A GEANT Simulation of the Neutron Wall Detector

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The goal of my REU project this summer has been to create a working simulation of the Neutron Wall Array. The Neutron Wall is a large array of 25 detector cells containing the liquid scintillator NE213. These individual detectors are position sensitive and have the capability to discriminate between neutron and gamma signals. In the experiment there are two Neutron Walls, each with an area of $2x2m^2$ each. The reason for using 2 walls of this large size is to obtain a large solid angle too compensate for the poor efficiency of neutron detectors. While charged particle detectors may have efficiencies of 100%, typical neutron detector efficiency is 10%, and a much lower number if it is necessary to detect two neutrons in coincidence [ref 1]. So, increasing the solid angle will cut down on the amount of beam time required to gather enough data. Over the course of the summer I have worked on producing an accurate simulation of this experiment in order to better understand the data from the real experiment. I have done this using a complicated C++ program, GEANT4, which is a powerful program that can account for many physics processes and can output many kinds of useful information. Upon completion of my work this summer I will have obtained simulated results on efficiency calculations and a response function for neutron energy, and I will leave the experimenters with a working simulation with which to continue using as needed for further analysis.

My project consisted of two parts. Before running simulations for the Neutron Wall itself, I had to be sure that the GEANT program was running correctly and accurately describing the physical processes involved in neutron detection. To do this I had to first simulate a detector whose efficiency and other properties had already been documented in a published research paper. For this “test” detector, I used the position-sensitive neutron detector (PSND) described in Reference 2. This detector consisted of a 1m long quartz tube of diameter 5.5cm filled with the liquid scintillator NE213. This detector was a good starting place because its geometry is similar to the individual detectors in the Neutron Wall, and it used the same scintillator.

The benefit of using this liquid scintillator is that it allows for pulse shape discrimination between neutron and electron interactions above 1MeV. This is because in the scintillator, neutrons and electrons deposit energy and create photons in a different manner. An electron will deposit its energy by a process known as Compton scattering. In this process a gamma will enter the scintillator and scatter off an electron. The photon will have transferred some amount of energy to the electron, depending on the angle of scattering, which creates more photons in the liquid that travel through the detector to the photomultiplier tubes at the ends of the detector. A neutron, however, deposits its energy by scattering an atom’s nucleus, which in the case of NE213 would be a proton (hydrogen nucleus) or a carbon nucleus. This kind of reaction produces delayed photons in the scintillator, and that take a longer time to reach the end of the tube. Therefore an analysis of the time it takes for the photons to reach the end of the tube vs. energy deposited will show a different shape for photons and neutrons, as can be seen in Fig. 2, which shows simulated data that I produced a little later in the project. The figure shows a longer tail for neutron pulse shape. The fact that I was able to reproduce this difference in my simulation was a good indicator that I was on the right track.

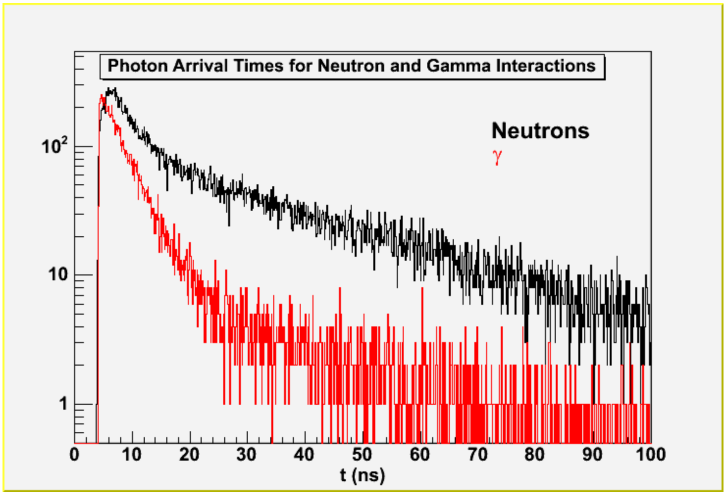


Fig. 2

After I had finished specifying the geometry of the detector, I first tested it to make sure the simulation would run. To start with I set up the program to shoot a beam of mono-energetic photons at the detectors center. The detector was oriented such that the beam axis, being the z-axis, was normal to the length of the tube. This simply means I simulated a specified number of photons with one given energy and sent them in the direction of the detector to see how they would interact. Once this process was working properly I had to do the same thing for neutrons. In GEANT, neutrons are probably the most difficult particle to simulate. This is because they are uncharged particles and many physical processes must be incorporated into the code to make sure they interact realistically.

The GEANT program is equipped with a particle “tracker” which is able to follow the processes involved in a particle interaction step by step. The tracker can tell me what part of my simulated space the particle is in, and what processes it undergoes at each step. This allowed for an initial analysis of the code by which I was able to verify that the particles I simulated were acting realistically in the detector. When I was sure that the process were running the way they were supposed to, it was time to run some rudimentary simulations to see if I could get some results for the detector that were close to what had been written in the PSND paper, and that were excepted properties of the scintillator. The first quantity that was determined was the detectors efficiency, which was also one of the main results I was hoping to produce for the Neutron Wall itself. The detectors efficiency is defined simply as the likelihood that a particle shot at the detector will interact. This quantity was relatively easily to get with my simulation. I set up the program to write out the energy deposited by a particle to a file, if the energy was greater than zero. The total number of points recorded was my number of hits, and I could divide this number by the total number of particles I shot at the detector to get a percent efficiency. In this manner I was able to make plots showing the efficiency versus particle energy and versus horizontal position at which the particles hit the detector, as shown below. The graph showing efficiency versus energy has a curve for a simulation with and without a threshold, a property I will explain later. The results that I produced were somewhat similar to what was in the paper, but I still had more work to do to refine the detector.

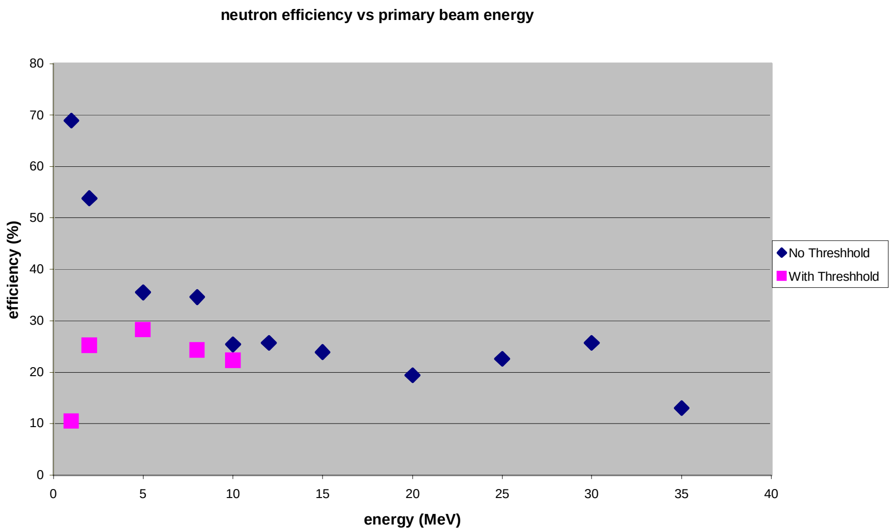


Fig 3

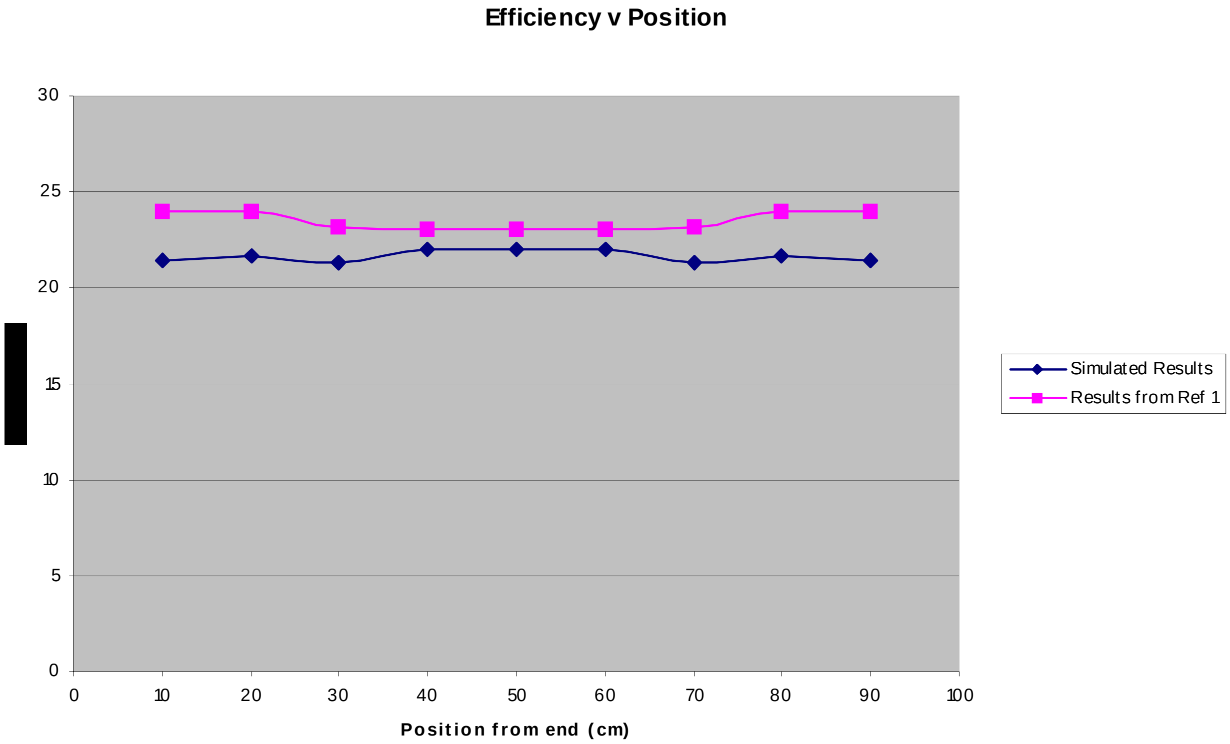


Fig 4

After initial simulations were run, I simulated the scintillation process. Moving to this step required adding photomultiplier tubes (PMTs) to either end of the detector. With this set up, particles interacting in the detector produced photons as described above. These photons traveled in both directions down the tube to the photomultipliers. Photons reaching the PMTs would then produce photoelectrons. In an actual experiment, the light output of these electrons is what is measured when a neutron deposits its energy in the detector. The number of electrons produced in the PMTs could be related to the amount of energy the original particle deposited. The number of photons produced is directly related to the energy deposited, and the number of photons that reach the PMT relates to the number of photoelectrons produced, through a quantity called the quantum efficiency. The quantum efficiency of my detector was set to 20%, which means that roughly 20% of the photons reaching the PMTs would create a photoelectron.

By setting up the scintillation process and the PMTs I was able to set the very important threshold parameter. The threshold in this case was a minimum energy deposited that would be read by the detector. In an actual experiment this quantity is able to be set by the experimenter and is a property of the detector electronics. This lets the experimenter focus on a certain energy range and may eliminate incorrect data from events, which produce too little energy. In my code I was able to set this by setting a minimum number of photoelectrons produced in each PMT. If the number of electrons produced was greater than this threshold number, the event was recorded into the output file. At this point, the output file I was writing too included the particles initial energy, the deposited energy, and the number of photons and electrons produced.

The threshold can have a large effect on the efficiency. As can be seen from fig.3. The curve relating efficiency to energy deposited changes drastically at low energies when a threshold is added to the simulation. One problem I had in matching the results from the PSND paper was that I was unsure of the threshold used in that particular experiment. However, this was not too much of a concern because my results were close enough to those in the paper, and I knew the threshold used in the neutron wall experiment.

Another interesting and useful bit of information I needed to get was a neutron energy response function. This response function is a curve fitting neutron energies to electron equivalent energies. In an actual experiment, the quantity measured for neutron energy deposited is the light output. So what a response function does is show what photon energy produces the same light output as a given neutron energy. This graph was somewhat complicated to extract from the data. First I fit a parabolic curve to graphs relating energy deposited to number of photoelectrons produced for neutrons and gammas. Then from the neutron function, I chose a number of points along the graph, and plugged the number of electrons into the photon function to see which photon energy values the neutron energies corresponded too. I was then able to fit another curve to these points to produce a response function. I was reassured to find out that my response function matched the accepted response function for NE213 relatively well, especially for higher energies.

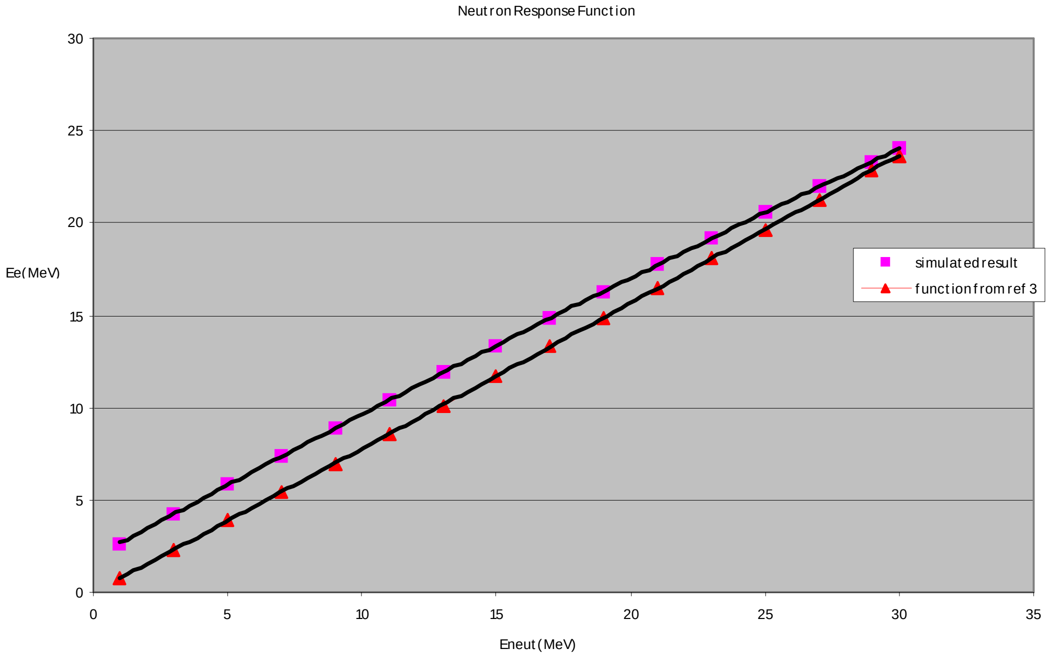
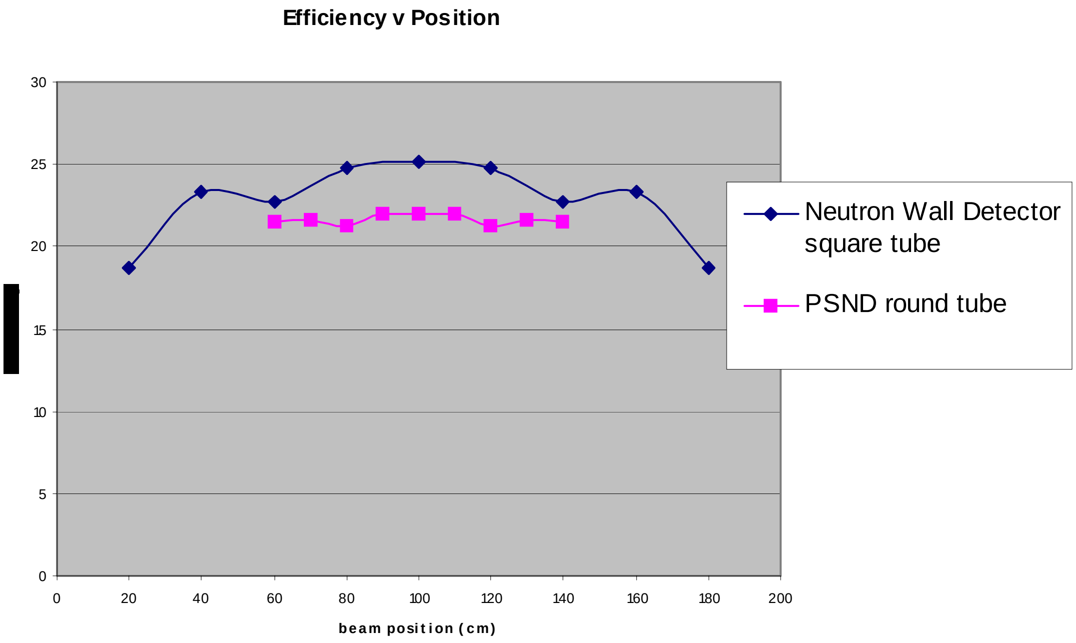


Fig. 5

With my simulated results matching fairly well with documented results, I was ready to change the detector geometry over to that of the neutron wall detector. The individual detectors were similar to the PSND that I had already simulated. The only differences being that now I used square tubes rather then cylindrical tubes, and now the tubes were 2 meters long. The cross sectional area of the detectors was 7.02cm by 5.75cm of NE213 inside a 3mm thick pyrex tube. My initial results for this new, single detector were similar to what I had obtained with the round tube. However with the longer tube, the efficiency seemed to drop much more at the ends of the tubes. This is expected due to the fact that much of the light produced at one end of the tube would be attenuated and not reach the PMT at the other end, and thus a hit would not be recorded (See Fig 6 Below).



Satisfied with the results of one tube, I replicated the single detector and placed 25 copies of it, stacked vertically with 3mm separating each tube. Then with the addition of an aluminum cover to the front and back of the array of detectors, the Neutron Wall geometry was complete. Below is a picture of the Neutron Wall as constructed in my GEANT code.

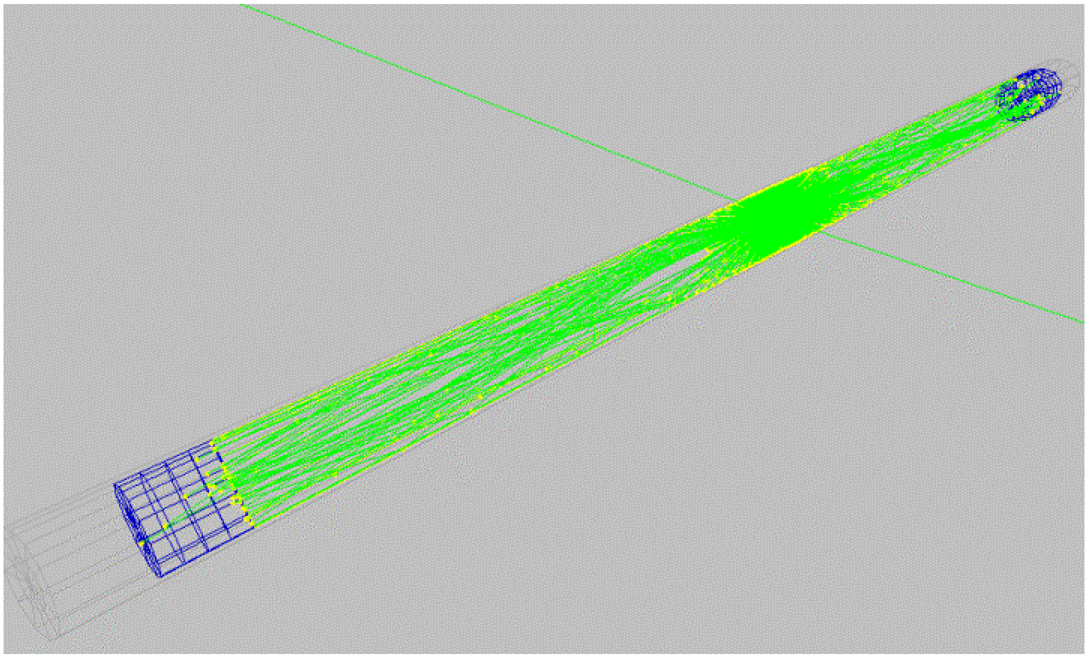


Fig 7

When working with the entire neutron wall array, another factor comes into play for the efficiency, the geometric efficiency. For one detector, the efficiency is calculated for particles that are known to enter the detector. When dealing with the whole array, I simulated particles to hit the wall at a random x and y position. Now, there is no guarantee that a particle shot at the wall will enter into any detector. The spacing between the detectors and the thickness of the pyrex glass make for about a 1cm gap between the scintillator areas in each detector. When this is compared to the vertical thickness of 7.02cm of NE213 in the detector, it is easy to see that a number of particles will pass through the neutron wall without hitting any scintillating liquid.

Finding the overall efficiency for the neutron wall array was essentially the ending point of my project. However, the GEANT code with I created is a complete simulation of the actual neutron detector array, which will have continuing value for the experimenters I worked with. GEANT's setup allows for quick and easy changes to the code to modify any parameter of the detector, and it is capable of producing a number of different kinds of results. Therefore, the cod I produced will can be adapted and refined as needed to get further information about neutron wall as needed. For this reason, I feel the code itself will prove to be more valuable than just the information that I produced with it over the course of the summer.

References

1. .Galonsky et al, "A large-area, position sensitive neutron detector with neutron/gamma-ray discrimination capabilities", A.Galonsky et al, Nucl. Instr. & Meth., 401, 329-344 (1997)
2. D.N.Vakhtin et al, "Position-sensitive neutron detector", D.N.Vakhtin et al, Nucl. Instr. & Meth., 477, 372-377 (2002)
3. R.A. Cecil et al, "Improved Predictions of Neutron Detection Efficiency for Hydrocarbon Scintillators from 1MeV – to about 300MeV", Nucl. Instr. & Meth. 161, 439-447 (1979).