CADMIUM CAPTURE-GATED NEUTRON DETECTOR DESIGN AND CONSTRUCTION

by

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ABSTRACT

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My research group and I have built a cadmium capture-gated neutron detector, as envisioned by Dr. Bart Czirr. This novel design is intended to address the growing need for a helium-3-free neutron detector for national security and scientific research. Our detector takes advantage of neutron interactions with a scintillating plastic moderator and neutron capture in cadmium. A neutron entering the plastic loses energy to nuclear scattering and knocks protons free from nuclei. The protons lose energy to Coulomb scattering, producing a pulse of light in the scintillating plastic. The slowed neutron is captured in cadmium foil and releases 9 MeV of gamma rays, which Compton scatter to produce a second light pulse. This double pulse signals a neutron capture. This neutron detector was constructed using methods developed by my group. Testing has shown that our detector is able to detect ionizing radiation and discriminate between neutrons and gamma rays.

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Chapter 1

Introduction

My research group and I have been working to build a new type of neutron detector. A cadmium capture-gated neutron detector has been built once before by Dr. Bart Czirr, from the Brigham Young University Physics Department. We are rebuilding this detector to show that it is reproducible, to improve on the construction methods, and to provide us with a replacement for the first prototype, which is currently being used for research at the University of Michigan. This new detector is intended to fill a growing need in the scientific community for an inexpensive and reliable neutron detector.

1.1 Background

Atoms are made of light, negatively charged electrons; heavy, positively charged protons; and heavy, non-charged neutrons. Neutrons that exist outside of atoms are known as neutron radiation. Neutron radiation can occur either from a nucleus being bombarded with high energies, or through spontaneous emission from some materials. Neutron radiation travels through most matter with minimal interaction. There are two ways that neutrons can interact with certain materials. A neutron can strike the nucleus of an atom causing it to recoil; the atom and neutron will recoil in different ways depending on the type of atom and the energy of the incident neutron. The other way neutrons can interact with matter is by striking the nucleus of an atom and being absorbed into the nucleus. When a neutron is absorbed into a nucleus, it can either be re-emitted or cause gamma radiation to be emitted [1]. When a neutron is absorbed, the mass of the nucleus increases. The amount that the mass of the nucleus increases is less than the mass of a neutron, and the mass that was not added to the nucleus is converted into energy in the form of gamma radiation. This is called neutron radiative capture.

When a neutron strikes a nucleus and is not absorbed, the nucleus will recoil. Either a proton or alpha particle can be expelled, or the nucleus can break into smaller nuclei called fission fragments. All common neutron detectors are based on either detecting the charged particles from these kinds of reactions or detecting gamma rays from neutron capture [2]. The energy these particles carry away from the atom will depend on the binding energy of the neutron (or other particle in question) and the energy of the incident neutron [3].

Because charged particle detection does not relate directly to my research, I will only briefly describe the most popular methods. When heavy charged particles move through matter, they interact with and lose energy to electrons in the matter, but they have very little interaction with nuclei [4]. Some electrons will be knocked free from their atoms. Ion chambers, Geiger counters, and gas-filled detectors all use an electrical field to move these electrons and detect particles by either the current or voltage produced from the moving electrons [5]. Semiconductor detectors utilize a similar method of using an electric field to separate an electron and hole (a positively ionized region) to produce a signal current [6]. A charged particle (or gamma ray) may excite the electrons of an atom: as the electrons fall back down into their ground states they fluoresce, giving off light which can be detected by a photomultiplier tube. A material that gives off light when exposed to energetic particles is called a scintillator [7].

Materials high in light elements, especially hydrogen, can absorb large amounts of energy when struck by neutrons. Neutrons lose energy as they collide with hydrogen nuclei, which are just protons. These materials, called moderators, slow down neutrons and change the direction they are traveling. The cross-sections of materials increase inversely with the speed of the speed of neutrons. For this reason moderators are commonly used with capture-based neutron detectors to increase the chances that a neutron will successfully be captured [8]. Fast neutrons have energies greater than 0.5 eV. A neutron with an energy of 1,000 eV has a speed of about 2,200 meters per second [9]. The 0.5 eV definition for fast neutrons is based on the fact that above 0.5 eV cadmium has a negligible neutron cross-section [10]. Because I am dealing with cadmium capture, this is an ideal cut-off energy. Without the moderator, there is a very low chance that neutrons will be captured. Depending on the application, a few centimeters to tens of centimeters of moderator will be used between the detector and the source. Unfortunately, moderators also eliminate any knowledge of the original energy of the captured neutron [11]. If a material is both a moderator and a scintillator, it can be used to detect neutrons. But it can also detect gammas, or any other kind of ionizing radiation [12]. Therefore, this kind of detector often has difficulty discriminating between different kinds of radiation.

1.2 Needs as of 2010

The demand for an effective neutron detector has dramatically increased in the past few years because of ^{3}He shortages. ^{3}He is favored for neutron detection because it has a particularly high neutron cross-section and can easily discriminate other particles (including gammas) from neutrons [13]. Because of the advantages of ^{3}He, the Department of Homeland Security has become the largest user of ^{3}He for use in detectors at portals (coming into the U.S.) [15]. The Department of Homeland Security is particularly interested in gamma insensitivity because there are many common gamma producing substances, such as bananas and kitty litter, but few neutron producing materials, like plutonium, which are all heavily controlled. Therefore, the Department of Homeland Security needs radiation detectors capable of detecting dangerous materials entering the U.S. without setting off alarms for harmless material. This has lead to the heavy use of ^{3}He detectors.

^{3}He does not naturally form on earth and can only be produced from exposing lithium, boron, or nitrogen to neutron radiation. In each case the neutron interaction produces tritium, which then decays into ^{3}He with a 12.4 years half-life [14]. Therefore, the supply of ^{3}He may lag behind demand by a decade or more waiting for powerful neutron sources to be built and tritium to decay. ^{3}He is used for security purposes, ultra low temperature physics, missile testing, road construction, oil well mapping, and medical imaging [15]. 3He is also used in nuclear power plant monitoring and particle physics. These areas are suffering from a dearth of ^{3}He. Because the Department of Homeland Security is a federal agency, it is able to purchase ^{3}He supplies before other groups. Currently, this is considered an international crisis by the scientific community and has many scientists working to provide at least partial solutions to the problem [16].

Chapter 2

Cadmium Capture Gated Neutron Detector

2.1 Principles

Our cadmium capture-gated neutron detector is intended to partially fill the role of ^{3}He neutron detectors, thus allowing scientific research and national security to continue despite the ^{3}He shortage.

The detector consists of sheets of scintillating plastic stacked side by side with a thin sheet of cadmium between each sheet of plastic. Because cadmium is very non-reflective, each sheet of cadmium is encased in aluminized Mylar. The entire mass of scintillator is then encased in another layer of aluminized Mylar so that no light can escape the detector. Aluminized Mylar is a thin, tough plastic coated with a highly reflective layer of aluminum. A photomultiplier tube is then placed on one end.

When a neutron enters the plastic scintillator, the neutron will lose energy, striking protons and knocking them out of their molecules. The protons then lose energy to Coulomb scattering in the plastic and will excite electrons in the process. Eventually,

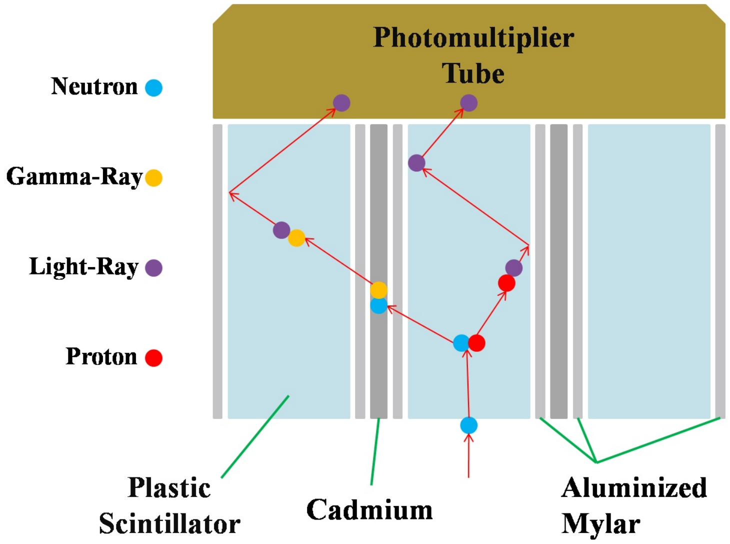

Figure 2.1 Cadmium capture-gated neutron detector schematic.

the energy is transferred to organic molecules in the plastic, as excited electrons in the plastic fall back to their ground states, which produces light. The light reflects around the inside of the detector until it reaches the photomultiplier tube and is detected as an electrical signal. After the neutron slows down, it may be captured in the cadmium. When this happens, 9 MeV of gamma rays are produced. Any number of gammas can be produced, but the average energy of each gamma ray is about 1 MeV. Those gammas can exit the cadmium in any direction, and some of them may be lost from the detector. Others gammas will Compton scatter, which excites electrons in the plastic and produces light that the photomultiplier tube will detect as a second signal [16]. We use this double pulse to differentiate neutrons in our detector from gamma rays.

To measure our neutron and gamma identification and discrimination properties, we will test the detector with radioactive ^{252}Cf, because it has a well-identified neutron and gamma spectrum. As prescribed by the Department of Energy, we will also test the detector with ^{137}Cs and ^{60}Co to determine gamma insensitivity [17]. We will know exactly what is entering the detector and will be able to record what is picked up by the detector, therefore determining its detection and discrimination efficiencies.

2.2 Plastic Scintillator Instructions

Our detector uses EJ-212 scintillating plastic, produced by Eljen Technology, because of its good scintillation properties and low cost compared to similar scintillating plastics. I have developed new methods for machining the EJ-212 because the method recommended by Eljen Technology often produced unsatisfactory results for our appliactions [18]. While machining the plastic, one must always remember that most scintillating plastics, including those produced by Eljen Technology, tend to have very low melting points. The melting point is 75^{o}C for EJ-212 [19].

EJ-212 comes in 12.25 inch by 12.25 inch by 10mm thick sheets. First, mark the sheets into rectangular sections appropriate to the size of the detector being built. Then, use a band saw to cut the plastic into individual rectangles. The recommended machining techniques of using a sharp band saw blade with four teeth per inch, moving at 1800 feet per minute works well [18]. The blade will always melt the plastic some; therefore, the plastic should be moved quickly through the blade to prevent excessive melting. Excessive melting can lead to material that was deposited on the band saw blade becoming embedded inside the plastic, deforming of the localized plastic surface, and potentially having the saw blade become stuck inside the plastic as the plastic quickly solidifies. Use a clean band saw blade to prevent material from becoming embedded in the plastic. According to Eljen Technology and my own experience, EJ-212 is also very susceptible to solvents and metal oils; therefore, only water should be used to cool or spay away particulates [18]. A miter saw would also work well because it makes long, straight cuts while leaving smooth edges. A sharp carbide blade should be used for a miter saw.

After cutting, use a four flute end mill with a 1500-2000 RPM rotation speed to mill each side. Either the end or side of the end mill gives good results. Mill each side at least twice, preferably four times, milling one direction and then the other and repeating for best results. Go very slowly with each pass to prevent deep groves from forming in the plastic. The surface should look cloudy, but be smooth enough that no grooves or scratches can be felt by hand. Milling with a two flute end mill, with lower RPMs, and moving the plastic quickly, as Eljen Technology recommends [18], will give initially good optical results, but the plastic will be full of deep grooves that will significantly increase the time required to polish because the plastic must be polished down as deep as the groves.

From this point on, wear cotton gloves to prevent your hand from leaving oil on the plastic. Latex gloves should not be used as they can leave streaks of material on the plastic.

Polishing should be done with either a polishing wheel made for plastic or gentle use of a polishing wheel made for metals. Two out of the three polishing wheels I tried that were made for metals left excessive damage, despite careful and gentle use. A polishing wheel designed for plastics is preferred. Either a metal polishing agent or plastic polishing agent will produce adequate optical results in the plastic, but the metal polishing agent will leave black residue that will take more effort to clean off than the plastic polishing agent.

To produce an even finish across the whole surface, move the plastic across the polishing wheel slowly. Never hold the plastic in the same spot for more than approximately a second or two. Move the plastic back and forth many times length-wise across the polishing wheel until the desired optical quality is achieved. Some smaller spots on the plastic may require additional polishing to produce adequate optical quality.

Figure 2.2 Finished scintillating plastic cylinder in front of a picture.

Most important, be very gentle while pushing the plastic against the polishing wheel, remembering that the plastic has a low melting temperature. If the plastic does melt in a section, it can take a very long time to polish out the damage, especially since polishing agent and burnt plastic will likely have been deposited beneath the surface of the plastic. It is often easiest to re-mill the damaged side and start the polishing process over. If the damage is very light, then a small blade can be used to dig out any particulates embedded beneath the surface of the plastic, and polishing can resume with the damaged spot requiring only a small amount of extra polishing time. After polishing with a wheel, use an abrasive cloth or 1000 grit sand paper. Go back and forth between the polishing wheel and the abrasive paper until a flawless finish is achieved. A good polish should look at least as clear as Fig. 2.2).

After polishing, hand-wash each piece of plastic with water and mild soap, such as hand soap. While washing, scrub the plastic with a very low abrasive material, such

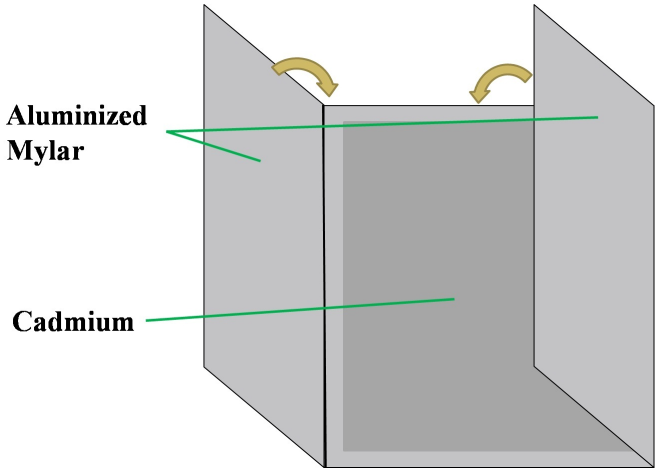

Figure 2.3 Aluminized Mylar folded around cadmium.

as cheese cloth, to prevent the plastic from being scratched during scrubbing. Be sure to clean away as much polishing agent and dust as possible. It will be difficult to remove polishing agent from any grooves that may remain if the plastic was milled too quickly. Dry the plastic with a fabric or paper that will not leave materials on the plastic. Avoid air drying because of the potential for drying spots to form on the plastic. Distilled water may be better than tap water, but is not required.

2.3 Cadmium Foil and Mylar Instructions

When handling cadmium you should always wear gloves, since cadmium is a toxic metal. Mark and cut the cadmium foil to fill the spaces between the pieces of plastic. Cadmium foil can effectively be cut with anything capable of cutting heavy paper. A paper cutter works well because it ensures a straight edge and generally comes equipped with a ruler.

When handling aluminized Mylar, you should wear cotton gloves to prevent leaving marks on the Mylar. Mark and cut the aluminized Mylar into pieces to fit around each piece of cadmium with a little overlap. Tape the Mylar around the cadmium

Figure 2.4 Cadmium foil after being cut.

ensuring that none of the cadmium can be seen. Double-sided tape works well for this because none of the tape can been seen. Cut off any extra Mylar that may be hanging over the top and bottom of the cadmium. When the cadmium and Mylar are finished they should look similar to Fig. 2.3) and Fig. 2.6).

2.4 Assembly Instructions

Arrange the plastic with the appropriate size of cadmium between each sheet of plastic. Although any geometry can be used, I used a cylindrical design. When the plastic and cadmium are all together and look cylindrical, measure and cut a long section of aluminized Mylar to wrap and tape around the cylinder. The long section should hang over the top by about to inch. Cut the parts that hang over every to 1 inch. These flaps will ensure that light cannot leave the detector through the edges they cover. For an example for what these flaps should look like, see the top of the detector in Fig. 2.7). Cut and tape a circle of Mylar onto the bottom of the cylinder. Tightly wrap tape around the cylinder to keep the plastic and cadmium from shifting.

Figure 2.5 Aluminized Mylar after being cut.

Figure 2.6 Cadmium with aluminized Mylar taped around it.

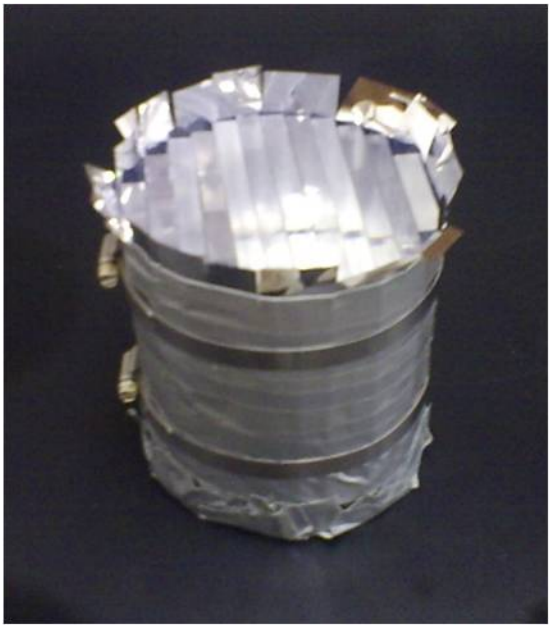

Figure 2.7 Finished detector cylinder.

Duct tape works well for this.

Attach two hose clamps around the cylinder to ensure no future shifting of components; the clamps should be equally spaced with each other and the top and bottom of the cylinder. Tighten the hose clamps snugly, but not too tightly since the plastic is fragile and may develop small cracks. Hose clamps are only appropriate for approximately cylindrical geometries. The finished cylinder should look similar to the one in Fig. 2.7).

Apply optical grease to the top of the cylinder, and then place the photomultiplier on top of the cylinder. Tape the photomultiplier and cylinder together. Do not use duct tape, since duct tape can leave a potentially troublesome residue if the photomultiplier tube and cylinder are ever separated; electrical tape is a better choice. Use enough tape to ensure the photomultiplier and cylinder are tightly connected. The finished detector should look similar to the one in Fig. 2.8).

The detector is now ready to be placed in a light-proof canister. With the appro-

Figure 2.8 Finished cadmium capture-gated neutron detector.

priate power supply, digitizer, computer, and programs, the detector is now ready to begin collecting data.

Chapter 3

Results

3.1 Data Collected

My research group and I have tested the cadmium capture-gated neutron detector by placing a ^{252}Cf source about 18 inches from the face of the detector. Some of these results are included in Fig. 3.1) and Fig. 3.2). The x-axis is in units of 10 ns per channel, and the y-axis is in arbitrary units of energy. In Fig. 3.1) the time between peaks is about 1s, and the energy of the second peak is usually a few MeV.

Because the neutron capture gives off 9 MeV of energy, we plotted the energy of the first and second pulse areas together of many double pulses in Fig. 3.3). From this, we compared the pulse area distribution of first pulses to second pulses. The time between the first and second pulses of a double pulse can be seen in Fig. 3.4). This indicates that most capture pulses will occur within a certain time of the trigger pulse.

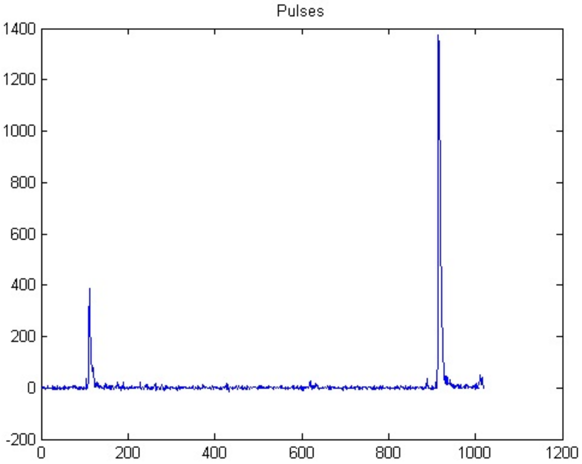

Figure 3.1 Double pulse indicating a probable neutron capture.

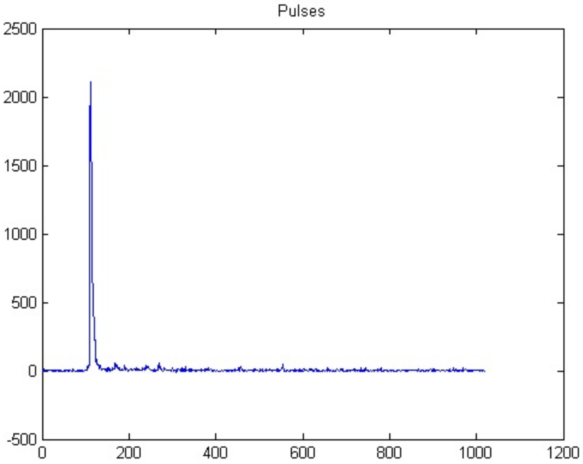

Figure 3.2 Single pulse indicates either a gamma or neutron that failed to capture.

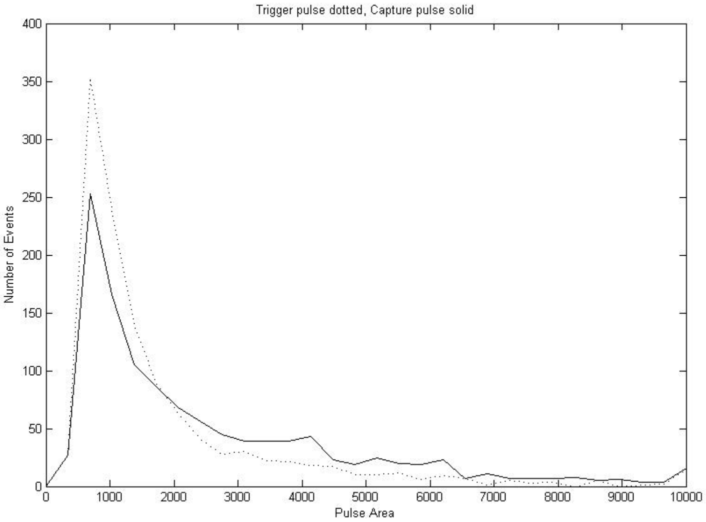

Figure 3.3 Trigger and capture pulse areas distribution.

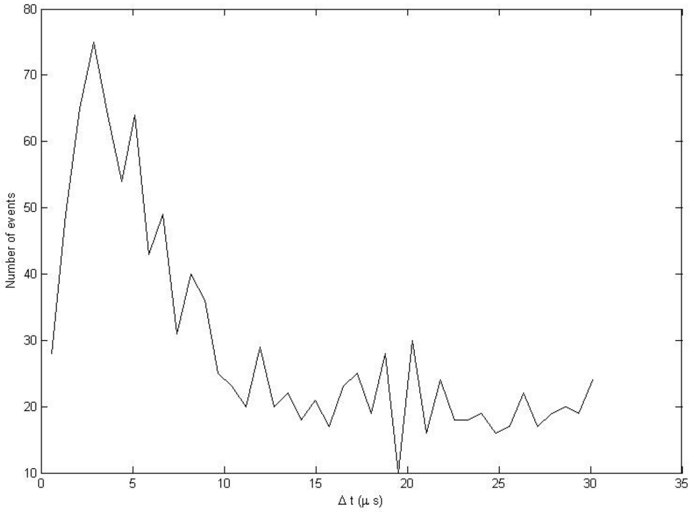

Figure 3.4 Time between the first and second pulses in a double pulse.

3.2 Analysis

For analyzing energy pulses, it is better to calculate the energy from the area under the pulse rather than by simply measuring the height. This is particularly important for research that gives broad pulses, where only taking the single highest part of a pulse could lead to deceiving energy results.

For a double pulse, there is no way of knowing if it was produced from a neutron capture, two gammas in rapid succession, or one gamma and one neutron that failed to capture. However, knowing that a neutron capture produces 9 MeV of gamma rays means that for a neutron capture, we will often have a large second pulse. Some of these gamma rays may escape the detector without ever producing a signal, so the capture pulse is not always large. However, we see in the pulse spectrum graph that the second pulse is often larger than the first pulse except for an anomalous area on the extreme left side of the graph. This indicates that we are detecting authentic neutrons for many of our double pulses. However the long tale of Fig. 3.4) supports that some pulses may be random coincidences, as we would expect true capture events to become fewer in the course of time.

The second program we used has only been able to analyze a few hundred double pulses so far, so any conclusions drawn from it will require future testing to verify. Using the second program, we can see in Fig. 3.3) that the capture pulse tends to be larger than the trigger pulse. This is consistently true if you demand the same minimum height from trigger and capture pulses.

From Fig. 3.4) we can see that the majority of second pulses occur within 7 μs to 12 μs of the first pulse. This can be used in future programs to set a cutoff time above which it cannot be safely assumed that a double pulse was from an authentic neutron capture. This will help us to eliminate some coincidental double pulses. However, we do need to decrease the accidental coincidence rate for the detector to be useful. One way of doing this is to increase the gain size of the detector so a larger fraction of the energy from the capture signal is detected. We plan on making a larger detector in the near future with more photo tubes.

For any given single or double pulse, it is impossible to know for certain what caused the event. However, by comparing large numbers of results to known gamma and neutron spectrums (such as from ^{252}Cf), we will be able to determine what percentage of the neutrons and gammas we are detecting. This will allow us to determine both the neuron detection efficiency and the gamma rejection efficiency of our detector.

Chapter 4

Conclusion

4.1 Summary

We are pleased to have finished a prototype neutron detector that shows promising results in neutron detection and gamma discrimination while still being simple to construct and operate. It appears that our cadmium capture-gated neutron detector will be able to fill of some of the current roles of ^{3}He. Specifically, our detector will be able to fill roles where neutron/gamma energies must be measured, and where researchers wish to discriminate between neutrons and gammas. This has potential applications in national security, particle physics research, oil well mapping, mineral mapping for construction, and nuclear power plant monitoring.

4.2 Future Research

Future research for this detector will include refining our program, optimizing the geometries of our materials, and testing detection efficiency. We will refine our program to better discriminate between single and double pulses, and to identify and disregard anomalous signals such as those from cosmic rays and triple pulses. We will also use Monte Carlo simulations to find optimal dimensions for the scintillating plastic and cadmium for maximizing neutron detection. We will also continue to compare our results to known radiation spectra to determine our detection efficiency.

We will be able to increase our gamma rejection efficiency by modifying our program according to data received already. We know that neutrons capture pulses have an absolute maximum to their area; therefore we can safely reject any doubles that have second pulses greater than the maximum. We can also see that the majority of second pulses come within about 10 μs of the first pulse, which can be used to reject double pulses that have second pulses that do not follow closely enough behind the first pulse to safely assume neutron capture.

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