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Recent developments in deuterated scintillators for neutron measurements at low-energy accelerators

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ABSTRACT

Deuterated (^{2}H-based) organic scintillators, unlike conventional ^{1}H-based scintillators can generate pulse-shape gated neutron energy spectra 1 to 30 MeV without need for time-of-flight (ToF). They are especially appropriate for measurements at high-intensity, low-energy accelerators where a pulsed beam is not available. Even when the latter is available, the loss in effective beam intensity combined with the need for suitable long-path ToF measurements can be very inefficient. In contrast, as we demonstrate, arrays of d- benzene scintillators (NE230, BC537, EJ315) and recently xylene-d10 (EJ301D) together with related digital signal processing (DSP) can provide highly efficient neutron energy measurements w/o n-ToF. We also report the recent synthesis and initial testing of crystalline d-stilbene as a neutron detector.

Contents

1. Introduction

In this paper we review the discovery of the neutron by Chadwick with a recoil proton detector, why one would use deuterated scintillators, the early work of Brooks et al. 1970–1980s, the recent UM

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work with benzene-d6 (C_6D_6; EJ315), the development of xylene-d10 (EJ301D), and future plans for development of new types of deuterated scintillators.

2. History

Although the neutron is a major constituent in normal matter, being neutral it could be considered the original weakly-interacting (E&M interactions at least), massive particle (WIMP). Although its existence was deduced shortly after the atomic nucleus was discovered in the early 1900s, it was not until the 1930s, i.e. fairly recently, that its existence and mass were established by James Chadwick [1]. Chadwick used a strong ^{210}Po–Be source to produce neutrons and a recoil-proton detector consisting of paraffin and other converters with a gas proton detector. This established that the radiation from the source was not gamma rays, but instead a massive neutral particle with a mass near that of the proton. The use of a proton converter such as paraffin to detect neutrons is still the basis for many neutron detectors many years later including organic, ^{1}H-based liquid and plastic scintillators.

3. Why deuterated scintillators?

Recall that a proton and neutron are basically the *same* particle, thus n+p scattering (including charge exchange) in an organic scintillator has forward–backward symmetry yielding recoil protons in the scintillator with the full energy range of the incident neutron energy. Hence there usually is no distinct peak in the scintillator light output spectrum e.g. for energies in the range 1–30 MeV [2]. Long-path neutron time of flight (n-ToF) i.e. using a bunched, often pulse-selected beam is needed to obtain good-resolution neutron energy spectra. The latter are often needed in studies of (d,n), (α,n), (^{3}He,n) and similar nuclear reactions with neutron energies 1–30 MeV.

In contrast (Fig. 1) n+d scattering is asymmetric and at MeV neutron energies produces a forward-going deuteron recoil in a deuterated scintillator with 8/9 of the incident neutron energy. This, unlike ^{1}H-based scintillators, produces distinct "bumps" in the light output spectrum [2,3]. This is shown in Fig. 2 where we compare the light output of ^{1}H- and ^{2}H-based liquid scintillators (EJ315H and EJ315/NE230) for a typical (d,n) reaction using a CD_2 target yielding neutron reaction products up to 25 MeV [3]. Even without precise spectral unfolding (see below) one can often use the raw light spectrum from EJ315/NE230 to measure reaction cross sections in some cases without using neutron time-of-flight.

4. 1970s–1980s: Brooks et al., Lister et al.

Brooks et al. recognized the above features and developed deuterated-anthracene detectors and later benzene-d6 detectors (NE230,BC537) for neutron measurements [2]. However spectral unfolding techniques to obtain energy spectra were somewhat limited, although a number of useful (d,n) measurements with incident polarized deuterons were made by Lister et al. using these detectors [4]. Later, our U. Michigan (UM) research group and others likewise developed expertise in the use of deuterated scintillators, primarily NE230 (benzene-d6). These proved useful in measurements such as the (^{3}He,t) reaction to isobaric analog states. The latter have a neutron decay that can be detected in a coincidence measurement to provide very clean reaction spectra [5]. Likewise, a high-accuracy, low-background measurement searching for d-d cold fusion neutrons was made at UM using an inverted reaction cell with NE230 (Fig. 3). Energy-gated fusion neutron spectra could then be obtained directly from the light output spectra and a very low limit on the production of d-d fusion in the cell established [6].

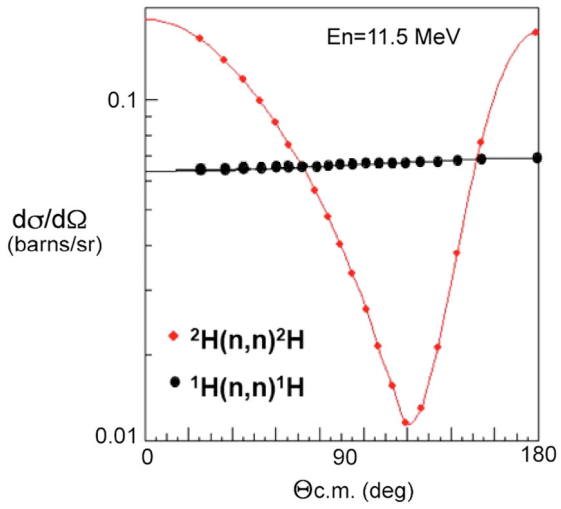

Fig. 1. (left): Comparison of n + ^{1}H and n + ^{2}H elastic scattering angular distributions (ENDF data).

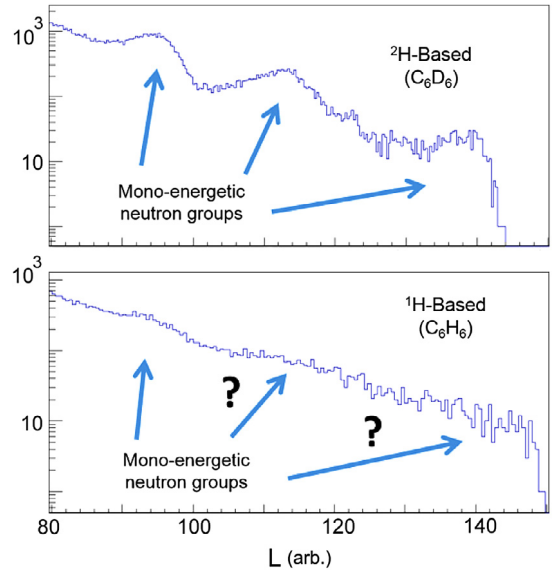

Fig. 2. (right) : Comparison of light-output spectra obtained for benzene-d6 (EJ315) and ^{1}H-based benzene (EJ315H) for a typical (d,n) reaction using a CD_2 target and E_d = 16 MeV [3].

5. Recent UM work

Given the early success at UM and elsewhere utilizing NE230 and BC537(benzene-d6) detectors, this was further pursued in several UM Ph.D. projects using both NE230 and their Eljen, Inc. equivalent, EJ315. Initial measurements, mainly of several (d,n) reactions, utilized an array of 2 in. dia × 2 in. deep (2″ × 2″) NE230 cells with analog electronics for pulse-shape separation of neutrons and gamma rays [7]. Again the extraction of neutron energy spectra was hampered due to the limited neutron unfolding procedures then available, and in particular the lack of good detector response data for mono-energetic neutrons [7].

Later as part of another UM Ph.D. project [3] arrays of 4″ × 6″ EJ315 and other detectors were developed (Fig. 4) and used in several nuclear reaction studies. This included development of an event-mode data acquisition system recording fully-digitized (DSP) scintillator PMT and n/γ pulse-shape discrimination (PSD) signals with post-processing for PSD, light output, and signal timing where appropriate [3]. These detectors were then utilized in another UM Ph.D. project examining