

## EXPERIMENT 11: NUCLEAR RADIATION

Introduction: In this lab, you will be investigating three types of emissions from radioactive nuclei. Two types of these emissions consist of charged particles, and the third is electromagnetic radiation. For one of the charged-particle emissions, you will first examine the relationship between the intensity of the emitted radiation and distance from the source. Secondly, for the electromagnetic radiation, you will place lead absorbers between the source of the radiation and your detector and measure the intensity of that part of the radiation which successfully passes through the lead. Finally, you will compare the abilities of all three type of emissions to pass through various absorbers.

IMPORTANT: Special concerns for nuclear radiation experiment

1. This lab involves the use of three different radioactive sources. All three are extremely weak and are quite safe if you use them sensibly; do not put them in your mouth or swallow them. You will be asked to trade your picture ID (one per lab group) for a set of three sources; the sets will be distributed by certified lab personnel. Use the sources as described below and promptly return them to their storage case. Your ID will be returned when you return the case containing all three sources.

The most stable nucleus is  ${}_{26}^{56}\text{Fe}$  (26 protons and 30 neutrons). Isotopes with mass numbers far from the naturally occurring average mass number (for example,  ${}_{6}^{14}\text{C}$  or  ${}_{26}^{59}\text{Fe}$ ) are usually unstable, and can spontaneously disintegrate, or decay, resulting in the emission of charged particles. In addition, all nuclei with more than 83 protons are unstable to some degree. The more unstable a nucleus, the more likely it is to decay within a given amount of time. If, in the process of disintegration, the charges which remain within a nucleus are caused to vibrate back and forth in (very high frequency) simple harmonic motion, then very high frequency electromagnetic radiation can also be emitted.

There are two primary modes of nuclear disintegration. In the first of these two, the nucleus breaks up by emitting two neutrons combined with two protons; this collection of four nucleons is the  ${}_{2}^{4}\text{He}$  nucleus, and is also known as an  $\alpha$  particle. The rare and highly unstable element radium ( ${}_{88}^{226}\text{Ra}$ ), famously discovered by Maria Sklodowska-Curie and her husband Pierre Curie,  $\alpha$  decays to radon ( ${}_{86}^{222}\text{Rn}$ ); half of any sample of  ${}_{88}^{226}\text{Ra}$  disintegrates to  ${}_{86}^{222}\text{Rn}$  plus an  $\alpha$  particle ( ${}_{2}^{4}\text{He}$ ) every 1600 years.

Unraveling the mystery of the second primary mode of nuclear disintegration (and of the weak nuclear force which causes it) occupied the attention of nuclear physicists for much of the 20<sup>th</sup> century. The neutron, outside of the nucleus, is not a stable particle. In a beam of free neutrons, half of the (remaining) neutrons will disintegrate every 15 minutes. When

the neutron disintegrates, what remains is a proton, an electron, and some antimatter (all with some kinetic energy); this does not mean that the neutron had been composed of a proton and an electron (and some antimatter). Neutrons are composed of three quarks, two down quarks and an up quark. The charge of an up quark is  $+\frac{2}{3}e$  and the charge of a down quark is  $-\frac{1}{3}e$ , so the total charge of the neutron is zero ( $2(-\frac{1}{3}e)+(+\frac{2}{3}e)$ ). Inside the disintegrating neutron, a down quark turns into an up quark plus a bundle of energy and charge having a charge of  $-e$  (the bundle of energy and charge is called a  $W$  particle); charge and energy are conserved during the disintegration. The quark count is then two up quarks and one down quark, which makes up a proton (with charge  $2(+\frac{2}{3}e)+(-\frac{1}{3}e)$ ). The bundle of energy and charge, after it escapes the neutron from which it arose, turns into an electron and a piece of neutral antimatter called an antineutrino. The mass of the antineutrino is, even today, poorly determined, but it is known to be on the order of a millionth of the mass of an electron; so for our detector, the antineutrino can be ignored. This same type of neutron disintegration is possible, though less likely, inside an unstable nucleus. For example, every 5700 years, half of any sample of  ${}^{14}_6\text{C}$  turns into  ${}^{14}_7\text{N}$ , giving off an electron and an antineutrino in the process. Since, in any living thing, the percentage of carbon that is  ${}^{14}_6\text{C}$  is a known quantity, this decay is famously used to determine the age of ancient artifacts which were made from plants or animals. This second type of decay is historically called beta ( $\beta$ ) decay, and thus the  $\beta$  particle is simply a moving free electron.

The nucleus which remains after an  $\alpha$  or  $\beta$  decay event is often “excited”, meaning that some of the nucleons in that nucleus are not left in their equilibrium positions (or more correctly, their equilibrium orbits). When these nucleons eventually “fall” into equilibrium, charges within the nucleus undergo very high frequency vibrations (more than  $10^{20}$  cycles per second); the frequency is so very high because the nuclear forces are so very strong. These vibrations result in the emission of electromagnetic waves having the frequency of the vibrating charges; these emissions are called  $\gamma$  rays, a third type of nuclear radiation. For  $\gamma$ 's, as well as  $\alpha$ 's and  $\beta$ 's, the words “rays” and “radiation” refer to trajectories. All three types of emissions travel in straight lines, *i.e.* they radiate directly outward from the source (for  $\alpha$ 's and  $\beta$ 's, this is only true in the absence of magnetic fields).

The surface of the Earth is continually bathed in a certain level of background radiation, which is largely due to the effects of very high energy cosmic rays (particles emitted by our sun, or other stars, which are so energetic that they get through our protecting magnetic field). Few of the cosmic rays actually reach the surface of the Earth; most collide with an air molecule at high altitude, producing a variety of energetic particles (such as muons, with a mass 200 times larger than the electron mass) which then do reach the Earth's surface.

## Procedure

You will measure the intensity of the nuclear emissions with a Geiger counter, as shown in the photograph below. The Geiger tube (sitting atop the box containing the counting electronics) is a metal cylinder, or can, filled with gas (He, Ne, or Ar); there is a thin metal wire at the center of the tube and there is a window at the tube's lower end through which radiation can enter (background radiation can also enter through the sides).



When high-energy radiation strikes a gas atom in the tube, the collision can ionize that atom, producing a positive ion and a free electron; the resulting brief current between the thin wire and the outer can is recorded as a count by the electronics. In the rack below the tube are six sets of slots which can be used to position the samples at various distances from the window at the lower end of the tube. The highest slot is used to position a sample 1.0 cm from the window, and each lower slot is an additional centimeter farther away.

### Part A: Variation of $\beta$ Intensity with Distance

1. Turn on the Geiger counter and set the high voltage to 420 V. This voltage is applied across the gap between the metal wire at the center of the tube and the outer can; this is the voltage which creates a current in the tube after a gas atom has been struck by the incoming radiation.
2. Take a count of background radiation in the room on this day by running the counter for ten minutes (set Count Interval to 10, then hit STOP followed by RESET followed by COUNT). Record the background count in Data Table 11.1. Calculate the background counts per minute; record that number at the top of all three data tables.

3. Properly certified lab personnel will be present to distribute the radioactive sources. Once your background count is finished, trade a picture ID for a set of sources. Keep the storage case, which will always contain two of the three sources, on your lab table but as far as possible from your Geiger tube.
4. Place the  $^{90}_{38}\text{Sr}$   $\beta$ -ray source, label side up, into a plastic sample holder; then position the holder as close as possible to the window of the Geiger tube (use the highest slot in the rack below the tube). Some fraction of the  $^{90}_{38}\text{Sr}$  nuclei at the center of this source are continually turning into  $^{90}_{39}\text{Y}$  nuclei (in 29 years half of the  $^{90}_{38}\text{Sr}$  nuclei will turn into  $^{90}_{39}\text{Y}$ ); some fraction of the energy released by each of these nuclear transformations appears as a fast-moving electron, also known as a  $\beta$  ray. Take a one-minute count of the  $\beta$  radiation now detected by the tube. Record the raw count and a corrected count in Data Table 11.1; the corrected number of counts per minute is gotten by subtracting the background counts per minute from the raw count. Repeat for all possible slots in the rack below the tube. Once you have finished, return the  $\beta$  source to the storage case.
5. Make a graph of the corrected counts per minute versus distance (distance on the horizontal axis); use a full sheet of graph paper.

#### Part B: Absorption of $\gamma$ Radiation by Lead

1. Place the  $^{60}_{27}\text{Co}$   $\gamma$ -ray source (label side up) in a plastic sample holder and position the holder in the fourth-highest slot (third from the bottom) in the rack below the tube. Some fraction of the  $^{60}_{27}\text{Co}$  nuclei at the center of this source are continually turning into highly-excited  $^{60}_{28}\text{Ni}$  nuclei (about half of the  $^{60}_{27}\text{Co}$  nuclei are transformed every five years); as the vibrating charges in these  $^{60}_{28}\text{Ni}$  nuclei gradually settle into their equilibrium positions within the  $^{60}_{28}\text{Ni}$  nucleus, they emit electromagnetic  $\gamma$ -rays of frequencies 2.8 and  $3.2 \times 10^{20}$  Hz. Take a one-minute count of the  $\gamma$  radiation now detected by the tube. Record the raw and corrected count rates in Data Table 11.2.
2. You will be supplied with a box of lead disks of varying thickness, and one lead slab of greater thickness. Select the thinnest disk, place it in appropriate plastic tray, and position that tray in the sample-holding rack just above the  $\gamma$ -ray source. Record the thickness of the lead disk, in mm, in Data Table 11.2. Then count for one minute and record the raw and corrected count rates in Data Table 11.2. Repeat for all thicknesses of lead available in your supply; you will need to support the thick lead slab on a piece of aluminum (instead of the plastic tray). Return the  $\gamma$  source to its storage case.
3. Make a graph of the corrected counts per minute in Data Table 11.2 versus lead absorber thickness (thickness on the horizontal axis); use a full sheet of graph paper.

### Part C: Compare Penetrating Ability of $\alpha$ , $\beta$ , and $\gamma$ Radiation

1. Position the  $\alpha$  particle source (label side DOWN) in the second-highest slot under the Geiger tube (again using the plastic sample-holding tray). Some fraction of the  ${}_{84}^{210}\text{Po}$  nuclei at the center of this source are continually disintegrating, turning into  ${}_{82}^{206}\text{Pb}$  plus an  $\alpha$  particle (every 138 days half of the  ${}_{84}^{210}\text{Po}$  nuclei disintegrate). Measure and record the counts-per-minute reading due to this source with no absorber between the source and Geiger tube; correct your recorded counts-per-minute by subtracting the background count rate. Repeat with a single piece of paper placed in between the  $\alpha$  source and the Geiger tube. If the uncorrected count rate does not fall nearly to background with a single piece of paper as an absorber, repeat the experiment once more with two pieces of paper as absorbers. Return the  $\alpha$  source to its storage case.
2. Replace the  $\alpha$  particle source with the  $\beta$  particle source. Measure and record the counts-per-minute reading due to this source in each of the following cases: (a) no absorber, (b) one piece of paper as an absorber (also two pieces if two were required for the  $\alpha$  source), (c) one piece of aluminum sheet as an absorber, and (d) two pieces of aluminum sheet as absorbers. In each case, correct for the background count rate. Return the  $\beta$  source to its storage case.
3. Replace the  $\beta$  particle source with the  $\gamma$ -ray source. Measure and record the counts-per-minute reading due to this source in each of the following cases: (a) no absorber, (b) one piece of paper as an absorber (also two pieces if two were required for the  $\alpha$  source), (c) one piece of aluminum sheet as an absorber, and (d) two pieces of aluminum sheet as absorbers. In each case, correct for the background count rate. Return the  $\gamma$  source to the storage case and trade the sources for your picture ID.

### Results

1. Looking at your graph for Data Table 11.1, describe qualitatively how count rate changes as a function of distance from a source of  $\beta$  rays.
2. We would like to find the quantitative relationship between count rate and distance from the source. In the space at the top of page 8, make a neat table of distance (in m),  $1/(\text{distance squared})$  (in  $1/\text{m}^2$ ), and corrected count rate. Two of the three columns are just copied from Data Table 11.1. Use proper labels and table headings. Show one example of your calculation of  $1/(\text{distance squared})$ .

Data Table 11.1 background = \_\_\_\_\_ counts in 10 min or \_\_\_\_\_ counts/min

distance (m)	Raw counts/min	Corrected counts/min
0.01		
0.02		
0.03		
0.04		
0.05		
0.06		

Data Table 11.2 background = \_\_\_\_\_ counts/min

lead thickness (mm)	Raw counts/min	Corrected counts/min
0		

Data Table 11.3 Absorption of Nuclear Radiation background = \_\_\_\_\_ counts/min

alpha source		
absorber	Counts/min	Corrected Counts/min
none		
1 piece of paper		
beta source		
absorber	Counts/min	Corrected Counts/min
none		
1 piece of paper		
1 aluminum sheet		
2 aluminum sheets		
gamma source		
absorber	Counts/min	Corrected Counts/min
none		
1 piece of paper		
1 aluminum sheet		
2 aluminum sheets		

3. Make a graph of corrected count rate versus  $1/(\text{distance squared})$  (corrected count rate on the  $y$  axis). Are you able to conclude that corrected count rate is proportional to the reciprocal of the square of the distance from the source?
  
4. Looking at your graph for Data Table 11.2, describe qualitatively how  $\gamma$ -ray count rate changes as a function of the thickness of lead absorbers.
  
5. Looking at your data in Data Table 11.3, compare the penetrating ability of  $\alpha$ ,  $\beta$ , and  $\gamma$  radiation. Be as quantitative as possible in your comparisons.







