Recent results on pp-chain solar neutrinos with the Borexino detector

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Measuring all neutrino components is the most direct way to test the standard solar model (SSM). Despite the great results obtained so far, important questions such as the solar metallicity remain open. A precise measurement of the solar pp chain and the CNO cycle would settle this controversy between high (HZ) and low (LZ) metallicity compositions of the Sun. Solar neutrinos allow the determination of oscillation parameters, in particular the θ_{12} mixing angle and, to a lesser degree the Δm_{12}^2 mass splitting. Furthermore the measurement of the electron neutrino survival probability Pee as a function of neutrino energy allows one to directly probe the MSW-LMA mechanism of neutrino oscillations In this work I will report the first simultaneous precision spectroscopic measurement of the complete pp-chain and its implications for both solar and neutrino physics with the Borexino detector.

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1 First Simultaneous Precision Spectroscopy of pp, ⁷Be, and pep

The Borexino *PhaseII* started after an extensive purification campaign consisting in six cycles of closed-loop water extraction, during which the radioactive contaminants were significantly reduced to: $^{238}\text{U} < 9.4 \times 10^{-20} \text{ g/g} (95\% \text{ C.L.})$, $^{232}\text{Th} < 5.7 \times 10^{-19} \text{ g/g} (95\% \text{ C.L.})$, ^{85}Kr , reduced by a factor ~4.6, and ^{210}Bi , reduced by a factor ~2.3.

For each event, the energy, the position and the pulse shape are reconstructed by exploiting the number of detected photons and their detection times. The energy resolution is ~ 50 keV at 1 MeV. The hardware energy threshold is $N_p > 20$, (total number of triggered PMTs) which corresponds to ~50 keV.

Events are selected removing internal (external) muons and applying a 300 (2) ms veto to suppress cosmogenic backgrounds. These vetos led to a total dead-time of about 1.5%.

The ²¹⁴Bi -²¹⁴Po fast coincidences from the ²³⁸U chain and unphysical noise events are removed; the fraction of good events removed is $\sim 0.1\%$ and it is estimated using MonteCarlo (MC) simulations and calibration data [1].

A Fiducial Volume (FV) cut is defined in order to reduce background from sources external to the scintillator in particular from the nylon vessel, from the SSS, and from PMTs. Thanks to this FV the innermost region of the scintillator is selected (71.3 t), contained within the radius R < 2.8 m and the vertical coordinate -1.8 < z < 2.2 m.

After these cuts the main background is due to radioactive isotopes in the scintillator itself: ¹⁴C (β^- decay, Q = 156 keV), ²¹⁰Po (α decay, E = 5.3 MeV quenched by a factor ~10), ⁸⁵Kr (β^- decay, Q = 687 keV), and ²¹⁰Bi (β^- decay, Q = 1160 keV) from ²¹⁰Pb. An additional background is also due to the pile-up of uncorrelated events coming mostly from ¹⁴C, external background, and ²¹⁰Po [1]. Other important contributions to the background are the residual external background, mainly due to γ 's from the decay of ²⁰⁸Tl, ²¹⁴Bi, and ⁴⁰K and the cosmogenic isotope ¹¹C (β^+ decay, τ = 29.4 min) that is continuously produced by muons through spallation on ¹²C. The Collaboration has developed a method called Three-Fold Coincidence (TFC) by which it it possible to tag events correlated in space and time with a muon and a neutron (¹¹C is often produced together with one or even a burst of neutrons). Furthermore, in order to better disentangle ¹¹C events, a e^+/e^- pulse-shape discrimination is applied [2, 3]. The TFC algorithm has (92 ± 4)% ¹¹C-tagging efficiency.

In order to extract the interaction rates of the solar neutrinos and the background species we maximize a binned likelihood function (through a multivariate approach) built as the product of 4 different factors; the TFC-subtracted energy spectrum, the TFC-tagged energy spectrum, the PS- \mathcal{L}_{PR} and the radial distributions of the events.

In the fit procedure the neutrinos signal and the background reference spectral

shapes are obtained with two complementary strategies; a first one based on the analytical description of the detector response function, and a second one fully based on MC simulations.

The interaction rates of pp, ⁷Be, and pep neutrinos are obtained from the fit together with the decay rates of ⁸⁵Kr, ²¹⁰Po, ²¹⁰Bi, ¹¹C, and external backgrounds due to γ rays from ²⁰⁸Tl, ²¹⁴Bi, and ⁴⁰K.

Because the degeneracy between the CNO ν and the ²¹⁰Bi spectral shapes we have constrained the CNO ν interaction rate to the HZ-SSM predictions, including MSW-LMA oscillations to $4.92 \pm 0.55 \text{ cpd}/100 \text{ t}$ [4] [5], $(3.52 \pm 0.37 \text{ cpd}/100 \text{ t}$ in case of LZ-SSM). The contribution of ⁸B ν 's has been fixed to the HZ-metallicity rate 0.46 cpd/100 t.

The ⁷Be solar ν flux is the sum of the two mono-energetic lines at 384 and 862 keV. The corresponding rate for the 862 keV line is $46.3 \pm 1.1^{+0.4}_{-0.7} \text{ cpd}/100 \text{ t}$, and it is compatible with the Borexino *phaseI* measurement. The total uncertainty of 2.7% for ⁷Be solar ν represents a factor of 1.8 improvement with respect *phaseI* result and is two times smaller than the theoretical error.

The pp interaction rate is compatible with precedent results and its uncertainty is reduced by about 20%.

To extract the pep neutrino flux we constrain the CNO one. With our sensitivity the ⁷Be and pp ν interaction rates are not affected by the hypothesis on CNO (i.e. ν 's HZ hypothesis vs LZ hypothesis). However, the pep ν interaction rate depends on it, being 0.22 cpd/100 t higher if the LZ hypothesis is assumed. In both cases the absence of pep reaction in the Sun is rejected at more than 5σ .

The e^- recoil spectrum induced by CNO neutrinos and the ²¹⁰Bi spectrum are degenerate and this makes impossible to disentangle the two contributions with the spectral fit. Due to this spectrum degeneration, it is only possible to provide an upper limit on the CNO neutrinos contribution, and in order to extract this number, we have further to break the correlation between the CNO and pep contributions. We exploit the theoretically well known pp and pep flux ratio in order to indirectly constraint the pep ν 's contribution. The interaction rate ratio R(pp/pep) is constrained to (47.8 \pm 0.8) (HZ) [4], [5] (Constraining R(pp/pep) to the LZ hypothesis value 47.5 \pm 0.8 gives identical results). We obtain an upper limit on CNO ν rate of 8.1 cpd/100t (95 % C.L.).

It is possible to combine the Borexino results on pp and ⁷Be ν fluxes in order to measure experimentally the ratio \mathcal{R} between the rates of the ³He-⁴He and the ³He-³He reactions occurring within the pp chain [6]. The value of \mathcal{R} tell us the competition between the two primary modes of terminating the pp chain and for this reason represent a valuable probe of solar fusion. In first approximation we can neglect the pep and ⁸B ν contribution and \mathcal{R} can be written as $2\Phi(^{7}\text{Be})/[\Phi(\text{pp})-\Phi(^{7}\text{Be})]$. The measured value is $\mathcal{R} = 0.178^{+0.027}_{-0.023}$, in agreement with the predicted values for $\mathcal{R} = 0.180 \pm 0.011$ (HZ) and 0.161 ± 0.010 (LZ) [4].

2 Improved measurement of ⁸B solar neutrinos with 1.5 kt·y exposure

For what concern the analysis ⁸B the energy threshold is set at 1650 p.e., which correspond to 3.2 MeV electron energy. The analysis is based on data collected between January 2008 and December 2016 and corresponds to 2062.4 live days of data. Data collected during detector operations such as scintillator purification and calibrations are omitted. The dataset is split into a low energy range (LE), with [1650, 2950] p.e., including events from natural radioactivity, and a high energy range (HE), with [2950, 8500] p.e.. This high energy region is dominated by external γ -rays following neutron capture processes on the SSS. Results from the HE sample use data from the entire active volume, while the LE sample requires a spatial cut to remove the top layer of scintillator (the motivation is due to the presence of PPO from the scintillator leak in the upper buffer fluid volume).

The total exposure is 1,519 t·y, and the time-averaged mass is 266.0 ± 5.3 ton (assuming a scintillator density of 0.8802 g/cm^3). For the LE sample the mass fraction, after the z-cut at 2.5 m, is 0.857 ± 0.006 .

The High Energy data sample is fitted with only two components, the ⁸B neutrinos and the external component from neutron captures, while the Low Energy sample requires three additional fit components, all due to ²⁰⁸Tl that is present in the bulk dissolved in the scintillator, at the surface intrinsic to the nylon vessel, and from emanation diffused from the nylon vessel into the outer edge of scintillator.

3 P_{ee} and ⁷Be and ⁸B ν fluxes

We can write the electron neutrino survival probability as function of the neutrino energy as shown in figure 1 (left). The value for flavor conversion parameters from the MSW-LMA solution are $(\Delta m_{12}^2 = 7.50 \times 10^{-5} \text{ eV}^2, \tan^2\theta_{12} = 0.441, \text{ and } \tan^2\theta_{13} = 0.022$ [7]). For the ⁸B neutrino source both the high-Z B16 (GS98) SSM and the low-Z B16 (AGSS09met) SSM are assumed [4, 8, 9]. Dots represent the Borexino results from pp (red), ⁷Be (blue), pep (azure), ⁸B neutrino measurements are in green for the LE+HE range, and grey for the separate sub-ranges. For the non mono-energetic pp and ⁸B dots are set at the mean energy of detected neutrinos, weighted on the detection range in electron recoil energy. The error bars include experimental and theoretical uncertainties

A first hint toward the solution of the solar metallicity problem could be obtained from the measurement of ⁷Be and ⁸B ν fluxes. We can define the reduced fluxes f_{Be} and f_{B} ($f_{\text{Be}} = \Phi(^{7}\text{Be})/\Phi(^{7}\text{Be})_{\text{HZ}}$, $f_{\text{B}} = \Phi(^{8}\text{B})/\Phi(^{8}\text{B})_{\text{HZ}}$). When we combine the new Borexino results on ν interaction rate with all the solar and KamLAND data we obtain the regions of allowed values. Figure 1 (right) shows the allowed contours together with the 1σ theoretical predictions for high metallicity and low metallicity SSM. There is a weak hint towards the HZ hypothesis, which is however not statistically significant; the discrimination between the high and low metallicity solar models is largely dominated by the uncertainties of the theoretical models.



Figure 1: Left: electron neutrino survival probability as function of the neutrino energy. Right: allowed contours in the $f_{\text{Be}}-f_{\text{B}}$ parameter space (see text).

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