Cadmium Capture-Gated Neutron Detector with ^{6}Li-Glass

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ABSTRACT

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We have modeled, built, and tested a neutron detector composed of three neutron detecting materials (cadmium, lithium, and scintillating plastic) into a single detector in an attempt to broaden the neutron energy detection range and to decrease the gamma-ray sensitivity compared to lithium-plastic or cadmium-plastic. Computational modeling optimizes the geometry of the detector. Initial testing of the efficiency of the detector has shown ability to discriminate a neutron signal from a gamma-ray signal in the ^{6}Li-glass. This work provides the foundation for further improvement of the detector concept.

Keywords: Neutron Detector, MCNP, Nonproliferation

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Chapter 1

Introduction

1.1 Overview

This work describes the modeling, building, and data acquisition of a cadmium capture-gated neutron detector with ^{6}Li-glass and plastic scintillator. I will refer to this as a combination detector, because it combines the neutron detection technology of both ^{6}Li-glass and cadmium. In this chapter I discuss the general motivation for making neutron detectors and the specific motivation for making a combination detector. I review the challenges associated with detecting neutrons. In Chapter 2 I describe the computational modeling, the construction of detector, and the data acquisition. In Chapter 3 I discuss the results and make recommendations for future work.

1.2 Motivation

Neutron counters are placed at the borders of the Untied States to prevent nuclear weapons material, such as plutonium, from being smuggled into the country. Current detectors used by the United States Department of Homeland Security (DHS) rely heavily on ^{3}He for neutron detection. ^{3}He is also used in other experiments for which efficiency and ability to discriminate neutrons from gamma rays are important. ^{3}He works well for these applications, however, there is a national shortage of this material [1]. A neutron detector that does not require ^{3}He is needed to maintain safe ports and protect against unsafe, unwanted shipments of fissile material.

One of the unique aspects about my project is that I have used cadmium in combination with the ^{6}Li-glass to detect a broader energy range of neutrons as described in section 1.3. ^{6}Li-glass's utility lies in its ability to detect very low energy neutrons. Using this unique combination of ^{6}Li-glass and cadmium, I will also have the advantage of low gamma sensitivity from the ^{6}Li-glass along with energy information from the proton recoil pulse in the plastic, and neutron capture in the cadmium. The combination detector provides 3 independent neutron signals.

The DHS places strict requirements on gamma sensitivity. The requirement is that there can only be one false neutron attribution for 10^6 gamma ray detections [2]. One of the challenges in neutron detection is that gamma rays often create a pulse similar to those given by neutrons. The combination detector is designed with the aim of achieving the required gamma ray insensitivity with pulse shape discrimination (PSD) in the post processing of the detector data. This process of separating gamma ray signals from neutron signals is described in section 2.5.

1.3 Background

Neutron detection is especially challenging because neutrons lack charge and therefore do not interact electrically with their surroundings. Neutrons are detected indirectly through their interactions with other particles. Neutron signals are also hard to distinguish from gamma ray signals. Gamma rays are present in naturally occurring materials and in almost all places where neutron detection would be done in the field. Therefore part of the DHS requirement is to detect neutrons in the presence of gamma rays with good discrimination between the two.

^{6}Li can capture a neutron, usually a low-energy neutron, and release an alpha particle and triton, the nucleus of a ^{3}H atom. The capture cross section of ^{6}Li increases as the energy of the particle decreases, so ^{6}Li-glass is very good at detecting low-energy neutrons. Depending on the momentum of the incoming neutron, two possible reactions are

$$^6\text{Li} + \text{n} \rightarrow {}^7\text{Li} + \gamma + 7.25 \text{ MeV} \tag{1.1}$$

and

$$^6\text{Li} + \text{n} \rightarrow {}^3\text{H}^+ + \alpha^{2+} + 4.78 \text{ MeV}. \tag{1.2}$$

When an alpha particle and a triton are emitted as in Eq. (1.2), several million electron volts of energy are deposited in the scintillating plastic. This produces a readily measurable light output toward the blue end of the visible spectrum. The light is detected with a photomultiplier tube (PMT). When a photon enters the PMT, it can eject a photoelectron from the cesium coating inside the photocathode. This electron is accelerated into a dynode where it ejects additional electrons. This amplification process is repeated in several stages until the output pulse is large enough to be used with conventional electronic devices. A single event typically produces many photoelectrons, producing a current pulse proportional to the light arriving at the photocathode. The shape of the output pulse depends on the characteristics of the PMT as well as the shape of the original light pulse. In our specific set-up the electrical pulse produced by the PMT is amplified and then put into a digitizer that converts the voltage into a digital signal. We use a Caen digitizer that has an input range of +1 V to -1 V, so we amplify the pulse from the PMT to make the largest pulses about 1 V in magnitude. The Caen digitizer digitizes the pulse voltage every 4 ns to produce a vector containing the pulse shape information. Each digital pulse is stored in a data file that is sent to a MatLab file for analysis.

A single pulse from the ^{6}Li-glass corresponds to the detection of a neutron. The BYU nuclear physics group's current detector models require PSD, as explained in section 2.4, to determine the fraction of the events detected correspond to neutrons and not false gamma ray detections. The

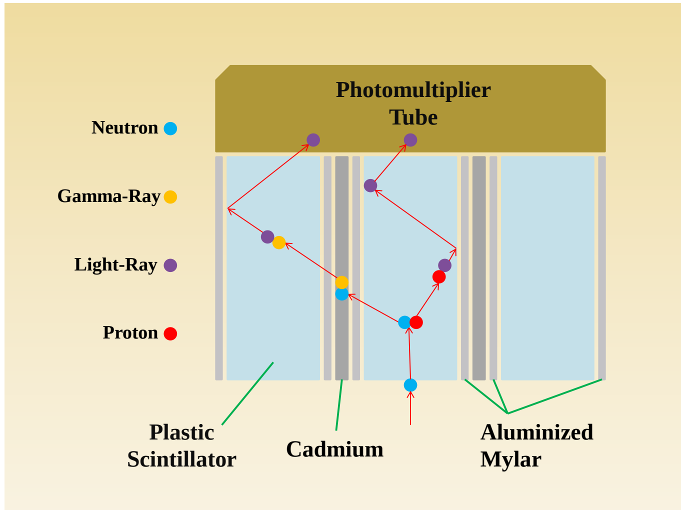

Figure 1.1 A typical path of neutron in the cadmium portion of the detector.

basic function of the ^{6}Li-glass detector is to signal the presence of a neutron. The ^{6}Li-glass can be fabricated into different shapes, sizes, and thicknesses to maximize its ability to detect neutrons. We have only used a single size, and varied the position within the detector.

As illustrated in Fig. 1.1, neutrons are moderated in the plastic by striking the hydrogen and carbon nuclei in the plastic. This causes the neutrons to lose energy. Because carbon is much more massive than neutrons, relatively little energy is lost when neutrons interact with carbon. An initial light pulse is produced when protons transfer their energy to scintillator in the plastic. We have labeled the first pulse the proton recoil pulse, as the proton generates the light. We describe the light output in terms of the energy of an electron that produces an equivalent amount of light. The units of light output are MeVee (MeV electron equivalent). The second light pulse is from the moderated neutron being captured in the cadmium, which we have labeled the cadmium capture pulse. When the neutron captures in a ^{113}Cd it becomes a ^{114}Cd. The nucleus decays to a more stable state by emitting 9 MeV of gamma rays.

1.4 Related Work

The BYU nuclear physics group is currently working on different detectors of varying materials and geometry for a range of applications. Adam Wallace is working on a detector that uses ^{6}Li-glass and scintillating plastic. This detector will have applications in detecting heavily moderated neutrons. The Li-detector is also useful for detecting fissile material surrounded by water used as a means to shield it from typical neutron detection. Steve Gardiner is working on a ^{6}Li-glass detector with specially made glass that should have a better gamma-neutron discrimination. By breaking up the ^{6}Li-glass and recasting it in water glass (sodium silicate), gamma rays loose most of their energy in the non-scintillating water glass. Nathan Hogan is working on a detector using cadmium and scintillating plastic. The cadmium detector gives information about the initial energy of the neutron. The cadmium detector also requires a double pulse to indicate the detection of a neutron as explained in section 1.3. Mr. Hogan will compare the efficiency of the cadmium detector to an identically built detector replacing the cadmium sheets with tin. Tin doesn't have a significant capture cross section for neutrons, so this will provide a background measurement for accidental double pulses. Our group is also working on multiple PMT configurations for a system of detectors to increase detection efficiency.

Chapter 2

Experimental Setup

2.1 Computational Modeling

Monte Carlo Neutral Particle (MCNP) is a computer code that simulates the motion and interactions of subatomic particles using Monte Carlo techniques. The code follows the path of a specified number of neutrons through the detector and sums up the probability of different interactions that may occur and that are illustrated in Fig. 2.1. The probabilities are based on large capture cross-section data libraries. These libraries are incorporated into the code. The most common neutron interactions in the combination detector include inelastic and elastic scattering, and capture. In the case of inelastic scattering, a gamma ray is emitted, however, in the combination detector this interaction is relatively uncommon. In the case of elastic scattering a neutron elastically collides with atoms in the detector: hydrogen and carbon, in the plastic, and cadmium. As explained in section 1.3 the light output from a nucleus hitting a hydrogen proton produces a signal. MCNP also gives us information about elastic collisions with the heavier carbon and cadmium atoms, but these produce a lesser signal, as their mass is much greater than the mass of the incident neutron. The neutron can also be captured in the detector as illustrated in the following equations.

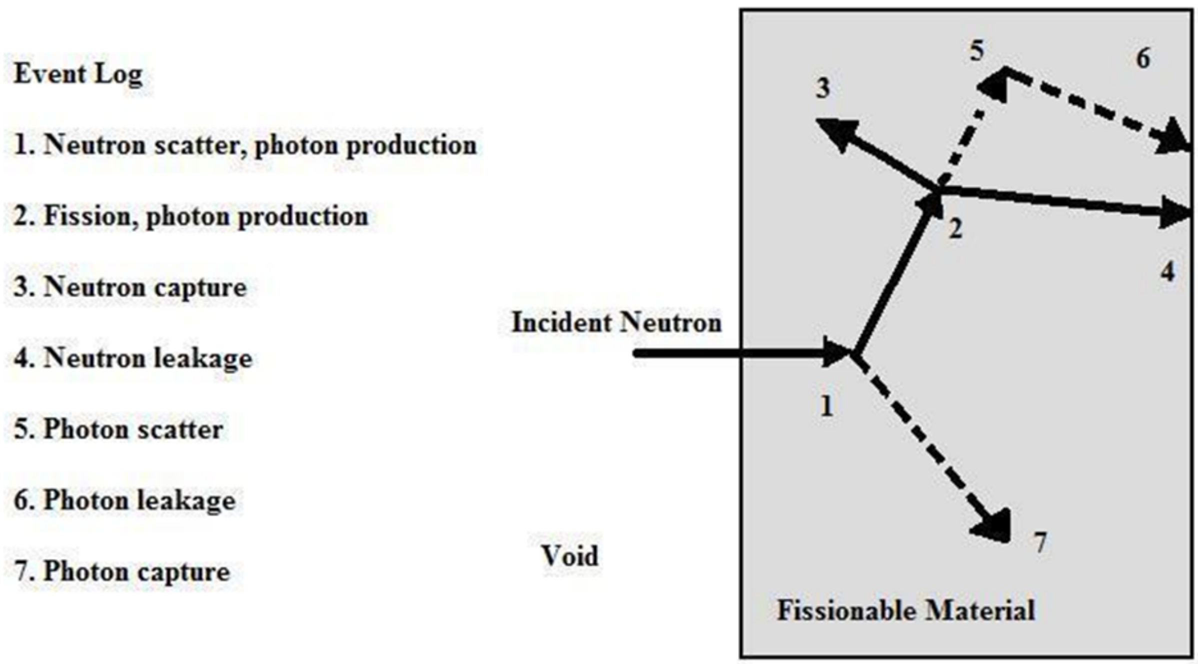

Figure 3: MCNP event log diagram

Figure 2.1 MCNP event log diagram shows the possible neutron paths in the detector [3].

$$\mathrm{n}+\mathrm{p}\rightarrow\mathrm{d}+\gamma\,2.2\ \mathrm{MeV} \tag{2.1}$$

$$^{113}\mathrm{Cd}+\mathrm{n}\rightarrow^{114}\mathrm{Cd}^{+}\rightarrow+^{114}\mathrm{Cd}\;groundstate+\gamma\,9\ \mathrm{MeV} \tag{2.2}$$

$$^{6}\mathrm{Li}+\mathrm{n}\rightarrow{}^{7}\mathrm{Li}\rightarrow^{3}\mathrm{H}+\alpha \tag{2.3}$$

MCNP takes certain geometries and specified sources, neutron sources in my case, and gives the statistical neutron flux in the detector for the specified parameters. The input of the code includes defining cells in the detector where the neutron will interact with the detector materials. A sample input file for the combination detector is in the Appendix.

We used MCNP to determine the detector geometry leading to the best neutron detection effi-

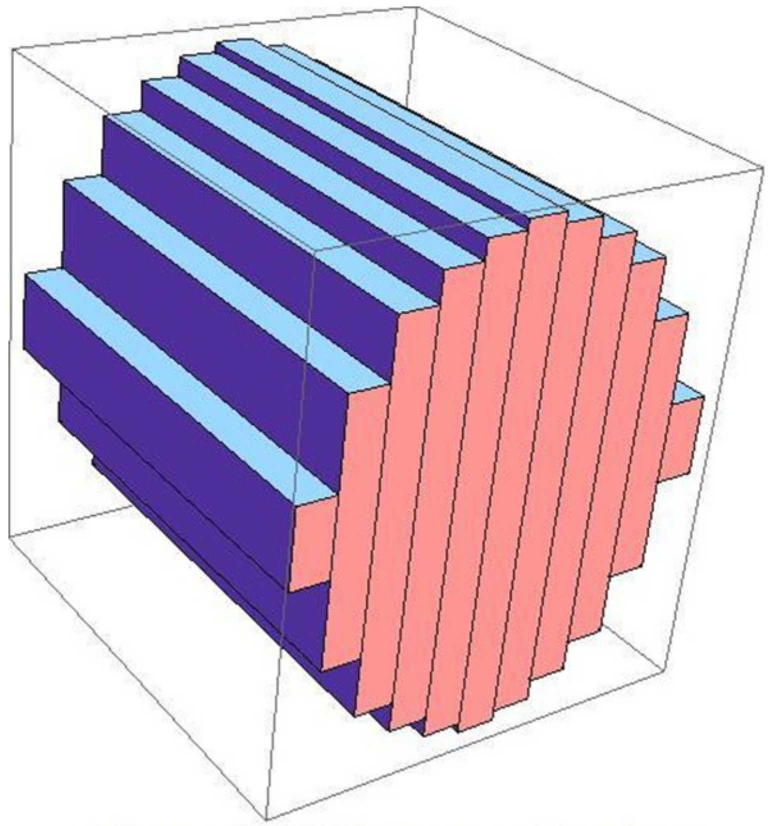

Figure 2.2 Geometry of the plastic in the detector.

ciency. We set up the geometry of the detector for the code input based on previous calculations done for the cadmium detector.

Figure 2.2 is a schematic of the geometry of the scintillating plastic in the combination detector. I added a sheet of ^{6}Li-glass to this geometry.

We use MCNP-PoliMi (PoliMi) to model what neutrons do in the scintillating plastic. PoliMi is a code that is used in addition to MCNP. It simulates each neutron-nucleus interaction as closely as possible, and gives additional information about the time, location, and energy loss of each neutron or gamma interaction. Specifically for my setup PoliMi gives information about the about the neutron interactions in the scintillating plastic. When neutrons capture in ^{6}Li or cadmium we do not need PoliMi, as the original MCNP gives a tally of capture events. Neutrons in plastic

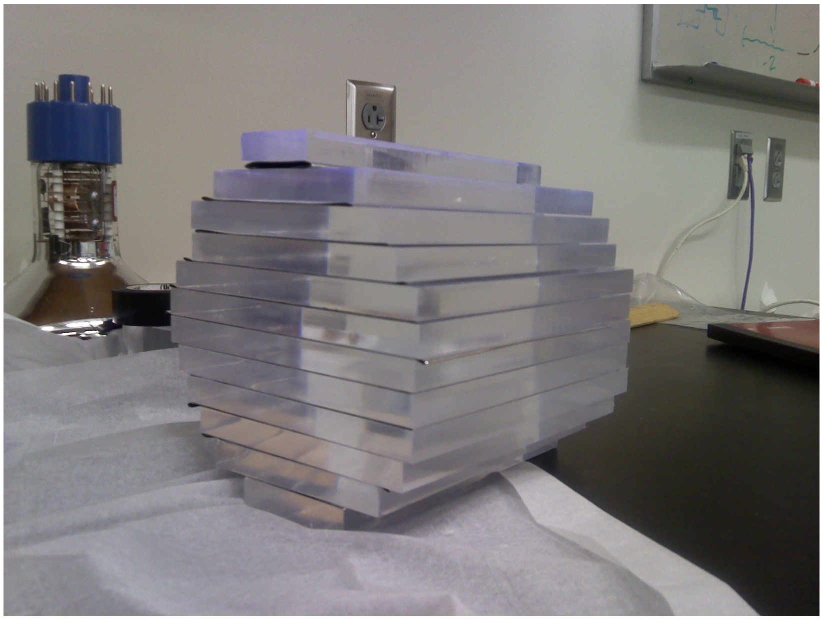

Figure 2.3 The plastic and cadmium inside of the combination detector.

scatter off of the hydrogen and carbon, losing energy as they do, and they eventually drift out of the plastic. PoliMi keeps track of each neutron collision.

2.2 Fabrication of Detector Prototype

The combination detector was made from an existing cadmium detector. There are twelve sheets of scintillating plastic measuring six inches long and varying widths to form a cylinder when stacked on one another, as seen in Fig. 2.3 The plastic is polished to a smooth, translucent finish on all four edges. Using the plastic from the cadmium detector we had to put all the plastic in a clamp and use an end mill to go over the end of the detector to make it optically smooth on both ends. The previous detector had only one smooth end because it did not incorporate ^{6}Li-glass into the design. After milling the end, I used fine grit sand paper on all the edges that had been milled. Then I polished all the edges using a buffing wheel for optimal optical transparency. Cadmium sheets measuring roughly the same size as the plastic were re-used from the cadmium

Figure 2.4 The cadmium sheets are sandwiched between the layers of plastic.

Figure 2.5 Optical grease on the end of the detector where the PMT would go.

detector. (The cadmium was shortened 3 cm, giving a space between the cadmium and ^{6}Li-glass, to reduce overlap of ^{6}Li and cadmium neutron capture, as explained in section 3.1.) I covered the cadmium sheets with aluminized mylar to improve optical properties. The cadmium sheets are then sandwiched between each layer of plastic. Figure 2.4 shows a side view of the inside of the combination detector. The clear plastic and shiny mylar reduce light absorbtion inside the detector. I put a layer of optical grease at both ends of the plastic, as seen in Fig. 2.5. On one end of the plastic I put a sheet of 6.35 cm diameter by 1 mm thick ^{6}Li-glass. On the opposite end I attached a PMT. I wrapped a layer of aluminized mylar around the outer surface of the scintillating plastic. I fastened it all together with electrical tape and hose clamps.

2.3 Sources

We used californium (^{252}Cf) as a neutron source to determine the overall detection efficiency of the detector. ^{252}Cf is an intense neutron emitter. It decays mostly by alpha emission, but has a 3.09 percent probability to decay by spontaneous fission. The most probable neutron energy emitted by ^{252}Cf is 0.7 MeV with an average energy of 2.1 MeV. The neutron energy spectrum of ^{252}Cf is similar to what would be expected of fissile materials in nuclear weapons.

We used ^{60}Co as a gamma source. The cobalt gamma spectrum is used to calculate the gamma sensitivity of the detector when used as a neutron detector. I calculated the gamma rate from the known activity (200.35 mCu) of the cobalt to be $1.48x10^{7}$ gammas/second.

2.4 Data Acquisition

The configuration of the detector and source for data acquisition can be seen in Fig. 2.6. We put the combination detector in a light-tight aluminum can. This was to ensure that the only light entering the PMT was coming from the scintillations and not from the surroundings. The output of the PMT passed into an Ortec 474 amplifier. The signal was amplified by a factor of ten. The amplification is used to fully utilize the 12-bit range of the Caen digitizer (Fig. 2.7), as explained in section 1.3. The output of the digitizer was stored on the computer. The digitizer was set to record 100,000 events. An event is recorded for any kind of light output detected. This number of events was enough events to analyze clearly what the detector was detecting, but not too many events to overload the computer's memory capacity.

Figure 2.6 The combination detector inside the light-tight can is placed 8 cm away from the source. Cement blocks and cans of water were placed around the source for personnel shielding.

Figure 2.7 The digitizer takes the voltage from the detector and converts it to a digital signal.

The detector was placed a distance of 20 cm from the ^{252}Cf. The ^{6}Li-glass face was directed toward the ^{252}Cf. Between the combination detector and the ^{252}Cf was 5 cm of lead to shield any gamma rays and non-neutral particles in order to achieve a more purely neutron source. Paraffin wax was placed around the ^{252}Cf to moderate and help reduce room return of the neutrons. Extra wax and cans of water were placed around the ^{252}Cf as shielding for people working in the lab.

2.5 Digitized Data Analysis

The digitized data are used to calculate the absolute efficiency of the detector. This efficiency is defined as the number of pulses recorded divided by the number of neutrons emitted by the source in a specific geometry. Since we know the activity of the source, we can determine the number of neutrons emitted. We can use this along with number of pulses recorded in the digitizer to calculate the intrinsic efficiency of the combination detector. This is the fraction of the neutrons entering the detector that are detected. The number of neutrons striking the detector is calculated from the source activity and the solid angle of the detector.

Figure 2.8 is an example of a light pulse in units of voltage per time. The red vertical lines define the area of the pulse. The area under the pulse is proportional to the light output. The black line divides the pulse into early and late light. The area to the left of the black line is defined as early light, while the area to the right of the black line is defined as the late light. Pulses from plastic and ^{6}Li-glass differ in shape because the glass pulses have much longer tails. If we compare early light to total (early + late) light, the plastic has a larger early/total ratio than the ^{6}Li-glass. By making a scatter plot of early vs total light for each pulse, we can decide whether a pulse is a neutron or a gamma ray.

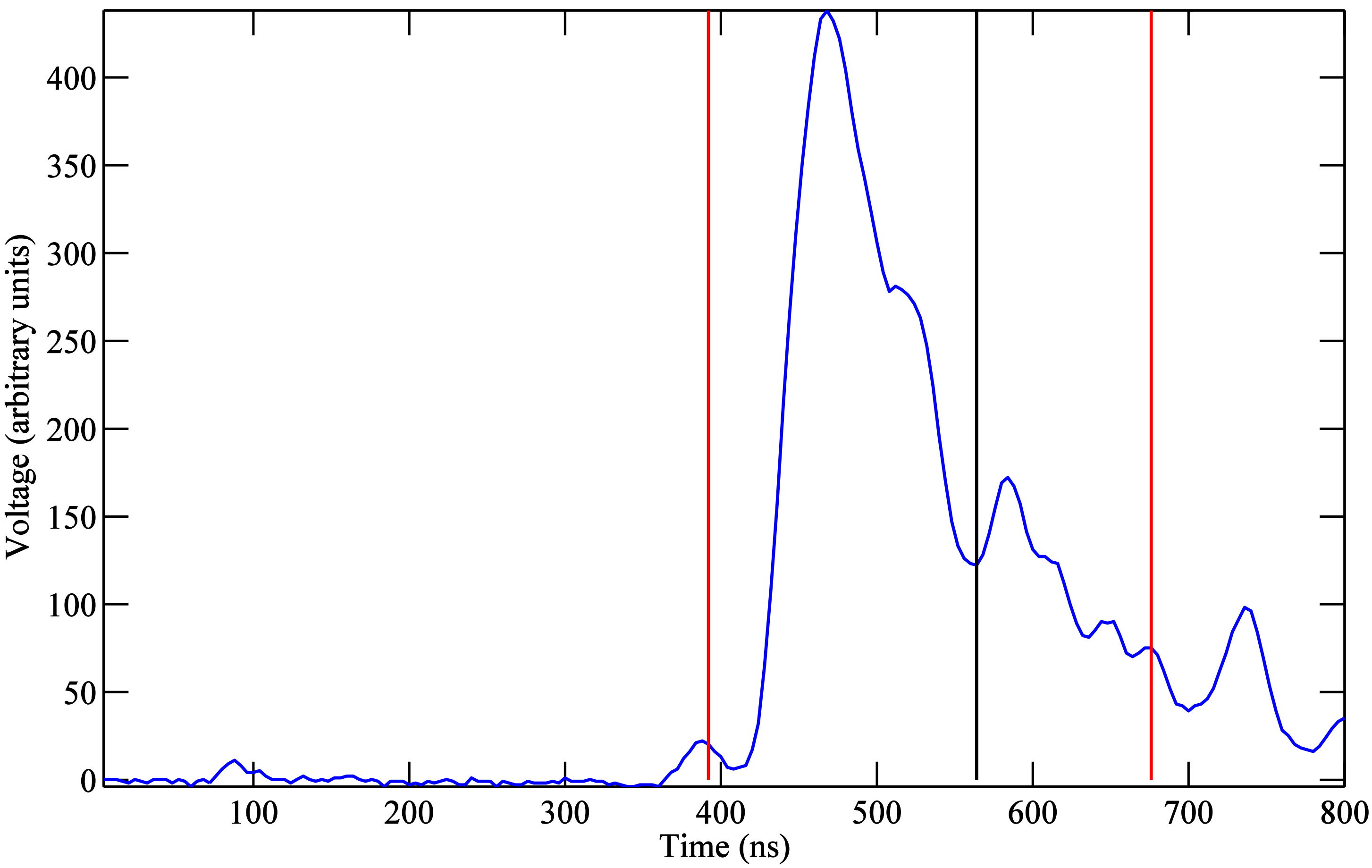

Figure 2.8 A typical pulse of light from the ^{6}Li-glass and plastic scintillator. The vertical lines divide the pulse into early and late light.

Chapter 3

Results

3.1 Computational Data Interpretation

MCNP calculates the fraction of neutrons that are captured out of all the neutrons that hit the detector. By modeling the combination detector in MCNP with the original geometry described, but varying the length of the cadmium sheets we determined that the optimal length to separate the ^{6}Li-glass from the cadmium was 3 cm. This provided only 20 percent efficiency loss of both the ^{6}Li-glass and the cadmium. The shortened cadmium allows some of the neutrons to moderate in the plastic and capture in the ^{6}Li-glass. When there is no separation all of the neutrons are absorbed in the cadmium. Figure 3.1 is a graph of each materials neutron detection efficiency with respect to separation distance.

PoliMi gives an idea of the light output from each material in the detector. The following Fig. 3.2 shows the fraction of neutrons detected relative to the light output threshold accepted. To be detected in plastic neutrons transfer energy to protons. The MeVee light output of protons is not a linear function of proton energy. The solid black lines represent proton energies that give rise to indicated light output in MeVee. The lines correspond to proton energies of 0.2, 0.3, 0.5, 1.0

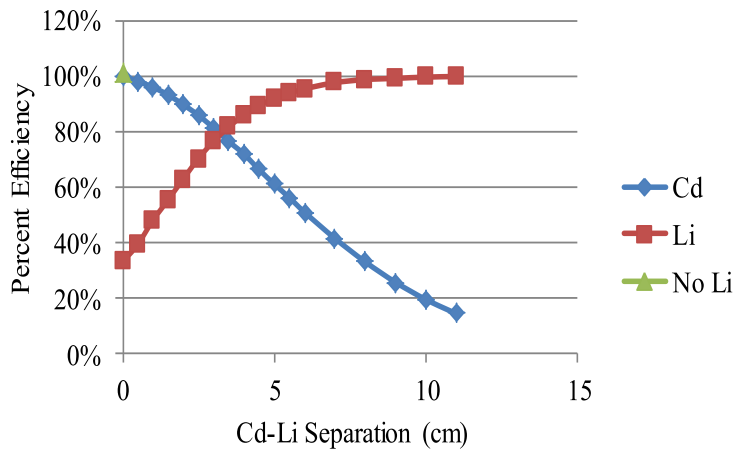

Figure 3.1 A plot of efficiency as a function of separation shows that a 3 cm separation gives 80 percent efficiency of each material.

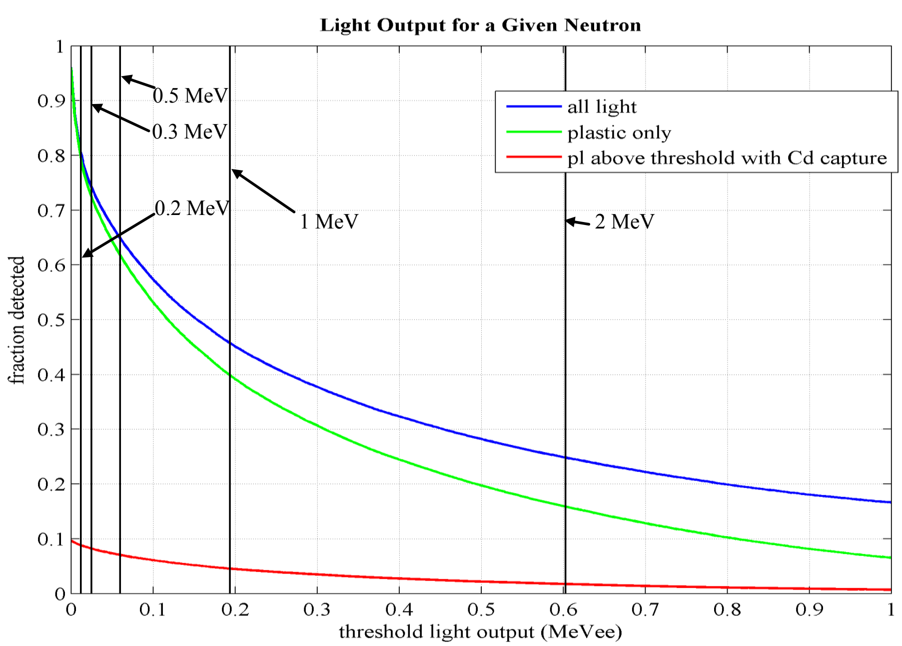

Figure 3.2 Fraction of detected light from each material in the detector in the presence of a ^{252}Cf neutron source.

and 2.0 MeV proton energies. Figure 3.2 illustrates that nearly all of the light is detected when the threshold is very low. In practice the light threshold is around 0.5 MeV.

PoliMi tells us the amount of time a neutron spends in a detector before it captures in the

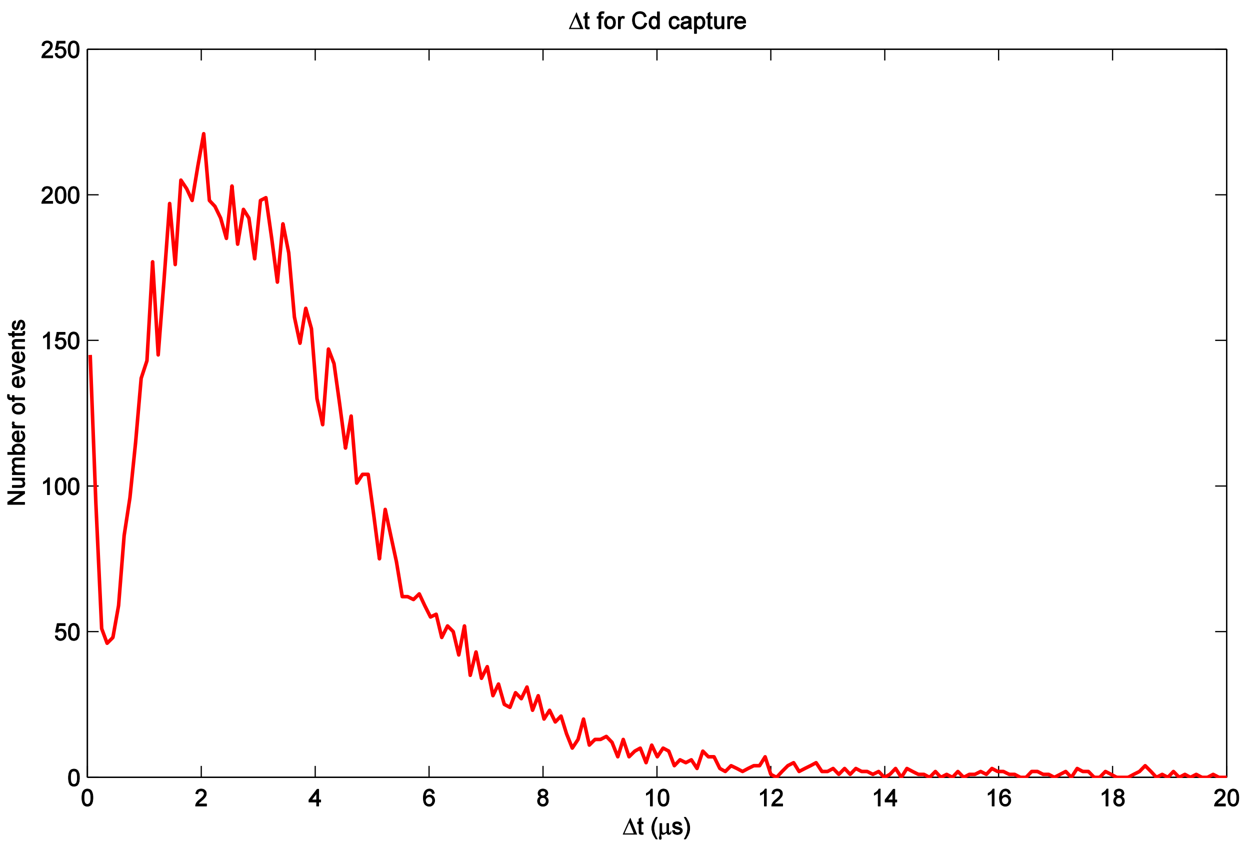

Figure 3.3 The delta t is the time it takes for a neutron to slow down and capture in the detector.

cadmium. The results of this are illustrated in Fig. 3.3. The delta t is the time it take for a neutron to slow down and capture in the detector.

3.2 Lessons From The Detector

We learned that our original concept of combining ^{6}Li-glass and cadmium will work. The current geometry of the detector allows analysis of neutron capture in the ^{6}Li-glass, but could be improved.

In order for the light from the neutron signal to reach the PMT it travels trough up to 15 cm of plastic and also reflects off the aluminized mylar. Upon further inspection we found that our

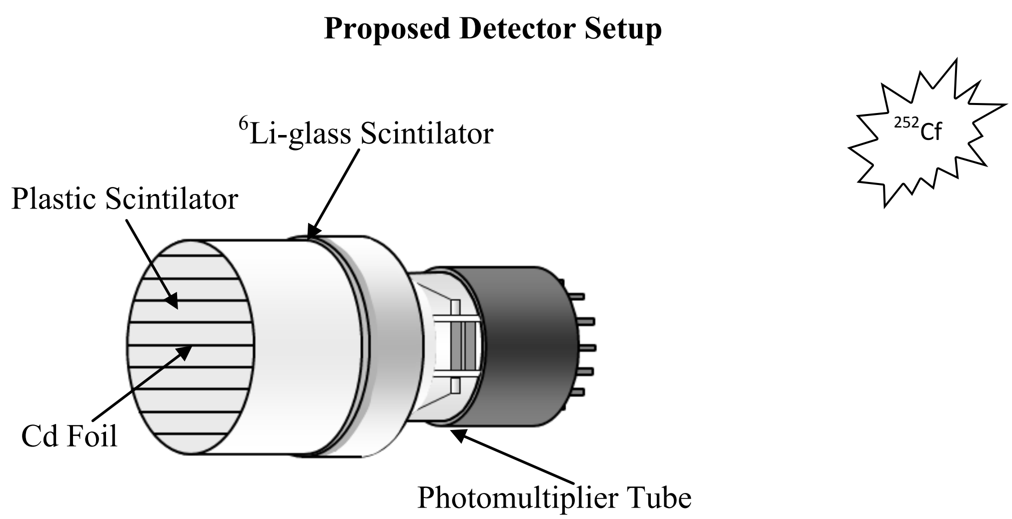

Figure 3.4 The new detector orientation should decrease the amount of light lost in the detector. or increase the amount of light that reaches the PMT.

original assumption that mylar had a reflectance of 95 percent was in error. Experimentally we found the reflectance to be closer to 85 percent. We think that detection for all detectors should be improved by placing the ^{6}Li-glass next to the PMT and moving the source to the other side of the PMT as illustrated in 3.4. The PMT and its base will not significantly affect the neutrons impinging on the detector.

3.3 Comparison With Detectors

The cadmium detector uses a double pulse to detect neutron capture in the cadmium. The combination detector should detect 80 percent of the doubles detected by the cadmium detector. It is difficult to do a direct comparison of this because in the MatLab program for analysis of double pulses in the cadmium detector, pulses from the ^{6}Li-glass scintillator are counted as doubles as well. We can distinguish the ^{6}Li-glass pulses from the cadmium capture pulses with PSD. The MatLab code used to count double pulses in the cadmium detector will need to be supplemented with the PSD coding.

The overall gamma sensitivity of the combination detector can be directly compared to the overall gamma insensitivity of the ^{6}Li-glass detector. Gamma insensitivity is found by comparing the early/late analysis of each detector in the presence of a gamma source with the early/late analysis of each detector in the presence of a neutron source. The detects one cobalt gamma in the neutron region for every 10^4 neutrons. The combination detector detects on cobalt gamma in the neutron region for every 10^5 neutrons. The combination detector appears to be an order of magnitude better at discriminating gamma ray signals from neutron signals than the ^{6}Li-glass detector.

3.4 Conclusions

Figure 3.5 shows a clear separation of neutrons from gamma rays in the combination detector. In the figure each point represents an event. Using PSD we are able to define a distinct neutron region. We have shown that it is possible to combine the functions of two independently successful designs. The combination detector gives two signals to indicate the detection of a neutron. The ^{6}Li-glass provides detection for low energy neutrons and the cadmium provides detection for higher energy neutrons. The two independent signals provide a reduced chance of false alarms at portal monitors when detecting nuclear material. The combination detector also provides a wider energy detection range of source neutrons.

3.5 Recommendations for Future Work

There are a few things that can be done to allow the light from neutrons in the ^{6}Li-glass to give a stronger and more uniform signal. The combination detector could be reconstructed so that the PMT is next to the ^{6}Li-glass as discussed in section 3.3. The aluminized mylar could be further

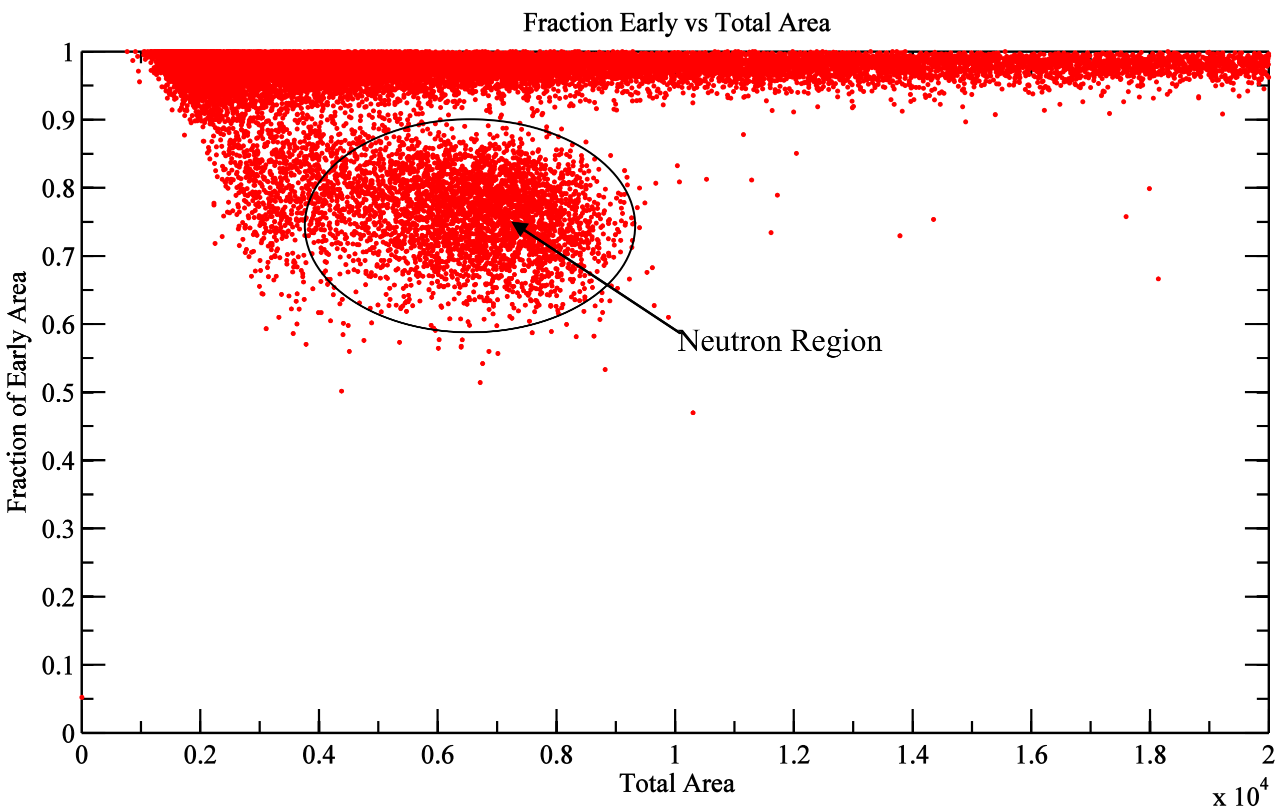

Figure 3.5 A scatter plot of the early light v. the total area.

characterized. A material with a higher reflectance could be used to replace it. The flat slab geometry of the scintillating plastic could be replaced with a wedge geometry. Wedge geometry should allow more light to reach the center of the PMT.

Light detected near the outer diameter of the PMT gives less intense signal than light detected near the center of the PMT. In order to increase the efficiency of the PMT the detector face could be masked off, to a fraction of the face size of the PMT.

Broken ^{6}Li-glass, mentioned in section 1.4, could be used in the place of the regular sheet of ^{6}Li-glass. This should reduce accidental gamma ray signals.

Appendix A

MCNP Input Deck Text File

```
Plastic scintilator, no 0.01cm Cd sheets, 12 slabs, Li Base, POLIMI
c ==============================================================================
c cell cards
c ===========
C         I have changed this to Cd.
1         2  -8.65  -1 -2 3 24 -53
2         2  -8.65  -1 -4 5 24 -53
3         2  -8.65  -1 -6 7 24 -53
4         2  -8.65  -1 -8 9 24 -53
5         2  -8.65  -1 -10 11 24 -53
6         2  -8.65  -1 -12 13 24 -53
7         2  -8.65  -1 -14 15 24 -53
8         2  -8.65  -1 -16 17 24 -53
9         2  -8.65  -1 -18 19 24 -53
10        2  -8.65  -1 -20 21 24 -53
11        2  -8.65  -1 -22 23 24 -53
C         Plastic Slabs
12        1  -0.86  -1 2 24 -53
13        1  -0.86  -1 -3 4 24 -53
14        1  -0.86  -1 -5 6 24 -53
15        1  -0.86  -1 -7 8 24 -53
16        1  -0.86  -1 -9 10 24 -53
17        1  -0.86  -1 -11 12 24 -53
18        1  -0.86  -1 -13 14 24 -53
19        1  -0.86  -1 -15 16 24 -53
20        1  -0.86  -1 -17 18 24 -53
```

```
21        1  -0.86  -1 -19 20 24 -53
22        1  -0.86  -1 -21 22 24 -53
23        1  -0.86  -1 -23 24 -53
C         What makes it hybrid
24        3  -2.50  -1 -25 52          $ Lithium base
25        1  -0.86  -1 -24 25          $ Plastic Between Cd and Li
C         Outside Things
c 52        2  -8.65  1 -54 57 -58    $ Cd wrapped around detector
53        0  1:-57:58 -56              $ Air outside detector
54        0  -1 -57 55                 $ Source ->A disk on the Li-glass front
C         Air
55        0  -1 -52 57                 $ Air between source and detector
56        0  -1 53 -58                 $ Air at back of detector
57        0  56                        $ Infinity and beyond

c Surface Cards
c ==============
1         cz  6.35
C         Planes orthogonal to (1,0,0) to divide wedges
2         px  5.29667
3         px  5.28667
4         px  4.23833
5         px  4.22833
6         px  3.18
7         px  3.17
8         px  2.12167
9         px  2.11167
10        px  1.06333
11        px  1.05333
12        px  0.005
13        px  -0.005
14        px  -1.05333
15        px  -1.06333
16        px  -2.11167
17        px  -2.12167
18        px  -3.17
19        px  -3.18
20        px  -4.22833
21        px  -4.23833
22        px  -5.28667
23        px  -5.29667
C         Plane orthogonal to (0,0,1) separating Cd from Plastic
```

```
24        pz  0.5
C         Plane separating Plastic from Li
25        pz  0.1
C         Outer Surfaces
52         pz  0.0          $  Front of the detector
53         pz  15.24        $  Back of the plastic
C 54       cz  6.45         $  outside of the Cd surrounding plastic
55         pz  -0.101       $  Face of source farthest from detector
56         so  50           $  Sphere separating detector from outside world
57         pz  -0.100       $  Face of source nearest detector
58         pz  15.34        $  Back of the detector

mode  n p                     $ Neutron Mode
c Material Cards
c ===============
m1    1001.            7.06   $ Hydrogen
      6012.            3.73   $ Carbon
mt1   benz.60t
m2    48000             1     $ Cd
m3    14000.     0.189        $ Li
      8016.      0.605
      3006.      0.189
      3007.      0.008
      12000.     0.002
      13027.     0.007
imp:n  1  24r   0 1 1 1 0  $ 25 repeated cells importance 1
imp:p  1  24r   0 1 1 1 0  $ 25 repeated cells importance 1
tmp1   2.55e-008       29r          $ All 30 cells at room temperature
sdef  POS=0 0 -0.101 CEL=54 ERG=D2 WGT=1 TME=0  $ Position, Cell, Energy of Cf
      RAD=D1 SUR=55 vec=0 0 1 dir=1             $ Energy defined in si2 and sp2
si1   H 0 6.35
sp1   D  -21  1
si2   H 0.015 0.035 0.055 0.075 0.095 0.115 0.135 0.165 0.195
      0.225 0.255 0.305 0.355 0.405 0.455 0.505 0.555 0.605
      0.655 0.705 0.755 0.805 0.855 0.905 0.955 1.05 1.15
      1.25 1.35 1.45 1.55 1.65 1.75 1.85 1.95 2.15
      2.35 2.55 2.75 2.95 3.25 3.55 3.85 4.15 4.45
      4.75 5.05 5.55 6.05 6.55 7.05 7.55 8.05 8.55
      9.05 9.55 10.05 10.55 11.05 11.55 12.05 12.55
      13.05 13.55 14.05 14.6 15.9 16.9 17.9 19.1 20.0
sp2   D 0 1.98e-3 2.64e-3 3.13e-3 3.54e-3
      3.88e-3 4.18e-3 6.75e-3 7.25e-3 7.67e-3
```

```
      8.04e-3 1.41e-2 1.48e-2 1.54e-2 1.58e-2
      1.61e-2 1.64e-2 1.66e-2 1.67e-2 1.68e-2
      1.68e-2 1.68e-2 1.68e-2 1.67e-2 1.66e-2
      3.12e-2 3.23e-2 3.15e-2 3.07e-2 2.98e-2
      2.88e-2 2.77e-2 2.67e-2 2.56e-2 2.46e-2
      4.60e-2 4.20e-2 3.81e-2 3.44e-2 3.10e-2
      4.07e-2 3.44e-2 2.89e-2 2.42e-2 2.02e-2
      1.68e-2 1.39e-2 1.80e-2 1.31e-2 9.84e-3
      6.83e-3 4.90e-3 3.52e-3 2.52e-3 1.81e-3
      1.29e-3 9.26e-4 6.62e-4 4.73e-4 3.38e-4
      2.41e-4 1.72e-4 1.23e-4 8.75e-5 6.21e-5
      4.78e-5 2.12e-5 1.06e-5 1.06e-5 6.01e-6
      2.15e-6
sd4   1.
f4:n  24                                $ Measure Li front
fm4   -1 3 105
t4    50 100 200 400 800 1600 3200 6400 12800
      25600 51200 1.0e+37
e4   0.025E-6 0.05E-6 0.1E-6 0.15E-6 0.2E-6 0.25E-6 0.3E-6
      0.4E-6 1.0E-6 1.0E-5 1.0E-4 1.0E-3 1.0E-2 1.0E-1 1.0 15.0
c WARNING: the two PHYS cards and the CUT:P card are ESSENTIAL for analog MC
phys:n J 15
PHYS:P 0 1 1
c The following CUT cards kill neutrons and photons having times
c exceeding 300 ns after the originating source event
C CUT:N 30
CUT:P 2J 0
thtme 30
prdmp 100000 100000
nps   100000
ctme  30
c
c Polimi Lines
c ==============
c j means jump space, 2j means jump two spaces
IDUM 0 1 1 1 2J 25 1 2 3 4 5 6 7 8 9 19 11 12 13 14 15 16 17 18
     19 20 21 22 23 24 25
RDUM  0.000000001 0.000000001
FILES 21 DUMN1
dbcn  0 0 0 0 0 0 0 1 0 10 0 0 0 0
print -20 -32 -35 -80 -85 -86 -90 -98 -110 -120 -128 -130 -160 -161 -162
```

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