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SOX: search for short baseline neutrino oscillations with Borexino

M Vivier[4], M Agostini[24], K Altenmüller[24], S Appel[24], G Bellini[15], J Benziger[19], N Berton[4], D Bick[5], G Bonfini[14], D Bravo[22], B Caccianiga[15], F Calaprice[18], A Caminata[3], P Cavalcante[14], A Chepurnov[25], K Choi[30], M Cribier[1,4], D D'Angelo[15], S Davini[26], A Derbin[17], L Di Noto[3], I Drachnev[26], M Durero[4], A Etenko[12], S Farinon[3], V Fischer[4], K Fomenko[2], D Franco[1], F Gabriele[14], J Gaffiot[4], C Galbiati[18], C Ghiano[3], M Giammarchi[15], M Goeger-Neff[24], A Goretti[18], M Gromov[25], C Hagner[5], T Houdy[1,4], E Hungerford[27], Aldo Ianni[14], Andrea Ianni[18], N Jonquères[7], K Jedrzejczak[8], M Kaiser[5], V Kobychev[9], D Korablev[2], G Korga[14], V Kornoukhov[10], D Kryn[1], T Lachenmaier[11], T Lasserre[1,4], M Laubenstein[14], B Lehnert[28], J Link[22], E Litvinovich[12,13], F Lombardi[14], P Lombardi[15], L Ludhova[15], G Lukyanchenko[12,13], I Machulin[12,13], S Manecki[22], W Maneschg[6], S Marcocci[26], J Maricic[30], G Mention[4], E Meroni[15], M Meyer[5], L Miramonti[15], M Misiaszek[8,14], M Montuschi[23], P Mosteiro[18], V Muratova[17], R Musenich[3], B Neumair[24], L Oberauer[24], M Obolensky[1], F Ortica[16], M Pallavicini[3], L Papp[24], L Perasso[3], A Pocar[21], G Ranucci[15], A Razeto[14], A Re[15], A Romani[16], R Roncin[14,1], N Rossi[14], S Schönert[24], L Scola[4], D Semenov[17], H Simgen[6], M Skorokhvatov[12,13], O Smirnov[2], A Sotnikov[2], S Sukhotin[12], Y Suvorov[29,12], R Tartaglia[14], G Testera[3], J Thurn[28], M Toropova[12], C Veyssiére[4], E Unzhakov[17], R B Vogelaar[22], F von Feilitzsch[24], H Wang[29], S Weinz[31], J Winter[31], M Wojcik[8], M Wurm[31], Z Yokley[22], O Zaimidoroga[2], S Zavatarelli[3], K Zuber[28] and G Zuzel[8]
Borexino collaboration

[1]AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 75205 Paris Cedex 13, France
[2]Joint Institute for Nuclear Research, 141980 Dubna, Russia
[3]Dipartimento di Fisica, Università degli Studi e INFN, Genova 16146, Italy
[4]Commissariat à l'Énergie Atomique et aux Énergies Alternatives, Centre de Saclay, IRFU, 91191 Gif-sur-Yvette, France
[5]Institut für Experimentalphysik, Universität, 22761 Hamburg, Germany
[6]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[7]Commissariat à l'Énergie Atomique et aux Énergies Alternatives, Centre de Saclay, DEN/DM2S/SEMT/BCCR, 91191 Gif-sur-Yvette, France
[8]M. Smoluchowski Institute of Physics, Jagiellonian University, 30059 Krakow, Poland
[9]Kiev Institute for Nuclear Research, 06380 Kiev, Ukraine
[10]Institute for Theoretical and Experimental Physics, 117218 Moscow, Russia
[11]Kepler Center for Astro and Particle Physics, Universität Tübingen, 72076 Tübingen, Germany.

[12]NRC Kurchatov Institute, 123182 Moscow, Russia
[13]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia.
[14]INFN Laboratori Nazionali del Gran Sasso, 67010 Assergi (AQ), Italy
[15]Dipartimento di Fisica, Università degli Studi e INFN, 20133 Milano, Italy
[16]Dipartimento di Chimica, Università e INFN, 06123 Perugia, Italy
[17]St. Petersburg Nuclear Physics Institute NRC Kurchatov Institute, 188350 Gatchina, Russia
[18]Physics Department, Princeton University, Princeton, NJ 08544, USA
[19]Chemical Engineering Department, Princeton University, Princeton, NJ 08544, USA
[20]Physics Department, Queen's University, Kingston ON K7L 3N6, Canada
[21]Amherst Center for Fundamental Interactions and Physics Department, University of Massachusetts, Amherst, MA 01003, USA
[22]Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
[23]Dipartimento di Fisica e Scienze della Terra Università degli Studi di Ferrara e INFN, Via Saragat 1-44122, Ferrara, Ital
[24]Physik-Department and Excellence Cluster Universe, Technische Universität München, 85748 Garching, Germany.
[25] Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, 119234 Moscow, Russia.
[26] Gran Sasso Science Institute (INFN), 67100 L'Aquila, Italy.
[27]Department of Physics, University of Houston, Houston, TX 77204, USA.
[28]Department of Physics, Technische Universität Dresden, 01062 Dresden, Germany.
[29]Physics and Astronomy Department, University of California Los Angeles (UCLA), Los Angeles, California 90095, USA.
[30]Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA.
[31]Institute of Physics and Excellence Cluster PRISMA, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany.

E-mail: `matthieu.vivier@cea.fr`

Abstract. The Borexino detector has convincingly shown its outstanding performances in the low energy regime through its accomplishments in the observation and study of the solar and geo neutrinos. It is then an ideal tool to perform a state of the art source-based experiment for testing the longstanding hypothesis of a fourth sterile neutrino with $\sim \mathrm{eV}^2$ mass, as suggested by several anomalies accumulated over the past three decades in source-, reactor-, and accelerator-based experiments. The SOX project aims at successively deploying two intense radioactive sources, made of Cerium (antineutrino) and Chromium (neutrino), respectively, in a dedicated pit located beneath the detector. The existence of such an $\sim \mathrm{eV}^2$ sterile neutrino would then show up as an unambiguous spatial and energy distortion in the count rate of neutrinos interacting within the active detector volume. This article reports on the latest developments about the first phase of the SOX experiment, namely CeSOX, and gives a realistic projection of CeSOX sensitivity to light sterile neutrinos in a simple (3+1) model.

1. Introduction

The standard three-neutrino oscillation paradigm, associated with small squared mass splittings $\Delta \mathrm{m}^2 \ll 0.1\mathrm{eV}^2$, has been successfully built up over the past decades with various techniques using solar, atmospheric, long baseline and medium baseline reactor neutrino experiments. However, this well-established picture might suffer from anomalous results both reported in the $\overset{(-)}{\nu}_{\mathrm{e}} \rightarrow \overset{(-)}{\nu}_{\mathrm{e}}$ disappearance and $\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{\mathrm{e}}$ appearance channels [1]. Those anomalies could jointly be interpreted as the existence of at least an additional fourth sterile neutrino, with mixing parameters $\Delta \mathrm{m}^2_{\mathrm{new}} \gg 0.1\mathrm{eV}^2$ and $\sin^2(2\theta_{\mathrm{new}}) \sim 0.1$.

The goal of the SOX experiment [2] is to definitively address the anomalous deficits reported in the detected neutrino count rates at short baselines in the $\overset{(-)}{\nu}_{\mathrm{e}} \rightarrow \overset{(-)}{\nu}_{\mathrm{e}}$ disappearance channel by the Gallium neutrino [3, 4, 5] and reactor antineutrino experiments [6], respectively. It consists in deploying an intense MeV neutrino source beneath the Borexino detector, and searching for both meter-scaled spatial and energy oscillation patterns in the detected neutrino spectrum, pushing the concept of neutrino "oscillometry" a step further compared to any previous neutrino oscillation experiments [7].

2. CeSOX: the first phase of the SOX experiment

The first phase of the SOX experiment will make use of an intense antineutrino generator (CeANG) deployed at the Borexino detector at the end of 2016. As such, $\bar{\nu}_e$ will be detected through the inverse beta decay (IBD) reaction, which has a 1.8 MeV energy threshold and is almost free of any backgrounds.

2.1. The Borexino detector

The Borexino detector [8] is an ultra low background neutrino detector, initially designed for the observation and study of solar and geo neutrinos. It is located deep underground under a 3800 meter water equivalent overburden at the Laboratori Nazionali del Gran Sasso (LNGS). As shown by figure 1, the detector conceptual design relies on nested spherical concentric volumes, which protect and gradually shield the innermost detection volume against radioactivity and cosmic ray particles. Going inward, the first sub-volume is contained in a stainless steel tank (R=9 m) and is filled up with ultrapure water acting both as a radioactivity shielding and a cosmic muon veto. The second sub-volume is contained in a stainless steel sphere (R=6.85 m), equipped with 2214 PMTs viewing the innermost central part of the detector, and is filled up with non-scintillating and transparent oil, also acting as a shielding against radioactivity. Finally, the third sub-volume is the inner detection volume (R=4.25 m) and is made of 300 tons of liquid scintillator contained in a transparent nylon vessel. The detector energy and vertex reconstruction performances are respectively 5% at 1 MeV and 15 cm.

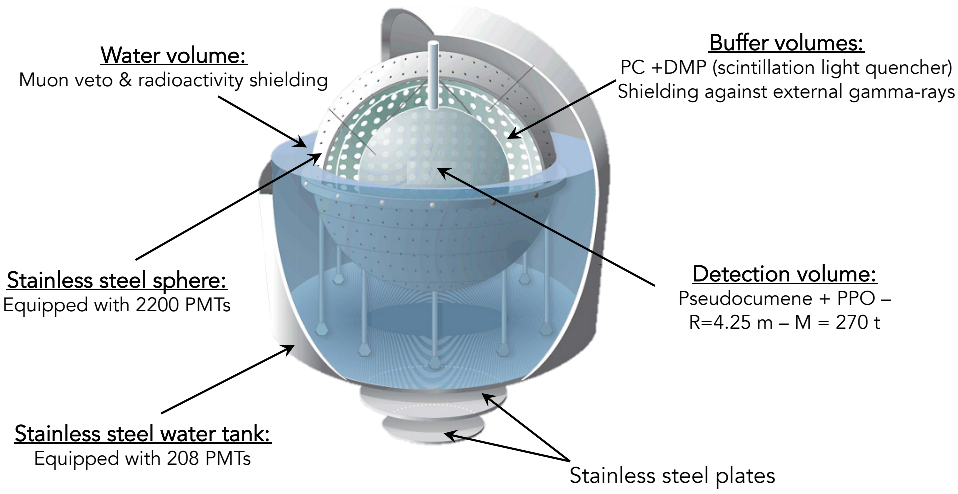

Figure 1. Schematic of the Borexino detector. See text for further details.

2.2. CeANG: the Cerium antineutrino generator

A radioactive $\bar{\nu}_e$ source suitable for the observation of short baseline oscillations must meet several requirements. Among the most important are a $\mathcal{O}$(100 kCi) activity to get reasonable statistics, an energy spectrum that extends well beyond the IBD energy threshold and a long half-life so that the source can be easily produced and transported up to the detector. The last two requirements are opposing and necessitate to use a pair of beta decaying isotopes, the father having a long half-life while the daughter has a short half-life. Four of such radioactive isotopes have been identified in nuclear databases, namely: ^{42}Ar $-^{42}$ K, ^{90}Sr $-^{90}$ Y, ^{106}Ru $-^{106}$ Rh and ^{144}Ce $-^{144}$ Pr. Having a half-life of 285 days and a beta end-point energy of 3 MeV, the ^{144}Ce $-^{144}$ Pr pair is the most suitable for the SOX science case. A detailed discussion about the choice of the best pair of radioactive isotopes for making a $\bar{\nu}_e$ generator in a source-based experiment can be found in [9].

3. Source related technical challenges and requirements

The production and transport of a ^{144}Ce-based $\bar{\nu}_e$ generator up to LNGS in Italy is technically and administratively challenging. This section summarizes the most important technical milestones that have to be completed to successfully perform phase 1 of the SOX experiment.

3.1. CeANG production

The production of the CeANG can be realized by isolating and extracting ^{144}Ce from spent nuclear fuel (SNF). The Russian SNF reprocessing company "Federal State Unitary Enterprise Mayak Production Association", hereafter PA Mayak, has been identified to be the only facility able to deliver such a source with PBq scale activity. Cerium separation and extraction, together with final source packaging and certification, takes several months. The first step of the Cerium extraction is a standard reprocessing of SNF, called the Purex® process, leading to extraction of Uranium, Plutonium and Neptunium and formation of a so-called a Purex raffinate which consists of fission and corrosion products, as well as lanthanides and actinides. In a second step, the Purex raffinate is purified from Strontium, Cesium and chemical elements after corrosion; and a feed solution consisting of lanthanides and actinides is formed after a double oxalate precipitation procedure. In a third step, Cerium fraction is separated from the feed solution using a complexing displacement chromatography method (see [9] and references therein). The final stage of the source production consists in calcining, pressing and inserting into a stainless steel capsule the Cerium oxyde. The final product will be made of a few kilograms of CeO_2 containing a few tens of grams of ^{144}Ce. The source delivery will happen in December 2016.

3.2. CeANG shielding

The identified ^{144}Ce $-^{144}$ Pr beta decaying pair for making the CeANG also emits gamma rays, that have to be shielded against both for biological protection purposes and to avoid source-induced backgrounds in the Borexino detector. The shielding material and dimensions are mostly driven by the 2.185 MeV gamma ray emitted with 0.7% intensity. Tungsten heavy alloys offer the best compromise among all the high density materials. A cylindrical tungsten heavy alloy shielding, with density larger than 18.0 g cm^{-3}, 60 cm height and diameter, has been designed and is currently being manufactured at Xiamen Honglu Inc., China. Such dimensions ensure a 19-cm thick shielding and a $\gtrsim 10^{12}$ gamma-ray attenuation factor along any directions. The corresponding radiation dose at contact for a 100 kCi (3.7×10^{15} Bq) source is less than 1 μSv/h, compelling with the safety regulations imposed by the International Agency for Atomic Energy (IAEA), French nuclear safety authority (ASN), as well as Italian nuclear safety authority for radioactive material transportation and handling. The shielding will be delivered early 2016.

3.3. CeANG transportation and deployment at LNGS

As for any radioactive material transportation, a certified container has to be used to ship the CeANG from PA Mayak up to LNGS. The so-called TN-MTR cask, jointly developed by CEA and the AREVA company for the transportation of spent nuclear fuel, has been identified and authorized for the transportation of the CeANG. The itinerary route has been decided, with a train transportation solution from PA Mayak to St Pertersburg harbor, a dedicated boat transportation from St Pertersburg to Le Havre and a final truck transportation solution from Le Havre up to LNGS. The complete transportation solution takes less than a month, and will limit the source activity loss below 5%. The expected delivery date at LNGS is end of December 2016.

3.4. CeANG characterization
A full and precise CeANG characterization is a fundamental requirement to achieve the best sensitivity over the light sterile neutrino mixing parameter space preferred by the short baseline anomalies. This section only deals with the CeANG activity measurement and the shape of the beta/neutrino spectrum. For the interested reader, reference [9] discusses other source specifications, such as source radioactive impurity content, which is especially important to control to avoid source-induced backgrounds in the SOX experiment.

3.4.1. Activity measurement A significant gain in the SOX sensitivity can be achieved if the source activity is known within $\mathcal{O}(1\%)$ precision (see section 4 for more details). Two calorimetric devices are currently being built and calibrated at CEA-Saclay and TUM/Genova, respectively, for measuring the heat power released by the CeANG. Although slightly differently designed, those two calorimeters work on the same principle, which consists in measuring the temperature in and out of a water loop circulating around the source. The temperature difference is related to the heat power released by the source, and hence on its activity through a power-to-activity conversion factor $\mathrm{P} = 215.6 \pm 1.3$ W/PBq (itself depending on the shape of the ^{144}Ce and ^{144}Pr beta spectra, see next subsection). Each calorimeter device has been carefully designed to minimize leaks, by using supsension platforms + insulations materials to limit conductive losses, a vaccum vessel to prevent any convection losses and a multilayer insulation + vaccum vessel thermalization system to avoid heat radiation. Characterization and calibration of these setups are currently on-going, using electrical sources and an Aluminium mock-up shielding.

3.4.2. Beta spectrum measurement The precision of the source activity measurement and the expected IBD interaction rate within the Borexino detector strongly depends on the shape of the CeANG beta spectrum. ^{144}Ce and ^{144}Pr beta spectra both present non-unique forbidden transitions, for which the spectral shape theoretical predictions are uncertain at the few % level. Furthermore, past beta spectrum measurements show discrepancies at the 10-15% level, which translates into a 10% uncertainty on the predicted IBD rate and would then spoil the calorimetric measurement. New measurements of the ^{144}Ce and ^{144}Pr beta spectrum shapes are thus necessary. Two setups, which use different techniques, have been developed for the ^{144}Ce and ^{144}Pr beta spectra measurement. A first setup uses a cylindrical plastic scintillator coupled to two high quantum efficiency photo-multiplier tubes, whereas a second setup uses a multiwire chamber in coincidence with a plastic scintillator to measure beta rays and suppress gamma-ray background. These setups are currently running and been calibrated at CEA-Saclay. A 5% uncertainty on the shape of the ^{144}Ce and ^{144}Pr beta spectra is expected, improving the prediction of the IBD rate within the desired specifications.

4. Projected sensitivity of CeSOX
The projected sensitivity of the CeSOX experiment to sterile neutrinos in the framework of a (3+1) model is shown on figure 2, in light of the two source-related systematic uncertainties discussed in the previous section. The baseline scenario for the sensitivity calculations is a 100

kCi CeANG generator placed 8.5 m away from the Borexino detector center, assuming a 1.5 year data taking time. In this scenario, a wide range of the sterile neutrino parameter space prefered by the $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ disappearance channel anomalies is covered at 95% C.L. Figure 2 also illustrates the gain in sensitivity by using the rate information brought by an activity measurement (solid curves on the left panel of figure 2) additionally to the shape information (dashed curve on the left panel of figure 2). The right panel of figure 2 shows the influence of the ^{144}Pr beta spectrum shape uncertainty, and confirms that a 5% precision for the beta spectrum measurement can be targeted without significantly degrading the sensitivity contours.

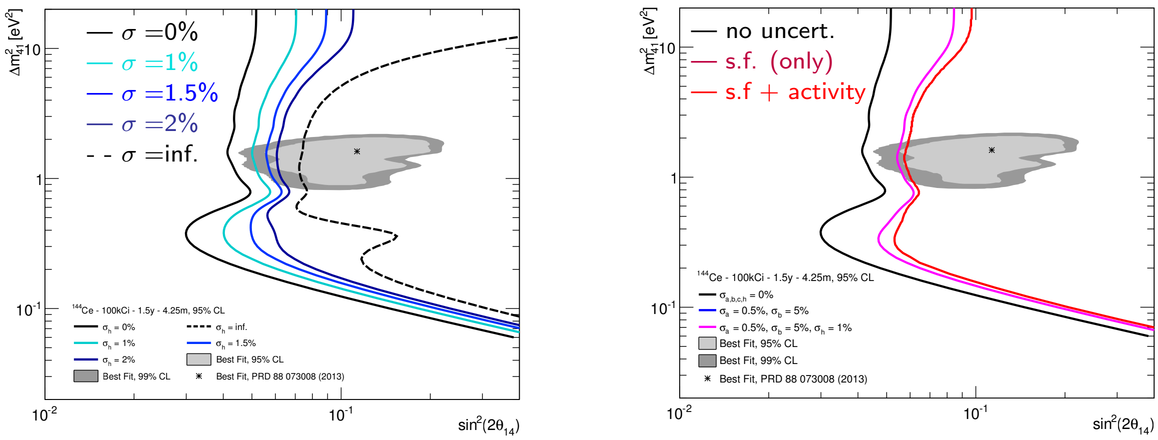

Figure 2. Sensitivity at the 95% C.L. of the CeSOX experiment to light sterile neutrinos in a simple (3+1) model. (Left) Impact of the source activity uncertainty on the rate+shape contours (solid lines) with respect to the shape-only contour (dashed line). (Right) Impact of the ^{144}Pr spectrum shape uncertainty on the rate+shape sensitivity contours.

5. Conclusions

The SOX experiment, which aims at testing the neutrino count rate anomalous deficits observed in short baseline experiments in the $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ disappearance channel, will soon start the first phase of its science program in December 2016. A PBq scale activity $\bar{\nu}_e$ source, made of ^{144}Ce, will be deployed underneath the Borexino detector . In this article, the most important milestones of the CeSOX project have been reviewed, with a special emphasis on the technical challenges that have to be addressed for the source production and transportation. Last but no least, a full characterization of the CeANG is simultaneously on-going in the SOX collaboration, which aims at minimizing the source-related systematic uncertainties. In light of these studies, it has been shown that the projected CeSOX sensitivity covers most of the light sterile neutrino parameter space preferred by the short baseline anomalies.

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