Recent Result from RENO

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Abstract. The Reactor Experiment for Neutrino Oscillation (RENO) started data-taking from August, 2011 and has measured the smallest neutrino mixing angle $\theta_{13}$ by observing the disappearance of reactor antineutrinos. Antineutrinos from the six reactors at Hanbit Nuclear Power Plant in Korea are detected and compared by the two identical detectors located in the near and far distances from the reactor array center. We present recent results on precisely measured $\sin^2 2\theta_{13}$ value and $|\Delta m_{ee}^2|$ based on spectral analysis using the 500 days of data sample, which are taken from August, 2011 to Jan, 2013.

1. Introduction
Since RENO published the result of the measurement of the smallest neutrino mixing angle $\theta_{13}$ [1], we have been updating its result using increased statistics and improved systematics. We also have made effort to measure $|\Delta m_{ee}^2|$ based on spectral analysis. The experiment has accumulated roughly 1400 live days of data as of September, 2015 and its data-taking is still continuing. We report the improved results of $\theta_{13}$ measurement using the 500 live days of data and the result of $|\Delta m_{ee}^2|$.

2. Experimental setup and detectors
RENO detects antineutrinos from the six reactors at Hanbit Nuclear Power plant in Yonggwang, Korea. The six pressurized water reactors with each maximum thermal output of 2.815 GW$_{th}$ (reactors 3, 4, 5 and 6) or 2.775 GW$_{th}$ (reactors 1 and 2) are lined up in roughly equal distances and span $\sim$1.3 km. Two identical antineutrino detectors are located at 294 m and 1383 m, respectively, from the center of reactor array. The far (near) detector is beneath a hill that provides 450 m (120 m) of water equivalent rock overburden to reduce the cosmic backgrounds. The far-to-near ratio of antineutrino fluxes measured in the two identical detectors considerably reduce systematic uncertainties coming from the reactor neutrino flux, target mass, and detection efficiency. The reactor-flux weighted baseline is 410.6 m for the near detector, and 1445.7 m for the far detector.

Each RENO detector consists of a main inner detector (ID) and an outer veto detector (OD). The main detector is contained in a cylindrical stainless steel vessel that houses two nested cylindrical acrylic vessels. The innermost acrylic vessel holds 18.6 m$^3$ (16.5 t) $\sim$0.1% Gadolinium (Gd) doped liquid scintillator (LS) as a neutrino target. An electron antineutrino is detected via the inverse beta decay (IBD) reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. The coincidence of a prompt positron signal and a delayed signal from neutron capture by Gd provides the distinctive signature of IBD events.
The central target volume is surrounded by a 60 cm thick layer of LS without Gd, useful for catching \( \gamma \)-rays escaping from the target region and thus increasing the detection efficiency. Outside this \( \gamma \)-catcher, a 70 cm thick buffer-layer of mineral oil provides shielding from radioactivity in the surrounding rocks and in the 354 10-inch Hamamatsu R7081 photomultiplier tubes (PMTs) that are mounted on the inner wall of the stainless steel container, providing 14% surface coverage. The outermost veto layer of OD consists of 1.5 m of highly purified water in order to identify events coming from outside by their Cherenkov radiation and to shield against ambient \( \gamma \)-rays and neutrons from the surrounding rocks. The OD is equipped with 67 10-inch R7081 water-proof PMTs mounted on the wall of the veto vessel. The whole surfaces of OD are covered with Tyvek sheets to increase the light collection. The more detail of detection methods and setup of the RENO experiment can be found elsewhere [2].

3. Energy calibration
An accurate energy measurement is essential for extracting \( |\Delta m^2_{ee}| \) from the spectral analysis. An absolute energy scale is calibrated by charges \( (E_{\text{vis}}) \) from radioactive sources of \(^{137}\text{Cs}\), \(^{68}\text{Ge}\), \(^{60}\text{Co}\), \(^{252}\text{Cf}\) and \(^{209}\text{Po} - \text{Be}\), and from IBD delayed signals of neutron capture on Gd. A charge-to-energy conversion is obtained by the function of \( E_{\text{vis}}/E_{\text{true}} = a + b/[1 - \exp(-cE_{\text{true}} + d)] \). The parameters of \( a, b, c \) and \( d \) are determined by a fit as shown in Figure 1. The energy scale difference of the near and far detectors is found to be less than 0.15% for \( 1 < E_\nu < 8 \text{ MeV} \) and this is taken into account as systematic uncertainty of spectral analysis. Figure 2 shows a good agreement between data and MC in the electron energy spectrum of \( \beta \)-decay from radioactive isotopes \(^{12}\text{B}\) and \(^{12}\text{N}\) that are produced by comis-muon interactions.

\begin{figure}[h]
\centering
\includegraphics[width=\columnwidth]{fig1.png}
\caption{Nonlinear response of scintillating energy obtained from the visible energies from several radioactive sources and IBD delayed signals in the far detector. The curves are the best fits to the data points and the charge-to-energy conversion function. The lower panels show fractional residuals of all calibration data points with respect to the best fit.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\columnwidth]{fig2.png}
\caption{Comparison of measured ans simulated energy spectra of the electrons from \( \beta \)-decay of unstable isotope \(^{12}\text{B}\) and \(^{12}\text{N}\), produced by cosmic muons. The far-to-near ratio of the spectra is shown in the lower panel.}
\end{figure}
4. Data analysis using the IBD events with neutron captured by Gd

With the 500 live days of data taken from August 2011 to Jan 2013, the far (near) detector observed 31,541 (290,775) electron antineutrino candidate events with a background fraction of 4.9% (2.8%).

Event triggers are formed by the number of PMTs with signals above 0.3 photoelectron (p.e.) threshold (NHIT). An event is triggered and recorded if the ID NHIT is larger than 90, corresponding to 0.5 to 0.6 MeV well below the 1.02 MeV as the minimum energy of an IBD positron signal, or if the OD NHIT is larger than 10. The event energy is measured based on the total charge ($Q_{\text{tot}}$) in p.e. collected by the PMTs. The following criteria are applied to select IBD candidate events: (i) $Q_{\text{max}}/Q_{\text{tot}} < 0.07$ where $Q_{\text{max}}$ is the maximum charge of a PMT, to eliminate PMT flasher events and external $\gamma$-ray events. (ii) a cut rejecting events that occur within a 1 ms window following a cosmic muon traversing the ID with an energy deposit (E) that is larger than 70 MeV, or with E between 20 MeV and 70 MeV for OD NHIT > 50; (iii) events are rejected if they are within a 700 ms window following a cosmic muon traversing the ID if E is larger than 1.5 GeV; (iv) 0.7 MeV < $E_p$ < 12.0 MeV; (v) 6.0 MeV < $E_d$ < 12.0 MeV, where $E_p$ ($E_d$) is the energy of prompt (delayed) event; (vi) $2 \mu s < \Delta t_{e^+n} < 100 \mu s$, where $\Delta t_{e^+n}$ is the time difference between the prompt and delayed signals; (vii) a multiplicity requirement rejecting correlated coincidence pairs if they are accompanied by any preceding ID or OD trigger within a 100 $\mu$s window before their prompt candidate.

In the final data samples, the remaining backgrounds are either uncorrelated or correlated IBD candidates. An accidental background comes from an uncorrelated pair of prompt- and delay-like events. Correlated backgrounds are fast neutrons from outside of ID, stopping muon followers, $\beta$-n emitters from cosmic muon induced $^9\text{Li}/^8\text{He}$ isotopes, and $^{252}\text{Cf}$, which was accidentally contaminated into both detectors during detector calibration work in October 2012. The $^{252}\text{Cf}$ background removal criteria can be found elsewhere [4].

Since our analysis is based on far-to-near ratio, only the uncorrelated uncertainties between the two detectors are considered as our systematic uncertainties. The uncertainties of the detection efficiencies are from spill-in events of IBD events that occur outside the target and produce a neutron capture on Gd in the target, Gd capture ratio, target protons, delayed energy cut, time coincidence cut and IBD cross section. The uncorrelated uncertainty of detection efficiency is estimated to be 0.2%. The reactor antineutrino flux depends on thermal power, fission fractions of the four isotopes, energy released per fission, and fission and capture cross sections. The uncertainties associated with the reactor antineutrino flux are 0.9% for uncorrelated errors as described in [1]. The uncorrelated uncertainties of energy scale is 0.15% as mentioned in the previous section. The energy dependent systematic uncertainties from background shape ambiguities are also evaluated and included in this analysis.

$|\Delta m_{23}^2|$ and $\sin^2 2\theta_{13}$ are determined by comparing measured far-to-near ratio of IBD prompt spectra to that of prediction. The following $\chi^2$ equation is constructed to extract best fit oscillation parameters using rate and spectral information [9].

$$\chi^2 = \sum_{i=1}^{N_{\text{bins}}} \left( \frac{N_{\text{obs}}^{d,i} - N_{\text{exp}}^{d,i}}{\sigma_{\text{scale}}} \right)^2 + \left( \frac{\xi}{\sigma_{\xi}} \right)^2 + \sum_{d=F,N} \left( \frac{b_{d}^{d}}{\sigma_{\text{bkrg}}} \right)^2 + \sum_{r=1}^{6} \left( \frac{f_{r}}{\sigma_{f_{r}}} \right)^2 + \left( \frac{e}{\sigma_{\text{scale}}} \right)^2$$

where $N_{\text{obs}}^{d,i}$ is the number of observed IBD events ($d =$ detector (FAR, NEAR)) in the $i$-th energy bin, $N_{\text{exp}}^{d,i}$ is the number of expected IBD events ($d =$ detector (FAR, NEAR)) and $U^i$ is the statistical uncertainty. $\xi$, $b_d^d$, $f_r$ and $e$ are pull parameters of detection efficiency, background, reactor antineutrino flux and energy scale, which are systematic uncertainty sources. $\sigma_{\xi}$, $\sigma_{\text{bkrg}}^d$, $\sigma_{f_{r}}$ and $\sigma_{\text{scale}}$ are their systematic uncertainties.
5. Absolute reactor neutrino flux

According to the very short-baseline (< 100 m) reactor experiments, the absolute reactor neutrino flux are measured to be less than what is expected from Mueller [5] and Huber [6] model. The deficit of observed reactor neutrino fluxes relative to the prediction indicates an overestimated flux or possible oscillation to sterile neutrinos. RENO also measured the absolute reactor neutrino flux and obtain about 3σ deficit from the Mueller and Huber model. The data to prediction measured from RENO is is 0.944 ± 0.021. Figure 3 shows the absolute reactor neutrino flux measurements from RENO and other short-baseline reactor experiments.

6. Result

We observed a clear deficit of reactor $\bar{\nu}_e$ in the far detector. A rate-only analysis using the deficit information only obtains $\sin^22\theta_{13} = 0.087 \pm 0.009$ (stat.) ±0.007 (syst.), where the world average of $|\Delta m^2_{ee}|$ is used [3]. The best-fit values obtained from the rate and spectral analysis are $\sin^22\theta_{13} = 0.082 \pm 0.009$ (stat.) ±0.006(syst.) and $|\Delta m^2_{ee}| = [2.62 \pm 0.22 \text{ (stat.)} \pm0.13 \text{ (syst.)}] \times 10^{-3} \text{eV}^2$. When we compare the observed IBD prompt spectrum with the best fit prediction obtained using reactor neutrino flux models by Mueller [5] and Huber [6], we have observed the excess of events around 5 MeV as shown in Figure 4. The amount of the excess is ~2.5% of the measured IBD prompt signal. It could not be accounted for by incorrect energy calibration or background estimation. According to a recent study, the excess could be explained by the $\beta$-decay of several isotopes such as $^{96}\text{Y}$ and $^{92}\text{Rb}$ in the fission process [7]. Figure 5 shows the measured survival probability of reactor $\bar{\nu}_e$ as a function of effective baseline $L_{\text{eff}}$ over $\bar{\nu}_e$ energy. The measured survival probability is determined from the the ratio of the observed counts to the expected counts without oscillation, where the expected counts are obtained by weighting near detector data.

Figure 3. The measured reactor neutrino rate to the theoretical prediction with Mueller [5] and Huber [6] model.

Figure 4. Comparison of observed and exected IBD prompt energy spectrum in the near (left) and far (right) detectors. A excess at around 5 MeV is clearly seen.
Figure 5. measured survival probability of reactor $\nu_e$ as a function of effective baseline $L_{\text{eff}}$ over $\nu_e$ energy. The measured survival probability is determined from the ratio of the observed counts to the expected counts without oscillation, where the expected counts are also obtained by weighting near detector data.

Figure 6 shows allowed regions of 68.3, 95.5 and 99.7% C.L. for the neutrino oscillation parameters $|\Delta m^2_{ee}|$ and $\sin^22\theta_{13}$.

7. Conclusion
In summary, RENO has observed clear energy dependent disappearance of reactor $\nu_e$ at far detector and determined $|\Delta m^2_{ee}|$ and $\sin^22\theta_{13}$ based on far-to-near ratio analysis using 500 days data sample. RENO also measured absolute flux and observed 3 $\sigma$ deficit from theoretical prediction. RENO is continuing to take data and we expect to measure $\sin^22\theta_{13}$ with 6% accuracy with 5 years of data and it will provide an important information on determination of the leptonic CP phase if combined with a result of an accelerator neutrino beam experiment [8].

References
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