Radioactivity: Random Decay Processes and Shielding Application

PS253 — Physics Laboratory for Engineers

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Safety Notices

⚠ **Lead (Pb) Warning** – The purpose of this lab necessitates the handling of lead (Pb) sheets.

Lead is a human health hazard if ingested or inhaled, and a long-term environmental hazard. Following the below safety guidelines minimizes any health risk.

DO NOT rub, bend, stretch, tear, cut, or deform the lead sheets in any way. Students seen 'playing' with the lead sheets will be asked to leave lab *immediately*.

⚠ **Personal Protective Equipment** – When handling the lead sheets you MUST wear nitrile gloves. It is advised you glove and handle the Pb with your non-dominant hand; this leaves your dominant hand free to write without further contamination.

⚠ **Personal Safety Practices** – DO NOT at any time consume food, drink liquids, or apply beauty or skincare products. Refrain from rubbing your face with your hands.

Before leaving lab you MUST wash your hands with soap and water.

Always place a paper towel or Kimwipe between the Pb sheets and the table, DO NOT place the Pb sheets on the bare table surface.

⚠ **Radioactivity Notice** – The radioactive sources used are license exempt quantities which are fully sealed in a resin container. The disk sources are safe to handle and pose no risk of acute exposure, it would require weeks of constant close contact to obtain a significant radiation dose.

Introduction

Alpha (α), beta (β), and gamma (γ) emissions are the three most common products released from unstable atomic nuclei that are relatively easy to measure. An unstable nucleus has a combination of neutrons and protons that does not effectively balance the repulsion between the positively charged protons with the attraction of the nuclear force felt by neutrons and protons. The decay of a single nucleus by α, β, or γ emission cannot be predicted exactly, it is a random process. The release itself is purely random, it is not affected by temperature, pressure, or any other environmental characteristic. It provides an ideal example for isolating and exploring the problem of *random intrinsic* variations, the natural uncertainty inherent to a value. If you want more information on radioactive decay including what other particles are emitted consult a textbook on modern physics.

In the first part of the experiment we measure the number of emissions from a sample of roughly $8 \cdot 10^{11}$ Cobalt-60 (Co-60) atoms, gathered in a set of hundreds of short time intervals. The number of emissions detected in each individual time interval fluctuates about some average, or mean, emission value. If you were to make a histogram of the number of emitted particles per time interval, and collect many trials, you would see the histogram takes on a "Gaussian" appearance around the mean. Theoretically, as the number of trials becomes increasingly large the histogram will approach the result of a Gaussian or Normal distribution function, but will never equal it exactly. Random variations and uncertainties in the results measured in engineering tests are undesirable. However, this experiment should make the point that repeated testing can provide enough data to determine a reliable mean value that is otherwise obscured by random variations, even random intrinsic variation. Although it will also be clear that in some cases nature creates its own uncertainty.

In the second part of the experiment the effectiveness of lead in stopping Co-60 gamma rays and the effectiveness of aluminum in stopping Strontium-90 (Sr-90) beta particles is tested. These tests provide some insight on the problems faced by spacecraft due to the emissions from the steady stream of particles and high energy photons produced by the nuclear processes in our sun as well as those from cosmic sources outside the solar system. Gamma (γ) and beta (β) emissions provide a steady low-level bombardment on spacecraft and instrumentation so blocking these from essential components is occasionally a design issue. From an experimental and application viewpoint, gamma rays are very similar to x-rays, typically having equal or higher energy, so this experiment provides an introduction to the concepts underlying a commonly used tool for engineering material analysis. Like γ-rays, x-rays can also be blocked by lead, which you would notice at the doctor or dentist when they place a lead shield vest on you during a scan. Historically and in astronomy, gamma rays are considered to be photons with energies greater than x-rays, with 100 keV being the dividing line. In particle physics, and in general a more modern view, gamma rays are defined as any photons emitted from processes involving atomic nuclei, subatomic particles, and radioactive decay whereas x-rays are produced from non-nuclear processes.

Table 1: Overview of easily detectable products from radioactive decay. *The ionizing potential of gamma rays is complicated and depends on their energy. Not many atoms will be ionized directly, but indirect ionization from secondary beta particles can be significant.

Radiation Type	**Constituent**	**Properties**
Alpha Particle, α	${}^{4}_{2}He^{2+}$ nucleus of 2 protons & 2 neutrons	+2e charge, 4u mass, 0 spin highly ionizing, low penetration, high bio-effectiveness
Beta Particle, β	1 electron β^- *or* 1 positron β^+	±1e charge, .0005u mass, ½ spin, ionizing, mid penetration, low bio-effectiveness
Gamma Ray, γ	1 photon of light, high energy electromagnetic wave	0 charge, 0 mass, 0 spin very penetrating, possible bio-effectiveness, can be ionizing*

Although we are working with miniscule amounts of radioactive material in our lab, the same materials become incredibly hazardous with even a few grams of material†. Cobalt-60 in particular

† Stolen Co-60 for medical scanner found unsealed, deadly. [Washington Post, Dec 5, 2013]

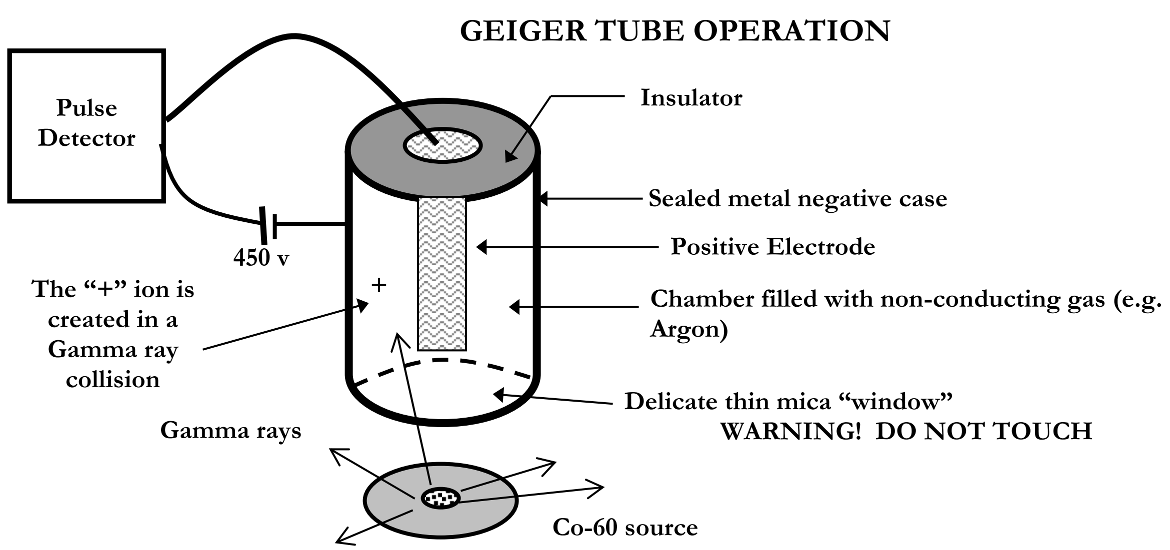
has many industrial and medical uses such as for cancer radiotherapy, food and medical sterilization. Although Co-60 is an entirely synthetic isotope (there is no natural source) occasionally stainless steel‡ consumer products are contaminated§ from improperly disposed of scrap metal.

Table 2: Radioactive decay properties** of Strontium-90 and Cobalt-60. The decay constant $\lambda = \ln 2 / T_{1/2}$ represents a probability of decay for any atom at any instant in time within the given time frame.

	Sr-90	Co-60
	β_1^- 546.0 keV	β_1^- 317.1 keV γ_1 1173.23 keV γ_2 1332.49 keV
Half-life $T_{1/2}$	28.79 years	5.2747 years
Decay Constant λ	$7.6344 \cdot 10^{-10}$ s^{-1}	$4.1669 \cdot 10^{-9}$ s^{-1}

Detection of Radioactive Decay

In any 1s interval the chance that a Cobalt-60 atom will emit gamma rays is 4.17×10^{-9}/s. The sample plastic disk used in this experiment contains about 800 billion CO-60 atoms, so in any one second the odds are that many emissions occur from such a large number. The radioactive sources used in this experiment have half-lives of a year or more so the average emission rate is very nearly constant over periods as short as a few hours. The total number of gamma rays detected in a one second interval will be measured for many hundreds of one-second-long trials.



The emissions are detected in a Geiger–Müller (GM) tube when a gamma ray excites an electron held by a neutral gas atom (normally a stable Noble Gas is used). The electron gains enough energy to be freed from the atom becoming a free moving negative charge; this also ionizes the gas atom creating a positively charged particle. The GM tube is designed so that very few ionizing particles are

‡ Radioactive stainless steel tissue boxes in NY. NBC New York, Jan 12, 2012
§ Radioactive contaminated belts, glowing fashion! Slate.com, Future Tense Blog, May 29, 2013
** Properties of radioactive isotopes and decay radiation obtained from the National Nuclear Data Center.

needed to create a runaway avalanche of free electrons, which changes the gas from an insulator to a conductor. When it conducts electricity, a pulse of current is the proof that an ionizing particle entered the tube and collided with one of the gas atoms in the detector.

Due to its construction and method of operation, the GM tube cannot determine the energy of the incident radiation, only a measure of the counts per time is recorded. This mode of operation is defined as *Multichannel Scaler (MCS)* mode. Another downside to the GM tube is that it actually stops working once the incident radiation rate becomes too large. The inert gas never gets a chance to deionize and the tube cannot reset to make another count. If your GM tube is reading zero counts it is more likely you are in serious danger rather than being perfectly safe!

Procedure – Random Natural Processes Experiment

⚠ **Caution** – Do not touch the transparent end of the GM tube. It is very fragile and sensitive.

1. Verify that the system components are properly assembled and ready:
    a. GM interface box with detector voltage switch set to 450 V.
    b. GM tube box connected to Pasco interface Digital Channel 1, and GM box connected to mains power and *ON*. Pasco interface is turned *ON*.
    c. Go to the course *Canvas* page, download the file *Radioactivity.cap*, and open the file with the *Capstone* program.
    d. When *Capstone* opens, in the left *Tools Palette*, click on the *Hardware Setup* button to check that a Geiger Counter sensor is on the correct port. Close the *Hardware Setup* window.
    a. The central display area should contain a small *Meter* display, a *Table* display, and a *Histogram* display. Using the Histogram display menu, select *Properties* and make sure *Histogram* > *Set Bin Width* = 1.
2. Adjust and test placement of the Co-60 source to obtain at least 100 mean counts/sample.
    a. In the lower *Controls Palette* of *Capstone*, set the *Sample Rate* to 5 seconds. Then under *Recording Conditions*, set the *Stop Condition* to *Time Based*, 25s. Click *OK*.
    b. Place the Co-60 source in the bottom of the tray and tube holder assembly with the label-side facing down.
    c. Click *Record* to take a sample dataset to see if you get at least 100 mean counts/sample.
    d. If your counts/sample mean is at least 100 then move on to the next step. Otherwise, set the Co-60 source on an aluminum plate and raise it closer to the Geiger tube to increase your # of detections. Repeat this until you obtain a counts/sample mean of at least 100.
3. Record your data run for the Random Processes Experiment.
    a. Change the *Recording Conditions* so the *Stop Condition* is 1500 seconds (25 minutes total).
    b. Click *Record* to start your 25-minute run. The total collection time needs to be very long because we are hoping to learn something about the statistics of random variables, and statistics works best with large amounts of data. After 25 minutes you should have 300 data points for radioactive detections per 5 seconds.

c. Over the course of the run, watch your displays as they populate, especially the *Histogram*. You should see that over time a Normal Distribution pattern starts to emerge.

d. When your run is finished, export the data into *Excel* by selecting the *Table* and clicking *ctrl+A* select, then *ctrl+C* copy. Open Excel and *ctrl+P* paste the data into *Excel.*

4. In *Capstone*, look at your *Table* of data. Record the *Mean*, *Standard Deviation*, *and Count* values for your lab report. Alternatively, you can calculate these in *Excel* after you exported the data.
5. In *Capstone*, select the *Histogram* display. Then in the main menu bar click *Display>Copy Display*. Create a new *Capstone* workbook page (*Workbook>Add Page*) and right-click paste the histogram onto the new page. Adjust the histogram so it fills the entire window. Finally, open the *Snipping Tool* application (*Windows Search "Snipping Tool"*) to take a screen capture of your histogram for your report.
6. Include this histogram in your report's *Results* section. In a few sentences, discuss the features of the histogram that are similar to a Gaussian curve and any features that differ.

Analysis – Radioactive Decay, a Random Natural Process

Assuming the half-life of the radioisotope source is much longer than the duration of an experiment then the average emission rate remains essentially constant. The average value of the instantaneous decay rate R_{avg} of a radioactive source follows the formula

$$R_{avg} = \frac{\ln 2}{T_{1/2}} N_o e^{-t \ln 2/T_{1/2}} \tag{1}$$

where N_0 is number of radioactive isotope atoms present at t = 0.0 seconds.

However, at the scale of the individual atom, radioactive decay is an uncorrelated random process. This follows from the fact that the disintegration of an individual atom is not coordinated, organized, or dependent on the state of any other atom. Each atom's internal stability is independent of every other atom. The Gaussian Distribution[††] statistical model can be used to describe the range of values the average rate of decay is likely to fall within. The standard deviation, or uncertainty, in Equation (1) is given by

$$\sigma_R = \sqrt{R_{avg}} \tag{2}$$

For example, if we find through experiment that R_{avg}=100 decays per second then the uncertainty on this is ±10 decays per second. The theoretical expectation is that 68% of all 1-second-long trials will yield results between 90-110 decays per second. In theory, 95% of all 1-second-long trials will yield rate results between 80-120 decays per second, or with the $\pm 2\sigma_{Ravg}$ range. Notice that as R_{avg} increases the uncertainty also increases, but more slowly. For example, R_{avg}=1000 decays per second would only have an uncertainty of ±32 decays per second.

[††] Technically discrete counts and count rates (over time, space, volume) are defined by the Poisson Distribution. However, at large R_{avg} it is easily approximated by a Gaussian with standard deviation $\sqrt{R_{avg}}$.

Questions for your Report: Does the data closely match the expectation that 68% of the trials lie within ±1σ of the mean decay rate? Do 95% of all trials fall within ±2σ of the mean decay rate? Given your data, you should be able to calculate these and perform percent differences to help answer the questions.

Procedure - Gamma and Beta Shielding Tests

7. Using a vernier caliper measure the thickness of one lead (Pb) sheet. You will need to measure each individual Pb sheet used, do not assume they are all equal thickness. You will need a total of eight Pb sheets.
8. Place the Co-60 disk source at the bottom position in the GM tube and tray holder.
9. Change the *Sample Rate* to 1 minute and *Recording Conditions >Stop Condition* to 180 seconds (3 samples).
10. Click *Record* to take three readings of the unshielded source (no blocking sheets). This acts as a known baseline.
11. Place one Pb sheet of measured thickness immediately above the Co-60 disk. Click *Record*. Take the mean count of the three samples as your decay events that made it to the detector. Record this along with the thickness of Pb (here zero) the particles had to travel through.
12. Repeat this for 2, 3, 4, 6, and 8 of the rectangular Pb sheets (7 trials, 21 samples in all).
13. Finally, repeat once more with zero Pb sheets but one 10-layer aluminum (Al) foil slide.

It is important to note that our detector is not recording every decay that happens from the source. Our detector has some fixed size, at some fixed distance away from the source. So it is only viewing decay products passing through a small solid angle. Not all particles passing through the detector will interact with it and be detected, some might pass through or be scattered out. However, we would expect this to remain stable over time. If you wanted to estimate the total number of decays you would need to multiply our detections by the full spherical surface area at our detector distance, and then adjust for the efficiency of the detector.

14. Replace the Co-60 source with the Sr-90 source. Be sure the label side of the disk is facing down to minimize absorption in the plastic disk. The beta emissions from Sr-90 are expected to show much less penetrating ability than the Co-60 gamma rays.
15. Repeat the same sampling procedure for the Sr-90 source as you performed for the Co-60 source, same sampling rate and recording conditions. Record mean counts for the following conditions:
    a. Zero absorbers between the Sr-90 source and the GM tube.
    b. 1 Pb sheet
    c. Combinations of aluminum (Al) foil slides containing 1, 5, 10, 20, 25, and 30 layers. The thickness of each foil layer is 1.3μm.

Analysis - Gamma and Beta Shielding Tests

The penetration of ionizing radiation through a material is modeled fairly simply. Assume the number of *absorbed* (lost) radiation *dN* is [negatively] proportional to the thickness *dx* of absorbing material and the number of incident (original) radiation, *N*.

$$dN = -\mu N dx \tag{3}$$

μ is a proportionality constant called the absorption coefficient most normally given in [cm^{-1}]. The minus indicates dN is a loss of incident radiation with increasing thickness.

Rearranging and integrating:

$$\frac{1}{N} dN = -\mu dx$$

$$\int_{N_0}^{N'} \frac{1}{N} dN = -\mu \int_0^x dx$$

$$\ln N' - \ln N_0 = -\mu x$$

$$\ln N' = -\mu x + \ln N_0 \tag{4}$$

Clearly Equation 4 is a linear equation. A plot of ln(N') vs. x should resemble a straight line with slope -μ. Hopefully by now it should be familiar to you that we can use a linear regression routine on this data to obtain our variable of interest (μ) along with an uncertainty for it based on this fit.

17. Plot the ln(N) vs. x for the Co-60 gamma ray shielding tests through lead. Produce a properly titled and labeled graph. From the plot and linear regression give the value of μ±uncertainty, which is the absorption coefficient for Pb of Co-60 gamma rays. Include this plot and your value for μ in your report's *Results* section.
18. Similarly, plot the ln(N) vs. x for the Sr-90 beta shielding tests through Al. Produce a properly titled and labeled graph. From the plot and linear regression give the value of μ±uncertainty, the absorption coefficient for Al of Sr-90 beta particles. Include this plot and your value for μ in your report's *Results* section.
19. Both Co-60 and Sr-90 were tested with no shielding, 1 Pb sheet, and 1 10-layer Al foil slide. Use simple ratios to compare how well the two materials did in blocking the different sources of radiation. For example,

$$\left(\frac{N_{1\,Pb-sheet}}{N_{no\ shielding}}\right)_{Co-60} \cdot 100\% \quad vs \quad \left(\frac{N_{1\,Pb-sheet}}{N_{no\ shielding}}\right)_{Sr-90} \cdot 100\%$$

would give an equal comparison of how much radiation from each source made it through the same thickness of Pb. Do this comparison for both Pb and Al. Discuss all your analysis and insights in your report's *Results* section.

Report Guidelines

- Include signed raw data sheet, or raw data with your report
- One column abstract, two column for everything else
- Correct units and sig-figs on all numbers
- Cite any item taken from the lab module
- Cite any work taken from anywhere else
- **Abstract:** brief summary of experiment – the what, the how, and the most important results.
- **Background:** Context, purpose, applications, basics of experiment, changes or omissions of procedure from the manual
- **Theory and Methods:** Explain formula for standard deviation, explain three types of radioactive decay, explain how each radioactive element tested decays, explain formula for shielding testing.
- **Discussion of Results:** Histogram, Plot for Co-60 shielding test, Plot for Sr-90 shielding test, values for μ_{Pb} and μ_{Al} with uncertainties, answer all questions and analysis asked throughout the manual, identify and describe at least two sources of uncertainty.
- **References:** Proper format as seen in Good lab report/ Example Reports
- **Calculations:** Show how to calculate standard deviation, Show calculation to confirm or refute 68% in one S.D.
- **Plot Data:** Tables including the data points collected for the Co-60 and Sr-90 shielding tests.

These are just guidelines. You may need to add more items as these are just some of the things expected.