



Meter-baseline tests of sterile neutrinos at Daya Bay

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ABSTRACT

We explore the sensitivity of an experiment at the Daya Bay site, with a point radioactive source and a few meter baseline, to neutrino oscillations involving one or more eV mass sterile neutrinos. We find that within a year, the entire $3+2$ and $1+3+1$ parameter space preferred by global fits can be excluded at the 3σ level, and if an oscillation signal is found, the $3+1$ and $3+2$ scenarios can be distinguished from each other at more than the 3σ level provided one of the sterile neutrinos is lighter than 0.5 eV.

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1. Introduction

The standard three neutrino (3ν) picture has been successful in explaining most oscillation data. However, data from the Liquid Scintillator Neutrino Detector (LSND) experiment [1] when interpreted as arising from $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations, indicate a deviation from the simple 3ν picture. The Mini-Booster Neutrino Experiment (MiniBooNE) [2] provides supporting evidence for the LSND result that oscillations involving an eV mass sterile neutrino may be at work. Additional support may be found in an upward revision in the estimate of the reactor $\bar{\nu}_e$ flux yield [3]. The fact that short baseline (SBL) reactor neutrino experiments do not detect the 3% larger flux (via a 7% larger event rate) could be explained as a consequence of oscillations to sterile states.

Popular scenarios that are consistent with the relevant data have either one sterile neutrino, with a $3+1$ mass spectrum (such that the nearly degenerate triplet of mass eigenstates is lighter than the remaining state), or 2 sterile neutrinos [4,5]. The 5 neutrino (5ν) case has 2 viable spectra: a $3+2$ spectrum in which the triplet is lighter than both sterile neutrinos, and a $1+3+1$ spectrum in which one sterile neutrino is lighter than the triplet and one is heavier. In all cases, the sterile neutrinos mix little with the active neutrinos.

Recently, it was suggested that a ten kilocurie scale ^{144}Ce – ^{144}Pr β -decay source could be placed inside a large liquid scintillator detector to study eV sterile neutrino oscillations on baselines of a few meters with 1.8–3.3 MeV neutrinos [6]. Distinct virtues of this technique are (1) that with a point-like source, an oscillation signature can be demonstrated as a function of both energy and baseline, (2) the short baseline may be easily adjustable, (3) ex-

isting detectors can be utilized, and (4) antineutrino source activity is reduced relative to that of neutrino sources previously used for the calibration of low-energy radiochemical solar neutrino experiments since the inverse β -decay cross section is higher than the neutrino–electron scattering cross section. Clear technical challenges are the feasibility of constructing such an intense radioactive source and of engineering suitable ultra-pure shielding of the source inside the detector. For a decisive measurement, Ref. [7] considered the possibility of an experiment at the Daya Bay site with a 500 kCi (1.85×10^{16} Bq) source. The configuration of the 4 detectors in the Far Hall at Daya Bay makes it possible to place the source outside the detectors thus circumventing one of the technical issues. In what follows, we treat the 500 kCi source as point-like although in reality it will have a finite spatial extent depending on the freshness of the fuel being used for its production, the production and transportation time, as well as the final density of cerium oxide that is limited to about 4.5 g/cm³. This approximation is valid since the size of the source will be small compared to the 6.5 m oscillation length of interest.

In this Letter we show that the parameter space preferred by global fits in the $3+1$, $3+2$ and $1+3+1$ scenarios will be stringently tested by the proposed multi-meter baseline $\bar{\nu}_e$ disappearance measurement at Daya Bay. For sterile neutrino masses below 0.5 eV, such a measurement can even distinguish between the $3+1$ and $3+2$ scenarios at the 3σ level. This enhanced sensitivity arises because knowledge of the ν_e fraction of the ν_4 and ν_5 mass eigenstates breaks the degeneracy in the sterile mixings to ν_e and ν_μ , both of which are required to explain the anomalous SBL data.

2. Sterile neutrino oscillations

For vacuum oscillations of MeV neutrinos from a radioactive source, the (CP phase-independent) ν_e and $\bar{\nu}_e$ survival probability

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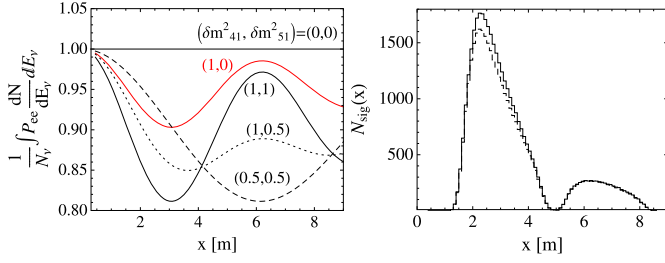


Fig. 1. Left: The energy-averaged ν_e survival probability as a function of distance for 3 + 1 and 3 + 2 sample points. $U_{e4} = 0.16$ (giving a $\sim 10\%$ oscillation amplitude), and in the 3 + 2 scenario, U_{e5} is also 0.16. Right: Event distributions for the chosen radioactive source-detector configuration. The solid and dashed curves show the cases of no active-sterile oscillations [7], and of oscillations with $\delta m^2 = 1 \text{ eV}^2$ and a 10% oscillation amplitude, respectively.

at distance L is

$$P_{ee} = 1 - 4 \sum_{i < j} |U_{ei}|^2 |U_{ej}|^2 \sin^2 \Delta_{ij}, \quad (1)$$

where $\Delta_{ij} = \delta m_{ij}^2 L / (4E_\nu)$ with $\delta m_{ij}^2 = m_i^2 - m_j^2$. i, j denote the mass eigenstates and take values from 1 to the total number of neutrinos. U_{ei} are elements of the mixing matrix. For the 3 + 1 spectrum, $\delta m_{43}^2 \simeq \delta m_{42}^2 \simeq \delta m_{41}^2 \simeq 1 \text{ eV}^2 \gg \delta m_{32}^2 \simeq \delta m_{31}^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2 \gg \delta m_{21}^2 \simeq 7.5 \times 10^{-5} \text{ eV}^2$. Then, $P_{ee}^{3+1} = 1 - \sin^2 2\theta_s \sin^2 \Delta_{41}$, with the definition, $\sin \theta_s \equiv U_{e4}$.

In the 5ν case, Eq. (1) includes a superposition of three oscillation frequencies corresponding to $\delta m_{41}^2, \delta m_{51}^2$ and δm_{54}^2 . We neglect the δm_{54}^2 contribution in what follows. Although the sterile neutrinos can mix with all three active neutrinos, P_{ee} depends only on the four parameters, $\delta m_{41}^2, \delta m_{51}^2, |U_{e4}|$ and $|U_{e5}|$ via

$$P_{ee}^{5\nu} = 1 - 4(1 - |U_{e4}|^2 - |U_{e5}|^2) \times (|U_{e4}|^2 \sin^2 \Delta_{41} + |U_{e5}|^2 \sin^2 \Delta_{51}). \quad (2)$$

Since $P_{ee}^{5\nu}$ is insensitive to the signs of Δ_{41} and Δ_{51} , ν_e disappearance data cannot distinguish between the 3 + 2 and 1 + 3 + 1 spectra for identical mixing matrix elements. (In principle, the spectra can be distinguished if the suppressed but nonzero δm_{54}^2 contribution to the right hand side, $-4|U_{e4}|^2 |U_{e5}|^2 \sin^2 \Delta_{54}$, is included.)

In the left panel of Fig. 1, we show the ν_e survival probability for several 3 + 1 and 3 + 2 sample points. For the sake of illustration, we have used somewhat large values of U_{e4} and U_{e5} . The significant variation in the survival probabilities over the first few meters for different $(\delta m_{41}^2, \delta m_{51}^2)$ choices reveals the strength of the method. For all curves in Fig. 1, P_{ee} is convolved with the $\bar{\nu}_e$ energy spectrum from the radioactive source.

3. Experimental set-up and procedure

The 500 kCi radioactive source at Daya Bay can be placed so that the 4 cylindrical detectors collect $\bar{\nu}_e$ data with baselines from 1 to 8 meters. Several possible source locations have been studied, each giving a different spatial coverage of $P_{ee}(L)$. We choose “Point B” in the jargon of Ref. [7], which is located halfway between two of the detectors, and samples 2 principal baselines. It provides superior sensitivity for $\delta m^2 \sim 1 \text{ eV}^2$ with an oscillation length of about 6.5 meters. The no oscillation signal event rate is about 38,000 in one year after accounting for the 66.3% decrease in source activity over a one-year period [7]. Event distributions as a function of baseline are shown in the right panel of Fig. 1; the detector energy and position resolutions are $9\%/\sqrt{E(\text{MeV})}$ and 15 cm, respectively [7]. Depending on the energy window used, the reactor neutrino background is expected

to lie between 22,000–32,000 events per year. However, this large background can be controlled because its shape will be known.

We take the detectors to be identical and adopt the following χ^2 for our analysis [7]:

$$\chi^2 = \sum_{i,j} \frac{(N_{i,j}^{\text{ex}} - N_{i,j}^{\text{th}})^2}{N_{i,j}^{\text{ex}}(1 + \sigma_b^2 N_{i,j}^{\text{ex}})} + \left(\frac{\alpha_s}{\sigma_s}\right)^2 + \left(\frac{\alpha_r}{\sigma_r}\right)^2, \quad (3)$$

where $N_{i,j}^{\text{ex}}$ is a simulated dataset and $N_{i,j}^{\text{th}}$ is the theoretical expectation for a given set of oscillation parameters, and i and j run over position and visible energy bins, respectively. $\sigma_s = 0.01$ and $\sigma_r = 0.01$ are the normalization uncertainties in the signal and reactor background fluxes, respectively, and $\sigma_b = 0.02$ is the bin-to-bin uncertainty [7]. α_s and α_r are nuisance parameters that are allowed to float. N^{ex} and N^{th} are given by

$$N_{i,j}^{\text{th/ex}} = (1 + \alpha_s) \tilde{S}_{i,j}^{\text{th/ex}} + (1 + \alpha_r) \tilde{R}_{i,j}, \quad (4)$$

where $\tilde{S}$ and $\tilde{R}$ ($= 28,000/\text{year}$) are the number of signal events from the source and the number of reactor background events, respectively.

The number of signal events (in all 4 detectors) with sterile neutrino oscillations is obtained by scaling the number of events for the 3ν case:

$$\tilde{S}_{i,j}^{\text{th}} = P_{ee}(L_i, E_\nu) S_{i,j}^{3\nu} \quad \text{with } S_{i,j}^{3\nu} = N_{\text{tot}} \frac{\Delta n}{\Delta E_{\text{vis}}} \bigg|_i \frac{\Delta n}{\Delta L} \bigg|_j, \quad (5)$$

where $\Delta n/\Delta E_{\text{vis}}$ and $\Delta n/\Delta L$ are normalized event distributions binned in visible energy and position, respectively, and $N_{\text{tot}} = 38,000$ is the total number of events for the 3ν case in one year. The positron's energy in an inverse neutron β -decay event is $E_\nu - (m_n - m_p)$. Subsequent pair annihilation in the scintillator produces visible energy,

$$E_{\text{vis}} = E_\nu - (m_n - m_p) + m_e \simeq E_\nu - 0.8 \text{ MeV}. \quad (6)$$

4. 3 + 1

We checked that in the 3 + 1 scenario our procedure yields a 95% confidence level (C.L.) sensitivity that is comparable to that of Ref. [7] for $\delta m_{41}^2 < 2 \text{ eV}^2$. The oscillation amplitude that fits the global SBL data is given by

$$\sin^2 2\theta_{\text{SBL}} = 4|U_{e4}|^2 |U_{\mu 4}|^2. \quad (7)$$

Daya Bay data could push $|U_{e4}|$ down far enough that the value of $|U_{\mu 4}|$ needed to obtain an amplitude that explains the SBL data could conflict with the current bound on $|U_{\mu 4}|$ shown in the left panel of Fig. 2.

Since a meter-baseline measurement at Daya Bay will be independent of the earlier data, it is reasonable to impose the constraint on $U_{\mu 4}$ as a prior. Then, Daya Bay can rule out most of the allowed region from a fit to LSND and MiniBooNE antineutrino data; see the right panel of Fig. 2.

5. 3 + 2 and 1 + 3 + 1

We first consider Daya Bay's sensitivity to the 5ν scenario without recourse to specific points, models or fits. We employ a grid in the $(\delta m_{41}^2, \delta m_{51}^2, |U_{e4}|, |U_{e5}|)$ parameter space, place a prior on the size of the mixing, $\min(|U_{e4}|, |U_{e5}|) = |U|_{\text{min}}$ in steps of size 0.01 from 0.10 to 0.15, and suppose a null result at Daya Bay. The 95% C.L. sensitivity in the $(\delta m_{41}^2, \delta m_{51}^2)$ plane is shown in Fig. 3. As

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