Ch. 9. Nuclear Chemistry

THE field of nuclear medicine was first established in 1934 with the production of artificial radioactive substances. This field uses the power of nuclear chemistry to cure cancer and other diseases or simply to visualize organs. In 1937, the first radioactive isotope was used to treat a person with leukemia at the University of California at Berkeley. Radioactive substances are now used to produce images of organs, such as the liver, spleen, thyroid gland, kidneys, and brain, and to detect heart disease. Today, procedures in nuclear medicine provide information about the function and structure of every organ in the body, which allows the nuclear physician to diagnose and treat diseases early. This chapter covers the basic principles of nuclear chemistry. You will learn the real meaning of radioactivity and how to quantify the effects of radiation or measure the duration of a radioactive chemical.

> “Nuclear power is one hell of a way to boil water.”
> *Einstein*

9.1 Radiation, particles & radioisotopes

Light elements have normally stable nuclei. Differently, heavier elements with atomic numbers larger than 20 tend to often have several isotopes–remember these are atoms of the element with a different number of neutrons–that have unstable nuclei. For these unstable isotopes, the forces that keep the nucleus together are not strong enough to stabilize the nuclei. An unstable nucleus is radioactive, which means that it will spontaneously emit radiation in the form of small particles. Not all radioactivity is the same and there exist different types of radiation, which we will address in the following. Table 9.1 reports common nuclear symbols.

`alpha radiation` Alpha radiation–referred to as α–is a type of radiation that contains alpha particles. These particles are indeed helium nuclei, with 2 protons, 2 neutrons, and a (2+) positive charge. Alpha particles are often represented as α or ${}^{4}_{2}\mathrm{He}$.

`beta radiation` Beta radiation–referred to as β–is a type of radiation that contains beta particles. These particles are indeed high-energy electrons with ($-$) negative charge. Beta particles are often represented as β or ${}^{0}_{-1}\mathrm{e}$.

`gamma radiation` Gamma radiation–referred to as γ–is a type of radiation that contains high-energy photons. These particles are indeed photons with no mass or charge. Gamma particles are often represented as γ or ${}^{0}_{0}\gamma$.

`protons` Protons in this chapter are often referred to as p or ${}^{1}_{1}\mathrm{H}^{+}$. These are positive charges.

`positrons` Positrons are the electron antiparticle, often referred to as β^{+} or ${}^{0}_{+1}\mathrm{e}$. They do have a positive charge.

▼Strawberries are normally treated with radiation

`neutrons` Neutrons are nuclear particles with no charge, often referred to as n or ${}^{1}_{0}\mathrm{n}$.

Sample Problem 1

Name or give the symbols for the following nuclear particles: beta particle, β^{+}, p and ${}^{0}_{0}\gamma$.

SOLUTION

Beta particles are represented by β or ${}^{0}_{-1}\mathrm{e}$. These particles are indeed simply electrons ejected during a nuclear decay. β^{+} represents a positron, an anti-electron. p stands for protons, a nuclear particle with positive charge. Finally, ${}^{0}_{0}\gamma$ represents gamma radiation.

STUDY CHECK

Name or give the symbols for the following nuclear particles: n, α and ${}^{1}_{1}\mathrm{H}^{+}$.

▼Ionization chamber smoke detectors contain a small amount of americium-241, a radioactive material

`Radioisotope notation` Radioisotopes–atomic isotopes that produce radiation–are written as ${}^{A}_{Z}\mathrm{X}$. For example, ${}^{14}_{6}\mathrm{C}$ is referred to as carbon-14. The number on the top is the mass number A, that is represented the total number of neutrons and protons in the isotope. The number on the bottom refers to the atomic number Z, that is, the total number of electrons in the atom. For example, the mass number of ${}^{14}_{6}\mathrm{C}$ is 14 whereas its atomic number is 6. ${}^{14}_{6}\mathrm{C}$ has 14 neutrons and protons and 6 electrons.

Sample Problem 2

Calculate the number of protons, neutrons and electrons of the following isotopes: ${}^{238}_{92}\mathrm{U}$, ${}^{24}_{13}\mathrm{Al}$ and ${}^{14}_{6}\mathrm{C}$.

SOLUTION

According to the isotope notation (${}^{A}_{Z}\mathrm{X}$), the number of top of the radioisotope is the mass number A that represents the number of protons plus neutrons, whereas the number of the bottom is the atomic number Z that represents the number of electrons. According to this, the number of electrons in an atom is Z. If an atom is neutral, the number of electrons and protons are the same, so the number of protons is also Z. The number of neutrons would hence be $A - Z$, as A is the number of protons+neutrons, and the number of protons is Z. We'll use a table below to obtain the electrons, protons and neutrons from A and Z.

▼An operating nuclear power plant produces very small amounts of radioactive gases

Radioisotope	A	Z	Electrons	protons	neutrons
${}^{238}_{92}\mathrm{U}$	238	92	92	92	146
${}^{24}_{13}\mathrm{Al}$	24	13	13	13	11
${}^{14}_{6}\mathrm{C}$	14	6	6	6	8

STUDY CHECK

Calculate the number of protons, neutrons and electrons of ${}^{99}_{43}\mathrm{Tc}$.

▼There are radioactive gases in the air we breathe

Table 9.1 Nuclear symbols

Particle Name		Symbol	Charge	Identity	Penetrating power	Discovery
Alpha	(α)	$^4_2$He	2+	Helium nucleus	Minimal	1899
Beta	(β)	$^{\ 0}_{-1}$e	-1	Electrons	Short	1899
Gamma	(γ)	$^0_0\gamma$	0	Electromagnetic radiation	Deep	1900
Neutrons	(n)	$^1_0$n	0	nuclear particle	Maximal	1932
Proton	(p)	$^1_1$H$^+$	$+1$	nuclear particle		1919
Positrons	(β^+)	$^{\ 0}_{+1}$e	$+1$	antiparticle		1932

9.2 Nuclear reactions

Isotopes–called emitters–spontaneously decompose producing new isotopes in a process called radioactive decay. In this decay, radiation is also emitted.

$$\text{Emitter} \longrightarrow \text{radiation} + \text{New isotope}$$

In the following, we will discuss the most important type of radioactive decay.

`alpha decay` Some isotopes produce alpha radiation, that is, they produce α particles on its decay. A nuclear reaction that produces an α particle ($^4_2$He) is called alpha decay. In alpha decay, the emitter decreases its mass number A four units and its atomic number Z two units.

$$\text{Emitter} \longrightarrow {}^4_2\text{He} + \text{New isotope}$$

`beta decay` Other isotopes produce beta radiation, that is, they produce β particles on its decay. A nuclear reaction that produces a β particle ($^{\ 0}_{-1}$e) is called beta decay. In beta decay, the emitter has the same mass number A as the product isotope. However, its atomic number Z decreases by one unit.

$$\text{Emitter} \longrightarrow {}^{\ 0}_{-1}\text{e} + \text{New isotope}$$

`positron emission` Certain isotopes decay by producing a positron, that is, they produce $^{\ 0}_{+1}$e particles on its decay. A nuclear reaction that produces $^{\ 0}_{+1}$e is called positron emission. In a positron emission, the emitter has the same mass number A as the product isotope. However, its atomic number Z increases by one unit.

$$\text{Emitter} \longrightarrow {}^{\ 0}_{+1}\text{e} + \text{New isotope}$$

`gamma decay` Some other isotopes produce gamma radiation in the form of γ particles on its decay. A nuclear reaction that produces a γ particle ($^0_0\gamma$) is called gamma decay. In this type of decay, no new isotope is produced. Gamma emitters are normally excited, that is they have higher energy than normal; we denote this with a * symbol. Exited particles tend to lose energy to become more stable. In gamma decay, the emitter and the product isotope, both have the same mass and atomic number.

$$\text{Emitter}^* \longrightarrow {}^0_0\gamma + \text{Emitter}^*$$

Sample Problem 3

Label the following nuclear reactions as: α, β or γ decay, or positron emission:

(a) $^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$

(b) $^{24}_{13}\mathrm{Al} \longrightarrow {}^{24}_{12}\mathrm{Mg} + {}^{0}_{+1}\mathrm{e}$

(c) $^{14}_{6}\mathrm{C} \longrightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$

(d) $^{99}_{43}\mathrm{Tc}^{*} \longrightarrow {}^{99}_{43}\mathrm{Tc} + {}^{0}_{0}\gamma$

SOLUTION

(a) This process produces $^{4}_{2}\mathrm{He}$ and therefore is alpha emission. (b) This process generates $^{0}_{+1}\mathrm{e}$ and therefore is positron emission. (c) This process produces $^{0}_{-1}\mathrm{e}$ and therefore is beta emission. (d) This process produces $^{0}_{0}\gamma$ and therefore is gamma emission.

STUDY CHECK

Label the following nuclear reactions as: α, β or γ decay, or positron emission:

(a) $^{127}_{55}\mathrm{Cs} \longrightarrow {}^{127}_{54}\mathrm{Xe} + {}^{0}_{+1}\mathrm{e}$

(b) $^{27}_{13}\mathrm{Al}^{*} \longrightarrow {}^{27}_{13}\mathrm{Al} + {}^{0}_{0}\gamma$

(c) $^{218}_{85}\mathrm{At} \longrightarrow {}^{214}_{83}\mathrm{Bi} + {}^{4}_{2}\mathrm{He}$

9.3 Unknown isotopes in nuclear reactions

Sometimes one needs to identify an unknown isotope $^{A}_{Z}\mathrm{X}$ in a chemical reaction. This means identifying the name X of the isotope, the atomic number Z as well as the mass number A. To do this, we will use the fact that the total mass number as well as the total atomic number should stay constant before and after the nuclear reaction. Let's break this idea down into an example.

Sample Problem 4

Identify the unknown isotope in the following nuclear reaction:

$$^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \longrightarrow {}^{A}_{Z}\mathrm{X} + {}^{1}_{1}\mathrm{H}$$

SOLUTION

We will solve this problem by using the fact that the total mass number as well as the total atomic number should stay constant before and after the nuclear reaction. In order to do this, we will calculate the total atomic number before the reaction (in the left) and the total atomic number after the reaction (in the right) and equal both values. We will do the same for the mass number.

	$^{4}_{2}$He	$^{14}_{7}$N	$\longrightarrow$	$^{A}_{Z}$X	$^{1}_{1}$H
A	4	14		A	1
Z	2	7		Z	1

Now we build up two equations, one for A and another for Z, from each of the columns (column 2 and 3) of the table:

$$4 + 14 = A + 1 \qquad \text{Equation for A from column 2 of the table}$$
$$2 + 7 = Z + 1 \qquad \text{Equation for Z from column 3 of the table}$$

We now solve for A geting a value of $A = 17$ and for Z, getting $Z = 8$. With the atomic number Z we can go to the periodic table and identify the name of the isotope. The element with $Z = 8$ is called oxygen, and the final answer would be: $^{17}_{8}\mathrm{O}$.

STUDY CHECK

Identify the unknown isotope in the following nuclear reaction:

$$^{241}_{95}\mathrm{Am} \longrightarrow {}^{A}_{Z}\mathrm{X} + {}^{4}_{2}\mathrm{He}$$

Table 9.1 Half-life for various isotopes and chemicals

Americium-241	432.2 years	Lutetium-177	6.71 days	Hydrogen-3	12.35 years
Barium-133	10.74 years	Molybdenum-99	66 hours	Technetium-99	213,000 years
Bismuth-212	60.55 minutes	Nickel-63	96 years	Indium-111	2.83 days
Cadmium-109	464 days	Phosphorus-32	14.29 days	Technetium-99m	6.02 hours
Calcium-45	163 days	Phosphorus-33	25.4 days	Indium-113m	1.658 hours
Carbon-14	5730 years	Plutonium-239	24,065 years	Tin-113 115.1	days
Cesium-137	30 years	Polonium-210	138.38 days	Iodine-123	13.2 hours
Chlorine-36	301,000 years	Radium-226	1600 years	Tungsten-188	69.4 days
Chromium-51	27.704 days	Radon-222	3.8235 days	Iodine-125	60.14 days
Cobalt-57	270.9 days	Rhenium-188	16.98 hours	Uranium-235	703,800,000 years
Cobalt-58	70.8 days	Rubidium-81	4.58 hours	Iodine-129	15,700,000 years
Cobalt-60	5.271 years	Selenium-75	119.8 days	Uranium-238	4,468,000,000 years
Copper-62	9.74 minutes	Sodium-22	2.602 years	Iodine-131	8.04 days
Copper-64	12.701 hours	Sodium-24	15 hours	Xenon-127	6.41 days
Copper-67	61.86 hours	Strontium-85	64.84 days	Iron-55	2.7 years
Gallium-67	78.26 hours	Strontium-89	50.5 days	Xenon-133	5.245 days
Gold-195	183 days	Sulfur-35	87.44 days	Iron-59	44.529 days
Ondansetron	360 min	Capecitabine	2400s	Carmustine	0.25h

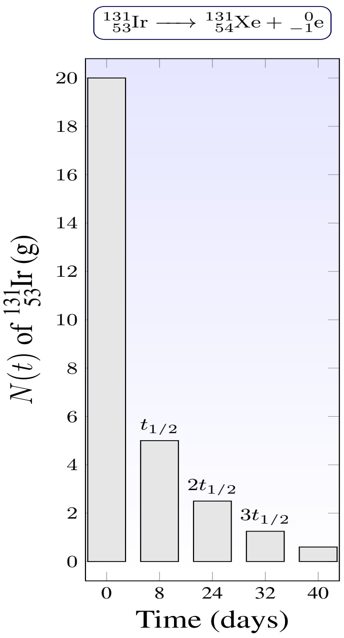
9.4 Half-life of a radioisotope

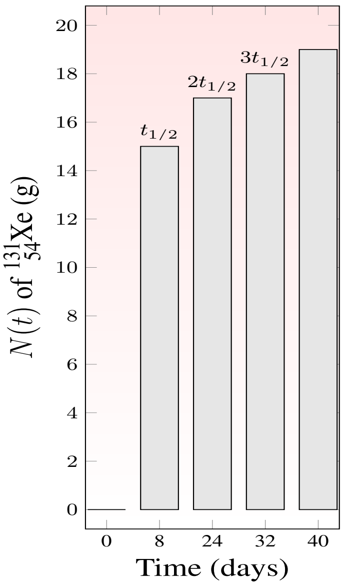
Radioisotopes–isotopes that decay producing radiation–are unstable and with time they eventually disappear given a more stable isotope. Some radioisotopes decay very quickly, such as the ones used in nuclear medicine to fight cancer. Other radioisotopes take longer to disappear.

`The concept of half-live` The half-life of an isotope represented as $t_{1/2}$ is the time it takes for an isotope to disappear reducing the sample mass to half the initial value. For example, $t_{1/2}$ for chromium-51 is 28 days and that means that after 28 days a sample of 1 gram of the radioisotope will indeed weigh 0.5 g. Table 9.1 reports half-lives of numerous isotopes. Samples of radioisotopes weigh less and less with time as they decompose producing more stable isotopes. Similarly, $t_{1/2}$ for strontium-90 is 38 years which means that a one-gram sample will take 38 years to reduce its mass to 0.5g. We can use the concept of half-life to compare the speed of decomposition of different radioisotopes. For example $t_{1/2}$ for strontium-90 is 38 years whereas $t_{1/2}$ for chromium-51 is 28 years. Hence, strontium-90 will exist longer than chromium-51.

Sample Problem 5

On one hand, Docetaxel is a chemotherapy medication used to treat a number of types of cancer with a half-life of 309600 seconds. On the other hand, Vandetanib is an anti-cancer medication that is used for the treatment of certain tumors





of the thyroid gland with a half-life of 1641600 seconds. Which medication will remain longer in the body?

SOLUTION

We will compare the half-lives of both medication using scientific notation to express the numbers so that we can clearly see how the numbers compare. $t_{1/2}$ for Docetaxel is 3.096×10^5 seconds, whereas $t_{1/2}$ for Vandetanib is 1.6416×10^6 seconds. We have that Vandetanib has a larger half-life and hence it will remain longer in the body.

STUDY CHECK

On one hand, Methadone is a synthetic Opioid agonist used for opioid maintenance therapy in opioid dependence and for chronic pain management with a half-life of 2×10^5 seconds. On the other hand, Fluoxetine, sold under the brand names Prozac, is an antidepressant with a half-life of 4 days. Which medication will remain longer in the body and how many time is the half-life of the largest remaining drug in comparison with the other?

Quantifying half-live The formula that related the amount of radioisotope with $t_{1/2}$ is:

$$\boxed{N(t) = N_o \cdot 0.5^{\left(\frac{t}{t_{1/2}}\right)}} \tag{9.1}$$

where $N(t)$ is the amount of isotope at a given time t, N_o is the initial amount of isotope, t is the time and $t_{1/2}$ is the half-life. $N(t)$ is often referred to as the activity of the radioisotope at a given time t. At the same time, while the radioisotope disappears, a new isotope–this time more stable than the radioisotope–starts forming. The amount of product formed $F(t)$ at a given time is:

$$\boxed{F(t) = N_o \cdot \left[1 - 0.5^{\left(\frac{t}{t_{1/2}}\right)}\right]} \tag{9.2}$$

After several half-lives So if the half-life is the time it takes for a radioisotope to decompose in half, what would happen after several half-lives? For example, imagine we have 20 grams of iridium-131 with a half-life of 8 days. When we prepare or hypothetically unseal the sample, we will have 20 grams of ^{131}Ir. After one half-life (8 days) we'll have 10 grams of ^{131}Ir. After two half-lives (16 days), we'll have 5 grams of ^{131}Ir. Similarly, after three half-lives (22 days), we'll have 2.5 grams.

Sample Problem 6

$^{131}_{53}I$ has a half-life of 8days. How many milligrams of a 50mg sample will remain after 10 days.

SOLUTION

We will following steps to solve this problem:

1 **Step one:** list of the given variables.

Given	Asking

Analyze the Problem	G	A
	$t_{1/2} = 8\text{days}$ $N_o = 50mg$ $t = 10days$	$N(t)$

2 **Step two:** use the half-life formula $N(t) = N_o \cdot 0.5^{\frac{t}{t_{1/2}}}$ to obtain the mass remaining of the radioisotope

$$N(t) = \underbrace{N_0}_{\text{50mg}} \cdot 0.5^{\frac{\overbrace{t}^{\text{10d}}}{\underbrace{t_{1/2}}_{\text{8d}}}}$$

3 **Step three:** solve for $N = 50 \cdot 0.5^{\frac{10}{8}} = 50 \cdot 0.5^{1.25} = 21mg$. The result means that after 10 days from the 50mg sample of radioisotope, only 21mg will remain due to radioactive decay.

STUDY CHECK $^{222}_{86}Rn$ has a half-life of 3.8 days. How many milligrams of a 25mg sample will remain after 15 days.

9.5 Radiation measurement, units and radiation effects

Beta and gamma radiation can be detected with a Geiger counter, which consists of a detector tube with a specific ionizing gas. When radiation enters the Geiger counter, it generates charged particles that produce a detectable electrical current. The larger the current the stronger the radioactive source. In the following, we will address the different units of radioactivity–activity, adsorbed dose, and biological damage– reported in Table 9.2 as well as the effects of radiation.

`Activity units` The radioactivity of an isotope often referred to as *activity*, can be measured in two different units: Curies (Ci) or becquerel (Bq). Curie was somehow the original unit employed to measure the radioactivity of radium and becquerel is a more modern unit of radioactivity. Bq is the SI unit of activity. Both units are related by:

$$\boxed{1Ci = 3.7 \times 10^{10} Bq} \quad \text{or} \quad \boxed{\frac{1Ci}{3.7 \times 10^{10} Bq}} \quad \text{or} \quad \boxed{\frac{3.7 \times 10^{10} Bq}{1Ci}} \tag{9.3}$$

Activity refers to the isotope and is also measured in disintegration per minute (cpm).

`Adsorbed dose` Whereas activity refers to the isotope, the adsorbed dose refers to the body that receives radiation. The unit for adsorbed dose is called rad (radiation adsorbed dose). This unit refers to the amount of radiation adsorbed per gram of material. The SI unit for adsorbed dose is called the gray (Gy).

`Radiation equivalent in humans, rem` Not all radiations have the same impact on the human body. The radiation equivalent in humans takes into account the different types of radiation to adjust the biological damage of radiation. The rem is the number of rads times a factor that depends on the radiation. This factor is one for beta and gamma radiation, being 20 for alpha particles. The following formula related REM with RAD:

$$\boxed{rem = rad \times Factor} \tag{9.4}$$

▼An old Geiger counter used to measure radiation

`Exposure to radiation` We are all somehow exposed to radiation every day. The reason for this background radiation is that many natural radioisotopes form the atoms of many materials such as brick, concrete, water, or even the air. Still, the daily exposure is very low and you should not be concerned by the effect of this background radiation.

Table 9.2 Radiation Measurement

Activity	curie (Ci)
	Becquerel (Bq) = 2.7×10^{-11} Ci
	1Ci = 2.22×10^{12} dpm
Dosage (D)	rad
	gray (Gy) =100rad
Damage (H)	rem
	Sievert (Sv) = 100rem

▼Nurses expose to radiation wear film badges to detect radiation exposure

`Dangers of radiation` Radiation units different than Ci or Bq are used to measure the impact of radiation on humans. The rem (radiation equivalent in humans) is a radiation unit that measures the direct biological effects of different kinds of radiation. The number of rems a person receives would determine the impact of the radiation on this person's health. As an example, radiation exposure under 25 rem is harmless and they cannot be detected. If a victim is exposed to 100 rem or higher, the person will suffer the symptoms of radiation sickness and will feel nausea, vomit, fatigue, and a reduction in white cell count. If a person is exposed to a dosage greater than 300 rem, that can lower the white-cell count to zero; the victim will suffer diarrhea, hair loss, and infection. Exposure to radiation of about 500 rem is expected to cause death in half of the people receiving that dose. Radiation dosages of about 600 rem would be fatal to all humans within a few weeks.

▼New Geiger counters

Sample Problem 7

Ioflupane is a radiopharmaceutical that helps visualize the brain of Parkinson patients. An injection of this drug has a 5mCi activity. Convert this value to MBq.

SOLUTION

You need to use the conversion factor between Bq and Ci, $\frac{1Ci}{3.7\times10^{10}Bq}$, as well as the conversion factor between mCi and Ci $\frac{1mCi}{1\times10^{-3}Ci}$, and Bq and MBq

$\frac{1MBq}{1\times10^6 Bq}$.

$$5\cancel{mCi}\times\frac{1\times10^{-3}\cancel{Ci}}{1\cancel{mCi}}\times\frac{3.7\times10^{10}\cancel{Bq}}{1\cancel{Ci}}\times\frac{1MBq}{1\times10^{6}\cancel{Bq}}=185MBq$$

STUDY CHECK

Quadramet is a radiopharmaceutical used treat pain when cancer has spread to the bone. A injection of this drug has a 740 MBq activity. Convert this value to mCi.

9.6 Radiation protection

Radioactivity results from the emission of very energetic and small particles. It can be extremely harmful when no proper protection is used. Therefore, all hospital personnel working with radioactive isotopes–radiologists, doctors, and nurses–need to be protected against radiation. Table 9.3 reports some useful information regarding radiation protection.

`alpha particles` Alpha radiation is made of very heavy particles (He nuclei) that can only travel between 2-4cm in the air before disappearing Inside your body they can penetrate only 0.05mm. A simple piece of thin clothing, a lab coat, gloves, or even our skin can protect us against alpha particles.

`beta particles` Beta radiation is made of lighter particles (electrons) that move much faster than alpha particles. Beta particles travel between 200-300cm in the air and between 4-5mm in body tissue. Heavy clothing such as lab coats or gloves is needed to protect you against this radiation.

`gamma particles` Gamma radiation can pass through many materials including body tissues. Gamma rays travel around 500 m in the air and more than 50cm in tissue. Only very dense shielding, such as lead or concrete, will protect you from this radiation.

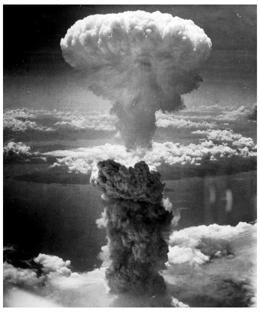
Table 9.3 Radiation protection

Particle	Travels in air	Travels in tissue	Protected with
α	2-4cm	0.05mm	thin clothing
β	200-300cm	4-5mm	heavy clothing
γ	500m	50cm	lead or concrete

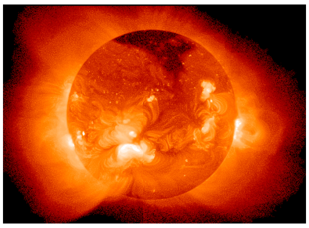
9.7 Radioactive gases: radon

Radon is a colorless, odorless radioactive gas produced by the radioactive decay of uranium. It is present in nearly all soils and very small levels of radon are found in the air we breathe every day. The problem occurs when radon gas enters our home and gets trapped. If you are breathing in too much radon, you will not feel sick right away. Only long-term exposure to high levels of radon can cause lung cancer and the risk is higher for those who smoke. While questions remain over the quantities and length of exposure, radon concerns are a fact of homeownership. Most residential real estate transactions require radon testing, and many states require radon mitigation for new construction. The recommended reference radon level is 100 $Bq \cdot m^3$ in dwellings. Testing your home for radon is easy and doesn't cost very much. You can test for radon yourself or hire a professional to do it for you. There are relatively simple tests for radon gas. Radon detection devices are commercially available. Digital radon detectors provide ongoing measurements giving daily, weekly, short-term and long-term average readouts via a digital display. Short-term radon test devices used for initial screening purposes are inexpensive, in some cases free.

▼Nuclear weapons are based on the principles of fission



▼The Sun generates its energy by nuclear fusion of hydrogen nuclei into helium.



9.8 Fusion and fission

This section will address nuclear fusion and fission. These two processes involve the liberation of a very large amount of energy and are the base for using nuclear processes as a source of energy.

`Nuclear fusion` Large energy quantities are released when two light isotopes combine to produce a heavier isotope. Nuclear fusion is the mechanism of energy production in the stars. Very high temperatures are required to initiate nuclear fusion and that is the reason why this source of energy has not been exploited on the earth yet. An example of fusion reactions found in the stars are:

$$\begin{gathered} {}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} \\ {}^{3}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{0}_{1}\mathrm{e} \end{gathered}$$

`Nuclear fission` Nuclear fission was discovered before the second world war when ${}^{235}_{92}\mathrm{U}$ was bombarded with neutrons. The result is the split of the atom into two different isotopes and the release of more neutrons:

$${}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

This process releases 26 million times more energy than the combustion of methane. As neutrons are produced in a fission process, they can already activate another uranium atom producing more neutrons. This is the essence of a chain reaction: a self-sustained fission process. If less than one neutron causes a new fission process the fission process will stop and the reaction is said to be subcritical. Differently, when exactly one neutron from each fission even produces another fission the process will sustain and the reaction is known as critical. When more than one neutron produced generates a new fission the fission process will escalate and the reaction is known as supercritical. During World War II, the Manhattan project was a united states research project to build a bomb based on the principles of fission. A fission bomb operates by suddenly combining subcritical masses of uranium, producing an enormous explosion.

Sample Problem 8

Identify the following reactions as fusion or fission:

$$\begin{gathered} {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{1}\mathrm{e} \\ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \longrightarrow {}^{137}_{52}\mathrm{Te} + {}^{97}_{40}\mathrm{Zr} + 2\,{}^{1}_{0}\mathrm{n} \end{gathered}$$

SOLUTION

The first nuclear reaction combines two hydrogen isotopes and hence it will be a fusion reaction. The second reaction results of the fragmentation–fission–of uranium and it will be fission.

STUDY CHECK

Identify the following reaction as fusion or fission:

$$^{3}_{2}He + ^{3}_{2}He \longrightarrow ^{4}_{2}He + 2\,^{1}_{1}H$$