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 new results on precisely measured $\sin^2 2\theta_{13}$ value and $|\Delta m^2_{ee}|$ based on spectral analysis using the 800 days of data sample, which are taken from August, 2011 to Dec, 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 $|\Delta m^2_{ee}|$ based on spectral analysis. In addition, we started to look at the reactor neutrino events of the neutron capture on Hydrogen. The experiment has accumulated roughly 800 live days of data until Dec. 2013 and its data-taking is still continuing. We report the improved results of $\theta_{13}$ measurement using the 800 live days of data and the preliminary result of $|\Delta m^2_{ee}|$.

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 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) ~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 \(^{209}\text{Po-B}\), and from IBD delayed signals of neutron capture on Gd. A charge-to-energy conversion is obtained by the function of \(\frac{E_{\text{vis}}}{E_{\text{true}}} = a + b/\left[1 - \exp(-cE_{\text{true}} + d)\right]\). The parameters of \(a, b, c\) and \(d\) are determined by a fit as shown in Figure 1 (a). The energy scale difference of the near and far detectors is found to be less than 0.15% for \(1 < E_p < 8\) MeV as shown in Figure 1 (b) and this is taken into account as systematic uncertainty of spectral analysis. Figure 1 (c) 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.

![Figure 1](image)

Figure 1. (a) Charge-to-energy conversion function. (b) Energy scale difference of the near and far detectors. (c) Comparison of measured and simulated energy spectra of electron from \(\beta\)-decay from radioactive isotopes \(^{12}\text{B}\) and \(^{12}\text{N}\) that are produced by comis-muon interactions.

4. Data analysis for the IBD events with neutron captured by Gd
With the 800 live days of data taken from 11 August 2011 to 31 December 2013, the far (near) detector observed 52,250 (470,787) electron antineutrino candidate events with a background
fraction of 12.0 % (5.6 %).

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 0.5~0.6 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. This selection criteria is more relaxed compared to our previous analysis \cite{1} to increase acceptance of signal and minimize any bias to the spectral shape while allowing more accidental backgrounds; (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.

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 \cite{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.

\[ |\Delta m^2_{ee}| \text{ and } sin^2\theta_{13} \text{ are determined by comparing measured far-to-near ratio of IBD prompt spectra to that of prediction. The following } \chi^2 \text{ equation is constructed to extract best fit oscillation parameters using rate and spectral information } \cite{8}. \]

\[
\chi^2 = \sum_{i=1}^{N_{\text{obs}}} \left\{ \frac{N_{\text{obs}}^{F,i} - N_{\text{exp}}^{F,i}}{U^i} \right\}^2 + \left( \frac{\xi}{\sigma_{\xi}} \right)^2 + \sum_{d=F,N} \left( \frac{b^d}{\sigma_{\text{bkg}}} \right)^2 + \sum_{r=1}^{6} \left( \frac{f_r}{\sigma_f} \right)^2 + \left( \frac{e}{\sigma_{\text{scale}}} \right)^2
\]

where \( N_{\text{obs}}^{d,i} \text{ is the number of observed IBD events (d = detector (FAR, NEAR)) in the i-th energy bin, } N_{\text{exp}}^{d,i} \text{ is the number of expected IBD events (d = detector (FAR, NEAR)) and } U^i \text{ is the statistical uncertainty. } \xi, b^d, f_r \text{ and } e \text{ are pull parameters of detection efficiency, background, reactor antineutrino flux and energy scale, which are systematic uncertainty sources. } \sigma_{\xi}, \sigma_{\text{bkg}}, \sigma_f \text{ and } \sigma_{\text{scale}} \text{ are their systematic uncertainties.} \]
5. Result
We observed a clear deficit of reactor $\nu_e$ in the far detector. A rate-only analysis using the deficit information only obtains $\sin^22\theta_{13} = 0.087 \pm 0.008$ (stat.) $\pm 0.008$ (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 $\sin^22\theta_{13} = 0.088 \pm 0.008$ (stat.) $\pm 0.007$ (syst.) and $|\Delta m^2_{ee}| = 2.52 \pm 0.19$ (stat.) $\pm 0.17$ (syst.) $\times 10^{-3}$eV$^2$. When we compare the observed IBD prompt spectrum with the best fit prediction obtained using reactor neutrino flux models by Mueller [4] and Huber [5], we have observed the excess of events around 5 MeV as shown in Figure 2. The amount of the excess is $\sim 2.5\%$ 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 $^{96}$Y and $^{92}$Rb in the fission process [6]. In Figure 3, the observed IBD prompt spectrum at far detector is compared to the prediction, which is obtained by weighting the observed near detector IBD spectrum. The observed far detector spectrum shows a clear energy-dependent disappearance of reactor $\nu_e$ and it is consistent with the prediction with the best fit oscillation parameters.

Figure 2. Comparison of observed and expected IBD prompt energy spectrum in the near (left) and far (right) detectors. A excess at around 5 MeV is clearly seen.

Figure 3. Comparison of the observed IBD prompt spectrum at far detector to the prediction, which is obtained by weighting the observed near detector IBD spectrum.

Figure 4 shows $1 \sigma$, $2 \sigma$ and $3 \sigma$ allowed region for the neutrino oscillation parameters $|\Delta m^2_{ee}|$ and $\sin^22\theta_{13}$. Figure 5 shows the measured survival probability of reactor $\nu_e$ as a function of effective baseline $L_{eff}$ over $\nu_e$ 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 also obtained by weighting near detector data.

![Figure 4](image)

**Figure 4.** $1\sigma$, $2\sigma$ and $3\sigma$ allowed region for the neutrino oscillation parameters $|\Delta m^2_{ee}|$ and $\sin^2 2\theta_{13}$.

![Figure 5](image)

**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.

6. Conclusion
In summary, RENO has observed clear energy dependent disappearance of reactor $\nu_e$ at far detector and could determine $|\Delta m^2_{ee}|$ and $\sin^2 2\theta_{13}$ based on far-to-near ratio analysis using 800 days data sample. RENO is continuing to take data and we expect to measure $\sin^2 2\theta_{13}$ with 5% 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 [7].

References
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