INTERACTION OF PLASMAS, PARTICLE BEAMS, _ AND RADIATION WITH MATTER

The Search for Sterile Neutrinos with SOX-Borexino¹

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Abstract—The aim of the SOX-Borexino project is to verify or falsify the existence of eV-scale sterile neutrinos. The existence of sterile neutrinos is suspected because of several anomalies, which were observed in pre-vious experiments. A \sim 3.7 PBq electron antineutrino source made of ¹⁴⁴Ce will be installed below the Borexino detector at LNGS, Italy, to search for short-baseline oscillations of active-to-sterile neutrinos within the detector volume. Source delivery and beginning of data acquisition is planned for end of 2016, preliminary results are expected already in 2017.

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1. INTRODUCTION

At present time, three different neutrino flavor states have been observed, in accordance with the Standard Model of particle physics: the electron neutrino ν_e , muon neutrino ν_μ and tau neutrino ν_τ , as well as their antiparticles. Also, since almost 20 years, the paradigm of neutrino oscillations is established: a neutrino, created in a weak interaction with a certain flavor, changes its flavor as it propagates. This can only be explained by adding neutrino masses to the Standard Model and describing the neutrino flavor eigenstates as superpositions of the mass eigenstates v_1 , v_2 and v_3 . Many experiments with solar, reactor, accelerator and atmospheric neutrinos could measure the mixing probabilities and the squares of the mass differences, but also observed anomalies, that cannot be explained by the "classical" oscillations:

• the Gallium anomaly: 2.9σ reduced v_e flux of calibration sources at the GALLEX and SAGE detectors (measuring integral solar v_e -flux via inverse beta decay of ⁷¹Ga) [1, 2];

• the reactor anomaly: a 2.8 σ overall deficit of observed to predicted \overline{v}_e flux from nuclear reactors [1, 3] (Fig. 1);

• LSND/MiniBooNE: 3.8 σ unexpected appearance of \overline{v}_e in \overline{v}_{μ} beams from accelerators [4, 5].

These anomalies could be explained by the existence of additional neutrinos. The existence of further weak interacting neutrinos is excluded by the decay width of the Z-boson, hence the additional neutrino would have to be a "sterile neutrino", that mixes in oscillations with the active neutrinos, but does not interact weakly, making it inaccessible through direct measurements. The best fit values of the sterile neutrino parameters to the anomaly data are $\Delta m_{41}^2 = 1.5 \text{ eV}^2$ and $\sin^2(2\theta_{14}) = 0.1$ (see for example [1]), corresponding to an oscillation length of ~1 m at 1 MeV. For comparison, the limit of $v_1 + v_2 + v_3$ by the Planck satellite data is 0.194 eV [6].

Sterile neutrinos are predicted by many theories. Many models contain more than one sterile neutrino. However, there are discrepancies between data of different experiments and also cosmology seems to favor a 3-neutrino picture. Therefore, more data are needed.

2. THE SOX EXPERIMENT

The SOX experiment (short distance neutrino oscillations with Borexino) aims to discover or refute sterile neutrinos in the eV mass-scale unambiguously. A PBq \overline{v}_e -generator will be placed in a small tunnel directly below the Borexino neutrino detector (Fig. 2) in order to observe short distance oscillations within the 270 ton active detector-volume. Borexino is built as spherical liquid-scintillating detector with ~2000 photo multiplier tubes, featuring graded shielding and a Cherenkov muon veto. Its outstanding performance is achieved through a high intrinsic radiopurity and the shielding from cosmic muons by 1400 m (3500 mwe) of rock inside the LNGS underground laboratory in Italy, guaranteeing real-timeneutrino-spectroscopy with an energy resolution of 5% and a vertex resolution of 14 cm at 1 MeV [7]. The expected signature in case of an eV-scale sterile neutrino is an oscillatory pattern in the \overline{v}_{e} count-rate, depending on the energy and distance from the \overline{v}_{e} -generator ("smoking gun signature", Fig. 3). The experiment is described in detail in [8].

A. The \overline{v}_e -Generator

The \overline{v}_e -generator is made of 2.5 kg ultra-pure ¹⁴⁴Ce, extracted from fresh spent nuclear fuel at FUSE PA in Mayak, Russia. At the beginning of data dating, the source activity will exceed 3.7 PBq. ¹⁴⁴Ce has a half life of 285 days and beta-decays into ¹⁴⁴Pr, that again decays with a half life of 17 minutes into stable ¹⁴⁴Nd (Fig. 4) The beta decay of ¹⁴⁴Pr has a Q-value of 3 MeV, hence it generates a sufficient amount of \overline{v}_e with an energy above the inverse-beta-decay threshold



Fig. 1. Measurements of several reactor-neutrino experiments and the ratio of observed to predicted \overline{v}_e -flux. The solid line shows the predicted flux, if a sterile neutrino with $\Delta m_{41}^2 = 2 \text{ eV}^2$ is added [11].



Fig. 2. The Borexino detector. The \overline{v}_e -generator is located in a pit below the detector.



Fig. 4. The 144 Ce- 144 Pr decay-scheme (reduced).

of 1.8 MeV. The inverse beta decay is Borexino's detection mechanism with the highest cross section. The shielding demanded by the extreme radioactivity is a massive 2.5 ton tungsten-alloy cylinder (Fig. 5). Signal discovery or exclusion is expected after 1.5 years and ~10000 \overline{v}_e detections.

The source activity and the shape of the \overline{v}_e -spectrum have to be known with unprecedented accuracy to ensure a satisfactory sensitivity for measuring the sterile-neutrino mixing-parameters [9].

B. Calorimetric Measurements

The \overline{v}_e -source activity is determined by measuring its heat output. Two thermal calorimeters are constructed for redundancy, one by CEA Saclay, the other one by the TUM and Genoa University groups. The maximum tolerance for the activity estimation is 1%. A cut-away of the TUM-Genoa calorimeter is shown in Fig. 6. A cooling liquid is passing through a copper heat exchanger, which is mounted around the \overline{v}_e -generator shield, the temperature change and the mass



Fig. 3. The expected signature without (top) and with an eV-scale sterile neutrino (bottom) with 1.5 years of data [12].



Fig. 5. The ¹⁴⁴Ce \overline{v}_e -source and its tungsten-alloy shielding.

flow are measured precisely. Thermal insulation is achieved by suspending the source and the heat exchanger with insulating Kevlar ropes inside a vacuum. Radiative heat transfer is minimized by thermalizing the outer shell of the vacuum tank to match the surface temperature of the heat exchanger, which again is surrounded by several layers of superinsulator foils. The error of the power measurement will be lower than 0.4%.

C. Spectrum

In order to reconstruct the source activity from its heat output as well as for rate analysis of the signal, precise knowledge of the source's spectral shape is required. The theory of the β -decay is well known: the



Fig. 6. A cut through the TUM-Genoa calorimeter.

shape of a β spectrum can be derived from Fermi's Golden Rule, including a Fermi function F(Z,W), which takes the Coulomb interaction of the relativistic β -particle with the electron cloud of the daughter nucleus into account, and a shape factor C(W), necessary for first-forbidden decays (the major decay branches of ¹⁴⁴Pr and ¹⁴⁴Ce are classified as first-forbidden):

$$N(W) = pW(Q - W + m_e c^2)^2 F(Z, W)C(W).$$

Here, W is the total energy of the β -particle and Q the maximum decay energy. The shape factor cannot be modeled theoretically, since this requires the calculation of nuclear matrix elements, about which is no consensus in theory. Previous measurements of the shape factors between 1956 and 1973 are in poor agreement (e.g. [10]). According to the shape factor chosen, reconstructed spectral shapes can differ up to 20%, resulting in a 10% variation of the expected antineutrino interaction rate in Borexino. Also, the source's thermal power would vary between 207–

213 W/PBq. Hence, new measurements of the ¹⁴⁴Ce-

¹⁴⁴Pr spectral shape are of utter necessity. Such measurements are in preparation at TUM and CEA, Saclay.

3. CONCLUSIONS

The combination of the famous detector Borexino and the high-activity antineutrino-generator will discover or refute the existence of eV-scale sterile neutrinos. A discovery of the first particle beyond the Standard Model would open a new era in fundamental particle physics and cosmology. A negative result would finally put an end to the discussions about the existence of the neutrino anomalies. In any case, SOX will probe the existence of new physics in low energy neutrino interactions and measure the neutrino magnetic moment. The experimental challenges faced are the

production of a pure 3.7 PBq ¹⁴⁴Ce-source and the development of precise thermal calorimeters and β -spectrometers. The beginning of data collection is scheduled to start shortly after source delivery in end of 2016.

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