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Solar neutrino results with Borexino I

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Borexino is a large-volume liquid scintillator detector installed in the underground halls of the Gran Sasso National Laboratory in Italy. The data taking started in May 2007, after several years of development of purification techniques and construction. The Borexino phase I ended after about 3 years of data taking. All Borexino results within its solar neutrino program and their physical implications have been reviewed: the first real time measurement of the ^{7}Be solar neutrino interaction rate, obtained with a precision below 5% and the absence of its day-night asymetry with 1.4% precision; the first direct evidence of the *pep* neutrino signal and the strongest experimental constraint of the CNO solar neutrino flux to date; the measurement of the solar ^{8}B neutrino rate with 3 MeV energy threshold. Borexino sets also the world best limits on hypothetical anti-neutrino fluxes from the Sun assuming undistorted ^{8}B spectrum.

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1. Introduction

In the past 40 years, solar neutrino experiments [1] have revealed important information about the Sun [2, 3] and have shown that solar ν_e undergo flavor transitions that are well described by Mikheyev–Smirnov–Wolfenstein Large Mixing Angle ("MSW–LMA") type flavor oscillations [4]. Reactor anti–neutrino ($\bar{\nu}_e$) measurements [5] also support this model. Solar neutrinos (ν_e) are expected to be produced in the two distinct fusion processes, in the main pp fusion chain and in the sub-dominant CNO cycle. Several distinct nuclear reactions produce both monoenergetic neutrinos (^{7}Be, pep) and neutrinos with continuous energy spectra (pp,^{8}B, CNO). The dominant solar neutrino flux has energies below 2 MeV while ^{8}B neutrinos extend to more than 10 MeV. The MSW model predicts a transition in the solar ν_e survival probability P_{ee} at energies of about 1-4 MeV from vacuum–dominated to matter–enhanced oscillations. This transition is currently poorly tested. Therefore, in order to test MSW-LMA thoroughly, to probe other proposed ν_e oscillation scenarios [6], and to further improve our understanding of the Sun (metallicity problem [7, 3]), it is important to measure the solar ν_e fluxes.

Borexino is a real–time large–volume liquid scintillator detector [8] installed in the underground National Gran Sasso Laboratory in Italy (3800 m water equivalent). It was designed to measure the 862 keV ^{7}Be solar ν_e. One of its unique features is the very low background level that allowed the first ^{7}Be-ν_e measurement [9] soon after the detector became operational in May 2007. This made Borexino the first experiment capable of making spectrally resolved measurements of solar ν_e's at energies below 1 MeV. Borexino performed also a measurement of the ^{8}B solar ν_e's with a recoil–electron energy threshold of 3 MeV [10]. Recent Borexino solar ν_e results, described in more details below, include a high–precision measurements of the ^{7}Be–ν_e interaction rate [11] and of the absence of its day–night asymmetry [12], the first measurement of pep-ν_e's rate and the strongest constraint up to date on CNO ν_e's flux [13]. Other Borexino results include the study of solar and other unknown $\bar{\nu}_e$ fluxes [14], observation of geo–neutrinos [15], experimental limits on the Pauli–forbidden transitions in ^{12}C nuclei [16], a search for 5.5 MeV solar axions produced in $p(d,^3He)A$ reaction [17], and a measurement of CNGS muon neutrino speed [18].

2. Borexino detector

Borexino detects low–energy solar ν_e via their elastic scattering off the electrons of $\sim$280 tons liquid scintillator, while $\bar{\nu}_e$ are detected via the inverse neutron β–decay reaction. The high light yield and the extreme radiopurity achieved allow the real–time detection of solar ν_e's down to about 20 keV of electron recoil energy. The main features of the Borexino detector [8] are illustrated in Fig. 1-Left. The active medium is a mixture of pseudocumene (PC, 1,2,4- trimethylbenzene) and a wavelength shifter PPO (2,5-diphenyloxazole, a fluorescent dye) at a concentration of 1.5 g/l. The scintillator is contained in a 125 μm thick nylon vessel with a radius of 4.25 m, shielded by the two PC buffers separated by a second nylon vessel which acts as a barrier against the inward radon diffusion. The scintillator and buffers are contained within a 13.7 m diameter stainless steel sphere (SSS) that is housed in a 16.9 m high cylindrical dome filled with ultra–pure water that serves as an additional passive shielding and as an active Cherenkov muon veto system [19]. The scintillation light is viewed by 2212 8$''$ PMTs mounted on on the inside surface of the SSS. The number of hit

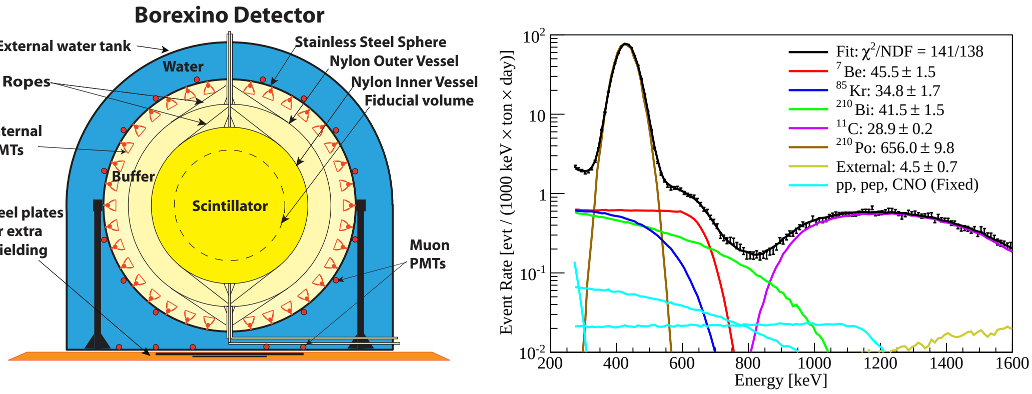

Figure 1: Left: The Borexino detector. **Right**: Borexino energy spectrum and a Monte Carlo based fit. Rate values in the legend are integrated over all energies and are quoted in units of counts/(day·100 ton).

PMTs is a measure of the deposited energy. The position of the scintillation event is determined by a photon time–of–flight method. There is no sensitivity to the intrinsic neutrino direction.

With the muon flux and external background highly suppressed, the crucial requirement for solar ν detection is a high scintillator radiopurity achieved via a combination of distillation, water extraction, and nitrogen gas stripping [20, 8]. Assuming secular equilibrium in the Uranium and Thorium decay chains, the Bi–Po delayed coincidence rates imply ^{238}U and ^{232}Th levels of (1.6 $\pm$ 0.1)$\times 10^{-17}$ g/g and (6.8 $\pm$ 1.5)$\times 10^{-18}$ g/g [8]. The radon progenies ^{210}Po and ^{210}Bi however, are higher than expected and are out of secular equilibrium. The ^{85}Kr presence is due to a small air leak during the detector filling. Systematic errors were reduced thanks to extensive calibration campaigns [21] performed deploying α, β, γ, and neutron sources within the scintillator volume.

3. Precision measurement of ^{7}Be neutrinos

In liquid scintillator detectors, neutrino induced events are not distinguished from the events due to natural radioactivity. The interaction rates of all species contributing to the total energy spectrum, shown after cuts in Fig. 1-Right for 740.7 live days, are obtained by fitting the energy spectrum to the expected ν_e and background spectra. The edge at 665 keV is due to the Compton–like spectrum of recoil e^-'s scattered by the 862 keV ^{7}Be-ν_e. The peak at 440 keV is due to ^{210}Po α's. The ^{11}C produced by muon interactions on ^{12}C has the continuous e^+ spectrum above 800 keV. Two independent fit methods were used, one Monte Carlo (MC) based and one using an analytic detector response function. In both methods, the weights for the ^{7}Be$-\nu_e$ and the main background components (^{85}Kr, ^{210}Po,^{210}Bi, and ^{11}C) were free fit parameters, while those of the *pp*, *pep*, CNO, and ^{8}B ν_e's were fixed to the SSM predictions assuming MSW–LMA oscillations. The MC method includes also external γ-ray background. The energy scale and resolution were floated in the analytic fits, while the MC approach automatically incorporates the detector response. The stability of the results was studied by repeating the fits with slightly varied characteristics.

The best estimate for the ^{7}Be–ν_e interaction rate in Borexino is $(46.0 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{syst}))$ counts/(day·100ton) [11]; 100 tons of Borexino scintillator contain 3.757×10^{31} e^-. This rate is 5σ below the predicted one without ν_e oscillations of (74.0 ± 5.2) counts/(day·100ton), based on

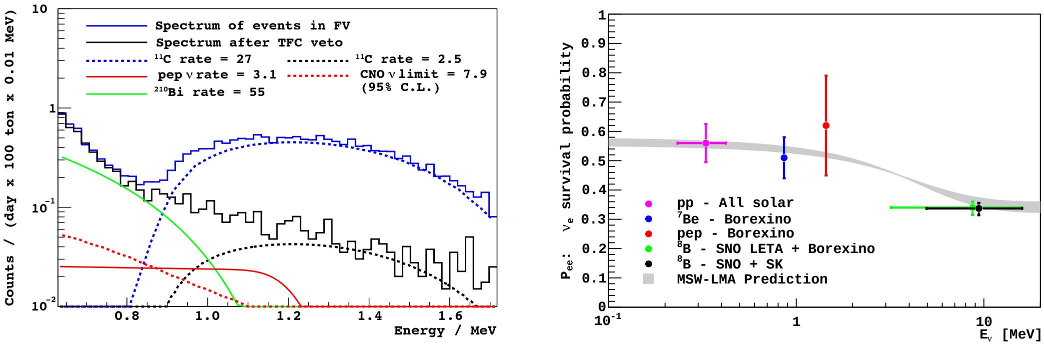

Figure 2: Left: Energy spectra before (solid blue) and after (solid black) the TFC veto. The estimated ^{11}C rate is shown before (dashed blue) and after (dashed black) the veto. The green line shows ^{210}Bi. The red lines represent the pep–ν_e best estimate (solid) and the CNO–ν_e upper limit (dashed). Rates in the legend are integrated over all energies and in units of counts/(day·100ton). **Right**: The P_{ee} as a function of ν_e energy. The grey band shows the MSW–LMA prediction with 1σ range of mixing parameters. The data points are described in the legend.

the high metallicity SSM flux [3]. The ratio of the measured to the predicted ν_e-equivalent flux is 0.62 ± 0.05. Under the assumption that the reduction in the apparent flux is the result of ν_e oscillation to ν_μ or ν_τ, we find $P_{ee} = 0.51 \pm 0.07$ at 862 keV. Alternatively, by assuming MSW-LMA solar neutrino oscillations, the Borexino results can be used to measure the ^{7}Be solar neutrino flux, corresponding to $\Phi_{^7\mathrm{Be}} = (4.84 \pm 0.24) \times 10^9$ cm^{-2} s^{-1}.

4. Search for a day-night asymmetry in the 862 keV ^{7}Be neutrino rate

We have searched for a change in the ^{7}Be–ν_e rate associated with matter effects possibly causing ν_e regeneration as they pass through the Earth during the night. The asymmetry between the night and day rates, R_N and R_D, is described by A_{dn} parameter

$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D}, \tag{4.1}$$

measured to be fully consistent with zero [12]: $A_{dn} = (0.001 \pm 0.012(\mathrm{stat}) \pm 0.007(\mathrm{syst}))$. The Δm^2_{12} region between $\sim 10^{-8}$ and 2×10^{-6} eV^2 is excluded by this result alone. In particular, the minimum A_{dn} expected in the LOW Δm^2 region is 0.117, more than 8.5σ away. The inclusion of this result in a global analysis of all solar ν data isolates the LMA solution of solar ν oscillations with very high confidence. For the first time this is done without the KamLAND $\bar{\nu}_e$ data [22] and thus without the assumption of CPT invariance in the neutrino sector.

5. First evidence of *pep* solar neutrinos and limit on CNO solar neutrino flux

The detection of pep and CNO ν_e's is more challenging than that of ^{7}Be ν_e's, as their expected interaction rates are $\sim$10 times lower and because of the background in the 1-2 MeV energy range, the cosmogenic β^+-emitter ^{11}C (lifetime: 29.4 min). Thanks to the extremely low levels of intrinsic background and to the novel background discrimination techniques Borexino provided the first time measurement of the solar pep–ν_e rate and the strongest limit on the CNO solar ν_e flux to date [13].

The 1.44 MeV pep ν_e's are an ideal probe to test the P_{ee} transition region predicted by the MSW–LMA model because, thanks to the solar luminosity constraint, its SSM predicted flux has a small uncertainty of 1.2% [3]. The detection of ν_e from the CNO cycle would be the first direct evidence of the nuclear processes that are believed to fuel massive stars (>1.5 $M_\odot$). The predicted CNO flux is strongly dependent on the solar modeling, being 40% higher in the High Metallicity (GS98) than in the Low Metallicity (AGSS09) solar model [2, 7].

The ^{11}C background can be reduced by the Three–Fold–Coincidence (TFC) space–time veto after coincidences between muons and cosmogenic neutrons produced with 95% probability together with ^{11}C. This veto relies on the reconstructed muon track and position of the neutron–capture γ-ray [19]. The resulting energy spectra before and after the TFC veto are shown in Figure 2-Left. The residual ^{11}C is still a significant background. We exploited the pulse shape differences between e^- and e^+ interactions in organic liquid scintillators [23] due to the finite lifetime of ortho–positronium as well as from the presence of annihilation γ–rays. An optimized pulse shape parameter was constructed using a boosted–decision–tree algorithm. The analysis is based on a binned likelihood multivariate fit performed on the energy, pulse shape, and spatial distributions of selected scintillation events whose reconstructed position is within the fiducial volume [13].

The best estimate for the pep–ν_e interaction rate in Borexino is (3.1 ± 0.6 (stat) ± 0.3 (syst)) counts/(day·100ton) [13]. This measured rate disfavors at 97% C.L. the predicted rate without ν_e oscillations, based on the SSM, of (4.47 ± 0.05) counts/(day·100ton). If this reduction in the apparent flux is due to ν_e oscillation to ν_μ or ν_τ, we find $P_{ee} = 0.62 \pm 0.17$ at 1.44 MeV. Alternatively, by assuming MSW–LMA solar ν_e oscillations, this can be used to measure the pep solar ν_e flux, corresponding to Φ_{pep} = (1.6 ± 0.3) $\times 10^8$ cm^{-2} s^{-1}, in agreement with the SSM. Due to the similarity between the electron–recoil spectrum from CNO ν_e's and the spectral shape of ^{210}Bi decay, whose rate is ∼10 times greater, we can only provide an upper limit on the CNO ν_e rate. Assuming MSW–LMA solar ν_e oscillations, the 95% C.L. limit on the solar CNO ν_e flux is 7.7×10^8 cm^{-2} s^{-1}. Our CNO limit is 1.5 times higher than the flux predicted by the High Metallicity SSM [3] and in agreement with both the high and low metallicity models.

6. Conclusions

Figure 2-Right summarizes the current knowledge of the P_{ee} for solar ν_e's to which Borexino has contributed significantly. All data are in a very good agreement with the MSW–LMA solution of neutrino oscillations and limit the range of predictions of non-standard interaction models. The precision measurement of the ^{7}Be solar ν_e rate validates the MSW–LMA solution of neutrino oscillation at 862 keV. Borexino measurement of the absence of the day–night asymmetry of the ^{7}Be solar ν_e flux excludes the LOW solution at more than 8.5 σ C.L. and, when combined with other solar neutrino data, allows to select the LMA region of neutrino oscillation parameters without assuming CPT invariance in the neutrino sector. Borexino has also achieved the necessary sensitivity to provide, for the first time, evidence of the rare signal from pep solar ν_e's and to place the strongest constraint on the CNO solar ν_e flux to date. This result raises the prospect for higher pre-

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cision measurements of *pep* and CNO interaction rates by Borexino II phase, if the next dominant background, ^{210}Bi, is further reduced by scintillator re–purification.

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