Lecture Notes

(Radioactivity)

Radioactivity:

- one of the first and most important clues to an understanding of the nucleus occurred with the discovery of the phenomenon later known as radioactivity in early 1896 by the French physicist Henri Becquerel

- it was another one of those "accidents" that illustrate how the trained and prepared mind is able to respond to an unexpected observation

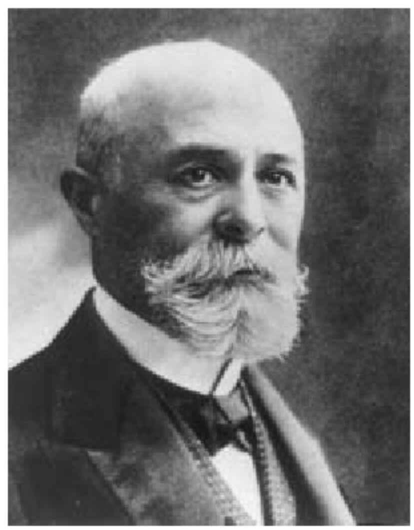


FIGURE 17.1 Henri Becquerel (1852–1908) received the 1903 Nobel Prize in physics together with Pierre and Marie Curie (for the discovery of natural radioactivity).

- Becquerel discovered that uranium salt crystals emit an invisible radiation that can darken a photographic plate even if the plate is covered to exclude light

- the radiation emitted by the crystals did not require external stimulation; this spontaneous emission of radiation was called radioactivity

- further experiments showed that there were other radioactive substances other than uranium; the most significant of these experiments were conducted by Marie and Pierre Curie

- one of the first results of the Curies' work was the discovery that thorium was radioactive; this was important because it showed that radioactivity was not confined to only uranium

- the Curies worked many years on finding and purifying other radioactive elements; they discovered polonium and radium; the activity of radium, it turns out, is a million times greater than that of uranium

MARIE AND PIERRE CURIE

Pierre Curie (1859–1906) studied at the Sorbonne in Paris. In 1878, he became an assistant teacher in the physical laboratory there, and some years later, professor of physics. He was well known for his research on crystals and magnetism. Pierre and Marie Sklodowska were married in 1895 (she was 28 years old). After their marriage, Marie chose radioactivity for her doctoral research. In 1898, Pierre joined his wife in this work. Their collaboration was so successful that in 1903 they were awarded the Nobel Prize in physics, which they shared with Becquerel. Pierre Curie was run over and killed by a horse-drawn vehicle in 1906. Marie Curie was appointed to a professorship at the Sorbonne, the first woman there to have this post.

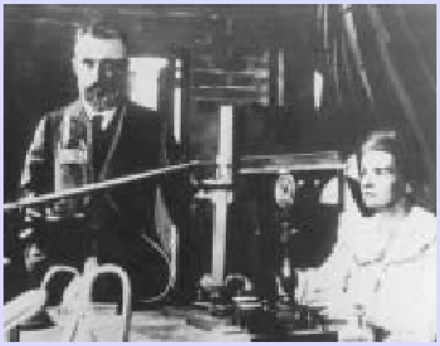
In 1911, Marie Curie was awarded the Nobel Prize in chemistry for the discovery of the two new elements, radium and polonium. She was the first person to win two Nobel Prizes in science. The rest of her career was spent in the supervision of the Paris Institute of Radium, a center for research on radioactivity and the use of radium in the treatment of cancer. During her visit to the U.S., a group of women

(a)

(b)

FIGURE 17.3 (a) Marie Curie. (b) Marie and Pierre Curie on a bicycling holiday. (*Continued*) presented her with the precious gifts of 1 gram of radium.

Marie Curie died in 1934 of leukemia, a form of cancer of the leukocyte-forming cells of the body, probably caused by overexposure to the radiations from radioactive substances during her research over more than three decades.



(c)

(d)

FIGURE 17.3 (*Continued*) (c) Marie and Pierre Curie in their laboratory; (d) Marie and Pierre Curie with their daughter, Irène, who later also received a Nobel Prize.

<u>Types of Radiation</u>:

- there are three type of radiation that can be radiated by a radioactive substance:
  1) <u>alpha (α) particles</u> - these are helium nuclei $^{4}_{2}He$
  2) <u>beta (β) particles</u> - these are electron (e^-) or positrons (e^+)
  3) <u>gamma (γ) particles</u> - these are high energy photons

- radiation can ionize molecules, including those in your body

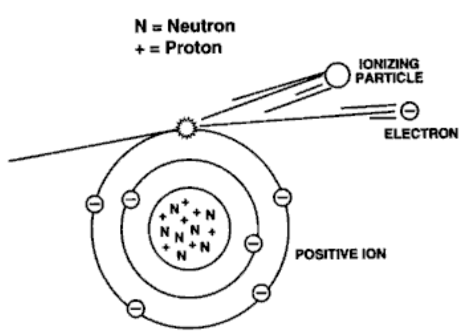
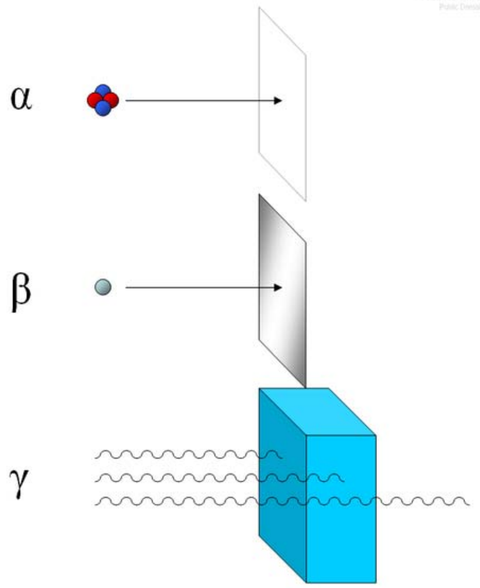


Figure 2-XIII. Electron Removal by Ionization

- the health effects of ionizing radiation will be discussed later in the lecture

Penetrating Power:

- the three types of radioactive decay have different levels of penetrating power



Alpha radiation consists of helium nuclei and is readily stopped by a sheet of paper. Beta radiation, consisting of electrons, is halted by an aluminum plate. Gamma radiation is eventually absorbed as it penetrates a dense material.

Isotopes:

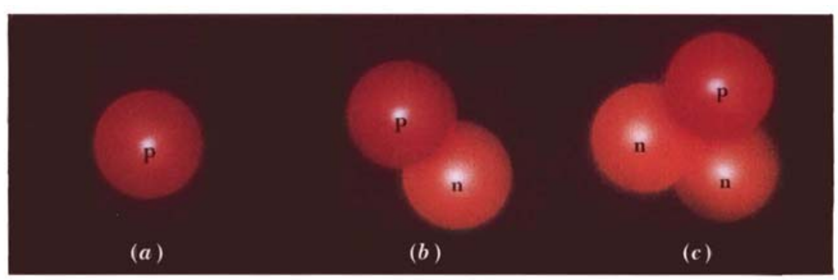
- all elements have nuclei that have differing masses; these different nuclei are called isotopes of the particular element

- isotopes have the same number of protons but different numbers of neutrons

- isotopes show different nuclear properties, but they all have the same chemical properties

- the most well know isotopes are those of hydrogen

Figure 25-4 Hydrogen has three isotopes: (a) hydrogen, (b) deuterium, and (c) tritium.



- hydrogen has only one proton; deuterium has one proton and one neutron, and tritium has one proton and two neutrons

- the isotopes of other elements do not have unique names like those of hydrogen; rather they use the following format

    - ${}^{A}_{Z}\mathrm{X}$; where *A* is the mass number, *Z* is the atomic number and X is the symbol of the parent element

- the mass number, *A*, is the sum of protons plus neutrons; this is also referred to as the nucleon number

- the atomic number, *Z*, is the number of protons; this determines what type of element you have

The Decay Process:

- radioactive nuclei spontaneously decay via alpha, beta, and gamma decay

- we can describe nuclear decay by use of chemical equations; the branch of chemistry dealing with decaying nuclei is called nuclear chemistry

- there are five different types of radioactive decay

1) Alpha Decay:

- if a nucleus emits an alpha particle, it loses two neutrons and two protons; therefore *Z* decreases by two and *A* decreases by 4

- the decay process for alpha particles is:

$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\mathrm{He}$$

- where X is called the parent nucleus and Y is called the daughter nucleus, for example:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

- when one element changes into another, as happens in alpha decay, the process is called spontaneous decay or transmutation

- as a general rule, (1) the sum of the mass numbers *A* must be the same on both sides of the equation and (2) the sum of the atomic numbers *Z* must be the same on both sides of the equation

- in order for alpha decay to occur, the mass of the parent must be greater than the combined mass of the daughter plus the alpha particle

- the excess mass is converted into energy of other forms and appears in the form of kinetic energy in the daughter nucleus and the alpha particle

- most of the kinetic energy is carried away by the alpha particle because it is much less massive than the daughter nucleus

- alpha decay is not very penetrating because the He atoms capture electrons before traveling very far; however it is very damaging because the alpha particles can knock atoms off of molecules

- alpha decay is the most common in elements with an atomic number greater than 83

2) <u>Beta Negative Decay</u>:

- when a radioactive nucleus undergoes beta negative decay, the atomic number increases by one through the addition of one proton

- at the same time, one neutron is lost so the mass of the daughter isotope is the same as the parent isotope

- beta negative decay is more penetrating than alpha decay because the particles are smaller; beta electrons can penetrate through about one cm of flesh before they are brought to a halt because of electrostatic forces

- beta negative decay is most common in elements with a high neutron to proton ratio

- the beta negative decay process is:

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + \mathrm{e}^{-} $$

- note that the nucleon number and total charge are both conserved in these decays; for example:

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + \mathrm{e}^{-} $$

- the emissions of an electron from the nucleus is surprising, because we know that the nucleus is composed only of protons and neutrons

- this can be explained by noting that the emitted electron is created in the nucleus by a process in which a neutron is transformed into a proton:

$$ {}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{p} + \mathrm{e}^{-} $$

- in beta negative decay we expect the electron to carry away most of the kinetic energy as opposed to the daughter nucleus; but experiments showed that some of the energy was missing

- it turns out that a third particle was being released during beta decay; it is called the neutrino, named by Enrico Fermi and proposed by Wolfgang Pauli

- the neutrino is given the symbol ν, and the antineutrino is given the symbol $\bar{\nu}$

- the neutrino has the following properties:
  1) zero electric charge
  2) a mass much smaller than the electron, but not zero
  3) very weak interaction with matter (very hard to detect)

- in beta negative decay, an electron and an antineutrino are emitted; for example

$$^{14}_{6}C \rightarrow ^{14}_{7}N + e^{-} + \bar{\nu}$$

3) <u>Beta Positive Decay</u>:

- in this reaction a positron is emitted; a positron is exactly like an electron in mass and charge force except with a positive charge

- a positron is formed when a proton breaks into a neutron with mass and no charge and a positron with no mass and the positive charge

- positron emission is most common in lighter elements with a low neutron to proton ratio

- in beta positive decay a positron and neutrino are emitted

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + \mathrm{e}^{+} + \nu$$

$$^{12}_{7}\mathrm{N} \rightarrow {}^{12}_{6}\mathrm{C} + \mathrm{e}^{+} + \nu$$

4) <u>Gamma Decay</u>:

- many times a nucleus that undergoes radioactive decay is left in an excited state; the nucleus can then undergo a second decay

- it can emit one or more high-energy photons; the process is very similar to the emission of light by an atom

- the protons and neutrons in the nucleus will release energy as they move from a higher energy level to a lower one

- the photons emitted in this de-excitation process are called gamma rays; they have much more energy relative to the energy of visible light

- gamma decay can result from a collision with another particle, but it is more common to see gamma decay after an alpha or beta decay

$$^{A}_{Z}\mathrm{X}^{*} \rightarrow {}^{A}_{Z}\mathrm{X} + \gamma$$

- in the example below, we have a beta decay that leaves an excited carbon atom which undergoes gamma decay; the excited atom is represented by an asterisk

$$^{12}_{5}\mathrm{B} \rightarrow {}^{12}_{6}\mathrm{C}^{*} + \mathrm{e}^{-} + \overline{\nu}$$

$$^{12}_{6}\mathrm{C}^{*} \rightarrow {}^{12}_{6}\mathrm{C} + \gamma$$

- note that gamma decay does not result in any change to the Z or A values

- gamma radiation is the most penetrating of all; these photons can pass through the body and cause damage by ionizing all the molecules in their way

5) **<u>Electron Capture</u>:**

- in this reaction a nucleus captures one of its own atom's inner shell electrons which reduces the atomic number by one

- this captured electron joins with a proton in the nucleus to form a neutron

- electron capture is common in larger elements with a low neutron to proton ratio

$$ {}^{A}_{Z}\mathrm{X} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{A}_{Z-1}\mathrm{Y} $$

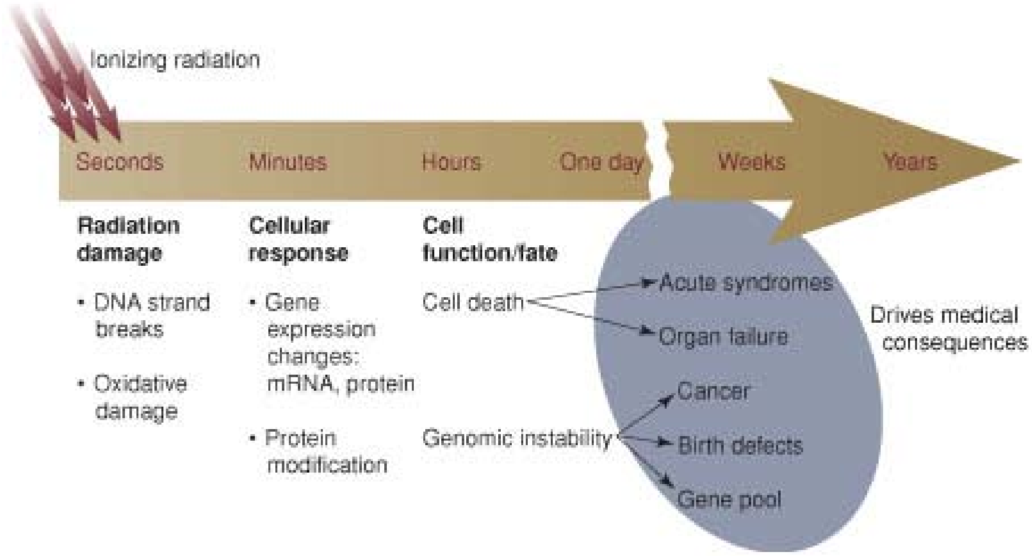
Table 25-2 | Changes in the Number of Protons, Neutrons, and Nucleons for Each Type of Radioactive Decay

	Changes in the Number of		
Decay	**Protons**	**Neutrons**	**Nucleons**
α	−2	−2	−4
β^-	+1	−1	0
Electron capture	−1	+1	0
β^+	−1	+1	0
γ	0	0	0

<u>Biological Effects of Radiation</u>:

- heavy and expensive shielding is sometimes needed in the study or use of radiations in accelerator and nuclear reactors, to protect people from the harmful effects of the rays

- the rays ionize and, consequently, break down molecules in living cells, causing radiation “burns,” fatal injuries to cells, damage that can lead to the growth of cancer cells, and dangerous mutations in the structure of the DNA molecules



- in some cases, these radiation shields are as much as 3 m thick, but they are effective, protecting workers at reactor stations and accelerator research facilities

- there are two categories of radiation damage:
  1) <u>Somatic</u> - damage to non-reproductive cells
  2) <u>Genetic</u> - damage to reproductive cells

- damage to the genes in reproduction can lead to defective offspring

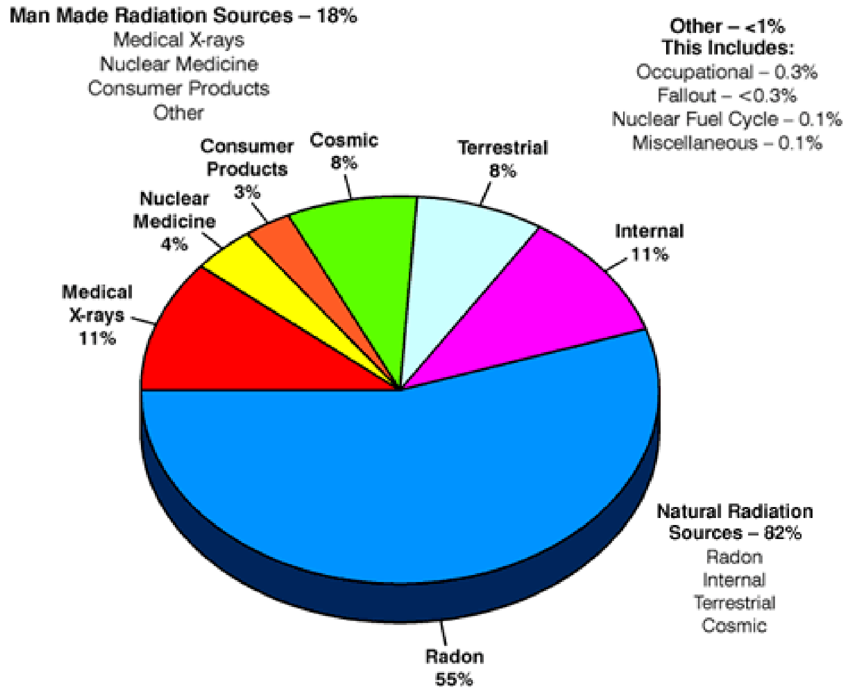
- the average annual dose of radiation is about 360 mrem; 200 mrem of which comes from radon (a chemically inert, but radioactive noble gas)

- a rem (***r***oentgen ***e***quivalent in ***m***an) is a unit of biological damage caused by radiation

- the upper limit of radiation dose recommended by the US government is 0.5 rem/yr

- an acute whole body dose of 400-500 rem results in a mortality rate of about 50%

Ionizing Radiation Exposure to the Public



The above chart is taken from the National Council on Radiation Protection and Measurements (NCRP) Report No. 93, "Ionizing Radiation Exposure of the Population of the United States," 1987.

This chart shows that natural sources of radiation account for about 82% of all public exposure while man-made sources account for the remaining 18%.

- as you can see in the pie-chart above, most of the radiation you receive comes from natural background radiation

- natural background radiation comes from 1) cosmic rays, 2) solar radiation, 3) terrestrial sources, and 4) radon

  1) <u>Cosmic rays</u> - the Earth, and all living things on it, are constantly bombarded by radiation from outside our solar system; this cosmic radiation consists of positively-charged ions from protons to iron nuclei; this radiation interacts in the atmosphere to create secondary radiation that rains down; the cosmic-radiation dose rate on airplanes is so high that, airline workers receive more dose on average than any other worker, including those in nuclear power plants

  2) <u>Solar rays</u> - while most of the Sun's output consists of light (solar radiation), particle radiation is also produced and varies with the solar cycle; these particles are mostly protons

with relatively low energies; the ionizing component of solar radiation is negligible relative to other forms of radiation on Earth's surface

3) <u>Terrestrial radiation</u> - most materials on Earth contain some radioactive atoms, even if in small quantities; most of the terrestrial non-radon-dose one receives from these sources is from gamma-ray emitters in the walls and floors when inside a house, or rocks and soil when outside

4) <u>Radon</u> - radon-222 is produced by the decay of radium-226 which is present wherever uranium is found; since radon is a gas, it seeps out of uranium-containing soils found across most of the world and may accumulate in well-sealed homes; it is often the single largest contributor to an individual's background radiation dose and is certainly the most variable from location to location; radon gas could be the second largest cause of lung cancer in America, after smoking

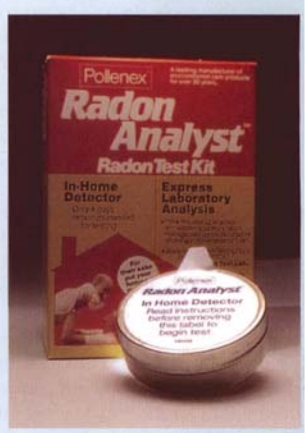
Radon

A source of radiation that is partly under our control is the radioactive gas radon. Much attention has been focused by the media on the presence of indoor radon, especially in the air of some household basements. This awareness came about in part because of energy conservation efforts. In attempts to reduce heating bills, many homeowners improved their insulation and sealed many air leaks. This resulted in less air circulation within homes and allowed the concentration of radon in the air to increase.

The source of the radon is uranium ore that exists in the ground; the ore's quantities vary geographically. Through a long chain of decays shown in the table, the uranium eventually becomes a stable isotope of lead. All the radioactive daughters are solids except one, the noble gas radon (Rn). This gas can travel through the ground and enter basements of homes through small (or large) cracks in the basement floors or walls. Because radon is an inert gas, it doesn't deposit on walls and leave the air. Thus, it can be inhaled into a person's lungs and become trapped there. In this case, each of the eight subsequent decays causes the lungs to experience additional radiation and possible damage. The maximum "safe" level of radon has been established by the Environmental Protection Agency at 4×10^{-12} curie per liter. Kits to test for excessive concentrations are available through retail outlets. If high levels are found, the homeowner can take measures to ventilate the radon and to block its entry into the house by sealing cracks around the foundation and in the basement.

Radioactive Decay

$^{238}_{92}U \rightarrow$	$^{234}_{90}Th$	$+\alpha$	(9.5×10^9 years)
	$^{234}_{91}Pa$	$+\beta^-$	(24 days)
	$^{234}_{92}U$	$+\beta^-$	(6.7 hours)
	$^{230}_{90}Th$	$+\alpha$	(2.5×10^5 years)
	$^{226}_{88}Ra$	$+\alpha$	(7.5×10^4 years)
	$^{222}_{86}Rn$	$+\alpha$	(1622 years)
	$^{218}_{84}Po$	$+\alpha$	(3.85 days)
	$^{214}_{82}Pb$	$+\alpha$	(3 minutes)
	$^{214}_{83}Bi$	$+\beta^-$	(27 minutes)
	$^{214}_{84}Po$	$+\beta^-$	(19.7 minutes)
	$^{210}_{82}Pb$	$+\alpha$	(10^{-4} seconds)
	$^{210}_{83}Bi$	$+\beta^-$	(19 years)
	$^{210}_{84}Po$	$+\beta^-$	(5 days)
	$^{206}_{82}Pb$	$+\alpha$	(138 days)



A commercially available kit for testing radon gas levels in homes.

- some human-made radiation sources affect the body through direct radiation, while others take the form of radioactive contamination and irradiate the body from within

- medical procedures, such as diagnostic X-rays, nuclear medicine, and radiation therapy are by far the most significant source of human-made radiation exposure to the general public

- the public also is exposed to radiation from consumer products, such as tobacco (polonium-210), building materials, combustible fuels (gas, coal, etc.), ophthalmic glass, televisions, luminous watches and dials (tritium), airport X-ray systems, smoke detectors (americium), road construction materials, electron tubes, fluorescent lamp starters, and lantern mantles (thorium)

Smoke Detectors

Many of the uses of radioactive isotopes are not often apparent to most of us. For example, some smoke detectors (Figure A) commonly found in our homes use radioactive americium to detect the smoke particles. As shown in the schematic diagram of Figure B, the weak radioactive source ionizes the air, allowing a small current to flow between the electrodes. When smoke enters the detector, the ions are attracted by the smoke particles and stick to them. The larger mass of the smoke particles causes them to move slower than the ions, reducing the current in the circuit and setting off the alarm.

Americium-241 is an alpha emitter with a half-life of 433 years, so the level of ionization does not decrease significantly over the lifetime of the detector. This isotope is obtained as a by-product of the processing of fuel rods from nuclear reactors.

Figure A A household smoke detector.

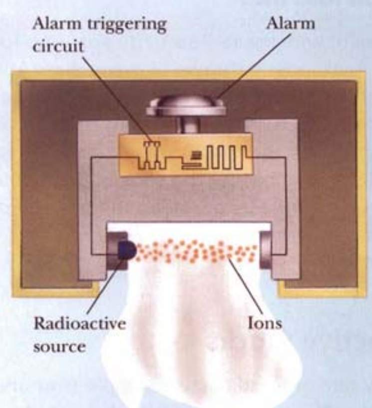


Figure B Diagram of a smoke detector.

<u>Commercial Uses Of Radiation</u>:

- objects for medical and industrial use are commonly sterilized by exposing them to radiation; most bacteria, worms, and insects are readily destroyed by exposure to gamma radiation from radioactive cobalt

- another form of sterilization occurs with the use of ingestion of radioactive nuclei by parasites in the use of radioactive tracers

- this method is very effective in destroying Trichinella worms in pork, salmonella bacteria in chickens, insect eggs in wheat, and surface bacteria on fruit and vegetables

- this process is also used to sterilize medical equipment while still in its protective covering

Half-Life:

- the half-life of a quantity subject to exponential decay is the time required for the quantity to decay to half of its initial value

- it can be shown that, for exponential decay, the half-life $t_{1/2}$ obeys this relation:

$$t_{1/2} = \frac{\ln(2)}{\lambda}$$

  - where

    - ln(2) is the natural logarithm of 2, and
    - λ is the decay constant, a positive constant used to describe the rate of exponential decay
    - the unit of λ is s^{-1}

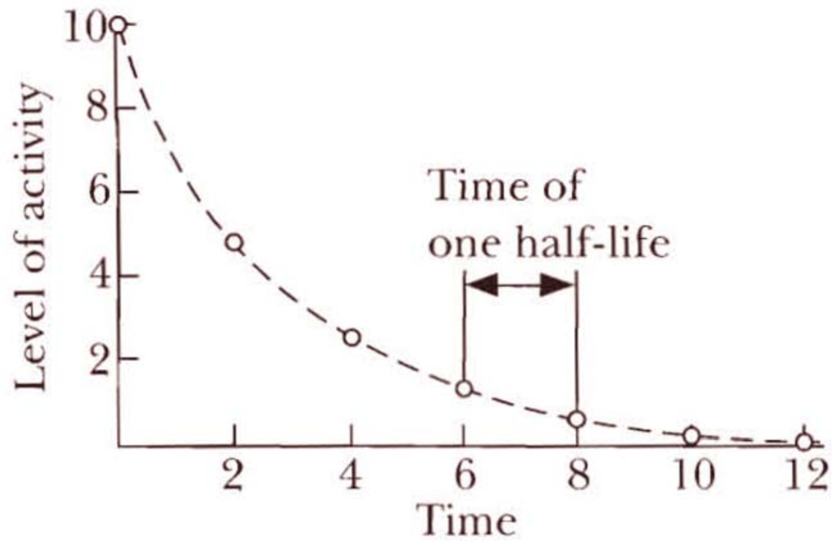


Figure 25-5 A graph of the activity of a radioactive material versus time. Notice that the time needed for the activity to decrease by a factor of 2 is always the same.

- the table at right shows the reduction of the quantity in terms of the number of half-lives elapsed

Number of half-lives elapsed	Fraction remaining	As power of 2
0	1/1	$1/2^0$
1	1/2	$1/2^1$
2	1/4	$1/2^2$
3	1/8	$1/2^3$
4	1/16	$1/2^4$
5	1/32	$1/2^5$
6	1/64	$1/2^6$
7	1/128	$1/2^7$
…	…	
N	$1/2^N$	$1/2^N$

- the following equation represents the relationship between the number of nuclei remaining, N, the number of nuclei initially present, N_0, the rate of decay, λ, and the amount of time, t

$$\ln\frac{N}{N_0} = -\lambda t$$

Radioactive Clocks:

- by using these equations, it is possible to calculate how much of a nuclear substance will be left after a certain time and how much of a substance originally existed

- knowing the half-life of a particular isotope and the products into which it decays, we can determine the relative amount of parent and daughter atoms and calculate how long the isotope has been decaying; in effect, we have a radioactive "clock" for dating events in the past

- living organisms contain carbon, which has two isotopes of interest, the stable isotope $^{12}_{6}C$ and the radioactive isotope $^{14}_{6}C$, which has a half-life of 5700 years

Radiocarbon dating of this skeleton found in the Tyrolean Alps has helped estimate that the man lived around 5000 years ago.

- cosmic rays bombarding our atmosphere continually produce $^{14}_{6}C$ to replace those that decay; because of this replacement, the ratio of $^{12}_{6}C$ to $^{14}_{6}C$ in the atmosphere is relatively constant

- while the plant or animal is living, it continually exchanges carbon with its environment and therefore maintains the same ratio of the two isotopes in the tissues that exists in the atmosphere

- as soon as it dies, however, the exchange ceases and the amount of ${}^{14}_{6}C$ decreases due to the radioactive decay

- by examining the ratio of the amount of ${}^{14}_{6}C$ to that of ${}^{12}_{6}C$ in the plant or animal, we can learn how long ago death occurred

WORKING IT OUT | Radioactive Dating

As an example of radioactive dating, suppose a piece of charred wood is found in a primitive campsite. To find out how long ago the campsite was occupied, one examines the ratio of carbon-14 to carbon-12 in the wood. Suppose that the ratio is only one-eighth of the atmospheric value. Because $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$, the tree died 3 half-lives ago. This gives an age of 3×5700 years = 17,100 years.