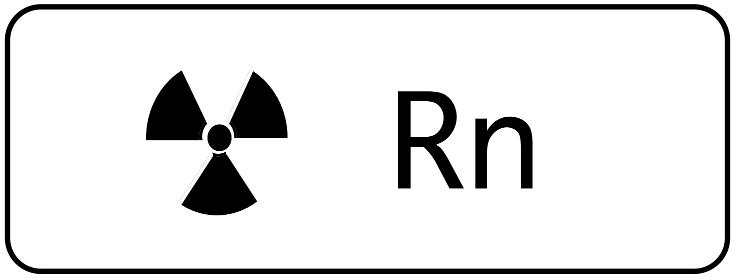
Name ____________________ Section _______ Date __________

UNIT 28: RADIOACTIVITY AND RADON

Approximate Time: Three 2 hour sessions



Motionless in appearance, matter contains births, collisions, murders and suicides. It contained dramas subjected to implacable fatality; it contained life and death. Such were the facts which the discovery of radioactivity revealed. Philosophers had only to begin their philosophy all over again and physicists their physics.

Eve Curie, 1937

OBJECTIVES

1. To learn about naturally occurring ionizing radiation and measure its relative level at different locations.

2. To develop a mathematical model to describe radioactive decay and to understanding the physical meaning of the decay constant and the half-life for a given decay process.

3. To use the mathematical model of decay processes to predict how the counting rate changes over time for a collection of very long-lived radioactive nuclei as well as for a collection of relatively short-lived radioactive nuclei.

4. To observe the statistical fluctuation of counts from a sample of thorium 232 – a naturally occurring radioactive material with a very long half-life.

5. To understand more about radiation safety in terms of the relationship between the properties of each type of radioactive material and its potential to do biological damage, and to learn why radon and its daughter elements pose a health risk.

6. To use the mathematics of radioactive decay processes to construct a theoretical prediction of how the radon 222 daughters increase and then decrease in amount over time and compare that prediction with actual data.

 Supported by FIPSE, U.S. Dept. of Education

OVERVIEW

10 min

The term *radiation* is commonly used to describe *invisible forms of energy moving through space*. A familiar form of radiation is the sound wave, which can move invisibly from place to place. The most common form of radiation is the electromagnetic wave. These waves include low energy radio waves, microwaves, visible light, x-rays, and high energy gamma rays. Electromagnetic waves appear to be made up of oscillating electric and magnetic fields like those you have been studying in the last few units. Other forms of radiation include the tiny alpha particles and beta particles that are ejected from the nuclei of certain elements which are called *radioactive* if they spontaneously emit radiation.

In this unit we are going to investigate energetic forms of radiation known as *ionizing radiation.* Ionizing radiation is defined as any type of radiation which is energetic enough to knock electrons out of atomic orbits around the nuclei of atoms and hence *ionize* the atom.

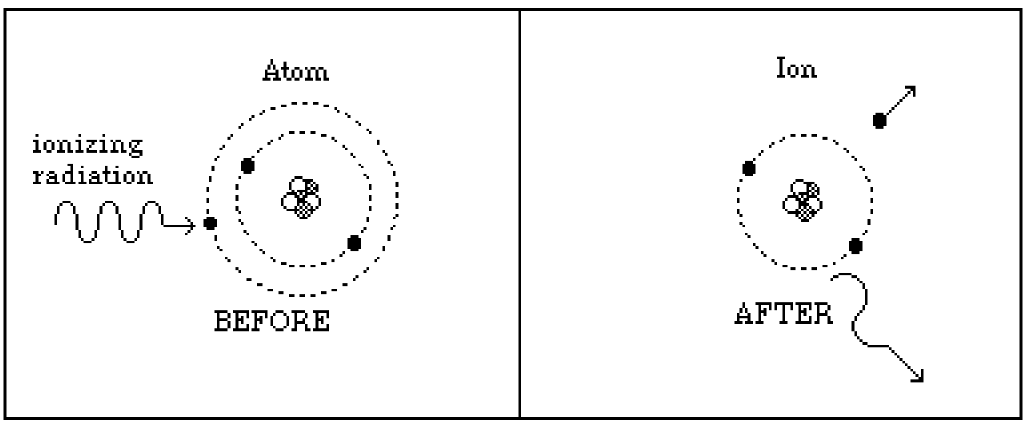


Figure 28-1: Schematic of ionizing radiation in the form of a gamma ray which knocks an electron out of an atom, leaving the atom ionized.

Ionizing radiation passes through our bodies all the time. It comes from cosmic rays and from radioactive atomic nuclei that exist naturally in the materials in our surroundings and in our own bodies. Radioactive radon gas is in the air we breath. In addition to naturally occurring radiation, we are exposed to man-made sources of ionizing radiation, including fallout from the testing of nuclear weapons, releases from nuclear power plants, and radioactive materials in tobacco smoke. Ionizing radiation is of special interest to us because exposure to ionizing radiation can do damage to our bodies.

In this unit you will measure the relative level of the background radiation in and around your classroom and explore ways to describe radioactive decay rates mathematically. Then you will learn about some of the properties of atomic nuclei and about several common types of radioactive decay. You will study a chain of successive radioactive decays in which a parent nucleus, uranium 238, emits ionizing radiation and is thereby transformed into a daughter nucleus which in turn decays into another *daughter* nucleus, and so on. It is this decay series that leads to the creation of radon 222. Finally, you will learn more about radon, why it is a health problem, how to measure its relative presence by collecting and counting radiation from two radon daughter elements, and how to calculate the theoretically expected creation and decay rates of these radon daughter elements as time passes.

Notes:

SESSION ONE: RADIATION AND RADIOACTIVE DECAY

5 min

The Discovery of Radioactivity

Just before the turn of the century, Henri Becquerel examined the salts of an unusually heavy rare metal called uranium and found that they caused photographic film surrounded by black paper to darken. He also found that the uranium salts caused an electroscope to discharge. The uranium salts gave off strange, tiny particles of radiation, or rays, in a phenomenon dubbed *radioactivity* by Marie Curie. Marie and her husband, Pierre, discovered that most of the radiation in the uranium salts came from a new element they called radium which had an atomic mass of 226. Over a span of four years ending in 1902 the Curies labored in a dingy shed with a leaky roof to extract one tiny gram of radium from eight tons of uranium ore residue. The biography of Madame Curie, written by her daughter, Eve, contains a fascinating account of the discovery of radium. It makes good summer reading! (Curie, Eve, Madame Curie, Doubleday, Doran & Co., 1937).

10 min

Natural Radiation in the "Background"

There are three natural sources of radiation that we are constantly exposed to: gamma rays and beta particles from radioactive minerals in the ground, the radioactivity in our own bodies, and atmospheric cosmic rays from outer space.

1. Radioactive Minerals: Radioactive elements were part of the original composition of the earth. These elements and the daughter elements formed as a result of their decay emit ionizing gamma and beta radiation that cause most of the exposure of humans to natural radiation. The key primary sources of natural radioactivity are potassium, thorium, and uranium.

2. Radioactive Materials in the Human Body:
The radioactive elements found in the human body come mostly from the ingestion of food, drinking water, and tobacco smoke which contain them. Potassium and radium (and its decay products) are the most common radioactive elements that are ingested. Some additional elements come from the inhalation of radon, an airborne noble gas, and its daughter products that become attached to dust particles. The alpha particles emitted by internal sources of radiation are the source of most of the exposure to ionizing radiation from materials in the body.

3. Cosmic Rays: About 2 x 10^{18} primary cosmic ray particles, consisting mostly of protons having energies of more than a billion electron volts, are incident on the earth's atmosphere each second. Most of the primary cosmic rays interact with atoms in the atmosphere and produce hundreds of secondary radiation particles, such as muons, electrons, and gamma rays. Sometimes these secondary particles of radiation arrive in bursts.

✍ Activity 28-1: Predicting Background Radiation

Suppose you were to take a radiation monitor outside and count the number of particles of ionizing radiation detected by the Geiger tube. Do you think you'll detect more radiation or less radiation than you would if you count inside with the Geiger tube? On the basis of the description of natural radiation you just read, explain your prediction.

25 min

Measuring Background Radiation

Let's use a small hand-held radiation monitor to measure the relative number a background counts in various places indoors and outdoors near your classroom. This will also give you a chance to reconsider the effects of statistical fluctuations on counting rates, which you observed in the second unit. For this activity you will need the following items:

- A Heathkit RM-4 Radiation Monitor
- A stop watch
- An MBL Radiation Counting System

The RM-4 Monitor contains a small Geiger tube that is capable of detecting gamma and beta particles that come either from cosmic rays or from the decay of radioactive elements. You'll be learning more about how the Geiger tube works in the next session.

You are to monitor background radiation both inside and outside:

Outside Background Radiation: Let's start with some outside measurements. To monitor radiation outside, take the monitor outside and turn the switch on the RM-4 Radiation Monitor from the off position to the audio position. The Monitor will now make a click whenever a gamma ray or beta particle passes through the Geiger tube and ionizes atoms in the gas inside the tube. **Note:** You can slide the upper switch to the "BATT" setting on the right to get a louder bleep rather than a click for the sound.

✍ Activity 28-2: Background Radiation Outside

Go outside and determine the number of counts/minute for four trials each lasting one minute. Record the results below and find the average and a standard deviation for your data.

Trial #	Counts/Min
1	
2	
3	
4	
Avg.	
Std. Dev	

Background Radiation in the Classroom: In order to monitor background radiation in the classroom you will use an MBL Radiation Counting System. This system, shown in the diagram below, allows you to attach the RM-4 Radiation Monitor you have been using to an interface which is in turn attached to the computer. When appropriate event counting software is loaded into the computer, you can take and display data automatically.

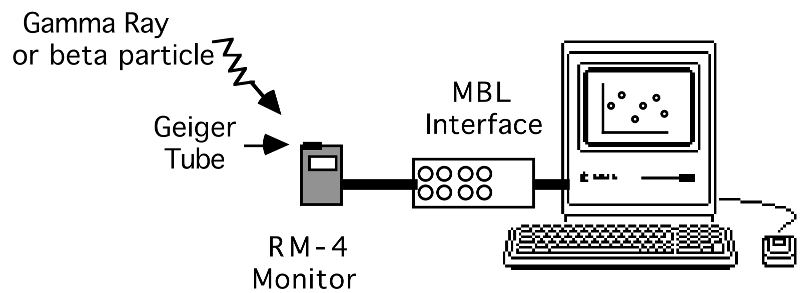


Figure 28-2: An MBL Radiation Counting System

You should consult Appendix B for detailed instructions for setting up the system and using the software.

The background counts may vary from place to place in the classroom. You will need to determine the background counting rate at your own table in order to correct future data. When you record future data you should attempt to locate your RM-4 monitor in the same place.

✍ Activity 28-3: Background Radiation at Your Table

(a) Place the Radiation Monitor in a convenient place on your lab table. Record the number of counts/minute for 10 one-minute long trials. Record the results below.

Trial #	cts/min	Trial #	cts/min
1		6	
2		7	
3		8	
4		9	
5		10	
Avg.			
Std. Dev.			

(b) In Unit 2 you explored the relationship between the standard deviation, σ, and the square root of the average number of counts in a counting interval. You should have found them to be about the same. Does this rule of thumb hold here? Compare the square root of the average number of counts/min to the standard deviation. Comment on the result of the comparison.

(c) Does there appear to be a statistically significant difference between the average of the two sets of counts recorded inside and outside? If so, was the difference what you predicted?

30 min

Radioactive Decay Rates

Radioactivity is now understood as a phenomenon in which neutrons and protons in a nucleus lose potential energy. Every once in a while, a nucleus in a collection of radioactive atoms ejects either a gamma ray, a beta particle, or an alpha particle. After the radiation is emitted, the neutrons and protons which are attracted to each other by the strong nuclear force move closer together. This process is similar to the one in which a mass loses potential energy by falling closer to the center of the earth.

Radioactivity is a statistical process in which each undecayed nucleus is in an unstable state. A series of slight disturbances can lead to a decay but not at a definite time. The best we can say is that a radioactive nucleus has a certain probability, λ, of undergoing a decay during a given period of time Δt. Let's predict what will happen to a large collection of radioactive nuclei *each of which has a known probability of decay*. We can do this by considering the behavior of a large collection of dice that are rolled once each minute.

✍ Activity 28-4: The Decay of Dice

(a) Assume that a *single* die represents a radioactive nucleus that hasn't undergone a decay yet. Suppose it is rolled sometime during a one minute period. If the die is not loaded, what is the relative probability, λ, that a "2" will come up during the first minute? **Note**: In probability theory relative probabilities are always numbers between 0 and 1 with 0 indicating that an event never happens and 1 indicating that an event is certain to happen.

λ = ________ /min

(b) Suppose you have a collection of N(0) = 300 undecayed dice at time 0. In general, the symbol N(t) represents the number of dice at some later time, t. If the dice in the collection are rolled once during the first minute, how many dice, ΔN, will have a "2" appear face up and hence will have decayed during the first minute?

# of decayed dice (out of 300) =

(c) How many dice, N(1), are left at the end of the first minute and what is the rate of decay $\Delta N/\Delta t$ during the first minute?

(d) If you were to remove the "decayed" dice (i.e. the "2's") and shake the remaining dice once again during the second minute, how many dice would have decayed and how many, N(2), would be left at the end of the second minute? What is the rate of decay $\Delta N/\Delta t$ during the second minute?

(e) Create a spreadsheet to calculate the number of undecayed dice, N(t) and the decay rate $\Delta N/\Delta t$ for the first 15 minutes, using the format suggested in the sample shown below. Note that a new column (F) is included to record experimental results and the natural log of N(t) is calculated in column (E) to see if the graph of lnN(t) vs. t is linear. *Be sure to format your columns as shown in the sample and save this file. You will be using it for other calculations.*

	A	B	C	D	E	F
1	Decay	Const	0.166	/min		
2						
3				Theory		Experiment
4	t	N(t)	ΔN(t)	ΔN(t)/Δt	ln(N)	ΔN(t)/Δt
5	min	min	Counts	Cts/min		Cts/min
6	0.0	300	50	50.00	5.70	
7	1.0	250	42	41.67	5.52	
8	2.0					
9	3.0					
10	4.0					
11	5.0					
	6.0					

Note that Δt=1.0 min

Since $\Delta N(t) = l\, N(t)\, \Delta t$ use the value in cell C1 in absolute form for this equation and copy down, so that the equation is =C1*B6*1.0

[AFFIX YOUR ACTUAL SPREADSHEET OVER THE SAMPLE]

(f) Let's see how good your theoretical predictions are. You and your classmates should roll the 300 dice during the first minute. Remove all the die that have a "2" on the top face representing decayed nuclei. How many are left? Repeat the procedure with the remaining dice 14 more times and fill the results into column (F) of the spreadsheet both in the printout above and in your computer version of it.

(g) Do the results match the theoretically expected results exactly? If not, attempt to explain why there are differences.

When you graph the number of dice as a function of time and then linearize the graph, you can determine which mathematical function describes a decay process in which there is a constant probability for decay of each object, such as a die or a radioactive nucleus, in a large collection. You can also determine an important quantity known as the *half-life*, $T_{1/2}$, of the material undergoing decay. *Half-life is defined as the time it takes for a material to decay to half of its original amount.*

✍ Activity 28-5: Graphing Decay & Determining Half-Life

(a) Transfer your spreadsheet data to your graphing routine and plot two graphs,one of N(t) vs. t and the other of lnN(t) vs. t. Add lots of tick marks to each of the graph axes so you can read numbers from the graphs. Affix the graphs in the space below.

(b) Examine the graph of N(t) vs. t. What is the approximate time it takes for the number of dice to decay from the original number of 300 to 150? How much additional time does it take for the number of dice to decay from 150 dice to 75 dice? What additional time do you think it will take for the dice to decay from 75 dice to 38 dice? What is the half-life of the dice if they are rolled once a minute?

(c) Suppose the dice decay constant were doubled so the probability of decay in each minute was twice as great. (This could be simulated by claiming that upon each roll of the dice, the decay occurs whenever a "2" or a "6" comes up.) What would happen to the half-life of a collection of dice rolled once a minute. In general, how do you think the decay constant, λ, is related to half life, $T_{1/2}$? Is it directly proportional, inversely proportional, or what?

---

20 min

The Formal Mathematics of Radioactive Decay

Those of you with a flair for mathematics will be delighted to discover that we can derive the mathematical equations describing radioactive decay using integral calculus. These equations can be used to do some important calculations in preparation for your observation of the counting rates associated with the decay of radon and its daughters.

Your experience with the decay of dice should convince you that the number of radioactive nuclei expected to decay in a given time is proportional to the number of undecayed nuclei at a given time, N(t), and to the amount of time over which the decay is measured. The constant of proportionality is represented by the decay constant λ. Thus for a very small time interval dt, we can write the equation

$$dN = -\lambda N(t)dt \qquad \text{[Eq. 28-1]}$$

The minus sign takes into account the fact that the collection of radioactive nuclei is getting smaller over time.

By re-arranging terms we can write this equation as

$$dN/N(t) = -\lambda dt \qquad \text{[Eq. 28-2]}$$

and proceed to take the integral of both sides of the equation so that we get

$$\int_{N(0)}^{N(t)} \frac{dN}{N} = -\int_{0}^{t} \lambda \, dt \qquad \text{[Eq. 28-3]}$$

Since the integral of 1/N is just the natural logarithm of N and the integral of dt is just t, this equation can be rewritten as

$$\ln N \Big|_{N(0)}^{N(t)} = -\lambda \quad t \Big|_{0}^{t} \qquad \text{[Eq. 28-4]}$$

✍ Activity 28-6: The Mathematics of Radioactive Decay

(a) Put in the limits of the integrals in equation 28-4 and take the exponent of each side of the resulting equation to show that the number of radioactive nuclei remaining after a time t is given by the expression $N(t) = N(0)e^{-\lambda t}$ where N(0) is the number of radioactive nuclei at t=0.

(b) How is the half-life, $T_{1/2}$, related to the decay constant, λ? You can derive this relationship easily by using equation 28-4 and letting N(t) = (1/2) N(0) when t= $T_{1/2}$. By using these procedures show that $T_{1/2} = \ln 2 / \lambda = 0.69/\lambda$.

(c) Did you predict an inverse proportionality between $T_{1/2}$ and λ in Activity 28-5(c)?

(d) Using the expression $N(t) = N(0)e^{-\lambda t}$ show that the counting rate dN/dt at time t is given by $dN/dt = -\lambda N(t)$.

SESSION TWO : DECAY SERIES , RADON AND HEALTH

Is Thorium 232 Really Long Lived?

The glow from a Coleman lantern mantel used commonly by campers is produced when the lantern fuel burns in the presence of thorium oxide. There are two types of thorium in a typical Coleman lantern mantel – thorium 232 with a half-life of 1.4×10^{10} years and thorium 228 with a half-life of 1.91 years.

You should be able to predict the counting rate from a sample of thorium 228 and thorium 232. Would you expect any change in counting rate during a one hour period of counting? In order to complete this activity you will need the following items:

- A Heathkit RM-4 Radiation Monitor
- A Coleman Lantern Mantle
- An MBL Radiation Counting System
- Scotch Tape

Before starting your measurements, place the Radiation Monitor at its usual location on the lab table and tape the lantern mantle directly in front of the Geiger tube. Set the run time for one hour and the interval for one minute.

✍ Activity 28-7: Counts from a Long-Lived Source

(a) Use the nuclear counting software to record the number of counts/minute for 60 one-minute long trials. At the end of the hour carefully transfer the data to a spreadsheet. Also record the average and standard deviation from the spreadsheet. See Appendix B for details. Affix a copy of the printout in the space below.

(b) In Unit 2 you explored the relationship between the standard deviation, σ, and the square root of the average number of counts in a counting interval. You should have found them to be about the same. Does this rule of thumb hold here? Compare the square root of the average number of counts/min to the standard deviation. Comment on the result of the comparison.

(c) Study the spreadsheet. Is there any *statistically significant** decrease in the decay rate of the thorium during the hour over which you took measurements? Can you explain your observations on the basis of the mathematical theory given a collection of nuclei with such a long half-life? (*By statistically significant we mean do the counts lie within one standard deviation of the average 2/3rds of the time?)

The Atomic Nucleus and Radioactive Emissions

Note: In order to study the phenomenon radioactivity, you need to know more about what physicists currently believe about the nature of atoms and their nuclei. Unfortunately, you lack the time and equipment to learn about these things by doing fundamental investigations. Thus, we're going to break from our usual pattern in this enterprise and tell you what's believed about the structure of atoms without answering the much more profound questions of why physicists believe what they believe about atoms.

All atomic nuclei are thought to consist of neutrons and protons held together, not by gravitational attraction or electric or magnetic forces, but rather by strong nuclear forces acting over a short range. The proton has the same magnitude of charge as the electron, but its charge is positive. It has a mass of almost 2000 times mass of the electron. The neutron has a similar mass but no electronic charge. Protons in the nucleus ought to fly apart as a result of the Coulomb repulsion between them; the fact that they don't is a testimonial to the power of the even stronger nuclear forces that are *always* attractive and act on both protons and neutrons. The number of protons in the nucleus determines how many electrons are in the vicinity of an electrically neutral atom. Thus, a neutral atom has the same number of electrons surrounding the nucleus as it has protons in the nucleus. It is the number of electrons in a neutral atom which determines how the atom behaves chemically. Each chemical element is defined by the number of protons it has in its nucleus. For example, hydrogen has one proton, helium has two protons, lithium has three protons, and so on.

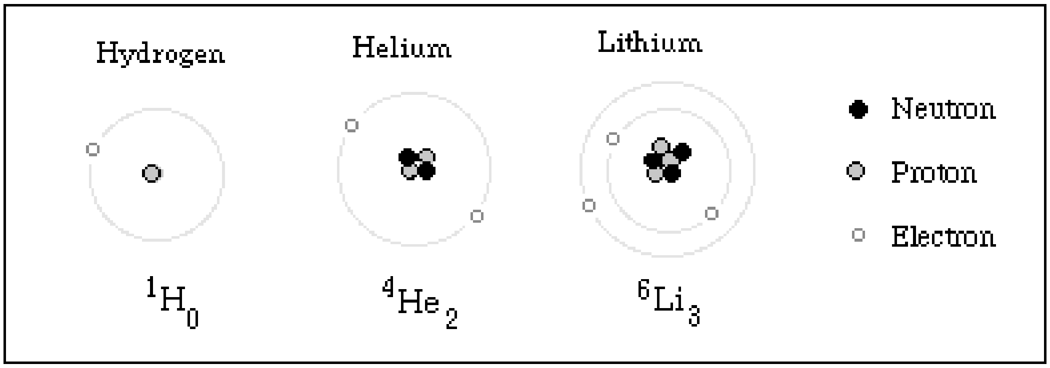


Figure 28-3: The three lightest chemical elements showing the number of protons that define the element along with the most common number of neutrons in the nucleus. The gray circle represents a proton, the black circle a neutron, and the white circle an electron. The diagram is simplified as electrons are not pictured by physicists as orbiting the nucleus of an atom in nice, neat circles.

Although the chemical behavior of an element is keyed to the number of its electrons and hence also to the number of its protons, *different atoms of an element do not always have the same number of neutrons in the nucleus*. We call different nuclei types of an elemen*t isotopes.* For example, even the very lightest element, hydrogen has three isotopes: hydrogen, deuterium, and tritium. This is shown in the following diagram.

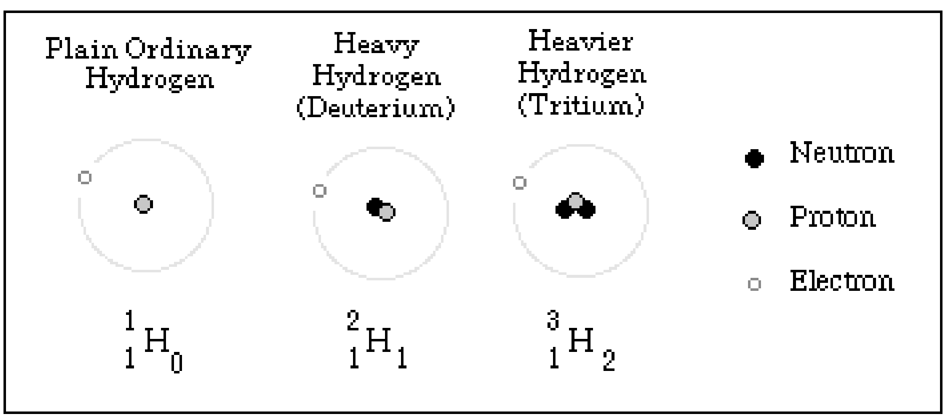


Figure 28-4: Three isotopes of hydrogen. Deuterium is of great interest as a fuel for the nuclear fusion process, which may allow mankind to have an abundant source of low-cost energy.

Ordinary hydrogen only has one proton in its nucleus. Deuterium has one proton and one neutron. Tritium has one proton and two neutrons.

Certain isotopes are unstable and decay by spitting out energetic particles. These isotopes are said to be *radioactive*. When this decay occurs some of the neutrons or protons rearrange themselves or are transformed in some way. The three most common particles given off in the decay process are known as the alpha particle, the beta particle, and the gamma ray respectively. The alpha particle is not really a single particle. It consists of a collection of two neutrons and two protons. In fact, it is the nucleus of the element helium, which ordinarily contains two neutrons and two protons. Thus, it has two fundamental units of charge.

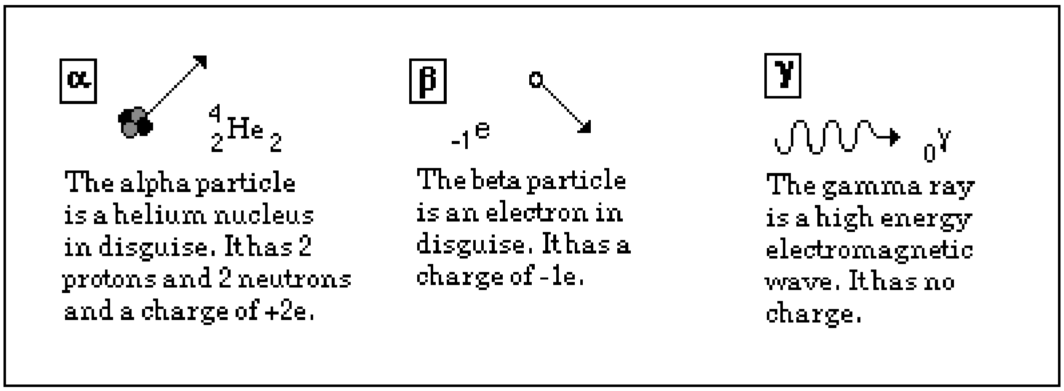


Figure 28-5: The most common types of radiation emitted by radioactive nuclei.

The beta particle is really a fast moving electron. Thus, it has a mass of only about 1/8000th of the mass of the alpha particle. The beta particle has a negative charge of one unit. The gamma particle is a high energy electromagnetic wave which consists of mutually perpendicular electric and magnetic fields that oscillate as it travels. It has momentum, but no mass or electric charge.

Detecting Ionizing Radiation with a Geiger Tube
The fact that alpha, beta, and gamma particles can ionize other atoms in their paths allows us to detect their passage electronically with a device called a Geiger tube. In a Geiger tube, an ionizing particle is passed into a cylinder of gas that has a high voltage between a central electrode and the outside of the cylinder. When electrons are knocked off of atoms the electrons flow toward the central electrode while the ions flow toward the outer wall of the cylinder. This creates a burst of current which can be amplified and sent to a computer or electronic counter so the passage of a particle of ionizing radiation can be recorded.

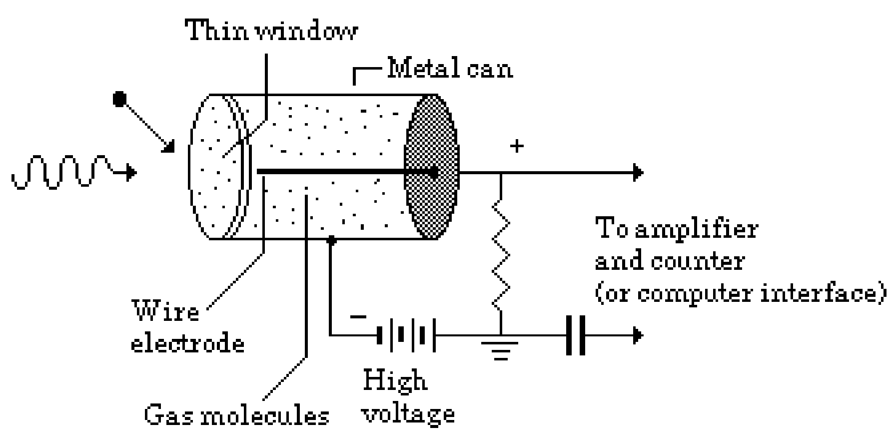


Figure 28-6: A schematic for the Geiger tube, which detects beta particles and gamma rays. The RM-4 Monitor has a Geiger tube and amplifier circuit in it.

A Geiger tube is best for detecting beta particles. Alpha particles are stopped in the thin window of mica at the end of the tube. Gamma rays travel very far without colliding with electrons and tend to pass on through the tube while beta particles ionize the gas in the tube.

The Health Effects of Radiation

This is a vast and controversial subject about which literally thousands of books have been written. It is widely accepted that alpha, beta, and gamma particles that are emitted from radioactive nuclei can penetrate into the body and ionize atoms and molecules in the body. This changes the chemical bonds inside of living cells. If enough of these changes occur inside a cell they can lead to the death of the cell, inaccurate reproduction of the cell, or malfunctioning of the cell. The degree of damage is believed to be roughly proportional to the amount of a given type of radiation a person is exposed to. It must be noted, however, that some scientists believe that very low amounts of radiation exposure will not cause permanent damage. They cite evidence that the body can repair itself. Others believe that any amount of radiation exposure can cause permanent damage. Currently, this remains an unsettled scientific controversy.

Based on studies of humans exposed to large amounts radiation and to animal studies in the laboratory, it is currently believed that radiation can increase the probability of an individual getting cancer five to twenty years after exposure and that radiation can cause mutations in the egg and sperm cells of potential parents that could lead to a higher incidence of genetic diseases in the population.

Ionizing radiation loses energy as it collides with atoms and molecules in its surroundings. It also fans out in all directions from the collection of radioactive nuclei that generate it. Shielding experiments indicate that typical alpha, beta, and gamma particles having approximately the same energy have quite different penetration power in materials. For example, alpha particles can be stopped by a sheet of paper or a couple of centimeters of air. Beta particles can be stopped by a thin book or about ten or twenty centimeters of air, while gamma rays might require several room lengths of air or several lead bricks to be stopped on the average. By reflecting on your study of mechanics and electricity and on the properties of the three particles being considered, you should be able to predict that alpha particles would be the least penetrating and gamma particles the most penetrating.

✍ Activity 28-8: Protecting Against Radiation Damage

(a) Why do you think alpha particles have the least penetrating power in matter? Why might gamma rays be the most penetrating?

(b) What is more dangerous, swallowing a source of alpha, beta, or gamma particles? Give reasons for your answer.

(c) What is more dangerous, having a source of alpha, beta, or gamma particles on the table in front of you? Give reasons for your answer.

(d) Suppose you have a high activity source of radiation on the table in front of you. Suggest two methods for protecting yourself from the radiation.

The Nucleus and Radioactive Decay Series

When an alpha or beta particle leaves the nucleus, charge and energy are carried away from the nucleus. Physicists continue to believe that these quantities are always conserved, even in nuclear decay. Thus, when the beta particle carries a unit of negative electron charge away the nucleus that is left behind must have an additional unit of positive charge. This will be the case if the beta decay occurs because a neutron has been transformed into a proton. A nuclear beta decay process is shown symbolically in the diagram below. Try to guess the meaning of the superscripts and subscripts. These will be explained in more detail below.

$$\underset{\text{neutron}}{{}^{1}_{0}\mathrm{n}} \longrightarrow \underset{\text{proton}}{{}^{1}_{+1}\mathrm{p}} + \underset{\text{electron}}{{}^{0}_{-1}\beta}$$

Figure 28-6: Symbolic representation of a neutron in the nucleus being transformed into a proton while spitting out a beta particle.

Whenever a decay occurs the nucleus rearranges itself so that it has less energy. The difference in energy of a nucleus before and after decay is carried away by the departing particle.

Because of the conservation of charge we can set up a scheme to do bookkeeping and figure out what element and which isotope of that element is left behind after a decay of a given type. The figure below outlines how we can display the one or two letter abbreviation for each chemical element and the number of protons and neutrons in a given isotope of that element.

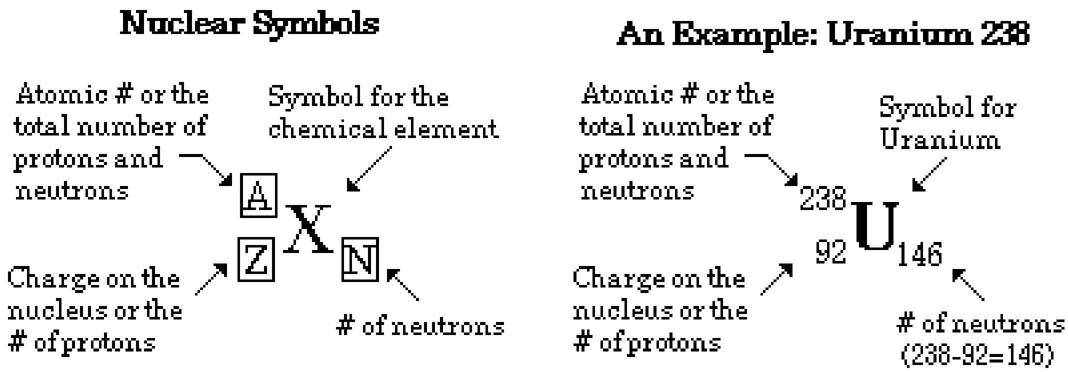


Figure 28-6: Symbols to display the neutrons and protons in nuclear isotopes in general and for the uranium 238 in particular.

Let's use the bookkeeping method to display the isotope that results after an alpha decay of uranium 238. This is shown below.

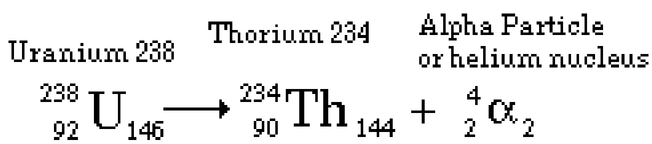


Figure 28-7: Symbols to display the neutrons and protons when the uranium 238 nucleus gives off an alpha particle.

Since the alpha particle carries away two units of charge in the form of protons, the charge on the daughter nucleus must be 90. A look at the periodic table in any introductory physics or chemistry text reveals that thorium has 90 protons. Once the symbol for thorium,, which is Th, is put in the rest of the bookkeeping can be done easily. There are two fewer neutrons and the atomic number (i.e. the number of protons and neutrons) is reduced by four units.

A similar job of bookkeeping can be done when thorium 234 undergoes a beta decay. This is shown in the diagram below.

Thorium 234 Protactinium 234 Beta particle or electron

$$ {}^{234}_{90}\mathrm{Th}_{144} \longrightarrow {}^{234}_{91}\mathrm{Pa}_{143} + {}^{0}_{-1}\beta_{0} $$

Figure 28-8: Symbols to display the neutrons and protons when the thorium 234 nucleus gives off an beta particle.

Radioactive Decay Series

Many of the heavy elements that were contained in the earth when it was formed contain extra neutrons and are just dying to settle down into being lighter elements. Some of these heavy elements decay into a daughter element; the daughter in turn is the parent of another element in the decay chain and so on. For example, uranium 238 is the head of a radioactive decay chain in which a series of alpha and beta decays (followed by one or more gamma decays) lead ultimately to an isotope of lead which is stable rather than radioactive. The uranium decay chain is depicted on the next page. It is of special interest because one of the key daughters in the decay series, radon 222, is now recognized as having the widespread potential for increasing the lung cancer risk in people who live in certain unventilated basement areas.

✍ Activity 28-9: Elements in the Radioactive Series

Study the decay series depicted below. By using the conservation of charge as exemplified in Figures 28-6, 28-7, and 28-8 figure out how many neutrons and protons the elements that go into each of the blank daughter rectangles should have. Check the periodic table and list of properties of elements contained in the Appendix of most standard introductory physics text books. Fill in the name, chemical element symbol, and atomic number for each of the "missing" elements on the chart.

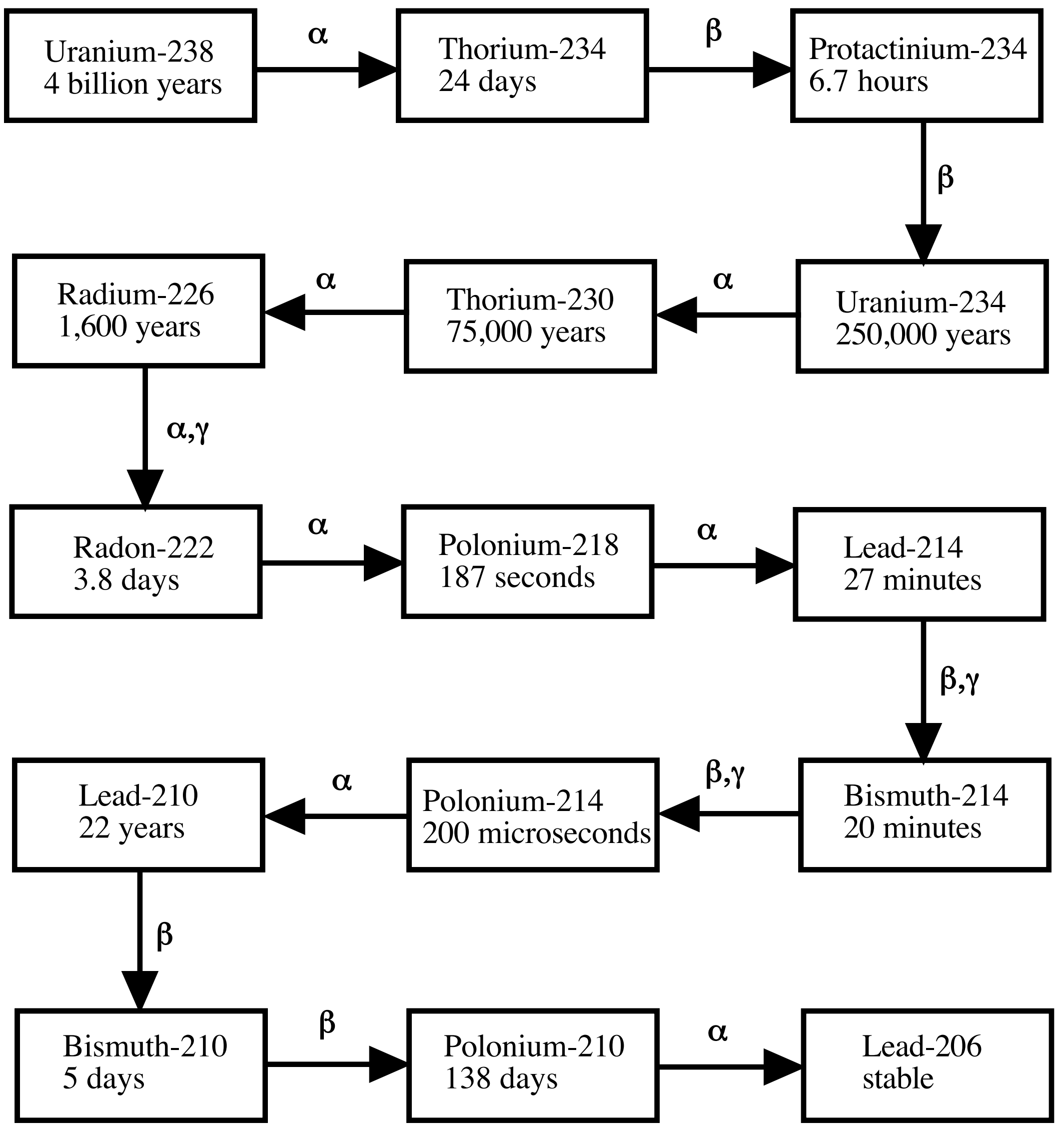


Figure 28-9: The Uranium-238 decay series shown above is one of several natural decay series which start with heavy isotopes of thorium or uranium.

The Radon Problem

Uranium 238 occurs naturally in soils. Some soils, like those in parts of Pennsylvania, contain more uranium than others. Uranium 238 has a half-life of over 10^9 years, a long time by our ordinary measures of time. Its going to stick around for a long, long time. As the uranium 238 steadily decays thorium 234 is formed. The thorium 234 begets protactinium which begets uranium 234 which begets thorium 230 which begets radium 226 which, in turn begets radon 222, and so on. All the parents and grandparents of radon 222 stay in the soils. These elements bond chemically to soil particles. You are safe from these radioactive elements unless you make a practice of eating dirt.

Unlike all the other daughter elements in the uranium 238 decay series, radon is a chemically inert gas. The electrons surrounding the radon atom like to stick close to the radon nucleus. They do not form chemical bonds with other elements. The radon gas is free to seep up through the soil and into the atmosphere where it spreads out and becomes diluted. However, in enclosed basement areas, and especially in new, well-insulated houses, it is possible that the radon gas will not escape into the atmosphere. People can breath radon-filled air into their lungs. The daughter products of radon can stick to the walls, dust particles, and dog fur in the home. Thus, radon and its daughters can invade the home and cause added exposure to both internal and external sources of ionizing radiation.

Heath officials and private citizens alike are looking for inexpensive, easy-to-use radon tests. If areas with high radon concentrations can be identified, then corrective measures can be taken to reduce the exposure of individuals to radon and radon daughter products.

Monitoring Radon with a Geiger Tube

A new method for identifying radon hot spots using a Geiger tube has been developed at Dickinson College.
In order to use this method you will need the following items:

- A piece of medical gauze (about 6" long)
- A blob of Vaseline
- A vacuum cleaner
- Scotch tape
- A plastic bag
- A basement area with an electrical outlet
- A Heathkit RM-4 Radiation Monitor
- An MBL Radiation Counting System

The general strategy of this approach to radon monitoring is to suck air through a piece of gooey Vaseline-filled gauze with a vacuum cleaner for about 30 minutes to collect radon daughters that stick to the Vaseline in the gauze. Two of the radon daughters, lead 214 and bismuth 214, are beta emitters with half-lives of 27 minutes and 20 minutes. These daughter elements are captured in the gauze and can then be transported to the radiation monitor immediately for counting. After recording counts from the gauze for about 4 hours, you should get data that yields a decay curve with a half-life somewhere in the 30 minute range.

Notes:

To Do This Experiment, You Must:

(1) *Reserve the equipment:* Sign up for an hour to use the vacuum cleaner and a basement area equipped with an electrical outlet.

(2) *PracticeHow to Transfer Data from the Nuclear Counting Software:* The MBL radiation counting system uses software for the nuclear counting. If you haven't already been successful at transferring the counts/interval data obtained by the nuclear counting software to a spreadsheet, take some data and practice this maneuver! This is an essential skill without which you might lose all your data.

(3) *Make Your Gauze Gooey:*
Just before your appointed hour rub a blob of Vaseline into a 6 inch long strip of medical gauze. *Make sure the Vaseline is rubbed in well enough that air can still pass through the gauze or else the vacuum cleaner will overheat.*

(4) *Mount the Gauze on the Vacuum Cleaner:*
Fold the gauze over several times and tape it to the *intake* end of the vacuum cleaner you have been assigned. Cover the intake with enough tape so that all the air coming into the vacuum cleaner must flow through the gauze. Leave at least a 1.5" X 1.5" area in which air can flow through the gauze so the vacuum cleaner doesn't overheat.

(5) *Set Up Your MBL Nuclear Counting System:*

(a) Clear your system disk of old files so you will have plenty of space for saving the long data file that will result from the radon monitoring.

(b) Load the nuclear counting software, plug in the RM-4 Monitor, and turn on the interface (See Appendix B for details). Make sure the system is counting properly.

(c) Set up the software with an interval of 1 minute and a run time of four hours. Place a DO NOT TOUCH SIGN on the computer with your names, the date, and the hours of use. You will need to reserve the computer for just under 5 hours.

(6) *Collect the Radon Daughters:*
Take the vacuum cleaner to the basement room you plan to monitor, plug it in and run air through the vacuum cleaner for exactly 30 minutes. Record the time of your data taking, any special conditions in the basement such as an open window, and its location in the space below.

(7) *Race Back to the MBL Nuclear Counting System:*
As soon as the 30 minute collection period is up run back to the lab with your sample. Fold the gauze up into a neat, small and flat wad. Put it in a thin plastic bag to prevent the Vaseline from getting all over. Seal the bag and tape it directly against the Geiger tube.

(8) *Collect Data on the Counting Rate vs. Time:*
Collect 240 one-minute intervals over the next four hours. You can go away now and come back in four hours to save your data file. DON'T FORGET TO COME BACK. OTHERS WILL NEED THE COMPUTER!

(9) *Transfer Your Data to a Spreadsheet:* Transfer your counts vs. seconds elapsed data into a spreadsheet and save the spreadsheet file. We will work with the data during the next session.

✍ Activity 28-10: Radon Monitoring Record

Record the following data:

Date of Monitoring __________

Location of Basement (Bldg, Room #) ___________

Special Conditions (Clean room, dusty room, ventilated, etc.)
____
____
____

Air Sample Start Time __________ End time *___________

Counting Start Time* ____________ End Time_________

No. of Counts/min in the first minute of counting __________

Avg. Background Counts/min at location of counting ________

Comments:

*Note: It's very important for you to know how many minutes elapse between the time you stop collecting radon daughters by turning off the vacuum cleaner and the time you begin counting the radiation emitted from the gauze.

SESSION THREE: FITTING THE RADON DATA WITH A THEORY

The radon data you collected is not easy to explain theoretically right off the bat. Take another look at the uranium 238 decay series chart. Notice that the radon gas decays into four daughters before decaying to lead 210, which is essentially stable for our purposes. Each daughter has its own half-life and type of particle it gives off. Instead of having separate decay curves we have linked decay curves. Thus, while the nuclei of a given daughter is decaying away as you count, the parent is creating new daughters of that type. What a headache! We are going to create the decay data for each of the daughters as if it were free to decay completely. We are then going to link all the simulated data to reflect the fact that each parent continues feeding its daughter. How closely will our theory of linked radioactive decay fit your experimental data? How significant is the radon level in the basement you monitored? Should people be living in that basement room or not?

Graphing the Data for dN/dt vs. t

You will need to prepare your spreadsheet data so it can be graphed and compared with the theory that you will be developing.

✍ Activity 28-10: Radon Monitoring Record

(a) Open up your radon data spreadsheet. Create a times column (in minutes rather thatn seconds), subtract the average background cts/min (in the room where you are doing the counting with the RM-4 Monitor) from the recorded counts/min, and put it in a column labeled corrected cts/min. **Note:** When making corrections, the number of counts/minute will be bouncing around so much due to statistical fluctuations that you may encounter zero or a negative number of counts in a given interval when background is subtracted. If this happens, simply set the corrected counts/minute to one. Why one??? Well, one is pretty darn close to zero, and given the way things bounce around its not a very big fudge. It's a fudge that will allow you to the take the natural log of one to get zero rather than the natural log of zero which would give you something nasty like $-\infty$.

(b) Transfer the data for the corrected value of dN/dt in counts/minute as a function of minutes to the graphing routine and graph the data. Affix the graph in this space. Go ahead and cover up these instructions!

About How Much Radon Gas Did You Detect?
The activity of radon gas in air is measured in picocuries per liter where 1 picocurie (pCi) represents 2.22 disintegrations of radon per minute. The Environmental Protection Agency (EPA) has warned that people should not be living in or spending a significant amount of time in any space that has a radon level of 4.0 pCi/liter or more. The average home has a radon level of 1.4 piC/liter. In roughly a million homes in the United States radon levels are 5 to 10 times higher than the EPA limit.

There are a number of techniques commonly used to determine radon levels in picocuries/liter. In order to have some estimate of what kind of radon level is in the space that you took you sample in, you will need to find a conversion factor between the counting rate you observed from the gooey gauze monitoring and the radon level in picocuries/liter. For example, suppose your instructor or someone in your class used another technique to find that a certain space had a radon level of 8.5 pCi/l. When using the gooey gauze method in that same space you found that 10 minutes after the vacuum cleaner was turned off, the corrected counting rate, dN/dt, detected in the Geiger tube was 50 counts/minute. Then your conversion factor from counts/minute to pCi/l would be given by the ratio of the two factors as shown below.

$$F = [8.5 \text{ piC/liter}] / [50 \text{ cts/min}] = 0.17 \ [\text{piC/liter}] / [\text{cts/min}]$$

✍ Activity 28-11: Calculating the Radon Level

(a) First let's determine the conversion factor, F, for your specific monitoring apparatus. Let C represent the number of pCi/liter you or your instructor obtained using a commercial monitoring device at a known location. Let G be the number of counts/minute detected by a radiation monitor during the eleventh minute (at 10 minutes) after the vacuum cleaner was turned off. Note both C and G must be determined by monitoring in the same space. Fill in the blanks below, if you can:

C = _________ pCi/liter G = __________ counts/minute

F = C/G = _____ [piC/liter] / [cts/min]

(b) Open up your radon data spreadsheet and determine the average counting rate dN/dt in counts/minute during the tenth, eleventh, and twelfth minute *after the vacuum cleaner was turned off* for the particular space you were monitoring.
Next use this value to calculate the approximate radon level in picocuries per liter.

Approximate Radon Level = F X dN/dt = ________ X________

____

PiC/liter

(c) With regard to its possible radon level and EPA warnings, would you be willing to live in the space you were monitoring?

(d) Your results are very approximate! List some of factors that might cause your result to fluctuate or be uncertain.

Developing a Model to Explain Your Decay Curve

Typically in a poorly ventilated basement room, the radon gas that diffuses up from the ground floats around in the room. Within 3.8 days approximately half the radon 222 atoms that come into the room at about the same time give off alpha particles and decay into polonium 218. Half of the polonium 218 decays into lead 214 within 3.1 minutes of the time it is produced, and so on. After a few hours the room contains a mixture of radon 222 and its daughters. If you were to develop a spreadsheet model of this process you would find that after a few hours the radon would reach *secular equilibrium* with its daughters Po 218, Pb 214, Bi 214, and Po 214. *A state of secular equilibrium is defined as the state in which each of the daughter products has the same activity or decay rate as the parent nucleus.* For the purposes of developing a model to describe our radon monitoring data, we only care about what happens over time to the two daughters that give off beta particles, Pb 214 and Bi 214.

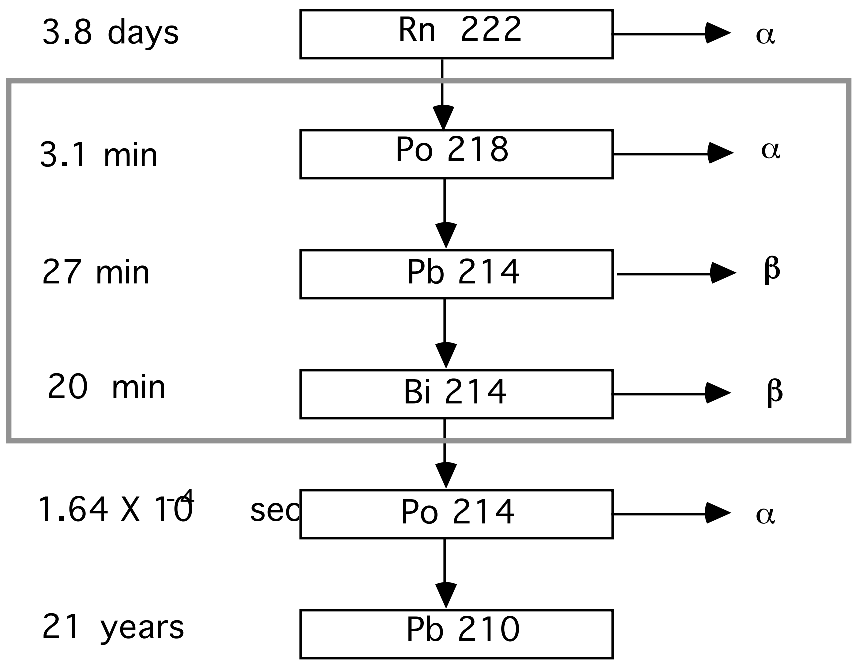


Figure 28-10: The portion of the uranium 238 decay series of interest in radon monitoring

What's the relative number of radon nuclei compared to the number of daughters within a few hours after the radon enters the room? In this scenario there are originally only radon atoms in the room.

✍ Activity 28-13: Relative Activity of Radon Daughters

(a) Review the results you obtained in Activity 28-6. What is the relationship between the decay constant, λ, and the half-life, $T_{1/2}$, of a radioactive isotope? Calculate the decay constant in terms of the probability of decay per minute for the radon nucleus and all the daughter nuclei shown in Figure 28-10.

λ_{Rn222} = __________ / min

λ_{Po218} = __________ / min

λ_{Pb214} = __________ / min

λ_{Pb210} = __________ / min

(b) Review the results you obtained in Activity 28-6. What is the equation for the activity or decay rate, dN/dt , as a function of the decay constant, λ, and the total number of radioactive nuclei, N(t), present at time t?

(c) Suppose there are 10 million radon atoms present in a liter of air in a room. Calculate the activity (or decay rate) for the radon 222.

(d) If the radon is in secular equilibrium with its daughters, what are the numbers of each of the daughter atoms? **Hint:** For Po 218 you should get N= 5754. What are the values of N for Pb 214 and Bi 214?

One more thing before getting on to the development of our spreadsheet model. Let's consider more carefully what you would expect to happen as particles of dust in a basement room accumulate on the gooey gauze while you run the vacuum cleaner.

✍ Activity 28-14: What's in the Dust?

Do you expect that radon atoms stick to particles of dust in the room? How about the polonium, lead, or bismuth daughters? Will they stick to dust particles in the room? Explain.

OK let's assume you've flipped off the vacuum cleaner and rushed over to start counting your sample immediately. Assuming no radons have stuck to the gooey gauze, then we have a mixture of just the daughter products. Assume that you have 5754 Polonium 218's in your piece of gauze and the appropriate number of other daughter atoms as calculated in Activity 28-13 (d). If the daughter elements are in secular equilibrium, let's figure out how one element now decays into another as time goes by and how many beta particles will be emitted each minute.

✍ Activity 28-15: The Radon Decay Model

(a) Suppose at time t=0 there are 5,754 polonium 218 atoms present in a liter of air in a room and 48688 atoms of lead 214. What is the activity or decay rate at time t=0 min for the Polonium 218? How many polonium nuclei are left at the end of the first minute? How many lead 214 nuclei exist at the end of the first minute because they have been produced in that minute?

(b) Let's check up on the lead 214 at the end of the second minute. How many lead 214 nuclei are lost due to decay? How many lead 214 nuclei are gained because of the decay of its parent atom polonium 218?

(c) Open the pre-prepared spreadsheet entitled "Radon SS Model". Study the first few rows. How do the numbers you just calculated in parts (a) and (b) compare with the ones in the spreadsheet for the number of each element?

(d) Hey, this spreadsheet is supposed to show a decay curve for the two daughters that emit beta particles! How come the counting rate for total betas is going up at first instead of down? **Hint:** What is happening to the polonium 218 at a rapid rate at first? How does this influence the lead 214 decay rate? Did you notice any evidence of this predicted upswing in the plot of your data requested in Activity 28-10 (b)?

(e) Mess around with the spreadsheet model and change the original number of polonium atoms until the total beta decay counting rate at time t=0 (from the time you turned off the vacuum cleaner) matches the value you obtained. Then graph the natural log of dN/dt vs. time. Label this as a model decay curve or a theoretical curve. Next do a similar plot of your data using exactly the same scale. Affix the two graphs in the space below. How do they compare?

Note: If you monitored a low radon area and don't have a decent decay curve to look at, please ask for and analyze data provided by the instructor.

The Radon Laboratory Report

You are to prepare a formal laboratory report describing the outcome of the class radon monitoring project. For this report you should do some outside reading on either the health effects of radiation or about the radon problem to include in your laboratory report. Please re-read the requirements for a formal laboratory report in the policy and procedures section of this activity guide. You may want to collect results from some of your classmates and try to figure out what is different about high and low radon areas on campus.

THE END
THAT'S ALL FOLKS!!
IT'S BEEN LOTS OF WORK AND LOTS OF FUN FOR ALL OF US

HAVE A GOOD SUMMER

UNIT 28 HOMEWORK AFTER SESSION ONE (MONDAY)

Before the next class period:

• Work Supplemental Problems SP28-1, SP28-2, and SP28-3 shown below.

SP28-1) One of the radioactive forms of thorium has a total of 228 neutrons and protons in its nucleus and has a fairly long half-life. In fact, thorium 228 has a half-life of 1.91 years. (That's a bit longer than the half-life of the dice collection you performed measurements on in the last session!). (a) Assume that time is measured in minutes, and calculate the decay constant of thorium using the equation derived in Activity 28-6(b). (b) Suppose you have a collection consisting of 6.02×10^{10} thorium 228 atoms (which is only 1/1000th of a mole of the thorium) and some type of a particle counter that captures and records all of the radiation emerging from the collection of atoms. What counting rate (in counts per minute) do you expect to see during the first minute of counting?

SP28-2) Consider the sample of thorium 228 atoms described in the previous problem. Use a spreadsheet and the equations you derived in Activity 28-6 (a) & (d) to calculate the number of radioactive nuclei and the decay rate for each of 60 minutes. Will there be any noticeable change in the decay rate of the thorium during a one hour counting session? Why or why not? Discuss this on the printout of the results you submit. Then save your computer file for further modification.

SP28-3) Consider a sample of 1000 radioactive lead 214 atoms having a half-life of 27 minutes. Use a spreadsheet and the equations you derived in Activity 28-6 (a) & (d) to calculate the number of radioactive nuclei and the decay rate for each of 60 minutes. Will there be any noticeable change in the decay rate of the lead during a one hour counting session? Why or why not? Discuss this on the printout of the results you submit. Then save your computer file for further modification.

UNIT 28 HOMEWORK AFTER SESSION TWO (WEDNESDAY)

Before the next class period:

• Use a vacuum cleaner to shlurp a collection of dust particles containing radioactive nuclei from radon daughters into a piece of gauze at some basement location on campus. (This process takes about an hour. See the Session Two Activity Guide Notes for detailed instructions).
• Return to the lab immediately with your sample, place it in a plastic bag and set up a four hour long run time with a counting interval of one minute. (This process takes about 10 minutes to set up at the beginning of the four hour run and about 20 minutes to save files and data at the end of the four hour time period. See the Session Two Activity Guide Notes for detailed instructions).

UNIT 28 HOMEWORK AFTER SESSION THREE (FRIDAY)

Before leaving for the summer

• Complete Unit 28 Activity Guide Entries

• Complete a Formal Laboratory Report on Radon Monitoring (See the Session Three Activity Guide Notes for more information)