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Solar neutrino detectors as sterile neutrino hunters

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Abstract. The large size and the very low radioactive background of solar neutrino detectors such as Borexino at the Gran Sasso Laboratory in Italy offer a unique opportunity to probe the existence of neutrino oscillations into new sterile components by means of carefully designed and well calibrated anti-neutrino and neutrino artificial sources. In this paper we briefly summarise the key elements of the SOX experiment, a program for the search of sterile neutrinos (and other short distance effects) by means of a ^{144}Ce - ^{144}Pr anti-neutrino source and, possibly in the medium term future, with a ^{51}Cr neutrino source.

1. Introduction

Neutrinos have often been the object of important discoveries, - and sometimes of truly unexpected results -, since the theoretical prediction of their existence in the 30's. The impressive sequence of measurements made by solar [1][2][3][4][5], atmospheric [6], reactor [7] and accelerator experiments [8][9][10] (complemented by pivotal theoretical and global analysis efforts, which have been crucial for the correct interpretation of the data, see e.g. [11] [12]) have proved that neutrino masses are tiny but not zero, have measured the three mixing angles, and

have established that neutrinos in matter exhibit resonant oscillations and flavour regeneration similar to $K_0 - \bar{K}_0$ regeneration in the quark sector. Matter oscillations [13] are crucial for the understanding of the suppression of solar neutrino flux and will be beneficial for next generation oscillation experiments aiming at the mass hierarchy determination and the search of CP violation.

The standard three neutrino scenario established by oscillation experiments is still incomplete. We do not know the size of the Dirac CP-violating phase and therefore the relevance of CP violation in the lepton sector, a parameter which might control far reaching cosmological consequences; we lack the knowledge of the neutrino mass hierarchy, whose importance is particularly relevant for next generation neutrino-less double beta decay experiments and for the construction of flavour-mass models; last, but surely not least, we do know whether neutrinos are truly neutral (Majorana) particles or Dirac fermions like all other fermions in the standard model. Future generation experiments like T2K, Nova, JUNO, ORCA, DUNE and all forthcoming neutrino-less double beta decay experiments will try to complete the picture.

A few experimental facts, however, seems to sing out of tune. The LSND collaboration in Los Alamos has published in 2001 [14] the observation of an excess of electron type anti-neutrino events in a beam obtained from stopping positive muons. The result is completely incompatible with the standard three flavours scenario mentioned above. Besides, a relatively recent reanalysis of calibration data of Gallium based solar neutrino experiments [15] obtained by means of ^{51}Cr and ^{36}Ar radioactive sources [16] and a new determination of reactor neutrino fluxes [17] indicate that short distance oscillation experiments with L/E of the order of one m/MeV yield systematically lower counting rates. These facts have led many authors to consider the hypothesis that these deficits are due to the existence of low mass (i.e. eV scale) sterile neutrinos mixed with standard neutrinos, although no simple theoretical model seems to be able to accomodate all results.

Some recent experimental results have strongly reduced the allowed parameter space for a single sterile neutrino [18]. However, it should be underlined that a single confirmed anomaly is sufficient to claim the failure of the Standard Model, so a thorough experimental assessment of the situation is mandatory. It is therefore highly desirable to test the existence of short distance neutrino oscillation anomalies in a clear and unambiguous way.

Existing large size ultra-pure solar neutrino detectors offer a unique opportunity to perform such a test. In particular, the Borexino experiment has developed the cleanest existing liquid scintillator detector ever built so far, and it has demonstrated the capability to measure both neutrino and anti-neutrino fluxes with extremely low background, good energy resolution, and good position reconstruction resolution.

In the following, we show that an experiment made with a well calibrated anti-neutrino or neutrino source located a short distance from Borexino or from a similar liquid scintillator detector may probe the reactor and gallium anomalies in a clear way, either confirming the existence of short distance oscillation or discarding this hypothesis down to mixing angles of the order of 10^{-2} with δm^2 of the order of 0.05 - 10 eV^2 . Future large volume detector, such as e.g. JUNO, could very easily go much further, probing the existence of oscillations even with mixing angles as small as a few 10^{-4} δm^2 of the order of 0.01 eV^2 or less.

2. The Borexino detector and the SOX experiment

As an example of the concept outlined, we describe here the only approved experiment of this kind, the SOX experiment (Short distance neutrino Oscillations with BoreXino) at the Laboratori Nazionali del Gran Sasso in Italy.

Borexino, a large volume ultra-pure liquid scintillator detector, has recently measured several low energy solar neutrino components [5] [19] [20] and has performed the first un-ambiguous detection of geophysical $\bar{\nu}_e$ [21]. Because of its extremely low background, even the tiny signal

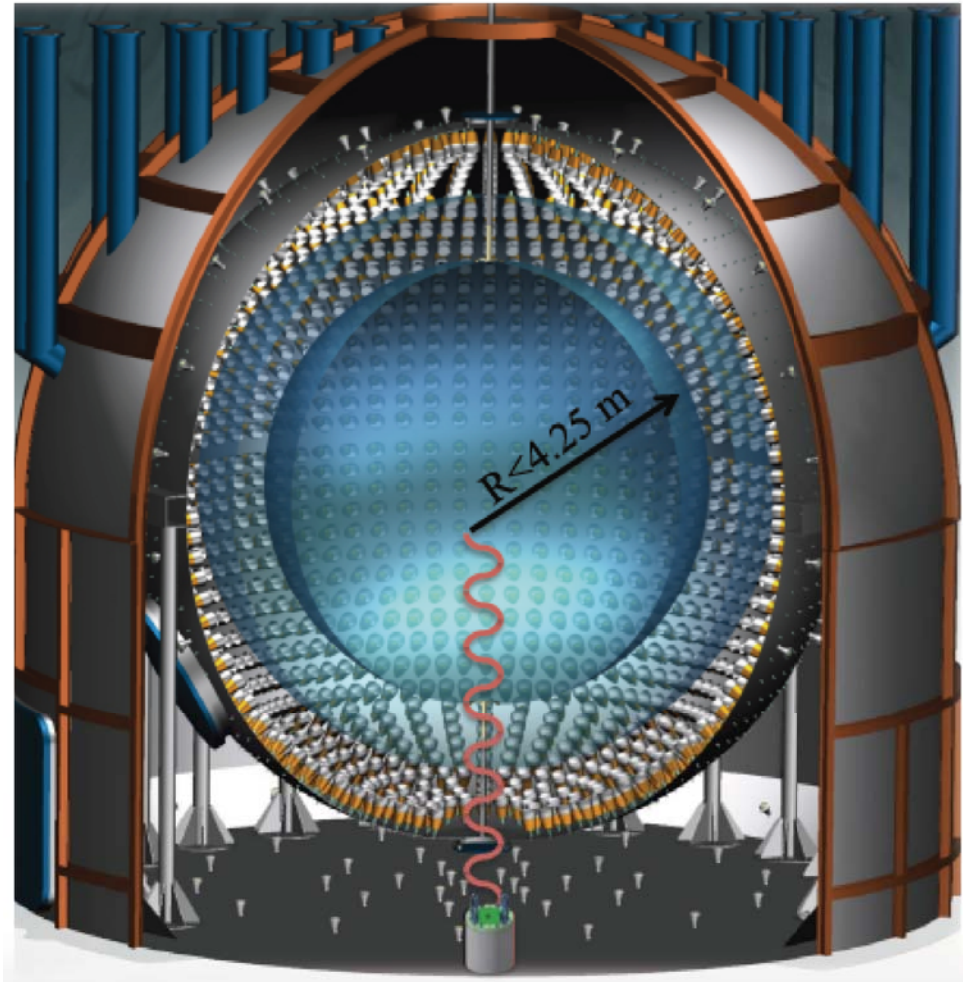


Figure 1. Layout of the SOX experiment. The ^{144}Ce - ^{144}Pr anti-neutrino source will be located beneath the Borexino detector in a special tunnel foreseen at the time of construction. The source will be nominally at 8.502 m from the center of the liquid scintillator core. The large Borexino size and the good spatial resolution (about 12 cm for anti-neutrino events) will allow oscillation waves detection from 3.5 to 12.5 m from the source.

of pep [19] and pp [20] solar ν_e could be observed. These features, together with its large radius (up to 11 m of active diameter with $\bar{\nu}_e$), a good light collection (about 500 p.e. / MeV) and a

good spatial resolution ($\sigma=12$ cm at 1 MeV) make Borexino a perfect environment for a short distance oscillation experiment.

SOX will be carried out by using, in a first instance, a ^{144}Ce – ^{144}Pr anti-neutrino source with a total activity of about 150 kCi deployed at 8.25 m from the center of the Borexino detector (see Fig. 1). The large size of the scintillator volume (contained in a nylon vessel of 4.25 m radius immersed and floating in a 6.85 m radius Stainless Steel Sphere) allows the detection of the order of a few 10^4 events and, even more important, the direct detection of hypothetical oscillations waves, as described in [22][23]. This feature is what makes SOX rather unique compared to other disappearance experiments made close to reactors or with neutrino beams.

The ^{144}Ce – ^{144}Pr $\bar{\nu}_e$ source, first proposed in [23], can be made by extracting Ce from exhausted nuclear fuel and by pressing CeO_2 powder within a properly designed stainless steel capsule. A few % of the Ce powder will be made of ^{144}Ce , but a few g of ^{144}Ce suffice to provide the necessary activity, so the total amount of Ce powder is of the order of 1 kg. The capsule is then sealed according to international regulations for the use and transportation of radioactive materials and inserted into a very thick W container (minimum thickness 19 cm) to virtually stop all unwanted radiation (mainly γ s). Stringent requirements are put on the purity of the CeO_2 purity to limit the emission of neutrons. The source will be manufactured by the PA Mayak company in Russia and delivered to Gran Sasso by means of a special container certified for the transportation of high activity radioactive materials. Transportation from the manufacturing site in Russia will happen by train to St. Petersburg, by ship to France, and then by truck from France to Gran Sasso.

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 possible neutrino sources. The existence of this tunnel is one of the reasons why SOX can be performed with no changes to the Borexino layout. The tunnel will be continuously ventilated and during data taking the source will be kept at constant temperature by means of a carefully controlled water cooling system to avoid transfer of heat from the source itself to the Borexino scintillator, whose extremely low background is known to be very sensitive to temperature variation, which triggers convection flows.

SOX will be at the same time a standard neutrino disappearance experiment and an innovative experiment for the direct detection of oscillation waves. The ^{144}Ce – ^{144}Pr $\bar{\nu}_e$ source will be precisely calibrated (at 1% level or better) by measuring with a high accuracy thermal calorimeter the heat released by the source [24]. Neutrino oscillations to invisible components (e.g. sterile neutrinos) effectively modulates the distribution of the events within the detection volume in a way that can unambiguously prove the existence of such oscillations. Fig. 2 (below) shows (dashed line) the sensitivity obtained by means of this model independent and intensity independent approach, while the same figure above shows the very specific dependence of the event count rate from the distance from the source and from the anti-neutrino energy. Such a pattern may prove the existence of oscillations beyond any reasonable doubt. The ^{144}Ce – ^{144}Pr $\bar{\nu}_e$ energy spectrum, particularly above the 1.8 MeV inverse beta decay threshold will be measured with dedicated experiments. This is important to be able to translate the calorimetric measurement into an uncertainty on the anti-neutrino flux above detection threshold and take properly into account the spectral shape of the emitted anti-neutrino. This ancillary measurement is not easy at all and is an important aspect of the project but we have no space here to cover this matter. Taking into account an additional global error of 1.5% due to liquid scintillator fiducial volume determination, a precise disappearance experiment becomes possible, yielding a combined sensitivity to a single sterile neutrino oscillations parameters shown as solid curve in Fig. 2. For more details see also [22][23].

The delivery of the source at Gran Sasso is currently foreseen for January 2018 and data taking will continue for 18 months, so first physics results will arrive in late 2018 or 2019.

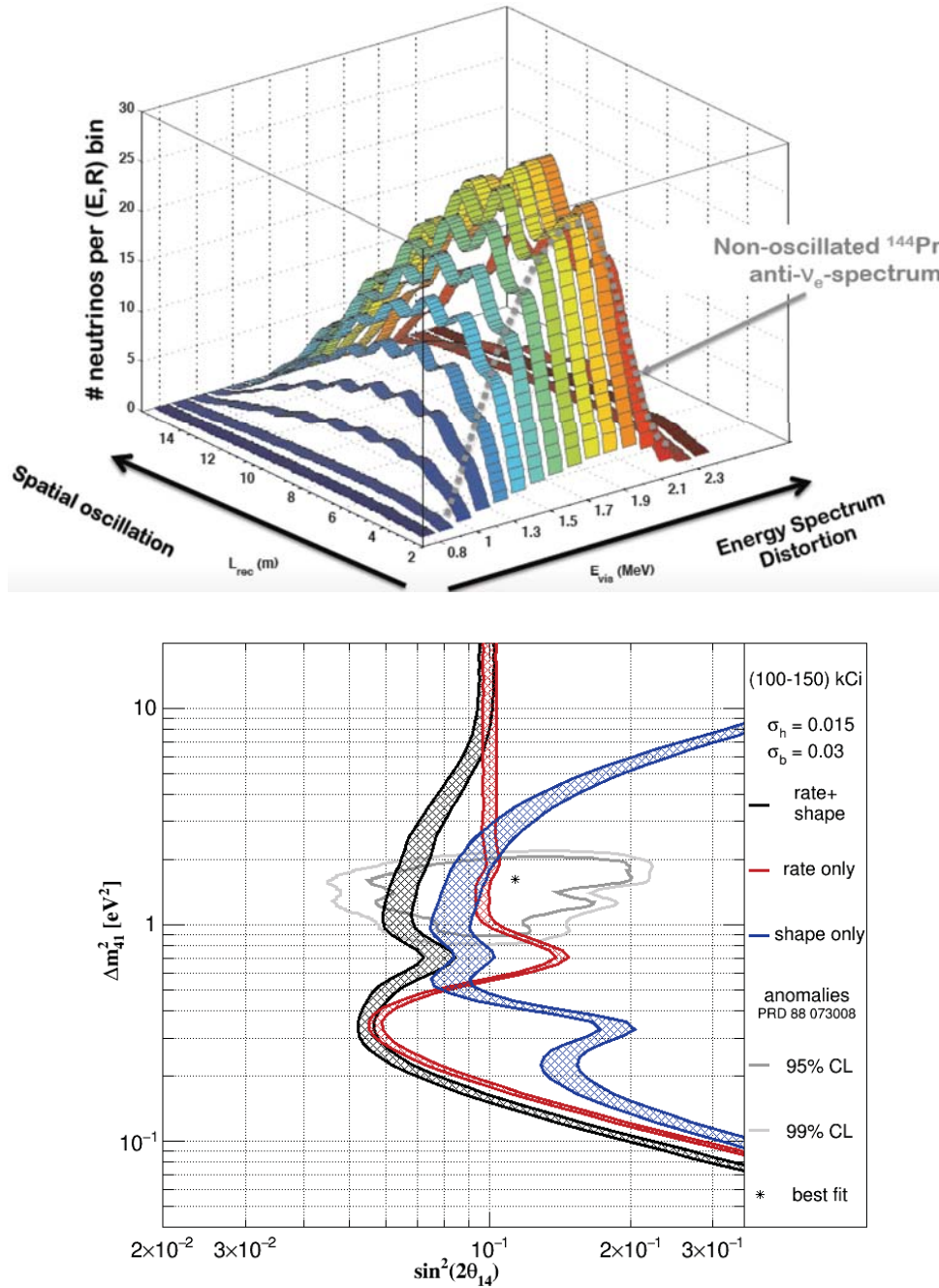


Figure 2. Above: the count rate distribution as a function of the distance from the anti-neutrino source and as a function of the energy. The existence of a single sterile neutrino mixed with electron anti-neutrinos could be clearly proved by the observation of such oscillations. Below: the sensitivity of the SOX experiment compared to the allowed region of the reactor anomaly. The blue, red and black bands show the sensitivity intervals for waves analysis only (blue), rate analysis only (red) and combined waves+rate analysis (black). For each band, the rightmost curve corresponds to a source activity of 100 kCi while the left-most curve corresponds to 150 kCi. The discovery power of the experiment if the reactor anomaly is indeed due to neutrino oscillations to sterile components is quite clear, being the wave analysis an essentially model independent and quite unique approach.

The SOX project includes as well a neutrino program by means of a ^{51}Cr source similar to that used in the 90s by the Gallex and SAGE collaborations. The enriched ^{50}Cr metal is available in Italy and a feasibility study is in progress to understand whether there is a viable way to irradiate the material and deliver to Gran Sasso a 2-4 MCi source. This part of the project is currently not funded and will be considered after the completion of the ^{144}Ce – ^{144}Pr anti-neutrino phase and the results of other sterile neutrino experiments.

The source technique could be adopted by other large volume liquid scintillator detectors, such as SNO+ or JUNO. The latter in particular, thanks to its huge size and high energy and position reconstruction resolution, might in principle perform an experiment one or two orders of magnitude better than SOX, despite the large background induced by the relatively close nuclear reactors.

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