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***On behalf of the Borexino collaboration**
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Abstract. Borexino is a large liquid scintillator experiment located at the underground INFN Laboratori Nazionali del Gran Sasso, in Italy. It was designed and built with the primary goal of real-time detection of low energy solar neutrinos, and in more than ten years of data taking it has measured all the neutrino fluxes produced in the proton-proton chain, i.e. the main fusion process accounting for 99% of the energy production in the Sun. Recently, after improvements and developments in both hardware and software, Borexino has provided the first observation of solar neutrinos emitted from the subdominant Carbon-Nitrogen-Oxygen (CNO) fusion cycle. All the crucial steps of the analysis strategy adopted to disentangle the signal of CNO neutrinos from backgrounds present in the detector will be described in this article.

1. Solar neutrino physics

In recent years, the study of neutrinos has provided a formidable impulse in understanding the functioning mechanism of stars. In general, stellar energy production is accounted for by two nuclear fusion processes devoted to the conversion of hydrogen into heavier atoms in the core of a star: the proton-proton (pp) chain and the carbon-nitrogen-oxygen (CNO) cycle. Their relative contribution depend on stellar mass and on its metallicity, defined as abundance of elements heavier than helium in the core. According to the Solar Standard Model predictions [1], the Sun produces most of its energy (∼99%) through the pp chain, while the subdominant CNO cycle is responsible for the remaining ∼1%. Both processes include several reactions leading to the emission of electron-flavour neutrinos, the so-called *solar neutrinos*, whose detection is the main goal of solar neutrinos experiments. Over the last few decades, many experiments worldwide have focused on the detection of neutrinos emitted from the Sun by the pp chain. For long time, the CNO cycle has been the missing piece for the complete understanding of processes fueling stars. Even though its contribution in the Sun is expected to be marginal, for stars with $M > 1.3\ M_{\odot}$ the CNO cycle is hypothesised to be the dominant mechanism for stellar energy production. Moreover, since it is catalyzed by elements heavier than helium, the corresponding neutrino fluxes are the most sensitive to the chemical composition of the Sun, thus representing the best available approach to tackle the longstanding "metallicity problem" [2].

2. Borexino detector

Borexino is a large organic liquid scintillator detector placed in the Hall C of the Laboratori Nazionali del Gran Sasso (LNGS), in Italy, below a natural shield of about 1400 m of rock (∼ 3800 m of water equivalent). The detection of neutrino events is based on scintillation light produced by elastic scattering of solar neutrinos with electrons. The detection material employed consists of ∼ 280 tons of ultra-clean organic scintillator (LS) [3], contained in a spherical nylon vessel of 4.25 m radius and 125 μm thickness. The LS mixture was chosen to ensure an energy resolution of ∼ 5 % at 1 MeV of deposited energy. The active core of the detector is surrounded by a series of concentric shells made of material with radio-purity increasing towards the inside, to achieve maximal radiopurity in the inner scintillating core. On the external surface, the detector is equipped with a set of 2112 PMTs, which functions to measure the number of detected photons and their arrival time, thus allowing reconstruction of energy and position of recoiling electrons. Borexino was mainly designed for real-time measurement of solar neutrinos at low energies, in the sub-MeV and MeV energy range. Thanks to the unprecedented level of radio-purity achieved, combined with the high light yield (∼ 500 p.e./MeV for 2000 PMTs), it has achieved several important results in solar and neutrino physics, culminating in the simultaneous measurement of the interaction rates of pp-ν, ^{7}Be-ν and pep-ν [4]. As will be discussed in the next section, the final phase (from July 2016 up to February 2020) of Borexino data taking was devoted to the first experimental measurement of CNO neutrinos [7].

3. Data selection and fitting strategy

In liquid scintillator detectors, neutrino-induced events are intrinsically indistinguishable, on an event-by-event basis, from most of the β or γ radioactive backgrounds present in the detector. Therefore, to maximize the signal-to-noise-ratio a set of selection cuts is applied, specifically devised to remove all the taggable backgrounds and non-physical events. Moreover, the backgrounds caused by radioactive materials in the apparatus outside the scintillator, the so-called *external backgrounds*, are drastically reduced with a fiducial volume cut, consisting in selecting events only in a specific software-defined portion of the scintillator. In Borexino, the fiducial volume for the CNO analysis corresponds to a sphere of 2.8 m radius with a cut on the vertical z axis (-1.8 m $< z <$ 2.2 m).

Another important source of background is represented by cosmogenic events.In particular, the ^{11}C isotope dominates the energy region between 1.1 MeV and 1.8 MeV, thus impacting significantly CNO neutrino-detection. In Borexino a dedicated tagging technique (known as Three Fold Coincidence, TFC) was adopted for the identification and removal of this contamination. In a nutshell, this algorithm rules out from data taking specific portions of the LS by exploiting the spatial and temporal coincidence of the events associated with the production of ^{11}C by cosmic muon spallation.Implementing this method, data are split in two distinct datasets: one enriched with ^{11}C (*TFC-tagged*) and the complementary depleted in ^{11}C

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(*TFC- subtracted*).

Finally, to further disentangle neutrino-induced signals from residual backgrounds, a multivariate analysis was adopted, based on the fitting of the spectrum of Borexino events with MC-simulated reference shapes (PDFs). The PDFs are produced by means of complete GEANT4-based Monte Carlo simulations, including all the processes occurring in the detector from the energy deposition to signal processing, with the aim of reproducing the energy spectra of all species detected by Borexino including all detector effects at 1% level.

In Borexino, the multivariate analysis is performed by maximizing a binned likelihood function, fitting simultaneously multiple likelihood with same parameters but related to different spectra: the energy spectrum (splitted in TFC-tagged and TFC-subrtacted) and the spectrum of radial distribution (RD). The latter includes only two reference shapes: the internal uniform component (neutrino-induced events combined with background distributed uniformly within the detector), and the external component.

The major obstacle of the CNO analysis is the strong anti-correlation between the CNO-ν and the β^- ^{210}Bi background, and to a lesser extent the pep-ν. To break this correlation and make Borexino sensitive to a CNO-ν signal [5], the contribution of these two backgrounds needs to be determined independently and constrained in the multivariate fit. The pep-ν rate can be safely constrained to the combination of SSM predictions, according to the preferred metallicity scenario, and global analysis of solar data excluding Borexino Phase III. Consequently, the most compelling aspect of the analysis is the independent constraint on the ^{210}Bi contaminant, which is supported by ^{210}Pb through the following sequence:

$$^{210}\text{Pb} \xrightarrow[Q_\beta=63.5\text{ keV}]{\tau\approx 32\text{ y}} {}^{210}\text{Bi} \xrightarrow[Q_\beta=1160\text{ keV}]{\tau\approx 7.23\text{ d}} {}^{210}\text{Po} \xrightarrow[Q_\alpha=5.3\text{ MeV}]{\tau\approx 199.1\text{ d}} {}^{206}\text{Pb} \qquad (1)$$

Assuming secular equilibrium, ^{210}Bi estimation is carried out tagging its daughter isotope, the ^{210}Po, which α decays giving a unique and easily recognizable signature. Unfortunately, this measurement is complicated by additional ^{210}Po contribution not in secular equilibrium with ^{210}Bi. The most problematic contribution is given by the contamination deposited on the inner surfaces of the nylon vessel, which can be carried inside the fiducial volume by convective currents triggered by temperature gradients in the liquid scintillator. To mitigate them, in 2016 the collaboration succeeded to thermally insulate the detector with a 20 cm thick layer of mineral wool and installed an active control system composed by 66 probes, to monitor detector and Hall C temperature.

In Figure 1, in which the distribution of ^{210}Po events in different detector positions are depicted as a function of time, the results of the temperature stabilisation effort are shown.: the large fluctuations of the ^{210}Po rate are strongly mitigated starting from the beginning of 2016.
Thanks to this achievement, a region of the detector with marginal out-of-equilibrium ^{210}Po contamination has been found: the so-called Low Polonium Field (LPoF). In this region the ^{210}Po reaches a minimum, allowing the estimation of an upper limit for the rate of ^{210}Bi.

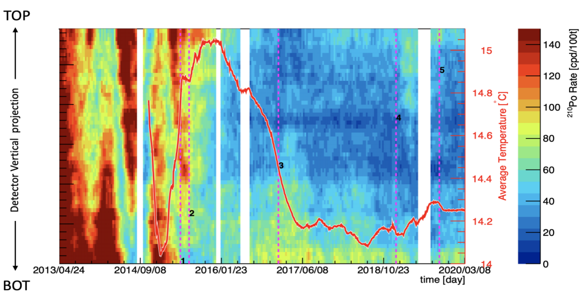

Figure 1. Distribution of ^{210}Po events in different detector positions from April 2013 to May 2020.

The minimum of the ^{210}Po distribution is estimated by means of a fitting procedure with a 2D paraboloidal function, performed in data bins of 1 month, yielding to the conclusion that the spatial position of the minimum along the z-axis (z_0) is stable over time. The final fit is performed on 20 tonnes of scintillator, considering the data set produced by aligning the distributions with respect to z_0 and summing up the time bins. Following this procedure is possible to extract the ^{210}Po minimum, thus the ^{210}Bi upper limit: $R(^{210}Bi) < 11.5 \pm 1.3$ cpd/100t. Systematics related to ^{210}Bi uniformity hypothesis, fitting methods and efficiency of alpha particle selection are considered.

4. Results and conclusions

The multivariate analysis was performed in the (0.32 - 2.64) MeV energy range, constraining in the fit both pep-ν and ^{210}Bi interaction rates. Many possible sources of systematic error have been investigated, including light yield, spectral shape of ^{210}Bi, detector energy response and deviations of the energy scale from the Monte Carlo model. The total amount of statistical error thus calculated is -0.5/+0.6 cpd/100t.

In conclusion, considering both statistical and systematic error the final CNO interaction rate is found to be $7.2^{+3.0}_{-1.7}$ cpd/100t at 68% C.L. , with a good p-value of the fit (0.3). As shown in left panel of Figure 2, the significance of the result in rejecting the hypothesis of absence of CNO is evaluated by means of the log-likelihood profile including all errors. This result is confirmed by a frequentist hypothesis test based on the *test statistic* $q = -2log\frac{\mathcal{L}(CNO=0)}{\mathcal{L}(CNO)}$ obtained from 13.8 millions of pseudo-data sets, where $\mathcal{L}$ is the maximum likelihood obtained by keeping the CNO rate fixed to zero or free. Both these methods allow to reject the no-CNO hypothesis with a significance better than 5.0σ.

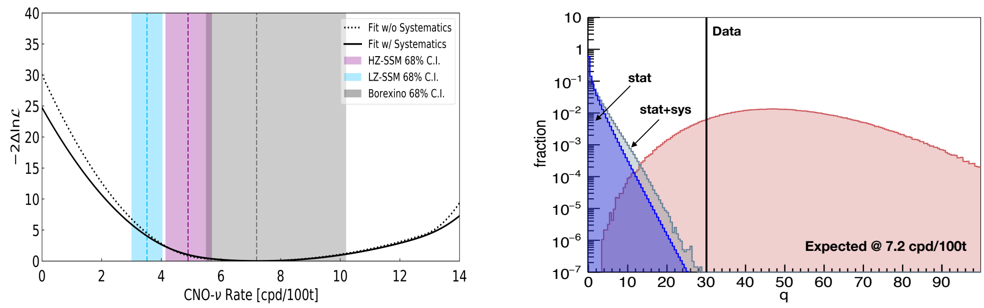

Figure 2. Left panel: negative log-likelihood profile from the multivariate fit with statistical error only (dashed line) and adding systematics (solid line). The three bands shows the 1σ confidence intervals for the LZ-SSM (azure) and HZ-SSM (violet) predictions for the CNO-ν rate and the corresponding rate evaluated in Borexino (grey). Right panel: distribution of the q *test statistic* from 13.8 millions Monte Carlo pseudo-data sets. The distributions obtained with no CNO with statistical only and statistical plus systematic error are shown along with the expected test statistics distribution for Borexino best fit value of CNO rate.

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