Constraints on the solar Δm^2 using Daya Bay and RENO data

Seon-Hee Seo*

Center for Underground Physics, Institute for Basic Science,
55 Expo-ro Yuseong-gu, Daejeon 34126, Korea

Stephen J. Parke†

Theoretical Physics Department, Fermi National Accelerator Laboratory,
P. O. Box 500, Batavia, Illinois 60510, USA

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We demonstrate that the currently running short baseline reactor experiments, especially Daya Bay, can put a significant upper bound on Δm_{21}^2 . This novel approach to determining Δm_{21}^2 can be performed with the current data of both Daya Bay and RENO and provides additional information on Δm_{21}^2 in a different L/E range (~ 0.5 km/MeV) for an important consistency check on the 3 flavor massive neutrino paradigm. Upper limits by Daya Bay and RENO and a possible lower limit from Daya Bay, before the end of 2020, will be the only new information on this important quantity until the medium baseline reactor experiment, JUNO, gives a very precise measurement in the middle of the next decade. In this study θ_{12} value is fixed since its impact on the Δm_{21}^2 measurement is relatively small as discussed in the Appendix.

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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, ν_1 and ν_2 . The splitting between these two neutrinos, $\Delta m_{21}^2 \equiv m_2^2 - m_1^2$, 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 (~ 1.5 km) reactor antineutrino experiments, Daya Bay [1] and RENO [2] both have enough data already collected (>2000 days) to constrain Δm_{21}^2 to be less than 3 times the KamLAND central value (7.5×10^{-5} eV²). By the end of the running time of these experiments, sometime in 2020, 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 Δm_{21}^2 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] and Sudbury Neutrino Observatory [5] solar neutrino measurements of Δm_{21}^2 , measurements of Δm_{21}^2 by Daya Bay and RENO are at a different L/E range (~ 0.5 km/MeV) than previous measurements. Furthermore, the ratio of Δm_{21}^2 to Δm_{31}^2 , at $L/E \sim 0.5$ km/MeV, is needed by the long baseline ν_e appearance experiments for the precision measurement of leptonic CP violation.

Currently the best measurement of the solar mass squared difference, Δm_{21}^2 , is from the long baseline reactor antineutrino experiment, KamLAND, which has determined

$$\Delta m_{21}^2 = 7.50_{-0.20}^{+0.20} \times 10^{-5} \text{ eV}^2, \quad (1)$$

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

$$\Delta m_{21}^2 = 5.1_{-1.0}^{+1.3} \times 10^{-5} \text{ eV}^2, \quad (2)$$

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

CPT invariance implies that the Δm_{21}^2 measured in reactor antineutrinos and solar neutrinos should be identical.

*sunny.seo@ibs.re.kr

†parke@fnal.gov

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However, at the 2σ 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, Δm_{21}^2 is an important parameter for the determination of the CP -violating phase, δ , in the long baseline neutrino¹ oscillation experiments (T2K [7], NOvA [8], DUNE [9], T2HK [10], T2HKK [11]) as the size of the CP violation is proportional to Δm_{21}^2 , as well as other parameters. In vacuum, at the first oscillation peak, $L/E \sim 0.5$ km/MeV, for $\nu_\mu \rightarrow \nu_e$:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \nu_e) \approx \pi J \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right) \quad (3)$$

where $J = \sin 2\theta_{12} \sin 2\theta_{13} \cos \theta_{13} \sin 2\theta_{23} \sin \delta \approx 0.3 \sin \delta$ is the Jarlskog invariant.

T2K's data point in the bievnet 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 1σ) could be caused by Δm_{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 Δm_{21}^2 , other possibilities are not completely excluded.

The future medium baseline reactor experiment JUNO ($L/E \sim 15$ km/MeV) will measure Δm_{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 and HyperK proposed experiments will make a precise measurement of Δm_{21}^2 using solar neutrinos, see [14,15] respectively.

In Sec. II, we discuss in detail the effects of changing Δm_{21}^2 on the oscillation probability. Then in Sec. 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

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

$$\begin{aligned} P_{13} &= \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}), \\ P_{12} &= \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{21}, \end{aligned} \quad (4)$$

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

¹In the rest of this paper, when referring to neutrinos, we mean neutrinos and/or antineutrinos.

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 ($L/E = 0.5$ km/MeV), we can approximate P_{13} and P_{12} as follows:

$$P_{13} \approx 0.08 \sin^2 \left(\frac{\pi}{2} \left(\frac{L/E}{0.5 \text{ km/MeV}} \right) \right) \quad (5)$$

$$P_{12} \approx 0.002 \left(\frac{L/E}{0.5 \text{ km/MeV}} \right)^2 \left(\frac{\Delta m_{21}^2}{7.5 \times 10^{-5} \text{ eV}^2} \right)^2. \quad (6)$$

For $\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2$, the P_{12} term is essentially negligible for all $L/E < 1$ km/MeV. This encompasses the L/E range of all current short baseline experiments.

However, consider the case that Δm_{21}^2 is 3 times larger than this value, i.e., $22.5 \times 10^{-5} \text{ eV}^2$, then

$$P_{12} \approx 0.02 \left(\frac{L/E}{0.5 \text{ km/MeV}} \right)^2 \left(\frac{\Delta m_{21}^2}{22.5 \times 10^{-5} \text{ eV}^2} \right)^2. \quad (7)$$

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

Therefore the short baseline reactor experiments can constrain Δm_{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 Δm_{21}^2 will be challenging for these experiments due to systematic uncertainties. As data above $L/E \sim 0.5$ km/MeV is important for this constrain, the Double Chooz experiment, which has no data with $L/E > 0.5$ 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

$$\frac{L}{E} \approx \frac{2\pi}{\Delta m_{ee}^2}, \quad (8)$$

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

$$\begin{aligned} 1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) &\approx \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \\ &+ \sin^2 2\theta_{13} \left[\sin^2 |\Delta_{ee}| + \sin^2 \theta_{12} \cos^2 \theta_{12} \Delta_{21}^2 \cos(2\Delta_{ee}) \right. \\ &\quad \left. - \frac{1}{6} \cos 2\theta_{12} \sin^2 2\theta_{12} \Delta_{21}^3 \sin(2\Delta_{ee}) + \mathcal{O}(\Delta_{21}^4) \right]. \end{aligned} \quad (9)$$

For $\Delta_{21} < 0.5$, only the first two of the terms of the right-hand side (RHS) of Eq. (9) are larger than 0.005 and

therefore relevant for the analysis.² Since the experiments of interest, Daya Bay and RENO, have an $L/E < 1$ km/MeV, the $\Delta_{21} < 0.5$ constraint corresponds to a $\Delta m_{21}^2 < 4 \times 10^{-4}$ eV² or 5 times the KamLAND value of 7.5×10^{-5} eV². Using additional terms of Eq. (9) will extent the range of applicability.

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

$$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx [\sin^2 2\theta_{13} + \sin^2 2\theta_{12} \cos^4 \theta_{13} (\Delta m_{21}^2 / \Delta m_{ee}^2)^2] \times (\Delta m_{ee}^2 L / 4E)^2. \quad (10)$$

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

$$\sin^2 \theta_{13} + \sin^2 \theta_{12} \cos^2 \theta_{12} (\Delta m_{21}^2 / \Delta m_{ee}^2)^2 = \text{constant} \approx 0.021$$

$$\text{or } \sin^2 \theta_{13} \approx 0.021 - 2 \times 10^{-4} \left(\frac{\Delta m_{21}^2}{7.5 \times 10^{-5} \text{ eV}^2} \right)^2 \quad (11)$$

to leading order in $\sin^2 \theta_{13}$. So as we vary Δm_{21}^2 from KamLAND value of 7.5×10^{-5} eV², we must also change $\sin^2 \theta_{13}$ from 0.021 so as to keep the combination in Eq. (11) unchanged.

In Fig. 1, we show the electron antineutrino disappearance probability as function of L/E , keeping the quantity given in Eq. (11) fixed, as we vary Δm_{21}^2 in multiples of 7.5×10^{-5} eV². Note that if $\Delta m_{21}^2 > 3 \times 10^{-4}$ eV² then there is no minimum³ around $L/E \approx 0.5$ km/MeV. The red points with error bars, represents the statistical uncertainties only, for a detector 1.6 km from a single reactor core which has 9×10^5 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 Δm_{21}^2 assuming systematic uncertainties are no larger than the statistical uncertainties. A lower limit on Δm_{21}^2 will be challenging.

²For small Δ_{21} , the disappearance probability depends on only three variables; $\sin^2 \theta_{13}$, Δm_{ee}^2 and the combination $\Delta m_{21}^2 \sin 2\theta_{12}$, see Appendix.

³For $\Delta_{21} < 1$, so that $\sin \Delta_{21} \approx \Delta_{21}$, one can find the minima by finding Δ_{ee} such that,

$$\frac{\Delta m_{21}^2}{\Delta m_{ee}^2} = -\frac{2 \tan \theta_{13} \sin 2\Delta_{ee}}{\sin 2\theta_{12} 2\Delta_{ee}}.$$

This equation has no solutions if $\Delta m_{21}^2 > 0.15 \Delta m_{31}^2$ or ~ 4 times the KamLAND central value.

FIG. 1. The exact electron antineutrino disappearance probability (solid) as a function of L/E as Δm_{21}^2 is varied in multiples [lines labeled = (0, ..., 6, 10)] of the KamLAND value of 7.5×10^{-5} eV². θ_{13} is also varied, see Eq. (11), to keep the same disappearance probability for $L/E < 0.2$ km/MeV. The red points with error bars, are the statistical uncertainties only, for a detector at 1.6 km from a reactor core with an exposure such that there are 900k events in this detector assuming the KamLAND value for Δm_{21}^2 . This number of events corresponds to 3000 days of Daya Bay data, see Table I. This figure demonstrates that the Daya Bay experiment can put an upper limits on Δm_{21}^2 of approximately 2 times the KamLAND central value or smaller, assuming the systematic uncertainties are smaller than the statistical uncertainties shown here. The dotted line is the two term approximation to the disappearance probability, see Eq. (9).

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 Δm_{21}^2 .

III. SIMULATIONS FOR DAYA BAY AND RENO USING GLOBES

Our sensitivity study on Δm_{21}^2 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_{eff} , and the number of observed IBD $\bar{\nu}_e$ events per day used.

TABLE I. L_{eff} and observed IBD $\bar{\nu}_e$ rates for Daya Bay and RENO derived from the GLOBES settings used in this study.

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

FIG. 2. Contour plot of Δm_{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 and Daya Bay respectively. Solid (red), dashed (blue) and dotted (black) lines represent 1σ , 2σ , and 3σ (2 dof) allowed regions, respectively. The point “x” is the input for the simulation given by Eq. (13). In the bottom row, we also show the 1σ uncertainty band on Δm_{21}^2 from KamLAND (cyan) and SNO/SK (yellow), see Eqs. (1) and (2). The value of $\sin^2 \theta_{12}$ is held fixed for this analysis, for a discussion on varying θ_{12} see Appendix.

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

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

where,

- (i) $O_i^{\text{F/N}}$ is the observed far-to-near ratio of IBD $\bar{\nu}_e$ events in the i th $E_{\bar{\nu}}$ bin,
- (ii) $X_i^{\text{F/N}} = X_i^{\text{F/N}}(f^r, \epsilon, s, b^d; \theta_{13}, \Delta m_{21}^2)$ is the expected far-to-near ratio of IBD $\bar{\nu}_e$ events for a given Δm_{21}^2 and θ_{13} pair,
- (iii) $U_i^{\text{F/N}}$ is the statistical uncertainty of $O_i^{\text{F/N}}$,
- (iv) f^r, ϵ, s , and b^d are pull parameters for systematic uncertainties of neutrino flux (σ_{flux}^r), detection efficiency (σ_{eff}), energy scale (σ_{scale}), and background (σ_{bkg}^d), 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 (N_1 and N_2) are used in the last pull term of the χ^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 Δm_{ee}^2 vs $\sin^2 2\theta_{13}$ sensitivity curves for both experiments.

True values used in the signal simulation are

$$\begin{aligned}\sin^2 \theta_{12} &= 0.304, \\ \Delta m_{21}^2 &= 7.65 \times 10^{-5} \text{ eV}^2, \\ \sin^2(2\theta_{13}) &= 0.085, \\ \Delta m_{31}^2 &= 2.50 \times 10^{-3} \text{ eV}^2.\end{aligned}\quad (13)$$

For this analysis the value of $\sin^2 \theta_{12}$ is held fixed. For discussion on varying θ_{12} , see Appendix.

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

Figure 2 shows the results of our simulation for contour plots of Δm_{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 ≈ 5 times more events in the far detector(s) than RENO, see Table I. Clearly, both of these experiments⁴ can constrain Δm_{21}^2 to be less than two to three times the KamLAND central value, i.e., $\Delta m_{21}^2 < 15\text{--}22 \times 10^{-5} \text{ eV}^2$. Setting a lower limit on Δm_{21}^2 maybe possible with Daya Bay if 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 Δm_{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, Δm_{21}^2 , now. A simulation study for these experiments was performed with and without systematic uncertainties using GLOBES. We have found that Δm_{21}^2 can be reasonably well constrained by Daya Bay 3000 live days of data to be less than twice the KamLAND central value at the 95% CL. Without systematic uncertainties Daya Bay can exclude $\Delta m_{21}^2 = 0$ with 1σ confidence level but when current systematic uncertainties are included only an upper bound can be set. Until JUNO measures Δm_{21}^2 with great precision in the middle of next decade, we expect the Δm_{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. In this study we fixed θ_{12} value since the uncertainty from θ_{12} variation is relatively small compared to the systematic uncertainties as discussed in Appendix. A truly realistic simulation and a true measurement of Δm_{21}^2 can only be performed by the short baseline reactor experiments, Daya Bay and RENO.

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APPENDIX: Δm_{21}^2 SENSITIVITY TO VARIATION OF θ_{12}

For the Daya Bay and RENO experiments, the disappearance probability is well approximated by

$$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \Delta_{ee} + \cos^4 \theta_{13} (\sin 2\theta_{12} \Delta_{21})^2, \quad (A1)$$

and therefore these experiments are only sensitive to variables $\sin^2 \theta_{13}$, Δm_{ee}^2 and the product $(\sin 2\theta_{12} \Delta_{21})$. That is, there is a degeneracy between $\sin 2\theta_{12}$ and Δm_{21}^2 as long as the product is same. So in principle the vertical axes of Fig. 2 could be replaced by

$$\Delta m_{21}^2 \Rightarrow \Delta m_{21}^2 (\sin 2\theta_{12}/0.92) \quad (A2)$$

where 0.92 is the value of $\sin 2\theta_{12}$ used to produce these figures.

By applying the 3σ level allowed range of $\sin^2 \theta_{12}$ for KamLAND, i.e., [0.20, 0.42], wider than for the SK/SNO, i.e., [0.27, 0.36], see [3–6], the Δm_{21}^2 measurement would have been affected by $\sim 13\%$ or less, as the dependence comes from $\sin 2\theta_{12}$ not $\sin^2 \theta_{12}$. Therefore the systematic uncertainties of the experiments on Δm_{21}^2 measurement, is much larger than the uncertainty from the variation of θ_{12} .

In conclusion, for the short baseline reactor experiments, variation of θ_{12} has relatively small impact on the measurement of Δm_{21}^2 as well as $\sin^2 2\theta_{13}$, Δm_{ee}^2 .⁵

⁴In [21], Fig. 3, Daya Bay gives constraints on a $3 + 1$ sterile neutrino model with 600 days of data. These constraints can be re-interpreted as a constraint on Δm_{21}^2 and the result is slightly better than 3 times the KamLAND value. Validating our conclusion of 2–3 times the KamLAND value is achievable.

⁵If the value of Δm_{31}^2 and/or Δm_{32}^2 is extract from the measurement of Δm_{ee}^2 then the sensitivity to $\sin^2 \theta_{12}$ is increased as well as sensitivity to the mass ordering.

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