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Radioactive Source Experiments in Borexino

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Most of the neutrino oscillation results can be explained by the three-neutrino paradigm. However several anomalies in short baseline oscillation data (L/E of about 1 m/MeV) could be interpreted by invoking a light sterile neutrino. This new state would be separated from the standard neutrinos by a squared mass difference $\Delta m^2_{new} \sim 0.1 - 1\,\mathrm{eV}^2$ and would have mixing angles of $\sin^2 2\theta_{ee} \gtrsim 0.01$ in the electron disappearance channel. This new neutrino, often called sterile, would not feel standard model interactions but mix with the others. We present the CeSOX and CrSOX projects to constrain the existence of eV-scale sterile neutrinos by deploying an intense radioactive β-source next to the Borexino detector.

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1. Introduction

The well established standard neutrino oscillation framework satisfactory explains most of neutrino data. It relies on three flavours $(\nu_e, \nu_\mu, \nu_\tau)$, mixture of three mass states (ν_1, ν_2, ν_3) separated by squared mass differences of $\Delta m^2_{21} = \Delta m^2_{\text{sol}} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\,\text{eV}^2$ and $\mid \Delta m^2_{31} \mid \approx \mid \Delta m^2_{32} \mid = \Delta m^2_{\text{atm}} = 2.32^{+0.12}_{-0.08} \times 10^{-3}\,\text{eV}^2$ [1], where "sol" and "atm" stand historically for solar and atmospheric experiments providing compelling evidence for neutrino oscillation (see [2] and references therein for a recent review). Beyond this minimal extension of the standard model, anomalous results have been reported in LSND [3], MiniBooNE [5, 6], and radioactive source experiments [7, 10, 11, 12]. In addition a new evaluation of the reactor neutrino fluxes [8, 9] led to a reinterpretation of the results of short baseline reactor experiments [18], the so-called Reactor Antineutrino Anomaly.

If not related to non understood experimental issues, results of the global fit of short-baseline neutrino oscillation experiments (see [19] for instance) show that the data can be explained by the addition of one or two sterile neutrinos to the three active neutrinos of the standard model, the so-called (3+1) and (3+2) scenarios, respectively. However some tension remains between appearance and disappearance data in the global fits, see [20].

2. Anomalous Oscillation Results and Sterile Neutrinos

In this section we focus on neutrino oscillation results with an L/E of about 1 m/MeV. A comprehensive review of all short baseline oscillation results and detailed statments on the current oscillation anomalies can be found in [25].

In 1995 the LSND experiment reported an excess in the $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance channel [3]. A similar experiment, KARMEN [4], did not report such an excess, however. In 2002 the MiniBooNE experiment confirmed this excess in both ν_e to ν_μ and $\bar{\nu}_e$ to $\bar{\nu}_\mu$ channels [5, 6]. The MiniBooNE results will be soon complemented by using a 170-ton LAr TPC in the same neutrino beam; the MicroBooNE experiment [23] will check if the low-energy excess is due to ν_e charged current quasielastic events. Event rates measured by many reactor experiments at short distances, when compared with a newly evaluated antineutrino flux, are indicating the disappearance of $\bar{\nu}_e$ [18]. In addition the results from the gallium solar neutrino calibration experiments reported also a deficit of ν_e in a similar L/E range [10, 11, 12].

The individual significances of these anomalies lie between 2.5 to 3.8 σ, and these results, not fitting the three-neutrino-flavor framework, are difficult to explain by systematics effects. If not experimental artifacts it is puzzling that each of them could be explained by oscillation to sterile neutrinos with a large mass squared difference, $\Delta m^2_{new} \gtrsim 0.1\,\text{eV}^2$, corresponding to an L/E of about 1 m/MeV.

Indeed the minimal neutrino mixing scheme provides only two squared-mass differences. A third one would be required for new short-baseline neutrino oscillations. It then require the introduction of a sterile neutrino ν_s [13, 14, 15, 16]. The minimal model consists of a hierarchical 3+1 neutrino mixing, acting as a perturbation of the standard three-neutrino mixing in which the three active neutrinos ν_e, ν_μ, ν_τ are mainly composed of three massive neutrinos ν_1, ν_2, ν_3 with light masses m_1, m_2, m_3. The sterile neutrino would mainly be composed of a heavy neutrino ν_4 with mass m_4 such that $\Delta m^2_{\rm new} = \Delta m^2_{41}$, and $m_1\,, m_2\,, m_3 \ll m_4$.

In 3+1 neutrino mixing, the effective flavor transition and survival probabilities in short-baseline neutrino oscillation experiments are given by

$$P^{\rm new}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \sin^2 2\theta_{\alpha\beta}\Delta_{41}\,(\alpha \neq \beta)\,, P^{\rm new}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha}\Delta_{41} \tag{2.1}$$

where $\Delta_{41} = \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$, and for $\alpha, \beta = e, \mu, \tau, s$, with the transition amplitudes

$$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha4}|^2|U_{\beta4}|^2\,, \sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha4}|^2\left(1 - |U_{\alpha4}|^2\right)\,. \tag{2.2}$$

The interpretation of both LSND and MiniBooNE anomalies in terms of light sterile neutrino oscillations requires mixing of the sterile neutrino with both electron and muon neutrinos. In addition, both OPERA and ICARUS experiments recently reported negative results for the search ν_e from the ν_μ CNGS beam [21, 22], although not testing fully the relevant space of oscillation parameters. Therefore when considering all data together no satisfactory global fit can be obtained (see [20] for instance). This is mainly due to the non-observation of ν_μ disappearance at the eV-scale [17], that is a generic prediction if the LSND signal implies a sterile neutrino. This negative results is not strong enough to rule out this hypothesis, however.

All these facts motivate a new experimental program. In what follows, we focus on the 3 active plus 1 sterile neutrino mixing scheme with $\Delta m^2_{\rm new}$ of the order of 0.1–1 eV^2.

3. Experimental Concept

To definitively test the short baseline oscillation hypothesis the new experiments must be sensitive to an oscillation pattern either in the energy spectrum, or in the spatial distribution of the neutrino interactions, or both. To cover the Δm^2 region of 0.1–1 eV^2 with MeV/GeV neutrinos the distance between the emitter and the detector has to be on the scale of 1-10 m / 1-10 km, respectively. Statistical and systematics uncertainties must be at the level of a few percents or less. Such an experiment could be performed with intense radioactive sources used as neutrino emitters.

New experiments have been proposed to clarify this anomaly, using a very intense ^{51}Cr neutrino generator next to the Borexino detector (10 MCi) or an antineutrino generator made of ^{144}Ce-^{144}Pr (100 kCi) next to KamLAND or Borexino. We review below the CeSOX and CrSOX experiments. Those projects aim to search for an energy-dependent oscillating pattern in event spatial distribution of active neutrino interactions that would unambiguously determine neutrino mass differences and mixing angles if oscillation to light sterile neutrinos is the explanation of the gallium and/or reactor neutrino anomalies.

4. CeSOX

AntiNeutrino Generator (ANG hereafter), is a β^- decaying nucleus producing $\bar{\nu}_e$ over a broad energy spectrum, up to the maximum endpoint energy ($\sim Q_\beta$) of its available β branches. The detection of $\bar{\nu}_e$ in liquid scintillator detectors relies on the Inverse Beta Decay (IBD) reaction:

$\bar{\nu}_e + p \to e^+ + n$. The IBD reaction cross-section is higher than the cross-section of neutrino scattering on electrons by roughly an order of magnitude at MeV energies. Furthermore, the IBD reaction signature is a time and space coincidence between the positron prompt energy deposition and the delayed gamma energy deposition coming from neutron capture. This signature allows a very efficient IBD candidate selection together with a powerful background rejection. The prompt signal visible energy is $E^{\mathrm{vis}}_{\mathrm{prompt}} = E_{\bar{\nu}_e} - Mc^2 + 2m_e c^2$, where $M = 1.293\,\mathrm{MeV/c^2}$ the mass difference between proton and neutron and $m_e = 0.511\,\mathrm{MeV/c^2}$ the electron mass, so that $1.022\,\mathrm{MeV} < E^{\mathrm{vis}}_{\mathrm{prompt}} < Q_\beta - 0.782\,\mathrm{MeV}$. In a non-doped scintillator, neutrons are mostly captured on hydrogen atoms, which then release a 2.2 MeV gamma ray. The time distribution between the prompt and delayed events follows an exponential law with a time constant which is equal to the capture time of neutrons on hydrogen $\tau \sim 200\,\mu\mathrm{s}$. Backgrounds to the IBD signal selection are of two types. The first type is the accidental background, which is made from two random energy depositions in a time window roughly corresponding to the hydrogen capture time. The second type of background is called correlated background. For instance, spallation of cosmic rays produces fast neutrons, that can thermalize and also be captured in the liquid scintillator, faking both a prompt and delayed energy deposition. Fortunately the above-mentioned backgrounds are negligible in Borexino.

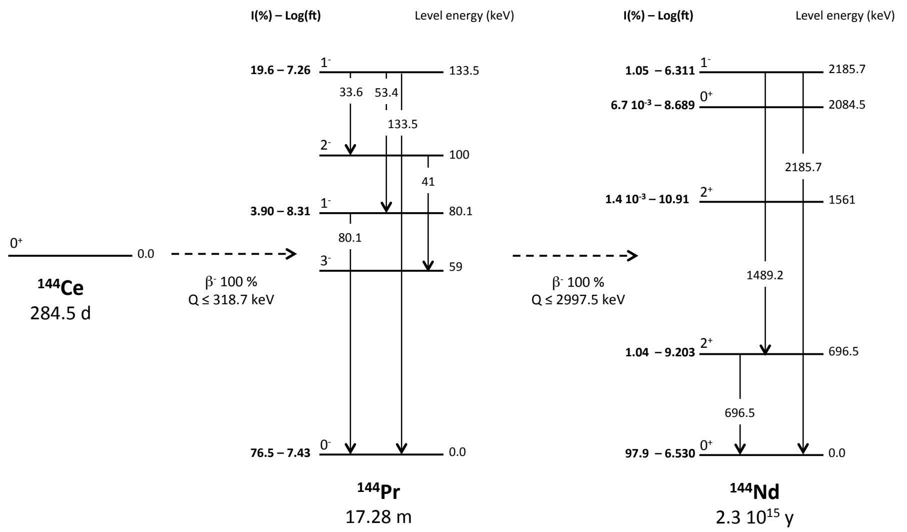

Figure 1: Simplified decay scheme of the ^{144}Ce-^{144}Pr couple. β branches with branching ratios greater than 0.001 % are displayed, along with the corresponding Log(ft) values, daughter nucleus level energies and spin parities.

The IBD reaction energy threshold is 1.806 MeV, and requires a source radioisotope with a high endpoint β^- decay. Since half-life and endpoint energy are strongly anti-correlated quantities for β^- decay, this requirement leads to look for nuclei with half-lives typically shorter than a day, then preventing the production and use of an ANG made of a single radioisotope. However, looking for a cascading pair of β^- decaying isotopes, the parent nucleus being a rather long-lived isotope and the daughter nucleus being a short-live isotope, could circumvent this difficulty. Another requirement is that the daughter isotope must have a β^- endpoint energy as high as possible above the IBD threshold to maximize the IBD reaction rate. The best pair of isotopes meeting these requirements has been identified as ^{144}Ce-Pr [26]. ^{144}Ce has a half-life of 285 d and ^{144}Pr a Q_β of 3.00 MeV.

Cerium was selected because of engineering considerations related to its possible extraction of rare earth from regular spent nuclear fuel reprocessing followed by a customized column chromatography, at a high purity level. The Russian spent nuclear fuel reprocessing company, Federal State Unitary Enterprise Mayak Production Association (hereafter FSUE "Mayak" PA), has been identified to be the only facility able to deliver a PBq scale sealed source of ^{144}Ce. Cerium separation and extraction together with final source packaging and certification is an operation lasting for several months. The first step of the cerium extraction is a standard reprocessing of nuclear spent fuel components, leading to a lanthanides and minor actinides concentrate. In a second step, cerium is separated using a complexing displacement chromatography method. The final product will be made of a 5-10 kilograms of sintered CeO_2 containing about 30 grams of ^{144}Ce, the other cerium isotopes, ^{140,142}Ce being stable. Inevitably, the extraction process leads to small lanthanide and minor actinide leftovers, that may be penalizing to realize a neutrino experiment. Firstly because these leftovers, if radioactive, could bias the activity measurement. The level of radioactive impurities must therefore be small enough (lower than the desired accuracy, i.e. $\lesssim 1\,\%$) to account for a negligible contribution to the source activity. This requirement can be achieved using complexing displacement chromatography techniques. Secondly, because radioactive leftovers can lead to source-induced backgrounds that could degrade the experimental sensitivity to short baseline oscillations. Detailed simulations of source-induced backgrounds in a spherical liquid scintillator detector has been carried out in order to specify the maximum level of such radioactive impurities in the ^{144}Ce source [31]. Thanks to available pressing technics the source fits inside a <15 cm-scale capsule, small enough to consider the Cerium volume as a point-like source.

^{144}Ce has a low production rate of high-energy γ rays ($>$ 1 MeV) from which the $\bar{\nu}_e$ detector must be shielded to limit background events. However, ^{144}Pr β^- decay is followed 0.7 % of the time by a 2.185 MeV gamma ray, as can be seen on the ^{144}Ce-^{144}Pr decay scheme presented on figure 1. This gamma ray could fall both in the prompt and delayed energy windows, then being an additional source of accidental background. Moreover, due to the very high activity of the ANG, this ray constitutes a major radiation protection concern. A dedicated high-Z material shielding, made for instance of lead or tungsten, is therefore necessary to suppress this background. A 19 cm thick tungsten alloy shielding with a density of 18 g/cm^3 provides an attenuation of 3.1×10^{-7} to the 2.185 MeV gamma ray, corresponding to a dose at 1 m of 0.01 mSv/h for a 5 PBq source. It has been designed to comply with dose limits imposed by international regulation and is currently being manufactured.

The logistic for transporting the source from the production site, PA Mayak in Russia, to the detector site is a major issue for such an experiment due to the necessary time required to certify the transport containers. The ANG will be transported by train from Mayak to Saint Petersburg, then by boat to Le Havre (France), and finally by truck to the Gran Sasso laboratory in Italy.

A precise knowledge of the source activity is mandatory, at the percent level. Calorimetric measurements will be used since the released heat is directly linked to the source β-decay activity. It is practical in the sense that the measurement does not require any sampling. Beyond the heat power measurement, great care must be taken in the calculation of the power-to-activity conversion constant. This quantity is calculated using the available information on the different ^{144}Ce and ^{144}Pr β branches from nuclear databases. The power-to-activity conversion constant for the ^{144}Ce-^{144}Pr couple is currently estimated to be $216.0 \pm 1.2\,\mathrm{W/PBq}$ with a 0.56 % uncertainty.

A precise knowledge of the full ^{144}Ce-^{144}Pr β spectrum is then necessary, mainly to evaluate the number of expected events above the IBD threshold. Therefore, the accuracy achieved by a rate+shape analysis will strongly depend on the $\bar{\nu}_e$ spectrum shape uncertainty. The ^{144}Ce-^{144}Pr β and $\bar{\nu}_e$ spectra are a combination of several β branches presented on figure 1. Among all possible ^{144}Ce and ^{144}Pr β transitions, only two transitions exhibit endpoint energies larger than the IBD reaction energy threshold. They come from the decay of ^{144}Pr and total 98.94 % of its decays. A few challenges arise for a precise β spectroscopic measurement of the ^{144}Ce-^{144}Pr couple. For example, the short period of ^{144}Pr makes it difficult to measure its associated β spectrum independently of ^{144}Ce β spectrum, especially at low energies (i.e. at energies greater than the IBD reaction threshold in the $\bar{\nu}_e$ case) where the two spectra overlap. A chemical separation of ^{144}Pr from ^{144}Ce will be performed to circumvent this issue. Because of the short ^{144}Pr half-life it requires a dedicated separating setup, such as chromatographic columns, installed in the vicinity of the β spectrometer. Several measurements are ongoing within the collaboration to perform the ^{144}Ce-^{144}Pr β spectrometry.

The deployment of the ^{144}Ce-^{144}Pr ANG will be done next to the main stainless steel vessel of the Borexino detector, between September and December 2016. Borexino is a large spherical liquid-scintillating detector with a fiducial volume defined by a radius of 4.25 m around the detector center. An activity of 4 PBq (relative to ^{144}Ce β^- decay rate) is necessary to achieve a statistics of 10 000 IBD candidates. The target region is surrounded by 2000 photomultiplier tubes and is included in a graded shielding and a Cherenkov muon veto. The detector is located inside the LNGS underground laboratory in Italy, shielded by 1400 m of rock. It is able to perform real-time neutrino-spectroscopy with an energy resolution of 5% and a vertex resolution of less than 15 cm at 1 MeV. The ANG will be located in the pit underneath the detector, at a distance of 8.3 m away from the target center.

The sensitivity to short baseline oscillations is evaluated by comparing the observed event rate, binned as a function of both energy and distance, with respect to the expected distribution in the presence of oscillations. The normalization uncertainty is here assumed to come from the uncertainty on the source initial activity, σ_{N}. Setting σ_{N} to ∞ allows an overall floating normalization and a sensitivity study which mostly uses shape distortions to look for oscillations ("free rate” analysis).

The estimated sensitivities to short baseline oscillations are shown on figure 2 (left) for both the rate+shape and free rate analysis. A 1.5 % systematic uncertainty on the initial source activity has been assumed for the rate+shape contours calculation.

Examples of the discovery potential of a ^{144}Ce-^{144}Pr ANG experiment to short baseline neutrino oscillations are illustrated on figure 2 (right). It shows the acceptance contours at the 99 % confidence level of the inferred oscillations parameters if one assumes $\Delta m^2_{\mathrm{new}}$ = 0.5, 1.5 eV^2, respectively.

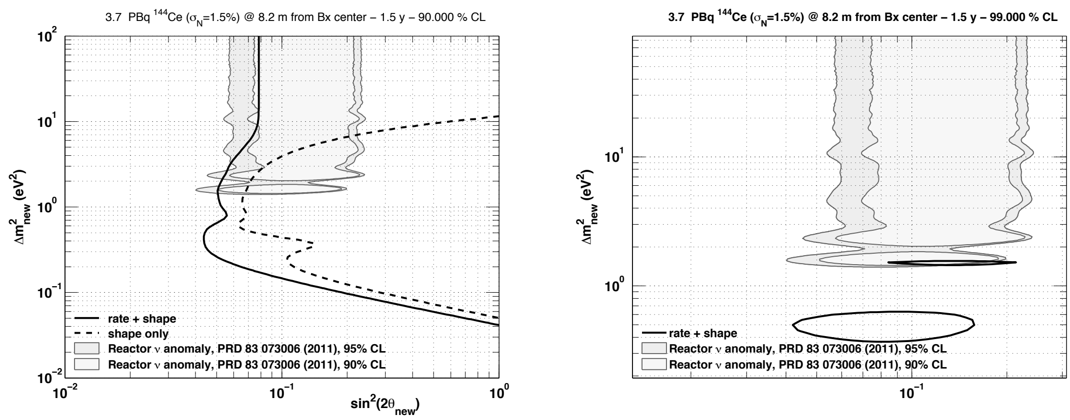

Figure 2: Sensitivity contours of the CeSOX experiment. Left: 90% exclusion contours. Right: 99% discovery potential contours.

5. CrSOX

A neutrino source uses the electron capture process to produce monoenergetic neutrinos. Several neutrino sources have already been produced to calibrate radiochemical solar neutrino experiments. Two nuclei are usually considered: ^{51}Cr and ^{37}Ar. The ^{51}Cr decays with a 27.7 day half-life, producing mainly 753 keV neutrinos, and in 10 % of decays 433 keV neutrinos with a 320 keV gamma, while the ^{37}Ar produces 814 keV neutrinos in any case with a 35 day half-life. The ^{37}Ar is therefore more suitable from the point of vue of heat and shielding issues, and benefits also of slightly longer half-life and slightly higher energy. Still chromium is much easier to handle. Both isotopes have to be produced by neutron irradiation in a nuclear reactor, through ^{50}Cr (n,γ) ^{51}Cr process and ^{40}Na (n,α) ^{37}Ar process respectively. Moreover, the (n,α) reaction has a threshold requiring irradiation with fast neutron.

The main drawback of neutrino source relies in the detection process, elastic scattering off electrons. The cross section of this process is low and the detection is very sensitive to backgrounds. Currently only Borexino, design to study solar neutrinos, has shown a low enough background control. The unique extreme radiopurity achieved in the liquid scintillator medium allows to control the irreducible contribution of ^{7}Be solar neutrinos. The experiment will consist in counting the number of observed events at each detector location and to compare it to the expectation without oscillations. The position of each event can be reconstructed with a precision of $\sim$12 cm at 1 MeV, which is enough for the range of Δm^2 of interest and smaller than the size of the source, a few tens of centimeters. The CrSOX experiment [27] will perform such an measurement with a 10 MCi ^{51}Cr source irradiated either in Russia (PA Mayak) or in the United-States of America, and deployed at 8.3 m from the center of the Borexino detector after the Cerium antineutrino generator.

6. Conclusion

The significance of each short baseline oscillation anomaly is moderate, but the concordance of their possible explanation with non-standard neutrino oscillation cannot be neglected and calls for new data.

A smoking gun signature of neutrino oscillations at short distances would be the observation of an oscillation pattern both in the reconstructed energy spectrum and spatial distribution of the neutrino events. Such an observation can be performed in a short-term and at a (relatively) modest cost through the deployment of an intense neutrino or antineutrino generator near an existing large liquid scintillator detector, like Borexino.

The ^{144}Ce-^{144}Pr couple has been identified to be the most suitable $\bar{\nu}_e$ emitter for this type of experiment. To realize the CeSOX experiment the production of 3-5 PBq of ^{144}Ce-^{144}Pr ANG already started at the facilities of the Russian FSUE "Mayak" PA company by reprocessing spent nuclear fuel. Meanwhile the Borexino detector is being upgraded and the necessary legal authorizations for deployment have been requested. Deployment is foreseen between September and August 2016. First results on the clarification of the short baseline neutrino oscillation anomalies might come as early as 2017.

After the CeSOX experiment a ^{51}Cr neutrino generator may be deployed in the same location in order to further improve our knowledge of short baseline oscillations.

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