Slow Liquid Scintillator Candidates for MeV-scale Neutrino Experiments

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Abstract

Liquid scintillator Cherenkov detectors are proposed by a few future neutrino experiments. The combination of a slow liquid scintillator, with a long scintillation emission time, and fast photomultiplier tubes may present a possible detection scheme for liquid scintillator Cherenkov lights. Neutrino detectors of this type could feature directionality and particle identification for charged particles so that better sensitivity is expected for low-energy (MeV-scale) neutrino physics, such as solar physics, geo-science, and supernova relic neutrino search. A slow liquid scintillator cocktail combines linear alkylbenzene (LAB), 2,5-diphenyloxazole (PPO), and 1,4-bis (2-methylstyryl)-benzene (bis-MSB). We studied the relevant physical aspects of different combinations of LAB, PPO, and bis-MSB, including light yield, time profile, emission spectrum, attenuation length of scintillation emission and visible light yield of Cherenkov emission. We also measured the optical transmission of acrylic, a material commonly used in liquid scintillator containers. Samples of LAB with around 0.07 g/L PPO and 13 mg/L bis-MSB are good slow liquid scintillator candidates, which allow good separation between Cherenkov and scintillation lights with a reasonable high light yields.

Keywords: Cherenkov, scintillation, slow liquid scintillator, neutrino detection

1. Introduction

Jinping Neutrino Experiment will focus on solar neutrino, geoneutrino, and supernova relic neutrino studies \cite{1-4}. Direction information and high energy resolution are important for low-energy, MeV-scale, neutrino signal selection and background suppression.

Liquid scintillator Cherenkov detectors (with either water- or oil-based liquid scintillators) present the advantages of both water and liquid scintillators, including low detection threshold, and direction reconstruction capability. A new approach for particle identification can also be established for background rejection in solar neutrino and supernova relic neutrino detection \cite{2}. The above features are also useful for neutrinoless double beta decay experiments \cite{3,7}, neutrino CP phase measurements \cite{8,9}, proton decay research \cite{10} and geoneutrino search \cite{11}. The THEIA \cite{12} and Jinping Neutrino Experiment \cite{11} could benefit from this interesting detection scheme. While the concept of diluted scintillators was pioneered in the context of the LSND experiment \cite{13}, but it has less light yield than that is not applicable to low-energy physics.

The concept of water-based liquid scintillators (WbLS) was proposed as early as in Ref. \cite{14}. More recent efforts toward achieving this purpose can be found in \cite{10,15-17}.

In Ref. \cite{18}, we built a detector to measure the separation of Cherenkov and scintillation lights with pure linear alkyl benzene (LAB). LAB features a long decay time constant of 35 ns and can be categorized as a slow liquid scintillator.

Good progress in this field was obtained in the CHESS \cite{19,20} experiment, which applied the photon detectors \cite{21} much faster than those commonly used in practice.

LAB is a good candidate for use in supernova relic neutrino detection \cite{2}, but its light yield is much lower than that of traditional liquid scintillators currently used in the neutrino experiments, especially low-energy solar neutrino experiments.
To maintain the directionality with enhancement of light yield, 2,5-diphenyloxazole (PPO) and 1,4-bis (2-methylstyryl)-benzene (bis-MSB) could be added to pure LAB [22, 23]. The addition of bis-MSB also shifts the emission spectrum toward wavelengths higher than 400 nm.

In this paper, we studied the effect of adding PPO and bis-MSB to the LAB. We scanned the light yields and time profiles of samples combining LAB with PPO and bis-MSB (Section 2) and then measured scintillation emission spectra (Section 3) and transmissions in a relevant material, acrylic (Section 4), a typical material for LAB containers. We further measured the attenuation length (Section 5) of one interesting sample with a long-arm apparatus, and performances of candidate samples for neutrino detection are discussed in Section 6. Finally, the results of our work are summarized in Section 7.

2. Scanning of light yield and scintillation time

2.1. Apparatus

The detector employed in this study is shown in Fig. 1; in the setup, four plastic coincidence scintillators were positioned vertically, and the resulting quadruple-coincidence signals were used as detector triggers for muons flying from top to bottom. Two other plastic anti-coincidence scintillators were placed next to the bottom coincidence scintillator to exclude muon shower events.

A volume of 15.4 L of a liquid scintillator sample was held in a 37 cm-height acrylic container placed between the second and third coincidence scintillators. PPO and bis-MSB were then weighed by an electronic balance (1 mg division minimal) and dissolved in a 500 mL beaker filled with LAB. Thereafter, the concentrated solution was poured into the acrylic container, and the mixture was completely stirred.

The acrylic container placed on the path of triggered muons to collect both scintillation and Cherenkov light in the sample. The inner surface of the acrylic container was lined by a layer of black coarse acrylic to suppress reflections. The top and bottom PMTs, which were designed symmetrically aligned with the acrylic container, were immersed in the liquid scintillator.

The light signals of six plastic scintillators and the liquid scintillator were collected by eight PMTs. The top and bottom PMTs used to acquire the signals of the liquid scintillator are the Hamamatsu model R1828-01. The parameters of the PMTs may be found in the PMT data sheet [24].

After a trigger, a 10 bit, 1 GHz flash analog-to-digital converter (FADC, model CAEN V1751) opened a 4096 ns window and read out the voltage waveforms of all eight PMTs. The waveforms were further analyzed offline.

2.2. Event selection

The expected signals were single vertically directed and minimum-ionizing muons, and two types of background events were vetoed (details of the data selection process may be found in Ref. [18]).

- Electronic noises, which arise mainly from the coherent noises induced by the power supply of the PMTs. The waveforms produced by this noise are much narrower than the physical PMT signals produced by photons. The application of waveform shape cuts is effective in removing these backgrounds.
- Muon showers, which may occur when an energetic muon spalls with an atom. This background was rejected by the two anti-coincidence channels. The charges of the four coincidence scintillators were also used as a data cut. The energy deposit in each coincident channel should follow a Landau distribution assuming minimum-ionizing particles. Events with significantly small or large charges compared with the averages in any of the channels were also rejected.

The average waveforms of the top and bottom PMTs of over 2000 selected candidates were used for
Cherenkov and scintillation light studies. Figures 2 and 3 show the typical average waveforms of a few combinations of the top and bottom PMTs, respectively. The relative difference of the gains and acceptances between the top and bottom PMTs were corrected in these figures. Scintillation light is detected by the top PMT. In the first 20 ns of detection, the amplitude of the bottom PMT waveform is higher than that of the top PMT waveform because of Cherenkov light. When the concentrations of PPO and bis-MSB are low, the prompt Cherenkov peak is more significant. After increasing bis-MSB, because of the absorption of the short-wavelength (less than 400 nm) light the number of Cherenkov photons decreased.

2.3. Time profile measurement

The waveform of the bottom PMT contains Cherenkov and scintillation light contributions and is convoluted by the PMT time response. The time profile can be expressed as

\[ f_b(t) = [A_c \delta(t - t_c) + A_s n(t - t_s)] \otimes \text{gaus}(\sigma_b), \]  

where \( A_c \) is the amplitude of the Cherenkov light, \( t_c \) is the mean arrival time of the Cherenkov light, \( A_s \) and \( t_s \) are the amplitude and start time of the scintillation light, respectively, \( \text{gaus}(\sigma_b) \) is the PMT time response function, \( \delta(t) \) represent the prompt Cherenkov emission time profile, and \( n(t) \) is the time profile of the liquid Cherenkov scintillator. In a binary or ternary scintillator system, emissions may feature a finite rise time or be slightly lengthened in duration due to the finite time of intermolecular energy transfer [25]. In organic solution scintillators, emissions present a finite rise time \( \tau_r \) and a decay time \( \tau_d \) so that

\[ n(t) = \frac{\tau_r + \tau_d}{\tau_d^2} (1 - e^{-t/\tau_r}) \cdot e^{-t/\tau_d} \]  

is the normalized scintillation light pulse shape.

In contrast to that of the bottom PMT, the voltage waveform of the top PMT includes only scintillation light contribution, which could be expressed as

\[ f_t(t) = A_s n(t - t_s) \otimes \text{gaus}(\sigma_t). \]  

Combining Eq. 1 and Eq. 2 the time profile \( \tau_r \) and \( \tau_d \) could be determined. For example, the rise and decay time constants were measured to be \( \tau_r = (1.16 \pm 0.12) \) ns and \( \tau_d = (26.76 \pm 0.19) \) ns, respectively, for the sample containing LAB, 0.07 g/L PPO, and 13 mg/L bis-MSB. The fitting results of the top and bottom PMT waveforms are shown in Figures 2 and 3.

2.4. Light yield measurement

The number of scintillation photoelectrons (PE) \( D_s \) at the bottom PMT could be derived with the following equation,

\[ D_s = \frac{A_s}{A_c}, \]  

where \( A_s \) represents a single PE charge obtained from PMT gain calibration and \( A_c \) is the fitting result from Eq. 1 and Eq. 2.

Dividing \( D_s \) by the detection efficiency \( \varepsilon_s \), the total number of scintillation photons \( N_s \) could be obtained,

\[ N_s = \frac{D_s}{\varepsilon_s} \frac{A_s}{A_c} = \frac{A_s}{\varepsilon_s \cdot A_c}. \]  

The detection efficiency was estimated with Geant4 [26, 27]-based Monte-Carlo simulation. The uncertainty of the efficiency is deduced with the uncertainties of the equipment parameters, including the PMT quantum efficiency, the reflection of the acrylic container, the position of the PMTs, and Birks’ constant (quenching effect) of the liquid scintillator. More details of the simulation could be found in [18].

The scintillation light yield could be calculated by

\[ L = \frac{N_s}{E_{vis}} = \frac{A_s}{\varepsilon_s \cdot A_c \cdot E_{vis}} \]  

where \( E_{vis} \) is the total visible energy, which could also be estimated by the simulation. Note that the distance from each PMT photo cathode to the light production center is about 20 cm, and the attenuation is not considered due the lack of precise attenuation spectra, which are also subject to change after purification.

For example, the sample of LAB with 0.07 g/L PPO and 13 mg/L bis-MSB, the numbers of measured PEs at the top and bottom PMTs are shown in Table 1. and uncertainties are all fitting errors. The number of detected Cherenkov PEs is 5.47 ± 0.22. Using Eq. 6 the scintillation light yield of the sample was measured to be (2.83 ± 0.43) × 10^3 photons/MeV.

|               | Top          | Bottom       |
|---------------|--------------|--------------|
| Cherenkov     | --           | 5.47 ± 0.22  |
| Scintillation | 56.1 ± 1.2   | 56.1 ± 1.2   |

Table 1: Measured photoelectrons at the top and bottom PMTs for the sample including LAB with 0.07 g/L PPO and 13 mg/L bis-MSB.

2.5. Time and light yield of scan

Samples with different concentrations of PPO and bis-MSB solution were studied. The decay times and
Figure 2: Typical average waveforms of the top PMT. Scintillation light is detected by the top PMT.

Figure 3: Average waveforms of the bottom PMTs. Both Cherenkov and scintillation light is visible.

Figure 4: Top PMT waveform fitting result for the sample of LAB with 0.07 g/L PPO and 13 mg/L bis-MSB.

Figure 5: Bottom PMT waveform fitting result for the sample of LAB with 0.07 g/L PPO and 13 mg/L bis-MSB.
scintillation light yields are plotted in Fig. 6 for all the samples we tested. The typical numbers for a few key samples were summarized in Table 2. The decay time constant and scintillation light yield showed a roughly inverse relationship, which indicates that the product of light yield and time constant could be a constant, analogous to the decay width theory of \( \Gamma = M \times \phi \), where \( \phi \), or the phase space, is the light yield, \( \Gamma \) is the decay width, \( 1/\Gamma \) is the decay time constant, and \( M \) is the decay matrix element. High concentrations of PPO and bis-MSB led to a higher light yields and faster time constants. These data points were distributed over a narrow band, thus restricting the range of light yields and time combinations.

### 3. Emission Spectrum

The emission spectrum of the candidate samples were measured using a RTI fluorescence spectrometer excited at 260 nm. The relevant spectra are shown in Fig. 7. The emission spectrum of LAB starts at about 320 nm and is in the UV region. With the addition of PPO (less than 2 g/L), the emission spectrum is fully red-shifted starting at about 335 nm. With 13 mg/L of bis-MSB, the emission spectrum is fully shifted to be above 390 nm to visible light. These emission spectra were implemented in the simulation for the estimation of detection efficiency in Section 2.

### 4. Optical Transmission of Acrylic

Acrylic is a common material used in the scintillator vessels of large-mass neutrino detectors. As the mechanical strength requirement of a kiloton-scale detector requires that the thickness of the vessel should be about 5.5 centimeters as in the SNO experiment [28], the optical transmission of acrylic cannot be ignored. In this section, we present a qualitative understanding of this transmission.

We used a deuterium lamp and a spectrometer to measure the transmissivity of several 10 mm-wide acrylic samples. The acrylic plate were placed between the deuterium lamp and spectrometer, and the two parallel optical surfaces of the sample were positioned normal to the direction of light propagation of the setup. The light intensity spectra \( K_1 \) and \( K_0 \) were measured with and without acrylic, respectively.

The ratio of \( K_1 \) and \( K_0 \) is a function of the transmissivity \( t \) and the reflectivity \( r \) of the acrylic surface and may be expressed as

\[
\frac{K_1}{K_0} = \frac{t(1-r)^2}{1-r^2}.
\]

Here, the formula is derived considering multiple reflections within the two acrylic sample surfaces assuming normal incident lights. The reflectivity \( r \) could be derived from the Fresnel formula and refractive index \( n \),

\[
r = \left( \frac{n-1}{n+1} \right)^2.
\]

Variations in transmissivity as a function of the wavelength could be calculated from Eq. 7 and Eq. 8 and the result is shown in Fig. 7. The acrylic is nearly transparent in the visible wavelength, i.e. > 400 nm, and becomes almost opaque in the wavelength range of below 270 nm. Note these are only a 10-mm thick samples, given an expected thickness beyond 5 cm, the emission light of the scintillator should be shifted toward a longer wavelengths to avoid absorption by acrylic vessels.
5. Attenuation Length of the Scintillator

We used a variable pathlength photometer to measure the attenuation of the slow liquid scintillator candidate [29, 30]. In this paper we focus on one sample, i.e, LAB with 0.07 g/L PPO and 13 mg/L bis-MSB. The emission spectrum of this sample partially overlaps with that of the LED light we used.

The schematic diagram of this photometer is shown in Fig. 8. An LED lamp is mounted at the top of the photometer. Light that is refocused from a lens travels through a diaphragm and a 1 meter-long stainless steel pipe filled with the liquid scintillator. The liquid level in the pipe could be controlled by a solenoid valve and a liquid level sensor. A PMT (Hamamatsu R7724, 51 mm diameter) is installed at the bottom of the equipment to receive light, and the wavelength of the maximum response is 420 nm [24].

The LED spectrum is not monochromatic, as shown in Fig. 9 so the one-exponential Beer-Lambert law is invalid. The intensity of light we received should be the weighted average of the LED spectrum $f(\lambda)$, or the summation of several exponentials,

$$I(x) = I_0 \int f(\lambda) e^{-x/L_1} d\lambda$$

Therefore, we used a two-exponential fit for convenience,

$$I(x) = I_0 \left[ A_1 e^{-x/L_1} + (1 - A_1) e^{-x/L_2} \right]$$

where $A_1$ and $L_1$ represent the long attenuation length component and $L_2$ represents the short attenuation component.
length component. The fitting results are shown in Fig. 10; here the long attenuation length \( L_1 \) is \((9.37 \pm 0.44) \text{ m}\) and the intensity coefficient \( A_1 \) is 92.5%.

The measured attenuation includes both the effects of absorption and scattering \([31, 32]\), and more careful studies can be carried out on a dedicated device to separate them. The result gives the indication that the sample is possible for a large detector. We also think the current result is limited by the status bis-MSB, and further improvement on the attenuation length, for example with much cleaner bis-MSB, is possible.

6. Candidate samples

The application in a liquid scintillator neutrino detector is estimated next. We assume the PMT photocathode coverage is 70%, the quantum efficiency of PMTs is 20% on average, and no efficiency loss from acrylic. For the effect of attenuation, the efficiency of propagation is roughly 50% when an event is in the center of a kiloton detector with 6.5 m radius. For the sample of LAB with 0.07 g/L PPO and 13 mg/L bis-MSB, the scintillation light yield is roughly \(2830 \times 70\% \times 20\% \times 50\% = 198 \text{ PE/MeV}\).

If the effective PMT photocathode can reach 100% \([33]\), high quantum efficiency PMTs with 30% efficiency are adopted, and the attenuation length is 15 m \([34]\), i.e. the average propagation efficiency is roughly 60%, the light yield can be increased to \(2830 \times 30\% \times 60\% = 509 \text{ PE/MeV}\). This satisfies the requirement in the Jinping proposal for solar neutrino study \([1]\).

The detection of diffusion supernova neutrino background does not have a stringent request on light yield \([2]\). The samples with 0.07 g/L PPO and 13 mg/L bis-MSB or the formulas with similar PPO and bis-MSB concentration will also satisfy the requirement.

7. Conclusion and outlook

In this paper, we studied several liquid scintillators (mix of LAB, PPO and bis-MSB solution) for neutrino experiments. The light yields and decay time constants of these samples were measured. The products of light yield and decay time constant approach a constant value. The emission spectrum of these samples are also reported. The attenuation length of the long attenuation length component was measured to be \((9.37 \pm 0.44) \text{ m}\), and the long component takes more than 90%. The samples of LAB with around 0.07 g/L PPO and 13 mg/L bis-MSB or the formulas with similar PPO and bis-MSB concentration showed good balance between the scintillation decay time and light yield; as such this combination could serve as good slow liquid scintillator candidates.

The scintillation solutes PPO and bis-MSB enhance the light yield and red-shift the emission spectrum toward more optical-transparent region. The concentration of PPO and bis-MSB will be optimized by using a larger test apparatus \([35]\) and performing more extensive offline simulations and analyses.

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