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Search for sterile neutrinos at RENO

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Abstract. The RENO experiment was designed to measure a neutrino mixing angle, θ_{13} , by detecting electron antineutrinos emitted from the Hanbit nuclear reactors in Korea, and succeeded to measure θ_{13} from the disappearance mode in three neutrino frame. We investigate the possibility of sterile neutrinos existence at RENO experiment and compare data with Monte Carlo generated in four neutrino frame. In this talk, we present some recent results using chi-square analysis method. The probability deficit curve as a function of an effective baseline and the excluded contour plot in $\sin^2(2\theta_{14}) - \Delta(m_{41})^2$ space will be shown.

1. Introduction

There has been large process of understanding about the neutrino oscillation phenomenon due to determination of the last mixing parameter θ_{13} , which is measured by reactor anti-neutrino experiments. Therefore, three-neutrino parameter scheme are almost known, but there are several neutrino oscillation anomalies. Thus, 3+1 neutrino scheme which includes the additional neutrino called sterile neutrino is proposed for explaining these anomalies. Especially, the past short baseline experiments with anti-electron neutrinos from a reactor is reinterpreted because of the update of reactor neutrino flux and neutrino cross section of inverse beta decay recently. These results show the possibility of the existence of sterile neutrino, and we need more studies

When combined with experimental data at baselines between 10-100 m these recent calculations suggest a $\sim 6\%$ difference between the measured and expected reactor antineutrino flux with a 3 sigma significance when taking into account all correlations. This is called the reactor anomaly. (Figure 1)

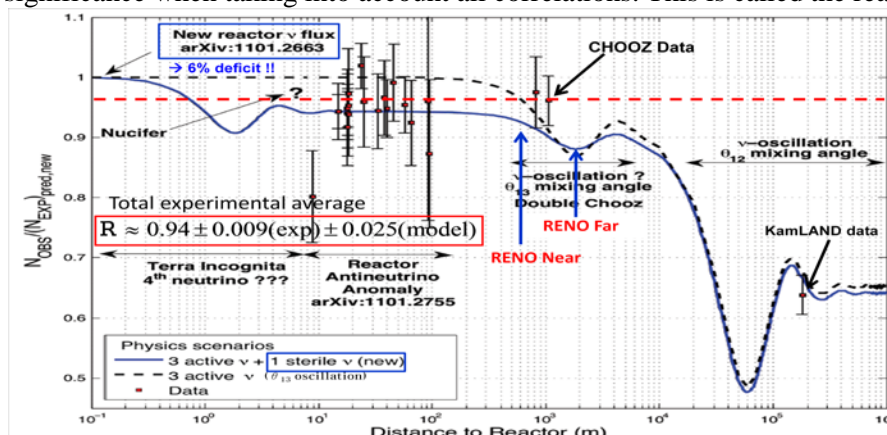


Figure 1. Results of short baseline experiments [1]

2. Spectral analysis using Far/Near ratio

The χ^2 for the rate + shape analysis is also based on the pull method described in Ref.[2], and is written as

$$\chi^2 = \sum_{P=\text{before,After}} \left\{ \sum_{i=1 \sim N_b} \frac{\left(\frac{N_{obs}^{F,P,i}}{N_{obs}^{N,P,i}} - \frac{N_{Exp}^{F,P,i}}{N_{Exp}^{N,P,i}} \right)^2}{(U_i)^2} \right\} + \text{Pull term} \quad \text{-(1)}$$

$$U_i = \frac{N_{obs}^{F,P,i}}{N_{obs}^{N,P,i}} \cdot \sqrt{\frac{N_{obs}^{F,P,i} + N_{bkg}^{F,P,i}}{(N_{obs}^{F,P,i})^2} + \frac{N_{obs}^{N,P,i} + N_{bkg}^{N,P,i}}{(N_{obs}^{N,P,i})^2}}$$

Oscillation parameters are determined using far/near ratio of IBD prompt energy spectrum.

The next parameters are defined by the following index:

- $N_{obs}^{d,P,i}$: The number of background subtracted inverse beta decay events, d = far and near detectors, and P = data set of live time (SetA, Set B) in the i^{th} energy bin.
- $N_{bkg}^{d,P,i}$: The number of total backgrounds, d = far and near detectors, and P = data set (Set A, Set B) in the i^{th} energy bin.
- $N_{exp}^{d,P,i}$: The number of expected inverse beta decay events, d = far and near detectors, and P = data set of livetime (Set A, Set B) in the i^{th} energy bin.

The 3+1 neutrino extension of unitary transformations from mass eigenstate to flavor eigenstate is given in terms of six mixing angles and three Dirac phases

$$U_F = R_{34}(\theta_{34})R_{24}(\theta_{24}, \delta_2)R_{14}(\theta_{14})R_{23}(\theta_{23})R_{13}(\theta_{13}, \delta_1)R_{12}(\theta_{12}, \delta_3) \quad \text{-(2)}$$

phases where $R_{ij}(\theta_{ij})$ is the rotation of the ij block by an angle of θ_{ij} and δ_k is Dirac phases. The survival probability of the electron antineutrino from reactor is,

$$P_{th}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sum_{i < j} 4 |\tilde{U}_{ei}|^2 |\tilde{U}_{ej}|^2 \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E_\nu} \right) \quad \text{-(3)}$$

It can be expressed as follows,

$$\begin{aligned} P_{th}(\bar{\nu}_e \rightarrow \bar{\nu}_e) = & 1 - c_{14}^4 c_{13}^4 \sin^2 2\theta_{12} \sin^2 \left(1.27 \Delta m_{21}^2 \frac{L}{E} \right) - c_{14}^4 c_{12}^2 \sin^2 2\theta_{13} \sin^2 \left(1.27 \Delta m_{31}^2 \frac{L}{E} \right) \\ & - c_{14}^4 s_{12}^2 \sin^2 2\theta_{13} \sin^2 \left(1.27 \Delta m_{32}^2 \frac{L}{E} \right) - c_{13}^2 c_{12}^2 \sin^2 2\theta_{14} \sin^2 \left(1.27 \Delta m_{41}^2 \frac{L}{E} \right) \\ & - c_{13}^2 s_{12}^2 \sin^2 2\theta_{14} \sin^2 \left(1.27 \Delta m_{42}^2 \frac{L}{E} \right) - s_{13}^2 \sin^2 2\theta_{14} \sin^2 \left(1.27 \Delta m_{43}^2 \frac{L}{E} \right) \quad \text{-(4)} \end{aligned}$$

U_{ei} is the element of the neutrino mixing matrix for the flavor eigenstate ν_e and the mass eigenstate ν_i , $\Delta m_{ji}^2 = m_i^2 - m_j^2$ being the mass-squared difference between the mass eigenstates ν_i and ν_j .

Physics data was acquired with the far and near detectors from August 2011.

The IBD candidates obtained 31541 events for a 500 day dataset in the far detector and 290775 events for a 500 day dataset in the near detector with a prompt energy range (1.2-8 MeV). To measure θ_{14} and Δm^2_{41} , Expected IBD templates are prepared with various oscillation parameters. The measured θ_{14} and Δm^2_{41} are points in the template sets, which have minimum χ^2 values calculated between the events observed and the expected templates. There are a total of 14448 expected templates in the region bounded by $0.001 < \theta_{14} < 0.99$ and $0.0001 < \Delta m^2_{41} < 0.2 \text{ eV}^2$ and $0.01 < \theta_{13} < 0.15$.

3. Summary

We used RENO data of 500 days. We investigate the possibility of sterile neutrinos existence at RENO experiment and compare data with Monte Carlo generated in four neutrino frame. We present some recent results using chi-square analysis method. We was analyzed in two ways. One way is fixed $\sin^2 2\theta_{13}$ and the other way is varying $\sin^2 2\theta_{13}$. We drawn Exclusion contours at 95% C.L. (Figure 2) and we checked consistent with standard 3-flavor neutrino oscillation model. Also, delta m able to set stringent limits in the region. (Figure 3) We checked about un-excluded parameters and excluded parameters.

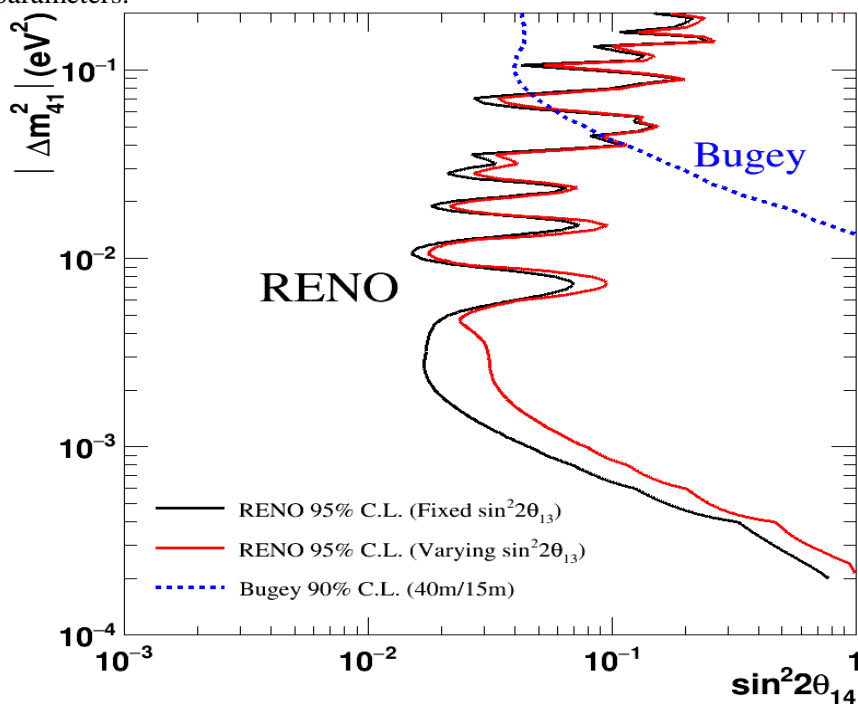
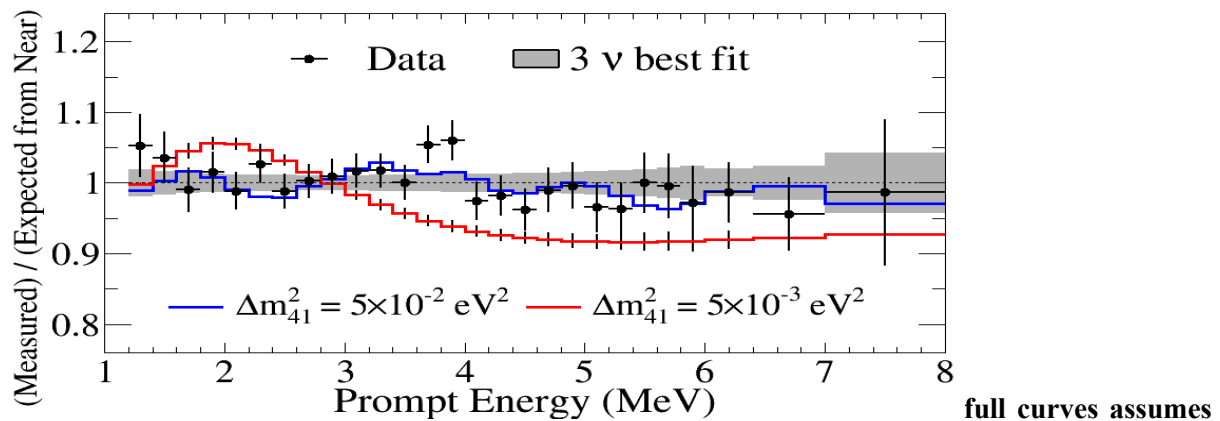


Figure 2. (Black line) The value of $\sin^2 2\theta_{13}$ were fixed. (Red line) The value of $\sin^2 2\theta_{14}$, $\sin^2 2\theta_{13}$, and Δm^2_{41} were unconstrained. Exclusion contours for the neutrino oscillation parameters $\sin^2 2\theta_{14}$ and Δm^2_{41} . Normal mass hierarchy is assumed for both Δm^2_{31} and Δm^2_{41} . The parameter space to the right side of the contours is excluded. For comparison, Bugey's 90% C.L. limit on ν_e disappearance is also shown as the blue dashed curve [3].



$\sin^2 2\theta_{14}=0.1$

Figure 3. (color online). Prompt energy spectra observed at far detector divided by the prediction from the near spectrum with the three-neutrino best-fit oscillation parameters from the previous RENO analysis. The gray band represents the uncertainty of the three-neutrino oscillation prediction, which includes the statistical uncertainty of the near data and all the systematic uncertainties. Predictions with $\sin^2 2\theta_{14}=0.1$ and two representative Δm^2_{41} values are also shown as the dotted and dashed curves.

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