Calibration and Reconstruction of the Daya Bay Antineutrino Detector

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Abstract. The Daya Bay Reactor Neutrino Experiment has produced the most precise measurements to date of the mixing angle $\theta_{13}$ and the mass-squared difference $|\Delta m^2_{ee}|$ in the electron antineutrino disappearance channel. In addition, the experiment has published a precision measurement of the reactor antineutrino flux and spectrum. Energy calibration and reconstruction are crucial to all of these measurements. Various approaches are used to understand the detector non-linearity, non-uniformity, energy scale and the related systematic uncertainties. The uncertainty of the detector-uncorrelated energy scale and the absolute energy response are less than 0.2% and 1%, respectively. Nevertheless, these uncertainties are among the leading contributors to the overall systematic uncertainties leading contributors of the systematic uncertainties and will continue to be studied.

1. Introduction
The Daya Bay Reactor Neutrino Experiment was designed to determine the neutrino mixing angle $\sin^2 \theta_{13}$ with a sensitivity better than 0.01[1]. To achieve this goal, one of the important strategies carries out a relative measurement with eight functionally identical antineutrino detectors(ADs). The ratio of the number of antineutrino events is given by

$$\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\varepsilon_f}{\varepsilon_n} \right) \left( \frac{P_{\text{sur}}(E, L_f, \theta_{13})}{P_{\text{sur}}(E, L_n, \theta_{13})} \right),$$

where $N_{f(n)}$ is the number of antineutrino events, $N_{p,f(n)}$ is the number of target protons, $L_f(n)$ is the distance between reactor and detector, $\varepsilon_f(n)$ is the detector efficiency, and $P_{\text{sur}}$ is the survival probability at the far(near) detector[2]. The detector-related systematics errors are greatly reduced by the precise determination on parameters, $N_{p,f(n)}^*, L_f^*$, and $\varepsilon_f^*$[1]. The dominant systematic uncertainty for the Daya Bay experiment comes from the relative energy scale. Therefore, it is crucial to have the energy scale as identical as possible for all of them in order to minimize the uncorrelated systematic uncertainties.

Calibration system Three automatic calibration units (ACUs) are mounted on the top of the detector, as shown in Figure 1. Each one contains 3 sources: LED, $^{68}$Ge, and $^{60}$Co and $^{241}$Am $^{13}$C. The ADs are calibrated periodically[2][4].

2. Calibration and Reconstruction
First of all, the PMT gain was calibrated by fitting the single photoelectron (SPE) peak in the PMT dark noise spectrum from physics data. It is the conversion constant from ADC to PMT.
output charge in p.e. (photoelectron)[3]. Figure 2 shows the mean charge per SPE averaged over all channels within each AD as a function of time.

Second, the light yield, which is defined by the total charge observed per MeV, was determined by fitting the weekly calibration source, $^{60}$Co, at the AD center (Calibration A) or spallation neutrons captured on Gd (Calibration B). For Calibration A, the mean of the peak is 2.505 MeV and was fit with a Crystal ball function plus a Gaussian. For the spallation neutrons captured on Gd, the dual peaks of 7.95 MeV and 8.54 MeV were fit with double Crystal ball functions[2][4]. Figure 3 shows the observed light yield versus time.

The energy response of the ADs depend on time and spacial position. Therefore, the energy reconstruction process needs to consider these dependencies. There are two reconstruction methods in the Daya Bay experiment: using the center-of-charge with correction based on $^{60}$Co events at different ACU locations (Reconstruction A) and using the charge-pattern templates comparing with Monte-Carlo(Reconstruction B). Then, the special non-uniformity was corrected by the correction function or map, which are from the calibration source and spallation neutron, respectively. The reconstruction energy is defined by $E_{\text{rec}} = E_{\text{vis}} \cdot F$, where $E_{\text{vis}}$ is the visible energy and F is the correction factor from the correction function or map.

3. Results

The Daya Bay experiment has one good process for the PMT gain and two independent methods on light yield and energy reconstruction. The performance of the energy calibration process was verified with the reconstructed energy of spallation neutron captured on hydrogen. Both $^{60}$Co (Calibration A) and spallation (Calibration B) methods present the energy stable within 0.2%, as shown in Figure 4. The calibration references were used to estimate the differences between ADs with two independent processes. The variations of the reconstructed energy are less than 0.2%, as shown in Figure 5.

For the Daya Bay experiment, an uncorrelated relative energy scale uncertainty less than 0.2% is achieved, as well as a stability of 0.2% in the energy response.

4. References

[1] X. Guo et al. [Daya Bay Collaboration], hep-ex/0701029.
[2] F. P. An et al. [Daya Bay Collaboration], Nucl. Instrum. Meth. A 685, 78 (2012).
[3] F. P. An et al. [Daya Bay Collaboration], Phys. Rev. D 93, no. 7, 072011 (2016).
[4] F. P. An et al. [Daya Bay Collaboration], Chin. Phys. C 37, 011001 (2013).
Figure 3. **Left**: The observed light yield versus time as obtained using weekly calibration $^{60}$Co at the AD center. **Right**: The observed light yield versus time from the spallation neutron source captured on Gd.

Figure 4. Stability of the reconstructed energy of spallation neutrons captured on Hydrogen. **Left**: using $^{60}$Co source at the AD center (Reconstruction A). **Right**: using spallation neutrons (Reconstruction B).

Figure 5. Comparison of the reconstructed energy between antineutrino detectors for a variety of calibration references using **Left** calibration with $^{60}$Co source (Reconstruction A) and **Right** calibration with spallation neutrons (Reconstruction B).