Neutron Attenuation in Polyethylene Using an AmBe Source

Dylan Barbagallo,[1, a)] Brooke Bolduc,[1] Brian Hassett,[1] Walter Johnson,[1] Kendrick Koumba,[1] Ally Leeming,[1] Phuc Mach,[1] Joe McCormack,[2] Molly McDonough,[1] and Jacqueline Nyamwanda[1, b)]

[1] *Department of Physics, Suffolk University, 20 Somerset St., Boston, Massachusetts 02108, USA*
[2] *Massachusetts General Hospital, Proton Center, 55 Fruit St., Boston, Massachusetts 02114, USA*

[a)] Corresponding author: dbarbagallo@su.suffolk.edu
[b)] jnyamwanda@suffolk.edu

Abstract. In this project an americium-beryllium (AmBe) neutron source was used to study the attenuation characteristics of polyethylene on an incident flux of varying neutron energies from 200 keV to 10 MeV. The linear absorption coefficient suitable for a single neutron energy was found to vary with absorber thickness due to the higher cross section for absorption of low-energy neutrons. The attenuation coefficient for a thickness greater than 15 cm was found to be associated with higher velocity neutrons.

INTRODUCTION

The research in this paper is based on a collaboration between the Suffolk University Physics department and the Radiation Oncology department at Massachusetts General Hospital in Boston. Neutrons are produced in several circumstances, such as high-energy photons hitting high-z materials in medical LINACs, nuclear reactors, and future spaceships traveling to Mars subject to high-energy cosmic rays. Neutrons of various energies have detrimental effects on humans, so it is important to understand the shielding properties of different materials. Materials with a large concentration of H atoms, such as polyethylene, are of interest given that collisions between neutrons and H atoms produce a large fractional energy loss of the incident neutrons, resulting in a high probability of neutron absorption. This paper concerns attenuation of neutrons ranging in energy from 200 keV to 10 MeV by polyethylene generated from an AmBe source.

EXPERIMENTAL APPARATUS

Source. For a neutron source, the AmBe source was used, courtesy of the Proton Center at Massachusetts General Hospital (MGH). This source (Am-241) has a known activity, which is A_{ct} 1.1×107 n/s. The neutron distribution as a function of energy is not known, but AmBe sources average at 4.2 MeV, with a maximum value of 11 MeV.[1] The energy spectrum of an AmBe source varies with composition of Am and Be but in general has a decreasing neutron flux with energy.[2, 3] To illustrate, data from this reference was used to calculate the percentage of neutron flux vs. energy from an AmBe source.

Detectors. In order to detect neutrons bubble detectors were used, which are insensitive to gammas and sensitive to neutron energies above 200 keV.[4] These detectors are available from Bubble Technology Industries (BTI) in Chalk River, Canada, and are the size of a test tube. Each detector consists of a plastic tube holding a polymer medium with microscopic liquid droplets dispersed throughout. When pressure on the polymer is released by unscrewing a plunger at the base of the tube, the droplets become metastable with vapor pressure in excess of ambient pressure and vaporize when exposed to recoils from neutron interactions.[5] The number of bubbles produced is proportional to the neutron dose, and each detector is calibrated by the manufacturer in bubbles/mrem. After exposure to radiation, the detectors contain bubbles (shown in Fig. 2) which that can be counted using ImageJ software.

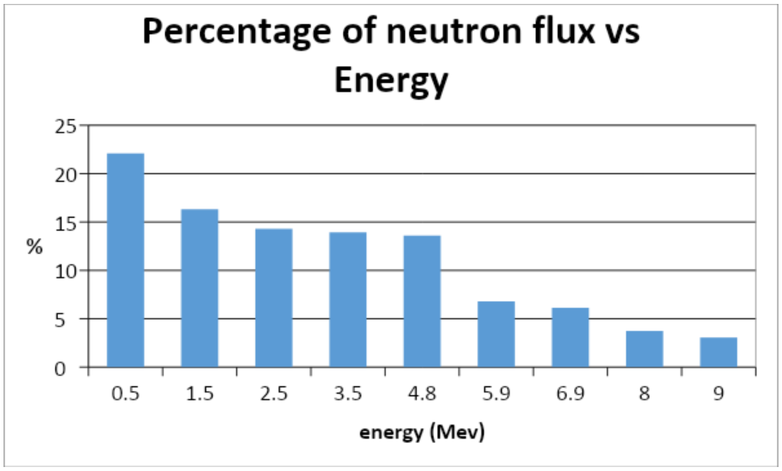

FIGURE 1. Sample dataset from an AmBe source.

Shielding. The absorbers were pure polyethylene rectangular blocks, each 1 inch in thickness. In order to produce varying thicknesses of shielding, blocks were stacked between the AmBe source and the bubble detector. Figure 2 shows four bubble detectors separated by 90°. Each detector is placed 35 cm from the center of the table where the cylindrical neutron source is placed.

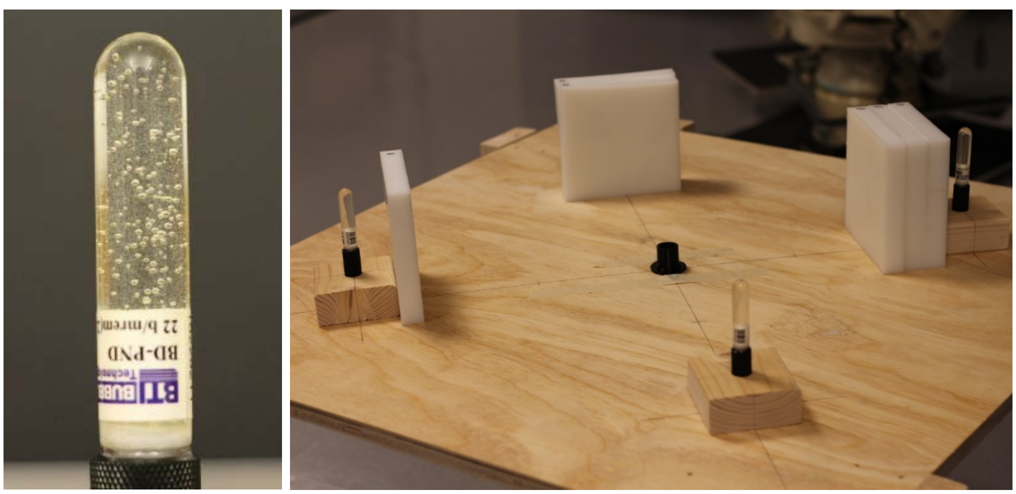

FIGURE 2. Left: An exposed bubble detector used for counting. Right: Experimental setup.

PROCEDURE AND CALCULATIONS

The intensity arriving at an unshielded bubble detector r_0 away from the source is given by

$$I_0 = \frac{Act}{4\pi r_0^2} \qquad \text{w/ } A_{ct} \ = \ 1.1 \times 10^7 \ \frac{\text{neutrons}}{\text{s}} \tag{1}$$

This includes all energies of neutrons emitted by the source and for 35 cm gives

$$I_0 = 715 \ \frac{n}{\text{cm}^2 \text{ s}} \tag{2}$$

This is the theoretical value (not measured) based on the activity of the source and includes neutrons of all energies.

The bubble detectors, however, are sensitive only to neutrons above 200 keV, so a bubble detector which is not shielded at this distance from the source will react to a theoretical intensity corresponding to

$$I_1 = \frac{A_{>200\text{ keV}}}{4\pi r_0^2} \tag{3}$$

This intensity was measured using the bubble detector, as described below, and gave the value

$$I_1 = 617\ \frac{\text{neutrons}}{\text{cm}^2\ \text{s}} \tag{4}$$

The difference between all the neutrons given by (2) and those above 200 keV given by (4) is a measure of the neutrons from our AmBe source which are below 200 keV arriving at 35 cm. This gives about 98 neutrons/cm^2 s, corresponding to about 14% of the total of 715 in (2). This is consistent with the 22% below 1 MeV shown above in Fig. 1 for a typical AmBe source.

If a rectangular slab of polyethylene of thickness d is placed in front of the bubble detector, then the intensity reaching the bubble detector is decreased and given by

$$I_2 = I_1 e^{-\mu d} \tag{5}$$

This equation holds for a value of μ for each neutron energy in the beam. For multiple energies in the incident flux the value of the attenuation coefficient is a weighted average depending on the distribution of energies in the beam.

This neutron intensity is determined by use of bubble detectors which determine dose delivered in time t, which is then converted to neutrons/cm^2 (fluence) over that time using calibration information from the bubble detector manufacturer. The conversion constant is

$$C = 3.7 \times 10^{-5}\ \text{mrem per}\ \frac{\text{neutrons}}{\text{cm}^2} \tag{6}$$

The measurement of the dose at the location is done by counting the bubbles produced:

$$B = \text{bubbles in detector}$$
$$S = \text{sensitivity} = \frac{\text{bubbles}}{\text{mrem}}$$
$$D = \text{dose in mrem}$$
$$D = \frac{B}{S} \tag{7}$$

There is an error in the dose due to uncertainty in the number of bubbles. This uncertainty has two sources: (1) errors in counting the number of bubbles and (2) statistical binomial errors associated with the number of counts.

After the experiment, each bubble detector was photographed four times at 90° angles, and then the bubbles were counted by different people and an average was taken:

$$\sigma_B = \text{error in the number of bubbles}$$
$$\sigma_{ct} = \text{error in the counting of the bubbles in the detector}$$
$$\sigma_{st} = \text{statistical error in the bubbles in the detector}$$
$$\sigma_B^2 = \sigma_{ct}^2 + \sigma_{st}^2 \tag{8}$$

The dose in mrem is determined by the fluence F, the number of neutrons/cm^2 delivered to the detector over the radiation time. The fluence F is the neutrons/cm^2 after some time t:

$$F = \frac{\text{neutrons}}{\text{cm}^2}\ \text{at the detector}$$

The fluence is determined from the dose using the factor C given in Eq. (6):

$$F = \frac{D}{C} \tag{9}$$

To measure the neutron intensity in neutrons/cm^2/s, use the fluence determined by the bubbles divided by the time:

$$I_{meas} = \frac{F}{t} \tag{10}$$

In this way the intensities mentioned above, I_1 and I_2, and the errors in each can be calculated.

The error in the intensity as shown above depends on the error in F and D and therefore the error in the number of bubbles shown in Eq. (8). There is also another consideration due to the solid angle subtended by the detector. The active area of the detector from top to bottom is 5 cm. The neutron source was positioned so that its center was the same height as the midpoint of the active area of the bubble detector, so from the source to the center of the bubble detector was 35 cm. However, the solid angle subtended by the detector was not all at the same distance r from the source because of increasing distance from the source as you move from the center of the detector to the top or bottom of the detector. To the top and bottom of the detector the distance was 35.09 cm. The intensity goes like $1/r^2$, so we can find the error in the intensity due to this effect by propagation of errors in r to the intensity. Using the maximum error in r as 0.09 we have

$$\frac{\sigma_I}{I} = \frac{2\sigma_r}{r} = 5.1 \times 10^{-3}$$

The result is that the solid angle effect at the detector produces an error of approximately 0.5%, which is negligible compared to the other errors in calculation of intensities and attenuation coefficient, as shown below in Table 1.

The effect of the absorber is shown by a decrease in neutron intensity from I_1 to I_2 expressed by the ratio

$$R = \frac{I_2}{I_1} \tag{11}$$

The error in the ratio R is obtained from the errors in the intensities:

$$\sigma_R^2 = \left(\frac{1}{I_1^2}\right)\sigma_{I_2}^2 + \left[\left(\frac{I_2^2}{I_1^4}\right)\right]\sigma_{I_1}^2 \tag{12}$$

From Eq. (5), to determine the absorption coefficient μ,

$$\mu = -\frac{1}{d}\ln\left(\frac{I_2}{I_1}\right) \tag{13}$$

The error in d is negligible, so the error in μ is given from the usual propagation of errors equation:

$$\sigma_\mu^2 = \left(\frac{\partial\mu}{\partial I_2}\right)^2\sigma_{I_2}^2 + \left(\frac{\partial\mu}{\partial I_1}\right)^2\sigma_{I_1}^2 \tag{14}$$

The result follows:

$$\sigma_\mu^2 = \left(\frac{1}{dI_2}\right)^2\sigma_{I_2}^2 + \left(\frac{1}{dI_1}\right)^2\sigma_{I_1}^2 \tag{15}$$

RESULTS AND DISCUSSION

The linear absorption coefficient calculated for each thickness of the polyethylene shield as described above gives the results shown in Table 1. The effectiveness of the absorber in decreasing the incident flux is clear from the plot shown in Fig. 3. An exponential fit shows the expected behavior, but it should be noted that the points below 10 cm thickness are consistently below the fit and the points for higher thickness are above the fit. This is consistent with the early layers of polyethylene removing the lower energy neutrons, which have a higher value of the absorption coefficient μ, and the latter layers being exposed to higher energy neutrons with a lower absorption coefficient. The average fit of the solid curve is a compromise between the two energy regions.

TABLE 1. Linear absorption coefficient calculated for each thickness of polyethylene.

Thickness (cm)	I_2/I_1	Fit	I_2/I_1 Err	μ	Err μ
0.000	1.00	1.00	0.000	Na	Na
2.540	0.632	0.719	0.111	0.181	0.069
5.080	0.472	0.516	0.76	0.148	0.032
7.620	0.326	0.371	0.046	0.147	0.019
10.160	0.267	0.267	0.044	0.130	0.016
15.240	0.136	0.138	0.019	0.131	0.009
17.780	0.126	0.099	0.018	0.116	0.008
20.320	0.110	0.071	0.0016	0.109	0.007

This is shown more clearly in Fig. 3, where the absorption coefficient is significantly higher at the lower values of thickness of absorber. This is discussed in more detail below.

Now consider the linear absorption coefficient μ as a function of thickness. The decreasing value of μ with increasing thickness is an interesting result associated with two factors: (1) an incident flux of neutrons from the AmBe source with a larger proportion of low-energy neutrons (as illustrated in Fig. 1), and (2) a higher absorption cross section for low-energy neutrons.[6] When the incident beam of mixed energy neutrons with a large fraction of low-energy neutrons approaches an absorber whose thickness is only a few centimeters, a larger fraction of low-energy neutrons is removed from the beam than high-energy neutrons. The attenuation for this small thickness results in a value of μ dominantly associated with low-energy neutrons.

From Fig. 3, it can be determined that 15 cm of polyethylene drops the flux to below 15% of the incident flux, and 20 cm drops it to about 10% of the neutron flux for the AmBe source studied. However, for a much larger thickness, over 10 cm, most of the low-energy neutrons have been removed in the first few centimeters of absorber so that the last few centimeters of the thickness are dominated by a beam mostly of high-energy neutrons and a correspondingly lower attenuation coefficient. The result is a steadily decreasing average attenuation coefficient with thickness as the proportion of neutrons in the beam becomes higher and higher energy for the latter layers of the thickness.

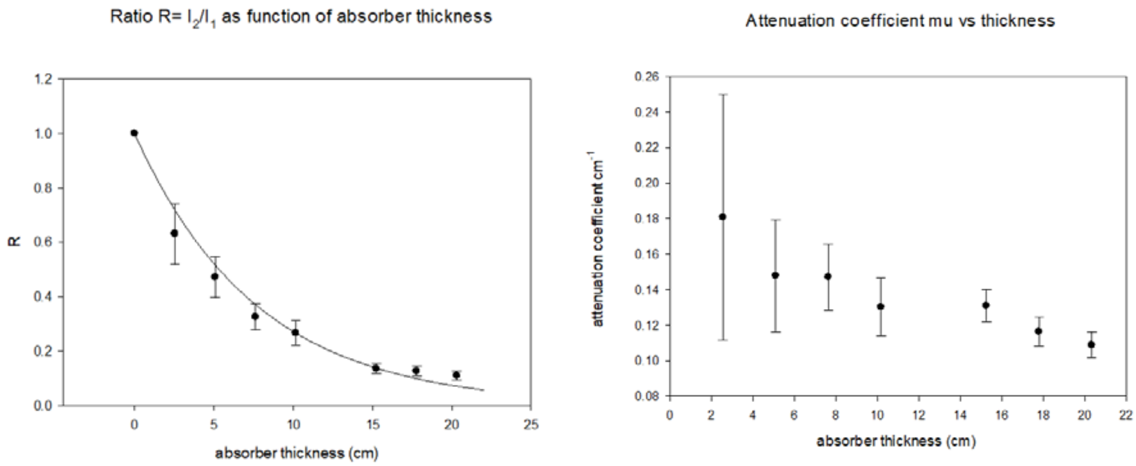

FIGURE 3. Left: Transmitted over incident flux vs. absorber thickness. Right: Absorption coefficient μ vs. absorber thickness.

If only the last three data points corresponding to a thickness greater than 15 cm are used, an average attenuation coefficient characteristic of high-energy neutrons can be obtained. The measured result is $\mu = 0.12 \pm 0.01$ cm^{-1}. This compares well to the value of 0.119 given for fast neutrons in Ref. 6.

CONCLUSIONS

The attenuation of neutrons from an AmBe source at Massachusetts General Hospital has been measured as a function of thickness for pure polyethylene absorbers. The results were obtained using bubble detectors sensitive to neutrons with energy greater than 200 keV. The attenuation coefficient shows a decreasing value with thickness as low-energy neutrons are removed from the first layers of the absorber and the measurements for thick absorbers produce values consistent with those in the literature for fast neutrons. For the energy distribution present in the neutron emissions from this AmBe source, a thickness of 20 cm of polyethylene will drop the flux to approximately 10% of the original value.

Next steps will involve using a series of bubble detectors with energy-dependent thresholds to determine the energy distribution of the AmBe source at MGH. The results can then be used to predict absorption of the incident flux with absorber thickness and compare with experimental results. Additional results will also be able to determine the energy distribution of the emerging beam after passing through an absorber of a certain thickness.

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