NUCLEAR SPECTROSCOPY

CASPAR LANT

Intermediate Experimental Physics II

Section:	002
Date Performed:	April $\sqrt{2}$, 2016
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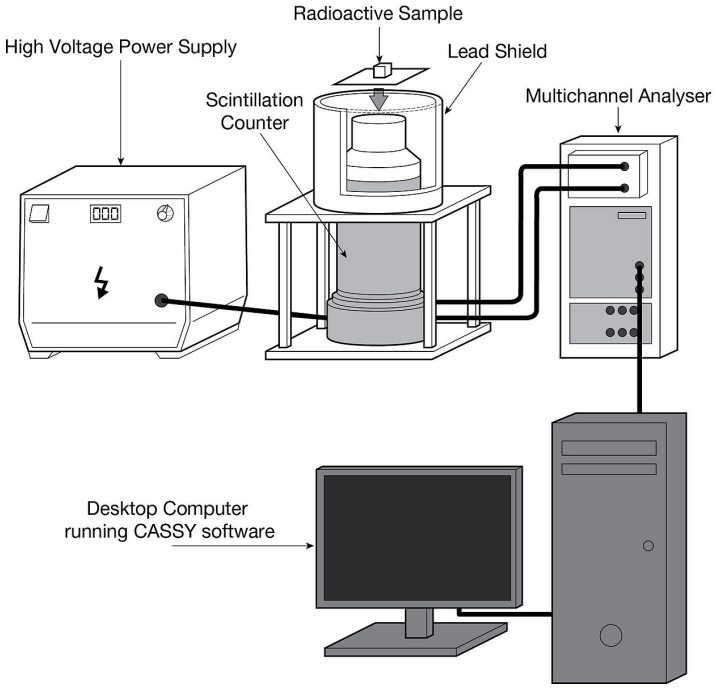

Date: May 6, 2016.

The Objective of this experiment was to familiarize ourselves with the technique of nuclear spectroscopy, and to explore the effects of using shielding materials in this technique.

1. Theoretical Background/ Abstract

Nuclear decay (or radioactivity) is a process that occurs in nuclei of unstable isotopes of typically heavy elements—those with high atomic number. In this process, an energetic proton or neutron will spontaneously decay into a beta particle or an alpha particle respectively, as well as some gamma rays to account for energy conservation. This process is said to be stochastic, making it impossible to predict when a particular atom will decay. Despite this, each isotope has some has some known probability for nuclear decay, so for a large arrangement of atoms, decay rate will be fairly predictable. The time it takes for half the atoms in a given substance to decay is known as its half-life. This value is consistent for all samples of a given isotope, but can vary tremendously across different substances. The shortest recorded half-life is on the scale of 10^{-23} seconds (Hydrogen-5 and -7), while the longest is held by Tellurium-128 at 10^{24} years, which is much longer than the universe has existed!

In this lab, we will examine the nuclear decay processes of Cesium-137, which has a half-life of 30.2 years. This may seem like too long a time for this isotope to be a good experimental subject, but it's actually ideal: The instruments we will use in this lab are sensitive to the decay of individual beta particles. For a 1 mole sample of Cesium-137, containing approximately Avogadro's number of atoms, we can expect to see a large amount of nuclear activity in our minute-scale sampling period. Isotopes with a longer half-life would decay too slowly, and those with short half-lives are to volatile to be studied, as their decay rate exceeds the sampling rate of our instrumentation.

When a radioactive isotope decays into its daughter product, it also emits gamma rays with a some regular frequency spectrum. Analyzing this spectrum can be used to identify the composition of the decaying source material. Examining the characteristic energy spectra emitted from a decaying radioactive isotope is known as nuclear spectroscopy.

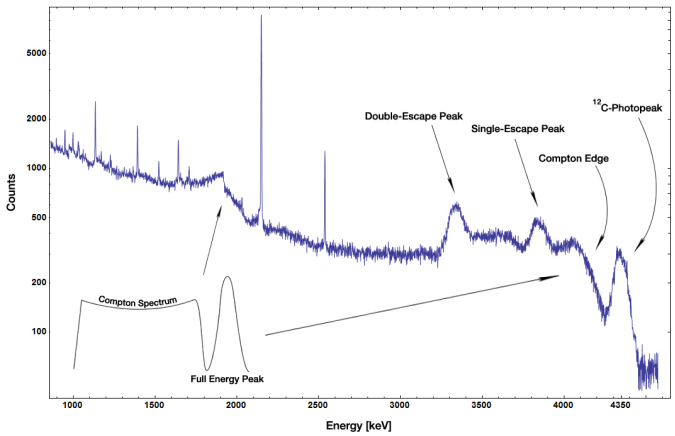

FIGURE 1. The Energy Spectrum of A Radioactive Isotope

Beta decay is a process in which the proton of an atom is transformed into a neutron, or vice-versa. This happens inside the atom's nucleus, which the resultant particles and energy soon escape. There are two types of beta decay, β^- and β^+. As you may have guessed, β^- decay produces a negatively charged particle (among other things), where β^+ produces a positively-charged particle, known as a positron.

$$p \to n + \beta^+ + \nu_e \tag{1}$$

Where β^+ is a so-called beta particle: a high-energy, high-speed positron emitted in radioactive decay. The twin decay process, β^--decay, is characterized by the following reaction formula:

$$n \to p + \beta^- + \bar{\nu}_e \tag{2}$$

β^- is again a beta particle, but this time it's an electron instead of a positron. $\bar{\nu}_e$ is an **electron anti-neutrino**, the antiparticle of the electron neutrino shown in Equation 1. It's largely there to make sure that energy is conserved in the decay process. To calculate the energy of a beta particle incident on our detector, we must take into account the energy lost by the ionization and excitation of particles in our detection apparatus. This gives us the following:

$$\frac{\mathrm{d}E}{\mathrm{d}x} \propto \frac{z^2 e^2 N Z}{m V^2} \tag{3}$$

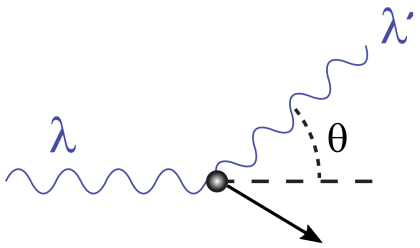

FIGURE 2. Compton Scattering

Where Z is the atomic number of the absorber, N is the atomic density of the absorber, in particles-per-length-cubed, and V is the speed of the radiation. $E, x, e,$ and$m$ hold the conventional meanings. The absorber in this lab makes use of the famous photoelectric effect, which won Einstein a nobel prize in the early 20th century. The so-called internal photoelectric effect occurs when an incident energized particle (classically a photon) causes an atom in the receptive material to eject an electron, which can be detected as a current. The ejected looses its energy quickly, but not before it is detected. The constant of photoelectric absorption (known as the absorption cross-section), which is a measure of how "receptive" a material is to an incident photon is approximated by the following:

$$\sigma_{pe} \approx \text{constant} \frac{Z^4}{(h\nu)^3} \tag{4}$$

Where h is Planck's constant, Z is again the atomic number of the atoms in the material, and ν is the frequency of the radiated/incident particle.

The Compton effect describes the scattering of a photon off a stationary electron. In this process, the photon loses some of its energy (given by $h\nu$), which we'll call E_γ. The final energy of the photon after scattering is given by:

$$E_{\gamma\prime} = \frac{1}{1 + (E_\gamma / mc^2)(1 - \cos\phi)} \tag{5}$$

ϕ is the angle through which the photon has been scattered, between 0 and 2π. This is illustrated in Figure 2. Lastly, the intensity of a gamma ray is given by equation 6, where μ is the linear attenuation coefficient, which characterizes how easily a material (in this case the bulk of our scintillator) can be penetrated by the the incident ray (per unit length—by dimensional analysis). A large linear

attenuation coefficient is descriptive of a material that quickly attenuates an incident gamma ray. This is shown symbolically by the following:

$$I = I_0 e^{-\mu x} \tag{6}$$

2. Experimental Procedure

(1) Turn on the amplifier and geiger counter assemblies.

(2) Turn on the computer and open the software interface.

(3) Ensure that all the connections are made between the geiger counter, the amplifier, and the software interface.

(4) Remove the 3 lead bricks from the front of the spectroscopy enclosure, making sure not to lick them in the process.

(5) Do not drop them on your feet either.

(6) Or your partner's feet.

(7) Place a test sample in the measurement enclosure to make sure that your geiger counter is working properly. Take a small spectroscopy measurement as well.

(8) Tune the measuring parameters to the settings marked in your lab manual: Multichannel Measurement, Number of Channels = 512, Measuring Time = 20 s, ✓ in Negative Pulses box, Gain Slider = X1

(9) Turn the voltage on the power supply to 600V.

(10) place the Cs-137 inside the spectroscopy enclosure.

(11) Return the lead bricks to the spectroscopy enclosure.

(12) Run the CASSY software interface and don't forget to save your datums.

(13) Place shields of varying composition and thickness in between the sample and the geiger counter.

(14) Observe their effect.

(15) Do the same for the Americanium.

3. Graphs and Tables

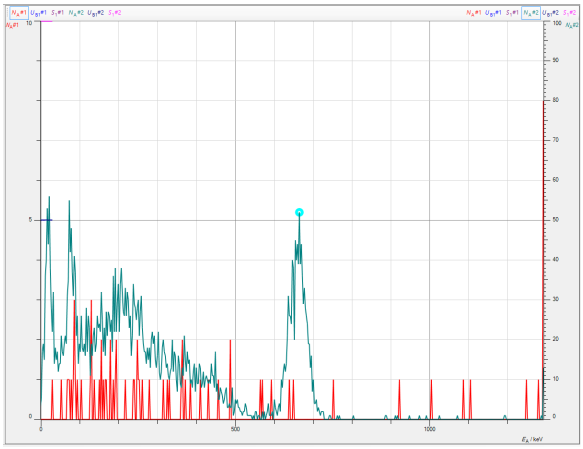

Figure 3.
Cs-137 and Background Noise

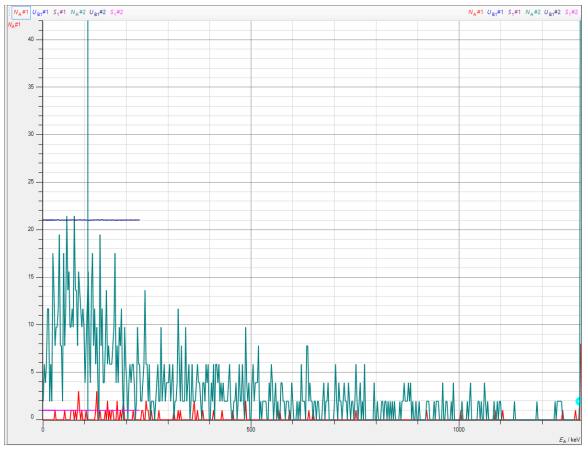

Figure 4.
Sr-90 and Background Radiation

Table 1. Energies of Peak Spectra in Two Materials

Material	bin #	Energy (keV)
Am-241	32	59.54
Cs-137	266	661.66

Table 2. Measuring the Effects of Various Shields

Material	Thickness (mm) ±0.1mm	N
None	0	10338
Aluminum	2.1	10345
Aluminum	3.1	10176
Copper	3.0	9495
Lead	1.1	9246
Lead	2.4	7862
Lead	3.4	6849
Lead	8.4	4980

As can be seen, aluminum seems to had no effect in blocking the radiation of Cesium-137. This is likely due to the fact that its absorption spectrum does not overlap with the emission spectrum of cesium. It is therefore said to be "transparent" to these energies. I would feel more confident in this assertion if we had been given a greater variety in thickness of aluminum shields, but alas, we were not. Lead, as you can plainly see from the above table as well as the python plot below, has a large effect on the shielding the beta radiation of cesium. It follows that a peak along its absorption spectrum lines up nicely with cesium's characteristic energy emission level. The absorption coefficient

that we determined for lead was about $e^{-0.42} \approx 0.6\mu/\text{mm}^2$, given by the exponent of the slope of our logarithmic plot (done to use the linear chi-squared fit technique).

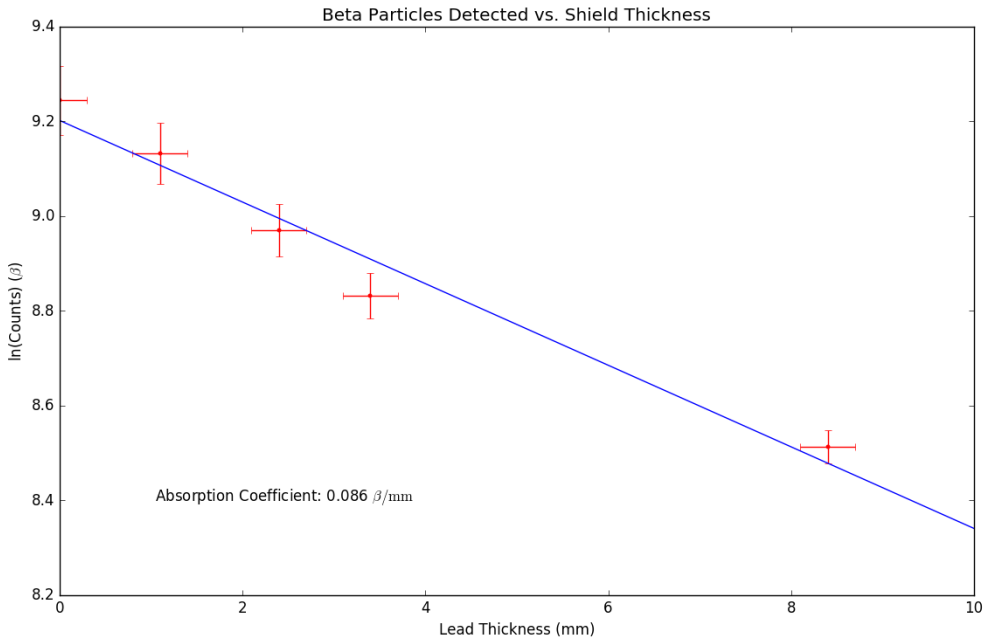

FIGURE 5. Calculating the Absorption Coefficient of Lead

4. QUESTIONS

(1) *How does the absorption coefficient depend on the mass density of the absorber?*

Given that lead, and very dense material, was a better absorber than copper (which is a less-dense material) is indication that higher mass density positively affects the absorption coefficient of a material. I'd guess, however, that this mass density is not the only factor that influences the absorption coefficient: other metrics, like the arrangement of atoms in a given material, also contribute to its absorption coefficient.

(2) *How does the absorption coefficient depend on the energy of the gamma ray?*

Higher energy gamma rays have less trouble getting through a material than less energetic rays, which is to say that the energy of a gamma ray in inversely correlated to the absorption coefficient of a shielding material.

5. Analysis

As you can see in table 2, aluminum seems to had no effect in blocking the radiation of Cesium-137. This is likely due to the fact that its absorption spectrum does not overlap with the emission spectrum of cesium. It is therefore said to be "transparent" to these energies. I would feel more confident in this assertion if we had been given a greater variety in thickness of aluminum shields, but alas, we were not. Lead, as you can plainly see from the above table as well as the python plot below, has a large effect on the shielding the beta radiation of cesium. It follows that a peak along its absorption spectrum lines up nicely with cesium's characteristic energy emission level. The absorption coefficient that we determined for lead was about $e^{-0.42} \approx 0.6\mu/\text{mm}^2$, given by the exponent of the slope of our logarithmic plot (done to use the linear chi-squared fit technique).

Unfortunately, the number of bins in the CASSY histogram exceeded the size of the buffer that my plotting library (Matplotlib) uses to store data. Python allocates virtual memory to a running python script to prevent accidental damage to computer architecture, and although I'm sure there is a way to disable this, I wasn't sure how to. This all meant that I was not able to plot the nuclear spectroscopy data in python to subtract my noise measurement from the signal. This will have produced some uncertainty in my measure of radiated particles, although presumably the level of noise (number of extraneous particles) was constant throughout my measurement period, so it's probably not something to worry about. Another source of uncertainty lies in the precision of the power supply, which only displayed 2 significant figures in a measurement of thousands of volts. The largest uncertainty source by far, however, was in my measurement of the shield widths. The error bars in figure 5 are given by my uncertainty in the measurement of shield width (I gave myself ± 0.3mm to work with). With the error bars in place, nearly all points touch the best-fit line, which convinces me that our other uncertainties can be discounted.

A final source of uncertainty is in the number of counts picked up by the scintillator. The instrument itself is very precise, but the enclosure of lead bricks around is far from unpeermeable. We can assume that the uncertainty in counts increases linearly with the number of counts, with a prefactor of one particle per hundred particles. That is, one erroneous particle for every hundred radiated particles. This ratio, 1/100, comes from integrating under the noise measurement.