Measuring the $^{127}$I, $\nu_e$ Charged-Current Cross-Section of NaI[Tl]

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## Contents

1 Introduction .................................................. 2
   1.1 Motivation ............................................. 2
   1.2 Historical Background ................................. 2
   1.3 Theoretical Calculation ............................... 3
   1.4 Interaction Details ................................. 5

2 Experimental Details .................................. 5
   2.1 The Spallation Neutron Source ....................... 5
   2.2 Sodium Iodide Array ................................. 6
   2.3 Neutrino Cube Design ............................... 9
   2.4 High Voltage ......................................... 10
   2.5 Data Acquisition .................................. 11

3 Results and Discussion ................................. 12
   3.1 Waveform Analysis ................................. 12
   3.2 Data Analysis ...................................... 13
   3.3 Backgrounds ....................................... 18

4 Conclusions and Future Work ......................... 20
Abstract

The primary objective of this experiment is to measure the cross-section of $\nu_e$ charged-current neutrino interactions on $^{127}\text{I}$. To measure this interaction, an array of twenty-four, 7.7 kg sodium iodide (NaI[Tl]) scintillating detectors will be deployed to the Spallation Neutron Source at Oak Ridge National Laboratory. The design of the detector array is presented here along with preliminary characterization and background measurements conducted at Duke University.

1 Introduction

1.1 Motivation

The purpose of this experiment is to improve upon previous measurements of the cross-section of charged-current neutrino interactions on $^{127}\text{I}$ by employing an array of NaI[Tl] scintillating detectors. The cross-section of low-energy neutrinos (1-300 MeV) has been experimentally measured on only a few nuclei, as shown in figure 1. The cross-section on $^{127}\text{I}$ has been measured by the Liquid Scintillator Neutrino Detector Experiment. However, uncertainties in the measurement can be improved by using the intense neutrino beam at the Spallation Neutron Source. Using the same array of detectors, an experiment can also be performed to investigate the possibility of measuring coherent neutrino-nucleus scattering on sodium. NaI[Tl] scintillating detectors are also potentially sensitive to supernova neutrinos [2].

1.2 Historical Background

The idea to use $^{127}\text{I}$ as a neutrino detector was first proposed by Dr. W.C. Haxton in 1988 following the success of the Homestake Solar Neutrino Experiment, which utilized $^{37}\text{Cl}$ as the target. He argued that a liquid iodine-based detector could be sensitive enough to measure astrophysical neutrinos and that it could help solve the solar neutrino problem. Dr. Haxton proposed an experiment using $^{127}\text{I}$ similar to the Homestake Experiment. Using $^{127}\text{I}$ as a target rather than $^{37}\text{Cl}$ has certain favourable aspects: $^{127}\text{I}$ has a 100% natural abundance, which means no extra work needs to be done to purify the samples; also, $^{127}\text{I}$ has an effective counting scheme, which affects the recovery of $^{127}\text{Xe}$ in liquid-based detectors; and $^{127}\text{I}$ has a high Coulomb barrier, which affects backgrounds from protons and $\alpha$ particles [2]. The energy of the neutrino capture is constrained by the excited states of $^{127}\text{Xe}$, shown in figure 2. The electron-neutrino charged-current cross-section on $^{127}\text{I}$ is solely dependent on the strength of the Gamow-Teller transition from the $\frac{5}{2}^+$ state of $^{127}\text{I}$ to the $\frac{3}{2}^+$ state of $^{127}\text{Xe}$ since the transition from the $\frac{5}{2}^+$ state of $^{127}\text{I}$ to the $\frac{1}{2}^-$ state of $^{127}\text{Xe}$ is forbidden. Since the energy of the neutrino capture is constrained, in liquid-based experiments which detect $^{127}\text{Xe}$ atoms, the cross-section on $^{127}\text{I}$ must be measured directly rather than inferred by the decay of mirror nuclei since the $\frac{3}{2}^+$ state of $^{127}\text{Xe}$ has no mirror nuclei decays [3] [2].

In his proposal, Dr. Haxton claimed that the rate of neutrino interactions per unit volume of $^{127}\text{I}$ detector could be more than an order of magnitude greater than in perchloroethylene, the primary reactant of the Homestake Experiment. In 1994, Dr. Engel et al. revisited those
numbers and calculated a theoretical cross-section between $2.10 \times 10^{-40}$ cm$^2$ and $3.10 \times 10^{-40}$ cm$^2$ for a quasiparticle neutrino [4]. In 2003, the Liquid Scintillator Neutrino Detector Experiment (LSND) at Los Alamos Meson Physics Facility (LAMPF) measured the cross-section on $^{127}$I to be $(2.84 \pm 0.91 \text{ stat} \pm 0.25 \text{ sys}) \times 10^{-40}$ cm$^2$ [3], compared to the cross-section on $^{37}$Cl, which was measured by the Homestake chlorine detector to be $(1.14 \pm 0.037) \times 10^{-42}$ cm$^2$ [5].

The experimental set-up proposed by Haxton for the iodine charged-current interaction was similar to that of the Homestake Experiment. A tank would be filled with $10^6$ kg of iodine with the $^{127}$Xe atoms being extricated by a circular gas flow. Collected $^{127}$Xe atoms would then be placed in a proportional counter and measured along with the values of counting and extraction efficiency to determine the total production rate.

The cross-section measurements conducted at the LAMPF used the same design as the one proposed by Dr. Haxton. The detector used at the LAMPF contained 2220 liters of NaI solution, which had a density of 1.614 g/cm$^3$ and was 50.8% NaI by mass, 1540 kg of which was $^{127}$I mass. The remaining 250 liters of the tank contained $^4$He gas for extracting the $^{127}$Xe atoms [3].

### 1.3 Theoretical Calculation

Dr. Engel et al. published two theoretical estimates of the $^{127}$I cross-section, first in 1991, then again in 1994. In 1991, they developed an approximation for odd-mass nuclei using a variation of the Quasiparticle Tamm-Dancoff Approximation (QTDA), which is an approx-
Figure 2: Weak transitions between different energy states of $^{127}$I and $^{127}$Xe. Shown for reference on the right are energy scales for proton-proton reaction along with $^7$Be and $^8$B solar-neutrinos [2].

A method for reducing the number of relevant energy states to the ground state and states close to the ground state. In 1994, Dr. Engel et al. returned to their calculations and corrected for uncertainties in their 1991 calculations [4].

Uncertainty in their theoretical measurement comes from uncertainty in the Gamow-Teller strength distribution, which determines the strength of weak-force interactions. The Gamow-Teller transition is a beta decay in which the spins of the emitted particles couple to total spin $S=1$, since both the emitted electron and electron anti-neutrino have spin $\frac{1}{2}$. Since no states of $^{127}$Xe are accessible by beta decay, the Gamow-Teller distribution can only be normalized. In order to calculate the total Gamow-Teller strength distribution, either the strength of the Gamow-Teller transition from the $\frac{3}{2}^+$ state of $^{127}$I to the $\frac{3}{2}^+$ state of $^{127}$Xe or the total integrated strength below the $\frac{3}{2}^+$ state of $^{127}$Xe must be measured [4].
1.4 Interaction Details

Equation 1 shows the $^{127}$I charged-current interaction, which is similar to that of the $^{37}$Cl interaction utilized by the Homestake Experiment given in equation 2.

\[
\nu_e + ^{127}I \rightarrow ^{127}Xe
\]  

(1)

\[
\nu_e + ^{37}Cl \rightarrow ^{37}Ar
\]  

(2)

The charged-current interaction on $^{127}$I is sensitive to neutrinos as low as 0.789 MeV. In this interaction, an electron neutrino interacts with a neutron through the weak force to produce a proton and an electron. This process of neutrino induced beta decay is shown in figure 3. Due to conservation of lepton number and kinematic constraints, this interaction is only sensitive to electron neutrinos ($\nu_e$). The liquid-based detectors proposed by Dr. Haxton and used by the LSND counted the number of $^{127}$Xe atoms produced in the charged-current interaction, but the scintillators used in the experiment described in this thesis are sensitive to electrons. The solid scintillating array also gives additional information about the path length of an electron neutrino traveling through the detector in addition to energy of the incident neutrino.

![Figure 3: Electron neutrino inducing beta decay on a neutron, forming a proton and an electron [6]](image)

2 Experimental Details

2.1 The Spallation Neutron Source

The Spallation Neutron Source at Oak Ridge National Labs was chosen for the site of this deployment for three primary reasons: Duke already has a presence at Oak Ridge from the Coherent collaboration; the equipment for the deployment is already at the SNS; and the SNS produces an intense neutrino flux within the desired range. The SNS reports a neutrino flux of $4.3 \times 10^7 \, \nu \, \text{cm}^{-2} \, \text{s}^{-1}$, one-third of which are electron neutrinos. The beam at the SNS
is pulsed at 60 Hz, which allows the use of timing as a coincidence check. Since neutrinos are not expected when the beam is not firing, events that occur outside of the 60 Hz timing windows can be discounted. Neutrinos produced at the SNS follow a distribution shown in figure 4 [7].

![Energy distribution of neutrinos produced at the SNS. Note that $\nu_e$ are produced with energies up to 50 MeV [7].](image)

**Figure 4:** Energy distribution of neutrinos produced at the SNS. Note that $\nu_e$ are produced with energies up to 50 MeV [7].

Neutrinos produced at the SNS and at the LAMPF are primarily from the decay of stopped pions, which is described in equations 3 and 4.

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \quad (3)
\]
\[
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (4)
\]

### 2.2 Sodium Iodide Array

The detectors used in this experiment are sodium iodide scintillating crystals doped with trace amounts of thallium iodide. Each crystal weighs 7.7 kg and is $2'' \times 4'' \times 16''$ not including the photo-multiplier tube and base. An image of one detector is shown in figure 5. These particular sodium iodide detectors were obtained from Pacific Northwest National Labs where they were developed by the Department of Homeland Security for a nationwide portal monitoring search [8]. They have been fitted with bases purchased from ScintiTech. Different bases have been tested, and the ones produced by ScintiTech have displayed the cleanest signals for their cost.

The rectangular geometry of the detector allows us to easily stack them into a $6 \times 4$
Figure 5: Single NaI[Tl] detector that is being used as a neutrino detector array for a total of twenty-four detectors. The entire set-up occupies an 18” × 18” footprint, allowing us to fit the array inside of a neutrino cube, as shown in figure 6.

Figure 6: Sketch-up Model of Sodium Iodide array inside of a neutrino cube

Using the electron neutrino flux of the SNS and the theoretical cross-section calculated by Dr. Engel et al., NaI detectors have a theoretical rate of 0.24 events crystal⁻¹ month⁻¹.
The entire array has a rate of 5.79 events month$^{-1}$. An image of the array set up at Duke University can be seen in figure 7. In addition, the array can be surrounded by plastic bricks filled with water in order to provide some passive shielding against neutrons and gammas. Neutrons have energies up to 1 MeV, and gammas can produce signals which may be confused for neutrinos. An image of this set-up can be seen in figure 8.

Figure 7: NaI array at Duke University with no shielding
2.3 Neutrino Cube Design

Several neutrino cubes have been deployed to the SNS and are already in position near the target area. The NaI array will sit inside one of these neutrino cubes. The neutrino cube rests on a steel pallet and consists of water bricks surrounding a steel plate. The detector will rest on this steel plate, and the water bricks serve to passively block neutrons and gammas. The roof of the neutrino cube is made up of two water bricks supported by beams attached to a steel plate.

Each water brick is 6” × 9” × 18”. An image of a single water brick can be seen in figure 9. Water was chosen as a shielding agent due to the high density of $^1$H nuclei. Hydrogen nuclei are close in mass to neutrons, and they are kinematically capable of fully stopping a neutron through a single elastic scatter. The mean logarithmic reduction of neutron energy per collision ($\xi$) is given by equation 5, where $A$ is the atomic mass of the target nucleus. For a hydrogen nucleus ($A=1$), the average energy of a neutron after collision is $\frac{1}{\xi}$ of the incident energy. As the atomic mass of the target nucleus increases, the average energy of a neutron after collision increases. Thus, hydrogen nuclei are the best candidate for stopping neutrons, and water is a cheap source of plentiful $^1$H nuclei [9].

$$\xi = 1 + \frac{(A - 1)^2}{2A} \ln\left(\frac{A - 1}{A + 1}\right)$$

(5)
2.4 High Voltage

Voltage is provided by a Power Design 1556B high voltage supply. Voltage is then supplied through a twenty-four output high-voltage splitter, designed and built for this experiment. Each dynode within the photo-multiplier tube must be positively biased with respect to the photo-cathode. Since the cathode is internally grounded, a positive voltage must be applied for each detector. A picture of the current high-voltage set-up showing both the supply and the splitter can be seen in figure 10.
2.5 Data Acquisition

The detectors deployed use sodium iodide as a scintillating material. When a particle hits the detector, it deposits a certain amount of energy. If enough energy is deposited to knock an electron from the valence band into the conduction band, energy will be re-emitted in the form of light (scintillation). In order to increase the light yield, the detector is doped with trace amounts of thallium iodide, which creates areas in which the normal energy band is lowered. This creates energy bands between the conduction band and the valence band, and when the excited electron drops down from these energy bands, it produces a visible photon. For charged particles, an electron-hole pair is produced. The hole, which is positive, drifts to an area with impurity from the thallium iodide (luminescence center) and ionizes it. The electron drifts to one of these ionized activators, creating an area with a lower activation energy. A drawing of these bands can be seen in figure 11 [10].

NaI[Tl] detectors have a high light yield, which is non-proportional to induced light at low energies. The highest non-proportionality occurs at around 10.5 keV. The dominant decay
time in NaI[Tl] is around 230 ns, followed by single electron pulses with a characteristic time of 150 ms. The phosphorescence decay accounts for approximately 9% of the overall light yield. At higher temperatures, the decay time increases.

After the photon is produced in the scintillator, it can then be detected by a photomultiplier tube. In the photo-cathode, the photon is absorbed, and the energy is transferred to an electron on the surface. That electron migrates to the surface of the photo-cathode and escapes. It then strikes a metal plate (dynode), which is positively biased with respect to the photo-cathode. Through the photo-electric effect, electrons are knocked off of the dynode. These photo-electrons are then accelerated to the next dynode since each dynode is positively biased with respect to the previous dynode, producing a shower of photo-electrons. The electron yield is proportional to the incident electron energy. Energy loss can occur through electron-electron collisions while migrating or through a potential barrier at the surface between the photo-multiplier tube and the scintillator. In addition, some signals are produced by electrons being excited by thermal energy.

Each photo-multiplier tube measures the waveform of the signal and sends its signal to a linear fan-out module (either a LeCroy Model 428 or a Phillips Scientific Model 744). One output goes to the digitizer (Struck SIS3316), and the other output goes to a fan-in module (Lecroy Model 428F). The signals from each detector are put through a discriminator (EG and G-ESN CS 8000), which produces a signal when the waveform passes a certain threshold, tied together, and put into an “OR” logic gate (Phillips Scientific Model 755). The signal from the logic gate is then put through an “AND” logic gate along with a 60 Hz clock signal to imitate the environment at the SNS. Only when the “AND” condition is met does the digitizer save data about the waveforms from each PMT. A diagram of the data acquisition system is shown in figure 12.

## 3 Results and Discussion

### 3.1 Waveform Analysis

After data are taken from the digitizer, an algorithm is run on the data set to analyze the recorded waveforms, shown in figure 13. The algorithm measures the baseline of the

![Figure 11: Energy bands within a scintillator. Activator state arise from impurities introduced by a doping agent [10].](image-url)
waveform, the time at which the waveform goes above a pre-set threshold, the integral of the waveform out to 1.25 \( \mu s \), the peak value, and which detector the waveform occurred in. This is achieved by iterating through each waveform, subtracting out the baseline, and checking whether the waveform goes above a certain threshold. The threshold was determined by calculating the standard deviation of the baseline and choosing a value that was twice as large.

The max value was determined by looking at each time bin in the waveform and finding the maximum value. The integral was determined by summing the values beyond when the waveform passes the pre-set threshold out to 313 bins. Since each bin is 4 ns, this amounts to 1252 ns. A value of 1.25 \( \mu s \) was chosen since after 1.25 \( \mu s \), the signal will have decayed to \( \frac{1}{e} \) of the original amplitude. The start time of the waveform is determined by when the signal passes the pre-set waveform. This value is then combined with the time that the waveform was triggered to determine the event time of the waveform. In addition, coincidence is stored for each waveform. Coincidence is defined as two signals occurring within 500 ns of each other. If no other signals are produced in the array, the event is labeled an anti-coincident waveform.

### 3.2 Data Analysis

By integrating all waveforms, an energy spectrum can be produced. The spectrum for a central detector biased at 1100 V can be seen in figure 14. Example waveforms from this spectrum can be seen in figures 15, 16, and 17. There are several features which are noticeable in this spectrum. There is a threshold from the electronics at 1 MeV. Any signals that are seen below this threshold arise from signals a signal in another detector triggering the discriminator. Signals less than 1 MeV are then picked up unintentionally. At 511 keV,
a peak appears due to electron-positron annihilation. At 1440 keV and 2615 keV, $^{40}$K and $^{208}$Tl peaks show up respectively. These two peaks were used to calibrate the energy scale of this detector. These gamma peaks are not affected by the coincidence since they only deposit energy in a single detector. Between the $^{40}$K and $^{208}$Tl peaks, Compton shelves are suppressed by the coincidence algorithm. The Compton Effect occurs when an electron inelastically scatters off of a photon and produces a gamma. Compton shelves appear when the gamma leaves the scintillator, depositing only a fraction of its energy in the detector. Because the gamma is able to escape the detector, it will likely be seen in an adjacent detector. Beyond the $^{208}$Tl peak, alphas begin to appear. Saturation effects from the photomultiplier manifest themselves starting at 10 MeV. This is an issue since the true energy of the signal is not recorded, leading to uncertainty in the higher-energy end of the spectrum.

In order to account for the high energy artifact and to reject the alphas, several cuts were made based on the 2D histogram, shown in figure 18. The saturation threshold was determined by observing non-linearity in the plot. The saturation effect was rejected by requiring an upper bound on the max value. Alphas were also observed offset from the rest of the histogram, and they were rejected by fitting a line to the histogram and rejecting values above that line. The histogram after these cuts were applied is shown in figure 19.

The spectrum after cuts were applied is shown in figure 20. In total, three cuts were applied: events in coincidence were rejected since neutrinos are not expected to go through multiple detectors; alphas were cut since they produce peaks within the 1-10 MeV range; and saturated events were cut since the true energy of those events is misrepresented. After the cuts were applied, a drop in background beyond 10 MeV is observed. However, the spectrum only shows energy up to 14 MeV. Since neutrinos are expected out to 50 MeV, the gain needs to be lowered to 800 V. Biasing the detectors amplifies the signal allowing the analysis of signals that would usually be below the trigger threshold of the detector. However, the detectors also have a saturation threshold independent of the bias voltage.
Figure 14: Energy spectrum from a central detector at 1100 V. Electronics threshold at 1 MeV, but some electron-positron annihilation can be seen at 511 keV. $^{40}$K and $^{208}$Tl peaks appear at 1440 keV and 2615 keV respectively. Compton shelves between the two gamma peaks are suppressed by the coincidence algorithm. Alphas appear beyond the $^{208}$Tl peak, and at 10 MeV, saturation effects start to appear, as evidenced by the plateau.

Figure 15: Example of a low-energy waveform, less than 1 MeV of energy deposited

Thus, the bias voltage of the detector needs to be balanced between being able to see signal and saturating the detector. By lowering the bias voltage from 1100 V to 800 V, the detector should be sensitive to higher energy particles that previously saturated the detector.

The spectrum for the same central detector biased at 800 V can be seen in figure 21. At 800 V, many of the key features which were seen at 1100 V disappear. However, some
Figure 16: Example of a waveform with medium energy, around 2.5 MeV deposited

Figure 17: Example of a waveform with high energy. Notice that the peak is flatter due to saturation effects from the PMT. Greater than 10 MeV deposited

saturation effects can still be seen at 800 V, as evidenced by the 2D histogram, shown in figure 22. The discriminator threshold is high enough that it cuts the alphas and any other signal below that. Because of this, the spectrum cannot be calibrated using the $^{40}$K and $^{208}$Tl peaks. However, muons are observed in the 800 V spectrum. Using a mean energy deposited by a muon of 62 MeV, the spectrum can be calibrated. The mean energy was calculated using a mean path length of 13.3 cm and an average stopping power ($\langle \frac{\delta E}{\delta x} \rangle$) of 1.304 MeV cm$^2$/g. After applying cuts to the saturation, a spectrum can be seen in figure 23. The spectrum displays energies between 5 MeV and 120 MeV. The upper bound on energy
Figure 18: 2D histogram showing integral of the waveform against the max value. The discriminator threshold, which is set by the electronics is set to 400 bins. The saturation threshold is set to 3500 bins. The line for cutting alphas is also shown.

Figure 19: 2D histogram showing integral of the waveform against the max value after saturation and alpha cuts have been applied. A small number of alphas remain due to uncertainty in the fitting algorithm.

covers the range of neutrinos expected at the SNS, but events below the lower bound are suppressed. Thus, the voltage must be increased in order to analyze the events below the 5 MeV threshold.
Figure 20: Energy spectrum from a central detector at 1100 V. Cuts were applied to reject high energy artifacts and alphas.

Figure 21: Energy spectrum from a central detector at 800 V. Muon peak can be seen at 62 MeV. Events below 5 MeV are suppressed by the electronics threshold. Saturation effects begin to appear at 130 MeV.

### 3.3 Backgrounds

Muons are considered a background in this experiment because the energy that is deposited by a muon in the scintillating crystal is close to the energy of an electron neutrino produced at the SNS. In the current configuration, muon vetoes can only be included directly above and below the array due to size constraints. Instead, the geometry of the array is utilized to
Figure 22: 2D histogram showing integral of the waveform against the max value. The discriminator threshold, which is set by the electronics is the same for both 800 V and 1100 V. The saturation threshold is set to 1800 bins. No alphas appear because they are too low in energy.

Figure 23: Energy spectrum from a central detector at 800 V. Cuts were applied to reject saturation effects. If a muon travels along the longest path length (16.703”), it will deposit 201.915 MeV. Since the muon energy is in the GeV range, this implies that a muon is able to pass through more than one detector. Note that this is not an all inclusive method as muons that clip the edges of a detector will only pass through that one detector.
For a fast, charged particle with speed $v$ and charge $z$, the stopping power in a target with atomic number density $Z$, atomic mass $A$, and mean excitation potential $I$ can be described by the Bethe equation, shown in equation (6).

$$\langle \frac{\delta E}{\delta x} \rangle = K z^2 \frac{Z}{A} \beta^2 \left[ \frac{1}{2} \ln \left( \frac{2m_e c^2 \beta^2 \gamma^2 w_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right]$$

In the Bethe equation (6), $K$ is a constant equal to $4\pi N_A r_e^2 m_e c^2$, $\delta(\beta \gamma)$ is the density energy correction to ionization energy loss, and $w_{max}$ is the maximum energy lost in a single collision [11].

Minimum ionization for muons occurs within the Bethe region, where the stopping power is solely a function of $\beta(\frac{v}{c})$. Most relativistic particles have a stopping power close to the minimum defined by the Bethe equation, and the distribution is skewed by rare events with a large single collision energy loss. For muons, energy loss can be attributed largely to ionization and atomic excitation which manifests itself in a continuous slowing-down approximation. It is important to note that the Bethe equation by itself tends to fail for single particles due to this reason. However, this can be corrected to first order using the Born approximation, and the Bloch correction and Barkas correction for higher orders. The Bloch correction has been included in equation (6) in the form of $\frac{\delta(\beta \gamma)}{2}$, and the Barkas correction adjusts for the dependance of stopping power on charge [11]. Work is currently being done to fit the muon peak evident in the 800 V energy spectrum to the Landau distribution described in the Bethe equation.

## 4 Conclusions and Future Work

Early work done at Duke University has demonstrated that a twenty-four detector array can be built with the high-voltage supply and digitizer currently on hand. In addition, this array will fit inside a neutrino cube which has already been deployed to Oak Ridge National Labs. Data analysis has shown that energy reconstruction based on the waveforms and coincidence between events works. With a bias voltage of 1100 V, the backgrounds and saturation greater than 10 MeV can be rejected by software that has been developed at Duke. In addition, alphas can also be suitably rejected. However, the dynamic range at 1100 V is not enough to see neutrinos, and preliminary work has shown that most of the pertinent energy range is below threshold at 800 V.

Moving forward, work needs to be done to investigate the energy spectrum at 900 V. In addition, the backgrounds need to be fully understood and compared to signal. One possible avenue of investigation is to employ a muon hodoscope to verify coincidence and investigate whether muon vetoes are needed on the top and on the bottom of the array. Once all the backgrounds are fully understood, the array can be deployed to Oak Ridge National Labs where it will begin taking data. Once the effectiveness of this array is assessed, methods for producing a larger array can be investigated.
References


