Cadmium Capture-gated Neutron Detector Analysis of the ^{235}U Fission Spectrum

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ABSTRACT

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An analysis of the ^{235}U fission spectrum measured using a cadmium capture-gated neutron detector is presented. A better knowledge of the fission spectrum of ^{235}U is beneficial for nuclear reactor and bomb design. The detection of low-energy neutrons from such fission is difficult when using pulse shape discrimination. A cadmium capture-gated neutron detector was used to analyze the fission spectrum of the ^{235}U fission chamber at Los Alamos Neutron Science Center. Capture-gated neutron detectors are more efficient at low energies because the cross section of neutron capture goes up as the inverse of energy. Also, they can discriminate well between gamma rays and neutrons at low energies because of the presence of a neutron capture pulse. The data show probable neutrons detected at energies lower than 0.5 MeV. However, due to discrepancies when compared with other data from the detector, we cannot draw any quantitative conclusions.

Keywords: Uranium 235,capture-gated neutron detector, fission spectrum, fission chamber

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 ^{235}U fission spectrum

Since the discovery of the massive amounts of energy released from a nuclear fission event, scientists have been studying the fission process to better understand it. Nuclear bombs were developed, which changed the world's outlook on war. Nuclear reactors were built to generate power for the world in an emission-free manner. The fission spectrum of ^{235}U has been studied for years because it is important for bomb and reactor designing and modeling.

For any of these devices to be worthwhile, the fission process must be self-sustaining from a chain reaction, where neutrons from an initial fission cause more fissions to occur and so forth. For a chain reaction to occur in ^{235}U, the neutrons which are released from a single fission event must go on to induce fissions in other ^{235}U atoms [1]. For the fission neutrons to induce other fission events, the fuel of ^{235}U atoms must be designed in such a way that the fission neutrons will interact with other ^{235}U atoms.

The cross section, for neutron-induced fission of ^{235}U goes up as the inverse of incident neutron energy, as shown in Fig. 1.1 [2]. Low-energy neutrons are much more likely to interact with the surrounding ^{235}U and cause it to fission. A moderator is usually present to slow down fission neutrons into the thermal energy region to increase the likelihood of inducing more fissions. A commonly used moderator is water because H atoms have basically the same mass as neutrons, causing the neutrons to lose a large fraction of their energy upon interaction.

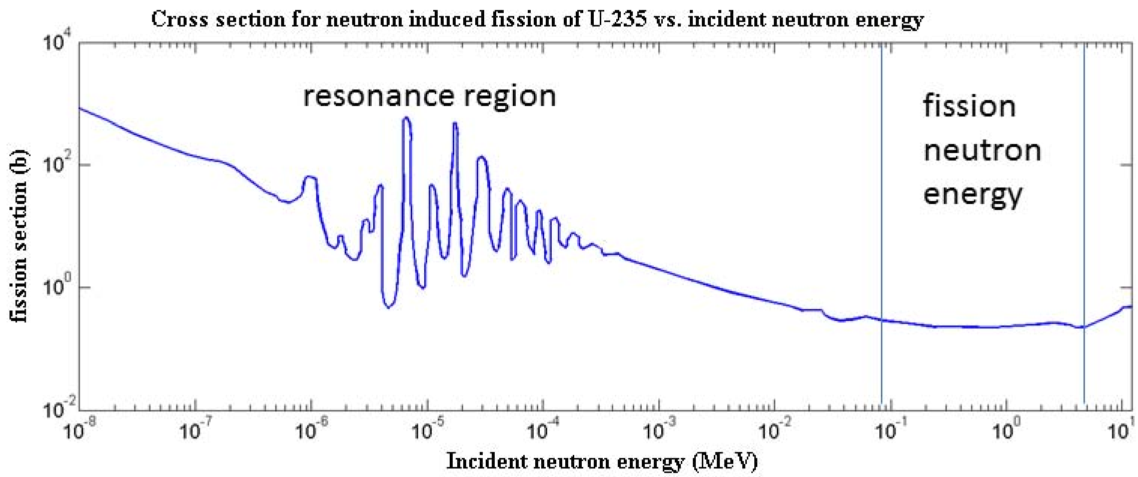

Figure 1.1 The cross section for fission of ^{235}U as a function of incident neutron energy. The cross section for fission goes up as the inverse of incident neutron energy. There is a resonance region well into the thermal neutron region where the probability of inducing fission is very high. The cross section for fission neutrons is pretty constant.

Since low-energy neutrons are so vital in causing chain reactions, much ongoing research has been done in studying the fission spectrum of ^{235}U. Currently at the Los Alamos Neutron Science Center (LANSCE), experiments are being performed to measure the neutron fission spectrum of ^{235}U as a function of incident neutron energy [3]. Different types of neutron detectors are being used in these experiments to measure the energy of the fission neutrons. However, with most detectors, it becomes very hard to detect neutrons with an energy less than 1 MeV, which is the important region for sustaining fission chain reactions.

1.2 Neutron detection

Neutrons are inherently difficult to detect because of their neutral charge. Many neutron detectors work by having neutrons impart kinetic energy to charged particles through collisions and subsequently detecting the moving charged particles. A scintillating material is often used to convert the energy of these charged particles into light, which can then be detected using a photomultiplier tube (PMT). Through this detection method, a neutron incident on the scintillating material will leave a pulse in a PMT. The pulse height and area left by the neutron in the PMT is dependent on the amount of kinetic energy it imparts to the scintillator. There is not a direct correlation between the pulse height or area and the incident neutron energy because neutrons of a given energy will not always impart the same amount of kinetic energy in the scintillating material. The energy of the neutron cannot be determined from the shape or size of the pulses it leaves in the PMT. Neutron energy is generally determined using a time-of-flight experiment by measuring the time it takes the neutron to travel a known distance, so it is important to be able to accurately determine the time a neutron pulse occurs.

When detecting neutrons in this manner, it is important not to confuse them with gamma rays, which, in addition to the neutrons, can also leave pulses in the PMT. It is common in neutron detection to use pulse shape discrimination (PSD) to differentiate neutron pulses from gamma-ray pulses. Detectors using liquid organic scintillators use this technique as their means of identifying neutrons. In this type of scintillator, neutron pulses tend to have long tail ends, whereas gamma-ray pulses do not [4]. By analyzing the shapes of the pulses, PSD can discriminate between neutrons and gamma rays quite well. It first integrates the pulse from its beginning to a chosen endpoint in the tail. Next, it integrates the same pulse from an optimized point after the peak of the pulse to the same endpoint in the tail. The ratio of these two integrations will be larger for neutrons because of their long tail. However, as the pulse heights get lower, the tails of the neutron pulses vanishes and it becomes harder to differentiate between neutron and gamma-ray pulses.

Since low-energy neutrons don't leave large pulses, it becomes hard to use PSD on them to confirm them as neutrons. In the energy regime below 0.5 MeV it becomes harder to confirm neutron pulses [4] because the distinguishing features between gamma-ray and neutron pulses go away. A gamma-ray pulse that is misidentified as a neutron pulse is called an accidental. Research is being done to decrease the accidental rate at low energies for PSD , but it is proving to be very challenging [4]. We need a new way to be able to detect low-energy neutrons. The nuclear research group at Brigham Young University (BYU) has developed a different type of neutron detector that does not use PSD to confirm neutrons.

1.3 Capture-gated Neutron Detectors

1.3.1 Detection methods

The detector developed by BYU uses the method of dual-pulse spectroscopy to detect neutrons. Instead of relying on the shape of the pulse to identify it as a neutron or gamma ray, we look for pairs of pulses. We use a scintillating material in the same manner as other detectors, such that incident neutrons collide with charged particles which then create a pulse seen by a PMT. We call this first pulse the proton-recoil pulse. However, embedded within our scintillator is cadmium, a material with a high neutron-capture cross section. The Cd captures the neutrons and upon de-excitation, emits a cascade gamma ray, which is seen on the PMT as the second pulse from the neutron. We call this second pulse the capture pulse. This process is illustrated as shown in Fig. 1.2 [5] . Thus, a neutron incident on the detector must produce two pulses to be considered a neutron. An example of these two pulses is shown in Fig. 1.3 [6].

In this method of neutron detection, we do have to worry about false doubles, which is when pulses from two different particles are recorded in close proximity in time. This can happen by recording a single pulse from a neutron and then another single pulse from a gamma ray or a

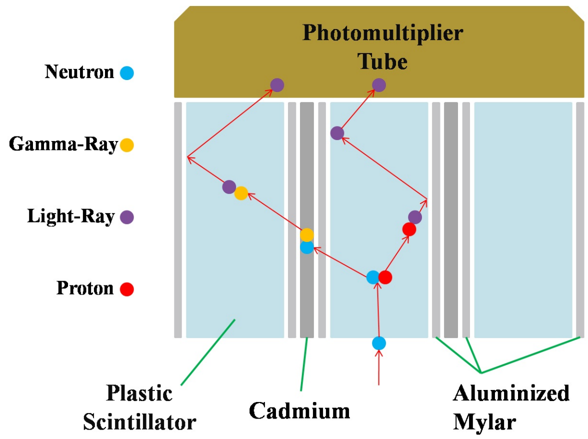

Figure 1.2 An incident neutron enters the plastic scintillating material and scatters off of a proton. The proton then scintillates and creates the first-pulse (proton-recoil pulse) in the PMT. The neutron continues on until it is captured in the Cd. A gamma ray is released from this reaction, which then goes on to create the second pulse (capture pulse) in the PMT.

different neutron. In our analysis process we take precautions to against false doubles by enforcing different requirements on the pulses to help ensure that the two pulses are correlated to the same neutron. These requirements are explained more fully in Chapter 2.

Our method of dual-pulse spectroscopy has the advantage over PSD with low-energy neutrons because it requires a capture pulse to confirm neutrons. Also, since the cross section for neutron capture goes up as the inverse of neutron energy, low-energy neutrons are more likely to capture and give us the required second pulse. This characteristic of our detector makes it a good candidate for analyzing the fission spectrum of ^{235}U.

1.3.2 Our detector

BYU has developed the "4-fold" Cd capture-gated neutron detector. It consists of 21 10 in. by 6 in. by 1 cm slabs of EJ200 hydrogen-rich plastic scintillator. Between each slab, there is a 0.1 mm thick sheet of Cd sandwiched between two sheets of aluminized mylar. On top of the slabs

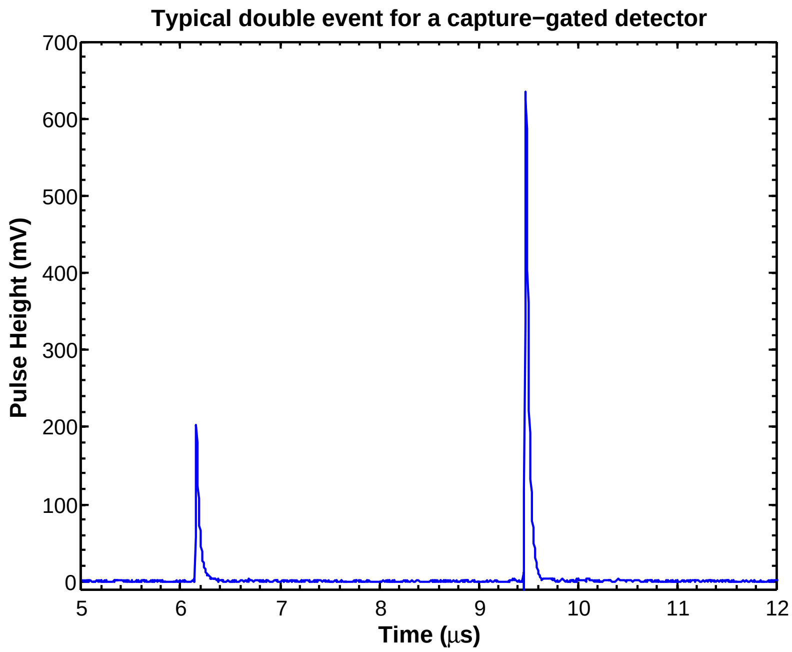

Figure 1.3 A proton-recoil pulse followed by a neutron-capture pulse. In order for the detector to detect a neutron, there must be two pulses recorded.

of scintillator we have four 5-inch R1250 Hamamastu PMTs. The whole detector is contained within a light-tight aluminum box. It is much larger in volume than a liquid scintillator detector to facilitate the neutron capture. The large volume of the hydrogen-heavy scintillator also serves as a moderator to help the neutrons slow down enough to capture. A diagram of the 4-fold detector is shown in Fig. 1.4.

In August 2013, our research group took the 4-fold to the Edwards Accelerator Lab at Ohio University to perform an efficiency calibration. The accelerator is a 4.5 MeV tandem pelletron-type accelerator, which accelerates deuterons that collide with an aluminum target, producing a beam of neutrons by the (d,n) reaction [7]. We used their time-of-flight tunnel to take data and calibrate the 4-fold detector. The calibration consisted of correctly setting the gain on each of the four phototubes so that we could see a wide range of neutrons in terms of energy. We took data for three days and were able to generate spectroscopic energy response functions unique to our

Figure 1.4 An exploded diagram of the 4-fold detector

calibrated detector.

Since neutrons of a certain energy will leave proton-recoil pulses of different peak heights and areas, we can generate pulse height and pulse area response function curves. Therefore, the calibrated 4-fold detector can be used as a spectrometer to identify the approximate energy of monoenergetic incident neutrons. If data generate response functions that do not match the shape of those from the calibration data, then either the neutron source is not monoenergetic at that energy, or the detector is not functioning properly.

1.4 Overview

We took our 4-fold detector to the Weapons Neutron Research facility (WNR) at LANSCE in August 2013, directly after calibrating it in Ohio, to analyze the fission spectrum of ^{235}U using their fission chamber. Due to the capture pulse requirement of our detector, we hoped to be able to detect neutrons of energies less than 1 MeV where neutron-gamma discrimination starts becoming difficult for detectors using PSD.

In this project, I was present at LANSCE during the data acquisition and have done all of the data analysis of the data obtained there. I wrote a majority of the MATLAB code used to analyze this data. I have also done most of the comparison of the LANSCE data with the calibration data obtained at Ohio University.

In our analysis of the data taken at LANSCE, our response functions did not match those from the calibration data from Ohio University. For a given energy, the curves are wider than the calibration data response function curves, which indicates that for a given neutron energy bin, more light is reaching the PMTs at Los Alamos that at the calibration facility at Ohio University. Possible reasons for this may be that the detector itself changed in the shipping process to LANSCE or that there is a lot of background contamination at LANSCE which could change our response functions. However, we did generate other plots in our analysis whose general shapes are appropriate for the detector, such as the time-of-flight histogram curve and the time between the proton-recoil and capture pulses histogram. However, there are also aspects of these plots which do not match our expectations, leading us to further believe that there is a background problem.

Chapter 2

Experimental Methods

2.1 Equipment setup

The neutron beam at the WNR research facility generates pulses every 1.8 μs. The accelerator accelerates protons up to 800 MeV which are incident on a tungsten target that creates bursts of neutrons of various energies [3]. This beam of neutrons is then collimated and sent into the target room.

Inside the target room, the collimated neutron beam is incident on the ^{235}U fission chamber. The fission chamber consists of nine foils of ^{235}U. The incident neutrons enter the fission chamber and cause fissions. The fission chamber is about 7 ft. above the ground to help reduce room return. Room return is when neutrons scatter from the floor or walls and then return back to be detected at later times. Such events at later times produce signals which are falsely interpreted as lower energy neutrons. Room return is very harmful to an experiment attempting to measure the fission spectrum of ^{235}U because it contaminates the true energy spectrum.

The 4-fold was placed 1.005 m from the fission chamber to detect the fission neutrons. We used a DT5720 CAEN digitizer that received signals from the neutron beam (channel 0), the fission chamber (channel 1) and the anodes (channel 2) and dynodes (channel 3) of the 4-fold. The dynode gain was set higher than the anode gain. The digitizer samples the signal every 4 ns and records the time spectrum of each pulse. We used the optical link of the CAEN to transfer the digitized data to our computer at a high rate. Our experimental setup is show in Fig. 2.1. The CAEN was set to trigger on the fission chamber so that every time there was a fission pulse, it would record 32 μs of data on all four channels with about 6.4 μs before the fission pulse. The neutron beam and fission pulse were set to record with zero-length encoding (ZLE), so that the CAEN would only record non-zero data points. The anode and dynode channels recorded all pulses in the PMT for the 32 μs.

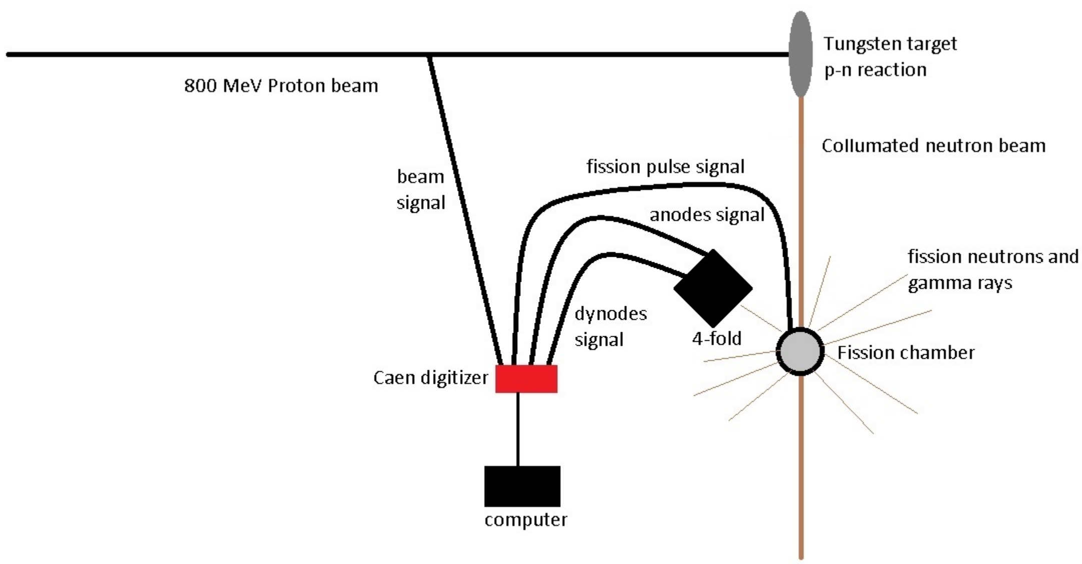

Figure 2.1 A digram of our equipment setup.

2.2 Fission chamber

The fission chamber had nine foils of ^{235}U that could fission and produce a fission pulse. For data analysis purposes, we calibrated each foil from the fission chamber to give off a unique pulse. We used electronic integrators to vary the area of each fission pulse so that we could distinguish them later in the analysis process. The electronics for each foil were separate and so each foil had its own inherent timing delay. We rely on accurate timing of the fission pulse to calculate the energy of the fission neutrons in our analysis process. Therefore, it was necessary to make each fission foil have a unique signal for us to accurately calculate neutron energies.

2.3 Data acquisition

We acquired data for about three days. In this time we obtained about 191 GB of data. We separated the data into files of 25 000 events each. An event is when there was a trigger from the fission chamber and the 32 μs of data from each channel are recorded. A typical event is shown in Fig. 2.2. We recorded about 5.5 million events.

2.4 Data Analysis

After the data were taken, we used a MATLAB code largely written by Kent Talbert and myself to analyze the data. The analysis starts by reading through the data and making summary files of the events. For each event, the program calculates the time of the beam pulse that caused the fission; the time and area of the fission pulse; and the time, peak height, and area of the first and second pulses from the detector for all of the two-pulse events. The beam pulse that caused the fission event to occur is considered to be the first beam pulse that comes before the fission pulse in time. When finding the pulses in the anodes and dynodes, the tallest peak is found first and is called

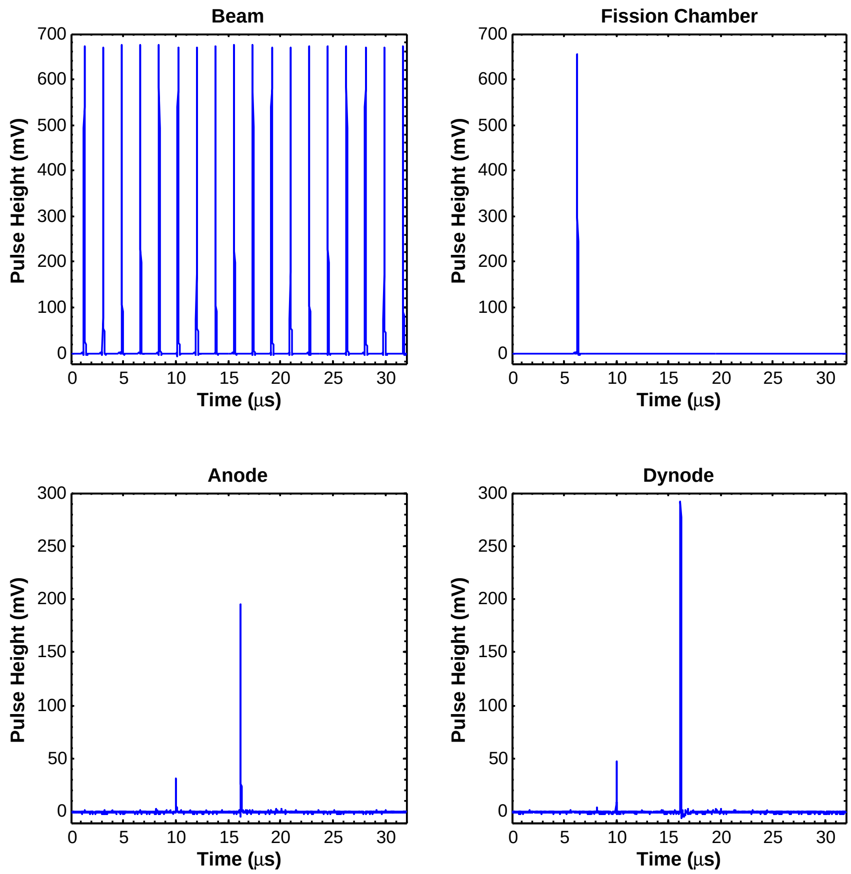

Figure 2.2 A typical event of 32 μs. The beam channel is in the upper left, the fission chamber in the upper right, the anodes in the bottom left, and the dynodes in the bottom right.

the trigger. Afterpulsing can occur, which is when a neutron collides with other protons after its first proton-recoil pulses, leaving other pulses until it captures in the cadmium. In order to not accidentally count these pulses, depending on the pulse height, the program zeros-out the data for a given amount of time after an initial pulse. Then it searches for other pulses, demanding that they be above 25 mV if they come later than the trigger pulse or above 2 mV if they come earlier than the trigger pulse. The program also requires that all pulses be within 16 μs of the trigger pulse to be considered correlated to the trigger pulse because this was how the detector was set up when it was calibrated. If exactly two pulses are identified by the program at this point, the event is considered a double and all of the information before mentioned is saved. If exactly three pulses are identified by the program, it saves the two largest pulses because these two are more likely correlated. If perchance they are not correlated, they will be subtracted out with the background later on in the analysis. All of the timing for the pulses is found using a constant-fraction discrimination (CFD) routine. If the beam channel is empty or if there is only a single pulse or more than three pulses recorded on the detector in the 32 μs, the event is considered invalid and nothing is saved. A summary file is made for every data file. The summary files then are all merged together into one large file and this is used in the rest of the analysis process.

To analyze the summary files, the events first must be split up according to which foil produced the fission pulse. The program does this by sorting through the events according to their fission pulse area and analyzes events according to their fission foil. To separate the different fission foils, a histogram of the fission pulse areas is made, which is shown in Fig. 2.3. It is interesting to note that not every foil in the fission chamber fissioned equally. The nine peaks in this histogram correspond to the nine different fission pulse areas. The programs groups the events into the nine different spikes in the histogram and analyzes them separate one from another. We must sort the events this way because each foil has a different timing offset unique to it that must be calculated separately in order to get good timing resolution for the time-of-flight of the neutron.

The program then starts to subtract out the background. When making the summary files, it limits the time between the pulses to be 16 μs because that matches how the detector was set up when it was calibrated. The program makes a histogram of the time between pulses as shown in Fig. 2.4. There are spikes every 1.8 μs which we believe to be caused by activity from the beam pulses that occur every 1.8 μs. The overall shape of the curve, ignoring the spikes, is a decaying exponential as it should be for this detector because the cross section for neutron capture in cadmium is only large at very low energies. High-energy neutrons are less likely to capture and cause a second pulse because they must lose much more energy to capture, thus resulting in

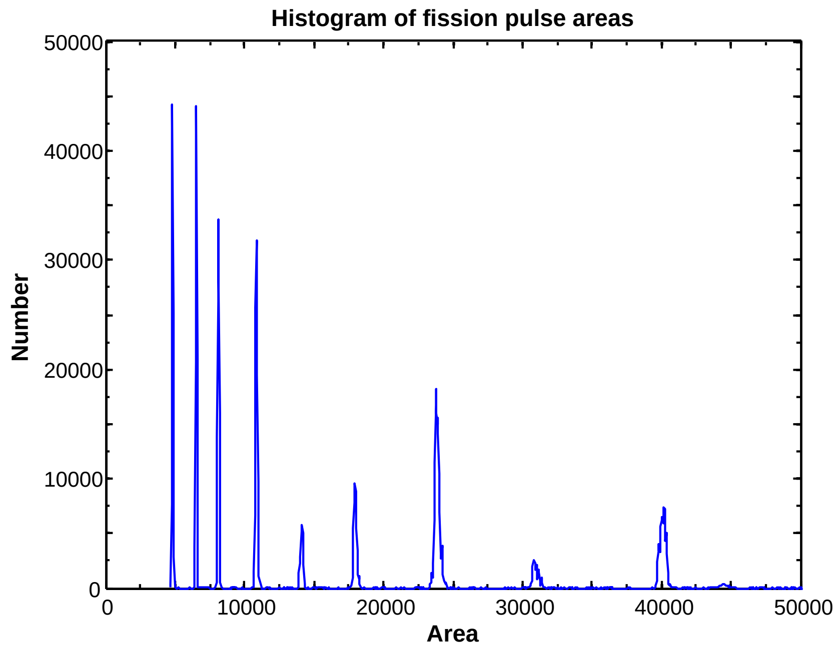

Figure 2.3 A histogram of the fission pulse areas for all the data. We integrated the nine foils to give nine distinct areas. These correspond to the nine peaks in the data. It is interesting to note that the foils do not fission equally.

a decaying exponential in our time between pulses histogram. We zero out the events that are in the spikes and do not analyze them because we cannot discriminate between background and foreground.

After zeroing out the events that are in the spikes and separating the events into their individual foils, a histogram is made of the time between the first pulse (proton-recoil) and the fission pulse for each fission foil. This corresponds to the time it takes the fission neutron to travel from the fission chamber to the detector and is called the time-of-flight spectrum. From the time of flight of the neutrons, we can calculate their energy. The histogram shows a sharp peak followed by a mound. The peak, which we call the gamma-flash, corresponds to fission gamma rays arriving at the detector all at the same time since gamma rays all travel at the speed of light. Due to timing delays in the cables, these gamma-flashes come in at some negative time in the histogram which

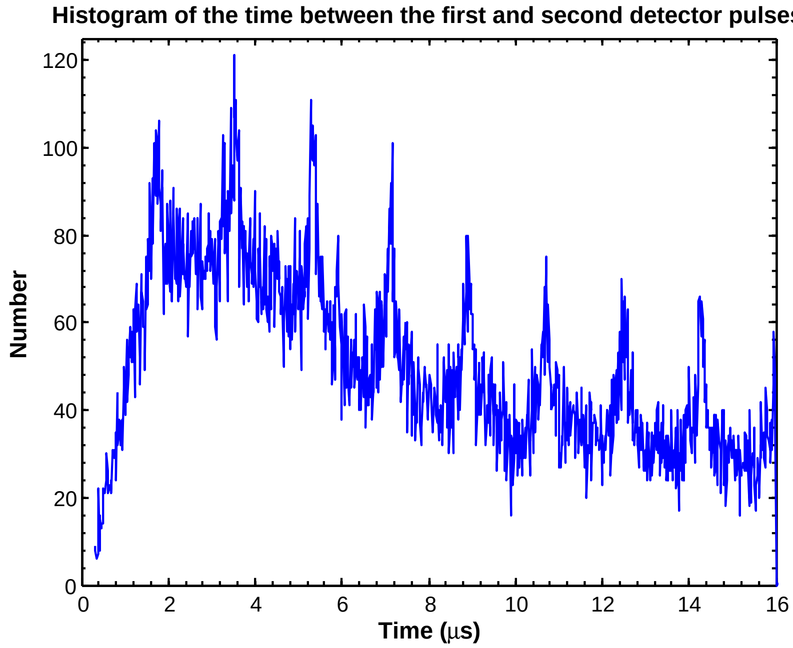

Figure 2.4 Histogram of the time between the two detector pulses for the events that fit in the neutron timing region for all the data. The spikes are likely correlated to activity from the beam. We do not analyze events contained within the spikes.

varies from foil to foil. Each foil is then offset by some time so that the gamma-flash appears at time 0 as a reference point. We then add the time it takes the fission gamma rays to travel from the fission chamber to the detector, thus making time 0 the fission event. We must take this gamma ray time-of-flight into account for calculating the energy of the neutrons. The mound after the gamma-flash is the neutron region and contains neutrons of energies from 35 MeV and below. After each foil is offset, they are summed together, giving the total time-of-flight histogram.

The program then subtracts out the background from the time-of-flight spectrum. The programs fits a linear curve to the baseline of the time-of-flight histogram and subtracts those events out. There are spikes every 1.8 μs, just like in the time between detector pulses histogram, that we believe to be correlated to the beam pulses, but they don't affect the neutron region because they come too late in time. The mound of neutrons dies out by 400 ns after the gamma-flash, whereas the first spike appears 1.8 μs after the gamma-flash. The time-of-flight histogram with background subtracted is shown in Fig. 2.5. With the background subtracted, the program converts the time-of-flight spectrum into a neutron-energy spectrum in MeV and plots a histogram as shown in Fig. 2.6. Table 2.1 shows the number of events before and after background subtraction.

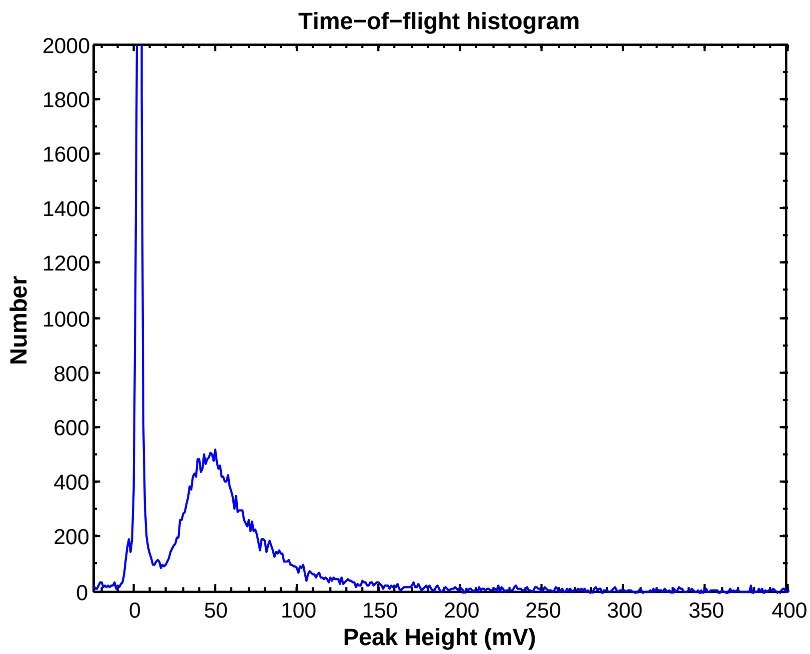

Figure 2.5 Histogram of the time between the fission pulse and the first pulse on the detector with background subtracted for all the data.

Table 2.1 Total number of doubles before and after background subtraction

	with background	background subtracted
total doubles	912971	86947
neutron lump	49862	27467
less than 1 MeV	22131	7820

Pulse height and area response function curves are then generated from the summary files of the data. This is done by isolating events within a selected energy range and making a histogram

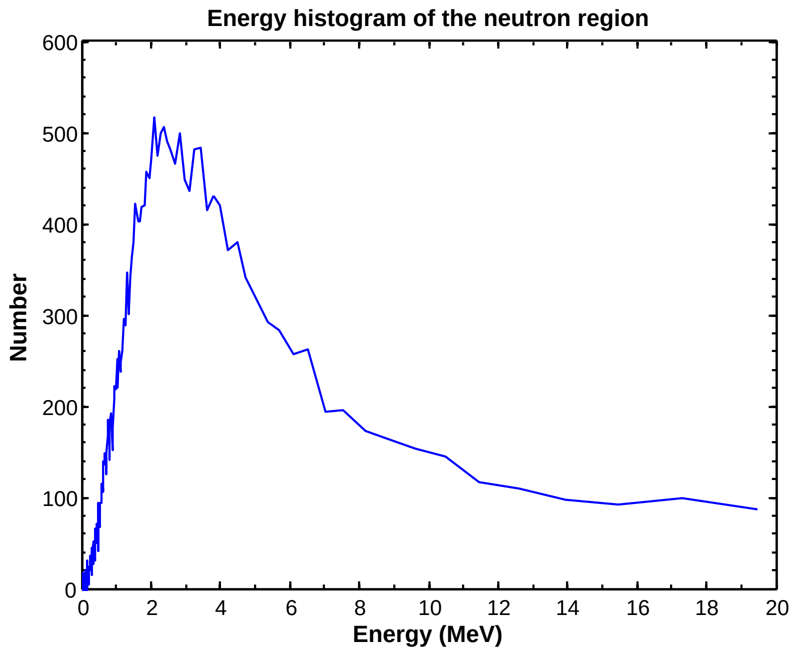

Figure 2.6 Histogram of the neutron region in energy bins with background subtracted.

of the first pulse height. These plots demonstrate the spectroscopic nature of our detector because neutrons of different energies generate different pulse-height and area histogram curves. Examples of these pulse-height response functions are shown in Figs. 2.7 and 2.8. Background subtraction for these plots is done by subtracting the response function out an energy much lower than expected from fission (representing the response function curve of the background).

We also analyze the singles spectrum of our data, where instead of isolating events where there was a fission event and two pulses on the PMT, we just look at the first pulse on the PMT, regardless of how many pulses occurred in the PMT during 32 μs event. From these data we are able to generate a time-of-flight histogram, an energy histogram, and response functions. Analyzing the data in this manner is similar to how PSD experiments work, because they only look at the first pulse. However, with our detector we cannot discriminate between neutron and gamma-ray pulse shapes. We are able to compare our singles response function curves to those generated from the calibration data and they do not match.

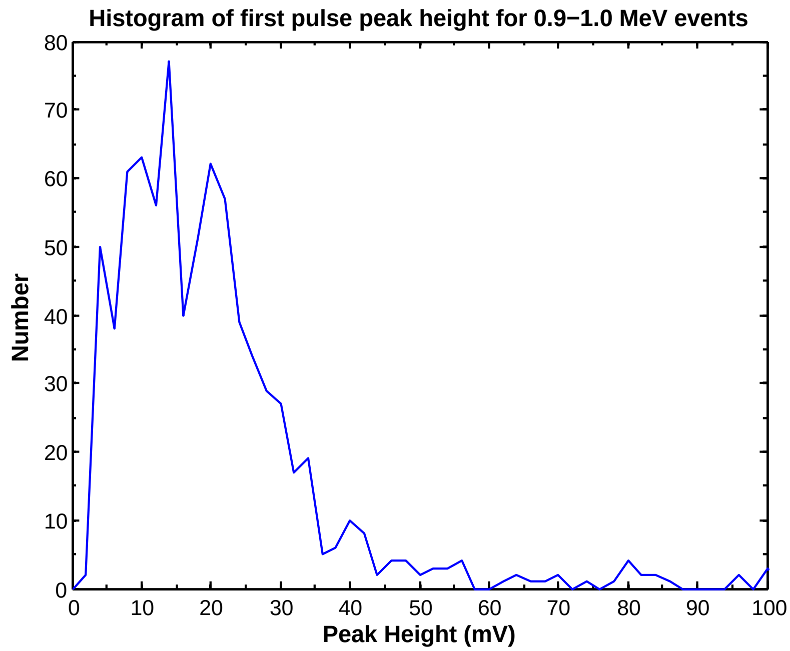

Figure 2.7 Histogram of the first pulse height for events centered at 0.95 MeV for all the data.

Since our response function curves do not match those generated during calibration, we realize that something is amiss and think it is a background problem. To check this, we investigate our rates. We analyze all of the raw data and looking at the fission pulses only and we measure the fission rate to be 44.4 fissions/sec. We were given information as to the amount of ^{235}U deposited on each of the foils and upon comparing of our individual foil rates with the mass of ^{235}U, we find no correlation between the two. We assume that about 2.5 prompt neutrons [8], and 6.5 prompt gamma rays [9] are released per fission of ^{235}U. These are rough estimates and both depend very much on the incident energy of the neutron inducing the fission. So, on average, 9 particles are released per fission of ^{235}U and we assume they are distributed isotropically. We calculate the solid angle of our detector to be roughly 0.0317 sr. This is approximately 0.25% of the solid angle of a sphere. Thus, when we calculate the rate we should be seeing from the fission chamber based on these estimations, we arrive at a rate of 1 event/sec. From our raw data we measure a rate of

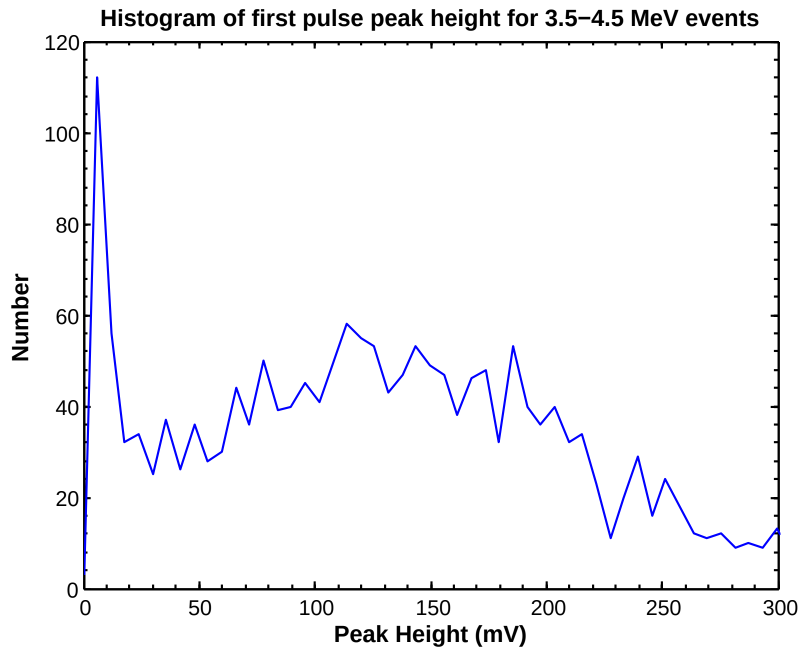

Figure 2.8 Histogram of the first pulse height for events centered at 4 MeV for all the data.

25.6 events/sec. We were told that the fission chamber is about 70% efficient. However, taking this efficiency into account we arrive at a calculated rate of 1.4 events/sec. Finally, if we arbitrarily match our measured foil rates correlate to the provided mass of ^{235}U and assume an efficiency of 70%, we arrive at a calculated rate of 1.8 events/sec. The only factor that we are assuming is the number of prompt neutrons and gamma rays released per fission, but in order to come near our measured rate of 25.6 events/sec, there would need to be an average of 129 prompt neutrons and gamma rays released per fission, which is clearly not physical. This leads us to believe that there is a major background problem with our data, most likely related to the beam.

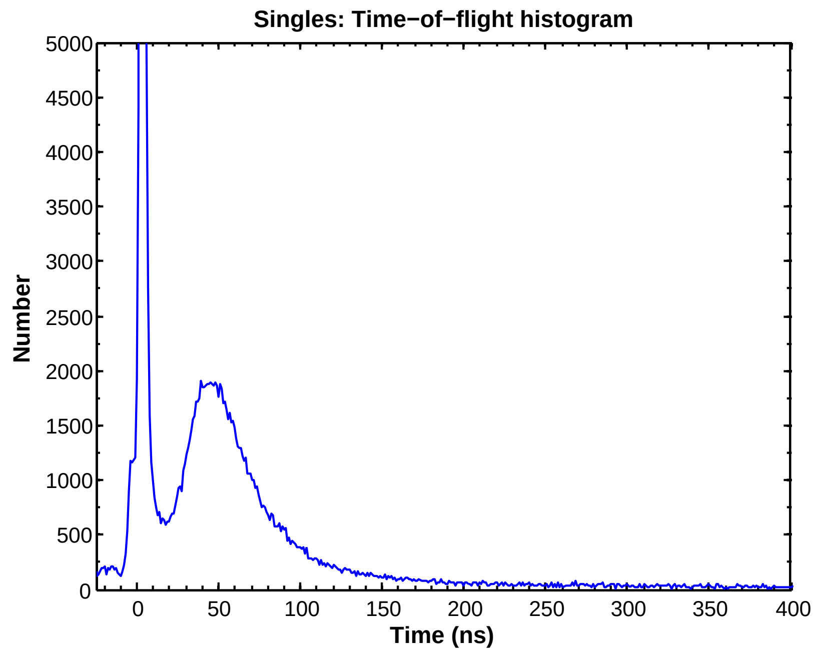

Figure 2.9 Time of flight spectrum for the singles analysis with background subtracted. It looks quite similar to the doubles spectrum (see Fig. 2.5), there are just more events

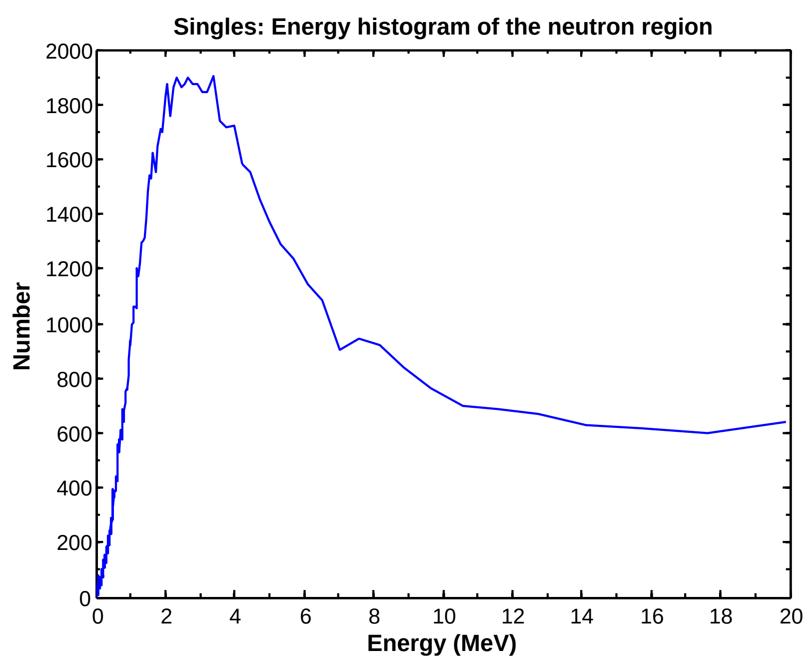

Figure 2.10 Energy histogram of the neutron region with background subtracted. It looks quite similar to the doubles spectrum (see Fig. 2.6), there are just more events

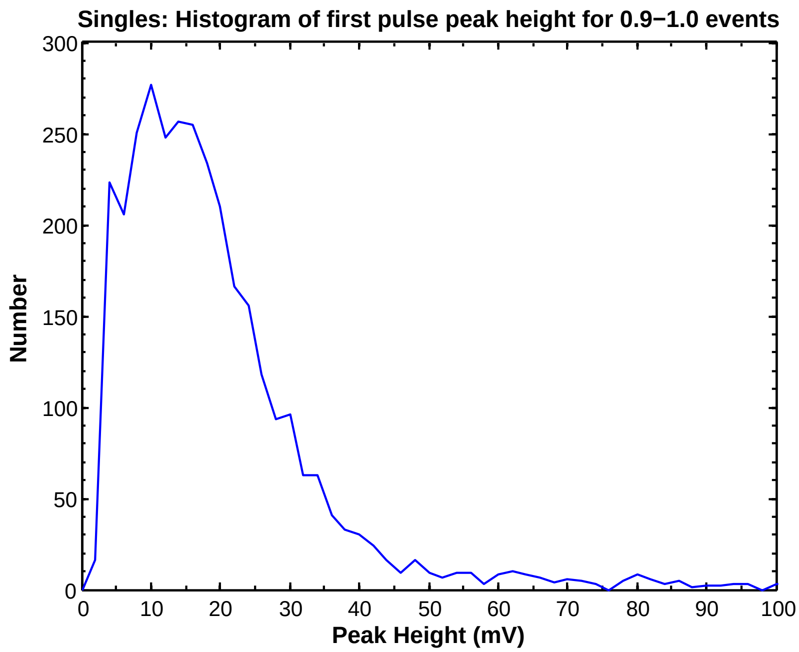

Figure 2.11 Histogram of the first pulse height for events centered at 0.95 MeV for singles data.

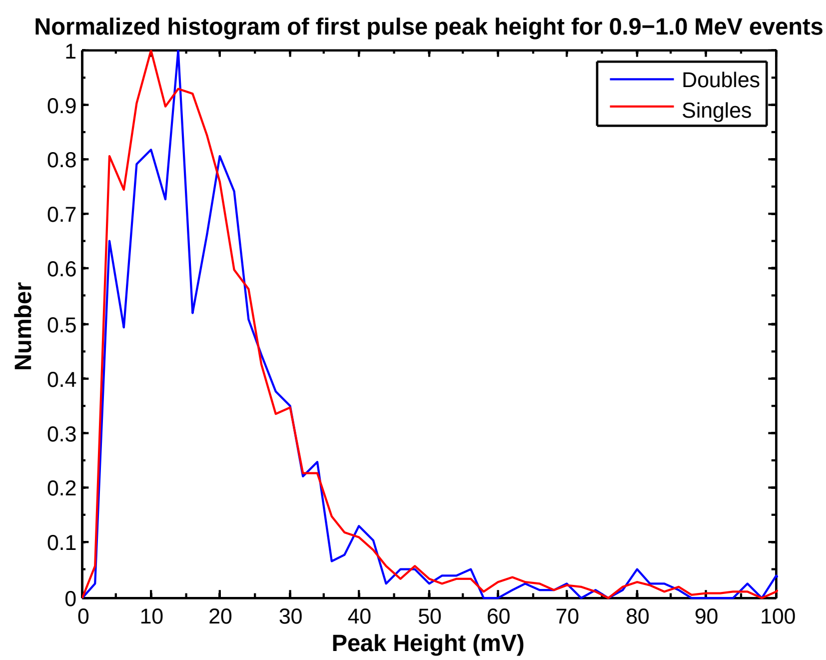

Figure 2.12 Normalized histogram of the first pulse height for events centered at 0.95 MeV for singles and doubles data.

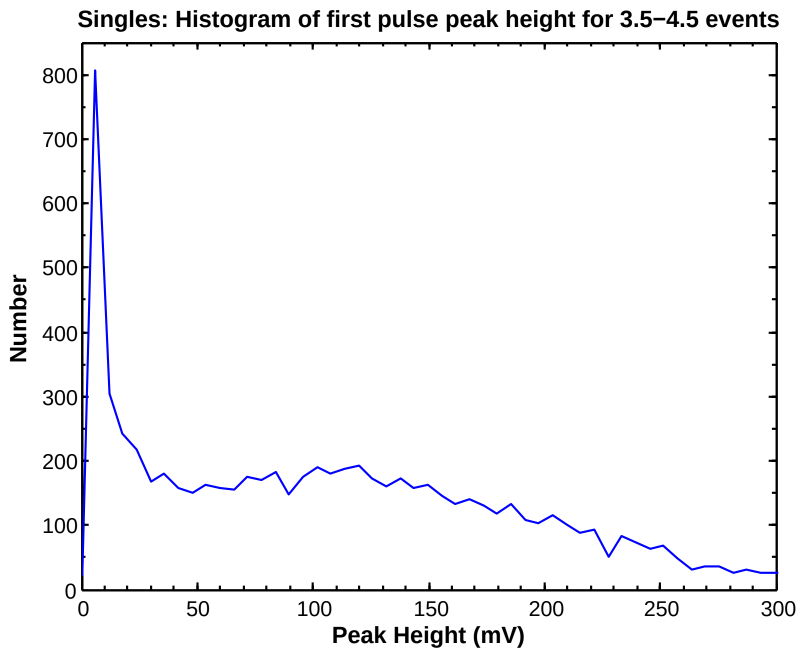

Figure 2.13 Histogram of the first pulse height for events centered at 4 MeV for singles data.

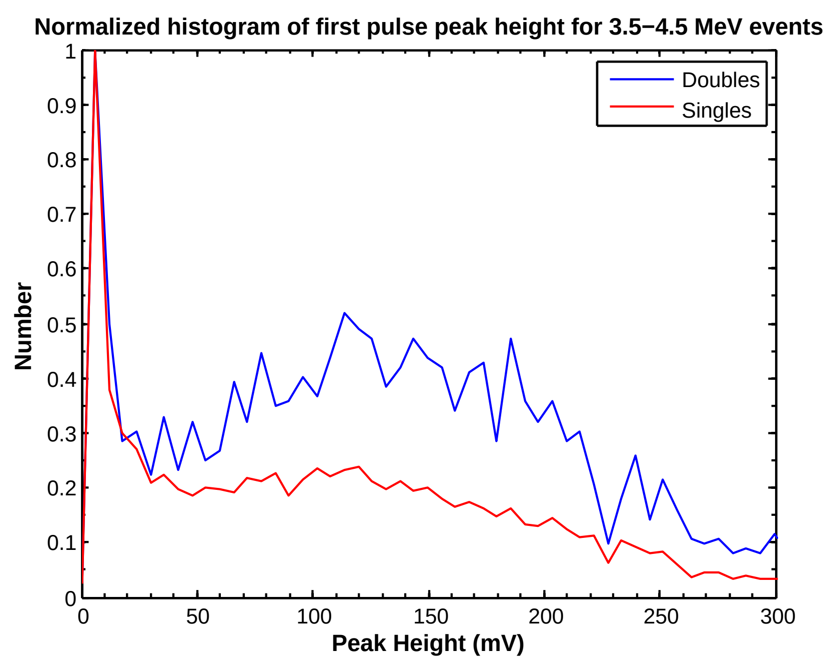

Figure 2.14 Normalized histogram of the first pulse height for events centered at 4 MeV for singles and doubles data.

Chapter 3

Results and Conclusions

3.1 Concerns

We are concerned about our data for a couple of reasons. In our energy spectrum, we are seeing neutrons with energies up to 35 MeV. This seems a little high for our detector and are probably accidentals because it is very unlikely that a 35 MeV neutron would be able to slow down fast enough to capture within our detector. The fact that we are seeing neutrons this high in energy could mean that we are cutting too much into the gamma-flash. The FWHM of our gamma-flash is 1.412 $\pm$ 0.002 ns for our doubles spectrum and 1.536 $\pm$ 0.0015 ns for our singles spectrum. Since this is a very narrow gamma-flash, that would infer that our timing calculations are pretty accurate. This resolution is due in part to the close distance (1.005 m) and also is inherent to the PMTs used. We have measured a spread of 2 ns in the timing capabilities of the Hamamatsu PMTs used depending on where the light pulse strikes the tube. The presence of 35 MeV neutrons in our energy spectrum after such a narrow gamma-flash would indicate that we are not subtracting out the all of the background.

Another cause for concern is the series of spikes visible in the histogram of the time between the two detector pulses as shown in Fig 2.4. The spikes are spaced by 1.8 μs which corresponds to the beam pulses. The spikes interfere with the typical decaying exponential shape for this curve. In the spikes, there are real neutron doubles as well as accidental doubles. We fit a function to our data to estimate how many events are in the spikes as shown in Fig. 3.1. A possible explanation for the accidentals in these spikes could be activity from a beam pulse other than that which caused the fission event leaving a second pulse uncorrelated to the first. Another possible explanation could be that there is a lot of room return affecting our spectrum. The events contained within the spikes were isolated and analyzed to see if there was a way to distinguish the real doubles from the accidental doubles within them. We were unable to see any difference in peak heights or pulse areas for events contained within the spikes and the surrounding regions. In the analysis process we have been ignoring all events contained within any of these spikes. Doing this will only cut down on our number of real pulses, while also eliminating accidentals.

Our biggest reason for concern lies in the fact that our spectroscopic response function curves for a given neutron energy bin do not match those generated from the calibration data taken at Ohio University. The detector was shipped directly from Ohio to Los Alamos and was set up using the same gain and voltages on the PMTs as at Ohio. The plots generated have similar shapes to those generated with the calibration data, but consistently go out to larger pulse heights as shown in Figs. 3.2 and 3.3. The response functions should be the same because they are only dependent on on the energy of the neutron. The fact that the curves are wider could indicate that there are high-energy neutrons that are mistakingly coming into the detector at late times. This could happen if high-energy fission or beam neutrons scatter and bounce off the floor and into the detector at late times, thus masking their real energy. We believe this is likely the case. We have reason to believe that a 7 ft. distance to the floor from the detector is not enough to completely cut out effects from room return based on previous experiments. Another possible explanation could be that the detector itself changed from the time it was calibrated. Perhaps something in the shipping process

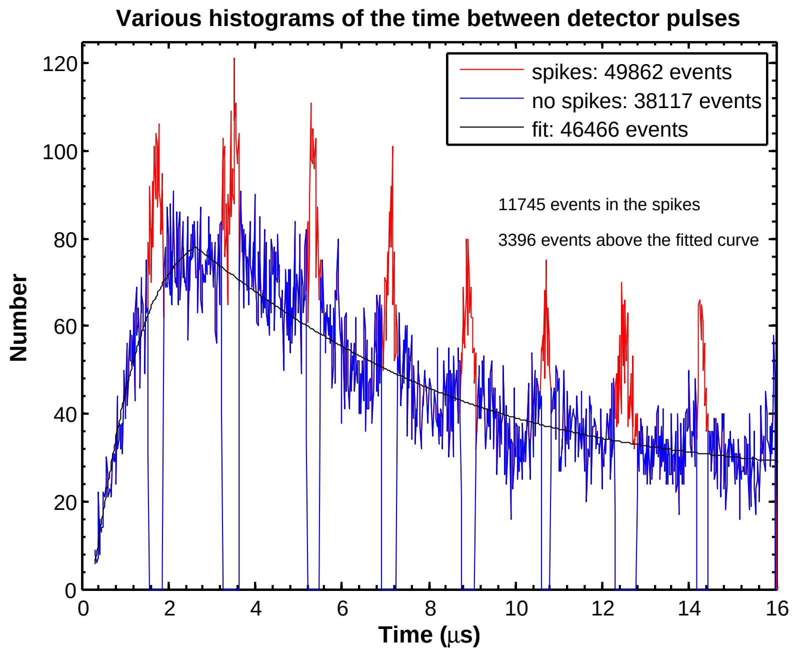

Figure 3.1 . The time between detector pulses spectra with spikes, without spikes, and a fitted function. Of all the events, 23.6% reside in the spikes, so we throw out that much of our raw data when we exclude the spikes in our analysis. However, only 6.8% of the events lie above the fitted curve, so if it were possible to determine which events these are we would increase of amount of raw data for analysis.

caused the optical properties of the detector to change. However, we find this unlikely, because the response functions are consistently wider than the calibration data, indicating that the light output of the detector improved. Thus, we believe room return is what is causing our response functions to be wider. This is our main reason for concern because these response function curves should match and we cannot give a definitive reason as to why they do not match. This discrepancy also means we cannot trust our data at all as to quantify the fission spectrum of ^{235}U.

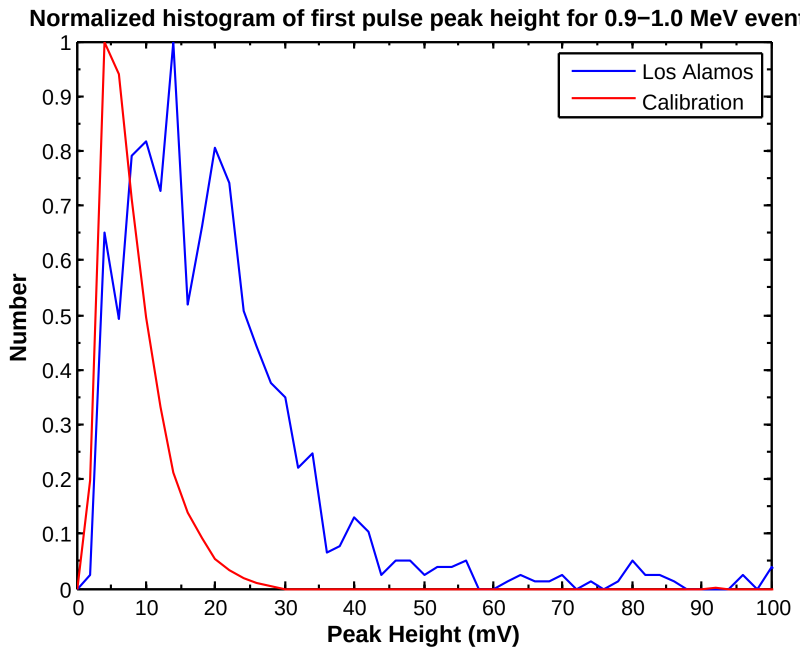

Figure 3.2 Comparison of the pulse height response function curve for the Ohio calibration data (red) and the Los Alamos data (blue) at 0.95 MeV. The Los Alamos curve is wider than the calibration curve, which could be suggestive of a change in the detector or high energy events coming in at later times. The curves are normalized to a maximum height of 1.

3.2 Conclusions

It appears that there is possibly a lot of high-energy background in the room, possibly from the beam and from room return. We are inclined to believe that it is coming from the beam and not the fission chamber because when we looked at our fission chamber rates and compared them to our single and double event rates, it is much too low. If this background is from room return, that would be very dangerous for any experiment that measures the fission spectrum of ^{235}U because it would taint the true fission spectrum. Most other experiments that are being done to measure the fission spectrum only take data for a couple hundred to a thousand nanoseconds [3,4] and only require one pulse. This is exactly what our response functions require and the fact that they do not match our calibration data is very concerning. The spectra reported by these experiments could be

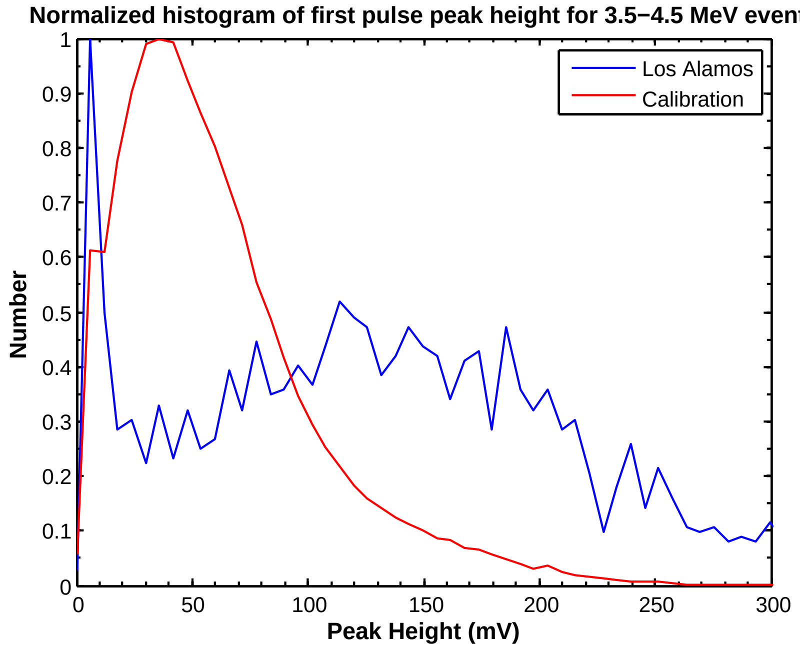

Figure 3.3 Comparison of the pulse height response function curve for the Ohio calibration data (red) and the Los Alamos data (blue) at 4.0 MeV. Again, the Los Alamos data is wider than the calibration data, which could be suggestive of a change in the detector or high energy events coming in at later times. The curves are normalized to a maximum height of 1.

badly contaminated if no measures are made to exclude room return effects.

In our data, we do get a good gamma-flash followed by the neutron region (see Fig. 2.5) which is expected for a time-of-flight experiment done with this detector. However, the spikes in the different spectra lead us to believe that there is a lot of unwanted activity in the room. Not knowing exactly how to account for these accidentals, we just ignore them and do not include them in our reported spectrum.

The purpose of our experiment was to push the low-energy limit for detecting neutrons of the ^{235}U neutron fission spectrum. However, we cannot trust our data at all because we have no way of being sure about what are real neutrons and what are accidentals. We have seen low-energy neutrons from the data we took at Ohio University, however we cannot trust what we see at low energies (see Fig. 3.4) from this data because we believe it is badly contaminated with background from our rates and response functions discrepancies. If we did not have discrepancies with our calibration data, we would have more confidence in our low-energy data and possibly be able to push the low-energy neutron threshold of PSD. We are unable to make any claim about the fission spectrum of ^{235}U based on our data, and our data suggests that our detector cannot function properly in the environment at LANSCE.

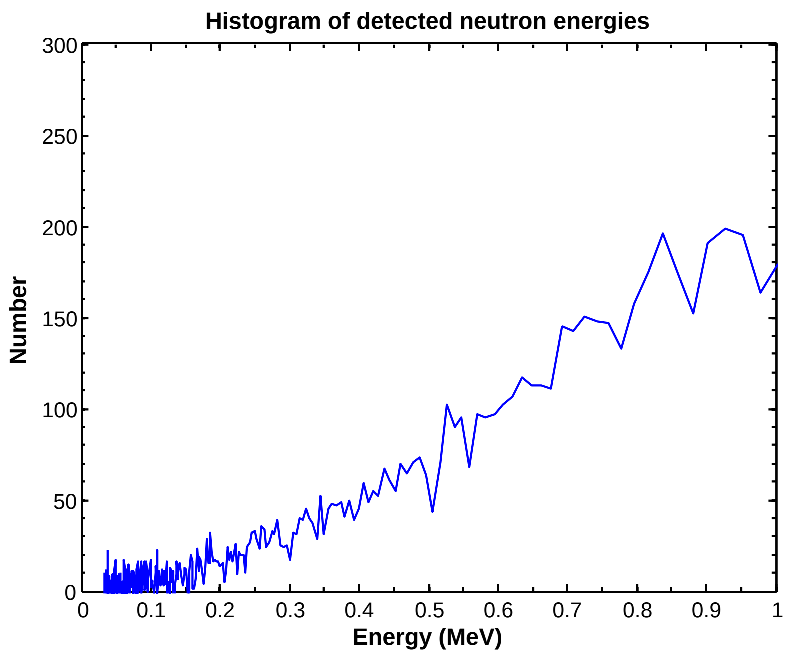

Figure 3.4 Histogram of the low-energy neutrons detected after background subtraction and ignoring the spikes in the time between pulses spectrum.

3.3 Direction for further work

We are concerned about the response functions not matching those generated during calibration. We have not dismantled the detector to this point, so we plan to perform time-of-flight experiments with the same voltage and gain settings as at Los Alamos to see if the response functions generated are the same as those from the calibration or the Los Alamos data. If they match those generated from the calibration data, then there is something else at Los Alamos that is tainting our spectrum. However, if they match those generated at Los Alamos, then our suspicions of the state of the detector changing can be strengthened. This testing of the detector will help us to be able to draw more definitive conclusions about our measured fission spectrum.

We also plan to test the effects of room return on neutron detection using our scissor lift. We have done experiments similar to this before, but we want to do it again because we think the problem may be room return at Los Alamos. The distance to the floor at Los Alamos is 7 ft. We can test our detector at various heights to see the effects of room return on our spectrum. This experiment can help us to determine the effects of room return on our detected fission spectrum.

We are also in the process of developing a Cf fission chamber to use here at BYU. With this built, we would be able to perform time-of-flight experiments and generate more response functions with the 4-fold. We would be able to recalibrate the 4-fold. Then we would like to take our fission chamber back to LANSCE and take data with the 4-fold with the beam off and with the beam on to see if the response functions change. If they do change when the beam is on, then that would be conclusive evidence that there is a problem with room return at the LANSCE facility. We want to do this experiment to double check our results. We have possibly stumbled upon a great problem that could be affecting numerous important and delicate experiments in a way that could have far-reaching consequences. We just want to double check our methods so that if there is a problem, it can be brought to light and fixed.

Finally, we are in the process of determining a new way of subtracting out the background from our data that is more event dependent. We believe that this will be more effective at getting rid of accidental events and hopefully clean up our different spectra. It will hopefully help us to resolve the discrepancies between the Ohio University calibration and Los Alamos data response functions.

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Index