

chapter 5

Radioactivity

CASE STUDY CONTINUED: Life After Cancer

Six months after Francine's treatment plan was completed, she returned to her doctor for another MRI. The scan showed that the tumour was completely eliminated. Her doctor informed her that she should come in after a year had passed to ensure the tumour would not reappear in that time. Her thyroid would continue to be monitored by regular ultrasound appointments over the next five years, along with her annual physical checkup. Because the cancer had not metastasized, Francine had an excellent chance of staying cancer-free.



Figure 5-1

A History of Radioactivity

While Roentgen was busy announcing his discovery of x-rays, French scientist Henri Becquerel was studying substances for the property of fluorescence in 1896. Fluorescence is a physical property of a substance that causes it to glow brightly when exposed to light. Becquerel studied the levels of fluorescence by placing the substances on photographic plates and recording the phenomenon. On a particularly cloudy day, Becquerel wrapped the photographic plates carefully and placed it in a drawer along with the substance he was studying – a compound containing **uranium** oxide.

Later, Becquerel wanted to use the plates for further fluorescence investigations. He discovered, though, that the plates that were in the drawer with the uranium compound were fogged – as if they had been exposed to sunlight. Since that had been impossible – he had wrapped them too carefully for that to occur – he concluded that the uranium compound was emitting some kind of invisible ray. This was the first recorded discovery of natural radiation. It would be two years after his discovery that Marie and Pierre Curie would report similar findings with the element **radium**. By then, the worldwide scientific community became interested in the phenomena associated with radioactivity.

The Curies, who were Polish scientists, were studying the natural radiation emitted by uranium compounds. They believed that there were other elements that were radioactive. It was through their experiments that both radium and polonium were discovered. Both of these elements are more radioactive than uranium.

Radium became a natural source for gamma rays and was used well into the 1950s. In the mid 1940s, synthetically produced sources for gamma rays started to replace the use of radium. These synthetically produced substances – cobalt and iridium – were cheaper to process.

The early studies of radioactivity led to many laboratory-related diseases, including loss of limbs and loss of life. Researchers diligently recorded the effects of radiation on living tissue at their own personal expense. It is through these forays into radioactivity and radiation that the area of health physics began to emerge – to promote the study of radiation, radioactivity and its effects, and to promote safe procedures in the handling, storage and experimentation with these substances.



Figure 5-2

Cancer Connection

Radium Cures Everything!... Or Does It?

Once radium was discovered, it began to be studied in detail in the early 1900s. Many scientists believed that the radioactive property of radium could help cure many ailments—toothaches, arthritis, PMS, stomach disorders, high blood pressure, goitre, cancer...you name it, and radium could cure it. Soon, medical doctors in hospitals were ordering patients to drink radium-laced water. Other patients were prescribed radium rub therapy, where radium ore was literally rubbed on a wound or sore area of the body. Dr. John Harvey Kellogg, founder of the Kellogg cereal company, set up a radium spa where patients could come for a day of radium treatments that included radium ore mud baths, breathing in radioactive steam, and finishing off with a refreshing radioactive glass of water.

Companies wanting to cash in on the cure-all craze began selling products such as **Radithor**, “Certified Radioactive Water” that was marketed as a cure-all as good as a radium spa treatment – but it was less expensive. Henry Cosmos invented the **Cosmos Bag**, a cloth bag filled with radium ore powder. Householders could wrap this bag around their arm, leg, or neck to ease pain and rid themselves of arthritis.

See other examples of radium-based “cures” at www.ornl.gov/ptp/collection/quackcures/quackcures.htm



Figure 5-3

Nuclear Model of the Atom

All substances are composed of **atoms**, the basic unit in particle theory. According to the nuclear model, an atom consists of a nucleus surrounded by electrons. The nucleus contains subatomic particles called **nucleons**. Both protons and neutrons are considered nucleons as they are located in the nucleus. **Electrons** have a negative charge; **protons** have a positive charge; **neutrons** are neutral and carry no charge.

The **strong nuclear force**, one of the four fundamental forces of physics, holds the nucleus together—it would have to be strong to force protons and neutrons to stay together in an incredibly tiny space. It is the **electromagnetic force**, another of the four fundamental forces, which holds atoms together and keeps electrons surrounding the nucleus. The electromagnetic force manifests itself through forces between charges (such as those between protons and electrons). This force is what determines atomic and molecular structure—the other three fundamental forces are negligible influences on structure.

Atoms are electrically neutral, containing the same number of protons and electrons. If an atom gains or loses electrons, and thus becomes negatively or positively charged, it is no longer an atom but an **ion**.

Atoms of the same element have the same number of protons and electrons, but can have differing numbers of neutrons in the nucleus. Variations of atoms of an element based on neutron-count are called **isotopes**. Isotopes of an element have the same **atomic number** as the element. The atomic number of an element represents the number of protons an atom of the element has. For instance, carbon has an atomic number of six. Isotopes of an element have differing **mass numbers**. The mass number of an element represents the total number of nucleons in an atom of the element.

Typically, one isotope of an element is more stable than other isotopes for the same element. If an isotope is unstable, it can radioactively decay and release an alpha particle or a beta particle (see Chapter 1) to become more stable. An isotope can also become more stable by releasing energy in the form of gamma rays.

Carbon has three naturally occurring isotopes: carbon-12, carbon-13, and carbon-14. Both ^{12}C and ^{13}C are stable. ^{14}C is the isotope of carbon that is used for radioactive carbon dating.

Uranium exists in nature in three forms: uranium-238 (almost 99% of all uranium), uranium-235 (almost 1% of all uranium), and uranium-234.

Cobalt exists naturally as cobalt-59 as we mentioned in an earlier chapter. However, with more than 22 radioactive isotopes of cobalt from which to choose from, there is one that became widely used in radiation therapy: cobalt-60. This isotope of cobalt is synthetically produced in Canada in reactors under licence from Atomic Energy of Canada.

Molybdenum has seven naturally occurring isotopes with mass numbers 92, 94, 95, 96, 97, 98, and 100. The isotope molybdenum-99 (^{99}Mo) is synthetically produced and is a vital part in the process of manufacturing radioactive isotopes for medical purposes.

Reality Check

Question | Does Food Become Radioactive When Irradiated? When Heated in a Microwave?

Origin: The most likely cause for these concerns stem from misuse of the microwave oven. The first microwave oven was put on the market in 1947 by the Raytheon Company of the United States. The oven stood 5½ feet tall, weighed over 750 pounds, and sold for approximately \$5000 each. With the advent of computer technology, microwave oven design has improved greatly and most households have at least one microwave oven. There is also some confusion over the difference between microwaving food and irradiating food in order to sterilize it.

Reality Check: Microwaves do not use ionizing radiation to heat food. However, ionizing radiation is being used to irradiate food—this to kill unwanted pests and prevent spoilage from the growth of bacteria and microscopic flora. According to Health Canada, food does NOT become radioactive when irradiated and there is no scientific evidence that suggests harmful chemical changes are produced during the process of irradiation. Though most people may think of the microwave oven when asked about food irradiation, in fact some foods on the market today go through a process of being irradiated before hitting store shelves in order to kill off bacteria that can cause illness or death.



Figure 5-4

Research Question:

Research the June 2008 YouTube phenomenon of videos on “microwaves, cell phones, and popcorn” attempting to show how cell phones can take raw kernels of corn and convert them into popcorn.

1. What is the hoax behind the videos? (How did they **really** pop the corn?)
2. Was there any motive for promoting these videos on YouTube?

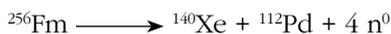


Figure 5-5

Radioactive Decay

Radioactive decay occurs naturally. There are three common types of radioactive decay that an isotope will use to spontaneously decay: alpha decay, beta decay, and spontaneous fission. In these processes, there are four options for the types of radioactive rays that are released: alpha rays, beta rays, gamma rays, and neutron rays.

If radioactive decay occurs through **spontaneous fission**, then the original atom splits to form two or more smaller atoms or **daughter nuclei**. The process involves release of extra neutrons or neutron rays. Fermium-256 typically undergoes spontaneous fission, and can form two daughter nuclei. We can show this process in the form of a chemical equation:



Xenon, palladium, and four extra neutrons are the products of this fission. Sometimes gamma rays are also emitted in the process, in order to make the two daughter nuclei more energy-stable.

When **alpha decay** is the process by which an atom radioactively decays, there is a chemical change that takes place: a daughter nucleus is formed and an **alpha ray** (alpha particle or helium atom) is released. Uranium-238 undergoes this process:



There are **three types of beta decay**: a beta-minus particle can be released, a beta-plus particle can be released, or an inner-orbiting electron can be absorbed by an unstable nucleus and changed into a neutron.

In our first form of beta decay, sometimes unstable atoms that have an excess of neutrons may attempt to stabilize by converting a neutron into a proton. This process emits an electron, or a beta-minus particle (beta ray). It would make sense that if this process occurs inside the nucleus, the electron created in the process could not exist inside the nucleus and therefore must be ejected. Iodine-131 undergoes this type of beta decay:



Note that with this type of beta-decay, the mass number remains the same. The atomic number, however, increases by one.

A second form of beta decay occurs when unstable atoms have an excess of protons for the size of the nucleus. To attempt to gain stability, the nucleus may convert a proton into a neutron and in the process a positron or beta-plus particle (beta ray) is emitted. Recall that a positron is like an electron, except that it has a positive charge. An example of this type of radioactive decay occurs in sodium-22:



For this type of beta decay, the mass number remains the same but the atomic number decreases by one.

The **third form** of beta decay occurs when unstable atoms attempt to gain stability by attracting an inner electron into the nucleus, where it combines with a proton to form a neutron. (See the “In the Media” section for this chapter to explore how this may be possible.) Iron-55 decays in this way:



Once again, the mass number remains unchanged but the atomic number decreases by one.

Questions:

- 1 If ^{14}C were to release an alpha particle, what would the daughter nucleus be? Write the chemical equation.
- 2 If ^{14}C were to release a positron, what would be the chemical equation for this process?
- 3 If ^{14}C were to release a beta-minus particle, what would be the chemical equation for this process? Why might ^{14}C release a beta particle instead of alpha or gamma rays?

In The Media

Quarks and Radioactive Decay

Quarks are a relatively recent discovery and addition to the nuclear model of the atom. Though many of our experimental results can be explained by using the three basic subatomic particles (protons, neutrons, and electrons), beta decay cannot be explained without discussing quarks.

While researchers were studying beta decay, the **weak nuclear force** was discovered. This force, one of the four fundamental forces, changes one flavour (or type) of quark into another. Protons and neutrons are each made up of three quarks. Another subatomic particle—the gluon—holds these quarks together. During beta decay, the weak interactive force breaks up the gluons and causes one quark inside a proton to change so that the proton becomes a neutron, or vice versa. Researchers continue to hone the nuclear model of the atom to include increasingly more subatomic particles – over two hundred, in fact!

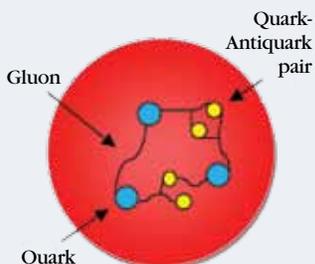


Figure 5-6

Half-Life

It is difficult to predict at what moment a radioactive atom will decay. It is possible, however, to discuss the length of time it takes one-half of the total number of atoms in a sample of a radioactive isotope to decay. This length of time is defined as the **half-life** or $T^{1/2}$ of the isotope. The half-life of carbon-14 is approximately 5730 days; the half-life of uranium-238 is about 4.47×10^9 years. Radium-226 has a half-life of 1600 years.

The **activity** of a radioactive sample is the number of disintegrations (decays) per second. If the sample starts out with a given number N of radioactive atoms, then over time the number of radioactive atoms decreases. To calculate the activity, we must take the change in the number of radioactive atoms, ΔN , and divide it by the time it took that change to occur, Δt . The number of disintegrations per second that occurs in any given sample is proportional to the original number of radioactive nuclei present, thus we can state that

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

where λ is a proportionality constant called the **decay constant**.

Because the amount of radioactive atoms present at any given time decreases exponentially, we can also write an equation to represent the number of radioactive nuclei, N , present at any given time t , assuming we know the original number of radioactive nuclei, N_0 :

$$N = N_0 e^{-\lambda t}$$

Alternatively, we can relate the half-life $T^{1/2}$ to the decay constant λ (with some substitution of one equation into another and natural logarithms coming into play) by the following formula:

$$T^{1/2} = \frac{0.693}{\lambda}$$

activity—the half-life of pennies

Obtain about 200 (or more) pennies and distribute them among your classmates. Initially, each penny represents an unstable nucleus. Each person should shake their pennies in a cup and then invert the cup so that each penny lies flat. A penny that comes up heads represents a nucleus that has decayed (and is assumed to now be stable), and a penny that comes up tails represents a nucleus that has not yet decayed—it is still unstable. Obtain the total number of pennies that come up tails—this is the number of unstable nuclei—and place them back inside the cups. Place a piece of masking tape over each of the pennies that have come up heads. They have decayed, but they are still part of the total mass and should be placed back in the cup. Repeat this several times until the number of pennies that remain in the game is less than 20.

Graph the number of unstable nuclei versus the toss number. Theoretically, we expect that approximately half of the coins should decay with each toss. The half-life for the pennies is the amount of time it takes to go through the above process.

Write up a laboratory report. Include in your report what type of safety considerations would need to be considered if the pennies were in fact truly radioactive.

Source: Don Metz, PhD. Senior 4 Physics (40S): A Foundation For Implementation. Manitoba Education, Citizenship and Youth, 2005.



Figure 5-7

Did You Know

Geiger Counters and Detecting Decay

Geiger counters are named after Hans Geiger, who developed a similar device in 1908 together with Ernest Rutherford. Geiger counters are devices used to detect alpha, beta and gamma radiation. They are rarely used to detect neutrons. Detection of alpha particles usually requires a specialized Geiger tube.

The device has a sensor in the shape of a tube. The tube is filled with an inert gas, such as helium or neon, which has the ability to conduct electricity briefly when a charged particle (which could be alpha, beta, or gamma) temporarily makes the inert gas conductive. This conductivity is amplified as a pulse of current, displayed on a gauge with a needle for measurement purposes and audible clicks. More clicks, and faster clicking, indicates more radiation present in the item being tested.

Approximately 20 years after developing the device with Rutherford, Geiger teamed up with a Ph.D. student of his (Walther Muller) to improve it. This is why the device is sometimes referred to as a Geiger-Muller counter.



Figure 5-8

Calculation Questions:

- 1 In 16 days the number of radioactive nuclei decreases to one-eighth the number present initially. What is the half-life (in days) of the mystery substance?
- 2 Francine's thyroid disorder was treated with an isotope of iodine, ^{131}I . If this isotope has a half-life of 8.05 days, what percentage of the radioactive material in the pill remains after one month (30 days)?
- 3 To make the dials of 1950s watches glow in the dark, radium-226 is painted on. Assuming that the mass of paint ending up on one watch is one-billionth of a kilogram, how much radium, in kilograms, disappears while the watch is in use for 50 years? (Assume the half-life of radium is 1600 years.)
- 4 Two radioactive substances Q and X are being observed by researchers, with equal amounts at the start of the experiment. Three days later, there are three times as many Q atoms as there are X atoms. If the half-life of the Q atoms is 2.0 days, find the half-life of the X atoms.
- 5 The number of radioactive atoms present at the beginning of an experiment is 5.0×10^{12} . The number of radioactive atoms present thirty days later is 8.2×10^{11} . What is the half-life (in days) of this substance?

Units of Measurement

Just as there are units of measurement for radiation exposure, absorbed doses, and relative biological equivalents, measurement units have been developed for radioactivity. The SI unit for activity is named in honour of one individual who studied it—Henry Becquerel. The unit of measurement is Becquerels (Bq). One Becquerel is equal to one radioactive decay per second. (Note that a Geiger counter records “counts per minute,” however this only indicates what is reaching the detector and does not tell us what the radioactive substance is actually doing.)

While Becquerel was studying radioactivity, so were the Curies. Thus, a second unit of measurement (not within the SI accepted units of measurement) was the Curie (Ci). One Curie was equal to the number of particles per second decaying from one gram of radium. When conversion was needed from Curies to Becquerels, the following factor was used:

$$1 \text{ Curie} = 37\,000\,000\,000 \text{ Becquerels}$$

$$\text{or } 1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

Review of SI Units of Measurement for Radiation and Radioactivity - What were they again?

Radiation Exposure (ions created in air): measured in *coulombs per kg (C/kg)*

Radiation Absorbed Dose: measured in *grays (Gy)*

Radiation Biologically Equivalent Dose (takes into account different absorption capabilities of different tissues and organs): measured in *Sieverts (Sv)*

Radioactivity (number of decays per second): measured in *Becquerels (Bq)*

Units of Measurement... another approach

(Remember what we began in Chapter 3?)

Imagine you are standing outside in the rain. If we were to use SI units for radiation and radioactivity and connect them to something about the rain:

- the *number of dust particles that become raindrops* would be comparable to **exposure**, measured in **coulombs per kg**
- the *amount of rain falling* would be like **radioactivity**. Measured in **Becquerels**
- the *amount of rain hitting you* would be like the **absorbed dose**, measured in **grays**
- *how wet you get* would be like the **biologically equivalent dose**, measured in **Sieverts**

activity—radioactivity of household object

For this activity, you will need to have your teacher access a Geiger counter and as many of the following household items that you can find: a watch made in the 1950s, a piece of Fiesta® pottery, a smoke detector, a piece of paper, a piece of plastic, a piece of lead, potassium chloride salt (KCl)—sold as “No Salt” in stores, and aluminium foil. You may need earphones or a speaker to be able to hear the clicks from the Geiger counter for some of these objects—in particular the potassium chloride salt.

Procedure:

1. Determine which items are radioactive at a distance of 5 cm from the Geiger counter—record the radioactivity readings from the Geiger counter.
2. Determine which items—paper, plastic, or lead—block radiation when placed between the Geiger counter and the radioactive substance, and by how much. What does this tell you about the kind of radiation being released—alpha, beta, or gamma?
3. Choose one radioactive object, and use the Geiger counter to measure radiation levels at 2 cm, 4 cm, 6 cm, 8 cm, and 10 cm from the object. How does distance affect radiation?
4. This last step will allow you to measure the attenuation of beta radiation from the potassium-40 isotope found in KCl (0.7% is K-40, the rest is K-39). Place one layer of aluminium foil over a pile of KCl. Use the Geiger counter at close range to measure beta decay. Place a second Al layer on top of the first layer, and measure beta particles again. What thickness of Al will reduce beta particles to half the original amount? What thickness will stop all beta decay particles from reaching the detector?

ESTIMATES OF RADIATION LEVELS: Natural and Synthetic

Level (mSv)	Duration	Description
0.001-0.01	Hourly	Cosmic ray dose on high-altitude flight, depends on position and solar sunspot phase.
0.219	Annual	Natural background radiation, including radon, in Winnipeg, Manitoba
0.46	Acute	Estimated largest off-site dose possible from March 28, 1979 Three Mile Island accident
1.4	Annual	Natural background radiation, including radon, in Nunavut
2	Annual	USA average medical and natural background
2.2	Acute	Average dose from upper gastrointestinal diagnostic X-ray series
6.4	Annual	High Background Radiation Area (HBRA) of Yangjiang, China
7.6	Annual	Fountainhead Rock Place, Santa Fe, NM natural
175	Annual	Guarapari, Brazil natural radiation sources
500-1000	Acute	Low-level radiation sickness due to short-term exposure
500-1000	Detonation	World War II nuclear bomb victims

Career Moves

Medical Physicist

Anita Berndt and Daniel Rickey are medical physicists working at CancerCare Manitoba. They are health care professionals with graduate training (Ph.D.) in the medical applications of physics and both have certification by the Canadian College of Physicists in Medicine (CCPM). Their work involves the use of radioisotopes, x-rays, ultrasound, magnetic and electric fields in diagnosis and therapy. Anita works in radiation therapy, which uses high-energy radiation in the treatment of cancer. Her role in radiation therapy includes treatment planning and radiotherapy machine testing, calibration, and troubleshooting. Daniel specialises in diagnostic imaging which uses x-ray, ultrasound, magnetic resonance, and nuclear medicine for imaging patients. His role in diagnostic imaging includes machine purchasing and installation, testing, quality control, and operation. Anita and Daniel have academic appointments with the University of Manitoba and so are also involved in research and teaching.

Career Connection Website – International Organization for Medical Physics: www.iomp.org



Figure 5-9
Manitoba medical physicists Daniel Rickey and Anita Berndt with the gamma knife located at the Health Sciences Centre in Winnipeg.

Chapter 5 Review: Concepts and Terms

Content: In the late 1800s to early 1900s, Henri Becquerel was the first to record natural radiation from an uranium source. The Curies reported similar findings with radium and polonium. In the mid-1940s, cobalt and iridium were easily and cheaply produced synthetically and became prime sources for gamma rays.

The nuclear model of the atom consists of a nucleus, containing subatomic particles called nucleons, surrounded by electrons. The strong nuclear force holds the nucleus together. The electromagnetic force keeps the electrons near the nucleus. Variations of atoms of an element based on neutron-count are called isotopes, which have the same atomic number but differing mass numbers. An unstable isotope can become more stable by releasing energy in the form of gamma rays.

Radioactive decay occurs naturally through release of alpha particles, beta particles, gamma rays, or neutron rays. If radioactive decay occurs through spontaneous fission, then the original atom splits to form two or more daughter nuclei (smaller atoms). When alpha decay occurs, a chemical change takes place and a daughter nucleus is formed from the original atom.

There are three types of beta decay. In the first form of beta decay, unstable atoms which have an excess of neutrons may attempt to stabilize by converting a neutron into a proton and emit an electron in the process. In the second form of beta decay, unstable atoms with an excess of protons in the nucleus may convert a proton into a neutron and emit a positron in the process. In the third form of beta decay, unstable atoms may attempt to stabilize by attracting an electron into the nucleus to combine with a proton and form a neutron.

The half-life of an isotope is the time it takes one-half of the total number of atoms in a sample of a radioactive isotope to decay. The activity of a radioactive sample is the number of disintegrations (decays) per second.

Terms of Interest:

activity	Geiger-Muller counter
Becquerel (Bq)	gluon
beta-minus particle	half-life
beta-plus particle	Henri Becquerel
Curie (Ci)	mass number
daughter nucleus	neutron
decay constant	neutron ray
electromagnetic force	nucleon
fission	quark
fluorescence	spontaneous fission
fundamental force	strong nuclear force
Geiger counter	weak nuclear force