Study of Tyvek reflectivity in water*

WANG Ling-Yu(王玲玉)[1,2;1)] LU Hao-Qi(路浩奇)[1] YANG Chang-Gen(杨长根)[1]
YU Ze-Yuan(于泽源)[1,2] XU Ji-Lei(徐吉磊)[1] LIU Jin-Chang(刘金昌)[1]
GUAN Meng-Yun(关梦云)[1] WANG Zhi-Min(王志民)[1] WANG Yi-Fang(王贻芳)[1]

[1] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: Tyvek is widely used as the inner lining material of water Cherenkov detectors. Therefore, information about its optical properties plays an important role in the simulation and reconstruction of particles passing through water Cherenkov detectors. In this paper, a water tank experiment is performed to study the Tyvek reflectivity in water. The so-called UNIFIED model, which is an optical model of surface reflection in Geant4, is adopted to describe the Tyvek reflectivity. Two key optical parameters are obtained from a comparison between the measured data and a Monte Carlo simulation.

Key words: water Cherenkov detector, Tyvek, surface reflection, UNIFIED model

PACS: 29.40.Cs **DOI:** 10.1088/1674-1137/36/7/011

1 Introduction

Tyvek is a paper-like material made with continuous, randomly distributed and nondirectional fibers of high-density polyethylene. Because of its high reflective properties, Tyvek is widely used as light reflector in water Cherenkov detectors, such as those in the Super-Kamiokande experiment [1], and the Pierre Auger experiment [2]. In the Daya Bay reactor neutrino experiment [3], Tyvek is deployed to divide the water Cherenkov detector in the veto system into inner and outer regions. The Daya Bay experiment is a low background experiment, which requires a very high muon veto efficiency (99.5%) to reduce the neutron background from cosmic-ray muons. In order to detect the muon efficiently, Tyvek is applied to improve the Cherenkov light collection. On the other hand, the Cherenkov light propagation is also useful for the muon track reconstruction. Thus it is very important to understand the optical properties of Tyvek well.

Because of its high opacity, Tyvek is usually regarded as a diffuse reflection material. In fact, it has both diffuse and specular reflection. In particular, the specular reflection ratio in water is larger than that in air. This has been studied in many measurements [4–6], which directly measure the intensity distribution of the reflected light by Tyvek in the plane of the incident light. However, the equipment is somewhat expensive and of a complicated design. Because the measurements are obtained underwater, all the processes need to be carefully operated to control the relative measurement uncertainty, and it is not easy to get the Tyvek reflectivity parameters. From these measurements, it can be concluded that different types of Tyvek have different surface reflections. In the water tank measurement [7], a type 1082D Tyvek is selected because it is thicker and less transparent than many other types. To enhance the mechanical strength, a complex film is made by combining two layers of 1082D Tyvek and a layer of white PE (100 μm) in the middle. A test is designed to measure the involved optical properties of this complex film, which are useful for the detector simulation and particle track reconstruction.

In Sec. 2, we present a surface reflection model which describes the photon behavior at the optical surface. The details of the water tank experiment

Received 30 September 2011, Revised 28 October 2011
* Supported by Ministry of Science and Technology of the People's Republic of China (2006CB808102)
1) E-mail: wangly@ihep.ac.cn

setup are introduced in Sec. 3. The experimental results are given in Sec. 4. Finally, the experimental conclusion is summarized.

2 Surface reflection model–UNIFIED model

To describe the reflection and transmission of light at a rough surface, Geant4 provides a fairly flexible optical model inspired by the work of Nayer et al. [8]. This UNIFIED model is applicable over a wide range of surface roughness and wavelengths. It allows the adjustment of parameters to control the relative contributions from the following components: specular reflection, diffuse (Lambertian) reflection, possible backscattering, and the total surface reflectivity. By using five parameters, the reflected intensity I is given as the following function:

$$I = R(\theta_{\rm i},n)[C_{\rm sl}g(\alpha_{\rm r};0,\sigma_\alpha)+C_{\rm ss}\delta(\theta_{\rm i}-\theta_{\rm r})\delta(\phi_{\rm r}) +C_{\rm bs}\delta(\theta_{\rm i}+\theta_{\rm r})\delta(\phi_{\rm r})+C_{\rm dl}\cos(\theta_{\rm r})] \quad (1)$$

with

$$C_{\rm sl}+C_{\rm ss}+C_{\rm bs}+C_{\rm dl}=1, \quad (2)$$

where $\theta_{\rm i}$ is the incident angle, $\theta_{\rm r}$ is the angle of reflection with respect to the average normal, and $\phi_{\rm r}$ is the angle between the projection of the reflected photon onto the average surface and the plane of incidence. The parameter $\alpha_{\rm r}$, which is the angle between the average surface normal and the microfacet normal, is assumed to follow a Gaussian distribution with standard deviation of σ_α, and σ_α characterizes the surface roughness. R is the total reflectivity of the surface, $C_{\rm sl}$ is the specular lobe constant; $C_{\rm ss}$ is the specular spike constant; $C_{\rm bs}$ is the backscatter spike constant; $C_{\rm dl}$ is the diffuse lobe constant, and its reflection intensity obeys the Lamberts' law [9]. Fig. 1(a) shows the polar angular distribution of the incident light on the rough surface and reflected by the rough surface, with the contribution from various sources identified. The coordinate system used in the model and the geometrical parameters in the Eq. (1) are drawn in Fig. 1(b).

According to the physical characteristics of Tyvek, the probability of the processes of specular spike and backscatter spike occurring is very small, thus $C_{\rm bs}$ and $C_{\rm ss}$ are usually set to zero, leaving, besides R, only $C_{\rm sl}$ and σ_α as the optical parameters. There are several measurements of the dependence of Tyvek reflectivity on the reflection angle [4–6]. A careful tuning of $C_{\rm sl}$ and σ_α in the UNIFIED model is tried to approximate the data found in Ref. [4]. The results show that $C_{\rm sl}$ varies from 0.51 to 0.78 with different incidence angles in water, while σ_α in radian is between 0.17 and 0.26. In the Pierre Auger experiment, the early study shows that $C_{\rm sl}$ is 0.2 and σ_α in radian is 0.2 [5, 10]. From their recent measured data of type 1056D Tyvek [6], the tuning results indicate that $C_{\rm sl}$ is about 3 to 4 times $C_{\rm dl}$ and σ_α is about 0.1.

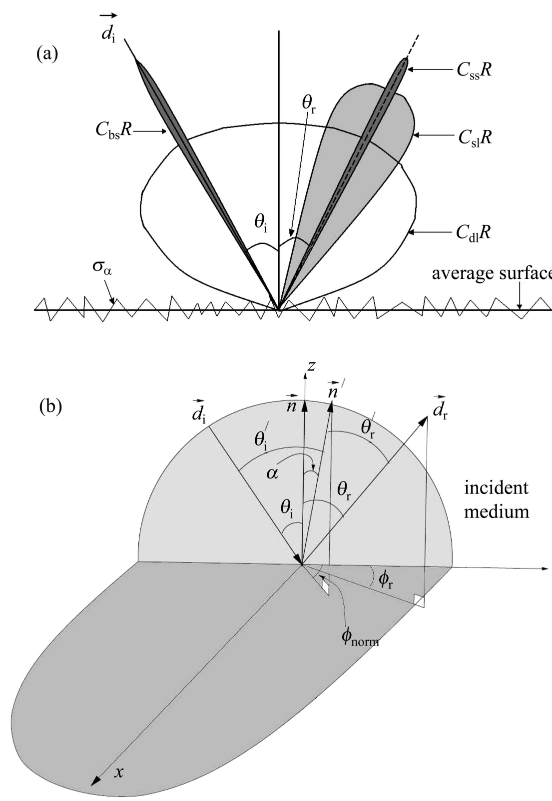

Fig. 1. (a) Polar plot qualitatively illustrating the components of radiant intensity in the UNIFIED model. The direction vector of the incident photon is given by $\vec{d}_{\rm i}$; (b) The coordinate system used in the surface model along with the definition of geometrical parameters.

3 Experimental setup and measurement

A water tank with dimensions 2.8 m×1.2 m×1.3 m has been built [7]. In the tank, two 8 inch EMI 9350KA photomultiplier tubs (PMT) are mounted for light collection, one is placed at the bottom and the other one on the side wall (Fig. 2(a)). For this experiment, only the bottom PMT is used, while the side one is used for another purpose. The Tyvek reflector is supported by a stainless steel frame (Fig. 2(b)), and it divides the tank into inner and outer parts. Two holes are cut on the Tyvek surface in order to protrude the PMT sensitive arc into the inner tank. The tank is filled with 4 tons of highly purified water. To keep high water transparency, a circulation and purification system has been constructed [7] (Fig. 2(a)). Water circulates independently in the inner and outer parts.

A violet (405 nm) laser diode (LDH-P-C-405) driven by the laser driver (PDL 800-B) is used as the light source in this measurement. It can emit light pulses as short as 70 ps FWHM at repetition rates from a single shot up to 80 MHz. In this measurement, the repetition frequency is set at 2.5 MHz. A laser focus system (Fig. 3) is designed to get a parallel laser beam. In this system, the compass is used to fix the laser focus system on the water tank and control the azimuth angle of the laser beam. The reflection mirror can change the zenith angle of the laser beam. This laser focus system is installed at the center of the top surface of the water tank (Fig. 4).

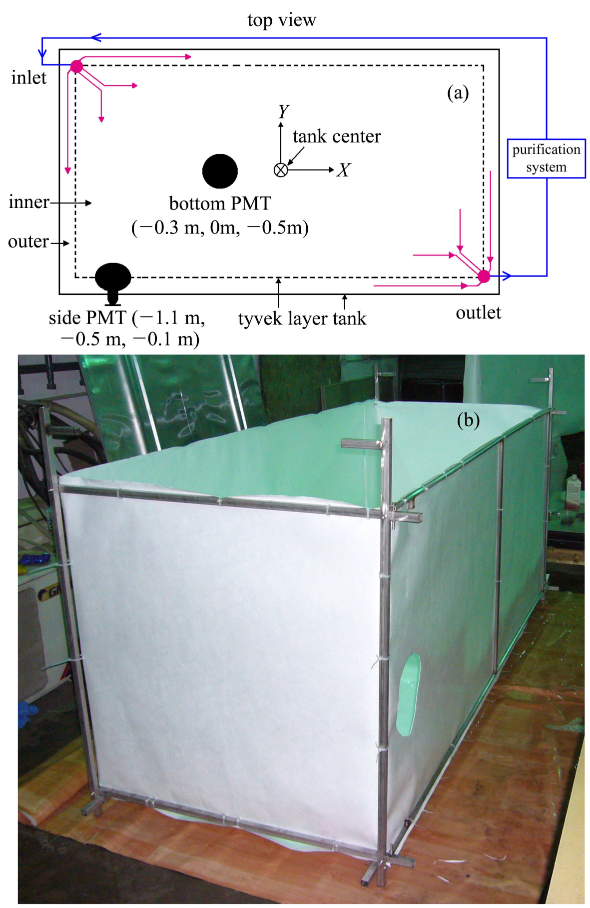

Fig. 2. (a) Circulation diagram; (b) Tyvek reflector on a stainless steel frame.

The emerging laser beam perpendicularly shoots onto the bottom Tyvek reflector, subsequently most of the photons are reflected between the top and bottom surface of the water tank. Each time they are reflected on the bottom Tyvek reflector, photons from the specular lobe component travel more or less $2H$ (H is the distance between the top and bottom Tyvek (Fig. 4)), the corresponding time-of-flight will increase by T_0 ($T_0=\dfrac{2H}{V_c}$, where V_c is the velocity of light in water). Thus the time interval of an adjacent pair of photons with a different number of multiple reflections is a multiple of T_0. The bottom PMT is a natural choice to record this time interval. This phenomenon is helpful for studying specular reflection characteristics.

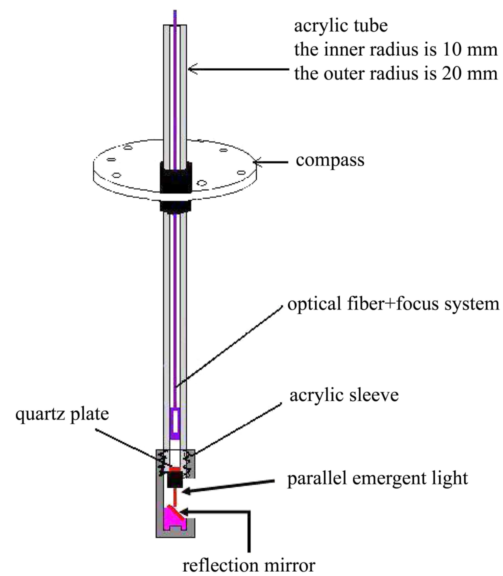

Fig. 3. The laser focus system.

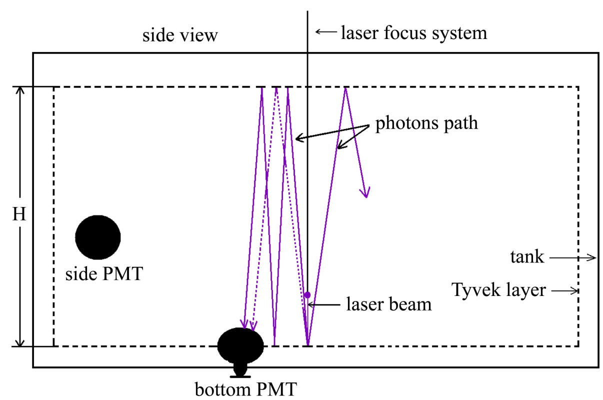

Fig. 4. The layout of the water tank from a side view. The reflected photons are received by the bottom PMT or are absorbed by water after multiple reflections.

For Tyvek material, if the specular reflection component is dominant, σ_α is small. The Monte Carlo simulation results based on the real Tyvek volume show that the time interval between adjacent reflected photons is T_0. When the number of incident photons is small, $2T_0$, $3T_0\cdots$ will appear (Fig. 5). When

C_{sl} is not big enough and σ_α is not small, under the same circumstances, the simulation results show that there is no time structure (Fig. 5). Therefore, the time interval between the adjacent reflected photons is sensitive to C_{sl} and σ_α.

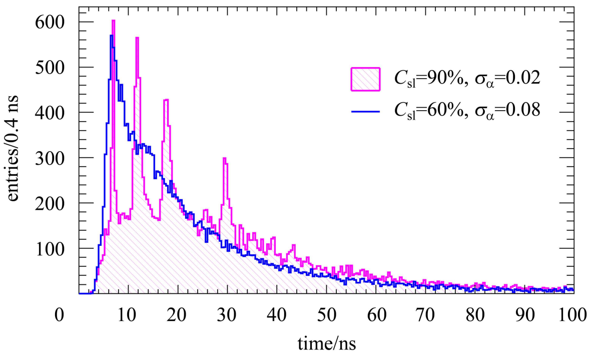

Fig. 5. The peak time interval distributions in the MC simulation.

The measurement is designed as Fig. 4 shows. When the laser flashes, a synchronous signal from the laser driver is also sent out to the digital oscilloscope (Lecroy WaveRunner 104Xi-A) and is used as the external trigger. Once there is a trigger signal, the oscilloscope records the PMTs' pulse shape in a 500 ns time window with a sample rate of 5 Gs/s.

4 Experimental results

Previous measurements demonstrate that the total reflectivity of the selected Tyvek is about 98% in water and the water attenuation length is above 20 m with two volume circulation [7]. This water transparency can ensure that photons with multiple reflections can be detected. Fig. 6 shows a typical waveform from the bottom PMT when the laser flashes once. Only the relative time between the peaks is meaningful, because the delay of the signal during their propagation in the cable has not been subtracted. The reflection peaks corresponding to the photons of different path lengths are clearly shown in the waveform. A peak finding program is developed to locate the peak time in each waveform and calculate the time intervals between adjacent peaks.

7.5 K independent waveforms from the bottom PMT are taken. All the values of the adjacent peak time interval are filled into a histogram. As shown in Fig. 7, there are three peaks at 7 ns, 13 ns and 19 ns respectively. These values can be explained by the geometry of the Tyvek reflector. The designed height of the Tyvek reflector is 1 meter. However, due to the two volume circulation, the water pressure in the inner and outer sections is different, and this difference results in shape deformations of the Tyvek reflector. Meanwhile, due to Tyvek buoyancy in water, the bottom Tyvek reflector rises by 10 cm. Constrained by the top stainless steel structure, the top Tyvek reflector can not float, moreover, it sags by 10 cm under the weight of the top stainless steel structure. With consideration of all these effects, the measured values agree well with the calculated values using the real Tyvek reflector geometry.

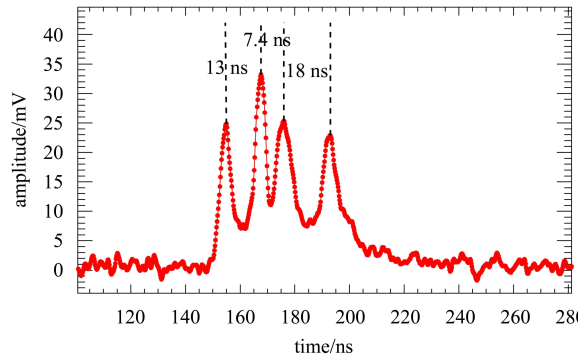

Fig. 6. A typical waveform from the bottom PMT when the laser flashes once.

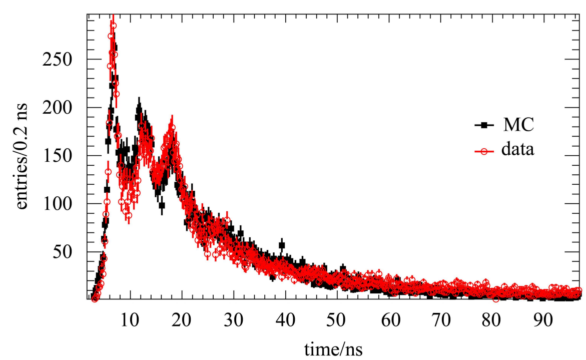

Fig. 7. Comparison between the measured data and the MC simulation on the peak time interval distribution. In the MC simulation, we set C_{sl}=85% and σ_α=0.06.

A Geant4 based Monte Carlo simulation program is developed and applied to simulate this water tank. For C_{sl} and σ_α, rough tuning results (Fig. 5(b)) show that small σ_α and large C_{sl} can make more and clearer peaks. Conversely, large σ_α and small C_{sl} can make less peaks or even no peak at all. These preliminary results reveal $0.6< C_{sl} <0.9$ and $0.02< \sigma_\alpha <0.08$. Detailed MC simulations tuning with different values of C_{sl} and σ_α in this range are carried out to search the proper values of the tested Tyvek.

In order to describe the agreement between the MC simulation and the measured data quantitatively, a χ^2 statistic is defined as [11]:

$$\chi^2=\sum_i \frac{\left(\sqrt{S/R}\cdot N_{\mathrm{R}}-\sqrt{R/S}\cdot N_{\mathrm{S}}\right)^2}{N_{\mathrm{R}}+N_{\mathrm{S}}}, \qquad (3)$$

where

$$S\equiv\sum_i N_{\mathrm{S}} \qquad R\equiv\sum_i N_{\mathrm{R}} \qquad (4)$$

are the respective numbers of total bin counts. $N_{\mathrm{S}}(N_{\mathrm{R}})$ is the MC (data) count in each bin of the peak time interval histogram.

Table 1 gives the reduced χ^2 values at different C_{sl} with σ_α=0.06 and Table 2 gives the reduced χ^2 values at different σ_α with C_{sl}=85%, respectively. The minimum reduced χ^2 value indicates the best agreement between the measured data and the MC simulation (Fig. 7). The best optical parameters are determined, i.e. C_{sl}=85% and σ_α=0.06 in radian.

Table 1. The reduced χ^2 values at different C_{sl} as σ_α=0.06.

C_{sl}	χ^2/ndf
60	2.19
65	2.22
70	2.04
75	1.81
80	1.77
85	1.64
90	1.79

Table 2. The reduced χ^2 values at different σ_α as C_{sl}=85%.

σ_α	χ^2/ndf
0.045	1.89
0.05	1.75
0.055	1.72
0.06	1.64
0.065	1.81
0.07	1.87
0.075	1.88
0.08	2.00

5 Conclusions

A new method for measuring the optical parameters of Tyvek is proposed. This method is indirect, however, it is flexible and easy to operate. The reflectivity of a complex film in water is studied in this paper. Its main constituent is 1082D Tyvek. The so-called UNIFIED model in Geant4 is applied to describe the surface reflection of this complex film. Only one case of the incident light being perpendicular to the Tyvek surface is studied in this experiment. Two key optical parameters of the UNIFIED model are determined by a comparison between the MC simulation and the measured data. They are useful to simulate the behavior of light in water Cherenkov detectors and are also useful to help understand the detector performance.

We gratefully acknowledge Prof. Jun Cao, Dr. Liangjian Wen and Zhicheng Tang for their help and discussions. Thanks also go to Ling Han for her help.

References

1 The Super-Kamiokande collaboration. Nucl. Instrum. Methods A, 2003, **501**: 418

2 The Pierre Auger collaboration. Nucl. Instrum. Methods A, 2008, **586**: 409

3 Daya Bay collaboration. arXiv: hep-ex/0701029, 2007

4 Chavarria Alvaro. A Study on the Reflective Properties of Tyvek in Air and Underwater (Senior Thesis). USA: the Department of Physics of Trinity College, Duke University, 2007

5 Filevich A et al. Nucl. Instrum. Methods A, 1999, **423**: 108

6 Arteaga-Velázquez J C et al. Nucl. Instrum. Methods A, 2005, **553**: 312

7 LU Hao-Qi. Study of Water Cherenkov and Prototype Detector of Daya Bay Experiment (Ph.D.Thesis) Beijing: Institute of High Energy Physics, CAS, 2009 (in Chinese)

8 Levin A, Moisan C. TRIUMF Internal Note TRI-PP-96-64.1996

9 Born, Max, Wolf, Emil. Principles of Optics, 5th edition. Printed in Great Britain at PAGE BROS(NORWICH) LTD: Pergamon Press Inc., 1975. 182–183

10 Tom McCauley, Tom Paul. GAP-2000-055

11 Press W H et al. Numerical Recipes. Third Edition. New York: Cambridge Univ. Press, 2007. 731–734