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Directionality measurement of CNO neutrinos with Borexino detector

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In the following, the first measurement of CNO solar neutrinos obtained by Borexino by exploiting the directional information retained by solar neutrino is summarized [1]. The Correlated Integrated Directionality (CID) method makes use of the sub-dominant Cherenkov light emitted by the Borexino liquid scintillator to correlate between the first few detected photons in each event and the known position of the Sun for each event and, therefore, to discriminate between the signal and the radioactive background on a statistical basis. By applying this technique to the complete 2007-2021 Borexino dataset, the hypothesis of no CNO neutrinos is rejected with >5σ posterior probability, without making use of any information on the background levels in the scintillator.

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1. Introduction

The Sun is continuously powered by thermonuclear reactions taking place in its innermost layers, who emit solar neutrinos as a by-product. For our star, the *pp* chain reactions make up approximately 99% of solar luminosity and are the main sources of solar neutrinos. The sub-dominant CNO cycle reactions use Carbon, Nitrogen and Oxygen nuclei as catalysts and make up only about 1% of the solar luminosity, while they are expected to play the main role in stars more massive and older than the Sun. Solar neutrinos represent a unique probe to expand our particle and astroparticle physics knowledge, since their precise measurements of their fluxes can be used both to investigate the MSW-LMA paradigm and to study the innermost part of the Sun [2].

2. Borexino detector

Borexino [3] has been a large-volume liquid scintillator detector, located in the Hall C of the Laboratori Nazionali del Gran Sasso (Italy). The mountain shielding (3800 m.w.e.) guarantees a suppression of the atmospheric muon flux by a factor of 10^{-6} with respect to the Earth surface. The primary scientific goal of the experiment consisted in the real-time measurement of solar neutrino fluxes. The detector design is based by the graded shielding principle, as shown in Fig. 1. The core of the detector is given by an inner scintillator region, which is located at the center of concentric spherical layers. This setup aims to minimize the background events rate coming from external sources, like the surrounding rocks and cosmic muons. The detector is equipped with 2112 PMTs installed on the inside of the Stainless Steel Sphere, that is a mechanical support sphere. The PMTs collect the photons emitted by the scintillator, also measuring the signal intensity and their arrival time. The precise determinations of these two quantities stand at the basis of the reconstruction of the energy and position of the events respectively.

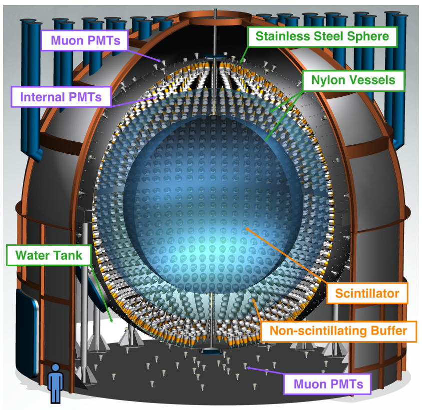


Figure 1: Schematic view of the Borexino detector.

For what concerns the solar neutrino spectroscopy, Borexino has been able to extend its original scientific scope thanks to its excellent and unprecedented radiopurity levels. This has been achieved by employing extremely radiopure materials, by shielding the central part of the detector and by performing dedicated purification campaigns. Indeed, by analyzing the Phase-I (2007-2011) and Phase-II (2011-2016) data taking periods, Borexino has been able to perform a complete spectroscopy of the solar neutrinos from the *pp* chain reactions [4–8]. By considering the most radiopure Phase-III dataset (2016-2020), Borexino also achieved the first experimental detection of the CNO neutrinos [9, 10]. This measurement plays a striking importance towards the solution of the long-standing solar metallicity problem.

3. Correlated and Integrated Directionality method

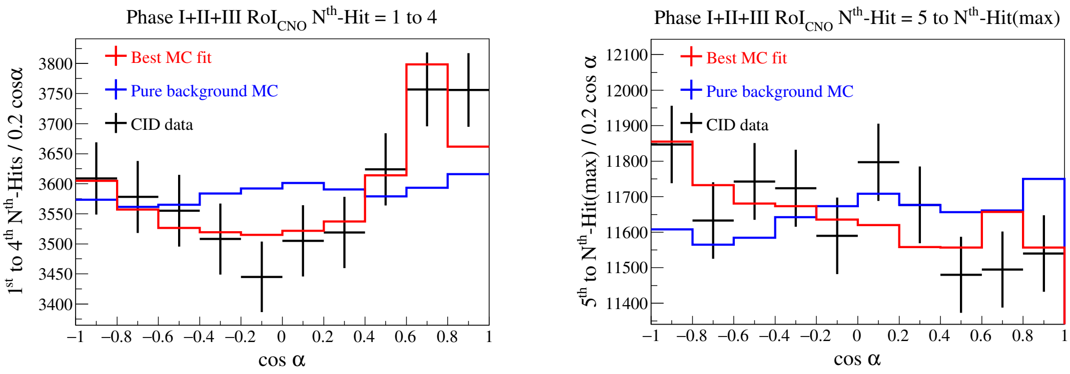
The novel "Correlated and Integrated Directionality" (CID) [11, 12] has been developed by the Borexino experiment to exploit the directional information carried by the scarce Cherenkov light induced by the scintillator electrons recoiling. Indeed, those Cherenkov photons which are emitted by electrons scattering after a neutrino interaction retain information on the direction of the incoming neutrino. We have exploited the CID technique to determine the CNO flux [1] with high significance, as an alternative method to the multivariate fit which had been extensively used in Borexino [9, 10].

An event-by-event directional reconstruction of events is not possible, as the scintillation photons are largely dominant in liquid scintillator detectors. For each PMT hit in an event, the CID analysis considers the $\cos\alpha$ quantity, where α is defined as the angle between the known solar neutrino direction and the photon direction of the hit given by the reconstructed position and the hit PMT position (as shown in Fig. 3 in [12]). The $\cos\alpha$ distribution can be exploited to statistically separate solar neutrino signal events from the background events. It follows that, to better discriminate the solar neutrino signal from the background ones, one should consider a large number of Cherenkov photons. Unfortunately, the Cherenkov light for a 1 MeV deposited energy is sub-dominant, being expected to amount about 1% of the total number emitted photons. The Cherenkov photons are emitted almost istantaneously, while the scintillation light is emitted with a slower time scale of ns or tens of ns: as a consequence the directional information is mainly included in the first hits of an event, after we correct the arrival time to the PMTs for the time of flight of each photon. In the current analysis we extend the number of early hits used for the CID analysis (up to 15th or 17th hit for Phase-I and Phase-II+III respectively) with respect to the previous Borexino works [11, 12], where only the first and the second hit have been used. In such a way, the directional information is exploited at best.

For Cherenkov photon hits from a solar neutrino interaction, the $\cos\alpha$ distribution is expected to show a characteristic peak at $\cos\alpha \sim 0.7$, while the $\cos\alpha$ distribution of scintillation photons will lack such a signature peak and is in the first order rather flat. For the background events, the $\cos\alpha$ distribution of all hits is expected to be practically the same as the distribution of the scintillation photons for solar neutrino events, i.e., rather featureless and without a peak. This is because the direction of Cherenkov photons from the background events is uncorrelated with the solar direction.

4. Results on CNO neutrino flux

The considered dataset for this analysis is the complete Borexino data taking one, extending from May 2007 to October 2021. The basic data quality cuts, to partially remove several backgrounds (muons and muon-induced events, noise events, radioactive decays from delayed coincidences), as well as the Three-Fold-Coincidence algorithm (TFC), have been applied to the dataset following [9,



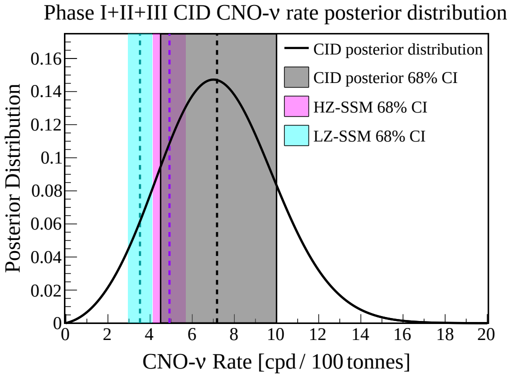
(a) **(b)**

Figure 2: Illustration of the CID data (black) and the best fit results (red) summed for the Phase-I + Phase-II+III in the $\mathrm{RoI}_{\mathrm{CNO}}$. The background-only Monte Carlo predictions (blue) scaled to the same total number of events is shown. (a) The sum of the first to fourth N^{th}-hits $\cos\alpha$ histograms shows the Cherenkov peak. (b) The sum of the fifth to the N^{th}-hit(max) $\cos\alpha$ histograms shows the effect the Δr_{dir} parameter on these later hits.

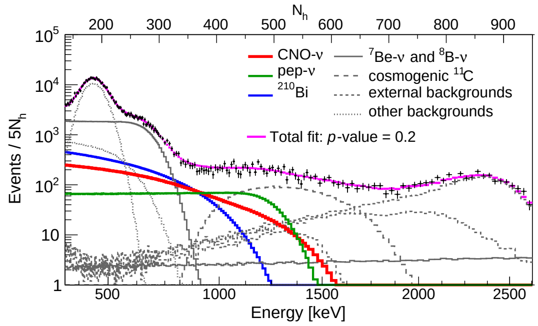
10]. The fiducial volume (FV) cut selects events in a central scintillator region within a sphere of radius R_{FV}, highly reducing the external background rate. The optimized cuts for Phase-I dataset are $R_{\mathrm{FV}} < 3.05$ m and $0.85\,\mathrm{MeV} < T_e < 1.3\,\mathrm{MeV}$, while for Phase-II+III the optimized cuts are $R_{\mathrm{FV}} < 2.95$ m and $0.85\,\mathrm{MeV} < T_e < 1.29\,\mathrm{MeV}$. An illustration of the CID data and the best fit results summed for the Phase-I + Phase-II+III is shown in Fig. 2a and Fig. 2b, with a total of 8964 events in the $\mathrm{RoI}_{\mathrm{CNO}}$ (where RoI stands for Region of Interest). The expected $\cos\alpha$ distributions for signal and background are obtained from Monte Carlo simulations.

The fitting strategy follows the procedure developed in previous CID analysis [12]. The fit returns the total number of solar neutrinos N_ν detected in the RoI, and the number of background events in the RoI. Additionally, two nuisance parameters are present. The first one is an effective Cherenkov group velocity correction ($\mathrm{gv_{ch}}$) which takes into account slight differences in the relative hit time distribution between scintillation and Cherenkov hits in data relative to the Monte Carlo simulations. In the previous CID analysis [11, 12], which focused only on Phase-I, this parameter was tuned by analyzing calibration γ sources data from the 2009 calibration campaign. Instead, in this analysis we want to exploit the complete Borexino dataset, for this reason we changed strategy to independently obtain this parameter: we have performed the same CID analysis in a lower energy region ($0.5\,\mathrm{MeV} \le T_e \le 0.8\,\mathrm{MeV}$), which contains mainly ^{7}Be neutrinos events contribution and backgrounds. The ^{7}Be neutrino number of events is constrained based on the SSM predictions, and we have tuned $\mathrm{gv_{ch}}$ to maximize the data-Monte Carlo agreement; the resulting $\mathrm{gv_{ch}}$ value has been is constrained in the main analysis $\cos\alpha$ fit. The second nuisance parameter, which in the $\cos\alpha$ fit is left free to vary, is the event position mis-reconstruction in the initial electron direction Δr_{dir}. This effect is an indirect consequence of the Cherenkov hits, since the reconstructed position is slightly biased towards early hit PMTs of the corresponding event.

The best fit values for the number of solar neutrinos in $\mathrm{RoI}_{\mathrm{CNO}}$ are $N_\nu = (6.9 + 2.4 - 2.2) \times 10^2$ (stat) for Phase-I and $N_\nu = (28.2 + 5.2 - 4.9) \times 10^3$ (stat) for Phase-II+III without inclusion



(a)



(b)

Figure 3: Left panel: the combined CID CNO-ν rate posterior distribution is shown in red. The blue, violet and grey bands show the 68% CI, for the low metallicity SSM B16-AGSS09met, the high metallicity SSM B16-GS98 predictions and the combined CID result, respectively. Right panel: multivariate fit results, projected over the energy dimension for the TFC-subtracted dataset. The sum of the individual contributions resulting from the fit (magenta line) is superimposed on the data (grey points). CNO neutrinos, ^{210}Bi and *pep* neutrinos contributions are displayed in solid red, dashed blue and dotted green lines, respectively, while the other spectral components (^{7}Be and ^{8}B neutrinos, other backgrounds) are shown in grey.

of any systematic uncertainties or corrections, with a good compatibility between the data and the Monte Carlo underlying model. The final result of the CID analysis for the number of solar neutrinos is given by the Bayesian posterior distribution of N_ν, marginalized over the nuisance parameters and convoluted with the systematic uncertainties, which are reported in Table II of [1]. Then, the N_ν posterior distribution can be deconvoluted with the expected posterior distribution for the sum of *pep* and ^{8}B neutrino events, to isolate the resulting $P(N_{\mathrm{CNO}})$ posterior distributions, shown in Fig. 3a. Considering the complete Borexino dataset, the probability that no CNO-ν events populate the RoI is associated to a one sided exclusion 5.3σ credible interval.

As an additional step, the CID analysis can be combined with the standard multivariate fit of Phase-III dataset, to improve the significance of the previous Borexino results on CNO neutrinos [9, 10]. To this purpose, the posterior distribution of N_ν previously shown can be included in the multivariate analysis likelihood as a multiplicative pull term. The TFC-subtracted energy part of the multivariate fit for the Phase-III dataset with the CID constraint applied is shown in Fig. 3b. The final CNO interaction rate is $6.7^{+1.2}_{-0.8}$ cpd/100 tonnes, which is associated to a significance against the absence of a CNO signal, of about 8σ. According to this result the CNO neutrino flux at Earth, considering the neutrino flavor conversion, is $\Phi_{\mathrm{CNO}} = 6.7^{+1.2}_{-0.8} \times 10^{8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$; this value is in agreement with the SSM B16-GS98 high metallicity Standard Solar Model. By combining this latter result with the previous ^{8}B and ^{7}Be neutrinos measurements by Borexino, the low metallicity SSM B16-AGSS09met model is disfavored at 3.2σ C.L, if the SSM B16-GS98 high metallicity model is assumed to be true.

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