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Abstract. The first simultaneous measurement of the interaction rates of \( pp \), \( ^{7}\text{Be} \), and \( pep \) solar neutrinos has been completed using the Borexino data and will soon be published. The results were obtained by performing a global fit to the Borexino Phase-II data in an extended energy range (0.186-2.97 MeV). The scope of Phase-II extends over 1291.51 days between December 2011 and May 2016 after an extensive scintillator purification campaign. The updated results are in agreement with the previous ones and have improved accuracy. Here we will highlight some details about the data analysis on Phase-II in the solar neutrino spectroscopy with Borexino.

1. Motivation

The Sun is powered by nuclear fusion reactions that burn hydrogen into helium (Fig. 1). Neutrinos that are the products of these reactions are the only carriers of information about the processes in the core of the Sun. The resulting spectra of the solar neutrinos are shown in Fig. 2 in units of \( \text{cm}^{-2}\text{s}^{-1}\text{MeV}^{-1} \) for continuous spectra and \( \text{cm}^{-2}\text{s}^{-1} \) for monoenergetic lines.

While the spectral shapes are defined by the fusion reactions, the total flux depends on the composition of the Sun, in particular the fraction of the heavy elements. Standard Solar Models (SSMs) are divided into two classes, low and high metallicity, depending on the fraction of elements heavier than helium. Current knowledge about these models does not provide enough information to determine the metallicity of the Sun. [1]
Figure 1: The *pp* chain and the CNO cycle.

By measuring the solar neutrino fluxes we are able to study the reactions in the *pp* chain (see Fig. 1). Furthermore, using the knowledge about the fluxes and assuming a certain solar model, we test the neutrino oscillations theory; while assuming the MSW-LMA theory [2] of neutrino oscillations we test SSMs. The flux of CNO neutrinos can help us solve the metallicity puzzle described above.

2. The Borexino detector

Borexino is a liquid scintillator detector the primary goal of which is measuring the fluxes of solar *ν*-s [3]. It is located in the Laboratori Nazionali del Gran Sasso in the mountains of Italy at 3800 m water-equivalent depth. In 2012 Borexino started Phase-II of data taking which is characterized by its higher sensitivity. This was made possible due to extensive purification campaigns in 2010 and 2011 after which the already unprecedentedly low radioactive background of the detector was improved even more.

The schematic representation of the detector is shown in Fig. 3. It is equipped with 2200 photomultiplier tubes (PMTs) mounted on the Stainless Steel Sphere (SSS) that point inwards into the Inner Detector (ID), which contains the scintillator; and 220 PMTs pointing outwards in the Outer Detector which serves the purpose of a Cherenkov muon veto. Apart from that, the ID contains two nylon spheres which protect the scintillator from radon diffusion from the outside. [4].

Figure 3: A schematic representation of the Borexino detector.
3. Analysis
The software selection applied to the acquired data from the Borexino detector is demonstrated on Fig. 4 and consists of:

- muon and muon daughter cut: removes the muons that pass through the ID and applies 300 ms dead time after the muon events
- fiducial volume cut: selects events farther from the edges of the SSS in order to remove background from the nylon spheres, the PMTs and the SSS.
- the three-fold coincidence (TFC) cut: selects exposure in which cosmogenic $^{11}$C events (Eq. 1) are expected

The TFC cut finds coincidences of a muon, a neutron after $\sim 250 \mu s$ (average time for neutron capture, Eq. 2) and a positron after 29.4 mins ($^{11}$C decay, Eq. 3) in a cylindrical volume following the muon path in order to determine cosmogenic $^{11}$C events. Applying the TFC cut, the whole exposure is divided into two sets: $\sim 40\%$ of exposure containing 92$\%$ of $^{11}$C, and $\sim 60\%$ of exposure containing 8$\%$ of $^{11}$C events.

\[ \mu + ^{12}C \rightarrow \mu + ^{11}C + n \quad (1) \]
\[ n + p \rightarrow D + \gamma \quad (2) \]
\[ ^{11}C \rightarrow ^{11}B + e^+ + \nu_e \quad (3) \]

To determine the rates of the background and the $pp$, $^7$Be, and $pep$ solar species, multivariate fits have been performed on the Borexino data using Monte Carlo (MC) as well as analytical approaches [5]. The resulting multivariate likelihood is the product of the four components:

\[ L_{MV}(\theta) = L_{TFC-tagged}(\theta) \cdot L_{TFC-sub}(\theta) \cdot L_{PS}(\theta) \cdot L_{RD}(\theta), \quad (4) \]

where TFC-tagged and TFC-sub are the two energy spectra enriched and depleted in $^{11}$C respectively, obtained after the TFC cut (see above); and RD and PS are the pulse-shape and the radial distributions of events respectively. The spectral shapes used to fit both of the energy spectra are shown in Fig. 5. The pulse-shape distribution is used to discriminate between electrons and positrons in order to determine the remaining $^{11}$C in the $^{11}$C-depleted spectrum. The radial distribution is used to distinguish external and uniform components which plays a role in fitting external backgrounds.

![Figure 4: Data before and after cuts.](image1)

![Figure 5: Spectra of recoiled electrons.](image2)
Apart from the MC method, the fit is performed using an analytical description of the detector response. In the analytical description of the energy scale a number of energy estimators is used: total number of hits \((N_h)\), photoelectrons \((N_{pe})\) and triggered PMTs \((N_p)\), as well as the number of PMTs triggered within the first 230 ns \((N_{p1})\) or 400 ns \((N_{p2})\).

The analytical model of the response describes the conversion from the deposited energy of the event to \(N_{pe}\):

\[
N_{pe}(E) = LY \left( Q(E) \cdot E + f_{Cher} \cdot Ch(E) \right),
\]

where \(LY\) is the light yield, \(Q(E)\) is the quenching function, \(f_{Cher}\) is a free Cherenkov tuning parameter, and \(Ch(E)\) is a function describing Cherenkov radiation; and the subsequent conversion to \(N_p\):

\[
N_p(E) = N_{live} \left( 1 - e^{-\frac{N_{pe}}{N_{live}}} \right) \left( 1 + P_t \frac{N_{pe}}{N_{live}} \right) \left( 1 - G_c \frac{N_{pe}}{N_{live}} \right),
\]

where \(N_{live}\) is the average number of live PMTs, \(P_t\) is a parameter for single electron response (tuned using calibrations), and \(g_c\) is a geometrical correction coefficient (tuned with MC).

The analytical approach allows several detector response parameters to be free which gives flexibility in modelling the detector response changing in time, and enables different ways of pile-up modelling.

4. Systematic studies

In order to achieve a high precision measurement, the fit has been performed multiple times using the MC as well as analytical approach. Various sources of uncertainty have been considered such as the choice of energy estimator, pile-up modelling, energy fit range and binning, \(^{85}\)Kr constraint, live time, scintillator density, fiducial volume, fit method (MC/analytical) and fit models. Fit models include uncertainties in the known detector response, spectra of the background and solar species based on extensive calibration campaigns in 2009.

5. Results and conclusions

For the first time the energy range of the fit was extended (0.186-2.97 MeV) in order to obtain information about the \(pp\), \(^7\)Be, and \(pep\) solar neutrinos simultaneously using Borexino Phase-II data (1291.51 days) \([6]\). The analysis yields an updated precision measurement of \(pp\)-\(\nu\) and \(^7\)Be-\(\nu\), discovery of \(pep\)-\(\nu\) and the most stringent upper limit on CNO-\(\nu\). The measurements are consistent with Phase-I and show improved precision. The results provide valuable information which can be used to analyse SSMs and solar metallicity.

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