Lab 1: Alpha Spectroscopy

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Abstract

Alpha-particle spectra of Americium-241 (^{241}Am) are collected across an open path through an evacuated chamber and across several absorption depths of nickel foil and gaseous air. A totally depleted silicon surface barrier detector provides a voltage response proportional to the kinetic energy of any alpha particle it absorbs, and this response is used to produce an energy-count spectrum for each situation of interest. Gaussian Distribution fits are used to model the response curves and determine their mean kinetic energies. Linear models describe the attenuation as a function of absorption depth. The alpha-particle spectrum of a radium sample is analyzed, and four alpha-particle peaks associated with the decay chain beginning with radium are identified. The Gaussian fits and energy scaling are not exceedingly accurate, but close enough to provide confirmation that these structures so exist and could be pin-pointed more precisely.

1 Introduction

Spectroscopy of alpha radiation is a method for testing and measuring the properties of any alpha emitter, which is a class of radioactive particles that emit alpha particles, a bound collection of two protons and two neutrons. This is one of the primary classes of radiation, along with beta and gamma radiation, and of these the only hadronic form of radiation. An alpha particle is emitted during alpha decay of a nucleus, when the nucleus gives off 2 protons and 2 neutrons. The isotope loses 2 from its atomic number, decaying into an isotope of a new element. Radium decays by emitting an alpha particle into the daughter element Radon, then Polonium, and then Lead. This isotope of Lead decays through beta decay – the emission of an electron and a neutrino – into Bismuth, which then decays through alpha emission into Thallium. Alpha particles created in this process often have kinetic energy near 5 MeV and are highly ionizing, but with a small penetration depth. They are therefore not considered a dangerous form of radiation unless ingested.

This exercise explores the kinetic energy spectrum of alpha particles emitted by an Americium-241 sample and a Radium sample. The physics student gains greater confidence in physical theory by confirming the alpha particle activity from the Americium sample, and quantifying the loss as a function of absorption depth through an impeding medium. The alpha decay chain beginning with Radium, consisting of four distinct alpha emission processes, is also confirmed.

2 Alpha Detector and Energy Profile

A totally depleted silicon surface barrier (ORTEC model B) is used to count alpha particles emitted by samples used in this study. This detector absorbs alpha particles, transducing their kinetic energy into electronic activity. The detector provides a signal in the form of a potential difference, proportional to the kinetic energy of the absorbed alpha particle. Signals are collected in this

way to generate each spectrum of alpha particle kinetic energy. The active detection area of the device was not measured, and this is a major oversight. Quantifications made in this work are fundamentally a flux through this single surface with constant area, so this oversight should not be consequential. As a rough estimate, the detection area is round with radius of approximately half of one centimeter.

Maestro software is used to operate a sensor on which 8191 channels monitor a linear domain of voltage inputs. This device monitors the alpha detector's output signal, and because this signal is proportional to the kinetic energy of the absorbed alpha particle, this setup provides a profile of the kinetic energy of particles absorbed by the detector. These data are saved to a plaintext file for analysis.

3 Energy-Domain Analysis

The primary mode of study here will be to compare energy values determined by fitting Gaussian Distributions whose means μ are associated with an average kinetic energy of an alpha particle from the incident emitter. To serve as a strong confirmation of undergraduate concepts, results need not be terribly precise. If the correct patterns are seen in the data, the processes will be confirmed, and if all values of energy agreed with published experimental values to within 30%, a generous tolerance, this would be very satisfactory. The Gaussian Distribution is not a very good fit for these data, but this rough determination may be sufficient under these tolerant criteria.

3.1 Calibration of Energy Scale

An unimpeded alpha particle spectrum is collected to calibrate the energy scale. Measurements of the vacuum were not taken at this stage, another glaring omission, but from vacuum measurements taken during other trials, it appears safe to assume a pressure of less than 40 millitorr. Processing by the gas molecules still in the chamber does reduce the observed kinetic energy, but this effect is likely to be insignificant. The Americium emission peak is fitted to a Gaussian distribution with parameters $(\mu = 7813.84, \sigma = 68.82)$ in channel units, drawn with a blue line in figure 1. This fit leaves a residual sum-of-squares of 183325; this poor quality measure is not surprising given the extreme length of the tail. The distribution is negatively skewed and so would likely better fit to a Mirror Gumbel Distribution. The energy scale is calibrated by setting the mean of the Gaussian peak μ to the experimentally-determined value $5.486MeV$(85% likelihood) [3], and $0V = 0MeV$.

3.2 Absolute Activity

The absolute activity I_α of the Americium-241 alpha emitter, in alpha particles per second, is computed from counts of alpha particles through the detector over a known amount of time. The number of alpha particles detected Σ_α is related by the solid angle subtended by the detector on the source, and the time the detector was live t_L, to the total number of alpha particles emitted by the sample. The cross-sectional area of the circular detector is πr^2, with r the radius of the detector, s is the distance from the source to the detector, and assuming there are no reflection effects, then

$$I_\alpha = \left(\frac{\Sigma\_\alpha}{t_L}\right)\left(\frac{4\pi s^2}{\pi r^2}\right). \text{ [2]}$$

There are three significant energy modes of the alpha emission from Americium-241, with varying probability of incidence: $5486keV(85\%probability)$; $5443keV(13\%)$; and $5388keV(1\%)$. [3] The sum of each peak must be added to obtain a total count of alpha particles detected.

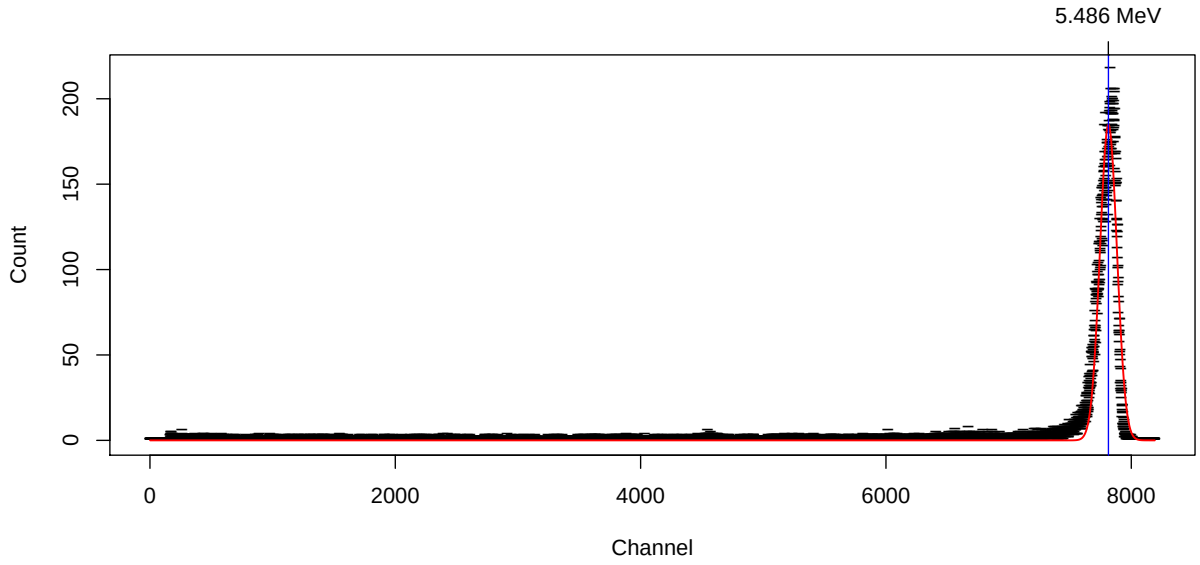

Figure 1: The alpha particle spectrum of an unimpeded Americium-241 source is collected and fitted to a Gaussian Distribution with mean channel 7813.84. The energy scale is calibrated to this value at $5.486 MeV$

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These peaks were impossible to discern from inspection, as the overall magnitude of the activity across that domain out-competed the nuanced distinction. The counts were summed over a bin deemed sufficient to cover all three modes based on the referenced relative energies. This bin is marked in red on figure 2.

The detector's radius is measured using a flimsy ruler as $5.25 \pm 0.5mm$ The Americium sample is placed $38.5 \pm 0.5mm$ from the detector, and the chamber is evacuated to $30 \pm 2.5 millitorr$. The detector is allowed to run for $3012.56 \pm .005 seconds$ and 11956 detections are registered in that time. The absolute activity computed with this technique is 854 ± 82 alpha particles per second. A standard unit for radioactive activity is the Curie, or microCurie μCi, and $1\mu Ci = 3.7 \times 10^4$ emitted particles [2], and in this case $I_\alpha = 0.034 \pm 0.0022 \mu Ci$.

4 Energy Loss through an Absorber

When an absorber is present between the alpha radiation source and the detector, alpha particles still reach the detector but with a reduced kinetic energy. This energy is lost mainly to ionization and excitation of atoms in the material [4]. This response is studied as alpha particles travel through a series of thin films and through typical air, which is primarily N_2 gas. In each case, the absorption depth is characterized by a Δx in units of mg/cm^2, which is a typical unit used to normalize depths between materials for comparison. This feature is used to compare the loss of energy through a thin film against the loss of energy through a gaseous absorber.

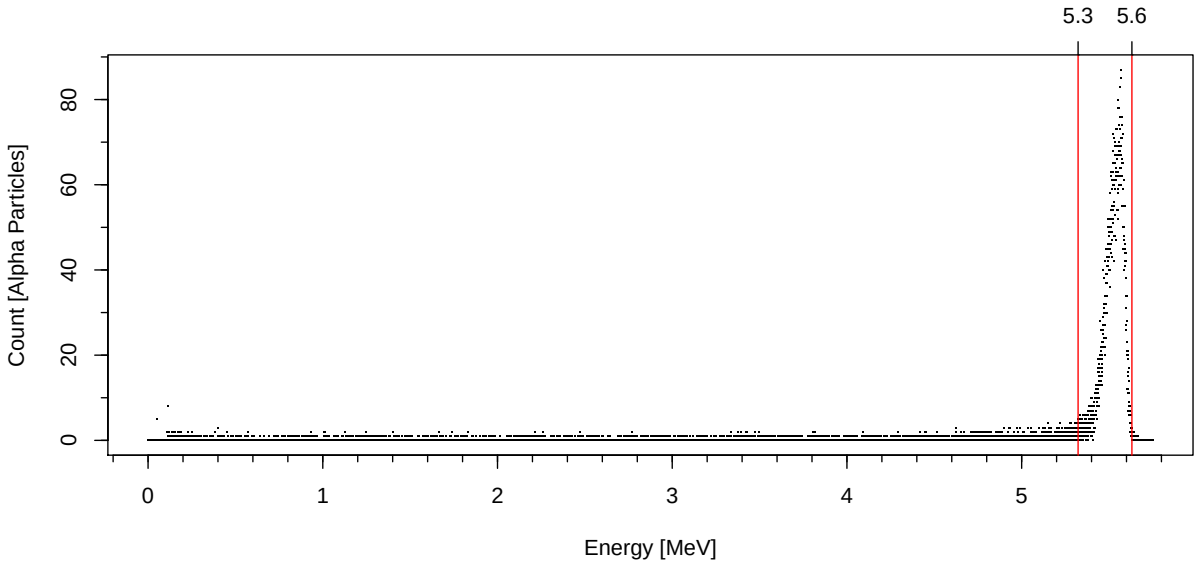

Figure 2: To determine the absolute activity of the Americium-241 alpha emitter, the number of alpha particle detections registered within the domain indicated by the two red lines are counted.

4.1 Interference from a Thin Film

A thin film placed between the source and the detector causes interference such that a loss of energy should be observed, proportional to the penetration depth of the foil. In order to build a rough model of this response function, 3 thicknesses of Nickel foil are placed between the detector and the source, and the average kinetic energy of the alpha particles emitted from the Americium-241 sample is computed using the Gaussian fit as outlined above for each condition. The thicknesses and computed average kinetic energies are tabulated below, with the error for the kinetic energy computed as the standard deviation of the mean, i.e., $\frac{\sigma}{\sqrt{n}}$. The density of Nickel near room temperature is extremly well-known to be approximately $\rho_{nickel} = 8908 mg/cm^3$. The absorption depth is therefore computed as $\Delta x = \rho_{nickel} T$ where T is the thickness of the absorber in centimeters.

4.2 Interference from a Gas

A gas can act as an attenuator similarly to a film. An alpha spectrum is collected under increasing pressure (8 settings total). The gas occupies the entire space between the source and the detecter, so the depth is exactly that distance, but at each step the density changes, dependent on the pressure. Here, air is used as the absorbant gas, and the pressure is reported by a simple spin gauge connected to the vacuum chamber. The density of air at room temperature can be estimated as $\rho_A = 1.28 mg/cm^3$, [1] and while this number is presented without uncertainty, it is an estimate only and can be considered accurate to the precision it is quoted here. Then, assuming any changes to equilibrium between gasses inside the chamber and outside occur quasistatically, the density of the gas ρ_P at a given pressure P can be related to its density at atmospheric pressure P_A as

$$\rho_P = \frac{P}{P_A} \rho_A.$$

From these densities, and using the distance from the source to the detector, an absorption

depth can be computed with the same units as the thin film, using the relationship

$$\Delta x = \rho_P s,$$

where s is the distance from the source to the detector.

Foil Depth $[mg/cm^2]$	Kinetic Energy $[MeV]$	ΔE $[MeV]$
0 ± 0.11	5.55 ± 0.0005	0 ± 0.0007
0.57 ± 0.11	5.26 ± 0.0006	-0.29 ± 0.0008
1.13 ± 0.11	4.95 ± 0.0006	-0.6 ± 0.0008
2.26 ± 0.11	4.38 ± 0.0007	-1.17 ± 0.0009
Gas Depth $[mg/cm^2]$	Kinetic Energy $[MeV]$	ΔE $[MeV]$
$0.0002 \pm 1.67 \times 10^{-5}$	5.53 ± 0.1	0 ± 0.1
1.02 ± 0.04	5.27 ± 0.1	-0.26 ± 0.1
1.68 ± 0.08	5.03 ± 0.1	-0.5 ± 0.1
2.35 ± 0.15	4.75 ± 0.1	-0.78 ± 0.1
3.03 ± 0.25	4.45 ± 0.1	-1.08 ± 0.1
3.70 ± 0.46	4.16 ± 0.1	-1.37 ± 0.1
4.38 ± 1.10	3.83 ± 0.1	-1.7 ± 0.1
5.06 ± 0.17	3.43 ± 0.1	-2.1 ± 0.1

Table 1: Alpha particle absorption depths and energy losses through foil and gaseous absorbers. Energy is lost primarily to ionization processes and electrostatic interactions with atoms and ions in the medium.

In both cases, the relationship between ΔE and Δx appears to be approximately linear. Performing a linear regression on each data set provides a slope and intercept describing the relationship, with reasonable fit goodness. For the foil, the response function

$$\Delta E \approx -0.52 \Delta x,$$

and for the gaseous absorber,

$$\Delta E \approx -0.42 \Delta x + 0.14.$$

5 Radium Alpha Decay Chain

The spectrum emergent from the alpha-beta decay chain that is fathered by Thorium is of interest to the physics student as another confirmation of the quantum mechanics theory taught as part of that education. The lab does not hold Thorium, but the Radium sample is the first daughter of an alpha decay process beginning with Thorium, and the lab does hold a Radium sample. Larson provides an excellent table of the various decay processes with expected observed kinetic energies of the alpha particles emergent from those processes. To confirm that these peaks exist, a sample of radium with unknown purity is placed in the detector vacuum chamber uninhibited, the chamber is evacuated, and the sensor is activated and left on to apparent convergence of the peaks.

Figure 4 predicts that four alpha particle kinetic energies should be observed by the detector: $5.78MeV; 6.88MeV; 7.53MeV$; and $6.67MeV$. In fact, four peaks are readily observable in the sensor output, and can be seen in figure 5. One could split these peaks and fit Gaussian or other

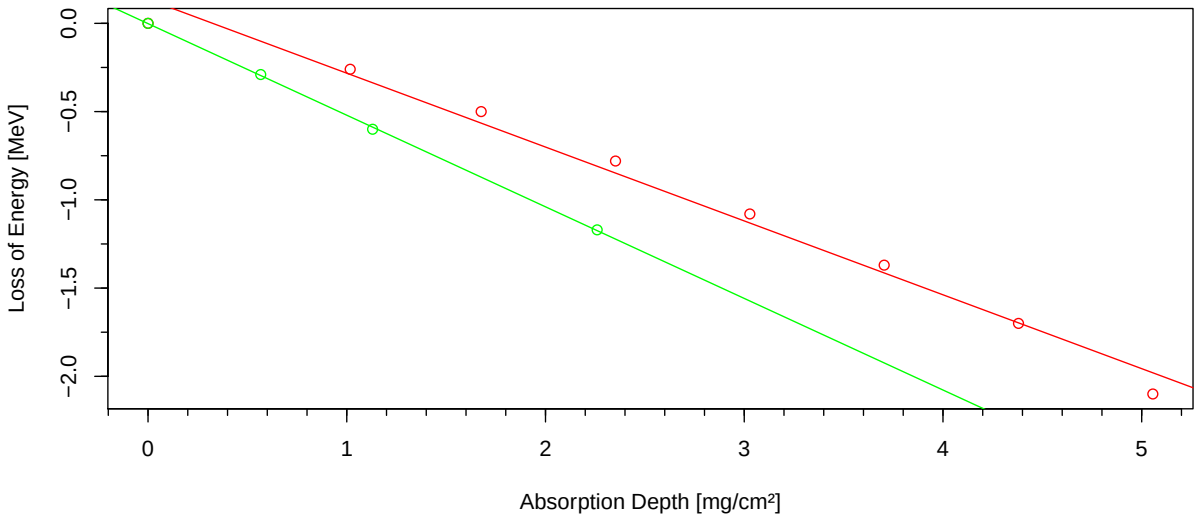

Figure 3: The green figure tracks ΔE as a function of absorption depth through the nickel foil. The Red figure tracks the same through the gaseous absorber (standard air).

Nuclide	Decay mode	Mean particle energy (MeV)	Half-life
^{227}Th	α	6.02	18.72 days
^{223}Ra	α	5.78	11.43 days
^{219}Rn	α	6.88	3.96 seconds
^{215}Po	α	7.53	1.78 ms
^{211}Pb	β	0.45	36.1 minutes
^{211}Bi	α	6.67	2.17 minutes
^{207}Tl	β	1.42	4.77 minutes
^{207}Pb			Stable

Figure 4: A table of decay processes beginning with Thorium and travering the Radium to Thallium chain. [5]

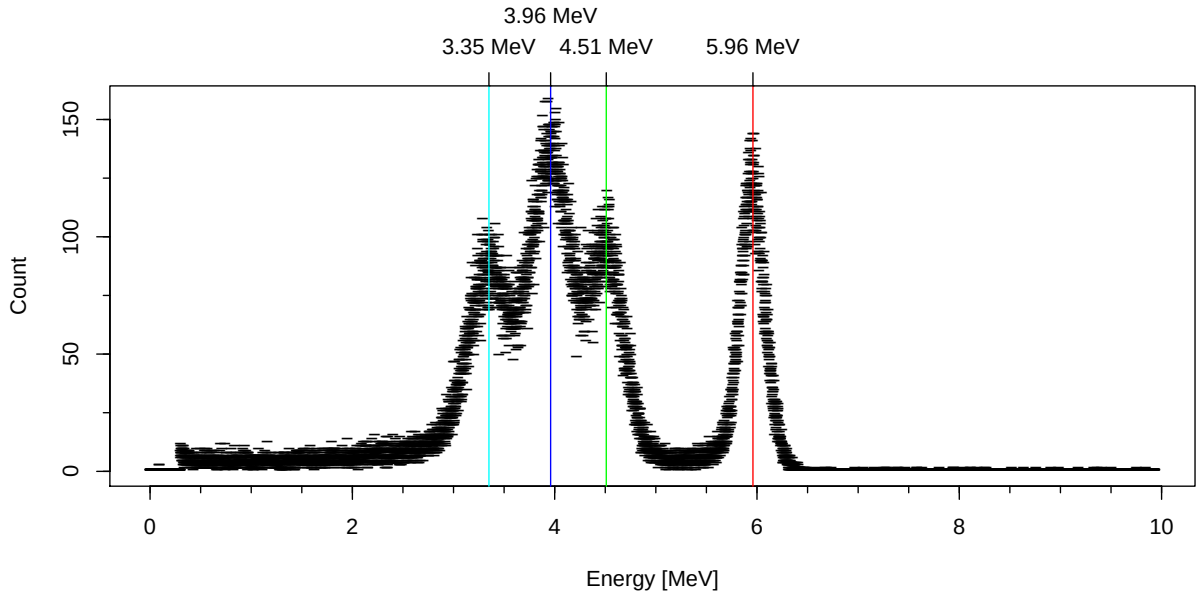

Figure 5: Four distinct peaks are observed when the radium sample activity is monitored. The scale appears miscalibrated by a significant amount, but the ratios of peaks approximately match those published by Larsen [5].

distributions to them to find their means and deviations. However, because this study does not require great precision (truly, it seems the existence of the decay chain is confirmed without any additional analyses), simply making a best guess of the mean using observation and a ruler should be sufficient. The *voltage* $\propto$ *energy* scaling used throughout this work was scaled too widely to fit the largest energy peak onto the spectrum, so the scaling was adjusted by a factor of $\frac{11}{18}$ by adjusting the amplification into the sensor by that amount.

6 Discussion

The known value for radioactivity of Americium-241 is given in terms of per mass ($3.43 Ci/gram$ [3]), but it was not possible to measure the mass of Americium in this sample. The sample is adorned with a screw of comparable length and volume, such that it would be exceedingly difficult to determine the mass of the Americium alone. It is therefore not possible to make a comparison to known values for this quantity. At least, the absolute activity, computed to be 854 ± 82 alpha particles emitted per second, or $0.034 \pm 0.0022 \mu Ci$, is within a reasonable domain of values.

The radium peaks clearly indicate that the energy scale is not well-calibrated. Lower energy peaks are farther from known experimental values – $5.96/7.53 \approx 0.79$ vs. $3.35/5.78 \approx .58$. This analysis would benefit greatly from more rigorous experimental controls and a finer tuning of the scale and fitting functions. Still, at 40% variance, with the variance as consistent as it is, these observations strongly support the existence of the Radium to Thallium alpha-beta decay chain.

The absorption response curves have a strongly linear nature. Of interest is the difference in slope between the response to the foil depth compared to that of the gaseous absorber. It seems that alpha radiation attenuates more strongly through the solid material than through open air. I believe this is mostly a failure of the simplifications and that the difference in slope might be

well-explained by some missed nuance that would inform the model of less interactions than it currently expects across the absorption depth. This does bode well for safety concerns, in that the hard response to passing through either material indicates that while alpha particles are strongly ionizing, they do not penetrate deeply into materials, supporting that idea that one's skin will provide a protective layer against this type of radiation. If the radiative source were ingested, however, the epithelium would no longer provide protection against harmful effects.

References

[1] *Air - Density and Specific Weight*. URL: http://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html.

[2] *Alpha Spectroscopy with Silicon Charged-Particle Detectors*. Instruction Manual. ORTEC. 801 South Illinois Ave., Oak Ridge, TN 37831-0895 U.S.A.

[3] *Americium-241*. Tech. rep. University of Cincinnati. URL: http://www.researchcompliance.uc.edu/Libraries/Isotopes/Am-241.sflb.ashx.

[4] *Energy Loss with Heavy Charged Particles*. Instruction Manual. ORTEC. 801 South Illinois Ave., Oak Ridge, TN 37831-0895 U.S.A.

[5] R. Larsen and Ø. Bruland. *Thorium-227 for use in radiotherapy of soft tissue disease*. WO Patent App. PCT/GB2004/001,654. Oct. 2004. URL: http://www.google.com/patents/WO2004091668A1?cl=en.