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Observation of CNO cycle solar neutrinos in Borexino

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Abstract. The Borexino detector, located at the Laboratori Nazionali del Gran Sasso in Italy, is a radiopure 280 ton liquid scintillator detector with a primary goal to measure low-energy solar neutrinos created in the core of the Sun. These neutrinos are a consequence of nuclear fusion reactions in the solar core where Hydrogen is burned into Helium and provide a direct probe of the energy production processes, namely the proton-proton (*pp*) chain and the Carbon-Nitrogen-Oxygen (CNO) cycle. The fusion of Hydrogen in the case of the CNO cycle, which is expected to contribute in the order of less than 1% to the total solar energy, is catalyzed by Carbon, Nitrogen, and Oxygen directly depending on the abundances of these elements in the solar core. The measurement of CNO neutrinos is challenging due to the high spectral correlation with the decay electrons of the background isotope ^{210}Bi and the *pep* solar neutrino signal. The experimental achievement of thermal stabilization of the Borexino detector after mid 2016, has opened the possibility to develop a method to constrain the ^{210}Bi rate through its decay daughter and α emitter ^{210}Po which can be identified in Borexino with an efficiency close to 100 percent on an event-by-event basis. Moreover, the flux of *pep* neutrinos can be constrained precisely through a global analysis of solar neutrino data which is independent of the dataset used for the CNO analysis. This conference contribution is dedicated to the first experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun which is at the same time the dominant energy production mechanism in heavier stars compared to the Sun.

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1. Solar Neutrinos

1.1. Production and Propagation

Solar neutrinos are produced in the core of the Sun (or any star) during the fusion of Hydrogen into Helium. The expected total solar neutrino flux is in the order of 65×10^9 neutrinos per cm^2s on Earth.

1.2. Standard Solar Model and the Metallicity Problem

The SSM is a system of differential equations based on a spherically symmetric model of a star in hydrostatic equilibrium with basic phyiscal principles. The main inputs for the SSM are the present day luminosity $L_\odot$, solar radius $R_\odot$, and the solar surface metal-to-hydrogen ratio (so-called *metallicity* $(Z/X)_\odot$) assuming that solar energy is produced by the *pp* chain and the CNO cycle. An output of the SSM are the solar neutrino fluxes which are divided into two classes of solar abundances, *low metallicity (LZ or AGSS09met-LZ)* [6, 7] and *high metallicity (HZ or GS98-HZ)* [5]. The LZ prediction is the most recent one but in tension with helioseismological data. In this regard, emerges the so-called *metallicity puzzle*. A precise measurement of the CNO-ν flux can help to unravel the metallicity problem as it is expected to have a high separation between HZ- and LZ-SSM predictions.

2. The Borexino Experiment

The detection principle of solar neutrinos in Borexino is neutrino-electron elastic scattering where the recoiled electrons induce scintillation light in the detector. Even if the solar neutrino flux is high (see Section 1.1), only about 200 neutrino events per day per 100 ton (cpd/100t) of scintillator mass are observed. The scintillation light yield in Borexino is about 500 photoelectrons per MeV in 2000 PMTs with an energy and position resolution of about 5% and 10 cm at 1 MeV, respectively. The Borexino data acquisition (DAQ) went from May 16th 2007 until October 7th 2021 (DAQ stop time) split into three phases: *Phase-I* (May 16^{th} 2007–May 16^{th} 2010), *Phase-II* (December 11^{th} 2011–May 22^{nd} 2016), and *Phase-III* (July 17^{th} 2016–October 7^{th} 2021). In Borexino, it is distinguished between three classes of backgrounds: internal (^{238}U and ^{232}Th chains, ^{14}C, ^{85}Kr, ^{210}Pb, ^{210}Bi, ^{210}Po), external (^{40}K, ^{214}Bi, ^{208}Tl), and cosmogenic (μ,n,^{11}C).

3. Observation of CNO cycle Solar Neutrinos

The first observation of CNO cycle solar neutrinos has been performed on a fraction the Phase-III dataset which went from July 17th 2016 until End of February 2020 corresponding to an exposure of 1072 days $\times$ 71.3 ton [1]. Here, the used fiducial volume (FV) mass is 71.3 ton which corresponds to a radial cut of 2.8 m and an asymmetric z-cut of $z > -1.8$ m and $z < 2.2$ m. The analysis is done in the range from 0.32 until 2.64 MeV.

3.1. Challenges of CNO Detection

3.1.1. Spectral Correlations and Constraints The biggest challenge in measuring CNO neutrinos is the high spectral correlation of the CNO-ν recoiled electron spectrum with the recoiled electron spectrum of the *pep*-ν signal from the *pp* chain and the β^- decay spectrum of ^{210}Bi. In order to get rid of these correlations, constraints are needed. The *pep*-ν rate can be constrained by doing a global analysis of solar neutrino data including the luminosity constraint linked to the well-known ratio of the *pp* to *pep* neutrino fluxes known from nuclear physics [4]. The result is $R_{pep} = (2.74 \pm 0.04)$ cpd/100t for HZ-SSM and $R_{pep} = (2.78 \pm 0.04)$ for LZ-SSM. It is more challenging to measure the ^{210}Bi contamination in the detector. In order to estimate the ^{210}Bi content, its decay daughter ^{210}Po can be used. Both are part of the ^{210}Pb decay chain:

$$^{210}\mathrm{Pb} \xrightarrow[32\,y]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[7.2\,d]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[199.6\,d]{\alpha} {}^{206}\mathrm{Pb}\text{ (stable)}. \tag{1}$$

The identification of ^{210}Po as it is a monochromatic α emitter can be done in Borexino on an event-by-event basis using multilayer perceptron discrimination variable (MLP). Moreover, assuming secular equilibrium, the rates of ^{210}Bi and ^{210}Po are equal. However, temperature gradients present in the detector caused convective motions of additional ^{210}Po events from the nylon vessel to move inside the central parts of the detector. This extra ^{210}Po source is responsible for the inequilibrium between the ^{210}Bi and ^{210}Po contents. A thermal insulation campaign in 2015 made it possible to reach a stable temperature gradient. This achievement made a ^{210}Bi constraint possible through the tagging of ^{210}Po events.

3.1.2. ^{210}Bi constraint: The Low Polonium Field In Phase-III, the Borexino collaboration succeeded to identifiy a *clean* ^{210}Po region with a mass of about 20 ton and with a paraboloidal shape, the so-called low ^{210}Po field (LPoF). It can be modelled by the following equation:

$$\frac{d^2R_{Po}}{d(\rho^2)dz} = [R(^{210}Po_{min})\varepsilon_E\varepsilon_{MLP} + R_\beta]\left(1 + \frac{\rho^2}{a^2} + \frac{(z-z_0)^2}{b^2}\right). \quad (2)$$

Here, $\rho^2 = x^2 + y^2$, z_0 is the minimum position of the LPoF along the z-axis, a and b are shape parameters along the ρ and z axes, respecitvely, ε_E and ε_{MLP} are the energy and MLP cut efficiency, respectively, applied to select ^{210}Po events, and R_β is the residual rate of β events after the selection of ^{210}Po-α events. Figure 1 shows the LPoF and Figure 2 the fit using Equation 2 leaving the minimum ^{210}Po rate, $R(^{210}Po_{min})$, free.

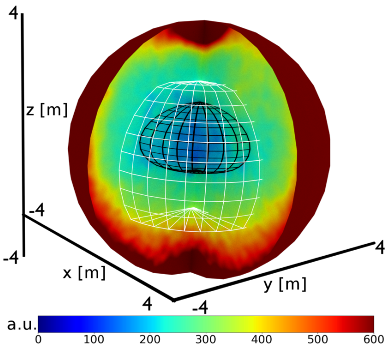

Figure 1. The Low Polonium Field (LPoF) shown in 3D and the color scale represents the intensity of the events in arbitrary units (a.u.). From [1].

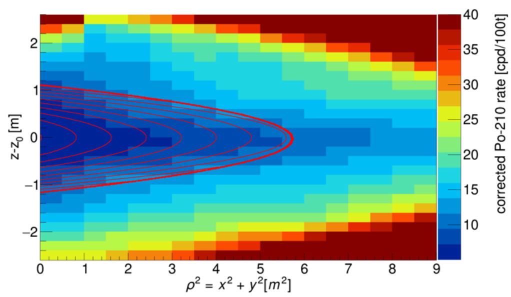

Figure 2. 2D fit of the aligned ^{210}Po dataset in Phase-III. The LPoF is about 80 cm above the equator. From [1].

The minimum ^{210}Po rate can be conservatively taken as the upper limit (UL) on the ^{210}Bi rate in the detector assuming that the ^{210}Bi rate cannot be greater than the $R(^{210}Po_{min})$ rate. Since the LPoF has a lower mass compared to the FV mass, it has to be proven that the ^{210}Bi rate is homogeneous within the FV. This has been done by studying the angular and radial distributions of β events and comparing the data with uniformly distributed pseudo events. The uncertainties have been considered as systematic uncertainties. The obtained UL on the ^{210}Bi rate including systematic uncertainties due to the fit, LPoF mass of the fit region, binning of the data histogram (typically 1 to 2 months), and residual rate of β events after α selection is:

$$R(^{210}\text{Bi}) \leq (11.5 \pm 1.3)\,\text{cpd/100t}. \quad (3)$$

3.2. Results and Implications

3.2.1. Spectral fit and Sources of Systematics The UL on the ^{210}Bi rate is applied as a semi-Gaussian and the *pep-ν* interaction rate as a symmetric Gaussian constraint in a spectral fit. The corresponding likelihood function is defined as [9]:

$$\mathcal{L}_{\mathrm{MV}} = \mathcal{L}_{\mathrm{E,sub}}^{\mathrm{TFC}} \cdot \mathcal{L}_{\mathrm{E,tag}}^{\mathrm{TFC}} \cdot \mathcal{L}_{\mathrm{R}}, \tag{4}$$

where $\mathcal{L}_{\mathrm{E,sub,tag}}^{\mathrm{TFC}}$ stands for the fit of the energy spectrum divided into a cosmogenic ^{11}C subtracted and enriched or tagged spectrum. Here, TFC stands for the *three-fold coincidence* veto which is a method to create a dataset with maximum ^{11}C suppression while at the same time saving as much exposure as possible. The last likelihood $\mathcal{L}_{\mathrm{R}}$ stands for a radial fit of events in the region from 1.2 to 2.5 MeV where the contribution of external backgrounds is crucial. The energy and radial fits are shown in Figures 3 and 4, respectively.

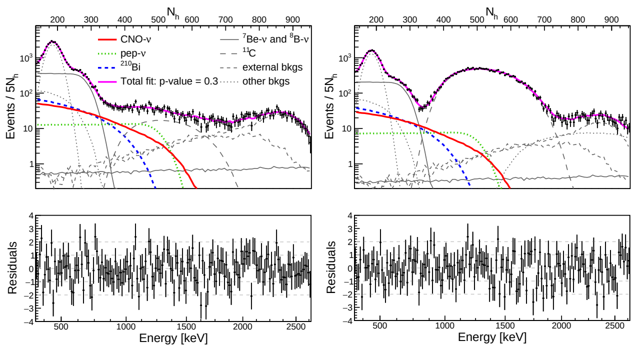

Figure 3. Simultaneous fit of the ^{11}C or TFC subtracted and ^{11}C or TFC enriched energy spectra. From [1].

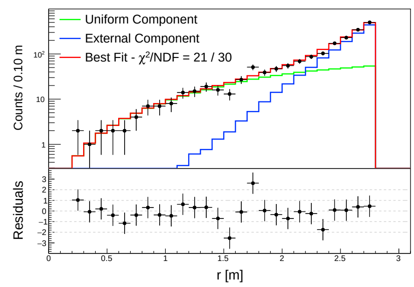

Figure 4. Radial fit of the uniform and external background components. From [1].

3.2.2. CNO-ν flux and Implications to Solar Metallicity The CNO-ν rate has been determined by doing a $\Delta\chi^2$-profiling.

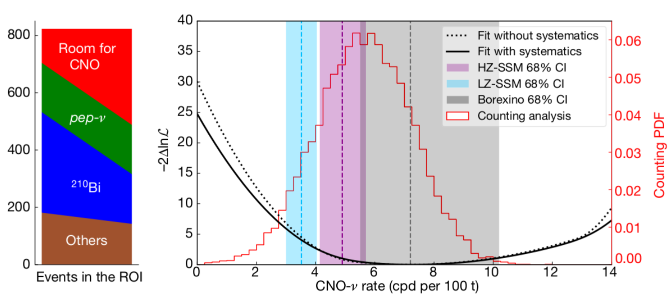

Figure 5. $-2\Delta\log\mathcal{L}_{\mathrm{MV}}^{\mathrm{min}}$-profile of the CNO-ν rate (in black: dotted curve = without systematics, solid curve = with systematics). The magenta area represents the HZ-SSM prediction (=(4.92 ± 0.78) cpd/100t), the cyan area stands for the LZ-SSM prediction (=(3.52 ± 0.52) cpd/100t), and the gray area for the Borexino 68% confidence level (C.L.). The region of interest (ROI) and the counting analysis (red distribution) will be discussed in the text. From [1].

The obtained result for the rate with systematics is $R(\text{CNO}) = (7.2^{+3.0}_{-1.7})\,\text{cpd}/100\text{t}$ corresponding to a flux of $\Phi(\text{CNO}) = (7.0^{+3.0}_{-2.0})\,\text{cm}^{-2}\text{s}^{-1}$. The discovery potential has been obtained by performing 13.8 million psuedo experiments and evaluating the profile likelihood test statistics. The obtained discovery potential based on a p-value evaluation yields a significance of 5σ at 99% C.L. [1, 8]. Moreover, the discovery potential from the profiling with systematics (solid profile in Figure 5) yields a significance of 5.1σ. Moreover, as shown in Figure 5, an independent counting analysis has been performed leading to a significance of 3.5σ applying a symmetric Gaussian constraint on the ^{210}Bi rate and using an analytical description of the spectral shapes. Here, the counting of events has been done in the ROI which is found as the region which maximizes the CNO signal-to-background ratio, i.e. 780–885 keV. Taking into account Borexino data only, the low metallicity (LZ-SSM) prediction is disfavored at a significance of 2.1σ when combining the obtained CNO-ν flux with the result of the ^{7}Be and ^{8}B neutrino fluxes from Borexino Phase-II [4].

4. Summary and Conclusions

The detection of neutrinos from the CNO fusion cycle is a scientific milestone in solar astrophysics. The *metallicity* question still remains open and an improved measurement of the solar neutrino flux from the CNO cycle can help to unravel this *puzzle*. The data-taking in Borexino stopped recently. However, the analysis of the data is ongoing towards improving the measurement of the ^{210}Bi constraint and analysing combined Borexino phases.

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