Constraints on the Solar $\Delta m^2$ using Daya Bay & RENO

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We demonstrate that the currently running short baseline reactor experiments, especially Daya Bay, can put a significant upper bound on $\Delta m^2_{21}$. This novel approach to determining $\Delta m^2_{21}$ can be performed with the current data of both Daya Bay & RENO and provides additional information on $\Delta m^2_{21}$ in a different $L/E$ range ($\sim 0.5$ km/MeV) for an important consistency check on the 3 flavor massive neutrino paradigm. A measurement by Daya Bay and limit by RENO will be the only new information on this important quantity until the medium baseline reactor experiment, JUNO, gives a very precise measurement early in the next decade.

I. INTRODUCTION

The fact that neutrinos have mass and mix is now well established by a large number of experiments. In this paper we concentrated on the mass difference squared between the two mass eigenstates that have the most electron neutrino, $\nu_1$ and $\nu_2$. The splitting between these two neutrinos, $\Delta m^2_{21} \equiv m_2^2 - m_1^2$, is responsible for the (anti-) neutrino oscillations observed at an $L/E = 15$ km/MeV and for the neutrino flavor transformations inside the Sun, hence the name the solar mass squared difference.

In this paper, we demonstrate that the currently running short baseline ($\sim 1.5$ km) reactor anti-neutrino experiments, Daya Bay [1] and RENO [2] both have enough data already collected to constrain $\Delta m^2_{21}$ to be less than 3 times the KamLAND central value ($7.5 \times 10^{-5}$ eV$^2$). By the end of the running time of these experiments, they will be able to constrain this parameter to less than twice the KamLAND value. Setting a lower limit maybe possible for the Daya Bay experiment with improvements on their systematic uncertainties. Upper, and maybe lower, limits from Daya Bay and RENO, will add independent information to our knowledge of $\Delta m^2_{21}$ and provide an important consistency check of the 3 flavor massive neutrino paradigm. While not capable of directly addressing the $\sim 2\sigma$ tension between KamLAND [3] reactor experiment ($L/E \sim 50$ km/MeV) and the combined Super KamiokANDE [4] & Sudbury Neutrino Observatory [5] solar neutrino measurements of $\Delta m^2_{21}$, measurements of $\Delta m^2_{21}$ by Daya Bay and RENO are at a different $L/E$ range ($\sim 0.5$ km/MeV) than previous measurements. Furthermore, the ratio of $\Delta m^2_{21}$ to $\Delta m^2_{31}$, at $L/E \sim 0.5$ km/MeV, is needed by the long baseline $\nu_e$ appearance experiments for the precision measurement of leptonic CP violation.

Currently the best measurement of the solar mass squared difference, $\Delta m^2_{21}$, is from the long baseline reactor anti-neutrino experiment, KamLAND, which has determined

$$\Delta m^2_{21} = 7.50^{+0.20}_{-0.20} \times 10^{-5} \text{ eV}^2, \tag{1}$$

see [3]. The only other measurement of $\Delta m^2_{21}$ comes from a combined measurement using the solar neutrino experiments principle Super Kamiokande (SK) and Sudbury Neutrino Observatory (SNO). This combined measurement is

$$\Delta m^2_{21} = 5.1^{+1.3}_{-1.0} \times 10^{-5} \text{ eV}^2, \tag{2}$$

from SNO [5]. Similar results can be found in SK [4] and Nu-Fit [6]. This solar neutrino determination of $\Delta m^2_{21}$ comes from the non-observation of the low energy up turn of the $^8$B neutrino survival probability by both SNO and SK and the observation of a day-night asymmetry by SK.

CPT invariance implies that the $\Delta m^2_{21}$ measured in reactor anti-neutrinos and solar neutrinos should be identical. However, at the $2\sigma$ level there is some tension between these two determinations of this important quantity. This tension could arise from a statistical fluctuation, some error in the analysis of one or more of the experiments or new physics.

Moreover, $\Delta m^2_{21}$ is an important parameter for the determination of the CP-violating phase, $\delta$, in the

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long baseline neutrino\(^1\) oscillation experiments (T2K [7], NOvA [8], DUNE [9], T2HK [10], T2HKK [11]) as the size of the CP violation is proportional to \(\Delta m_{21}^2\), as well as other parameters. In vacuum, at the first oscillation peak, \(L/E \sim 0.5 \text{ km/MeV}\), for \(\nu_\mu \rightarrow \nu_e\):

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) \approx \pi J \left( \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right)
\]

where \(J = \sin 2\theta_{13} \sin 2\theta_{12} \cos \delta \approx 0.3 \sin \delta\) is the Jarlskog invariant.

T2K\’s data point in the bi-event plane, see Fig 44 of [12],

\[N(\nu_\mu \rightarrow \nu_e) = 37 \quad \text{and} \quad N(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4\]

being outside the allowed region (by about 1 \(\sigma\)) could be caused by \(\Delta m_{21}^2\) being larger than KamLAND value, twice the KamLAND central value works well. Again, it is probably a statistical fluctuation but with only one precision measurement of \(\Delta m_{21}^2\), other possibilities are not completely excluded.

The future medium baseline reactor experiment JUNO (\(L/E \sim 15 \text{ km/MeV}\)) will measure \(\Delta m_{21}^2\) and \(\sin^2 \theta_{12}\) with better than 1\% precision, [13]. However, this experiment is under construction and the precision measurements of the solar neutrino oscillation parameters will not be available until approximately 5 years from now. In more than a decade from now, the DUNE & HyperK proposed experiments will make a precise measurement of \(\Delta m_{21}^2\) using solar neutrinos, see [14] and [15] respectively.

In section II, we discuss in detail the effects of changing \(\Delta m_{21}^2\) on the oscillation probability. Then in section III we explain and give the results of a simulation of both Daya Bay and RENO using 3000 live days of data with and without systematic uncertainties followed by a conclusion.

II. OSCILLATION PROBABILITY

The electron antineutrino disappearance probability, in vacuum, can be written as

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - P_{13} - P_{12} \quad \text{with}\]

\[
P_{13} = \sin^2 2\theta_{13} \left( \cos^2 \theta_{12} \sin^2 \Delta_{23} + \sin^2 \theta_{12} \sin^2 \Delta_{32} \right),
\]

\[
P_{12} = \sin^2 2\theta_{12} \cos^2 \theta_{13} \sin^2 \Delta_{21},
\]

where \(\theta_{12} \approx 33^\circ\) and \(\theta_{13} \approx 8^\circ\) are the solar and reactor mixing angles respectively and the kinematic phases are given by \(\Delta_{jk} \equiv \Delta m_{jk}^2 L/(4E)\). The \(P_{13}\) term is associated with the atmospheric oscillation scale of 0.5 km/MeV, and the \(P_{12}\) term is associated with the solar oscillation scale of 15 km/MeV.

Using typical fit values and considering a \(L/E\) range around the first oscillation minimum (\(L/E = 0.5 \text{ km/MeV}\)), we can approximate \(P_{13}\) and \(P_{12}\) as follows:

\[
P_{13} \approx 0.08 \sin^2 \left( \frac{\pi}{2} \left( \frac{L/E}{0.5 \text{ km/MeV}} \right) \right)
\]

\[
P_{12} \approx 0.002 \left( \frac{L/E}{0.5 \text{ km/MeV}} \right)^2 \left( \frac{\Delta m_{21}^2}{7.5 \times 10^{-5} \text{ eV}^2} \right)^2.
\]

For \(\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2\), the \(P_{12}\) term is essentially negligible for all \(L/E < 1 \text{ km/MeV}\). This encompasses the \(L/E\) range of all current short baseline experiments. However, consider the case that \(\Delta m_{21}^2\) is 3 times larger than this value, i.e. \(22.5 \times 10^{-5} \text{ eV}^2\), then

\[
P_{12} \approx 0.02 \left( \frac{L/E}{0.5 \text{ km/MeV}} \right)^2 \left( \frac{\Delta m_{21}^2}{22.5 \times 10^{-5} \text{ eV}^2} \right)^2.
\]

\(P_{12}\) is now no longer negligible compared to \(P_{13}\) at oscillation minimum (\(L/E = 0.5 \text{ km/MeV}\)) and \(P_{12}\) gets larger for \(L/E > 0.5 \text{ km/MeV}\) whereas \(P_{13}\) is getting smaller. In fact, at \(L/E = 1 \text{ km/MeV}\), \(P_{12}\) would be as large as \(\sin^2 2\theta_{13} (0.08)\) for this value of \(\Delta m_{21}^2\).

Therefore the short baseline reactor experiments can constrain \(\Delta m_{21}^2\) to be less than 2 to 3 times the current best fit value depending on the experiment, Daya Bay or RENO, run time and the confidence level. Setting a lower bound on \(\Delta m_{21}^2\) will be challenging for these experiments due to systematic uncertainties. As data above \(L/E \sim 0.5 \text{ km/MeV}\) is important for this constrain, the Double Chooz experiment, which has no data with \(L/E > 0.5 \text{ km/MeV}\), is not considered.

Since the position of the first oscillation minimum for \(P(\bar{\nu}_e \rightarrow \bar{\nu}_e)\) is given by

\[
\frac{L}{E} \approx \frac{2\pi}{\Delta m_{ee}^2},
\]

where \(\Delta m_{ee}^2 \equiv c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2\) (at least for small \(\Delta m_{21}^2\)), it is natural to write the disappearance probability in terms of \(\Delta m_{ee}^2\) and \(\Delta m_{21}^2\) as follows, [16] \& [17]:

\[
1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} + \sin^2 2\theta_{13} \left( \sin^2 |\Delta_{ee}| + \sin^2 \theta_{12} \cos^2 \Delta_{21} \cos(2\Delta_{ee}) - \frac{1}{6} \cos 2\theta_{12} \sin^2 2\theta_{12} \Delta_{21}^2 \sin(2\Delta_{ee}) + O(\Delta_{21}^4) \right).
\]

For \(\Delta_{21} < 0.5\), only the first two of the terms of RHS of eq. (9) are larger than 0.005 and therefore relevant for the analysis\(^2\). Since the experiments of interest, Daya Bay

\(^2\) For small \(\Delta_{21}\), the disappearance probability depends on only three variables; \(\sin^2 \theta_{13}, \Delta m_{ee}^2\) and the combination \(\Delta m_{21}^2 \sin 2\theta_{12}\).
and RENO, have an $L/E < 1 \text{ km/MeV}$, the $\Delta_{21} < 0.5$ constraint corresponds to a $\Delta m^2_{21} < 4 \times 10^{-4} \text{ eV}^2$ or 5 times the KamLAND value of $7.5 \times 10^{-5} \text{ eV}^2$. Using additional terms of eq. (9) will extend the range of applicability.

For small values of $L/E (< 0.2 \text{ km/MeV})$, where there is large statistics from the near detectors,

$$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 4 \left[ s^2_{13} c^2_{13} + s^2_{12} c^2_{12} (\Delta m^{2}_{21}/\Delta m^{2}_{ee}) \right]^2 \times (\Delta m^{2}_{ee} L/4E)^2.$$  \hfill (10)

To keep the disappearance probability the same as we vary $\Delta m^{2}_{21}$, at these small $L/E$, we must keep the quantity in $[\cdots]$ in the above equation unchanged. If we also keep the position of the first minima fixed by holding $\Delta m^{2}_{ee}$ fixed (see eq. (8)), then

$$s^2_{13} + s^2_{12} c^2_{12} (\Delta m^{2}_{21}/\Delta m^{2}_{ee})^2 = \text{constant} \approx 0.021$$

or

$$s^2_{13} \approx 0.021 - 2 \times 10^{-4} \left( \frac{\Delta m^{2}_{21}}{7.5 \times 10^{-5} \text{ eV}^2} \right)^2$$  \hfill (11)

to leading order in $s^2_{13}$. So as we vary $\Delta m^{2}_{21}$ from KamLAND value of $7.5 \times 10^{-5} \text{ eV}^2$, we must also change $s^2_{13}$ from 0.021 so as to keep the combination in eq. (11) unchanged.

In Fig. 1, we show the electron anti-neutrino disappearance probability as a function of $L/E$, keeping the quantity given in eq. (11) fixed, as we vary $\Delta m^{2}_{21}$ in multiples of $7.5 \times 10^{-5} \text{ eV}^2$. Note that if $\Delta m^{2}_{21} > 3 \times 10^{-4} \text{ eV}^2$ then there is no minimum around $L/E \approx 0.5 \text{ km/MeV}$. The red points with error bars, represents the statistical uncertainties for a detector 1.6 km from a single reactor core which has $9 \times 10^5$ events. Clearly, an experimental setup with this number of events in the far detector, 1.6 km from a reactor core, will be able to set an upper limit smaller than 3 times the KamLAND central value for $\Delta m^{2}_{21}$ assuming systematic uncertainties are no larger than the statistical uncertainties. A lower limit on $\Delta m^{2}_{21}$ will be challenging.

In the rest of this paper, we report on a simulation of the setups for Daya Bay and RENO experiments, to estimate the constraints these experiments can place on $\Delta m^{2}_{21}$.

III. SIMULATIONS FOR DAYA BAY AND RENO USING GLOBES

Our sensitivity study on $\Delta m^{2}_{21}$ for the short baseline reactor experiments, Daya Bay and RENO, is performed using GLoBES [18]. In this study 3000 live days of data are assumed for both experiments and systematic uncertainties are taken into account as described in [19] for Daya Bay and [20] for RENO. Table I lists the effective baselines, $L_{\text{eff}}$, and the number of observed IBD $\bar{\nu}_e$ events per day used.

To find the best fit values of $\Delta m^{2}_{21}$ and $\sin^2(2\theta_{13})$, a $\chi^2$ formalism with pull parameters is constructed using the far-to-near ratio method to cancel out correlated systematic uncertainties. The $\chi^2$ is given by

$$\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \frac{(O_i^{F/N} - X_i^{F/N})^2}{U_i^{F/N}} + \sum_{r=1}^{6} \left( \frac{f}{\sigma_{\text{flux}}} \right)^2 + \left( \frac{\epsilon}{\sigma_{\text{eff}}} \right)^2 + \left( \frac{s}{\sigma_{\text{scale}}} \right)^2 + \sum_{d=N,F} \left( \frac{\mu_d}{\sigma_{\text{bkg}}} \right)^2,$$  \hfill (12)

where,

- $O_i^{F/N}$ is the observed far-to-near ratio of IBD $\bar{\nu}_e$ events in the $i$-th $E_{\bar{\nu}}$ bin,
TABLE I. $L_{\text{eff}}$ and observed IBD $\bar{\nu}_e$ rates for Daya Bay and RENO derived from the GLoBES settings used in this study.

|       | $L_{\text{eff}}$ (m) | Daya Bay | RENO |
|-------|----------------------|----------|------|
| Near  | (400.4, 512.6)       | 367.0    |      |
| Far   | 1610                 | 1440     |      |
| IBD $\bar{\nu}_e$ rate | Near | (1320, 1195) | 617.2 |
|       | Far                 | 297.8    | 61.35|

FIG. 2. (Color online) Contour plot of $\Delta m_{21}^2$ vs. $\sin^2 2\theta_{13}$ for the RENO experiment (left column) and Daya Bay (right column) without (top row) and with (bottom row) systematic uncertainties. 3000 live days of data with 61 & 298 IBD $\bar{\nu}_e$ events/day in the far detector were used, for RENO & Daya Bay respectively. Red, blue, and green lines represent 1σ, 2σ, and 3σ (2 dof) allowed regions, respectively. The point “×” is the input for the simulation given by eq. 13. In the bottom row, we also show the 1σ uncertainty band on $\Delta m_{21}^2$ from KamLAND (cyan) and SNO/SK (yellow), see eq. 1 and 2.
• $X^{F/N} = X_i^{F/N}(f, \epsilon, s, b^d, \theta_{13}, \Delta m_{21}^2)$ is the expected far-to-near ratio of IBD $\pi_\nu$ events for a given $\Delta m_{21}^2$ and $\theta_{13}$ pair,

• $U_i^{F/N}$ is the statistical uncertainty of $O_i^{F/N}$,

• $f, \epsilon, s,$ and $b^d$ are pull parameters for systematic uncertainties of neutrino flux ($\sigma_i^{\text{flux}}$), detection efficiency ($\sigma_i^{\text{eff}}$), energy scale ($\sigma_i^{\text{scale}}$), and background ($\sigma_i^{\text{bkg}}$), respectively.

The indices $r$ and $d$ represent $r$-th reactor and $d$-th detector, respectively. Both Daya Bay and RENO have six reactors. For Daya Bay, two near detector sets (N1 and N2) are used in the last pull term of the $\chi^2$ due to their differences in the baselines, backgrounds, and systematic uncertainties [19]. As a cross check of our simulations we have reasonably well reproduced the $\Delta m_{ee}^2$ vs. $\sin^2 2\theta_{13}$ sensitivity curves for both experiments.

True values used in the simulation are

$$\sin^2 \theta_{12} = 0.304, \quad \Delta m_{21}^2 = 7.65 \times 10^{-5} \text{ eV}^2,$$

$$\sin^2 (2\theta_{13}) = 0.085, \quad \Delta m_{31}^2 = 2.50 \times 10^{-3} \text{ eV}^2. \quad (13)$$

To minimize the $\chi^2$, expected values for different pairs of $\Delta m_{21}^2$ and $\sin^2 (2\theta_{13})$ are compared to the simulated signal $\pi_\nu$ data from 1.8 to 8 MeV with 31 energy bins.

Figure 2 shows the results of our simulation for contour plots of $\Delta m_{21}^2$ vs. $\sin^2 (2\theta_{13})$ sensitivities using 3000 live days of data for RENO and Daya Bay, respectively, without (top) and with (bottom) systematic uncertainties. Adding systematic uncertainties effects RENO less than Daya Bay, because after 3000 days of data taking, Daya Bay has $\approx 5$ times more events in the far detector(s) than RENO, see Table I. Clearly, both of these experiments can constrain $\Delta m_{21}^2$ to be less than two to three times the KamLAND central value, i.e. $\Delta m_{21}^2 < 15 - 22 \times 10^{-5}$ eV$^2$. Setting a lower limit on $\Delta m_{21}^2$ maybe possible with Daya Bay if modest improvements in their systematic uncertainties, over those used for this simulation, can be achieved. We encourage both Daya Bay and RENO to perform a measurement of $\Delta m_{21}^2$ using their more precise information on their experiments.

IV. CONCLUSION

We have argued that Daya Bay and RENO can add to the information of the solar mass squared difference, $\Delta m_{21}^2$, now. A simulation study for these experiments was performed with and without systematic uncertainties using GLoBES. We have found that $\Delta m_{21}^2$ can be reasonably well constrained by Daya Bay 3000 live days of data to be less than twice the KamLAND central value. Without systematic uncertainties Daya Bay can exclude $\Delta m_{21}^2 = 0$ with 1$\sigma$ confidence level but when current systematic uncertainties are included only an upper bound can be set. Until JUNO measures $\Delta m_{21}^2$ with great precision early next decade, we expect the $\Delta m_{21}^2$ measurement by Daya Bay can play an important role for the leptonic CP violation measurement by T2K and NOvA and provides an important consistency check on the 3 flavor massive neutrino paradigm. A truly realistic simulation and a true measurement of $\Delta m_{21}^2$ can only be performed by the short baseline reactor experiments, Daya Bay and RENO.

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