Calibration campaign of the Borexino detector for the search of sterile neutrinos with SOX

L Collica\(^1\), D Bravo Berguño\(^{1,2}\), K Choi\(^3\) and M Nieslon\(^y\)\(^4\)
on behalf of the Borexino/SOX Collaboration:

M Agostini, K Altenmüller, S Appel, V Atroshchenko, Z Bagdasarian, D Basilico, G Bellini, J Benziger, D Bick, G Bonfini, D Bravo, B Caccianiga, F Calaprice, A Caminata, S Caprioli, M Carlini, P Cavalcante, A Chepurnov, K Choi, O Cloué, L Collica, M Cribier, D D’Angelo, S Davini, A Derbin, X P Ding, A Di Ludovico, L Di Noto, I Drachnev, M. Durero, S Farinon, V Fischer, K Fomenko, A Formozov, D Franco, F Gabriele, J Gaffiot, C Galbiati, M Gschwender, C Ghanem, M Giannarchi, A Goretti, M Gromov, D Guffanti, C Hagner, T Houldy, E Hungerford, Aldo Ianni, Andrea Ianni, N Jonquère, A Jany, D Jeschke, V Kobychev, D Korahlev, G Korga, V Kornoukhov, D Kryn, T Lachenmaier, T Lasserre, M Laubenstein, E Litvinovich, F Lombardi, P Lombardi, L Ludhova, G Lukyanenko, L Lukyanenko, I Machulin, G Manuzio, S Marcocci, J Marcic, G Mention, J Martyn, E Meroni, M Meyer, L Miramonti, M Misiaszek, V Muratova, R Musenich, B Neumaier, L Oberauer, B Opitz, V Orekhov, F Ortica, M Pallavicini, L Papp, Ø Penek, N Pilipenko, A Pocar, A Porcelli, G Ranucci, A Razeto, A Re, M Redchuk, A Romani, R Roncin, N Rossi, S Rottenanger, S Schönert, L Scola, D Semenov, M Skorokhvatov, O Smirnov, A Sotnikov, L F S Stokes, Y Suvorov, R Tartaglia, G Testera, J Thurn, M Toropova, E Unzhakov, C Veyssière, A Vishneva, M Vivier, R B Vogelaar, F von Feilitzsch, H Wang, S Weinz, M Wojcik, M Wurm, Z Yokley, O Zaimidoroga, S Zavatarelli, K Zuber and G Zuzel

\(^1\) INFN Milano, \(^2\) Virginia Tech, \(^3\) University of Hawaii, \(^4\) University of Mainz

E-mail: laura.collica@mi.infn.it

Abstract. The SOX (Short distance Oscillations with boreXino) experiment aims to investigate possible anomalous oscillatory behaviours in neutrinos, including the existence of sterile neutrinos, by exploiting the very low radioactive background of the Borexino detector. A calibration campaign is crucial to achieve a deeper understanding of the energy response and the spatial reconstruction accuracies of the detector. It will be performed with a suite of low-activity radioactive sources which will map the whole active volume, especially nearby the inner vessel. The calibration points at the border of the active zones will be extremely important to study the neutron detection efficiency. The calibration system, already used in Borexino Phase-I, allows the insertion of the sources without perturbing the radio-purity of the detector. The calibration campaign will take place a few months before the beginning of the SOX experiment. In this work, we describe in detail both the calibration hardware and the calibration strategy.

1. Introduction

Neutrino physics is a powerful probe to investigate new physics beyond the Standard Model. Some experimental anomalies at accelerators and at reactors\(^1\),\(^2\),\(^3\) suggest anomalous oscillatory behaviour in neutrinos and could be explained introducing at least one additional sterile neutrino state which guides the neutrino oscillations at short distances, with a square mass \(\Delta m_{14}^2 \approx 1\)eV\(^2\).

Recent results published by the Daya Bay experiment\(^4\) weaken the reactor anomalies, however the accelerator anomalies have still to be understood. \(\Delta m_{14}^2 \approx 1\)eV\(^2\) can be probed with a short baseline disappearance experiment operating at meter-scale distances and MeV-scale energies.
Figure 1. a) The setup for the SOX experiment. The pit that will contain the antineutrino generator is 8.5 m distant from the detector center. b) Predicted distributions of events as a function of the distance L and the anti-neutrino energy E, with sterile oscillations and mixing parameters $\sin^2(2\theta) = 0.15$ and $\Delta m^2 = 2eV^2$.

SOX [5] will test this parameter region detecting the antineutrino flux coming from a $\approx 100$ kCi $^{144}$Ce $\rightarrow^{144}$Pr antineutrino generator (CeANG) positioned in a pit under the Borexino detector (see Fig. 1-a). The Borexino experiment [6] is located deep underground at the Gran Sasso Laboratory (3800 m.w.e.) in Italy. The core of the detector is 278t of ultra-pure organic liquid scintillator contained in a nylon vessel of 4.25 m radius, surrounded by 2212 photomultipliers (PMTs). A non-scintillating buffer fills the space between the nylon vessel and a stainless-steel sphere (SSS) of 6.85 m radius, which supports the PMTs. The entire detector is enclosed in a cylindrical tank filled with ultra-pure water and instrumented with 208 PMTs, acting as an active Cherenkov muon veto and as a passive shield against external $\gamma$s and neutrons.

The antineutrinos produced by CeANG have a continuous spectrum with an endpoint at 2.99 MeV. This allows the investigation of a larger parameter space if the energy is reconstructed with precision. The lifetime of $^{144}$Ce is about 400 days and 10000 events are expected in 1 year and an half of data taking.

Anti-neutrinos are detected inside Borexino via inverse beta decay, providing a clear coincidence signature with a prompt positron annihilation and a delayed neutron capture [7]. Two methods will be used for the analysis: the standard disappearance technique and the oscillometry measurement within the detector volume (see Fig. 1-b). For the first technique, the CeANG activity must be known with precision and a calorimetric measurement will be employed [8]. For the second technique, the precise knowledge of the activity is not necessary since a possible oscillation pattern would be visible independent of any activity estimate.

A new calibration campaign is planned to map the detection efficiency, the energy and position reconstruction of the detector in the whole active volume. Different from the 2008-2010 campaign, which was focused on solar neutrino analysis, the new campaign will concern the whole active volume with an expanded set of source types specifically chosen for the SOX analysis.

2. The calibration campaign
2.1. Motivation
The detection of antineutrinos will be almost background free and the event reconstruction could be done in the whole active volume to maximise the available statistics. However, events at the border likely do not deposit their whole energy in the scintillator, but experience energy losses in the non-scintillating buffer. As a consequence, the detection efficiency decreases significantly
Figure 2.  a) Detection efficiency as a function of the distance to vessel, for neutron and positron events as obtained by MC. b) Comparison between data and MC for the event rate of the neutron calibration source, shown as a function of the vessel distance. c) The agreement between MC and data for the energy response of different gamma sources is shown. Data are from the last calibration campaign of Borexino.

close to the vessel border as it is shown for the simulated neutron and positron events in Fig. 2-a. This decrease should be reproduced very accurately by the MC to have a precise estimate of the expected rate. The Monte Carlo-data agreement for the neutron calibration source in the last calibration campaign was < 2% for the central part of the detector while it reaches up to 4% for events which are closer than 50 cm to the vessel border (see Fig. 2-b). It is thus crucial to map the detector response to antineutrino events in the whole active volume, through neutron and positron sources. Besides, an excellent agreement between Monte Carlo and data is obtained for the energy spectra of the γ calibration sources (see Fig. 2-c) used in the last campaign in 2009 [9]. In the new campaign a subset of these γ sources will be used, together with a source (60Co−108m Ag), put in two different point at the same time, to study the inner vessel symmetry and position reconstruction effects.

2.2. Setup and system handling

The well-tested Borexino calibration system will be exploited. The insertion of sources will be performed via series of interconnecting rods (3.8 cm x 100 cm): a Teflon tether tube enters the detector alongside the rods and it is used to adjust the hinge angle to the desired position (see Fig. 3-a). Arm segments can be added or removed and φ-rotations can be performed. The entire system is housed in a Class 100 clean room to avoid perturbing the radio-purity of the detector and all manipulation is performed inside a Low Argon and Krypton Nitrogen (LAKN) filled glove box to minimise radon contamination (see Fig. 3-b).

The source location system is composed of 6 CCD cameras and it will be exploited to find the position of a IR-LED attached to the source (see Fig. 3-c). The system is characterised by a precision of about 1 cm in the center of the vessel. The source can be deployed in almost the whole scintillator volume. To avoid touching the vessel, a safety distance of 15-20 cm will be kept while due to hardware constraints (tether, mechanics) some regions will not be reachable. This is illustrated in Fig. 3-d.

2.3. Sources

Different types of low-activity radioactive sources will be deployed inside Borexino to map the whole active volume, especially nearby the inner vessel where no calibration data are available so far. A list with the radioactive sources and their characteristics is reported in Tab. 1.

An extensive calibration with the neutron source (241Am9Be) will be done to map the neutron detection efficiency and energy response. α (222Rn) and positron (68Ge−68 Ga) sources will be used to respectively map the accuracy of the position reconstruction and the positron detection efficiency. Mono-energetic γ sources will be exploited to study the energy response on-axis. An
Figure 3.  a) Picture of the Internal Detector (ID) shot by one of Borexino 6 CCD cameras. The calibration source insertion system is visible. b) Picture of the glove box that will be used for inserting and manipulating the sources. c) Picture of the new IR LED Source Location System that will enhance visual location of the calibration sources in the active volume. d) The portion of the inner vessel which is reachable by the source insertion system is indicated.

| Source Type | Type | \( E \) [MeV] | scan |
|-------------|------|---------------|------|
| \( ^{241}\text{Am}^{9}\text{Be}(^{+\text{nat}\text{Ni}}) \) n | 0-9 | on-axis, off-axis, radial, \( \phi \) |
| \( ^{222}\text{Rn} \) \( \alpha, \gamma \) | 5.5, 6.0, 7.4; 0-3.2 | on-axis, off-axis, \( \phi \) |
| \( ^{68}\text{Ge} - ^{68}\text{Ga} \) \( \beta^+ \) | 0-1.9 (+1.02) | on-axis, off-axis, radial, \( \phi \) |
| \( ^{85}\text{Sr}, ^{54}\text{Mn}, ^{65}\text{Zn}, ^{40}\text{K} \) \( \gamma \) | 0.5, 0.8, 1.1, 1.5 | on-axis |
| \( ^{60}\text{Co}-^{108m}\text{Ag} \) \( \gamma \) | 1.2-1.3, 0.4-0.6-0.7 | on-axis |

Table 1. The list of radioactive sources elements which will be used in the upcoming campaign is shown. The radionuclides, emitted particle types, energies and the planned scans in the inner vessel are shown.

| Source Type | Type | \( E \) [MeV] | scan |
|-------------|------|---------------|------|
| \( ^{241}\text{Am}^{9}\text{Be}(^{+\text{nat}\text{Ni}}) \) n | 0-9 | on-axis, off-axis, radial, \( \phi \) |
| \( ^{222}\text{Rn} \) \( \alpha, \gamma \) | 5.5, 6.0, 7.4; 0-3.2 | on-axis, off-axis, \( \phi \) |
| \( ^{68}\text{Ge} - ^{68}\text{Ga} \) \( \beta^+ \) | 0-1.9 (+1.02) | on-axis, off-axis, radial, \( \phi \) |
| \( ^{85}\text{Sr}, ^{54}\text{Mn}, ^{65}\text{Zn}, ^{40}\text{K} \) \( \gamma \) | 0.5, 0.8, 1.1, 1.5 | on-axis |
| \( ^{60}\text{Co}-^{108m}\text{Ag} \) \( \gamma \) | 1.2-1.3, 0.4-0.6-0.7 | on-axis |

UV LED system will be also employed for the energy calibration of Flash ADC data taking system at high energies. A quartz vial, with 2.5 cm diameter and a neck for attachment to the rod, is used for the \( ^{68}\text{Ge} - ^{68}\text{Ga} \), \( \gamma \), and \( ^{222}\text{Rn} \) sources. The positron source will be contained in a micropipette within the vial to minimise energy losses induced by glass (see Fig. 4-a) while the \( \gamma \) and \( ^{222}\text{Rn} \) sources will be dissolved respectively in water and scintillator (see Fig. 4-c). The neutron source will be put in a 3 mm lead capsule contained inside of a Delrin holder, which could be lined with 5 mm of nickel (see Fig. 4-b). The lead is used to stop \( \gamma \)s, the Delrin is exploited to moderate neutrons and the nickel foils will be employed to generate high-energy \( \gamma \)s.

2.4. Strategy

Different types of scan (on-axis, off-axis, \( \phi \) and radial) will be carried out inside the active volume of Borexino. To plan and visualise them, a flexible 3D computer model has been developed. As an example, Fig. 5-a shows how the sources will be placed on equidistant shells with distances from 4.5 to 9.25 m from the pit, while Fig. 5-b shows the \( \phi \)-scans that will be performed to check the vessel symmetry.

A total of 245 calibration points will be used for the neutron source, while a subset will be used for the other sources. More calibration points will be investigated in the South hemisphere due to an higher source flux compared to the North hemisphere and since the shape of the inner vessel in the bottom holds the largest uncertainties. A combination of CCD camera-based, database and source-based studies will be exploited to achieve a better definition of the fiducial volume in the area with the largest density of SOX events.
Figure 4. a) The $^{68}\text{Ge} - ^{68}\text{Ga}$ positron spectrum and associated distortions due to interaction with the glass are shown for different micropipette configurations. b) The holder for the neutron source is shown. c) The quartz vial that will be used for gamma, $\alpha$ and positron sources is shown.

Figure 5. The calibration scheme as visualised by the 3D computer model. a) Sources will be placed on equidistant shells from the source that correspond to the same antineutrino flux. The radial scan is also shown and will be used for the detection efficiency characterisation. b) Dedicated phi-scans will map the vessel symmetry.

3. Outlook
The SOX experiment aims to investigate possible anomalous oscillatory behaviour in neutrinos by placing a high activity source below the Borexino detector. The measurement will start approximately in April 2018. A deep understanding of the detection efficiency, energy, and position response is necessary for an accurate analysis and a good sensitivity. For this reason, a new calibration campaign of the Borexino detector with radioactive sources has been planned and will be executed before the beginning of the SOX experiment.

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