

Measurement and Shielding of Alpha-Induced Fast Neutrons on ^{13}C and ^{11}B

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Abstract—Fast neutrons generated by alpha-induced reactions on ^{13}C and ^{11}B present a radiation-protection challenge for high-energy helium ion implantation systems. Neutron energies from the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{11}\text{B}(\alpha, n)^{14}\text{N}$ reactions were measured for helium beam energies of 1.5–2.7 MeV using a $\text{Cs}_2\text{Li}_6\text{YCl}_6\text{:Ce}$ scintillation detector. Ultrathin targets minimized beam-energy loss and enabled direct measurement of the highest kinematically accessible neutron energies. The measured spectra were used as source terms in GEANT4 and OpenMC simulations of borated-polyethylene shielding thicknesses of 1–40 cm. Representative shielding-response results are presented for neutron energies of 0.1–8 MeV, along with attenuation maps as functions of neutron energy and shield thickness. These measurements and calculations provide experimental input for radiation transport modeling and shielding design for next-generation high-energy light-ion implantation accelerators.

Index Terms—Fast neutrons, helium ion implantation, borated polyethylene, neutron shielding, CLYC detector, neutron spectroscopy, GEANT4, OpenMC, alpha-neutron reactions.

I. INTRODUCTION

High-energy helium ion implantation is increasingly relevant for semiconductor device manufacturing, particularly for power-device applications such as insulated-gate bipolar transistor (IGBT) devices. Hydrogen and helium implantation can be used to modify carrier lifetime and switching speeds. As the energy of the helium beam increases, the probability of nuclear reactions between incident alpha particles and target nuclei increases, potentially generating fast neutrons. For ion-implantation accelerators, the source of neutrons produced can be difficult to characterize experimentally because neutron production depends on beam energy, beamline configuration, beam current, geometry, and secondary interactions. When considering practical shielding calculations, the use of measured neutron spectra instead of estimated neutron distributions from reaction kinematics can reduce the overall uncertainty when evaluating shielding requirements for industrial accelerator configurations.

The $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{11}\text{B}(\alpha, n)^{14}\text{N}$ reactions are of practical interest because carbon and boron may be present in ion-implantation systems, process materials, and accelerator components. Depending on the incident helium energy and the reaction channel, the emitted neutrons may fall in the fast-neutron regime (neutron energies above 1 keV), where shielding behavior is strongly dependent on neutron energy.

Fast neutrons interact primarily through nuclear scattering and absorption processes, unlike charged particles whose interactions are usually described by charged particle stopping

powers. Hydrogen-rich materials such as polyethylene are effective in attenuating energetic neutrons through elastic scattering from protons. Borated polyethylene (BPE) captures thermal neutrons using boron absorption reactions in both ^{11}B and ^{10}B . However, the effectiveness of BPE depends on the neutron energy, the thickness of the shield, the concentration of boron, and the angular distribution of the neutron energies from the source. Mitigating neutron production requires reliable knowledge of both the angular distribution and the energy spectrum of the emitted neutrons.

The purpose of this work is to combine experimental neutron spectroscopy with a material-specific Monte Carlo shielding model. The neutron energy spectra produced by the reactions $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{11}\text{B}(\alpha, n)^{14}\text{N}$ were measured using a $\text{Cs}_2\text{Li}_6\text{YCl}_6\text{:Ce}$ (CLYC-6) scintillation detector. Neutron energies were measured using a CLYC-6 scintillator, which provides pulse-shape discrimination fast-neutron spectroscopy through the $^{35}\text{Cl}(n, p)$ secondary reaction channels [1], [2]. The measured spectra were used as source terms in GEANT4 and OpenMC simulations of BPE shielding, and the results of the codes compare transmission factors of selected neutron energies.

II. EXPERIMENTAL SETUP

Measurements were performed on an Axcelis VXE LT ion implanter at the MIT-Bates Linear Accelerator Center. Helium beams from 1.5 to 2.7 MeV were directed onto thin carbon and boron targets mounted in a custom aluminum chamber, as shown in Fig. 1.

The target chamber incorporated beam collimation, secondary-electron suppression, and tungsten shielding to minimize neutron production from unintended beam interactions. A schematic is shown in Fig. 1. Natural carbon and boron films were deposited on 6 mm thick with 25.4 mm diameter tungsten backings using PLD-MBE PVD [3]. The carbon and boron targets contained 1% ^{13}C and 81.1% ^{11}B , respectively. Both films were approximately 25 nm thick, corresponding to an areal density of $6.15 \pm 0.02 \mu\text{g}/\text{cm}^2$.

The CLYC-6 detector was positioned to a source-to-detector distance of 5.1 cm from the targets. The geometric efficiency for the detector in this configuration was calculated as $5.24\% \pm 0.35\%$. Angular distributions were measured from 0° to 120° . A 20° wedge insert, notched to clear the radius of the chamber, allowed precise angular positioning. An overhead schematic is shown in Fig. 1, with the CLYC detector at 0° .

Neutron spectroscopy with the CLYC-6 detector relied on fast-neutron interaction channels $^{35}\text{Cl}(n, p)$ to characterize neutrons from the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{11}\text{B}(\alpha, n)^{14}\text{N}$ reaction. For the beam energies used in this work, 1.5 MeV to 2.6 MeV, the emitted neutron energy range is approximately 1–5 MeV, producing a discrete full-energy peak shifted by the reaction Q value of +615 keV for $^{35}\text{Cl}(n, p)$ [1], [2]. Expected neutron energies were calculated from standard two-body reaction kinematics as a function of beam energy and laboratory angle and were compared with the measured neutron spectra.

III. SHIELDING SIMULATION

The experimentally measured neutron-energy spectra were used as source terms in GEANT4 [4] and OpenMC [5] neutron-transport simulations. Calculations were performed using GEANT4 version 11.3.0 with G4NDL version 4.7.1 and the QGSP_BIC_HPT physics list. OpenMC version 0.15.3 was used with neutron-interaction data from ENDF/B-VIII.0 [6]. Borated-polyethylene slabs with thicknesses from 0.1 to 40 cm were modeled for neutron energies relevant to the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{11}\text{B}(\alpha, n)^{14}\text{N}$ reactions. The modeled BPE had a density of 0.992 g/cm³ and contained 10 wt.% natural boron. Identical material compositions, source distributions, and geometries were used in both models.

Each configuration was simulated using $N = 1E+5$ source-neutron histories. The transmission fraction, or the ratio on incident to transmitted neutrons through the BPE block, and angular distribution were recorded. The agreement between GEANT4 and OpenMC was quantified using the relative transmission residual

$$R(E, h) = 100 * \frac{T_{G4}(E, h) - T_{OMC}(E, h)}{T_{OMC}(E, h)}, \quad (1)$$

where $T_{G4}(E, h)$ and $T_{OMC}(E, h)$ are the downstream transmission fractions predicted by GEANT4 and OpenMC, respectively, for incident neutron energy E and BPE thickness h .

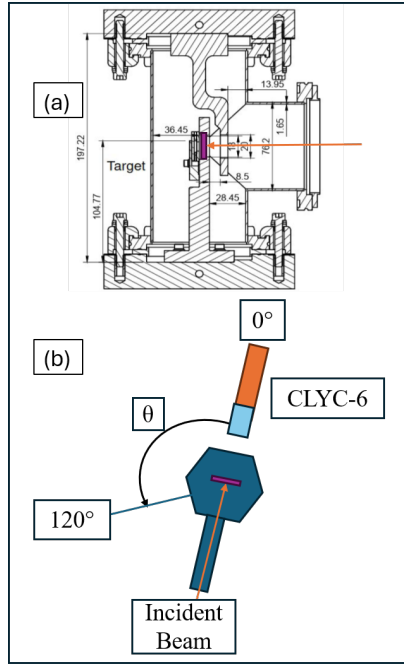


Fig. 1. Experimental configuration. (a) Target chamber; (b) Top-down view of experimental setup with CLYC-6 detector is shown at the 0° position.

IV. NEUTRON SPECTROSCOPY AND SIMULATION RESULTS

Figure 2(a) shows the GEANT4 output of neutron transmission in BPE over incident energies of 1–8 MeV and shield thicknesses of 0.1–40 cm. Transmission through the BPE stack decreases as the BPE thickness increases and exhibits a dependence on incident neutron energy. With contour lines outline 0.1, 0.2, ..., 0.99 transmission ratios given a gaussian energy spread around imputed experimental neutron energies. Figure 2(b) shows the comparison of the transmission ratio of GEANT4 and OpenMC for selected energies of incident neutrons of 3 and 8 MeV. This provides direct estimates of the thickness of BPE required to achieve a specified attenuation between the models. The corresponding angular distributions of transmitted neutron through the BPE layer from GEANT4 are shown in Fig. 2(c). These distributions characterize the forward-directed and scattered components of the transmitted neutron field, with a relative maxima at approximately 30 degrees. Figure 2(d) shows the relative GEANT4–OpenMC neutron transmission residuals given Eq.1. Lower energy neutrons exhibit greater disagreement between the models at high thickness of BPE compared to higher energy neutrons between models.

For experimental neutron energy spectra acquisition, digital pulse processing pulse shape discrimination (DPP-PSD or PSD) digitization method was employed. Neutron events were isolated using a PSD gate, and the corresponding pulse-height spectra were used to isolate the $^{35}\text{Cl}(n, p)$ fast-neutron response.

For each beam energy and observation angle, the coated-target spectrum was background-subtracted using a bare-tungsten measurement normalized to the suppressed beam current. The single-group character of the measured spectra is consistent with the reaction energetics. For $^{13}\text{C}(\alpha, n)^{16}\text{O}$ at $E_\alpha = 2.605$ MeV, the available energy is insufficient to populate the first excited state of ^{16}O at 6.049 MeV; therefore, neutron emission proceeds predominantly to the ground state ^{16}O [7], [8]. For the $^{11}\text{B}(\alpha, n)^{14}\text{N}$ measurements, the energy available in the $^{14}\text{N} + n$ exit channel is below the 2.313-MeV first excited state of ^{14}N , restricting neutron emission to the branch of ground-state ^{14}N [9].

In Figure 3(a,b), the $^{11}\text{B}(\alpha, n)^{14}\text{N}$ is observed via the PSD distribution centered around 0.9 ± 0.05 at $\theta = 70^\circ$ and $E_\alpha = 2.16$ MeV. At $E_\alpha = 2160$ keV in in Fig 3.a,b, the peak $^{35}\text{Cl}(n, p)$ is cleanly resolved with a centroid of 2602 ± 153.4 keV, consistent with the expected 2717 keV.

Figure 3(d) presents the projection of the PSD neutron energy spectra at $\theta_{\text{Lab}} = 120^\circ$ for $E_\alpha = 2605$ keV on a ^{13}C target. The expected neutron energies were 3.562 ± 0.016 MeV at 120° . The (n,p) centroid of 3949.77 ± 269.22 keV is likewise consistent with an expected neutron energy of 4177 keV. For the lower energy peak labeled (5), further detector modeling attributes this to an excited state decay from the n,p peak.

The isolated $^{35}\text{Cl}(n, p)$ peaks show that each measurement condition was dominated by a single neutron-energy group with a finite spread. The source energy in the GEANT4 and

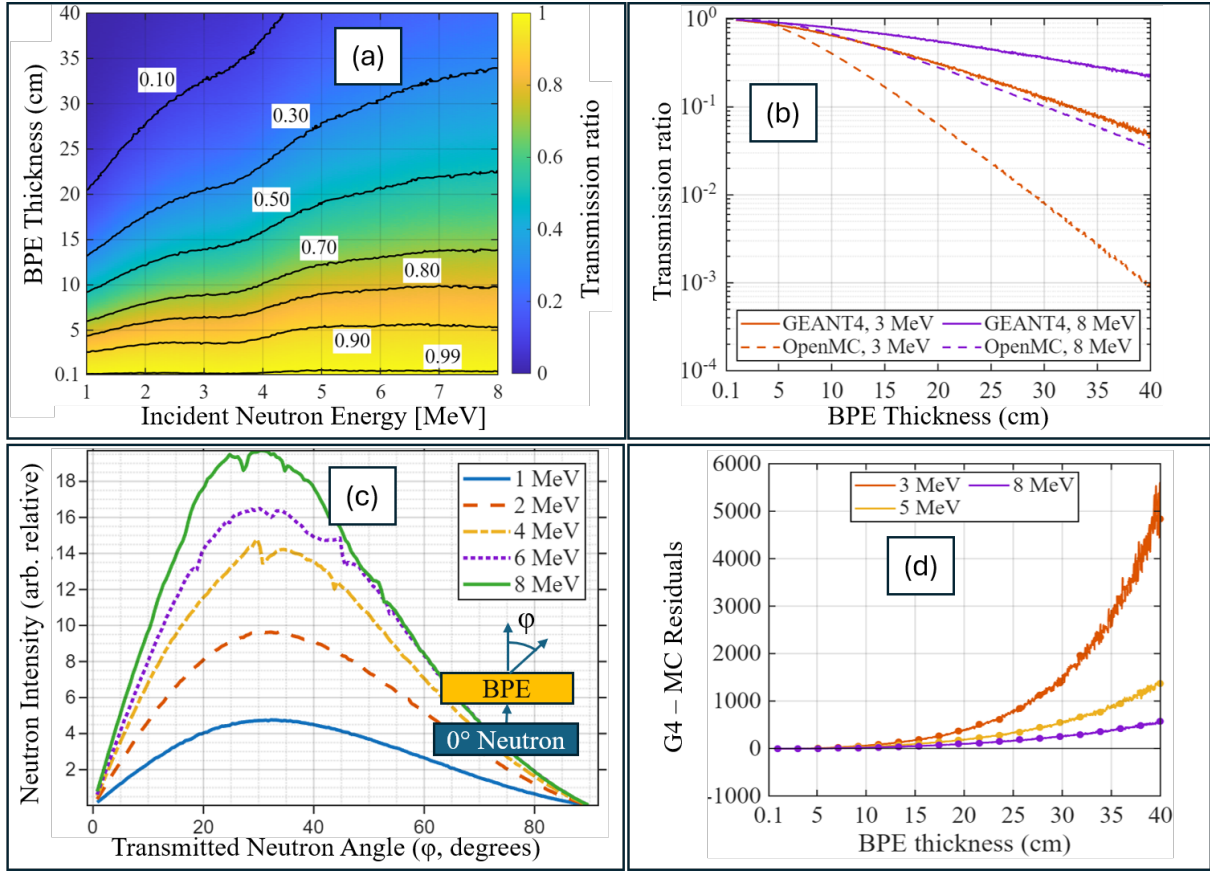


Fig. 2. Simulation output for the BPE slab in GEANT4 and OpenMC. (a) GEANT4 output of 2D BPE thickness vs neutron energy with the z-axis being neutron transmission from 0 to 1, (b) GEANT4 vs OpenMC, the attenuation of neutrons vs shield thickness with selected energies, (c) GEANT4 output of the angular distribution of transmitted neutrons exiting the shielding face for a range of energies, and (d) is the residuals comparison OpenMC and GEANT4 (See Eq.1) for selected neutron energies for shield thicknesses of 0.1 to 40 cm.

OpenMC simulations was modeled as a Gaussian distribution, with its mean and standard deviation obtained from the reconstructed neutron-energy centroid and fitted peak width, respectively.

V. DISCUSSION

Generally, ion-implantation systems would broadened neutron energy distributions when compared to thin target spectroscopy. This because reactions occur over a greater material thicknesses and will involve beam-energy loss and secondary interactions generating a spectrum of lower neutron energies. The thin targets used in this work isolate the highest kinematically accessible neutron energies from the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{11}\text{B}(\alpha, n)^{14}\text{N}$ reactions and therefore the measured centroids and spreads provide useful source terms for shielding calculations. GEANT4 and OpenMC show that the BPE shielding performance strongly depends on the incident neutron energy and thickness. However, GEANT4 results show scattering redistributes the transmitted field in an angle peaking at approximately 30 degrees from the normal of the BPE face. Comparing the two models via residual analysis quantifies shows a great discrepancy between the outputs given neutron energies lower than 3 MeV, but for 8 MeV neutrons the models

had agreement within an order of magnitude. Although the slab geometry omits penetrations and surrounding accelerator structures, the measured source distributions and independent transport calculations provide a basis for preliminary shielding assessments of high-energy helium ion implantation systems.

VI. CONCLUSIONS

Fast-neutron spectra from $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{11}\text{B}(\alpha, n)^{14}\text{N}$ were measured with a CLYC-6 detector for helium beam energies of 1.5–2.7 MeV and laboratory angles from 0° to 120° . Thin carbon and boron targets limited beam-energy loss to less than 10 keV, enabling direct measurement of the highest kinematically accessible neutron energies. The $^{35}\text{Cl}(n, p)$ response revealed one dominant neutron-energy group at each measurement condition, and the reconstructed peak centroids and widths were used to define Gaussian source-energy distributions for transport calculations. GEANT4 and OpenMC simulations evaluated neutron transmission through 0.1–40 cm of 10-wt.% natural-boron polyethylene for incident neutron energies from 1 to 8 MeV. The calculated attenuation exhibited a strong dependence on energy and thickness, while transmission residuals show 1-2 order of magnitude deviation over the 1 - 8 MeV neutron range used in this work.

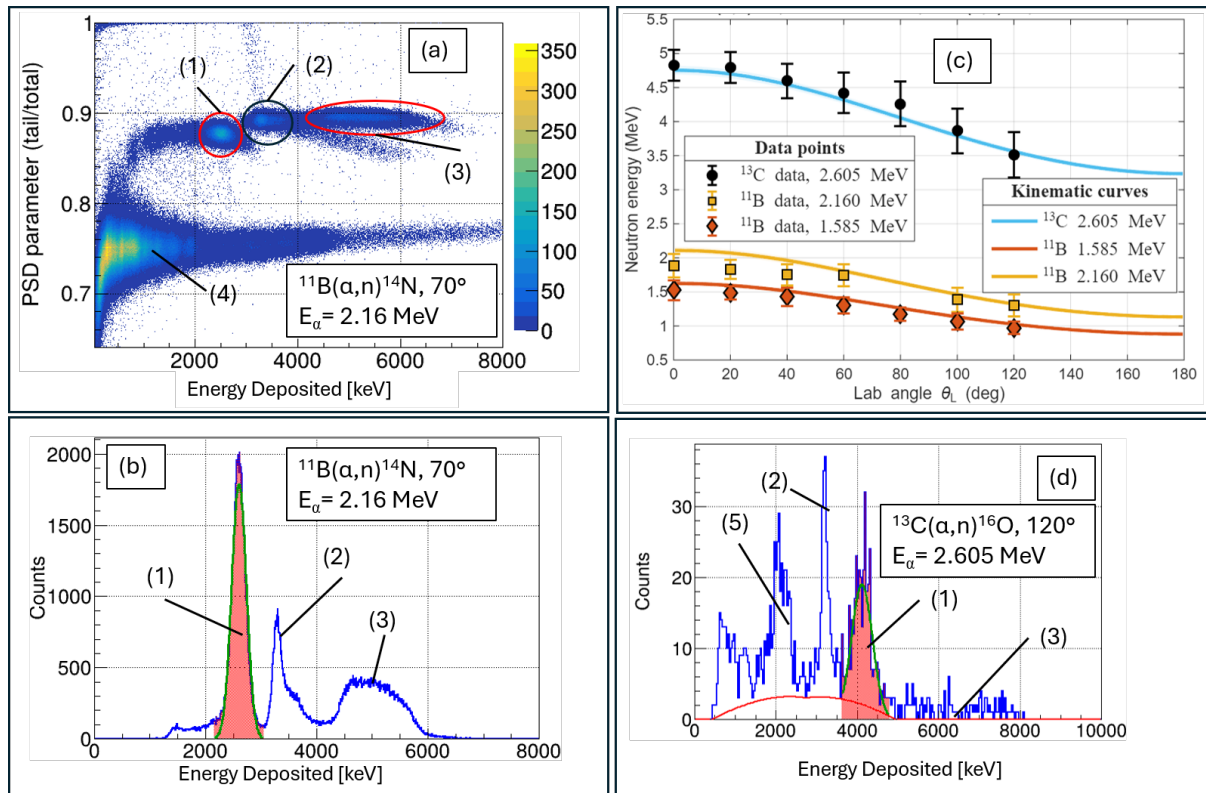


Fig. 3. CLYC-6 neutron-spectroscopy results. (a) Tail-to-total PSD ratio versus waveform integral for $^{11}\text{B}(\alpha, n)^{14}\text{N}$ at $E_\alpha = 2.160$ MeV and $\theta_{\text{Lab}} = 0^\circ$. Labeled features correspond to: (1) $^{35}\text{Cl}(n, p)$ fast-neutron events, (2) the thermal-neutron $^6\text{Li}(n, \alpha)t$ peak, (3) the fast-neutron $^6\text{Li}(n, \alpha)t$ response, and (4) photon events. (b) Corresponding neutron-gated pulse-height spectrum using a PSD gate of 0.88 ± 0.05 . (c) Measured neutron energy versus laboratory angle for the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{11}\text{B}(\alpha, n)^{14}\text{N}$ reactions, with calculated two-body kinematic curves. (d) Neutron-gated energy spectrum for $^{13}\text{C}(\alpha, n)^{16}\text{O}$ at $E_\alpha = 2.605$ MeV and $\theta_{\text{Lab}} = 120^\circ$. (5) Secondary (n,p) peak.

The combined measurements and simulations provide experimentally derived source terms and transport benchmarks for preliminary shielding design of high-energy helium ion implantation systems.

ACKNOWLEDGMENT

Peter DeRosa: Writing - Drafting & editing, Methodology, Visualization, Conceptualization, Data Curation, Formal Analysis. Arthur Zangi: Writing - review & editing, Data curation, conceptualization, Investigation. Wilhelm Platow: Writing - review & editing, Supervision, Project administration, conceptualization. Zachary Hartwig: Writing - review & editing, Supervision, Project administration, Conceptualization.

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