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# Study of a prototype water Cherenkov 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 $\theta_{13}$. The anti-neutrino detectors are shielded by highly purified water against radioactivity and spallation neutrons from surrounding rocks. The water also serves as a Cherenkov detector to tag cosmic-ray muons, which induce main backgrounds. In order to study water purification and details of the detector response, a prototype water Cherenkov detector is constructed at the Institute of High Energy Physics (IHEP), Beijing. The detector is divided by Tyvek into two sections and viewed by two 8 in. photomultipliers. Cosmic-ray muons are used for detector response studies and a Monte Carlo simulation based on the Geant4 package shows good agreement with the experimental data.



## 1. Introduction

The water Cherenkov detector is widely used in particle physics experiment, such as Super-Kamiokande experiment [1], Pierre Auger experiment [2], and also the Daya Bay reactor neutrino experiment (Daya Bay) [3]. Daya Bay is designed to measure the neutrino mixing angle $\theta_{13}$ with a sensitivity of $\sin^2 2\theta_{13} < 0.01$ at 90% confidence level. To reach the goal, eight identical anti-neutrino detectors are mounted with optimized baselines near the Daya Bay nuclear plant, which is one of the most prolific anti-neutrino sources in the world. The anti-neutrino detectors are shielded by highly purified water against radioactivity and spallation neutrons from surrounding rocks. The water also serves as a water Cherenkov detector to tag muons.

Each water Cherenkov detector is divided into two sections by Tyvek partitions and viewed by several hundred photomultipliers. The water is highly purified and its quality is maintained by a local circulation/purification system. In order to understand the water Cherenkov detector better, a prototype of the detector with dimensions $2.8\ \mathrm{m} \times 1.2\ \mathrm{m} \times 1.3\ \mathrm{m}$ was constructed at IHEP to (1) study the circulation and purification, and finalize the design for Daya Bay; (2) study the response to cosmic-ray muons, help to develop and verify the Daya Bay Monte Carlo simulation software; (3) obtain practical experience for detector construction.

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## 2. Construction of the prototype detector

A water tank made of 1 cm thickness PP (polypropylene) with a circulation and purification system has been built (Fig. 1). In the tank, two 8 in. photon-multipliers (PMTs, previously used in the MACRO experiment, type: 9350 KA) are mounted, one at the bottom and the other on the side wall (Fig. 1). The effective PMT photocathode surface coverage is 0.6%, similar to the real water Cherenkov detectors of Daya Bay. There are two phases in the prototype experiment: in Phase I, only a simple empty water tank was constructed to test water quality [5], and in Phase II, the water tank is divided into two sections by Tyvek, which is mounted on a stainless steel frame (Fig. 1), and the second phase will be discussed in the following. The tank is filled with highly purified water from the IHEP water purification plant, sealed and the space above the water was filled with nitrogen. The inside pressure is about 1.5 cm water equivalent higher than atmospheric pressure.

The circulation and purification system composed of one pump, one 1 μm filter, one ultra-violet (UV) sterilization stage, one polishing cartridge, one 0.22 μm filter, one flowmeter and one resistivity cell (Fig. 2). Water circulation is driven by the pump whose speed can be controlled. The 1 μm filter removes relatively large solids from the water, and the UV stage is used to kill bacteria, to decompose organic substances and to reduce the total organic carbon in the water. The polishing cartridge is filled with high quality dowex ion exchange resin to purify the water. The 0.22 μm filter removes relatively small solids and prevents resin

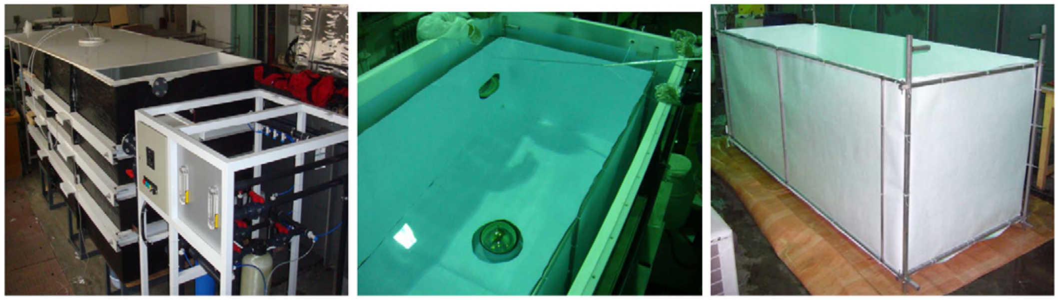

**Fig. 1.** The water tank with circulation and purification system (left). Two PMTs are mounted, one at the bottom, the other one on a side wall (middle). Tyvek mounted on a stainless steel frame, to be put into the tank (right).

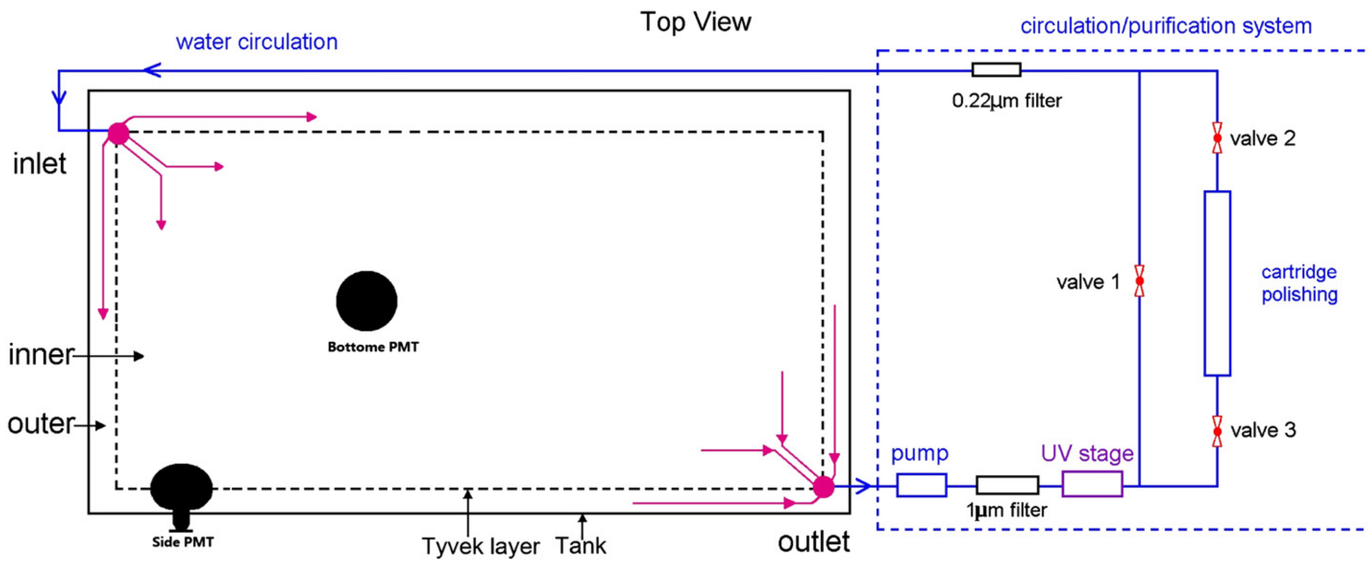


**Fig. 2.** Diagram of the water tank with circulation and purification system.

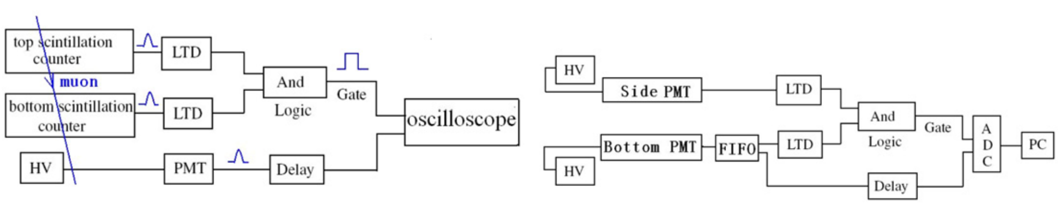


**Fig. 3.** Diagram of PMT signal measurements with an oscilloscope (upper). Diagram of bottom PMT spectrum measurements (lower).

beads escaping into the water tank. The water resistivity is monitored by the resistivity cell with 2% uncertainty, and the resistivity of purified water is 16.7 MΩ cm, similar to the water from the IHEP water station.

In the process of construction, we accumulated successful experience about material cleaning, Tyvek installation. Together with the prototype running, we understood the water circulation and purification well. A model of water quality has been constructed and matches with the experimental data well [5]. All of these contribute lot in the Daya Bay water Cherenkov detector installation and integration.

## 3. Study of cosmic-ray muons response

The water Cherenkov detector in Daya Bay has two major functions: suppress natural radioactivity and spallation neutrons from environment; tag cosmic-ray muons efficiently ($\geq 99.5\%$) [3]. To meet the first goal, anti-neutrino detectors are surrounded by 2.5 m water at least [4]. The second goal requires good optical propagation property, and in Daya Bay, it requires large water absorption length ($\geq 30$ m) and good Tyvek reflectivity ($\geq 80\%$). The inefficiency is mainly induced by short-track muons, which generate less Cherenkov photons in the detector. Good optical propagation results better collection of photons and increases tag efficiency.

In the prototype experiment, cosmic ray muons are utilized to study optical properties and results meet the requirements of Daya Bay, indicating that the water circulation and purification system, Tyvek, material cleaning, etc. can be used in Daya Bay.

### 3.1. Experiment setup

There are three steps: firstly, vertical incidence muons are selected with two plastic scintillation counters (dimension 1 m $\times$ 0.3 m, one at the top and one at the bottom of the water tank), and PMT signals are recorded by an oscilloscope. Secondly, PMT charges of vertical incidence muons are also integrated in an

ADC. Finally, PMT charges of all incidence muons are integrated and compared with MC (Fig. 3).

In the PMT charge spectrum study, PMTs are calibrated with a low intensity LED before being installed into the water tank. LED intensity was carefully tuned to get the single photon–electron (SPE). The measured spectrum, as shown in Fig. 4, is fitted with a convoluted function (1) [7]. From the fitting results, one P.E. equals 5.74 ADC channels after pedestal subtraction

$$S_{real}(x) = S_{ideal}(x,\mu,Q_1,\sigma_1) \otimes B(x,w,\sigma_0,\alpha) \tag{1}$$

$$S_{ideal}(x,\mu,Q_1,\sigma_1) = P(n,\mu) \otimes G_n(x,Q_1,\sigma_1) \tag{2}$$

$$B(x,w,\sigma_0,\alpha) = \frac{1-w}{\sigma_0\sqrt{2\pi}} e^{-x^2/2\sigma_0^2} + w\theta(x)\alpha e^{-\alpha x}. \tag{3}$$

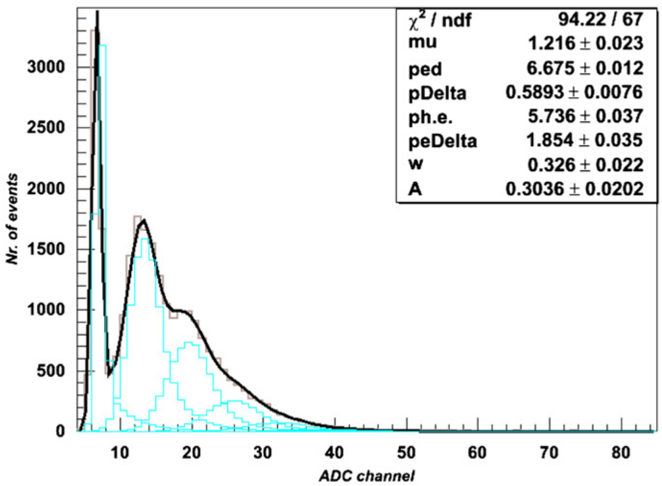


**Fig. 4.** PMT SPE spectrum fitting.

### 3.2. Monte Carlo simulation

A simulation program based on GEANT4 [6] is used to simulate muon responses in the prototype detector.

There are several factors with important influence on the simulation results: muon generation on the surface, PMT modeling, Tyvek reflectivity, absorption length of water. A standard formula (Gaisser's formula [8]) is used to generate muons (Fig. 5), with mean $\theta$ value 37° and mean energy about 7 GeV.

In the simulation, the PMT is described by a simple model including only the photocathode with proper quantum efficiency. PMT response is not an ideal impulse function, and effects such as noise and charge broadening should be taken into account. In the simulation, if a PMT receives $N$ photons in one event, the final output would be a gain normalized sum of sampling $N$ times of $G_1(x)$ and one time of $B(x)$, which are from the fitted single photoelectron spectrum of each PMT. Collection efficiency of a PMT cannot be determined *ab initio*, and an effective value 0.6 is put into simulation. The value can be tuned by comparing with data.

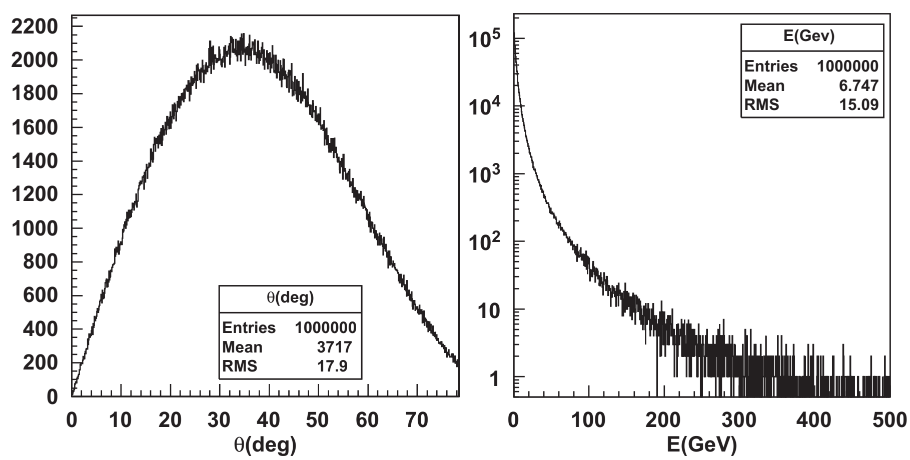


**Fig. 5.** Muon zenith angle (left) and energy (right) distribution on the ground.

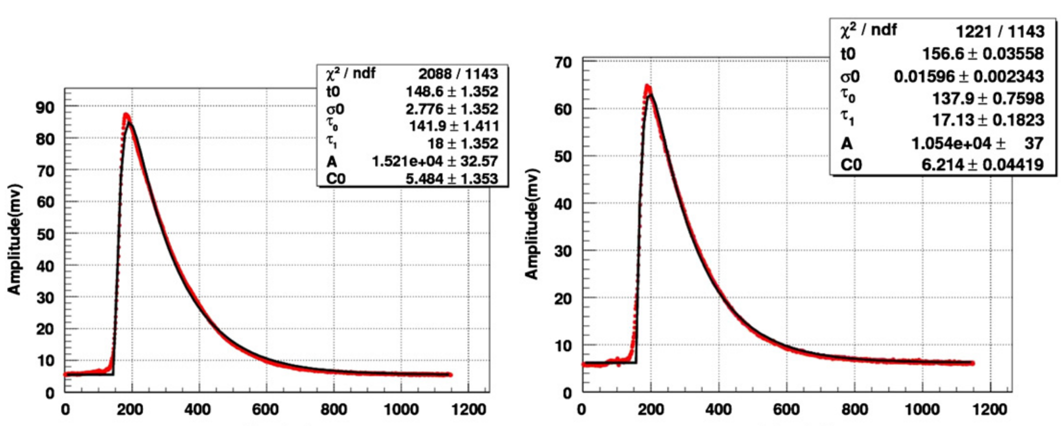


**Fig. 6.** PMT signal fitting for the bottom PMT (left) and side PMT (right).

In the simulation, the initial Tyvek reflectivity is 0.8 and the water absorption length is 30 m, which are the requirements of Daya Bay. By comparing with data, these values can be estimated.

## 4. Results

### 4.1. PMT signal study for vertical incidence muons

The PMT signals are recorded by an oscilloscope. The signal persists for as long as 400 ns, since Cherenkov photons can reflect many times on Tyvek. An exponential function (4) is used to describe the relationship between hit time and amplitude with the Tyvek reflection. $\tau_0$ is the effective attenuation time of water

$$i(t) = \frac{1}{\tau_0} e^{-t/\tau_0}. \tag{4}$$

To describe the time diffusion induced by the PMT transition time fluctuation, time dispersion from electronics, etc., a gauss function (5) is introduced

$$g(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(t-t_0)^2/2\sigma^2}. \tag{5}$$

Finally, considering the existence of an RC electric circuit between the output of the PMT and the input of the oscilloscope, the PMT signals can be expressed as (6)

$$I(t) = i(t) * g(t) * \frac{1}{RC} e^{-t/RC}. \tag{6}$$

In the measurements, 10,000 signals are recorded and their average is fit with the above function (Fig. 6). $\tau_0$ is $140 \pm 5$ ns.

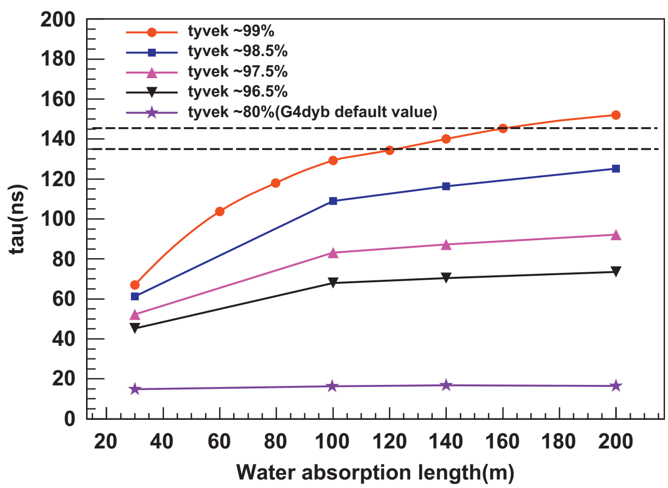


**Fig. 7.** Mean decay time to Tyvek reflectivity and water attenuation length.

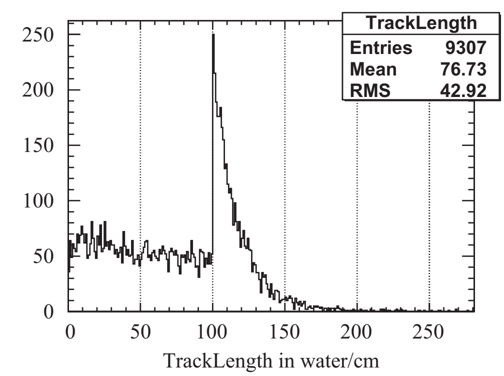


**Fig. 10.** Muon track lengths in the water tank.

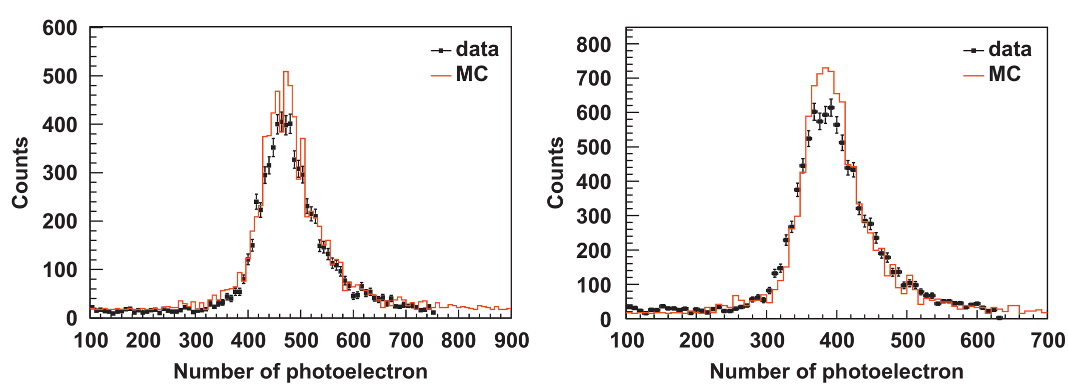


**Fig. 8.** Comparison of experimental and simulation spectra: left for the bottom PMT and right for the side one.

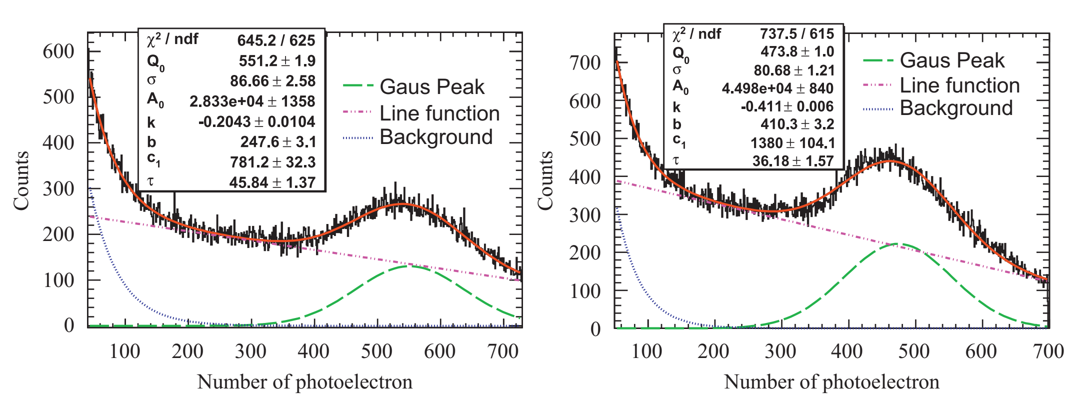


**Fig. 9.** PMT spectrum fitting: left for the bottom PMT and right for the side one.

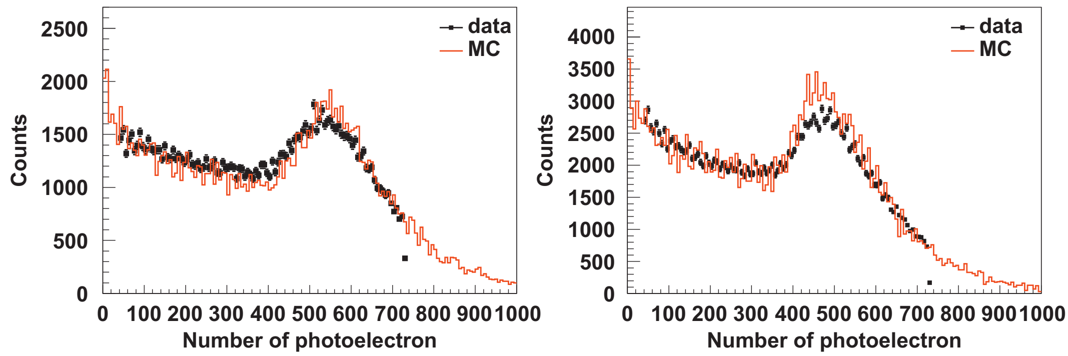


**Fig. 11.** PMT spectrum comparison with simulation: upper for the bottom PMT and lower for the side one.

But in simulation, using the default configuration, the simulated $\tau_0$ is 70 ns, indicating that the Tyvek reflectivity and water absorption length should be larger than the default values, and requirements of Daya Bay can be fulfilled. To estimate them, they are varied in a two-dimensional space, and the simulated $\tau_0$ is shown in Fig. 7.

In general, the Tyvek reflectivity and water absorption length cannot be determined by one data point $\tau_0$. However, when studying PMT charge spectrum, their effects are correlated, because PMT charge is related to $\tau_0$ directly. For further PMT charge study, the Tyvek reflectivity is set to 0.99, and the water absorption length is set to $140 \pm 20$ m. It is possible that the two values have bias, but their combined effects to PMT charge would not be biased.

### 4.2. PMT spectrum study for vertical incidence muons

Using the vertically incident muons, the PMT charge is measured with an ADC that is triggered by the coincidence of two scintillation counters.

In the simulation, muons with small energy (less than 200 MeV) would stop in the water, but in measurements, muons passing through two scintillation counters should not stop in the water. So, when analyzing simulation data, muon track lengths are required to be larger than 1 m.

In accordance with the experimental data, the collection efficiency of the bottom PMT is adjusted to 0.69 in simulation, and the side PMT is 0.60. Then, simulation agrees with the experimental data well, as shown in Fig. 8.

### 4.3. PMT spectrum for muons from all incidence directions

In this measurement, muons from all directions of incidence are utilized, and the scintillation counters are not large enough to cover the entire water tank and provide a trigger. So to reduce noise in the measurement, the trigger is sent to the ADC only when signals from two PMTs coincide within 400 ns (Fig. 3).

The measured charge spectrum is shown in Fig. 9. To understand the spectrum, it is fitted with the sum of an exponential function for background, and a Gaussian pulse linear function for the signal. The exponential background mainly comes from the external environment, including electrons from $\gamma$ ($^{208}$Tl, etc.) scattering, charged particles from muons which do not pass through the water tank, etc. In the signal part, it is known that for a minimally ionizing muon, the number of Cherenkov photons is proportional to its track length, so the fitting indicates that there should be a linear part and a peak in muon track length distribution, and from fitting the ratio of these two components is about 4.5. Muon track lengths in simulation are shown in Fig. 10 and clearly a linear part with a peak appear in the spectrum. The ratio of linear part and peak is also about 4.5. The agreement indicates that the fitting function is reasonable, the background part is reasonable, and we understand the spectrum.

Using the surface muon generator, material properties from the above sections, PMT charge spectra are simulated and compared with the experimental data, as shown in Fig. 11. In the experimental data, the exponential backgrounds have been subtracted. Good agreement is shown between simulation and experiment and indicates that we understand the prototype's material properties and response.

## 5. Conclusions

A prototype water Cherenkov detector with a dimension of $2.1\ \text{m} \times 1.2\ \text{m} \times 1.3\ \text{m}$ for the Daya Bay experiment is constructed to study technical details, water circulation and purification, and cosmic-ray muons response. By the prototype, we understand the water circulation and purification, accumulate experience. PMT signals are studied and the water effective attenuation time is determined to be $140 \pm 5$ ns. In addition, PMT charges are recorded using an ADC. A detailed Monte Carlo simulation of the prototype detector shows an excellent agreement with the experimental data, demonstrating the prototype, including Tyvek reflectivity, water absorption length and PMT responses are understood; the optical propagation properties have fulfilled the requirements of Daya Bay. With the GEANT4 simulation program, we also have good knowledge about the Daya Bay water Cherenkov detector.

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