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SOX : Short Distance Neutrino Oscillations with Borexino

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Abstract

The Borexino detector has convincingly shown its outstanding performance in the in the sub-MeV regime through its unprecedented accomplishments in the solar and geo-neutrinos detection, which make it the ideal tool to unambiguously test the long-standing issue of the existence of a sterile neutrino, as suggested by several anomalies: the outputs of the LSND and Miniboone experiments, the results of the source calibration of the two Gallium solar ν experiments, and the recently hinted reactor anomaly. The SOX project will exploit two sources, based on chromium and cerium, which deployed under the experiment will emit two intense beams of ν_e (Cr) and $\bar{\nu}_e$ (Ce). Interacting in the active volume of the liquid scintillator, each beam would create a spatial wave pattern in case of oscillation of the ν_e (or $\bar{\nu}_e$) into the sterile state, which would be the smoking gun proving the existence of the new sterile member of the neutrino family. Otherwise, its absence will allow setting very stringent limit on its existence.

Keywords: SOX, sterile neutrinos, anomalous oscillations, chromium-51, cerium-144, Borexino

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1. Introduction

Neutrino measurements by real-time detectors −of which Borexino is a world-class example, and the first to measure in real time the dominant, sub-MeV solar spectrum [1], including the first direct detection of the neutrinos coming from the reaction that produces 99.77% of the Sun's energy release, the *pp* chain [2]− have confirmed neutrino oscillations between its three known flavour states, and their enhancement due to the weak interactions with the electrons in matter. Borexino's results have excluded several (Δm^2, $sin^2 2\theta$) solutions for this MSW effect, such as LOW (day-night asymmetry null result for the ^{7}Be neutrino flux), or *Just-So* (absence of anomalous modulation in the annual variation of the ^{7}Be flux) −showing a clear preference for the *Large Mixing Angle* (LMA) parameters.

In addition, Borexino aims to clarify the question of the existence of neutrino oscillations into **additional states**, beyond the three known ν_e, ν_μ and ν_τ; in particular, into the so-called *sterile states*, detectable only as a deficit in a 'regular'-neutrino flux. The *Short-distance Oscillations with Borexino* (SOX) project aims to explore the mass-scale of $\sim 1eV^2$. This low L/E region is mostly unexplored: there are phase-space areas where sterile neutrinos may exist, even in light of constraints by recent experiments.

2. The Borexino detector

Borexino is a neutrino detector based on the principles of ultra-radiopure liquid scintillator and graded shielding. The overburden of the mountains of the Gran Sasso d'Italia, under which the Laboratori Nazionali del Gran Sasso (LNGS) are located, provide ∼3600 meters of water-equivalent shielding against cosmic backgrounds. The detector itself is surrounded by a domed tank filled with ultra-pure water, which serves as a Čerenkov muon veto, with an efficiency greater than 99.99%. Inside said water tank, an 18-meter-diameter Stainless Steel Sphere (SSS), filled with ∼1100 tons of pseudocumene (PC), has 2212 inward-facing photomultiplier tubes (PMTs) mounted on its walls. This volume is separated by two ultra-low-radioactivity nylon spheres: the outer vessel (OV), used to prevent radon gas emanating from the SSS's hardware from reaching the center of the detector; and the inner vessel (IV), which separates the buffer region outside the IV, doped with dimethylphthalate (DMP, 2 g/L), used to quench light emission; from the interior of the IV, doped with 2,5-diphenyloxazol (PPO, 1.5 g/L), used to shift the UV scintillation light to a longer wavelength closer to the maximum PMT efficiency. Finally, software cuts generate a ∼100-ton, radiopurest fiducial volume (FV) specially tailored for each particular data analysis [3].

The light yield is ∼500 photoelectrons/MeV, with a threshold of ∼60 keV (∼180 keV for analysis purposes). Scintillation light in Borexino can be generated in many ways indistinguishable from the neutrinos elastic-scattering off electrons in the PC: thus the extreme radiopurity levels sought and mantained. In order to filter out these background events, specific scintillator purifications, software discrimination of events and calibrations are used, on top of cleanliness and hardware design. Unprecedented levels of several 10^{-19} g of ^{238}U-^{232}Th/g of scintillator have been achieved, with outstandingly low levels of other backgrounds too. ^{210}Po and ^{210}Bi have been observed out of equilibrium, and their levels can still be improved. While polonium can be tagged out thanks to the pulse-shape discrimination techniques developed, and has been decaying away mostly uninterruptedly, bismuth shows erratic levels that may be caused by stirring of the inner scintillator volume or some other cause −however, hardware improvements, purification strategies and analysis techniques are being developed with the aim to minimize its (already small) impact to a negligible level.

Four major calibration campaigns have taken place since Borexino's activation in 2007, using different types of radiation sources (α, β, γ, neutrons) with energies ranging from the detector's lowest threshold to ∼10 MeV. Since most of these activities involved placing the calibration source *inside* the FV, special care was taken not to contaminate the pristine environment with long-lifetime radioactive substances: this was successfully achieved in all cases [4].

3. SOX project

Indications of the existence of more than 3 neutrino flavors have existed since the *LSND experiment* ($\bar{\nu_\mu} \rightarrow \nu_e$ at 20-60 MeV and a 30-meter baseline) saw an unexpected excess at 3.8σ in the 1990s [5]. Later, *gallium experiments (GALLEX and SAGE)*, based on ν_e disappearance, gave further −albeit weak− support to this extra oscillation hypothesis[6, 7], along with a recent *re-evaluation of nuclear reactor $\bar{\nu}$ fluxes*[8], showing a systematic deficit in short (10-100m) baselines at $\sim 2.5\sigma$. Theoretical frameworks exist which could provide support for these results, including the existence of a ∼ 1eV *sterile* (since it does not couple with the Z^0 boson and, therefore, does not interact weakly) neutrino state which mixes with the three known weak eigenstates [9]. Still, there are also ambiguous and even contradictory results (MiniBooNE, MINOS, Planck's new data...) which generate tensions between the apparent anomalies observed.

In this climate of urgent need of further experimental data to confirm or reject the ample but confusing existing evidence, Borexino will use its sensitivity to check for anomalous rate deficits and unexpected spatial neutrino oscillations in the mostly-unexplored low L/E region (~1 m/MeV), measuring the flux coming from external or internal ν sources [10].

3.1. SOX-A (external sources)

Borexino was built over a small tunnel (~1 m^2 cross-section) designed for placing radioactive sources directly under the experiment, requiring no modifications to the detector itself or a disruption of normal operations. The aim of SOX-A is to deploy high-intensity ν_e and $\bar{\nu}_e$ sources inside this pit, at ~8.25m from the center of the detector (see Figure 1).

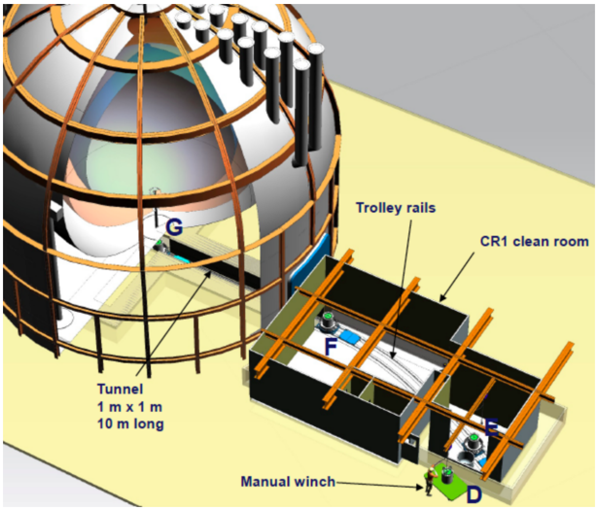

Figure 1: Rails leading the source from cleanroom-1 (CR1) to under Borexino in the SOX pit

SOX-Cr

A ~10MCi ^{51}Cr source would mainly produce neutrinos with a very similar energy to the golden channel Borexino has demonstrated to be able to measure very accurately: the ^{7}Be solar neutrino (862keV), and subdominantly with an energy close to that of the spectrum cutoff of the just-measured pp solar neutrinos. The decay scheme for ^{51}Cr follows the electron capture decay:

$$^{51}Cr + e^{-} \rightarrow ^{51} V + \nu_e; t_{1/2} = 27.7d$$
$$\mathrm{E}_{\nu} \sim 750 \text{ keV } (90\%), 430 \text{ keV } (10\%)$$

A 320keV γ is emmited (b.r. ~10%), which can be attenuated to negligible levels ($< 200\mu$S/h in direct contact with the shielding) with a few centimeters of tungsten shielding which, however, needs to be thickened due to minute levels of impurities in the chromium that produce higher-energy γs which would otherwise be an issue for the experiment or the handling of the source. Thermal limits are not an issue however, and active cooling will not be necessary: the hottest point inside the source object would be less than half of the sinterization temperature of chromium (750 °C), and the outside surface would be at less than 90 °C, further cooled down by releaseable aluminum fins. Should an activity of 10MCi in a single source be too technically challenging, the sensitivity would remain largely untouched (with a slightly worse signal-to-noise ratio) if two sources of ~6MCi were deployed in separate campaigns.

Quick transportation strategies (due to ^{51}Cr's low halflife: $t_{1/2}$ =27.7 d) and installation permissions for a ~100-day campaign are also underway. The available stock of 38%-^{50}Cr-enriched, ^{53}Cr-depleted material from GALLEX has been acquired and is expected to be used, with the possibility of procuring new, higher-enriched chromium if needed. It will be irradiated in a high-flux nuclear reactor: the High-Flux Isotope Reactor (HFIR) in Oak Ridge National Laboratory, USA; or the Mayak reactor in Russia. Preliminary MonteCarlo simulations on the expected activity have already being performed. A ~1% source activity determination is paramount for the sensitivity of the measurement. To this end, gamma and ^{51}V-assay of representative samples and, most notably, full-source calorimetry will be performed.

SOX-Ce

Recently, the plan to deploy a ~150kCi ^{144}Ce-^{144}Pr antineutrino source in the same pit has been approved for the timeframe of late 2015 / early 2016. This source was expected to be used in the internal SOX campaigns (SOX-B and -C), but a re-evaluation of its capabilities has shown it can be complementary to the ^{51}Cr when inserted in the pit. This campaign will be known as *SOX-Ce*, distinguishing it from the other external source campaign *SOX-Cr*.

The SOX-Ce campaign would need to be much longer than SOX-Cr's, on the order of 1.5 years to accumulate around the same level of signal events (~ 10^4), owing to the ~296-day halflife of ^{144}Ce which

β-decays to ^{144}Pr. It then decays rapidly (τ =17 minutes) to ^{144}Nd, emitting a wide spectrum of $\bar{\nu}_e$s with high enough threshold to allow for inverse β-decay reactions to take place (IBD_{thr} = 1.806 MeV). This last decay suffers, for our purposes, from a large theoretical and experimental uncertainty in its shape. An important effort is taking place to create MonteCarlo estimates and produce a high-quality measurement of its β spectrum from cerium oxide samples. Praseodynium decay also produces a copious amount of high-energy γs, which need a thicker tungsten shielding for attenuation −however, owing to the lesser amount of cerium needed (~47g, or ~9kg of CeO_2) compared to chromium, the size of the complete source remains roughly equal. Additionally, backgrounds are expected to be much lower, if intrinsic source-induced γs or neutrons are avoided, and Borexino's geo-$\bar{\nu}$ results demonstrate the detector's outstanding capabilities in IBD measurements.

The source material can be separated from spent nuclear fuel rods through chemical processes and displacement chromatography techniques to create powdered oxide, which then would be pressed for compactification and insertion in the shielding. Thermal emission will be important (~1.2kW at delivery), likely requiring active thermal control to avoid convection currents in the detector.

Design for both sources' shielding and containers is maturing and reaching the industry tender level. Waterflow calorimeters will be built to perform a decay measurements and independently verify impurity contents. In the case of SOX-Cr, where the source activity determination requirements are more stringent than in the cerium case, and owing to its much shorter lifetime, calorimetry will be performed continuously while the source is deployed under the detector, to minimize uncertainties. Calorimeters design is mostly finalized and a prototype with resistive heaters will soon be starting acceptance tests for SOX-Ce.

The accrued data will be analyzed with **rate** (more sensitive to θ_{14}, just looking for the difference in counting rates between the expected level with no anomalous oscillations, taking into account the well-known source activity; and the measured one) and **rate+shape** techniques: oscillations from ~1eV neutrinos would be discernible within both Borexino's size and position resolution, given that their characteristic wavelength would fall between these two limits, by virtue of the well-known relationship:

$$L_{osc}(m) = \frac{E(MeV)}{1.27\Delta m^2(eV^2)}$$

This would provide a direct measurement of both Δm^2_{14} and θ_{14}, covering most of the gallium+reactor anomaly phase space (see Figure 2). Best-fit values for the current allowed space would be covered so as to generate a discovery / exclusion signal at 5σ. Oscillometry for SOX-Ce would, in fact, be feasible to observe both within the detector volume *and* due to the spectral distribution of neutrino energies. Some backgrounds, like ^{210}Po, are expected to have decayed away when SOX-Cr is deployed: in fact, the main irreducible background will be solar neutrinos. Other precision results are expected, such as studies of the neutrino magnetic moment, a much lower-energy (~1MeV) measurement of the Weinberg angle than any limits currently available and the g_A and g_V parameters at low energies.

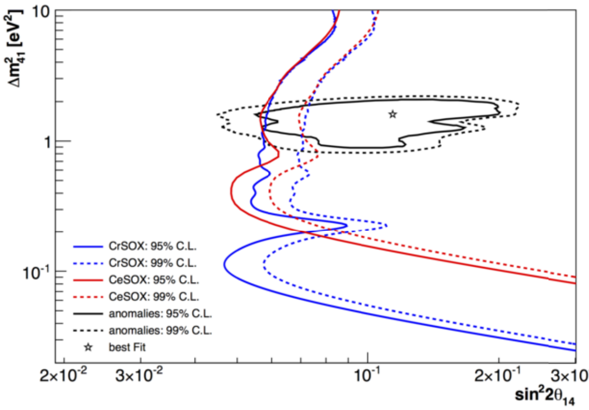

Figure 2: Allowed parameter space according to one of the latest global fits [11] and Borexino's SOX-A chromium and cerium campaigns' expected coverages

3.2. SOX-B and C (internal sources)

Additional ~75kCi ^{144}Ce-^{144}Pr internal sources will be fabricated from other batches of spent nuclear fuel. SOX-B will deploy it inside the water tank (~2017), while SOX-C is designed to use the whole SSS as the FV, placing it in the center of Borexino around 2017 or later. These projects will require a refurbishment of the detector, and more challenging active cooling for the source, but are expected to cover all of the gallium+reactor anomaly 99%-allowed phase space to 95% and 99% C.L. respectively, according to the Monte Carlo model developed with an expected number of statistical samples (2000 events) generated for each pair of the oscillation parameters, and a 15-day period of stable data-taking just prior to source deployment to accurately constrain the backgrounds at the time (see Figure

3). A sphere of 1.5-m radius around the source was excluded from the analysis for the SOX-C MonteCarlo as a conservative estimate of the fiducial cut needed for discrimination of the source-emitted Bremsstrahlung and γ backgrounds.

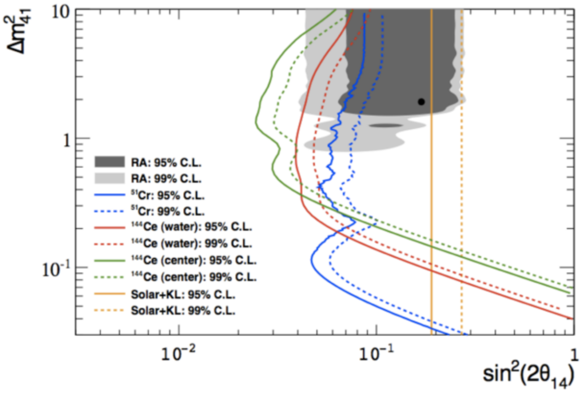

Figure 3: Expected sensitivity of the internal source projects (SOX-B and SOX-C) with ^{144}Ce-Pr $\bar{\nu}$ sources compared to that of the external chromium campaigns (SOX-Cr) and the allowed parameter space for the reactor anomaly.

4. Conclusions

Borexino aims to build upon its past and recent successes in solar spectroscopy (neutrinos from the pp, pep, ^{7}Be, ^{8}B reactions, CNO flux limit...) and geo-neutrino detection by the multi-step SOX source program, designed to test the current anomalous neutrino oscillation discussion in the low L/E region, by deploying high-intensity neutrino and antineutrino sources outside (SOX-A, divided in a ^{51}Cr and ^{144}Ce-^{144}Pr campaigns, SOX-Cr and SOX-Ce) and inside (SOX-B & C) the detector. This will enable most of the anomalies' allowed parameter space to be covered, verifying or disproving the light sterile neutrino hypothesis and shedding light on the issue of anomalous neutrino oscillations.

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