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Directional analysis of sub-MeV ^{7}Be solar neutrinos in Borexino

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Summary. — Borexino is a liquid scintillator detector located at the Laboratori Nazionali del Gran Sasso (LNGS), Italy with the main goal to measure solar neutrinos. Liquid scintillator detectors are excellent neutrino detectors due to their high light yield and thus a low energy threshold and high energy resolution. But, they suffer from the loss of directional information that is typically present in water Cherenkov neutrino detectors. However, in a liquid scintillator, there is still a subdominant amount of Cherenkov light emitted much faster with respect to the slower, yet dominant scintillation light. Borexino has successfully exploited this Cherenkov light signal from the first few PMT hits of an event to provide the first ever directional measurement of sub-MeV solar neutrinos, through the novel technique called Correlated and Integrated Directionality (CID). This is also the first signature of directionality in neutrinos elastically scattering off electrons in a liquid scintillator detector. Through this measurement, the ^{7}Be interaction rate in the detector has also been extracted. Future liquid scintillator detectors can benefit from this method for background suppression and disentanglement of signals from different directions.

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1. – Introduction

Neutrino detection at present is either performed with Liquid Scintillator (LS) or Water Cherenkov detectors. In a LS detector like Borexino, when a neutrino scatters off an electron, the recoil electron excites the LS molecules, which in turn emit isotropic scintillation light with a wavelength distribution and time profile that depends on the LS. In water Cherenkov neutrino detectors such as SNO and Super-Kamiokande, the recoil electron scattered off by the neutrino produces Cherenkov light which can then be used for direction reconstruction, a powerful tool for background rejection and separation of different signals on an event-by-event basis. In recent years, there has been an increased interest in developing techniques for the hybrid detection of scintillation and Cherenkov light with the goal to obtain a directional signature in scintillator detectors.

Borexino is a 280-ton LS detector located at LNGS, Italy. Its main goal is the measurement of solar neutrinos, and has provided a complete spectroscopy of *pp*-chain solar neutrinos and the first direct evidence of CNO-cycle solar neutrinos. While an event-by-event directional reconstruction is not possible in a traditional LS detector like Borexino, it is still possible to obtain directional information by correlating the first few PMT hits of an event rich in Cherenkov photons to the well-known position of the Sun. This article explains the directional analysis of sub-MeV, specifically ^{7}Be solar neutrinos, using the directional Cherenkov light emitted in the first few nanoseconds of the event through a novel technique called *Correlated and Integrated Directionalty*.

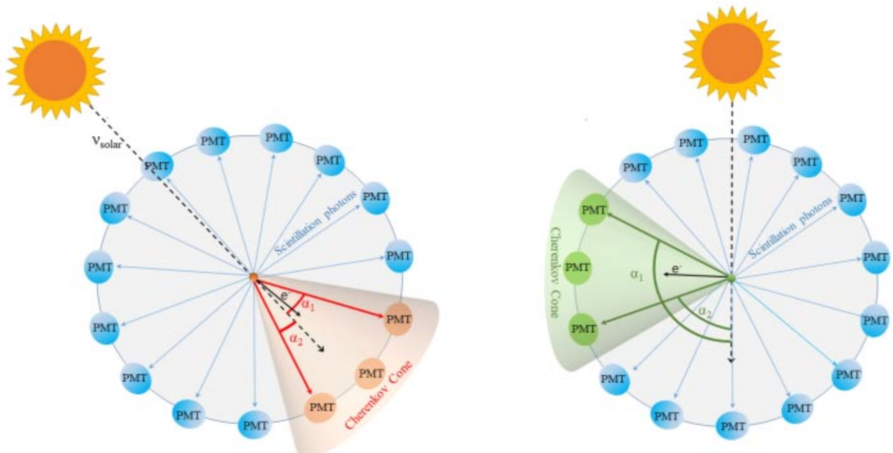
2. – Correlated and Integrated Directionality (CID)

Solar neutrinos interact in LS via elastic scattering off electrons. The angle between the recoil electron and the neutrino direction follows the energy-momentum conservation with the free electron approximation. In Borexino, Cherenkov light is emitted if the energy of the electron is $>0.16\,\mathrm{MeV}$, considering the refractive index of ≈ 1.55 @ $400\,\mathrm{nm}$ [1].

Figure 1 shows the principle of the *Correlated and Integrated Directionality* (CID) method. The recoil electron is scattered roughly in the direction of the solar neutrino and the corresponding scintillation and Cherenkov hits are detected at the PMTs. Unabsorbed Cherenkov photons will hit PMTs in the forward direction of the solar neutrino while scintillation light will hit the PMTs isotropically. The position of the Sun and the direction of solar neutrinos is well known as events are detected in real time. The $\cos\alpha$ can be calculated for each PMT hit, where α is 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. Solar neutrino events and radioactive background in Borexino will produce a PMT hit pattern which is different for scintillation and Cherenkov light. This clear signature can then be used to statistically disentangle the solar neutrino and background components.

3. – Analysis strategy and methods

The main goal of this analysis is to show that using the *Correlated and Integrated Directionality (CID)* method it is possible to provide a statistically significant measurement on the number of solar neutrinos (^{7}Be, *pep*, CNO). The number of solar neutrinos $N_{\mathrm{solar}-\nu}$ can be measured by performing a χ^2-fit on the CID ($\cos\alpha$) distribution of data



(a) (b)

Fig. 1. – Schematic representation of the angular correlation, expressed by the angle α between the direction of emitted photons and the position of the Sun with respect to Borexino for different event types. Electron recoiling off a solar neutrino (a) and an electron from the intrinsic radioactive background (b) at the center of the detector produces a Cherenkov cone (red arrows and green arrows respectively) pointing forward in the direction of the Sun and isotropic scintillation photons (blue arrows). The Cherenkov photons and, in turn, the PMT hits trigered by the recoil electron from the solar neutrino are correlated to the incoming direction of the solar neutrinos. The Cherenkov photons from the background have no correlation to the Sun's direction. α_1 and α_2 are the directional angles of the first and second photons [5].

using the MC directional PDFs of ^{7}Be (dominant signal) and ^{210}Bi (dominant background). The measurement can then be converted to the ^{7}Be neutrino interaction rate, expressed in counts per day (cpd) per 100 ton of LS, using the known exposure and the efficiency of the selection cuts, and the Standard Solar Model (SSM) predictions of the CNO and *pep* neutrino rates.

The dataset for this analysis comprises Phase-I, Phase-II, Phase-III of the Borexino experiment. The data events for this analysis have been selected using almost the same selection cuts used in the standard solar neutrino analyses of Borexino [3]. However, only a small energy Region of Interest (ROI) between 0.5 and 0.8 MeV is used so as to have a high amount of ^{7}Be solar neutrinos. The Fiducial Volume (FV) is an enlarged spherical volume of 132.1 t (Phase-I and II) or 99.3 t (Phase-III) when compared to the smaller and asymmetrical standard fiducial volumes of $\sim$70–75 t used for the low energy spectral analyses of Borexino. In addition, an α/β discrimination cut is applied to suppress the ^{210}Po α background. The ROI consists mainly of ^{7}Be solar neutrinos, and a small amount of CNO and *pep* solar neutrinos. The dominant background in this ROI is the radioactive ^{210}Bi background, a β emitter.

The detected PMT hits of all the selected data events are ordered in time after corrected with their Time-of-Flight (ToF). A simple straightforward approach to select Cherenkov photons would be to apply a time cut until when the Cherenkov light is dominant. But, systematic sub-nanosecond differences between data and MC have been observed in Borexino. Even though this effect does not affect event-based algorithms such as position reconstruction, it is significant for the CID analysis. The relative ordering of hits in MC is however still well-simulated. Consequently, an "Nth-hit method" has been adopted for the CID analysis. $\cos\alpha$ distributions of the 1^{st}, 2^{nd},...,N^{th} hits of all the selected events are first constructed. Then, in order to maximize the amount of Cherenkov photons, a cut is applied on the N^{th} hit. This N^{th} hit cut is chosen based on MC and the first two hits have been chosen where the Cherenkov to scintillation ratio is high.

The number of solar neutrinos $N_{\mathrm{solar}-\nu}$ for the selected β-like data events is extracted from the fit of their $\cos\alpha$ distribution with the MC based PDFs, i.e., $\cos\alpha$ distributions of ^{7}Be signal and ^{210}Bi background, using a χ^2-fit defined as follows:

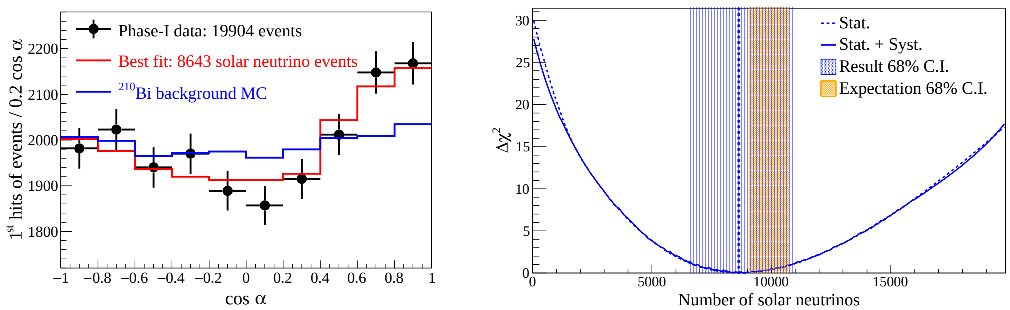
$$\chi^2(N_{\mathrm{solar}-\nu}) = \sum_{n=1}^{N}\sum_{i=1}^{I}\left(\frac{\left((\cos\alpha)^{D}_{n,i} - (\cos\alpha)^{M}_{n,i}\big(N_{\mathrm{solar}-\nu}, \Delta r_{\mathrm{dir}}, gv^{\mathrm{corr}}_{\mathrm{ch}}\big)\right)^2}{(\sigma^{D}_{n,i})^2 + (\sigma^{M}_{n,i})^2}\right.$$

$$\left. + \frac{(gv^{\mathrm{corr}}_{\mathrm{ch}} - 0.108\,\mathrm{ns\ m^{-1}})^2}{(0.039\,\mathrm{ns\ m^{-1}})^2}\right) \tag{1}$$

The index n runs from 1 to the selected N^{th} hit $= 2$ and the index i runs from 1 to the total number of bins I in the range $-1 < \cos\alpha < +1$. The number of bins I has been optimised to 60. $(\cos\alpha)^{D}_{n,i}$ and $(\cos\alpha)^{M}_{n,i}$ are the $\cos\alpha$ values for the i^{th} bin of the n^{th} hit of data and MC, respectively, and, $\sigma^{D}_{n,i}$ and $\sigma^{M}_{n,i}$ are their corresponding statistical errors. The systematic shift in the reconstructed vertex position of the electron Δr_{dir} and an effective correction of the group velocity $gv^{\mathrm{corr}}_{\mathrm{ch}}$ for Cherenkov photons are sufficient to parameterize differences between data and MC. Both are treated as nuisance parameters in the analysis. The group velocity correction $gv^{\mathrm{corr}}_{\mathrm{ch}}$ is applied for Cherenkov photons in the MC, estimated using gamma calibration sources from the 2009 calibration campaign [2] and it is treated as nuisance parameter using a Gaussian pull term for Phase-I. The best fit value has been estimated as $(0.108 \pm 0.039)\,\mathrm{ns\,m^{-1}}$ [6]. The systematic parameter Δr_{dir}, arises due to the difference between the true and reconstructed positions of the detected electron, and is treated as a free nuisance parameter in the fit.

4. – Results and conclusions

A χ^2 fit has been performed on the Phase-I data as described in the previous section. Since a Cherenkov calibration has been possible in Phase-I, the group velocity correction $gv^{\mathrm{corr}}_{\mathrm{ch}}$ has been treated as a nuisance parameter with a Gaussian pull term, leading to a measurement on the number of solar neutrinos. This is shown in fig. 2. The figure on the left shows the first hits of all the selected in Phase-I, compared to the best fit and the background MC. It can be seen that the data cannot be explained just by the background. The $\Delta\chi^2$ profiles for the first two hits with and without systematic uncertainty (6.9%) are shown on the right figure. It can be seen that the no-directionality signal can be excluded with >5 sigma significance. The resulting number of solar neutrinos is $N_{\mathrm{solar}-\nu} = 8643^{+2171}_{-1969}(\mathrm{stat.}) \pm 597(\mathrm{syst.})$ [5]. The 68% CI is well in agreement within the SSM expectations [4] as seen in fig. 2. Since there is no Cherenkov calibration for Phase-II and III, the datasets were only compared to the background MC and they were found to be incompatible with $>5\sigma$ significance. The measured solar neutrinos from Phase-I can be further converted into the ^{7}Be interaction rate as discussed in the previous Section and this is given as $R(^{7}\mathrm{Be}) = 39.7^{+12.0}_{-11.0}\,(\mathrm{stat.+syst.})\,\mathrm{cpd/100t}$ [5].



(a) (b)

Fig. 2. – (a) $\cos\alpha$ distributions of the first hits of all the selected events (black points) compared with the best fit curve for the resulting $N_{\mathrm{solar}-\nu} = 8643$. All curves are normalized to the data statistics. It can be seen that the data points cannot be explained by the background-only hypothesis. (b) $\Delta\chi^2$ profiles of the first and second hits from the fit as a function of $N_{\mathrm{solar}-\nu}$ with (blue solid line) and without (blue dotted line) the systematic uncertainty. The no-neutrino signal hypothesis (pure background, S/T=0) can be rejected with $\Delta\chi^2 > 25$, $> 5\sigma$. The 68% CI from the $\Delta\chi^2$ profile is represented by the blue shaded band and the best fit value is shown as a vertical blue dotted line. The 68% CI of the the solar neutrino signal expected based on the Standard Solar Model (SSM) prediction is shown as a shaded orange band [5].

The successful measurement of solar neutrinos in a high light yield liquid scintillator detector using only the fit of the directional distribution provided by Cherenkov light and no fit of the energy spectrum is an important proof of principle for the CID method presented here. Thus, this method can be developed further for a joint analysis with a typical spectral fit. Future solar LS experiments can readily benefit from the CID method even without specialized hardware or LS mixtures for the separation of Cherenkov and scintillation light. A dedicated e^- Cherenkov calibration is highly recommended to benefit from CID, even if an event-by-event direction reconstruction based on Cherenkov light is expected to be not possible.

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