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Measuring fast neutrons with large liquid scintillation detector for ultra-low background experiments

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ABSTRACT

We developed a 12-liter volume neutron detector filled with the liquid scintillator EJ301 that measures neutrons in an underground laboratory where dark matter and neutrino experiments are located. The detector target is a cylindrical volume coated on the inside with reflective paint (95% reflectivity) that significantly increases the detector's light collection. We demonstrate several calibration techniques using point sources and cosmic-ray muons for energies up to 20 MeV for this large liquid scintillation detector. Neutron–gamma separation using pulse shape discrimination with a few MeV neutrons to hundreds of MeV neutrons is shown for the first time using a large liquid scintillator.

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1. Introduction

The Sanford Underground Research Facility (SURF) was chosen as a site for ultra-low background experiments. The current two experiments are the direct detection of dark matter utilizing xenon with the Large Underground Xenon (LUX) [1] experiment and the search for neutrinoless double-beta using germanium with the MAJORANA DEMONSTRATOR [2]. Understanding the in situ background levels is extremely important for these rare-event physics experiments. Although positioning experiments in a deep underground laboratory significantly suppresses the background caused by cosmic-ray muons, the residual muons still create fast neutrons [3]. The intensity of the muon-induced neutrons depends largely on the depth of the underground laboratory [3]. The energy spectrum, multiplicity, and angular distribution of the muon-induced neutrons are not particularly well measured. In addition, there are also fast neutrons from (α,n) reactions that are created in the surrounding rock by natural radioactivity. In this paper we demonstrate a neutron background characterization technique that has been developed for a large liquid scintillation detector.

One major problem in neutron detection is the separation of neutrons from the electromagnetic background caused by gamma rays from the environment and internal contamination of the detector materials. The pulse shape discrimination technique, which uses the difference in the shape of the scintillation pulses generated by neutrons and gamma rays, has been implemented successfully with small neutron detectors for many years [4–8]. Unfortunately, small neutron detectors (of a few liters or less) have low efficiency when detecting neutrons and are high cost compared to size and efficiency. For the successful neutron background characterization, we require a higher efficiency of neutron detection and a broader energy sensitivity, along with lower cost per detector. The development of a relatively large volume detector increases the possibility of significantly improving the neutron detection efficiency. More importantly, it opens a window for exploring the neutron energy at a few MeV up to a few hundred MeV. Although most of the neutron–gamma discrimination experiments were carried out using small detectors, the possibility of neutron–gamma discrimination using time of flight (TOF) measurements have also been investigated using a large neutron detector [9]. In this work we investigate the possibility of using a large volume detector for the direct detection of neutrons with energy of a few ten MeV, with pulse shape discrimination to distinguish from gamma rays.

2. Experimental setup

We have constructed a liquid scintillation detector that is 1 m long and 5 in. (12.7 cm) in diameter. This detector is fabricated using an aluminum cylindrical housing with two Pyrex windows on each side of the cylinder attached to PMTs. To mitigate light loss, the inner surface of the detector was covered with reflective paint EJ520 (Eljen Technology) that has 95% reflectivity.

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The reflective paint makes scintillation photons scatter multiple times from the detector walls, which partially compensates for the relatively poor PMT photo-cathode coverage. The detector volume was filled with liquid scintillator EJ301, which is specifically designed for neutron–gamma discrimination. Scintillation light is collected by two 5-in. Hamamatsu R4144 PMTs attached to both Pyrex windows. Optical grease is used to couple the PMTs with the Pyrex windows to avoid optical mismatch and reflections. The geometry of the detector setup is presented in Fig. 1. The total photo-cathode coverage of the detector is at about 3% and the PMT quantum efficiency is about 20% for photons with a wavelength of 300–700 nm. The EJ301 is composed of carbon and hydrogen atoms, and has a H/C ratio of 1.212 and a density of 0.874 g/cm^3. Its light output is 78% as of anthracene with a maximum emission at 425 nm, which exactly corresponds to the most sensitive region of the Hamamatsu PMTs.

Contamination of oxygen in the liquid scintillator results in a reduction of light output. In order to minimize the amount of oxygen contamination, the scintillator was thoroughly purged with dry argon and then the detector volume was sealed before the measurements were performed. The operational voltages of both PMTs were determined to be 2000 V at which the PMT gain is 1.4×10^6 [10]. The DAQ consists of a fast flash ADC that analyzes the PMT output signal. The sampling frequency of the flash ADC is 170 MHz, providing a signal amplitude every 5.88 ns. The maximum amplitude the ADC can handle is 4096. If the peak sample of an event extend to be greater than 4096, we categorize it as a saturated event. In order to avoid saturation from high energy events, especially those close to the PMTs, both PMT output signals are attenuated at 23 dB before connecting to the DAQ. The pedestal level of the ADC is found to be ~1295 for PMT0 and ~1267 for PMT1 under the high voltage of 2000 V. The ADC is controlled by a program based on the MIDAS data acquisition system software [11]. The electronic system is shown in Fig. 2.

Fig. 1. The setup of our liquid scintillation detector. The aluminum foil pans are required for safety in case of leaks.

3. Energy and position calibration procedures

For a large scintillator, the detector response to energy with each individual PMT is determined by the energy deposition and the position where the incident particles interact with a target in the scintillator. This position dependence is caused by the attenuation of the light in the tube [12]. To obtain the position information, the charge ratio from the two PMTs is used to characterize the position of an incident particle. The following criteria are applied to select events:

(1) Both PMTs must be triggered.
(2) Both signals must not saturate the ADC.
(3) Time coincidence is within 30 ns, which is the time difference of the largest sample in the pulse between two PMTs.

Assume an energy deposition of E_{tot} is created at a distance of X (distance to the middle, see Fig. 3.), the light collection by two PMTs L_{left} and L_{right}, and the total light yield L_{tot} proportional to E_{tot}. Without any energy loss, the total light yield would be evenly split by the two PMTs, $L_{left} = L_{right} = 0.5L_{tot}$. In reality we have to consider light attenuation, especially for such a big detector. Taking l as the attenuation length in the scintillator and D as the total length of the tube, a simple calculation in Eq. (1) shows that the position can be determined by the combination of L_{left} and

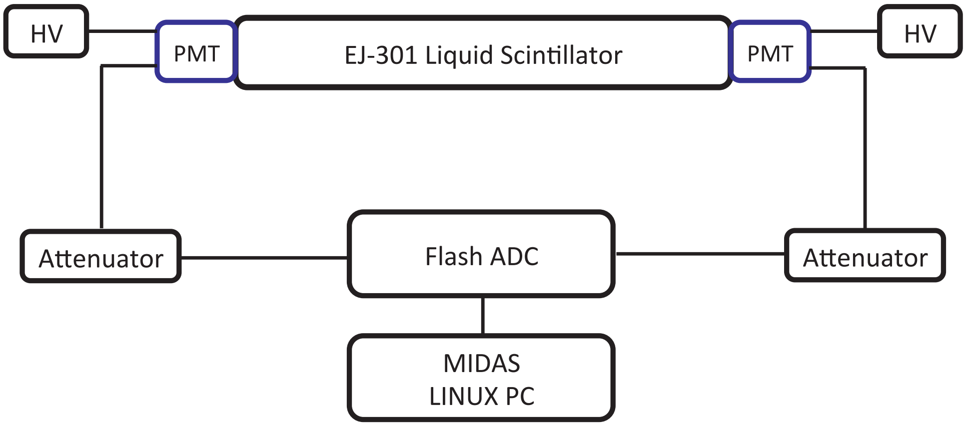

Fig. 2. The electronic system of the detector.

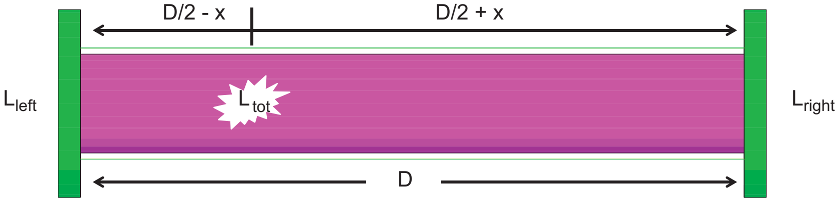

Fig. 3. Position of the incident particle and the total light yield being split and collected by individual PMTs.