# Angular Dependence of Compton Scattering Within Plastic Scintillators As a Way to Calibrate a Detector

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## Abstract

In recent years the study of neutrinos has been very prevalent in particle physics. They are challenging to detect, so many teams have created more extensive and accurate detectors. NuLat is one of these projects, made of 125 plastic scintillator cubes. Here, four optically isolated scintillators are connected to photomultiplier tubes (PMTs). We are using these detectors to observe the gamma rays associated with the decay of Na-22. There are two main ways in which we designed this experiment to reduce noise and see precisely what we are looking for. Firstly, we chose Na-22 because it is a positron emitter; it goes through beta-plus decay and emits two 511 keV gamma rays, which we will collect on either side of the source. Those gamma rays are spatially correlated, so we can be confident we see the 1275 keV gamma ray (a 1275) where we want to. Secondly, those are put in coincidence with the 1275 that will Compton scatter from one scintillator to another. The coincidence between all four detectors allows us to reduce counted events to primarily those that involve only the gamma rays produced in the decay of Na-22 while also giving us the advantage of knowing where each gamma ray goes. We will also create many different geometric arrangements of the scintillators, allowing us to observe the energy and rate of events for various angles of Compton scattering. We will use what we learn here to help us calibrate each cube in the NuLat detector much more easily.

## Introduction

Neutrinos and their detection have been a prominent topic in the physics research community. These extraordinarily light and neutral-charged particles are not easy to detect. Wolfgang Pauli theorized the existence of the neutrino in the year 1930. He predicted its existence because of the lack of energy conservation observed in beta decays [1]. Nearly three decades later, in July of 1956, Cowen and Reines were the first to detect a neutrino [2]. Without charge, they do not interact with the electromagnetic force. Neutrinos are very light and can pass through most matter. We can detect neutrinos because they occasionally collide with the material inside a detector and deposit a small amount of energy. These events are uncommon, so eliminating random noise and other events, such as muon showers or other cosmic particles, is imperative.

NuLat is a relatively small neutrino detector comprising a 5x5x5 array of plastic scintillator cubes. Each cube is roughly 6 cm across, making the dimensions of the detector a cube with each side length 30 cm. The other components of the detector make it much larger in actuality. Particles may interact with each cube to deposit energy in a few different ways. Gamma rays are a common source of energy to interact with the scintillators. We may see Compton scattering, photoelectric effect, or pair production from gamma rays depending on their energy. Often, the incident photon scatters and may interact with another cube within the detector. Because of this, we must understand the behavior of the scintillators when they receive energy from incident particles. It will also be essential to look at the energy output graph, as the energy deposited depends on the interaction [3].

We want to read the energy deposited in plastic scintillator cubes from a known source. We will also vary the angle and observe the spectra to ensure that the interaction behaves in a way that agrees with our understanding of Compton scattering.

The plastic scintillator cubes in the NuLat detector and each of our tabletop ones convert the energy they receive during collisions into near-visible light. The light guide funnels this light into the PMT, which converts the photoelectrons into pulses that we can see and read with the computer or the oscilloscope and discriminator [4]. Eventually, we will work backward and figure out what energy gamma rays we detect in the NuLat detector by the energies that each ray deposits. We can get a good sense of this by using a source of known gamma rays. In this experiment, we use Na-22.

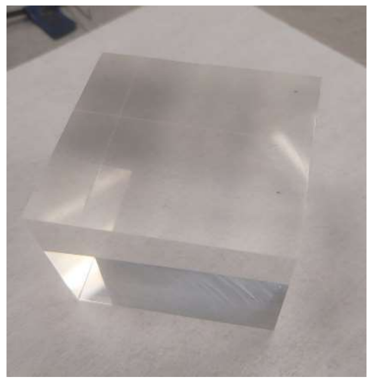

Figure 1: A plastic scintillator cube

Sodium-22 decays through beta-plus; it emits a positron when it turns into neon-22. The positron eventually slows down and annihilates with an electron, and because of the conservation of energy and linear momentum, it emits two 511 keV gamma rays (511s) in opposite directions. The neon produced in the decay is left in an excited state, returning to the ground state almost immediately. In doing so, the neon emits a gamma ray, which is known to be 1274.5 keV (later referred to as a 1275). With the behavior of these gamma rays known, we can arrange up to four of our detectors to pick up data according to our predictions [5].

Even if we know the gamma rays and where we expect them to go, the detector efficiency plays a role in whether or not we get a count or any energy deposited for that event. Efficiency plays a more significant role once we start using the coincidences because the probability that they make it to each cube is increasingly smaller, but so is the chance that it interacts with the scintillator each time. We can tell that the possibility decreases because the front of the cube face is a fixed area representing some solid angle or proportion of the “sphere” encompassing the point source. We know that the surface area of a sphere is proportional to the radius squared, so if we have a constant area for the cube and the surface area it takes up increases proportional to the radius squared, then the percent of the area the front face will take up decreases as the inverse of the radius squared. All of this only really matters if the point source is isotropic, meaning it has a chance to emit the photons in any direction with equal probability. Sodium-22 is isotropic.

We set cubes one and two to detect the 511s and cube zero to detect the 1275. Inside cube zero, the 1275 will tend to Compton scatter, meaning the gamma ray will deflect from its path off an electron within the cube. The gamma ray may leave this event at different angles. Generally, we see that higher energy rays preferentially forward scatter. We place cube three in various positions depending on the angle we are observing. We will see different amounts of energy deposited within cube zero for various angles. We want to see how observing different angles will change the rate of events we detect in our quadruple coincidence and the amount of energy deposited within each cube. Looking at the energy spectra for cubes zero and three will help us reconstruct a known event, which will eventually help recreate events of unknown origin in the larger NuLat detector.

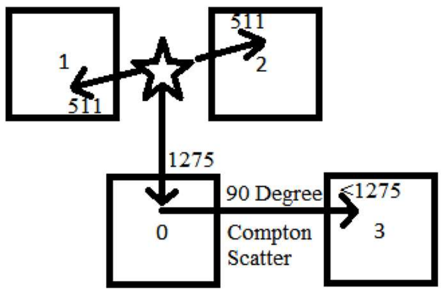


Figure 2: General configuration and labels for the scintillators

## Methods & Limitations

Here, we use four optically isolated detectors, each made of three parts: a plastic scintillator cube, a light collimator, and a photomultiplier tube (PMT). The three parts are held together and wrapped in aluminum foil and blackout tape. Each PMT is output to a Fan In/Out module we use as a splitter, as we need to send the signal to the discriminator and the oscilloscope. The discriminator flips the output pulse from the PMT and combines it with the original pulse after waiting a short amount of time, allowing it to count the pulse easier as the resultant signal crosses zero. The discriminator will then output a binary one. This setup is the same for each PMT, and after the discriminator, we wire them to a coincidence unit. The coincidence unit will only output a logical one if all its inputs are logical ones as well. We then feed the output of this coincidence unit to a counter/scaler that we can control with a timer. The way that we set this up ensures that we only count events in coincidence and send them to the digitizer. Counting only coincidences will eliminate any events we are not looking for in that specific trial.

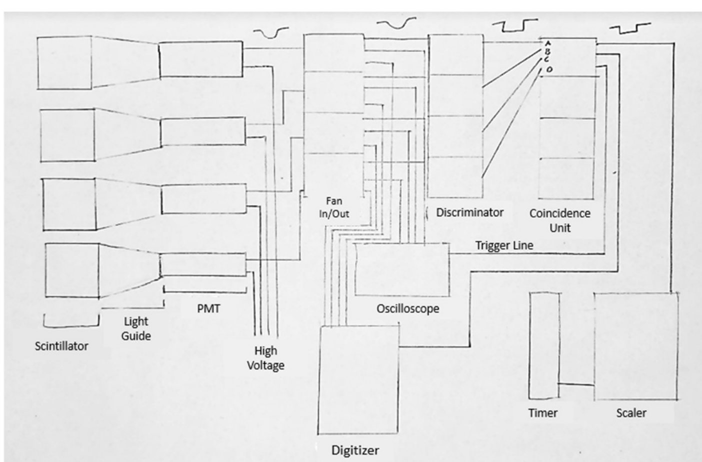


Figure 3: Signal logic to allow single and up to four-fold coincidence detection

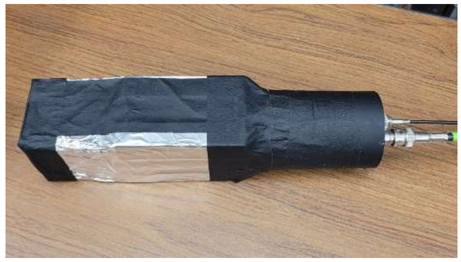

Figure 4: A detector made of a scintillator, collimator, and a PMT

We measure the distance between cubes zero and three from center to center, with all cubes oriented the same way to replicate what we will look at inside the NuLat detector. We set the distance to 10.5 cm; this distance allows for a practical rate and is far enough to confirm we are looking at the 1275. We took longer runs to gather more data in one set rather than many smaller runs, as we are looking at spectra, and a well-defined energy continuum is vital for analysis. Each collection of data was taken over 60,000 seconds or roughly 17 hours. The three main angles to observe are 0°, 45°, and 90°.

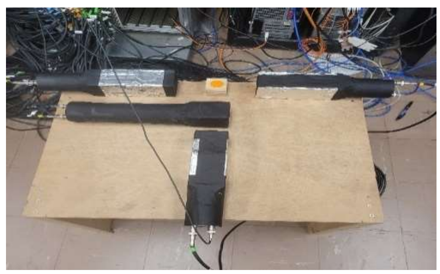

Figure 5: Quadruple coincidence setup for 0°

The further back we placed the scintillators set to detect the 511s, the more confident we could be that it receives those 511s, albeit at a reduced rate. The distance we placed them was 4 cm from the source to the face of the cube. They will stay there for every angle we look at.

The main limitation of this experiment is that the size of these cubes makes it impossible to take up just one specific angle without moving them extremely far from the source. By keeping them close, we achieve a higher rate which helps keep the runs within a reasonable time. The varying angles make it so that the spectra may show more energies, but there should still be a peak at the energy we expect from the angle we measure from center to center. It is also of note that when all the cubes are too close to the source, we risk some of the 511s scattering into cube zero. We will observe the spectra in a triple coincidence to find the distance at which the 511 contamination is negligible.

Another limitation is that we may see scattering in different materials besides the scintillators. If one of the gamma rays hits the table before it is detected in the cube, we may see a different energy than we were expecting in either the first or second cube it may interact with.

The strength of the source plays a role in the amount of data we can gather in a set amount of time. We hadn't had full access to a more active sample for the entire program. Initially, we were working with around a third of a microcurie sample. It had made it challenging to collect quadruple-coincidence data, as the rates were so low we would have needed several days for each configuration—runs that long are not very reasonable. We had to balance the rate of coincidences and sharpness of our peaks, which became much easier once we received our ten microcurie source, as it was roughly 30 times stronger.

The figures above show that the scintillators are cubic, and the PMTs are cylindrical. The difference in face shapes causes a non-uniform light collection, which can help explain some of the tails in our graphs below.

## Results

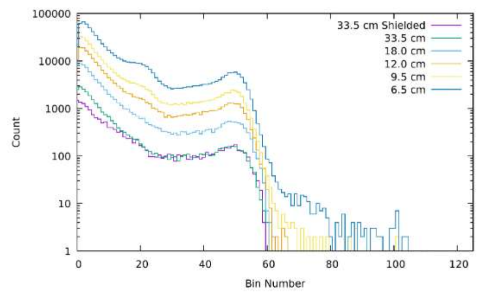


Figure 6: 511 Contamination by the distance of cube zero

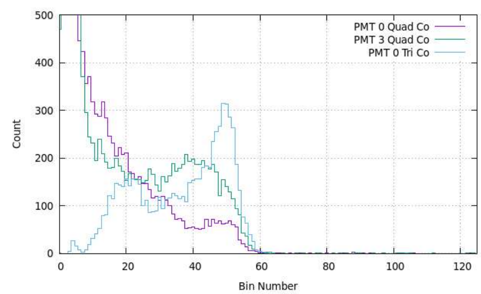


Figure 7: Quadruple Coincidence spectra with a Triple Coincidence for reference at 0°

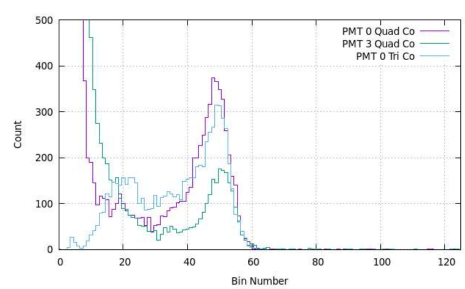


Figure 8: Quadruple Coincidence spectra with a triple Coincidence for reference at 90°

## Discussion and Ambitions

Figure 6 demonstrates how we can eliminate 511 contamination in cube zero by moving it further from the source and cubes one and two. Graphically, we can see that contamination is negligible once we reach 18 cm. The NuLat detector is roughly 30 cm across, so we can collect data with similar dimensions as if we were looking at some cubes within the detector. The purple and green lines show the difference between shielded and unshielded runs. We reduce the lower energy parts of the spectra by placing lead between cubes one and two and cube zero.

Figure 7 shows that cube zero generally sees less energy deposited if we restrict the angle. It is the most restricted, as forward scattering doesn't deposit much energy. It isn't inherently clear that there is a peak, as there are other low-energy depositions, but what we see in PMT three resembles what we expected. Figure 8 shows that if we restrict the energy to a higher angle, the energy deposited there will show up as we expect in a peak that we can see. The relative location of all the peaks is as we predicted. This graph initially brought the problem with the x-axis scale to light. Although they are in the correct relative location, they are not quite in the right place relative to the origin. We also noticed this problem in some of our other graphs. One potential issue is something as simple as the origin being in the wrong spot. We must further analyze the scaling issue in this project's next steps.

The energy spectra we have graphed allow us to be sure we are observing what we would like to. Figuring out the scale on the axes and converting bin numbers to energy would be helpful. Another step would be to place the source on top of the array, and if we can identify the angle between the first and second Compton scattering, we will know what energy to expect in a given cell. Placing the source above a particular column and looking at a single horizontal plane is one way we can do this. If the only light is in that plane, then it is likely that the first Compton scatter is directly under the source and that the angle at which it scattered was 90°. If the detector reads a different energy, we can calibrate accordingly. Unknown events will be easier to analyze once we can confidently recreate known events in the larger detector.

At some point, it may be beneficial to redo some of the runs with all the PMTs farther away. We had them relatively close at times because of the restriction we had on time, but clearer spectra would help with analysis. The rate drops significantly as we try to clean up the signal. We reduced much of the scattering from PMTs one and two back to PMT zero by placing lead shielding on their front sides; however, the rate was severely decreased. Pulling them farther back also helps sharpen the graphs, but the rate falls off by the inverse square of the distance. We found a perfect mix of accuracy and rate for what time we had, but it can certainly be improved upon so long as there is adequate time to collect data.

Others in the lab are beginning to work on code to calibrate the detector. Having code to do this for us would make the process much easier, but it is a rather large project and may take some time, as will most other steps in calibrating the NuLat detector.

In conclusion, the four-cube setup showed us that it should be possible to use this setup to calibrate the entire NuLat detector.

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