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Short distance neutrino Oscillations with BoreXino: SOX

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Summary. — Several anomalies coming from neutrino experiments may be pointing towards new physics: these hints suggest the existence of one (or more) sterile neutrinos. SOX is a short-baseline experiment devoted to shed light on this intriguing hint, by looking for disappearance of $\bar{\nu}_e$ from a ^{144}Ce - ^{144}Pr source with the Borexino apparatus.

1. – Introduction

Flavour oscillations in the neutrino sector have been clearly assessed by several experiments on solar, atmospheric, reactor and accelerator neutrinos. The large amount of experimental data accumulated so far provides a coherent picture in the standard three-flavour scenario, leaving however room for possible extension to non-standard physics. In particular, several experimental hints, both in appearance and disappearance mode, have accumulated throughout the past 20 years and may indicate the existence of one or more sterile neutrinos. These hints include the so-called reactor anomaly [1, 2] ($\bar{\nu}_e$ disappearance), gallium anomaly [3] (ν_e disappearance), as well as the LSND result [4] ($\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam), confirmed later on by the miniBooNE experiment [5] (which observes also ν_e appearance). Each one of these results taken by itself has low statistical significance ($\sim 3\sigma$). However, they could be simultaneously accommodated in a scenario where one (or more than one) new family of neutrinos mixes with the active ones at a characteristic Δm^2 of the order of 1 eV^2 . A non-ambiguous confirmation of the sterile neutrino hypothesis would be a major breakthrough for particle physics: for this reason several experiments based on different techniques and different neutrino sources (accelerator, reactor ...) have been proposed to shed light on this puzzle.

SOX is a unique experiment in this respect: it will exploit the unprecedented radiopurity of the Borexino apparatus to perform a short-baseline disappearance experiment

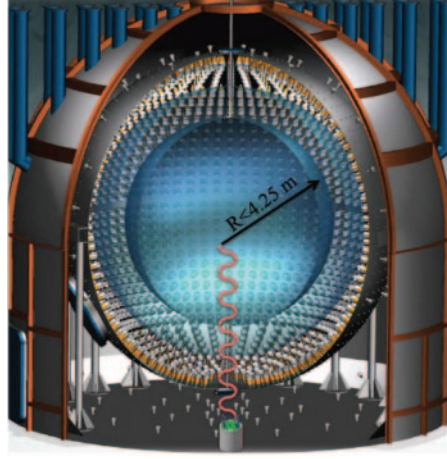


Fig. 1. – Borexino detector schematic layout with the cerium source underneath the detector.

in nearly background free conditions, by locating a ^{144}Ce - ^{144}Pr anti-neutrino source at ~ 8 meters from the detector center. This paper is organized as follows: sect. **2** will discuss briefly the characteristics of the Borexino apparatus and the basic concept of the SOX experiment. Section **3** is devoted to the ^{144}Ce - ^{144}Pr source and its characterization. Section **4** will give details on the main features of the SOX experiment and how they will impact its sensitivity to sterile neutrinos. Finally, sect. **5** will overview the on-going activities to prepare SOX and its current schedule.

2. – The SOX experiment

SOX (Short distance ν_e Oscillations with boreXino) is a proposal based on the Borexino detector. Borexino was originally designed to detect solar neutrinos using the liquid scintillator technique [6]. It is located under the Gran Sasso mountain in Italy and is taking data since 2007. The detector scheme is shown in fig. 1. The core of Borexino is 300 tons of ultra-pure liquid scintillator (pseudocumene + 1.5 g/l of PPO) contained in a 4.25 m radius, 120 μm thick nylon vessel. In order to shield the scintillator from external background, the vessel is immersed in 1000 tons of pure liquid (pseudocumene + DMP, a light quencher) contained in a Stainless Steel Sphere (SSS) of 7 m radius. To further increase shielding, the SSS is surrounded by 2000 tons of ultra-pure water contained in a cylindrical dome. The water in the external part of the detector serves also as an active shield to suppress the residual background due to cosmic muons which are able of penetrating underground. In order to do so, 200 photomultiplier tubes are mounted on the external part of the SSS to detect the Cerenkov light emitted by muons which cross the water. The intrinsic radiopurity of the scintillator has been brought to exceptional levels thanks to the successful purification strategy developed during 15 years of dedicated R&D studies [7].

Borexino has published several results on solar neutrinos, which include the measurement of the ^7Be neutrino flux with total error below 5% and its day/night asymmetry [8,9], the measurement of the ^8B neutrino flux down to the unprecedented threshold of 3 MeV [10], the first observation of neutrinos from the pep and pp reactions [11,12].

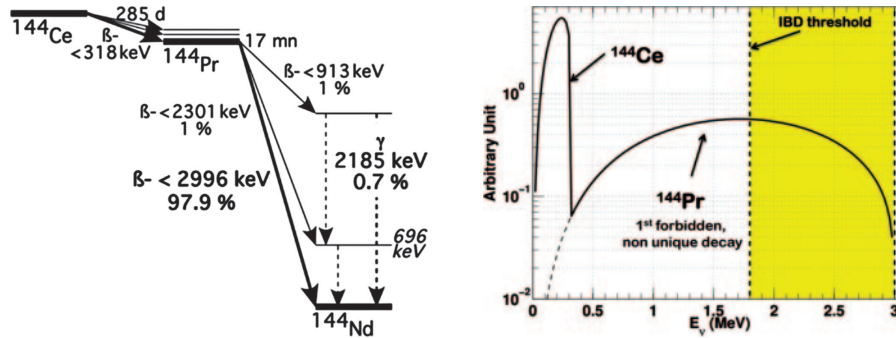


Fig. 2. – Decay scheme for ^{144}Ce - ^{144}Pr (left); energy spectrum of the emitted anti-neutrinos (right).

The SOX project foresees to put a ^{144}Ce - ^{144}Pr anti-neutrino source in an existing pit underneath Borexino at 8 meters from the center of the detector. This provides a straightforward way to test the sterile neutrino hypothesis in disappearance mode. Taking into account the distance of the source from the detector and the anti-neutrinos energies ($E < 3\text{ MeV}$), SOX can probe $\Delta m^2 \sim 1\text{ eV}^2$ which is the region where anomalies have emerged.

A unique feature of SOX is the possibility to identify the oscillation pattern of the ν_e survival probability

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 \theta_{14} \sin^2 \frac{1.27 \Delta m_{14}^2 (\text{eV}^2) L (\text{m})}{E (\text{MeV})},$$

thus providing a convincing proof of the nature of the phenomenon. This can be done thanks to the good position and energy reconstruction capability of SOX ($\sigma_E/E \sim 10\%$ and $\sigma_x \sim 10\text{ cm}$, @1 MeV). Oscillometry, in combination with the total flux measurement enhances the discovery potential of SOX with respect to the pure disappearance search especially for values of Δm^2 between 0.1 eV^2 and 5 eV^2 , since in these cases the characteristic oscillation length is comparable to the detector size.

3. – The ^{144}Ce - ^{144}Pr anti-neutrino source

Anti-neutrinos are detected via the inverse beta decay reaction (IBD) $\bar{\nu}_e + p \rightarrow n + e^+$ which has a threshold of 1.8 MeV . For this reason a suitable anti-neutrino source must have $Q > 1.8\text{ MeV}$. In general, this high Q -value requirement is in contradiction with the request of a relatively long lifetime ($\tau > 1\text{ month}$). Therefore the most interesting candidate sources are not based on single isotopes, but involve a two-element cascade starting with a long-lived low- Q nucleus that decays to a short-lived high- Q nucleus.

^{144}Ce - ^{144}Pr was first proposed in [13] and has emerged as the most promising anti-neutrino source for sterile neutrino search: its decay scheme and spectrum are shown in fig. 2. ^{144}Ce decays β^- to ^{144}Pr with an end-point of 318 keV ($\tau = 411\text{ days}$). ^{144}Pr decays β^- with an end-point of 2.996 MeV immediately afterwards ($\tau = 15\text{ minutes}$). ^{144}Ce and ^{144}Pr are therefore in secular equilibrium. One advantage of ^{144}Ce is that it has a relatively high Q -value and therefore a high cross-section and large number of anti-neutrinos above the IBD threshold. In addition, it produces a smaller number of high energy gammas ($E > 1\text{ MeV}$) with respect to similar types of source (for example

^{90}Sr - ^{90}Y), therefore reducing radio-protection and radiopurity issues. Cerium is a relatively abundant component of the spent nuclear fuel: from 1 ton of material it is possible to extract, after processing, up to 2.4 kg of cerium. Approximately 1 kg of Ce powder is needed to reach the required activity of 100–150 kBq. The CeO_2 powder must satisfy very stringent requirements on radiopurity in order to limit the emission of neutrons. The source will be manufactured by the PA Mayak company in Russia: CeO_2 will be contained in a properly designed stainless steel capsule, sealed according to international regulations for the use and transportation of radioactive materials. In order to shield γ 's emitted by the source this capsule will be inserted into a thick W container (minimum thickness 19 cm). The source will be transported from the manufacturing site in Russia to St. Petersburg by train, then to France by ship, and will finally reach its destination in Gran Sasso by truck. The total transportation time will be of ~ 3 weeks, corresponding to a 5% loss of activity for the source. The contract with the PA Mayak company has been signed in January 2017 and foresees the delivery of the source between January and March 2018.

3.1. Determination of the source activity and spectrum. – The SOX sensitivity to sterile neutrinos strongly relies on the precise characterization of the ^{144}Ce - ^{144}Pr source, in particular for what concerns its activity and spectrum. Both quantities are in fact crucial to estimate the reference total rate of events expected in SOX in the no-oscillation hypothesis, which is important for the “rate-analysis” (see sect. 4). Furthermore, the precise knowledge of the source energy spectrum is important for oscillometry.

The ^{144}Ce activity will be determined at the required accuracy (1–2% level) following a calorimetric approach, based on the measurement of the heat released by the source. Two different isothermal calorimeters have been realized in order to have redundancy. The activity measurement will be performed both before and after the data taking. In both calorimeters the power emitted by the source is transferred to water: in one case (CEA calorimeter) the source and shielding will be immersed in a water vessel; in the other (TUM-Genova calorimeter) a water line is circulating in a copper heat exchanger that is encompassing the shielding. The power will be determined by precisely measuring the difference in temperature and density of the in-going and of the out-going water, as well as the water mass flow. Heat losses are minimized by operating the calorimeters in a vacuum tank and adding super insulation foils. A blind test of the calorimeters with an electrical mock-up of the source has shown the capability to reach (and even go beyond) the designed precision goal of 1%. Figure 3 shows a picture of the two calorimeters which will be used in SOX.

For what concerns the source spectrum, the main ^{144}Pr -decay branch follows a non unique first forbidden decay that cannot be directly determined from theory. Furthermore, published measurements show large disagreements up to 10%. This uncertainty can significantly affect our capability to determine the source activity which relies on the calorimetric measurement of the source power P (see above) and on the precise knowledge of the mean energy of the electron spectrum $\langle E_e \rangle$ (activity = $P/\langle E_e \rangle$). Furthermore, uncertainty in the spectral shape can deform the antineutrino spectrum and therefore mimic oscillations in the shape. Within the SOX project, two measurements are in progress exploiting β -spectrometers based on plastic scintillators: one will measure the ^{144}Pr electron spectrum only, the other will measure both the ^{144}Pr and the ^{144}Ce electron spectra. Additionally, a measurement with a 4π acceptance spectrometer (PERKEO III [14]) is proposed to achieve an absolute precision better than 0.03 on the ^{144}Pr electron spectrum shape factor b .

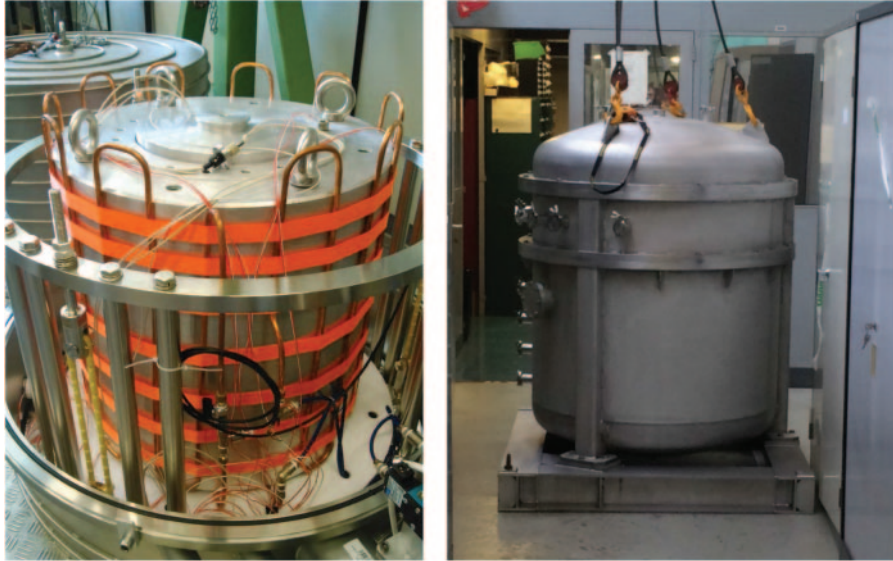


Fig. 3. – The two calorimeters which will be used to determine the ^{144}Ce - ^{144}Pr source activity: TUM-Genova one (left) and CEA one (right).

4. – SOX sensitivity

SOX data-taking will start in early 2018 and will last approximately 1.5 y (we recall that the cerium source has a lifetime of 411 days and extending data-taking longer would not significantly increase the statistics). This will allow to collect a relatively large number of anti-neutrino interactions, ~ 10000 events. All scintillator volume can be used in the

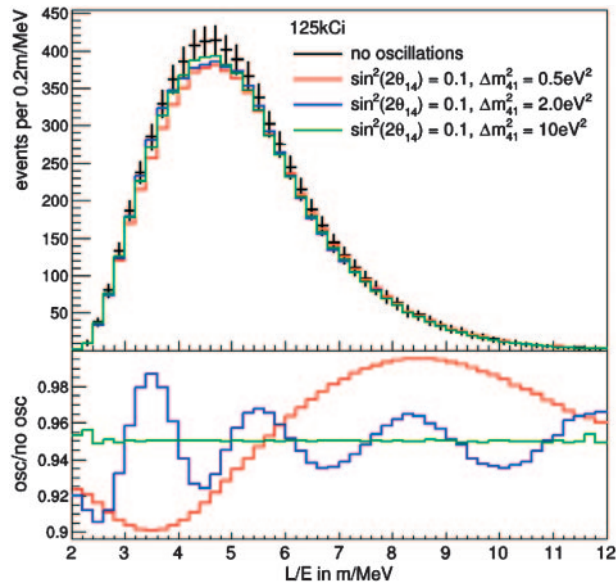


Fig. 4. – Expected number of events as a function of L/E for 3 different values of the oscillation parameters (top panel). The bottom panel shows the ratio of oscillation *vs.* no-oscillation rate for each one of the 3 cases: a clear oscillatory pattern can be seen.

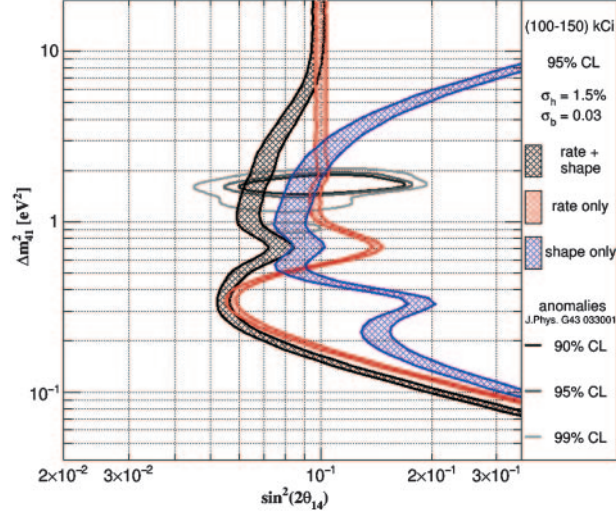


Fig. 5. – Exclusion plot (95% C.L.) in the Δm_{14}^2 - $\sin^2(2\theta_{14})$ parameter space. “Rate analysis” only (red), “shape analysis” only (blue), “rate+shape analysis” (black). The bands correspond to different values of the source activity, between 100–150 kCi; the total uncertainty on the rate is assumed to be 1.5%. SOX will be able of covering most of the parameter space allowed by the experimental anomalies (black closed curves; see [15] for details).

analysis, since the inverse beta decay (IBD) reaction used to detect anti-neutrinos is virtually background-free, thus making the fiducial volume cut not necessary. As already outlined in sect. 2, SOX will take advantage of two complementary pieces of information: the total rate of detected anti-neutrinos, which is the basis of the so-called “rate-analysis” and the distribution of the detected anti-neutrinos as a function of L (distance to the source) and E (energy of the event), which is the base for the “shape analysis” (or oscillometry). The importance of the “shape analysis” is evident in fig. 4 which shows the expected number of events as a function of L/E for 3 different values of the oscillation parameters (top panel). The bottom panel shows the ratio of oscillation *vs.* the no-oscillation rate for each one of the 3 cases. For Δm^2 values of the order of $\sim eV^2$ oscillation waves can be resolved within the detector, thus providing a powerful smoking gun for the sterile neutrino existence.

The 95% exclusion plot in the Δm_{14}^2 - $\sin^2(2\theta_{14})$ parameter space is shown in fig. 5. The red and the blue bands define the regions excluded by the “rate” and “shape” analyses taken separately (regions excluded are to the right of the curves). For each band, the rightmost curve corresponds to a source activity of 100 kCi while the leftmost curve corresponds to 150 kCi. The black band shows the exclusion power of the combined “rate+shape analysis”: it is clear that the sensitivity is greatly enhanced when both pieces of information are exploited. In particular, shape is important for $0.5 eV^2 < \Delta m_{14}^2 < 5 eV^2$ where oscillations can be resolved. For $\Delta m_{14}^2 > 5 eV^2$ instead the oscillation length is smaller than the detector resolution and the sensitivity is driven by the “rate analysis” only. For $\Delta m_{14}^2 < 0.5 eV^2$ the oscillation length is much larger than the detector’s dimension and the sensitivity is again driven by the “rate analysis” only. SOX will be able of covering most of the parameter space allowed by combining all the experimental anomalies (black closed curves; see [15] for details).

5. – Status and perspectives

The SOX experiment is going to start soon at Laboratori Nazionali del Gran Sasso. Most of the activities to prepare the site for the source arrival have been completed. In particular the Borexino Clean Room has been enlarged and equipped with rails to simplify the operations of unloading and insertion of the source under the Borexino detector. The tungsten container in charge of shielding γ 's emitted by the source is ready and currently in Gran Sasso together with the two calorimeters designed to measure the source activity. A complete rehearsal of the procedure for the source unloading and insertion underneath the detector will be performed with a mock-up of the source. The contract with the Mayak provider has been signed and foresees delivery of the ^{144}Ce - ^{144}Pr source no later than March 2018. So, taking into account also transportation, SOX data-taking will start by April 2018.

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