Hunt for $\theta_{13}$ with LENA

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Abstract. In a hunt for by far missing neutrino mixing angle $\theta_{13}$ the accelerator experiments have recently indicated non-zero value and the dedicated reactor neutrino experiments are moving towards the data-taking phase to confirm that. The small effect of $\theta_{13}$ to the neutrino oscillation probabilities can be also complementarily probed using artificially made source of mono-chromatic neutrinos with low energies originated from electron capture processes. Due to the small energy of neutrino and tiny interaction cross section, and the expected scale of $\theta_{13}$ support the use of large liquid scintillation detector. In this work, the estimated sensitivities for measurement of mixing angle $\theta_{13}$ is presented in context of proposed LENA detector. Instead of the existing and earlier investigated neutrino source $^{51}$Cr, more feasible source candidate $^{75}$Se is used. The search for possible sterile neutrino flavors is also discussed.

1. Introduction

The motivation of using few hundred keV neutrinos for oscillation studies emerge from the fact that the spacial oscillation pattern have not been observed yet within single detector. The idea of studying neutrino oscillations with this kind of oscillometric way have been earlier proposed for spherical gaseous TPC detector[1] and discussed also within large cylindrical liquid scintillation detector like LENA[2]. Global results of neutrino oscillation parameters practically restricts the oscillometric studies to $\theta_{13}$ and $\Delta m^2_{31}$. Recent results from T2K and Minos [3],[4] indicate non-zero $\theta_{13}$ make the discussion of oscillometric measurement relevant. The spacial pattern of neutrino events inside one detector with current values of $\theta_{13}$ and $\Delta m^2_{31}$ seems to beyond the reach. In this paper the focus is on experimental requirements and challenges of measurement of $\theta_{13}$ and as a first approximation the total events collected by whole detector is used to determine the sensitivities. Main background signal for this kind of measurement comes from solar $^7$Be neutrinos and the experimental threshold set by the $^{14}$C content of target material is taken into account. The recent re-analysis of results from past reactor experiments have made space for sterile neutrino flavors. As a side product of our hunt for $\theta_{13}$, we have find large liquid scintillation detector like LENA can verify the existence of sterile neutrinos and true oscillometric measurement of sterile neutrino oscillation parameters can be made.
2. Experimental aspects

2.1. Neutrino oscillations

The signal to measure is the deficit of electron neutrinos caused by neutrino oscillation. The current values of neutrino mass squared differences lead to large differences in oscillation lengths. The oscillation length set by $\Delta m_{21}^2$ is about 32 times longer than the one governed by $\Delta m_{31}^2$ and hence different oscillation components can be measured practically independently. By assuming $\Delta m_{31}^2 \approx \Delta m_{32}^2$ and neglecting term containing $\Delta m_{21}^2$, the survival probability of electron neutrino have simple formula

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{ij}) \sin^2\left(\frac{\Delta m_{ji}^2 L}{4E}\right)$$

(1)

where $i$ and $j$ describe the mass states, $\theta_{ij}$ and $\delta m_{ji}^2$ corresponding mixing angle and mass squared difference, $E$ neutrino energy and $L$ is the distance neutrino have propagated.

2.2. Detection principle

The proposed LENA (Low Energy Neutrino Astronomy)[2] is a large next generation hydrocarbon -based liquid scintillation detector. The target material is enclosed to the cylindrical tank with diameter $\approx 30$ m and height $\approx 100$ m) and the inner surface of the tank is covered by photosensors. The physics program of LENA contains the measurement of neutrinos from different low energy sources (Sun, supernovae, Earth, etc.) as well as search of proton decay. The man-made low energy neutrino source widens the physics program from astroparticle physics to the fundamental particle physics. The detection of low energy electron neutrinos in liquid scintillation detector is based on measuring the light produced by the recoil electrons from neutrino-electron scattering process. Deposited energy of recoil electrons converts to scintillation photons, which are detected.

2.3. Backgrounds

There are two main unavoidable sources of background which limit the sensitivity of $\theta_{13}$ measurement. The external background signal comes from solar $^7$Be neutrinos ($E_\nu = 862$ keV). The main limiting intrinsic background comes from radio carbon ($^{14}$C) contamination of target material itself. This decay has endpoint energy of $\approx 154$ keV and leads to experimental threshold of around 200-250 keV. Both background signal are visible in Borexino results in figure1: $^7$Be red and $^{14}$C yellow.

![Figure 1. The spectrum of visible energy of different low energy components measured by Borexino experiment[5].](image)

2.4. Sources for mono-energetic neutrinos

Suitable neutrino source can be produced by neutron bombardment in nuclear reactor. This kind of source ($^{51}$Cr) have been produced and used for solar neutrino experiment GALLEX to calibrate the detector and check the results [6]. The energy of produced neutrinos should be as low as possible to fit most of the oscillation pattern inside the detector, but exceeding the threshold set by $^{14}$C. As a rule of thumb the oscillation length $L \ [m] \approx E \ [keV]$. To get reasonable
statistics the number of irradiation-measurement cycles (initial neutrino intensity and half-life of produced isotope) play crucial role. Some candidate isotopes and their properties are listed in Table 1.

3. Case: $^{75}$Se
In the search of $\theta_{13}$ the energy of already available $^{51}$Cr source tends to be too high to accommodate the sufficient signal of deficit inside the 100 m detector. Hence, another possible source should be investigated. $^{75}$Se is selected because its availability and lower neutrino energy (450 keV). Maximum recoil electron energy is 287 keV which exceeds the background from $^{14}$C. The initial neutrino intensity of $7\times10^{17}$ can be achieved and the oscillation length becomes $\sim$460 m. Length is still relatively large compared to detector length, but it is much shorter than oscillation length for $^{51}$Cr ($\sim$762 m). In this example case six cycles of 120-day measurement is assumed. In the left panel of figure 2 the crucial effect of $^{14}$C threshold to the sensitivity of $\theta_{13}$ measurement is shown. Figure shows also the optimal source distance from detector top ($\sim$38 m). In right panel of figure 2 shows the statistical sensitivity for $\theta_{13}$ measurement with different $\sin^2(2\theta_{13})$ values with solar background and threshold of 200 keV from $^{14}$C. If the accelerator and reactor experiments observe $\theta_{13}$ be large enough measurement of electron neutrinos with LENA can be used as a complementary measurement.

![Figure 2](image-url)

**Figure 2.** Left panel: Statistical sensitivity for measurement of $\theta_{13}$ with solar neutrino background and different threshold from $^{14}$C. Right panel: Statistical sensitivity with different values of $\sin^2(2\theta_{13})$. 

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**Table 1.** Some candidate isotopes and their properties for mono-energetic electron neutrino source

| Nuclide | T$_{1/2}$ (d) | Q (keV) | $E_\nu$ (keV) | $E_{e,max}$ (keV) | $\nu$-Intensity (kg$^{-1}$s$^{-1}$) |
|---------|--------------|---------|--------------|------------------|-------------------------------|
| $^{37}$Ar | 35 | 814 | 811 | 617 | $8.3\times10^{15}$ |
| $^{51}$Cr | 28 | 753 | 747 | 560 | $2.3\times10^{16}$ |
| $^{75}$Se | 120 | 863 | 450 | 287 | $1.1\times10^{14}$ |
| $^{113}$Sn | 116 | 1037 | 617 | 436 | $8.0\times10^{11}$ |
| $^{145}$Sm | 340 | 616 | 510 | 340 | $2.0\times10^{12}$ |
| $^{169}$Yb | 32 | 910 | 470 | 304 | $1.1\times10^{15}$ |
4. Sterile neutrino search

Recent analysis of reactor neutrino production and global analysis of neutrino parameters allow the existence of sterile neutrino flavors. In $3 + 1$ neutrino analysis leads to the oscillation parameters of $\sin^2(2\theta_{14})=0.14\pm0.08$ and $\Delta m^2_{41}>1.5$ eV$^2$[7]. By using the $^{51}$Cr source the oscillation length of sterile neutrino oscillation pattern becomes $\sim$1.2 m. Estimated position resolution of LENA of this kind of energies is couple of tens of cm. The oscillation pattern can be seen inside the detector providing the first real oscillometric measurement. The cumulative events collected by a half sphere from the top of the LENA detector is shown in figure 3.

![Cumulative events inside of half sphere. The $^{51}$Cr source is located straight next to top of the detector. Total events (black) and unoscillated events from chromium (blue) are overlapping. The deficit of events (green) is clearly exceeding the background from solar neutrinos (yellow) and 6-sigma statistical limit (red dotted).](image)

Figure 3.

5. Conclusion

Recent result of non-zero $\theta_{13}$ motivates the complementary measurement of $\theta_{13}$ by using monoenergetic electron neutrino source and large liquid scintillation detector (LENA). Observing the oscillation pattern along the detector seems to be beyond the reach at this time, but $\theta_{13}$ can be derived by analysing the event rates collected by the whole detector and $^{75}$Se looks feasible candidate for that. The recent revision of reactor neutrino data opens the door for one or more sterile neutrino flavors. Suggested mass squared difference region opens a way to true oscillometric measurement with detector like LENA. The most promising candidate for this is $^{51}$Cr due to higher energy and longer oscillation length.

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