

Short distance neutrino Oscillations with BoreXino: SOX

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Borexino, a large volume liquid scintillator detector installed at Gran Sasso laboratory, demonstrated extraordinary sensitivity with respect to neutrino and antineutrino detection, reporting the best up to date results on low energy solar neutrino fluxes and performing geo-neutrino detection. Energy and position of 1 MeV events in Borexino are reconstructed with a precision of 5% and 14 cm respectively. These performances together with extremely low background provides an excellent opportunity for the study of short distance neutrino oscillations on the eV mass scale with artificial neutrino sources.

The possible layouts for ^{51}Cr (monoenergetic neutrino) and ^{144}Ce – ^{144}Pr (antineutrino from β -decay) source experiments in Borexino and the expected sensitivity to sterile neutrinos for three possible designs of the experiment are presented.

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1. Introduction

The collected experimental data on neutrinos generally fit into the three-flavor oscillation model. Nevertheless, there is a number of experimental indications (its discussion is out of the scope of current presentation) that oscillations of neutrinos with $\Delta m^2 \sim 1 \text{ eV}^2$ are possible. The existence of oscillations at a scale of 1 eV naturally entails the existence of an extra type of neutrino. Indeed, $\Delta m_{12} \sim 10^5 \text{ eV}^2$ and $\Delta m_{23} \sim 10^3 \text{ eV}^2$ have been established by now. If there are three types of neutrino then Δm_{13} is not an independent parameter, and it is inevitably of the same order of magnitude as the greatest of Δm^2 . The number of types of neutrino $n=3 \pm 0.01$ was determined from the experimental Z boson decay width; therefore, if there is a fourth type of neutrino, it must be neutral (sterile) in terms of weak interactions. Thus the search for neutrino oscillations at the $\Delta m^2 \sim 1 \text{ eV}^2$ scale turns out to be a search for a sterile neutrino. Regardless of the theoretical interpretations, the existence of experimental anomalies is a problem to be solved. If interpretation of the anomalies as neutrino short-base oscillations is the case, the corresponding oscillations pattern with characteristic dimension of the order of 1 meter can be searched for with a large position-sensitive detector irradiated with a compact neutrino source.

2. Borexino detector and SOX experiment

The Borexino detector [1] has been constructed with aim of precision measurement of the solar ^7Be neutrino flux. It is located at the underground laboratory of LNGS in central Italy. The detector, a large unsegmented liquid scintillator (LS) calorimeter, is taking data since May 2007. A binary mixture of pseudocumene and PPO at a concentration of 1.5 g/l is used as LS. Neutrinos are detected via elastic scattering on electrons, this is untagged reaction demanding unprecedented levels of intrinsic radioactivity of LS for its registering. Antineutrinos are effectively detected via inverse β -decay on proton, the capture of thermalized neutron on proton provides a tag for the reaction, two time-spatial correlated events could be easily distinguished from the random coincidence events.

The Borexino large size (the spherical sensitive volume has 8.5 m in diameter) and possibility to reconstruct an interaction point (with a precision of 14 cm at 1 MeV energy deposit) makes it an appropriate tool for searching of sterile neutrinos. If the oscillation baseline is about 1 m (which corresponds to $\Delta m^2 \sim 1 \text{ eV}^2$), exposure of the detector to a compact powerful neutrino source should give rise to a typical oscillation picture with dips and rises in the spatial distribution of events density with respect to the source. Right beneath the Borexino detector, there is a cubical pit (side 105 cm) accessible through a small squared tunnel (side 95 cm) that was built at the time of construction with the purpose of housing neutrino sources for calibration

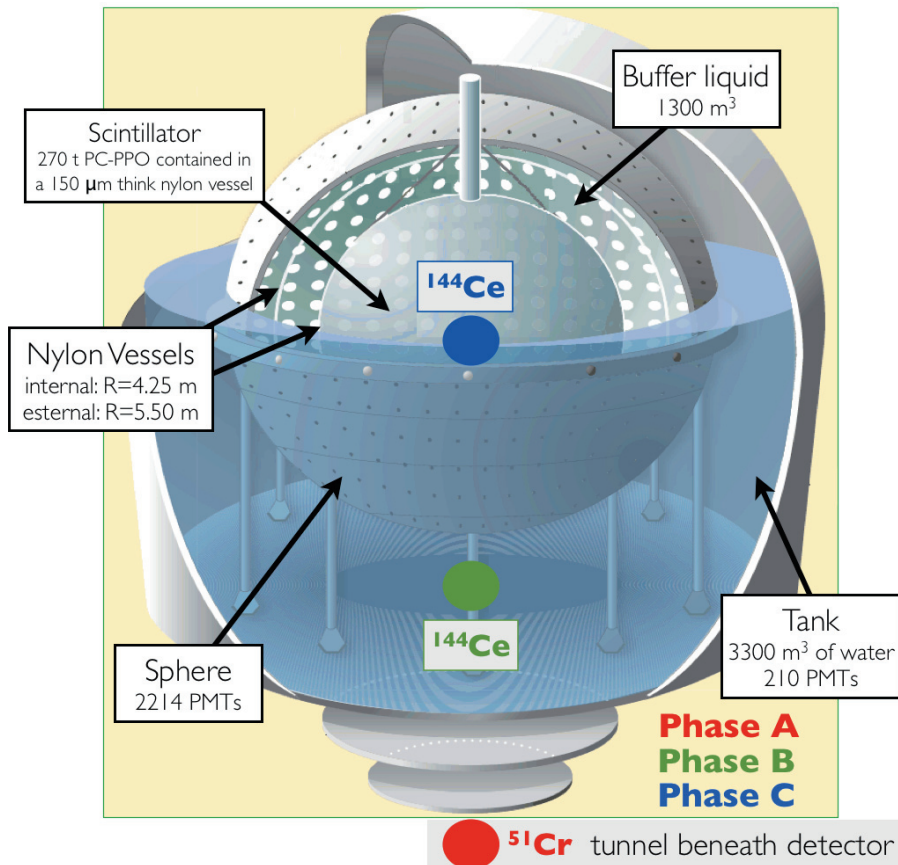


Fig. 1. Layout of the Borexino detector and the approximate location of the neutrino and anti-neutrino sources in the three phases.

purposes. Using this tunnel, the experiment with neutrino source can be done with no changes to the Borexino layout. The center of the pit is at 8.25 m from the detector center, requiring a relatively high activity of the neutrino source in order to provide detectable effect.

The experiment SOX (for Short distance neutrino Oscillations with BoreXino) [2] will be carried in three stages with gradually increasing sensitivity:

Phase A a ^{51}Cr neutrino source of 200-400 PBq activity deployed at 8.25 m from the detector center (external with respect to the detector);

Phase B deploying a ^{144}Ce - ^{144}Pr antineutrino source with 2-4 PBq activity at 7.15 m from the detector center (placed in the detector's water buffer);

Phase C a similar ^{144}Ce - ^{144}Pr source placed right in the center of the detector.

Figure 1 shows a schematic layout of the Borexino detector and the approximate location of the neutrino and anti-neutrino sources in the three phases. Two types of neutrino sources are considered. The ^{51}Cr source will be produced by irradiating a large sample of highly enriched ^{50}Cr in a nuclear reactor providing a high thermal neutron flux ($\approx 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$). The ^{144}Pr based source could be produced by chemical extraction of Ce from exhausted nuclear fuel [3]. ^{51}Cr decays via electron capture into ^{51}V , emitting two neutrino lines of 750 keV (90%) and 430 keV (10%), while ^{144}Pr decays β into ^{144}Nd with an end-point of 3 MeV (parent ^{144}Ce decays too, but end-point of its β -decay is below the IBD threshold). Fig. 3 shows the decay levels

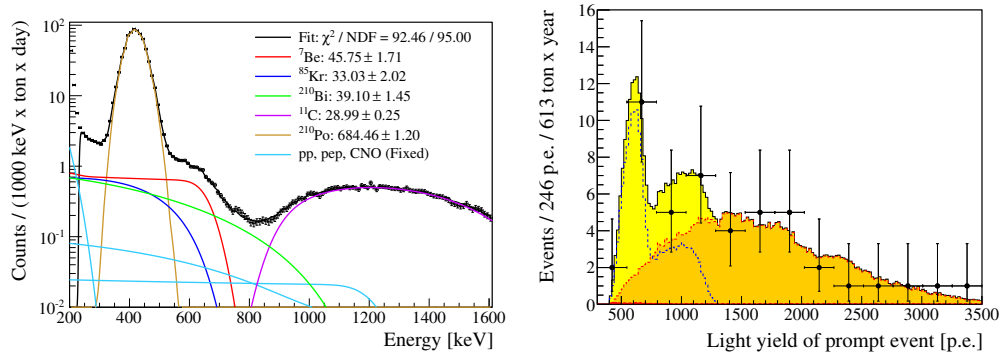


Fig. 2. Left: experimental Borexino neutrino spectrum from the Phase I [4] fitted with spectral components including spectra of recoil electrons for solar neutrino and spectra of identified radioactive backgrounds (count is presented in cpd/100 tones of LS); Right: experimental Borexino antineutrino spectrum obtained with 1353 days of data [5].

of ¹⁴⁴Ce and ¹⁴⁴Pr (Fig. 3 left) and the energy spectrum of the emitted $\bar{\nu}_e$ (Fig. 3 right). As it is clear from the figure, the ¹⁴⁴Pr life-time is too short to allow the fabrication of a pure ¹⁴⁴Pr source, but the parent ¹⁴⁴Ce nucleus has acceptable life-time of the order of one year. The portion of the spectrum above the 1.8 MeV detection threshold is the only of importance for the experiment. Elastic scattering of $\bar{\nu}_e$ on electrons induce negligible background.

Backgrounds for neutrino source measurement consists of spectrum of electrons recoil from solar neutrinos, and of spectra from residual radioactive contaminations. The experimental spectrum for the Phase I of Borexino experiment with all identified spectral contributions is shown in left side of Fig. 2. After the purification performed before passing to the Phase II the contamination in ²¹⁰Bi decreased from 40 to 20 cpd/100 tones, ⁸⁵Kr is now compatible with zero, monoenergetic ²¹⁰Po has decayed and its count is ~1 cpd/t. Thus, in general, the sensitivity of the Phase II has improved compared to the first Phase.

Backgrounds for antineutrino source measurement contains mainly geoneutrino and reactor antineutrino components as shown in right side of Fig. 2. The shown spectrum corresponds to 1353 days of the data taking and contains 46 events, thus the background for antineutrino source is negligible. We expect an increase of the random coincidences count in the Phase C, but it can be suppressed by excluding region close to the source (~1.5 m).

The ⁵¹Cr experiment in Phase A will benefit from the experience of Gallex and SAGE that used similar sources in the past [6] [7]. The source activity of 200–400 PBq is challenging, but only a factor 2–4 higher than what already done by Gallex and SAGE in the 90's. The ¹⁴⁴Ce–¹⁴⁴Pr experiment in Phases B and C doesn't require high source activity. The activity of the source in these cases should be 2.3 PBq for the external source and about 1.5 PBq for the internal one. In both cases, the sensitivity can be enhanced by inserting PPO in the buffer liquid, in order to increase the scintillator volume.

The Phase C is the most sensitive but it can be done only after the shutdown of the solar neutrino program, because it needs modification of the detector. The Phases A and B will not disturb the solar neutrino program of the experiment, which is supposed to continue until the end of 2015, and do not require any change to Borexino hardware. They will not only probe a large fraction of the parameters' space governing the oscillation into the sterile state, but also provide a unique opportunity to test low energy ν_e and $\bar{\nu}_e$ interactions at sub-MeV energy.

The challenge for the Phase C is constituted by the large background induced by the source in direct contact with the scintillator, that can be in principle tackled thanks to the correlated nature of the $\bar{\nu}_e$ signal detection. In Phase B this background, though still present, is mitigated by the shielding of the buffer liquid.

Borexino can study short distance neutrino oscillations in two ways: by comparing the detected number of events with expected value (disappearance technique, or total counts method), or by observing the oscillation pattern in the events density over the detector volume (waves method). In the last case the typ-

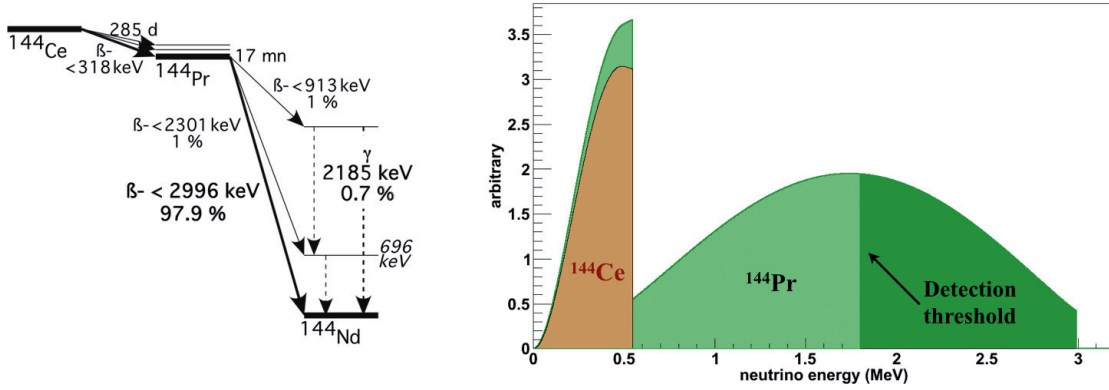


Fig. 3. Left: decay scheme of ^{144}Ce and ^{144}Pr source; Right: energy spectrum of the emitted $\bar{\nu}_e$. Only the portion of the spectrum above 1.8 MeV can be detected via inverse β decay on protons.

ical oscillations length is of the order of 1 meter, taking into account the values of Δm_{41}^2 inferred from the neutrino anomalies and considering the typical energy of radioactive decay of 1 MeV. The two-flavor oscillations are described by:

$$P_{ee} = 1 - \sin^2 2\theta_{14} \sin^2 \frac{1.27\Delta m_{41}^2 (eV^2)L(m)}{E(\text{MeV})}$$

where θ_{14} is the mixing angle of the ν_e (or $\bar{\nu}_e$) into sterile component, Δm_{41}^2 is the corresponding squared mass difference, L is the distance of the source to the detection point, and E is the neutrino energy. The variations in the survival probability P_{ee} could be seen on the spatial distribution of the detected events as the waves superimposed on the spatuual events. Oscillation parameters can be directly extracted from the analysis of the waves. The result may be obtained only if the size of the source is small compared to the oscillation length. The ^{51}Cr source will be made by about 10-35 kg of highly enriched Cr metal chips which have a total volume of about 4-10 l. The source linear size will be about 15-23 cm, comparable to the spatial resolution of the detector. The ^{144}Ce - ^{144}Pr source is even nore compact. All simulations shown below takes into account the source size.

In Phase A the total counts method sensitivity is enhanced by exploiting the fact that the life-time of the ^{51}Cr is relatively short. The known time-dependence of the signal, and the concurrent assumption of the stable background significantly improves the sensitivity. In Phases B and C this time-dependent method is not effective because the source life-time is longer (411 days), but this is compensated by the very low background and by the larger cross-section. The total counts and waves methods combined together yield a very good sensitivity for both experiments. Besides, the wave method is independent on the intensity of the source, on detector efficiency, and is potentially a nice probe for un-expected new physics in the short distance behavior of neutrinos or anti-neutrinos.

3. Sensitivity of SOX

The sensitivity of SOX with respect to oscillation into sterile neutrino was evaluated with a toy Monte Carlo. Expected statistical samples (2000 events) were generated for each pair of oscillation parameters. We assume a period of 15 weeks of stable data taking before the source insertion in order to accurately constrain the background. The background model includes all known components, identified and accurately measured during the first phase of Brexino. We built the confidence intervals from the mean χ^2 for each couple of parameters with respect to the non-oscillation scenario. The result is shown in Fig. 4, as one can see fro the figure the reactor anomaly region of interest is mostly covered.

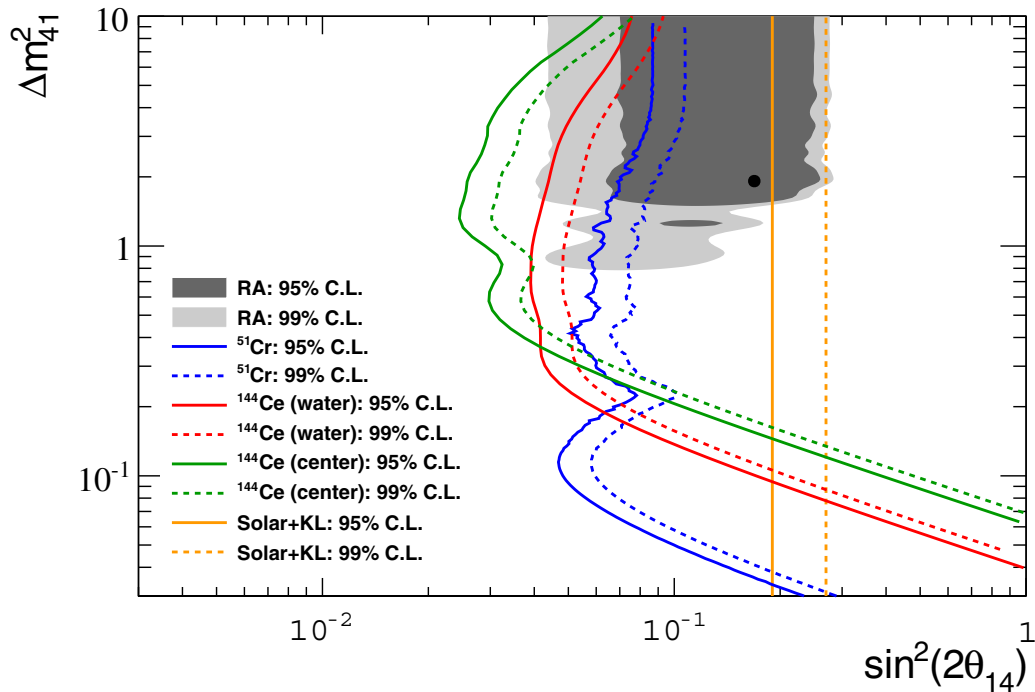


Fig. 4. Sensitivity of the Phase A (^{51}Cr external, blue), of Phase B (^{144}Ce – ^{144}Pr external, red) and Phase C (^{144}Ce – ^{144}Pr center, green). The grey area is the one indicated by the reactor anomaly, if interpreted as oscillations to sterile neutrinos. Both 95% and 99% C.L. are shown for all cases. The yellow line indicates the region already excluded in [8].

The simulation for the Phase A are shown for a single irradiation of the ^{51}Cr source up to the initial intensity of 370 PBq (10 MCi) at the site. A similar result can be obtained with two irradiations of about 200 PBq if higher intensity turns out to be beyond the technical possibilities. The single irradiation option is preferable and yields a slightly better signal to noise ratio.

The physics reach for the ^{144}Ce – ^{144}Pr external (Phase B) and internal (Phase C) experiments, assuming 2.3 PBq (75 kCi) source strength and one and a half year of data taking is shown in the same figure (Fig. 4). The χ^2 based sensitivity plots are computed assuming significantly bigger volume of liquid scintillator (spherical vessel of 5.5 m radius), compared to the actual volume of liquid scintillator (limited by a sphere with 4.25 m radius) used for the solar phase. Such an increase will be made possible by the addition of the scintillating fluor (PPO) in the inner buffer region (presently inert) of the detector. We have also conservatively considered exclusion of the innermost sphere of 1.5 m radius from the analysis in order to reject the gamma and bremsstrahlung backgrounds from the source assembly. Under all these realistic assumptions, it can be noted from Fig. 4 that the intrinsic ^{144}Ce – ^{144}Pr sensitivity is very good: for example the 95% C.L. exclusion plot predicted for the external test covers adequately the corresponding reactor anomaly zone, thus ensuring a very conclusive experimental result even without deploying the source in the central core of the detector. The background included in the calculation is negligible, being represented by about $5 \bar{\nu}_e$ events per year from the Earth (geo-neutrinos) and from distant reactors, with negligible contribution from the accidentals (see Fig. 2). It is worth to stress that the three ingredients at the origin of this good performance are the very low background due to the $\bar{\nu}_e$ coincidence tag, the larger cross-section due to the higher source energy, and the deployment of the source closer or directly within the active volume detector, yielding a larger geometrical acceptance.

4. Conclusions

Borexino an ideal detector to search for the neutrino oscillation on the short base of ~ 1 m. Proposed by collaboration staged approach provides an opportunity to reach gradually the maximum sensitivity, starting from the simplest case of an external ^{51}Cr source which doesn't require the modification on of the existing layout, and pointing later for two ^{144}Ce – ^{144}Pr more sensitive experiments after the corresponding modification of the experimental setup. All threes stages provide a comprehensive sterile neutrino search which will either confirm the effect or reject it in a clear and unambiguous way. Particularly, in case one sterile neutrino with parameters corresponding to the central value of the reactor anomaly, SOX will surely discover the effect, prove the existence of oscillations and measure the parameters through the “oscillometry” analysis.

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