After the KamLAND results, the remaining important targets in neutrino experiments are to measure still unknown 3 basic parameters; absolute neutrino mass scale, CP violation phase $\delta_{CP}$ and last mixing angle $\theta_{13}$. The angle $\theta_{13}$ among them is expected to be measured in near future by long baseline accelerator experiments and reactor experiments. In this paper, a realistic idea of high sensitivity reactor measurement of $\sin^2 2\theta_{13}$ is described. This experiment uses a giant nuclear power plant as the neutrino source and three identical detectors are used to cancel detector and neutrino flux uncertainties. The sensitivity reach on $\sin^2 2\theta_{13}$ is $0.017 \sim 0.026$ at $\Delta m^2_{13} \sim 3 \times 10^{-3} eV^2$, which is five to seven times better than the current upper limit measured by CHOOZ.

1. Introduction

The year 2002 was a fruitful year for neutrino physics. The SNO group showed that the solar neutrino deficit is due to neutrino transformation\(^1\). The KamLAND group observed large deficit in reactor neutrinos and excluded all the solar neutrino solutions except for LMA\(^2\). K2K group confirmed\(^3\) SuperKamiokande (SK) results of atmospheric neutrino oscillation\(^4\). From these observations, four out of seven elementary parameters of neutrinos have been measured. The measurements of remaining parameters, such as mixing angle $\theta_{13}$, absolute scale of neutrino mass and CP violating phase $\delta_{CP}$ are the next crucial issues.

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The mixing parameter \( \sin^2 2\theta_{13} \) can be measured by disappearance of reactor \( \bar{\nu}_e \) at energy/baseline range to be around \( \Delta m_{13}^2 \), as shown below.

\[
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E_\nu}
\]

(1)

The current upper limit of \( \sin^2 2\theta_{13} \) was measured by CHOOZ group using reactor \( \bar{\nu}_e \) to be \( \leq 0.12 \) if \( \Delta m_{13}^2 \sim 3 \times 10^{-3} eV^2 \). In order to improve the sensitivity, a realistic idea of new-generation reactor experiment is being investigated. It uses a giant nuclear power plant of multi reactor complex as the neutrino source. Identical detectors are placed at approximately oscillation maximum baseline and near the reactors. The data from those detectors are compared to cancel systematic uncertainties when extracting the disappearance rate. This near/far detector strategy was originally proposed by Kr2Det group. Together with optimized baselines, detector improvements and far/near strategy, our experiment can improve the sensitivity for \( \sin^2 2\theta_{13} \) significantly better than the CHOOZ experiment.

2. Physics Motivations

There is a number of reasons why reactor \( \theta_{13} \) measurement is important.

(1) \( \theta_{13} \) is the last neutrino mixing angle whose finite value has not yet been measured. Especially it is important to know how small \( \theta_{13} \) is, while other two mixing angles are large unlike quark sector.

(2) The size of \( \theta_{13} \) is related to the detectability of leptonic \( \delta_{CP} \) in future long baseline (LBL) accelerator experiments. The sensitivity to \( \delta_{CP} \) changes rapidly at around \( \sin^2 2\theta_{13} \sim 0.02 \) and the knowledge of \( \sin^2 2\theta_{13} \) down to this range will give important guideline to make strategies for future LBL \( \delta_{CP} \) experiments.

(3) The reactor measurement of \( \sin^2 2\theta_{13} \) is complementary measurement to LBL \( \sin^2 2\theta_{13} \) experiment which measures \( \nu_e \) appearance probability in \( \nu_\mu \) beams; \( P(\nu_\mu \to \nu_e) \). The probability at \( E_\nu/L = \Delta m_{23}^2/2\pi \) is expressed in eq.(2). (For simplicity, the matter effect is ignored.)

\[
P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} - \frac{\pi}{2} \frac{\Delta m_{23}^2}{\Delta m_{12}^2} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin \delta_{CP}
\]

(2)

Using best fit oscillation parameters measured by SK and KamLAND, the coefficient for \( \sin 2\theta_{13} \sin \delta_{CP} \) in the 2nd term is calculated to be around
0.04. Because $\sin \delta_{CP}$ is totally unknown, the 2nd term becomes full ambiguity when determining $\sin^2 \theta_{13}$. Moreover, there is degeneracy of $\theta_{23}$. That is, even if $\sin^2 2\theta_{23}$ is determined by $P(\nu_\mu \rightarrow \nu_\mu)$ measurements, there are two solutions for $\sin^2 \theta_{23}$ if $\sin^2 2\theta_{23}$ is not unity. Namely, if $\sin^2 2\theta_{23} = 0.92$, which is the current lower limit from SK, $\sin^2 \theta_{23} = 0.64$ or 0.36. These circumstances are described in detail in the references$^9$. Fig.-1 shows the relation of the appearance probability and $\sin^2 2\theta_{13}$, taking into account these ambiguities. The sensitivity of the JHF experiment, for example, on $\sin^2 2\theta_{13}$ is limited to $\approx 0.025$ ($= 0.015$) depending upon possible $\theta_{23}$ degeneracy is (is not) taken into account$^{10}$.

![Figure 1](image.png)

Figure 1. The relation between $\sin^2 2\theta_{13}$ and $\nu_\mu \rightarrow \nu_\mu$ appearance probability at $\Delta m^2_{23}$ energy-distance range. The matter effect is ignored for simplicity. Two bands which corresponds to two $\theta_{23}$ solutions for $\sin^2 2\theta_{23} = 0.92$ are displayed. The width of each band is due to unknown $\sin \delta_{CP}$. Even if appearance probability is precisely measured, there are intrinsic ambiguities on $\sin^2 2\theta_{13}$.

On the other hand, the reactor experiment is pure $\sin^2 2\theta_{13}$ measurement and by combining reactor data and LBL data, there is a possibility to resolve ambiguities of $\theta_{23}$ degeneracy and $\Delta m^2_{23}$ hierarchy and even access to $\sin \delta_{CP}^6$.

3. The Experiment

In this experiment, three identical detectors are built in the site of Kashiwazaki-Kariwa nuclear power plant (NPP) which is operated by Tokyo Electric Power Company. The Kashiwazaki NPP has 7 reactors, producing total thermal energy of 24.3GW. This is the most powerful NPP in the world. Using large-power nuclear power plant is profitable for not only obtaining high event rate but also realizing low background to signal
ratio at a given depth underground. The relative locations of reactors and detectors are shown in the fig.-2. Although, the far/near distance ratios between the reactors and detectors are not unique, the uncertainty introduced from the variations of the distances are estimated to be only 0.2%. The detector is CHOOZ like detector as shown in the fig.-3. The central part; the $\bar{\nu}_e$ target is 8.5 ton Gadolinium loaded liquid scintillator. The component of the liquid scintillator is the PaloVerde type, which was proven to be stable in an acrylic container\textsuperscript{11}. The Gd concentration is 0.15% which is 1.5 times higher than that of CHOOZ scintillator. The higher Gd concentration is intended to increase the neutron absorption efficiency on Gd and to reduce the systematic uncertainty associating with the inefficiency. Our preliminary study shows that the scintillator is stable with 0.15% Gd concentration. The reactor $\bar{\nu}_e$ is detected by the following inverse $\beta$ decay reaction.

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

(3)

The positron annihilates with electron within a few nano seconds after slowing down in the scintillator material, then produces two 0.511MeV $\gamma$'s. These process produces a prompt signal, whose energy is between 1MeV and 8MeV. On the other hand, the produced neutron is thermalized quickly and absorbed by Gd, producing $\gamma$ rays whose total energy amounts
Figure 3. Schematic view of the detector. The $\bar{\nu}_e$ target is 8.5ton Gd loaded liquid scintillator. The $\bar{\nu}_e$ target is surrounded by 70cm thick $\gamma$ catcher scintillator. The $\gamma$ catcher scintillator is surrounded by 60cm thick buffer scintillator with very slight light output. The outer most layer is muon anti-counter made of the same scintillator as the buffer region. The far detector will be placed at the bottom of 200m shaft hole with diameter 6m. The near detectors will be placed at the bottom of 70m depth shaft hole.

to 8MeV. The neutron absorption occurs typically 20$\mu$s after the prompt signal. By requiring the timing correlations between the positron signal and the neutron signal, backgrounds can be severely suppressed. The 2nd layer is unloaded liquid scintillator whose light output is adjusted to be
the same as the $\bar{\nu}_e$-target scintillator. This layer works as $\gamma$-ray catcher. When neutrino events occur near the detector edge, $\gamma$-rays from positron annihilation and neutron absorption may escape from the detector. The $\gamma$-ray catcher is used to catch such $\gamma$-rays and to reconstruct the original energy. The energy threshold for prompt signal is set to be below minimum positron energy (1.022MeV). In this way no systematic ambiguities associated with threshold cut is introduced. The fiducial volume is defined by the existence of correlated signals. That is, when 8MeV of energy deposit is observed after associating prompt signal whose energy is greater than 1MeV, this event is considered to be $\bar{\nu}_e$ event, regardless the positions of prompt and delayed signals. As no position cut is necessary, this method is free from position reconstruction error. The total volume of the liquid scintillator in the acrylic vessel can be measured precisely from the liquid level in the thin calibration pipe even if there is a distortion of the vessel after the installation. The 3rd and 4th layers are also liquid scintillator which has a very slight scintillation light output. These layers work as a shield of gamma rays and as cosmic ray anti-counters. The slight light output is to detect low energy muons whose velocity is below the Cherenkov threshold. Intense calibration work will be essential in this experiment to monitor the detector condition change. The whole detector will be placed in the bottom of the shaft hole with 6m diameter and 200m depth (far detector) and 70m depth (near detectors). Digging such shaft holes can be done using existing 6m diameter vertical drilling machine. The background rate is expected to be less than 2%. The major component of the background comes from fast neutrons produced in nuclear interaction caused by cosmic rays going through the rock near by. The visible energy distribution of the prompt signal in the fast neutron backgrounds was measured to be flat by CHOOZ group at the energy range below 30MeV\(^5\) and this kind of background rate can be estimated by using the event rate within non-reactor-$\bar{\nu}_e$ energy range, such as below 1MeV and beyond 10MeV.

The systematic error in CHOOZ experiment was 1.7% (detector associated) $\oplus$ 2.1% (neutrino flux associated). By improving the detector system as described above, the detector associated systematics will reduce to 1.1%. When the far and near detectors are compared the ambiguity in neutrino flux mostly cancels. Even without cancellation of the detector associate systematics, the systematic error at this stage can be reduced to 1.1%. Prediction of how good the detector systematics cancellation will be is difficult. However, in Bugey case, their systematic error reduced to be half of the original error after comparing three detectors \(^{12}\). If the same ratio
is applied to this case, the detector associated systematics is expected to be reduced to 0.5% after taking near/far ratio. All these considerations are summarized in the table-1 and the total systematic error will be 0.5\textendash{}1\%, where \sim1\% is for the case that the detector cancellation does not work so well.

In two years of operation, 40,000 neutrino events will be recorded in far detector and ten times more in each near detector. The statistic error will be 0.5\%. The 90\% CL sensitivity of this experiment is shown in the fig.-4. At $\Delta m^2 \sim 3 \times 10^{-3} eV^2$, the sensitivity of 0.017\textendash{}0.026 is expected. This is five to seven times better limit than CHOOZ and comparable to the LBL sensitivity on $\sin^2 2\theta_{13}$.

| Detector                                      | Flux | Total |
|-----------------------------------------------|------|-------|
| (1) Original (CHOOZ)                          | 1.7  | 2.1   | 2.7  |
| (2) Detector Improvement                      | 1.1  | 2.1   | 2.4  |
| (3) Far/Near $\bar{\nu}_e$ flux Cancellation | 1.1  | 0.2   | 1.1  |
| (4) Far/Near Detector Cancellation            | 0.5\sim1 | 0.2 | 0.5\sim1 |

4. Summary and Discussions

The reactor measurements of $\sin^2 2\theta_{13}$ is important because it is a pure $\sin^2 2\theta_{13}$ measurement and plays complimentary role to LBL experiments. The Kashiwazaki experiment is realistic. By comparing 3 improved CHOOZ like detectors placed at appropriate locations from multi reactors, it is possible to measure $\sin^2 2\theta_{13}$ down to 0.017 to 0.026. If this experiment observe positive result, the accessibility to $\sin \delta_{CP}$ is high for future LBL experiment. Also there is a chance to determine $\theta_{23}$ degeneracy, $\Delta m^2_{23}$ hierarchy, by combining with LBL data, and even to obtain a clue to nonzero $\sin \delta_{CP}$ before going to $\bar{\nu}$ mode. If this experiment observes negative result, it means that $\nu_3$ component in $\nu_e$ is very small, while all other components are hundred times larger. This peculiar fact may become a key information to build unified theory of elementary particles.

Acknowledgments

FS thanks to Prof. A.Piepke for providing a sample of Gd loaded liquid scintillator and giving us precious advice of the treatment. FS thanks to Prof. H. de Karret for useful discussions about CHOOZ experiment.
Figure 4. The expected 90% CL exclusion region of this experiment for the case of $\sigma_{sys}=1\%$ and 0.5% obtained by rate only analysis. At $\Delta m^2 \sim 3 \times 10^{-3} \text{eV}^2$, $\sin^2 \theta_{13} < 0.026$ and $< 0.017$ are possible, respectively.

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