

INVESTIGATING RADIOACTIVITY

- OBJECTIVE:**
1. To see how to measure radioactivity.
 2. To see the statistical nature of radioactivity.
 3. To observe how nuclear radiation decreases due to
 - a) spreading out
 - b) absorption by material

THEORY: There are two types of atoms: stable and unstable. All the light and middle elements (such as hydrogen, helium, carbon, gold, lead) have both stable and unstable types called *isotopes*. The higher mass atoms (such as uranium, thorium, and plutonium) have no stable isotopes. *Radioactivity* occurs when an unstable atom emits a particle (or particles) from its nucleus and becomes a different element (which may or may not be stable). The emitted particles are referred to as *nuclear radiation*.

There are three main particles emitted from radioactive atoms: *alpha particles* (α), *beta particles* (β), and *gamma rays* (γ). An α particle is a particle consisting of two protons and two neutrons stuck together. A β^- particle is an electron*. A γ ray is a high energy bundle of light (a *photon*). [*There are radioactive sources that emit β^+ (positron). The positrons will then annihilate with nearby electrons and produce gamma rays which are more penetrating. We will only work with β^- (electron) sources.]

The α 's and β^- 's are easily stopped by thin paper, clothes, even air. They are only dangerous if they are ingested or inhaled. The γ 's are not easily stopped and so are generally more dangerous (at least in high quantities).

Because there are different particles, we have different instruments to detect the different particles. We will investigate the Geiger counter which is good for detecting β^- 's, very bad for detecting α 's, and not very good at detecting γ 's. Our first source will be a β^- emitter.

Part I: The Geiger Counter

PROCEDURE:

1. CAUTION: *The window in the Geiger-Mueller tube is very thin, so be careful in handling the tube.* Examine the Geiger-Mueller (G-M) tube. Note the thin membrane covering the one end of the tube - it must be thin in order to permit β^- 's to enter. The tube is filled with a low pressure gas. As β^- particles enter the tube, they ionize the gas atoms, i.e. they remove electrons from the gas atoms as they collide with the atoms. Note the thin wire down the center of the tube. There will be a voltage difference between this wire and the outer part of the tube that will cause the free electrons to accelerate toward the wire. As the electrons race to the wire, they collide with more atoms and remove more electrons which join the race. This "avalanche effect" creates a current pulse that can be counted once the electrons reach the wire. We assume that each current pulse counted (a *count*) corresponds to one β^- particle.
2. Make sure the two voltage controls are turned down. Then plug in the counter and push the POWER button. Push the STOP button and then push the RESET button: the counter should now read zero. To see if the counter is operating correctly, set the time switch on 1 minute, press the TEST button, and then press the COUNT button. The display should now be counting. After one minute the counter will stop and the display should read 3600. (Can you guess why it should read 3600?) If it doesn't, call the instructor over.

3. Get a beta source from the instructor. The source is inside the hole in the aluminum cylinder. Position the cylinder with the hole facing upwards on the tray and place the tray in the highest shelf possible so that it will slide in under the G-M tube. Press the STOP button, press the RESET button (and the display should return to zero), press the TEST button to turn off the test function, and set the TIME switch to MANUAL. Press the COUNT button. The counter will probably not be counting. Increase the voltage (but do NOT go over 1000 volts) slowly until the counter does start to count. The voltage where the counter just starts to count is called the *threshold voltage*. After you have determined the threshold voltage, increase the voltage by about 80 volts above the threshold voltage. This will be the *operating voltage* for the rest of the experiment and should not be changed.
4. Press the STOP button (and the counting should stop), press the RESET button (and the display should return to zero), and set the TIME switch to one minute. We are ready to start measuring radioactivity.
5. Remove the radioactive source from underneath the G-M tube, and take a one minute reading by pressing the COUNT button. This will give the background count.

REPORT:

1. Record the threshold voltage and operating voltage for your G-M tube.
2. Record the background count rate in counts/minute (cpm).

Part 2: Radioactivity as a Process Involving Probability**PROCEDURE:**

1. Now position the source back underneath the G-M tube placing it as high as you can. Now take a one minute reading (by pressing the RESET button and then the COUNT button). Repeat this procedure three times (so you have four readings). Normally you would expect to get the same reading if you repeat the same procedure, but radioactivity is based on probability so you probably will not get the exact same reading each time.
2. To demonstrate the randomness of probability, you have 18 coins on the desk. If you flipped all 18, you would expect to get about 9 heads and 9 tails. Go ahead and flip all 18 and count the number of heads. See if you get exactly nine heads. Repeat this procedure three times (so you have four trials) and see if all the readings are close to the expected result of nine.

REPORT:

1. Express your four count rates in cpm. Find the average count rate. While the four count rates are probably different, they should be fairly close. Probability theory states that the majority of the readings should be within $average \pm \sqrt{average}$. Is this so for your count rates?
2. Because coins have a high probability of being heads ($P=0.5$), whereas most radioactive atoms have a low probability of decaying in a small time period (such as a minute), the expected distribution for number of heads is slightly different than for number of decays. Probability theory states that most of the counts of heads will be within $average\ no. \pm \sqrt{NP(1-P)}$ where N

is the number of coins flipped per trial ($N = 18$) and P is the probability of getting a head for one coin ($P = 0.5$). The average number of heads is nine so we expect that most of the trials will give a number of heads in the range of $9 \pm \sqrt{(18)(0.5)(1-0.5)} = 9 \pm \sqrt{4.5} = 9 \pm 2.1$. That is, most of the trials will give a number of heads between 7 and 11. Is this true for your trials?

Note that if we apply the same formula for radioactive decay, we get the result used in Step 1. Because the probability of a nucleus decaying is very low, $1 - P \approx 1$, so

$\sqrt{NP(1-P)} \approx \sqrt{NP} = \sqrt{\text{average}}$. This approximation is not valid for the coins since P is large and it would be incorrect to state that the range expected for the number of heads is $9 \pm \sqrt{9} = 9 \pm 3$.

Part 3: Absorption of Radiation

PROCEDURE:

1. Let's return to the counter and radioactive source. See if the counting is affected by distance: place the source further from the G-M tube and see if the count rate changes. I suggest taking a couple of counts to see how the values average out.

Does distance from the source affect the level of radiation?

According to theory, the level of radiation from a source should decrease with distance due to two reasons: a) as you get farther away, the radiation has to spread out and hence the amount hitting the detector decreases (unless the source is aiming it in a tight beam); b) as you get farther away, the material in between the detector and the source will absorb some of the radiation and hence decrease the amount reaching the detector. Even air will tend to stop radiation: air will stop α and β^- radiation fairly well, but does little to stop γ radiation

2. Place the source back in its original position. Now place an aluminum plate over the source and take a measurement. Does the plate completely stop the radiation?

3. Now ask the instructor for a new source of radiation. The new source of radiation has both β^- and γ particles. Take a reading with the source as close to the detector as possible.

4. Now move the source further away from the detector and take another measurement. Does the extra distance decrease the reading?

5. Place the source on the third shelf (leaving room for two plates to go on top). Take a reading at this level. Now place one aluminum plate on the source and take a reading. Does the one plate completely stop all the radiation? If it doesn't, place a second plate over the source and take another reading.

As we saw in Step 2 above, the aluminum plate essentially stops all the β^- 's. However, the plate is not very good at stopping the γ 's. A second plate will stop a few more of the γ 's but since the β^- 's have all been stopped by the first plate, the second plate has only a small effect on the count.

One reason the effect of one plate is so dramatic while the second plate does little is due to the G-M tube itself. The G-M tube is very efficient in detecting β^- 's, but is not very good at detecting

γ 's. Hence when there are a lot of β^- 's, you get a high count rate. When you have the same number of γ 's as you had β^- 's, the count rate will be only a fraction of what it was for the β^- 's. The first plate effectively removes the β^- 's while only slightly absorbing the γ 's. But due to the inefficiency of the G-M tube in detecting γ 's, the count rate goes way down. The second plate then only slightly decreases the γ 's causing only a slight decrease in the reading.

6. a) Now take off the second aluminum plate and replace it with a lead sheet. Take a reading. Does the lead plate stop the γ 's better than the aluminum plate?

b) Now switch plate positions: put the lead plate over the source and then the aluminum plate over the lead plate, and take a reading. Are the two readings the same, or does the order of plates make a difference?

We can explain this result by considering what happens to the γ 's. The γ photon can be absorbed or scattered by knocking an electron out of an atom and that electron will have a lot of energy. That high energy electron then is essentially a β^- particle and the GM tube will count it as such. Since the lead plate is better at absorbing γ 's, the count rate will be higher by the GM tube even though the γ radiation has decreased. With the aluminum plate, there is less γ 's absorbed and so less high energy electrons emitted.

REPORT:

1. Answer all of the questions posed in the Procedure.

2. Take a look at the Nuclear Data Tables in the Appendix. Discuss the information with your instructor as time permits.

NUCLEAR DATA TABLES

I. UNITS OF RADIOACTIVITY:

Activity: Curie (Ci) = 3.7×10^{10} dis/sec (activity of 1 gm of Ra²²⁶)
MKS: Becquerel (Bq) = 1 dis/sec = 27 pCi

Exposure: Roentgen (R) = $(1/3) \times 10^{-9}$ Coul created per cc of air at STP
MKS: (no name) 1 Coul/kg = 3876 R

Absorbed Dose: rad = .01 J/kg (usually, 1 R of exposure will give 1 rad of absorbed dose)
MKS: Gray (Gy) = 100 rads

Dose Equivalent: rem = rad * RBE, where RBE (relative biological effectiveness factor) depends on radiation type:

<u>TYPE</u>	<u>RBE</u>	<u>TYPE</u>	<u>RBE</u>
x-ray, gamma	1	fast neutron	10
beta	1-2	proton	10
slow neutron	4-5	alpha	10-20

II. SOURCES OF RADIATION:

Background:

level depends on location: California (minimum) = 115 mrem/year
Colorado (maximum) = 250 mrem/year

due to: cosmic rays - higher elevation means higher dose rate
ground - depends on type of rocks and dirt
internal - from naturally occurring radioactive isotopes such as K⁴⁰, C¹⁴, and others [There are 260 grams of K, or 31 mg of K⁴⁰ in a 75 kg person which gives an activity = 0.217 mCi = 8,000 Bq. 18% of body weight is carbon, or 1.7×10^{-14} gms of C¹⁴ in a 75 kg person which gives an activity = .078 mCi = 2,900 Bq.]

Other sources (in addition to background):

1 chest x-ray:	40
1 gastro-intestinal track x-ray	210
1 NY-LA flight at 35,000 ft:	2
one year living next to nuclear plant	1
living one year in median home (.9 pCi/ℓ)	180

(Mainly due to Rn gas trapped in home. Rn levels measured in pCi/liter or WL where 1 pCi/ℓ = .005 WL = 200 mrem/yr. EPA recommended max = 4 pCi/ℓ = 800 mrem/yr. 1% of all houses have > 10 pCi/ℓ = 2000 mrem/yr.)

III. ACUTE DOSE EFFECTS: (dose obtained within a few weeks)

20,000 mrems: measureable transient blood changes
150,000 mrems: acute radiation sickness
200,000 mrems: death in some people
350,000 mrems: death in 50% of people

*localized doses (not whole-body doses) for cancer treatment: » 10,000,000 mrems

IV. RECOMMENDED LIMITS:

500 mrems/year for general population
5,000 mrems/year for special occupations

V. LONG TERM EFFECTS - LINEAR HYPOTHESIS vs HORMESIS HYPOTHESIS:

(neither has been proven at low doses, but recent research points toward hormesis)

LINEAR: According to the latest BEIR report, there is a .79% chance of a latent cancer death for every 10,000 mrems of acute dose. (There is an 18.33% chance of contracting cancer for all other causes.) This is based on the idea that a single hit could cause a cell to become cancerous.

HORMESIS: No radiation is a little bad, a little radiation is good, a lot is very bad; based on analogy with minerals (a little is necessary, a lot is toxic) and vaccines (a less dangerous infection builds up body defenses).

VI. COMPARATIVE ENERGY FIGURES:

QUANTITY	ENERGY (Joules)	AMOUNT TO POWER 1000 MW PLANT FOR 1 YEAR (9.5×10^{16} J)	radiation per 1,000 MW-yr
1 gram of U ²³⁵	8.2×10^{10}	3.6 tons *	250 person-rems
1 barrel of oil	6.3×10^9	15 million barrels	50 person-rems
1 ton of coal	2.9×10^{10}	3 million tons	400 person-rems
1 ft ³ natural gas	1.1×10^6	86 billion ft ³	30 person-rems
1 cord of white oak	3.1×10^{10}	3 million cords**	?
yearly U.S. sunlight	6×10^{22}	40 square miles ***	?
yearly U.S. wind	1×10^{20}		?
geothermal			200 person-rems

[1980 U.S. energy consumption (all forms) ~ 1×10^{20} Joules ~ 100 quads (1×10^{15} BTU's = 1 quad)]

NOTES:

* The 3.6 tons of U²³⁵ includes a factor of 1/3 due to incomplete use of fuel due to poisoning of rods. This much U²³⁵ demands 100 tons of enriched uranium which demands about 100,000 tons of uranium ore at .5% metal (a high but not the highest grade ore). If reprocessed, this much fuel will last roughly 5 times longer due in part to the creation of U²³⁵ by reactions inside the reactor.

** The 3 million cords would take 6 million acres of untended forests or 550,000 acres of tended forest. On a per-pound basis, all woods contain approximately the same energy. Untended hardwood forests generate 0.5 cords per acre per year, thus you would need 6 million acres to supply one power plant. Cultivated Southern forests generate 11 times more per acre per year, thus you would need about 550,000 acres for one power plant. [640 acres = 1 sq. mile, so need 860 sq. miles]

*** The 40 square miles comes from the yearly average of 200 Watts/m² and assumes a 10% efficiency in converting sunlight into electricity & 50% spacing for maintenance.

VIII. WASTE PRODUCTS FOR 1000 MW ELECTRIC PLANT PER YEAR:

nuclear: 120 tons/year if not reprocessed (5 tons/year if reprocessed) + tailings

coal: 500,000 tons/year of solid wastes + tailings

+ 150,000 tons/year of sulfur dioxide

+ nitrogen oxides equivalent to 200,000 automobiles

+ chemical carcinogens released (e.g., arsenic, cadmium)

solar: to make solar collectors and the frames and all accompanying equipment requires 1,000 times the materials of an equivalent coal or nuclear plant.