Hunts for Light Sterile Neutrino

Constraining θ_{14} with Daya Bay and other reactor ν experiments

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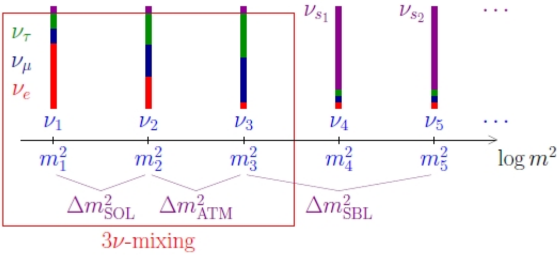
Overview

One could naturally imagine additional sterile neutrinos, which are neutral leptons with no ordinary weak interactions except those induced by mixing. In principle they can have any mass.



One of the strong theoretical motivation for the existence of sterile neutrinos is the generation of ν masses, which introduces the **right-handed neutrinos**, which is expected not to take part in any kind of interactions (except those induced by mixing with active left-handed neutrinos.)

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According to Seesaw Mechanism, the mass of usual active (left-handed) neutrinos is related to the mass sterile neutrino:

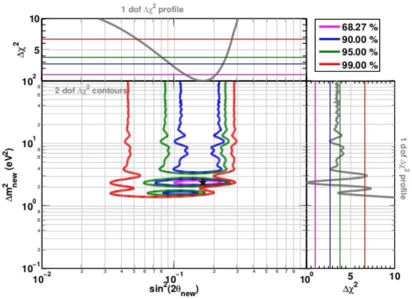
$$m_\nu \propto \frac{1}{M_R},$$

Therefore, traditionally, the mass of sterile neutrino is expected to be very large (could be as large as $O(10^{15})$ GeV).

However, there may also exist light sterile neutrinos, which have larger mixings with the active neutrinos and may affect the ν oscillation phenomena.

The Reactor Anomaly

In 2011, a new reactor flux (ν/fission) has been provided. The new calculation reveals that the flux is higher than what was previously expected.
This implies that reactor neutrino experiments should have totally observed a deficit of $\bar{\nu}_e$ of 6%, which may suggest one more oscillation term, corresponding to large Δm^2_{41}.



$$\sin^2(2\theta_{14}) = 0.14 \pm 0.08 \pm 0.04, |\Delta m^2_{41}| > 1.5\mathrm{eV}^2$$

G.Mention et al. (**arXiv:1101.2755**), a global fit of available data including combination of reactor experiments, MiniBooNE reanalysis, etc.

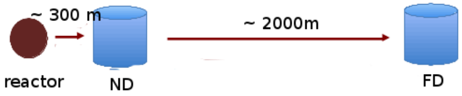
The Reactor Anomaly is disappearance anomaly —
Less $\bar{\nu}_e$ are observed than predicted by the calculation.

This may come from the uncertainties in nuclear physics,
(P.Huber **arXiv:1106.0687**)

or from the new physics in neutrino (eg. mixing with sterile neutrinos).
More experiments are required before making any conclusions.

The Daya Bay Experiment

The strategy of Daya Bay and other long baseline reactor experiments



$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 (\frac{\Delta m_{31}^2 L}{4E})$$

By comparing P_{ee}^{Near} and P_{ee}^{Far}, the value of θ_{13} can be measured.

The relative measurement of Daya Bay (and also Reno) with multiple baselines has the benefit of

- Cancel absolute reactor flux uncertainty;
- Cancel absolute detector efficiency uncertainty.

Thus Daya Bay and Reno can measure θ_{13} very precisely.
However, it is not the case in measuring sterile neutrino mixing, which relates to the absolute normalization.

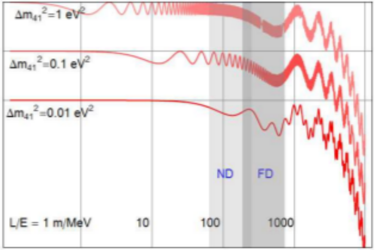
Sterile Neutrino Measurement in Daya Bay

If we take the 4th neutrino into account, then

$$P_{ee} = 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2(\frac{\Delta m^2_{31}L}{4E}) - \sin^2 2\theta_{14}\sin^2(\frac{\Delta m^2_{41}L}{4E}) \qquad (1)$$

However, according to the LSND and previous reactor anomaly result, Δm^2_{41} is expected to be larger than 0.1 eV^2. The sterile oscillation is expected to be too fast to be observed ($\phi_{\mathrm{osc}} \equiv \frac{\Delta m^2_{41}L}{4E} \gg 2\pi$).

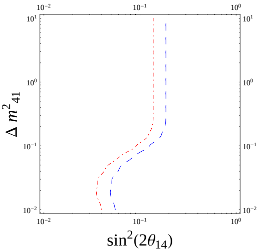
arXiv:1303.6173



In this case, $\sin^2(\frac{\Delta m^2_{41} L}{4E})$ would be just averaged out.

$$P_{ee} \Rightarrow P_{ee,\mathrm{avg}} = 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2(\frac{\Delta m^2_{31} L}{4E}) - \frac{1}{2}\sin^2 2\theta_{14} \qquad (2)$$

The last oscillation term is independent on the value of L/E, which means that $\sin^2(2\theta_{14})$ cannot be measured by the comparison of near and far detectors.



(simulation from GLoBES)

Data Analysis

We analyzed the previous data of Daya Bay

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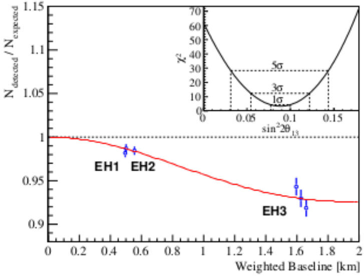


with the equation

$$P_{ee} = 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2(\frac{\Delta m^2_{31}L}{4E}) - \sin^2 2\theta_{14}\sin^2(\frac{\Delta m^2_{41}L}{4E})$$

† The absolute normalization factor of Daya Bay is not determined yet. I just used a normalization error to constrain the floating of $N_{\mathrm{detected}}/N_{\mathrm{expected}}$.

Normalization Uncertainties

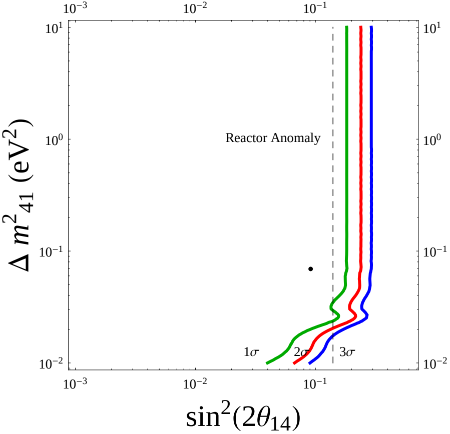
The Uncertainties

Detector Related			
Correlated		Uncorrelated	
Combined	1.9%	Combined	0.2%

Reactor Related			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power(W_{th})	0.5%
IBD reaction/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

In the relative measurement of θ_{13}, only the uncorrelated sys errors and the stat errors are concerned.
However, if Δm^2_{41} is > 0.1 eV^2, the dominant errors would be the correlated normalization error. The official value of the combined reactor-related error is around 3%.

Analyzed the data with the "dybOscar" package (from Maxim Gonchar, Dmitry Naumov, Wei Wang), with 3.5% overall normalization error.

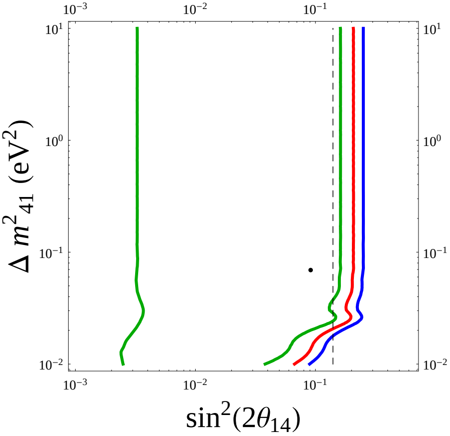


R.H.S of the curves is the excluded area.

Our best fit value : $\sin^2 2\theta_{14} = 0.088$.

Vertical black dash line represents the best-fit value from the first Reactor Anomaly paper, $\sin^2 2\theta_{14} = 0.14$ (G.Mention et al. **arXiv:1101.2755**)

In the optimistic case, the overall normalization error could be reduced to around 2.76%.



The allowed ranges of $\sin^2 2\theta_{14}$–Δm^2_{41}.

We still cannot rule out the reactor anomaly, but may be able to exclude a zero value for $\sin^2 2\theta_{14}$ with a significance of 1 - 2 σ?

Summary

- The reactor anomaly further suggests the existence of light sterile neutrino. However more experiments are required to clarify the picture.
- Long baseline reactor experiments like Daya Bay, Reno may be able to measure $\Delta m^2_{\mathrm{sterile}}$, but they may be able to offer the upper bound of the mixing angle θ_{14}.
- The overall normalization error is important in our sensitivity. If it could be reduced, Daya Bay can constrain θ_{14} in a smaller range. At the moment my analysis suggests that the best-fit value of θ_{14} could be slightly smaller than the first reactor anomaly paper suggest.
- In theory, small Δm^2_{41} could also exist. In this case, Daya Bay and Reno could measure the sterile neutrino oscillation much better.

Thank You

Appendix–LEP Experiment

$$N_\nu = \frac{\Gamma_{\text{invs}}}{\Gamma_{l\bar{l}}} \left(\frac{\Gamma_{l\bar{l}}}{\Gamma_{\nu\bar{\nu}}} \right)_{\text{SM}}$$

l stands for the leptons. Γ_{invs} is the so-called invisible width, which represents the Z-decays into neutri- nos (and maybe other invisible particles). $\frac{\Gamma_{\text{invs}}}{\Gamma_{l\bar{l}}}$ is measured by the experiment but $\left(\frac{\Gamma_{l\bar{l}}}{\Gamma_{\nu\bar{\nu}}} \right)_{\text{SM}}$ is calculated according to the Standard Model.

Appendix–LSND result

In the past 10 years, more and more hints suggest the possible existence of light ν_s.

The first evidence is from the LSND experiment.

- $$P_{\alpha\beta} \simeq \sin^2 2\theta_{\alpha\beta} \sin^2 \frac{\Delta m^2 L}{4E},$$
  $$P_{\alpha\alpha} \simeq 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta m^2 L}{4E}.$$

  The value of L/E in LSND is in the order 1 m/MeV, which is too small for Δm_{21}^2 and Δm_{31}^2 to produce any significant oscillation.
- The data from **LSND** experiment, found indication that a $\bar{\nu_\mu} \to \bar{\nu_e}$ oscillation with $\Delta \mathrm{m}^2 \sim 0.3$ - 6 eV^2.
  (A.Aguilar [LSND Collaboration] **hep-ex/0104049**)

  Three mass-square splittings, $\Delta \mathrm{m}^2_{\mathrm{LSND}} \gg \Delta \mathrm{m}^2_{\mathrm{atm}} \gg \Delta \mathrm{m}^2_{\mathrm{sol}}$, thus (at least) a fourth light neutrino state is necessary.

Appendix–RH ν, Dirac and Majorana mass term

(a) Right-handed (b) Left-handed

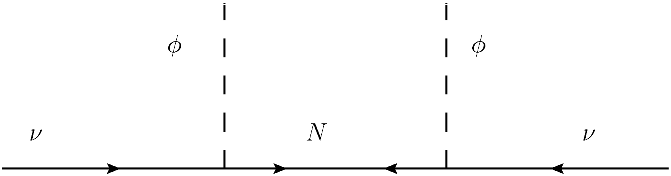
$$\mathcal{L}_{\text{Dirac}} \sim Y_{\alpha\beta} H \bar{\nu}_{L\alpha} \nu_{R\beta}, \quad \text{cannot explain the smallness of } m_\nu.$$

$$\mathcal{L}_{\text{Majorana}} \sim \overline{\nu^c}_{R\alpha} M_{R_{\alpha\beta}} \nu_{R\beta}, \quad \text{can produce a small } m_\nu.$$

Appendix–Seesaw

Including both the Dirac and Majorana mass terms, the mass terms of neutrino are given by

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Mass}} &= \bar{\nu}_{L\alpha} M_{D_{\alpha\beta}} \nu_{R\beta} + \frac{1}{2} \overline{\nu^c}_{R\alpha} M_{R_{\alpha\beta}} \nu_{R\beta} + h.c. \\
&= \frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \overline{\nu^c}_R \end{pmatrix} \begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} + h.c.
\end{aligned}
$$



Appendix–Normalization Uncertainties

$$\chi^2 = \sum_{d=1}^{6} \frac{[M_d - T_d(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \epsilon_d) + \eta_d]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6} (\frac{\epsilon^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}) \quad (3)$$

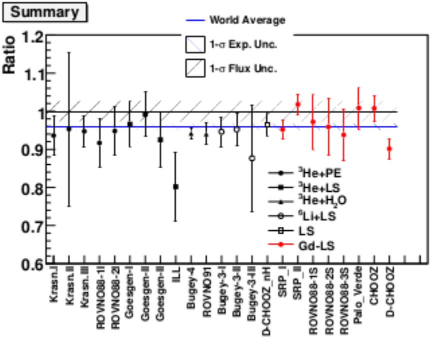
$\Rightarrow$

$$\chi^2 = \sum_{d=1}^{6} \frac{[M_d - T_d(1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \epsilon_d) + \eta_d]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6} (\frac{\epsilon^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}) + \frac{\varepsilon^2}{\sigma_{\mathrm{norm}}^2} \quad (4)$$

Appendix–Update of Reactor Anomaly

Recently, C.Zhang et al. reanalyzed the reactor anomaly with the updated reactor experiments data. The the absolute ratio ($N_{\rm obs}/N_{\rm pred}$) of Double CHooz, and the best-fit value of $\sin^2(2\theta_{13}) = 0.089$ obtained in Daya Bay are also taken into account.

C.Zhang, X.Qian and P.Vogel (**arXiv:1303.0900**)



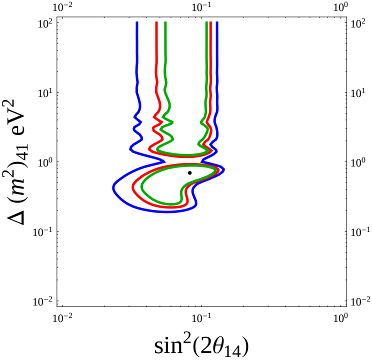
The updated average deficit of $\bar{\nu}_e$ is reported to be 0.959, which means that the significance of reactor anomaly is weakened.

Appendix–Update of Reactor Anomaly

Using the updated reactor experiment data from **arXiv:1303.0900**, and the following equation,

$$\chi^2(\theta_{14}, \Delta m_{41}^2) = [P(\theta_{14}, \Delta m_{41}^2) - R]^T W^{-1} [P(\theta_{14}, \Delta m_{41}^2) - R].$$

(Where R is the absolute ratio ($N_{\mathrm{obs}}/N_{\mathrm{pred}}$), W is the covariance matrix which describes the correlation between different reactor experiments. **arXiv:1303.0900**)



$\sin^2(2\theta_{14}) = 0.082$

Appendix–The average of probability

$$\langle P_{\alpha\beta}\rangle = \frac{1}{2}\sin^2 2\theta[1 - \langle\cos(\frac{\Delta m^2 L}{2E})\rangle] \qquad (\alpha \neq \beta),$$

where $\langle\cos(\frac{\Delta m^2 L}{2E})\rangle = \int \cos(\frac{\Delta m^2 L}{2E})\phi(\frac{L}{E})d\frac{L}{E}$,

we consider the simplest case,

$$\phi(\frac{L}{E}) = \frac{1}{\sqrt{2\pi}\sigma_{L/E}}\exp[\frac{(L/E - \langle L/E\rangle)^2}{2\sigma^2_{L/E}}], \qquad \text{with } (\frac{\sigma_{L/E}}{\langle L/E\rangle})^2 = (\frac{\sigma_L}{\langle L\rangle})^2 + (\frac{\sigma_E}{\langle E\rangle})^2;$$

Therefore

$$\langle\cos(\frac{\Delta m^2 L}{2E})\rangle = \cos(\frac{\Delta m^2}{2}\langle\frac{L}{E}\rangle)\exp[-\frac{1}{2}(\frac{\Delta m^2}{2}\sigma_{L/E})^2].$$

C.Giunti and C.W.Kim, (text book) **Fundamentals of Neutrino Physics and Astrophysics**

Appendix–If Δm^2_{41} is small

Despite the LSND result, there are also literatures focus on small Δm^2_{41} **(arXiv:0809.5076, arXiv:1303.6173)**.

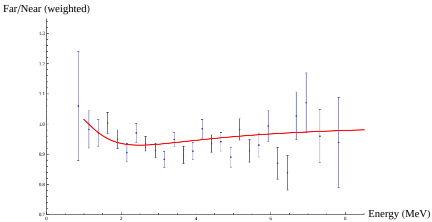
If Δm^2_{41} is at the order of 10^{-2} eV^2, Daya Bay may be able to measure it. $\phi_{\mathrm{near}} = \dfrac{1.27 \times 0.01 \times 300}{E} \sim \pi$, $\phi_{\mathrm{far}} = \dfrac{1.27 \times 0.01 \times 2000}{E} \gg \pi$,

which means

$$\frac{P_{\mathrm{near}}}{P_{\mathrm{far}}} \sim \frac{1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2(\frac{\Delta m^2_{31}L}{4E}) - \sin^2 2\theta_{14}\sin^2(\frac{\Delta m^2_{41}L}{4E})}{1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2(\frac{\Delta m^2_{31}L}{4E}) - \frac{1}{2}\sin^2 2\theta_{14}}$$

The relative measurement and the future shape analysis may help at this point.

Appendix–If Δm^2_{41} is small



If there exists fourth neutrino, and $\Delta \mathrm{m}^2_{41} = 0.025\ \mathrm{eV}^2$, $\sin^2 2\theta_{14} \sim 0.1$,