Calibration of a cadmium capture-gated neutron spectrometer

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A senior thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Bachelor of Science

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April 2014

ABSTRACT

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The cadmium capture-gated neutron spectrometer utilizes a dual-pulse signal from incoming neutrons to differentiate between neutrons and gamma rays. We have built such a detector and performed a time-of-flight experiment at Ohio University to measure incident neutron energy. We determined the detector efficiency as a function of neutron energy for neutrons with energies 0.5 MeV - 9 MeV. The detector has a peak efficiency of 12% for 2 MeV neutrons. The cadmium capture of the neutrons provides a low energy neutron detection boost that keeps the efficiency above 9% for neutrons with energy less than 2 MeV. A properly calibrated cadmium-capture gated neutron detector can be used to measure low energy neutrons from fission sources.

Keywords: Cadmium capture, neutron detection

ACKNOWLEDGMENTS

I would like to thank Dr. Lawrence Rees for his guidance and assistance throughout my undergraduate studies. I would also like to thank Bart Czirr for all the help he gave to me in understanding the experiment and leading me in the right direction throughout my work.

Parts of this work were funded by NNSA Grant no. DE-FG52-10NA29655 and DHS Award no. 2010-DN-077-ARI039-02.

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Chapter 1

Introduction

1.1 Background and Motivation

The neutron was first discovered in 1932 by James Chadwick. Prior to this, Rutherford's idea of the nuclear atom had revealed that most of the atomic mass was centered in the nucleus. The atomic mass was on average double that of the atomic number leading some to postulate that perhaps electrons were bound inside the nucleus to cancel out the charge of some of the protons (see Laughlin 1983). However this idea didn't last long; quantum mechanics showed that this was impossible because there was simply not enough energy available in the atom to contain the electrons in the nucleus. There had to be something else in the nucleus that helped account for the atomic mass.

It wasn't until 1930 that the mystery began to unfold. Bothe and Becker found that a neutral radiation was produced when beryllium was bombarded with alpha-rays. While initially thought to be gamma-rays, experiments by Curie and Joliot showed that when paraffin was bombarded with this radiation, the paraffin ejected protons with an energy inconsistent with the gamma-ray model. In 1932 using a similar experiment as Curie and Joliot, Chadwick successfully described this radiation as the neutron which had a mass nearly equivalent to the proton. This discovery eliminated the atomic mass issue and began the nuclear age (see Laughlin 1983).

With the advent of the nuclear age came the fear that nuclear materials in the wrong hands, could have devastating effects. The U.S. Department of Homeland Security (DHS) employs large amounts of ^{3}He neutron detectors to watch for incoming nuclear materials into the country. While this service prevents nuclear materials from getting into the wrong hands it has also caused a world shortage of available ^{3}He. This shortage has affected many of the various other applications which ^{3}He is used for. Due to this shortage, DHS along with many other research institutions have begun looking into alternative methods for detecting neutrons from nuclear materials (Kramer 2011).

1.2 Detecting Neutrons

1.2.1 Neutron Detection Methods

Neutron detection is inherently difficult because the neutron carries no charge. The most common neutron detection techniques involve indirect detection of the neutron through its interaction with charged particles or atomic nuclei. A typical example of an indirect detection of a neutron is a neutron colliding with a proton causing the neutron to transfer some of its kinetic energy to the proton, which would then be detectable. This is analogous to the ejection of electrons from a surface from neutral photons bombarding the surface. The two techniques that are of importance for this thesis project are: detection using a scintillating material and detection through neutron capture in atomic nuclei.

Detecting a neutron through a scintillating material requires the neutron to collide with protons sending the protons travelling through the scintillator. A scintillating material is created in such a way that when a charged particle travels through the material, photons will be emitted. These photons are emitted due to charged particles interacting with the molecules that make up the scintillator. The charged particles impart energy to the molecules, exciting them. When the molecules then de-excite back to the ground state, photons are emitted which are then easily detectable by a photomultiplier tube (PMT). The number of photons emitted is proportional to the amount of energy given to the molecule from the charged particle. Scintillating material comes in a variety of forms including plastic, liquid and glass.

Neutron detection can also be achieved by using the capture of neutrons in atomic nuclei. Certain nuclei have a high cross-section for neutron capture. Once the neutron has been captured it causes a reaction which, whether directly or indirectly, produces charged particles. The charged particles are then detectable through the use of a scintillator and PMT or through other methods. Common neutron capture materials include helium-3, cadmium, lithium, and boron.

1.2.2 Cadmium Capture-gated Neutron Detection

While scintillator and neutron capture detection methods can be effective, they are frequently clouded by gamma rays that undergo Compton scattering with electrons, causing a false-positive from a charged electron (Stevanato et al. 2013). Pulse shape discrimination (PSD) is a common method used to identify pulses in the PMT made from the interaction with neutrons and those that are not neutrons. PSD typically requires high resolution in the PMTs to ensure accuracy. Unfortunately PSD is quite difficult and it is easy to misidentify pulses. The method presented here employs a combination of scintillator and capture detection techniques—the capture-gated method. This method seeks to eliminate the need for PSD by looking instead for two pulses in the PMT that are within a short time of each other; by requiring two pulses in the PMT the probability of a false-positive is significantly decreased (Cranberg 1967). The two pulses will be referred to as the proton-recoil pulse and the capture pulse.

A neutron entering the detector will initially interact with protons in the hydrogen-rich scintillating material. This interaction will cause the protons to travel through the scintillator and excite the molecules, resulting in the emission of photons which are detected by the PMT (the proton-recoil pulse). The size of the recoil pulse in the PMT is determined by the amount of energy the neutron gives to the proton. The neutron will collide with multiple protons which will over time moderate the neutron or in other words decrease the neutron's kinetic energy.

As the neutron loses kinetic energy the probability of the neutron being captured increases. The detector discussed here utilizes cadmium as the capture material. A neutron in the detector undergoes the following process once sufficiently moderated:

$$n + ^{113}\mathrm{Cd} \rightarrow ^{114}\mathrm{Cd}^{*} \rightarrow ^{114}\mathrm{Cd} + \gamma \tag{1.1}$$

Once the neutron is captured, gamma rays are emitted when the cadmium de-excites. The gamma rays will then Compton scatter in the scintillator causing a second burst of photons from the scintillator. This is the capture pulse. In summary, when a neutron enters the detector two pulses are made in the PMT: the proton-recoil pulse and the cadmium capture pulse (see Fig. 1.1).

For a cadmium capture-gated detector to work as designed, the neutron must lose enough kinetic energy to be captured before it exits the detector. If the detector fails to moderate the neutron quickly enough, the neutron will exit the detector and will go undetected. To increase the probability of a neutron being moderated sufficiently to be captured, the detector needs to have a large volume (Reines et al. 1954). The detector presented here utilizes a large volume of scintillating material to moderate the neutrons and four PMTs to detect the photons produced in the scintillator.

1.3 Project

My project and purpose of this thesis was to calibrate a 4-fold cadmium capture-gated neutron detector through a time-of-flight experiment using a beam of neutrons produced at the Edwards Accelerator Laboratory at Ohio University. In a time-of-flight experiment, the incident neutron

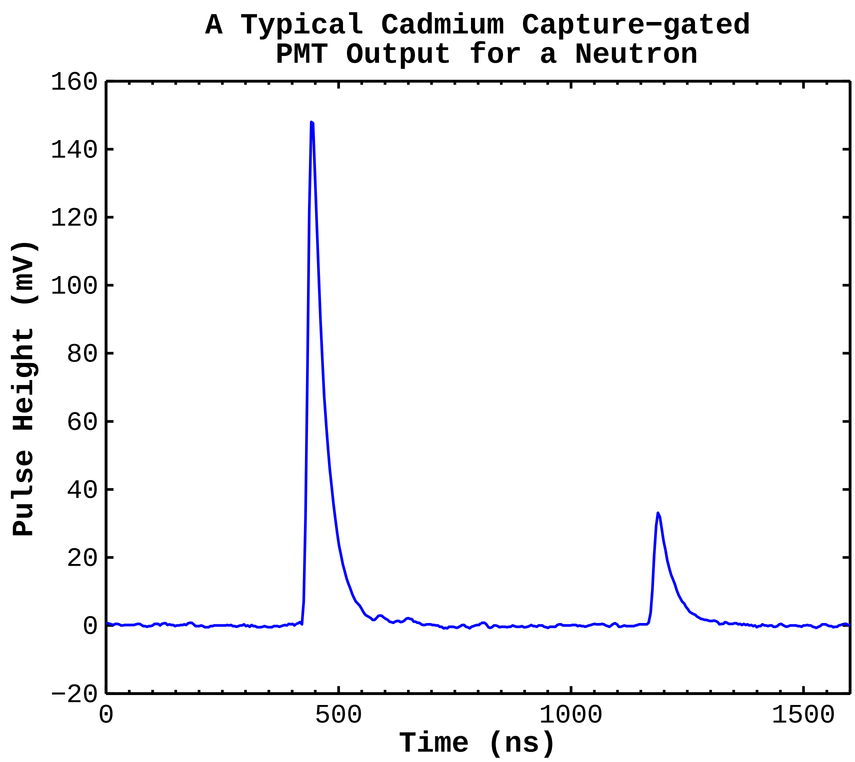

Figure 1.1 Two unique PMT pulses help to ensure neutron detection and avoid false-positives. The first pulse is due to proton-neutron scattering in the scintillator and the second pulse is due to the neutron being captured in the cadmium.

energy is calculated by knowing when the neutron was emitted versus when it was detected in the detector, along with the distance the neutron traveled to the detector. When a neutron is emitted from the accelerator, a pulse is created (beam pulse) which is recorded by the computer. The beam pulses can then be correlated with the proton-recoil pulses in the detector to calculate the energy of an incident neutron. The detector is then calibrated by calculating the efficiency of the detector at particular energies by comparing the number of neutrons detected at a particular energy vs. the number of incident neutrons at the detector at the same energy.

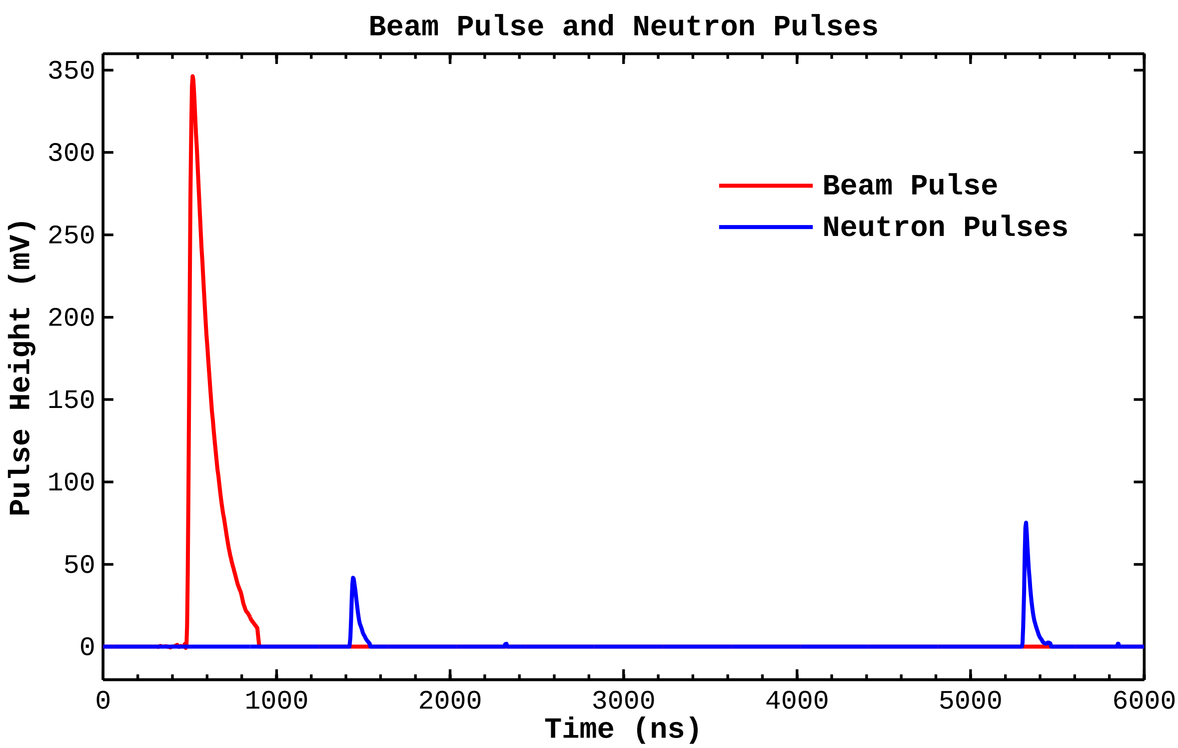

Figure 1.2 The energy of an incident neutron on the detector is calculated by measuring the time between the beam pulse (when the neutron was emitted), and the proton-recoil pulse (when the neutron was detected).

Chapter 2

Methods

2.1 Detector Design

Cadmium capture-gated neutron detectors require that the neutron is sufficiently moderated in order to achieve capture. As previously mentioned if the neutron fails to capture, it will exit the detector and will be lost. In the past the nuclear physics research group at BYU has built and tested cadmium capture-gated neutron detectors, but the overall efficiency was low; through computational models we have come to the conclusion that by increasing the overall volume of the detector we will increase the probability of a neutron capture. A larger detector volume means a larger volume of scintillating material for the neutron to moderate in. The detector presented here has approximately four times the volume of our previously calibrated cadmium capture-gated detectors. To accommodate this larger volume, four PMTs are used to ensure collection of as much light as possible from the scintillating material.

The detector consists of 21 sheets of scintillating material separated by aluminized-Mylar and cadmium foil. When a neutron enters the detector it initially interacts with the scintillating material resulting in an emission of photons. The photons are emitted isotropically. To detect the photons, an aluminized-Mylar layer provides a reflective material to help guide the light to the PMTs. The neutron will moderate and eventually be captured in the cadmium resulting in another burst of emitted photons. The cadmium foil is sandwiched between sheets of aluminized-Mylar to guide the photons (see Fig. 2.1).

The detection material is kept in a portable light-tight aluminum box. The four PMTs are put in a square pattern. There is gap of air in the middle of the detection material. Since there is no PMT in that area and any light produced in those cells would be lost. The air gap prevents the neutrons from interacting with the scintillator or the cadmium in the PMT dead zone (see Fig. 2.2).

2.2 Experimental Setup

As previously mentioned, to calibrate and measure the efficiency of our detector, we traveled to Ohio University to utilize the Edwards Accelerator Lab. The accelerator utilizes a beam of deuterons incident on an aluminium plate to produce a beam of neutrons. The neutrons then travel down a tunnel to the detector. The detector was placed 20.102 meters from the location where the neutrons were emitted from the aluminium target. The four PMTs from the detector had their signals added to each other and sent into a CAEN waveform digitizer (model DT5720) to convert the voltage output from the PMTs into a digital signal for a computer to analyze at a later time. The CAEN triggered on every pulse above 25 mV coming from the PMTs. When the CAEN triggered, 16 μs of data would be saved before the pulse and 16 μs of data would also be saved after the pulse to look for a second pulse. Along with the pulses from the detector, the CAEN would also record the beam pulses coming from the accelerator each time a neutron was emitted.

The experiment was run for 36 hours with approximately 80 000 000 events saved. An event is a 32 μs chunk of data where there is at least one pulse above 25 mV. The accelerator had varying beam currents and to ensure consistency in the data only events with the same beam currents were

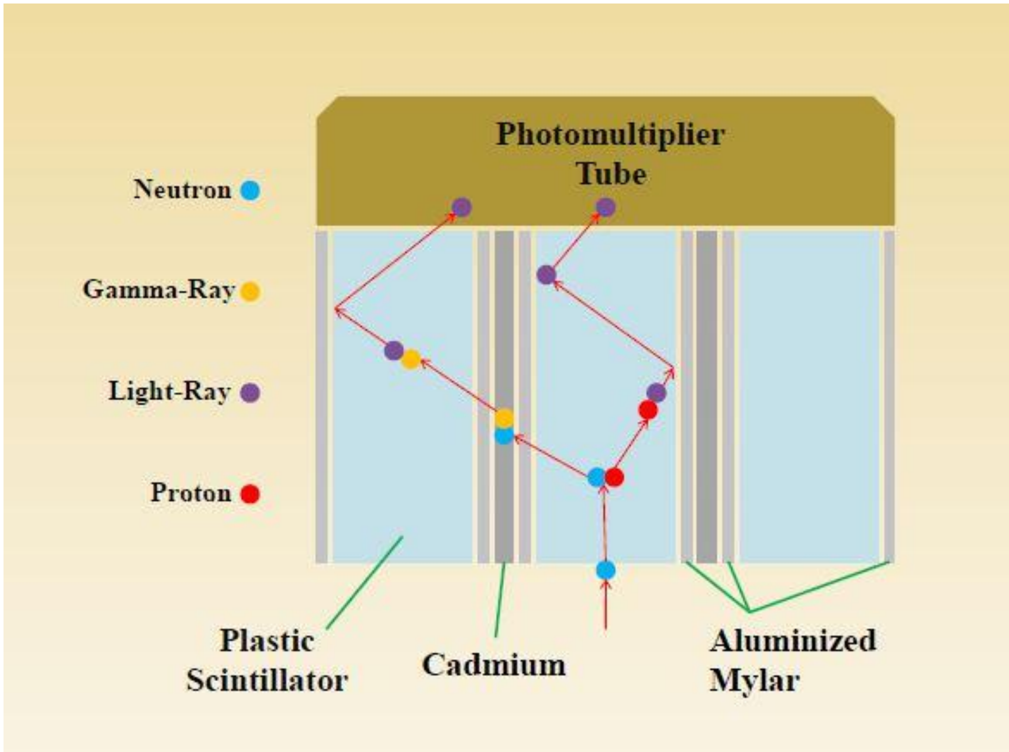

Figure 2.1 An incoming neutron into the detector will first interact with protons in the plastic scintillator. The protons will scatter and travel through the scintillator resulting in the emission of light that will be detected at the PMT creating the first pulse. As the neutron collides with the protons it will slow down, once the neutron has lost a sufficient amount of its energy it will be captured in the cadmium foil which will result in the emission of more light to be detected in the PMT resulting in the second pulse seen in the detector.

analyzed together. In the end, 46 951 211 events with the same beam current were analyzed. There were other smaller chunks of data with similar beam currents that were analyzed separately to evaluate the detectors efficiency at different beam currents.

Figure 2.2 An exploded view of the detector. The detector consists of 4 photomultiplier tubes to detect the light from the detection medium and 21 sheets of plastic scintillator with cadmium foil and aluminzed-Mylar inbetween each sheet of plastic. The aluminzed-Mylar helps the light reflect and ensure as much light as possible reaches the PMTs. The PMTs and the detection material are held in a light-tight aluminium box.

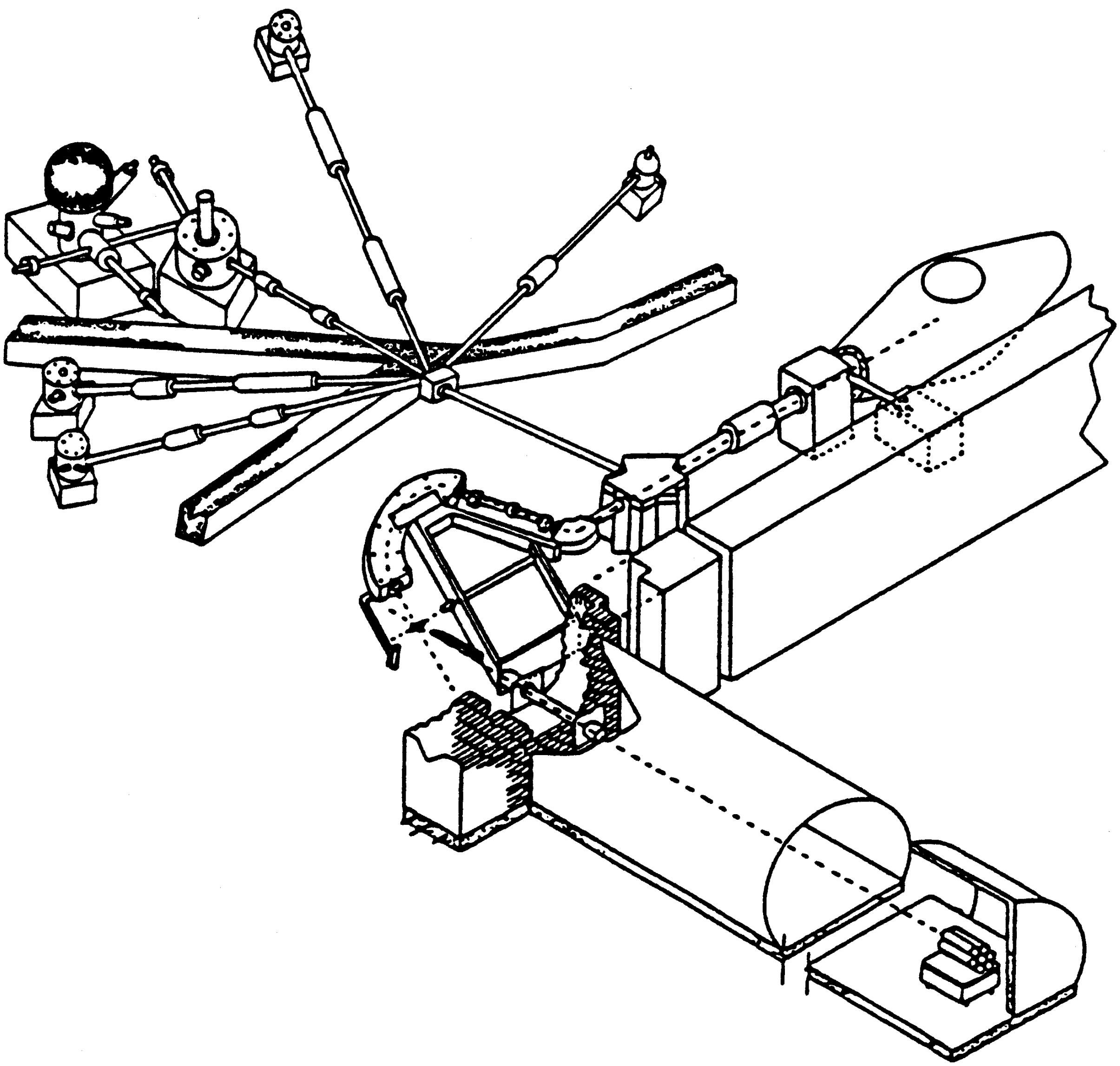

Figure 2.3 The time-of-flight experiment was performed at the Edwards Accelerator Lab. The accelerator produces a beam of deuterons (dashed line in the upper-right portion of the diagram) which interact with an aluminium plate producing neutrons. The neutrons then travel to the detector down the tunnel (bottom right corner of the diagram).

2.3 Computational Methods

The data analysis was a multistage process to refine the neutron identification and ensure as few false-positives in the data as possible. The analysis process is as follows (see Fig. 2.4): (1) Find all events with an acceptable set of two pulses. (2) Correlate beam pulses with detector pulses. (3) Remove events where the two pulses in the detector are too far apart. (4) Remove background. (5) Isolate the neutron flux. (6) Calculate the detector efficiency. Details for each of these steps can be found below.

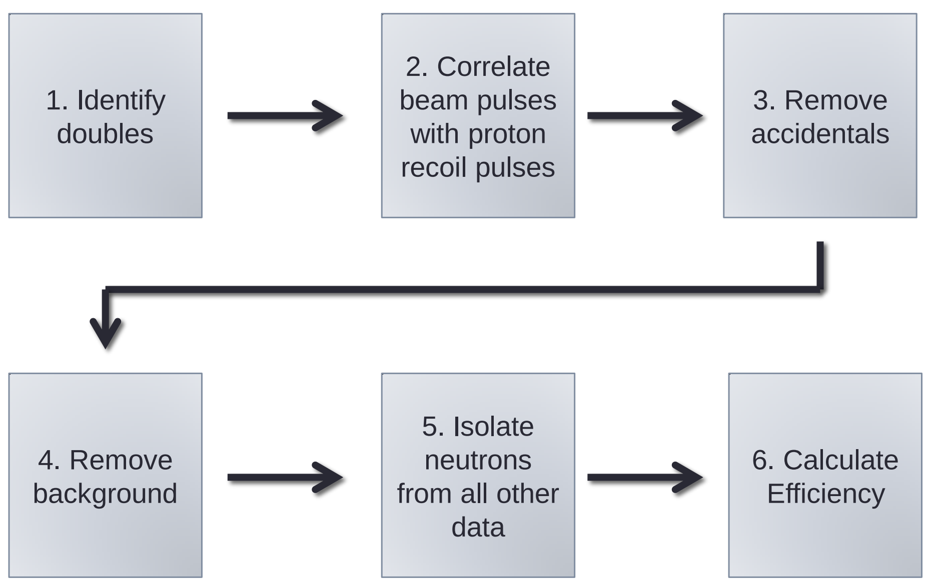

Figure 2.4 Analysis of the data is a multistage process. The initial pass through the data identifies all events that contain two pulses. The events are then correlated with the proper beam pulse to determine the time-of-flight for that particular event. Accidentals and background are removed to ensure as few false-positives as possible. Finally the neutrons are identified and the efficiency is calculated.

Step 1. The 32 μs of data for each event were saved as 8000 data points (channels), each channel 4 ns apart. The first pass through the data in the analysis examines each event and determines the number of pulses in it. Depending on where the pulse is located in the 8000 channels will determine if it is an acceptable pulse. For pulses before channel 4000 (the trigger pulse), the pulses are allowed to have a minimum height of 2 mV. If the pulse is after the trigger pulse the minimum height is 25 mV. This is due to the fact that the proton-recoil pulse height is dependant on the neutron's energy; low energy neutrons will produce very small proton-recoil pulses, whereas high energy neutrons will produce large pulses. Large pulses are often accompanied by many smaller pulses immediately following the main pulse. To account for these smaller pulses a capture pulse is not looked for until 280 ns after the proton-recoil pulse.

For any event, if there is only one pulse, or more than three pulses, the event is thrown out as unusable. When an event contains three pulses the two largest pules are chosen, while this does introduce some accidentals into the data it has been found to give more neutrons than accidentals. For events with two pulses, various parameters describing the event are saved to an array for later analysis. The parameters saved are: area of the first pulse, area of the second pulse, pulse height for the first pulse, pulse height for the second pulse, the location of each of the two peaks and the beam pulse. When determining where a pulse is located a constant fraction discriminator is used to give the pulse location independent of peak height so that all peaks are treated equally. Once all the events have been analyzed, the array is saved as a summary file to make the next stage of analysis take significantly less time.

Step 2. The second pass through the data correlates beam pulses with proton-recoil pulses. Events missing a beam pulse, due to the proton-recoil pulse being correlated with a previous beam pulse, are thrown out since there isn't a good way to determine the energy of those neutrons. The time between the beam pulse and the proton-recoil pulse is then calculated for each event, along with the time between the proton-recoil pulse and the capture pulse. Using this information it is then possible to remove many of the accidentals (events that have two pulses but are not really neutrons).

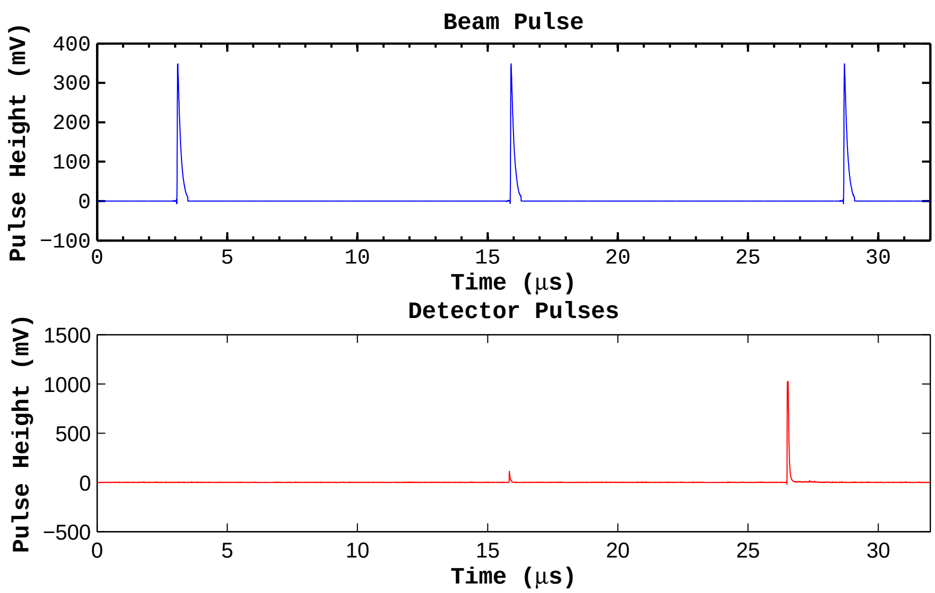

Figure 2.5 A typical event saved by the CAEN. There is only one pulse in this event meaning that this event will be thrown out and not analyzed further. There are three beam pulses. If this were a double then one of the three beam pulses would be correlated to the proton-recoil pulse. This is always the beam pulse immediately preceding the proton-recoil pulse.

Step 3. A majority of the accidentals are removed by looking at the features of the cadmium capture pulse and the time between it and the proton-recoil pulse. The first events removed as accidentals are events where the time between the proton-recoil pulse and the capture pulse is greater than 2800 channels. This is because after 2800 channels we begin to have a higher accidental rate due to the occurrence of the next beam pulse. Looking at Figure 2.6 there is a huge spike in the data around channel 3200. This spike is caused from neutrons and gamma-rays from the next beam pulse. For the events around that spike we can't tell if we are relating a proton-recoil pulse to its capture pulse, or if we are relating two pulses from two separate neutrons as one neutron. While this step may end up throwing away good neutron events, the idea is that more accidental events will be thrown out than good events which will improve the overall quality of the data.

The distribution in Figure 2.6 lacks a smooth distribution that we would expect from neutrons.

This is an indication of accidentals in the doubles data. To remove the accidentals the post-trigger threshold is adjusted. The post-trigger threshold controls the minimum height a cadmium capture pulse must have. When the data was initially analyzed the post-trigger threshold was only 5 mV. Through trial and error it was found that a value of 25 mV removes most of the accidentals and gives the significantly smoothed distribution in Figure 2.7.

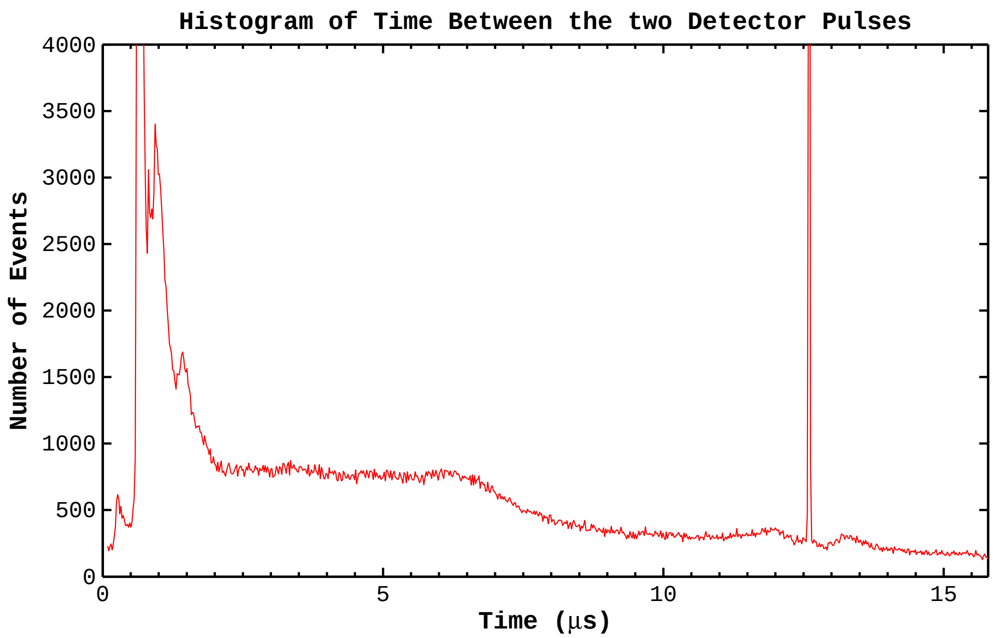

Figure 2.6 The time between the proton-recoil pulse and the cadmium capture pulse in the detector prior to any accidental subtraction. The distribution between the two pulses is uneven and has various spikes, this is an indication of many accidentals in the doubles data. To remove these spikes we define the minimum height that a cadmium capture pulse must have. As the threshold for this pulse is changed most of the accidentals are removed.

Step 4. The time between the beam pulse and the proton-recoil pulse is looked at a bit closer. Looking at Figure 2.8 there is a noticeable vertical offset to the entire histogram, this is due to accidentals being randomly distributed in time. An accidental event has an equal probability of being any time after the beam pulse. To account for this offset a linear fit for the timing distribution at late times (6000 ns-10000 ns after the start time) is subtracted from all bins in the histogram. Before removing the remaining accidentals the data needs to be shifted to account for the delay in

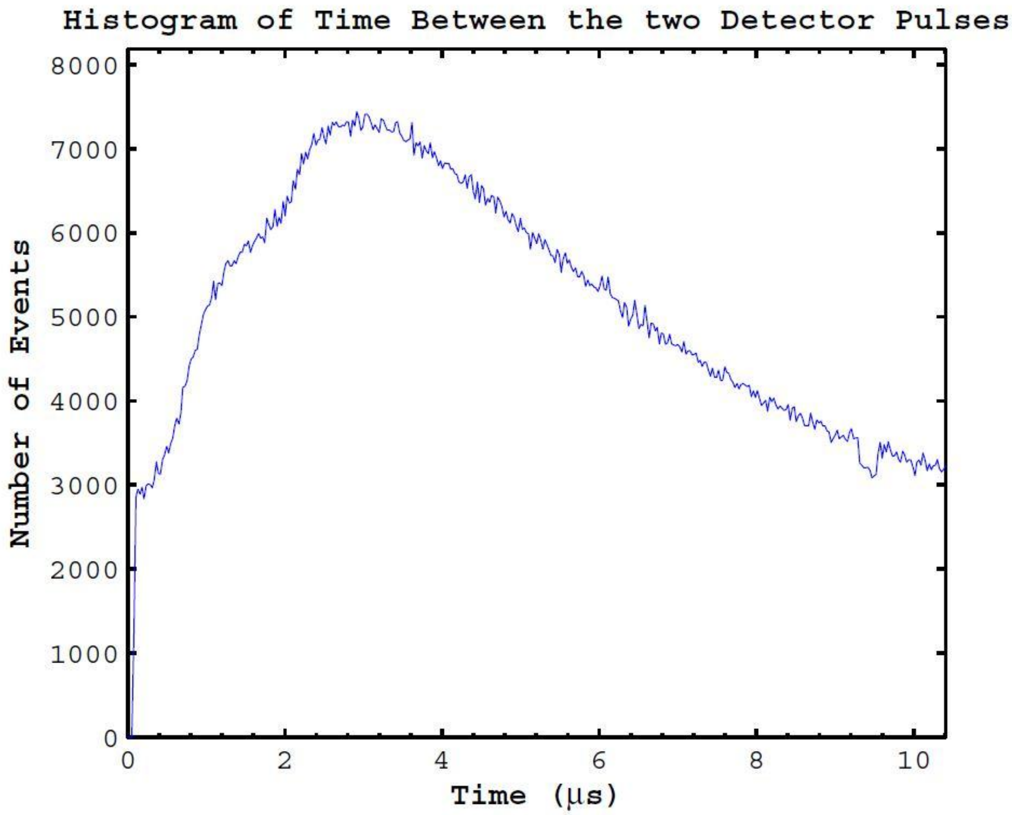

Figure 2.7 The time between the proton-recoil pulse and the cadmium capture pulse in the detector after accidentals are removed. The distribution is cut off just after 10 μs. This is because the next neutron from the accelerator is emitted and causes uncertainty in the correlation of the two detector pulses. This is not a feature inherent in the detector but rather caused by the use of the accelerator. Most accidentals are removed at this point by having required that the cadmium capture pulse has a peak height of at least 25 mV.

the time it takes for the beam pulse to reach the detector. Looking back to Figure 2.5 there is a tall narrow pulse (gamma flash). This pulse corresponds to a burst of gamma rays from the accelerator that accompany the neutron. The events in the gamma flash are all accidentals but they have all arrived at the detector at the same amount of time since they are all traveling at the speed of light. Using this pulse we can shift all the data so that the gamma flash pulse is aligned with the correct time it takes a gamma ray to travel to the detector from the accelerator.

The accelerator produces neutrons with energies ranging from around 0.4 MeV - 12 MeV. Due to this limited range of neutron energies there is a clear gap between the gamma flash and the neutron lump. This is caused by the fact that no neutrons reach the detector in a short enough period of time to fall into that timing region.

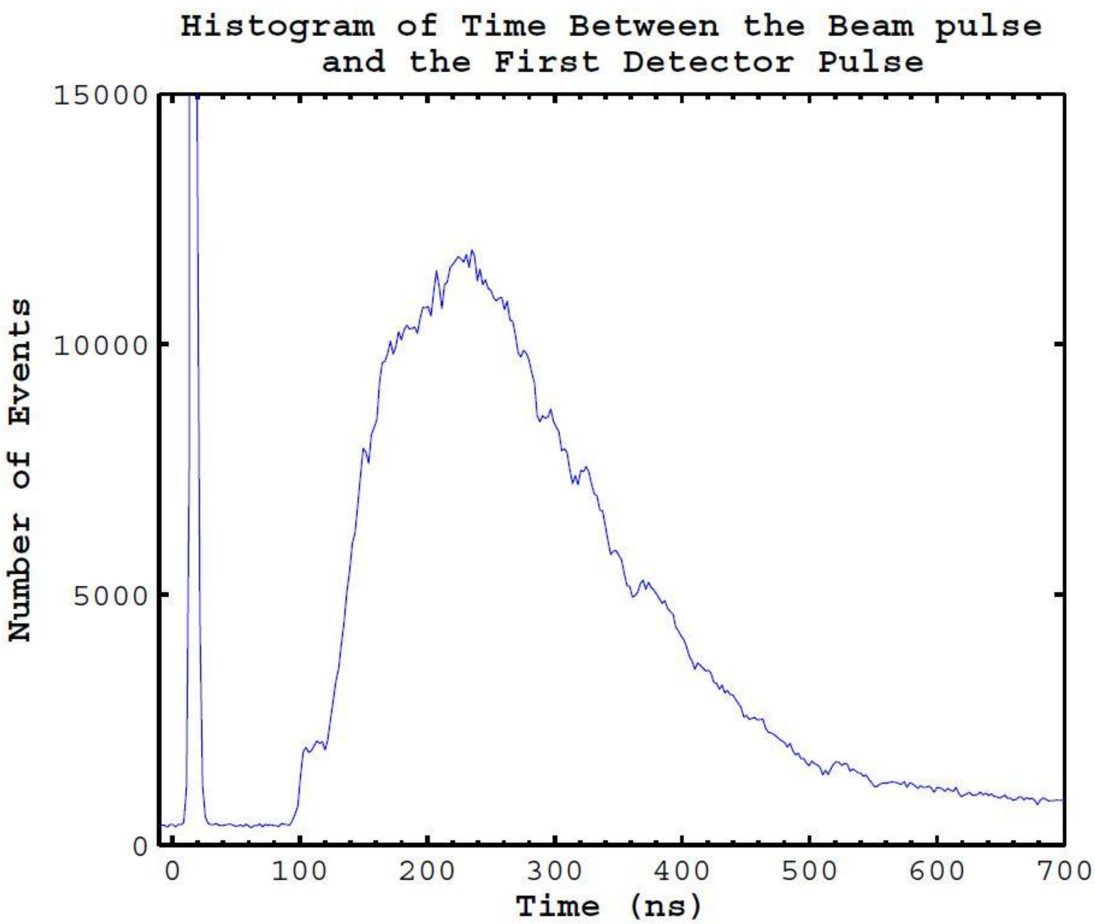

Figure 2.8 Each event is correlated with the correct beam pulse. The time between the beam pulse and the proton-recoil pulse is shown above. There is a large narrow pulse near 10 ns. This narrow pulse is caused by gammas incident on the detector. When a neutron is emitted from the aluminium, a large number of gammas is also emitted. The gammas travel at the speed of light and arrive at the detector all at the same time giving the narrow pulse, the gamma flash. This gamma flash is useful for defining a start time. There is also a slight vertical offset apparent in this histogram. This is attributed to background radiation. It is random in time and so we assume it to be flat across the entire distribution. We subtract this offset to remove the background counts.

Step 5. The neutron flux is isolated from all the data. The accelerator neutron flux only ranges from around 0.4 MeV - 12 MeV. This gives a narrow band of time in which neutrons could arrive at the detector. All events that come too soon after the beam pulse or too late after the beam pulse won't be real neutrons and are removed. The remaining events are assumed to be neutrons. Of the 3 511 691 doubles, only 1 008 100 of them are actually neutrons (See Tab. 2.1).

Table 2.1 During the computer analysis of the data, single pulse events and accidental doubles are removed. Approximately 85% of the events only have one pulse, and another 10% are accidental doubles. The remaining 5% of the events are neutrons.

Total Events	Total Doubles	Neutrons
46 951 211	3 511 691	1 008 100

Step 6. After passing through the data for the final time, having thrown out anything that would be identified as a false-positive, the remaining data were compared with the incident neutron flux to determine the efficiency of the detector according to the energy of the incident neutron. Ohio University provided us with the incident neutron flux from the accelerator. The data and the incident flux were binned into 50 keV bins (see Fig. 2.9). At this point the efficiency was ready to be calculated. The efficiency is just the percentage of the incident neutrons that were detected. Removing the false-positives in the data was the most difficult portion of the experiment and took many iterations of analysis to determine which events were actually neutrons.

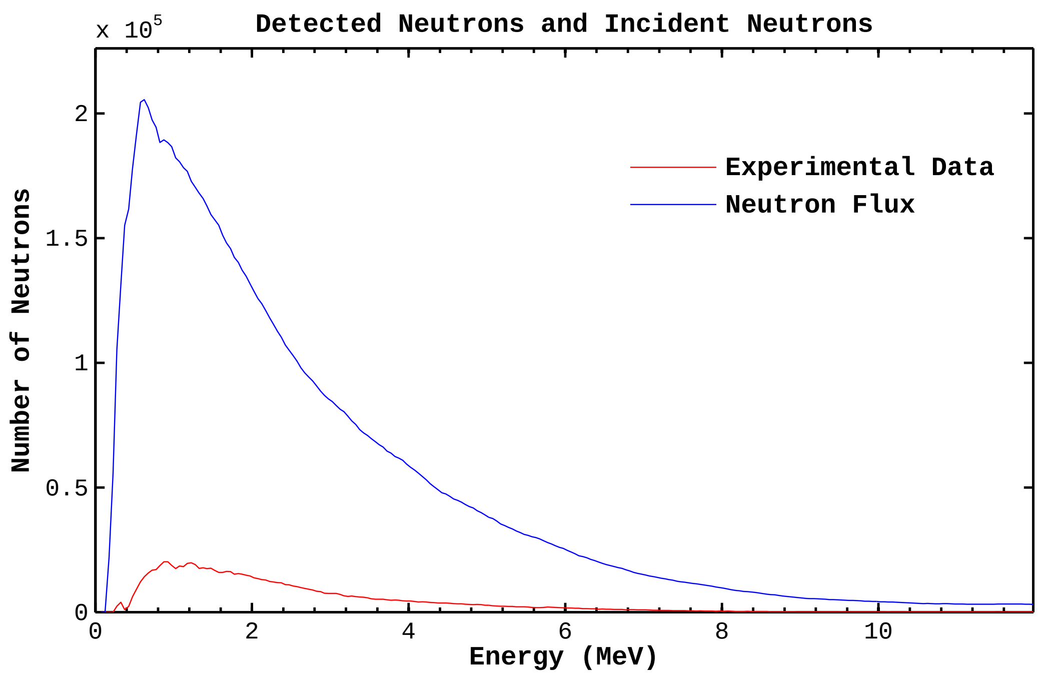

Figure 2.9 The total neutrons per energy detected in the detector plotted against the total neutron flux incident upon the detector. The efficiency vs. neutron energy is then easily calculated as a percentage of the neutrons detected vs. the incident neutrons.

Chapter 3

Results and Conclusions

3.1 Results

Our data consisted of 46 951 211 events, of which only 1 008 100 were confirmed to be actual neutrons. To ensure that the analysis had been consistent we looked at the peak height distribution of the first peak for particular neutron energies to ensure that the distribution didn't change from run to run. We mainly used the peak height distributions for 1 MeV and 4 MeV neutrons.

By comparing the 1 MeV and 4 MeV peak height distributions we can see the effect of the cadmium capture in the detector. In the 4 MeV distribution the most populous peak height is near 100 mV and decays down to near 350 mV; whereas in the 1 MeV peak height distribution the most populous peak height is near 15 mV and decays down to near 100 mV. In order for the CAEN to save an event from the detector there must be at least one pulse above 25 mV. At 1 MeV the peak height distribution of the first peak has a max at only 15 mV; this means that the second pulse in the detector must be above 25 mV. The first pulse is always the proton-recoil pulse. Without the cadmium capture the lower energy neutrons would have all been missed, the CAEN would have never triggered. By requiring two pulses in the detector the range of detectable neutron energies is extended down to 500 KeV; it may be found to be even lower in future experiments.

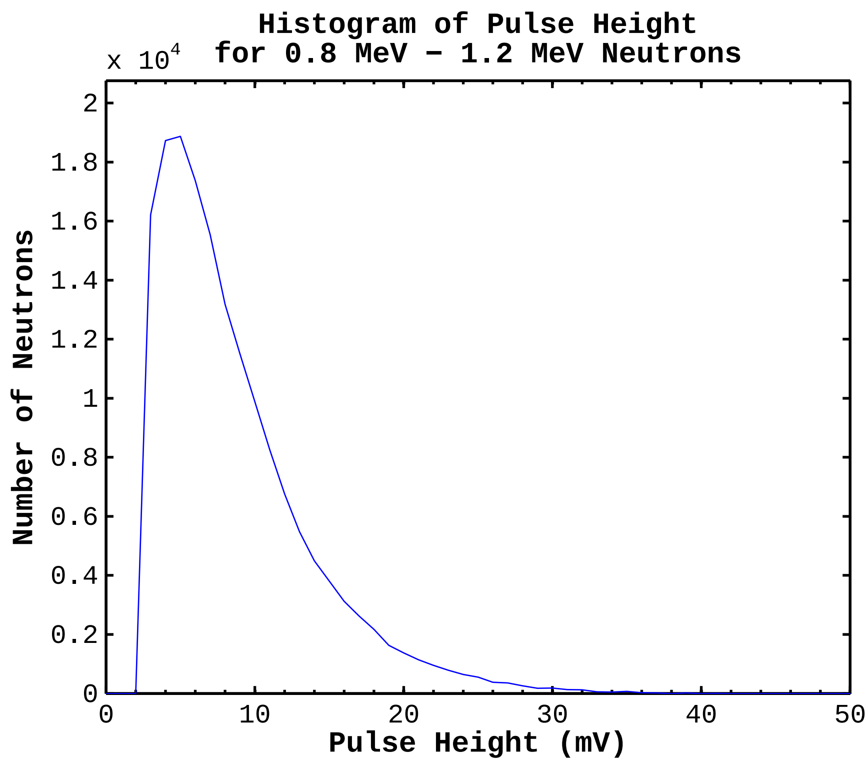

Figure 3.1 The peak height distribution of the first pulse made by 1 MeV neutrons in the detector.

The peak height distributions also provide the spectroscopic features of the detector. As you will note in Fig. 3.1 and Fig. 3.2 the 1 MeV peak height distribution is significantly more narrow than the 4 MeV peak height distribution. As the energy of the neutron increases, the probability of a larger peak increases. The 4 MeV peak height distribution has peaks that are 300 mV whereas the 1 MeV peak height distribution has no peaks above 50 mV. This trend of widening of the peak height distribution is consistent for all energies of neutrons that we detected.

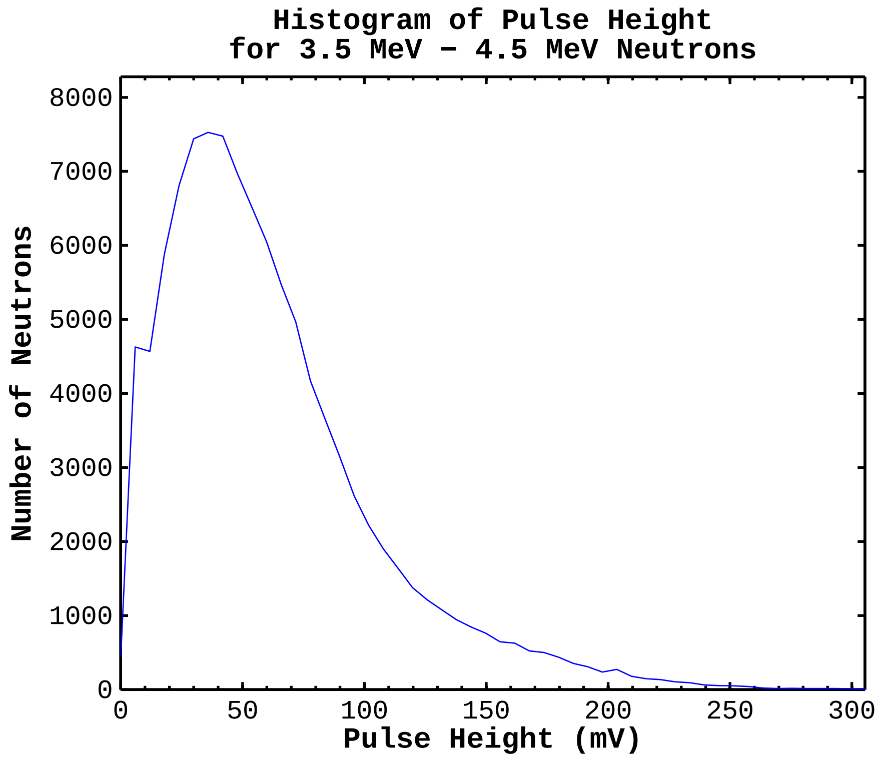

Figure 3.2 The peak height distribution of the first pulse made by 4 MeV neutrons in the detector.

3.2 Detector Efficiency

To calculate the efficiency of the detector we compared the incident neutron flux to the detected neutrons. The incident neutron flux was provided by Ohio University. The incident flux is not uniform for all neutron energies. The detected neutrons reflect this lack of uniformity.

The efficiency of the detector peaks at 2 MeV with an efficiency of 12% (see Fig. 3.3). Below 2 MeV the efficiency remains above 10% down to 500 KeV. The efficiency decays down to 4% at 12 MeV. The efficiency for higher energies drops off because while the higher energy neutrons will leave a signature in the scintillator they will exit the detector before they are moderated sufficiently to be captured in the cadmium. By requiring two pulses in the detector the efficiency for higher energy neutrons is diminished. In order to improve the efficiency more moderation is required to ensure that all the neutrons that interact in the scintillator are also captured in the cadmium.

Various computer simulations using a computer algorithm called Monte Carlo for Neutral Particles (MCNP), produced by Los Alamos National Laboratory, were performed to determine what the theoretical efficiency of the detector should be. We used a version called MCNP-PoliMi (Pozzi et al. 2003) which tracks each neutron in the detector interaction by interaction. This is a difficult calculation that requires many assumptions. Despite the complexity of the calculation the theoretical calculation and the experimental data align quite nicely. They have similar shapes and similar values (see Fig. 3.3).

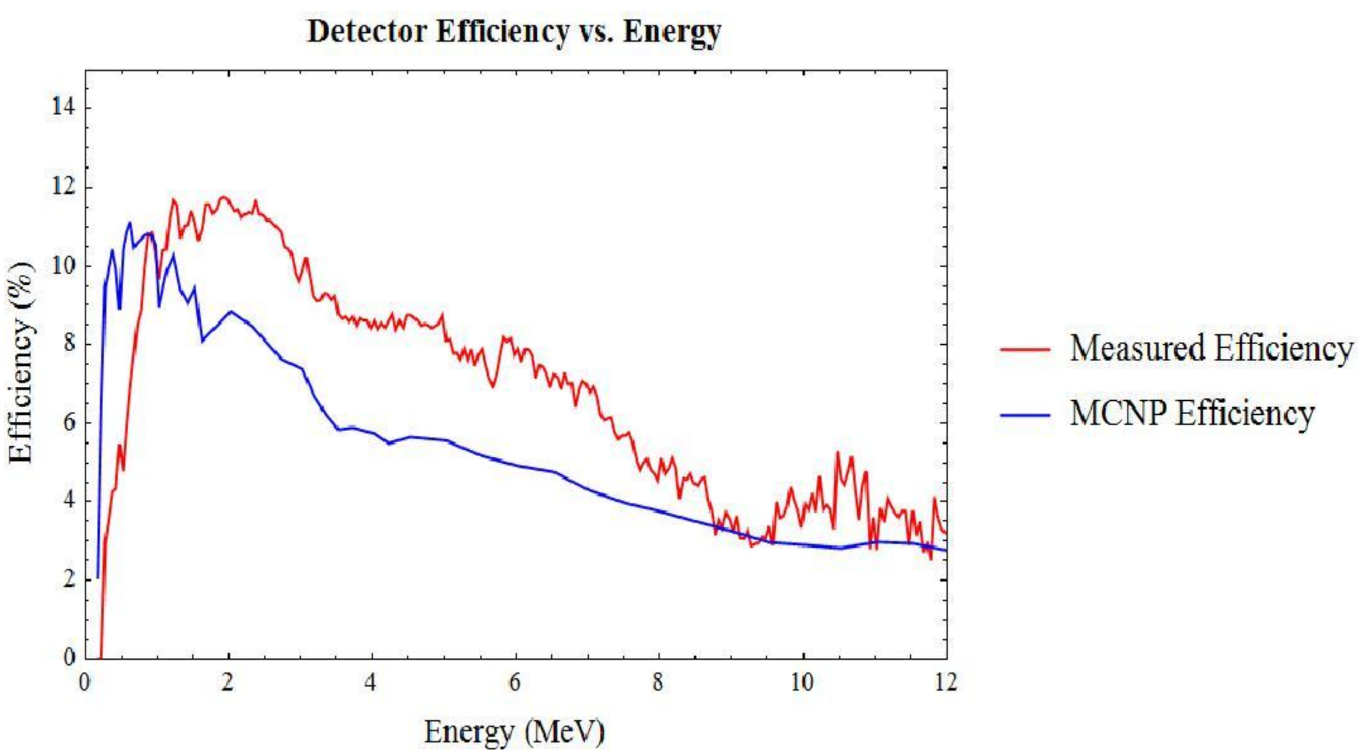

Figure 3.3 The overall efficiency of the detector based on incident neutron energy. The efficiency of the detector is near 11% for lower energy neutrons and decays down to around 5% at higher energies. The higher energies drop off because the higher energy neutrons exit the detector before being moderated sufficiently to be captured in the cadmium. The MCNP calculated efficiency has a similar shape to the experimental data.

Knowing the efficiency of the detector allows the detector to be properly calibrated for future use. Once calibrated the detector can be used to measure the energy spectrum of neutron emitting materials. By knowing the efficiency for a particular neutron energy in the detector then measurements of a neutron emitting material can be corrected to give the proper neutron flux from the material.

3.3 Conclusion

The efficiency of our cadmium capture-gated neutron detector is perhaps too low to be a good replacement to the ^{3}He neutron detectors used by the Department of Homeland Security. By requiring two pulses in the detector, one from the scintillator and one from the cadmium capture, neutrons are more easily identifiable from gamma rays. The one downside to requiring two pulses is that to get a neutron to capture in the cadmium it has to moderate sufficiently to be captured without leaving. To increase the overall efficiency of our detector we need a larger volume of moderation material.

Utilizing the two pulses created in the detector, a neutron can be identified. Through careful consideration of the data, nearly all of the false-positives can be removed. While the efficiency is not high the detector is still useful for its spectroscopic purposes and for its use in laboratory applications where the efficiency isn't an important issue. By using two pulses the detector is capable of identifying low energy neutrons better than many other available neutron detectors. This makes it a valuable asset in looking at low energy neutron emission.

Future work will use the now calibrated detector to look at the low energy neutron emission from a uranium fission chamber. Work is also being done to find a way to modularize the detector. The detector consists of four PMTs currently, but the efficiency is low due to neutrons escaping from the detector before capture. To counter this problem we are going to make a modular design using single PMT detectors that can be stacked into a larger volume to ensure neutron moderation.

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