PROCEEDINGS OF SCIENCE

Recent Results from RENO

ChangDong Shin[*][†]
Chonnam National University
E-mail: `scd0211@gmail.com`

The Reactor Experiment for Neutrino Oscillation (RENO) started data-taking from August, 2011 and has successfully measured the smallest neutrino mixing angle θ_{13} by observing the disappearance of reactor electron antineutrinos. Electron antineutrinos from the six reactors at Hanbit Nuclear Power Plant in Korea are detected and compared by the two identical near-and-far detectors. In 2016, RENO has published an updated value of θ_{13} and its first measurement of Δm^2_{ee} based on energy dependent disappearance probability. RENO has made efforts to reduce systematic uncertainties based on a careful understanding of backgrounds and analysis methodology. The measured prompt spectra show an excess of reactor electron antineutrinos around 5 MeV relative to the prediction from common reactor models. In this talk, we present a precise measurement of θ_{13} and Δm^2_{ee} using more data and improved systematic uncertainties.

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[*] Speaker.
[†] for RENO collaboration

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1. Introduction

RENO has published the result of its first measurement of the smallest neutrino mixing angle θ_{13} in 2012 [1], an then an updated value of θ_{13} and its first measurement of $|\Delta m^2_{ee}|$ based on energy dependent disappearance probability using 500 days of data in 2016 [2]. The detail description has been submitted to PRD [3]. RENO has accumulated about 1500 live days of data as of September 2015. We report updated results of θ_{13} and $|\Delta m^2_{ee}|$ measurements with improved systematic uncertainties using the 1500 live days of data and the observation of an excess at ~5 MeV in reactor antineutrino spectrum. A measurement of absolute reactor neutrino flux using RENO data will be also shown. The results of using neutron capture events on hydrogen will also be submitted soon.

2. Experimental setup and RENO detector

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. Figure 1 shows a layout of the RENO experiment. 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.

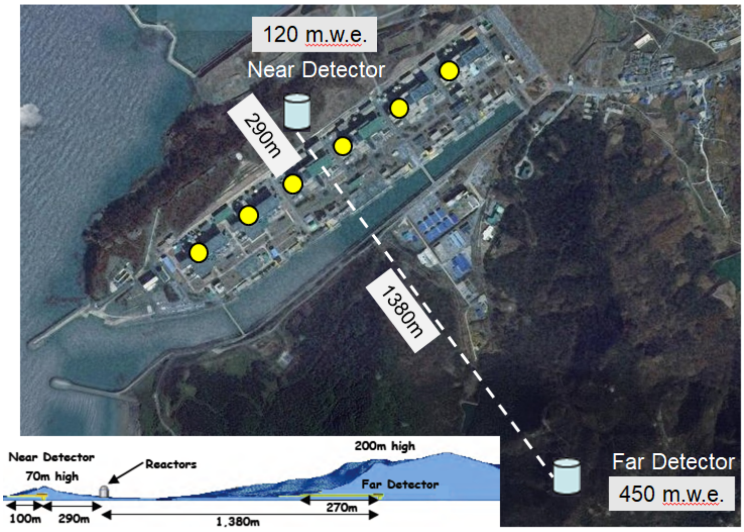

Figure 1: Top view of the six reactors in Hanbit nuclear power plant and the location of the two detectors. Side view of the RENO experimental layout is shown at the bottom.

Each RENO detector consists of a main inner detector (ID) and an outer veto detector (OD) as shown in Figure 2. 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, $\overline{\nu}_e + p \to e^+ + n$. 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 γ-rays escaping from the target region and thus increasing the detection efficiency. Outside this γ-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 γ-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 detail of detection methods and setup of the RENO experiment can be found elsewhere [4].

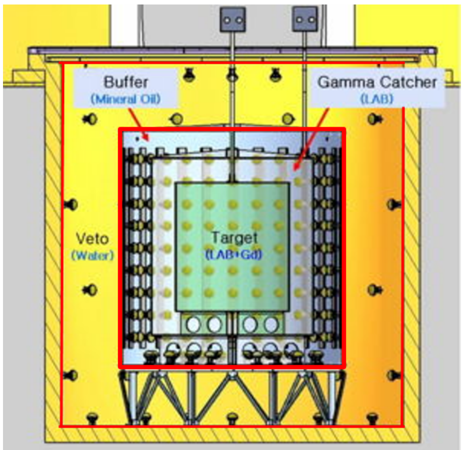

Figure 2: View of RENO detector. The detector consists of four concentric cylindrical detector, from center to outer, target, γ-catcher, buffer, and veto region.

3. IBD rate and backgrounds

The RENO experiment has been investigated for background since the results were published on 2016. As a result, the amount of background and uncertainties are significantly reduced via additional cuts and improved background removal algorithms as shown in Figure 3.

We compared the expected flux and the observed rate from the thermal power and isotope fraction. Some periods at ND are excepted due to UPS noise. At the Hanbit nuclear power plant, some of the reactors are turned on/off during the data-taking period due to maintenance or fuel replacement. The expected rates include oscillation effect with best fit, weighted fluxes by the thermal power and the fission fractions of each reactor. The observed rate well describes the change in the expected rate with time as shown in Figure 4.

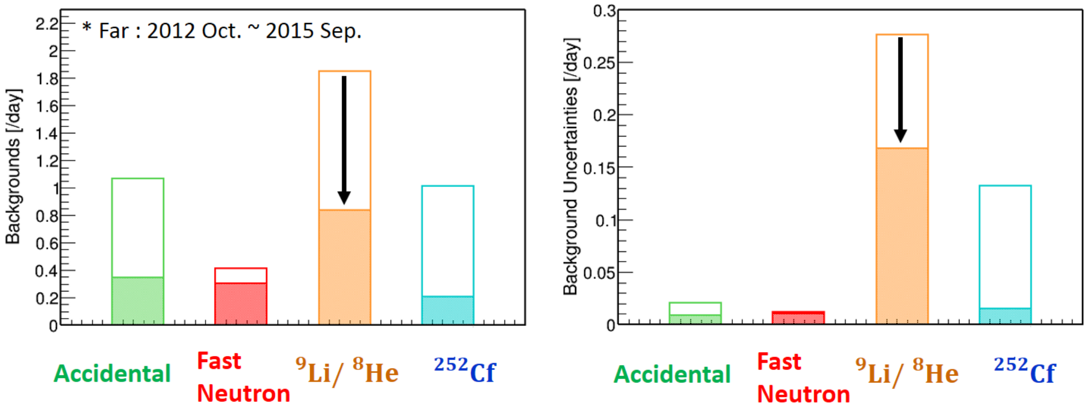

Figure 3: Background rate and uncertainties. We have significantly reduced the background rate and uncertainty.

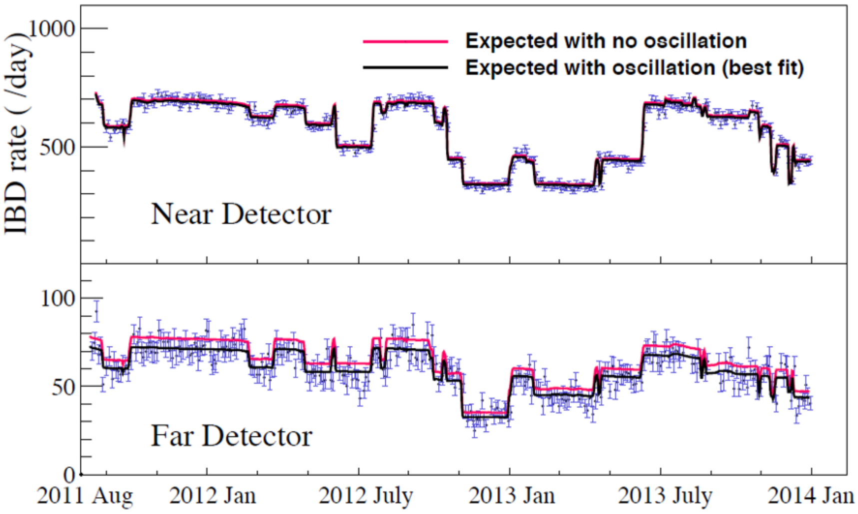

Figure 4: Daily IBD rate of data at the Near and Far detector.

4. Rate and shape analysis

Figure 5 shows a spectral comparison between the observed IBD prompt spectrum and the prediction from a reactor neutrino model [5, 6] and the best-fit oscillation results. A clear spectral discrepancy is observed in the region of 5 MeV in both detectors. The MC predicted energy spectra are normalized to the observed events out of the excess range $3.6 < E_p < 6.6$ MeV. The excess of events is estimated as about 2.5% of the total observed IBD events in both detectors. The fractional difference is also shown in the lower panel.

Furthermore, the 5 MeV excess is observed to be proportional to the reactor thermal power. Figure 6 shows a clear correlation between the 5 MeV excess rate and the total IBD rate that is proportional to the reactor thermal power. This indicates that the 5 MeV excess comes from reactors.

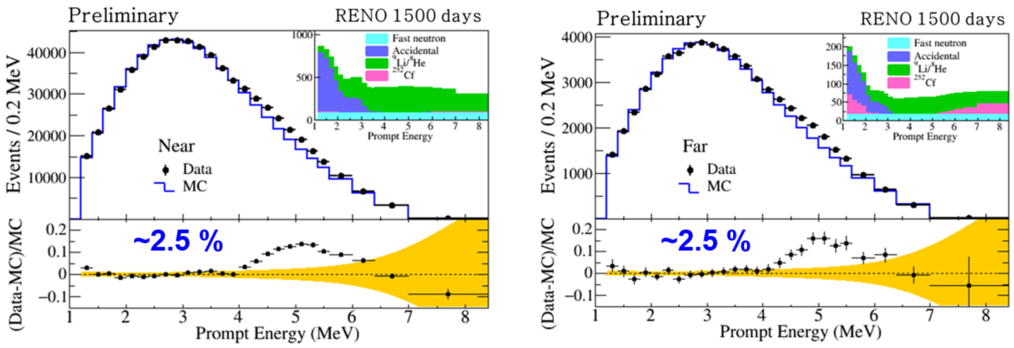

Figure 5: Comparison of observed and expected IBD prompt energy spectrum in the near (a) and far (b) detectors. The expected distributions are obtained from the best-fit oscillation results. The excess at around 5 MeV is clearly seen. A spectral-only comparison is made by normalizing the MC predicted energy spectra to the observed events out of the excess range $3.6 < E_p < 6.6$ MeV.

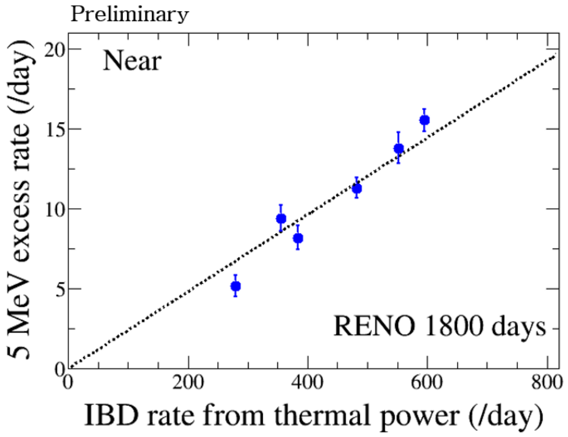

Figure 6: Correlation between the 5 MeV excess rate and the total IBD rate. The IBD rate is proportional to the reactor thermal power. This indicates that the 5 MeV excess comes from reactors.

We have observed a clear energy dependent deficit of reactor $\overline{\nu}_e$ in the far detector. The best-fit values obtained from the rate and spectral analysis are $\sin^2 2\theta_{13}$ = 0.086 ±0.006 (stat.) ±0.005 (syst.) and $|\Delta m^2_{ee}| = [2.61^{+0.15}_{-0.16}$ (stat.) $^{+0.09}_{-0.09}$ (syst.)] $\times 10^{-3} eV^2$. Figure 7 shows allowed regions of 68.3, 95.5 and 99.7 % C.L. in the $|\Delta m^2_{ee}|$ and $\sin^2 2\theta_{13}$ plane.

5. Measurement of absolute reactor neutrino flux

In this section, we report a measurement of reactor antineutrino flux using RENO near-site data. The flux normalization R is obtained from the χ^2 fit using rate-only information in the best fitted $\sin^2 2\theta_{13}$. The best fit R obtained is 0.913 ± 0.021 with the Huber-Mueller model [5, 6]. The deficit of observed reactor neutrino fluxes relative to the prediction indicates an overestimated flux or possible oscillation to sterile neutrinos. Figure 8 shows the RENO measurement of flux normalization R with other reactor experiments, which also demonstrate deficit of observed reactor

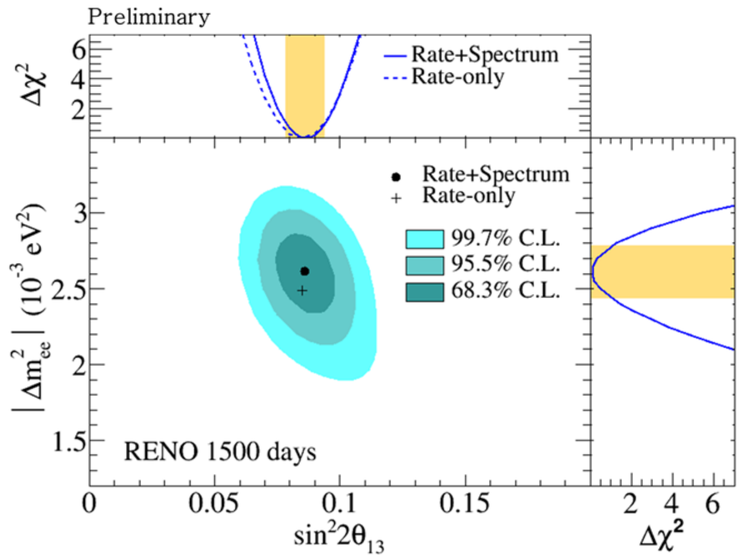

Figure 7: Allowed regions of 68.3, 95.5 and 99.7 % C.L. in the $|\Delta m^2_{ee}|$ and $\sin^2 2\theta_{13}$ plane. The best-fit values are given by the black dot. The $\Delta\chi^2$ distribution for $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ are also shown with an 1 σ band. The rate-only result for $\sin^2 2\theta_{13}$ is shown by the cross.

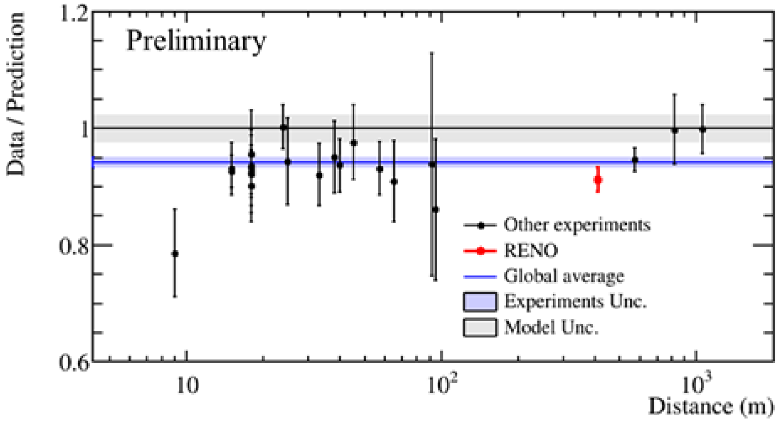

Figure 8: The flux normalization R measured from various reactor experiments with the Huber-Mueller model [5, 6]. The RENO result is shown at the baseline (411 m) of near-site.

neutrino fluxes, which is so called "reactor antineutrino anomaly". Recently, there has been some investigation on the possibility that the reactor anomaly is due to miscalculation of one or more of the ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu antineutrino fluxes [8, 9]. RENO also has been doing the measurement of IBD yield of individual isotope. Study on fuel dependent variation of reactor antineutrino yield and spectrum using RENO data is in progress and the results will be published soon.

6. n-H IBD analysis

The (n-H) analysis is more difficult than (n-Gd) analysis due to many backgrounds. How-

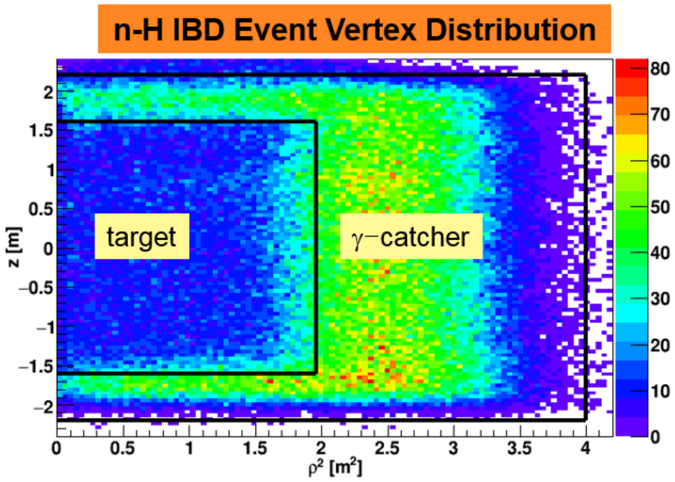

Figure 9: The vertex distribution of n-H IBD events.

ever, if the background can be successfully removed, it also can measure mixing angle (θ_{13}). An analytical technique has been developed to effectively remove the background. In addition, the (n-H) analysis can use events in both target and γ-catcher as shown in Figure 9, which has more than twice statistics of (n-Gd). And (n-H) data of 1500 live days is statistically sufficient for the analysis. Therefore, a sufficient amount of neutrino signal can be obtained through optimization of selection cuts. The neutrino mixing angle θ_{13} is measured by rate-only analysis. The final result is $\sin^2(2\theta_{13}) = 0.097 \pm 0.013\ (\text{stat.}) \pm 0.015\ (\text{syst.})$.

7. Summary and prospects

RENO has observed a clear energy dependent disappearance of reactor $\overline{\nu}_e$ at far detector and updated the result of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ measurement based on far-to-near ratio analysis using of 1500 days of data. RENO is going to take data until the end of 2018 and expect to measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ with 6% accuracy 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 [10].

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