IL NUOVO CIMENTO **39 C** (2016) 317
DOI 10.1393/ncc/i2016-16317-7

Colloquia: La Thuile 2016

New results from RENO and future RENO-50 project

S. B. Kim

KNRC, Department of Physics and Astronomy, Seoul National University
Seoul 08826, South Korea

received 26 July 2016

Summary. — RENO (Reactor Experiment for Neutrino Oscillation) has obtained a more precise value of the smallest mixing angle θ_{13} and the first result on neutrino squared-mass difference $|\Delta m^2_{ee}|$ from an energy- and baseline-dependent disappearance of reactor electron antineutrinos ($\overline{\nu}_e$) using 500 days of data. Based on the ratio of inverse-beta-decay (IBD) prompt spectra measured between two identical far and near detectors, we obtain $\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$ and $|\Delta m^2_{ee}| = [2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})] \times 10^{-3}\,\text{eV}^2$. An excess of reactor antineutrinos near 5 MeV is observed in the measured prompt spectrum with respect to the most commonly used models. The excess is found to be consistent with coming from reactors. A future reactor experiment of RENO-50 is proposed to determine the neutrino mass hierarchy and to make highly precise measurements of θ_{12}, Δm^2_{21}, and $|\Delta m^2_{ee}|$.

1. – Oscillation of reactor antineutrinos

In the present framework of three flavors, neutrino oscillation is described by a unitary Pontecorvo-Maki-Nakagawa-Sakata matrix with three mixing angles (θ_{12}, θ_{23} and θ_{13}) and one CP phase angle [1, 2]. Neutrino oscillation was discovered in the atmospheric neutrinos by the Super-Kamiokande experiment in 1998, and the mixing angle θ_{23} was measured [3]. The solar neutrino oscillation was observed by the SNO Collaboration in 2001, and the mixing angle θ_{12} was determined [4]. The 2015 Nobel prize in physics was awarded to Kajita and McDonald for the discovery of the neutrino oscillations. All of the three neutrino mixing angles were measured to provide a comprehensive picture of neutrino transformation in 2012 when the reactor neutrino experiments determined the smallest mixing angle θ_{13} [5-7]. The next round of neutrino experiments is under consideration or preparation to determine the CP violation phase and the neutrino mass splitting type.

Reactor neutrino measurements can determine the mixing angle without the ambiguities associated with matter effects and CP phase. The RENO experiment has significantly reduced uncertainties associated with the measurement of θ_{13} using two identically performing detectors at locations near and far from reactors. Reactor experiments with a baseline distance of $\sim$1 km can determine the mixing angle θ_{13} and an effective squared mass difference $|\Delta m^2_{ee}|$ based on the $\overline{\nu}_e$ survival probability P [8],

$$
\begin{aligned}
1 - P &= \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \\
&\quad + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\
&\approx \sin^2 2\theta_{13}\sin^2\Delta_{ee} + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21},
\end{aligned} \tag{1}
$$

where $\Delta_{ij} \equiv 1.267\Delta m^2_{ij}L/E$, E is the $\overline{\nu}_e$ energy in MeV, and L is the distance between the reactor and the detector in meters. The effective squared mass difference is defined by $\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32} = \Delta m^2_{32} + \cos^2\theta_{12}\Delta m^2_{21}$ [9]. Note that θ_{13} and $|\Delta m^2_{ee}|$ can be unambiguously determined without being affected by the oscillation due to θ_{12} at the RENO baseline.

2. – The RENO experiment

RENO is the first reactor experiment to take data with two identical near and far detectors in operation, from August 2011. In early April 2012, the experiment successfully reported a definitive measurement of θ_{13} based on the rate-only analysis of deficit found in $\sim$220 live days of data [7]. RENO has collected more than 1500 live days of data as of March 2016. In this workshop, we present a more precisely measured value of θ_{13} and our first determination of $|\Delta m^2_{ee}|$, based on the rate, spectral and baseline information of reactor $\overline{\nu}_e$ disappearance using $\sim$500 live days of data [10].

Six pressurized water reactors at Hanbit (known as Yonggwang) Nuclear Power Plant in South Korea, each with a maximum thermal output of 2.8 $\mathrm{GW_{th}}$, are situated in a linear array spanning 1.3 km with equal spacings. The identical near and far antineutrino detectors are located at 294 m and 1383 m, respectively, from the center of the reactor arrays. The reactor flux-weighted baseline is 410.6 m for the near detector and 1445.7 m for the far detector. The reactor $\overline{\nu}_e$ is detected through the IBD interaction, $\overline{\nu}_e + p \rightarrow e^+ + n$, with free protons in hydrocarbon liquid scintillator (LS) with 0.1% gadolinium (Gd) as a target. The coincidence of a prompt positron signal and a signal delayed by a mean time of $\sim$27 μs from the neutron capture by Gd (n-Gd) provides the distinctive IBD signature against backgrounds. 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 [11]. Each RENO detector utilizes 16 tons of $\sim$0.1% Gd-doped LS as a $\overline{\nu}_e$ target [7, 10].

3. – Energy calibration

The event energy is determined from the total charge ($Q_{\rm tot}$) in photoelectrons (p.e.) that is collected by the PMTs and corrected for gain and charge collection variations using the neutron capture peak energies. An absolute energy scale is determined by $Q_{\rm tot}$ of γ-rays coming from several radioactive sources, and from IBD delayed signals of neutron capture on Gd. A charge-to-energy conversion function is generated from the peak energies of these γ-ray sources. The observed $Q_{\rm tot}$ of a γ-ray source is converted to the corresponding $Q_{\rm tot}$ of a positron ($Q^c_{\rm tot}$) using a GEANT4 Monte Carlo simulation (MC). The true energy ($E_{\rm true}$) of a positron interaction is the sum of the kinetic energy and the energy from its annihilation. The converted $Q^c_{\rm tot}$ of IBD prompt energy (E_p) is

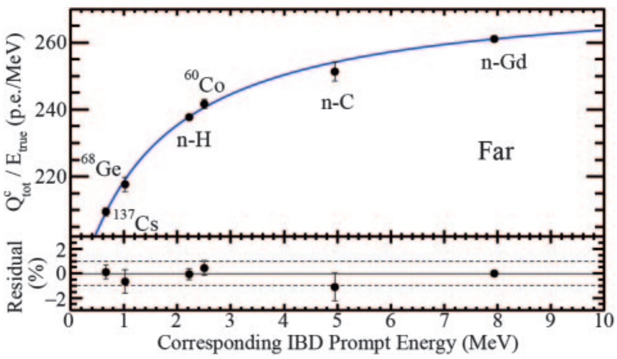

Fig. 1. – Non-linear response of the scintillating energy obtained from the visible energies of γ-rays coming from several radioactive sources and IBD delayed signals in the far detector. The curve is the best fit to the data points.

estimated by taking into account the difference in the visible energies of the γ-ray and positron through the MC. The RENO MC includes measured optical properties of LS and the quenching effect of γ-ray at low energies [11].

The upper panel of fig. 1 shows non-linear response of the measured Q^c_{tot} to E_{true}, especially at low energies, mainly due to the quenching effect in the scintillator and the Cherenkov radiation. Deviation of all calibration data points with respect to a best-fit parametrization is within 1% as shown in fig. 1, lower panel. The energy scales of the near and far detectors are compared using identical radioactive sources, and the difference is found to be less than 0.15% for $E_p = 1$–$8\,\text{MeV}$.

4. – IBD candidates and background estimation

We have analyzed the first 500 days of data in the period between August 2011 and January 2013, to obtain spectral measurements of θ_{13} and $|\Delta m^2_{ee}|$ that are reported in ref. [10]. Event selection criteria are applied to obtain clean IBD candidates with a delayed signal of neutron capture by Gd. Applying the IBD selection criteria yields 31541 (290775) candidate events with E_p between 1.2 and 8.0 MeV for a live time of 489.93 (458.49) days in the far (near) detector. In the final data samples, the remaining backgrounds are either uncorrelated or correlated IBD candidates. An accidental background comes from an uncorrelated pair of a prompt-like event due to gamma rays from radioactivity in the surrounding rock, LS and PMTs, and detector noise events, and a delayed-like event of neutron capture on Gd. Correlated backgrounds are: i) energetic neutrons that are produced by cosmic muons traversing the surrounding rock and the detector, enter the inner detector, and interact in the target to produce a recoil proton as a prompt-like signal; ii) β-n emitters from decays of cosmic-muon–induced ^{9}Li/^{8}He isotopes; and iii) multiple neutron events from a tiny amount of ^{252}Cf that was accidentally introduced into both detectors during detector calibration in October 2012. The total background rates are estimated to be 17.54 ± 0.83 and 3.14 ± 0.23 events per day for near and far detectors, respectively. The remaining background fraction is $4.9 \pm 0.4\%$ in the far detector, and $2.8 \pm 0.1\%$ in the near detector. The average daily observed IBD rates after subtracting backgrounds are 616.67 ± 1.44 and 61.24 ± 0.42 per day for the near and the far detectors, respectively. Since the rates and shapes of all the backgrounds

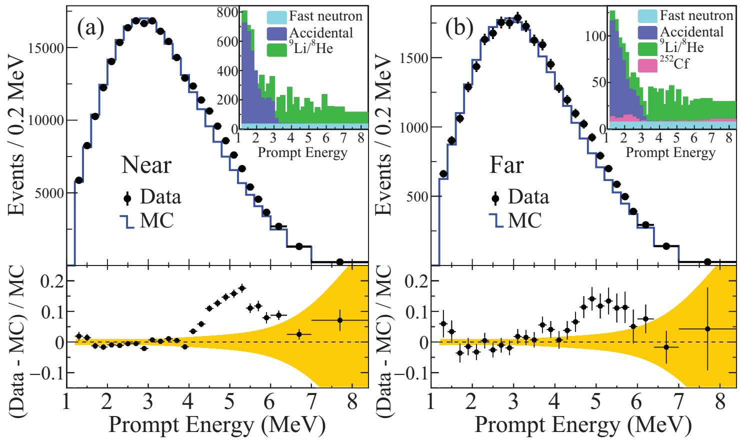

Fig. 2. – Spectral comparison of observed and expected IBD prompt events in the (a) near and (b) far detectors. The expected distributions are obtained using rate and spectral analysis results discussed later. The observed spectra are obtained from subtracting the background spectra as shown in the insets. A shape difference is clearly seen at 5 MeV. A spectral deviation from the expectation is larger than the uncertainty of an expected spectrum (shaded band).

are measured from control data samples, their uncertainties are expected to be further reduced with more data.

5. – Results

Systematic uncertainties have been significantly reduced since the first measurement presented in ref. [7]. The decrease of systematic uncertainties mainly comes from background reduction and more precise estimation of background rates. For example, the most dominant background uncertainty of ^{9}Li/^{8}He is reduced from 29% (48%) to 15% (10%) in the far (near) detector. The reduction was possible due to additional background removal by optimized rejection criteria, increased statistics of the ^{9}Li/^{8}He control sample, and a new method of estimating the background rate in the IBD candidates from the background dominant energy region.

The expected rate and spectrum of reactor $\overline{\nu}_e$ are calculated for the duration of the physics data taking, taking into account the varying thermal powers and fission fractions of each reactor. We observe a clear deficit of reactor $\overline{\nu}_e$ in the far detector. Using the deficit information only, a rate-only analysis obtains $\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat.}) \pm 0.007(\text{syst.})$, where the world average value of $|\Delta m^2_{ee}| = (2.49 \pm 0.06) \times 10^{-3}\,\text{eV}^2$ is used [12]. The total systematic error of $\sin^2 2\theta_{13}$ is reduced from 0.019 to 0.007, mostly due to the decreased background uncertainty, relative to the first measurement [7] while the statistical error is reduced from 0.013 to 0.009.

RENO has obtained an unprecedentedly accurate measurement of the reactor neutrino flux and spectrum. Figure 2 shows the observed spectra of IBD prompt signals for the near and far detectors after background subtraction, compared to the prediction that is expected from a reactor neutrino model [13, 14] and the best-fit oscillation results. The subtracted background spectra are shown in the insets. A clear spectral difference is observed in the region centered at 5 MeV. The excess of events constitutes about 3% of the total observed reactor $\overline{\nu}_e$ rate in both detectors. Furthermore, the excess is observed

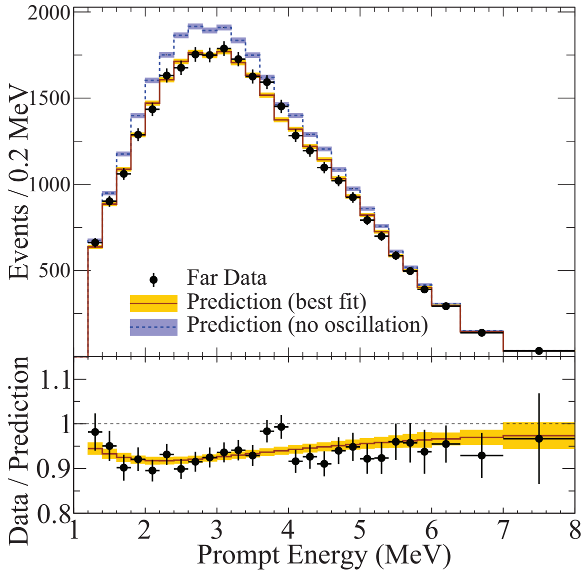

Fig. 3. – Top: comparison of the observed IBD prompt spectrum in the far detector with the no-oscillation prediction obtained from the measurement in the near detector. The prediction from the best-fit results to oscillation is also shown. Bottom: ratio of reactor $\overline{\nu}_e$ events measured in the far detector to the no-oscillation prediction (points) and ratio from MC with best-fit results folded in (shaded band). Errors are statistical uncertainties only.

to be proportional to the reactor power. This observation suggests a need for reevaluation and modification of the current reactor $\overline{\nu}_e$ model [13, 14].

Because of the unexpected structure around 5 MeV, the oscillation amplitude and frequency are determined from a fit to the measured far-to-near ratio of IBD prompt spectra. The relative measurement using identical near and far detectors makes the method insensitive to the correlated uncertainties of the expected reactor $\overline{\nu}_e$ flux and spectrum as well as detection efficiency. To determine $|\Delta m^2_{ee}|$ and θ_{13} simultaneously, a χ^2 is constructed using the spectral ratio measurement and is minimized [10]. The χ^2 is minimized with respect to the pull parameters and the oscillation parameters. The best-fit values obtained from the rate and spectral analysis are $\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$ and $|\Delta m^2_{ee}| = [2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})] \times 10^{-3}\,\text{eV}^2$ with $\chi^2/NDF = 58.9/66$, where NDF is the number of degrees of freedom. The dominant systematic uncertainties are those of the energy scale difference and the backgrounds.

Figure 3 shows the background-subtracted, observed spectrum at the far detector compared to the one expected for no oscillation and the one expected for the best-fit oscillation at the far detector. The expected spectra are obtained by weighting the spectrum at the near detector with the oscillation or no-oscillation assumptions using the measured values of θ_{13} and $|\Delta m^2_{ee}|$. The observed spectrum shows a clear energy-dependent disappearance of reactor $\overline{\nu}_e$ consistent with neutrino oscillations.

Figure 4 shows the measured survival probability of reactor $\overline{\nu}_e$ as a function of an effective baseline L_{eff} over $\overline{\nu}_e$ energy E_ν in the far detector, in good agreement with the prediction that is obtained from the observed distribution in the near detector, for the best-fit oscillation values. This result demonstrates clear L_{eff}/E_ν-dependent disappearance of

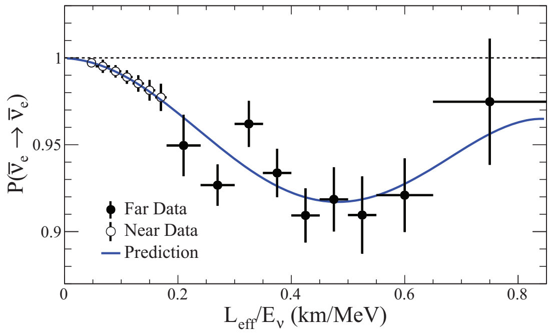

Fig. 4. – Measured reactor $\overline{\nu}_e$ survival probability in the far detector as a function of L_{eff}/E_ν. The curve is a predicted survival probability, obtained from the observed probability in the near detector, for the best-fit values of $|\Delta m^2_{ee}|$ and $\sin^2 2\theta_{13}$. The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

reactor $\overline{\nu}_e$, consistent with the periodic feature of neutrino oscillation. Note that L_{eff} is the reactor-detector distance weighted by the multiple reactor fluxes, and E_ν is converted from the IBD prompt energy. The measured survival probability is obtained by the ratio of the observed IBD counts to the expected counts assuming no oscillation in each bin of L_{eff}/E_ν.

In summary, RENO has observed clear energy-dependent disappearance of reactor $\overline{\nu}_e$ using two identical detectors, and obtains $\sin^2 2\theta_{13} = 0.082 \pm 0.010$ and $|\Delta m^2_{ee}| = (2.62^{+0.24}_{-0.26}) \times 10^{-3}\,\mathrm{eV}^2$ based on the measured periodic disappearance expected from neutrino oscillations. With the increased statistics of the 500 day data sample and the significantly reduced systematic error, RENO has produced a precise measurement of the mixing angle θ_{13}. The exciting result provides a comprehensive picture of neutrino transformation among three kinds of neutrinos and opens the possibility to search for CP violation in the leptonic sector.

The systematic error of θ_{13} is estimated as $\delta \sin^2 2\theta_{13} = 0.006$, mainly coming from uncertainties of reactor neutrino flux, detector efficiency and backgrounds. The background estimation is entirely based on the control data samples, and thus the uncertainty is expected to be reduced with more data. Based on a total of 5 years of data, the RENO experiment is expected to obtain a measured $\sin^2 2\theta_{13}$ value with a precision of 7% according to its design goal. With a better understating of systematic uncertainties, it could become as good as 5%, and can be even smaller if a measurement with neutron capture on hydrogen as a delayed signal is combined. Precise measurements of θ_{13} by the reactor experiments will provide the first glimpse of the CP phase angle if accelerator beam results are combined [15].

The RENO Collaboration has obtained the first measurement of $|\Delta m^2_{ee}|$ based on the energy- and baseline-dependent oscillation effects. The measured value of $|\Delta m^2_{ee}| = (2.62^{+0.24}_{-0.26}) \times 10^{-3}\,\mathrm{eV}^2$ is consistent with $|\Delta \bar{m}^2| = (2.50^{+0.23}_{-0.25}) \times 10^{-3}\,\mathrm{eV}^2$, obtained by the MINOS Collaboration [16], and $|\Delta m^2_{32}| = (2.51 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$ (normal mass hierarchy) or $|\Delta m^2_{13}| = (2.48 \pm 0.10) \times 10^{-3}\,\mathrm{eV}^2$ (inverted mass hierarchy), reported by T2K Collaboration [17], using ν_μ beams. The excellent agreement between Δm^2_{ee} and $|\Delta m^2|$ strongly supports the paradigm of three generations of neutrinos. The RENO's current precision of $|\Delta m^2_{ee}|$ measurement is roughly 10%, and its ultimate precision will reach $\sim$5%, quite close to the ratio of $\Delta m^2_{21}/|\Delta m^2_{31}| \approx 3\%$, so that it may provide a hint on the neutrino mass splitting type.

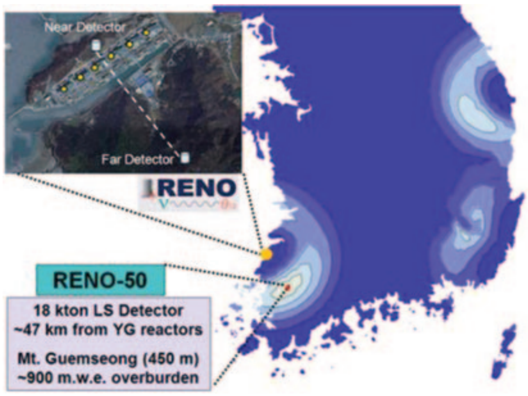

Fig. 5. – The RENO-50 detector will be located underground, beneath Mt. Guemseong in the city of Naju, 47 km away from the Hanbit nuclear power plant. The contours of different colors indicate the sensitivity of the mass hierarchy determination. The perpendicular direction from the reactor alignment has the highest sensitivity.

The near detector has made a precise measurement of the reactor antineutrino spectrum, and observed a clear spectral difference in the region of 5 MeV. This observation suggests a need for reevaluation and modification of the current reactor $\overline{\nu}_e$ model as well as for reconsideration of the so-called reactor anomaly.

6. – RENO-50: future reactor experiment for neutrino mass hierarchy

An underground detector of RENO-50 [18] under proposal will consist of 18000 tons of ultra-low-radioactivity liquid scintillator and 12000 high quantum efficiency 20 inch photomultiplier tubes, located at roughly 50 km away from the Hanbit nuclear power plant in South Korea where the neutrino oscillation due to θ_{12} takes place at maximum. The experimental arrangement is sketched in fig. 5. The detector is expected to detect neutrinos from nuclear reactors, the Sun, Supernovae, the Earth, any possible stellar object and a J-PARC neutrino beam as well. The main goals are to determine the neutrino mass ordering and to measure the unprecedentedly accurate (<0.5%) values of θ_{12}, Δm^2_{21}, and $|\Delta m^2_{ee}|$. It is expected to detect 5600 events of a neutrino burst from a supernova in our galaxy, $\sim$1000 geo-neutrino events for 6 years, and $\sim$200 events of muon neutrinos from the J-PARC beam every year. The RENO-50 will observe the manifestation of mass hierarchy in the oscillation effect if it establishes an extremely good energy resolution of $\sim$3% at 1 MeV. The energy resolution can be achieved by maximized light collection greater than 1000 photoelectrons per MeV. The improvement requires an increased photosensitive area using 12000 20 inch PMTs, the use of high (35%) quantum efficiency PMTs, and an increased attenuation length of LS up to 25 m.

The high-precision measurements of θ_{12}, Δm^2_{21}, and $|\Delta m^2_{ee}|$ can make a strong impact on explaining the pattern of neutrino mixing and its origin. They will also provide useful information on the effort of finding a flavor symmetry. A RENO-50 proposal has been submitted for full construction funding. A R&D funding is allocated from the end of 2014, and will continue in the next 3 years. R&D efforts will be made on demonstrating the feasibility of a 3% energy resolution at 1 MeV, essential for determining the neutrino mass hierarchy. If the construction funding is timely made, we expect to start the experiment in 2021.

* * *

The RENO experiment is supported by the National Research Foundation of Korea (NRF) Grant No. 2009-0083526 funded by the Korea Ministry of Science, ICT, and Future Planning. We gratefully acknowledge the cooperation of the Hanbit Nuclear Power Site and the Korea Hydro and Nuclear Power Co., Ltd. (KHNP). We thank KISTI for providing computing and network resources through GSDC, and all the technical and administrative people who greatly helped in making this experiment possible.

REFERENCES

[1] Pontecorvo B., *Sov. Phys. JETP*, **7** (1958) 172.
[2] Maki Z., Nakagawa M. and Sakata S., *Prog. Theor. Phys.*, **28** (1962) 870.
[3] Super-Kamiokande Collaboration (Fukuda Y. *et al.*), *Phys. Rev. Lett.*, **81** (1998) 1562.
[4] SNO Collaboration (Ahmad Q. R. *et al.*), *Phys. Rev. Lett.*, **87** (2001) 071301; **89** (2002) 011301.
[5] Double Chooz Collaboration (Abe Y. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 131801.
[6] Daya Bay Collaboration (An F. P. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 171803.
[7] RENO Collaboration (Ahn J. K. *et al.*), *Phys. Rev. Lett.*, **108** (2012) 191802.
[8] Petcov S. T. and Piai M., *Phys. Lett. B*, **533** (2002) 94.
[9] Nunokawa H., Parke S. and Zukanovich Funchal R., *Phys. Rev. D*, **72** (2005) 013009.
[10] RENO Collaboration (Choi J. H. *et al.*,) *Phys. Rev. Lett.*, **116** (2016) 211801, arXiv:1511.05849.
[11] RENO Collaboration (Park J. S. *et al.*), *Nucl. Instrum. Methods A*, **707** (2013) 45.
[12] Particle Data Group (Olive K. A. *et al.*), *Chin. Phys. C*, **38** (2014) 090001.
[13] Mueller Th. A. *et al.*, *Phys. Rev. C*, **83** (2011) 054615.
[14] Huber P., *Phys. Rev. C*, **84** (2011) 024617; **85** (2012) 029901(E).
[15] T2K Collaboration (Abe K. *et al.*), *Phys. Rev. D*, **88** (2013) 032002; *Phys. Rev. Lett.*, **112** (2014) 061802.
[16] MINOS Collaboration (Adamson P. *et al.*), *Phys. Rev. Lett.*, **107** (2011) 181802; **110** (2013) 251801.
[17] T2K Collaboration (Abe K. *et al.*), *Phys. Rev. Lett.*, **112** (2014) 181801.
[18] See a talk given by Soo-Bong Kim at International Workshop on RENO-50 toward Neutrino Mass Hierarchy, Seoul, South Korea, 13–14 June, 2013; also see a talk given by Liangjian Wen at 26th International Conference on Neutrino Physics and Astrophysics, Boston, USA, 2–7 June, 2014.