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Abstract. Borexino, located at the Laboratori Nazionali del Gran Sasso in Italy, is a liquid scintillator detector that measures solar neutrinos via elastic scattering off electrons. The scintillation process of detection makes it impossible to distinguish electrons scattered by neutrinos from the electrons emitted from the decays of radioactive backgrounds. Due to the unprecedented radio-purity achieved by the Borexino detector, the real time spectroscopic detection of solar neutrinos from both the pp chain and CNO fusion cycle of the Sun has been performed. With the newly presented analysis, it is now possible for the first time, to perform the directional detection of the sub-MeV solar neutrinos and extract the ^{7}Be interaction rate using the few Cherenkov photons emitted at early times, in the direction of scattered electrons with an energy threshold of 0.16 MeV in the liquid scintillator. The angle which correlates the direction of the Sun and the direction of the emitted Cherenkov photons is a key parameter to extract the neutrino signal from data. This article will describe the strategy used in the evaluation of various systematic effects including the geometric conditions of the detector and the data selection cuts that can influence the shape of the directional angle distribution for backgrounds, which is crucial to disentangle the directional sub-MeV solar neutrino signal from the isotropic background in data.

1. Introduction

Borexino is an ultra-pure 280 tons liquid scintillator detector (LS), which is located at the Laboratori Nazionali del Gran Sasso in Italy. Since the Borexino detector is located in deep underground lab of LNGS at a depth of about 3800 m.w.e, the cosmogenic muon background is highly suppressed by a factor of 10^6. The effective light yield in the Borexino detector is 500 photoelectrons per 1 MeV of deposited energy with 2000 photomultiplier tubes (PMTs). In Borexino, solar neutrinos are detected by means of elastic scattering of electrons. The recoiled electron excites the LS molecules, which emits dominant isotropic scintillation light with a wavelength distribution and time profile that depends on LS. The subdominant Cherenkov light, which contributes less than 1% of all PMT hits, is also emitted by electrons with a threshold energy of 0.16 MeV considering refractive index of 1.55 @ 400 nm. Cherenkov photons are emitted in a cone towards the traveling direction of forward scattered electron and hence, Cherenkov photons preserves the directionality of the solar neutrinos. Another characteristic of Cherenkov photons is that they are emitted earlier than the scintillation photons as the emission of scintillation photons follows exponential decay time distribution.

In Borexino, event by event directional reconstruction is not possible due to dominance of scintillation photons which hit the PMTs isotropically. So, we adopt a novel method called *Correlated and Integrated Directionality* (CID) method [1] to obtain the directional information of the solar neutrinos. In this technique, the first few PMT hits of an event are correlated with the known position of the Sun. The resulting angular ($\cos\alpha$) distribution is defined as the cosine of angle between the direction of the Sun and the direction of hit PMT with respect to the reconstructed event position. For the solar neutrino events, a non-flat angular distribution due to Cherenkov photons hits is expected with peak at $\cos\alpha \to 1$. While for the background events, the distribution should be flat as the direction of emitted electron is uncorrelated to the direction of the Sun. As the scintillation photons from both solar neutrino and background events are emitted isotropic in direction, this also results in a flat angular distribution. However, the observed distribution for backgrounds is not entirely flat due to the reasons described later.

2. Fit strategy

For the directional analysis of the solar neutrinos, the dataset corresponding to the Phase-I, Phase-II and Phase-III period of the Borexino experiment has been taken into account. The selection cuts for the data events are almost the same as those applied in the standard solar analysis of Borexino [2]. There are some additional cuts applied that differ from the standard solar analysis which are listed as following:

- **Fiducial Volume** : An enlarged fiducial volumes of spherical shape with $R < 3.3$ m and mass 132.1 t (for Phase-I and Phase-II) and $R < 3.0$ m and mass 99.3 t (Phase-III) are chosen for this work.
- **Energy cut** : In order to maximise the number of ^{7}Be solar neutrino events over the total events, the Region of Interest (ROI) of approximately 0.5-0.8 MeV is chosen for all the phases. This also means that there is no contribution from external backgrounds which is of concern for solar neutrino spectroscopy analysis.
- **Pulse shape discrimination cut**: A neural network algorithm called Multi-Layer Perceptron (MLP) is used to reject the ^{210}Po α background events with 99% efficiency.

After the data selection, the ROI mainly consists of ^{7}Be solar neutrino events (89% of solar neutrino events) with a relatively small contribution from CNO and *pep* solar neutrinos. The main backgrounds for this analysis are ^{210}Bi and ^{85}Kr which decay via emitting β.

The detected PMT hits for each event are sorted in time after subtracting their time of flight (ToF) and by looking at their relative order in time. The $\cos\alpha$ distributions are constructed for 1st hit, 2nd hit ... and up to N^{th} hit for all events. The value of N^{th} hit is chosen using Monte

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Carlo (MC) studies and is determined to be two hits such that the ratio of Cherenkov photons to scintillation photons is high.

Then, the $cos\alpha$ distribution of selected data events is fitted with the distributions of Monte Carlo probability density functions (PDFs) of ^{7}Be signal and ^{210}Bi background using a χ^2 fit and the number of solar neutrinos events is extracted, which is demonstrated in [3]. The fit of Phase-I dataset also includes the effective correction on refractive index for Cherenkov photons, which is done to take into account the difference in the relative time distribution of Cherenkov and scintillation photons in Monte Carlo and in data as described in [4].

3. Systematic sources

The effects of various systematic sources on the measurement of number of solar neutrinos events and the extraction of ^{7}Be neutrinos interaction rate have been studied. They are summarised in Table 1 and are described as following:

Distortion of $cos\alpha$ distribution for backgrounds

The expected shape of $cos\alpha$ distribution for backgrounds should be flat. However, it is not found to be the case in this analysis and depends on various effects. Using the toy Monte Carlo simulations, the effect of various geometric effects like the shape of fiducial volume, distribution of the PMTs and spatial distribution of the events has been studied for the cause of distortion of shape of $cos\alpha$ distribution for backgrounds. They are listed below:

- **Fiducial Volume** : In the standard Borexino solar neutrino analysis, asymmetric fiducial volume with radius R < 3.0 m with vertical coordinate −1.67 m < z < 1.67 m for Phase-I and R < 2.8 m with the vertical coordinate −1.8 m < z < 2.2 m for Phase-II and III is used. Since such a asymmetric fiducial volume has been found to cause non-flat $cos\alpha$ distribution for backgrounds, a spherical fiducial volume is chosen. A larger fiducial volume is possible here because external backgrounds does not influence the ROI of this analysis as mentioned in the previous section.
- **Distribution of PMTs**: The shape of $cos\alpha$ distribution for backgrounds is highly dependent on the PMT distribution. In the case of a ideal scenario of infinite number of PMTs and their uniform spatial distribution, a flat distribution of $cos\alpha$ distribution for backgrounds is expected. Using the toy MC study, it has been found that the finite number of PMTs and their asymmetric spatial distribution causes non-flat distribution of $cos\alpha$ distribution for backgrounds. Since Borexino Monte Carlo simulation follows the real PMT distribution same as the distribution in data, this effect does not contribute to the systematic error on the final results.
- **Distribution of events**: The non-uniform spatial distribution of background events also causes deviation from the expected flat $cos\alpha$ distribution. By injecting the non-uniformity in the distribution of events in the toy simulation at the level of data corresponding to different periods, the contribution of this effect on the final fit has been estimated to be negligible.

Choice of N^{th} hit and binning of $cos\alpha$ distribution

The first two hits of an event has been selected for the construction of $cos\alpha$ distribution which contributes to the systematic error. By performing the fit using different N^{th} hit cuts (2,3 and 4), the error due to this selection is estimated to be 1.4%. The number of bins for the $cos\alpha$ distribution has been selected to be 60 bins using a MC study and the error due to this selection is estimated to be 6.7% by doing analysis with 40, 60 and 120 bins.

Selection of PMTs

It was found that the systematic differences in time behaviour of PMTs for only first few hits of the event were present in data and MC. Therefore, in order to have the agreement in the qualitative time behaviour of the PMTs in data and MC for the selected first hits, the selection of PMTs is done. This poses an systematic uncertainty of 1.2%.

Exposure and MLP efficiency

The error due to uncertainty on the selected exposure is dominated by error on position reconstruction as the selection of events inside the fiducial volume is done using position reconstruction. For spherical fiducial volume of radius 3.3 m, the error on exposure is 4.6%. The uncertainty on MLP efficiency is estimated to be 1.0% considering its change with time.

Theoretical predictions of CNO and pep neutrino interaction rates

Since the measurement of number of solar neutrinos is performed using CID method, it is required to fix CNO and *pep* solar neutrino interaction rates to extract the interaction rate of ^{7}Be solar neutrinos as they have indistinguishable shape of $cos\alpha$ distribution from ^{7}Be which have been studied using Monte Carlo simulations. In order to do so, their rates have been fixed to high metallicity (HZ) Standard solar model (SSM) predictions. As their rates predicted by HZ-SSM differ from those of low metallicity (LZ) SSM predictions, this contribute as a systematic uncertainty of +2.5% on the rate of ^{7}Be solar neutrinos. Taking into account the errors of theoretical predictions, the error on the rate of ^{7}Be solar neutrinos is found to be 1.5%. Combining both the errors, the final error on the rate of ^{7}Be solar neutrinos due to fixing of CNO and *pep* solar neutrino rates is estimated to be $^{+2.9}_{-1.5}$%.

Table 1. The different sources of systematic uncertainty for the number of solar neutrinos and the ^{7}Be interaction rate in the ROI.

Source	Uncertainty [%]
Choice of Nth Hit	1.4
Selection of PMTs	1.2
Choice of histogram binning	6.7
Number of solar neutrinos	6.9
Exposure	4.6
MLP variable	1.0
CNO and *pep* rates	$^{+2.9}_{-1.5}$
^{7}Be rate	$^{+8.8}_{-8.4}$

Considering the systematic sources such as the choice of Nthhit, binning of $cos\alpha$ distribution and the selection of PMTs distribution, this results in the total systematic uncertainty of 6.9% on the number of solar neutrinos in Phase-I. The final systematic uncertainty on the resulting ^{7}Be interaction rate by taking into account all the effects mentioned above is $^{+8.8}_{-8.4}$%. The details on the results can be found in [3].

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