RESULTS FROM THE BOREXINO EXPERIMENT*

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on behalf of the Borexino Collaboration

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Borexino is a real-time experiment for low energy neutrino spectroscopy, operating at the Laboratori Nazionali del Gran Sasso (Italy). Borexino is the first experiment to report a real-time observation of low energy solar neutrinos below 4.5 MeV, which were not accessible so far with the state-of-the art detector technologies because of natural radioactivity. The results reported in this work present the real-time measurement of the low energy (0.862 MeV) ^{7}Be solar neutrinos with the Borexino detector from an analysis of 192 live days in the period from May 16, 2007 to April 12, 2008, totaling a 41.3 ton·yr fiducial exposure to solar neutrinos. Additionally we show data on solar ^{8}B neutrinos with an energy threshold of 2.8 MeV.

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1. Introduction

The neutrino oscillations were discovered for atmospheric neutrinos. However, many years earlier solar neutrino experiments presented the deficiency of electron neutrinos, which is now also explained in terms of the neutrino oscillations. Elements of the neutrino PMNS mixing matrix are deduced from studies of solar, reactor, atmospheric and accelerator neutrinos. The real time measurement of the flux of sub MeV solar neutrinos is presently very valuable to confirm the low energy behavior of the neutrino survival probability P_{ee} predicted by the LMA-MSW scenario: in fact, neutrino oscillations are expected to be dominated by matter effects for energies higher than about 3 MeV and by vacuum effects below 0.5 MeV [1]. Therefore, the first simultaneous measurement of the neutrino survival probability P_{ee} in the vacuum and in the matter enhanced oscillation regions, is of great importance. An additional physics result already obtained by Borexino concerns best limits for CNO flux, ν magnetic moment and Pauli principle violation.

2. The Borexino detector

Borexino is a large unsegmented calorimeter with an active mass of 278 tons of organic liquid scintillator (Pseudocumene (PC) — 1,2,4 trimethylbenzene, doped with 1.5 g/l of PPO — 2,5 diphenyloxazole) contained in a 125 μm thick nylon vessel having 8.5 meter diameter. The Inner Vessel (IV) is made of Nylon-6 carefully selected and handled in order to achieve maximum radiopurity [2]. 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 improves the effectiveness of the system as a barrier against ^{222}Rn emanated from the external materials (steel, glass, PMT materials) diffusing inward into the fiducial volume.

A stainless steel sphere (13.7 m diameter), surrounding the scintillator vessel, houses the 2212 photomultipliers (PMTs) that detect the scintillation light. All but 384 PMTs are equipped with light concentrators that are designed to reject photons not coming from the active scintillator volume. The volume between the two spheres is filled again with Pseudocumene with small amount (5 g/l) of DMP (dimethylphthalate) that is added as a light quencher in order to further reduce the scintillation yield of pure PC [3, 4]. A cylinder of 18 m diameter and 16.9 m height filled with ultrapure water contains the sphere and act both as radiation shield and as Čerenkov detector used to identify (and veto) muons. The tank is equipped with 208 PMTs that collect light in water. The muon flux is of the order of 1 $m^{-2}h^{-1}$, which corresponds to about 4000 muons per day crossing the detector.

Key features of the PC/PPO solution that we adopted as liquid scintillator are high scintillation yield (10^4 photons/MeV), high light transparency (the mean free path is typically 8 m) and fast decay time (≈ 3 ns). High scintillation yield is essential for good energy resolution. The fast time response allows to reconstruct the scintillation position with high spatial precision and gives the possibility to discriminate between β-like events and events due to α particles. The isotropy of the light emission forbids the reconstruction of the neutrino arrival direction which would be a powerful tool to discriminate signals from background.

The amount of emitted light and the time distribution of the photons must be measured in order to determine the energy and the position of a scintillation event. Digital boards connected to the front-end circuit of each PMT record two signals. The voltage amplitude is measured for the energy determination and photon arrival time is used for the position reconstruction. More detailed information on the Borexino design and instrumentation is available in Ref. [3].

3. Radiopurity and background levels

Solar neutrinos are detected by their elastic scattering on the electrons of the scintillator. The shape of the energy spectrum of recoil electrons is the only strong signature available in the data: events induced by γ or β radioactivity cannot be distinguished from the signal on a event by event analysis but only through their spectral shape. This fact, together with the expected low signal rate (from few tens counts/(day·100 ton) to less than one event/(day·100 ton) depending on the solar neutrino spectral component) strongly demands for an extremely high radiopurity detector.

Borexino has reached, and in some case also exceeded, the design requirements about radiopurity. Ultra low operating backgrounds in the detector (from internal and external sources) are obtained using the principle of graded shielding with the scintillator at the center of a set of concentric shells of increasing radiopurity. All internal components of the detector were selected for low radioactivity. Underground purification of the scintillator by distillation, water extraction, nitrogen stripping and ultra-fine filtration were key for the Borexino detector to remove contaminants from dust (U, Th, K), from the air (^{39}Ar, ^{85}Kr) and from cosmogenically produced isotopes (^{7}Be).

The study of the time correlated events belonging to the ^{238}U and ^{232}Th radioactive chains yields, under the assumption of secular equilibrium, an internal contamination for ^{238}U of $1.6 \pm 0.1 \times 10^{-17}$ g/g and for ^{232}Th of $6.8 \pm 1.5 \times 10^{-18}$ g/g [5]. The concentration of these contaminants is significantly lower than the design value of 10^{-16} g/g and it is not the main issue of the ^{7}Be analysis. On the contrary, the most important background is due to the β decay of ^{85}Kr with 687 KeV end point having a rate of the same order of magnitude of the ^{7}Be signal. The ^{85}Kr content in the scintillator, 29 ± 14 counts/(day·100 ton), was probed through the rare decay sequence $^{85}\mathrm{Kr} \rightarrow {}^{85m}\mathrm{Rb} + \mathrm{e}^{+} + \nu_e$, $^{85m}\mathrm{Rb} \rightarrow {}^{85}\mathrm{Rb} + \gamma$ (branching ratio 0.43%, $\tau = 1.5\ \mu$ s). Additional identified background sources come from ^{210}Bi and ^{11}C decays. The last isotope is produced by muons interacting with the scintillator.

4. Data analysis and results

The curves presented in Fig. 1 (upper) are the results of 192 live days of measurement. The solid black line demonstrates the raw data with the 3 most basic cuts already applied. This means, that only single clustered events are accepted in order to reject pile up or fast coincidences. Second, all muons are neglected. This tagging can be performed using the OD as an active muon veto. The efficiency is 99.5%. In addition, muons and neutrinos can be distinguished by pulse shape analysis using the ID. The remaining inefficiency is reduced to less than 10^{-3}. And third, as a logical consequence, all events detected in a 2 ms time window after each muon, are rejected in order to avoid muon induced secondaries. The dashed blue curve is obtained using a fiducial volume cut to reject external γ background: The allowed detector volume corresponds to the innermost 100 tons ($\sim$ 3.25 m radius). Also the radon induced ^{214}Bi–^{214}Po coincidences are removed from data. The large ^{14}C peak remains at the lower energy range of the observed spectrum, which therefore will not influence the results of the ^{7}Be neutrinos. Another remaining obvious part is the still present ^{210}Po peak at about 190 pe. It can be rejected by α/β pulse shape discrimination (dotted red curve). In both cases, dashed blue and dotted red line, the compton like edge of the ^{7}Be neutrinos (300–350 pe) and the ^{11}C spectrum (400–800 pe) become visible [6]. In Fig. 1 (bottom), as final result, the fits applied to the remaining data are presented [5]. Two independent methods are used for this evaluation and come to consistent results (expressed in counts/(day·100 ton), statistical errors only): 49 ± 3

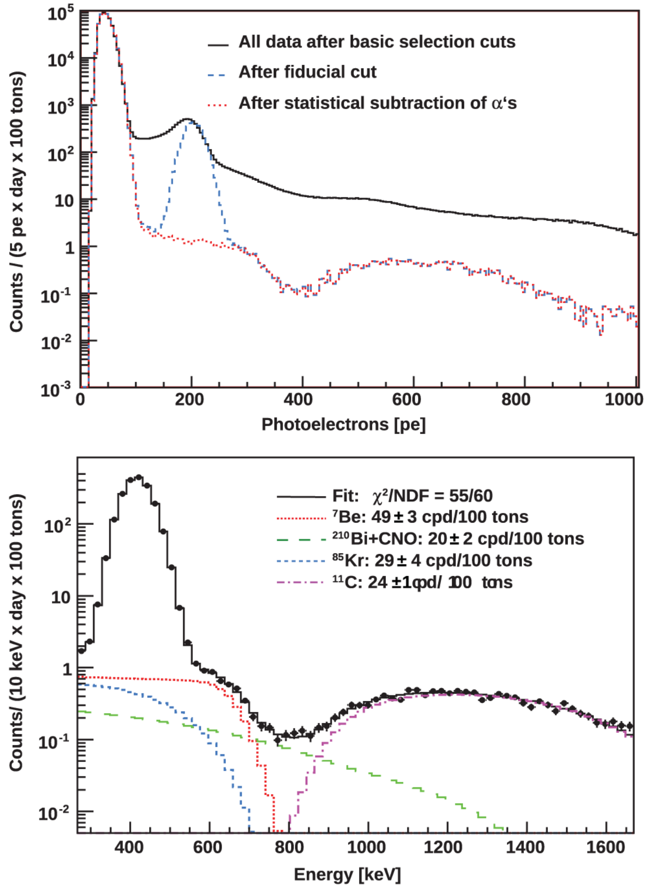

Fig. 1. Upper: The raw photoelectron charge spectrum after the basic cuts (solid black), after the fiducial cut (dashed blue), and after the statistical subtraction of the α-emitting contaminants (dotted red). All curves scaled to the exposure of 100 day·ton. Bottom: Spectral fit in the energy region 260–1670 keV prior to statistical αs subtraction.

for ^{7}Be, 20 ± 2 for a sum of CNO-neutrinos and ^{210}Bi, 29 ± 4 for ^{85}Kr, 24 ± 1 for ^{11}C. With an estimation of the systematic error (8.5%), our best value for the interaction rate of the 0.862 MeV ^{7}Be solar neutrinos is $49 \pm 3_{\rm stat} \pm 4_{\rm sys}$ counts/(day·100 ton). The rate expected without neutrino oscillation for the high metallicity Standard Solar Model (SSM) (BS07(GS98)) is (74 ± 4) counts/(day·100 ton). The ratio between the measured value and the value predicted by the high metalicity SSM is calculated to be $f_{\rm Be} = 1.02 \pm 0.10$. The observed survival probability at the ^{7}Be energy of 862 keV is $P_{ee} = 0.56 \pm 0.10$. The no oscillation hypothesis ($P_{ee} = 1$)

is rejected at 4σ C.L. So, Borexino results confirm the MSW-LMA neutrino oscillation scenario and provides the first direct measurement in the low-energy vacuum MSW regime.

In addition, a ^{8}B neutrino rate of $(0.26 \pm 0.04_{\rm stat} \pm 0.02_{\rm sys})$ counts per day and 100 tons down to an energy of 2.8 MeV can be reported [7]. The corresponding ν_e flux of $(2.65 \pm 0.44_{\rm stat} \pm 0.18_{\rm sys}) \times 10^6$ cm^{-2} s^{-1} is in agreement with the MSW-LMA SSM prediction and SNO or Super-Kamiokande results. Assuming the BS07(GS98) SSM, the mean survival probability is 0.35 ± 0.10 at the effective energy of 8.6 MeV. The no-oscillation scenario can be excluded using this preliminary analysis at a 4.2 σ C.L. Borexino is the first experiment with the ability to simultaneous measure solar neutrinos from the vacuum region (^{7}Be) and from the matter-enhanced oscillation region (^{8}B). The ratio between the two different survival probabilities for ^{7}Be and ^{8}B neutrinos is 1.60 ± 0.33, 1.8 σ different from unity. Still at relatively low significance, this result confirms the transition between low energy vacuum dominated and high energy matter enhanced solar neutrino oscillation, as predicted by the MSW-LMA solution.

Another interesting result obtained with 192 days of the Borexino data is the new strongest limit on the effective neutrino magnetic moment. The study of the maximum allowed deviations from the pure electroweak electron recoils shape for ^{7}Be neutrinos performed with Borexino data lead to the new limit on the effective neutrino moment of $\mu_\nu < 5.4 \times 10^{-11}\ \mu_B$ at 90% C.L. [5].

5. The future of Borexino

Given the unprecedented purity levels already achieved in Borexino, there are plenty of goals which we would like to achieve. A broad investigation of the solar ν spectrum is well within our reach. The results of two calibration campaigns are expected to contribute to a significant reduction of systematic errors on the fiducial volume and on the energy calibration. 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. The detection of geo-neutrinos in Borexino is also in progress and we expect to collect a statistically significant sample of events in few years. A measurement of terrestrial neutrinos could be used to probe geophysical models. Borexino has also strong potential in the field of supernovae (anti-) neutrinos. Detection of low energy neutrinos from the last stages of nuclear burning may help to foresee a massive star death a few days before its core collapse [8]. Borexino Collaboration joined the SNEWS project which involves an international collaboration of experimenters representing current supernova neutrino detectors.

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REFERENCES

[1] A.Yu. Smirnov, `arXiv:hep-ph/0305106v1`, talk given at the 11th Workshop on Neutrino Telescopes, Venice, March 11–14, 2003.

[2] J. Benziger *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A582**, 509 (2007).

[3] G. Alimonti *et al.* [Borexino Collaboration], *Nucl. Instrum. Methods Phys. Res.* **A600**, 568 (2009).

[4] G. Alimonti *et al.* [Borexino Collaboration], *Nucl. Instrum. Methods Phys. Res.* **A609**, 58 (2009).

[5] C. Arpesella *et al.* [Borexino Collaboration], *Phys. Rev. Lett.* **101**, 091302 (2008).

[6] C. Arpesella *et al.* [Borexino Collaboration], *Phys. Lett.* **B658**, 101 (2008).

[7] G. Bellini *et al.* [Borexino Collaboration], `arXiv:0808.2868v3 [astro-ph]`.

[8] A. Odrzywolek, M. Misiaszek, M. Kutschera, *Astropart. Phys.* **21**, 303 (2004).