Expected Statistical and Systematic Errors in $\sin^2 2\theta_{13}$ from RENO

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Abstract

An experiment, RENO (*R*eactor *E*xperiment for *N*eutrino *O*scillation), is under construction to measure the smallest and unknown neutrino mixing angle (θ_{13}) using anti-neutrinos emitted from the Yonggwang nuclear power plant in Korea with world-second largest thermal power output of 16.4 GW. The experimental setup consists of two identical 15-ton Gadolinium loaded liquid scintillator detector located near and far from the reactor array to measure the deviations from the inverse square distance law. The near and far detectors are to be placed roughly 290 m and 1.4 km from the center of the reactor array, respectively. The experiment is planned to start data-taking in early 2010. An expected number of observed anti-neutrino is roughly 5 000 per day and roughly 100 per day in the near detector and far detector, respectively. An estimated systematic uncertainty associated with the measurement is less than 0.5%. Based on three years of data, it would be sensitive to measure the neutrino mixing angle in the range of $\sin^2(2\theta_{13}) > 0.02$. This sensitivity is five times better than the current limit obtained by CHOOZ.

1. Introduction

Since neutrino oscillations now have been established, the next step is to map out the parameters associated with neutrino masses and mixings. There are three mixing angles (θ_{12}, θ_{23}, θ_{13}) and one phase angle (δ).

The third angle, θ_{13}, has not yet been been measured to be nonzero but constrained to be small in comparison by the CHOOZ reactor neutrino experiment. A high precision measurement of reactor anti-neutrino oscillation can be achieved by a multiple detector experiment because the experiment sensitivity would be nearly unaffected by the uncertainties related to anti-neutrino source and interaction [1]. Reactor measurements have the property of determining θ_{13} without the ambiguities associated matter effects and CP violation. In addition, the detector for an initial reactor measurement is not necessarily large, and the construction of a neutrino beam is not needed. The RENO experiment will try to measure θ_{13} or at least improve the current constraint using reactor neutrinos.

With θ_{13} determined, measurements of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations using accelerator neutrino beams impinging on large detectors at long baselines will improve the knowledge of θ_{13} and also allow access to matter or CP violation effects.

1.1. Neutrino oscillations in reactor experiments

Because neutrinos from reactors have low energy of the order of a few MeV, they do not have enough energy to produce muons or taus through charged current interaction. Therefore, any reactor experiments can only be disappearance experiments, which measure the survival probability $P(\bar{\nu}_e \to \bar{\nu}_e)$. It was shown in Ref. [2] that the survival probability does not depend on the CP and phase δ. And because of the low energy neutrinos and short baseline, matter effects are negligi-

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Fig. 1 Overview of Yonggwang nuclear power plant and location of the plant.

ble in reactor experiments [3]. Thus one can use the neutrino survival probability in vacuum to model the neutrino oscillations in the reactor experiments and the survival probability can be approximated as

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right). \tag{1}$$

The value of θ_{13} will be obtained from the second term subtracting the third term from the experimental measurement of $\bar{\nu}_e$ disappearance probability of P_{dis}=1-P($\bar{\nu}_e \rightarrow \bar{\nu}_e$) in the Equation 1. The first oscillation maximum of the second term occurs near the baseline of $\sim$ 2 km. The third term is negligible and thus the disappearance probability is almost equal to the second term within a few kilometers of the baseline. Thus, the best measurement of θ_{13} could be possible at the first oscillation maximum. As the baseline goes longer than 50 km, the third term contribution becomes dominant in P_{dis}. RENO will measure the survival probability at a baseline of about 1.4 km with most probable neutrino energy of about 3.8 MeV (1.8 MeV to 8 MeV).

2. The RENO Experiment

RENO experiment is one of future reactor experiments using anti-neutrinos emitted from the Yonggwang nuclear power plant in Korea. The Yonggwang nuclear power plant is located in the west coast of southern part of Korea, about $\sim$ 400 km from Seoul as shown in Fig. 1. The power plant has six reactors producing total thermal output of 16.4 GW_{th}, the second largest in the world. The reactors at the Yonggwang nuclear power plant are Pressurized Water Reactors (PWR). There are six reactors and the reactor units 1 and 2 are of the Combustion Engineering (CE, now Westinghouse) System 80 design. Units 3 to 6 are of the Korean Standard Nuclear Power Plant (KSNP) design, which incorporates many improvements on the CE System 80. The first reactor, unit 1, became operational in 1986 and the last one, unit 6, in 2002.

The Yonggwang nuclear power plant with world-second largest thermal power output of 16.4 GW, is an intense source of low energy anti-neutrinos suitable for measuring neutrino oscillations due to θ_{13}. The anti-neutrino fluxes from the nuclear reactors are measured nearby before their oscillations, and measured again

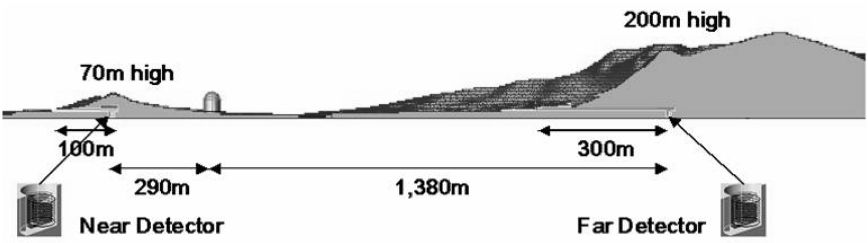

Fig. 2 A schematic layout of the RENO experiment. The near and far detectors will be located 290 m and 1.4 km, respectively, away from the reactor array center.

at a distance of about 1.4 km away from the reactor center. A neutrino mixing parameter θ_{13} is obtained by finding the reduction of neutrino fluxes by comparison of the two measured fluxes.

The experimental setup consists of two 15 ton liquid scintillator detectors with one at a near site, roughly 290 m away from the reactor array center, and the other at a far site, roughly 1.4 km away from the reactor array center as shown in Figure 2. The near detector will be constructed at underground of a 70 m high hill, and the far detector at underground of a 200 m high mountain.

An interesting feature of RENO is to have a sufficient overburden for the near detector due to a 70 m hill of 2.8 g/cm^3 rock which is quite close (290 m) to the center of the reactor array. A detector close to the nuclear cores is necessary for cancelling the systematic uncertainties related to the nuclear reactors such as ambiguities of the anti-neutrino flux and spectrum, as well as for reducing systematic uncertainties related to the detector and to the event selection. The near detector laboratory will be located inside the restricted area of the Yonggwang nuclear power plant. The 200 m high mountain consists of hard rocks with a density of 2.8 g/cm^3.

3. The RENO Detector

The RENO detector consists of a neutrino target, a gamma catcher, a buffer and a veto as shown in Figure 3. Target and gamma catcher vessels will be made from acrylic plastic material, having transparency to the light of wavelengths above 400 nm. The acrylic vessels should contain aromatic liquids without leak and changing properties for a long term period, roughly more than 10 years. They should not develop any chemical reaction with the scintillating liquids of neutrino target, gamma catcher and buffer for a long time period.

The neutrino target consists of 0.1% Gd loaded liquid scintillator in a cylindrical acrylic container of 140 cm in radius, 320 cm in height, and 8 mm in thickness. It has a total volume of 19.7 m^3 and a target mass of 15.4 tons.

Gamma catcher surrounds the neutrino target with 60 cm thick unloaded liquid scintillator of 35.6 m^3 in volume and 27.7 tons in mass. The gamma catcher is contained in a cylindrical acrylic vessel of 200 cm in radius, 440 cm in height, and 12 mm in thickness. The gamma catcher vessel should be chemically compatible with mineral oil of the buffer region as well as the scintillating liquids inside. This scintillating volume is necessary for efficient tagging of the gammas from neutron capture by Gd and from positron annihilation, and for rejecting the backgrounds from the fast neutrons.

A 70 cm thick non-scintillating liquid surrounds the gamma catcher to reduce the accidental backgrounds coming from outside (mainly from radioactivity in the photomultiplier tubes), by almost two orders of magnitude. A total of 92.4 m^3

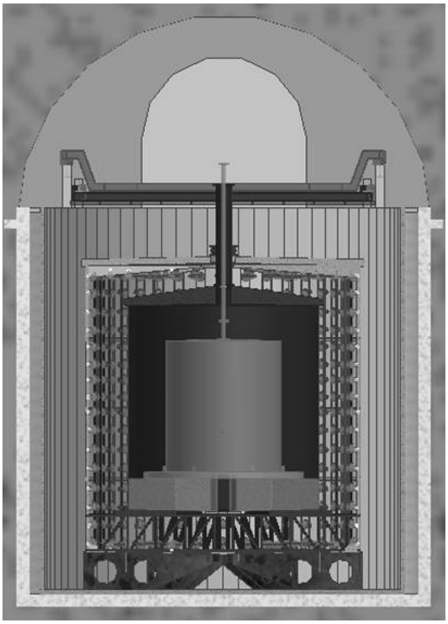

Fig. 3 A schematic view of RENO detector. A neutrino target of 19.7 m^3 Linear Alkyl Benzene (LAB) based liquid scintillator doped with Gd is contained in a transparent acrylic vessel, and surrounded by 35.6 m^3 unloaded liquid scintillator of gamma catcher and 92.4 m^3 non-scintillating buffer. Should put names to components.

(71.2 tons) mineral oil is contained in a stainless steel vessel of 280 cm in radius, 600 cm in height, and 4 mm in thickness. This buffer is necessary for keeping the single rate below 10 Hz in the neutrino target and gamma catcher regions.

A total of 537 8-inch photomultipliers in a uniform array are mounted from the inner surface of the buffer vessel, providing a 13.8% photo-sensitive surface coverage. The cylindrical steel vessel optically isolates the inner detector part from the outer veto system.

A 1 m thick water layer of 215 tons surrounds the whole inner detector with a volume of 147.7 m^3 (114.4 tons). A total of 8-inch 67 PMTs are mounted in front of Tyvek reflector on a cylindrical steel tank. It is useful for vetoing cosmic muons and reducing backgrounds coming from its surrounding rock.

4. Detection of Neutrino Events

The fissile material in the reactors mainly consists of ^{235}U and ^{239}Pu, which undergoes thermal neutron fission. The dominant ^{238}U is fissile only for fast neutrons but also undergoes fission process by thermal neutron capture and produces ^{239}Pu. Similary, ^{241}Pu is generated from ^{239}Pu. Other fissile materials contribute only at the 0.1% level. These four isotopes release similar energy when they undergo fission [4]. Therefore, even though the makeup of the fissile material in the reactor changes over a refuelling cycle, the average mean energy per fission does not change significantly. Assuming ~ 200 MeV per fission, there are 3.1×10^{19} fissions per GW_{th}. Since one fission causes about six neutrino emissions above ~ 2 MeV on average [5, 6, 8, 7], the neutrino intensity can be estimated to be $\sim 2 \times 10^{20}$ $/(\mathrm{GW}_{th} \cdot \mathrm{s})$.

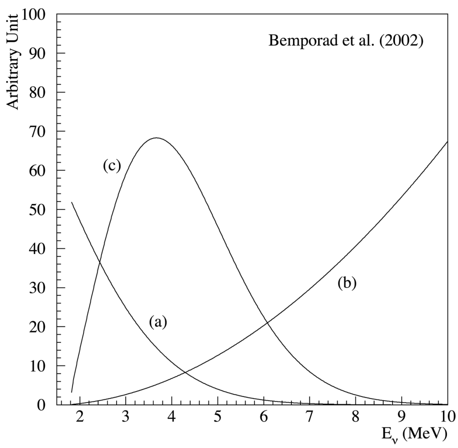

Fig. 4 Reactor $\bar{\nu}_e$ flux (a), inverse beta decay cross section (b), and interaction spectrum at a detector based on such reaction (c) in Ref. [9]. The cut-off at 1.8 MeV is due to the minimum neutrino energy required for inverse beta decay process.

Fission fragments from these isotopes sequentially β decay and emit electron anti-neutrinos. The purity of the anti-neutrinos is very high and electron-neutrino contamination is only at a 10^{-5} level above an inverse β decay threshold of 1.8 MeV.

The neutrinos are radiated isotropically from the reactor core and, therefore, the inverse square law applied on the neutrino intensity at a distance.

Figure 4 shows the neutrino flux, inverse beta decay cross section, and interaction spectrum at a detector in arbitrary units calculated in Ref. [9]. The most probable neutrino energy interacting at a detector is $\sim$ 3.8 MeV.

5. Statistical Error

The Yonggwang nuclear power plant has six Pressurized Water Reactors (PWR), with average total thermal power outpu of 16.4 GW$_{th}$. These six reactors are lined up in roughly equal distances and spans $\sim$1.3 km. The near and far detectors are to be located 290 m and $\sim$1400 m from the center of the reactor array, respectively. Therefore, distances of the reactor cores from the near and far detectors are different. We considered neutrino flux from each reactor according to $1/r^2$ for both of non-oscillation and oscillation calculation.

5.1. Observed neutrino spectrum and event rate

The number of detected anti-neutrinos, N_{ij}, is given by

$$N_{ij} = \frac{1}{4\pi r_{ij}^2}\left(\frac{P_i}{\bar{E}_i}\right)(n_p)_j \times \int \left(\frac{dn}{dE_\nu}\right)_i \sigma dE_\nu \tag{2}$$

where $(n_p)_j$ is the number of free protons on j-th detector, r_{ij} is the distance of j-th detector from the i-th reactor, P_i is the power output of i-th reactor, $\bar{E}$ is the mean energy per fission of i-th reactor, $\left(\frac{dn}{dE_\nu}\right)_i$ is the wighted neutrino spectrum per fission from i-th reactor, and σ is the inverse beta decay cross section.

Table 1 Calucations of the observed neutrino events

	Near	Far
IBD events/yr	1.0×10^6	3.8×10^4

Table 2 Summary of statistical errors

	Near	Far
stat. error/5yrs	0.05%	0.3%
stat. error/10yrs	0.04%	0.2%

$\left(\frac{dn}{dE_\nu}\right)_i$ can be esimated by using six parameter polynomial exponent for ^{235}U, ^{239}Pu, and ^{241}Pu [10] and by using three parameter polynomial exponent fit for ^{238}U [10]

In calculations, we assumed that the target volume is the 15 ton with $(PC(20\%)+Dodecane(80\%))$, which corresponds to 1.3×10^{30} protons and $sin^2 2\theta_{12} = 0.8$, $\Delta m^2_{21} = 7 \times 10^{-5} eV^2$, $sin^2 2\theta_{13} = 0.01$, $\Delta m^2_{13} = 2.4 \times 10^{-3} eV^2$.

Therefore, we calculated the observed anti-neutrino rate of the data for a year and summarized in Table 1. Accordingly, we can estimate the statistical error of the data for 5 years and 10 years as shown in Table 2.

6. Systematic Error

RENO will use two identical detectors in order to cancel or decrease significantly the systematic uncertainties that would limit the sensitivity to θ_{13}. The total systematic error of the RENO experiment is expected to be less than 0.5% as goal as shown in Table 3.

There are two main sources of systematic uncertainties: reactor and detector. For a reactor with only one core, all uncertainties from the reactor can be canceled precisely by using the far detector and the near detector assuming the distances are precisely known. However, the Yonggwang nuclear power plant has six reactor cores. Thus, there is a residual uncertainty in the extracted oscillation probability associated with the uncertainties in the knowledge of the reactor power levels. The correlated uncertainties will cancel in the near/far ratio if we know the distance precisely. Optimistically, we assumed that each reactor power fluctuates randomly by 1% for the uncorrelated uncertainty. We performed the pseudo experiments with our reactor configuration and obtained the number of events at near and far correlated for the power fluctuation for each reactor. In the results, the systematic uncertainty due to the power uncertainty is about twice as the power uncertinty in %. Hence, we can expect to get reactor power related uncertainty less than 0.2% if we get less than 0.1% on the uncorrelated individual reactor power uncertainty. (We note that both Chooz and Palo Verde achieved total reactor power uncertaintes of 0.6-0.7%)

As for the uncertainties on the detector, RENO detector design has the steel shield named Buffer as a non-scintillating region, which allow us to reduce several systematic sources considered in CHOOZ experiment as shown in Table 3. The accidental background like the single rate from PMT radioactivity can be shield by the Buffer region.

The signature of a neutrino event is a prompt signal of positron followed by the neutron capture on Gd creating gammas with about 8 MeV. The positron deposits the energy and then annihilates, yielding two photons each with 0.511

Table 3 Summary of systematic errors

	Systematic source	Chooz(%)	RENO(%)
Reactor related absolute normalization	Reactor anti-neutrino flux and cross section	1.9	<0.1
	Reactor power	0.7	0.2
	Energy released per fission	0.6	<0.1
Number of proton in target	H/C ratio	0.8	0.2
	Target mass	0.3	0.2
Detector efficiency	positron energy	0.8	0.1
	positron-geode distance	0.1	0.0
	neutron capture	1.0	0.1
	capture energy containment	0.4	0.1
	neutron-geode distance	0.1	0.0
	neutron delay	0.4	0.1
	positron-neutron distance	0.3	0.0
	neutron multiplicity	0.5	0.05

MeV, thus experimentally visible energy is with the minimum energy of 1.022 MeV. The reconstructed energy will have a tail below 1 MeV since the finite energy resolution of 6.5% at 1 MeV. We studied the change of the anitneutrino event rate assuming the energy scale uncertainty of 2% by Monte Carlo simulation. In the results, the efficiencies are 99.23%, 99.14%, 99.05% for the positron energy cuts at 0.98 MeV, 1.0 MeV, and 1.02 MeV. Accordingly, we produce a 0.09% uncertainty in the anti-neutrino event rate.

Similary, the neutron signal will be applied the energy cut to discriminate it from the prompt signal. With the assumption of the energy scale uncertainty of 1%, the efficiencies are 94.52%, 94.31%, 94.11% for the neutron energy cuts at 5.94 MeV, 6.0 MeV, and 6.06 MeV. Accordingly, we produce a 0.2% uncertainty in the anti-neutrino event rate.

In addition, the neutron detection efficiecncy relies upon the probability to capture on Gd and the delayed time cut. We studied the relation between the neutron capture fraction on Gd and the capture time with the various concentration of Gd by Monte Carlo simulation. In the results, 1μs difference between the capture time in near and far at 0.1% Gd gives about 0.4% change in the Gd captured fraction. We obtained the capture time, $(30.1\pm0.4)\mu$s, using simulation with 10000 anti-neutrino events. Therfore, we can measure the capture time to 0.5% precision providing the Gd capture fraction to 0.1% uncertainty.

As for the delayed time cut, if the delayed event window of $0.3 < T < 200\mu$s is determined to $\sim$10ns precision due to the electronics precision, the resulting uncertainty associated with missed events is $\sim$0.03%. However, we use a more conservative value of 0.1%.

7. Sensitivity

The goal of RENO is to improve the sensitivity on $sin^2 2\theta_{13}$ by an order magnitude relative to the current best limit. This will be achieved by reducing both statistical and systematic errors, less than 1.0%. An expected number of observed anti-neutrino is roughly 5,000 per day and roughly 100 per day in the near detector and far detector, respectively. An estimated systematic uncertainty associated with the measurement is less than 0.5%. Based on three years of data, it would be sensitive to measure the neutrino mixing angle in the range of $sin^2 2\theta_{13} > 0.02$

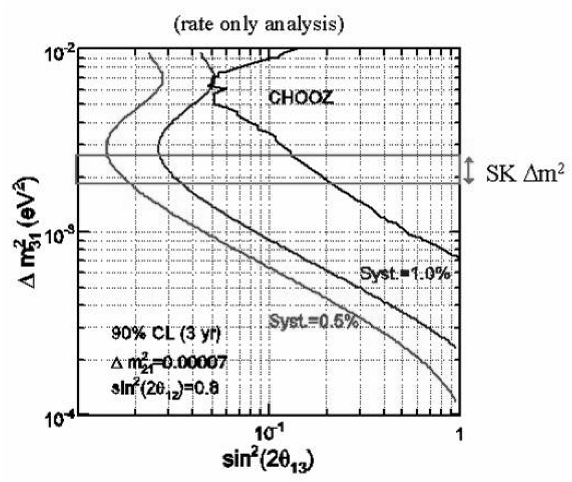

Fig. 5 Expected 90% CL limits for one (left) and three (right) years of running with the total systematic uncertainty of 0.5% (red) and 1.0% (blue). The total efficiency of 70% was assumed. Also shown is the excluded region by CHOOZ experiment.

as shown in Fig. 5. This sensitivity is five times better than the current limit obtained by Chooz.

8. Summary

The RENO experiment will try to measure θ_{13} or at least improve the current best limit by an order magnitude using two identical detectors. Data-taking is planned to start in early 2010. Based on three years of data, it would be sensitive to measure the neutrino mixing angle in the range of $sin^2 2\theta_{13} > 0.02$ with the systematic error of 1%.

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