Energy Deposition in Polymers

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1 Introduction

A typical day in 2011 saw 932,456 people cross into the U.S. (258,191 by air 48,073 by sea, and 621,874 by land) [?]. In addition there was 64,483 truck, rail and sea containers with 253,821 privately-owned vehicles [?]. As shown in Figure 1 there are numerous entry points into the U.S. that are interconnected by a networks of rail and highways. In the interdiction of special nuclear material it is desirable to detect and seize the material before it enters into this complex network. Radiation Portal Monitors (RPMs) are passive radiation detection systems implemented at over a thousand border crossings, designed to determine if cargo contains any nuclear material in a safe, nondestructive and effective manner[?]. The Department of Homeland Security (DHS) continues to fund research through the Domestic Nuclear Detection Office (DNDO) in order to develop replacement technologies for the current ^{3}He RPMs as ^{3}He cannot be economically replaced. There are several alternatives to ^{3}He being considered and all, with the exception of gas filled proportional detectors involve the detection of neutrons from scintillation events of the energy deposited in the material from the neutron absorption reaction. These detectors (among other requirements outline in Table 1) must be able to effectively discriminate between gamma (which can occur in medical isotopes) and neutrons (which are likely to be a signature of special nuclear material).

Neutron detectors often utilize a material doped with an isotope of large thermal cross section for absorption such as ^{6}Li or ^{10}B. When these materials absorb a neutron the nucleus of the isotope becomes unstable and fissions into reaction products. These reaction products (having an initial kinetic energy from the Q-value of the neutron absorption reaction) travel through the material, transferring their kinetic energy to the material. Photon interactions in the detector occur when a photon scatters of a single electron in a Compton scattering event (Table 2). This Compton electron then produces a cascade of secondary electrons in the material, which depending upon the energy may or may not deposit a majority of it's energy in the detector. The difference in the transfer of kinetic energy from charged particle to electrons and from photon interactions (Compton scattering) to electrons introduces an opportunity to exploit the difference in energy deposition in order to maximize the discrimination between neutron and photon interactions in a detector.

Table 1: Replacement Detector Requirements [?]

Parameter	Specification
Absolute neutron detection efficiency	2.5 cps/ng of ^{252}Cf (in specified test configuration)
Intrinsic gamma-neutron detection efficiency	$\epsilon_{int,\gamma n} \leq 10^{-6}$
Gamma absolute rejection ratio for neutrons (GARRn)	$0.9 \leq$ GARRn ≤ 1.1 at 10 mR/h exposure
Cost	$ 30,000 per system

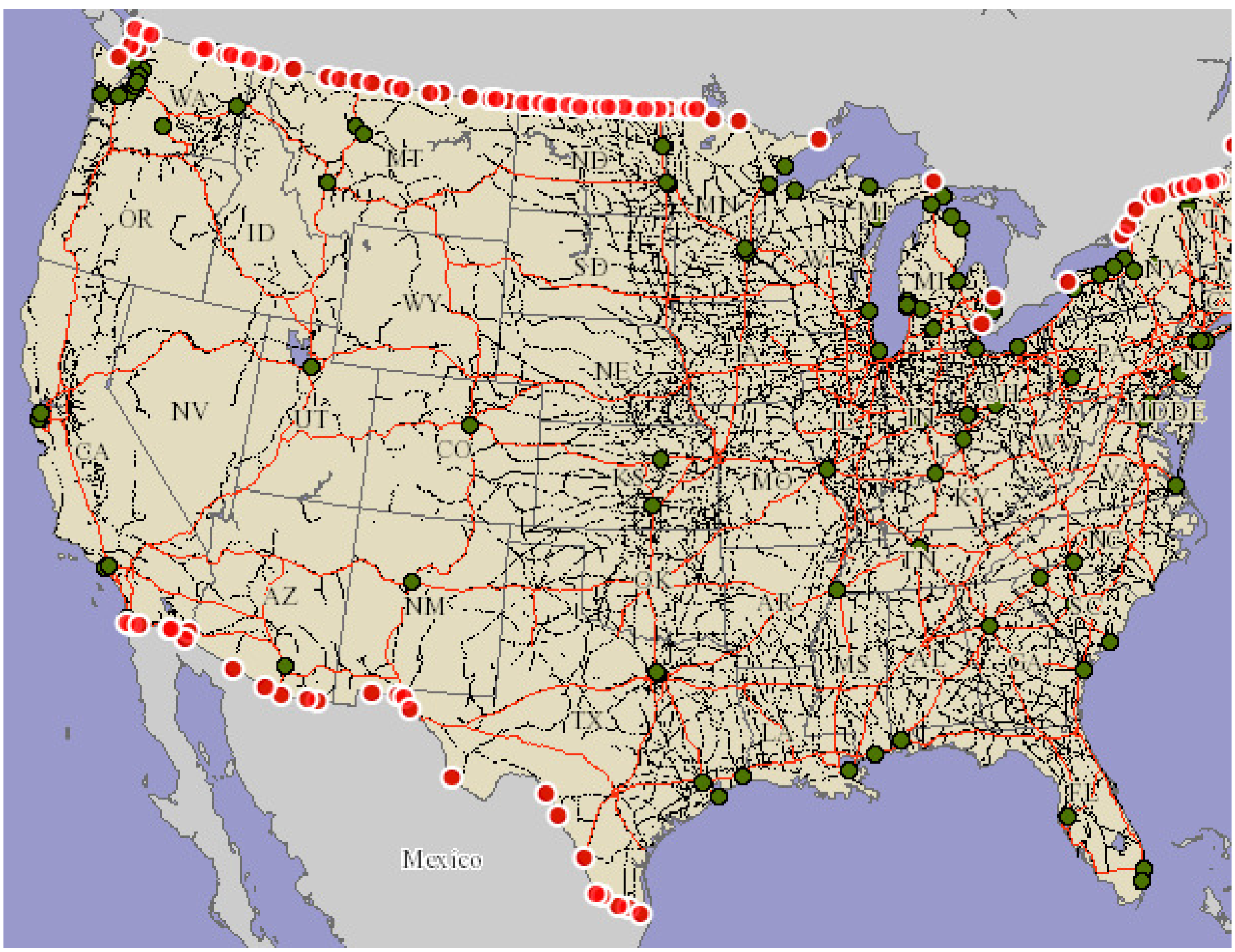


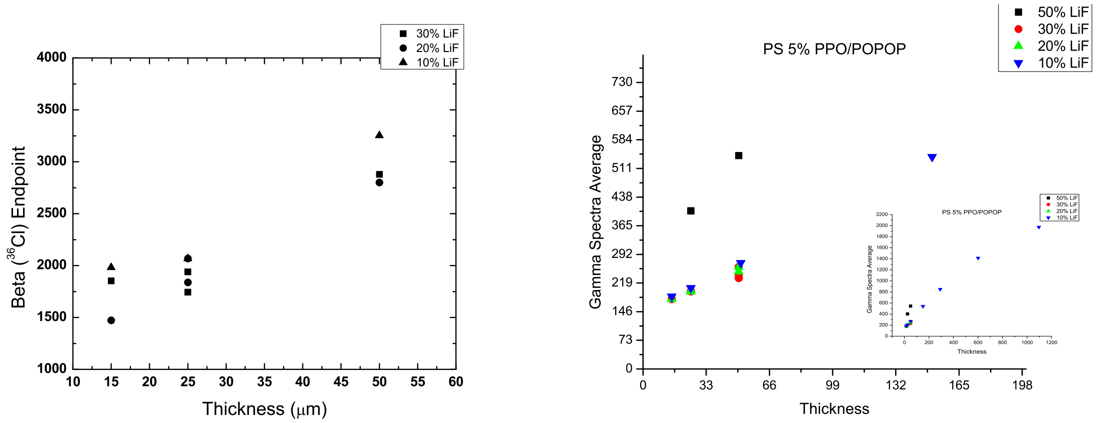
Figure 1: Portal Entry Points into the U.S.

Table 2: Maximum Energy of Secondary Electrons from Compton Scattering

	Photon Energy (MeV)	Maximum Compton Energy (MeV)
^{137}Cs	0.662	0.478
^{60}Co	1.17, 1.33	0.960, 1160

This document is organized as follows. A brief overview of the interaction of charged particles in matter will be provided in Section 2, as well as some preliminary experiments demonstrating the range of secondary electrons to aid in neutron-gamma discrimination. The GEANT4 toolkit was used for the modeling of the energy deposition. Section 3 will provide an overview of the GEANT4 toolkit. Section 4 will provide details on how the GEANT4 toolkit was implemented for this particular simulation, as well as providing validation of the calculations preformed by the GEANT4 toolkit in Section 5. In the 6 the results of this model applied to a single film will demonstrate the enhanced ability of neutron-gamma discrimination through secondary electrons.

Figure 2: Spectra properties as a function of film thickness



(a) Beta Spectra Endpoints for a 5% PS film

(b) Gamma Spectra Averages for PS films

2 Previous Work

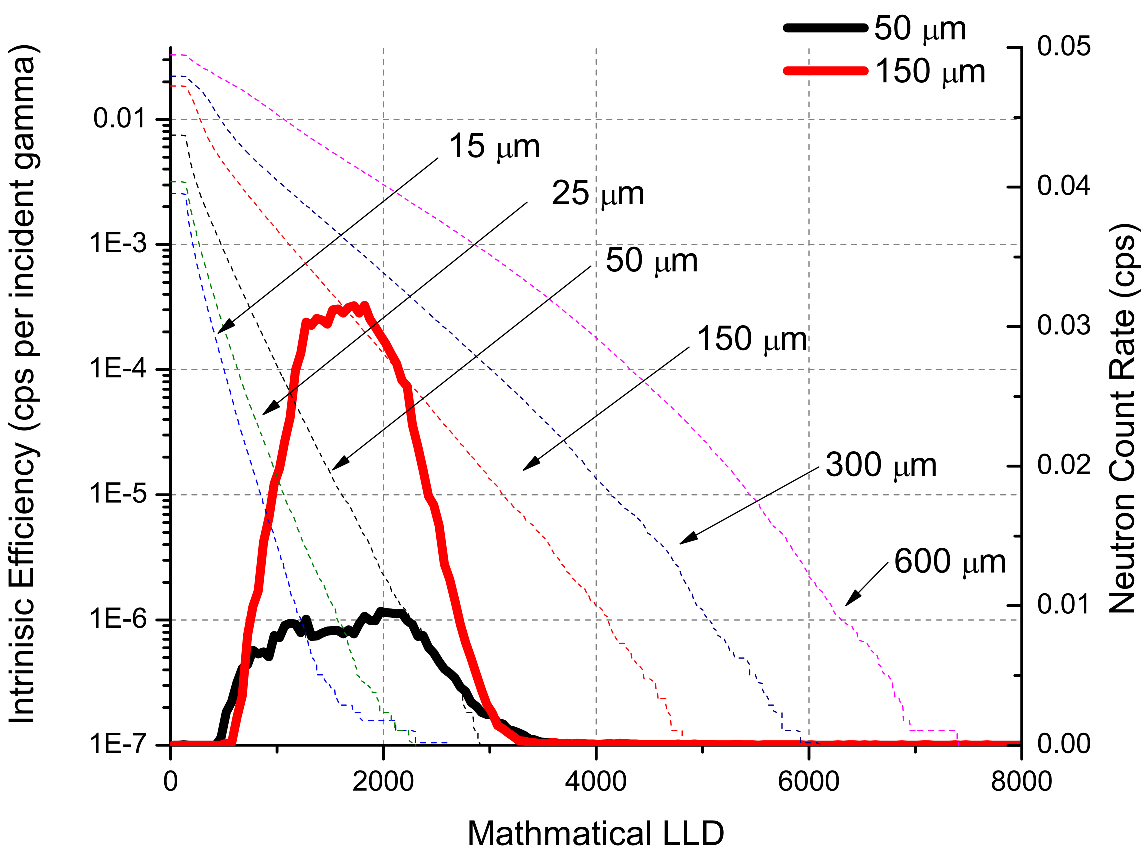
Previous work on the energy deposition of thin focused on spectra measurements from fabricated films as wells as single collision energy loss spectra. A sequence of 10% ^{6}LiF, 5% PPOPOPOP films in a PS matrix cast to thickness between 15 and 600 μm where fabricated and the response was measured from a gamma source as well as a neutron source. These experiment results are shown in 2.1.

2.1 Spectra Measurements

Evidence that the secondary electrons contribute to energy loss can be seen in Figure 2 where there is an increase in the endpoint of the spectra as films become thicker. This increase in the spectra endpoint is indicative of the film producing more light, and as the light collection geometry remained constant the increase in the endpoint is attributed to a larger energy deposition in the 50 μm film compared to the 15 μm or 25 μm film. Figure 3 shows the intrinsic efficiency of these film (from spectra obtained from a ^{60}Co source). As the film thickness increases the pulse height discriminator at which an intrinsic efficiency of one in a million ($\epsilon_{int,\gamma} \leq 10^{-6}$) is reached also increase. The neutron spectra (shown in the solid lines) does not increase in light yield with increasing thickness, further providing an indication that the thickness of the films can be optimized to maximize the neutron count rates[1] while minimizing the response of the detector to photons.

[1] The neutron count rate is increased with thickness by the increased mass of the detector

Figure 3: Gamma intrinsic efficiency (dashed lines) plotted against neutron counts (solid)



3 Introduction to GEANT4

GEANT4 (GEomentry ANd Tracking) is a free, open source Monte Carlo based physics simulation toolkit developed and maintained at CERN widely used in the physics community. A GEANT4 simulation starts with a run which contains a set number of events. An event is particular process of interest to the user, such as shooting a single particle at a detector. Typical usage might be to have a run be firing 1,000 neutrons at a detector, were each neutron is a single event.

3.0.1 Organization of the GEANT4 Toolkit

The GEANT4 toolkit is divided into eight (8) class categories:

- Run and Event - generation of events and secondary particles.
- Tracking and Track - transport of a particle by analyzing the factors limiting the step size and by applying the relevant physics models.
- Geometry and Magnetic Field - the geometrical definition of a detector (including the computation of the distances to solids) as wells as the management of magnetic fields.
- Particle Definition and Matter - definition of particles and matter.
- Hits and Digitization - the creation of hits and their use for digitization in order to model a detectors readout response.
- Visualization - the visualization of a simulation including the solid geometry, trajectories and hits.
- Interface - the interactions between the toolkit and graphical user interfaces and well as external software.

There are then three classes which must be implemented by the user in order use the toolkit. These classes are:

- `G4VuserDetectorConstruction` which defines the geometry of the simulation,
- `G4VUserPhysicsList` which defines the physics of the simulation, and
- `G4VUserPriamryGeneratorAction` which defines the generation of primary events.

Five additional classes are available for further control over the simulation:

- `G4UserRunAction` which allows for user actions

4 Methods

For convince a subversion repository was created to manage the developed code base, and all source code is available by anonymous checkout from `http://www.murphs-code-repository.googlecode.com/svn/trunk/layeredPolymerTra` Revision 360 was the code base used to generate the results shown in 6.

4.0.2 Detector Geometry

The geometry was setup such that it is possible to define multiple layers of detectors, as shown in Figure 4. This was done by creating a

Listing 1: Listing

4.0.3 Physics Lists

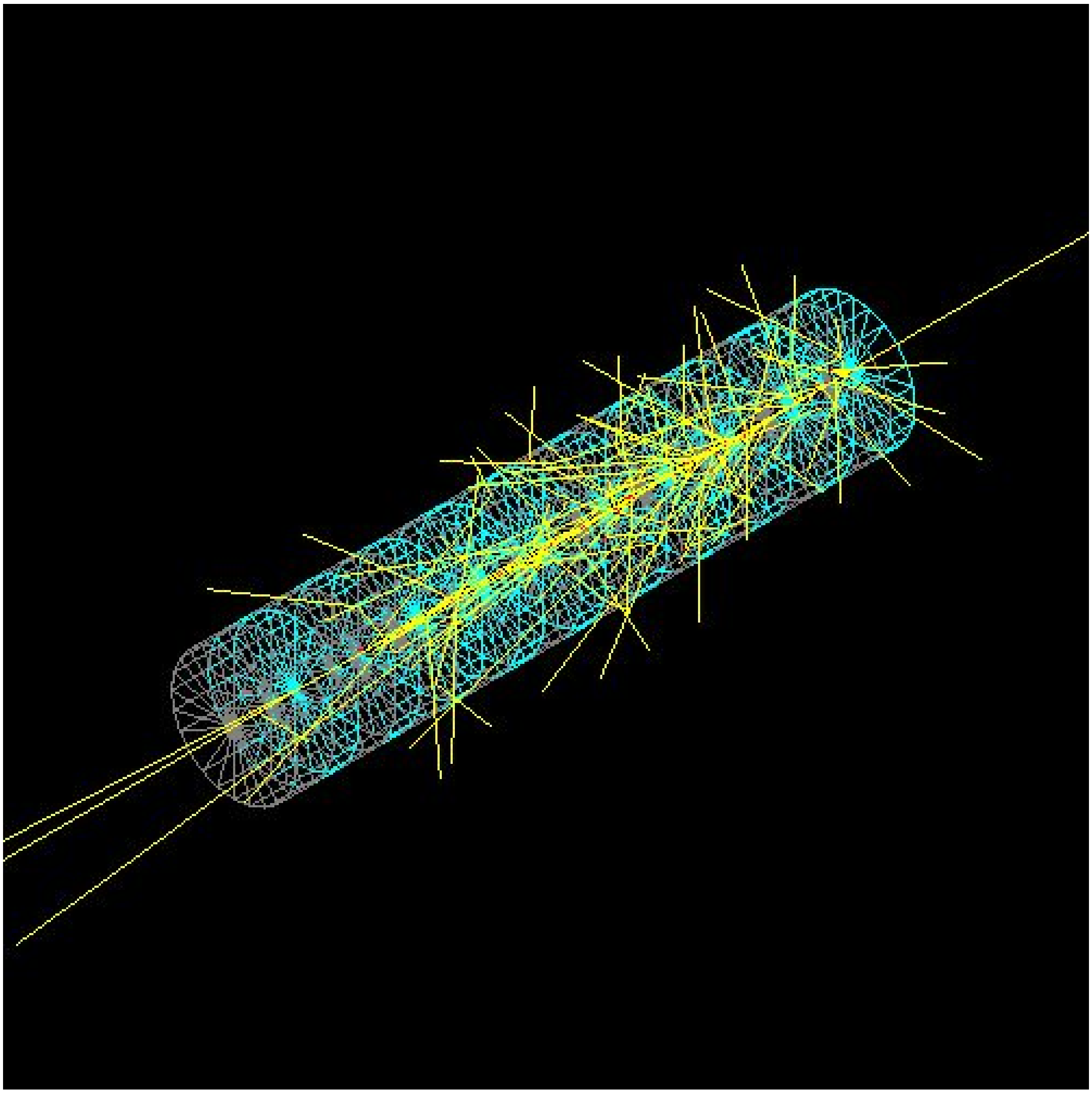
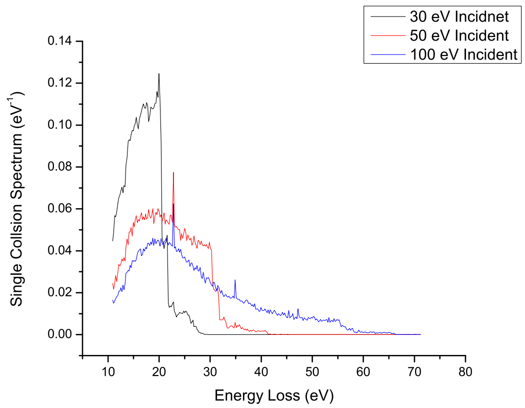
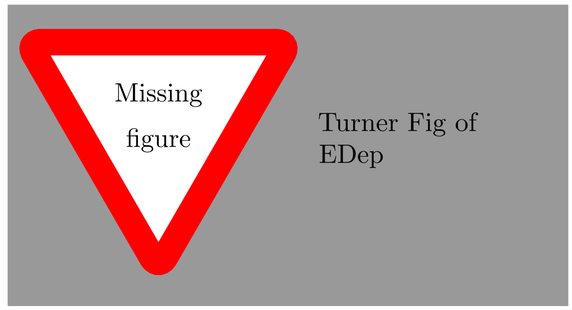


Figure 4: 10 Layer Detector with a simulated gamma event

Figure 5: Single Collision Energy Loss of Water



(a) Simulated



(b) Turner

5 Simulation Validation

5.1 Energy Deposition Validaiton

The energy deposition was tested by reproducing the single collision energy loss spectra in water. The `PhysicsList` was extended to include `G4DNAPhysics` and the detector material was set to the NIST defination contained in the toolkit with `G4Material* H2O = man->FindOrBuildMaterial("G4_WATER")`.

5.2 Spectra Validaiton

The simulation was validated by computing the weighted average of the energy deposition 5.1 and comparing it to the spectra average defined in 5.2.

$$< E >= \frac{\int_0^\infty \phi(E) E dE}{\int_0^\infty \phi(E) dE} \text{where} \tag{5.1}$$

$$< \mu >= \frac{\int_0^\infty f(x) x dx}{\int_0^\infty x(x) dx} \text{where} \tag{5.2}$$

Figure 6: Gamma Simulation Agreement

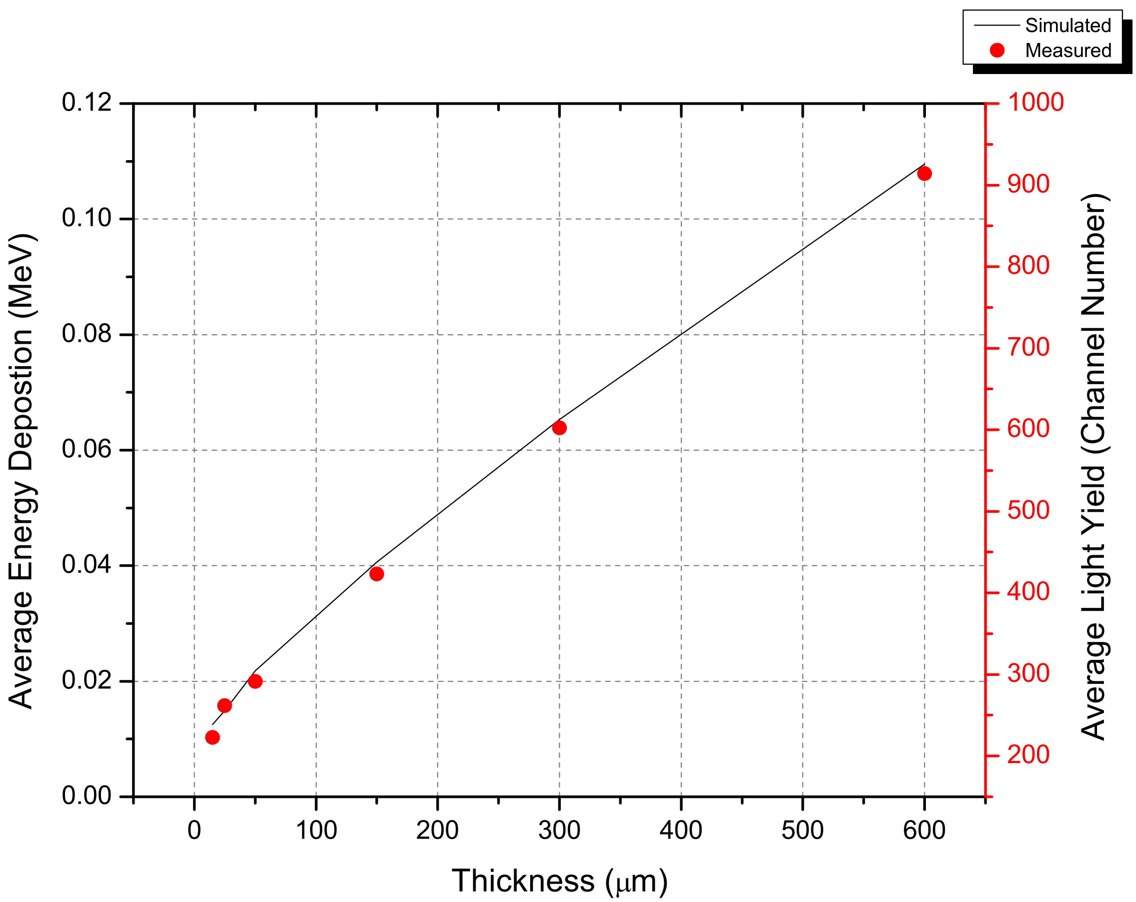
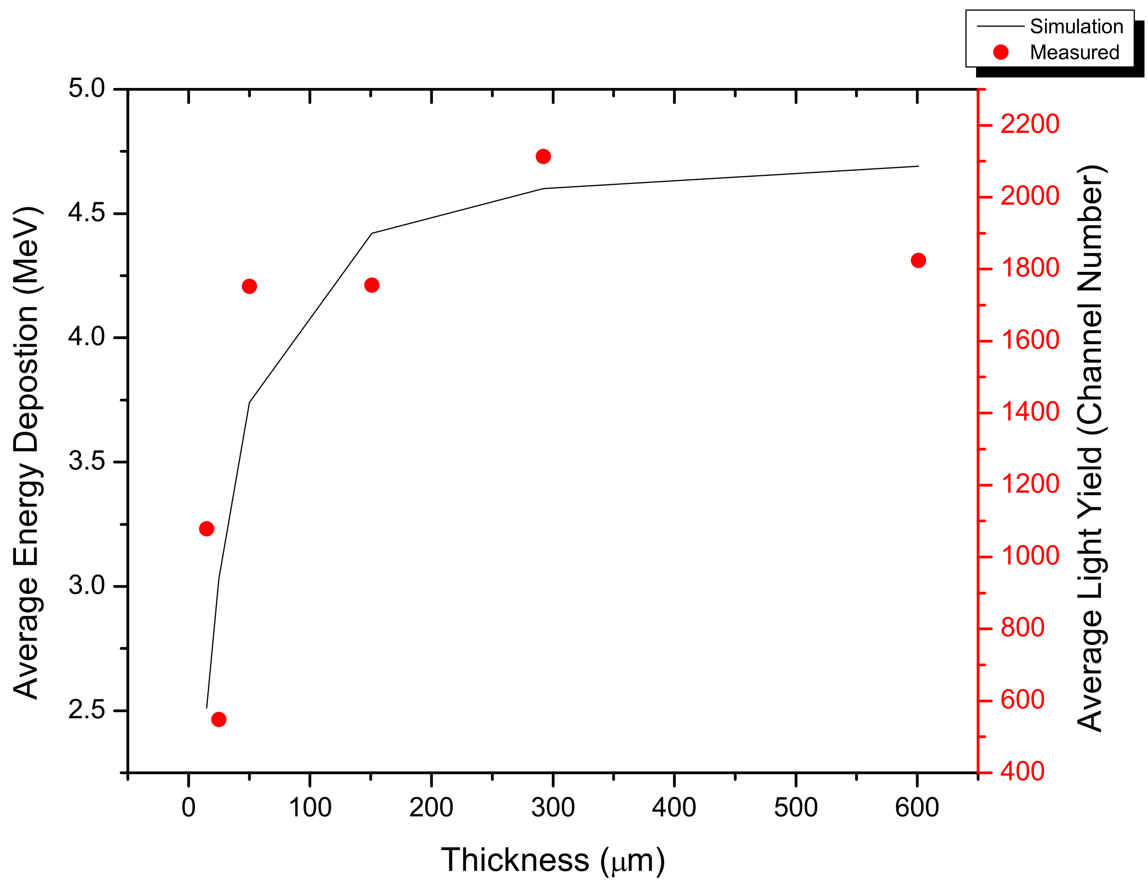


Figure 7: Neutron Simulation Agreement



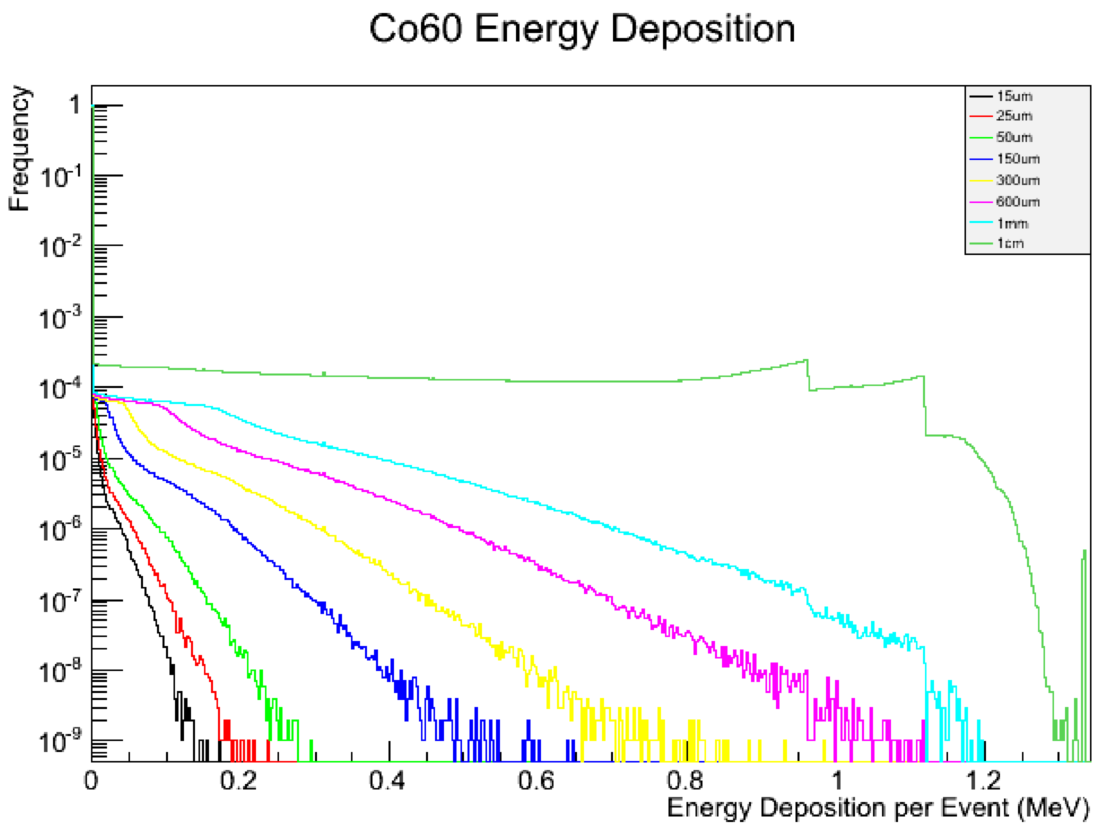


Figure 8: Simulated Energy Depositon for a Single Film (gammas)

6 Results

Write Results Section

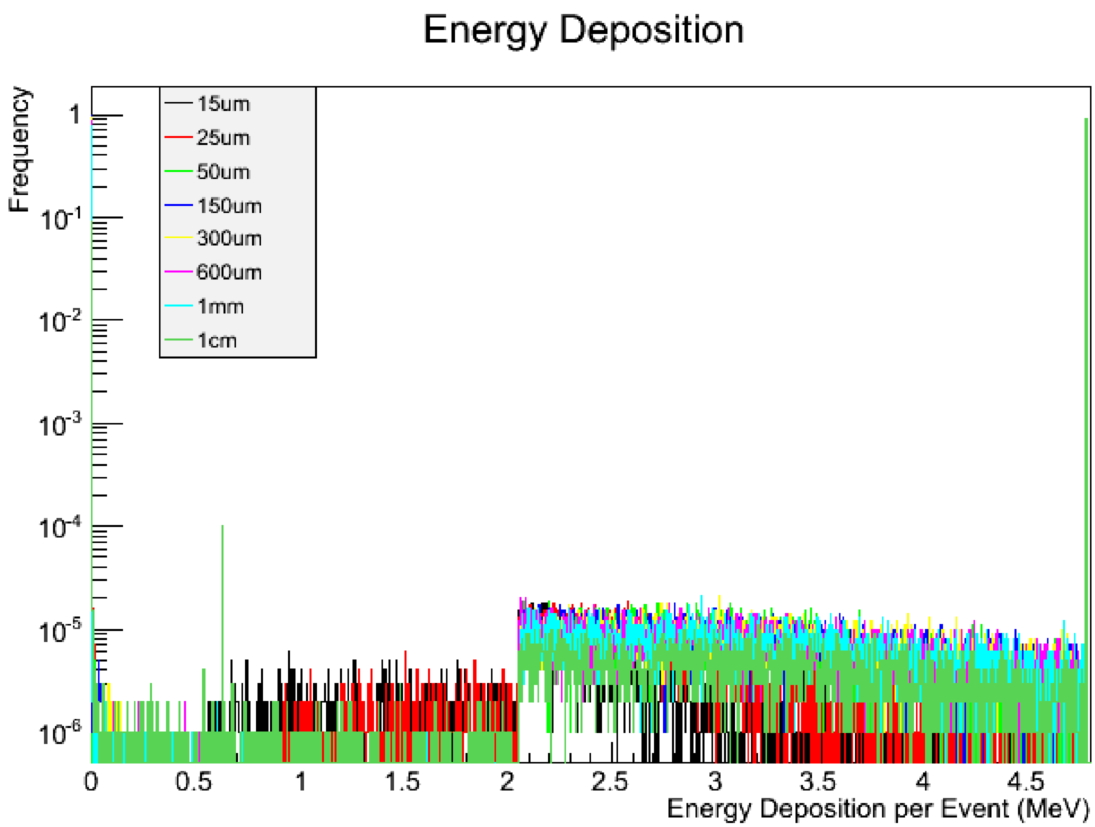


Figure 9: Simulated Energy Depositon for a Single Film (neutrons)

.1 GEANT4 Implementation

Visible light in GEANT4 is known as an optical photon. An optical photon has momentum ($\vec{p} = \hbar\vec{k}$), corresponding to the energy and direction of the photon, as well as a polarization ($\vec{e}$). The GEANT4 toolkit breaks up light transport into two parts; the creation of the optical photon an the transport of the optical photon through the material. Each of these are material dependent properties which need to be supplied by the user. This done by creating a material properties table G4MaterialPropertyTable, of which the following properties are available:

- `RINDEX`
- `ABSLENGTH`

.1.1 Scintillation Process

The number of optical photons generated by GEANT4 is proportional to the energy lost during the step, determining the energy from the empirical emission spectra of the material. In GEANT4 this is accomplished by creating a `G4Scintillation` process.[2]

```
#include "G4Scintillation.hh"

G4Scintillation* theScintProcess = new G4Scintillation("Scintillation");

theScintProcess->SetTrackSecondariesFirst(true);
theScintProcess->SetScintillationYield(7500.0/MeV);
theScintProcess->SetResolutionScale(1.0);
theScintProcess->SetScintillationTime(45.*ns);
```

.1.2 Optical Photon Transport

There are three classes of optical photon interactions in GEANT4:

- Refraction and reflection
- Bulk Absorption
- Rayleigh scattering

Of these only refraction and reflection are necessary. [?]

[?]

[2] As the scintillation properties are attached to the process and not the material GEANT4 is incapable of more than one scintillation material in any given application.