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Research Article

Study on the Neutrino Oscillation with a Next Generation Medium-Baseline Reactor Experiment

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For over fifty years, reactor experiments have played an important role in neutrino physics, in both discoveries and precision measurements. One of the methods to verify the existence of neutrino is the observation of neutrino oscillation phenomena. Electron antineutrinos emitted from a reactor provide the measurement of the small mixing angle θ_{13}, providing rich programs of neutrino properties, detector development, nuclear monitoring, and application. Using reactor neutrinos, future reactor neutrino experiments, more precise measurements of θ_{12}, Δm^2_{12}, and mass hierarchy will be explored. The precise measurement of θ_{13} would be crucial for measuring the CP violation parameters at accelerators. Therefore, reactor neutrino physics will assist in the complete understanding of the fundamental nature and implications of neutrino masses and mixing. In this paper, we investigated several characteristics of RENO-50, which is a future medium-baseline reactor neutrino oscillation experiment, by using the GloBES simulation package.

1. Introduction

Over the last decade, great progress has been made in understanding the neutrino sector of elementary particle physics. The discovery of neutrino oscillations is a direct indication of physics beyond the standard model. It provides a unique new window to explore physics at the Grand Unification Energy scale. While the absolute neutrino mass has not yet been measured, neutrino oscillation implies that neutrinos have a nonzero mass and are mixed together. Neutrino oscillations are described by the three Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing angles (θ_{12}, θ_{23}, and θ_{13}), one CP violating phase, and two independent mass squared differences (Δm^2_{31}, Δm^2_{21}) [1, 2]. The mixing angles, (θ_{12}, θ_{23}, and θ_{13}), have been measured using atmospheric, solar, accelerator beam, and reactor neutrino experiments. Among the mixing angles, (θ_{12}, θ_{23}), the values are relatively well measured. θ_{12} was measured using solar neutrinos and the KamLAND experiment [3, 4], while θ_{23} was measured using atmospheric neutrinos and the long baseline accelerator K2K experiment [5, 6]. However, for the θ_{13} value, until the year 2012, the best upper limit was set by the Chooz reactor antineutrino disappearance experiment [7]. The reactor experiments (Double Chooz, Daya Bay, and RENO) have measured θ_{13} and provide accurate information on $\sin^2 2\theta_{13}$ [8–10]. In addition, reactor neutrino experiments make accurate measurements of reactor neutrino fluxes and spectra to search for sterile neutrinos [11–13]. Also, future accelerator based neutrino experiments will provide a rich program of measuring CP violation and matter effects. However, in the long baseline experiments, degeneracies and parameter correlations occur among θ_{13}, the CP violation phase (δ_{CP}), neutrino mass hierarchy, and θ_{23}. The possibility of measuring the CP violation effect can be fulfilled only if the value of θ_{13} is precisely measured. Combining the results from the accelerator and reactor-based experiments could offer the first glimpse of δ_{CP} without the necessity for long running accelerators with antineutrino beams [14].

After the RENO experiment, RENO collaboration plans to construct an underground detector of RENO-50 consisting of 18,000 tons of ultralow-radioactivity unloaded liquid scintillator (LS) and high quantum efficiency (QE) photomultiplier tubes (PMTs). At ~50 km from the reactor center, the neutrino oscillation takes place maximally due to θ_{12}. An

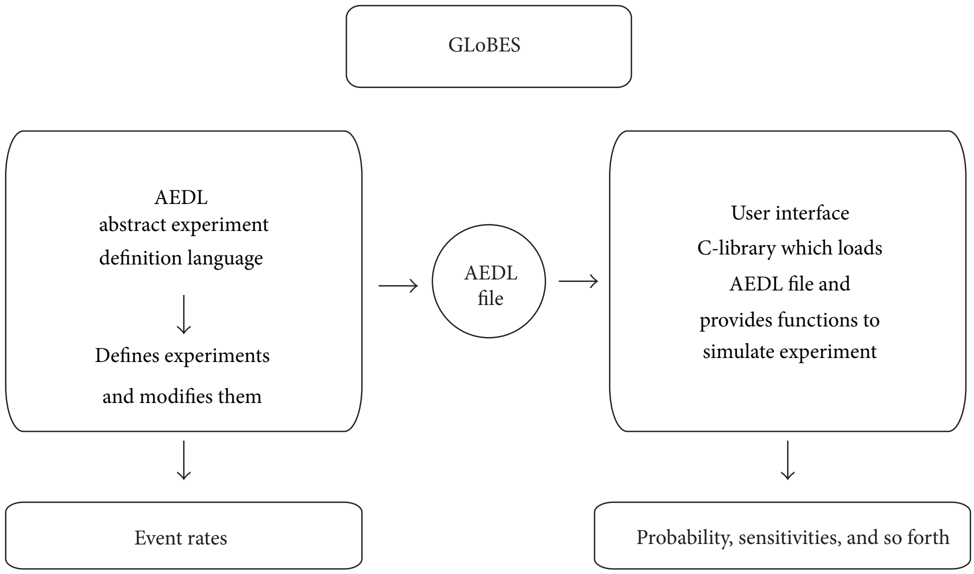

Figure 1: Schematics of GLoBES package, which mainly consists of two parts: AEDL and user interface C-library.

experiment with the baseline of ~50 km could be a natural extension of the current RENO θ_{13} experiment.

For this study, we used the general long baseline experiment simulator (GLoBES) [15]. Developed by Patrick Huber, Joachim Kopp, Manfred Lindner, Mark Rolinec, and Walter Winter, GLoBES is a computer-based simulator used for long baseline neutrino oscillation by setting a neutrino source, baseline, and detector. GLoBES is the only open source software and is based on the C-library language. As shown in Figure 1, GLoBES consists of two parts. Firstly, abstract experiment definition language (AEDL) provides the experimental setup for neutrino sources. Secondly, the C-library corresponds to the detector for processing to provide oscillation probabilities, rate vectors, and χ^2-values.

2. Results from RENO

2.1. Experimental Setup. The Reactor Experiment for Neutrino Oscillation (RENO) is a reactor-based neutrino oscillation experiment to measure the smallest neutrino mixing angle (θ_{13}) using electron antineutrinos emitted from the Hanbit (previously named Yonggwang) nuclear power plant in Korea. It is located on the west coast of the 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 $\mathrm{GW_{th}}$. The six reactors, each with a maximum thermal output of 2.8 $\mathrm{GW_{th}}$ (reactors 3, 4, 5, and 6) or 2.9 $\mathrm{GW_{th}}$ (reactors 1 and 2), are aligned roughly equal distances and span ~1.3 km. The RENO uses two identical near and far detectors to reduce systematic uncertainties. The near and far detectors are placed approximately 290 m and 1.4 km away, respectively, from the center of the reactor array. The near detector (ND) is located under a 70 m high hill with an overburden of ~110 m.w.e. (meterwater equivalent) and the far detector (FD) is placed under a 260 m high mountain with an overburden of ~450 m.w.e. [10, 16].

2.2. Result on θ_{13} Measurement. Data-taking began at RENO in August, 2011. A clear disappearance of reactor antineutrinos is observed. At RENO, the value of $\sin^2 2\theta_{13}$ with two identical detectors has been successfully measured. The measured value using rate-only analysis is $\sin^2 2\theta_{13} = 0.100 \pm 0.010$ (stat.) $\pm$ 0.015 (sys.), corresponding to 6.3σ significance for 403 days data [10]. Therefore, the current size of the total error is ±0.018 [10]. Based on the next three years of projected data-taking, the statistical error will be ±0.006 and the systematic error will reach ±0.005. Therefore, RENO will reach $\sin^2 2\theta_{13}$ at an 8% precision level.

In current RENO environment, there are mainly three types of backgrounds which mimic IBD signals: accidental, fast neutron and the $^{9}\mathrm{Li}/^{8}\mathrm{He}$ backgrounds. The accidental backgrounds are caused by external gammas such as radioactivity from detector and environment. The estimated accidental background rate is 3.61 ± 0.05 (0.60 ± 0.03) events/day for the ND (FD) [10]. In addition, when atmospheric muons pass through rocks surrounding detector, fast neutrons are produced and the estimated fast neutron background rate is 3.14 ± 0.09 (0.68 ± 0.04) events/day for the ND (FD) [10]. Furthermore, when an energetic muon interacts with $^{12}\mathrm{C}$ in liquid scintillator, unstable isotopes such as $^{9}\mathrm{Li}$ and $^{8}\mathrm{He}$ emitting (β, n) followers are produced and mimic IBD signals. Currently, the $^{9}\mathrm{Li}/^{8}\mathrm{He}$ background uncertainty is the largest contribution to the uncorrelated systematic error in the current results and its value is 13.73 ± 2.13 (3.61 ± 0.60) events/day for the ND (FD) [10]. By combining these three backgrounds, the total background rate is estimated as 20.48 ± 2.13 (4.89 ± 0.60) events/day for the ND (FD). After subtracting backgrounds, currently daily observed IBD rates are 737.69 ± 2.57 (70.13 ± 0.74) events/day in the ND (FD), respectively [10]. Therefore the level of signal/noise (S/N) ratio is ~37 (15) for the ND (FD). The ratio of observed to expected numbers (without oscillation) of antineutrinos in the FD is 0.929 ± 0.006 (stat.) ± 0.009 (syst.). A clear ~7% of disappearance of the reactor antineutrinos in the FD is seen [10]. Further reductions of these backgrounds will continue at RENO by requiring a tighter muon veto cut. Furthermore, a spectral shape analysis will maximize the use of energy-dependent information in the data.

3. Physics Reach and Sensitivity of RENO-50

A relatively large value of θ_{13} allows us to explore mass hierarchy (MH) and neutrino CP violation effects (δ_{CP}) from the reactor, accelerator, atmospheric, and very long baseline neutrino experiments. The reactor experiment can determine the neutrino mass hierarchy. Identifying the neutrino mass hierarchy is possible by using a precision measurement of the electron antineutrino survival probability from a nuclear reactor. The survival probability $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ of the $\overline{\nu}_e$ disappearance probability can be written as follows:

$$\begin{aligned}
1 - P(\overline{\nu}_e \longrightarrow \overline{\nu}_e) &= 4\sum_{j>k} |U_{ej}|^2 |U_{ek}|^2 \sin\left(\frac{\Delta m^2_{jk} L}{4E}\right) \\
&= \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \\
&\quad + \cos^4\theta_{13} \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \\
&\quad + \sin^2\theta_{12} \sin^2(2\theta_{13}) \cos\left(\frac{\Delta m^2_{31} L}{2E}\right) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \\
&\quad \pm \frac{1}{2} \sin^2\theta_{12} \sin^2(2\theta_{13}) \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) \sin^2\left(\frac{\Delta m^2_{21} L}{2E}\right).
\end{aligned} \tag{1}$$

Here, $\pm$ is the mass hierarchy difference. The oscillations are governed by two quadratic mass splittings: Δm^2_{21} and Δm^2_{31}. Figure 2 shows the $\overline{\nu}_e$ disappearance probability as a function of L with the current best values of Δm^2 and $\sin^2 2\theta_{12}$ and $\sin^2 2\theta_{13}$ at the upper bound. At smaller L, only the θ_{13} contribution appears. As the distance increases, the θ_{12} contribution will appear. A large θ_{12} neutrino oscillation effect appears at ~50 km. In the KamLAND experiment, a 40% disappearance of $\overline{\nu}_e$ was observed at the baseline of 180 km [17]. Figure 3 shows the reactor neutrino spectrum at ~50 km for normal hierarchy (NH) and inverted hierarchy (IH). From the large deficit of $\sin^2 2\theta_{12}$, θ_{12} can be precisely measured.

In order to distinguish between normal and inverted mass hierarchy, an extremely good energy resolution of more than 3% is required, as shown in Figure 4. Energy resolution can be expressed as follows:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} + b. \tag{2}$$

Term a depends on energy resolution. For better energy resolution, we need to increase the number of photoelectrons,

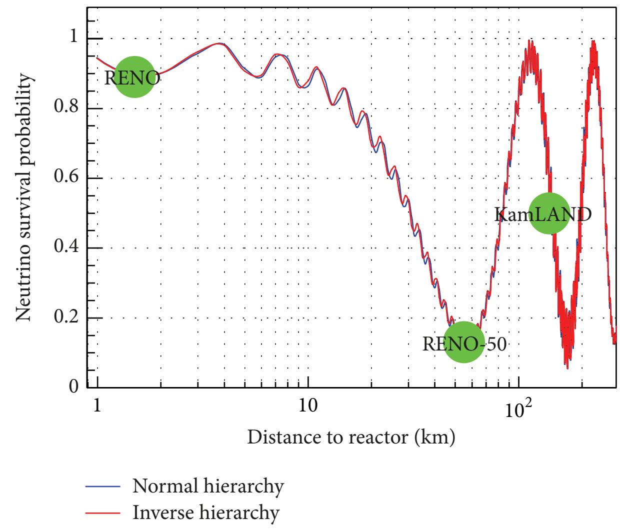

FIGURE 2: Survival probability of $\overline{\nu}_e$ as a function of distance (L). Normal hierarchy (NH) and inverted hierarchy (IH) drawn. RENO-50 is located at ~50 km from the reactor center. The KamLAND experiment is ~180 km away from the reactors.

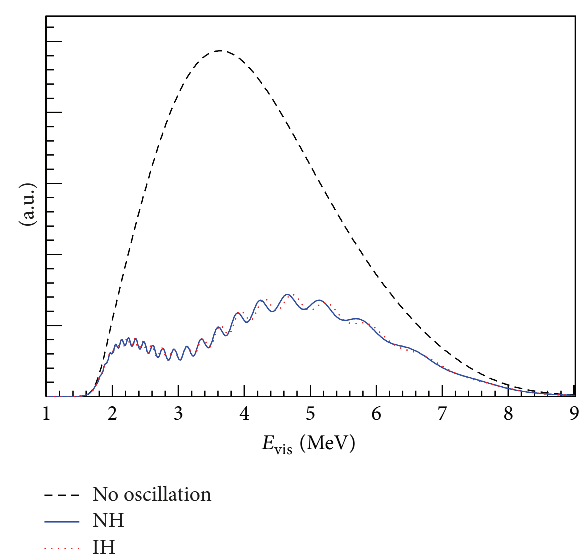

FIGURE 3: Reactor neutrino spectrum at 50 km for normal hierarchy (NH) and inverted hierarchy (IH). Due to oscillation, deficit of neutrinos will be observed.

N_{pe}. Term b is an energy independent term caused by random processes and is related to PMT noise, thermal noise and electronic noise, and so forth. Currently, the KamLAND energy resolution is at a ~6% level. In order to achieve 3% energy resolution, RENO-50 will use high transparency liquid scintillator (LS) which will be used at RENO-50 linear alkyl benzene (LAB, C_nH_{2n+1}–C_6H_5), where n = 10~13 is a base candidate solvent for LS [18–21]. Through the careful purification and production process of the base solvent, the attenuation length will be increased from 15 m to 25 m. Most dirty material used in the LS is PPO ($C_{15}H_{11}NO$, 2,5-diphenyloxazole), which is a fluor used to

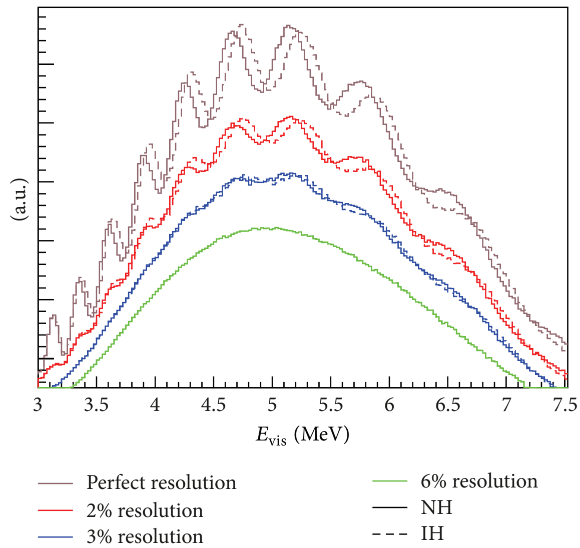

FIGURE 4: Survival probability with different energy resolutions. Solid line refers to NH and dashed line refers to IH. Energy resolution affects the sensitivity significantly.

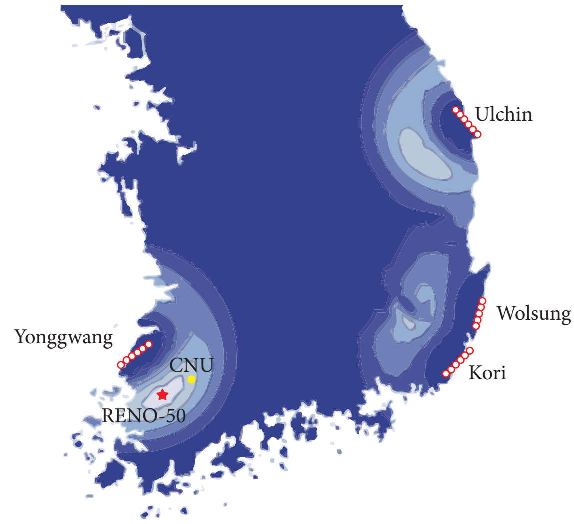

FIGURE 5: RENO-50 candidate site. The asterisk (∗) is a candidate site for RENO-50. The direction to RENO-50 strongly affects the sensitivity. Distribution of four reactors (Ulchin, Wolsung, Kori, and Yonggwang) is considered.

produce light emission. By using better quality PPO with no impurities, LS quality will be enhanced. Using 15,000 20-inch PMTs will provide large photocathode coverage from 34% to 67%; Hamamatsu 20-inch PMTs will be used, which have an enhanced quantum efficiency (QE) from 20% to 35%. By adding more PPO 5 g/L from 1.5 g/L, 1.5 times more light yield (LY) in the liquid scintillator can be obtained.

4. Experimental Site and Detector for RENO-50

Korea has 4 nuclear reactor power plant sites (Ulchin, Wolsung, Kori, and Yonggwang). RENO-50 is dedicated to the Yonggwang nuclear power plant. The contribution from other nuclear power plants can be negligible. In RENO-50, RENO will be used as a near detector, so that precise reactor neutrino fluxes can be measured. In the KamLAND case, this site is surrounded by 53 Japanese commercial nuclear power plants. Therefore, all of the nuclear reactors are served as a source. A careful survey of the candidate site for RENO-50 has been performed. Several conditions for the selection of the site are required. This should provide a sufficient overburden to reduce cosmic backgrounds. Furthermore, interference among reactor sites and reactor cores significantly affects the sensitivity. The direction of RENO-50 is decided to maximize this sensitivity. A RENO-50 candidate site is shown in Figure 5. An optimal candidate site is at the 450 meter high Mt. Geumseong located in the city of Naju. This corresponds to a ~900 m.w.e. overburden and it is located 47 km away from the Yonggwang nuclear power plant.

The RENO-50 detector will use 18,000 tons of ultralow-radioactive liquid scintillator (LS) as shown in Figure 6. The diameter of the RENO-50 detector is 30 m and the height is 30 m and is 18 times larger than the KamLAND detector. It consists of three layers: from the inner to the outer structure, it is target, mineral oil (MO) layer, and the water veto layer. A total of 15,000 20-inch high efficiency PMTs will be installed and this will provide 67% surface coverage. Based on these detector configurations, the number of neutrino events for a year as a function of the baseline is shown in Figure 7. Observed reactor neutrino rate is estimated as ~15 events/day. Table 1 shows a comparison between RENO-50 and KamLAND.

5. Physics with RENO-50

5.1. Mass Hierarchy. In principle, the mass hierarchy (MH) from precision measurements of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$ can be determined using $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$. For NH, $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$. For IH, $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$. Advantage of reactor neutrino experiments is to determine MH independently from the CP phase and matter effects. In addition, a relatively smaller size detector can be employed, unlike the next generation megaton detectors. However, in the RENO-50 case, the determination of MH is challenging, as it requires an extremely high energy resolution of more than 3%. By using an 18 kton detector, RENO-50 will acquire ~3σ significance with 3 years data-taking.

5.2. Precise Measurement of Mixing Parameter θ_{12} and Δm^2_{21}. In RENO-50, the near and far detectors of RENO could be used as near detectors and thus would reduce the 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

$$P = \cos^4\theta_{13}\left[1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)\right]. \qquad (3)$$

TABLE 1: Comparison between RENO-50 and KamLAND.

Experiment	Oscillation reduction	Reactor flux	Detector size	Systematic 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%

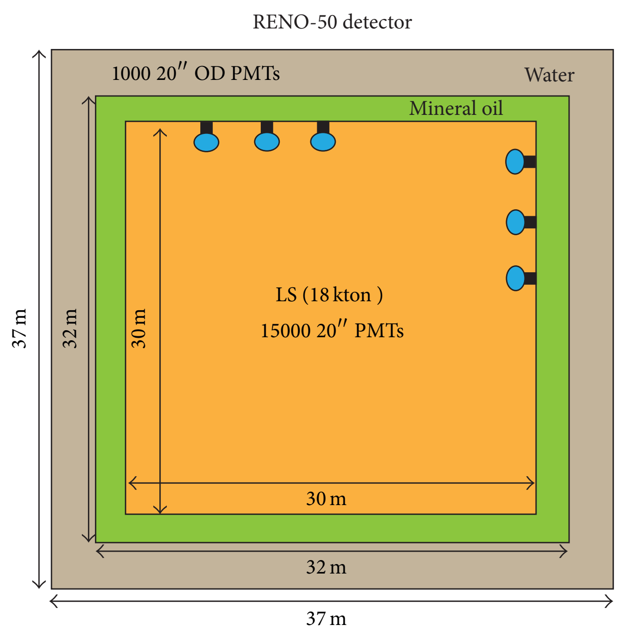

FIGURE 6: Conceptual design of RENO-50 detector. KamLAND detector is ~1 kton LS and RENO-50 18 kton LS. 15000 20-inch PMTs will be used. RENO-50 is 18 times larger than the KamLAND detector.

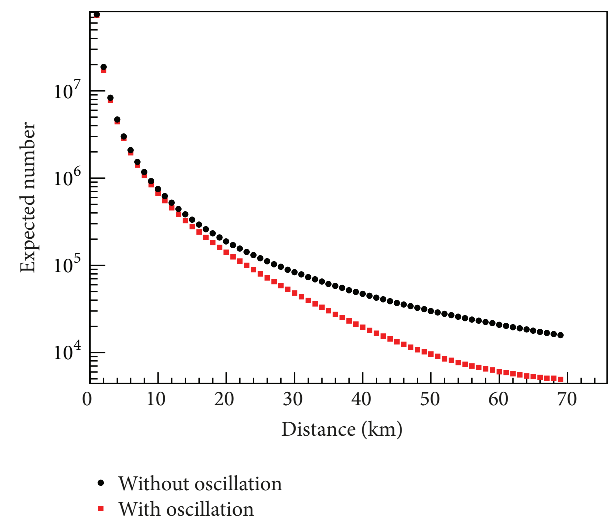

FIGURE 7: Number of neutrino event for a year with oscillation (rectangular) or without oscillation (circle) as a function of baseline from Yonggwang nuclear site.

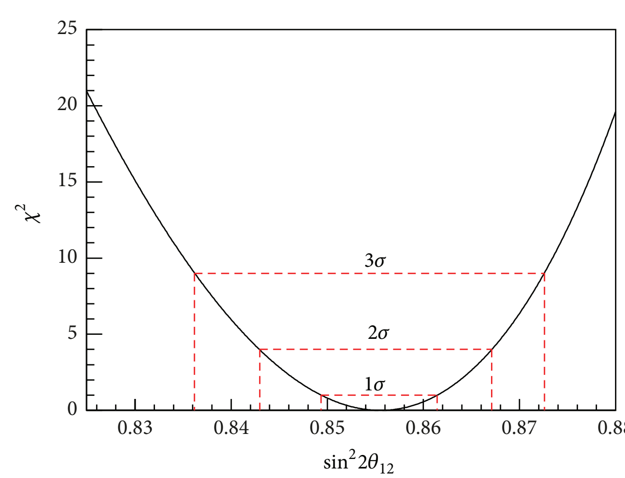

FIGURE 8: χ^2 distribution as a function of $\sin^2 2\theta_{12}$.

The oscillations due to θ_{12} and Δm^2_{21} were observed in the KamLAND experiment [3, 4]. Because the antineutrino survival probability becomes minimal for $\sin^2(\Delta m^2_{21} L/4E) \approx 1$, the optimal baseline for measuring θ_{12} is about 50~70 km. Namely, $P \approx 1 - \sin^2 2\theta_{12}$ is very sensitive to the value of θ_{12}. The RENO-50 detector is expected to improve the error of the θ_{12} value. The current value of $(\delta \sin^2\theta_{12})/(\sin^2\theta_{12})$ is at a ~5.4% level [3, 4]. RENO-50 will improve this value to ~1.0% (1σ) in 1 year. Furthermore, $(\delta\Delta m^2_{12})/(\Delta m^2_{12})$ will be improved from the current value of 2.6% to ~1.0% (1σ) in 2 years. Figure 8 shows the χ^2 distribution as a function of $\sin^2 2\theta_{12}$.

The sensitivity of the experiment to $\sin^2 2\theta_{12}$ is calculated using the pull approach through pseudoexperiment [16]. The χ^2 function is written as follows:

$$\chi^2 = \sum_i \frac{\left[N^i_{\text{obs}} - \left(1 + a + \xi^i + f_r\right) N^i_{\text{exp}} - (1 + b_d) B^i\right]^2}{N^i_{\text{exp}} + B^i + (\sigma^i_b B^i)^2} + \frac{a^2}{\sigma^2_a} + \sum_i \left(\frac{\xi^i}{\sigma_\xi}\right)^2 + \frac{f^2_r}{\sigma^2_f} + \frac{b^2_d}{\sigma^2_b}. \tag{4}$$

χ^2 consists of pull terms with observed neutrino events (N^i_{obs}), expected events (N^i_{exp}), background (B^i), and systematic uncertainties for neutrino energy bin i. Here, a is global normalization and 2.5% (σ_a) uncertainty is used. ξ^i, f_r, and b_d are pull parameters. For calculation, detection uncertainty 1.5% (σ_ξ), reactor uncertainty 3% (σ_f), and background uncertainty 5% (σ_b) are used.

5.3. Neutrino Burst from a Supernova. The RENO-50 detector filled with highly purified 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. We assume that the energy of 3.0×10^{53} erg is released during the burst. The background in the RENO-50 detector in a 10-second period is low enough for an observation of the neutrino signals from the supernova burst. The RENO-50 detector contains 1.35×10^{33} free protons, 0.81×10^{33} carbons, and 6.21×10^{33} electrons. The RENO-50 detector would observe ~4000 events from a supernova at 8 kpc [22, 23]. RENO-50 will serve as a long-term astronomical neutrino telescope over 10 years after RENO has recorded data for the θ_{13} measurement.

5.4. Solar Neutrinos. With an ultralow activity liquid scintillator such as the Borexino level, RENO-50 will search for the matter effect on neutrino oscillation [24]. Therefore, the center of the sun can be probed. Furthermore, the standard solar model would be examined and tested.

5.5. Geoneutrinos. Geoneutrinos are electron antineutrinos produced by β-decays of ^{238}U, ^{232}Th, and ^{40}K decay in the earth's crust and mantle. They provide the surface information on the content of radioactive elements for the entire planet. Their detection can provide information on the sources of the terrestrial heat flow on the present composition and on the origins of the earth. Therefore, the heat generation mechanism inside the earth can be investigated. KamLAND first measured geoneutrinos in 2005 and its value was 40.0 ± 10.5 (stat.) ± 11.5 (sys.) terrestrial neutrino units (TNU) [25]. In addition, the Borexino detectors are currently collecting geoneutrino data and have reported that the signal rate is 64 ± 25 (stat.) ± 2 (sys.) TNU, after correcting for detection efficiency and the background subtraction [26]. Furthermore, several proposed experiments (e.g., SNO+, Lena, Hanohano, and Earth) will measure geoneutrinos as their primary goals [27–29]. For geoneutrino detection, all experiments use the inverse beta decay (IBD, $\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$) process. The threshold energy of IBD is 1.8 MeV. The measured shape of neutrino spectrum will be essential for determining the observation of geoneutrinos and their radioactive progenitors. The RENO-50 detector is large enough for the sensitive geoneutrino measurement and is able to observethem.

5.6. Reactor Neutrino Physics. Currently, RENO observes ~70 reactor neutrino events per day at the near detector and ~700 events at the far detector. The RENO and RENO-50 detectors will detect an order of 1 million neutrino events per year. They will measure the flux and energy distribution of the reactor neutrinos with a greater accuracy than previously. This information would then lead to a meaningful comparison of thermal power and reactor fuel loading between measurements and calculations. Such comparison will allow us to measure real-time and direct reactor thermal power with the RENO and RENO-50 detectors. In addition, a precise determination of the reactor neutrino spectrum might be useful for reducing the flux uncertainty [11–13]. Therefore, the reactor neutrinos could be used as an application for the direct monitoring of nuclear fuels and fuel evolution without the need to stop running the nuclear plant.

5.7. Other Physics Topics. Neutrino beams produced from J-PARC (Japan Proton Accelerator Research Complex) in Japan are airborne and appear on Korean peninsula, which is ~1000 km away from J-PARC. J-PARC beams with an off-axis angle (~3°) can reach the RENO-50 detector at the level of ~400 per year. Furthermore, RENO-50 will test nonstandard physics such as sterile neutrino physics. The discovery of sterile neutrinos would have a revolutionary impact on neutrino physics [30–34]. While recent neutrino oscillation results are understood in the framework of 3 active neutrino mixings, they do not completely exclude the admixture of sterile neutrinos [35, 36]. The liquid scintillator neutrino detector (LSND) collaboration implied that gave sterile neutrinos comes from the unconfirmed observation on $\nu_\mu \rightarrow \nu_s$ [37–39]. Mixing with sterile neutrinos based on the LSND signal predicts that the disappearance of the reactor neutrinos with $\Delta m^2 \sim \mathrm{eV}^2$ is very close to the current upper bound from the Bugey experiment [40]. Meanwhile, a scalar field of acceleron associated with the dark energy of the universe implies mass varying neutrinos. Possible couplings of acceleron to matter fields could introduce a very different feature of neutrino oscillation parameters. The mass varying neutrinos could also produce a possible effect in RENO-50. Combined data from the reactor and accelerator neutrino experiments with different path lengths in air and matter will give meaningful information on the mass-varying neutrinos.

6. Summary of RENO-50 and Outlook

A surprisingly large value of θ_{13} will strongly promote the next round of neutrino experiments to find the CP phase and determine the mass hierarchy. The main goals of RENO-50 are to measure the most accurate (1%) value of θ_{12} and to attempt to determine the neutrino mass hierarchy. RENO-50 is expected to detect neutrinos from nuclear reactors, the Sun, Supernova, the Earth, any possible stellar objects, and J-PARC neutrino beam. It could act as a neutrino telescope.

RENO-50 is a long-term operational and multipurpose detector. A candidate site has been found at the 450 meter high Mt. Geumseong, 47 km from the Hanbit nuclear power plant. RENO-50 requires an inclined tunnel to obtain a deeper location. It will use 18,000 tons of ultralow-radioactivity unloaded liquid scintillator and 15,000 20-inch high quantum efficiency PMTs with a 67% surface coverage. The current RENO detectors can serve as near detectors. The sensitivities are studied to determine the MH. Determining MH is very challenging, but not impossible with very good energy resolution of more than a 3% level. In addition, neutrino oscillation parameters, θ_{12} and Δm^2_{12}, will be precisely measured at less than a 0.5% level, which can constrain new physics. In summary, the RENO-50 reactor experiment with the medium baseline of ~50 km is expected to perform high-precision measurements of θ_{12}, Δm^2_{21}, and Δm^2_{31} and to determine the mass hierarchy. It will provide nuclear fuel monitoring with reactor neutrinos. Reactor experiments have played and will play an important role in both new discoveries and precision measurements in the neutrino sector. Therefore, a complete understanding of neutrino oscillation will provide an opportunity to explore new physics.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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