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Solar neutrino physics with Borexino

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Summary. — We report the direct measurements of ^{7}Be and ^{8}B solar neutrino signal rates performed with the Borexino detector at the Laboratori Nazionali del Gran Sasso.

PACS `26.65.+t` – Solar neutrinos.
PACS `29.40.Mc` – Scintillation detectors.

1. – Introduction

Borexino [1,2] is a real-time experiment for solar low energy neutrino spectroscopy, operating since May 2007 at the underground Gran Sasso National Laboratories. Solar neutrinos are detected by means of their elastic scattering off electrons in a liquid-scintillator target: 278 tons of pseudocumene doped with 1.5 g/l of PPO. The scintillator is housed in a thin (125 μm) nylon vessel and is shielded by a buffer of 1000 tons of pseudocumene. 2212 photomultiplier tubes, mounted on a stainless steel sphere (SSS), detect the scintillation light. Finally, the SSS is installed inside a 3000 m^3 water tank which provides the necessary shielding against rock-induced external backgrounds and is used as a Cerenkov detector to veto the residual muons.

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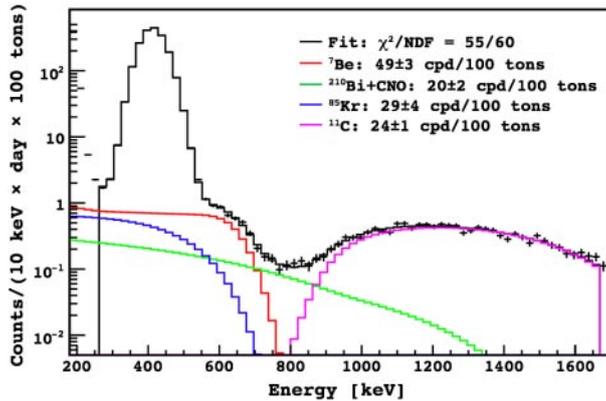
Fig. 1. – Spectral fit in the energy region 260–1670 keV before the α subtraction.

The Borexino purification strategy relies on filtration at the level of $0.05\,\mu$m, multi-stage distillation and high-purity nitrogen sparging. Borexino obtained an excellent level of radiopurity in the innermost scintillator target: ^{238}U contamination is at $(1.6 \pm 0.1) \times 10^{-17}$ g/g and the ^{232}Th contamination at $(6.8 \pm 1.5) \times 10^{-18}$ g/g.

2. – ^{7}Be rate measurement

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. The dominant background contributions are muons, external background and fast delayed events (^{214}Bi-^{214}Po, ^{212}Bi-^{212}Po), rejected exploiting the Cerenkov detector, applying a radial cut of 3 m (the innermost 100 tons of scintillator), and thanks to the time and spatial correlations, respectively.

The measured spectrum in 192 days of data taking is shown in fig. 1. The peak at ~ 400 keV is due to a ^{210}Po contamination still present in the liquid scintillator after purification and filling. ^{210}Po can be statistically subtracted by use of the pulse shape discrimination. The high-energy component of the spectrum is dominated by the cosmogenic ^{11}C, produced underground by muons interacting with ^{12}C in the liquid scintillator.

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 ^{7}Be solar neutrinos is $49 \pm 3_{\text{stat}} \pm 4_{\text{syst}}$ c/d/100 ton.

3. – ^{8}B rate measurement

This measurement is based on 245.9 live days of data-taking in the target mass of 100 tons.

The 2.8 MeV energy threshold is imposed by the 2.6 MeV γ's from the β-decay of ^{208}Tl, due to radioactive contamination mainly in the photomultiplier tubes. The data selection, like in the ^{7}Be measurement, requires rejection of muons (and secondaries), external background and fast coincidences. Short-lived ($\tau < 2$ s) cosmogenic isotopes, ^{12}B, ^{8}B and ^{8}Li, produced in the scintillator by the residual muon flux, are removed
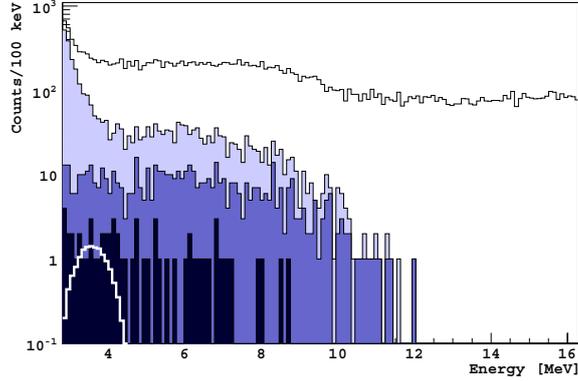
Fig. 2. – (Colour on-line) Energy spectra of candidate events after application of several cuts. The black line represents all events. The light blue- and blue-filled spectra are the samples after the muon cut and fiducial volume cut, respectively. The dark blue-filled spectrum is the final set of data after all cuts and before statistical subtraction of ^{208}Tl (white line).

by vetoing the detector for 5 s after each muon crossing the scintillator (dead time of 23.4%, live-time reduced to 187.9 d). Among long-lived ($\tau > 2$ s) cosmogenic isotopes, the only contribution is given by ^{10}C decays, tagged and rejected by the triple coincidence with the parent muon and neutron capture on proton. The effect of each step of the analysis sequence described above is shown in fig. 2. The intrinsic ^{208}Tl contribution, from the ^{232}Th chain, is measured, by analyzing the delayed coincidences of its branching competitor, ^{212}Bi-^{212}Po, and statistically subtracted.

The ^{8}B interaction rate has been measured in $0.26 \pm 0.04_{\rm stat} \pm 0.02_{\rm syst}$ c/d/100 tons. above 2.8 MeV [3,4]. Both the measured rate and spectrum (fig. 3) are in agreement with the rate (0.26 ± 0.04 c/d/100 tons) and the spectrum predicted by the Standard Solar Model [5], including the MSW-LMA solution ($\Delta m^2 = 7.69 \times 10^{-5}$ eV^2, $\tan^2 \theta = 0.45$ [6]).

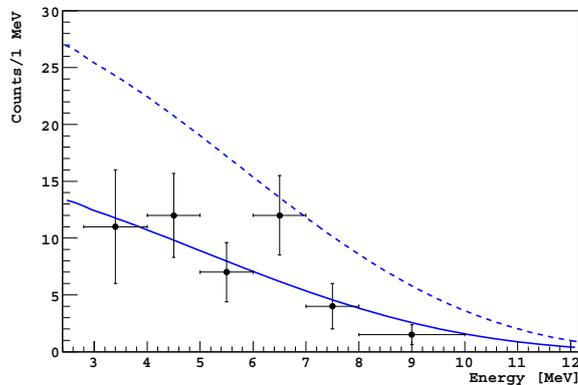Fig. 3. – Energy spectrum of the events surviving all cuts and after statistical ^{208}Tl subtraction. The expected electron recoil spectrum due to oscillated (not oscillated) ^{8}B ν interaction, as determined from the BS07(GS98) solar model, is represented by the solid (dashed) line.
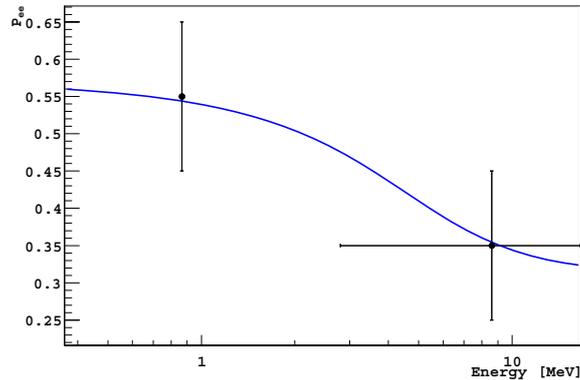
Fig. 4. – Electron neutrino survival probability as a function of the neutrino energy sources assuming the BS07 solar model and the oscillation parameters from the MSW-LMA solution ($\Delta m^2 = 7.69 \times 10^{-5}\,\mathrm{eV}^2$ and $\tan^2\theta = 0.45$ [6]). Dots represent the Borexino results from ^{7}Be and ^{8}B measurements.

4. – Conclusions

The Borexino ^{7}Be 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: $f_{pp} = 1.005^{+0.008}_{-0.020}$, 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: $f_{\mathrm{CNO}} < 6.27$ (90% CL).

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% CL) [2].

Electron neutrino survival probabilities have been estimated for both ^{7}Be neutrinos (0.56 ± 0.10 at $0.862\,\mathrm{MeV}$) and ^{8}B (0.35 ± 0.10 at the mean energy of $8.6\,\mathrm{MeV}$). The agreement between the Borexino results and the LMA-MSW oscillation prediction is shown in fig. 4 [3, 4].

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