Improved Measurement of Reactor Flux and Spectrum at Daya Bay

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Abstract. A new measurement of the reactor antineutrino flux and energy spectrum by the Daya Bay experiment is reported. With a live time of 621 days, more than 1.2 million inverse beta decay (IBD) candidates were collected by eight antineutrino detectors (ADs) deployed in two near (560 m and 600 m flux-weighted baselines) and one far (16400 m flux-weighted baseline) underground experimental halls. The IBD yield was measured and the ratio to the predicted flux using the Huber+Mueller (ILL+Vogel) model was determined to be $0.946 \pm 0.020 (0.992 \pm 0.021)$. A 2.9 $\sigma$ deviation was found in the measured IBD positron energy spectrum compared to the predictions. In particular, an excess of events in the region of 4-6 MeV was found with a local significance of 4.4 $\sigma$.

Reactor antineutrino experiments provided the first experimental observation of neutrinos [1] and made the first discovery of non-zero neutrino mixing angle $\theta_{13}$ [2] with a significance above 5$\sigma$. Over the last five decades, reactor antineutrino experiments have measured the antineutrino flux and spectrum at various distances from nuclear reactors ranging from $\sim$10 m to several hundred kilometers. In 2011, evaluations of the reactor antineutrino flux and spectrum [3, 4] revealed a deficit in the data compared to the expected flux. This discrepancy is commonly referred to as the “reactor antineutrino anomaly” [5] and may be a sign of new physics or insufficient fissile antineutrino modeling. An accurate measurement of reactor antineutrino spectrum at Daya Bay can shed light on this issue and provide valuable input to next generation reactor antineutrino experiments.

Reactors are a pure source of electron antineutrinos, $\bar{\nu}_e$, which are produced by four primary isotopes: $^{235}$U, $^{238}$U, $^{239}$Pu, and $^{241}$Pu. The number of $\bar{\nu}_e$ with energy $E$ emitted from a reactor at a time $t$ can be calculated using

$$
\frac{d^2\phi(E,t)}{dEdt} = \frac{W_{th}(t)}{\sum_i f_i(t) e_i} \sum_i f_i(t) S_i(E) c_{i}^{ne}(E,t) + S_{textmSNF}(E,t),
$$

where the sums are over the four primary isotopes, $W_{th}(t)$ is the reactor thermal power, $f_i(t)$ is the fraction of fissions for isotope $i$, $e_i$ is the thermal energy released per fission, $S_i(E)$ is the $\bar{\nu}_e$ energy spectrum per fission, $c_{i}^{ne}(E,t)$ is the correction to the energy spectrum due to reactor non-equilibrium effects of long-lived fission fragments, and $S_{SNF}(E,t)$ is the contribution from spent nuclear fuel (SNF). Two fissile antineutrino spectrum models (ILL+Vogel model and Huber+Mueller model) were used for $S_i(E)$ to predict the reactor antineutrino flux and spectrum. The ILL+Vogel model refers to the conventional ILL model [7, 6, 8] of $^{235}$U, $^{239}$Pu, and $^{241}$Pu, and the theoretical model of $^{238}$U from Vogel [9]. The Huber+Mueller model refers
to the recent re-evaluation of $^{235}$U, $^{239}$Pu and $^{241}$Pu from Huber [4], and that of $^{238}$U from Mueller et al. [3].

Reactor antineutrinos were detected via inverse beta decay (IBD) reactions in the gadolinium-doped liquid scintillator (GdLS) of the Daya Bay ADs. The total number of detected IBD events was evaluated using the inputs from Eq. 1, the baselines from the six reactors to the eight detectors, the number of target protons in each AD, the IBD reaction cross section, the detection efficiency, and the $\bar{\nu}_e$ survival probability.

This document presents the analysis results in Ref. [10] based on a 621-day dataset comprised of more than 1.2 million IBD candidates, providing a factor of 3.6 times more statistics over the results presented in Ref. [11]. IBD candidates were selected by requiring a time coincidence between a prompt signal from an IBD positron, and a delayed signal from an IBD neutron after capturing on Gd, as described in Ref. [2]. A detailed study of the IBD event selection efficiencies was carried out using Monte Carlo (MC) simulation packages based on GEANT4. An absolute detection efficiency was defined combining effects caused by the number of target protons, and the IBD selection criteria. Evaluation of the detection efficiency yields $\epsilon = 80.6 \pm 1.9\%$, which is common for the eight identically designed ADs.

A normalization factor $R$ was defined to scale the measured reactor antineutrino rate to that predicted rate. The value of $R$, together with the value of $\sin^2 2\theta_{13}$, were simultaneously determined with a $\chi^2$ fit using the IBD rates in eight ADs. Fig. 1 shows the ratio of the detected to expected non-oscillation $\bar{\nu}_e$ signals. The normalization deficit yields $R = 0.946 \pm 0.021 (0.992 \pm 0.021)$ when compared with the Huber+Mueller (ILL+Vogel) model. Daya Bay’s measurement of the reactor antineutrino flux is consistent with past experiments. Including Daya Bay in the global fit, we obtained $R_g = 0.943 \pm 0.008 \ (\text{exp.}) \pm 0.023 \ (\text{model})$. After correction of the oscillation effect for each AD using the best-fit value of $\sin^2 2\theta_{13} = 0.085$, the measured IBD yield for each AD is expressed in two ways: the yield per GW$_{th}$ per day, $Y$, and equivalently, the yield per nuclear fission, $\sigma_f$. The measured IBD yields are consistent among 8 ADs after further correcting for the small variations of fission fractions among the different ADs. The average IBD yield in the four near ADs is $Y = (1.55 \pm 0.03) \times 10^{-18} \text{ cm}^2/\text{GW/day}$, or $\sigma_f = (5.92 \pm 0.12) \times 10^{-43} \text{ cm}^2/\text{fission}$.

Extending the study from the integrated flux to the energy spectrum, the measured prompt-energy spectra of the four near-site ADs were combined after background subtraction and compared with predictions. To convert the predicted antineutrino spectrum to the prompt-energy spectrum, the detector response was determined taking into account the effects of energy loss in the inactive acrylic vessels, and models of energy scale and energy resolution based on the calibration data. Fig. 2 shows the observed prompt-energy and its comparison with the predictions. The spectral uncertainty of the measurement is composed of the statistical, detector response and background uncertainties.

Agreement between a prediction and the measured spectrum was quantified with the $\chi^2$ defined as $\chi^2 = \sum_{i,j} (N_{i}^\text{obs} - N_{i}^\text{pred}) V^{-1} (N_{j}^\text{obs} - N_{j}^\text{pred})$, where $N_{i}^\text{obs(pred)}$ is the observed (predicted) number of events at the $i$-th prompt-energy bin and $V$ is the covariance matrix that includes all statistical and systematic uncertainties. A comparison to the Huber-Mueller model yields a $\chi^2$/dof of 46.6/24 in the full energy range from 0.7 to 12 MeV, corresponding to a 2.9 $\sigma$ discrepancy. As shown in Fig. 2, the spectral discrepancy in the region of 4–6 MeV is clearly visible. The local significance for the 2 MeV window between 4 and 6 MeV was evaluated. We obtained a $\Delta \chi^2$/dof value of 37.4/8, corresponding to the p-value of $9.7 \times 10^{-6}$ (4.4$\sigma$).

The Daya Bay experiment will continuously improve the measurement of the reactor antineutrino flux and spectrum with more statistics and improvement on the detector energy response with new calibration data.

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Figure 1. Ratio of the detected to expected non-oscillation $\bar{\nu}_e$ signals at the 8 ADs located in three experimental halls as a function of the effective baseline. The oscillation survival probability at the best-fit value is given by the red curve. The uncertainty of the model prediction is shown as the gray band around unity.

Figure 2. (A) Comparison of predicted and measured prompt energy spectra. The prediction is based on the Huber+Mueller model and normalized to the number of measured events. The hatched and red filled bands represent the square-root of diagonal elements of the covariance matrix ($\sqrt{(V_{ii})}$) for the reactor related and the full systematic uncertainties, respectively. (B) Ratio of the measured prompt energy spectrum to the predicted spectrum. (C) The defined $\chi^2$ distribution ($\tilde{\chi}_i$) of each bin (black solid curve) and local p-values for 1 MeV energy windows (magenta dashed curve).

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