



Development of an array of liquid-scintillator-based bar detectors: SABRE

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ABSTRACT

An array of neutron detectors based on liquid scintillator technology has been developed for nuclear reaction studies, in particular measurements with radioactive ion beams (RIBs). Reaction measurements with RIBs often involve low reaction yields and high gamma-induced backgrounds, which requires high solid angle coverage, high efficiency, and background reduction capability. The kinematics of the reaction neutrons require energy and position determination with good resolution, but preferably without a large number of readouts to minimize cost. To address these requirements, the Scintillation Array of Bars for Reaction Experiments (SABRE) consists of five 12" long, 2" diameter bar detectors filled with organic liquid scintillator and capped at both ends with individually read-out superbialkali photomultiplier tubes (PMTs). In-house purification of the scintillator mixtures resulted in improved light collection. Discussion of the liquid scintillator development and the design and commissioning of SABRE will be presented.

1. Introduction

Neutron detection is an important tool in experimental nuclear physics. Major thrusts in nuclear physics include the evolution of single-particle structure, the limits of nuclear binding, the origin of the heavy elements, and the nuclear matrix elements relevant to neutrinoless double beta decay. In these and many other studies, the spectroscopic detection of neutrons can provide insight: the single-nucleon transfer reaction (d,n) preferentially populates strong proton-single-particle states in unstable nuclei; neutron elastic and inelastic scattering can elucidate the nature of neutron-dense matter such as neutron skins; (α ,n) reactions on low-mass seed nuclei emit a large neutron flux in the interiors of Asymptotic Giant Branch stars, driving nucleosynthesis; the charge-exchange (p,n) reaction can provide information on electron capture in supernovae; and (^3He ,n) proton-pairing reactions on potential $0\nu\beta\beta$ candidates can validate nuclear matrix element calculations. In these example cases as in many others, the reaction of interest must be performed in inverse kinematics with a radioactive ion beam (RIB), which may have low reaction yields, and which compresses the neutron kinematics making position (angular) resolution important. Hence, efficient detection of the energy and interaction point of fast (\sim MeV) neutrons emitted in the reaction is crucial, driving a need for position-sensitive, high solid angle, high resolution detectors for neutron spectroscopy.

Various types of neutron detector materials have been employed for fast neutron detection, including plastic scintillators and organic liquid scintillators. These materials do not moderate the neutron energies before detection and therefore may be used for spectroscopy via the neutron time-of-flight (nToF) technique. However, in many cases a continuous background of gammas may be expected, both from natural background sources as well as beam-induced radiation. This extra background cannot be removed using standard time-of-flight techniques, but can be removed using the technique of pulse shape discrimination (PSD) for neutron/ γ discrimination. Both standard plastic and liquid scintillator are inexpensive and easy to fabricate, but plastic scintillators have limited neutron/gamma (n/ γ) discrimination capability. So-called "PSD plastic", or plastic scintillator designed with PSD capability (for example, [1]), can become prohibitively expensive when used in the large quantities needed for RIB-driven measurements. Organic liquid scintillators, however, exhibit strong inherent n/ γ PSD for low-cost standard materials while maintaining time-of-flight capability, and hence were chosen for the design of SABRE. Particularly in the era of radioactive ion beams (RIBs) where production via fragmentation or even the beam itself may produce background gamma rays via decay, pulse shape discrimination is of tremendous use in enabling the next generation of nuclear physics measurements with neutrons.

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2. Development of SABRE

2.1. Liquid scintillator development

Liquid scintillator technology has been utilized in nuclear physics applications for decades; see, for example, Refs. [2–4]. In the current work, effort was made to optimize and purify the scintillator mixtures for the SABRE detectors. While it is possible to use the non-nToF technique of spectrum unfolding with deuterated organic scintillators [5], for cost reasons this technique was not employed for SABRE, and only hydrogenated organic scintillators were considered. A benefit of using liquid scintillators is the ability to easily deploy the scintillator material in detectors of various geometries, allowing the development of the active detection materials to be decoupled from the development of specific detector arrays or implementations.

While liquid scintillator mixtures are available commercially, in-house development provides several benefits. It allows the liquid scintillator formulation (or “cocktail”) to be purified to stricter standards, and to be tuned to meet various experimental objectives, such as PSD threshold, light output, ease of handling, or other considerations which might be required for next-generation radioactive ion beam facilities, such as the Facility for Rare Isotope Beams (FRIB). Based on the work of Ref. [3,4], an initial “standard” liquid scintillator cocktail composed of naphthalene, 2,5-diphenyloxazole (PPO), and 1,4-bis(5-phenyloxazol-2-yl) benzene (POPOP) was produced, with p-xylene as the solvent. The introduction of naphthalene is known to enhance pulse shape discrimination properties [6]. Using a 2” diameter borosilicate glass test cell as shown in Fig. 1 coupled to a 2” diameter Hamamatsu superbialkali photomultiplier tube (PMT; Model: R6231-100-01 ASSY), this “standard” mixture was tested and its PSD performance was found to be comparable to several commercially available organic liquid scintillators. Because this initial composition was previously demonstrated in the literature [3,4] and was similar to what was commercially available, it was used as a reference for the improvements discussed below.

All reagents were acquired through Sigma Aldrich with an initial reported purity of 99% or greater. Scintillation-grade naphthalene and anhydrous p-xylene were used. The p-xylene was further purified in-house by triple distillation into a collection flask containing 4Å molecular sieve, to remove any remaining water left in the solvent. The fluors PPO and POPOP were used without further purification, as their concentrations in the cocktail were very low. It was noted that the scintillation grade naphthalene exhibited a yellow/brown contaminant which severely affected the attenuation length of the scintillator (discussed in more detail later). This contaminant was successfully removed by a multi-step purification process, which involved triple recrystallization from methanol followed by sublimation. Fig. 2 shows the appearance of naphthalene throughout each stage of the purification process, along with their associated Fourier Transform Infrared (FTIR) spectrograms. While no attempt was made to identify the contaminant compound or compounds, Fig. 2 clearly shows a reduction in the broad feature between 9–9.5 μm after purification, accompanied by a visible change in the material color. The attenuation length of the scintillator for light at 420 nm increased from 1.2 m using the raw naphthalene material to ~ 3 m after purification, as determined with small liquid samples and a spectrometer. Scintillator cocktails were prepared using standard Schlenk air-free handling techniques. Transfer of the liquid scintillator between each purification and mixing step, as well as into the detector volume, was performed using cannulation into evacuated and argon-purged flasks. Final transfer of the scintillator to the bar detector was performed using a special 1/4” Swagelok adapter retrofit for a cannula, and the scintillator was bubbled with argon to help remove any remaining contaminants from exposure to air. The reader is directed to Ref. [7] for detailed explanations of the purification techniques used in the current work. The best-performing cocktail (see Section 3 for a description of the performance) was a mixture of 60 g/L purified naphthalene, 4 g/L PPO, and 0.2 g/L POPOP in purified p-xylene.



Fig. 1. Photograph of the 2” diameter x 2” length borosilicate glass test cell with purge and septa ports.

Because exposure to air or moisture can cause deterioration to organic liquid scintillators, a small sample of each batch of scintillator cocktail made in-house was kept in a small, air-tight, light-free container labeled with its composition and date. This allowed later comparison between the cocktail as made and the cocktail as it appeared in a SABRE detector, in order to track any potential “aging” or contamination of the scintillator. Throughout the course of the tests described in this paper (cf. Section 3), no noticeable deterioration to the scintillator in the detectors was observed.

2.2. Detector array development

The use of scintillator arrays for neutron detection is well established (cf. Ref. [8–11] for example). For the low reaction yields which may be present with radioactive beam measurements, large solid angles need to be covered, necessitating the use of large volumes of neutron detection material. A major disadvantage to the large “neutron wall” type arrays of plastic scintillator bars such as MONA-LISA [12], LENDA [10], and VANDLE [11], when employed for reaction studies with RIBs, is the lack of neutron/gamma discrimination. Such non-PSD plastic scintillator, while simple to fabricate, requires additional external information to suppress the gamma background. Typically, a coincidence detector, usually measuring the beam-like recoil particle, or a timing signal from the accelerator, such as the RF, is required in order to separate neutrons and gammas via time-of-flight. This effectively separates neutrons from prompt gammas, but does not suppress the random background gammas which can dominate over the reaction products of interest by orders of magnitude. Prototype detectors based on PSD plastic, such as PANDORA [13], can be prohibitively expensive when purchased or fabricated in the large volumes needed for RIB reaction measurements. Organic liquid scintillators, on the other hand, provide good n- γ discrimination and can be fabricated in large quantities for relatively modest cost, and hence were chosen for the SABRE bars.

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