Beta Decay

Glen Adams

May 31, 2024

Abstract

This experiment was successful in measuring the β^- energy spectrum for $^{137}_{55}$Cs as it decays into $^{137}_{54}$Ba via the use of spectroscopy. This experiment was able to gather qualitative data on the ejection of K and L shell electrons, as well as indirectly provide evidence for the existence of neutrinos. Furthermore, this experiment was able to provide qualitative data on the shape of the electron kinetic energy process, as well as qualitative data on the beta decay endpoint energy [2] of (0.5296 ± 0.0046)MeV, which is within 3% of the calculated value of 0.514MeV [2]

1 Introduction

Radioactive decay is one of the most important processes in nuclear physics. There are 3 types of radioactive decay which can occur as a result of an unstable nucleus; alpha (α), beta ($\beta^{\pm}$), and gamma (γ). Although alpha and gamma decay are relatively straight forward, beta decay is slightly more complicated. Beta decay is a special type of radioactive decay in which a nucleus emits an electron or positron. When this process occurs, a quantized amount of energy is released which the electron carries [2]. Although energy must be conserved during this process, the amount of energy that the electron carries away is not entirely consistent, as it can carry away a range of energies. This suggests that something else is carrying away this deficit in energy, and in the case of beta decay a neutrino or antineutrino ($\nu, \overline{\nu}$) carries some of the decay energy [2]. The main goal of this experiment is the investigate beta decay from ^{137}Cs, and ultimately determine a maximum allowable energy that the electron can carry away during this process.

2 Theory

Beta decay is a type of radioactive decay which is caused by a neutron changing in to a proton or visa versa, which is motivated by the Weak Force [1, 2]. This process occurs as follows [1]

$$\begin{aligned} n &\rightarrow p + e^- + \overline{\nu_e} \\ p &\rightarrow n + e^+ + \nu_e \end{aligned} \tag{1}$$

where n is a neutron, p is a proton, e^-, e^+ is a electron and positron, and $\nu_e, \overline{\nu_e}$ is an electron neutrino and electron antineutrino respectively. Alternatively, this can be rewritten for decays of atomic nuclei [1]

$$\begin{aligned} (A,Z) &\rightarrow (A,Z+1) + e^- + \overline{\nu_e} \\ (A,Z) &\rightarrow (A,Z-1) + e^+ + \nu_e \end{aligned} \tag{2}$$

here, A is the mass number of an nucleus, and Z is the atomic number of a nucleus. This experiment uses a radioactive isotope of Caesium ($^{137}_{55}$Cs) to produce beta decays. This process occurs as follows [2]

$$
\begin{aligned}
{}^{137}_{55}\mathrm{Cs} &\rightarrow {}^{137}_{56}\mathrm{Ba} + e^- + \overline{\nu_e} \\
{}^{137}_{55}\mathrm{Cs} &\rightarrow {}^{137}_{54}\mathrm{Ba} + e^+ + \nu_e
\end{aligned} \tag{3}
$$

during this process, the isotope of Caesium decays into Barium, emitting a beta particle. For the purposes of this experiment, only the decay in which an electron is created will be examined (β^-). When this reaction occurs, the kinetic energy produced by the process will be shared between the electron and neutrino. The total amount of energy is always constant, however the proportion of energy shared will vary. This means that the electron will exhibit a *spectrum* of energies [2]. This total amount of kinetic energy can in some cases be given entirely to the electron. This quantity is measurable, and is called the beta decay endpoint energy [1].

Another process that can be viewed in the ${}^{137}_{55}\mathrm{Cs}$ beta spectrum is the emission of electrons in the K ($1s$) shell of electrons [2]. This is due to these electrons gaining energy from the nucleus when it decays from an excited state into the ground state. Typically, this would emit gamma radiation, however this energy can be transferred to the electron, giving it a distinct amount of quantized energy [2]. This process can also occur for electrons in the L shell, which will overlap with the K shell in the energy spectrum. The distribution of this energy will have a single value, and can be thought of as a δ function in the beta decay spectrum.

3 Experimental Techniques

This experiment begins with a source of beta decays, which in this case is the radioactive isotope caesium 137. As discussed in section 2, only β^- decays will be considered in this experiment. Once a decay occurs, the electrons will be influenced by an external magnetic field which is created by an electromagnet, controlled externally by a power supply. This magnetic field will cause the electron's to experience a force according to the *Lorentz Force*, $F = q(\vec{E} + \vec{v} \times \vec{B})$ [2, 3]. Here, $\vec{v}$ is the electron's velocity vector, $\vec{E}$ is the electric field vector, and $\vec{B}$ is the magnetic field vector. In this case there is no electric field, so this relation simplifies to $F = q\vec{v} \times \vec{B}$. The beta decays emitted by the caesium will point in all directions. If an electron happens to be traveling orthogonal to the external magnetic field, it will experience a force orthogonal to both the electrons velocity vector and the magnetic field, which will ultimately cause it to move in a circular path [2]. This is the mechanism used by this experiment measure the kinetic energy of the electrons.

The radioactive source is placed a distance of $2R$ away from the detector, which in this case is a Geiger-Müller Detector [3]. Since the electrons travel in a circular path, their equation of motion can be solved using the Lorentz Force [2]

$$
F = q\vec{v} \times \vec{B} \rightarrow F = evB \tag{4}
$$

Here, e is the charge of the electron. Note that the cross product is dropped due to $\vec{v}$ and $\vec{B}$ being orthogonal. Using the relation for centripetal acceleration $a_c = \frac{v^2}{r}$ allows for the radius of the circular path traveled to be solved for [2]

$$
ma_c = evB \rightarrow \frac{mv^2}{r} = evB \tag{5}
$$

$$
r = \frac{mv}{eB} \tag{6}
$$

This relation shows that only electrons that travel on a circular path with radius R (half the distance to the detector) will end up in the detector and be counted and put into a histogram. This means that the electrons being counted must have a very specific velocity corresponding to a given magnetic field magnitude B [2]. This ultimately allows the energy distribution of the electrons to be determined, as B can be varied using the power supply. Since electrons are emitted at different angles, electrons with different kinetic energies can potentially reach the detector for the same B value. To combat this, a *baffle* [2, 3] is placed in the path of the electrons, which limits the number of angles an electron can take and still reach the detector [2]. It is important to note that the cavity between the source and detector is placed under a vacuum to reduce noise in the detector [3].

In order to measure radioactive counts versus magnetic field, the voltage applied to the electromagnet was slowly incrementally ramped. This was done by first calibrating the using a Gaussmeter. By recording the field versus voltage at several different points, a regression can be done on the data, which will later allow the field to be ramped linearly based on the fitting parameters. When controlling the voltage via a computer, it was noticed that the field produced by the electromagnet was relatively constant up until a voltage threshold of $\sim$1.5V. This issue arises due to hysteresis effects inside of the electromagnet. Therefore, all runs of data were collected with computer controlled voltages $>$1.5V.

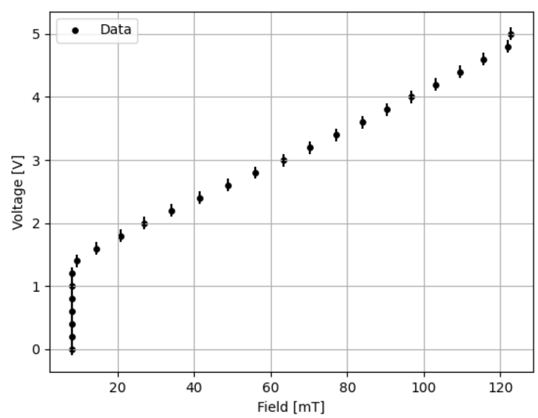

Figure 1: Plot of raw calibration data.

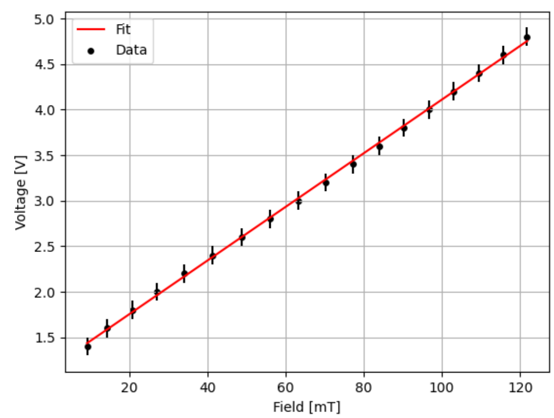

Figure 2: Plot of fitted calibration data. Points were removed from start and end of dataset to isolate linear regime.

Once data was collected, it could be converted from counts versus magnetic field to counts versus energy via the equations [2]

$$E_\beta = \sqrt{(m_0c^2)^2 + (ecBr)^2} - m_0c^2 \tag{7}$$

where c is the speed of light, e is the charge of an electron, B is the magnitude of the magnetic field, m_0c^2 is the rest energy of the electron, and r is given as 3.81cm [2].

Ultimately, there were several software challenges that made collecting data for this experiment more difficult. Under ideal circumstances, a program on the computer would simultaneously ramp the magnetic field and count decays via the Geiger Detector. Unfortunately, this program was not working, so this process had to be performed manually. This involved starting two program simultaneously; one that ramps the magnetic field, and the other which records counts from the Geiger Detector over a given time. This approach worked relatively well, however on the final day of data recording the computer used for this experiment would not boot, which seized any more data collection. Given more time, more data runs with smaller step sizes and longer amounts of time between steps would have been taken. This would have given a higher resolution data set to analyse, however the data that was recorded was deemed sufficient to recover the beta decay end point energy.

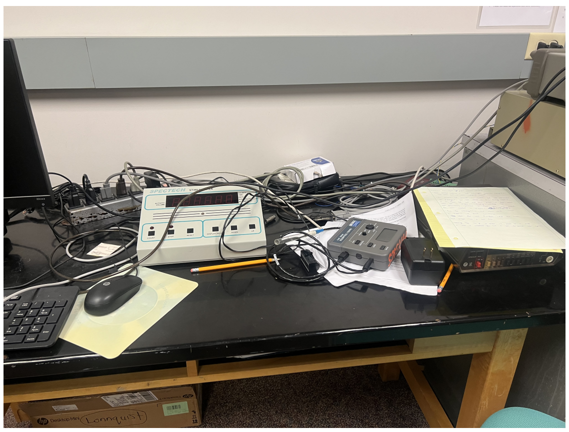

Figure 3: Image of the experimental setup, showing the computer (far left), electronics box controlling the Geiger-Müller Detector (white box with SPECTECH label), and Gaussmeter (small grey box).

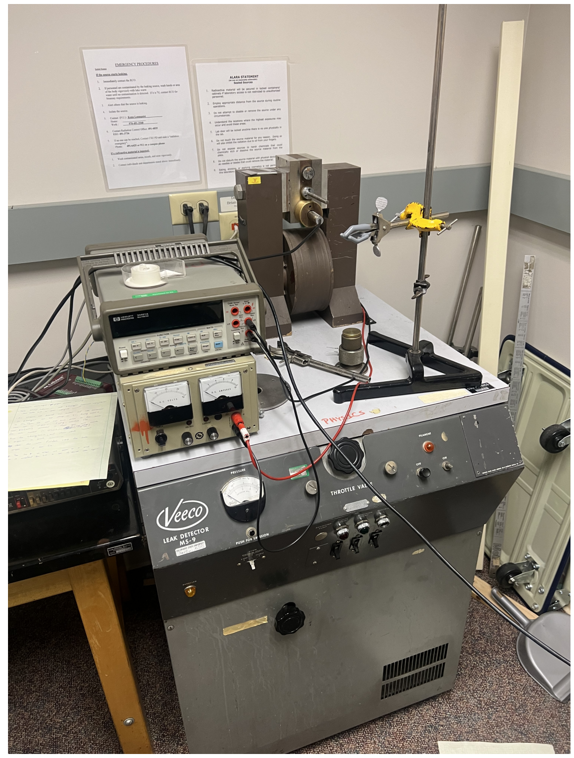

Figure 4: Image of the experimental setup, showing the vacuum pump (large apparatus labeled Veeco), power supply, digital multimeter, and detector/electromagnet apparatus (brown apparatus close to the wall).

4 Results

The following results were obtained with a Geiger-Müller Detector voltage of 720V, a voltage sweep range from 1-5V, and a voltage increment of 0.04V.

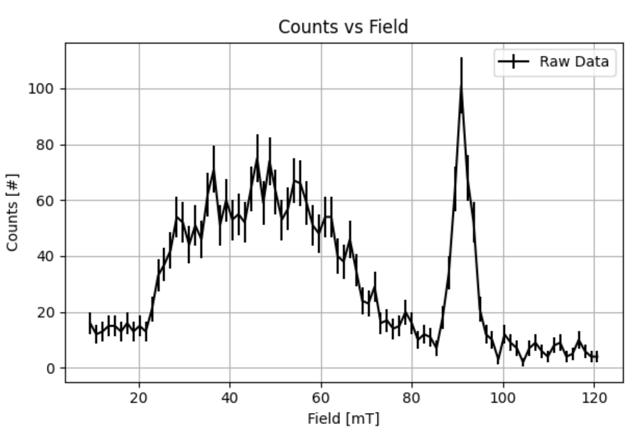

Figure 5: Plot of the first run as counts versus magnetic field.

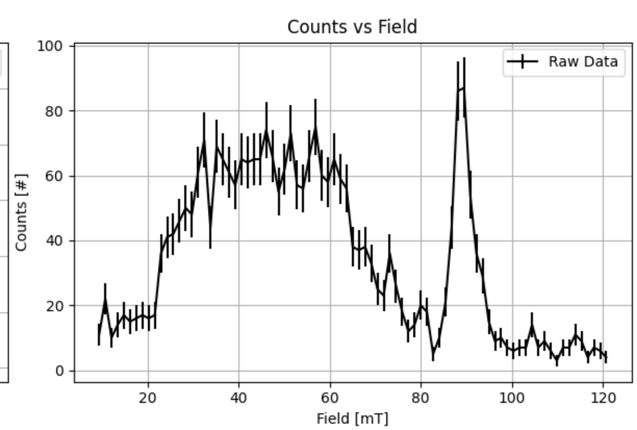

Figure 6: Plot of the second run as counts versus magnetic field.

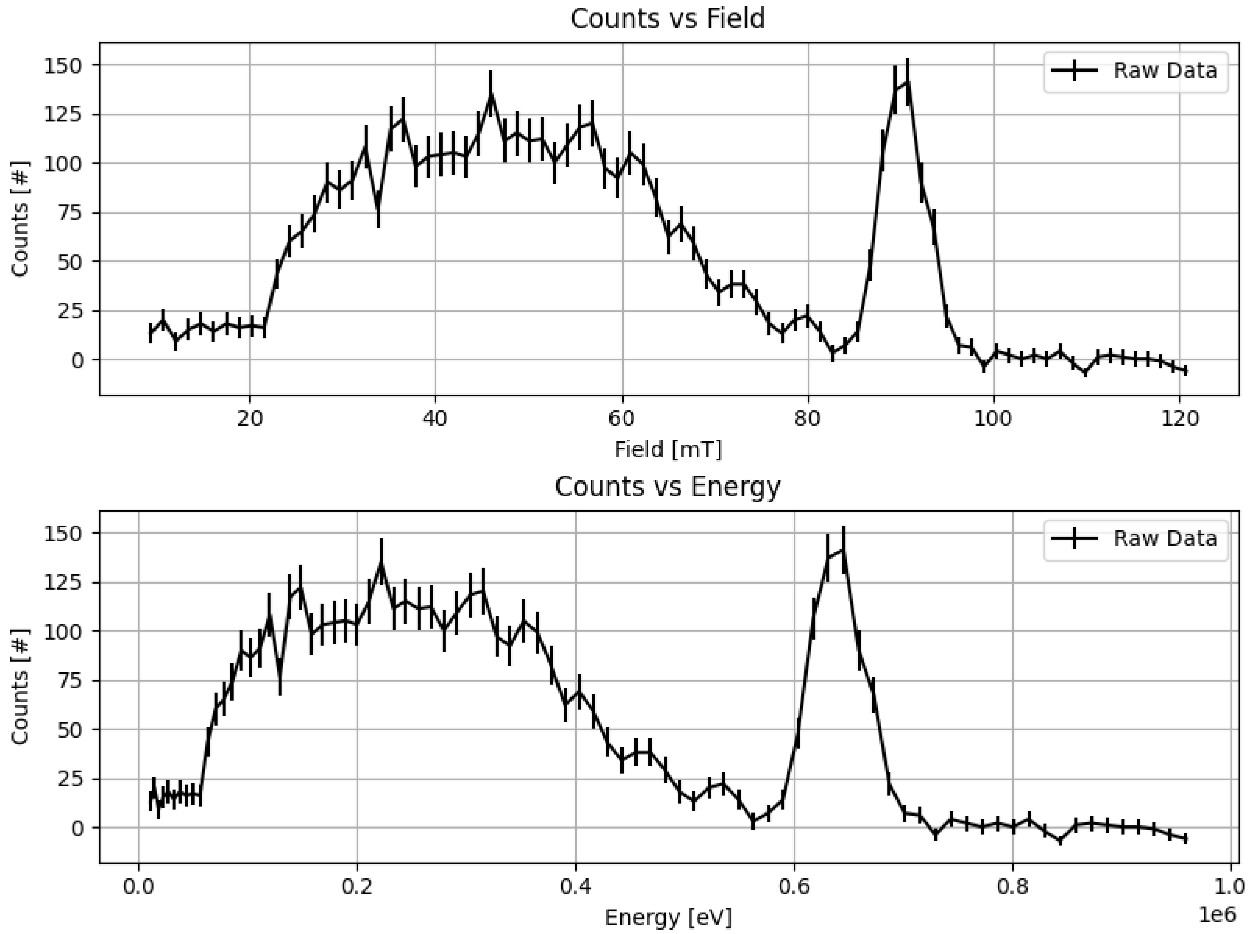

Figure 7: Plots of runs 1 and 2 combined, as well as a conversion from magnetic field to kinetic energy. Additionally, the small count background from $>$100mT has been averaged and then subtracted from the dataset.

As seen in figures 5, 6, 7, the number of counts from the detector are plotted against B. The large spike in counts near $\sim$90mT is due to the K and L shell electrons as mentioned in section 2. As seen in figure 7, B is converted to E_β via Eq. 7.

A further calibration is applied to the data using the fact that the K shell electrons will have an energy of 624.2keV [2]. An offset can be applied to the data which will shift the K shell peak in the data to the correct value. First a Gaussian is fit to the peak, and then the offset is applied as follows in figure 8.

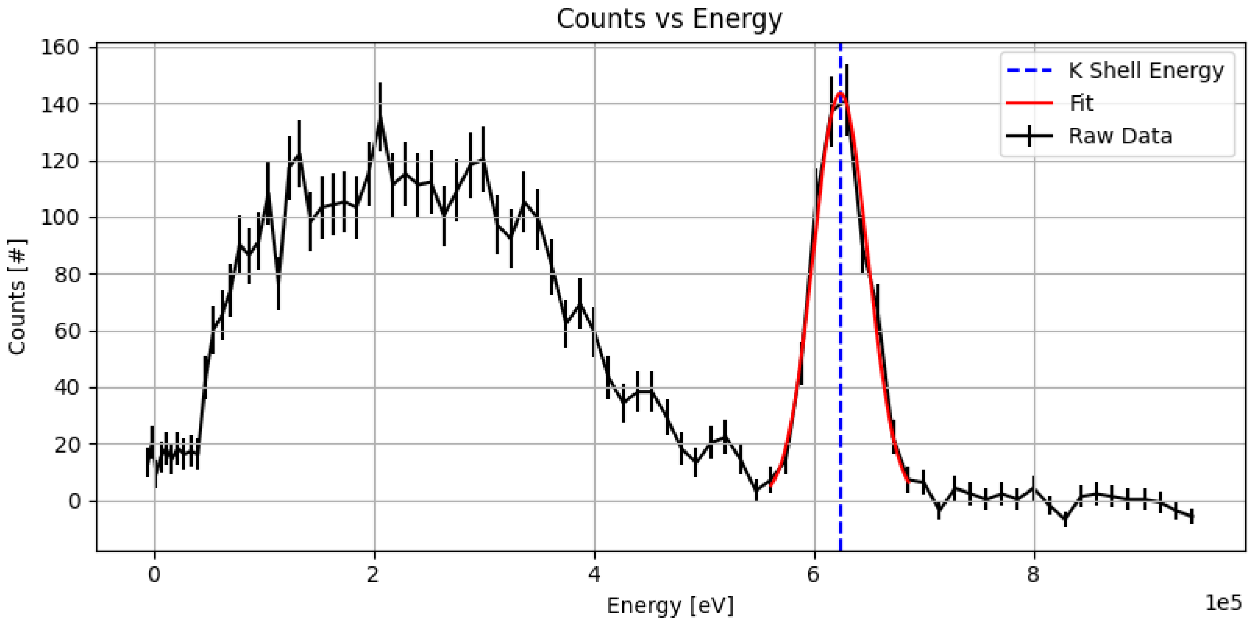

Figure 8: Plot of the data after the K shell calibration step. As shown, the peak of the Gaussian fit is aligned with the K shell energy value.

To find the beta decay endpoint energy, two functions were fit to this plot, one being a quadratic fit, and the other being a linear fit. The intersections between these functions and the Gaussian in figure 8 was then calculated and then averaged together to obtain an estimate for the endpoint energy.

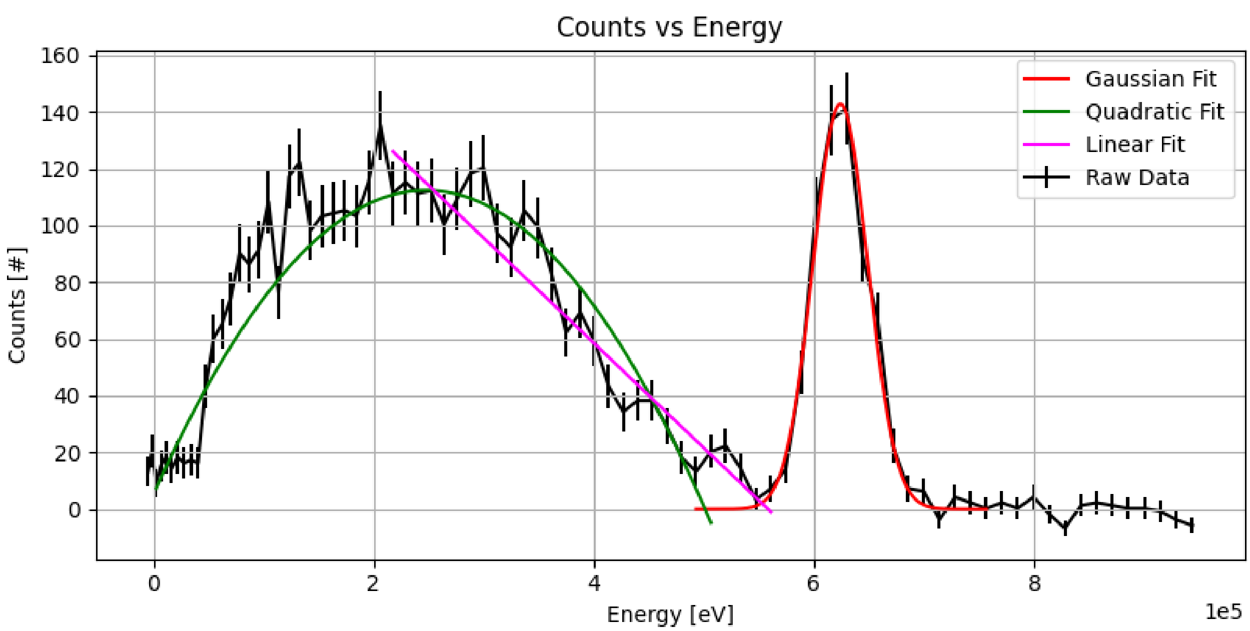

Figure 9: Plot showing the intersections between a quadratic and linear fit, and a Gaussian.

The final estimated value of the beta decay endpoint energy is estimated to be (0.5296 ± 0.0046)MeV. This value is within 3% of the accepted value of 0.514MeV [2], with an error of %8.6. Although this estimated value is relatively close to the calculated value, it is over 4 standard deviations away, suggesting a systematic or statistical error is present within this experiment. Realistically, this discrepancy is a result of both. Firstly, the limited amount of data collection done for this experiment is obviously detrimental, as the ideal voltage and count resolution could not be tested. Secondly, The method used to determine the endpoint is not exactly accurate or precise, as it simply overshot and undershot the accepted value, and averaged them. Additionally, it is known that this data is convolved with a Gaussian, as the K shell and L shell energies should be δ functions, and not Gaussians as suggested in section 2. This convolution ultimately ”smears” the dataset. In theory, a deconvolution could be performed on this dataset, however this proved to be difficult in practice.

5 Conclusions

This experiment was a relatively successful attempt at determining the beta decay endpoint energy of Caesium 137. Additionally, it indirectly provides evidence of the existence of neutrinos, as it is clear to see that the energy of the electrons is distributed, rather than being a single quantized value. Although there were several technical hurdles involved in performing this experiment, it was still successful in providing quantitative and qualitative data which was used to estimate the values in question. If this experiment were to be redone, the main parameters that would be changed would be the step size of the voltage ramp, as well as a longer collection time between steps. This would allow for a finer resolution of data which could allow for a better endpoint energy estimation, as well as separating the K and L shells in the spectrum.

References

[1] Michael Spiro Jean-Louis Basdevant, James Rich. *Fundamentals in nuclear physics: from nuclear structure to cosmology*. Advanced Texts in Physics. Springer, 1 edition, 2005.

[2] Colorado State University. Beta ray spectroscopy, 2020.

[3] Colorado State University. Quick start: Beta ray spectroscopy, 2020.