PROCEEDINGS OF SCIENCE

Search for a Light Sterile Neutrino at Daya Bay

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The Daya Bay reactor neutrino experiment's unique configuration of multiple baselines from six 2.9 GW_{th} nuclear reactors to eight antineutrino detectors deployed in two near (effective baselines $\sim$500 m and $\sim$600 m) and one far ($\sim$1600 m) underground experimental halls makes it possible to test for oscillations to a fourth (sterile) neutrino in the 10^{-3} eV^2 $< |\Delta m^2_{41}| <$ 0.3 eV^2 range. In this talk, I will present Daya Bay's latest results on the search for light sterile neutrino mixing. The relative spectral distortion due to the disappearance of electron antineutrinos was found to be consistent with that of the three-flavor oscillation model. The resulting limits on $\sin^2 2\theta_{14}$ constitute the world's best in most of the sub-eV mass region.

38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA

*Speaker.

PoS(ICHEP2016)946

1. Introduction

The three-neutrino mixing framework, in which the flavor eigenstates (ν_e, ν_μ, ν_τ) mix with the mass eigenstates (ν_1, ν_2, ν_3) via the PMNS matrix has been extremely successful in explaining the results observed in most solar, atmospheric, reactor and long-baseline accelerator neutrino oscillation experiments. Despite this success, the hunt for the possible existence of additional neutrinos is actively pursued.

In the simplest extension of the Standard Model where only one sterile neutrino is considered in addition to the three active ones, if the neutrino mass is much smaller than its momentum, the probability that an $\bar{\nu}_e$ produced with energy E is detected as an $\bar{\nu}_e$ after traveling a distance L is given by

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - 4 \sum_{i=1}^{3} \sum_{j>i}^{4} |U_{ei}|^2 |U_{ej}|^2 \sin^2 \Delta_{ji}, \tag{1.1}$$

where U_{ei} is the element of the neutrino mixing matrix for the eigenstate ν_e and the mass eigenstate ν_i, $\Delta_{ji} = 1.267 \Delta m^2_{ji} (\mathrm{eV}^2) \frac{L(\mathrm{m})}{E(\mathrm{MeV})}$ and $\Delta m^2_{ji} = m^2_j - m^2_i$ is the mass-squared difference between the mass eigenstates ν_j and ν_i.

When $|\Delta m^2_{41}| \gg |\Delta m^2_{31}|$, the parameters $\Delta m^2_{41}, \Delta m^2_{42}$ and Δm^2_{43} are virtually indistinguishable, and Eq. 1.1 can be approximated to

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 \; - \; \sin^2 2\theta_{14} \sin^2 \Delta_{41} - \sin^2 2\theta_{13} \sin^2 \Delta_{31}. \tag{1.2}$$

Thus, to first order, evidence for light sterile neutrino mixing consists of an additional spectral distortion with a frequency different from standard three-neutrino oscillations.

2. Daya Bay Experiment

The Daya Bay Reactor Neutrino Experiment is designed to precisely measure the neutrino mixing angle θ_{13}, via the relative comparison of antineutrino rates and energy spectra at different baselines. Two near underground experimental halls (EH1 and EH2) and one far hall (EH3) houses a total of eight functionally identical antineutron detectors (ADs) in the configuration shown in Fig. 1. The results of this work is derived from the first 217 days of data acquired with six ADs deployed, and an additional 404 days with all eight ADs in operation.

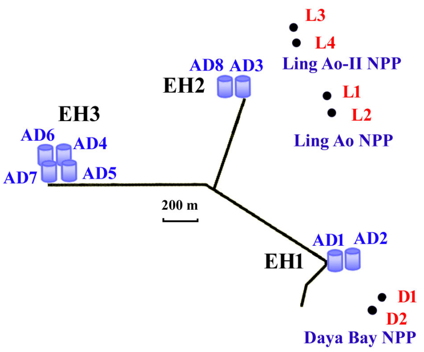

Figure 1: Layout of the Daya Bay experiment. The dots represent reactor cores, labeled as D1, D2, L1, L2, L3 and L4. The Daya Bay experiment started data-taking with six antineutrino detectors (AD1-AD6) installed in three experimental halls (EH1-EH3). In Oct 2012, two additional detectors (AD7 and AD8) were installed in EH3 and EH2, respectively.

Reactor antineutrinos are detected via the inverse beta decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. The IBD candidates used for this light sterile neutrino search is identical to the data set that was used in Daya Bay's θ_{13} measurement [1]. A summary of the IBD candidates for the 6-AD and 8-AD periods, together with the estimated background levels and the baselines of the three experimental halls to each pair of reactor cores, is shown in Table 1.

Table 1: Summary of total number of IBD candidates and backgrounds, and baselines of the three experimental halls to the reactor pairs. Statistical and systematic errors are included.

Site	IBD candidates		Backgrounds		Mean Distance to Reactor Cores (m)		
	(6-AD)	(8-AD)	(6-AD)	(8-AD)	Daya Bay	Ling Ao	Ling Ao-II
EH1	205135	408678	4076.6 ± 462.4	7547.9 ± 908.0	365	860	1310
EH2	93742	383402	1580.3 ± 147.8	5791.2 ± 586.5	1348	481	529
EH3	41348	108907	1878.9 ± 94.6	2105.2 ± 208.1	1909	1537	1542

The search for sterile neutrino mixing at Daya Bay is carried out through a relative comparison of the antineutrino rates and energy spectra at the three experimental halls. The unique configuration of multiple baselines to three pairs of nuclear reactors allows exploration of Δm^2_{41} spanning more than three orders of magnitude. Fig. 2 shows the ratios of the observed prompt energy spectra at EH2 and EH3 to the best fit prediction from EH1 in the three-neutrino case. In this figure, the data are compared with the four-neutrino mixing scenario assuming $\sin^2 2\theta_{14} = 0.05$ for two representative Δm^2_{41} values, illustrating that the sensitivity at $\Delta m^2_{41} = 4 \times 10^{-2} (4 \times 10^{-3})$ eV^2 originates primarily from the relative spectral shape comparison between EH1 and EH2 (EH3).

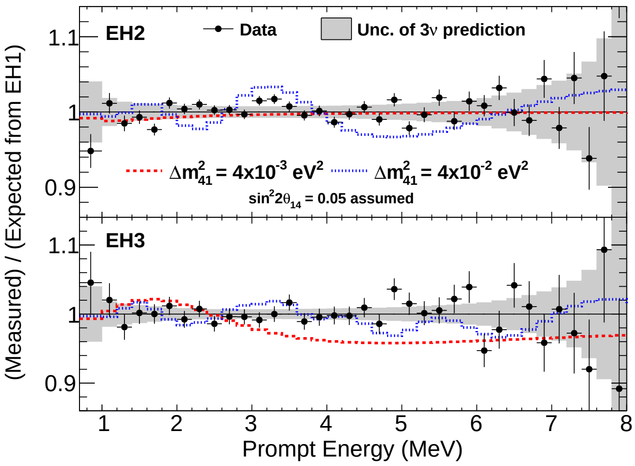

Figure 2: Prompt energy spectra observed at EH2 (top) and EH3 (bottom), divided by the prediction from EH1 with the three-neutrino best fit oscillation parameters from the Daya Bay analysis [1]. The gray band represents the one-standard-deviation uncertainty of the three-neutrino oscillation prediction. Predictions with $\sin^2 2\theta_{14} = 0.05$ and two representative Δm^2_{41} values are also shown as the dotted and dashed curves.

3. Results

The minimum χ^2 value obtained with a free-floating Δm^2_{41}, $\sin^2 2\theta_{14}$ and $\sin^2 2\theta_{13}$ is $\chi^2_{4\nu}/\mathrm{NDF} = 129.1/145$, where NDF stands for the number of degrees of freedom. The corresponding value in the three-neutrino scenario, in which $\sin^2 2\theta_{13}$ is the only free parameter, is $\chi^2_{3\nu}/\mathrm{NDF} = 134.7/147$. The p-value of observing $\Delta\chi^2 = \chi^2_{3\nu} - \chi^2_{4\nu} = 5.6$ without sterile neutrino mixing is determined to be 0.41 using a large sample of Monte Carlo pseudo-experiments. No apparent signature for sterile neutrino mixing is observed.

The limits in the $(|\Delta m^2_{41}|, \sin^2 2\theta_{14})$ plane are set by two independent approaches, the first of which follows the Feldman-Cousins method [2], the second approach uses the $\mathrm{CL_s}$ statistical method [3, 4]. Fig. 3 shows the 95% exclusion contours from both methods. These results set the most stringent limits to date on $\sin^2 2\theta_{14}$ in the $2\times10^{-4}\ \mathrm{eV}^2 \lesssim |\Delta m^2_{41}| \lesssim 0.2\ \mathrm{eV}^2$ region.

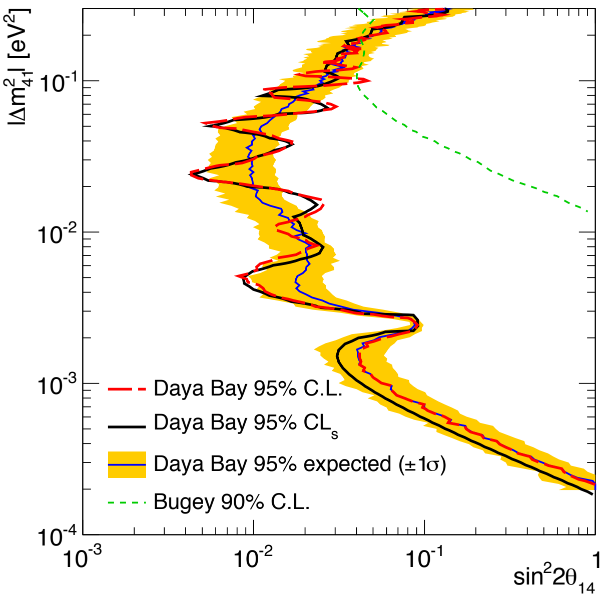

Figure 3: Exclusion contours in the $(\sin^2 2\theta_{14}, |\Delta m^2_{41}|)$ plane, under the assumption of $\Delta m^2_{32} > 0$ and $\Delta m^2_{41} > 0$. The red long-dashed curve represents the 95% C.L. exclusion contour with the Feldman-Cousins method [2]. The black solid curve represents the 95% $\mathrm{CL_s}$ exclusion contour [3]. The expected 95% C.L. 1σ band in yellow is centered around the sensitivity curve, shown as a thin blue line. The region of parameter space to the right side of the contours is excluded. For comparison, Bugey's [5] 90% C.L. limit on $\overline{\nu}_e$ disappearance is also shown as the green dashed curve.

References

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