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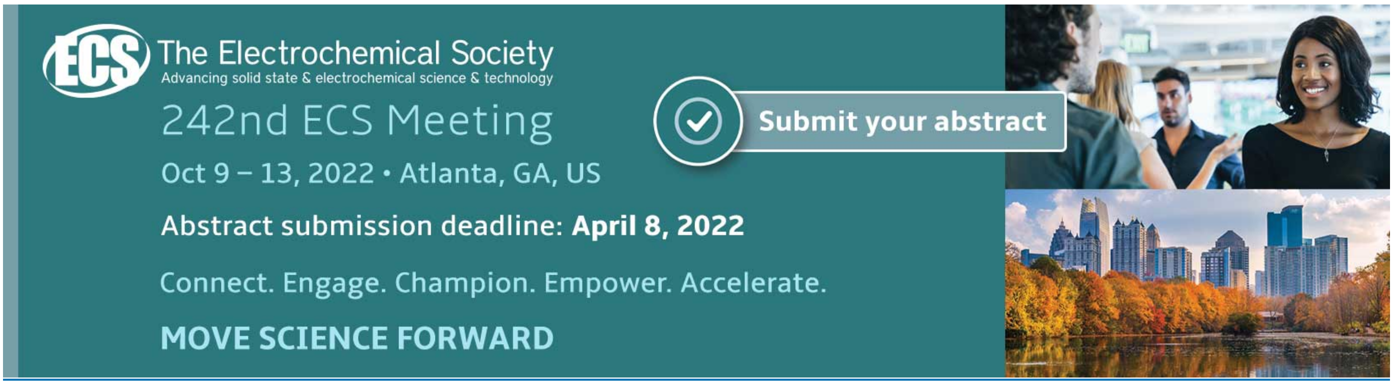

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Directional measurement in Borexino: Calibration of Cherenkov photons in a liquid scintillator detector using gamma sources

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Abstract. Borexino is a 280-ton liquid scintillator detector located at the Laboratori Nazionali del Gran Sasso (LNGS), Italy. The main goal of Borexino is to measure solar neutrinos via elastic scattering off electrons in the liquid scintillator. The electrons are then detected by the photo-multiplier tubes via isotropically emitted scintillation photons. However, in the first few nanoseconds after a neutrino interaction, Cherenkov photons ($<1\%$ of all detected photons) are also produced in the scintillator for electrons with kinetic energy >0.16 MeV. Borexino has successfully obtained the first directional measurement of sub-MeV solar neutrinos, and the ^{7}Be solar neutrino interaction rate, through the exploitation of this Cherenkov light signal. This is performed through the so-called *Correlated and Integrated Directionality* (CID) method, by correlating the first few detected photons to the well-known position of the Sun and integrating the angle for a large number of events. This measurement requires a calibration of the relative time differences between Cherenkov and scintillation photons. In Borexino, we obtain this through gamma calibration sources namely, ^{40}K and ^{54}Mn. A group velocity correction estimated through the gamma sources is then used for the solar neutrino analysis. This article will discuss the analysis strategy and methods used for this calibration, and provide motivation for a dedicated Cherenkov calibration in next-generation liquid scintillator detectors.

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1. Introduction

Borexino is a high light yield (500 photoelectrons per MeV) liquid scintillator (LS) solar neutrino detector [1]. Therefore, it never had a dedicated calibration for the sub-dominant Cherenkov photons that are emitted much faster with respect to the scintillation light following a neutrino event. However, a directionality measurement of solar neutrinos that exploits the small Cherenkov signal warrants a dedicated calibration for the sub-nanosecond time differences between data and Monte-Carlo (MC). The *relative* time differences between Cherenkov and scintillation light in Borexino MC have been calibrated using gamma sources from the 2009 calibration campaign [3] for the first directional measurement of sub-MeV solar neutrinos [2]. Since the effective wavelength spectrum of detectable Cherenkov photons in Borexino has never been measured in-situ and the refractive index used in the MC has a finite accuracy, the relative group velocities of scintillation and Cherenkov photons can be different in data and MC. This can essentially increase or decrease the ratio of Cherenkov photons in the first hits when the Cherenkov light has a significant contribution.

A group velocity correction $gv_{\rm ch}^{\rm corr}$ is applied to Cherenkov photons in the MC as shown in Equation (1). This correction essentially changes the old PMT hit time $t_{\rm ch-old}^{\rm ToF}$ of Cherenkov photons to a modified hit time $t_{\rm ch-new}^{\rm ToF}$ using the MC photon track length $L_{\rm true}$.

$$t_{\rm ch-new}^{\rm ToF} = t_{\rm ch-old}^{\rm ToF} - (gv_{\rm ch}^{\rm corr} \cdot L_{\rm true}) = t_{\rm ch-old}^{\rm ToF} - \left(\frac{\Delta n_{\rm ch}}{c} \cdot L_{\rm true}\right). \quad (1)$$

The group velocity correction $gv_{\rm ch}^{\rm corr}$ has the unit of ns m^{-1}. This relation can be further expressed as a function of the effective change in the refractive index at a particular wavelength $\Delta n_{\rm ch}$. Since the MC is changed at the lowest level where the true origin and track length of each photon are known, the results obtained from the γ calibration are applicable also to the MC Cherenkov photons of recoil electrons from solar neutrinos. The value of the $gv_{\rm ch}^{\rm corr}$ can be obtained by producing angular distributions of gamma calibration data and MC. The interaction of MeV γs in the Borexino LS is dominated by Compton scattering on multiple electrons, before they lose energy and get absorbed by the LS molecules. The electrons in turn excite the LS molecules that emit isotropic scintillation light, as well as an overall relatively small amount of Cherenkov light (~0.2-0.5%, depending on energy according to MC). This is depicted in Figure 1. As the Compton electrons tend to be scattered more in the forward direction, their initial direction is correlated to the γ direction and as such, their Cherenkov photons are also more likely to produce hit patterns correlated to the γ direction. Thus using the reconstructed γ direction, it is possible to define a correlated angular distribution:

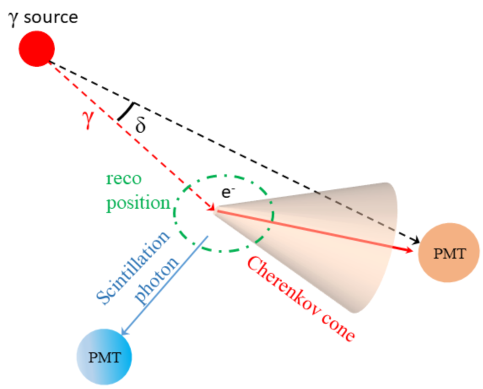

Figure 1. Schematic representation of the $\cos\delta$ angle used for the Cherenkov calibration with gamma sources [2] (see text for more details).

$$\cos\delta_i = \frac{(\vec{r}_i^{\rm \,PMT} - \vec{r}_{\rm source}) \cdot (\vec{r}_{\rm rec} - \vec{r}_{\rm source})}{|(\vec{r}_i^{\rm \,PMT} - \vec{r}_{\rm source})||(\vec{r}_{\rm rec} - \vec{r}_{\rm source})|}. \quad (2)$$

Equation (2) defines the directional angle $\cos\delta$ of the PMT hits used for this calibration, calculated using the position of the PMT that detected the hit $\vec{r}_i^{\rm \,PMT}$ and the reconstructed position of the γ event $\vec{r}_{\rm rec}$. Here $|(\vec{r}_{\rm rec} - \vec{r}_{\rm source})|$ is the reconstructed gamma direction, based on the reconstructed event position.

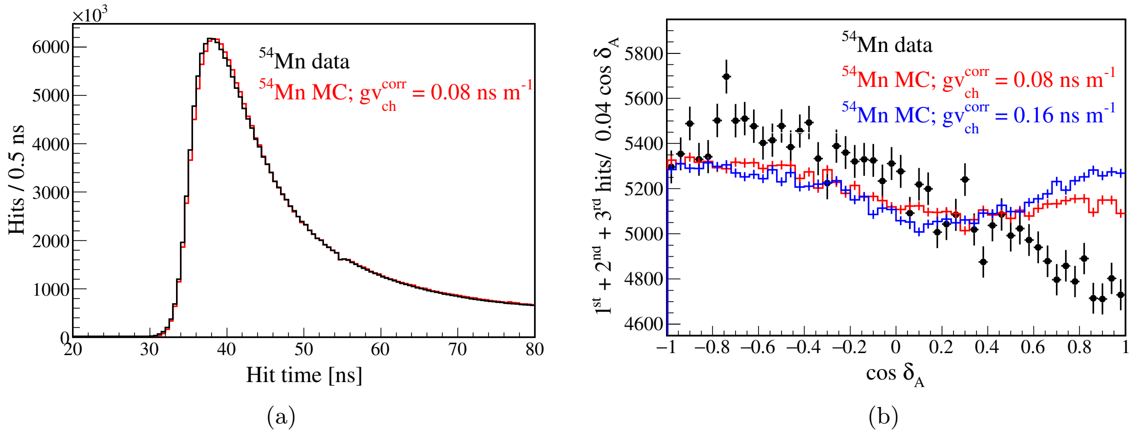

Figure 2. (a) Time-of-Flight corrected hit times for PMT hits of all events in data (black) and MC (red) of the ^{54}Mn gamma calibration source. The distributions are normalized to have the same area. (b) $\cos\delta$ distributions of the ^{54}Mn source where the direction of data (black) and MC (red, blue) is reconstructed with the same unmodified direction reconstruction PDF [2].

2. Analysis strategy and methods

The gamma sources used for this analysis are ^{54}Mn and ^{40}K sources with Q-values of 0.834 MeV and 1.460 MeV, respectively [3]. The sources were placed at the center of the detector and their position is known with an uncertainty of 1 cm, measured by CCD cameras during the calibration campaign. The photon hits of each recorded event are sorted in time after Time-of-Flight (ToF) subtraction similar to the directional analysis of solar neutrinos [2]. The first three hits of the events were then used for the analysis as they were found to be most sensitive to the $gv_{\mathrm{ch}}^{\mathrm{corr}}$ using a MC study [2].

Ideally, a χ^2-fit can be performed on any of the γ sources using the $\cos\delta$ PDFs of data and MC by leaving the $gv_{\mathrm{ch}}^{\mathrm{corr}}$ as a free parameter. However, unlike the solar analysis, where the direction of the solar neutrinos is well known due to the position of the Sun, here the direction of the γ must be reconstructed (see Equation 2). This direction reconstruction introduces a systematic difference between data and MC. Figure 2(a) shows the ToF corrected PMT hit time distributions for ^{54}Mn data and MC. While they look similar, they are significantly different within their statistics in the first few nanoseconds. The reconstruction of an event position in Borexino is based on the time distribution of the collected photons [3]. This means that the differences of the underlying hit time distributions of data and MC will produce different reconstructed positions for the same true event position. This effect can be seen in Figure 2(b), where the sum of the $\cos\delta$ distributions of the first 3 event hits is shown for data and two different $gv_{\mathrm{ch}}^{\mathrm{corr}}$ MC simulations. It can be seen that there is no $gv_{\mathrm{ch}}^{\mathrm{corr}}$ for which MC agrees with data. The time differences between data and MC can be empirically described as a first Gaussian derivative. This function is then added to the Borexino position reconstruction PDF (which is a function of the hit times) to produce a modified position reconstruction PDF, and therefore a modified direction reconstruction PDF. This is done separately for data and each $gv_{\mathrm{ch}}^{\mathrm{corr}}$ MC [2]. Many different sets of such PDFs are produced for the analysis. For the ^{54}Mn source the different $gv_{\mathrm{ch}}^{\mathrm{corr}}$ MC simulations are well in agreement with data and there is no sensitivity left for a fit on $gv_{\mathrm{ch}}^{\mathrm{corr}}$, but the systematic difference of the direction reconstruction has been resolved using this method. For the ^{40}K source, the different $gv_{\mathrm{ch}}^{\mathrm{corr}}$ simulations are now distinguishable, as ^{40}K has more Cherenkov photons (higher energy) than ^{54}Mn, and therefore has sensitivity for a $gv_{\mathrm{ch}}^{\mathrm{corr}}$ fit. The $gv_{\mathrm{ch}}^{\mathrm{corr}}$ is fitted using a χ^2-fit of the $\cos\delta$ histograms of ^{40}K data and MC [2].

3. Results and Conclusions

The $gv_{\mathrm{ch}}^{\mathrm{corr}}$ is fitted with the ^{40}K data and MC using a χ^2-fit, after correcting the direction mis-reconstruction using ^{54}Mn data and MC. The ^{54}Mn, ^{40}K data were analyzed for a number of different sets of direction reconstruction PDFs. The result is shown in Figure 3 where the best fit $gv_{\mathrm{ch}}^{\mathrm{corr}}$ is plotted as a function of the χ^2/ndf between the ^{40}K data and MC $\cos\delta$ histograms. The red points are the fit results on data for different sets of direction reconstruction PDFs, with the red dotted line showing the best estimate at $0.108\,\mathrm{ns\,m^{-1}}$. The blue squares are the fit results of a MC study with an injected value of $0.10\,\mathrm{ns\,m^{-1}}$ shown with the dotted blue line.

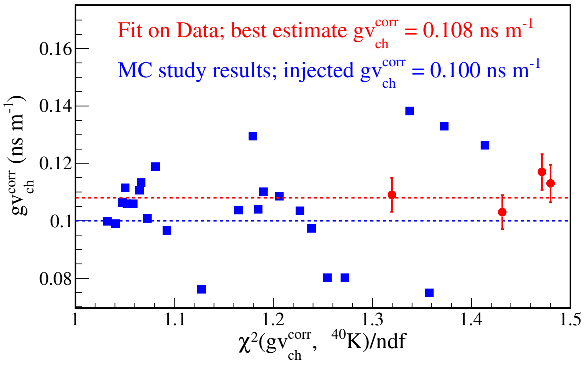

Figure 3. The $gv_{\mathrm{ch}}^{\mathrm{corr}}$ fit results of the gamma Cherenkov calibration as a function of χ^2/ndf of the ^{40}K $\cos\delta$ histograms. The red data points are the $gv_{\mathrm{ch}}^{\mathrm{corr}}$ estimated from the fit between data and MC, for which the best estimate $0.108\,\mathrm{ns/m}$ is given by the red dotted line. The blue squares represent the extracted $gv_{\mathrm{ch}}^{\mathrm{corr}}$ from MC studies, falling in the same χ^2/ndf space, for an injected $gv_{\mathrm{ch}}^{\mathrm{corr}} = 0.10\,\mathrm{ns/m}$ represented by the blue dotted line.

Different direction reconstruction PDFs used can result in different fitted $gv_{\mathrm{ch}}^{\mathrm{corr}}$ values and this systematic uncertainty has been evaluated in a MC study. The MC study has been performed in the same way as the data analysis for many different sets of direction reconstruction PDFs to estimate the possible offset between the injected and extracted values. It can be seen in Figure 3 that for an injected value $gv_{\mathrm{ch}}^{\mathrm{corr}} = 0.10\,\mathrm{ns\,m^{-1}}$, different values of $gv_{\mathrm{ch}}^{\mathrm{corr}}$ are extracted and this effect is the major source of systematic uncertainty

Taking the fit value with the best $\chi^2(gv_{\mathrm{ch}}^{\mathrm{corr}},^{40}K)$ as the result of the Cherenkov group velocity correction gives: $gv_{\mathrm{ch}}^{\mathrm{corr}} = 0.108 \pm 0.006(\mathrm{stat}). \pm 0.039(\mathrm{syst.})\,\mathrm{ns\,m^{-1}}$. This group velocity correction is an *effective* correction, as it changes only the timing of Cherenkov photons relative to that of scintillation, in such a way that there is an agreement between the directional data and MC $\cos\delta$ distributions of the ^{54}Mn and ^{40}K gamma sources. This can be further expressed as a change in the refractive index, according to Equation (1), $\Delta n_{\mathrm{ch}} = 0.032 \pm 0.012$. This is only a 2% correction, considering the refractive index of ≈1.55 @ 400 nm [4]. It can be concluded that the use of γ sources for Cherenkov calibration is not optimal since it gives a relative systematic uncertainty of 36% on the group velocity correction. Next-generation liquid scintillator detectors should perform a dedicated e^- Cherenkov calibration. However, it is still possible to measure the solar neutrino signal, even with this relatively large uncertainty on $gv_{\mathrm{ch}}^{\mathrm{corr}}$ and after the study of other various systematic effects [6], as demonstrated in [2, 5].

References

[1] Alimonti G *et al.* (Borexino Collaboration) 2009 *Nuclear Instruments and Methods A* **600** 568–93
[2] Agostini M *et al.* (Borexino Collaboration) 2021 *arXiv:2109.04770*
[3] Agostini M *et al.* (Borexino Collaboration) 2012 *Journal of Instrumentation* **7** P10018
[4] Agostini M *et al.* (Borexino Collaboration) 2018 *Astroparticle Physics* **97** 136–59
[5] Martyn J *et al.* (Borexino Collaboration) Parallel talk 267 *Proceedings of TAUP 2021*
[6] Singhal A *et al.* (Borexino Collaboration) Poster 270 *Proceedings of TAUP 2021*