Search for Sterile Neutrinos with the Borexino Detector

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Several observed anomalies in the neutrino sector could be explained by a fourth (sterile) neutrino with a squared mass difference in the order of $1\,\mathrm{e}V^2$ to the other three standard neutrinos. This hypothesis can be tested with an artificial MCi neutrino (^{51}Cr) or a kCi anti-neutrino (^{144}Ce$-^{144}$Pr) source deployed near or inside a large low background detector like Borexino. The SOX project (Short baseline neutrino Oscillation with BoreXino) aims for the detection of sterile neutrinos and will also allow to measure the neutrino magnetic moment, the electroweak mixing angle as well as the g_V and g_A coupling constants at low energy.

1 Introduction

The leptonic flavor mixing of neutrinos has been well established by a number of experiments. In the common picture, the three neutrino flavors $(\nu_e, \nu_\mu, \nu_\tau)$ are linear combinations of the three neutrino mass eigenstates (ν_1, ν_2, ν_3) separated by the two squared mass differences of $\Delta m^2_{21} = 8 \cdot 10^{-5}\,\mathrm{e}V^2$ and $\Delta m^2_{31} = 2.4 \cdot 10^{-3}\,\mathrm{e}V^2$.

However, a number of short baseline experiments have measured a neutrino deficit with respect to the expectations. These results are commonly defined as *neutrino anomalies.* From the historical point of view the LSND result has been the first result which was inconsistent with the standard scenario and pointed to the possibility of the existence of a fourth (sterile) neutrino (3+1 model). Recently, the re-calculation of the $\bar{\nu}_e$ flux from reactors together with the re-evaluation of the inverse beta decay cross section (due to the change of the neutron life-time), resulted in an observed anti-neutrino deficit of about 7% for experiments within 100 m of the reactors. This discrepancy is known as the reactor anomaly and could be explained by a fourth (sterile) neutrino [1].

In the nineties, two solar neutrino experiments (GALLEX and SAGE) performed calibration campaigns with artificial neutrino sources (^{51}Cr and ^{37}Ar) to check their detector efficiencies. Both experiments observed independently a lower neutrino flux than expected and a recent global re-analysis confirmed the anomaly at 3σ [2].

One powerful method to probe the neutrino anomaly is to repeat similar source experiments with more intense ν_e and $\bar{\nu}_e$ sources at a large low background detector like Borexino [3, 4, 5]. Thanks to the good energy and vertex resolution, it might even be possible to observe the characteristic neutrino oscillation pattern within the detector, if the Δm^2 is in the favored range of $1\,\mathrm{e}V^2$ and the mixing angle is not to small.

2 The Borexino detector

Borexino is a 300 t liquid scintillator detector designed for the real-time detection of solar neutrinos at the LNGS in Italy [6]. The detection of the solar ν_e is performed by neutrino electron scattering (NC+CC) and via the inverse beta decay (IBD) for the $\bar{\nu}_e$ geo-neutrinos. Borexino has provided a precise spectroscopy of solar neutrinos [7], including recently the first direct detection of the primary pp neutrinos from the Sun [8].

The Borexino detector consists of a nylon vessel with an diameter of 9.5 m (target area) surrounded by the buffer and water tank as shielding. The scintillation light originating from neutrino interactions are detected by 2,214 PMTs mounted on the so-called *stainless steel sphere.*

The inner nylon vessel contains the liquid scintillator composed from PC (pseudocumene, 1,2,4-trimethylbenzene) and PPO (2,5-diphenyloxazole) as a wavelength shifter. As part of a R&D effort, Borexino has reached an unprecedented radio-purity. Currently, the ^{238}U and ^{232}Th concentration is as low as 10^{-19} g/g. Other backgrounds include ^{85}Kr, ^{210}Bi and most importantly ^{210}Po. The energy response throughout the detector volume was carefully measured and calibrated by radioactive sources. At 1 MeV the energy resolution was determined to 4.5% and the vertex resolution is about 15 cm at 0.7 MeV [5].

3 Search for sterile neutrinos with the Borexino detector

The search for possible light sterile neutrinos can be performed by using either monochromatic neutrino sources like ^{51}Cr or ^{37}Ar, or by using intense anti-neutrino sources (^{144}Ce, ^{106}Ru or ^{90}Sr) with a continuous β-spectrum. The size of the source used by an experiment should be as compact as possible to observe the characteristic (anti-)neutrino oscillation pattern. The Borexino experiment will use the ^{144}Ce anti-neutrino source and possibly the ^{51}Cr neutrino source.

3.1 Anti-neutrino emitters in Borexino

During the first phase of the SOX project an anti-neutrino source with a continuous β-spectrum will be placed underneath the Borexino detector (8.25 m from the detector center). The detection of the $\bar{\nu}_e$ is then performed via the inverse beta decay (IBD), $p+\bar{\nu}_e \rightarrow e^{+}+n$. The signature is provided by the positron annihilation (prompt signal) followed by the neutron capture on hydrogen (delayed signal). This coincidence allows an efficient way to suppress background and is often referred to as the golden channel of neutrino physics. The anti-neutrino detection was successfully applied for the geo-neutrino analysis [9] and is also widely used by other experiments [10]. A suitable $\bar{\nu}_e$ source must have $Q_\beta > 1.806\,\mathrm{MeV}$ (above the IBD threshold) and a half life long enough to allow the production and transportation of the source to the detector [11]. The Borexino collaboration has decided to use ^{144}Ce$-^{144}$Pr, which features $Q_\beta\left(^{144}Pr\right)$ of 2.996 MeV. ^{144}Ce can be extracted from spent nuclear fuel followed by column chromatography. Due to the high IBD cross-section [12] the source activity can be in the order of 100 kCi.

3.2 Neutrino emitters in Borexino

As a further option the deployment of a neutrino source underneath the Borexino detector is under consideration. For that purpose the ^{51}Cr source used by the GALLEX experiment could be refurbished. ^{51}Cr is an electron capture source, $^{51}\mathrm{Cr} + e^{-} \rightarrow {}^{51}\mathrm{V} + \nu_e$, featuring four monochromatic neutrino lines. In 81.6% (8.5%) of the time it decays to the ground state of ^{51}V and emits a 747 keV (752 keV) ν_e, while in 9% (0.9%) of the time a 427 keV (432 keV) ν_e is emitted to the first excited state of ^{51}V followed by the emission of a 320 keV γ. The dominant ν_e line is very similar to the 0.862 MeV ν_e from the radioactive decay of ^{7}Be in the Sun. The ^{51}Cr source will be produced by neutron irradiation of ^{50}Cr at nuclear reactors. Natural chromium consists mainly of ^{52}Cr (83.9%) and ^{53}Cr (9.5%). Since ^{53}Cr has a relatively large thermal neutron cross section of 18.7 barn, enriched ^{50}Cr has has to be used in order to reach the desired activity of 5-10 MCi.

3.3 Sensitivity and expected results

The analysis of short baseline neutrino oscillation in Borexino can be performed in two ways. The standard disappearance procedure is a rate analysis. If neutrino oscillation occur, the expected number of events with respect to the non-oscillation scenario will be lower. This technique relies on a precise knowledge of the source activity and background estimation. The second technique is called oscillometry and is an almost unique feature of the Borexino experiment or of a similar large liquid scintillator detector [5]. The physics potential of the SOX concept is shown in Figure 1. During the first phase the cerium source and possibly the chromium source will be placed underneath the detector. This will allow testing the parameter region currently favored by global fits. Depending on the results, the cerium source might also be placed inside the water tank or in the center of the detector.

4 Conclusion

The Borexino detector is an ideal candidate to search for sterile neutrinos. During the first phase of the experimental setup, an anti-neutrino source will be placed in a tunnel underneath the large low background detector Borexino. The source will arrive at the end of 2015 at the

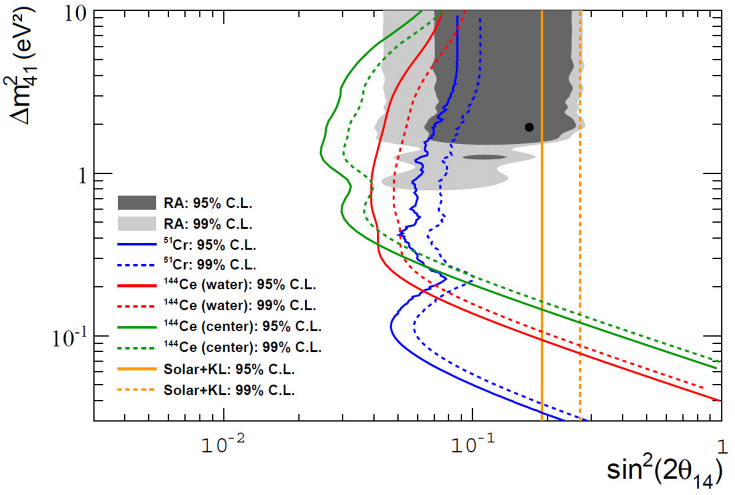

Figure 1: Sensitivity for the SOX project [3]. The cerium source sensitivity for the first phase (see text for details) is similar to the sensitivity of the shown chromium source.

Laboratori Nazionali del Gran Sasso. First results are expected in 2016. Additional physics of the SOX concept includes studies of the magnetic moment of the neutrino as well as the measurement of the Weinberg angle [3].

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