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Rayleigh scattering and depolarization ratio in linear alkylbenzene

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ABSTRACT

It is planned to use linear alkylbenzene (LAB) as the organic solvent for the Jiangmen Underground Neutrino Observatory (JUNO) liquid scintillator detectors, due to its ultra-transparency. However, the current Rayleigh scattering length calculation for LAB disagrees with the experimental measurement. This paper reports for the first time that the Rayleigh scattering of LAB is anisotropic, with a depolarization ratio of $0.31 \pm 0.01(\mathrm{stat.}) \pm 0.01(\mathrm{sys.})$. We use an indirect method for Rayleigh scattering measurement with the Einstein–Smoluchowski–Cabannes formula, and the Rayleigh scattering length of LAB is determined to be 28.2 ± 1.0 m at 430 nm.

1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment designed to determine the neutrino mass hierarchy and precisely measure oscillation parameters by the medium baseline vacuum oscillations of reactor antineutrinos [1,2]. It is to be located in a 700 m deep underground laboratory at Jiangmen, China.

The design of JUNO is based on the principle of highly purified liquid scintillator (LS) as the central detector, surrounded by ten-thousands of photomultiplier tubes (PMTs) and tons of ultra-pure water outside as an external shield. The central detector consists of a 20,000 tons of linear alkylbenzene (LAB) based LS in a spherical vessel with a diameter of 34.5 m, and the energy resolution is designed to be $3\%/\sqrt{E(\mathrm{MeV})}$, corresponding to 1200 photoelectrons (p.e.) collected by the PMTs per MeV. The antineutrinos are detected via the inverse beta decay reaction $\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$. LAB scintillation light generated from positron annihilation and neutron capture is red-shifted by the primary and secondary wavelength shifter [3], 2,5-diphenyloxazole (PPO) and pbis[2-methylstyryl]benzene (bis-MSB), and has to transverse the whole LS vessel before arriving at the photomultipliers. As a consequence, the transparency of LAB to the shifted scintillation light (e.g. 430 nm) is essential [4]. This has brought a great challenge to both technical LAB purification and optical parameter measurement.

The event location and energy reconstruction are determined by optical modeling, which includes Rayleigh scattering length, absorption length and attenuation length [5]. However, the absorption length, which describes the energy of a photon being absorbed to heat, is difficult to measure directly. An indirect method calculating from the attenuation length and scattering length is proposed [6]. Currently the attenuation length of LAB at 430 nm has been measured [7–9], while the measured scattering length of 40 m [10] differs from the calculated 30 m [11]. These motivate a precise measurement of LAB Rayleigh scattering length at the scintillation wavelength of LS.

2. Rayleigh scattering

Rayleigh scattering, developed by Rayleigh in 1899 [12], describes light elastically scattering off the molecules in a medium. For the gaseous state, this theory was successfully applied to independently isotropic molecules, and modified by Cabannes by introducing a depolarization ratio to describe the anisotropy of molecules. For the liquid state, due to the strong interaction effects between molecules, Einstein and Smoluchowski proposed scattering to be caused by the random motion of molecules, which leads to fluctuations in density and dielectric constant. The Rayleigh length of liquids can be described by the Einstein–Smoluchowski–Cabannes (ESC) formula [11]:

$$l_{Ray} = \left\{ \frac{8\pi^3}{3\lambda^4} \left[\frac{(n^2-1)(2n^2+0.8n)}{n^2+0.8n+1} \right]^2 kT\beta_T \frac{6+3\delta}{6-7\delta} \right\}^{-1}. \tag{1}$$

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Here λ is the wavelength of scattered light, n the refractive index, k the Boltzmann constant, T the absolute temperature, β_T the isothermal compressibility and δ the depolarization ratio. For the JUNO experiment, the temperature of the LS detector will be controlled at $T = 20 \pm 1$ °C and the quantum efficiency of the PMTs is optimized at $\lambda = 430$ nm. Recently, the β_T of LAB at three temperatures over 4 to 23 °C has been measured by the vibrating tube method [13]. The refractive index n of LAB from the same batch in the range between 400 nm and 630 nm has been reported [11].

The depolarization ratio δ can be measured at $\theta = 90^\circ$ scattering angle with a vertically polarized incident beam according to [11,14]

$$\delta_{90^\circ} = \frac{2I_h}{I_h + I_v}. \tag{2}$$

The subscripts designate the components analyzed in the scattered beam. v and h are the vertically and horizontally polarized components, respectively. If we define the depolarization ratio fraction $f = I_h/I_v$, we can get $\delta = 2f/(f+1)$.

3. Experimental setup

This experiment is designed to measure the depolarization ratio δ_{90°. The setup is shown in Fig. 1. The light source is a PicoQuant LDH pulsed laser diode with adjustable output up to 10 mW at 40 MHz repetition rate. Its wavelength is 405 nm instead of 430 nm because this was the closest available pulsed laser to 430 nm, and LAB has a negligible absorption/emission in this wavelength region [3]. The beam from the laser has a divergence of 0.32 mRad, producing a beam diameter at the sample cell of less than 1 mm. The incident beam is collimated with two variable apertures, as well as vertically polarized (polarization $< 1\%$) with a Glan–Thompson polarizer. Fluctuations in the intensity of the light source are monitored by use of a reference PMT-I (Hamamatsu R2083) with a grey filter in front to block a portion of the incident light. The samples are held in a quartz cuvette with 5-cm path lengths. The scattered light from the sample is then polarized by a Glan-Laser calcite polarizer with 100,000:1 extinction ratio which is installed on a motorized rotation mount with 1 in. precision. For this measurement the selected polarization component is either vertical or horizontal to the plate defined by the incident beam and scattered light. A Hamamatsu R1828 PMT-II with single photon response capability is installed after to count the number of scattered photons. The performance of the PMT-II is monitored with a blue LED. Both laser diode and LED are trigged by a pulse generator. This experiment was held in a dark room with room temperature controlled at 23 °C.

The signals from both PMTs are recorded by a CAEN DT5720 waveform digitizer with 4 nm time resolution (250 MS/s) and a total range of 2 V at 12 bit resolution. The trigger of the data acquisition (DAQ) system is shared from the same pulse generator, and is set to be 1 kHz with a 4 μs time window. The trigger for the laser diode is set to burst mode, 60 pulses with 5 ns time width are sent in this time window. Both the signal from the PMTs (usually PMT signals are less than 20 ns) and the thermal noise or radioactive background are recorded by the DAQ.

4. Photoelectron counting

The intensity of scattered light is estimated by counting the number of p.e., and then the depolarization ratio fraction f can be written as

$$f = \frac{N_h}{N_v} = \frac{\sum_{i=0}^{\infty} i \cdot N_h^i}{\sum_{i=0}^{\infty} i \cdot N_v^i}. \tag{3}$$

However, the horizontal and the vertical component of scattered light are measured separately, which requires careful consideration of normalizing the experimental conditions such as the stability of laser diode and DAQ data taking time period.

We propose a new method for estimating the fraction f. Assuming a Poisson distribution for the photons scattered and the p.e. number leaving the photocathode, and taking the number of incident photons to be N, we can rewrite this as

$$f = \frac{\sum_{i=0}^{\infty} i \cdot \frac{N_h^i}{N}}{\sum_{i=0}^{\infty} i \cdot \frac{N_v^i}{N}} = \frac{\mu_h}{\mu_v}. \tag{4}$$

Here μ is the expected value for the Poisson distribution.

Due to the long Rayleigh scattering length, the expected value μ should be rather small. The output of the PMT could be altered by dark noise, which causes a number of random coincidences to be detected. Therefore, in order to have the random coincidence contribution at the level of 1%, it is necessary to have $\mu \geq f_{dark} \cdot \tau_{gate}/0.01$. Here f_{dark} is the frequency of dark noise, which is 4KHz for PMT-II, and τ_{gate} is the ADC gate, which is 40 ns. It gives $\mu \geq 0.016$ to have a negligible contribution from the dark noise spectrum.

For a smaller $\mu < 0.016$, the observed Poisson distribution includes two parts. The first is the scattered photon response contribution, and the second is the dark noise of the PMTs coming from thermionic emission from the photocathode or radioactive background. The latter can be assumed to be a Poisson distribution as well. These two Poisson distributions are not correlated. Thus

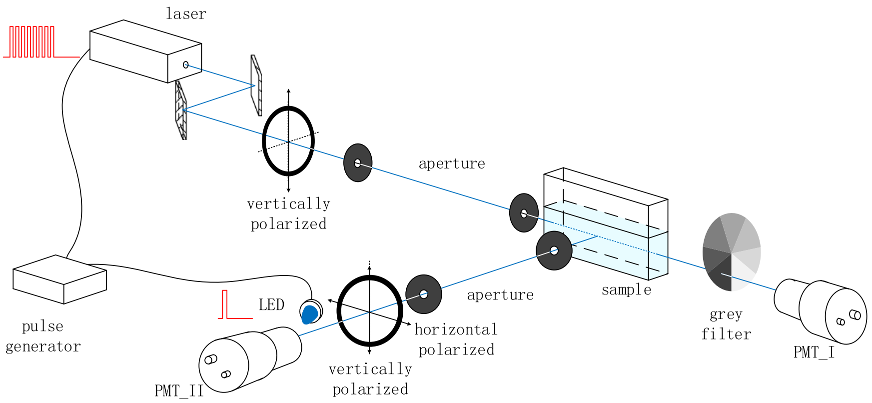

Fig. 1. Sketch of the experimental set-up.