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# A Water Tank Prototype for the Cerenkov Calorimeter*

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**Abstract** The water tank prototype with a dimension of 1m × 1m × 13m was constructed as a building block of the Cerenkov calorimeter for very long baseline neutrino oscillation experiments. The effective attenuation length of the water tank was measured to be (5.74±0.29)m, and the light collection probability as a function of the incident angle of the particle is studied. Results are compared with a Monte Carlo simulation based on GEANT4 package which incorporates detailed optical processes. A good agreement is achieved and the water tank is feasible for the construction of the Cerenkov calorimeter.

**Key words** neutrino, oscillation, detector, calorimeter

## 1 Introduction

Water is one of the most economic materials for large scale neutrino detectors. Water Cerenkov ring image detectors have been successfully employed in large scale experiments such as Super-Kamiokande[1], MiniBooNE[2] and IMB[3], etc. However such kind of detectors are not suitable for neutrinos with an energy more than ~4GeV due to complications of showers, therefore they are not the choice for very long baseline neutrino oscillation experiments. Water Cerenkov calorimeter[4], made up by a matrix of water tanks, is similar in a sense to the crystal calorimeter in accelerator experiments. Cerenkov light produced in the water tank is sufficient to have a good energy resolution, and the event pattern of the energy deposit in the water tank matrix can be used to identify neutrinos undergoing charge current interactions[4]. It is a cheap solution for the long baseline neutrino oscillation experiments at a scale of 100—1000kt, and also applicable to cosmic-ray physics and astrophysics[4]. Reports about these kind of applications can also be found in Ref. [5].

In this paper we report results from a study of a full size prototype, compared with the results from a GEANT4[6]-based full Monte Carlo simulation.

## 2 Water tank construction

The radiation of Cerenkov light occurs when a charged particle moves through a dispersive medium faster than the group velocity of light in the same medium. Photons are emitted on the surface of a cone, opening at an increasingly acute angle with respect to the particle's momentum direction as the particle slows down. The number of Cerenkov photons generated by the primary particle, d$N$, is:

$$\mathrm{d}N \approx 370(1-1/(n^2\beta^2))\mathrm{d}p\mathrm{d}x, \qquad (1)$$

For $\beta = 1$, d$N \approx 300$ photons/cm in the wavelength window of $300\text{nm} < \lambda < 600\text{nm}$.

A water tank prototype made of PVC with the dimension of 1m × 1m × 13m is built as shown in Fig. 1. The inner wall of the tank is covered by the Tyevk film 1070D from DuPont. At each end of the tank there is a Winston Cone[7] which can collect parallel

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light at its focal point, where an 8-inch photomultiplier is installed. The Winston cone is again made of PVC, covered by the aluminium film with protective coating. Cerenkov light produced by through-going charged particles are reflected by the Tyvek and Al film and collected by photomultipliers at the focus of the Winston cone. At the top of the tank there is an air gap (about 1cm) above the water level which serves as a total reflector for photons with certain incident angles.

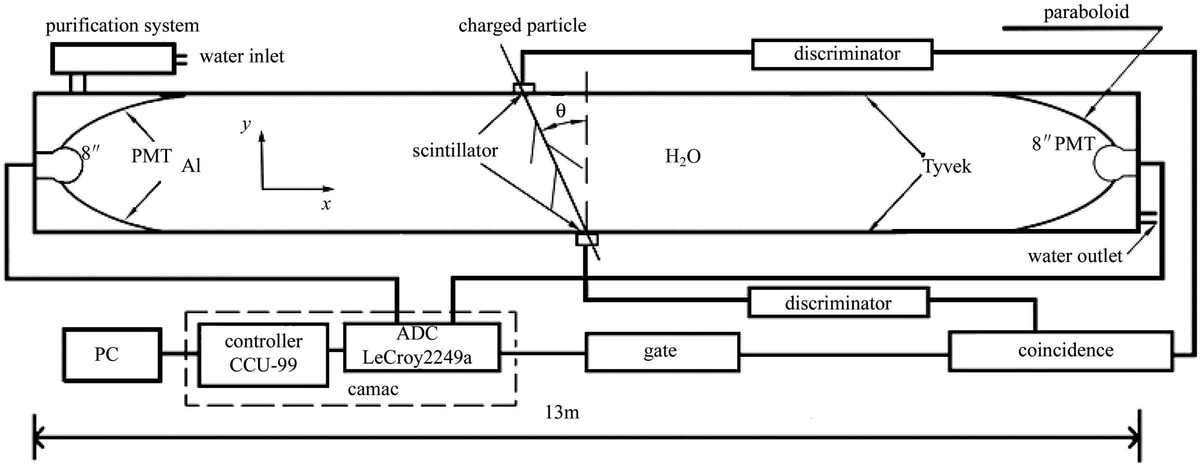

Fig. 1. Schematics of a water tank of the Cerenkov calorimeter.
The middle point of the tank is set as the origin of the coordinate system.

Tyevk is a diffuse reflector with a very high reflectivity which is measured in the frequency range of visible light as shown in Fig. 2. Although it is naively believed that mirror reflector such as Al film has a better light collection for such a long optical module, our simulation shows that their performances are actually very similar[8]. The dominant factor is the bulk reflectivity. The good mechanical and chemical properties of Tyvek lead us to use it in order to have an easy handling and less aging effect in the deionized water. Tyvek as a reflector in water has been used by many experiments, including Super-Kamiokande, KamLAND, and Auger experiment[9].

Since the Winston cone needs a mirror reflection to collect light, a selected Al film is used. Al film has a very high reflectivity (98%) in theory, but it is easy to be oxidized in water and lose its reflectivity. A protective coating is hence needed and the reflectivity is measured to be typically 90%, as shown in Fig. 2.

In order to have a good water transparency, clean de-ionized water with a resistance of more than 10MΩ is used. The water is again purified by a simple system with a 0.1μm filter, which can increase the transparency by a factor of two. The water absorption length as a function of wavelength used in Monte Carlo simulation is obtained by scaling down the curve from the Auger experiment[10] based on our experimental data, as shown in Fig. 2. The phototube used is 9350KB from EMI, and its quantum efficiency[11] is shown in Fig. 2.

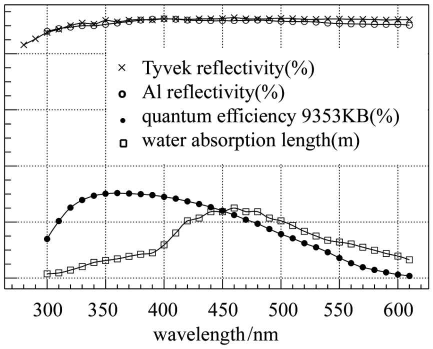

Fig. 2. The water absorption length by adjusting that from Auger experiment, the quantum efficiency of the PMT 9350KB from EMI, and the measured reflectivity of Tyvek and Al as a function of wavelength.

Cosmic-muons, triggered by two scintillator counters at the top and the bottom of the tank, are the primary charged particles which generate Cerenkov photons. The muon flux at the sea level is about $1.8\times10^{-2}/(\mathrm{cm}^2\cdot\mathrm{s})$, and the area of scintillation counters is 20cm×44cm, hence it takes typically 10 hours to accommodate one spectrum. Such a small trigger counter is selected to control the error due to the incident position, angle and the pass length of muons. A displacement of one of the two trigger counters in $x$ direction(see Fig. 1) can define the incident angle of the muons. In addition, between two runs a calibration run with the trigger counters at $x=0.5$m was taken to monitor the water quality.

The setup also includes a C205 ADC from CAEN to measure the charge of muon and the single photoelectron for calibration, a N844 discriminator from CAEN to generate trigger signals and the gate signal for ADC.

GEANT4 is a C++ toolkit providing the machinery necessary to define the detector geometry and material properties and to simulate particle transport and interactions in the detector materials. Most relevant physics processes have been incorporated, including ionization, delta ray production, multiple Coulomb scattering, bremsstrahlung, and Cerenkov radiation for charged particles. Optical photons produced by processes such as Cerenkov radiation(including Cerenkov radiation from delta rays) may then subject to Rayleigh scattering, absorption, and optical boundary interactions. The reflection and transmission of light at a rough surface is modelled in GEANT4 using a flexible optical model, unified model, to accommodate the main features of both physical and geometrical optical models of surface reflection over a wide range of surface roughness and wavelengths[12]. It allows adjustment of parameters to control the relative contributions of specular reflections from both the average surface normal and the normal of a micro facet at the surface, diffuse(Lambertian) reflection, possible backscattering, and overall surface reflectivity[13].

A GEANT4-based simulation program of the water tank is developed, and proper optical models and parameters of optical surfaces are selected and tested. Since the construction of the water tank is similar in many ways to that of the Auger detector[10], some of the parameter values in our simulation program are very similar[14]. Optical models and their parameters have been discussed in Ref. [8].

## 3　Results and discussions

### 3.1　PMT's single-photoelectron spectrum

Single photoelectron spectrum(SPE) is measured before each run in order to calibrate the system since signal amplitudes normalized to that of SPE provide a unique measure of light collected by photomultipliers. SPE can be measured in many ways, one of which is the so-called "thermal noise" method. In total darkness, a photomultiplier can still generate pulses due to thermal emission of single electron by photocathode, equivalent to the charge spectrum of single photoelectron. Thermal emission of electrons by dynodes constitutes the noise below the SPE peak. A SPE spectrum of the PMT 9350KB, applying a high voltage of 1550V at the room temperature(about 15℃), is measured as shown in Fig. 3. Since the ADC used is only 12 bit, the working voltage(1550V) of the PMT is selected to avoid saturation of ADC for cosmic-muons at all positions along the water tank. The SPE spectrum is obtained by a self-trigger with a threshold of 2mV and a gate width of 100ns. The first peak corresponds to the pedestal, the second peak comes from the dynode noise above the 2mV threshold, and the last peak is from SPE, whose position will be used as the normalization to count number of photons. It is clear from the figure that the PMT has a good peak-to-valley ratio of about 1.5 and its noise is small enough.

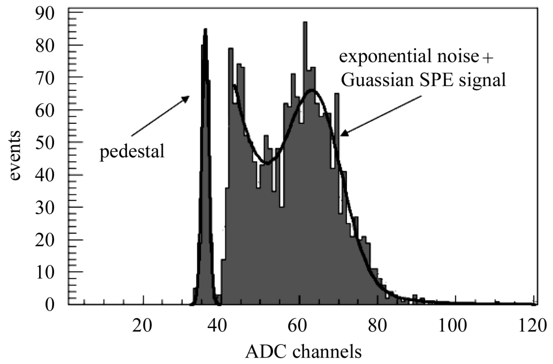

Fig. 3.　Single-photon spectrum of the PMT 9350KB at a high voltage of 1550V.

### 3.2 Position dependent response of the water tank

Light collected for cosmic-muons is a function of distance from the incident point of the muon to the phototube, since the water transparency and reflectivity of the Tyvek film is not perfect. Such a position dependent response of the tank is critical to its energy resolution and pattern recognition capability. Typically it is characterized by an exponential behavior of $\mathrm{e}^{-x/\lambda}$, where $x$ is the distance of the muon event to the phototube and $\lambda$ is the characteristic parameter, often called "effective attenuation length".

The characteristic parameter $\lambda$ depends on the water transparency, the reflectivity of the Tyvek film, and the geometry of the tank. Fig. 4 shows the charge spectrum collected at $x=0.5$m with an incident angle of 0°. Using the trigger scintillation counters to define the muon incident location, keeping the $y$ coordinate constant as indicated in Fig. 1, the total light collected as a function of $x$ at several locations is obtained as shown in Fig. 5. An exponential fit yields the measured effective attenuation length of the water tank of (5.74±0.29)m. The line represents the Monte Carlo prediction by adjusting the scale of the water absorption length as shown in Fig. 2, until the effective attenuation length is in agreement with that of the measurement. As what is discussed later, this tuning is justified by the agreement between data and Monte Carlo prediction for both the effective attenuation length and the angular dependent response.

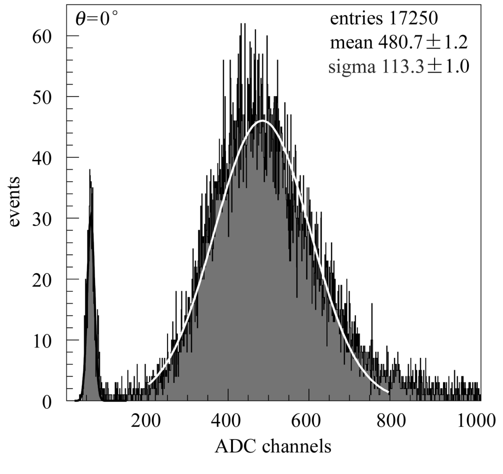

Fig. 4. Charge spectrum collected at $x=0.5$m with an incident angle of 0°.

It can be seen from Fig. 5 that, for a through-going muons entering the center of the tank, a total of ~20 photoelectrons by each PMT will be collected, corresponding to a statistical fluctuation of about $7\%/\sqrt{E}$. Based on the Monte Carlo simulation, the number of photons at various stages of the photon transport in the water tank is listed in Table 1. From the table, it can be seen that about 74% of light is lost due to the Tyvek reflection and water absorption. The Winston cone has a collection efficiency of 3.1%, the same as the ratio of PMT surface area to that of the water tank cross section. It means that the Winston cone did not improve the light collection efficiency, but the uniformity of the light collection.

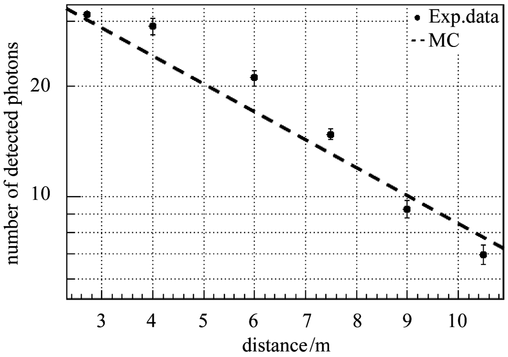

Fig. 5. Position dependent response of the water tank to cosmic-muons. $x$ is the distance from trigger counters to the PMT at right. The line represents the Monte Carlo prediction with an effective attenuation length of 5.79m. The measured effective attenuation length of the water tank is (5.74±0.29)m.

Table 1. Number of photons at various stages of the photon transport in the water tank from Monte Carlo simulation.

| | |
|---|---|
| No. of Cerenkov photons produced | 35156.9±178.7 |
| No. of photons entering Winston cones | 9274.4±76.2 |
| No. of photons hitting the glass surface of two PMTs | 288.1±18.3 |
| No. of photoelectrons collected by two PMTs | 41.5±2.8 |

There are several ways to improve the light collection of the water tank: (a) The water absorption length can be improved with a more sophisticated purification system. In fact the Super-Kamiokande experiment reached an absorption length of about 90m[15], a factor of 3 better than what was reached here; (b) The reflectivity of the inner liner can be improved by using the newly-developed plastic reflectors, VM2000 or ESR from 3M Co.[16]. They have a reflectivity better than 99%, which can increase the total light collected by more than 50%. In a word, it is possible to increase the light collection by a factor of two, corresponding to a statistical fluctuation of about $5\%/\sqrt{E}$ for each tank.

### 3.3 Angular dependent response of the water tank

Since Cerenkov light produced is not isotropic, and its direction is correlated to that of the incident charged particles, the total light collected by phototubes at each end of the water tank is also correlated to the incident angle of the particles. By using trigger counters to define the incident angle as shown in Fig. 1, response of the water tank to through-going charged muons with incident angles varying from 0° to 50° are measured. The bottom trigger scintillator is fixed at $x=0.5$m, and the top trigger scintillator is moved along the $-x$ direction. After normalizing the track length to 1m, results are shown in Fig. 6(a) together with the predictions from the Monte Carlo simulation. Since the only free parameter to be tuned in the Monte Carlo prediction is the overall scaling of the water absorption length as discussed before, the good agreement between data and Monte Carlo simulation for both the effective attenuation length and the angular dependent response shows that the optical behavior of the water tank is largely understood.

As can be seen from Fig. 6(a), the number of photoelectrons is approximately constant for incident angles less than 30°. This is confirmed by the Monte Carlo simulation, and true at almost all locations of the tank, as shown in Fig. 6(b). This is significant since during the event reconstruction, this factor can be ignored and the energy resolution of neutrino event can be maintained at a reasonably good level. It should be mentioned that the experimental data of the right PMT is only used in the above analysis because the surface of the left PMT was covered by some Tyvek accidently. After the completion of the measurement of effective attenuation length of water, the quality of water had worsened and the calibration runs were taken before each measurement. The data points of Fig. 6(a) is corrected by using calibration runs.

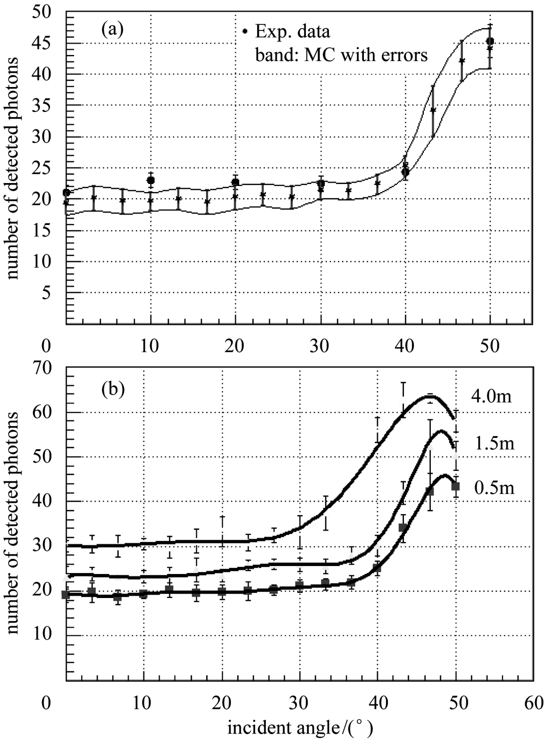

Fig. 6. (a) The measured angular dependent response of the water tank together with the Monte Carlo prediction. The band indicates the statistical error of the Monte Carlo prediction. The track length of all the data points are normalized to 1 meter; (b) The Monte Carlo results of the angular response as a function of distance from the incident point to the phototube.

## 4 Summary

Water Cerenkov calorimeter is a good candidate for very long baseline neutrino oscillation experiments. A full size water tank prototype, with a dimension of 1m×1m×13m, made of PVC with reflective inner liner was built. The effective attenuation length and the angular response of the tank was measured, and good agreement with a GEANT4-based full Monte Carlo simulation was obtained. The light yield, the total light collection efficiency, the effective attenuation length and the angular dependent response of the tank are all good enough for the long baseline neutrino oscillation experiment, and they can be further improved.

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# 水基切伦科夫量能器模型的研究*

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**摘要** 为了研究极长基线中微子振荡, 构造了一个大小为1m×1m×13m水基切伦科夫量能器模型. 测量得到的水箱的有效衰减长度为(5.74±0.29)m, 并且研究了光的收集能力随入射粒子角度变化的关系. 同时发展了基于GEANT4软件包, 包含有详细的光学过程的模拟程序, 所得到的模拟结果与实验测量有很好的一致性. 说明水箱可以作为水基切伦科夫量能器的可行性的方案.

**关键词** 中微子 振荡 探测器 量能器

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