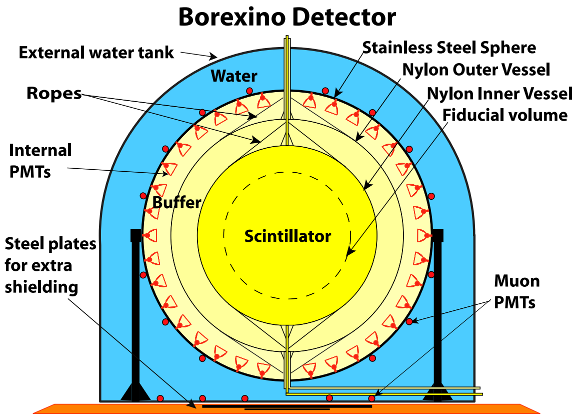

Figure 1. A scheme of the Borexino detector.

2. Detector description

The Borexino detector is located under the Gran Sasso mountain in the Laboratori Nazionali del Gran Sasso, Italy. It detects solar ν via their elastic scattering on the electrons of liquid scintillator. This scintillator, the active medium of the detector, is a mixture of pseudocumene (PC, 1,2,4- trimethylbenzene) and PPO (2,5-diphenyloxazole, a fluorescent dye) at a concentration of 1.5 g/l. To reach ultra low background conditions and to reduce external background (γ's from the photomultiplier tubes (PMTs) and γ's and neutrons from the rock), the design of Borexino is based on the principle of graded shielding (Fig. 1). The inner core scintillator is at the center of a set of concentric shells of increasing radiopurity (inwards). The 278 tons of scintillator are contained in a 125 μm thick nylon Inner Vessel (IV) with a radius of 4.25 m. The scintillation light is viewed by 2212 8" PMTs (ETL 9351) mounted on a Stainless Steel Sphere (SSS) with a radius of 6.85 m. The volume between the IV and SSS, so called buffer region and the innermost passive shield, is filled with 1000 tons of mixture of pure PC and 5.0 g/l DMP (dimethylphthalate) quenching the residual PC scintillation. A second nylon outer vessel (OV) with radius of 5.50 m surrounds the IV and divides the buffer region into the inner and outer buffer. The OV acts as a barrier against the inward diffusion of radon and other external background contamination. The outermost shield are 200 tons of ultra-pure water filling a steel-made, cylindrical dome with diameter of 18 m and height of 16.9 m, enclosing the SSS. The external water serves apart being a passive shield also as an active Cherenkov radiator to detect residual cosmic muons crossing the detector. The Cherenkov light is detected by 200 PMTs (same type as the inner ones) mounted on the SSS outer surface.

The key features of the Borexino detector and details of its components have been thoroughly described in [4,5].

2.1. Radiopurity and background levels

Besides reducing external background, the key requirement for measuring low–energy ν with Borexino is an extreme radiopurity of the scintillator itself. The rate of background events must be lower or comparable to the expected ^{7}Be–ν interaction rate, *i.e.*, ~50 counts/(day·100 tons). During 15 years of dedicated R&D studies, the Borexino collaboration developed a purification strategy which proved to be effective in removing the most dangerous contaminants [6]. In particular, the contamination due to ^{238}U and ^{232}Th was brought to the unprecedented levels of (1.6 $\pm$ 0.1) $\times$ 10^{-17} g/g and (6.8 $\pm$ 1.3) $\times$ 10^{-18} g/g, respectively, one order of magnitude better than the designed goal of 10^{-16}g/g.

Contamination with ^{85}Kr emitting electrons with energies partially overlapping with energies of electrons scattered by ^{7}Be–ν, is evaluated to be (29 $\pm$ 14) counts/(day·100 tons). A big error on the contamination level comes from the fact that it is deduced via a special delayed coincidence tag with a small branching ratio of 0.43%.

Other important background in sizable, though tolerable amount is α emitter ^{210}Po. Its contamination at the beginning of data taking was about 80 counts/day/ton, decaying afterwards following the intrinsic 200 days lifetime.

By far the major contaminant is ^{14}C, a β-emitter with 156 keV end point, which is naturally present in the organic liquid scintillator. Its isotopic ratio is evaluated from the data acquisition trigger rate, dominated by the ^{14}C events, to be $^{14}C/^{12}C = (2.7 \pm 0.6) \cdot 10^{-18}$, perfectly suited for the planned analysis threshold of ~200 keV.

A dominant background at energies above 800 keV is cosmogenically produced ^{11}C. It is observed at an average rate of 25 counts/(day·100 tons), which is the range of predictions of the previous studies [7,8], though slightly higher.

With the exception of the first couple of months after the end of the filling, the detected radon contamination is very limited, at the level of few counts per week. The major source of these radon events is its emanation from the IV nylon surface.

2.2. Event reconstruction and detector performances

Borexino is a self-triggering multiplicity detector. A data acquisition trigger is produced when at least 25 PMT pulses occur within a tunable time window (60-99 ns), what corresponds to a threshold of ~40 keV. When a trigger occurs, a 16 μs gate is opened and time and charge of each triggered PMT is detected. The time is measured by a Time to Digital Converter with a resolution of about 0.5 ns, while the charge (after integration and shaping of the PMT anode pulse) is measured through an 8 bit Analog to Digital Converter. The readout sequence can also be activated by the outer muon detector via a trigger system, which fires when at least six outer PMTs detect light in a time window of 150 ns. Regardless of the trigger type, data from both the inner and outer detectors are acquired.

The offline software identifies the shape of the scintillator pulse and reconstructs the position of the energy deposit in the scintillator by means of a time-of-flight based likelihood method. Energy of the incident particle is a function of the integral number of photoelectrons detected by all PMTs. The calibration of the energy scale has been obtained by several methods, namely by studying the end-point of the ^{14}C spectrum, fitting the ^{11}C energy spectrum and by keeping the LY as a free parameter in the global fit. All these methods provide a consistent LY value of about 500 photoelectrons/MeV of deposited energy. The energy resolution scales roughly as $5\%/\sqrt{E(\mathrm{MeV})}$, while the position resolution is about 40 cm @ 150 keV.

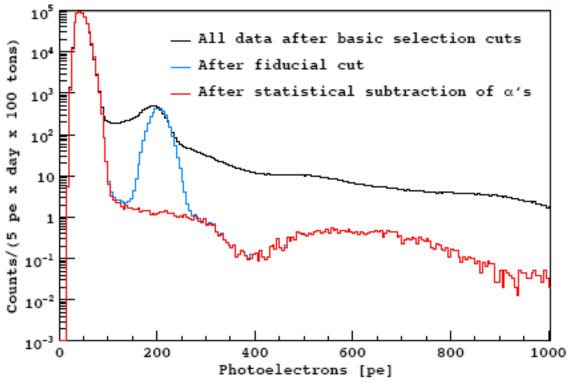

Figure 2. The raw charge spectrum and the effects of different analysis cuts. Details in the text.

3. Data analysis

3.1. Extraction of the ^{7}Be neutrino flux

The presented results concerns 192 live days between May 2007 and February 2008. Event selection is performed according to these criteria: *i*) Only single cluster events are accepted, to exclude pile-up and fast coincidences. *ii*) Muons, *i.e.* signals which have triggered the outer detector are rejected. *iii*) After each muon crossing the scintillator, all events within a 2 ms time window are rejected. *iv*) The Radon induced ^{214}Bi-^{214}Po sequences are removed together with signals of the ^{214}Pb precursor. *v*) To remove the external background, only signals reconstructed within a spherical fiducial volume (FV), corresponding to about 1/3 of the IV volume, are accepted. To remove background near the IV poles, the vertical distance from the equatorial plane is required to be < 1.7 m. The combined loss of fiducial exposure due to the cuts $i) - iv)$ is 0.7%. The FV cut $v)$ results in a fiducial mass of 78.5 tons. Fig. 2 demonstrates the effect of these cuts. The initial spectrum with only cuts $i) - iii)$ applied (solid black line) has two prominent components: ^{14}C below 80 photoelectrons (pe) and ^{210}Po at about 190 pe. The spectrum obtained after $i) - v)$ cuts (solid blue) demonstrates the dramatic effect of the external background removal. At this stage also the Compton-like edge due to the electrons scattered on ^{7}Be–ν (300-350 pe) and the broad ^{11}C spectrum (400-800 pe) become visible. The red curve is the spectrum left after the rejection of the ^{210}Po peak possible with a powerful α–β discrimination technique.

The final spectrum is fitted to a global signal-plus-background model to extract quantitatively the value of the ^{7}Be–ν flux. Two independent analyses provided consistent results. The fit is performed roughly from 200 keV, thus including the extreme ^{14}C tail, to about 1800 keV, encompassing the entire ^{11}C region. Free parameters are the LY and the amplitudes of ^{7}Be– and CNO–ν, ^{85}Kr, ^{14}C, and ^{11}C spectra. The *pp*– and *pep*–ν spectra are included in the fit, but at their nominal model value (high metallicity [9] Standard Solar Model (SSM) [10], BS07(GS98)). The fit results (Figs. 3 and 4) expressed in counts/(day·100 tons) are (statistical errors only): 49 ± 3 for ^{7}Be–ν, 25 ± 3 for ^{85}Kr (consistent with the estimate from the delayed coincidence analysis), 23 ± 2 for a sum of CNO–ν and ^{210}Bi (at this stage these two cannot be disentangled), and 25 ± 1 for ^{11}C.

We estimate the systematic error to be ±8.5%, with the major contributions due to the FV and energy scale determinations. Our best value for the ^{7}Be–ν interaction rate is $(49 \pm 3_{\rm stat} \pm 4_{\rm sys})$ counts/(day·100 tons). The expected signal for non-oscillated solar ^{7}Be–ν in the BS07(GS98) model is (74 ± 4) counts/(day·100 tons) corresponding to a flux of $(5.08 \pm 0.25) \times 10^9$ cm^{-2}s^{-1}. For the flux normalization constant f, the ratio between the measured (MSW-LMA scenario [11]) and predicted (BS07(GS98)) ν flux, we obtain $f_{\rm Be} = 1.02 \pm 0.10$. The resulting survival probability at the ^{7}Be–ν energy is $P_{ee} = 0.56 \pm 0.10$ and the no oscillation hypothesis, $P_{ee} = 1$, is rejected at 4σ C.L.. Therefore, Borexino on one hand spectacularly confirms the MSW-LMA ν oscillation scenario, and on the other provides the first direct P_{ee} measurement in the low–energy vacuum MSW regime [12].

We then explore the constraint on the f_{pp} and $f_{\rm CNO}$ after the new Borexino measurement [3] together with the results of radiochemical experiments [13,14] and SNO [15]. We determine $f_{pp} = 1.04^{+0.13}_{-0.19}$ (1σ) and $f_{\rm CNO} < 6.27$ (90% C.L.)

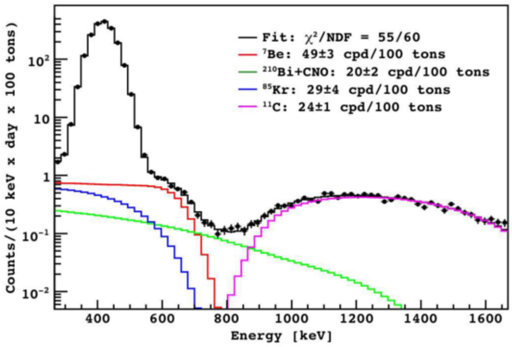

Figure 3. Borexino spectrum obtained after applying the analysis cuts. The ^{7}Be–ν rate is determined by a global fit. Details in the text.

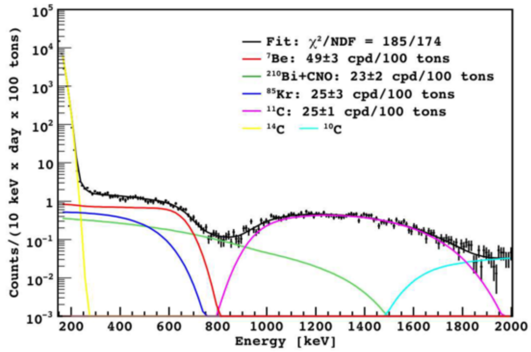

Figure 4. Borexino spectra and fit, analogical to the one shown in Fig. 3, but after statistically subtracting the α's from ^{210}Po decay.

by using the 1-D χ^2–profile method [16]. The result on f_{pp} represents the best experimental value at present obtained without the luminosity constraint. The result on $f_{\rm CNO}$ translates into a CNO contribution to the solar luminosity $< 5.4\%$ (90% C.L.) which is also at present the best limit. We remark that the BS07(GS98) model predicts a CNO contribution on the order of 0.9%.

3.2. Neutrino effective magnetic moment

In a case of a non-null ν magnetic moment, the electroweak cross section is modified by the addition of an electromagnetic term $d\sigma/dT_{EM} = \mu_\nu^2 \pi \alpha_{em}^2 / m_e^2 [1/T - 1/E_\nu]$ where E_ν is the ν energy and T is the electron kinetic energy. The shape of the solar ν spectrum is sensitive to the possible presence of a non–null magnetic moment, and the sensitivity is enhanced at low energy since $d\sigma/dT_{EM}$ is proportional to $1/T$. Using the CTF data we have reported an upper limit of $5.5 \times 10^{-10} \mu_B$ [17], while from the data presented here we provide currently the best experimental limit of $5.4 \times 10^{-11} \mu_B$ (90% C.L.).

3.3. Extraction of the ^{8}B neutrino flux

We report the measurement of the ^{8}B solar ν interaction rate based on the analysis of the 245.9 live days of data [18,19]. The extreme radio–purity of Borexino, combined with the efficient software rejection of cosmogenic background, allows to investigate the recoiled electron spectrum, induced by ^{8}B solar ν, down to the unprecedented energy threshold of 2.8 MeV. Borexino is therefore the first experiment providing the real-time measurement of ^{8}B-ν below 5 MeV. The major background sources at the energies above 2.8 MeV are muons, gammas from the neutron capture, radon emanation from the nylon vessel, short–lived ($\tau < 2$ s) and long–lived ($\tau > 2$ s, ^{10}C) cosmogenic isotopes, and bulk ^{232}Th contamination (^{208}Tl).

The rate of ^{8}B solar ν interaction (above 2.8 MeV) is $(0.26 \pm 0.04_{\rm stat} \pm 0.02_{syst})$ counts/(day·100 tons). This corresponds to an equivalent ν_e flux of $(2.65 \pm 0.44_{\rm stat} \pm 0.18_{syst} \times 10^6)$ cm^{-2}s^{-1}, as derived from the elastic scattering only, in good agreement with existing measurements and predictions. The corresponding ^{8}B mean ν_e survival probability, assuming the BS07(GS98) SSM, is 0.35 ± 0.10 at the effective energy of 8.6 MeV. The no-oscillation model is excluded at the 4.2σ C.L.. Together with the ^{7}Be–ν measurement described above, Borexino provides the first simultaneous measurement of solar ν from the vacuum region (^{7}Be-ν) and from the matter-enhanced oscillation region (^{8}B-ν) (Fig. 5). Eliminating the common sources of

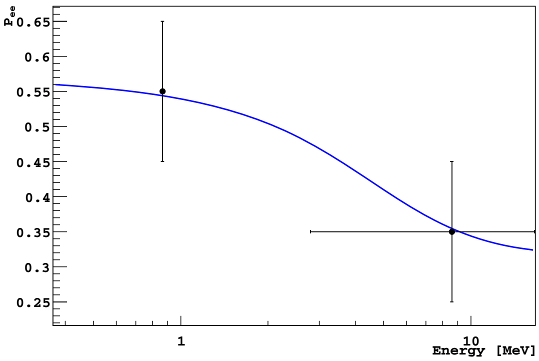

Figure 5. P_{ee} as function of the ν energy (line), evaluated for the ^{8}B-ν source (assuming BS07(GS98) and MSW-LMA). Dots represent the Borexino results from the ^{7}Be– and ^{8}B–ν measurements. The error bars include also the theoretical expected–flux uncertainty.

systematic errors, the ratio between the measured survival probabilities for ^{7}Be– and ^{8}B–ν is 1.60 ± 0.33, 1.8σ different from unity. This confirms the existence of the transition between the low–energy vacuum dominated and high–energy matter enhanced solar ν oscillations predicted by the MSW–LMA solution.

4. Future perspectives

Given the exceptional, unprecedented purity results achieved in Borexino, further measurements beyond the ^{7}Be– and ^{8}B–ν, are prospectively possible in the future. A broad investigation of the solar ν spectrum is well within our reach. After the calibration campaign in the near future, the systematic error can be substantially reduced. We aim at reducing the error of the ^{7}Be-ν measurement down to 5%. A feasibility of measurement of *pep*, CNO and possibly *pp* solar ν is under an extensive study. It is important to note also a strong potential of Borexino in the field of geo–ν and supernovae (anti-)neutrinos.

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