Radioactivity

APPARATUS

1. Geiger Counter / Scaler
2. Cesium-137 sealed radioactive source
3. 20 pieces of paper
4. 8 aluminum plates
5. 10 lead plates
6. Graph paper - log-log and semi-log
7. Survey Meter (1 unit for the lab)

INTRODUCTION

This experiment will introduce you to some of the properties of radioactivity and its interaction with matter, and principles used in shielding from exposure to radiation.

The source used is small (about 1μCi) sealed in plastic, and not hazardous when handled carefully. (1 Curie = 1 Ci = 10^{10} decays per second.)

The radioactive source for this experiment is $^{137}\mathrm{Cs}_{55}$, which decays primarily to an excited state of $^{137}\mathrm{Ba}_{56}$ by emitting a beta(β)-ray (an electron) and an anti-neutrino. The excited barium loses energy by emitting a gamma(γ)-ray (a photon of high energy).

Symbolically:

$$^{137}\mathrm{Cs}_{55} \longrightarrow {}^{137}\mathrm{Ba}^*_{56} + {}^{0}\mathrm{e}_{-1} + \bar{\nu} \qquad \text{with a half-life of 30 years}$$

followed by

$$^{137}\mathrm{Ba}^*_{56} \longrightarrow {}^{137}\mathrm{Ba}_{56} + \gamma(662\ \mathrm{keV}) \qquad \text{with a half-life of 2.6 minutes.}$$

Note that in the original reaction, called a β-decay, one neutron is replaced by a proton and an electron (the β ray) is emitted. Since a third particle, an anti-neutrino $\bar{\nu}$ is emitted, the electron carries off a variable fraction of the total energy of 510 keV.

The radiation emitted from the source consists of two types, (β-rays and γ-rays. Both can produce ions in the gas contained in the Geiger-Müller tube. A high electric potential between the central wire and outer cylindrical electrode of the Geiger-Müller tube accelerates any ions produced so that they, in turn, can produce further ions. This results in a surge of current and a signal in the external circuit. As soon as the ions are cleared, the tube is recharged and is ready to detect another ionizing event.

PROCEDURE

Part I: Start up

Plug the sealer into the AC socket, and turn it on. Set the voltage to 300 V. Sign out a source from your instructor. The same student should sign it back in.

Place the source in a plastic slide with the side marked TOP facing up.

Place the slide in the highest slot, closest to the detector. Wait 5 minutes before proceeding.

Part II: Radiation Intensity vs. Distance

A. Locate the START/STOP and RESET switches at the right side of the scaler. Starting the counter engages a timer that will stop the counting after one minute. The reading is then the intensity in Counts Per Minute (CPM). DO NOT PRESS STOP until after you have recorded the intensity. (It produces some electrical noise that increases the count) If the sealer doesn't count, increase the voltage in 50 V steps. At the point you begin to obtain counts, increase by another 50 V and leave it set at that point.

Do not exceed 450 V.

You should have at least 4000 CPM in the top slot. If not, check that the correct side is up. Consult your instructor if flipping the source over doesn't help,

B. Set up a data table with the following headings:

Slot	Count 1 [CPM]	Count 2 [CPM]	Average [CPM]	Distance [cm]
...	...	...	...	...

We take the average of two readings to reduce the variation due to the random nature of the radioactive decay process. The highest slot is 1 cm from the detector and each slot is 1 cm further away. Take readings at each of the six slot positions

C. We expect the intensity N, at distance r to decrease from N_1, (the intensity in the highest slot, at a distance of 1 cm from the source) following a power law:

$$N = N_1\, r^{-n} \tag{1}$$

By using logarithms we can transform equation 1 into a straight line of slope $-n$:

$$log\,(N) = log\,(N_l) - n\, log\,(r)$$

To avoid having to actually compute the logarithms, we use log-log graph paper. Each graph line is positioned at a distance proportional to the logarithm of the numerical value indicated by the scale. For example, the distance from 1 to 2 is 0.30 times the distance from 1 to 10, since log(2)=0.30.

You must choose the power of 10 for each decade on the logarithmic scales. Graph your data on the log-log paper.

D. Draw the single straight line that best fits your data points. A transparent straight edge (like a plastic ruler) is helpful. Finding the slope of this line is a three step process:

- Select two widely separated points on the straight line (not data points) and record both sets of values (N_1, r_1) and (N_2, r_2).
- Take the logarithms of all four values.
- Calculate the slope:

$$n = \frac{log\,(N_1) - log\,(N_2)}{log\,(r_1) - log\,(r2)}$$

QUESTION 1: If the radiation is emitted uniformly in all directions, i.e. equally over the surface of a sphere surrounding the source, what would he the value of n in equation (1)? Hint: The detector can be considered a small disk of area A on the spherical surface at a distance r.

E. To compare our experimental value of n with the theoretical one you found above, we need to determine the uncertainty in the experimental value. This is especially difficult in this experiment. At large N (over 10,000 CPM) we may lose counts because some radiation arrives before the Geiger-Müller tube, has recharged from the previous count (the "dead time"). At small N (under 100) many of our counts may be due to cosmic rays ("background radiation"). Moreover, since our detector has a cylindrical shape rather than a that of a flat disk, there is a variation in the distance from the source that can vary over a few millimeters. Experience with this equipment has shown that the uncertainty in the experimental value of the slope is about 8% of the expected value. Determine the uncertainty Δn, using this value.

Compare your value with the theoretical value by calculating the uncertainty ratio,

$$UR = \frac{|n - n_{theory}|}{n}$$

A small value of UR (less than 1) indicates excellent agreement, while a large value (greater than 5) indicates disagreement. Intermediate values raise questions that may be difficult to resolve without repeating the experiment.

How well does your value for n agree with theory?

Part III: Absorption of Radiation by Matter

A. Place the shelf with the source in the fourth slot from the top. Place the absorber holder in the third slot. Record the intensity for two successive periods, and its average N_A , This reading will be included in each subsequent graph, but may not fall on the line that fits the remainder of the data.

B. **Paper:** Set up a table with headings:

m	Count 1 [CPM]	Count 2 [CPM]	Average [CPM]
1	...	...	...
2	...	...	...

Place one sheet of paper (m = 1) on the absorber holder. Record two one minute counts and compute the average. Repeat for 2, 4, 8, 13, and 18 sheets of paper. Since each interaction of the radiation with atoms in the material is a separate event, and each electron or γ-photon absorbed reduces the number that pass through the next layer of material, we expect the intensity detected after passing through m sheets to follow the relation:

$$N = N_0 e^{-km}$$

where the attenuation constant k involves the thickness of the paper and the density of electrons in the material. (Most of the interactions between this radiation and matter primarily involve electrons.) Taking logarithms:

$$log\,(N) = log\,(N_0) - k\ m\ log\,(e)$$

This is again a straight line, but now we need to plot a logarithm against a number. To simplify this process we use semi-log paper, that has one set of graph lines at distances proportional to the logarithms and the other set uniformly spaced.

Choose appropriate powers of 10 for the logarithmic scale, noting that the reading from paragraph A, N_A (for m = 0) will also be plotted, and values m = 0 to 18 span the linear scale.

C. Aluminum: Remove the paper and place one aluminum plate on the absorber shelf Start a new section of your data table under the same headings. Record two counts and their average. Repeat for 2, 4, 8, and 12 plates.

Plot your data on the same graph as the paper, using the same scale for m. Draw the best straight line that fits the data. Do not include N_A. Do draw the line all the way across the graph.

QUESTION 2: Why does the straight line for aluminum intersect the left axis (m = 0) at a point well below N_A? Hint: What kind of radiation is emitted from this source?

D. Lead: Remove the aluminum and place one sheet of lead on the absorber shelf. Start a new section of the data table. Record two counts and their average. Repeat for 2, 4, 6, and 9 sheets of lead. Since the thickness of the lead sheets is TWICE the thickness of the aluminum, m is DOUBLE the number of lead sheets when we plot it on the same graph.

Plot your data and again draw a straight line that fits the data. (Label each line at the right.)

QUESTION 3: How does the intersection with the left axis compare with that for aluminum? Why?

QUESTION 4: Which is the better absorber of the penetrating type of radiation? How do your graphs indicate this?

QUESTION 5: We might suppose that the absorbing power of a material depends on the density of atoms rather than electrons. A material of density ρ, atomic mass A, and atomic number Z, has a density of atoms proportional to ρ/A, and a density of electrons proportional to $Z\rho/A$.

	ρ [kg/m^3]	Z	A
Aluminum	2,700	13	27
Lead	11,300	82	207

Compare the ratios of atomic density and the electron density for the two materials. Which is more consistent with your observations?

Part IV. The Survey Meter

Get the survey meter.

Turn the control knob to HV (High Voltage ON). The needle should move to HV. Turn to the ×100 scale. (Scale readings need to be multiplied by 100.) Place the Cesium source on the table, with TOP showing. Bring the probe as close as possible. Reduce the scale (×10 or ×1) until a reading is obtained and record it. (Remember the multiplier) Units are mr/h = milliroentgen/hour.

Hold the probe about 10 cm from the source. Record the reading. Take another reading far away from any sources, the "background". How effective is a distance of 10 cm in shielding from the Cesium source?

Sign the source back in.