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Systematic Study of (d,n) Reactions at E_d = 16 MeV Using a Deuterated Scintillator Array

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Abstract. We have developed a multi-element deuterated liquid scintillator array for the study of reactions involving neutrons utilizing high-speed digital signal processing. A systematic study of (d,n) reactions at E_d = 16 MeV on ^{9}Be, ^{11}B, ^{13}C, ^{14}N, ^{15}N, and ^{19}F has been conducted from 10^o to 160^o (lab). In addition to previously unmeasured back-angle cross sections, this data can complement existing and future (^{3}He,d) measurements as an analog to (p,γ) for astrophysics applications.

1 Introduction

Neutron spectroscopy measurements incur additional challenges over charged particle detection. Primarily, this arises from their lack of charge leading to an inability to easily detect them directly. This only permits indirect methods for detection. Neutron time-of-flight (n-ToF) has been the primary method for detection of energetic neutron spectroscopy applications. This becomes problematic for high background / low cross sections measurements due to a number of factors including low absolute efficiency, limited timing resolution, room-return neutrons, muon b.g., or flight-path limitations. We have developed a modular deuterated scintillator array to face these challenges, which is capable of neutron spectroscopy without n-ToF [1,2] denoted as the University of Michigan Deuterated Scintillator Array (UM-DSA). The array is currently comprised of up to six 5.08 cm dia. x 5.08 cm cylindrical EJ-315 (Eljen – 315 deuterated benzene based scintillator) and another six 10.16 cm dia. x 15.24 cm cylindrical EJ-315 liquid scintillation detectors. The liquid organic scintillators exhibit good digital pulse shape discrimination (DPSD). Typical configuration involves the detectors fixed to adjustable aluminium mounts, secured to an 80/20 aluminium frame. This allows for quick and adaptable configurations to be made for varying experimental conditions including measurements over a large angular range. High-speed waveform digitizers record scintillation pulses at either 1 or 2 GS/s at 10-bit resolution (CAEN V1751) or up to 5 GS/s at 12-bit resolution (CAEN V1742). Commissioning experiments were conducted by running a systematic study of (d,n) reactions at E_d = 16 MeV at the University of Notre Dame (UND).

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2 Experimental Method

The measurement campaign was conducted at the UND Nuclear Science Laboratory using the FN tandem Van de Graaff accelerator. Isotopically enriched solid and gas targets (see table 1 for detailed list), were bombarded with a 100 MHz pulsed deuteron beam at E_d = 16 MeV. A 5.08 cm x 5.08 cm diameter gas cell with 10 µm thick Havar® entrance and exit windows was used for the gas targets. A target of ^{9}Be was included to provide a direct comparison with data taken at E_d = 16 MeV using conventional n-ToF method. The beam was dumped into a graphite faraday cup shielded with borated-water containers, borated polyethylene pellets, and 60 cm x 60cm x 60 cm lead block cave to reduce the beam induced background. Care was taken to minimize beam-induced background since this technique does not rely on n-ToF, thus beam induced background can only be eliminated by shadow bar measurements and with timing gates when timing information is applicable. Timing information from the pulsed beam for this series of measurements was used to establish timing gates to reduce beam-induced background. 5.08 cm dia. x 5.08 cm cylindrical EJ-315 deuterated liquid scintillation detectors were located 50 cm from the target to the face of the detector. Waveforms were digitized at 1 GS/s with 10-bit resolution using the CAEN 1751 waveform digitizer for an acquisition window of 400 ns. The close proximity of the detectors to the target was chosen to maximize count rates while preserving the angular resolution.

Table 1. List of targets and areal densities

Target	**Areal density (mg/cm^2)**
^{9}Be	1.85
^{13}C	8.55
^{11}B	23.1
^{14}N	3.2
^{15}N	3.7
^{19}F	8.0

3 Analysis and Discussion

3.1 Waveform Processing and Particle Discrimination

Digitized waveforms were processed using a custom analysis package written in C++ by the authors with routines specific for analysis and discrimination of fast scintillation pulses. The analysis package contains routines which are based on traditional analog pulse-processing techniques. This permits an intuitive approach to analysis thus facilitating faster competency with new users. Each waveform was baseline corrected. A peak-finding routine was used to determine multiple peaks in a given waveform. If two peaks occur within the integration range of each other the region was noted as “dead time”. No attempt was made to extract the individual pulses from these events because of their infrequency (< 0.1 % of events). The choice of the terminology “dead time” has to be made clear, as technically the digitizer is capable of continuous digitization until the onboard memory becomes full thus has no intrinsic dead time. Leading edge timing using a constant-fraction discrimination method, amplitude, rise-time, fall-time and width was then determined. Finally, a pulse shape discrimination routine was used for identification of recoil particle type.

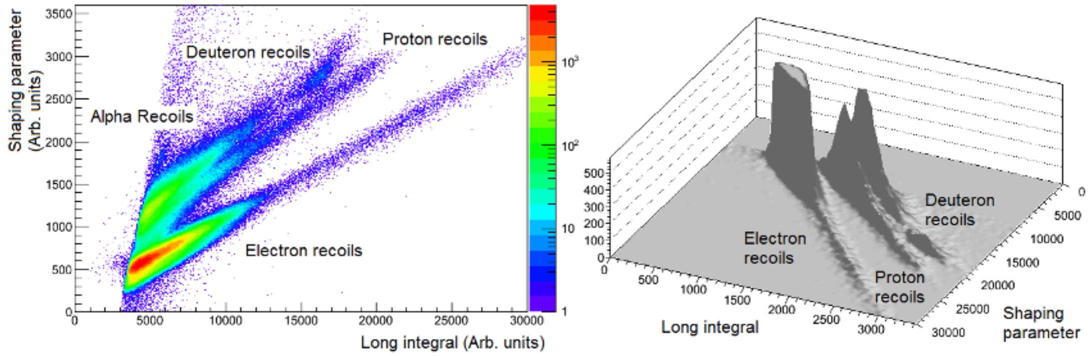

Figure 1. DPSD of α/d/p/e discrimination from the reaction 5.08 cm dia. x 5.08 cm cylindrical EJ-315 deuterated-liquid scintillation detector

Recoil particle identification and subsequent discrimination was accomplished using the charge integration technique in which a comparison is made of long and short anode pulse integrals. These integrals are a measure of the total light yield (i.e. prompt + delayed fluorescence) and the delayed fluorescence contribution of a recoil-particle interaction, respectively. In digital processing, this is made by computing the numerical integral, in our case using a trapezoidal method, over the entire pulse and the short integral from a user-defined offset (typically 25 ns from 50% amplitude of the leading edge) to the end of the pulse. The choice of the offset parameter was made by maximizing the Figure-of-Merit (FOM) for recoil electron-deuteron-proton separation. Good n/γ separation is observed down to 100 keV_{ee}.

3.2 Ground State Relative Cross Sections

Ground-state cross sections were extracted using the deuteron recoil-peak analysis technique described in [1]. As shown in figure 1, the DPSD shows good discrimination of recoil electrons, protons, deuterons, and alpha particles. It is important to obtain good discrimination of protons and deuterons in order to gate on the recoil deuterons. Protons from deuteron breakup do not exhibit a recoil peak and thus can mask and distort the shape of the recoil peak. This inclusion leads to a broadening of deuteron recoil peaks which effectively reduces the resolution. Recoil peaks were observed up to E_n = 30 MeV (i.e. g.s. neutrons from $^{11}B(d,n)^{12}C$ at 10^o lab).

Deuteron recoil-peak efficiency was simulated using the Monte Carlo code MCNP-PoliMi and measured experimentally using the $^2H(d,n)^3He$ reaction to determine neutron fluence by ^3He recoil tagging. Efficiency corrected relative cross section are shown in Figure 2. $^9Be(d,n)^{10}B$ shows good agreement to the measured data of Park, et al measured at E_d = 16 MeV using n-ToF. More complete efficiency measurements are underway and will permit extraction of spectroscopic information using DWBA.

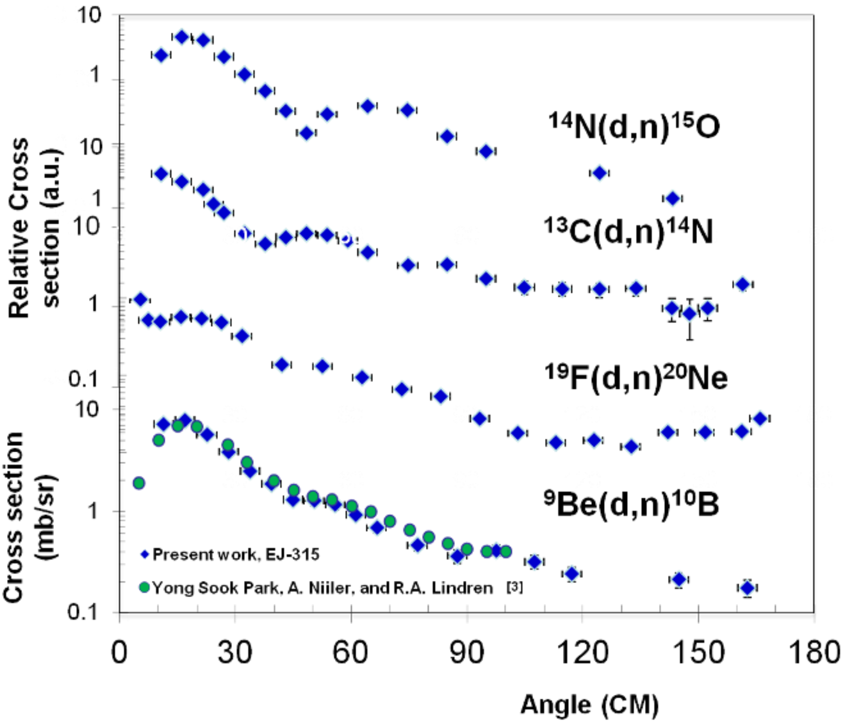

Figure 2. Extracted ground state cross sections for ^{14}N, ^{13}C, and ^{9}Be, $^{19}F(d,n)$ measure at E_d = 16 MeV using a 5.08 cm dia. x 5.08 cm cylindrical EJ-315 deuterated liquid scintillation detector.

4 Conclusion

A systematic study of (d,n) reactions has been completed on gas and solid targets with the UM-DSA at UND. The array shows good DPSD characteristics down to 100 keVee. Analysis of deuteron recoil peaks and subsequent measured angular distributions show that the array can be used for neutron spectroscopy studies without the use of n-ToF up to at least E_n = 30 MeV. As noted in [1], recoil protons from breakup can mask recoil peaks and thus good PSD is essential for low statistics or high resolution experiments. Experiments are currently underway for the study of (^{3}He,n) to medium mass nuclei at E_n > 20 MeV. Efficiency measurements are currently underway and will permit extraction of spectroscopic factors information using DWBA. Future plans are to study neutron-producing reactions such as (p,n), (d,n), and (^{3}He,n) with radioactive nuclear beams, where high Q-values and low beam intensity make n-ToF measurements difficult.

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