Measuring Electron Response in NaI(Tl) using Compton Coincidence Technique

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The scintillation efficiency of electron recoils in liquid xenon (LXe) is not well measured at low energies. The Compton coincidence technique (CCT) is set up using a NaI(Tl) detector and HPGe detector to measure the energy dependence of the light yield in the NaI(Tl) detector from which we can extract the scintillation effieciency. This technique allows for the detection of low energy electron recoils and the non-proportional response of the material. Eventually the material will be replaced with LXe to measure both the electron recoil and nuclear recoil response as a function of deposited energy. This will aid in the distinction between electron and nuclear recoil interactions with LXe as well as improving our understanding of the mechanisms of energy deposition in LXe.

I. INTRODUCTION

A. The Search for Dark Matter

Experiments and observational data of the Universe have come to show that there exits non-baryonic matter that cannot be seen within the range of the electromagnetic spectrum. This matter is known as Dark Matter. Currently, one of the most promising candidates for Dark Matter is weakly interacting massive particles, WIMPs [1]. These particles have properties that allow them to make up most of the mass in the universe while remaining undetectable to most detectors. The XENON collaboration has set out to build detectors using LXe and placed under a mountain in Gran Sasso, Italy, to block out cosmic radiation, muons and many other solar and terrestrial radiation sources, allowing a higher sensitivity to detect such particles as WIMPs.

Similarly to neutrons, WIMPs are expected to interact with the nuclei of the Xe atoms, rather than the electrons, depositing energy via a nuclear recoil. These energies are very low, down to 1 keV, where the scintillation response for LXe has not been accurately measured.

B. Compton Scattering and Coincidence Technique

The Compton Coincidence Technique (CCT) is the method by which collimated, gamma rays with energy hv deflect off an electron via Compton scattering into a detector and the scattered gamma rays of energy hv' coincidentally interacts in the second detector [2]. The CCT setup is shown in Fig. 1. This technique allows for the detection of low energy deposition in the first detector which would not be possible using low energy gamma sources with a single detector. Low energy gamma rays may not penetrate through the surface of the detector and thus the CCT allows the use of high energy gamma sources, while detecting a wide range of low energy deposition.

The photons with energy hv emitted from the gamma source are directly visible by the detector being characterized. Some of these photons will undergo Compton

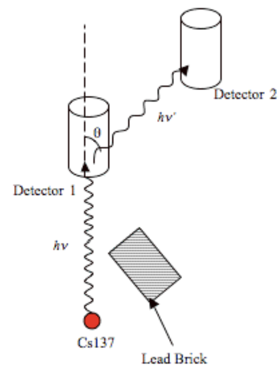

FIG. 1: Detector setup for Compton Coincidence Technique

scattering, where the incident photon is deflected off an electron at an angle θ. Part of the energy is transmitted to the electron, which is ejected from its shell, while the remaining energy is scattered as a lower energy photon, hv' [3]. The amount of energy deposited into the electron is given by

$$E_e = hv - hv' \tag{1}$$

where E_e is the electron recoil energy, hv is the incident gamma ray energy and hv' is the scattered photon energy. This amount of energy deposited depends on the scattered photon energy, which in turn is inversely proportional to the cosine of the angle θ as shown by the Compton equation,

$$hv' = \frac{hv}{1 + (\frac{hv}{m_e c^2})(1 - cos(\theta))}, \tag{2}$$

where $m_e c^2$ is the rest-mass of an electron.

Setting the second detector at an angle θ from the direction of the incident gamma ray interacting in the first detector, Eq. 2 can be used to find the energy of the scattered photon that will hit the second detector and then use Eq.1 to find the electron recoil energy deposited in the first detector. The main idea of CCT is to measure the electron energy deposited into the first detector, by only taking data when the coincidence of events in both

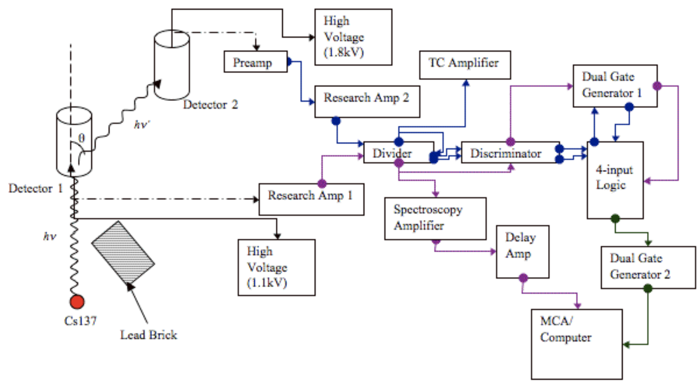

FIG. 2: Blcok diagram of the experiment setup used for CCT.

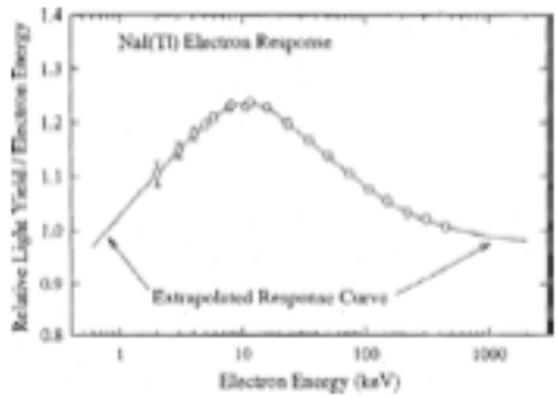

FIG. 3: Measured electron response for NaI(Tl) [4]

detectors occurs. This technique can be done at a large range of angles, producing a Compton continuum [2].

II. EXPERIMENT

A. Electronics

The electronic setup used for the CCT is shown in Fig. 2. Both of the detectors are connected to a positive high voltage power supply. Once the original signal from the detectors is amplified through Research Amps, the pulse will trigger the Dual Gate Generator 1 to open a 0.5 μs gate. The signal then passes onto the 4-input Logic which is triggered when the coincidence of a pulse from each detector occurs. This signal then gets passed onto the second Dual Gate Generator, which opens a gate for the low energy (LE) detector data from detector one to be recorded. The gate and amplified delayed LE signal are sent into the MCA card. Both of the signals are sent through a discriminator before the Dual Gate Generator 1. For the LE signal, the discriminator is used to discriminate the actual energy pulse from any background noise. The high energy (HE) signal is sent through the discriminator to allow for an upper and lower limit to be set around the expected energy given by Eq. 2 for an angle θ. Setting this discrimination on the HE detector allows for the removal of most accidental coincidences that can occur. Accidental coincidences are when an outside photon interacts with the second detector at the same moment a photon from the source interacts with the first detector.

From the source, the gamma rays are directed towards the first LE detector where they will undergo their first Compton interaction. Lead bricks are used to shield the second detector from a visible line of sight from the source. The second detector is placed at an angle, θ with respect to the incident gamma ray path. When a Compton scattering event occurs and the gamma ray is sent off at the same angle as the second detector it will deposit its remaining energy in that detector. When this coincidence occurs, the electronics are triggered and the LE data is recorded on the MCA. The first detector is set as the LE detector because ultimately a range of angles, θ, that will provide low energy deposition in the first detector and the remaining higher energy deposition in the second detector will be used to measure the LE response of the material in the first detector.

III. RESULTS

A. NaI(Tl)

The first experiment of CCT was done with two NaI(Tl) scintillators. The scintillation efficiency is well known for this type of scintillator and is a good test for the electronics and the CCT. NaI(Tl) has a non-proportional light yield response at energies lower then 200 keV as presented by W. W. Moses and shown in Fig. 3 [4].

Setting up the two scintillators at an angle of 30^o and placing the source, Cs137, a distance away from the first detector, the expected electron deposition in the first detector is 100 keV. Fig. 4 shows the Monte Carlo simulation of the expected spectrum in the first detector without any discrimination set on the HE detector. The large width of the distribution at low energies is due to the range of angles allowed by the large NaI(Tl) crystals in the scintillators. Without the discrimination on the energy of the second detector a wider range of angles become allowed. The 100 keV peak is buried inside this large peak. There was no lead brick incorporated into the Monte Carlo simulation so a backscatter off the second detector and into the first create the absorption peak around 190 keV. This peak is not expected in the real data because the lead brick will block the gamma rays from the second detector. Fig. 5 shows the collected data from the background, coincidence with no discrimination on the HE detector and the difference between the two. The background is collected from the first detector

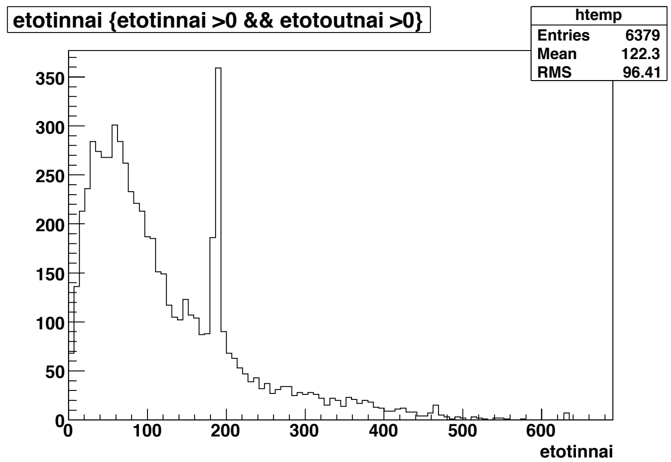

FIG. 4: Monte Carlo simulation of the energy deposition in the first detector without discrimination on the second detector, where θ is 30^o. Both detectors are NaI(Tl) scintillators.

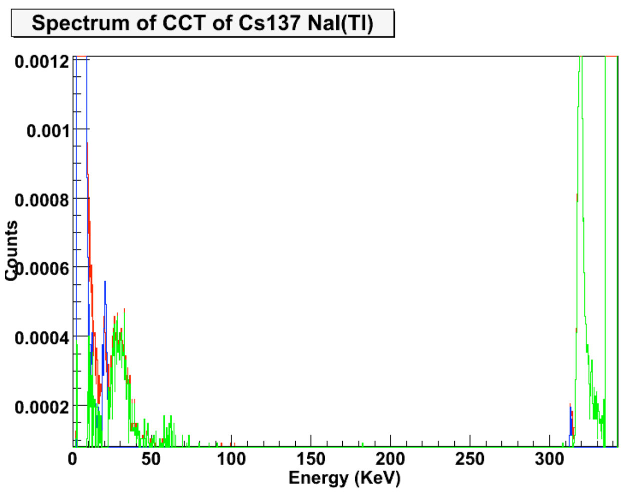

FIG. 5: LE detector background from the Cs137, 100 μCi source in blue, the coincidence of the two detectors as energy deposited the LE detector, in red, and the difference between the two, in green.

with no coincidence with the second detector and the energy deposition from the source. The difference spectrum shows no peak at 100 keV, where one is expected from Eq. 2 and Fig. 4. It was found that the gates from the two scintillators were not aligned properly and so did not allow for coincidences to occur and so all the measured energies were from accidental coincidences. It was observed that with the resolution of the NaI(Tl), the discrimination on the energy of the second detector was hard to achieve in practice. NaI(Tl) does not have the best resolution possible and so is not desirable to use as the second detector.

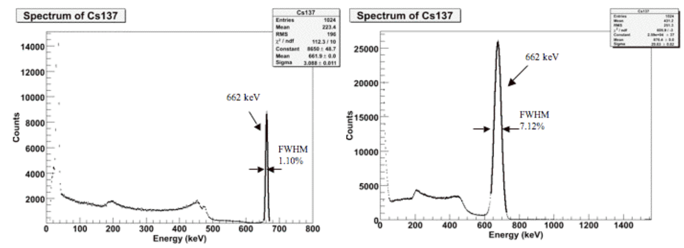

FIG. 6: (a) Spectrum of Cs137 with HPGe detector. (b) Spectrum of Cs137 with NaI(Tl)detector.

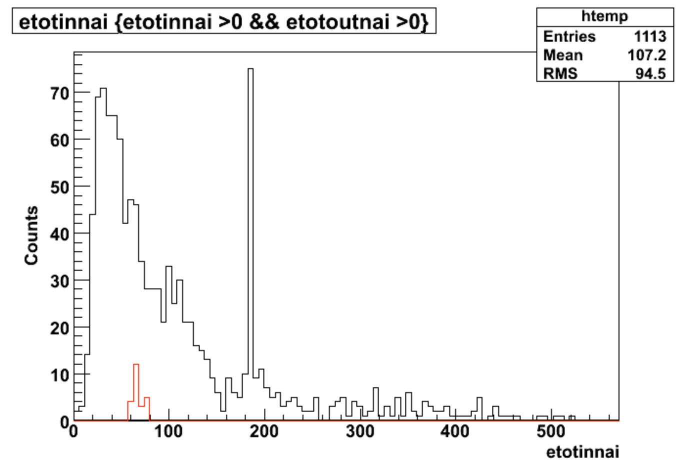

FIG. 7: Monte Carlo simulation of the energy deposition in the first detector with HPGe as the second detector at an angle 24.4^o. Black line is without discrimination on the second detector and red line is with the discrimination range on the second detector.

B. HPGe

The second detector was replaced with a high purity germanium detector (HPGe), which has a full width half maximum (FWHM) resolution of about 1% taken with a Cs137 source with energy of 662 keV compared to the 7% of the NaI(Tl) detector as shown in Fig. 6. This high resolution allows the discrimination to be more easily set and a more exact energy deposition to be measured.

The HPGe replaced the second NaI(Tl) detector and was placed at an angle 24.4^o from the line of the incident photon interacting with the first detector. From Eq. 2 the energy deposition of 68.7 keV in the first detector will allow for a Compton coincidence in the two detector. Data was first taken without the discrimination set on the second detector, and the results shown in the Fig. 8 are more promising then with the two NaI(Tl) detectors. The Monte Carlo with and without the discrimination can be seen in Fig. 7.

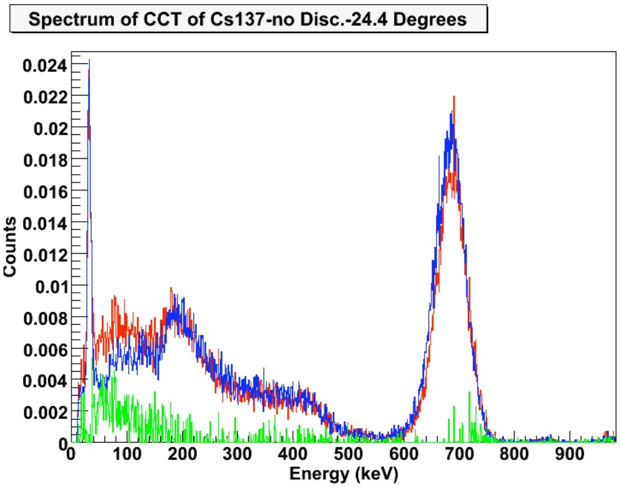

FIG. 8: The background spectrum for Cs137, in blue, and the coincidence spectrum for Cs137, in red, in the NaI scintillator and HPGe detector. The green is the difference between the two. We can see the peak at low energies. This peak is expected when the threshold is set for the Ge detector.

IV. DISCUSSION

Fig. 7 shows the Monte Carlo of the expected energy deposition in the first detector using HPGe as the HE detector. The black line shows the spectrum without a discrimination of the HPGe detector. Similarly to the NaI(Tl) there is a large peak at the low energies from the angle range from the large NaI(Tl) crystal. The expected 68.7 keV is buried within this larger peak. However, when the discrimination is simulated, shown in red in Fig. 7, the backscattered peak gets cut out and only a small peak around 68.7 keV remains. So, here the simulation shows that this CCT should work using HPGe as the second detector and provide low energy results in the LE detector.

The first data collected using the HPGe was without discrimination applied to the second detector. The results can be seen in Fig. 8, where blue is the background spectrum of Cs137 with the NaI(Tl) detector, red is with the coincidence of the two detectors, and green in the difference between the background and coincidence. The green shows where the Compton coincidences occurred. As is shown, there appears to be a peak around 68.7 keV where expected.

The next step is to take data using discrimination on the HPGe detector and at a variety of angles. The HPGe detector shows to be the desirable detector to use as the HE detector because of its high resolution. It will allow for easier discrimination and thus more accurate low energy deposition results in the first detector.

V. CONCLUSIONS AND FUTURE

This paper explains the process of setting up a Compton Coincidence Technique experiment using simple detectors and taking the data to show that CCT works. First, two NaI(Tl) detectors were used and the results show that NaI(Tl) as the HE detector does not provide a high enough resolution to allow for the desired low energy results in the first detector. The next step was to replace the second detector with a HPGe detector which has a noticeably higher resolution. This detector showed to provide better results in the first detector and thus will be the detector used in the future of the this experiment.

The next step to this project is to replace the LE detector with a LXe detector. The CCT will be used to create a plot of the ionization and scintillation yield for electron recoils as a function of the energy deposited in LXe. A neutron detector will be used in place of the HPGe detector for the measurement of scintillation efficiency for nuclear recoils. A large range of angles will be used to get a complete plot for both low and high energy depositions in the LXe as well as using a gamma ray source and a neutron source, yielding electron recoil and neutron recoil energies, respectively. This plot will improve our understanding of the distinction between electron and nuclear recoils in LXe, down to low energies. This will aid toward the identification of WHIMPs in the search for dark matter.

Acknowledgments

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