Pulse-shape Discrimination Studies of ^{230}Th Decay Alpha Particles Using the XIA UltraLo-1800

Approved by ______________________________

Professor Jodi Cooley

Pulse-shape Discrimination Studies of ^{230}Th Decay Alpha Particles Using the XIA UltraLo-1800

A Senior Thesis Presented to the Undergraduate Faculty of the Dedman College of Southern Methodist University

in

Partial Fulfillment for the Degree of Bachelor of Science with Distinction with a Major in Physics by

Andrew Posada

April 2017

ACKNOWLEDGEMENTS

The author of this paper would like to thank and express his sincerest gratitude to Professor Jodi Cooley for her unwavering support and guidance through this project and college career. He would also like to thank Dr. Rob Calkins for his constant mentorship and assistance from day one. The experience and insight gained through this research is invaluable and would not have been possible without either. He would like to thank Stuart Coleman, Brendan McNally, and Dr. Mike Kelsey for their contributions to the project. The author would like to thank Dr. Randall Scalise who made physics accessible and engaging throughout his physics career. He would also like to thank the SMU Hamilton Scholar program for making this project possible. Lastly, the author would like to thank his parents for their unconditional support through all his endeavors.

Abstract

The construction of a second-generation dark matter detector to be built in Sudbury, Canada, requires the characterization and identification of radiopure materials. Detection of the elusive dark matter particle will need to avoid unwanted background particle interactions in the detectors. Particle detectors can be used to assay and screen materials to identify those that meet specifications for appropriate amounts of radioactive substance on their surfaces. To make the process of identifying and characterizing such radiopure materials more efficient and accurate, the sensitivity of this detector must be increased. This study focuses on the implementation of electric field distortion analysis to discriminate alpha particle decays from material samples of interest and intrinsic tray backgrounds for the XIA counter. Presented here is the implementation of software used to simulate a 2015 pulse-shape discrimination study and verify its results. We simulate ^{230}Th decay in an electric field in the XIA counter in the presence of a square copper sample that will distort the electric field. This simulation confirms a 2015 study that electric field distortion does cause a difference in induced charge pulse shapes, however the effect is not significant enough to allow pulse shape discrimination between decays emitted from the sample and those emitted from the tray.

Introduction

Dark matter is believed to constitute approximately 80% of all matter in the universe. Naturally, this has become an area of increased study as this elusive matter has never been observed, yet roughly makes up a fourth of our universe's content. Experiments around the world are currently underway to detect dark matter. The SuperCDMS experiment is a collaborative effort that uses particle detectors to listen for the rare interactions of dark matter particles with matter. Because of constant cosmic rays bombarding the Earth's atmosphere, the experiment was carried out deep underground in Soudan, Minnesota, to avoid unwanted interactions caused by the consequent cosmic ray showers. It becomes obvious that with such an elusive subject to find, detector sensitivity becomes extremely important. In addition to cosmic ray interactions, particle detectors must also be concerned with radioactive ^{210}Pb atoms that accumulate on the surfaces of the detectors and surrounding materials due to radon particle decays from the ambient air. All these sources of decay interfere with the dark matter search. To increase the sensitivity of a dark matter detector, the experiment must be built with materials that are as radiopure as possible. Radiopurity is achieved when there are no radiative elements on or in a sample. Particle detectors can be used to validate that materials are *clean* enough to construct SuperCDMS SNOLAB, a next generation dark matter detector that will be built in Sudbury, Canada.

The XIA alpha particle detector is the most sensitive alpha counter on the market, however it not only registers particles from the sample being studied, but also alpha particles from the sample tray (i.e. backgrounds). Particles originating from the tray are background events that we want to identify in order to increase the sensitivity of the XIA. Differentiating alpha particles stemming from a sample rather than from the tray would allow for a more accurate characterization of materials that would be used to construct the dark matter experiment. There is a need to increase the sensitivity of the XIA counter to have greater confidence that the materials to be used in the construction of the SuperCDMS SNOLAB experiment are as radiopure as possible.

Southern Methodist University owns and operates its very own XIA Ultra-Lo 1800 alpha particle counter located in the LUMINA laboratory within the Physics Department. The XIA acts as a parallel plate capacitor with argon gas filling the space in between[4]. A schematic of the various components in the XIA is illustrated in Fig. 1.1. The bottom of the instrument consists of a grounded electrode upon which a copper sample will be placed to be studied. The top of the instrument holds two configurable electrodes at a positive voltage. These electrodes, the anode and the guard, are configurable to two different configurations: a 707 cm^2 circular counting region and another 1800 cm^2 square counting region as illustrated in Fig. 1.2. Additionally, the XIA contains field shapers on the sides that ensure that the electric field lines inside are parallel throughout the entire volume, seen in Fig. 1.2. As charged particles travel through the electric field, they ionize the argon gas leaving behind an ionization track of the argon's ions and electrons. These free electrons drift through the electric field in the XIA inducing a time varying charge on the anode. This induced charge is then processed through a proprietary integrating circuit which is the output, or pulse shapes, for each detected particle.

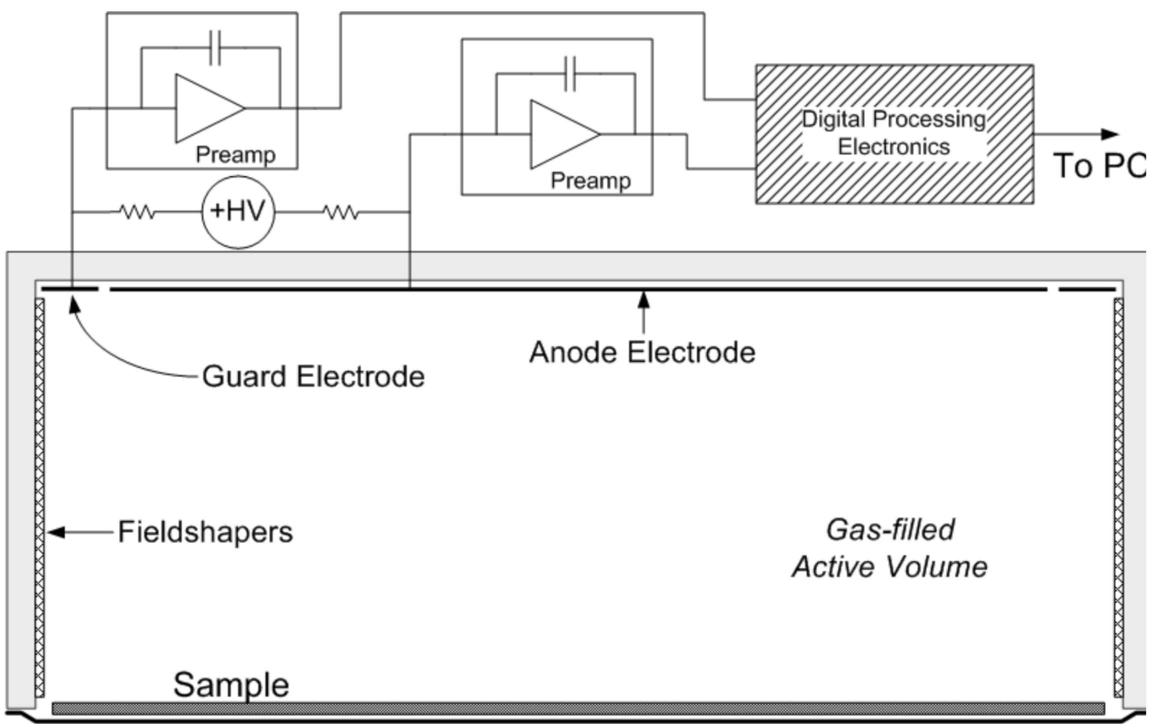

Figure 1.1. Schematic of the XIA inner chamber and electronics.[4]

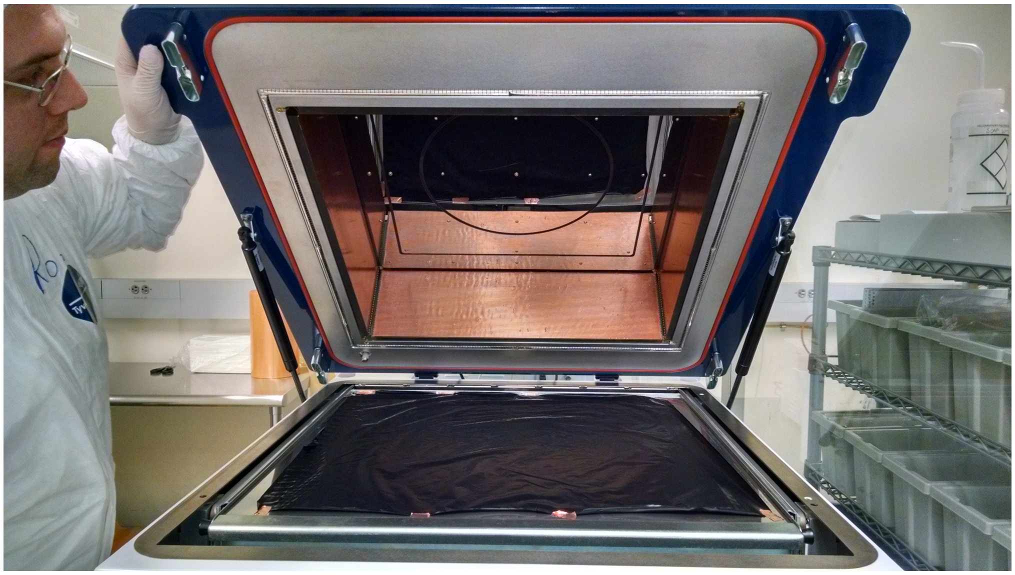

Figure 1.2. A view of the inside of the XIA. The copper sidings inside are the field shapers that keep the electric field uniform at the edges.

The electron drift is highly dependent on the electric field inside of the XIA. Because of this, we hypothesize that a distortion caused by the geometry of a conductive copper sample in the electric field would alter electron drift times and ionization tracks enough to allow a differentiation in the output pulse shapes of particles that have originated on the sample from those originating on the tray. The idea of pulse-shape discrimination is currently being implemented to a smaller degree to reject ionizations resulting from the argon gas, however, moving forward with a more refined pulse-shape discrimination algorithm, discrimination of backgrounds from the tray may be achieved by exploiting electric field distortions with a conductive sample.

An experiment was carried out in the summer of 2015 where a calibrated ^{230}Th disk sample was placed in the XIA at various locations around the tray. The emitted alpha decay particles were then counted by the XIA. To test the hypothesis, a square copper sample was placed in the middle of the tray to distort the electric field inside the XIA. The ^{230}Th disk was then placed at the same locations as before to compare the induced current with and without an electric field distortion from the sample. This experimental setup was simulated to verify the results of the 2015 study's conclusion that electric field distortions do not produce significant differences in induced charge pulse shapes to discriminate background tray events.

Software

This research project relies heavily on the integration of a variety of different software packages. Each software package is specialized and focused to simulate specific aspects of the study. To model all the aspects of the experiment, the following software packages were used, and their implementation is discussed below.

1. *Geant4*[1]

   This was the primary software package used to model the geometry of the XIA particle counter. The geometry included the inner chamber of the housing and much of the Fondren Science building where the XIA counter resides[6]. The main purpose of Geant4, however, was to calculate the passage of the emitted charged particles through matter. In this simulation, it was used to model the ionization tracks in the argon gas caused by the emitted alpha particles.

2. *Garfield++*[7]

   Geant4 can create ionization clusters in the argon gas, however, the drifting of electrons resulting from this ionization cannot be handled by Geant4. Garfield++ was used to implement the drifting of electrons through the electric field.

3. *Magboltz*[2]

   Magboltz is used in conjunction with Garfield++ to calculate the transport of electrons as they drift in the argon gas. The software solves the Boltzmann transport equations for the drifting of charges.

4. *COMSOL*[3]

   The electric fields used in this simulation were all modeled with COMSOL, a Multiphysics simulation software package. A geometric model of the XIA was created in COMSOL to simulate the parallel-plate-like electric field in the XIA for electron drifting. COMSOL was also used to calculate and model the weighing fields required by the

Shockley-Ramo theorem that put the anode and guard in different configurations shown in Fig. 2.2 – 2.5. The electric fields were modeled both with and without the field distorting sample in place. These fields were then exported to text files as a set of grid points which were then interpolated by Garfield++ to drift the electrons in the argon gas.

5. ROOT

   ROOT is a software framework used for big data processing in scientific studies. In this project, it was used to create histograms of the induced current on the anode, as well as for integration techniques that are discussed below.

An issue encountered was recreating the electronic simulation of the XIA that integrates the induced charge on the anode. It is known that the circuitry is set up as a basic op-amp integrator, however, the exact components and values are not known due to proprietary issues. Additionally, the circuitry includes its own filter. Since we did not have access to this proprietary information, a simple mathematical integration of the induced current was used. Fortunately, this was sufficient to gather results needed to carry out the experiment.

Experimental Configuration and Analysis

Testing the hypothesis requires results from alpha particles emitted with and without electric field distortion. To do this, a team at SMU conducted a series of experiments in the summer of 2015 using the XIA under these conditions. A calibrated ^{230}Th sample was used as a radioactive source for controlled alpha decay to produce an induced charge in the anode. Seven different locations were selected for the 2mm thick and 1” diameter ^{230}Th disk to be placed. With foresight of where the electric-field distorting copper sample was going to be placed, the locations were chosen where the field would have the highest distortion, at the edges of the copper sample, and the lowest distortion, the center of the copper sample. The sample placement configurations are shown in Fig. 2.1.

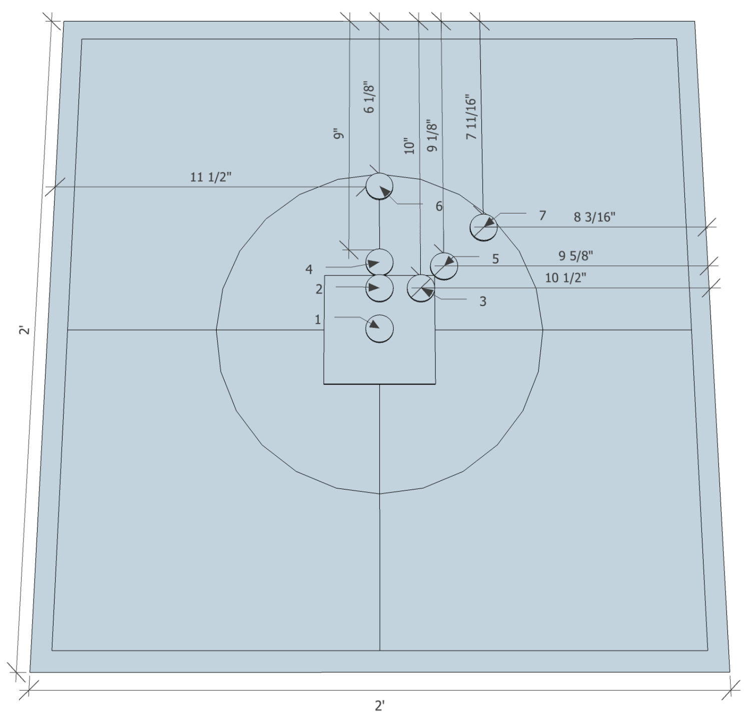

Figure 2.1. The seven ^{230}Th sample positions that were analyzed in this experiment. Position 1 is the exact center of the circular 707 cm^2 electrode counting region. Positions 2 and 4 lie on the inner and outer edge of the copper sample, respectively. Positions 3 and 5 are those expected to have the highest field distortion lying on the inner and outer side of the corner of the copper sample, respectively.

The experiment was modeled and simulated under ideal conditions to study the feasibility of using pulse shapes to discriminate between events originating from the tray from those originating from the copper sample and to verify the results of the 2015 experiment. To do this, the software described in the *Software* section was used to model the alpha particle drift and current induction in the anodes. The current induction required the implementation of the Shockley-Ramo theorem[5]. This allows for the calculation of instantaneous induced current on an electrode due to a moving charged particle near an electrode. This induced current can be found using the following relation:

$$I = qvE_v \tag{1}$$

where I is the instantaneous induced current, q is the charge of the traveling particle, v is the particle's velocity, and E_v is the component of the electric field in the direction of v. To implement the Shockley-Ramo theorem, weighing fields had to be computed to be used in Eq. 1. The electric fields used had to be modeled under the following conditions: charged particle removed, electrode set to a unit potential, 1V, and all other conductors grounded. The electric field under this condition is known as the weighing field. The counting regions that were used have four different configurations. The weighing fields for each configuration are shown in Fig. 2.2 – 2.5.

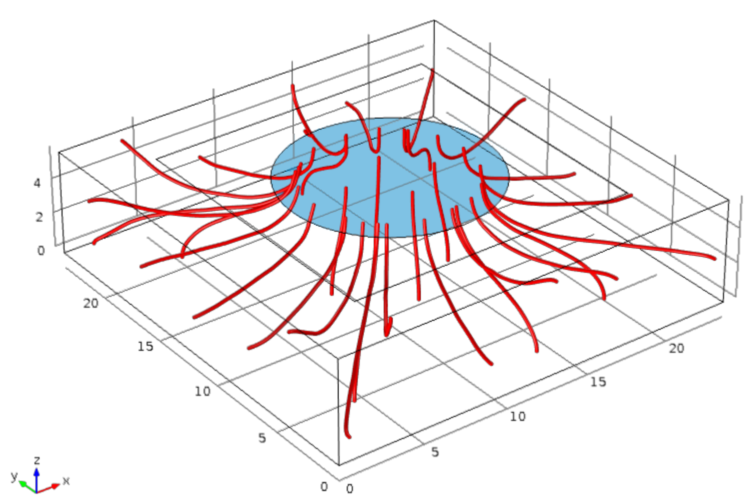

Figure 2.2. Weighing field (red lines) in the first configuration where the blue shaded circular 707 cm^2 counting region on the top portion is set to the unit potential, and all other conductors are grounded.

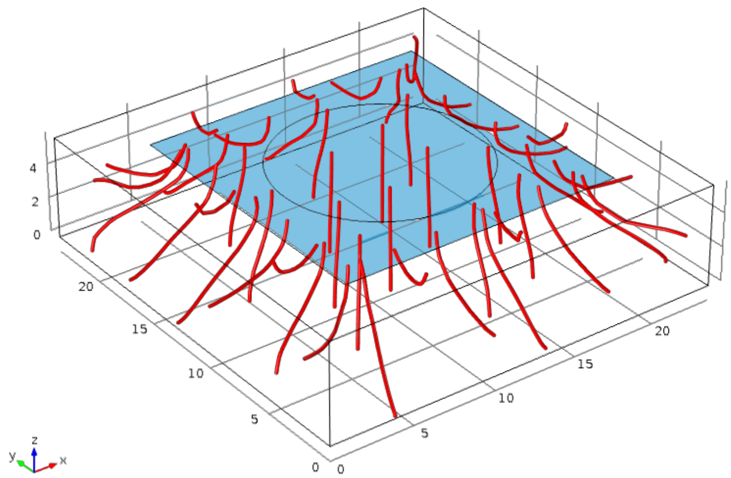

Figure 2.3. Weighing field (red lines) in the second configuration where the square immediately surrouding the blue shaded circular region, the anode, is additionally set to the unit potential while all other conductors are grounded. This is the 1800 cm^2 counting region configuration.

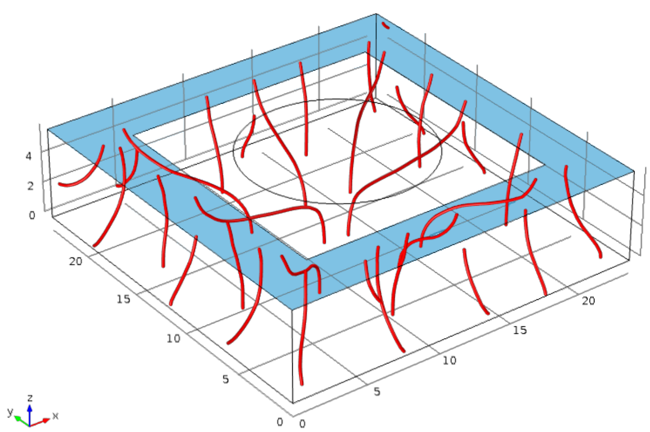

Figure 2.4. Weighing field (red lines) in the third configuration where the outer guard channel (blue shaded) is set to the unit potential while all other conductors are grounded.

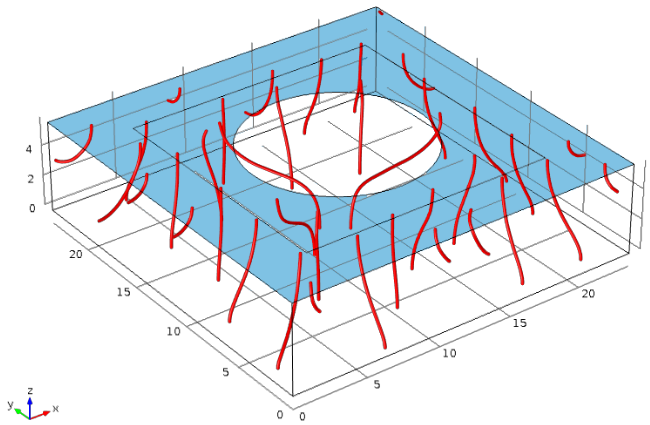

Figure 2.5. Weighing field (red lines) in the fourth configuration where the guard and the anode (blue shaded) are set to the unit potential while all other conductors are grounded.

In addition to these weighting fields, the static parallel-plate-like electric field between the tray and the anode was also modeled in COMSOL. The electric field lines illustrated in Fig. 2.6 show the lines along which the electrons drift. The distorted electric field due to the addition of a copper sample is shown below.

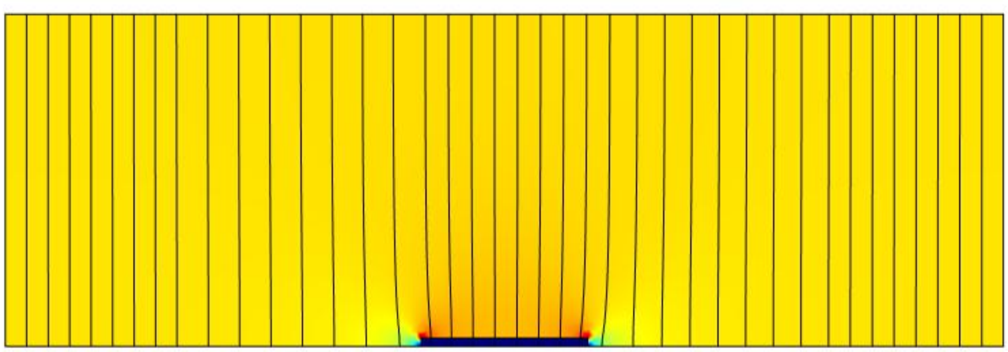

Figure 2.6. A side view of the electric field in the XIA with the addition of the copper sample. The high electric field density is shown in red at the edges of the copper sample.

Results

As the argon gas is ionized in the XIA by the alpha particles from the ^{230}Th decay, the charged particles induce a charge on the electrodes on the top of the instrument. We expect the induced charge on the anode to peak as the charge accelerates towards it. This result was confirmed and is illustrated in Fig. 3.1 and 3.2.

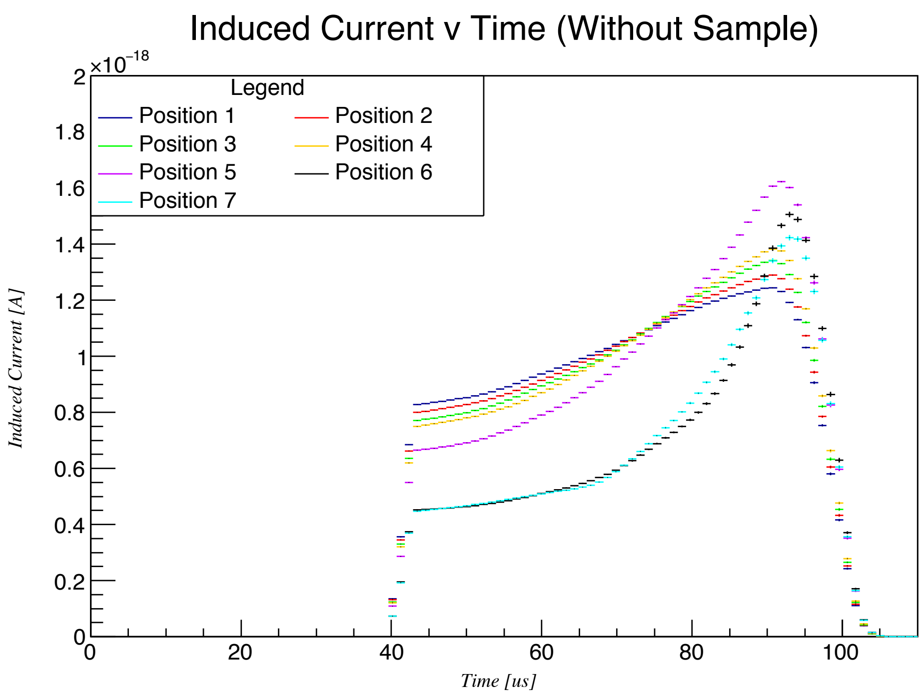

Figure 3.1. A plot of the induced current on the anode when the ^{230}Th sample is placed at each of the seven positions as a function of time without the inclusion of a copper sample.

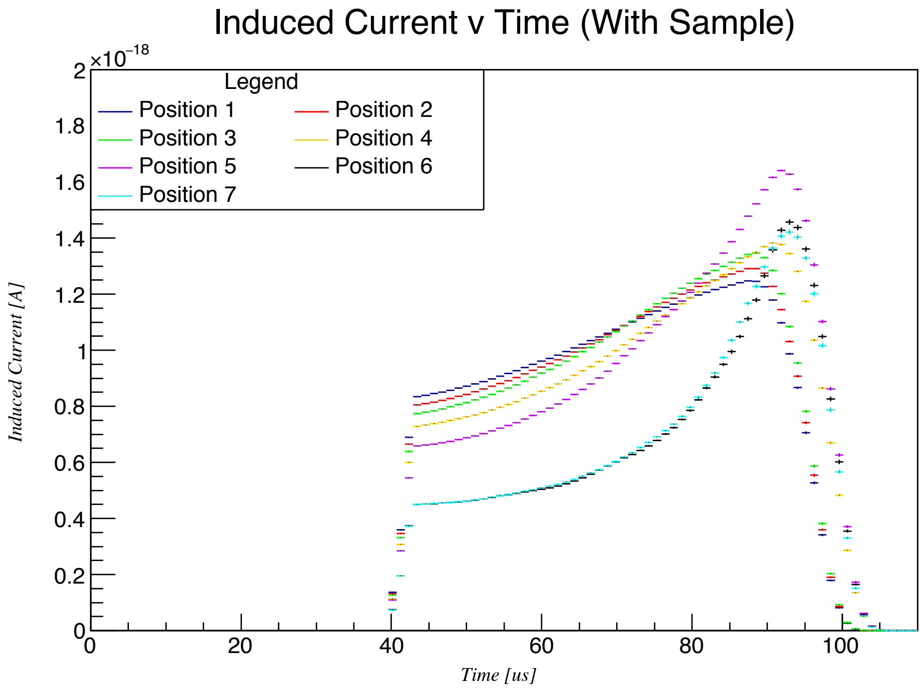

Figure 3.2. A plot of the induced current on the anode when the ^{230}Th sample is placed at each of the seven positions as a function of time with the inclusion of a copper sample. *Note*: the only meaningful difference from Fig. 3.1 is a slight vertical shift in the plots.

To verify the results of the 2015 experiment, the output of the XIA had to be simulated. Because the XIA's circuitry is proprietary, the time-varying induced current was mathematically integrated to mimic the integrating circuit used in the XIA, illustrated in Fig. 1.1. Position 1 is used as a control where the least electric field distortion is expected. Additionally, positions 4 and 5 are expected to cause the biggest difference in the integrated result due to the corner of the copper sample creating a large electric-field distortion. Below are histograms showing the integrated induced current where red represents the *absence* of the copper sample, and blue represents the *inclusion* of the copper sample. The histograms are placed so that the histogram on the left represents the result under the Shockley-Ramo configuration shown in Fig. 2.2 and the histogram on the right represents the result for the Shockley-Ramo configuration shown in Fig. 2.3.

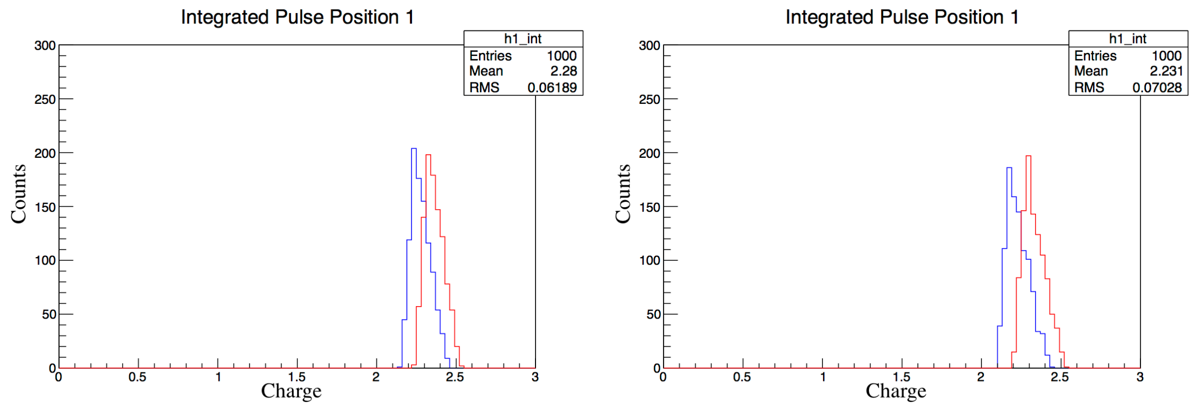

Figure 3.3. Histogram of the integrated induced current (on an arbitrary scale) plotted against time for ^{230}Th sample in position one. Red lines represent the *absence* of the copper sample, and blue lines represent the *inclusion* of the copper sample. The left histogram represents the 707 cm^2 counting region and the right represents the 1800 cm^2 counting region.

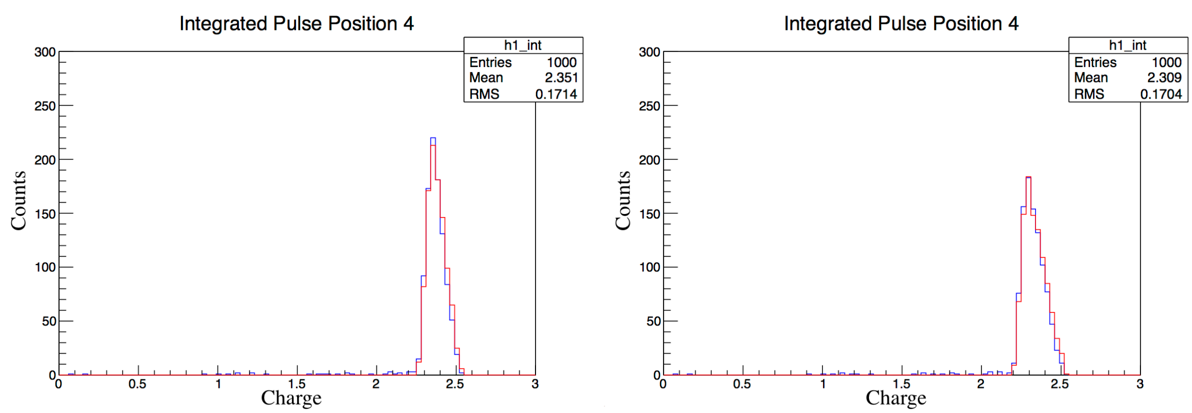

Figure 3.4. Histogram of the integrated induced current (on an arbitrary scale) plotted against time for ^{230}Th sample in position four. Red lines represent the *absence* of the copper sample, and blue lines represent the *inclusion* of the copper sample. The left histogram represents the 707 cm^2 counting region and the right represents the 1800 cm^2 counting region.

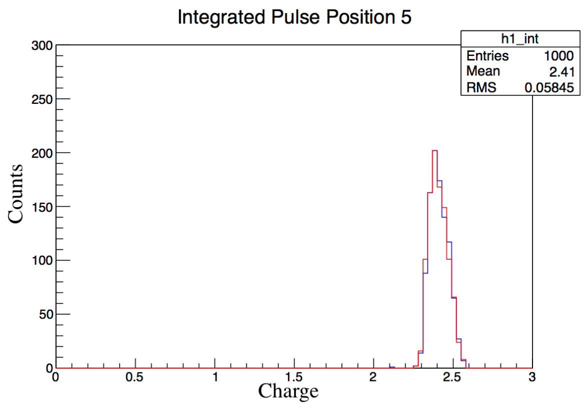

Figure 3.5. Histogram of the integrated induced current plotted (on an arbitrary scale) plotted against time for ^{230}Th sample in position five. Red lines represent the *absence* of the copper sample, and blue lines represent the *inclusion* of the copper sample. The left histogram represents the 707 cm^2 counting region and the right represents the 1800 cm^2 counting region.

To increase the sensitivity of the XIA counter, a discernable difference in integrated pulses needed to be observed to create a discriminating variable. Fig. 3.3 – 3.5 show that the results do not vary at all. Position 1, Fig 3.3 shows a left horizontal shift with the inclusion of the copper sample. This, however, is not due to the distortion of the copper field. With the addition of a copper sample, when the ^{230}Th sample was placed in position one, its vertical position had to be adjusted to be placed on the surface of the copper sample. This results in a shorter drift time for the charged particle to reach the anode. Positions 4 and 5 showed the biggest difference in results when the copper sample was added in comparison to all the other positions and their respective configurations. This difference, however, was still not enough to show a clear differentiation of background events. Therefore, it is not obvious that a conductive sample geometry, such as a square copper block, allows for the identification of particle origination.

Conclusion and Outlook

After simulating the 2015 experiment, we have shown that electric field distortion analysis cannot lead to the identification of unwanted particle detection, even under ideal circumstances. Therefore, the results achieved by the 2015 study were verified.

Future Work

This simulation modeled the experiment under ideal conditions and ignored other real-world complications that could alter the results of the simulation. Further work can be carried out on this study to model a more realistic and comparable simulation of the actual experiment. The following are several factors that were not considered in the simulation that may be implemented for more accurate results.

As mentioned before, the proprietary circuitry in the XIA created an obstacle for recreation of pulse shapes. Future studies could implement the basic op-amp integrator that the XIA uses to output the pulse shapes of the experiment. This would be able to replace the current simple mathematical integration that attempts to do what the op-amp integrator does.

The simulation in this study did not implement the presence of a dielectric. Being that the argon gas exists between the parallel-plate like capacitor in the XIA, the electric field should be adjusted so that it accounts for the argon gas dielectric. The absence of this dielectric contributes to the lack of parallelism to the real-world experiment and makes the recreation of the pulse shape more difficult to obtain.

The results of this study should be run through the pulse reconstruction software so they can be more directly compared to the data produced by the actual experiment.

These all would contribute to a more accurate representation of the experiment; however, this would not change the conclusion of this analysis. A more accurate simulation would, however, be beneficial for future studies with the XIA and contribute to a better understanding of the instrument.

References

[1] Agostinelli, S. et. al "Section A: Accelerators, Spectrometers, Detectors and Associated Equipment." *Nuclear Instruments and Methods in Physics Research* 506.3, Jul. 2003: 250-303.

[2] Biagi, Stephen. "Transport of electrons in gas mixtures." *Magboltz*., 3 Dec. 2014. Web. 10 Apr. 2017.

[3] COMSOL. "Version 5.2a." *INTRODUCTION TO COMSOL Multiphysics,* 2016

[4] LLC, X. UltraLo-1800 Alpha Particle Counter User's Manual. XIA LLC, 2013.

[5] Ramo, S. "Currents Induced by Electron Motion." *Proceedings of the IRE*27.9, 1939: 584-85.

[6] Redl, P. J Low Temp Phys (2014) 176: 937. doi:10.1007/s10909-014-1102-z

[7] Schindler, H. "Version 2017.1." *Garfield User Guide*