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The research on the measurement of water quality based on reflection cavity

Yiyue Tang,[a,*] **Xinxin Chen,**[a] **Juntao Zhang,**[a] **Qinghong Zhang,**[a] **Xiurong Li,**[b] **Fengrong Zhu**[a] **and Long Chen**[a,*]

[a] *School of Physical Science and Technology, Southwest Jiaotong University Chengdu, 611756, Sichuan Province, China*

[b] *Key Laboratory of Particle Astrophyics Experimental Physics Division Computing Center, Institute of High Energy Physics, Chinese Academy of Sciences, 100049 Beijing, China*

E-mail: longchen@swjtu.edu.cn

The passage of high-energy particles through water, air, and some other similar media produces Cherenkov light. Cherenkov detectors are widely used for detecting primary high-energy cosmic rays or gamma rays. The quality of the media is important for the experiments because the contaminants can absorb the light and reduce the precision of the reconstruction of the extensive air showers. Here we developed a method, similar to the integrating ring-down spectroscopy for evaluating the water quality. This method induced the laser as light source, the bucket with high reflective diffused material in the inner wall to reflect the light, photomultiplier tube (PMT) to record the waveform of light signal. We choose copper sulfate solution to find the relationship between solution concentration, the attenuation length of water, and the reflectivity of inner-wall material. The results proved the feasibility of the reflection cavity. This method can also be applied on the monitor of atmosphere, water pollution and cave safety, etc.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

https://pos.sissa.it/

PoS(ICRC2023)492

1. Introduction

LHAASO is a ground-based detector array built on Haizi Mountain in Daocheng County, Sichuan Province, China[1]. It is mainly composed of three parts: the square kilometer array (KM2A), the Water Cherenkov Detector Array (WCDA) and the Wide-Field-of-view Cherenkov Telescope Array (WFCTA)[2]. Water Cherenkov Detectors have been used in many experiments, such as the Daya Bay reactor[3], the Pierre Auger [4] , and subsequent Baikal-GVD[5].

Measuring absorption of water is important for the Water Cherenkov Detector, because water absorption can directly affects the detection. The attenuation length of water is affected by absorption and scatter. Usually, the attenuation length is obtained by using a long tube to measure the light intensity of photons passing through water at different distances[6], then the absorption length is got by subtraction the affect the scatter. The reflection cavity can be used to measure absorption length without the influence of scatter, by measuring the effective attenuation length of photon in the detector. In order to know whether the absorption length is accurate, a solution measurement method is proposed based on reflection cavity[7] to monitor the cleanliness of water, and the relationship among the solution concentration, effective attenuation length, and the reflectivity. The experimental results show that the error of effective attenuation length is less than 5%. This method can also be extended to air, water pollution, environmental safety, resource exploration and so on.

2. Principle and apparatus

2.1 Principle

When the photon propagates in the barrel, part of it is absorbed or scattered by water, and part of it is absorbed or reflected by the reflecting material. After dozens of reflections, the probability of the photon hitting the reflecting material is consistent with the probability of hitting the PMT to generate the signal, which can be expressed by the following formula:

$$N = N_0 e^{-\frac{x}{\lambda}} (f \times r)^{\frac{x}{L}} \tag{1}$$

Where N_0 is the number of incident photons, N is the number of outgoing photons, f is the reflectance of the material, r is the proportion of reflective material to the inner wall, L is the average step length, λ is the absorption length of water, and x is the propagation distance of the photon[7].

When the number of photons is large enough, after dozens of reflections, the average step length of each time will become stable, and the average step length value can be calculated by $\frac{4V}{S}$. $N_0 \times f \times r$ is the number of photons left in the bucket after the first reflection, and the number of reflections of photons in the bucket is $\frac{x}{L}$, so the number of surviving photons after several reflections of the reflecting material is $N_0(f \times r)^{\frac{x}{L}}$.We know that the attenuation of light follows $I = I_0 e^{-\alpha x}$, where the attenuation coefficient is called α, the reciprocal relationship with the attenuation length, and when the medium is a uniform medium, the light does not scatter, and α includes only the absorption part, that is, the reciprocal of the absorption length[8]. So add the attenuation of light itself in the medium, and you get Eq.1. The number of photons is proportional to the light intensity, and we call the total absorption length generated by the device the effective absorption length (λ_y), then the following formula can be obtained:

$$I_0 e^{-\frac{x}{\lambda_y}} = I_0 e^{-\frac{x}{\lambda}} (f \times r)^{\frac{x}{L}} \tag{2}$$

Our existing device r tends to 1, so we can get the relationship between the effective absorption length, the absorption length of water, the reflectivity of the material, and the average step length[7, 9]:

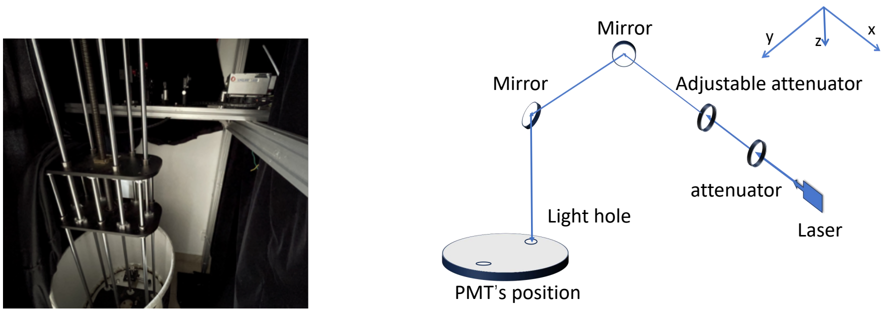
$$\lambda_y = \frac{1}{\frac{1}{\lambda} - \frac{lnf}{L}} \tag{3}$$

Through the acquisition and processing of oscilloscope, the effective attenuation time can be obtained by fitting $I_0 e^{-\frac{t}{\tau}}$, and the effective absorption length λ_y can be obtained by multiplying the propagation speed of the photon in the medium by the effective attenuation time. By changing the average step size, the absorption length of the medium and the reflectivity of the material can be obtained.

2.2 Experimental apparatus

As shown in Figure 1(a), the measuring device consists of a laser of 532 nm wavelength with a pulse width of 7 ns, a PMT, a bucket, and a lifting platform. The diameter of the bucket is 50 cm, and we use the lid to change the volume of the bucket to change the average step size. We designed five grooves on the cover of the lifting platform, one to place the PMT, and the other four holes can be used as input holes for the light source. As shown in Figure 1(b), the laser is attenuated by the attenuator and is introduced into the hole through the mirror.

In order to avoid light leakage and the photon directly hitting the PMT without attenuation, we set up black cloth around the shelf, and separate the light inlet hole from the PMT with black cloth.



(a) (b)

Figure 1: Experimental apparatus and optical path diagram.

3. Solution verification

3.1 Principle of solution method

In the reflection cavity, the effective absorption length of the measured water is λ_y. In order to know whether this data is accurate, we design a method using the solution to verify it. As shown in Figure 2, after adding a solution with a sufficiently small volume relative to the original volume, the attenuation of light, in addition to the absorption of photons by water, the optical path that disappears after reflection in the figure, and the absorption and reflection of the reflecting material, is also composed of the added small part of the solution:

$$\frac{I}{I_0} = e^{-\frac{x_y}{\lambda_y}} e^{-\frac{x_v}{\lambda_v}} \equiv e^{-\frac{x_y + x_v}{\lambda_q}} \tag{4}$$

Where λ_y is the effective absorption length of the water to be measured, λ_v is the absorption length of the added concentrated solution, and λ_q is the total effective absorption length after adding the concentrated solution.

Here, we choose a copper sulfate solution with a certain concentration of c_1 as the drop solution, and the relationship between the concentration and the optical path can be obtained.

$$c = \frac{n}{V} = \frac{c_1 V_1}{V_v + V_y} = c_1 \frac{x_v}{x_y + x_v} = c_1 \frac{\frac{x_v}{x_y}}{1 + \frac{x_v}{x_y}} \tag{5}$$

$$\frac{1 + \frac{c}{c_1 - c}}{\lambda_q} = \frac{1}{\lambda_y} + \frac{\frac{c}{c_1 - c}}{\lambda_v} \tag{6}$$

Where V is the total volume after titration, V_v is the volume of the dripping solution, V_y is the volume of pure water, and c is the concentration of the diluted solution.

Defined by absorbance: $A = lg(I_0/I_1)$ and Beer's law : $A = abc$, A is absorbance, a is absorbance coefficient, b is distance, and c is concentration. Among them, the absorption coefficient is the molar absorption coefficient, which represents the absorbance of the solution when the concentration of the solution is 1 mol/L and the thickness of the liquid layer is 1 cm. And the absorption length definition: the distance traveled when the light intensity decays to an increasing 1/e, that is:$I_1 = I_0 e^{-\frac{x}{\lambda}}$. The absorption coefficient can be obtained, the relationship between the absorption length of the solution and the initial concentration:

$$a \lambda_v c_1 = lg \frac{I_0}{I_1} = lge \tag{7}$$

The relationship between the initial concentration, dilution concentration and effective absorption length and the effective absorption length after adding the solution is obtained:

$$\frac{1}{\lambda_q} = \frac{1}{\lambda_y} \frac{c_1 - c}{c_1} + \frac{ac}{lge} \tag{8}$$

It can be seen that at a certain wavelength, by changing c, the absorption length at 0 concentration can be obtained, thus verifying λ_y.

3.2 Determination of absorption coefficient

Considering the properties of the reflective material (PE), the copper sulfate solution was chosen.

The principle of the spectrophotometer is based on Luangburbier's Law: $A = lg(I_0/I_1)$. T3202S is a UV-VIS spectrophotometer that adopts dual beam detection by Shanghai Youke Instrument Co., LTD. It places the reference substance and sample solution in two light paths respectively.

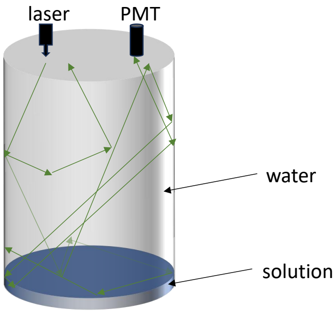


Figure 2: Schematic diagram of solution method.

In the experiment, industrial distilled water and copper sulfate pentahydrate were used to prepare different concentrations of copper sulfate solution. The conductivity of distilled water is less than 1 μS/cm, and the purity of copper sulfate was more than 99%. The reagent is weighed on an electronic scale with an accuracy of one percent. Copper sulfate solution with 7 molar concentrations as shown in Figure 3 was prepared. At different wavelengths, the absorption coefficient is different. With distilled water as the reference solution, a test wavelength is selected every 2 nm in the range of 400 nm-800 nm, and the spectrum shown in Figure 3 below is obtained. In Figure 3, it can be seen that the greater the concentration at the same wavelength, the greater the absorbance. Because of the absorbance range measured by the instrument, the maximum absorbance can only be measured to 3, so the upper limit of instrument measurement is reached when the concentration is higher and the wavelength is larger. When the absorption coefficient is consistent with the absorption coefficient 0.9015[10] at 600 nm, the absorption coefficient at 532 nm can be obtained as 0.1019 by linear fitting of absorbance at different concentrations, as shown in Figure 4. In Figure 4, the intercept is not 0, and the source of the error guess that the accuracy of the spectrometer is 0.001, while at short wavelength and low concentration, there is a certain error in the value due to the limitation of accuracy.

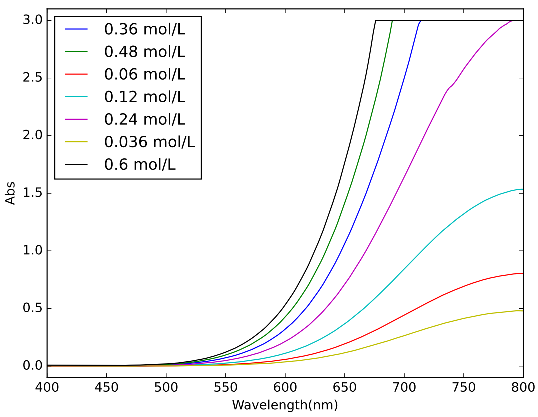


Figure 3: Absorption spectrum.

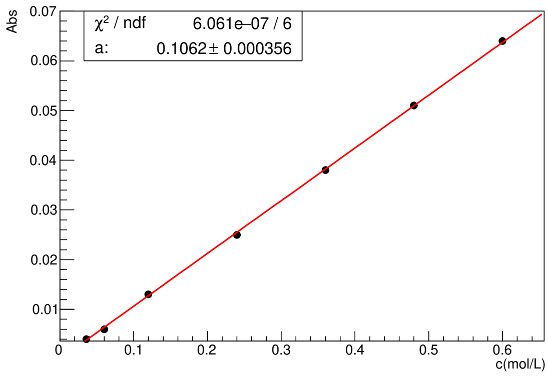


Figure 4: Absorption coefficient of copper sulfate solution at 532nm.

Table 1: Effective attenuation length fitting results(mm).

Altitude(cm)	concentration(mol/L) 0.0002	0.0006	0.0008	0.0010	0	fit0	fita
30	871	814	771	730	947	919 ±15	0.1158±0.0125
40	940	862	820	766	993	999 ±17	0.1249±0.0116
50	969	892	848	792	1020	1029 ±18	0.1187±0.0116

* fit0: The fit results in a concentration of 0, fita: The absorption coefficient obtained by fitting.

4. Results of solution method and discussion

4.1 Effective absorption length and fitting results

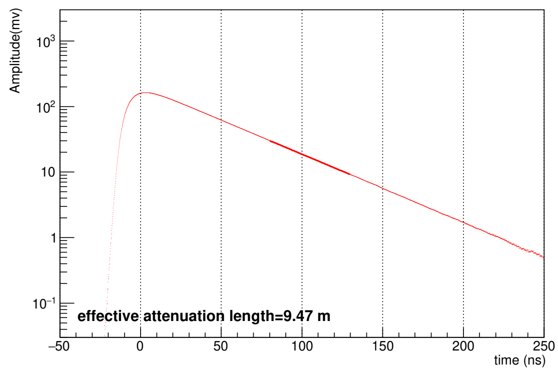


Figure 5: The effective attenuation length obtained by the device under 532 nm laser.

As shown in Figure 5, the signal collected by PMT tends to be stable after many reflections and shows exponential attenuation. By fitting $I_0 e^{-\frac{t}{\tau}}$, the effective attenuation time and thus the effective attenuation length can be obtained. In order to ensure the homogenization of photons in the barrel and the influence of pulses after removal, the interval 50ns-100ns is fitted.

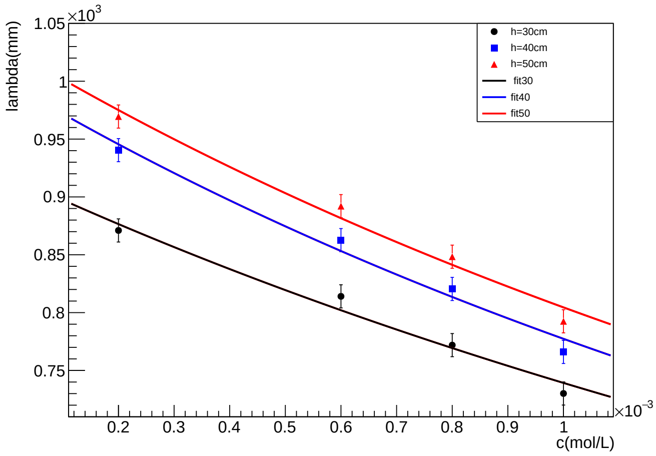


Figure 6: The effective attenuation time and absorption coefficient obtained by fitting three sets of data with the height of 30 cm, 40 cm, and 50 cm.

It can be seen from the fitting results Table 1 that the error between the fitting effective attenuation length and the measured result is less than 5%, and the absorption coefficient deviation is relatively large, within 20%. Figure 6 is the result of fitting Eq.8 for the data in Table 1. fit30, fit40 and fit50 indicate fitting curves with a height of 30 cm, 40 cm, and 50 cm. It can be seen that there are certain errors between the measured data and fitting curves, and the error deviation of each height is consistent, which is believed to be caused by the volume error of the barrel.

4.2 Discussion

This method has a rough range for determining the absorption length of water, but it still has some errors.

We consider possible sources of error: The inner wall reflective material is not evenly pasted, resulting in uneven reflectivity of the reflective material in different height areas. Bulge and other phenomena, resulting in volume errors. When the height is changed, the wear of the reflective material and the adjustment of the measuring instrument and the luminous instrument cause the deviation of each measurement value. As for the error of the absorption coefficient, a deeper understanding of the data is under way.

This method can not only verify the absorption length of water but also measure the cleanliness of water quality, which can be applied to the monitoring of air, water pollution, resource exploration, cave safety, etc.

Acknowledgements

This work was supported by National Key R&D program of China (2021YFA0718403) and NSFC (12105233, 12173039).

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