NaI Detector and Photo-multiplier Tubes

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Abstract

A NaI Compton suppression system was developed to eliminate the background caused by Compton scattering in a HPGe detector. Simulations are complete and now it is time to test the components of the NaI(Tl) detector and construct the dual counter system.

1. Introduction

1.1. NAA and LZ

The Neutron Activation Analysis project (NAA) started with the goal of improving the amounts of uranium, thorium, and potassium in titanium metal next-generation extremely low background experiments, such as the LZ experiment. LZ is the second-generation dark matter detector which will be replacing the LUX detector.

Neutron activation analysis is done by exposing a sample, such as Ti to a neutron source, such as a nuclear reactor core, which activates the impurities of U, Th, and K. After exposure, counting the sample allows for the assessment of the impurity of the Ti up to parts per billion. To count the sample we use the HPGe detector to detect gamma rays released by the impurities in the titanium. This is important because these impurities in the titanium can lead to false events in LZ.

1.2. Background

1.2.1. Scintillators and PMT's

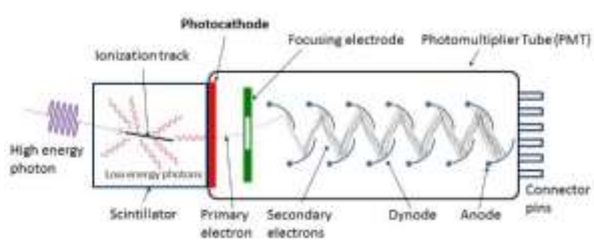

Figure 1: Schematic of a photo-multiplier tube.

Scintillation is when a charged particle, like an electron, goes through a material and excites the atoms inside the material which then release photons, which you can collect with a photo-multiplier tube (PMT). The number of low energy photons released is proportional to the amount of energy deposited from the initial charged particle [1]. This is illustrated in Figure 1.

PMT's come in many shapes and sizes and are extremely sensitive to light. They are used with a scintillator in order to detect single or small numbers of photons. The PMT gives out a pulse proportional to the number of photons hitting it.

When a scintillator emits low energy photons, they pass through the photocathode, which then releases an electron into the PMT body, where there is an electric field. In order to create this electric field inside the PMT, they are powered by a HV (high voltage) machine. This single electron travels to a “leaf” in the PMT which is hit by the electron after it gains velocity from the electric field, which then causes the leaf to release more electrons. This pattern repeats with the number of electrons increasing as they cascade leaf by leaf through the PMT. At the end of this process the PMT releases a voltage pulse which we can then analyze.

1.2.2. Gamma Ray Interactions

There are three types of gamma ray interactions: photoelectric effect, Compton scattering, and pair production. The photoelectric effect is when a gamma ray photon comes in to a material and gives all of its energy to an electron. This is a full deposition of its energy. Compton scattering occurs when a photon comes in and only gives part of its energy (a partial deposition) to an electron and then continues on now at a lower energy level where it can either continue to Compton scatter additional times or terminate with the photoelectric effect. Pair production is a gamma ray that turns into an electron-positron pair; this process is completely out of the energy range for this project.

For the energy range that is important to this research project Compton scattering is the most significant. All these processes give off electrons and one way to detect the processes is by scintillation.

1.3. Gamma Ray Detectors

1.3.1. HPGe Detector

The high purity Germanium detector (HPGe) is a p-type semiconductor, extremely accurate gamma-ray counter with active and passive shielding and came with electronics and software from ORTEC. It is protected by four inch lead shielding with a copper lining and is cryogenic, requiring liquid nitrogen cooling [3].

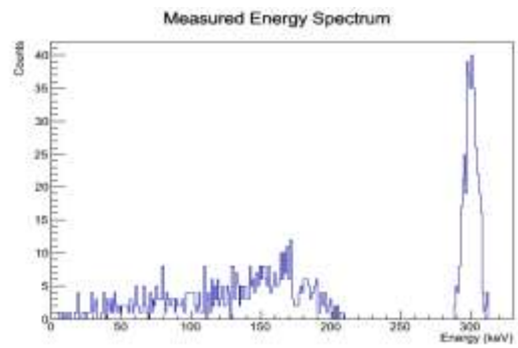

Image courtesy of Richard Ott

Figure 2: Simulated Spectrum given from partial energy deposition (left) and full energy deposition (right) of a photon.

The HPGe detector is used in the NAA project to count an activated Ti sample in order to assess its impurity. This detector works great, but has a substantial flaw which arises when Compton scattering occurs and the gamma ray does not terminate inside the crystal and escapes. In Figure 2 above, the peak on the right shows an example of a full energy deposition of a photon, while the background shown on the left illustrates a partial deposition of the photons energy resulting after a Compton scatter when the gamma ray escapes.

1.3.2. Compton Suppression System

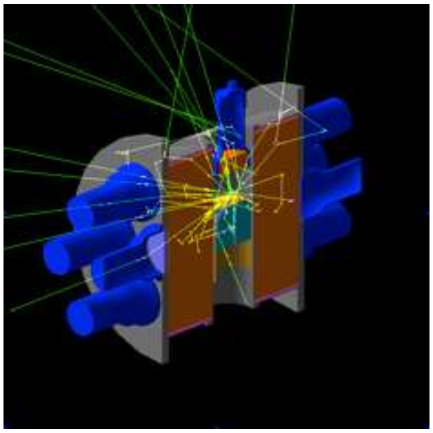

Image courtesy of Josh Frye (NSSC alumnus)
Figure 3: CAD simulation of NaI Detector.

A Compton suppression system was developed in order to reduce the Compton background in the spectrum. This was accomplished with a large NaI(Tl) crystal scintillator and an array of PMT's (Figure 3 above). The NaI detector has poorer energy resolution than the HPGe detector, and was therefore designed to surround the HPGe detector [3]. The detectors then will be synchronized and if a photon is detected in the outer detector, the event is marked in the inner detector. Simulations show a reduction of Compton background by roughly a factor of 10.

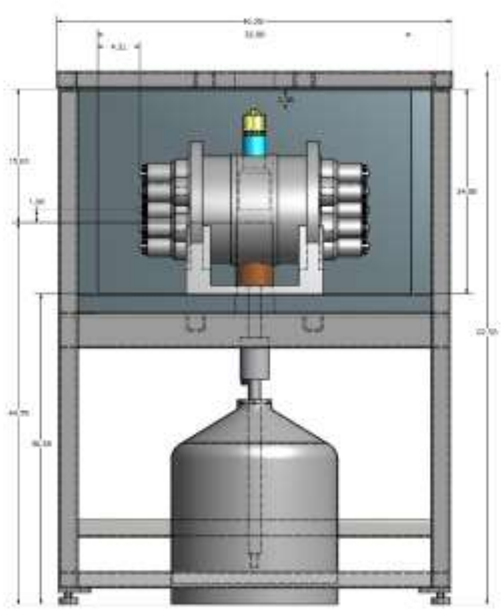

Diagram curtesy of Dave Hemer
Figure 4: Diagram of dual detector integration.

In order to integrate these two detectors a new design was implemented to expand the lead shield around both detectors elevated above the liquid nitrogen dewar, illustrated in Figure 4. The integration also requires replacing the electronics and software to integrate the HPGe and NaI(Tl) signal (work of graduate student James Morad).

2. PMT Discussion

2.1. Procedures

2.1.1. PMT's and PMT Bases

Image curtesy of Ray Gerhard
Figure 5: Images of PMT Base.

The NaI(Tl) detector came with fourteen PMT's, for an array of seven to each side, and 3 bases which we knew nearly nothing about. Due to the lack of bases our electrical engineer, Ray Gerhard, made new bases for all the PMT's which are sleeker and more versatile (Figure 5 above). This left a series of questions that I needed to answer:

Do the PMT's work at all?
Do they output useful signals?
Will the PMT's work with Ray's new bases?
Will they detect single photon events?
Do they each need to be calibrated individually?

2.1.2. Trials and Errors

By observation it was clear that two PMT's were clearly broken and would need to be replaced, however the other 12 visually looked like they were in decent condition. Initially the voltage range these PMT's operated under, let alone the optimal voltage, was unknown. We quickly discovered that these PMT's are very old which delayed our finding the operating range that they would function at safely.

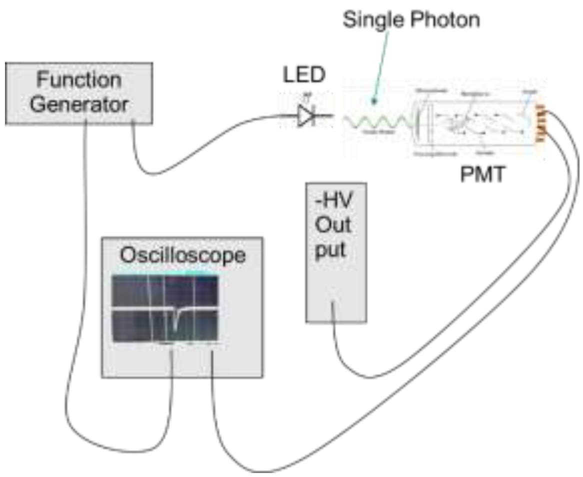

Figure 6: Schematic of PMT test setup.

To test the PMT's we connected a pulse generator to a LED and set the LED to a very dim setting where we could still see it in the dark room, in order to be sure it was outputting photons. Then I wired a PMT to a base that came with them and through that base to a high voltage power supply. Both the PMT base and the LED were then connected to an oscilloscope. Using this base that came with the PMT's I ran a series of tests triggering off the LED on each PMT at different voltage ranges from 1200V – 1500V to make sure they all emitted a pulse. This confirmed that each PMT worked, however there was a lot of noise in the system.

At this point we were able to obtain a better oscilloscope, a function generator to replace the pulse generator, and a much less noisy HV machine, creating the setup in the diagram shown in Figure 6 above. We also discovered that the PMT's could handle up to about 1850V, so we expanded the data collection to range from 1200V – 1800V in 50V increments. I then tested each PMT with the new equipment, method, and Ray's bases to confirm that the PMT's worked with the new bases.

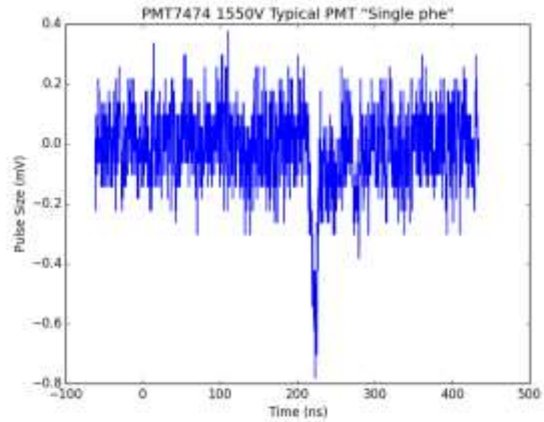

Figure 7: Single pulse from PMT detecting single photon event.

After confirming that the PMT's worked with the new hardware I lowered the LED's settings from the function generator to confirm if the PMT's could detect single photon events. To try and ensure that the LED was emitting single photons we set the LED at a low enough setting that we were only getting pulses from the PMT every 10-20 frames at a middle setting of 1550V for the PMT, not triggering directly off the function generator and LED anymore (illustrated in Figure 7 above). I collected 2000 frames at each voltage increment, and an additional 10,000 frames at certain midrange voltages such as 1550V.

2.2. Results and Analysis

2.2.1. PMT Characteristics

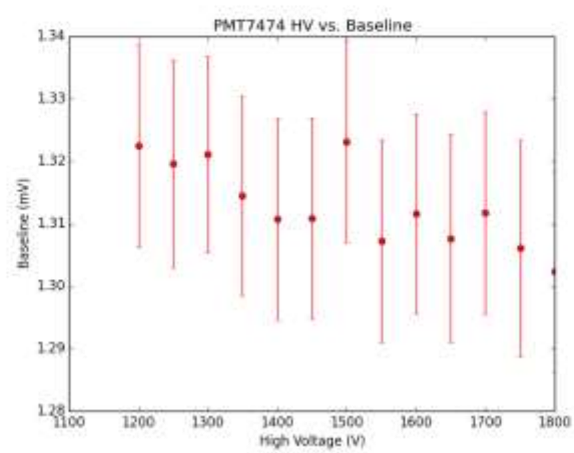

Figure 8: Graph of Baseline of PMT with error bars.

In Figure 8 above, the plot shows the baseline of a PMT with error bars for one of the PMT's with respect to the high voltage setting. The baseline is a DC offset in the signal that needs to be removed. From the very small scale for the baseline it is apparent that it does not differ much as the voltage is increased. This shows that the PMT is stable at these voltage ranges which is crucial for accurate measurements of single phe. A single phe is a single photo-electron. It is ejected into the body of the PMT from the photocathode interacting with a photon emitted from the scintillator.

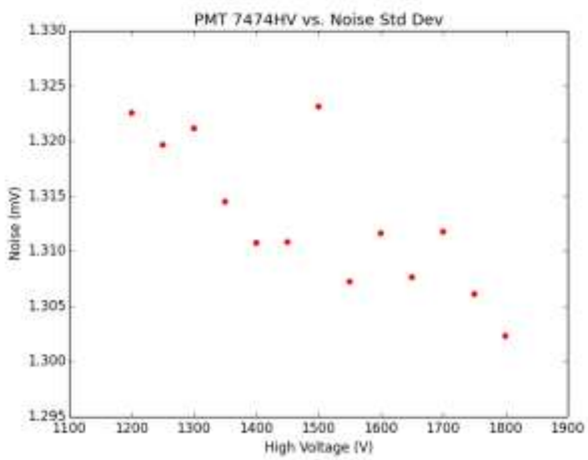

Figure 9: Plot of standard deviation of noise from PMT.

Figure 9 is a plot of the standard deviation of the noise from the same PMT as in Figure 7 and 8. In this plot the scale for the noise is very small, illustrating how the noise does not differ much and is very consistent throughout the different voltage ranges, further illustrating how the PMT is stable. I made plots like Figure 7, 8, and 9 using the programming language Python and the data collected for each of the 12 working PMT's and they all had similar results.

2.2.2. PMT Calibration

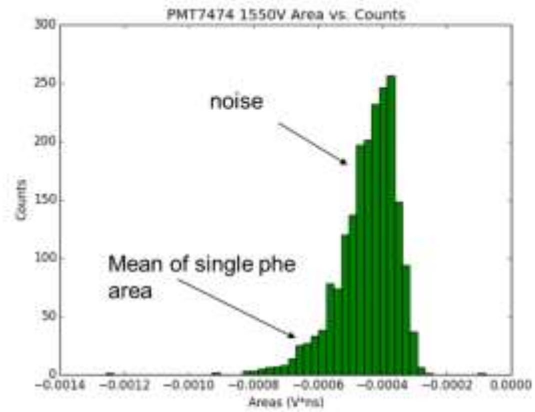

Figure 10: Histogram of the area of PMT pulses and counts.

Figure 10 is a histogram plot of the area of the PMT pulses and counts. It contains two different peaks, however the important peak, the mean of the single phe area, is on the left and is being drowned out by the noise on the right. This histogram shows that a preamp is necessary in order to bring out the values we want from the noise (no preamp was originally available, so this confirms it as a necessity).

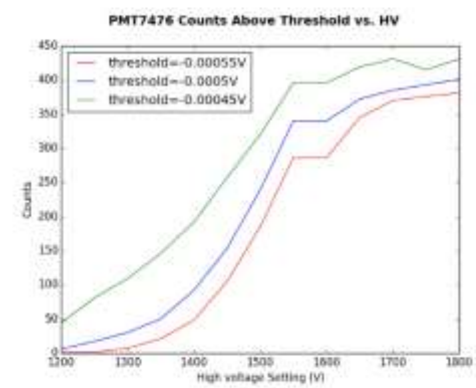

Figure 11: Plot of Counts above threshold vs HV.

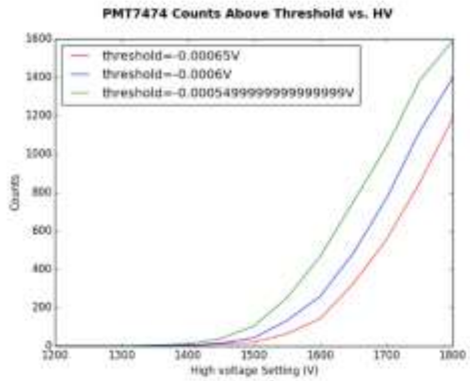

Figure 12: Plot of counts above threshold vs HV.

In addition to needing to know the mean of single phe area to properly calibrate the system for the PMT's, it is also necessary to know where to set the threshold for the PMT pulse in order to detect single photons from the NaI scintillator. Figure 11 and 12 are plots of the high voltage setting and the single phe counts using different thresholds. Figure 11 is a plot of what we would like to see with a threshold, with the plateau in the midrange for this PMT, while Figure 12 is an example of what we do not want to see in our threshold plots with no plateau, showing that threshold to be incorrect.

From this data, for this PMT specifically, a smaller increment of data collection may be needed, such as with 5V increments, between 1550V and 1600V in order to better calibrate the PMT and find its optimal operating range more accurately. The findings were similar for the other PMT's.

3. Assembly and Construction

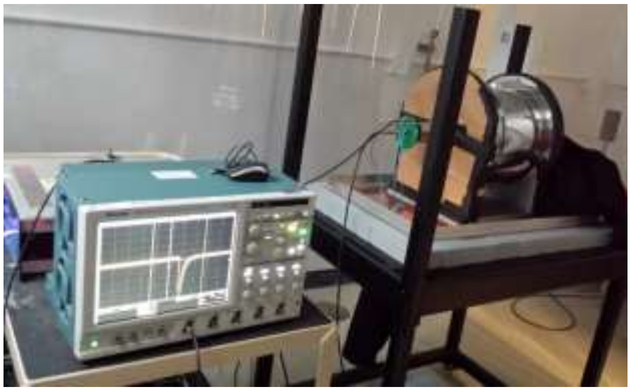

Figure 13: Image of testing NaI scintillator with PMT and oscilloscope.

In addition to obtaining and analyzing data from the PMT's I have put a lot of work this summer into the physical construction of the NaI project. I helped assess, reshape, and coat the lead bricks for the expanded shielding for the comb-ined detectors and assisted in assembling parts together. I also helped test the NaI(Tl) scintillator during construction to con-firm that the crystal was outputting photons, illustrated in Figure 13.

4. Conclusion

In summary for the PMT's 12 of the 14 work and react to single phe's, the other two do not work at all and must be replaced to continue with the 14 PMT design. We also know that a preamp should be used to better clarify the pulses from the noise. Now we have a greater idea of what the proper operating voltage for these PMT's are, as well as a better idea of what an appropriate setting for the threshold can be in the data analysis when integrating the NaI(Tl) PMT data with the HPGe Data. Ultimately the PMT's are about ready to go with just a little tweaking left to do.

In the near future the goals of this project are to finish construction of the new expanded dual detector system, synchronizing the NaI detector with the HPGe detector through a DAQ, and then integrating the new electronics and software.

5. Acknowledgements

I would like to acknowledge Mani Tripathi for allowing me to assist in his project group this summer and Richard Ott for his invaluable assistance and guidance throughout my whole project. I would also like to thank Rena Zieve for organizing the whole REU experience at UC Davis and the NSF for funding the REU program.

References

[1] Knoll, Glenn F. *Radiation Detection and Measurement, 3rd ed*. New York. 2000. Print.

[2] M. Fechner. arXiv:1101.4000 [physics.ins-det].

[3] Ott, R. A. "A Compton Suppressed Gamma-Ray Counting System for Radio-Assay of Materials". UITI 2014. Walnut Creek, CA. June 4, 2014.