Precise measurement of reactor antineutrino spectrum flux and spectrum at RENO

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Abstract. The RENO(Reactor Experiment for Neutrino Oscillation) experiment is to measure the smallest neutrino mixing angle theta13 using anti-neutrinos emitted from the Hanbit nuclear power plant in Korea. It is essential to compare the observed and expected fluxes of reactor antineutrinos for determining the neutrino disappearance probability. The expected reactor neutrino flux is calculated from the reactor thermal power and the fission rate of individual fuel isotope. Time-dependent fuel composition changes not only neutrino fluxes but also it distort the antineutrino spectrum. In this presentation, we describe how to derive the expected reactor neutrino fluxes and spectrum at both near and far detectors and report an excess in the observed spectrum near 5 MeV at RENO.

1. Measurement of reactor antineutrino flux

1.1 Expected rate of IBD interaction at RENO

The expected number of reactor antineutrino observed in the detector is calculated like following[1].

\[ n = \frac{N_p \xi}{4\pi R^2} \left( \sum \alpha_i \sigma_i \right) \left( \sum \alpha_i E_i \sigma_{\bar{\nu}} \right) \]  

(1)

where \( N_p \) is number of protons, \( \xi \) is the detection efficiency of the detector, \( R \) is the distance between the center of the detector and the fuel core of the reactor, \( i \) represents four isotopes (\(^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu\)), \( \alpha_i \) is fission fraction of each isotope, \( E_i \) is energy release per fission, \( \sigma_{\bar{\nu}} \) is the cross section averaged over the antineutrino spectrum. The calculation has been done with Huber-Mueller reactor antineutrino spectrum model [2][3]. By the way, to compare the expected IBD rate with the measured one, we should take into account detection efficiency and dead time. Table 1 summarize the IBD selection efficiencies (or detection efficiencies) and their uncertainties, which are estimated using data-driven method for prompt energy > 1.2 MeV. The dead time corresponding to 500 days of data is summarized in Table 2.

1.2 Determination of normalization factor \( R \)

A normalization factor \( R \) is defined to scale the expected IBD rate to measured one. The value of \( R \) is determined with a \( \chi^2 \) minimization. where \( O_d \) is the number of observed IBD events, \( b_d \) is the number of background events, \( T_d \) is the number of expected IBD events, \( \sigma_d \) is the background uncertainty, \( \sigma_{f,uncor} \) is uncorrelated reactor uncertainty, \( \sigma_{f,cor} \) is correlated reactor uncertainty, \( \sigma_{\xi,uncor} \) is uncorrelated detection uncertainty, and \( \sigma_{\xi,cor} \) is correlated detection uncertainty. \( f_{uncor}, f_{cor}, \xi_{uncor}, \) and \( \xi_{cor} \) are their corresponding pull parameters.
For the measurement of $\sin^22\theta_{13}$, we have used far-to-near ratio in $\chi^2$ minimization. However, here, we do not use far-to-near ratio in order to determine the normalization factor, $R$. Therefore, correlated uncertainties are included unlike far-to-near ratio analysis. The best fit $\sin^22\theta_{13}$ value (0.0871) from rate only analysis and world average $|\Delta m^2_{ee}|$ ($2.492 \times 10^{-3}$eV$^2$) are used to correct the expected IBD rate for three-flavor neutrino oscillation and then $R$ is determined.

Table 1. Summary of IBD selection efficiencies and their uncertainties.

|                           | Efficiency (%) | Uncorrelated | Correlated |
|---------------------------|----------------|--------------|------------|
| Detection                 | 85.49          | 0.1          | 0.47       |
| Spill-in correction       | 102.02         | 0.042        | 0.61       |
| IBD cross section         | 0.13           |              |            |
| Target protons            | 0.03           | 0.1          |            |
|                           |                |              |            |
| IBD selection (%)         |                |              |            |
| DAQ                       | 99.77          | 0.01         | 0.01       |
| $Q_{on}/Q_{off} < 0.07$   | 100.00         | 0.02         | 0.01       |
| $\Delta R < 2.5$ m       | 99.99          | 0.02         | 0.01       |
| Prompt energy ($1.2 < E_p < 8$ MeV) | 98.78  | 0.01         | 0.09       |
| Delayed energy ($E_p > 6$ MeV) | 92.15  | 0.05         | 0.5        |
| Capture time ($2 < \Delta t < 100$ msec) | 96.44  | 0.01         | 0.45       |
| Combined                  | 75.62          | 0.13         | 1.04       |

Table 2. Summary of dead time for 500 days data

|               | Far               | Near              |
|---------------|-------------------|-------------------|
| Before cf     | 13.616 ± 0.003    | 26.605 ± 0.003    |
| After cf      | 20.116 ± 0.126    | 33.424 ± 0.058    |

1.3 Result

The best fit value of $R$ estimated using 500 days RENO data is $0.946 \pm 0.0017$ (stat.) $\pm 0.0207$ (sys.) with Huber and Mueller model (2011). Nineteen past short-baseline (< 100 m) measurements from Ref.[4] and the measurements from Daya Bay, Chooz and Palo verde from Ref.[4] are shown in Figure 1. The predictions of the previous data are corrected for three flavor neutrino oscillation using world average value ($\sin^22\theta_{13} = 0.093$, $|\Delta m^2_{ee}| = 2.492 \times 10^{-3}$eV$^2$) [5]. The global average of $R$ is $0.942 \pm 0.009$ (expt) $\pm 0.025$ (model). RENO’s measurement of the reactor antineutrino flux is consistent with the past experiments.

Figure 1. Data/Prediction as a function of baseline. The prediction is with Huber-Mueller model and corrected for world average three-flavor neutrino oscillations[5] at each baseline.
2. Measurement of reactor antineutrino spectrum

2.1 Observation of an excess at 5 MeV

A discrepancy between the experimental data and theoretical prediction of the reactor antineutrino flux, as “reactor antineutrino anomaly”[6], is known in 2011. This may be a sign of new physics or insufficient fissile antineutrino modeling[7].

\[
\chi^2 = \sum_{i=1}^{n} \left( \frac{N_{\text{data}} - N_{\text{pred}}}{\sigma_{\text{data}}^{\nu} + \sigma_{\text{pred}}^{\nu}} \right)^2 + \sum_{i=1}^{n} \left( \frac{N_{\text{cor}}^{\nu} - N_{\text{exp}}^{\nu}}{\sigma_{\text{cor}}^{\nu}} \right)^2 \geq 5 \text{ MeV excess fraction is determined using the } \chi^2 \text{ fitting, and the } \alpha \text{ is an excess fraction. The fraction of 5 MeV excess to total observed IBD is } 2.46 \pm 0.27(\%), \text{ and its significance is } 9.0 \sigma \text{ shown in Figure 2.(left).}
\]

For the accurate study, 1400 days of near detector data are used for prompt energy spectra. The measured spectrum is compared with prediction. 5 MeV excess fraction is determined using the \( \chi^2 \) fitting, and the \( \alpha \) is an excess fraction. The fraction of 5 MeV excess to total observed IBD is 2.46 ± 0.27(%), and its significance is 9.0 \( \sigma \) shown in Figure 2.(left).

![Figure 2](image)

Figure 2. (Left) Comparison the spectrum Data/Prediction. (Middle) The correlation of 5 MeV excess with reactor power. (Right) The correlation with \( ^{235}\text{U} \) fuel isotope fraction.

2.2 Correlation of 5 MeV excess

In Figure 2.(Middle), 5 MeV excess has a clear correlation with reactor thermal power. And there seems to be a weak correlation, 1.2 \( \sigma \), between 5 MeV excess and \( ^{235}\text{U} \) fraction. More data will provide a clear answer on the correlation.

References
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