An automated light yield measurement setup for liquid scintillator

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Abstract

Tellurium-130 is a promising candidate for neutrinoless double beta decay (0 $\beta\beta$) search due to its high natural abundance. However, it is challenging to dope tellurium into liquid scintillator at desired level while minimumly affecting the optical properties like light yield and transparency. Lots of R&D work are needed to develop the optimized recipes, where quick and robust characterizations of samples are highly demanded. In this paper, we present an automated setup designed for the efficient and precise measurement of light yield in liquid scintillators. This setup can measure up to eight sets of samples in a measurement round. The systematic uncertainty is less than 2%. This setup is playing a crucial role in the optimization of liquid scintillator formulations.

Full Text

Abstract

We present an automated light yield measurement setup for liquid scintillator. Tellurium-130 is a promising candidate for neutrinoless double beta decay (0 $\beta\beta$) searches due to its high natural abundance. However, doping tellurium into liquid scintillator at the desired concentration while minimally affecting optical properties such as light yield and transparency presents a significant challenge. Extensive R&D is required to develop optimized recipes, necessitating quick and robust sample characterization. This paper describes an automated system designed for efficient and precise measurement of light yield in liquid scintillators, capable of measuring up to eight sample sets in a single measurement round with systematic uncertainty below 2%. This setup plays a crucial role in optimizing liquid scintillator formulations.

Keywords: Neutrinoless double beta decay, liquid scintillator, light yield

Introduction

The concept of neutrinoless double beta decay (0 $\beta\beta$) was first proposed by W.H. Furry in 1939 [**?**]. The Schechter-Valle black box theorem [**?**] demonstrates that if 0 $\beta\beta$ occurs, neutrinos must be Majorana particles—meaning the neutrino is its own antiparticle [**?**]. This implies violation of lepton number conservation during the decay process, suggesting symmetry breaking and the potential existence of new physics. Neutrinoless double beta decay has become a focal point in neutrino physics research, providing insights into the absolute neutrino mass scale. Numerous collaborations have explored this phenomenon, including KamLAND-Zen [**?**], CUORE [**?**], PandaX [**?**], EXO [**?**], LEGEND [**?**], and many other experimental groups.

Tellurium (Te) is one of the prime candidates for neutrinoless double beta decay studies. Moreover, liquid scintillators are widely used in neutrino detection due to their advantageous properties. A natural extension is to incorporate tellurium into liquid scintillator to facilitate measurements of neutrinoless double beta decay. However, the doping process is expected to significantly impact light yield, resulting in degraded energy resolution. Therefore, extensive measurements of light output in tellurium-doped liquid scintillator (Te-LS) are necessary to optimize the formulation.

This paper presents the experimental design and apparatus, simulations and data analysis methods, measurement results for liquid scintillator, and error analysis.

II. Experimental Design

To achieve enhanced sensitivity, it is essential to maximize the tellurium concentration in the liquid scintillator. However, increasing amounts of tellurium may significantly degrade the scintillator' s optical properties. Therefore, the challenge is to maintain good optical properties while doping more Te into the liquid scintillator.

In our previous work [**?**], Te-LS doped at 0.5% mass fraction exhibited a light yield of approximately 60% compared to undoped LS, with a 5% measurement error. To facilitate optimization of light yield, we require an automated setup capable of measuring multiple samples simultaneously while suppressing measurement uncertainties.

To achieve these objectives, we have designed an experimental apparatus composed of a glove box, rotating motor, photomultiplier tube (PMT), and digitizer, as detailed in Figure 1 [Figure 1: see original paper]. The glove box provides an anoxic environment, while the rotating motor facilitates automated batch measurements. The PMT and digitizer are utilized to receive and store signals.

A. Radioactive Source

The radioactive source is ^{207}Bi, with a half-life of 31.22 years [**?**]. The decay mode is β^+/EC, resulting in the excited daughter nucleus ^{207}Pb. Following de-excitation of ^{207}Pb, internal conversion electrons are emitted with dominant energies of 481 keV, 975 keV, and 1047 keV. Notably, peaks with higher energy exhibit less disturbance and higher resolution, making them ideal for energy calibration.

The source consists of multiple discs with a diameter of 25.4 mm, compressed together by an embedded ring. The front disc serves as a protective isolation layer, while the bottom disc is coated with ^{207}Bi and functions as the signal disc, which has an effective area diameter of 5.08 mm. The overall structure is compatible with the diameters of the sample bottle, PMT, and support structure, where the diameter of the effective component is significantly smaller than that of the sample bottle. Consequently, minor positional variations of the source discs within the support structure do not result in substantial changes in the deposition of the effective component within the sample.

B. Glove Box

Oxygen molecules in liquid scintillator can cause quenching effects that reduce light yield [**?**]. Therefore, we require a glove box to maintain the entire experimental setup in an oxygen-free environment through vacuum pumping and nitrogen purging. The glove box is a VGB-3A model from Changshu Tongrun Electronic Technology Co., Ltd., capable of achieving a vacuum pressure of -0.1 MPa. During the experiment, the glove box remains closed to maintain a nitrogen environment, with different sample batches changed through the glove ports.

C. Rotating Motor

To reduce systematic errors caused by sample differences, we designed a rotating motor equipped with eight identical sample holders evenly distributed angularly. It is adapted from the Y200RA300 model from Beijing Jiangyun Optoelectronic Technology Co., Ltd. Each sample holder has a diameter of 26 mm, slightly larger than the sample bottle diameter of 25 mm. A Tyvek reflective film is added to enhance scintillation light collection efficiency. The rotating motor can be remotely controlled by a computer and programmed for custom movement patterns. During measurement, the radioactive source and PMT remain stationary while the motor moves the sample to be tested into position.

The accuracy of motor rotation is crucial for ensuring consistent sample positioning. The step size of the rotation motor is one degree. We tested the repeatability of rotation and found the impact on light collection efficiency to be negligible. After eight rotations of 45°, the sample reaches exactly the same position. Any uncertainty introduced by rotation accuracy is evaluated and

properly included as part of the position-dependent uncertainty discussed in Section IV.

D. PMT

The PMT used is the R1924A model from Hamamatsu, with a diameter of approximately 25 mm that couples to the sample bottle size. The most sensitive wavelength is 420 nm, matching the peak wavelength of liquid scintillation [**?**]. The PMT is operated at a high voltage of 1100 V with a gain of 7.5×10^6.

E. Digitizer

The PMT signal is digitized and read out by the NDA6110 model digitizer from Jinan Laboratory of Applied Nuclear Science. It is a 4-channel, 14-bit, 1 GSPS device. The pulse width of signals in this experiment is on the order of tens of nanoseconds, with waveforms saved for offline analysis.

F. Measurement Procedure

The measurement procedure is illustrated in Figure 2 [Figure 2: see original paper]. The first step involves vacuum pumping the glove box. The sample bottle placed inside is opened in advance. As vacuuming progresses, the pressure difference between the inside and outside of the sample increases, causing oxygen in the sample to be continuously released and pumped away. Once the pressure reaches the vacuum pump limit, the pump is stopped and the extraction valve closed, maintaining the glove box at ultra-low pressure for one day. During this period, oxygen content in the sample continues to decrease. Subsequently, nitrogen with 99.9999% purity is introduced to restore normal pressure. The experiment is not conducted in vacuum to prevent deterioration of the PMT base insulation performance, which could lead to discharge and damage. The oxygen level in the glove box is maintained at approximately 300 ppm.

Measurement of the first sample begins after properly configuring the PMT and digitizer parameters. Once sufficient data are accumulated, the digitizer stops acquisition. The motor then rotates the next sample into measurement position, and the digitizer resumes recording. This process continues until all samples are measured. By properly programming the motor motion timing and digitizer acquisition windows, a fully automated measurement process is achieved, ensuring precise and efficient data collection.

G. Simulation

A Geant4 simulation was developed to guide the design and understand the expected spectrum from ^{207}Bi in the setup. The liquid scintillator (LS) has the same composition as JUNO LS [**?**], which utilizes LAB as the solvent mixed with 2.5 g/L PPO as fluor and 3 mg/L bis-MSB as wavelength shifter. The simulation reproduced the experimental setup for light yield measurement, including key

elements such as: precise positioning and dimensions of the radioactive source, sample bottle, and PMT; incorporation of Tyvek reflective film surrounding the sample bottle and the air gap between sample and source; and inclusion of various physical processes like scintillation, Cherenkov radiation, Rayleigh scattering, refraction, and attenuation.

Following simulation of one million events, the distribution of ^{207}Bi deposited energy is depicted in Figure 3 [Figure 3: see original paper]. The energy deposition histogram reveals two distinct sets of adjacent main energy peaks along with their corresponding Compton platforms. The first set includes electrons with energies of 481 keV and 553 keV, while the second consists of electrons with energies of 975 keV and 1047 keV.

III. Data Measurement and Analysis

In the experiment, we arranged eight liquid scintillator samples. Each sample was measured for 15 minutes to accumulate at least 50,000 events. Maintaining a consistent environment during each measurement round—including temperature, humidity, and PMT operational status—helps minimize systematic errors.

A. Waveform Analysis

Each waveform contains 1000 sample points at 1 ns sampling interval. The signal trigger condition requires 8 consecutive points showing a monotonically increasing trend (rising edge), all exceeding a threshold of 4 mV. The trigger point is set at position 100, allowing baseline calculation using data prior to the trigger point, specifically by averaging values from the 10th to 80th points. Examination of waveform data indicates a signal duration of approximately 60 nanoseconds. In this analysis, integrated charge is calculated using the integral of the difference between values from the 90th to 160th points and the previously obtained baseline.

The measured data spectrum is compared with Monte Carlo simulation in Figure 4 [Figure 4: see original paper]. The main peak in the data spectrum is dominated by conversion electrons around 1 MeV. Data and MC simulation shapes agree reasonably well at the high-energy end. This peak is used to characterize light yield for different samples.

B. Spectrum Fitting

The charge spectrum for the ^{207}Bi source is fitted to determine the peak position. In actual data analysis, limited resolution can significantly affect the energy distribution, causing the main energy peak to deviate from a simple Gaussian representation. For comparison with simple Gaussian fitting, we expanded the fitting range to include the Compton plateau preceding the peak position and employed a combination of quadratic, exponential, and Gaussian functions, as shown in Figure 5 [Figure 5: see original paper]. Among these three

approaches, the quadratic function and Gaussian function yielded the smallest χ^2 value, which was very close to that of simple Gaussian fitting. Nevertheless, variations in peak values obtained from different fitting methods—which are used for relative light yield calculation—will be discussed in Section IV. To avoid introducing additional systematic error, we used simple Gaussian fitting for all samples.

IV. Systematic Error

As previously noted, variations in sample positioning can introduce systematic errors in individual measurement rounds, while changes in the experimental environment between different rounds can also contribute. Additionally, small discrepancies in sample content during preparation, variations in sample bottle manufacturing, and the fitting method described in Section III can further introduce systematic errors.

To quantify these systematic errors, we used non-doped standard liquid scintillator for study. We distributed the standard liquid scintillator equally among eight sample bottles for measurement, ensuring that inherent differences between samples and bottles were considered. We then conducted several measurement rounds to account for environmental variations over time. The final measurement results were analyzed using the same fitting method applied in Section III, yielding the results presented in Figure 6 [Figure 6: see original paper].

Position. A difference in measured light yield for the same samples placed in different sample holders was observed, with differences up to 6% as shown in Figure 6. This difference is repeatable and expected to be primarily caused by the fit of Tyvek in the holder. We take one measurement as the nominal correction for position-dependent differences. Subsequent measurements at different times show deviations at different positions after correction are mostly within 2%. We take the RMS of these values and assign a 1.9% position-dependent uncertainty.

Environmental conditions. By analyzing variations in light yield of samples at the same position across different measurements in Figure 6, systematic errors introduced by different measurement cycles can be identified. The data indicate that systematic error associated with position is significantly greater than that caused by environmental variations. This is largely due to effective temperature control provided by air conditioning, which minimizes temperature fluctuations to $\pm 0.5^{\circ}$C. Additionally, the sealed glove box environment ensures that oxygen content changes during a single measurement round do not significantly impact results.

Fitting method. By analyzing effects of different analytical methods applied to the same sample, systematic errors introduced by various approaches can be identified as shown in Figure 5. This includes differences in fitting functions

for a single sample, as well as variations in fitting ranges due to minor spectral shape discrepancies across multiple measurements.

In summary, through statistical analysis of the data, the final systematic error values are obtained as shown in Table 1 .

Location	Environmental conditions	Fitting method	Total Systematic errors

Table 1. Results for systematic errors.

V. Conclusion

In this study, we developed an automated measurement system to accurately determine the light yield of liquid scintillator. This system enables simultaneous measurement of up to eight Te-LS samples. The results demonstrate that the system can achieve a systematic error of approximately 2.0%, meeting stringent requirements for optimizing Te-LS formulations. This automated system not only enhances the efficiency of batch testing but also provides a robust framework for future Te-LS research. By enabling precise light yield measurements, this innovation paves the way for optimizing Te-LS composition, thereby improving performance in detecting rare events like neutrinoless double beta decay.

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Figure Captions

Fig. 1 [Figure 1: see original paper]. (a) The rotating motor with eight sample holders. The radioactive source is positioned on the grey support frame directly above the sample bottle, while the PMT is located on the support frame directly below it. (b) The glove box. (c) The oxygen monitor (up) and the motor controller (down).

Fig. 2 [Figure 2: see original paper]. Measurement procedure of light yield measurement. Detailed information is described in the main text.

Fig. 3 [Figure 3: see original paper]. Energy deposition in liquid scintillator.

Fig. 4 [Figure 4: see original paper]. Energy deposition revisited and total photons received in PMT in simulation.

Fig. 5 [Figure 5: see original paper]. Measurement and fitting results for a LS sample.

Fig. 6 [Figure 6: see original paper]. Light yield for Standard LS in different locations and measurements.

Note: Figure translations are in progress. See original paper for figures.