Simulation of an AmBe source and Helium-3 Thermal Neutron Detectors

Using GEANT4

Samuel de Jong
Department of Physics and Astronomy
University of Victoria

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1 Introduction

1.1 AmBe neutron source

The University of Victoria has a 241-AmBe neutron source, which produces neutrons using the following reaction [3]:

$$^{241}_{95}\text{Am} \rightarrow \ ^{237}_{93}\text{Np} + ^{4}_{2}\text{He} + \gamma \tag{1a}$$

$$^{9}_{4}\text{Be} + ^{4}_{2}\text{He} \rightarrow \ ^{12}_{6}\text{C} + ^{1}_{0}\text{n} + \gamma \tag{1b}$$

with an activity of 168 GBq (measured at 185 GBq in 1966). The energy spectrum of an AmBe source can be found in Fig 1. The configuration of the University of Victoria's AmBe source can be found in [4]. The neutron rates from five different AmBe sources is measured in [5]. From this, it is determined that an AmBe source produces $6.08\pm0.17\times10^4$ neutrons/GBq. For the 168 GBq source, this corresponds to $1.02\pm0.03\times10^7$ neutrons/s.

1.2 Helium-3 Tube

When a thermal neutron (with an energy of 0.025 eV) passes through the active area of the detector, it may be captured by a ^{3}He atom [1]:

$$^{3}_{2}\text{He} + ^{1}_{0}\text{n} \rightarrow \ ^{3}_{1}\text{H} + ^{1}_{1}H + 764 \text{ keV} \tag{2}$$

The cross section for this reaction decreases as the energy of the neutron increases, as shown in Fig 3. The ^{3}H and proton ionize the gas in the tubes. This ionization produces a signal on a sense wire in the centre of the tube.

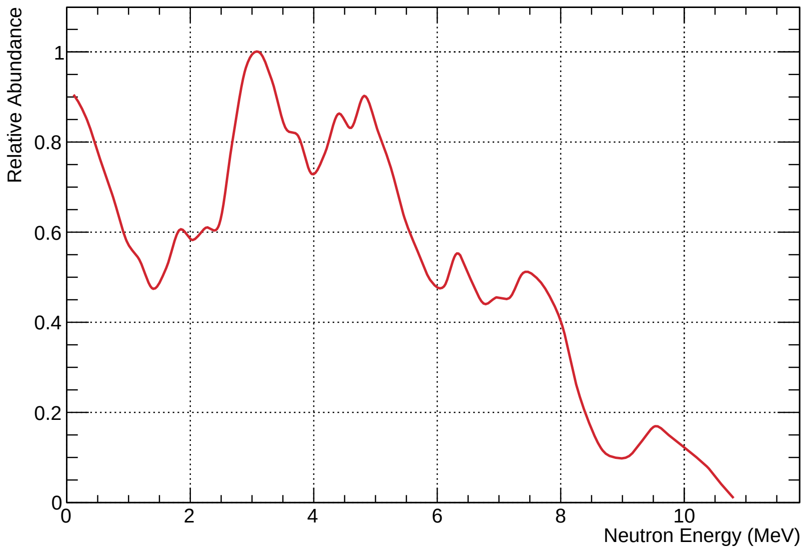


Figure 1: Energy spectrum of neutrons from AmBe source [2].

Figure 2: Helium-3 tube

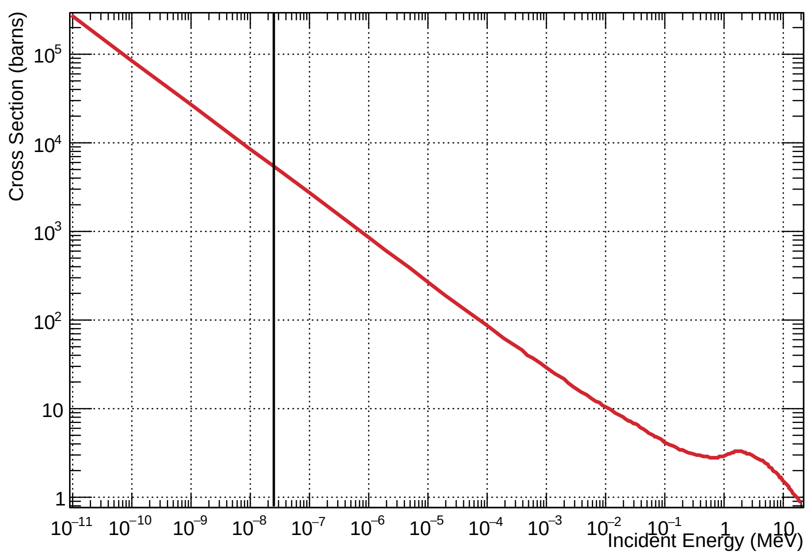


Figure 3: Cross section of neutron capture by helium-3 as a function of neutron energy. The vertical black line corresponds to upper range of the energy of thermal neutrons [6].

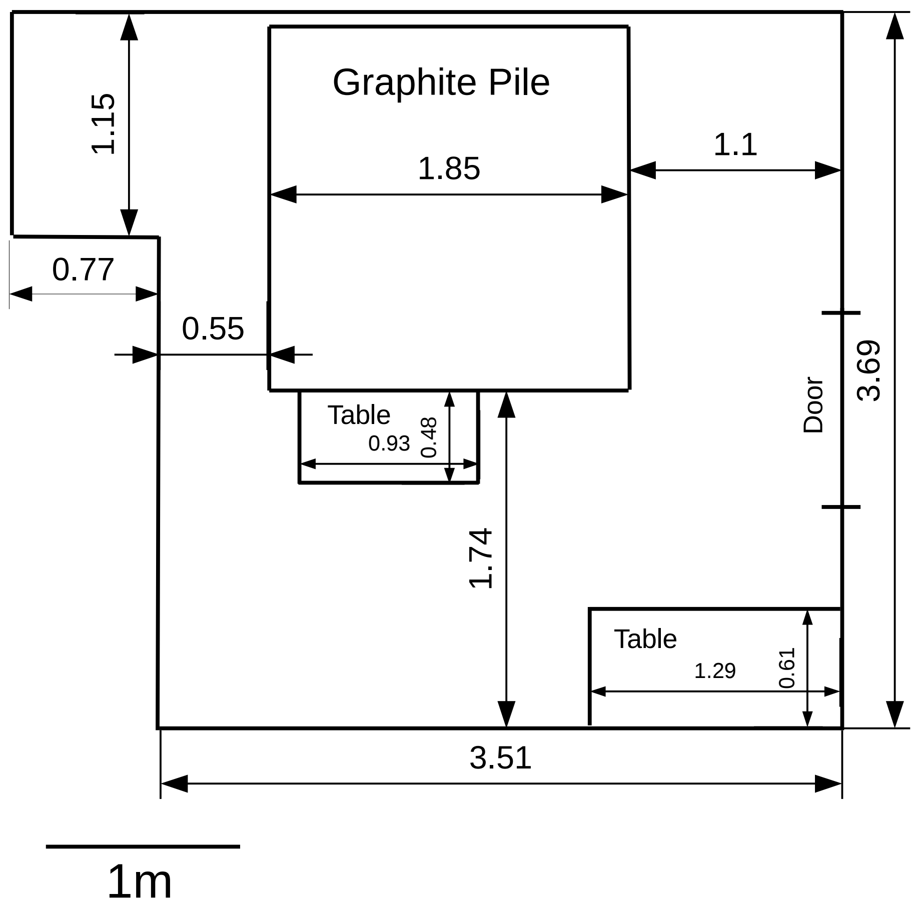


Figure 4: Scale drawing of the pile room

2 Geometry

The centre of the geometry is defined to be the centre of the graphite cube. All other positions are taken relative to this point. The geometry of the pile room is read into the simulation from four files:

Room.xml contains geometry of the room. The dimensions of the room, the material the walls are composed of, the thickness of the walls, and the position of the centre of the room relative to the graphite are all contained in this file. The default dimensions are taken from fig 4, the default material is G4_CONCRETE, GEANT4's implementation of concrete, and the thickness is assumed to be 20cm. The door to the room and the small alcove on the left of fig 4 have been omitted from the room description.

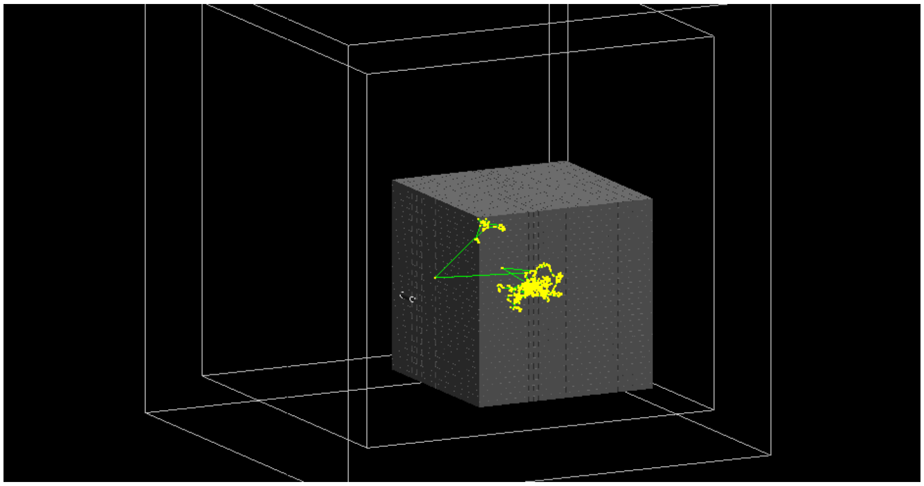


Figure 5: Geometry as implemented in GEANT4. Yellow lines indicate the trajectory of a neutron event.

Graphite.xml contains the geometry of the graphite. The graphite pile is composed of layers of criss-crossed rods of graphite, as shown in fig 6.

For simplicity, only the dimensions of one rod are defined in the xml file, as well as the number of layers in the pile. The default length of a rod is 92.5 cm with width of 5.285 cm. Each layer is two rods long and 35 wide, as shown in fig 7, with each layer rotated 90° with respect to the previous. The pile is composed of 35 layers. The length and width if each rod is reduced by a Gaussian distributed random number in order to simulate the imperfect stacking and variation in rod dimensions of the actual pile.

The material of the pile is G4_GRAPHITE with a small boron impurity. The density and the purity of the graphite (in %) are specified in the xml file.

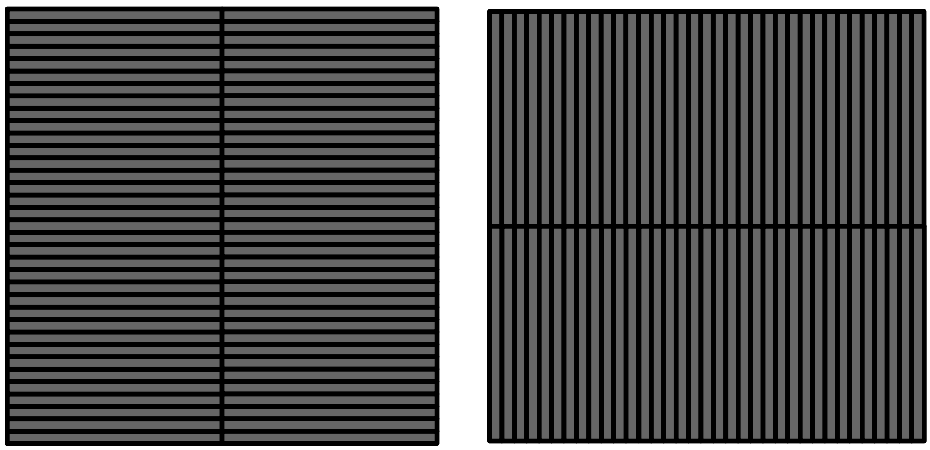
HE3TUBE.xml contains the geometry of the helium-3 tubes. The dimensions of the tubes are based on fig 8. The xml file can contain several tubes, each of which is implemented in the simulation.

misc.xml contains the geometry of any other object, such as a polyethylene shield. Both boxes and cylinders can be implemented. The position of the object can be with respect to the origin (the centre of the graphite) or with respect to one of the helium-3 tubes. The xml file can contan several objects, all of which will be implemented in the simulation.

3 Output Ntuples

A root file containing two ntuples is produced by the simulation:

Figure 6: Photograph of the graphite pile showing rods



(a) layer 1 (b) layer 2

Figure 7: Arrangement of rods in alternating layers

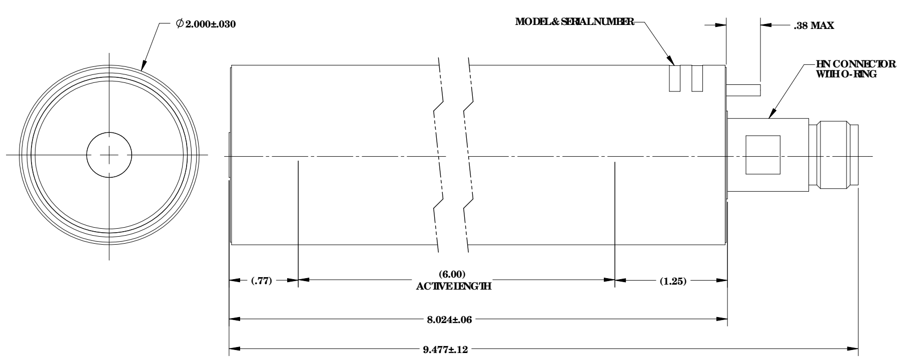


Figure 8: Schematic of helium-3 tube

Branch	Description
Ekin_n_PostGraphite	Kinetic energy of a neutron after leaving the graphite
Etot_n_initial	Initial energy of neutron
TotalEnergyDeposited	Total energy deposited by a proton and tritium
leftWall	1 if the neutron left the wall of the room
he3TubeXPos	X position of tube containing a neutron hit
he3TubeYPos	Y position of tube containing a neutron hit
he3TubeZPos	Z position of tube containing a neutron hit
EDEPinHe3	a vector of the energy deposits in the helium-3 tubes
PIDinHe3	a vector of the PID of particles causing energy deposits in the helium-3 tubes
neutronHits	The channel number of a tube where a hit occured
diffusionRadius	a vector containing 100 radius values between 30 and 70 cm
diffusionFlux	a vector containing the number of neutrons which cross a sphere defined by each entry in diffusionRadius

Table 1: Branches in the PileRoomSim ntuple

geometry contains the geometry of the room, graphite cube, helium-3 tubes, and the miscellaneous objects. This ntuple has only one entry.

PileRoomSim contains the simulation results. By default, only events containing a neutron hit in a helium-3 tube are saved, but it is possible to save all events. The branches in this ntuple summarized in table 1

4 Determination of Boron Contamination

4.1 Diffusion length approach

Why??

In the winter of 2017, and undergraduate student at UVic performed an experiment which measured the diffusion length of thermal neutrons in the graphite of the neutron source. The result of this experiment was a diffusion length of (0.429 ± 0.008) m [7]. The accepted value for the diffusion length on graphite is 0.503 m. I hypothesized that the difference between the measured value and the accepted value was due to a small boron impurity on the graphite.

I performed a measurement of the diffusion length in the simulated graphite pile. The diffusion length is related to the neutron flux by this relationship:

$$\phi = A \cdot exp(-\gamma r) \tag{3a}$$

$$\gamma^2 = 1/L^2 \tag{3b}$$

Where ϕ is the neutron flux, r is the distance from the source, and L is the diffusion length.

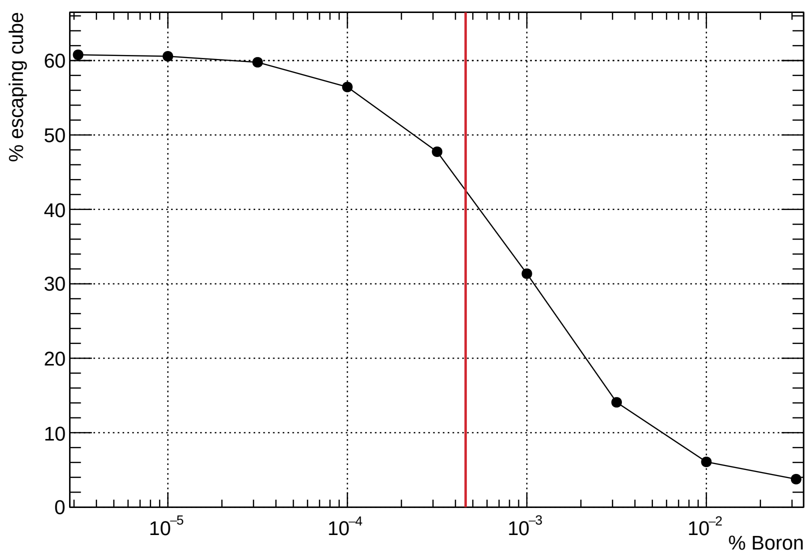


Figure 9: Fraction of neutrons which escape the graphite as a function of the % boron

In the simulation the number of neutrons which enter or exit a shell of radius r was counted, then divided by the surface area of the shell to get the neutron flux:

$$\phi = \frac{N_{\text{neutrons}}}{4\pi r^2} \tag{4}$$

This was plotted against the distance from the source (see fig 10) was then fit to

$$\phi = p_0 \cdot exp(p_1 r) + p_2 \tag{5}$$

so that $L = 1/p_1$. The range of r was chosen so that a diffusion length of 0.503 m would be produced by pure graphite.

This process was repeated with boron impurites added (see fig 11). The boron contamination which produced a diffusion length of 0.429 m was $4.63\times10^{-4}\%$ or 4.63 ppm boron.

4.2 Face measurement approach

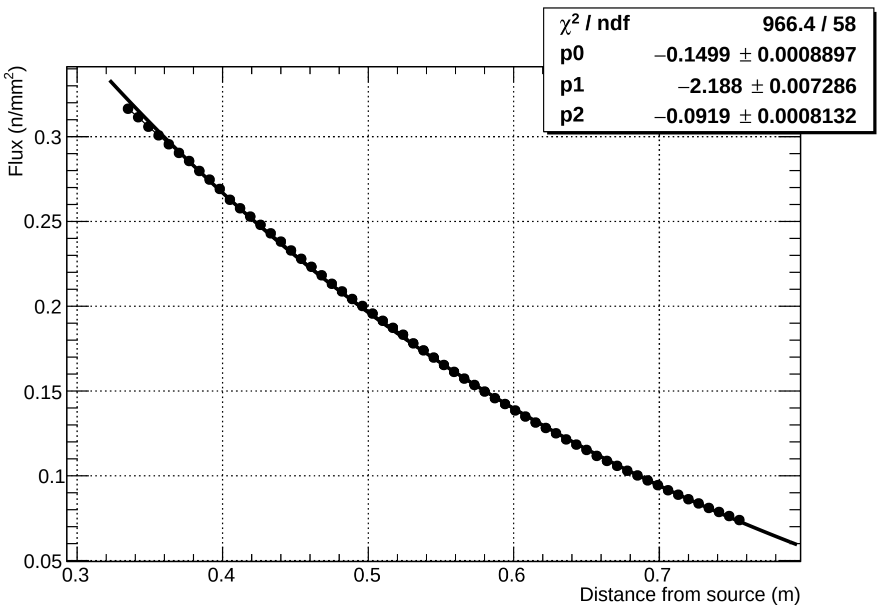


Figure 10: Neutron flux as a function of distance from the source for pure graphite

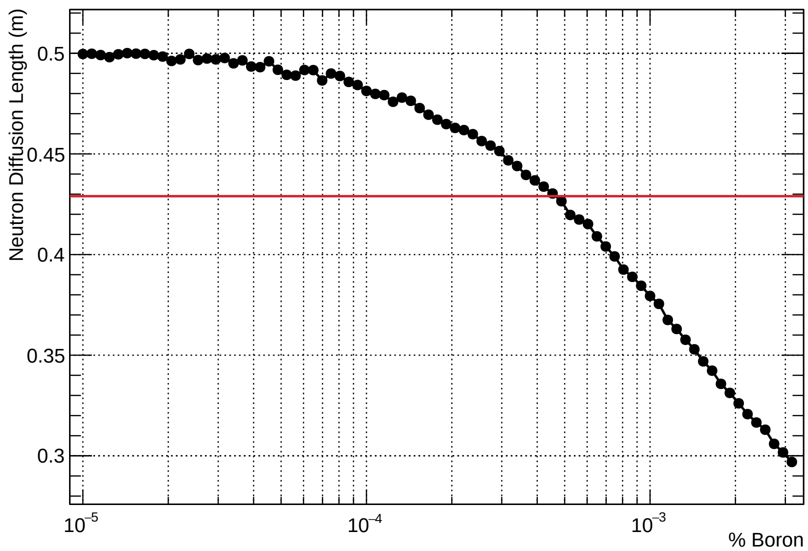


Figure 11: Neutron diffusion length as a function of boron contamination. The red line indicates the value of the diffusion length from the undergraduate experiment.

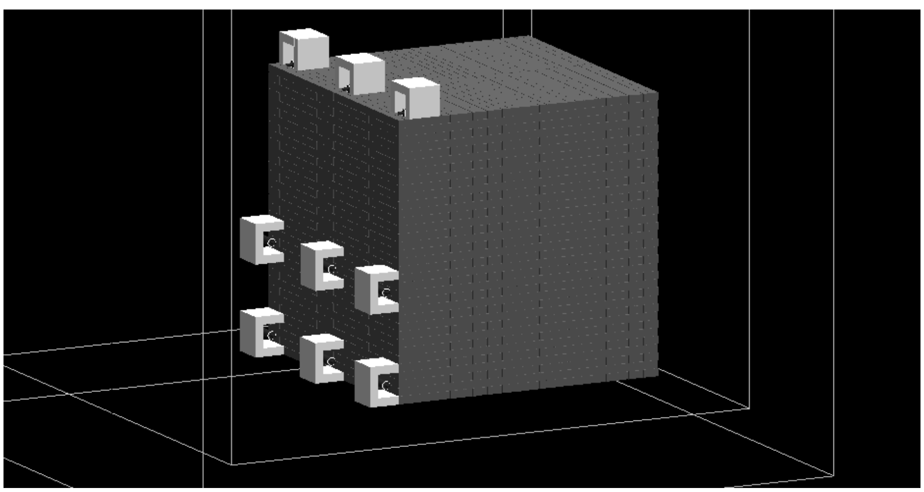


Figure 12: Locations of measurement on the face of the graphite.

References

[1] Oed A. Detectors for thermal neutrons. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 525(12):62 – 68, 2004. Proceedings of the International Conference on Imaging Techniques in Subatomic Physics, Astrophysics, Medicine, Biology and Industry.

[2] Kluge H and Weise K. The neutron energy spectrum of a 241Am-Be (alpha, n) source and resulting mean fluence to dose equivalent conversion factors. *Radiation Protection Dosimetry*, 2(2):85–93, 1982.

[3] Barschall HH. *Neutron sources: for basic physics and applications*, volume 2. Pergamon, 1983.

[4] Geiger KW and Hargrove CK. Neutron spectrum of an Am241-Be (α, n) source. *Nuclear Physics*, 53:204–208, 1964.

[5] Lebreton L, Zimbal A, and Thomas D. Experimental comparison of 241Am–Be neutron fluence energy distributions. *Radiation protection dosimetry*, 2007.

[6] Brookhaven National Laboratory. Evaluated nuclear data file. http://www.nndc.bnl.gov, December 2011.

[7] Deanna Pineau. Thermal diffusion of neutrons in graphite. *UVic undergraduate lab report*, 2017.