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Omnibus experiment: CPT and CP violation with sterile neutrinos

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Abstract. We propose to probe both the CPT and CP violation together with the search for sterile neutrinos in one do-it-all experiment. This omnibus experiment would utilize neutrino oscillometry with large scintillator detectors like LENA, JUNO or RENO-50 and manmade radioactive sources similar to the ones used by the GALLEX experiment. Our calculations indicate that such an experiment is realistic and could be performed in parallel to the main research plan for JUNO, LENA, or RENO-50. Assuming as the starting point the values of the oscillation parameters indicated by the current global fit (in 3 active + 1 sterile scenario) and requiring at least 5 sigma confidence level, we estimate that with the proposed experiment we would be able to detect CPT mass anomalies of the order of 1% or larger.

1. Introduction

Determination of the phase of the CP violation in the leptonic sector is the main goal of the two largest and most ambitious neutrino experiments proposed so far: LAGUNA-LBNO [1] in Europe and DUNE [2] in the USA. Discovery of CPT violation would be of even more fundamental importance but there are currently no coordinated plans to search for it. Equally significant is verification of the sterile neutrino hypothesis and, if confirmed, determination of the relevant oscillation parameters. We propose to probe both the CPT and CP violation together with the search for sterile neutrinos in one do-it-all experiment. Such omnibus experiment would utilize neutrino oscillometry with large scintillator detectors like LENA [3], JUNO [4], or RENO-50 [5].

A very strong argument to consider such an experiment already now is the fact that construction of JUNO has started (in January 2015) and the expected commissioning date is 2020 [4]. It would naturally be naïve to expect that a single experiment would answer the key questions of neutrino physics. However, since the 20 kton liquid scintillator detector is now firmly on the horizon and is likely to deliver the first data well ahead of the long baseline experiments, we propose to widen its research program to include oscillometry with strong radioactive sources similar to the ones used by the GALLEX experiment [6].

2. Neutrino oscillometry

Oscillometric approach has been explained in details in our previous publications [7-10]. It is a well-know fact that oscillation length scales linearly with the neutrino/antineutrino energy. For instance, in the well-known case of the mixing angle θ_{13}, the formula may be reduced to a very simple form: $L_{13}(\mathrm{m}) \approx E_\nu(\mathrm{keV})$. It means that 300 keV neutrinos have the oscillation length of only about 300 m. Naturally, there is no need to re-measure θ_{13}, but this example shows that even for active neutrinos a large detector with good sensitivity at low energies would be able to register a significant part of the oscillation curve instead of measuring only at the near and far location, as it is the case for the proposed long- and mid- baseline oscillation experiments.

Of the three main technologies proposed for giant neutrino observatories [11]: Water Cherenkov, Liquid Argon TPC, and Liquid Scintillator (LS) only LS has the required sensitivity in the sub-MeV range. The largest of the currently operating LS detector is KamLAND [12]. It has the fiducial mass of 1 kton and the inner diameter of 13 m. JUNO [4], scheduled for commissioning in 2020, will have 20 kton fiducial and 34.5 m diameter while LENA [3] aims at 50 kton inside of a 100 m long cylinder. RENO-50 [5] proposes a 30 m diameter, 30 m high cylinder.

2.1. Oscillometry with sterile neutrinos

The existence of sterile neutrinos was proposed as an explanation of anomalies in short baseline accelerator experiments: LSND [13], and MiniBooNE [14] as well as in gallium-based solar neutrino experiments: GALLEX [6], and SAGE [15]. Anomalies were also reported in the reactor neutrino spectra at short distances [16]. There is still no solid evidence for the existence of sterile neutrinos. If they do exist, they would have to conform to the constrains imposed by the outcome of the previous experiments. As a result, the oscillation parameters used in simulations can, for practical reasons, be narrowed down to the phase space indicated by the current global fit [17]. In particular, one of the anticipated features is a very short oscillation length as compared to the known neutrino flavors. This makes sterile neutrinos very well suited for oscillometric studies.

2.2. Neutrino sources

The linear scaling between neutrino energy and its oscillation length imposes the need to choose a source of neutrinos to suite the experiment. As the choice is limited, most experiments propose the use ^{51}Cr [18] as a source of practically mono-energetic electron neutrinos. ^{51}Cr decays with $T_{½} = 27.7$ days via electron capture. The ~750 keV neutrinos come from the 90.1% branching ratio to the ground state of ^{51}V. The expected activity at the start is of the order of 300 PBq [18]. For the electron antineutrinos there are no mono-energetic sources but the continuous spectrum characteristic of the beta decay can be “monochromatized” taking advantage of the 1.8 MeV threshold of the inverse beta decay – the golden detection channel. In this case the favourite choice [19] is the ^{144}Ce – ^{144}Pr mother – daughter combination providing detectable neutrinos with energies in the 1.8 – 3 MeV bin accounting for 48.5% of the emitted electron anti-neutrinos. The half-life of the source is determined by ^{144}Ce with $T_{½} = 258$ days. The daughter nucleus decays with $T_{½} = 17$ min. The expected activity at the start of the measurement is around 4.6 PBq.

3. Proposed experiment

To generate multiple oscillation patterns within the active volume of the detector the proposed experiment assumes the existence of sterile neutrinos. Lack of such patterns would allow us to set new stringent limits for the existence of right-handed neutrinos but it would also exclude the possibility to probe CPT violation. The main goal of the proposed experiment is to measure and compare oscillation parameters obtained for electron neutrinos (^{51}Cr source) and antineutrinos (^{144}Ce – ^{144}Pr). If there are differences, the CPT symmetry has been clearly violated. However, if no differences are observed, the opposite conclusion cannot be derived, as there are many ways to break that symmetry. In fact, most current theories concerning CPT violation do not anticipate particle/antiparticle mass asymmetries [20]. Nevertheless, this is exactly the point that we propose to verify. It is also worthwhile to notice that finding asymmetry in the survival probability between electron neutrinos and antineutrinos would indicate not only CPT violation, but also CP violation [10].

Experimental details are described in [10]. We have considered two scenarios: (i) placing of a strong radioactive source in the center of JUNO [4] – a spherical detector, (ii) placing of a source on the top of LENA [3] – a cylindrical detector. While the first option is the best as far as detection efficiency and symmetry are concerned, the second is considerably easier to realize, as the integrity of the LS tank does not have to be compromised.

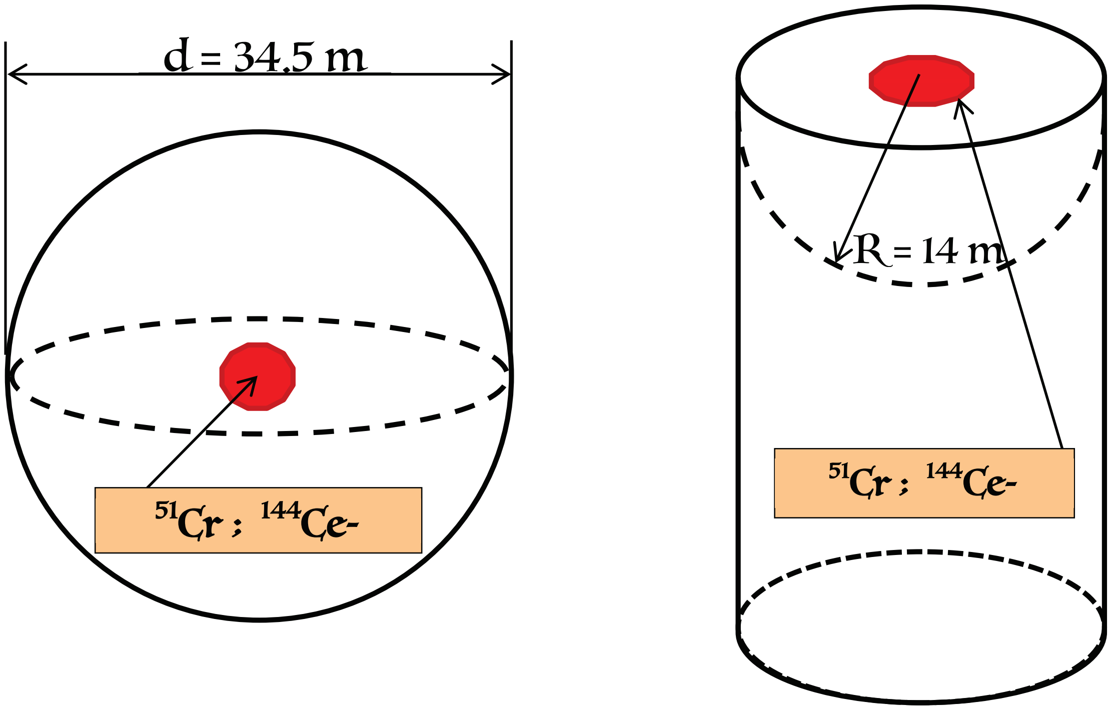

Figure 1. Considered experimental geometries. Left panel: the source is located in the center of a spherical detector. Right panel: the source is located on the top of a tall, cylindrical detector. The dimensions and the other key parameters were taken from the specifications provided for JUNO and LENA.

4. Simulation results

The proposed experiment will be sensitive to two of the new oscillation parameters associated with the sterile neutrinos: θ_{ee} and Δm_{41}^2. The former governs the oscillation amplitude. The later determines the frequency. The accuracy of amplitude measurements is limited by several factors including the uncertainty in the determination of the source activity. For that reasons also the extracted θ_{ee} will be known with a relatively poor accuracy. Fortunately, since we expect to observe up to 10 oscillation minima (for neutrinos) and 3 (for anti-neutrinos), our Δm_{41}^2 sensitivity will be considerably better allowing the search for anomalies manifested as mass asymmetry.

Fig. 2 illustrates the outcome of the simulations. It shows the sensitivity to extract Δm_{41}^2 value at the 5σ confidence level as a function of the Δm_{41}^2. At the present stage, we have limited the phase space of oscillation parameters used for the calculations to the immediate vicinity of the values indicated by the current global fit [17], that is $\Delta m_{41}^2 = 1$ eV, and $\sin^2 2\theta_{ee} = 0.1$. The range of Δm_{41}^2 is from 0.4 to 5.0 eV^2. For the $\sin^2 2\theta_{ee}$ we have used two values: 0.1 and 0.05. The calculations were made for two detector geometries: a sphere (JUNO) with the source in the center (left panels), and a cylinder (LENA) with the source on the top (right panels). The dimensions and the other key parameters were taken from the specifications provided by JUNO and LENA publications. The active volume for JUNO was a sphere and for LENA a semi-sphere with R = 14 m. The assumed resolution in the relevant range of the visible energy (0.4 – 1.2 MeV) was 3.7 – 6.4% for JUNO and 12.6 – 7.3% for LENA. The energy dependent position resolution was, respectively, 6 – 4 cm and 13 – 7 cm.

The simulations were done for two radioactive sources. The top panels summarize the results with ^{144}Ce-^{144}Pr source. The simulated exposition lasted 300 days and assumed 4.6 PBq activity at the start. The two bottom panels show the outcome of the simulations for the ^{51}Cr source. The exposition was 55 days and the activity at the start was 300 PBq. The continuous black lines are to guide the eye only.

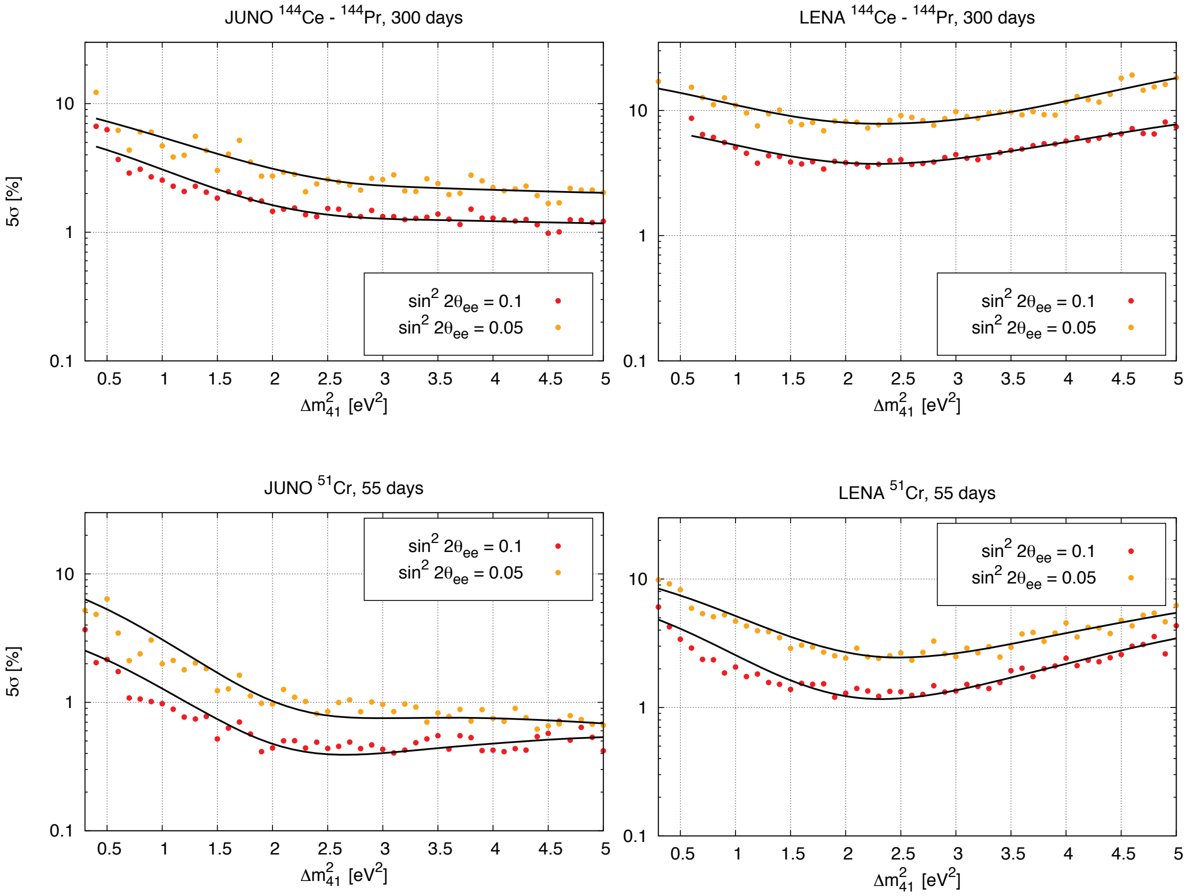

Fig.2. Outcome of the simulations showing the sensitivity to extract Δm_{41}^2 at 5σ confidence level.

5. Conclusions

In view of the ongoing and planned experiments it is expected that within a few years the existence of the sterile neutrinos will be clarified. Especially relevant would be the outcome of the proposed Borexino SOX experiment [21] as it would use, albeit on a considerably smaller scale, the same sources and the same detection method. Clearly, if the sterile neutrinos do exist, the Omnibus experiment would be of a fundamental importance to the study of their properties and the physics behind it. The cost of such an experiment would be relatively modest and it would not compromise the main research goals proposed for the new large-scale liquid scintillator detectors. For that reason, even if Borexino SOX would yield a negative result, it would be still worthwhile to perform the oscillometric measurements on a large scale using detectors like JUNO, LENA, or RENO-50.

Our results show that in a favorable case (^{51}Cr) one may expect sensitivity of a few per-mille in the determination of Δm_{41}^2. In the case of ^{144}Ce-^{144}Pr source the sensitivity is just over one percent. It may not be sufficient to detect subtle effects but it would provide an independent probe in the search for the symmetry violations in the leptonic sector.

While it is clear that placing the source in the center of a spherical detector yields the best results, the case of a cylindrical detector with the source outside of the active volume is only slightly worse. In any case, the Omnibus approach should be considered already during the planning and construction stage of JUNO, LENA, and RENO-50.

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