Sensitivity studies of sterile neutrinos using coherent neutrino-nucleus scattering with reactor antineutrinos

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Introduction

The tiny mass of neutrinos is a combination of three mass eigen-states, which is established by several experiments using solar, atmospheric, reactor, and accelerator-based neutrinos. Several experiments have observed anomaly in neutrino oscillation at short baseline. The disappearance of $\overline{\nu}_e$ while propagating from the source to detector due to Active-Sterile Neutrino (ASN) oscillations with the squared mass difference $\Delta m^2 \sim 1$ eV^2. At present the study on neutrino is in precision era. In worldwide many experiments are going on and some of them are planned to measure the neutrino cross-section. Coherent elastic neutrino-nucleus scattering (CEνNS) is a standard model (SM) process in which the low energy neutrinos scatter off the atomic nucleus coherently through the neutral-current weak interactions [1]. For low-energy neutrinos (< 50 MeV), the CEνNS process has a larger cross-section for neutron-rich targets as compared to other known processes. Further, the CEνNS is a threshold-less process in contrast to IBD. Although, having a larger cross-section, the CEνNS process has not been observed earlier due to the difficulty in measuring the low-energy recoil nuclei.To this end, a feasibility study has been carried out for measuring the CEνNS process and to ascertain the ASN mixing sensitivity of various types of the detector by placing them at short baseline (L$\leq$ 30m) through CEνNS channel.

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CEνNS scattering cross-section and oscillation probability

The differential CEνNS scattering cross-section is given by

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2}{8\pi}\left[Z(4\sin^2\theta_W - 1) + N\right]^2 \times A\left(2 - \frac{TA}{E_\nu^2}\right)|f(q)|^2 \quad (1)$$

where A, N, Z are the mass number, number of neutrons and number of protons in the nucleus, respectively. Further, E_ν is the incident neutrino energy, T is nuclear recoil energy, $(T_{\max}(E_\nu) = 2E_\nu^2/(A+2E_\nu))$, G_F is the Fermi coupling constant, θ_W is the weak mixing angle and $f(q)$ is the nuclear form factor for a momentum transfer q. The main advantage of considering the CEνNS process for finding the ASN mixing sensitivity is due to its larger cross-section as compared to IBD cross-section. This enables the use of smaller size detectors in the CEνNS measurements. The compact detector will minimize the neutrinos path length uncertainty. The 3+1 generation oscillation model is reduced to two flavor framework for a small value of mixing angle θ_{14} and at a few meters (< 100 m) source to detector distance. Then the $\overline{\nu}_e$ survival probability can be approximated as

$$P_{\nu_e\nu_e}(E_\nu, L) \simeq 1 - \sin^2 2\theta_{14}\sin^2\left(\frac{1.27\Delta m_{41}^2 L}{E_\nu}\right), \quad (2)$$

where E_ν is the neutrino energy (in MeV), L is the path length (in m) between the source and the detector, and Δm_{41}^2 is the squared masses difference (in eV^2) between the two neutrino

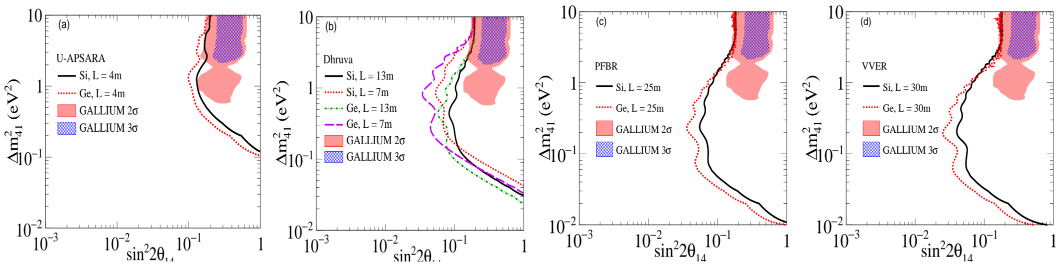

FIG. 1: ASN mixing sensitivity at 95 % C.L. for the Ge and Si detectors placed at fixed distances from the U-Apsara, DHRUVA, PFBR and VVER reactors.

mass eigen-states. The ASN oscillation parameters Δm^2_{41} and $\sin^2 2\theta_{14}$ are represented by

$$\Delta m^2_{41} = m^2_4 - m^2_1\,; \quad \sin^2 2\theta_{14} = 4|U_{e4}|^2(1-|U_{e4}|^2), \tag{3}$$

where $U_{e4} = \sin\theta_{14}$, one of the elements of unitary mixing matrix.

χ^2 analysis and ASN of detectors

The potential of different detectors have been explored on finding the active-sterile neutrino(ASN) oscillation sensitivity using neutrinos produced from various types of reactor facilities in India.The exclusion limit has been obtained for each value of Δm^2_{41} by scanning over the various values of $\sin^2 2\theta_{14}$ to determine the boundary of the corresponding χ^2 (e.g. $\chi^2 = 5.99$ for 95.0% confidence limit (C.L.)). The definition of χ^2 is considered from Ref. [2] which is given by

$$\chi^2 = \sum_{n=0}^{N} \left(\frac{R^{th}_n - R^{ex}_n}{\sigma(R^{ex}_n)} \right)^2 + \sum_{i=0}^{k} \xi_i^2, \tag{4}$$

where, n is the number of energy bins, R^{ex}_n, R^{th}_n are the number of events obtained from the simulations with oscillation (expected) and without oscillation (theoretically predicted) events, respectively. The R^{th}_n carries the information about the systematic uncertainties given by

$$R^{th}_n = R'^{th}_n \left(1 + \sum_{i=0}^{k} \pi^i_n \xi_i \right) + \mathcal{O}(\xi^2) \tag{5}$$

Figure 1(a) shows the sensitivity by placing the detectors at 4 m from U-Apsara research reactor core. Figure 1(b) shows the sensitivity of the detector by placing it at 7.0 m and 13.0 m from DHRUVA reactor core. Figure 1(c) shows the sensitivity of the detector at 25 m PFBR reactor core, and Fig. 1(d) shows the sensitivity for the detectors placed at 30 m from the VVER power reactor core. The shape of the sensitivity curve in the region of small values Δm^2_{41} ($\Delta m^2_{41} \lesssim 1.0\ eV^2$) shows a linear dependence between $\sin^2 2\theta_{14}$ and Δm^2_{41} in the logarithmic scale. This happens as typical neutrino oscillation lengths are larger compared to the size of the detector, and the $\overline{\nu}_e$ survival probability mentioned in Eq. 2 is approximately given by $P_{\nu_e\nu_e}(E_\nu, L) \approx 1 - C \sin^2 2\theta_{14} \times \left(\Delta m^2_{41}\right)^2$, where C is a constant. In the region with larger Δm^2_{41} values, the systematic uncertainties related to the neutrino source dominate over the statistical uncertainties. The detector energy resolution also affects the high frequency oscillation-induced deformations. Further, the detail study on ASN mixing sensitivity of detector will be presented in future.

References

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