New results from RENO & prospects with RENO-50

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Abstract. This paper briefly describes recent progress of RENO and next generation future prospect of the reactor neutrino oscillation experiment, RENO-50. Recently the RENO experiment has updated its latest value on sin^22\theta_{13} and provided new results on 5 MeV excess, \Delta m^2_{ee}, \theta_{13} with n-H analysis, absolute antineutrino flux measurement, and sterile neutrino search. It gives rich programs of neutrino properties, detector development, nuclear monitoring and application. Using reactor neutrinos, the future RENO-50 experiment will search for more precise measurement of \theta_{12}, \Delta m^2_{12} and mass hierarchy.

1. RENO

1.1 Experimental setup
RENO (Reactor Experiment for Neutrino Oscillation) is a reactor-based neutrino oscillation experiment to measure the smallest neutrino mixing angle (\theta_{13}) using electron antineutrinos emitted from the Hanbit nuclear power plant in Korea. It is located on the west coast of southern part of Korea, about 300 km from Seoul. The power plant consists of six pressurized water reactors producing a total thermal power of 16.4 GW_{th}. The six reactors each with maximum thermal output of 2.8 GW_{th} (reactors 3, 4, 5 and 6) or 2.66 GW_{th} (reactors 1 and 2) are lined up in roughly equal distances and span ~1.3 km. RENO uses two identical near and far detectors to reduce the systematic uncertainties. The near and far detectors are placed roughly 290 m and 1.4 km away from the center of the reactor, respectively. The near detector (ND) is located underneath a 70 m tall hall with an overburden of ~110 metres water equivalent (mwe) and the far detector (FD) is placed underneath a 260 m tall hall with an overburden ~450 mwe [1, 2].

1.2 Detector
The RENO detector consists of four concentric cylindrical layers: the target, the \gamma-catcher, the buffer, and the veto [2, 3]. The acrylic vessel holding the target liquid is surrounded by the \gamma-catcher. The target is filled with 16 metric tons of linear alkyl benzene-based 0.1% gadolinium (Gd)-loaded liquid scintillator (GdLS) [4–6]. The \gamma-catcher holds 28 mass tons of unloaded liquid scintillator (LS). Outside the \gamma-catcher, a 70 cm thick buffer layer is filled with 76 metric tons of a non-scintillating liquid, mineral oil (MO, C_{n}H_{2n+2}, n=11~44). This 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 buffer container [2, 7]. The outermost layer is the 1.5 m thick veto system and filled with highly purified water. This layer tags events coming from outside by Cherenkov radiation and also shields against ambient cosmic-rays and neutrons from the surrounding rock. Sixty-seven 10-inch R7081 water-proof PMTs are mounted on the wall of the veto vessel [2, 7]. All surfaces of the veto layer are covered with Tyvek sheets to increase the light collection.

1.3 The detection principle for reactor neutrinos
The reactor antineutrinos are detected through the inverse beta decay process (IBD, \bar{\nu}_e + p \rightarrow e^+ + n) followed by neutron capture. The prompt positron annihilates and yields 1~8 MeV of visible energy. The neutron is captured by a hydrogen, and it gives off a gamma with an energy of 2.2 MeV.
On the other hand, the delayed neutron capture signal can produce several gammas with a higher total energy of ~8 MeV with a mean delay of approximately 30 μs later if LS is loaded with a small amount of Gd, having a large neutron capture cross section. Therefore, GdLS significantly increases the efficiency of identifying the delayed signal against the low energy backgrounds [8, 9]. The coincidence of a prompt positron signal and a delayed signal from neutron capture by Gd provides the distinctive signature of IBD.

1.4 Data sample and backgrounds
RENO began data-taking in August, 2011. For about 500 days data-taking period between August 2011 to January 2013, the near (far) detector accumulated 290,775 (31,541) electron antineutrino candidate events [10]. This is about twice more data collected compared with the previous result published in 2012 [1]. Event rates of the observed IBD candidates and the estimated background at ND/FD are summarized in Table 1 [10]. Systematic uncertainties are classified into two categories related to reactor and detection. All systematic uncertainties have been significantly reduced since the first measurement presented in [1].

| Detector               | Near detector | Far detector |
|------------------------|---------------|--------------|
| IBD rate               | 616.67±1.44   | 61.24±0.42   |
| Total bkg rate         | 17.50±0.83    | 3.14±0.23    |
| Live time (days)       | 458.49        | 489.93       |
| Accidental rate        | 6.89±0.09     | 0.97±0.03    |
| $^9$Li/$^8$He rate     | 8.36±0.82     | 1.54±0.23    |
| Fast neutron rate      | 2.28±0.04     | 0.48±0.02    |
| $^{252}$Cf contamination rate | 0.00±0.01 | 0.14±0.03 |

1.5 Results and summary
Based on the number of events at the near detector and assuming no oscillation, RENO finds a clear deficit with a far-to-near ratio. Therefore, a clear disappearance of reactor antineutrinos is observed. The best-fit value for rate only analysis is $\sin^22\theta_{13} = 0.087 \pm 0.009$ (stat.) $\pm 0.007$ (syst.). Furthermore, a shape analysis was also done. RENO obtains $\sin^22\theta_{13} = 0.082 \pm 0.009$ (stat.) $\pm 0.006$ (syst.), and $|\Delta m^2_{ee}| = 2.62_{-0.22}^{+0.21}$ (stat.) $^{+0.12}_{-0.15}$ (syst.) for our first (rate + shape) analysis. For the independent measurement of $\theta_{13}$ value, n-H analysis was performed. From this, $\sin^22\theta_{13} = 0.086 \pm 0.012$ (stat.) $\pm 0.015$ (syst.) was measured. Within 3 years, the mixing angle of $\theta_{13}$ expects to be measured to ~6% precision level. Fig. 1 shows that the observed spectrum of IBD prompt signals in the far detector is compared to non-oscillation expectations based on measurements in the near detector. This disagreement of the spectra provides further evidence of neutrino oscillation. In addition, RENO showed the 5 MeV excess from reactor neutrinos spectrum and observed a clear energy-dependent disappearance of reactor antineutrinos. Measurement of absolute reactor neutrino flux shows that the ratio of data and prediction, $R$, is 0.946 ± 0.021. Finally, the excluded region for sterile neutrinos search is explored. Our results are consistent with standard three-flavor neutrino oscillation model in the $10^{-3}$eV$^2 < \Delta m^2 < 0.1$eV$^2$ mass range.
FIG. 1: Observed spectrum of the prompt signals in the FD with the no-oscillation prediction obtained from the measurement in the ND. A shape difference is clearly seen at 5 MeV.

2. RENO-50
After the RENO experiment, the RENO collaboration plans to construct an underground detector: RENO-50. At ~50 km from the reactor center, the neutrino oscillation due to $\theta_{12}$ takes place at maximum. An experiment with the baseline of ~50 km could be a natural extension of current RENO $\theta_{13}$ experiment. The main goals of RENO-50 are to measure the most accurate (1%) value of $\theta_{13}$ and to attempt determination of the neutrino mass hierarchy. The RENO-50 is expected to detect neutrinos from nuclear reactors, the Sun, Supernova, the Earth, any possible stellar object and a J-PARC neutrino beam [11]. It could act as a neutrino telescope. RENO-50 needs $100M for 5 year’s construction. Facility and detector construction will be scheduled from 2016 to 2021. Operation and experiment will be started from 2022. Currently funding for RENO-50 is being sought. Fig. 2 shows $\bar{\nu}_e$ disappearance probability as a function of $L/E$ with the current best values of $\Delta m^2$ and $\sin^22\theta_{12}$, and $\sin^22\theta_{13}$ at the upper bound [11]. There is large $\theta_{12}$ neutrino oscillation effect at ~50 km. The KamLAND experiment has observed a 40% disappearance of $\bar{\nu}_e$ at the baseline of 180 km [12]. Currently KamLAND energy resolution is at the level of ~6%. In order to achieve 3% energy resolution, RENO-50 will use high transparent liquid scintillator. Through careful purification and using better quality of PPO, the attenuation length will be increased from 15 m to 25 m. Using 15,000 20-inch PMTs will provide large photocathode coverage from 34% to 67%. In addition, Hamamatsu 20-inch PMTs having enhanced quantum efficiency from 20% to 35% will be used.
FIG. 2: The survival probability of $\bar{\nu}_e$ as the ratio of the distance to the neutrino energy ($L/E$). Normal hierarchy and inverted hierarchy are drawn.

2.1 Experimental site and RENO-50 detector
There are four nuclear reactor power plant sites (Ulchin, Wolsung, Kori and Hanbit) in Korea. RENO-50 is dedicated to the Hanbit nuclear power plant. A contribution from other nuclear power plants is negligible. In RENO-50, RENO will be used as near detectors, so that precise reactor neutrino fluxes can be measured. A careful survey of candidate sites for RENO-50 has been performed. An optimal candidate site is found at the 450 meter high Mt. Guemseong located at the city of Naju, ~50 km from the Hanbit nuclear power plant. RENO-50 is considering an inclined tunnel to obtain a deeper location. This corresponds to ~900 mwe overburden. RENO-50 detector will use 18,000 tons ultralow-radioactive liquid scintillator (LS). The diameter is 30 m and the height is 30 m. It is 18 times bigger than KamLAND detector. It consists of three layers: from the inner to outer, these are target, MO layer, and water veto layer. A total of 15,000 20-inch high efficiency PMTs will be installed and this will provide 67% surface coverage. Table 2 shows the comparison between RENO-50 and KamLAND.

Table 2. Comparison between RENO-50 and KamLAND.

| Experiment | Osc. reduction | Reactor flux | Detector size | Sys. Error (flux) | Error on $\sin^2 2\theta_{12}$ |
|------------|----------------|--------------|---------------|-------------------|-------------------------------|
| KamLAND    | 40%            | 53           | 1 kton        | 3%                | 5.4%                          |
| RENO       | 77%            | $6 \times 14.7$ | 18 kton      | ~0.3%             | 0.4%                          |

2.2 Physics with RENO-50

2.2.1. Mass hierarchy
Reactor experiments can determine the neutrino mass hierarchy (MH). The advantage of reactor neutrino experiments is to determine MH independently from CP phase and matter effects. However, in RENO-50 case, determination of MH is challenging. It requires extremely good energy resolution better than 3%, as shown in Fig. 3 [11]. By using 18 kton detector, RENO-50 will get ~3$\sigma$ significance with 3 years data-taking.
FIG. 3: Survival probability with different energy resolution. Solid line is normal hierarchy and dashed line is inverted hierarchy.

2.2.2 Precise measurement of mixing parameter $\theta_{12}$
In RENO-50, the near and far detectors of RENO could be used as near detectors, and thus would reduce relevant systematic uncertainties significantly. For baselines longer than 50 km, the reactor antineutrino oscillations due to $\Delta m^2_{31}$ average out and the survival probability becomes

$$P = \cos^4 \theta_{13} \left[ 1 - \sin^2 2\theta_{12} \sin \left( \frac{\Delta m^2_{21} L}{4E} \right) \right]$$

The oscillations due to $\theta_{12}$ and $\Delta m^2_{21}$ were observed in the KamLAND experiment [12]. Because the antineutrino survival probability becomes minimal for $\sin \left( \frac{\Delta m^2_{21} L}{4E} \right) \sim 1$, the optimal baseline for measuring $\theta_{12}$ is about 50–70 km. Namely, $P \approx 1 - \sin^2 2\theta_{12}$ is very sensitive to the value of $\theta_{12}$. The RENO-50 detector is expected to improve the error of the $\theta_{12}$ value. The current value of $\frac{\delta \sin^2 2\theta_{12}}{\sin^2 2\theta_{12}}$ is $\sim 5.4\%$ level [13]. RENO-50 will improve this value to $\sim 1.0\%$ (1$\sigma$) in 1 year. Furthermore, $\frac{\delta \Delta m^2_{12}}{\Delta m^2_{12}}$ will be improved from current 2.6% to $\sim 1.0\%$ (1$\sigma$) in 2 years.

2.2.3. Neutrino burst from a supernova
The RENO-50 detector filled with LS will be sensitive to a burst of neutrinos of all flavors from a Galactic supernova in the energy range of a few to tens of MeV. The time scale of the burst is tens of seconds. The background in the RENO-50 detector in a 10 second period is low enough for an observation of the neutrino signals from supernova burst. The RENO-50 detector would observe $\sim 6000$ events from a supernova at 8 kpc [14, 15].

2.2.4. Solar neutrinos
With ultra low activity liquid scintillator such as that achieved by Borexino, RENO-50 will search for matter effect on neutrino oscillation [16, 17]. Therefore the center of the Sun can be probed. Furthermore, the standard solar model would be examined and tested.

2.2.5. Reactor neutrino physics
The RENO and RENO-50 detectors will detect on the order of million neutrino events per year. They will measure the flux and energy distribution of the reactor neutrinos with a greater accuracy than
ever. This information would lead to meaningful comparison of thermal power and reactor fuel loading between measurements and calculations. In addition, a precise determination of the reactor neutrino spectrum might be useful for reducing the flux uncertainty. Therefore, reactor neutrinos could be used as an application for the direct check of nuclear non-proliferation treaties.

2.2.6. Other physics topics

J-PARC beams with off-axis angle (~3°) can reach RENO-50 detector at the level of ~400 events per year. Furthermore, RENO-50 will test on non-standard physics such as sterile neutrino physics. While recent neutrino oscillation results are understood in the framework of three active neutrinos mixing, they do not completely exclude admixture of sterile neutrinos [18, 19].

2.3 Summary of RENO-50

RENO-50 is a long term operation and multi-purpose detector. Determining mass hierarchy is very challenging but not impossible with very good energy resolution better than 3% level. In addition, neutrino oscillation parameters, $\theta_{12}$ and $\Delta m^2_{12}$, will be precisely measured less than 0.5% level, which can constrain new physics. In summary, RENO-50 reactor experiment with longer baseline of ~50 km is being pursued to perform high-precision measurements of $\theta_{12}$, $\Delta m^2_{21}$, and $\Delta m^2_{31}$, and to determine the mass hierarchy.

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