Borexino and solar neutrinos

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Abstract

Borexino, a large volume detector for low energy neutrino spectroscopy, is currently running underground at the Laboratori Nazionali del Gran Sasso, Italy. The measured interaction rate of the 0.862 MeV ^{7}Be neutrinos equals to $49\pm3_{\rm stat}\pm4_{\rm syst}$ counts/(day·100 ton). The hypothesis of no oscillation for ^{7}Be solar neutrinos is inconsistent with the Borexino measurement at the 4σ C.L.. This is the first direct measurement of the survival probability for solar ν_e in the transition region between matter-enhanced and vacuum-driven oscillations.

Borexino is a large volume liquid scintillator detector for the real-time measurement of low energy solar neutrinos below 4.5 MeV [1]. It is located deep underground ($\simeq$ 3800 meters of water equivalent, m w.e.) in the Laboratori Nazionali del Gran Sasso (Italy), where the muon flux is suppressed by a factor of $\approx 10^6$.

Solar neutrinos are detected in Borexino through their elastic scattering on electrons in the scintillator. Electron neutrinos (ν_e) interact through charged and neutral currents. The electrons scattered by neutrinos are detected by means of the scintillation light retaining the information on the energy. The basic signature for the mono-energetic 0.862 MeV ^{7}Be neutrinos is the Compton-like edge of the recoil electrons at 665 keV.

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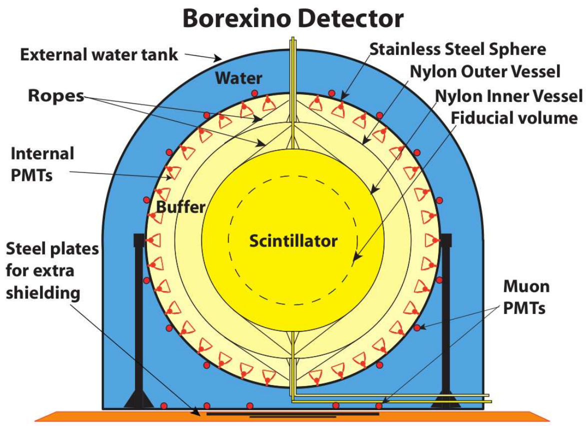

Figure 1: Schematic drawing of the Borexino detector.

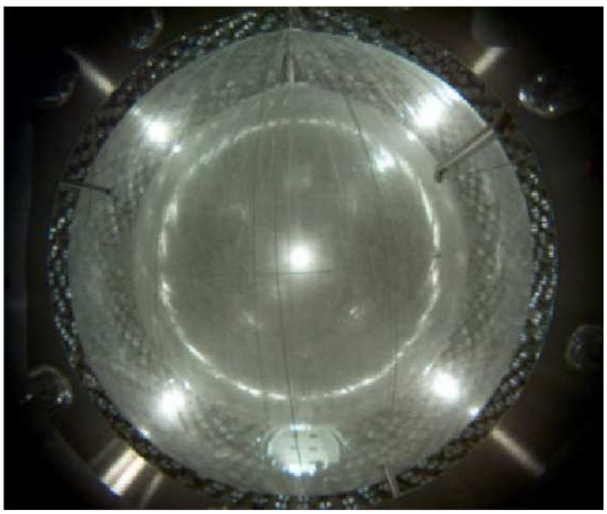

Figure 2: The Inner and Outer Nylon Vessels installed and inflated with nitrogen in the Stainless Steel Sphere.

The key features of the Borexino detector are described in Refs. [1, 2, 3]. Borexino (see Fig. 1) is a scintillator detector with an active mass of 278 tons of pseudocumene (PC, 1,2,4-trimethylbenzene), doped with 1.5 g/liter of PPO (2,5-diphenyloxazole, a fluorescent dye). The scintillator is contained in a thin (125 μm) nylon vessel [4] (as shown in Fig. 2) and is surrounded by two concentric PC buffers (323 and 567 tons) doped with 5.0 g/l of dimethylphthalate (DMP), a component quenching the PC scintillation light. The two PC buffers are separated by a second thin nylon membrane to prevent diffusion of radon towards the scintillator. The scintillator and buffers are contained in a Stainless Steel Sphere (SSS) with diameter 13.7 m. The SSS is enclosed in a 18.0-m diameter, 16.9-m high domed Water Tank (WT), containing 2100 tons of ultrapure water as an add! itional shield. The scintillation light is detected via 2212 8" PMTs uniformly distributed on the inner surface of the SSS [5, 6]. Additional 208 8" PMTs instrument the WT and detect the Cherenkov light radiated by muons in the water shield, serving as a muon veto.

The key requirement in the technology of Borexino is achieving extremely low radioactive contamination, at or below the expected interaction rate of 0.5 counts/(day·ton) expected for ^{7}Be neutrinos. The design of Borexino is based on the principle of graded shielding, with the inner core scintillator at the center of a set of concentric shells of increasing radiopurity. All components were screened and selected for low radioactivity [7], and the scintillator and the buffers were purified on site at the time of filling [8, 9]. Position reconstruction of the events, as obtained from the PMTs timing data via a time-of-flight algorithm, allows to fiducialize the

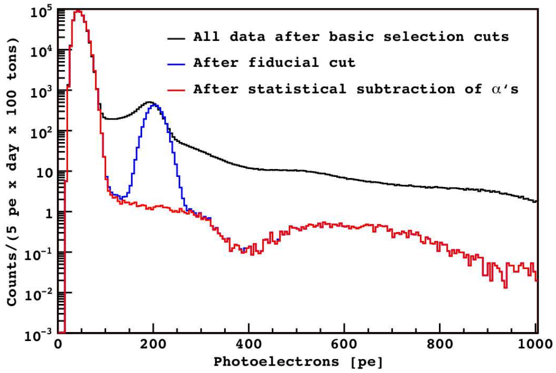

Figure 3: The raw photoelectron charge spectrum after the basic cuts i–iii (black), after the fiducial cut iv (blue), and after the statistical subtraction of the α-emitting contaminants (red). All curves scaled to the exposure of 100 day·ton. Cuts described in the text.

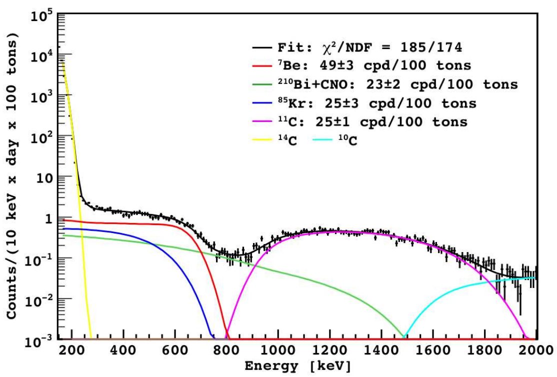

Figure 4: Spectral fit in the energy region 160–2000 keV.

active target: approximately 2/3 of the scintillator serves as an active shield.

Events are selected by means of the following cuts:

i Events must have a unique cluster of PMTs hits, to reject pile-up of multiple events in the same acquisition window.

ii Muons and all events within a time window of 2 ms after a muon are rejected.

iii Decays due to radon daughters occurring before the ^{214}Bi-^{214}Po delayed coincidences are vetoed. The fraction surviving the veto is accounted for in the analysis.

iv Events must be reconstructed within a spherical fiducial volume corresponding approximately to 1/3 of the scintillator volume in order to reject external γ background. Additionally, we require the z-coordinate of the reconstructed vertex, measured from the center of the detector, to satisfy $|z|<1.7$ m in order to remove background near the poles of the inner nylon vessel.

The combined loss of fiducial exposure due to the cuts i-iii is 0.7%. The fiducial cut iv results in a fiducial mass of 78.5 tons.

The black curve in Fig. 3 is the spectrum of all events surviving the basic cuts i-iii: below 100 photoelectrons (pe) the spectrum is dominated by ^{14}C decays (β^-, Q=156 keV) intrinsic to the scintillator [10] and the peak at 200 pe is due to ^{210}Po decays (α, Q=5.41 MeV, light yield quenched by $\sim$13), a daughter of ^{222}Rn out of equilibrium with the other isotopes in the sequence. The blue curve is the spectrum after the fiducial cut iv. The red curve is obtained by statistical subtraction of the α-emitting contaminants, by use of the pulse shape discrimination made possible by the PC-based scintillator [11]. Prominent features include the Compton-like edge due to ^{7}Be solar neutrinos (300–350 pe) and the spectrum of ^{11}C (β^+, Q=1.98 MeV, created in situ by cosmic ray-induced showers, 400–800 pe).

The study of fast coincidence decays of ^{214}Bi-^{214}Po (from ^{238}U) and ^{212}Bi-^{212}Po (from ^{232}Th) gives the contamination for ^{238}U of $(1.6\pm0.1)\times10^{-17}$ g/g and for ^{232}Th of $(6.8\pm1.5)\times10^{-18}$ g/g. The ^{85}Kr content in the scintillator was probed through the rare decay sequence $^{85}\mathrm{Kr} \rightarrow {}^{85\mathrm{m}}\mathrm{Rb} + e^+ + \nu_e$, $^{85\mathrm{m}}\mathrm{Rb} \rightarrow {}^{85}\mathrm{Rb} + \gamma$ (τ=1.5 μs, BR 0.43%) with a delayed coincidence tag. The activity of ^{85}Kr equals to 29±14 counts/(day·100 ton).

The light yield and the interaction rate of ^{7}Be solar neutrinos was determined by fitting the α-subtracted spectrum in the region 100–800 pe, accounting for the presence of several possible contaminants. We obtain a light yield of about 500 pe/MeV for β's at the minimum of ionization with the energy resolution $5\%/\sqrt{E\,[\mathrm{MeV}]}$. The weights for ^{14}C, ^{11}C, and ^{85}Kr are left as free parameters in the fit. The ^{214}Pb surviving cut iii is independently determined and its weight in the fit is fixed. Weights for *pp* and *pep* neutrinos are fixed to the values expected from the Standard Solar Model (SSM) [12] and from a recent determination of $\sin^2 2\theta_{12}$=0.87 and Δm^2_{12}=7.6×10^{-5} eV^2 [13], which correspond to the Large Mixing Angle (LMA) scenario of solar neutrino oscillation via the MSW effect [14]. The spectra for CNO neutrinos and ^{210}Bi are almost degenerate and c! annot be distinguished prior to removal of the ^{11}C background [15, 16]: we use a single component whose weight is a free parameter. Two independent analysis codes report consistent spectra and results, shown in Fig. 4 and summarized in Table 1. A further check was performed by fitting the spectrum obtained prior to statistical α's subtraction, obtaining consistent results, as shown in Fig. 5.

Several sources, as summarized in Table 2, contribute to the systematic error. The total mass of scintillator (315 m^3, 278 ton) is known within ±0.2%. Not so yet for the fiducial mass, which is defined by a software cut. We estimate the systematic error to be ±6% on the basis of the distribution of reconstructed vertexes of uniform background sources (^{14}C, 2.2 MeV γ-rays from capture of cosmogenic neutrons, daughters of Rn introduced during the filling with scintillator) and on the basis of the inner vessel radius determined from the reconstructed position of sources located at the periphery of the active volume (^{212}Bi-^{212}Po coincidences emanating from ^{228}Th contaminations in the nylon of the inner vessel and γ-rays from the buffer volumes). The uncertainty in the detector response function results in a large systematic error, as small variations in the energy response affect the balance of counts attributed by the fit to ^{7}Beand ^{85}Kr. The global systematic uncertainty planned to be reduced with the forthcoming deployment of calibration sources inside the detector.

Taking into account systematic errors, the measured interaction rate of the 0.862 MeV ^{7}Be solar neutrinos equals to $49\pm3_{\mathrm{stat}}\pm4_{\mathrm{syst}}$ counts/(day·100 ton). The expected signal for non-oscillated solar ν_e in the high metallicity SSM [12] is 74±4 counts/(day·100 ton) corresponding to a flux $\Phi(^7\mathrm{Be})=(5.08\pm0.25)\times10^9$ cm^{-2}s^{-1}. In the MSW-LMA scenario of solar neutrino oscillation, it is 48±4 counts/(day·100 ton), in very good agreement with our measurement.

In the MSW-LMA scenario, neutrino oscillations are dominated by matter effects above

Table 1: Fit Results [counts/(day·100 ton)].

^{7}Be	$49\pm3_{\mathrm{stat}}$
^{85}Kr	$25\pm3_{\mathrm{stat}}$
^{210}Bi+CNO	$23\pm2_{\mathrm{stat}}$
^{11}C	$25\pm1_{\mathrm{stat}}$

Table 2: Estimated Systematic Uncertainties [%].

Total Scintillator Mass	0.2	Fiducial Mass Ratio	6.0
Live Time	0.1	Detector Resp. Function	6.0
Efficiency of Cuts	0.3		
Total Systematic Error			8.5

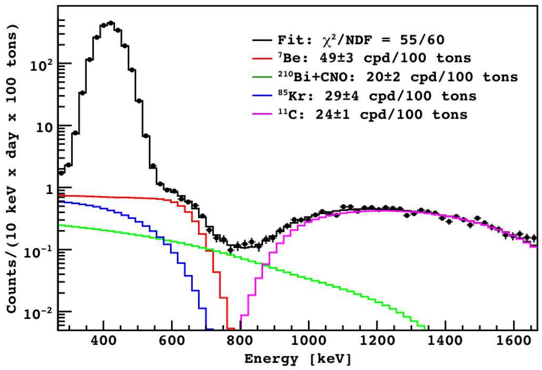

Figure 5: Spectral fit in the energy region 260–1670 keV prior to statistical α's subtraction.

3 MeV and by vacuum effects below 0.5 MeV [17]. The ^{7}Be neutrinos lie in the lower edge of this transition region. The measured interaction rate of ^{7}Be neutrinos depends on the solar ν_e flux and on the survival probability P_{ee} at the energy of 0.862 MeV. At present, the only direct measurement of P_{ee} is in the matter-dominated region by observation of ^{8}B neutrinos above 5 MeV [18]. The measurement of P_{ee} in and below the transition region is an important test of a fundamental feature of the MSW-LMA scenario.

Under the assumption of the constraint coming from the high metallicity SSM (6% uncertainty on ^{7}Be neutrinos flux), we combine in quadrature systematic and statistical error and we obtain P_{ee}=0.56±0.10 (1σ) at 0.862 MeV. This is consistent with P_{ee}=0.541±0.017, as determined from the global fit to all solar (except Borexino) and reactor data [13]. The no oscillation hypothesis, P_{ee}=1, is rejected at 4σ C.L..

Prior to the Borexino measurement the best estimate for $f_{\rm Be}$, the ratio between the measured value and the value predicted by the high metallicity SSM [12] for the ^{7}Be neutrinos flux, was $1.03^{+0.24}_{-1.03}$ [19], as determined through a global fit on all solar (except Borexino) and reactor data, with the assumption of the constraint on solar luminosity. From our measurement, under the assumption of the constraint from the high metallicity SSM and of the MSW-LMA scenario, we obtain $f_{\rm Be}$=1.02±0.10. Correspondingly, our best estimate for the flux of ^{7}Be neutrinos is $\Phi(^7{\rm Be})=(5.18\pm0.51)\times10^9$ cm^{-2}s^{-1}.

Future goals of Borexino operation are aimed on the real-time measurement of *pp*, ^{8}B and CNO solar neutrino fluxes, detection of reactor and geo antineutrinos and posible Supernova observations. This year the Borexino detector will provide the monitoring of neutrino beam coming from CERN to Gran Sasso Laboratory.

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