PROCEEDINGS OF SCIENCE

The SOX project: a search for sterile neutrinos with BoreXino

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The unmatched radio–purity of its liquid scintillator and the large detector size make Borexino an ideal apparatus for the study of neutrino oscillations at very short distance and, particularly, for the search of sterile neutrinos of mass scale of the order of 1 eV.

We present here three possible experiments with neutrino and anti–neutrino artificial sources located close to or inside the Borexino detector and discuss their sensitivity to sterile neutrinos. Expected sensitivities on electron neutrino magnetic moment, electroweak mixing angle, and couplings to axial and vector currents are shown as well.

XV International Workshop on Neutrino Telescopes
March 11-15 2013 Venice, Italy

*Speaker.

 http://pos.sissa.it/

PoS(Neutel 2013)026

1. Introduction

In the last two decades the existence of three flavor neutrino mixing was firmly established by a set of beautiful and well known experiments which exploited solar, atmospheric, reactor, and accelerator neutrinos. These experiments have measured the three mixing angles and have identified two quite different mass scales, one of the order of $\approx 7.5\ 10^{-5}$ eV^2 related to ν_e-ν_μ squared mass difference (so called 'solar' scale because it is the most relevant for solar neutrino oscillations) and the second one about 30 times bigger related to ν_e-ν_τ or ν_μ-ν_τ mass difference (so called 'atmospheric' scale because firstly discovered by means of atmospheric neutrinos oscillations). However, a set of appearance and disappearance experiments at relatively small distance (L/E $\approx$ 1 m MeV^{-1}, corresponding to much bigger mass scales) have yielded results that are not in agreement with the standard three neutrino scenario. These controversial results are commonly defined as 'neutrino anomalies'.

The LSND result [1] has been the first short distance neutrino oscillation experiment inconsistent with the standard scenario. More recently, the MiniBooNE experiment [2] did not help to clarify the situation, not being able either to rule out or firmly confirm the LSND result. In 2013 [3], the Icarus experiment has narrowed the LSND allowed region, without excluding it and pointing to relatively high masses of $\approx$1 eV^2. Gallium solar neutrino experiments Gallex and SAGE [4] have both performed calibration runs with neutrino sources made of ^{51}Cr and ^{37}Ar. Both experiments, when independently calibrated by other means, consistently yielded neutrino fluxes lower than expected. Globally, the "gallium anomaly" was confirmed at 3σ level even by a recent analysis which includes more refined cross section measurements [5]. Even in the case of the Gallium anomaly the preferred mass scale for sterile neutrinos is 1-10 eV^2.

Another indication comes from new calculations of the $\bar{\nu}_e$ flux produced by fission reactors [6] [7] and from the re-analysis of old experimental results obtained with detectors located at short distance (10-100 m) from the reactors. The new calculation, supposedly more accurate, shows that all experiments but one have measured a $\bar{\nu}_e$ flux significantly lower than expected. Although a recent re-evaluation of the reactor neutrino anomaly in view of the known and large θ_{13} agrees with the standard scenario [8], other authors confirm the existence of the anomaly at 2.7σ level [9].

Although earlier CMBR data seemed to confirm the anomaly and favor a number of relativistic degrees of freedom corresponding to more than three neutrinos [10], recent more accurate data of Planck [11] prefers the standard scenario. A fourth neutrino, however, is not excluded.

All anomalies are by themselves not completing convincing, and for all of them it is possible to suggest reasonable experimental explanations. However, it is intriguing to note that all anomalies point quite consistently to new physics at the scale of about 1 eV. Besides, if any one of them is true, new physics is necessary to explain it. We believe therefore that a better and possibly conclusive experimental investigation of these effects is the only way to solve the controversy.

A powerful method to probe the anomalies and possibly test conclusively the sterile neutrino(s) hypothesis is to repeat similar source experiments [12] [13] [14] with a more intense ν_e (or $\bar{\nu}_e$) source and a larger, better understood, and lower background detector. We show in this conference that the ultra-low background Borexino detector at LNGS is a unique and almost ideal place to perform such an experiment, and either confirm the existence of new physics in the neutrino sector or finally solve the long standing debate about the existence of sterile neutrinos. More details about

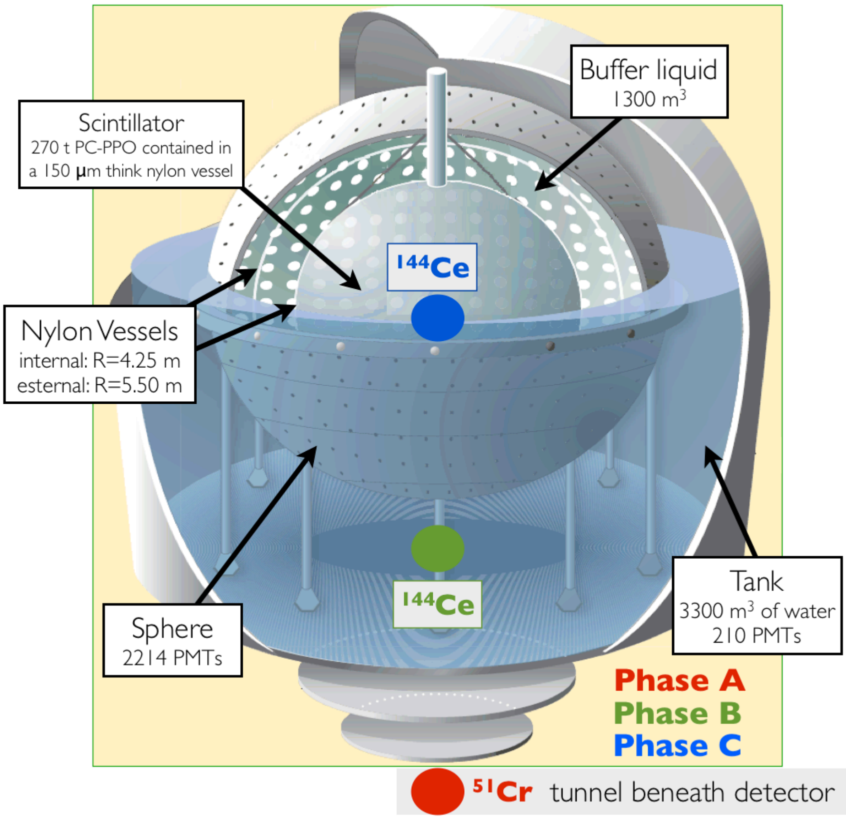

Figure 1: Layout of the Borexino detector and the approximate location of the neutrino and anti-neutrino sources in the three phases: Phase A with a ^{51}Cr neutrino source in a small pit right below the detector center; Phase B with a ^{144}Ce-^{144}Pr anti-neutrino source located right beneath the stainless sphere and within the water tank; finally, Phase C, with a ^{144}Ce-^{144}Pr anti-neutrino source located inside the scintillator volume.

sterile neutrino search with Borexino can be found in [15].

This paper is structured as follows: in section 2 we very briefly describe the main features of the Borexino detector, with particular emphasis to those which make it a unique apparatus for the search of sterile neutrinos and for the study of very low energy neutrino physics with artificial sources; in section 3 we describe the three phases of the SOX project; in section 4 we show the sensitivity of the three phases to sterile neutrino search and to other physics goals which can be achieved with the sources in Borexino; finally, section 5 summarizes the conclusions.

2. The Borexino detector

The Borexino experiment is fully described elsewhere [16] [17]. We report here only a very brief description which aims at keeping the paper as self consistent as possible.

Borexino is a liquid scintillator detector designed to provide the largest possible fiducial volume of ultra-clean scintillator. The detector is schematically depicted in Fig. 1, which also shows the possible locations of the neutrino sources. The inner part is an unsegmented Stainless Steel Sphere (SSS) that is both the container of the scintillator and the mechanical support of the PMTs.

Within this sphere, two thin nylon vessels separate the scintillator volume in three shells of radii 4.25, 5.50 and 6.85 m, the latter being the radius of the SSS itself. The inner nylon vessel contains the liquid scintillator, a solution of PC (pseudocumene, 1,2,4-trimethylbenzene) as a solvent and PPO (2,5-diphenyloxazole) as fluor at the concentration of 1.5 g/l. The second and the third shell contain PC with a small amount (5 g/l at the beginning of Borexino data taking, later reduced at 3 g/l) of DMP (dimethylphthalate), which is added as a light quencher. The SSS is contained within a high domed Water Tank (WT) of 18 m diameter and 16.9 m height filled with 2100 t of ultra-pure water and instrumented with 208 PMTs which detect the muon Cherenkov light. The WT also serves as shielding against external radiation [18] [19].

A long R&D effort, started in the 90's with the CTF detector [20][21][22][23] and continued until the filling of the Borexino detector in 2007 have yielded an unprecedented and currently unequalled level of radio–purity of the Borexino liquid scintillator core. The concentration of ^{238}U and ^{232}Th in the scintillator is now as low as 10^{-19} g/g, while ^{85}Kr background was reduced in 2010 below detection threshold, with an upper limit of a few cpd in 100 tonnes of scintillator. The only relevant background for the scope of this letter are the residual ^{210}Po peak, almost completely due to ^{210}Po not in equilibrium with ^{210}Pb, and a small amount of ^{210}Bi, corresponding to a few tens of cpd in 100 tonnes of scintillator. These numbers were somewhat higher in the data taken from 2007 to 2010 [24][25][26][27] and were reduced by an extensive purification campaign in 2010-2011.

Neutrinos and anti–neutrinos are respectively detected by means of the scintillation light emitted either by elastically scattered electrons or by inverse beta decay on protons. The effective light yield and the uniformity of the response throughout the detector volume was carefully measured and calibrated with radioactive sources [28]. The best fit gives 500 photoelectrons/MeV, yielding an energy resolution of 4.5% at 1 MeV. The light pulse is a few 100 ns long and pulse shape analysis separates β-like from α-like events efficiently [29], an important feature to separate residual ^{210}Po αs from solar and ^{51}Cr neutrinos. The position of each event is reconstructed by time–of–flight with a resolution of about 15 cm at 0.7 MeV. The distance from the source of each neutrino event can be known with that precision. See [30] for more details. We recall that neutrino events are intrinsically indistinguishable from solar neutrinos and β–like radioactivity events, so the extraction of the signal can be done through a spectral analysis only. Anti-neutrinos events, on the contrary, are easily tagged through the standard Reines-Cowan technique [31] [32].

3. The SOX experiment

The SOX experiment (Short distance neutrino Oscillations with BoreXino) will be done by means of two kind of artificial neutrino sources: in a first instance (Phase A) a ^{51}Cr ν_e source of 200-400 PBq activity will be put in a small pit below the Borexino detector at a distance of 8.25 m from the center; in a second phase (Phase B) a ^{144}Ce–^{144}Pr $\bar{\nu}_e$ source with 2-4 PBq activity at will be inserted into the WT at 7.15 m from the center. Finally (Phase C), a similar ^{144}Ce–^{144}Pr $\bar{\nu}_e$ source will go into the center of the liquid scintillator volume. Fig. 1 shows the approximate location of the sources in the three phases.

The Phase C is in principle the most attractive because its sensitivity is definitely higher, as shown later. However, it can be accomplished only after the conclusion of the solar neutrino pro-

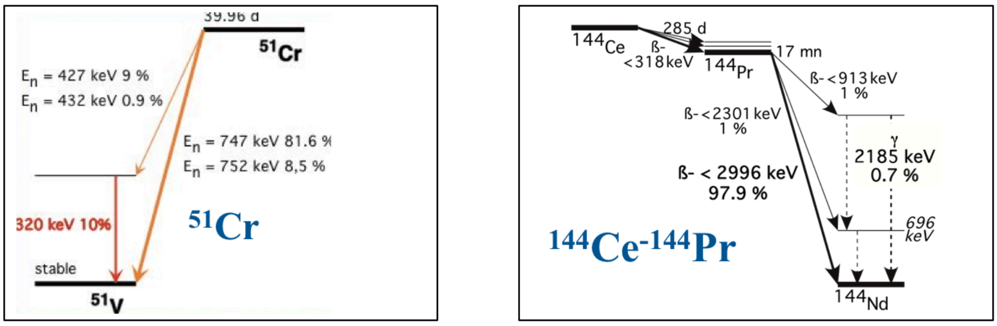

Figure 2: Left: EC decay levels of ^{51}Cr; Right: β decay levels of ^{144}Ce–^{144}Pr

gram (Borexino Phase 2) and requires relevant changes to the Borexino detector. On the contrary, the Phases A and B, though yielding a slightly lower sensitivity, may be done any time even during the solar neutrino phase of the experiment, which is supposed to continue until the end of 2015, and do not require any detector upgrade. Phase A and B 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 [33]. The Phase A will benefit from the experience of Gallex and SAGE that in the 90's prepared similar sources [34] [35] and is therefore the one that is expected first.

Under the floor of the WT there is a cubical pit (side 105 cm) which is accessible through a small squared tunnel (side 95 cm). The pit was built at the time of construction with the purpose of housing possible neutrino sources. The existence of this tunnel is one of the reasons why the ^{51}Cr experiment (Phase A) 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 source activity for ^{51}Cr of 200-400 PBq. These values are challenging, but only a factor 2-4 higher than what already done by Gallex and SAGE in the 90s and, according to preliminary simulations, feasible with existing reactors. In the ^{144}Ce–^{144}Pr experiment (Phase B) the two order of magnitude lower attainable activity suggests to deploy the source both externally at 7.15 m from the center (within the water tank, Phase B) or, even better, within the detector itself (Phase C). 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 useful volume for $\bar{\nu}_e$ detection from the current 321 m^3 up to 697 m^3.

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.

4. Sensitivity and expected results

The ^{51}Cr source will be produced by irradiating a large sample of Cr (highly enriched in ^{50}Cr and depleted in ^{53}Cr) in a nuclear reactor that may accommodate such a large volume of Cr and yield a high thermal neutron flux ($\approx 10^{15}$ cm^{-2} s^{-1}). The amount of Cr may vary from 10 kg up to 35 kg, depending on the level of enrichment. Candidate reactors under investigation are the Oak Ridge National Laboratory HIFR in Tennesse and the Ludmila reactor in the Mayak region in Russia. The advantage of ^{51}Cr is that it generates a quasi monochromatic neutrino beam via electron capture into ^{51}V, emitting two monochromatic neutrino lines of 750 keV (90%) and 430 keV (10%). The 750 keV line will be used by SOX, making oscillation analysis much simpler. Fig. 2-left shows the decay scheme of ^{51}Cr.

The ^{144}Ce–^{144}Pr source is done by chemical extraction of Ce from exhausted nuclear fuel [14]. ^{144}Pr decays β into ^{144}Nd with an end–point of 3 MeV (^{144}Ce decays β too, but is below threshold). Fig. 2-right shows the sequence of ^{144}Ce–^{144}Pr β decays. Note that the very short life–time of ^{144}Pr makes impossible the production of a pure Pr source.

Short distance neutrino oscillations can be studied by Borexino in two ways, one of which is a key and almost unique feature of the Borexino experiment or of similar large liquid scintillator detectors. The first way is the standard disappearance technique: if oscillations occur, the count rate is lower than that expected in absence of oscillations. The second way is to detect oscillation waves within the detector volume [12]: due to the fact that the values of Δm^2_{41} inferred from the existing neutrino anomalies is of the order of 1 eV^2 and that the energy of radioactive induced neutrinos is of the order of 1 MeV, the typical oscillations length amounts to a few m and the resulting oscillations waves can be directly “seen” with a large detector like Borexino. This is easily understood from the well-known two-flavor oscillation formula:

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

where θ_{14} is the mixing angle of the ν_e (or $\bar{\nu}_e$) into sterile component, Δm^2_{41} is the corresponding squared mass difference, L is the distance of the source to the detection point, and E is the neutrino energy. The imprinting of the survival probability P_{ee} on the spatial distribution of the detected events is shown in Fig. 3-left, for the ^{51}Cr source (Phase A), indicating that for appropriate values of θ_{14} and Δm^2_{41} the oscillations are clearly visible, if exists, as waves superimposed on the event profile in space. It is evident from the figure that the experiment would also be sensitive to any deformation of the shape, so in this sense the experiment is truly model independent. Oscillation parameters can be directly extracted from the wavelength and amplitude of the wave in case of oscillations with a single sterile component. More complex scenarios would require more data.

This sensitivity can be obtained only if the linear dimensions of the source are not much bigger than Borexino spatial resolution of 15 cm. The volume of the ^{51}Cr source will depend on the final level of isotopic enrichment of the material and on its chemical and physical form. The maximum expected size is at most 25 cm and is therefore comparable with the position reconstruction resolution of the events. The ^{144}Ce–^{144}Pr source is made of a few hg of Ce and its size is negligible. In all simulations shown below the source size effect is included. Fig. 3-right shows the same pattern for Phase B in a 3D plot, where the correlation between the waves and the reconstructed $\bar{\nu}_e$ energy is evident. This pattern is very powerful and allows to reconstruct θ_{14} and Δm^2_{41} even if the $\bar{\nu}_e$ spectrum of the ^{144}Ce–^{144}Pr is not mono-chromatic.

In Phase A the total counts method sensitivity is enhanced by exploiting the fact that the lifetime of the ^{51}Cr is relatively short. The known time-dependence of the signal, and the concurrent

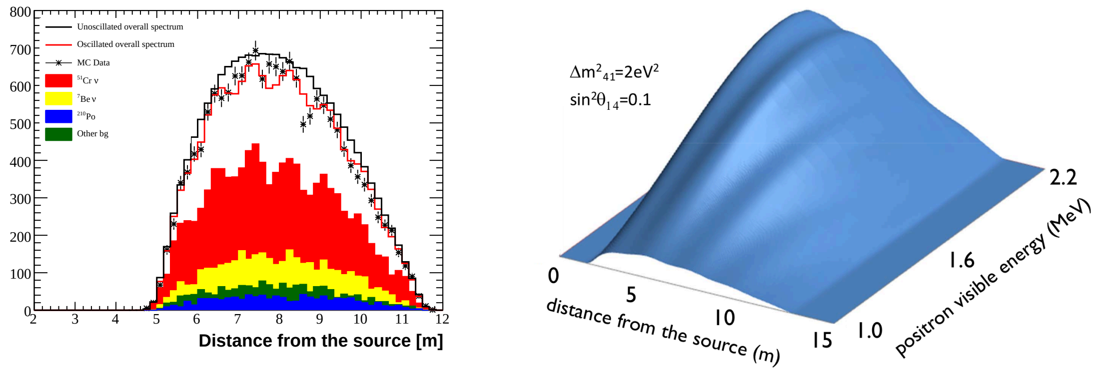

Figure 3: Left: example of a possible outcome of the ^{51}Cr experiment (Phase A) with $\sin^2(2\theta_{14})$=0.3 and Δm^2_{41}=2 eV^2. The signal (red band) is dominating at all distances from the source. The oscillatory behavior allows to reconstruct θ_{14} and Δm^2_{41}. Right: the oscillometry pattern as a function of the reconstructed (positron) visible energy for the Phase B experiment. A similar distance–energy correlation is expected in Phase C.

assumption that the background remains constant along the measurement (a fact that we know from Borexino data) 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 more than 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. In the following, we report the sensitivity of the three phases. The sensitivity plots are compared with the contours of the reactor anomaly and with the mixing angle upper bound obtained from the solar data analyzed with the now known value of θ_{13}.

For the ^{51}Cr experiment we assume to achieve 1% error in the measurement of the source activity, and 1% error in the knowledge of the fiducial volume with which we select the candidate events. The first number is challenging, but feasible (in 1995 Gallex experiment obtained about 2% precision). Preliminary analysis has shown that a precision of 1% in the activity might be obtained with a carefully designed and precisely calibrated isothermal calorimeter in which the activity is measured through a very precise knowledge of the heat released by the source. The calorimeter will be designed to allow the calorimetric measurement both during and after the data taking. The second one is even conservative: with a careful calibration by means of standard sources, the achievement of better than 1% knowledge of fiducial volume is realistic [25].

For the ^{144}Ce–^{144}Pr experiments we assume instead a 1.5% source intensity precision; furthermore, due to the correlated nature of the signal, we do not consider applying a fiducial volume cut (the whole scintillator coincides with the active volume) and therefore we omit the corresponding error. However, we include a 2% experimental systematic error, uncorrelated between energy and space bins, to account for residual systematic effects.

The sensitivity of the 370 PBq ^{51}Cr source test is evaluated assuming to deploy the source in the tunnel under the detector (8.25 m from the center) and after 6 days from its activation. The only

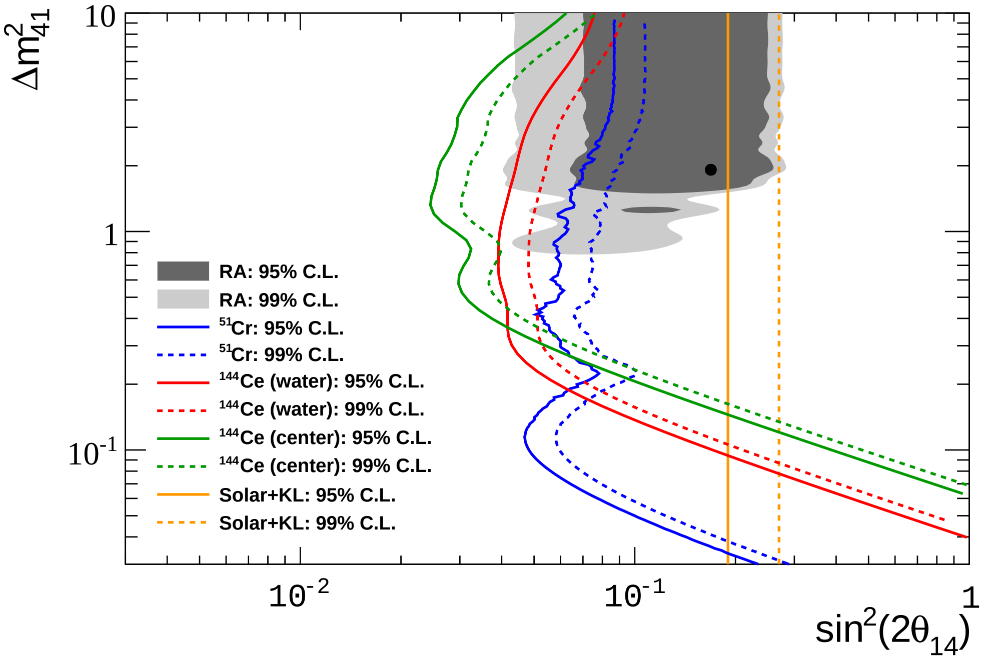

Figure 4: Sensitivity of the Phase A (^{51}Cr external, blue), of Phase B (^{144}Ce–^{144}Pr external, red) and Phase C (^{144}Ce–^{144}Pr center, green). The grey area is the one indicated by the reactor anomaly, if interpreted as oscillations to sterile neutrinos. Both 95% and 99% C.L. are shown for all cases. The yellow line indicates the region already excluded in [36].

expected background components are solar neutrinos (mostly ^{7}Be, which Borexino has accurately measured) and small amounts of radioactive contaminants intrinsic to the scintillator. The latter, in particular, are mostly due to the sizable ^{210}Po (τ = 199.6 days) content of the scintillator, for which we predict at the time of the test (around 2015) a rate of about 11.8 cpd in 133 tons of scintillator (selected as fiducial volume for the measurement), and in the energy region of interest, [0.25–0.7] MeV. The constant background is due to long living (>10 y) isotopes intrinsic to the scintillator, like ^{210}Pb (through the daughter ^{210}Bi) and ^{85}Kr, to solar neutrinos, and to gammas from the detector materials. The result is shown in Fig. 4. It is evident from the figure that the reactor anomaly region is mostly covered.

Our baseline plan is to reach this sensitivity with a single irradiation of 370 PBq (10 MCi). A similar result can be obtained with two irradiations of about 200 PBq. A single irradiation is preferable and yields a slightly better signal to noise ratio. The two-irradiations option, however, is acceptable and yields very similar results. We remind that, because of the un-avoidable γ background from the source, we cannot put the ^{51}Cr source inside.

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 Fig. 4. The χ^2 based sensitivity plots are computed assuming an active radius of 5.5 m, compared to the current active radius of 4.25 m 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. It can be noted from Fig. 4 that the Phase A and B sensitivities are very good, offering a conclusive experimental result even without deploying the source in the center.

SOX will yield additional physics. The electroweak angle θ_W can be directly measured at MeV scale from the ν_e-e$^-$ cross–section with an expected precision of 2.6%. This value is better that any other obtained at this energy scale. Furthermore, Phase A will provide significant information about neutrino magnetic moment [37][38] and improve the best result obtained so far [39]. By combining Phase A and Phase C the vector (g_V) and axial (g_A) current coefficients of the low energy Fermi interaction can be measured. In the standard model $g_V = -\frac{1}{2} + 2\sin^2\theta_W$ and $g_A = -\frac{1}{2}$. The best measurement at relatively low energy (10 GeV) was obtained by the CHARM II experiment [40]. As shown in [15] Borexino can obtain a similar (actually a little better) precision at much lower energy, where the existence of additional non-standard interactions might more easily probed.

5. Conclusions

Borexino is an ideal detector to probe the existence of sterile neutrinos. The staged approach proposed in this paper, first envisioning an external ^{51}Cr source and later two ^{144}Ce–^{144}Pr experiments, is a comprehensive sterile neutrino search which will either confirm the effect or reject it in a clear and unambiguous way. The Borexino program was made possible by funding from INFN (Italy), NSF (USA), BMBF, DFG, and MPG (Germany), NRC Kurchatov Institute (Russia), and MNiSW (Poland). We acknowledge the generous support of the Gran Sasso National Laboratories (LNGS). The SOX project is funded by ERC Advanced Grant 320873.

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