Measurement of Liquid Scintillator Properties Using the 70 MeV Quasi-monochromatic Neutron Beam

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This group is preparing a sterile neutrino experiment, JSNS^2 at J-PARC Materials and Life Science Experimental Facility (MLF)[1)]. The MLF beam line produces $\bar{\nu}_\mu$ in the decay of stopping muon (μ^+). The energy of $\bar{\nu}_\mu$ is E~40 MeV. The JSNS^2 experiment detects $\bar{\nu}_e$ produced by $\bar{\nu}_\mu$ oscillation at a baseline L=24 m.

$$\mu^+ \xrightarrow{\text{Decay at rest}} \bar{\nu}_\mu \xrightarrow{\text{Oscillation(4th neutrino)}} \bar{\nu}_e \tag{1}$$

Neutrino oscillation at this E/L can not be explained by the standard 3 neutrino flavor oscillations and if it is observed, it indicates that 4th neutrino, called sterile neutrino, exists.

The $\bar{\nu}_e$ is detected in liquid scintillator (LS) using the inverse beta decay interaction, followed by the neutron capture γ's.

$$\bar{\nu}_e + p \rightarrow e^+ + n: \quad n + {}^{A}\mathrm{Gd} \rightarrow {}^{A+1}\mathrm{Gd}^* \rightarrow {}^{A+1}\mathrm{Gd} + \gamma s\left(\Sigma E_\gamma \sim 8\mathrm{MeV}\right) \tag{2}$$

The $\bar{\nu}_e$ turns to positron in the inverse beta decay interaction and the positron emits scintillation light whose amount is approximately proportional to the energy of the incident neutrino. The proton turns to neutron in the interaction. The neutron quickly thermalizes in the liquid scintillator and, typically 30 μs after, is captured by gadolinium and produces γ-rays whose total energy is 8 MeV. By taking the delayed coincidence between the positron signal and the neutron capture signal, $\bar{\nu}_e$ is identified.

The main background for this process is fast neutrons produced in interactions of cosmic-ray muons and surrounding materials. Since the mass of the neutron and proton is almost the same, when the fast neutron collides with a free proton in the liquid scintillator, it transfers its energy efficiently to the proton and loses its energy quickly and finally be captured by the gadolinium.

$$n + p \rightarrow p + n: \quad n + {}^{A}\mathrm{Gd} \rightarrow {}^{A+1}\mathrm{Gd}^{*} \rightarrow {}^{A+1}\mathrm{Gd} + \gamma\mathrm{s}\left(\Sigma E_{\gamma} \sim 8\mathrm{MeV}\right) \qquad (3)$$

This event pattern is very similar to that of $\bar{\nu}_e$ signal, (2), and if the recoiled proton emits scintillation light equivalent to that of e^+, the fast neutron signal mimics the $\bar{\nu}_e$ signal. A possible method to remove the fast neutron background is to use, so called, pulse shape discrimination (PSD) technique. Since the proton mass is much larger than it's kinetic energy, the *dE/dx* is much larger than that of positron signal. In this case, the ratio of the slow component and fast component of the scintillation signal becomes larger than that from light particles such as electron, positron or γ-ray. By measuring this property, the fast neutron signal can be removed from the neutrino signal.

The PSD capability may depend on the energy. However, PSD data for JSJS[2] neutrino energy range are scarce. Therefore, we performed the direct measurement of the PSD capability of our own liquid scintillator candidate using the 70 MeV quasi-monochromatic neutron beam at CYRIC. In addition to the measurement of the PSD capability, the scintillation quenching properties of the proton and the corresponding Birks constant at the neutrino energy range was also measured.

Figure 1 shows the conceptual layout of the experiment. The quasi-monochromatic neutron beam is produced by hitting lithium target with 70 MeV CYRIC proton beam. The energy of the neutron beam is measured by the Time of Flight (ToF1). Figure 2a shows the energy spectrum of the neutron beam measured by ToF1. A clear peak is observed at around 60 MeV.

Scattered-off neutrons from the Target LS are detected by Tagging LS. The energy of the scattered-off neutron is measured by ToF2. For elastic scattering with proton, the energy of the scattered proton is uniquely determined from the scattering angle. Figure 2b shows an example of the correlation between the visible energy of the Target LS (detailed energy calibration was not performed yet at this stage) and the energy of the neutron escaped from the Target LS measured by ToF2. The neutron selection in the Tagging LS using its PSD data was performed to further reduce the γ-ray background. A clear proton elastic scattering peak is seen in Fig. 2b. We performed the measurements at three different angles and used the neutrons with monotonously decreasing energy distribution to cover wide energy range.

After detailed energy calibration of the liquid scintillator, the quenching factor of the proton was measured. There are a lot of measurements of quenching properties of scintillation light from liquid scintillators but most of them were performed at lower energies. Therefore, it is important for us to measure the quenching factor of protons for energy range of ~40MeV. Figure 3 shows relation between the energy deposit in the target LS measured by the ToF1 and ToF2 and the visible energy. The visible energy is smaller than the energy deposit and the energy shift is parametrized as the Birks formula as shown below.

$$\frac{dL}{dx} = \frac{S\left(dE/dx\right)}{1 + k_B\left(dE/dx\right)} \tag{4}$$

where dL/dx is the scintillation light emission per unit path length. k_B is called the Birks constant which represents the quenching value. S is the conversion factor between dL/dx and dE/dx. For example, if there is no quenching (k_B=0), $S=(dL/dx)/(dE/dx)$. dE/dx is obtained from Monte Carlo simulation. From this experiment, the Birks constant is measured as

$$k_B = 0.012\,\mathrm{mm/MeV}.$$

This value is consistent with the values measured at low energy experiments. This result will be implemented in the Monte Carlo simulation for $JSNS^2$ experiment.

Next, the PSD capability of our liquid scintillator was measured. Figure 4a shows the energy dependence of the PSD parameter (ratio of the tail charge and total charge of signals). The ratio does not change much for energies up to 50 MeV. The width becomes narrower due to larger photoelectron statistics. This data indicates the PSD technique is still useful for this energy range. Figure 4b shows expected PSD parameter distribution in real detector calculated by Monte Carlo simulation using the PSD information obtained in this experiment. The Figure 4b shows that the separation of neutron and neutrino is very good and that the reduction of the fast neutron background using the PSD is satisfactory for the $JSNS^2$ experiment. The $JSNS^2$ experiment can go forward safely based on these results.

References

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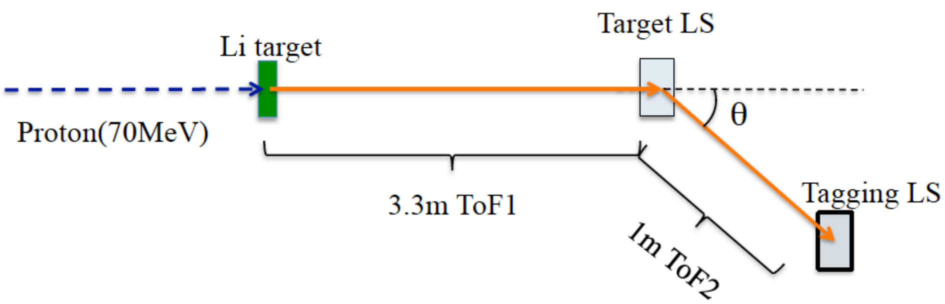


Figure 1. Set up of the experiment. The Target and Tagging LS is contained in a 100cc glass vial. The angle of the tagging LS was changed to cover a wide energy range in the target LS.

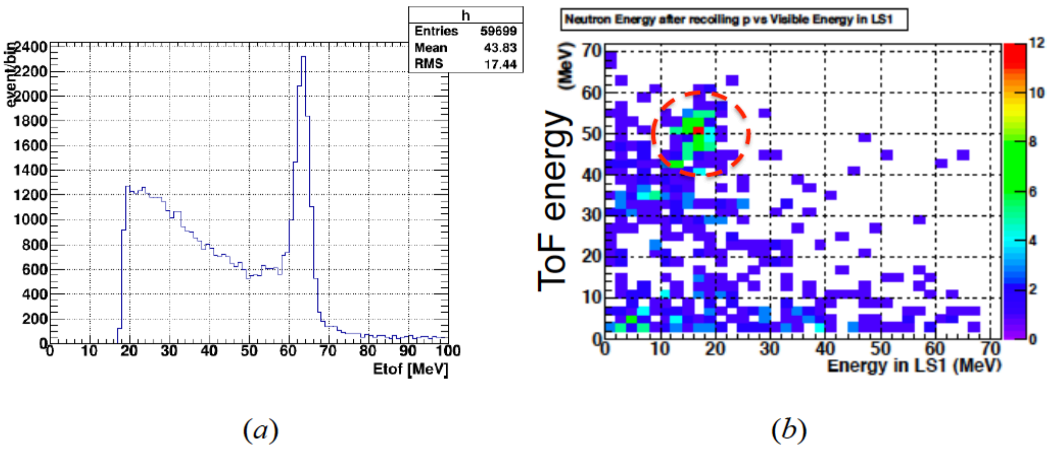


Figure 2. (a) The neutron beam energy measured by the ToF1. (b) The relation between the visible energy of the Target LS and the energy of the escaped neutron measured by the ToF2 (vertical axis).

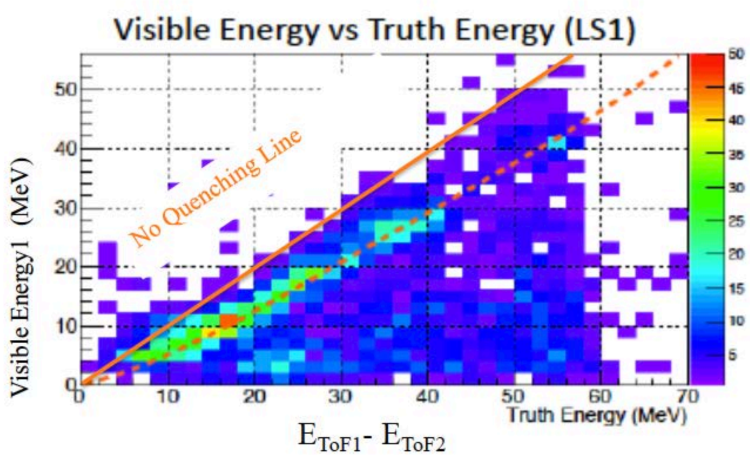
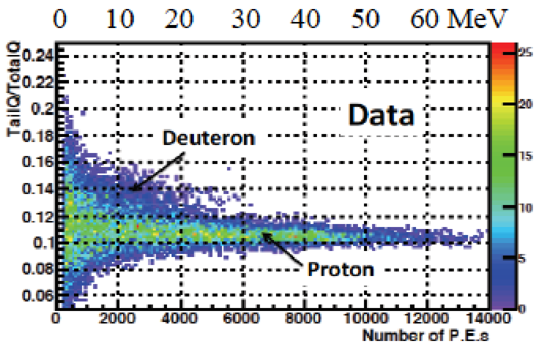
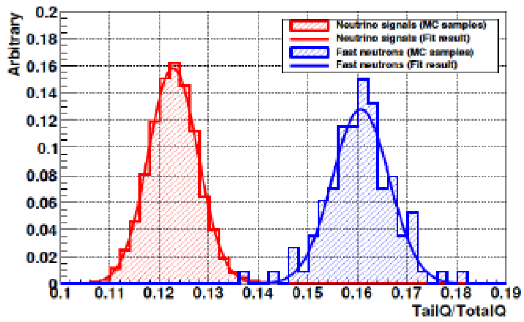


Figure 3. Quenching of scintillation light of proton. The horizontal axis is the deposited energy and the vertical axis is the visible energy for recoiled proton.



(a)



(b)

Figure 4. (*a*) Energy dependence of the PSD parameter (Tail and Total Charge ratio). 10,000 p.e. corresponds to roughly 50MeV. (*b*) Comparison of the PSD parameter distribution for neutrino like events (red) and neutron like events (blue).