Axion Detection with Germanium Detectors

Hannah LeTourneau
Department of Physics, Whitworth University, 300 W. Hawthorne Rd., Spokane, WA 99251
(Dated: August 30, 2013)

The MAJORANA DEMONSTRATOR, currently being constructed at Sanford Underground Research Facility in Lead, South Dakota, is an array of germanium detectors which will be used primarily to search for neutrinoless double beta decay, which would demonstrate that neutrinos have a Majorana mass term and that lepton number is not conserved. The detector could also be used to detect solar axions. Knowing the crystal axis orientation of the detectors in the array can lead to greatly improved sensitivity to solar axions. This summer, I investigated a novel method for determining the crystal axis orientation of Ge detectors.

I. BACKGROUND

A. Neutrinoless Double Beta Decay

Neutrinos are one of the least understood fundamental particles. This is mainly because they can only interact with matter through the weak force and gravity, so direct observations are very difficult to make because a detector must interact with what is being detected in order to generate a signal. However, neutrinos are also not affected by the medium through which they propagate, which means they can reveal properties of the source that other observations cannot. Neutrinos are known to oscillate between three different flavors.

It is known that neutrinos have mass; however, the absolute scale of the neutrino's mass is unknown, as is the mechanism by which neutrinos obtain mass. One possibility is the Higgs-induced Dirac mass term, which is the mechanism by which other standard-model fermions (such as electrons and positrons) obtain mass. Another option is the Majorana mass term, proposed by Ettore Majorana, which implies that the neutrino is its own antiparticle, and would be verified if neutrinoless double beta decay were to be detected.[1] The investigation of neutrino mass and oscillation is a step away from the Standard Model towards alternative models of physics. Verification of the Dirac or Majorana mass term would give insights to such alternative models by constraining possible neutrino mass terms. These measurements also have important implications for cosmology, astrophysics, matter-antimatter symmetry, dark matter, and dark energy.[2]

Neutrinoless double beta decay ($0\nu\beta\beta$) is an energetically possible decay for several species that has yet to be observed. It is "the simultaneous conversion of two neutrons into two protons with the emission of two electrons" [1]. Conservation of lepton number is violated by the decay, so detection would verify that lepton number is not conserved. Also, if the rate of this decay is measured, the neutrino mass could be calculated. Kinematic experiments have ruled out masses above the MeV range, so detectors must be sensitive to extremely slow decay rates, on the order of 10^26 years or longer. Germanium detectors arrays are a good technology choice for such searches because germanium-76 is a natural source of these decays, also that the source is the detector. Germanium detectors also have exquisite energy resolution, which helps lift the ($0\nu\beta\beta$) decay peak above backgrounds. Germanium is also relatively easy to enrich and process.[1]

B. Majorana Demonstrator

The MAJORANA DEMONSTRATOR is currently being constructed in Lead, South Dakota. It consists of 40 kg of germanium detectors, of which 30 kg are enriched to 86% Ge-76. The primary design consideration is extremely low background, so the detector is located 4850' underground. The detector has 2 cryostats, both of which are made of ultra-clean electroformed copper that is produced underground. There also is a lead shield around the detector, in addition to a copper shield and muon veto. The background goal is 3 counts per ton-year exposure in the $0\nu\beta\beta$ peak. Over 100 scientists from 16 different institutions work on the Demonstrator.[3]

C. Solar Axion Study

Although the primary goal of the MAJORANA DEMONSTRATOR is to detect $0\nu\beta\beta$ decay, it could also be used to detect solar axions. The axion is a theoretical particle proposed to solve the strong CP problem of quantum chromodynamics. The particle is also a cold dark matter candidate, because it would interact so little with other matter. It is postulated that axions would couple to photons via quarks (the Primakov interaction). Stars are possible sources of axions as photons may be converted to axions by the strong electromagnetic fields in the stellar interior.[4] The axions would then travel out from the star radially, in an "axion wind". To an observer on Earth, the Sun is the strongest source of stellar axions. The angle of approach of these solar axions would vary diurnally, as the Earth rotates. These photons would be detected by the germanium detector when they deposit energy via another Primakov interaction with the electromagnetic field of the crystal lattice, in a process analogous to Bragg scattering of x-rays. The amount of energy deposited varies with the angle of incidence with the crystal axes, resulting in a forest of peaks in the 1-10 KeV range that oscillate up and down in energy with a 1-day period. Such a detection signature would be unique to solar axions, and would allow for significant discrimination from backgrounds at these low energies.

D. Germanium Detectors

At liquid-nitrogen temperatures, germanium detectors are semiconductor detectors. Semiconductors are crystal structures which contain either too many electrons or too many holes. Holes are gaps left by electrons and can be understood as positive charges. An impulse of energy, such as that deposited by incident ionizing radiation, gives electrons enough energy to jump from the valance band to the conduction band, which leaves a hole. In the electric field in the crystal interior, the electrons will move toward the anode and the holes toward the cathode at a rate linearly proportional to the electric field.

This motion of the drifting charges in the vicinity of the contact electrodes induces a current whose amplitude is proportional to the drift velocity and whose integral is proportional to the total amount of energy deposited in the crystal. Energy depends on the Shockley-Ramo theorem:

$$Q = q * W(x) \tag{1}$$

where Q is the charge induced at the electrode, q is the charge of an individual charge carrier, and W(x) is the weighing function, which describes how the collection varies with space. The most significant part of the equation is weighing function, which depends on the position dependence of signal propagation in the material. Small electrodes are used for this reason, because they give increased signal dependence of the weighing function, which gives increased resolution in pulse shape analysis. Because the electrical signal itself detected by the probe does not depend on the source, analysis must be done of the signal over time to determine source properties such as energy. Roughly 2.9 eV are required to make an electron-hole pair in germanium, resulting in hundreds of charge carriers for energy depositions as low as 1 KeV. This, coupled with germanium's small Fano Factor (13%) is responsible for its fine energy resolution.[2]

The detector used, MJ60, is a point contact detector, which means that it is a right cylinder grown as a single crystal of germanium with a small electrode at the center of one of the circular surfaces. The other electrode covers the rest of the crystal, with the exception of a small gap of passivated material surrounded the previously mentioned electrode that prevents current from flowing across the detector surface between the two electrodes.[5] This electrode geometry results in low electric fields and hence slow drift throughout the bulk of detector that funnel in toward the point contact where they rapidly accelerate. This gives a sharp signal response at the moment the holes arrive at the point contact.

As mentioned above, the crystal structure of germanium affects signal propagation and energy deposition of axion events. Germanium is a cubic crystal, and the Czochralski pulling technique used to grow the cylindrical single crystals typically results in one of the (100) crystal axes parallel to the cylindrical axis; so features of the crystal repeat every 90 ° around the circular faces. The two azimuthal (100) planes are denoted schematically with black dotted lines in Fig. 1. A detailed explanation is given in Li et al[6], but the gist of the matter is that signals travel fastest and the most energy is deposited when the drift motion of incident axion direction lies within a (100) crystal plane. Signals travel slowest and the least energy is deposited in the (110) planes at 45°, denoted by the white dashed lines in Fig. 1. The transition between the maximum and minimum is smooth, so it looks like a sinusoidal wave with a periodicity of 90 °. A direct way to locate the crystal axes is to examine the rise time of detector pulses, as is demonstrated in Fig. 2. The rise time is the time required for the amplitude of the pulse to rise from a low percent of the total value, such as 1% or 10%, to a high percent, such as 90% or 99%.

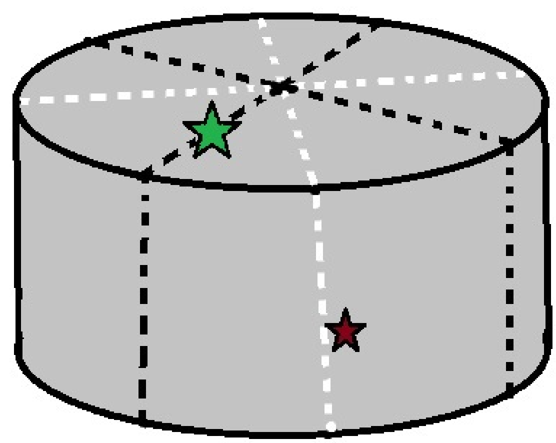

FIG. 1. Sketch of a germanium crystal. The black dashed lines represent the two (100) crystal axes planes within which charge drifts travel fastest, which the white lines represent (110) planes within which charges travels slowest. The stars represent interaction locations, whose resulting signals are draw schematically in Fig. 2

.

E. Motivation for Novel Crystal Axis Technique

As is discussed in Sec. I C, solar axions would arrive at different angles throughout the day, resulting in peaks

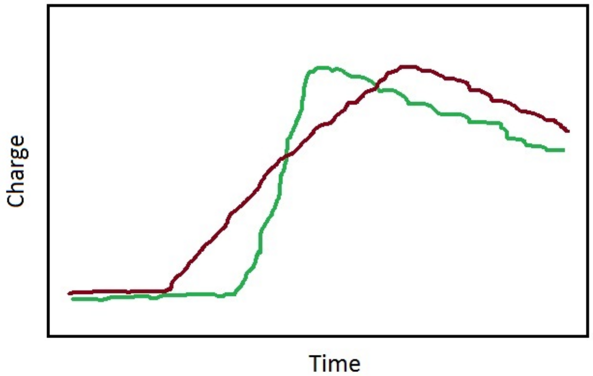

FIG. 2. Sketch of charge pulses from the events marked by stars in Fig. 1. Note how the rise time of the green one is much shorter than the red.

whose energies oscillate up and down as a function of time with a 1 day period. The Cryogenic Dark Matter Search (CDMS) experiment, located in Soudan, MN, is a similar experiment to Majorana Demonstrator in that it uses arrays of germanium detectors to search for axions. The CDMS collaboration has shown that the angle of the arrival of the axions can be predicted, and that knowledge of the angle of the arrival, when correlated with knowledge of the crystal axis orientation, can be used to perform a two-dimensional searach in energy and time to significantly improve the sensitivity for solar axions.[4]

The traditional method to determine the crystal axis orientation involves using a goniometer and collimated low energy radiation source to take runs at many angular positions. The average rise time of the pulses from the low energy peak can be calculated, and studied for angular correlation. The GERmanium Detector Array (GERDA), located in Gran Sasso National Laboratory (LNGS) in Italy, is another similar experiment to Majorana Demonstrator. They have demonstrated use of the conventional method using the 59.5 KeV peak of americium-241, and found the variation to be as expected, although the 1%-90% rise time difference from directly on axis to between axes is less than 5% of the value.[5]

The americium-241 method is impractical for the Majorana Demonstrator because the best opportunity for performing such measurements during crystal mounting occurs during detector string characterization when a string of crystals is housed in a thick cryostat, which would greatly attenuate the low energy gammas. Also, although the Demonstrator is housed below ground to reduce cosmic ray background,the detector string characterization stand is not surrounded by lead shielding, making the measurements susceptible to strong gamma background from potassium-40 and from thorium and uranium decay chains in the rock surrounding the detector. There is also some electronic noise in the system, which would make it harder to accurately interpret the detector signals. To avoid these problems, we have developed an alternative method using a high-energy thorium-232 source.

Most of the thorium-232 decay chain is very short-lived, with half-lives on the order of hours or minutes. Therefore, after a few years, a sample of thorium-232 can be assumed to be in secular equilibrium, which means that the activities of all the components of the decay chain are equivalent. The actual peak measured is the 2615 KeV peak of thallium-208, which is the final step of the thorium-232 decay chain before lead-208, the stable end. Because thallium-208 is at the end of the chain, it is important that the source is old enough that the thallium has grown in. All of the sources we used were this old.

The thallium-208 Compton shoulder peak gammas are high enough in energy that they can penetrate any interstitial cryostat materials on the way to the detector. However, they also penetrate far into the detector, in contrast to the circularly-collimated americium-241 source used by GERDA, which results in point-like depositions near the crystal surface. Because the crystal axis is invariant with respect to the height of the cylinder, two lead bricks were used to collimate only the horizontal direction (see Sec. IV B). This gives a plane of interaction through the detector. Because of the symmetry of the crystal axes, the interactions on the other half of the crystal should have the same rise time if they are penetrating that far. Still, the high-energy thallium-208 gammas typically Compton-scatter multiple times in the detector, resulting in interactions outside the collimation plane and complicating the rising-edge structure of the pulse. To avoid the multiple scatters, we restrict the risetime analysis to only those pulses within 30 KeV of the 2615 KeV gamma's Compton shoulder. This pulse ensemble should be dominantly single-site, consisting of a single high-energy deposition in the collimation plane. The varying drift paths within the interation plane will still result in rise times that vary more broadly than the angular variation to be extracted. However, the near-universality of pulse shapes in a point-contact detector yields much less variation than for other detector geometries. Still, extraction of the angular variation will require high statistics.

F. MJ60 System

The detector used for these studies is MJ60, which is a point contact natural germanium detector manufactured by PHDs Co. in Oak Ridge, TN. The bias voltage was varied between 0 and 1600 V in the course of these investigations. The detector is depleted at 1500 V. After the leakage current and detector capacitance were measured and a goniometer assembly was constructed (see Sec. IV), the detector was biased to 1500 kV and operated for several weeks as crystal axis orientation measurements were taken. The ideal operating voltage of 1500 kV was determined by measurement of the leakage current and detector capacitance (see Sec. II and Sec. III, respectively). The leakage current set the upper limit for the operating voltage, and the detector capacitance the lower.

II. LEAKAGE CURRENT

A. Motivation

Leakage current is current detected that results from free electrons flowing outside of the detector being detected by the signal probes. It is an indication of the health of the detector; newer detectors tend to have lower leakage currents which increase with age. Leakage current contributes to electronic noise, so managing leakage current is crucial to accurate data interpretation. High leakage current also can damage delicate preamplifier components. Knowledge of the leakage current at different voltages allows for understanding of the detector, as well as for one to bias the detector without damaging it. The leakage current is highest when the change in bias is highest, so care must be taken when increasing the voltage. Due to this, the process of bringing the detector up to (or down from) the proper bias voltage takes around 20 minutes. Measurement of the leakage current provides valuable information about the upper limit of bias voltage with which is possible to operate the detector.

B. Procedure

In order to measure the leakage current, a circuit was attached to the preamplifier of MJ60. The circuit converts the leakage current in pA into mV between the output of the circuit and ground. In order to measure the leakage current, the bias voltage was slowly increased from 0 V to 1.5 kV, with approximately 5 minute pauses every 100 V in order to obtain the most accurate measurement of current possible. Due to the transient nature of leakage current, even with these pauses, the value usually fluctuated by 5 to 10%. Leakage current was measured with this method many times over the course of the summer, but only one representative data set is shown in Fig. 3.

C. Results

As can be seen in Fig. 3, the leakage current increases as voltage is initially applied, levels off shortly before depletion from 800 to 1200 V, and increases again after depletion. The large increases at 1550 V and 1600 V are

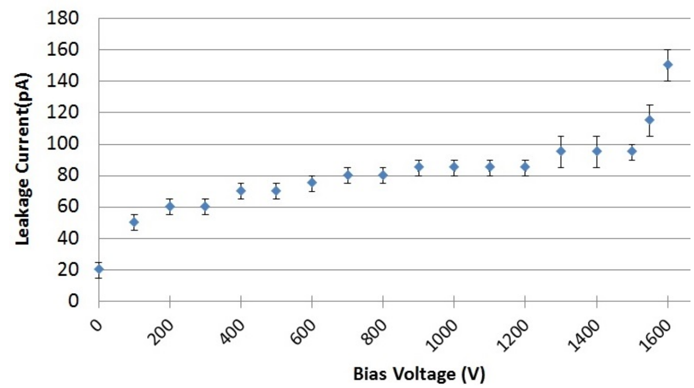

FIG. 3. Leakage current as a function of bias voltage.

not an outliers; this is an expected indicator that the detector should not be operated above 1500 V at the risk of damaging electrical components. The measurement at 1550 V was made in order to verify that the maximum limit to operate well at is 1500 V. It is probable that a more accurate measurement of leakage current could have been made by giving the additional time for the charges to settle at each voltage increment, or by increasing the number of voltage increments, but this measurement is suitable for the purpose of roughly determining the upper operating voltage limit and assessing detector health.

III. DETECTOR CAPACITANCE

A. Motivation

Because the detector consists of two probes at held at different voltages and separated by a semi-conductor, it is a capacitor, of which the capacitance can be measured. As the bias voltage applied to the detector increases, the capacitance is expected to decrease. Higher values of capacitance increase the amount of noise, so the desired capacitance sets the lower limit on bias voltage applied. Majorana Demonstrator detectors are expected to be below 3 pF at the depletion voltage, as is described in the standard operating procedure, “Characterizing a string in a String Test Cryostat”.

B. Procedure

The procedure followed is as described in the standard operating procedure referenced above. The detector was biased to 1600 V, the maximum given by leakage current measurements. A square wave pulser, of 100 mV magnitude, was fed into the high voltage input on the detector. An oscilloscope was attached to the output of the detector, and the magnitude of the output wave was measured. The voltage was lowered in steps of 100 V down to 0 V, and the magnitude of the output wave at each increment was measured. In order to get increased resolution of the capacitance near depletion, measurements were made every 10 V from 1500 V to 1300 V.

C. Results

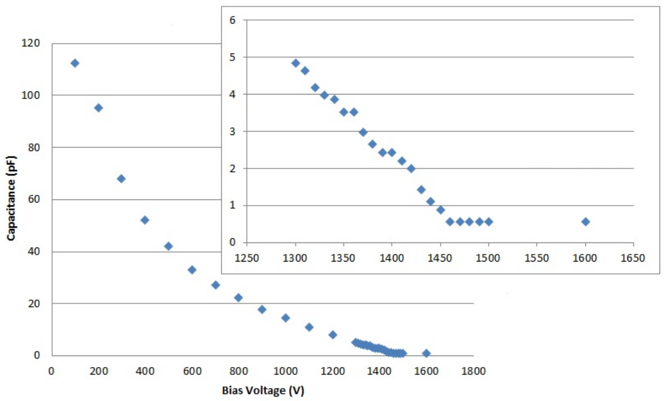

FIG. 4. Detector capacitance as a function of bias voltage. Insert highlights region around depletion.

As can be seen in Fig. 4, the capacitance decreases sharply as the voltage is increased, as is expected. The value of capacitance at depletion, 1400 V, is 2.42 pF, which is less that the desired value of 3 pF, so the detector is up to Majorana Demonstrator standards. Because the capacitance continues to decrease as the voltage increases, the optimal lower limit of the bias voltage is as high as possible due to leakage current. As has already been determined in Sec. II, the detector should not operate higher than 1500 V. This voltage was chosen as the final operating voltage, because it satisfies both constraints.

IV. CRYSTAL AXIS ORIENTATION

A. Radioactive Source

Two different thorium-232 sources were used in this investigation. First, 7.902 g of Th salt was loaded into a cylindrical vial of diameter .6" and height 2". However, the scans with this source (see Sec. IV C) had a low count rate and were noisier than ideal, and the source could be improved in a few ways. About 12 percent of gammas in the range of interest are absorbed in .6" of thorium according to NIST, which means that some of the gammas produced in the back half of the source don't even make it to the detector. Also, even at 1/4" collimation much of the source remained obscured behind the lead bricks. To improve upon these aspects, a second source comprised of 24.445 grams of ThO_2 was procured and placed in a glass tube 30 cm in length and 5 mm internal diameter. The height of the tube allows for the full height of the collimator to be filled, and the narrow width means that a very low percentage of the gammas will be blocked by the rest of the source.

B. Experimental Set-up

A goniometer was used to position the collimated source around the side of MJ60. MJ60 was aligned in the center of the goniometer by a custom machined plastic collar. The initial alignment was marked on the goniometer, the collar, and MJ60, in order to ensure that all runs would have the same angular values. The goniometer consists of a mobile cart on a protractor that can be moved between 0 ° and 190 °, and locked in position when desired. The cart has a surface area of about a foot squared; the collimator assembly was built on top of it. Due to the width of the cart, scans were only made between 30 ° and 160 ° in a variety of angular increments, further discussed in Sec. IV C. The final design for the collimator consisted of two lead bricks, 2" by 4" by 8"', balanced on their ends and separated by 1/4" (see 5 for details). The separation was calibrated with a piece of aluminum. Another lead brick was placed in front of the collimator in order to block the low energy gammas, while the higher energy ones passed through, to reduce noise.

Signals generated by probes in the detector electrodes first pass through a preamplifier, which converts the tiny charge pulse to a robust voltage pulse. These signals travel through a long coaxial cable to a Struck Innovative Systemmes SIS3302 100 MS/s 16-bit FADC, which does analog to digital conversion. The digitizer applies a trapezoidal filter to estimate event amplitudes. Ideal settings for the many parameters were determined by minimizing gamma peak widths. ORCA was used to record the data, and then it was converted to ROOT format to be further processed.

C. Procedure

Data were collected every 10 ° from 30 ° to 160 ° for 15 minutes at each position. 10 minute scans were used initially, but soon the switch was made to 15 minutes due to the higher statistics. At first, scans were taken every 5 °, but the switch was made to 10 ° when the run length switched to 15 minutes in an effort to save time, because the oscillatory pattern should still be visible with these parameters. In order to halt preamplifier oscillations, the circuit was damped by measuring the resistance across the leakage current monitoring circuit, further discussed in Sec. V A.

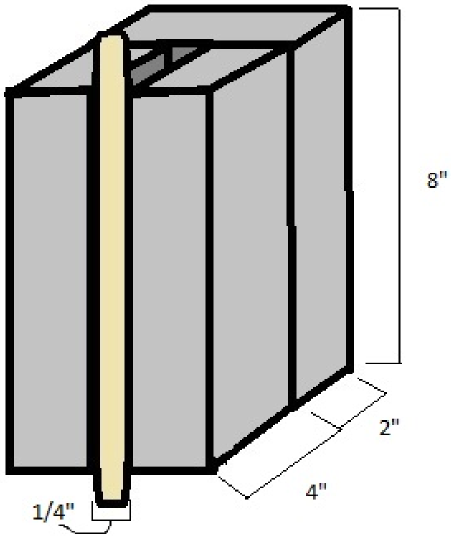

FIG. 5. A sketch of the back view of the collimator with the thorium source.

D. Analysis

As discussed in Sec. I D, the most effective method of determining the crystal axis orientation is to examine the rise time of the current pulses. However, this method is not suitable for this analysis, because of the high noise of the pulses and the extensive pulse processing required. An example of a low-noise pulse can be seen in Fig. 7. Even with the low level of noise shown, it is very difficult for the software to determine what the rise time is, and most pulses had more noise than this one. Therefore, an indirect method of calculating the rise time was performed, by dividing the maximum amplitude of each pulse in the thallium-208 Compton shoulder by its energy. This measurement serves a way to visualize rise time because the current pulse is the time derivative of the charge pulse, so that a faster or slower mobility should imprint itself as a slightly taller or shorter current pulse peak relative to the deposited energy.

The data is collected first by ORCA. It is then converted to ROOT format with majorcaroot, and then is further processed in ROOT. The GAT routine 'Process Ortec Acceptance Data' is then used to determine the time points of the waveforms. Energy cuts are then made in order to ensure that only the thallium-208 peak's Compton shoulder is examined, and then a histogram of maximum current/energy for each waveform within the thallium-208 peak in the run is generated. The histogram is fit with a Gaussian, in order to determine the mean value. This process is repeated for all of the runs, and then the mean values of amplitude/energy is graphed as function of angle. In theory, this graph would show the sinusoidal dependence of the mean value on the degree.

E. Results

The results for a run with 15 minute collection time at 10° degree increments are shown in Fig. 6. The amplitude is in arbitrary units from the analog to digital conversion, and the energy is also in ADC units which scale linearly to KeV. As can be seen from Fig. 6, no clear sine wave was obtained, although some trends can be observed. This is most likely due to limitations of our analysis process, or noise in the detector setup. Noise will be addressed in Sec. **??**, and additional analysis that could be done will be discussed in Sec. VI.

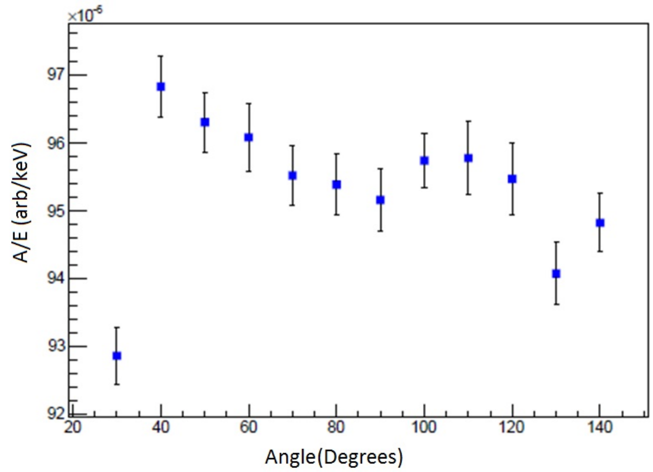

FIG. 6. A/E as a function of degree.

V. SOURCES OF ERROR

A. Electronic Noise

One of the biggest challenges with this set-up is reducing the amount of noise to reasonable values. Figure 7 is an example of a waveform with relatively low noise. This is about as accurate as the system can currently resolve; the noise is about 10% of the rise time. The differences observed in rise time by the GERDA Collaboration[5] are less than 5% of the total rise time, so the noise completely washes out the signal. Also, most pulses are more similar to those in Fig. 9, where the noise is roughly 30% of the total rise time. Obviously, noise is the major limiting factor to the analysis.

Steps were taken to reduce noise; the data in Fig. 6 is from the set after the most measures were taken. All cables leading to and from the detector were wrapped together with spiral wrap, to prevent ground loops. Also, other devices were unplugged from the NIM cart that the power supply, preamplifier power, and data card were in to reduce the chances of noise from them.

However, the largest source of noise in the system is most likely the preamplifier. Pulses similar to Fig. 8 appeared only when the multimeter was not across the circuit which measured leakage current. When the multimeter was measuring voltage, as usual, the oscillations diminished by approximately half, and when the multimeter was measuring resistance they vanished. All data in Fig. 6 was taken with the multimeter measuring resistance. The leakage current the detector was designed to operate at is lower than what it currently is at, so it could be causing problems. Regardless, the presence of a 10 MΩ resistor to ground (from the multimeter when measuring resistance) seems to fix the problem, so one could be permanently attached to the circuit, but ideally the problem would be fully understood. MJ60 is also very sensitive to microphonics, so more work could be done to reduce those as well.

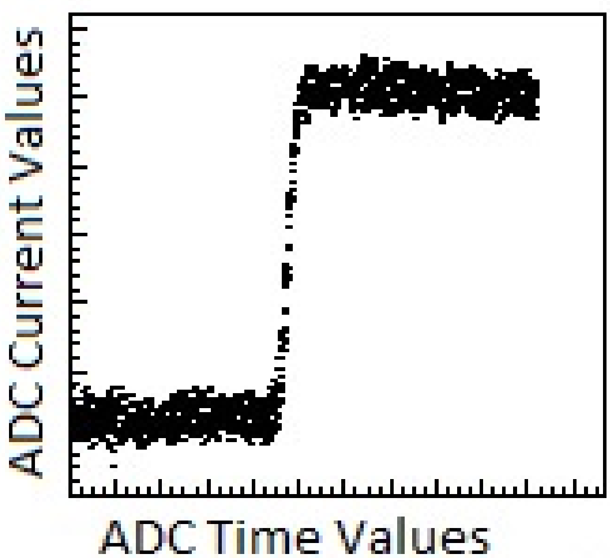

FIG. 7. Waveform with relatively low noise.

B. Other Sources

The primary other source of inconsistency in the data is low statistics. With 15 minute runs, about 300 counts were obtained in the thallium-208 peak, so increasing that number of counts would hopefully reduce the effect of random noise. Of course, this would make the process take much longer. Different types of statistical analysis could be used, as well.

VI. CONCLUSIONS AND FUTURE IMPROVEMENTS

Several characteristics of the point contact detector germanium detector MJ60 were successfully determined experimentally, including the leakage current, detector capacitance, and ideal operating voltage. Also, an attempt was made to locate the axes of the crystal, which did not succeed due to high electronic noise and low statistics. However, a system was constructed which should be capable of these measurements, so hopefully with additional reduction of noise and better processing the axis orientation can be found with this technique.

The crystal axis orientation process could be improved in a number of ways, both with respect to the physical

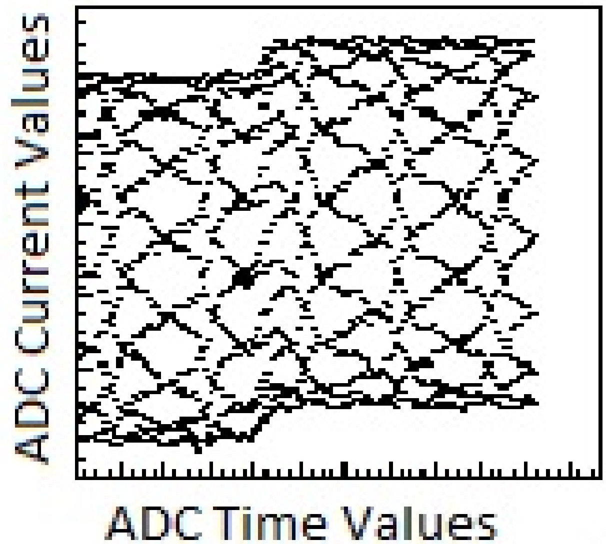

FIG. 8. Waveform displaying oscillations consistent with preamplifier problem.

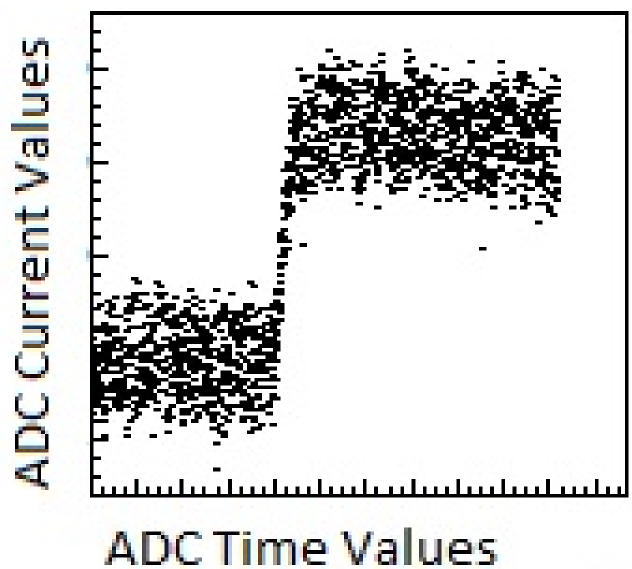

FIG. 9. Waveform with typical noise.

set-up as well as the data analysis. The most important thing is to figure out where the noise is coming from in the preamplifier, in order to fix the problem in a more permanent manner than with an ohmmeter. Also, it is possible that there is noise coming from the NIM crate or nearby lab benches. With respect to analysis, additional work could be done to smooth the waveforms. Another technique is to construct super pulses for each angular measurement, which are the addition of all of the pulses from one run. In theory, the pulses would be much larger than the random noise then, and the rise time could be directly calculated. However, this method is more computationally intensive, and the amount of noise present complicates it significantly.

[1] Stefan Schonert. Neutrinoless double beta decay. *IOP Science*, 203, 2010.

[2] Dusan Budjas. *Germanium detector studies in the framework of the GERDA experiment*. PhD thesis, Heidelburg University, Heidelburg, Germany, May 2009.

[3] MAJORANA Collaboration. The majorana neutrinoless double-beta decay experiment pre-conceptual design proposal. `http://www.npl.washington.edu/majorana/webfm_send/3`, November 2006.

[4] Z. Ahmed et al. "Search for Axions with the CDMS Experimend". *Physical Review Letters*, 103, 2009.

[5] M. Agostini. "Signal modeling of high-purity Ge detectors with a small read-out electrode and application to neutrinoless double beta decay search in Ge-76". *IOP Science JINST*, 6, 2011.

[6] Ming-Fu Li et al. "Modeling Study of the Impact of Surface Roughness of Silicon and Germanium UTB MOSFETs". *IEEE Transactions on Electron Devices*, 52, 2005.