Measurement of Reactor Antineutrino Oscillation Amplitude and Frequency at RENO

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The RENO experiment reports more precisely measured values of θ13 and |Δm2e3| using ∼2200 live days of data. The amplitude and frequency of reactor electron antineutrino (ν̄e) oscillation are measured by comparing the prompt signal spectra obtained from two identical near and far detectors. In the period between August 2011 and February 2018, the far (near) detector observed 103 212 (850 666) 12e events with a background fraction of 4.8% (2.0%). A clear energy and baseline dependent disappearance of the prompt signal spectra obtained from two identical near and far detectors. In the period spanned by the prompt signal spectra obtained from two identical near and far detectors. In the period spanning 1.3 km with equal spacings, the reactor flux-meters.

The first measurement of |Δm2e3| by RENO was reported based on the rate, spectral, and baseline information of reactor ̄νe disappearance using ∼500 live days of data [7,8]. In this Letter, we present more precisely measured values of θ13 and |Δm2e3| using ∼2200 live days of data. The systematic uncertainty in the measurement is reduced due to a better understanding of backgrounds and an increased data size.

The RENO experiment has been in data taking since August 2011. Identical near and far ̄νe detectors are placed 294 and 1383 m, respectively, from the center of six reactor cores of the Hanbit Nuclear Power Plant so that a ratio measurement may cancel out possible correlated systematic uncertainties between them. The plant consists of six pressurized water reactors, each with a maximum thermal output of 2.8 GWth, that are situated in a linear array spanning 1.3 km with equal spacings. The reactor flux-weighted baseline is 410.6 m for the near detector and 1445.7 m for the far detector.
A reactor $\bar{\nu}_e$ is detected through the inverse beta decay (IBD) interaction, $\nu_e + p \rightarrow e^+ + n$, in a hydrocarbon liquid scintillator (LS) with 0.1% gadolinium (Gd). A prompt signal from the positron annihilation releases energy of 1.02 MeV as two $\gamma$ rays in addition to the positron kinetic energy. The neutron after thermalization is captured by Gd with a mean delayed time of $\sim 26$ $\mu$s and produces several $\gamma$ rays with the total energy of $\sim 8$ MeV. The RENO LS is made of linear alkylbenzene with fluors. A Gd-carboxylate complex was developed for the best Gd loading efficiency into LS and its long-term stability [9].

The observed $Q_{\text{tot}}$ is reduced by $\sim 15\%$ of the initial operation value due to a decrease in the LS attenuation length, and by $\sim 10\%$ due to unplugged flashing PMTs. The decreased attenuation length is caused by loose air tightening around the detector chimney region and most likely introducing oxygen and moisture into the LS. The attenuation length remains unchanged after careful air shielding with nitrogen gas. A nonuniform charge response in the detector volume is developed by the decreased attenuation length. A spatial correction using the delayed energy peak is applied to recover a uniform charge response.

In this measurement we use 2193.04 (1807.88) live day data in the far (near) detector, taken in the period between August 2011 and February 2018. The near data sample in the period of January to December 2013 is not used because of detection inefficiency caused by an electrical noise coming from an uninterruptible power supply. A small amount of $^{252}\text{Cf}$ was accidentally introduced into both detectors during detector calibration in October 2012. Most
are fast neutrons from outside of the ID, β-n emitters from cosmic-muon induced \(^{9}\)Li/\(^{9}\)He isotopes, and \(^{252}\)Cf contamination. The remaining background rates and spectral shapes are obtained from control data samples [7,8]. The total background rates are estimated to be 2.24 ± 0.10 and 9.53 ± 0.28 events per day for far and near detectors, respectively. The total background fraction is 4.76 ± 0.20% in the far detector, and 2.03 ± 0.06% in the near detector. The observed IBD and background rates are summarized in Table I.

The prompt energy difference between the near and far detectors contributes to the uncorrelated systematic uncertainties associated with a relative measurement of spectra at the two detectors and is estimated by comparing the energy spectra of various γ-ray sources using the charge-to-energy conversion functions. The uncorrelated energy scale difference is found to be less than 0.15% from all of the calibration data.

The average detection efficiency of the near and far detectors is 76.47 ± 0.16%, with an uncorrelated systematic uncertainty of 0.13%. Main contributions to the uncorrelated uncertainty come from different efficiencies between the two detectors associated with the Gd-capture fraction and the delayed energy requirement. The uncorrelated systematic uncertainty on the Gd-capture fraction is estimated at 0.1% due to the difference of Gd concentration between the two detectors. The uncertainty on the delayed energy requirement is estimated at 0.05% from the delayed energy uncertainty of 0.15%. A fractional error of the detection efficiency is 0.21%, to be used as the uncertainty of the far-to-near detection efficiency ratio. A detailed description of the detection efficiency can be found in Ref. [8].

The expected rates and spectra of reactor \(\bar{\nu}_e\) are calculated for the duration of physics data taking by taking into account the varying thermal powers, fission fractions of four fuel isotopes, energy release per fission, fission spectra, and IBD cross sections [14–20]. The total uncorrelated systematic uncertainty of reactor flux is estimated at 0.9%. The total correlated uncertainty of reactor flux is 2.0% and is canceled out in the far-to-near ratio measurement.

We observe a clear deficit of the measured IBD rate in the far detector with respect to the expected one, indicating the reactor \(\bar{\nu}_e\) disappearance. Using the deficit information only, a rate-only analysis obtains \(\sin^2 2\theta_{13} = 0.0874 ± 0.0050(\text{stat}) ± 0.0054(\text{syst})\), where the world average value of \(|\Delta m_{ee}^2| = (2.56 ± 0.05) \times 10^{-3}\text{ eV}^2\) is used [21].

The total systematic error of \(\sin^2 2\theta_{13}\) is reduced from 0.0068 to 0.0054, mostly due to the decreased background uncertainty, relative to the previous measurement [7,8], while the statistical error is significantly reduced from 0.0091 to 0.0050.

Figure 1 shows a shape comparison between the observed IBD prompt spectrum after background subtraction and the prediction from a reactor \(\bar{\nu}_e\) model [18,19] and the best-fit oscillation results. The fractional difference between data and prediction is also shown in the lower panel. A clear discrepancy between the observed and MC predicted spectral shapes is found in the region of 5 MeV in both detectors. For the spectral shape comparison, the MC predicted spectrum is normalized to the observed one in the region excluding 3.6 < \(E_\gamma\) < 6.6 MeV. This observation suggests the need for reevaluation and modification of the current reactor \(\bar{\nu}_e\) model [18,19].

We observe a clear energy dependent disappearance of reactor \(\bar{\nu}_e\) in the far detector. Even with the unexpected structure around 5 MeV, the oscillation amplitude and frequency can be determined from a fit to the measured far-to-near ratio of IBD prompt spectra because of its cancellation in the ratio measurement. The relative measurement using identical near and far detectors makes the method insensitive to the correlated uncertainties of expected reactor \(\bar{\nu}_e\) flux and spectrum, as well as to the detection efficiency. For determination of \(|\Delta m_{ee}^2|\) and \(\theta_{13}\) simultaneously, a \(\chi^2\) with pull parameter terms of systematic uncertainties is constructed using the spectral ratio measurement and is minimized by varying the oscillation parameters and pull parameters as described in Refs. [7,8].

The systematic uncertainty sources are embedded by pull parameters with associated systematic uncertainties. The pull parameters allow variations from the expected far-to-near ratio of IBD events within their corresponding systematic uncertainties. The uncorrelated reactor-flux uncertainty is 0.9%, the uncorrelated detection ratio uncertainty is 0.21%, the uncorrelated energy scale uncertainty is 0.15%, and the background uncertainty is 5.61% and 3.26% for the far and near detectors, respectively.

The best-fit values obtained from the rate and spectral analysis are \(\sin^2 2\theta_{13} = 0.0896 ± 0.0048(\text{stat}) ± 0.0047(\text{syst})\) and \(|\Delta m_{ee}^2| = [2.68 ± 0.12(\text{stat}) ± 0.07(\text{syst})] \times 10^{-3}\text{ eV}^2\) with \(\chi^2/\text{NDF} = 47.4/66\), where NDF is the number of degrees of freedom. The statistical errors are reduced almost by a factor of 2 with respect to the previous measurement [7,8].

The systematic error of \(|\Delta m_{ee}^2|\) is significantly reduced by 45%, while that of \(\sin^2 2\theta_{13}\) is reduced by 15%. The background uncertainty contributes ±0.0021 to the systematic error of \(\sin^2 2\theta_{13}\). The dominant contribution to the systematic error is due to the uncertainties.
FIG. 1. Spectral shape comparison of observed and expected IBD prompt events in the near and far detectors [13]. The observed spectra are obtained from subtracting the remaining background spectra as shown in the insets. The expected distributions are obtained from the best-fit oscillation results that are applied to the no-oscillation MC spectra. The deviation from the expectation near 5 MeV is larger than the uncertainty of the measured spectrum at the near detector[13]. The expected spectrum at the far detector compared to the one expected with no oscillation at the far detector. The observed spectrum at the far detector shows a clear energy dependent disappearance of reactor $\bar{\nu}_e$ consistent with the neutrino oscillations. Figure 3 shows 68.3%, 95.5%, and 99.7% C.L. allowed regions for the neutrino oscillation parameters $|\Delta m^2_{ee}|$ and $\sin^22\theta_{13}$.

The survival probability of reactor $\bar{\nu}_e$, is a function of a baseline over neutrino energy. Because of having multiple reactors as neutrino sources, an effective baseline $L_{\text{eff}}$ is of reactor flux $(\pm 0.0032)$ and detection efficiency $(\pm 0.0032)$. The systematic error of $|\Delta m^2_{ee}|$ comes mostly from the energy scale uncertainty. The measured value of $|\Delta m^2_{ee}|$ corresponds to $|\Delta m^2_{32}| = (2.63 \pm 0.14) \times 10^{-3}$ eV$^2$ for the normal neutrino mass ordering and $(2.73 \pm 0.14) \times 10^{-3}$ eV$^2$ for the inverted neutrino mass ordering, using measured oscillation parameters of $\sin^2 \theta_{12} = 0.307 \pm 0.013$ and $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV$^2$ [21].

Figure 2 shows the background-subtracted, IBD prompt energy spectrum at the far detector compared to the one expected with no oscillation and the one expected with the best-fit oscillation parameters at the far detector [13]. The expected spectrum with no oscillation at the far detector is obtained by weighting the measured spectrum at the near detector with no-oscillation assumptions in order to include the 5 MeV excess. The expected spectrum with the best-fit oscillation parameters is obtained by applying the measured values of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to the one expected with no oscillation at the far detector. The observed spectrum at the far detector shows a clear energy dependent disappearance of reactor $\bar{\nu}_e$ consistent with the neutrino oscillations. Figure 3 shows 68.3%, 95.5%, and 99.7% C.L. allowed regions for the neutrino oscillation parameters $|\Delta m^2_{ee}|$ and $\sin^22\theta_{13}$.

The survival probability of reactor $\bar{\nu}_e$, is a function of a baseline over neutrino energy. Because of having multiple reactors as neutrino sources, an effective baseline $L_{\text{eff}}$ is
defined by the reactor-detector distance weighted by the IBD event rate from each reactor. Figure 4 shows the measured survival probability of reactor $\bar{\nu}_e$ in the far detector as a function of an effective baseline $L_{\text{eff}}$ over $\bar{\nu}_e$ energy $E_{\nu}$. The observed $L_{\text{eff}}/E_{\nu}$ distribution is obtained by summing up the daily distributions weighted by a daily IBD rate. The measured survival probability is obtained by the ratio of the observed IBD events to the expected ones in each bin of $L_{\text{eff}}/E_{\nu}$. A predicted survival probability distribution in the near detector as a function of an effective baseline $L_{\text{eff}}$ is determined by the reactor-detector distance weighted by the $\nu_{\text{IBD}}$ event rate from each reactor. Figure 4 shows the distribution with no oscillation in each bin of the ratio of the observed IBD events to the expected ones.

The measured survival probability of reactor $\bar{\nu}_e$ is obtained by summing up the daily distributions weighted by a daily $\nu$.

In summary, RENO has observed a clear energy dependent disappearance of reactor $\bar{\nu}_e$ using two identical detectors and has obtained $\sin^2 2\theta_{13} = 0.0896 \pm 0.0068$ and $|\Delta m^2_{ee}| = (2.68 \pm 0.14) \times 10^{-3}$ eV$^2$ based on the measured periodic disappearance expected from the neutrino oscillations. With the increased statistics of the 2200 day data sample and the reduced background rates, RENO has produced a precise measurement of the reactor $\bar{\nu}_e$ oscillation amplitude and frequency. The measured uncertainty is reduced from 0.0100 to 0.0068 for $\sin^2 2\theta_{13}$, and from $0.25 \times 10^{-3}$ eV$^2$ to $0.14 \times 10^{-3}$ eV$^2$ for $|\Delta m^2_{ee}|$, relative to the previous measurement [7,8]. RENO’s measured values of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ are compared with other experimental results in Fig. 5. It would provide important information on the determination of the leptonic $CP$ phase if it were combined with the results of an accelerator neutrino beam experiment.

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FIG. 4. Measured reactor $\bar{\nu}_e$ survival probability in the far detector as a function of $L_{\text{eff}}/E_{\nu}$ [13]. The curve is a predicted survival probability, obtained from the observed probability in the near detector, for the best-fit values of $|\Delta m^2_{ee}|$ and $\sin^2 2\theta_{13}$. The $L_{\text{eff}}/E_{\nu}$ value of each data point is given by the average of the counts in each bin.

FIG. 5. Comparison of experimental results on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{\nu_e\nu_e}|$ for normal (NH) and inverted (IH) mass hierarchies. The world average values and the experimental results of Daya Bay [22], Double Chooz [23], T2K [24], MINOS [25], and NO$\nu$A [26] are taken from Ref. [21].

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