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Study of a prototype detector for the Daya Bay neutrino experiment ☆

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ABSTRACT

The Daya Bay reactor neutrino experiment is designed to precisely measure the neutrino mixing angle θ_{13}. In order to study the details of the detector response and finalize the detector design, a prototype neutrino detector with a scale of 1/3 in diameter is constructed at the Institute of High Energy Physics (IHEP), Beijing. The detector is viewed by 45 8″ photomultipliers, which are calibrated by LED light pulse. The energy response of the detector, including the resolution, linearity, spatial uniformity, etc., is studied by radioactive sources ^{133}Ba, ^{137}Cs, ^{60}Co, and ^{22}Na at various locations of the detector. The measurement shows that the detector, particularly the specially designed optical reflectors, works as expected. A Monte Carlo simulation based on the Geant4 package shows a good agreement with the experimental data.

1. Introduction

The Daya Bay reactor neutrino experiment (Daya Bay) [1] is designed to measure the neutrino mixing angle θ_{13} with a sensitivity of $\sin^2 2\theta_{13} < 0.01$ at 90% confidence level (C.L.). The Daya Bay nuclear power complex, located at Shenzhen in Guangdong province of China, 55 km from Hong Kong, is one of the most prolific sources of antineutrinos in the world. The site is adjacent to mountainous terrain which is ideal for underground detectors to perform low background neutrino experiment.

The Daya Bay cylindrical anti-neutrino detector (AD) is designed with three concentric zones: the inner most zone filled with Gd-loaded liquid scintillator (GdLS), the middle zone filled with normal liquid scintillator (LS), and the outermost zone filled with transparent mineral oil. A prototype of AD with a scale of 1/3 in diameter is constructed at the Institute of High Energy Physics (IHEP) in Beijing, P.R. China to (1) verify the detector design principles of AD, such as reflectors, energy response, uniformity of the response, etc.; (2) practise detector calibration; (3) help to develop and verify the Daya Bay Monte Carlo simulation software; and (4) obtain practical experiences for detector construction. In this paper, we report our study with this prototype.

2. Construction of the prototype detector

In order to simplify the construction while not compromise the main goals, the prototype is chosen to have only two-zones as shown in Fig. 1: The inner zone is confined by a 1 cm thick cylindrical acrylic vessel with 0.9 m diameter and 0.98 m height, filled with ~0.5 ton liquid scintillator (LS). The scintillator is made of 70% mineral oil, 30% mesitylene, 5 g PPO/L, and 10 mg bis-MSB/L. The outer zone, filled with ~4.8 tons mineral oil, is confined by a 2 m diameter and 2 m height stainless steel vessel. There immerses three supporting rings on which 45 8″ photomultiplier tubes (used for MACRO, type: EMI 9350KA) are mounted. The distance between neighbor rings is 40 cm. The middle ring is actually 1.5 cm higher than the center of the acrylic vessel. The dome of the PMT glass is 22 cm from the outer surface of the acrylic vessel. The inner surface of the stainless steel vessel and supporting rings are painted black to eliminate reflective light.

Two reflectors with a diameter of 1.3 m, using Al films with a reflectivity of 85%, are installed at the top and bottom of the stainless steel cylinder. This is equivalent to increase the effective PMT photocathode surface coverage from 10% to ~14%. Two reflectors are located at $z = 95$ cm (top) and $z = -100$ cm (bottom), relative to the acrylic vessel center.

At the top of the acrylic vessel, there is a 60 cm long, 5 cm diameter vertical pipe at the center of the cylinder for calibration and liquid filling. Six LEDs are clung near the outer surface of the acrylic vessel for PMT gain calibration.

The prototype is surrounded by a cubic muon veto detector which has actually five sides (except the bottom), each with a dimension of $3\,m \times 3\,m$. The top of the veto is composed of 20

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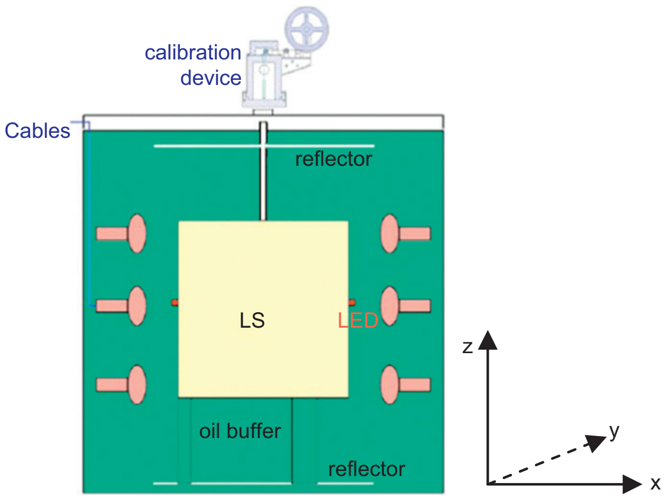

Fig. 1. Side view of the schematic structure of the prototype.

Fig. 2. The prototype detector: rack to mount the muon veto (left) and the mounted muon veto detectors (right).

plastic scintillator counters with a thickness of 5 cm, a width of 15 cm, and a length of 3 m, used previously for the TOF system of the BES experiment. Each of the other 4 side veto is composed of 9 1 m $\times$ 1 m square scintillator counters, which were used for the L3+C experiment. Fig. 2 is the photograph of the prototype, showing the rack for mounting the muon veto and the mounted scintillator counters.

3. DAQ and measurement system

The trigger and readout boards for the prototype experiment, based on the VME standard, are actually prototype boards for the Daya Bay experiment. An energy sum trigger, which integrates the total charge of all PMT channels is provided by this first version of the trigger board. In the readout board, a 10-bit Flash ADC gives the integral charge and a 9-bit timer gives the relative hit time of each PMT [1].

The muon detector system, which just provides a muon veto signal to the energy sum trigger, is realized by standard NIM electronics.

A DAQ software migrated from that of the BESIII experiment, reads the data from the FIFO buffer of the readout board and records them in a computer disk.

A total of six LEDs are mounted on the acrylic walls to calibrate the gain of PMTs. The light output is carefully adjusted in order to get the single photoelectron (P.E.) peak for each PMT. The measured PMT single P.E. spectrum, as shown in Fig. 3, is fitted to a convoluted function formula [2,3], as in following:

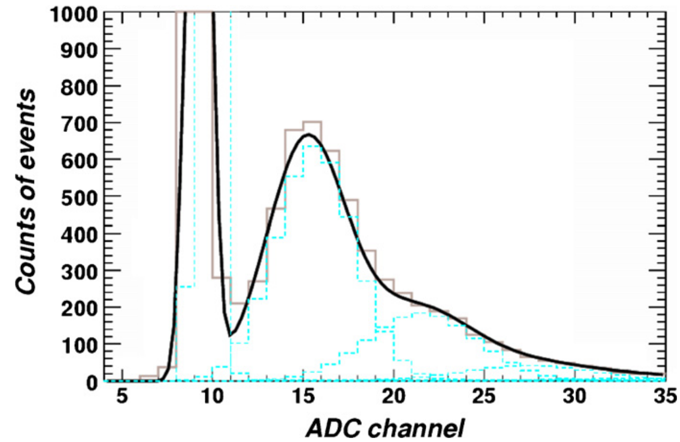

Fig. 3. Fitted spectrum for PMT gain calibration.

$$SER(x) = \sum_{n=0}^{N_{\max}} P(n;\mu) \otimes G_n(x) \otimes B(x)$$

$$= \sum_{n=0}^{N_{\max}} \frac{\mu^n e^{-\mu}}{n!} \times [(l-w)G_n(x-Q_0) + wI_{G_n \otimes E}(x-Q_0)]$$

$$G_n(x) = \frac{1}{\sigma_0\sqrt{\pi n}} \exp\left(\frac{(x-nQ_1)^2}{2n\sigma_1^2}\right)$$

$$B(x) = \frac{(1-w)}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{(x-Q_0)^2}{2\sigma_0^2}\right) + w\alpha\, \exp(-\alpha(x-Q_0))$$

The average gain of PMTs is about 5×10^7, and a single P.E. peak on average is about 5.5 ADC accounts after pedestal substraction.

Radioactive sources of ^{133}Ba, ^{137}Cs, ^{60}Co, and ^{22}Na are placed at the detector center, one at a time, through the calibration pipe to get the energy response. The measured charge in ADC for each radioactive source is converted into the photoelectron using the calibrated PMT gain. The trigger threshold is set at a charge sum of 30 photoelectrons, corresponding to a gamma energy deposition of about 110 keV. Fig. 4 shows the logic diagram for the data taking.

4. Monte Carlo simulation

We use a Geant4 [4] based Monte Carlo simulation program to simulate the energy response of the prototype.

To precisely simulate the detector response, all important optical parameters are measured as a function of wavelength, such as the emission spectrum of the liquid scintillator, the attenuation length of the scintillator and the mineral oil, the reflectivity of the Al film and the inner surface of the stainless steel tank, the transmission of the acrylic vessel, the index of refraction of the scintillator, the oil, the acrylic, etc. The light yield of the LS [5] is measured relative to an anthracene. Since it is difficult to obtain the absolute light yield accurately, it is determined by fitting the prototype data, which is actually very close to the measured value.

Several different PMT optical models are tested against PMT angular response measurements. These optical models include different effects of light transmission, reflection and refraction in and on PMT glass, photocathode, and inner mercuric surface of the PMT back. It turns out that only a simple model including only the photocathode with a proper quantum efficiency agrees well with the measurements [6].

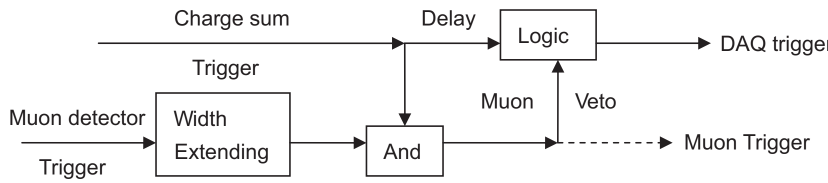

Fig. 4. Block diagram of DAQ.

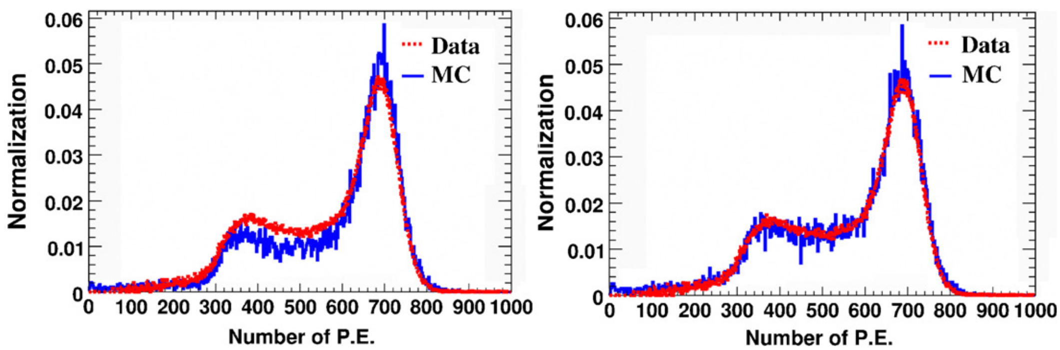

Fig. 5. Energy spectrum of the ^{60}Co source in comparison with Monte Carlo simulation. Left: no sealing material is included in the simulation. Right: the sealing material is included in the simulation.

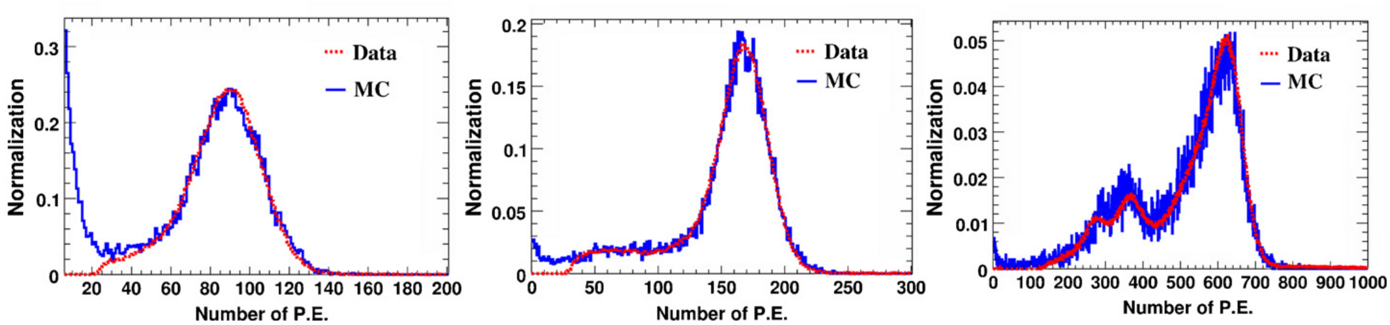

Fig. 6. Comparisons of data and MC spectra of ^{133}Ba (left), ^{137}Cs (middle) and ^{22}Na (right).

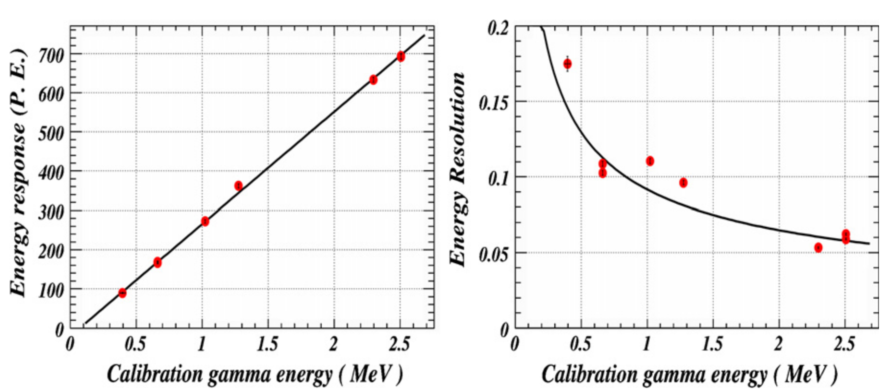

Fig. 7. Linearity of the energy response (left, a) and energy resolution (right, b) of the prototype at the center of the prototype.

PMT output is not an ideal impulse function. Effects such as the charge broadening and noise shall be taken into account. In our simulation, if a PMT receives N photoelectrons in one event, its final output will be a gain normalized sum of sampling N times of $G_1(x)$ and one time of $B(x)$, which all are got from the fitted single photoelectron spectrum of each PMT.

The simulation shows that the response of detector is sensitive to the light yield of LS, the reflectivity of Al reflectors and the reflectivity of the inner surface of the stainless steel tank, but not sensitive to the attenuation length of LS, oil, and acrylic vessel if they are longer than 7, 13, and 1 m, respectively, at the wavelength larger than 420 nm.

As an example, the energy response of the prototype detector to a ^{60}Co γ source sealed by organic plastics with a thickness of 0.3–0.5 cm, together with the Monte Carlo simulation, is shown in Fig. 5. The outer dimension of the source package is 2 cm in diameter and 1.2 cm in height. Clearly some γ-rays lost their energy in the sealing material, and the effect can be simulated by Monte Carlo, as shown in Fig. 5.

5. Result

5.1. Energy response

The detector response to the γ-ray sources ^{133}Ba, ^{137}Cs, and ^{22}Na are obtained by placing sources into the detector along the calibration pipe at the center of the detector cylinder. The obtained energy spectra are compared to their respective Monte Carlo simulations as shown in Fig. 6. Good agreements are obtained, showing that the energy response of the prototype detector has been reasonably understood.

The linearity and energy resolution of the detector can be obtained from this data set, as shown in Fig. 7. A linear fit of Fig. 7a gives the total light yield, namely, the energy to photoelectron conversion factor of the prototype at the detector center, being 286 P.E./MeV. This is slightly better than that of the Daya Bay detector since the PMT coverage is slightly higher here [1]. The energy resolution is obtained by a fit to Fig. 7b, giving $9.2\%/\sqrt{E}$ (MeV). The detector light yield and the energy resolution are all in good agreement with our expectation, confirming our confidence to the detector design of the Daya Bay experiment.

5.2. Space uniformity of the energy response and energy leakage

To study the space uniformity of the energy response and the position dependence of the prototype, the ^{137}Cs source is placed at various locations in the detector along the cylindrical axis and the respective energy spectrum is obtained. The center of the acrylic vessel is defined to be the origin of the coordination system.

Fig. 8 shows the energy spectra of the ^{137}Cs source at different positions in comparison with Monte Carlo simulation. The source position at 50 cm is actually above the LS vessel while the source at −48 cm is at the bottom of the LS vessel. The difference can be seen from their energy spectra. We intend to measure the energy response at position of 50 cm to check the consistence of data and MC simulation. All the spectra in Fig. 8 show very good agreement between data and MC simulation, particularly at the edge of the LS vessel where a large energy leakage is expected. By extracting information from Fig. 8, the energy response and energy resolution at different locations are shown in Fig. 9. Clearly at the top and bottom of the detector, the total energy collected in the sensitive detector is smaller and hence the energy resolution is poorer than that at the center. The asymmetry between the positive and negative source position mainly comes from the offset of PMTs in the Z-axis by 1.5 cm upward. The perfect agreement between data and Monte Carlo shows that the detector is well understood, which is extremely important to control systematic errors in the Daya Bay experiment.

The uniformity of the future Daya Bay 3-zone anti-neutrino detector will have a better space uniformity in energy response

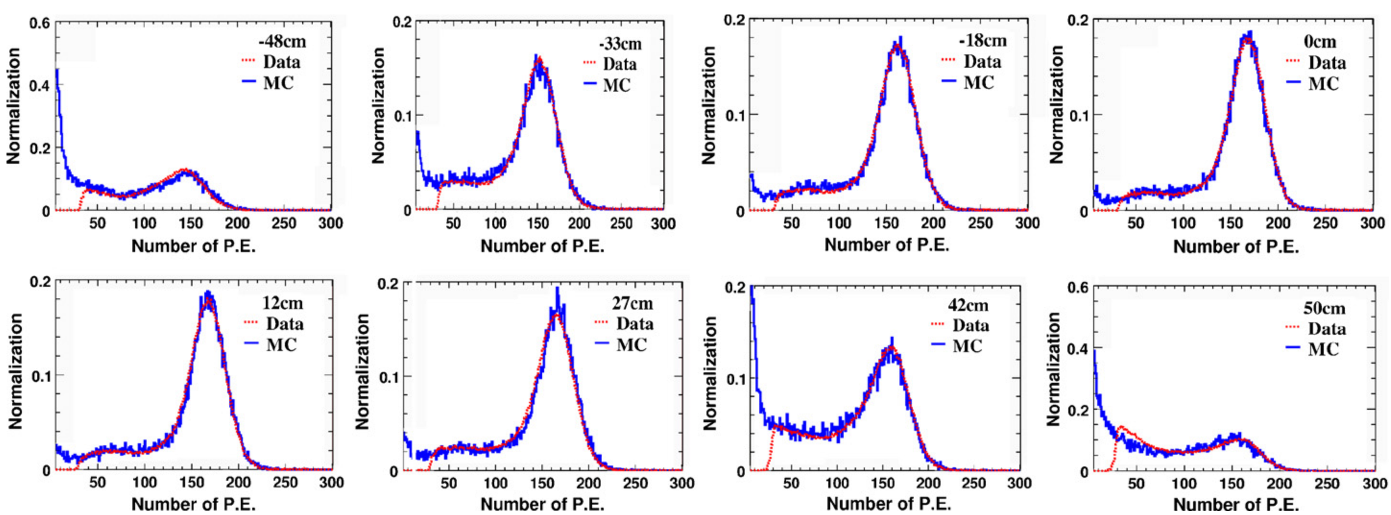

Fig. 8. The spectra of ^{137}Cs at different locations along the cylindrical central axis, and the comparison with Monte Carlo simulation.

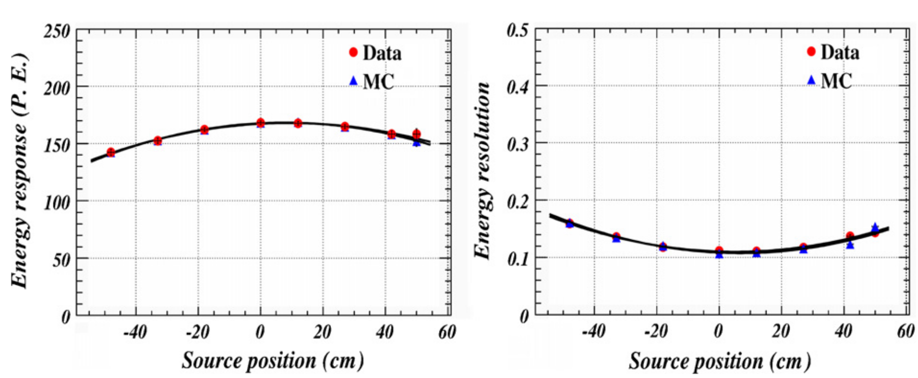

Fig. 9. Energy response of ^{137}Cs at different locations along the cylindrical central axis in comparison with Monte Carlo simulation.

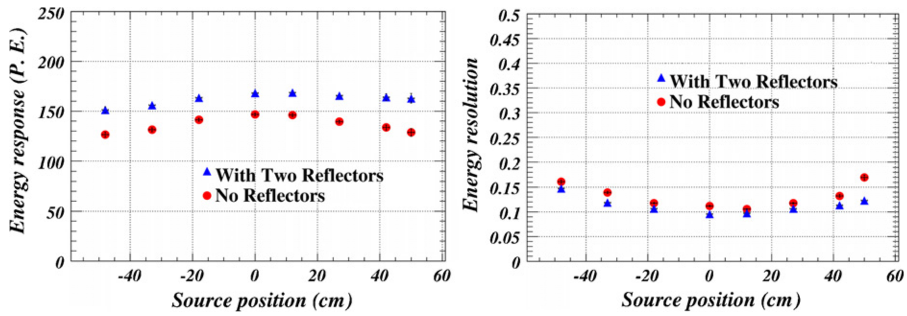

Fig. 10. Energy response of the prototype with and without two reflectors for a ^{137}Cs source at different locations along the central cylindrical axis (energy response (left); energy resolution (left)).

since there will be a 45 cm thick gamma-catcher filled with LS, which will fully contain the gamma energy deposition at the edge [1].

5.3. Effect of reflectors

As described before, there are two reflectors at the top and bottom of the prototype to increase the total light collection, improve the detector's energy response and the space uniformity of the detector.

Fig. 10 shows the Geant4 simulation with and without the two reflectors. With two reflectors, the total light collection increases by 15–26% at different position and its resolution improves by 10–30% compared to the case without reflectors. It should be noted from Fig. 9 that, the simulated results with two reflectors are consistent with the experimental data, showing that the reflectors are well understood and no additional systematic errors associated with it.

6. Conclusion

A 2 m in diameter and 2 m high cylindrical prototype detector for the Daya Bay experiment is constructed to study technical details and the energy response. The photocathode coverage of 10% by 45 8″ PMTs is increased to 14% by two optical reflectors at the top and the bottom of the cylinder. The total light collection of $\sim$286 P.E./MeV and the energy resolution of $\sim 9.2\%/\sqrt{E}$ (MeV) is obtained by using γ-ray sources. The spatial response of the detector is also studied by placing γ-ray sources at various locations along the Z-axis. A detailed Monte Carlo simulation of the detector show an excellent agreement with data, demonstrating that this prototype, including LS light yield, optical characters of the detector and PMT response is primarily understood. With the Geant4 simulation program based on this prototype, we also have a good knowledge about the future Daya Bay anti-neutrino detector.

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