RENO & RENO-50*

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Abstract

This paper briefly describes development, recent progress of RENO and future prospect of the reactor neutrino oscillation experiment, RENO-50. The RENO experiment has measured θ_{13} and provided clean information on $\sin^2 2\theta_{13}$. It gives rich programs of neutrino properties, detector development, nuclear monitoring and application. Using reactor neutrinos, a future reactor neutrino experiment, RENO-50, will search for more precise measurement of θ_{12}, Δm^2_{12} and mass hierarchy, etc.

RENO

Experimental setup

RENO (Reactor Experiment for Neutrino Oscillation) is a reactor-based neutrino oscillation experiment to measure the smallest neutrino mixing angle (θ_{13}) using electron anti-neutrinos emitted from the Yonggwang (new name: Hanbit) nuclear power plant in Korea. It is located on the west coast of southern part of Korea, about 400 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 with each 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. The 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 array, respectively. The near detector (ND) is located underground a 70 m high hill with an overburden of ∼110 mwe and the far detector (FD) is placed underground a 260 m high mountain with an overburden ∼450 mwe [1, 2].

Detector

The RENO detector consists of four concentric cylindrical layers: the target, the γ-catcher, the buffer, and the veto [2, 3]. The acrylic vessel holding the target liquid is surrounded by the γ-catcher. The target is filled with 16 mass tons of linear alkyl benzene ($C_nH_{2n+1}-C_6H_5$, n = 10∼13)-based 0.1% gadolinium (Gd)-loaded liquid scintillator (GdLS) [4–6]. The γ-catcher holds 28 mass tons of unloaded liquid scintillator (LS). Outside the

γ-catcher, a 70 cm thick buffer layer is filled with 76 mass tons of a non-scintillating liquid, mineral oil (MO, C_nH_{2n+2}, n=11$\sim$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 provides events coming from outside by Cherenkov radiation and also shields against ambient cosmic-rays and neutrons from the surrounding rocks. Sixty-seven 10-inch R7081 water-proof PMTs are mounted on the wall of the veto vessel [2, 7]. The whole surfaces of veto layer are covered with Tyvek sheets to increase the light collection.

The detection principle of reactor neutrinos

The reactor antineutrinos are detected through the inverse beta decay process (IBD, $\bar{\nu_e} + p \to e^+ + n$) followed by neutron capture. The prompt positron annihilates and yields 1$\sim$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 $\sim$8 MeV 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.

Data sample and backgrounds

RENO began data-taking from August, 2011. For about 500 days data-taking period between August 2011 to January 2013, the near (far) detector accumulated 290775 (31541) 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 I [10]. Systematic uncertainties are classified into two categories related to reactor and detection. All systematic uncertainties have been significantly reduced since the first measurement

Detector	Near detector	Far detector
Selected events	290775	31541
Accidental rate (per day)	6.89 ± 0.09	0.97 ± 0.03
^{9}Li/^{8}He rate (per day)	8.36 ± 0.82	1.54 ± 0.23
Fast neutron rate (per day)	2.28 ± 0.04	0.48 ± 0.02
^{252}Cf contamination rate (per day)		0.14 ± 0.03

TABLE I: Event rates of the observed IBD candidates and the estimated backgrounds at 1.2 $< E_p <$ 8.0 MeV, where E_p is IBD prompt energy.

presented in [1].

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 thus obtained is $\sin^2 2\theta_{13} = 0.087 \pm 0.009$(stat.) $\pm$ 0.007(syst.), where the world average value of $|\Delta m^2_{ee}|$ is used [11]. Therefore, curerrently RENO has measured $\sin^2 2\theta_{13}$ at ∼11% precision level. Within 3 years, the mixing angle of θ_{13} expects to be measured to ∼5% precision level [12]. 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 [10]. This disagreement of the spectra provides further evidence of neutrino oscillation.

RENO-50

After RENO experiment, RENO collaboration plans to construct an underground detector of RENO-50. At ∼50 km from the reactor center, the neutrino oscillation due to θ_{12} takes place at maximum. An experiment with the baseline of ∼50 km could be a natural extension of current RENO θ_{13} experiment. The main goals of RENO-50 are to measure the most accurate (1%) value of θ_{12} and to attempt determination of the neutrino mass hierarchy. The RENO-50 is expected to detect neutrinos from nuclear reactors, the Sun,

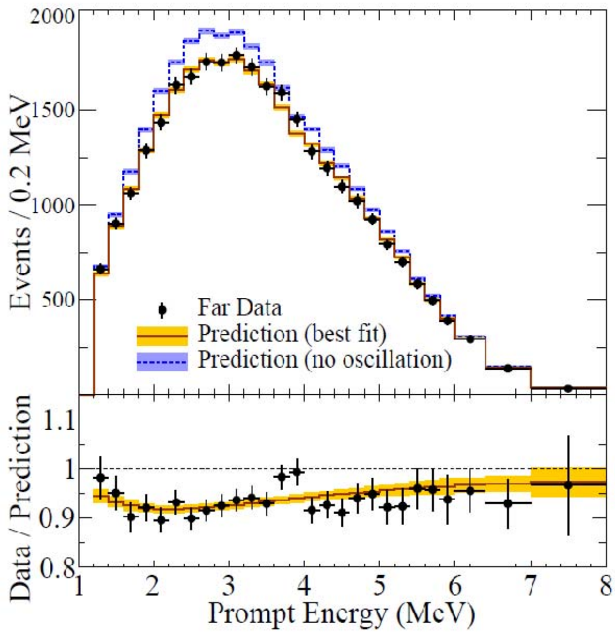

FIG. 1: Observed spectrum of the prompt signals in the FD with the no-oscillation prediction obtained from the measurement in the ND.

Supernova, the Earth, any possible stellar object and a J-PARC neutrino beam [13]. It could be acting 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 2020. Currently funding for RENO-50 is applied. Fig. 2 shows $\bar{\nu}_e$ disappearance probability as a function of L/E with the current best values of Δm^2 and $\sin^2 2\theta_{12}$, and $\sin^2 2\theta_{13}$ at the upper bound [13]. There is large θ_{12} neutrino oscillation effect at ∼50 km. The KamLAND experiment has observed a 40% disappearance of ν_e at the baseline of 180 km [14].

Currently KamLAND energy resolution is ∼6% level. In order to achieve 3% energy resolution, RENO-50 will use high transparency liquid scintillator. Through careful purification and using better quality of PPO, attenuation length will be increased from 15 m to 25 m. Using 15,000 20-inch PMTs will provide a large photocathode coverage from 34% to 67%. In addition, Hamamatsu 20-inch PMTs having an enhanced QE from 20% to 35% will be used.

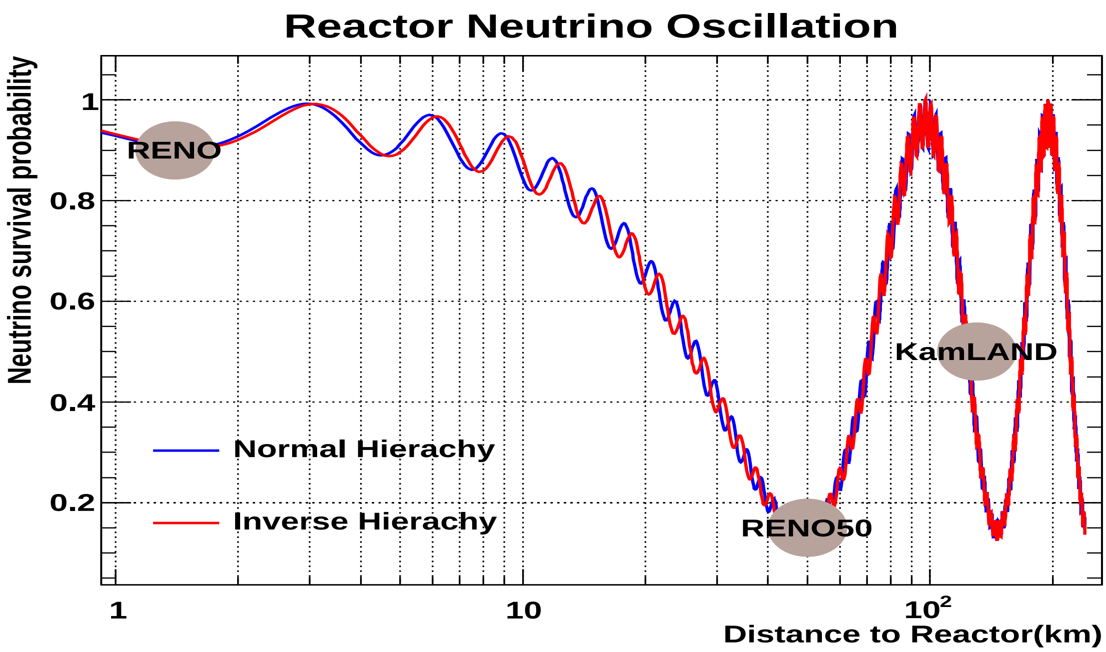

FIG. 2: The survival probability of $\bar{\nu}_e$ as the ratio of the distance to the neutrino energy (L/E). Normal hierarchy and inverted hierarchy are drawn.

Experimental site and RENO-50 detector

There are four nuclear reactor power plant sites (Ulchin, Wolsung, Kori and Yonggwang) in Korea. RENO-50 is dedicated to the Yonggwang nuclear power plant. A contribution from other nuclear power plants can be negligible. In RENO-50, RENO will be used as near detectors, so that precise reactor neutrino fluxes can be measured. Careful survey on candidate site 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 18000 tons ultra-low-radioacivite liquid scintillator (LS). Diameter is 30 m and height is 30 m. It is 18 times bigger than KamLAND detector. It consists of three layers: from the inner to outer, it is target, MO layer, and water veto layer. Total 15000 20-inch high efficiency PMTs will be installed and this will provide 67% surface coverage. Table II shows the comparison between RENO-50 and KamLAND.

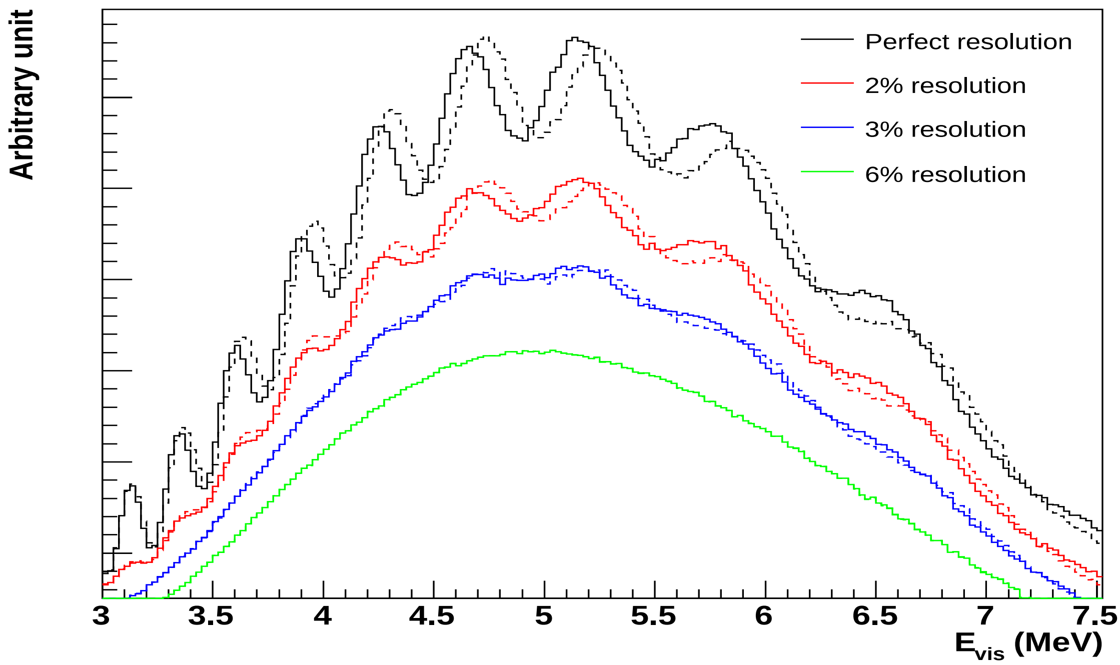

FIG. 3: Survival probability with different energy resolution. Solid line is normal hierarchy and dashed line is inverted hierarchy.

Experiment	Oscillation reduction	Reactor flux	Detector size	Sys. error (flux)	Error on $\sin^2 2\theta_{12}$
KamLAND	40%	53	1 kton	3%	5.4%
RENO-50	77%	6 × 14.7	18 kton	~0.3	0.4%

TABLE II: Comparison between RENO-50 and KamLAND.

Physics with RENO-50

1. Mass hierarchy

Reactor experiments can determine the neutrino mass hierarchy (MH). 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 [13]. By using 18 kton detector, RENO-50 will get $\sim 3\sigma$ significance with 3 years data-taking.

2. Precise measurement of mixing parameter θ_{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 Δm^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 θ_{12} and Δm^2_{21} were observed in the KamLAND experiment [14]. Because the antineutrino survival probability becomes minimal for $\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) \approx 1$, the optimal baseline for measuring θ_{12} is about 50 $\sim$ 70 km. Namely, $P \approx 1 - \sin^2 2\theta_{12}$ is very sensitive to the value of θ_{12}. RENO-50 detector is expected to improve the error of the θ_{12} value. Current value of $\frac{\delta\sin^2\theta_{12}}{sin^2\theta_{12}}$ is $\sim$5.4% level [15]. RENO-50 will improve this value to $\sim$1.0% (1σ) 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% (1σ) in 2 year.

3. Neutrino burst from a supernova

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 [16, 17].

4. Solar neutrinos

With ultra low activity liquid scintillator such as Borexino level, RENO-50 will search for matter effect on neutrino oscillation [18, 19]. Therefore the center of the Sun can be probed. Furthermore, the standard solar model would be examined and tested.

5. Reactor neutrino physics

The RENO and RENO-50 detectors will detect an 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.

6. Other physics topics

J-PARC beams with off-axis angle ($\sim 3^o$) can reach RENO-50 detector at the level of $\sim$400 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 3 active neutrino mixing, they do not completely exclude admixture of sterile neutrinos [20, 21].

In the mean while, a scalar field of acceleron associated with the dark energy of the universe provides an idea if mass varying neutrinos. Possible couplings of acceleron to matter fields could introduce a very different feature of neutrino oscillation parameters. RENO-50 may test a possible effect due to the mass varying neutrinos because of different path lengths in air and matter.

Summary of RENO-50

RENO-50 is a long term operational 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, θ_{12} and Δm^2_{12}, will be precisely measured less than 0.5% level, which can constraint new physics. In summary, RENO-50 reactor experiment with longer baseline of $\sim$ 50 km is under pursuit to perform high-precision measurements of $\theta_{12}, \Delta m^2_{21}$, and Δm^2_{31}, and to determine the mass hierarchy.

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