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Light output response of EJ-309 liquid organic scintillator to 2.86–3.95 MeV carbon recoil ions due to neutron elastic and inelastic scatter☆

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ABSTRACT

We present the first measurements of energy-dependent light output from carbon recoils in the liquid organic scintillator EJ-309. For this measurement, neutrons were produced by an associated particle deuterium–tritium generator and scattered by a volume of EJ-309 scintillator into stop detectors positioned at four fixed angles. Carbon recoils in the scintillator were isolated using triple coincidence among the associated particle detector, scatter detector, and stop detectors. The kinematics of elastic and inelastic scatter allowed data collection at eight specific carbon recoil energies between 2.86 and 3.95 MeV. We found the light output caused by carbon recoils in this energy range to be approximately 1.14% of that caused by electrons of the same energy, which is comparable to the values reported for other liquid organic scintillators. A comparison of the number of scattered neutrons at each angle to a Monte Carlo N-Particle eXtended simulation indicates that the ENDF/B-VII.1 evaluation of differential cross sections for 14.1 MeV neutrons on carbon has discrepancies with the experiment as large as 55%, whereas those reported in the JENDL-4.0u evaluation agree with experiment.

1. Introduction

Organic scintillator detectors are used as fast neutron detectors in a variety of applications. Detector systems employing organic scintillators exist or are under development with applications including nuclear nonproliferation and international safeguards [1], nuclear medicine [2], neutrino detection [3], and weakly interacting massive particle (WIMP)/dark matter detection [4–6]. Organic scintillators have several desirable attributes as neutron detectors [7] including fast timing properties, pulse shape discrimination capabilities, and some spectroscopic capability because of the preservation of information about the energy of incident neutrons.

As the application space for organic scintillators expands, the demands for increasingly accurate light output data increase. Advanced neutron imaging detection systems rely on light output data to accurately reconstruct neutron source locations [8]. Dosimetry systems use light output data to determine the energy deposited in each event, enabling energy-dependent flux-to-dose conversions [9]. In many nonproliferation applications, it is desirable to reduce the detection threshold to increase the efficiency of the detector system, which typically increases the sensitivity and reduces the required measurement time.

A large body of work exists about characterizing the light output in organic scintillators because of the interactions between neutrons and hydrogen nuclei [10–17]. However, in some application areas, improvements to carbon light output data would benefit the analysis of experimental data and the fidelity of Monte Carlo simulated detector response. For example, in some WIMP studies, interactions with carbon are expected to provide the sought-after signal [4,5]. In neutron detection applications, as neutron energy increases, so does the importance of accurately accounting for the light from carbon recoils; at higher energies, the interaction cross section for carbon exceeds that of

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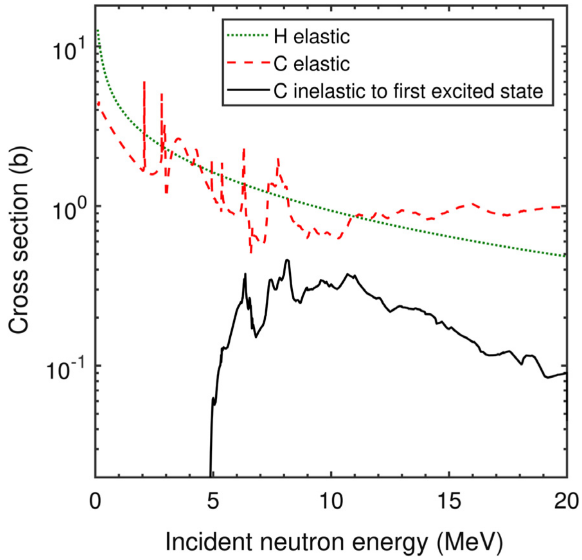

Fig. 1. (Color online) Elastic and inelastic neutron scattering cross sections on hydrogen and carbon, from ENDF/B-VII.1 [21,22].

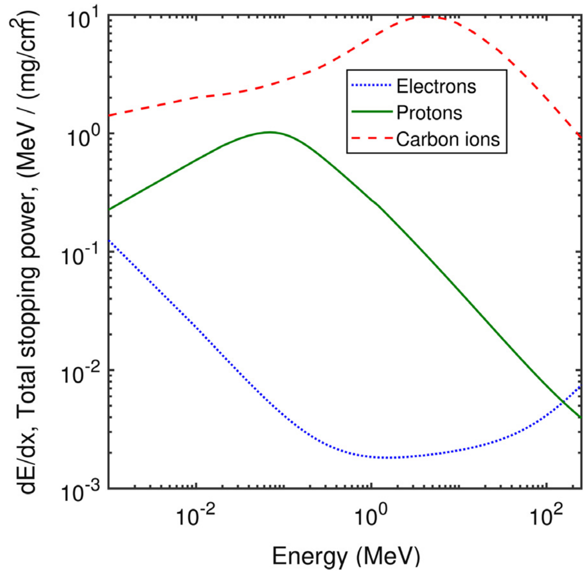

Fig. 2. (Color online) Total stopping power of electrons and protons in EJ-309 liquid scintillator, generated using the National Institute of Standards and Technology ESTAR database [28] and the SRIM-2012 package [26,27].

hydrogen. Examples of the use of high-energy neutrons include active interrogation systems that use 14.1 MeV neutrons from deuterium–tritium (D–T) neutron generators for nonproliferation applications and external beam radiation therapy systems for medical applications that produce neutrons with energies as high as 250 MeV.

Publications reporting the light output resulting from carbon interactions are scarce [10,11,18,19]. One contributing factor is the difficulty of isolating instances of carbon-only interactions. The carbon signal is usually dominated by the hydrogen signal, and careful experimental design is required to isolate and extract the carbon signal. This paper reports an effective method for characterizing the light output from single-scatter events on carbon nuclei in organic scintillator detectors that uses both elastic and inelastic scatter reactions and presents the first measurements of the light output for carbon recoils in EJ-309 [20] in the energy range of 2.86–3.95 MeV.

Table 1
Basic properties of EJ-301 and EJ-309 liquid organic scintillators.

Properties	EJ-301	EJ-309
Light output (% Anthracene)	78	80
Scintillation efficiency (photons/1 MeV e−)	12,000	12,300
Wavelength of maximum emission (nm)	425	424
Mean decay times of first 3 components (ns)	3.16 32.3 270	–
Bulk attenuation length	(2.5–3)	>1
Refractive index	1.505	1.57
Flash point (°C)	26	144
Boiling point (°C at 1 atm)	141	290–300
Vapor pressure (mm Hg. At 20 °C)	–	0.002
No. of H atoms per cm^3	4.82	5.43
No. of C atoms per cm^3	3.98	4.35
No. of electrons per cm^3	2.27	3.16

2. Background

Organic scintillators are composed of hydrocarbons. Neutrons deposit energy in the scintillator through scattering on hydrogen and carbon nuclei, and the recoiling nuclei interact with the scintillation molecules to produce scintillation light. Fig. 1(a) shows the cross sections from the Evaluated Nuclear Data File (ENDF/B-VII.1) [21] for three interaction channels: elastic scatter on hydrogen and elastic and inelastic scatter (to the first excited state) on carbon, for the energy range from 0.1 to 20 MeV. At low energies, the hydrogen cross section dominates, but as neutron energy increases the carbon elastic scatter cross section approaches and then surpasses hydrogen. The inelastic scatter cross section exhibits a low-energy threshold because the incident neutron must have sufficient energy to excite the carbon nucleus to its first excited state.

Ionization quenching results in a reduction in the amount of light produced by neutron interactions versus the amount produced by a γ ray depositing equal energy [23,24]. The magnitude of quenching is proportional to ionization density; if the excited scintillator molecules are created closer together, they have a higher chance to interact with each other, which reduces the amount of light emitted. Recoil electrons generally have low stopping powers, and the light can be considered largely unquenched. Protons have dramatically higher stopping powers than electron recoils, which leads to higher ionization densities and greatly reduced light output as a function of energy deposited. Heavier particles, such as α particles and carbon ions, have even higher stopping powers, so they produce less light. Birks [23], Voltz [24], Craun [25], and others have proposed equations for light output that include quenching terms that depend on the stopping power of the recoil particle in the detector material, dE/dx. Fig. 2 shows the total stopping powers in EJ-309 of electrons, protons, and carbon ions, which were determined using the SRIM software package [26,27] and the National Institute of Standards and Technology's ESTAR database [28]. These stopping power values are used throughout this work.

In previous characterization of proton light output in scintillators [13,17,29], the investigators used the approach of Kornilov [12] to identify the pulse heights corresponding to single proton recoils. The method uses the time-of-flight of neutrons from a white neutron source to determine the incident energy. Neutrons can deposit any fraction of their energy to recoil protons, so each neutron energy bin produces a broad pulse height distribution (PHD). Moreover, multiple scatter events are common in organic scintillators of appreciable size, carbon scatter events occur, and detector resolution broadens what would otherwise be a clear "edge" corresponding to full-energy depositions to a single proton. Therefore, to determine the appropriate pulse height-to-energy relationship, one must either take a fraction of the edge or use Kornilov's approach of taking the derivative of the PHD and fitting a Gaussian to the result, where the mean of the Gaussian corresponds to the single full-energy proton event. However, these techniques cannot be used to