The first year of Borexino

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Borexino is an experiment designed to detect in real-time low energy solar neutrinos. It is installed at the Gran Sasso Underground Laboratory and has started taking data in May 2007. We report the direct measurement of the $^7$Be solar neutrino signal rate after 1 year of data taking. Implications and perspectives are discussed.

1. Introduction

The Sun is an intense source of electron neutrinos, produced in the nuclear reactions of the proton-proton chain and of the CNO cycle. Solar neutrinos provide a unique probe for studying both the nuclear fusion reactions that power the Sun and the fundamental properties of neutrinos.
In particular, neutrino oscillations, described in the Large Mixing Angle (LMA) Mykhayev-Smith-Wolfenstein (MSW) [1, 2] theory, offer a solution to the solar neutrino problem, the long standing discrepancy between the observation of the solar neutrino flux in the pioneer radiochemical and water Cherenkov experiments [3] and the prediction of the Standard Solar Model [4].

A central feature of the LMA-MSW solution is the prediction that neutrino oscillations are dominated by vacuum oscillations at low energies (<2 MeV) and by resonant matter-enhanced oscillations, taking place in the Sun’s core, at higher energies (>5 MeV).

Borexino is the first experiment to report a real-time observation of low energy solar neutrinos in the vacuum oscillation regime by the direct measurement of the low energy (0.862 MeV) ⁷Be solar neutrino interaction rate. We report here the results [5, 6] from an analysis of 192 live days of Borexino detector live-time in the period from May 16, 2007 to April 12, 2008, totaling a 41.3 ton yr fiducial exposure to solar neutrinos.

Solar neutrinos are detected in Borexino through their elastic scattering on electrons in the scintillator. Electron neutrinos (νe) interact through charged and neutral currents and in the energy range of interest have a cross section 5 times larger than νμ and ντ, which interact only via the neutral current. The electrons scattered by neutrinos are detected by means of the scintillation light retaining the information on the energy, while information on the direction of the scattered electrons is lost. The basic signature for the mono-energetic 0.862 MeV ⁷Be neutrinos is the Compton-like edge of the recoil electrons at 665 keV, as shown in Figure 1.

A strong effort has been devoted to the containment and comprehension of the background, since electron-like events induced by solar neutrino interactions can not be distinguished, on an event-by-event basis, from electrons or photons due to radioactive decays. The main challenge is then to reduce the background in the active mass in order to reach a signal-to-noise ratio of 1 an intrinsic radiopurity of 4 10⁻⁵ Bq/kg is required both for ²³⁵U and ²³²Th contaminations. The Borexino purification strategy relies on filtration at the level of 0.05 µm, multi-stage distillation and high purity nitrogen sparging.

2. The Detector

The Borexino detector is located at the Gran Sasso National Laboratories (LNGS) in central Italy, at a depth of 3800 m.w.e.. Neutrinos are detected via elastic scattering off electrons in liquid scintillator. The sketch of the detector is shown in Figure 2. The active target consists 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 and is shielded by two concentric PC buffers (323 and 567 tons) doped with 5.0 g/l of a scintillation light quencher (dimethylphthalate). 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 a diameter of 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 ultra-pure water as an additional shield. The scintillation light is detected via 2212 8” photomultiplier tubes (PMTs) uniformly distributed on the inner surface of the SSS. Additional 208 8” PMTs instrument the WT and detect the Cherenkov light radiated by muons in the water shield, serving as a muon veto. A detailed description of the detector can be found in [5].

An event in Borexino is recorded when at least 25 PMT pulses occur within a time window of 99 ns (the corresponding energy threshold is about 40 keV). When a trigger occurs, a 16 µs gate is opened and time and charge of each PMT pulse is collected. The offline software identifies the shape and the length of each scintillation pulse and reconstructs the position of the energy deposit in the scintillator by means of a time of flight technique. Pulse shape analysis is performed to identify various classes of events, among

![Figure 1: Neutrino spectra expected in Borexino (accounting for the detector’s energy resolution). The solid black line represents the neutrino signal rate in Borexino according to the most recent predictions of the Standard Solar Model [4] including neutrino oscillations with the LMA-MSW parameters [2]. The solid red line illustrates the contribution due to ⁷Be neutrinos. pp neutrinos contribute to the spectrum below 0.3 MeV and the edge at 1.2 MeV is due to p-e-p neutrinos.](image-url)
which electronic noise, pile up events, muons, α and β particles.

3. Event Selection and Spectral Fits

The analyzed energy range is 250–800 keV. The event selection relies on the following cut criteria:

1. The event must have a unique reconstructed cluster of PMT hits, in order to reject pile-up events and fast coincident events in the same acquisition window. The efficiency of this cut is nearly 100% because the very low triggering rate results in a negligible pile-up.

2. Events with Čerenkov light in the water tank detector are identified as cosmic muons and rejected.

3. All the detector is vetoed for 2 ms after each muon crossing the scintillator. In this way, muon-induced neutrons (mean capture time ∼ 250 µs) and spurious events like after-pulses are rejected. The measured muon rate in Borexino (muons that cross the scintillator and buffer volume) is 0.055±0.002 s⁻¹. The dead time introduced by this cut is negligible.

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

5. The events must be reconstructed within a spherical fiducial volume corresponding nominally to 100 ton in order to reject external γ background (Figure 3). Another volumetric cut (z<1.8 m) was applied in order to remove a small background from ²²²Rn daughters in the north pole of the inner vessel, resulting in a nominal fiducial mass of 87.9 t.

In Figure 4 the measured spectrum in 192 days is shown before and after the cuts. It can be noticed that an important peak is present in the data after the fiducial volume cut. This peak is due to a ²¹⁰Po contamination still present in the liquid scintillator after purification and filling. ²¹⁰Po is produced in decay chain segment starting from ²¹⁰Pb. ²¹⁰Pb decays to ²¹⁰Bi which has an end-point energy at about 1 MeV. The measured activity of ²¹⁰Po is clearly not in equilibrium with a ²¹⁰Bi source, as shown in Figure 5. Moreover, the measured decay trend has a mean life compatible with ²¹⁰Po. Even if ²¹⁰Pb contamination is high with respect to the expected signal, it can be efficiently identified in the offline analysis with the pulse shape discrimination, shown in Figure 4.
A filter based on the time response of the PC-based scintillator [8], slower for α particles than for β’s, discriminates the 210Po events. The red curve in Figure 4 shows the effect of the statistical subtraction of the α-emitting contaminants, by use of the pulse shape discrimination.

The study of fast coincidence decays of 214Bi-214Po (see Figure 6) and 212Bi-212Po, yields, under the assumption of secular equilibrium, to the estimation of 238U contamination equal to (1.6±0.1)×10^{-17} g/g and of 232Th equal to (6.8±1.5)×10^{-18} g/g. The 85Kr content in the scintillator was probed by looking the delayed coincidence in the secondary branch of 85Kr decay throughout the metastable level 85mRb (BR =0.43%). Our best estimate for the activity of 85Kr is 29±14 counts/(day·100 ton).

From the spectrum in Figure 8 the expected Compton-like edge due to 7Be solar neutrinos is well visible. Moreover, it can be seen that at high energy the spectrum is dominated by a cosmogenic component well known, the 11C. 11C is produced underground by muons interacting with 12C in the liquid scintillator. This background depends on the depth of the underground laboratory [9, 10].

The spectra within the fiducial volume was studied with and without the α statistical subtraction. Results are shown in Figures 8 and 9. In the spectral fits, the contribution of CNO neutrinos is combined with that of 210Bi which is not known. The two spectra are degenerate in the 7Be region. The 7Be, the 85Kr, the 11C as well as the light yield are free parameters of the fit. A light yield of about 500 P.E./MeV is found for β’s, and the energy resolution scales approximately as 5%/√E [MeV].

Systematic uncertainties come mainly from the total scintillator mass (0.2%), the fiducial mass definition (6%) and the detector response function (6%). Taking into account systematic errors, our best value for the interaction rate of the 0.862 MeV 7Be so-
Figure 9: Spectral fit in the energy region 160-2000 keV.

Solar neutrinos is $49 \pm 3 \text{ (stat)} \pm 4 \text{ (syst)} \text{ counts/(day100 ton)}$. The corresponding flux solar neutrino flux $\Phi(7\text{Be })=(5.08 \pm 0.25) \times 10^9 \text{ cm}^{-2} \text{ s}^{-1}$ is evaluated assuming the oscillation parameters, $\sin^2 2\theta_{12}=0.87$ and $\Delta m_{12}^2=7.6 \times 10^{-5} \text{ eV}^2$, from [2], in good agreement with expectations.

4. Results and Perspectives

The expected neutrino interaction rate in case of no oscillations is $74 \pm 4 \text{ counts/(day100 ton)}$. The Borexino measurement of the $7\text{Be}$ neutrino rate confirms the oscillation hypothesis at $4 \sigma$, in agreement with the MSW-LAM prediction.

Under the assumption of the SSM constraint the solar neutrino survival probability is measured to be $P_{ee}=0.56 \pm 0.10$.

The Borexino measured rate can be combined with the other solar neutrino measurements to constrain the flux normalization constants of the other solar neutrino fluxes. This leads to the best determination of the pp solar neutrinos flux, obtained with the assumption of the luminosity constraint: $f_{pp}=1.005 \pm 0.029$ where $f_{pp}$ is the ratio between the measured and predicted pp neutrino fluxes. With the same technique, Borexino obtained the best limit on the CNO flux: $f_{CNO}<6.27 \text{ (90\% C.L.)}$.

The low energy solar neutrino spectrum is sensitive to the possible presence of a non-null magnetic moment. We exploited this feature to determine the best upper limit to the neutrino magnetic moment $(5.4 \times 10^{-11} \mu_B, 90\% \text{ C.L.})$ [6].

The first Borexino results have shown for the first time the feasibility to measure solar neutrinos in the sub-MeV range in real-time. Moreover, the high level of radio-purity achieved allows to investigate other solar neutrino sources. In particular, CNO and p-e-p neutrino detections depend on the possibility to tag and reject event by event cosmogenic $^{11}\text{C}$ background.

Thanks to the excellent scintillator radio-purity, Borexino has also the opportunity to measure the $^8\text{B}$ neutrino spectrum with the lowest energy threshold so far. A dedicated analysis with the energy threshold at 2.8 MeV is in progress.

References

[1] S.P. Mikheev and A.Yu. Smirnov, Sov. J. Nucl. Phys. 42, 913 (1985); L. Wolfenstein, Phys. Rev. D 17, 2369 (1978); P.C. de Holanda and A.Yu. Smirnov, JCAP 0302, 001 (2003).

[2] S. Abe et al., (KamLAND Collaboration), arXiv:0801.4589v2, submitted to Phys. Rev. Lett. (2008).

[3] B.T. Cleveland et al., Ap. J. 496, 505 (1998); K. Lande and P. Wildenhain, Nucl. Phys. B (Proc. Suppl.) 118, 49 (2003); R. Davis, Nobel Prize Lecture (2002). W. Hampel et al. (GALLEX Collaboration), Phys. Lett. B 447, 127 (1999); J.N. Abdurashitov et al. (SAGE collaboration), Phys. Rev. Lett. 83, 4686 (1999); M. Altmann et al. (GNO Collaboration), Phys. Lett. B 616, 174 (2005); K.S. Hirata et al. (KamiokaNDE Collaboration), Phys. Rev. Lett. 63, 16 (1989).

[4] J.N. Bahcall, A.M. Serenelli, and S. Basu, Astrophys. J. Suppl. 165, 400 (2006); C. Peña-Garay, talk at the conference Neutrino Telescopes 2007", March 6-9, 2007, Venice, http://neutrino.pd.infn.it/conference2007/

[5] C. Arpesella et al. (Borexino Collaboration), Phys. Lett. B 658, 101 (2007).

[6] C. Arpesella et al. (Borexino Collaboration), accepted for publication on Phys. Rev. Lett., arXiv:0805.3813 (2008).

[7] G. Alimonti et al. (Borexino Collaboration), submitted to Nucl. Instr. Meth. A, arXiv:0806.2400 (2008).

[8] H.O. Back et al.(Borexino Collaboration), Nucl. Instrum. Meth. A 584 98-113 (2008).

[9] C. Galbiati et al., Phys.Rev.C 71 055805 (2005).

[10] H. Back et al. (Borexino Collaboration), Phys. Rev. C 74, 045805 (2006).