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SOX : Short Distance Neutrino Oscillations with Borexino

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In the last years, several neutrino oscillation experiments reported results not compatible within the 3-neutrino model, that hint at the existence of light sterile neutrinos. To test this hypothesis, the SOX (Short distance neutrino Oscillations in BoreXino) experiment will search for oscillations from active to sterile neutrinos by placing a radioactive ^{144}Ce-$\bar{\nu}_e$ source underneath the liquid scintillator detector Borexino. Oscillations will be observed via a reduction of the detected interaction rate of the antineutrinos and an oscillatory pattern as a function of the neutrino energy and travelled distance. Data taking is going to start in beginning of 2018 and first results are expected within this year.

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1. Introduction

Neutrinos and the phenomena of neutrino oscillations have been extensively studied in the last years. Although the overall picture seems in agreement with the Standard Model of three neutrino flavors, there are data from neutrino oscillation experiments hinting at more sterile neutrino states. The accelerator experiment LSND [1] measured an excess in the $\bar{\nu}_e$ - rate from a $\bar{\nu}_\mu$ - beam with L/E $\sim$ 1m/MeV at $\sim 3.8\sigma$. Furthermore after the recalculation of the reactor spectrum and a new determination of the neutron lifetime, reactor experiments observe less events than predicted with $\sim 2.8\sigma$ significance [2]. The solar experiments GALLEX and SAGE used for their calibration ^{37}Ar and ^{51}Cr artificial sources. In a reanalysis [3] a deficit of $\sim 3.0\sigma$ was found.

The analysis of all global data from anomalous neutrino oscillation experiments [4] with the assumption of one sterile neutrino (3+1) points to a light neutrino with a mass of $\sim$1 eV. This would imply oscillation lengths of the order of one meter from active to sterile neutrinos. Therefore, this oscillations can be searched for by a liquid scintillator detector with a good energy and spatial resolution. SOX will use the Borexino detector, which has already shown in the past its capability of measuring neutrino as well as antineutrino fluxes [5]. Using the knowledge about the ultra-pure liquid scintillator detector, a ^{144}Ce antineutrino source will be placed close to it to perform an oscillatory and disappearance measurement at the same time. This article will give an overview about the project, especially the experimental setup, the source and its characterization, the signal, and the projected sensitivity.

2. The experimental setup

The Borexino detector [6] is located at the Laboratori Nazionali del Gran Sasso in Italy under a rock overburden of 3800 mwe. A schematic drawing of the setup is shown in Figure 1. It is composed of two independent light detector systems, namely the inner (ID) and the outer detector (OD), divided by a stainless steel sphere (SSS) with radius of 6.85 m. The active medium of 270 t pseudocumene (PC) with the wavelength shifter PPO at a concentration of 1.5 g/l is contained in a 150 μm nylon vessel at a radius of 4.25 m. The surrounding mixture of PC and DMP shields against external background and quenches at the same time scintillation light arising in this volume. Therefore, the 2218 photomultipliers (PMTs) mounted on the inner surface of the SSS collect mainly the scintillation light from the innermost medium. The energy of an event is reconstructed with the measured hit pattern and the interaction point via time-of-flight. Borexino has a light yield of $\sim 10^4$ photons/MeV and an attenuation length of $\sim$10 m at 430 nm leading to an energy resolution of 5% at 1 MeV and a spatial resolution of $\sim$15 cm at 1 MeV. The OD is filled with 2100 t of ultra-pure water that acts as shielding and muon veto. The emitted Cherenkov light from traversing muons is collected by 208 PMTs mounted on the outer surface of the SSS and the floor of the water tank. The antineutrino source will be deployed 8.5 m below the detector center in a tunnel of only 1 m height. Further shielding against neutrons and gamma rays from the source is achieved by two carbon steel plates between the source and the detector of 8 m x 8 m x10 cm and 4 m x 4 m x 4 cm.

For characterizing the Borexino detector a calibration system has been developed and calibration campaigns were already performed in the period between 2008 and 2011 [7]. Another calibration campaign will be carried out in 2017 to describe especially the detector response at large radii.

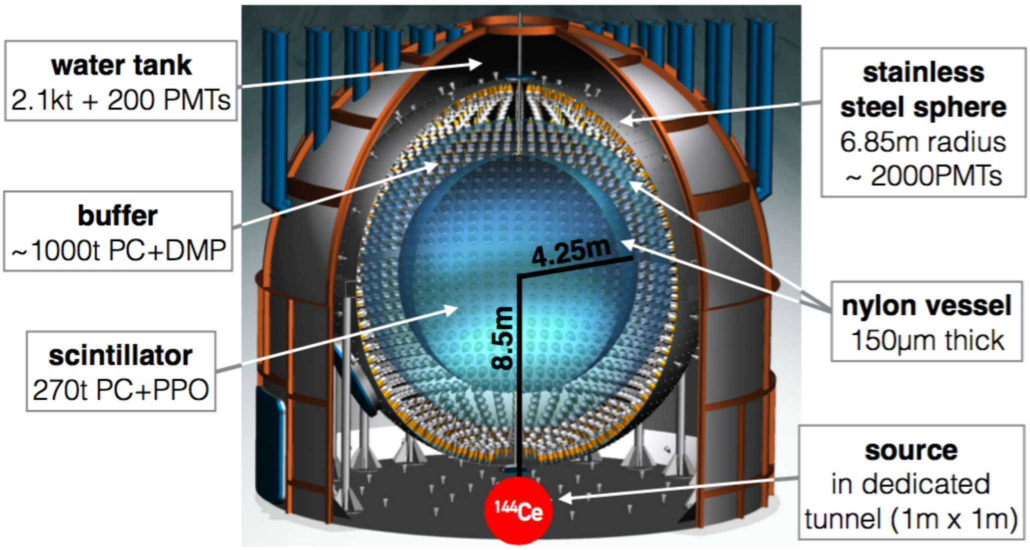

Figure 1: Scheme of the Borexino detector. The active scintillator medium of 270 t PC + PPO is contained in a 150 μm thick spherical vessel of 4.25 m radius. 2218 PMTs mounted on the inner surface of the SSS collect the scintillation through which the energy and position can be reconstructed. The source will be located 8.5 m below the detector center.

3. The ^{144}Ce source

An intense search has been done to find the ideal isotope for a radioactive antineutrino source [8]. A long life time for the production, transportation and the measurement itself is needed, as well as a high Q-value to observe a high fraction above 1.8 MeV - the energy threshold of their detection reaction: the inverse beta decay (IBD). ^{144}Ce fulfills all the requirements by β-decaying with a long half-life of 250 d into ^{144}Pr, which decays shortly (τ_{Pr} = 17 min) via another β-decay into the stable ^{144}Nd with Q_{Pr} = 3 MeV. Only the antineutrinos from the ^{144}Pr-decay will be observed since the Q-value of the ^{144}Ce-decay of 300 keV is below the IBD threshold. Moreover the production of the source has to be feasible and efficient. ^{144}Ce arises as a production isotope in nuclear reactors. FUSE PA Mayak is extracting ^{144}Ce over several complex separation steps from spent nuclear fuel. In the end, 4 kg of CeO_2 with an activity between 100 and 150 kCi will be pressed into a stainless steel capsule of 170 mm height. ^{144}Pr decays with $\sim$2% to exited states of ^{144}Nd leading to a high energy gamma of 2.2 MeV with a branching ratio of $\sim$0.7%. A 19 cm thick W-alloy shielding with the demand of attenuate the emitted gamma line of 2.2 MeV by a factor of 10^{12} has been produced at Xiamen Ltd. in China and was already delivered.

The characterization of the antineutrino source is a key ingredient of the experiment. To determine the power emitted by the source two redundant thermal calorimeters have been developed. In both measurements the power is transferred to water and is determined by $P \propto \dot{m}\Delta h(T,\rho)$, where $\dot{m}$ is the water mass flow and Δh(T, ρ) the difference of the enthalpy that is measured by the in- and outgoing values of temperature and density. Heat losses are minimized by operating the calorimeters in a vacuum tank and adding super insulation foils. The main difference between the two setups is the water circuit: in the one setup the whole source and shielding is immersed in a water vessel, whereas in the second case a water line is circulating in a copper heat exchanger that is encompassing the shielding. By performing a blind measurement it has been shown that the achieved precision is already better than the aspired goal of 1%.

The electron - and therefore also the antineutrino - spectrum of the main ^{144}Pr-decay branch follows a non unique first forbidden decay that cannot be directly determined from theory. Also published measurements show large disagreements up to 10%. The spectral shape can be described with a shape factor b. Un uncertainty in the spectral shape can not only deform the antineutrino spectrum and therefore mimic oscillations in the shape, but also change the mean energy of the electron spectrum. With the relation activity = power / (mean energy per decay), this can lead to over- or underestimating the activity and, hence, misinterpreting the oscillation rate. Therefore, two measurements based on plastic scintillators are ongoing. Additionally, a measurement with a 4Π-acceptance spectrometer is proposed to achieve an absolute precision better than 0.03 on the shape factor b.

4. Signal and Sensitivity

The emitted antineutrinos interact via the IBD: $\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$. In this reaction the antineutrino transfers almost all its energy to the positron that gives a prompt signal by annihilating with an electron, where two 511 keV γ-rays are emitted. The neutron thermalizes and after the mean time of 250 μs it is captured either on Hydrogen or on Carbon in 1% of the cases. The exited nuclei give the delayed signal by emitting a 2.2 MeV or 5 MeV respectively. This coincidence in time and space leads to an almost background free experiment. For a measurement time of 1.5 y, ∼10000 events are expected. In Figure 2 Monte Carlo simulations of the expected signal for different oscillation parameters are shown. The lower pad gives the ratio between the oscillation hypothesis and the no oscillation hypothesis. It can be seen that for Δm^2_{41}-values of $\sim \mathrm{eV}^2$, oscillations can be resolved within the detector. Such oscillations are a smoking gun signature for the existence of a sterile neutrino.

The 95% CL exclusion limits for a 3+1 sterile model is shown in Figure 3. A rate (in red) and a shape analysis (in blue) can be performed independent from each other. The activity range from 100 to 150 kCi is represented by the shaded area. The shape-sensitive $\Delta \mathrm{m}^2_{41}$-range is exactly there, where the oscillations can be resolved within the detector ($0.5\,\mathrm{eV}^2 < \Delta \mathrm{m}^2_{41} < 5\,\mathrm{eV}^2$). For oscillation lengths smaller than the spatial resolution (high $\Delta \mathrm{m}^2_{41}$-values), only an averaged rate deficit can be measured. This explains the drop in the shape sensitivity, but the remaining stable sensitivity in the rate. Also for oscillation lengths larger than the detector size (small $\Delta \mathrm{m}^2_{41}$-values) the sensitivity of a shape analysis is lost, but still the rate deficit can be analyzed. For the combination of a rate and shape analysis (in black) almost the whole best fit region of the anomalies can be excluded. In this analysis the expected systematic uncertainties have been taken into account: a total uncertainty of the normalization rate of 1.5% and an uncertainty of the ^{144}Pr spectral shape of an absolute error of 0.03 are assumed.

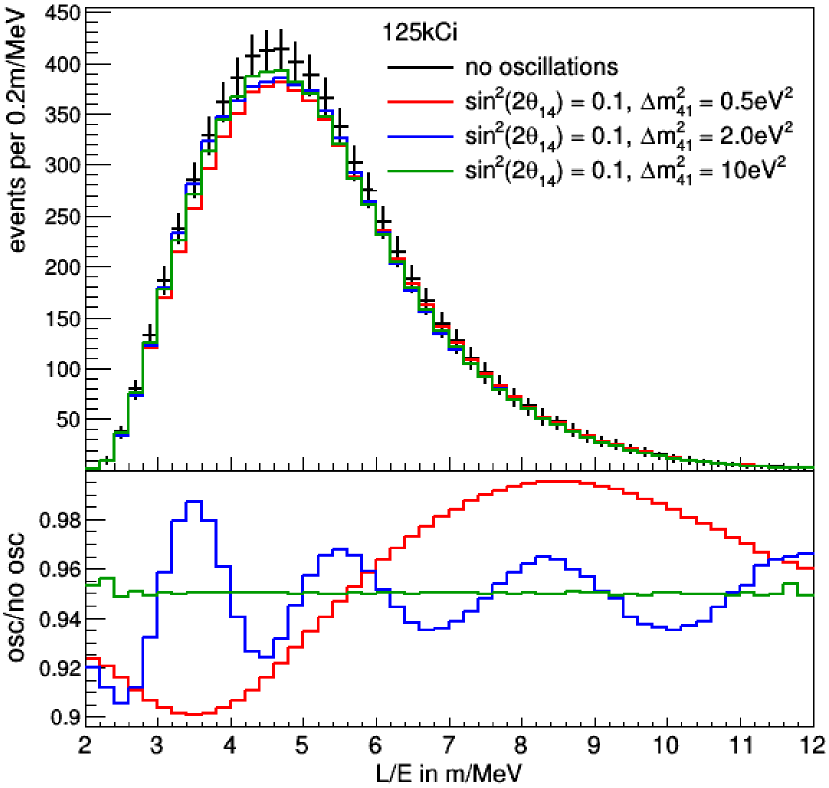

Figure 2: Expected signature as a function of distance (L) over reconstructed energy (E) for a 125 kCi ^{144}Ce source underneath Borexino. On the top the count rate for different mixing scenarios is shown, whereas on the bottom the ratio of the count rate of mixing and no oscillation hypothesis is depicted. Observing these oscillations would be a smoking gun signature.

5. Conclusions

SOX aim's to look for sterile neutrinos with a high intensely ^{144}Ce antineutrino source. The produced antineutrinos are detected by the 270 t liquid scintillator Borexino detector, where energy and interaction position can be reconstructed with a high accuracy. If a sterile neutrino exists, an oscillatory pattern in energy and distance would be visible and, therefore, an analysis in the rate as well as in the shape can be performed. To minimize systematic uncertainties, the antineutrino source is characterized by several redundant measurements of its power and spectral shape. Also, a new Borexino calibration campaign is in preparation for 2017. Data taking is going to start in beginning of 2018.

In case of a positive signal a second step of the SOX program could be to test this result with a ^{51}Cr ν_e-source [9].

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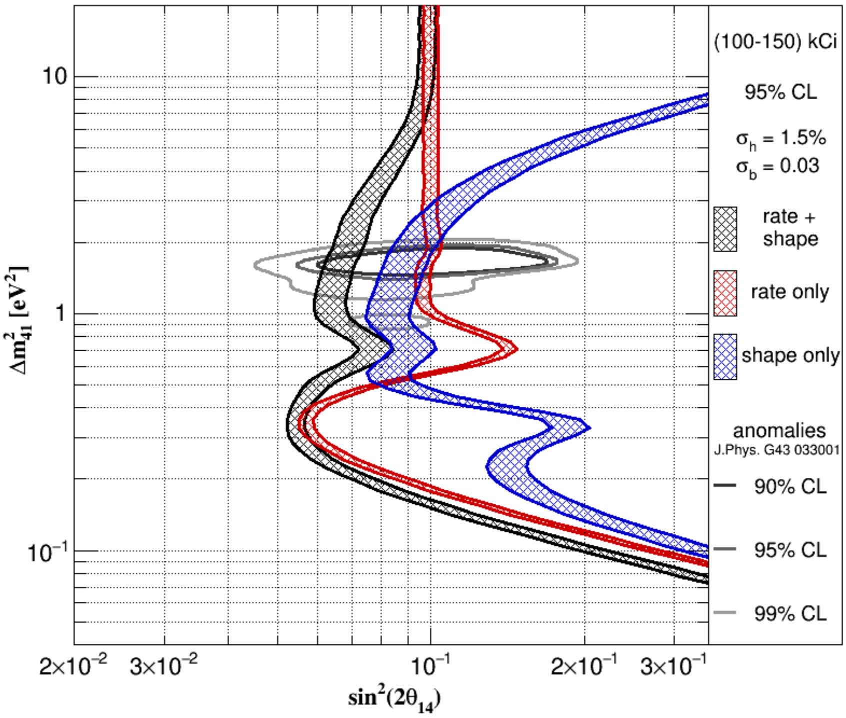

Figure 3: 95% CL exclusion limits for a 100-150 kCi ^{144}Ce source in the Δm^2_{41} - $\sin^2(2\theta_{41})$ - plane compared to the preferred regions of a global fit to the anomalies from [4]. The analysis can be split in rate only (red), shape only (blue). With the combined rate + shape analysis (black) almost the whole 90% CL of the anomaly region can be excluded. Here the total uncertainty in the normalization of 1.5% and an absolute error of 0.03 in the neutrino spectral shape is taken into account.

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