γ-Ray Spectroscopy with HpGe(Li) Detector

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Abstract

The main purpose of this experiment is to get the isotopic ratio of a uranium ore sample, called a "Yellow Cake". The steps which will be addressed in this report are: collecting data on various radioactive sources like ^{133}Ba, ^{137}Cs, ^{152}Eu and a combination of ^{235}U/^{238}U. Then by organizing data as histograms you can extract information to get calibration relation, efficiencies, efficiency functions for low and higher kev energy ranges, and eventually getting isotopic abundance of a sample. All of this is based on most importantly the reliability of the HpGe detector. In nature Uranium samples are either characterized as natural, depleted, enriched [1]. Based on what type of characterization the source is, isotopic abundances range from 0.72 % for natural abudances, 0.2-0.3 % for depleted and over 3-5 % for enriched [2]. For this particular experiment we measured the abundance of the yellow cake to about 0.00277 ± 0.00005. Which is about approximately 0.28 % closely matching depletion values in literature. [3] (Word Count: 163).

1 Introduction

1.1 Motivation

Gamma-Ray Spectroscopy is a methodology of studying gamma decays and the energy spectra of γ's specifically. Gamma rays can be classified as higher energy range electromagnetic radiation in the MeV range. The specific ranges can be from 0 MeV to 10 MeV for initial emission of gamma rays [4]. Gamma rays are made by either nuclear reaction processes or decay processes. This lab specifically focuses on the decay processes. Gamma ray photons are specifically created when a nucleus in an excited state de-excites and emits the photon [4]. The main reason we're doing this is to study decay processes of multiple sources that can be detected by the germanium detector. What we should see is Gaussian-like peaks or delta peaks that demonstrate that specific gamma energies and processes are being detected well and have good statistics [1]. The information that we get from the sources, thanks to the germanium detector, is what helps us get the isotopic ratio of

the uranium ore. By precisely measuring the energy and intensity of these gamma emissions, we can identify specific isotopes present in the sample and quantify their respective counts and other parameters. Additionally, this analysis allows us to understand the specific decay chains and the half-lives of the isotopes. We also not only care about see sharp peaks but being able to get good energy values that match with literature, get a calibration of detector, getting relative efficiencies that determine power law form and most importantly measuring the uranium source able to identify isotopes that are representative of their specific gamma with the Uranium series or Actinium series decay chain.

1.2 Summary of Experiment

HpGe Detector is a device that measures gamma ray spectroscopy of many various radioactive isotopes and is a particle detector. A question that may arise is what is the underlying process of the detector? Essentially, it has a p-junction and an n-junction which is the structure of semiconductor devices in the language of valence bands, conduction bands, holes, and electrons. A p-junction contains the holes and the n-junction the electrons. Excitation's of electrons/hole pairs is what gets it to move from valence band to conduction band. If an electric field is applied that field decreases the band-gap between the valence and conduction bands allowing flowing of electrons which is what create current within a semiconductor device like for example a diode. For this experiment gamma decay or specifically electromagnetic radiation goes through intrinsic layer of the scintillating crystal within the semiconductor device. This itself allows electrons to be able to move from valence to conduction band creating a proportion of electric signal per energy deposit, it then goes through a pre-amplifier to make it a voltage pulse, an amplifier to strengthen the signal and get rid of experimental noise to then be able to be read and digitized by an ADC to a DAQ to see a spectrum like pattern on a screen[1] (Word Count Section 1: 481).

2 Theory

The key concepts to understand in this lab are the quantum interactions of light with matter, specifically for three main processes: Photoelectric Effect, Compton Scattering, and Pair Production. Since the main premise of the lab is to measure the isotopic abundance of uranium, it is also important to have a comprehensive understanding of decay schemes, including the Uranium Series and Actinium Series. Additionally, an understanding of gamma-ray spectroscopy principles and the mechanisms behind each interaction is crucial to interpreting the data collected from uranium samples accurately.

2.1 Photoelectric Effect

The Photoelectric Effect is the matter interaction process between a photon and an atom, where the photon, through interactions with the atom, completely transfers its energy to produce a photoelectron. The energy of the electron is basically the photon energy minus the binding energy (work

function) of the electron in the atom [1]. The Photoelectric Effect represents lower energies in a gamma-ray spectrum, typically seen as distinct peaks at characteristic energies.

2.2 Compton Scattering

Compton Scattering is another matter interaction process between a photon and an electron. In this interaction, photons and electrons elastically scatter off each other based on varying scattering angles, resulting in different energy and momentum transfers. This means that the energy and momentum transfer between a photon and electron varies at different scattering angles [1]. In a gamma-ray spectrum, Compton processes represent middle energy ranges, appearing as a continuous distribution or a Compton edge.

2.3 Pair Production

Through the Coulomb field, a photon with energy exceeding 1.02 MeV can interact in such a way that it completely converts into an electron-positron pair. Pair production cannot occur if the threshold energy isn't reached. This process is significant in gamma-ray spectroscopy, as it indicates higher energy interactions [1] and typically produces a continuum beyond the threshold.

2.4 Uranium Series

This is the decay chain series for ^{238}U. It prominently features alpha and beta decay processes, which involve the emission of particles as the nucleus transforms. The decay chain for this series follows: astatine, bismuth, lead, polonium, protactinium, radium, radon, thallium, and thorium, ultimately terminating with lead-206. Most of these isotopes make up the composition of uranium in its natural state. There is also an associated energy loss to neutrinos of about 51.7 MeV [1].

2.5 Actinium Series

This is the decay chain series for ^{235}U, where alpha and beta decay processes are also prominent. The series progresses as follows: actinium, astatine, bismuth, francium, lead, polonium, protactinium, radium, radon, thallium, and thorium, ultimately ending with the stable isotope lead-207. There is an energy loss of about 41.6 MeV to neutrinos throughout this series [1]. This series, similar to the uranium series, provides insight into the various isotopic transformations of uranium in nature (Word Count Section 2: 603).

3 Experimental Methods

Experimental Flow Chart

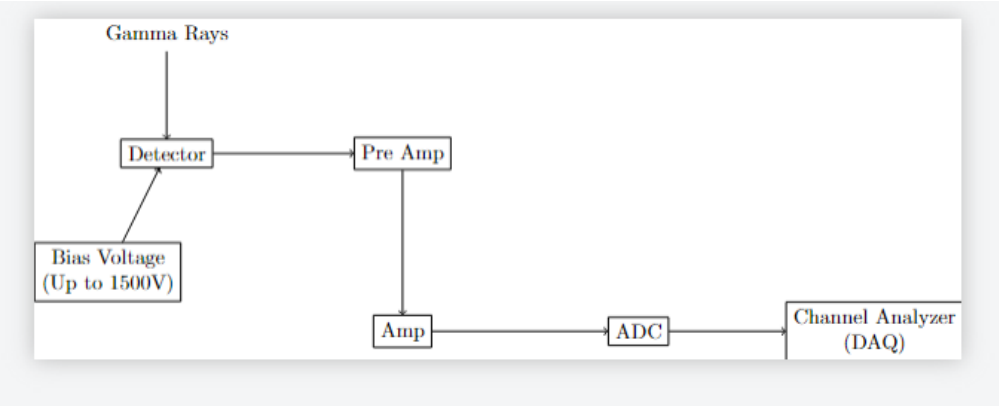

Figure 1: Flow chart view of the experimental setup.

Germanium Detector

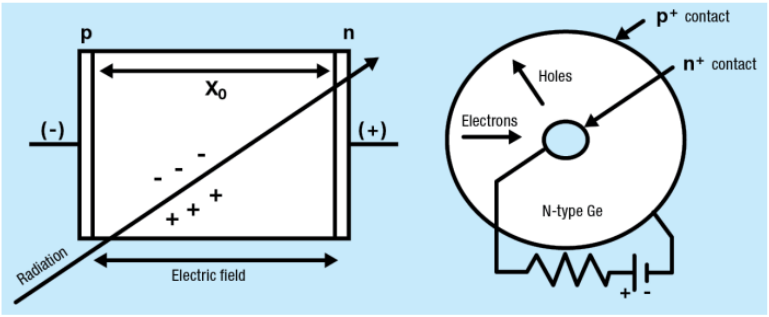

Figure 2: HpGe(Li) Detector Schematic.

Amplifier setting

Parameter	Value
Full Gain	1.195
Course Gain	20
Sharping Time	3 μs
Total Gain	23.9

Table 1: Gain and Sharping Time Parameters

3.1 Description of Apparatus

The equipment that was used for this lab was electronic cords that connected to scope, Amplifier, high voltage/bias shutdown connection, preampamplifier, and shutdown interlock. The germanium detector, with a power supply, DAQ, and oscilloscope were used. The Germanium detector is the most important piece of device in the experiment to where all of our information comes through. As stated earlier, a γ ray from the source goes through the detector to the crystal to where electrons are ejected forming electron/hole pairs. (Figure 2).

3.2 Experimental Procedure

Procedure goes like this; setup all necessary connections and turn the terminal to where we can setup our disk space. Then check if the detector Dewar has been properly setup and cooled because if not it can create a serious issue called thermal leakage and that's an issue because energy resolution and being able to distinguish peaks would be greatly diminished. The temperature has to be kept 60-80K always. Start biasing up to 1500 volts from every 20 volt interval. Each interval entails having to watch oscilloscope to stabilize signal then you keep increasing power supply until you reach 1500 volts. Once that's setup you then go and data collect every source. Each source emits gammas rays which its energy transfer to the crystals electron through various matter processes addressed earlier to finally become an ejected electron having weak signal. The next stage it to go through the electrodes of a PMT to accelerate, to finally at a preamplifier to where that weak electrical signal is strengthen. Next, it goes through an amplifier to get rid of experimental noise, then to an ADC to digitize to a count on a specific channel number, which we as the experimenter can see the spectrum. All of this was described by flow chart of (Figure 1). The gain settings we used to defined and properly get our spectrum's are defined by (Table 1). All of this is saved by our own disk space we defined within the experiment t which we converted the data to xy files to be analyzed later. The sources we used as our main study were ^{133}Ba, ^{137}Cs, ^{60}Co, ^{152}Eu, ^{235}U, and ^{238}U.

3.3 Observed phenomena

With the right gain settings chosen what we observed for each source was the desired spectrum that we expected to see. For this stage, we knew we needed to see peaks patterns on the terminal to match peak patterns already established in literature. Mainly we used the Firestone Tables, and the Idaho Gamma source to see if were getting the right peak patterns for each source [5, 6]. More specifically we looked at specific peaks shapes and see if we could identify them in literature and take a guess what they were. This was mainly important for uranium because it helped us identify which sides represent uranium-235 and uranium-238 peaks.

3.4 Sources Of Error and Minimization

The biggest uncertainty type of question we had in data collection process was how many counts gave us enough information to say such collection was a good one. We did not want to have too little statistics to where we couldn't see the big picture of knowing behavior of samples and detector. So for barium, cesium, and cobalt we got decent peak patterns for about 10-15 min of data collecting where peaks were seen well enough and having count precision from about 2-5%. For europium to uranium sources we decided systematically we would do 3 data collections of those samples and then analyze. The times ranges from 10-15 min, 30 min, 40 min for each times processing of each the samples. Eventually it was good enough counts because we got precision's from 2-3%. (Word Count Section 3: 602)

4 Analysis and Results

Equations List

$$N_S = N_T - N_B \quad (1)$$

$$\sigma_{\text{count}} = \sqrt{N_T + N_B} \quad (2)$$

$$\sigma_{\text{count}} = \sqrt{N} \quad (3)$$

$$R = E_{\text{fit}} - E_{\text{lit}} \quad (4)$$

$$E_{\text{fit}} = aX + b \quad (5)$$

$$I_{\text{exp}} = \left(\frac{N_{\text{res}}}{N_{\text{ref}}}\right) I_{\text{ref}} \quad (6)$$

$$\epsilon_r = \frac{N_i I_{\text{ref}}}{N_{\text{ref}} I_i} \quad (7)$$

$$\sigma_{\epsilon_r} = \sqrt{\left(\frac{\sigma_{\text{count}}}{N_i}\right)^2 + \left(\frac{\sigma_{I_{\text{ref}}}}{I_{\text{ref}}}\right)^2 + \left(\frac{\sigma_{N_{\text{ref}}}}{N_{\text{ref}}}\right)^2 + \left(\frac{\sigma_I}{I}\right)^2} \quad (8)$$

$$\sigma_{\epsilon_r} = \sqrt{\sigma_{\text{frac}}} \cdot \epsilon_r \quad (9)$$

$$\epsilon(E) = aX^2 + bX + C \quad (10) \quad \text{(Low energy: 0-500 keV)}$$

$$\epsilon(E) = aX + b \quad (11) \quad \text{(High energy: 700-1500 keV)}$$

$$N_S = N_{\text{corr}} \cdot \epsilon_r \quad (12)$$

$$N_{\text{corr}} = N_d \cdot I_{\text{abs}}(\%) \quad (13)$$

$$\lambda = \frac{\ln(2)}{t_{1/2}} \quad (14)$$

$$N_{\text{atoms}} = \frac{N_d}{\lambda} \quad (16)$$

$$\text{R} = \frac{N_{235}}{N_{238}} \quad (17)$$

$$\sigma_{\text{Ratio}} = \text{R} \cdot \sqrt{\left(\frac{\sigma_{N_{235}}}{N_{235}}\right)^2 + \left(\frac{\sigma_{N_{238}}}{N_{238}}\right)^2} \quad (18)$$

Ba-133

	Peak 2	**Peak 3**	**Peak 4**	**Peak 5**
N_s (counts)	663	1755	4563	613
N_b (counts)	180	0	0	0
N_T (counts)	843	1755	4563	613
E_L (keV)	276.400	302.851	356.013	383.848
E_F (keV)	276.2961	302.796	356.013	383.92
$\frac{\sigma}{\sqrt{N_s}}$	0.12	0.07	0.04	0.12
σ_{E_L}	0.001	0.001	0.001	0.001
σ_{cal}	0.0069	0.007	0.006	0.06
R (keV)	-0.104	-0.055	0.025	0.072
$\bar{X}$ (channel)	1563.71	1700.76	1976.12	2120.21
σ_{count}	39	42	68	25

Table 2: Ba-133 Peak Parameters

Co-60

	Co-60 Peak 1	**Co-60 Peak 2**
N (counts)	1446	1184
E_L (keV)	1173.237	1332.501
E_F (keV)	1173.28	1332.41
$\frac{\sigma}{\sqrt{N}}$	0.12	0.15
σ_{E_L}	0.004	0.005
σ_{cal}	0.016	0.02
R (keV)	0.043	-0.089
$\bar{X}$ (channel)	6202.74	7025.74
σ_{count}	38	34

Table 3: Co-60 Peak Parameters

Cs-137

	Cs-137 Peak 1
N (counts)	2262
E_L (keV)	661.657
E_F (keV)	661.658
$\frac{\sigma}{\sqrt{N}}$	0.077
σ_{E_L}	0.003
σ_{cal}	0.007
R (keV)	-0.004
$\bar{X}$ (channel)	3556.72
σ_{count}	48

Table 4: Cesium Peak Results.

Calibration Parameters

	Value
a_1	0.193356
b_1	-26.057
Cov(a,b)	-4.12×10^{-8}
σ_a	0.000004
σ_b	0.012

Table 5: Calibration Fit values for function.

Eu-152: Peaks 1-4

Peaks	**1**	**2**	**3**	**4**
N_T (counts)	20758	3478	7179	842
N_s (counts)	19458	2878	6819	468
N_b (counts)	1300	600	360	374
σ_{count}	150	64	87	35
$\frac{\sigma}{\sqrt{N_s}}$	0.018	0.056	0.037	0.25
E_L (keV)	121.782	244.697	344.279	443.965
E_F (keV)	120.370	244.490	344.360	444.106
σ_{E_L}	0.001	0.001	0.001	0.003
σ_{cal}	0.0092	0.000054	0.006	0.006
R (keV)	-1.412	-0.207	0.081	0.141
$\bar{X}$ (channel)	757.292	1399.21	1915.57	2431.59

Table 7: Eu-152 Parameters Peaks 1-4.

Eu-152 Peaks 5-9

Peaks	**5**	**6**	**7**	**8**	**9**
N_T (counts)	1434	1199	795	963	1038
N_s (counts)	840	912	519	657	1005
N_b (counts)	374	287	278	307	33
σ_{count}	43	39	33	36	33
$\frac{\sigma}{\sqrt{N_s}}$	0.16	0.16	0.23	0.21	0.17
E_L (keV)	778.904	964.079	1085.869	1112.069	1408.006
E_F (keV)	778.821	963.810	1085.510	1111.680	1407.350
σ_{E_L}	0.002	0.018	0.024	0.015	0.003
σ_{cal}	0.0086	0.012	0.014	0.006	0.020
R (keV)	-0.083	-0.269	-0.359	-0.389	-0.656
$\bar{X}$ (channel)	4162.67	5119.40	5748.83	5884.15	7413.28

Table 9: Eu-152 Peaks Parameters 5-9.

Efficiencies for Eu-152 Peaks

Peaks	**Energy (keV)**	**Efficiency**
Peak 1 (745-775 channel)	121.782	1.000 ± 0.001
Peak 2 (1385-1410 channel)	244.697	0.557 ± 0.014
Peak 3 (1900-1940 channel)	344.279	0.374 ± 0.0060
Peak 4 (2420-2445 channel)	443.965	0.218 ± 0.016
Peak 5 (4140-4200 channel)	778.821	0.094 ± 0.0049
Peak 6 (5100-5140 channel)	964.079	0.091 ± 0.0039
Peak 7 (5860-5920 channel)	1085.87	0.075 ± 0.0048
Peak 8 (7660-7710 channel)	1112.07	0.071 ± 0.0039
Peak 9 (7380-7440 channel)	1408.01	0.070 ± 0.0024

Table 10: Efficiencies Fit Parameters.

Efficiency Fit Parameters

Energy Range	Parameter	Value	Uncertainty
0-500 keV	a ($p0$)	1.4×10^{-6}	1.2×10^{-6}
	b ($p1$)	-0.0027	0.00084
	c ($p2$)	1.12	0.14
700-1500 keV	a ($p0$)	-3.67×10^{-5}	7.2×10^{-6}
	b ($p1$)	0.120	0.0086

Table 11: Fit Function Parameters for Efficiencies.

Eu-152 Reference Values and Uncertainties (1st Peak)

Parameter	Value	Uncertainty	Units
Reference Count (N_{ref})	19458	149	Counts
Intensity Reference (I_{ref})	28.37	0.13	%

Table 12: Reference Values.

Counts and Intensities for Peaks 2-9 of Eu-152

Peak	Counts (N_i)	Count Uncertainty (σ_{N_i})	Intensity (I_i) (%)	Intensity Uncertainty (σ_{I_i})
Peak 2	2878	64	7.53	0.04
Peak 3	6819	87	26.57	0.11
Peak 4	468	35	3.13	0.014
Peak 5	840	43	12.97	0.06
Peak 6	912	39	14.63	0.06
Peak 7	519	33	10.13	0.05
Peak 8	657	36	13.54	0.06
Peak 9	1005	33	20.85	0.09

Table 13: Eu-152 Counts and Intensities

^{235}U and ^{238}U Peak Parameters

Parameter	U-235 Peak (185.715 keV)	U-238 Peak (1001.7 keV)
Channel Range	1080-1105	5280-5340
Total Counts (N_t)	48816	4580
Background Counts (N_b)	7033	279
Signal Counts (N_s)	41783 ± 236	4301 ± 70
Mean	1092.45 ± 0.013	5311.3 ± 0.070

Table 14: Uranium Parameters

^{235}U and ^{238}U Parameters

Parameter	U-235	U-238
Efficiency	0.678	0.0834
Corrected Counts	61583 ± 248	51560 ± 227
Branching Ratio (%)	57.2 ± 9.0	0.842 ± 0.008
Total Decay Counts (N_{sum})	1077 ± 33	61235 ± 247
Decay Constant (λ) (yr^{-1})	9.85×10^{-10}	1.55×10^{-10}
Half-life ($t_{1/2}$) (yr)	$(7.03 \pm 0.05) \times 10^{8}$	$(4.469 \pm 0.003) \times 10^{9}$
Number of Atoms (N_{atoms})	1.09×10^{12}	3.95×10^{14}

Table 15: Calculated Uranium Parameters

Isotopic Ratio and Uncertainty

Parameter	Value
Isotopic Ratio ($\frac{\text{U-235}}{\text{U-238}}$)	0.00277 ± 0.00005

Table 16: Isotopic Ratio.

Barium Plot

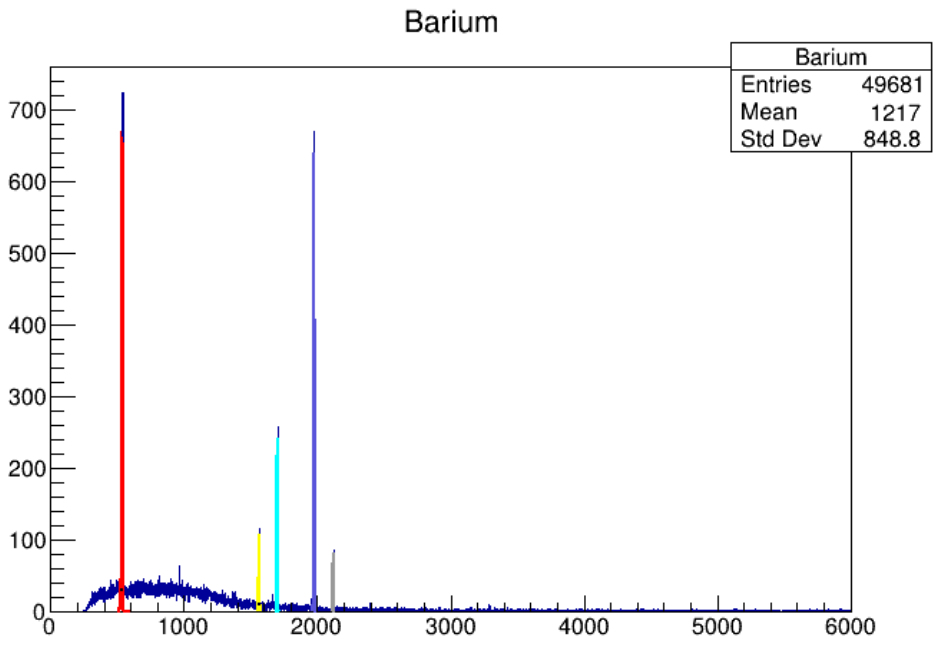

Figure 3: Barium Spectrum.

Cobalt Plot

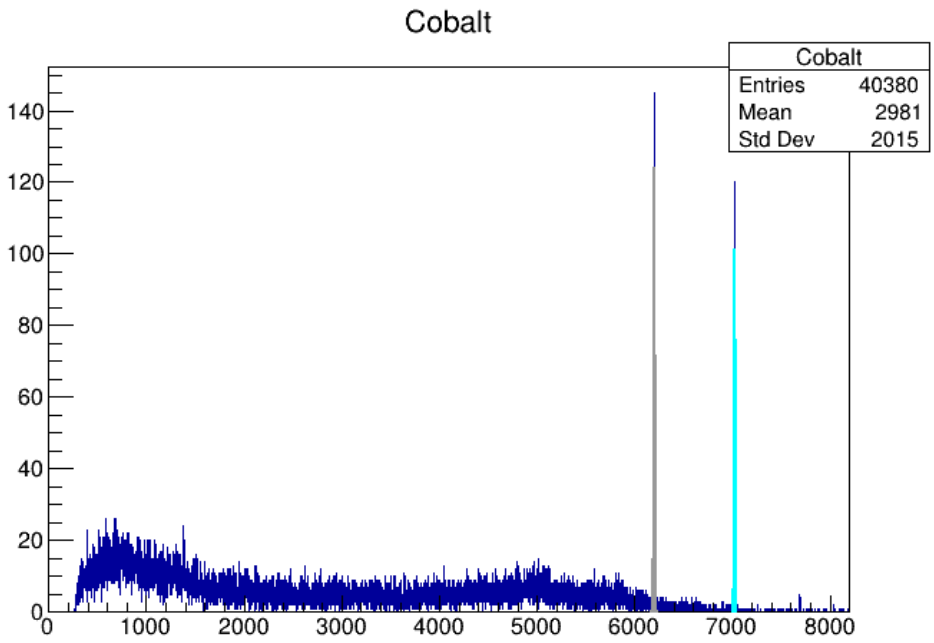

Figure 4: Cobalt Spectrum.

Cesium Plot

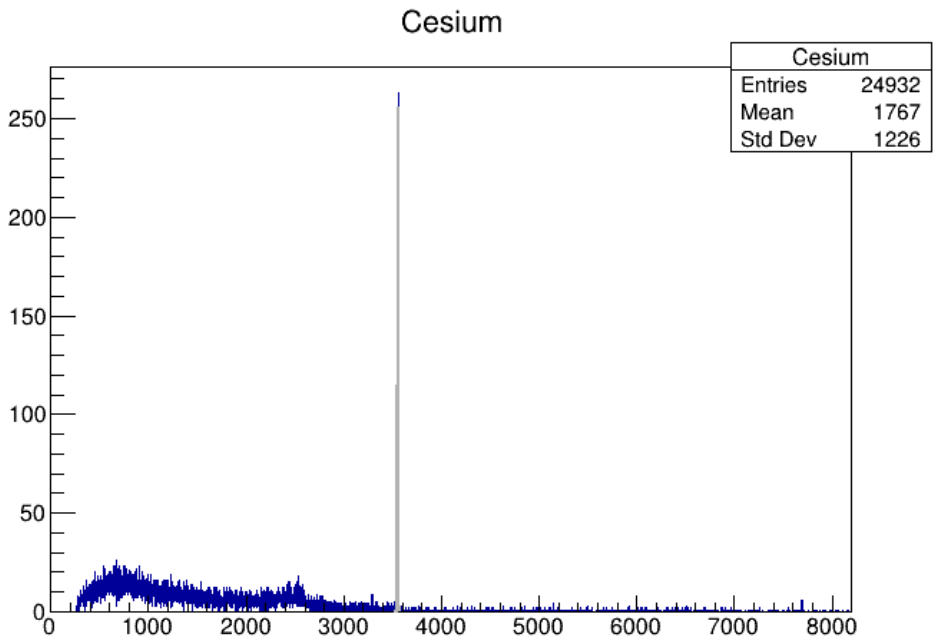

Figure 5: Cesium Spectrum.

Calibrations Plot

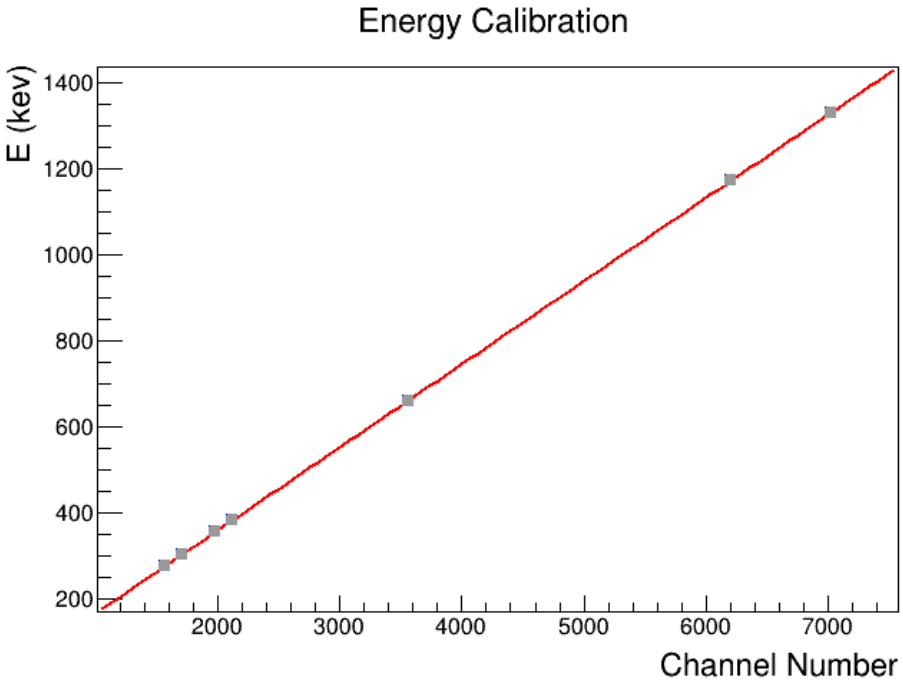

Figure 6: Calibrations Fit.

Europium Plot

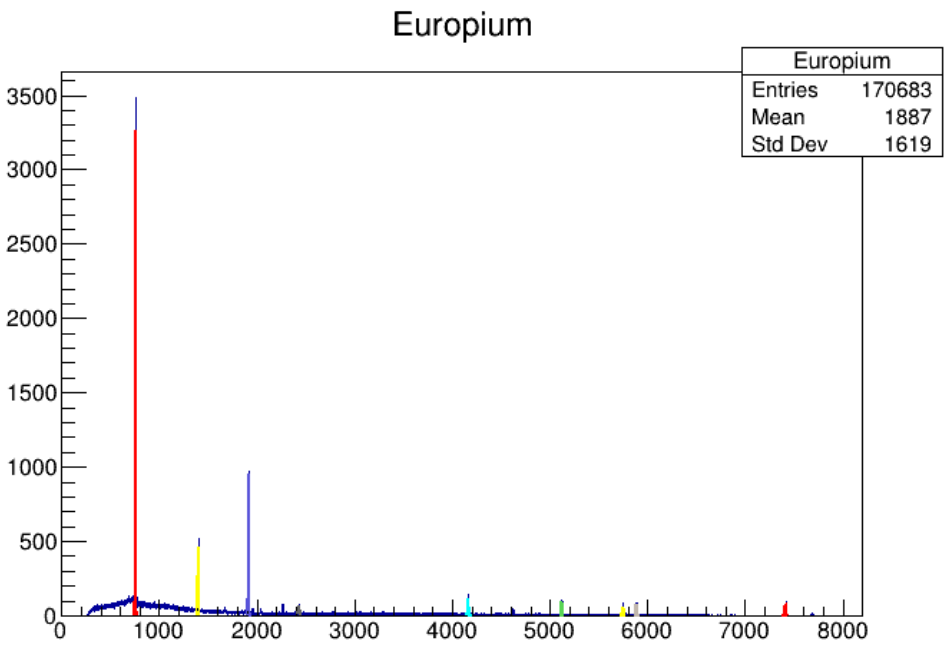

Figure 7: Eu-152 Spectrum.

Efficiencies Plot

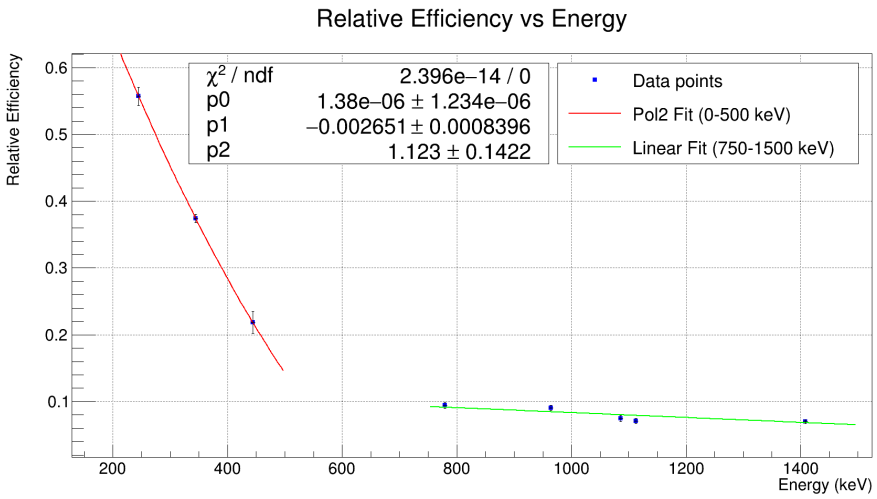

Figure 8: Efficiencies.

Uranium Plot

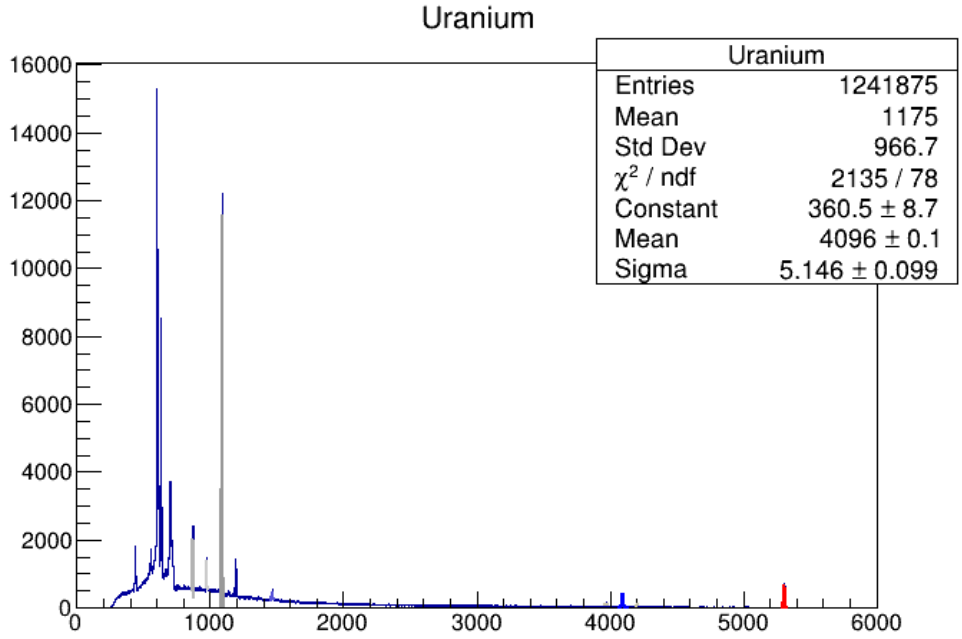

Figure 9: Uranium-235 and Uranium-238 Spectrum..

4.1 Discussion of Results

Once you have all your data files made and are finished with data collection, one of the first things to do is to organize data into an histogram and plot/display it like how (Figures 3-5, 7, 9) are displayed. Then we fitted each peak to peak of each source starting with Barium, Cesium, and Cobalt. I specifically used ROOT for all data analysis; to get mean counts, signal counts, multiple uncertainties and of the first three sources. Then, we compared to online sources like NUDAT, Idaho Gamma Charts, Firestone tables to do peak matching and get literature energy values [5, 6, 7]. This also displayed by tables 2-4 in the text. Then we performed calibration as demonstrated by (Figure 6) and obtained a linear relation that defines a linear relationship between channel number and peak energies. That is defined in (Table5) obtained a parameter a which is a slope term in units (Bin/Energy) and an intercept term b. This then lead us to a crucial element of this experiment which is to see how good our detector can do peak matching by calculating residual and fit and literature energy values. The residuals passed our criteria by being ¡ 2kev which demonstrated that it does good at matching peaks and reliable. Now we perform same process on Europium by organizing it into a histogram, fitting it, getting parameter values, but more importantly using same resources to get absolute intensities and to get efficiencies (Figure7), (Table7) [7]. Now you use Europium Counting parameters and uncertainties and absolute intensities, and literature energies and uncertainties to get efficiencies and uncertainties to be able to get a function form for low and higher kev regions(Figure8), (Table10). Then at the final steps load Uranium data as a histogram,

fit it, identify U-235 and U-238 regions, get those signal counts, count uncertainties and branching ratios from literature. Then for U-235 and U-238 region perform and efficiency correction on each count, get a decay count by dividing by branching ratios, and decay constant of 238/235 to get individual number of atoms of 235 and 238(Figure9), (Table14), (Table15). Then we took the isotopic ratio =which showed that the source was depleted. The value from (Table16), was about .28 +/- 0.005% which is about what one expects for depleted ore which from literature defines around 0.2-0.3% [3] (Word Count Section 4: 393).

5 Conclusion

5.1 Summary of Results

The two main goals of our experiment was how well the can the detector match peaks through residuals/calibration and what is the isotopic abundance of out uranium source. The Residuals we obtained were all less than around 2 kev. The isotopic abundance we measured was .28 +/- 0.005%. Which this shows that the source was depleted and it matches the range of depleted uranium abundance of uranium-235 and uranium-238.

5.2 Further Questions

The next thing I would like to do is to see how good can the detector can do with different uranium ore cross-sections and even different uranium sources. Also, can we get same measurement with different experiment apparatus like shooting the gammas at rectangular scintillation cross-sectional and other (Word Count Section 5: 120).

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