CHAPTER 28

Nuclear Physics

28.1 THE ATOMIC AGE

Radioactivity and nuclear energy have become some of the most important concerns facing society since the Second World War. The benefits to society are immense but so too are the problems they bring. In this chapter we will be examining some aspects of nuclear physics that will help to answer questions such as these:

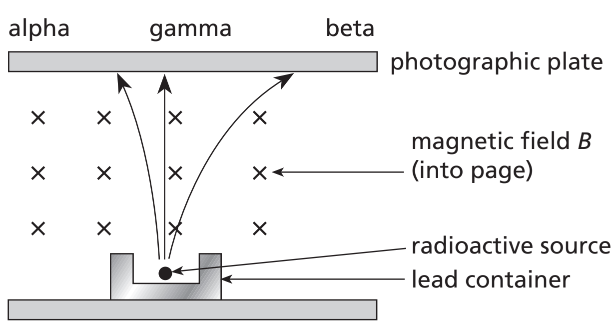
- When you irradiate food with gamma rays, does the food become radioactive?
- Can you accurately tell the age of bones millions of years old?
- If gamma radiation can go straight through the body, how can it kill cancer tumours?
- Why do you need a fission bomb to start a fusion bomb?
- Why does an airline pilot get exposed to more radiation than an air traveller?
- I thought electrons were negatively charged; how can you get a positive one?

28.2 PROPERTIES OF NUCLEAR RADIATION

In the previous chapter, the history and properties of nuclear radiation were described. Let's expand on these:

- Any radiation that can remove an electron from an atom and create a heavy positive ion and free electron is termed **ionising radiation**. Ionising radiations include electromagnetic radiation (gamma rays, X-rays, and ultraviolet radiation) as well as energetic particles such as alpha and beta particles. Gamma rays are said to be **nuclear radiation** because they are created within the nucleus; X-rays come from the electron cloud around the nucleus.
- By the early 1900s, the properties of alpha, beta and gamma radiation had been measured, allowing physicists to better understand the process of radioactivity. The deflection of the particles in a magnetic field is shown in Figure 28.1**(a)** and how they pass through matter is shown in Figure 28.1**(b)**.

(a)



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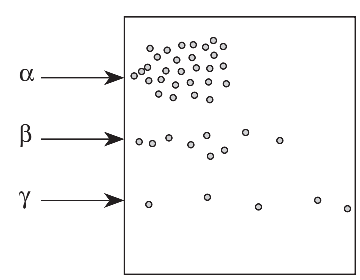


Figure 28.1
(a) Deflection of alpha, beta and gamma rays by a magnetic field.
(b) Ionising ability.

Alpha (α) particles $^{4}_{2}He$

As they collide with matter, alpha particles slow down, transferring their kinetic energy to the other molecules, shaking many of them apart and leaving a trail of positive and negative ions in their wake.

Beta (β) particles $^{0}_{-1}e$

Beta particles are electrons moving at high speed ranging from 0.3 to 0.99 times the speed of light (3×10^{8} m s^{-1}). Because of their speed and smallness, they are more penetrating than alpha particles and can travel about 1 m in air before slowing down to become just like the surrounding electrons.

Gamma (γ) rays

Gamma radiation differs from alpha and beta radiation in that it is not made up of charged particles and is not deflected in electric or magnetic fields. Instead, gamma rays are electromagnetic radiation of extremely short wavelength (about 10^{-13} m). Since they have no charge they have tremendous penetrating power because they interact with the absorbing material only via a direct head-on collision with an electron or nucleus. Materials such as lead are good absorbers of gamma radiation mainly because of their high electron density. Even so, gamma rays can still penetrate up to 10 cm of lead.

DETECTING NUCLEAR RADIATION 28.3

One of the most common means of detecting radiation is by Geiger–Müller counters but also used are photographic plates, electroscopes, spark chambers and cloud chambers, and by fluorescence.

Fluorescence

When ionising radiation strikes certain substances such as ZnS, diamond or barium platinocyanide, a large number of individual flashes or scintillations can be seen under a microscope. Tedious counting of flashes over a set period was used by Rutherford and his co-workers in the early 1900s. These **scintillation detectors** slowly lost favour until 1947, when **photomultiplier tubes** were developed to count the scintillations electrically. Today, semiconductor detectors are used.

Photographic plates

Becquerel's discovery of radioactive emissions was based on the fogging of photographic plates. As the ionising particles strike the silver chloride or bromide grains in the gelatin emulsion on the plate they change them into silver atoms. On development, the silver is 'fixed' and the unaffected salts are removed. This leaves a permanent photographic record of the particles' tracks.

EI Activity 28.1 PHOTO DETECTIVE

If you print your own photos or know someone who does, you may like to test the effect of nuclear radiation on an unexposed sheet of photographic paper.

1 Place a sheet of the paper in one of the black plastic bags it normally comes in and tape it closed.

2 Under teacher supervision, place three radioactive specimens, one each of α, β and γ-type radiation, on top of the plastic for an hour and record their positions.

3 Develop the paper and see if the results agree with both the penetrating properties mentioned above and the ability of the radiation to fog the paper.

4 Was the image clear? How could you test it without the plastic bag?

Electroscope

Marie Curie measured the activity of fluorescent salts using an electrometer, invented by her husband Pierre and his brother Jacques. It is based on the principle of the **electroscope**, which should be familiar to you (Figure 28.2). When the air surrounding a negatively charged electroscope is ionised, the positive ions will be attracted to the electroscope and cause the leaves to collapse. The rate of collapse will be proportional to the ionisation produced in the air above. The **electrometer** is similar but has a pointer instead of leaves.

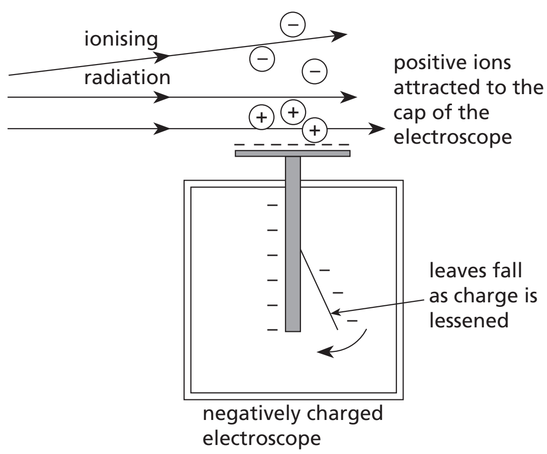


Figure 28.2
A leaf electroscope.

Geiger–Müller counters

Figure 28.3 shows a **Geiger–Müller tube**, commonly known as a **Geiger counter**. It consists of a thin positively charged central wire surrounded by a negatively charged tube filled with a low pressure inert gas. When a radioactive particle enters the tube through the window, it ionises a few atoms. The resulting free electrons are drawn to the positive wire. However, the electric field is so strong that these electrons gain sufficient energy to ionise more atoms of gas. More free electrons are created and the process is repeated many times. This avalanche of electrons is collected by the central wire, creating a signal used to record the passage of the original particle of radiation.

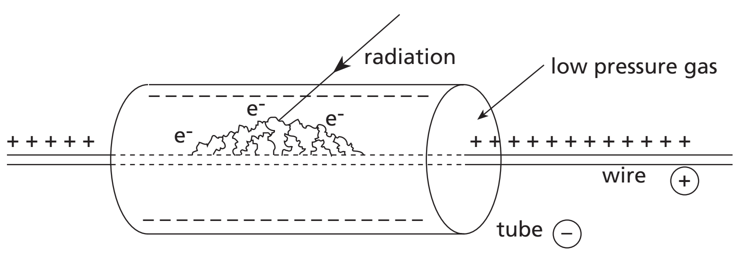


Figure 28.3
A Geiger–Müller tube.

Cloud chambers and bubble chambers

The **cloud chamber** was invented by Scotsman Charles Wilson (1869–1959) and is based on the tendancy of drops of moisture to condense on gaseous ions. When an ionising particle passes through air that is supersaturated with water or other vapour, the liquid droplets form a visible 'cloud track' indicating the path of the particle. Cloud chambers consist of a small container in which a small amount of alcohol is added and the resulting vapour cooled with dry ice (–40°C) to cause condensation. Vapour trails behind jet aircraft are from a similar process of condensation. The tracks of alpha particles can be readily seen as white lines against a black background. They are short, wide tracks. Beta particles produce longer thinner tracks.

Figure 28.4
A cloud chamber.

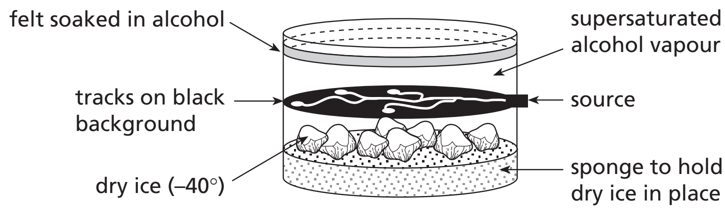


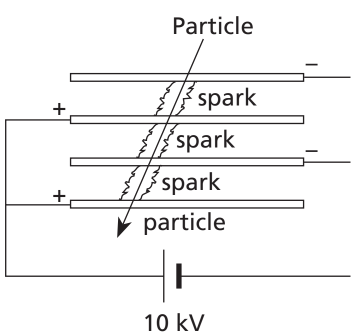
Photo 28.1
A bubble chamber.

In 1952 Glasser invented the **bubble chamber**, which uses a superheated liquid (e.g. liquid H_2 or isopentane) instead of a supercooled vapour. Radioactive particles ionise the liquid and the resulting positive ions provide sites for the formation of bubbles from the boiling liquid. The bubbles show the path of the radiation. The advantage of the bubble chamber is that it can show tracks of very short-lived high-energy particles such as the type produced by particle accelerators. The low gas density in the cloud chamber is insufficient to cause interactions with these short-lived particles.

Spark chambers

A spark chamber consists of a set of parallel plates spaced closely together. Alternate plates are grounded and the ones in between are kept at a very high voltage (about 10 kV). When a charged particle passes them, the ions produced in the gas leave a trail of ions and electrons between the plates, providing a conducting path for a spark to jump. (See Figure 28.5.)

Figure 28.5
Path of an ionising particle in a spark chamber.



SR Activity 28.2 INTERFACING THE GEIGER COUNTER

After the Chernobyl nuclear power plant explosion in the Ukraine in 1986, Russian authorities tried to withhold news of the leak for as long as possible. Meanwhile, in London, several senior physics students had interfaced their school's Geiger counter to a computer and left it running over the weekend to monitor background radiation in London. They were completely unaware of the accident in Russia. When they examined the data on the Monday morning, they were astonished to see that they had logged incredibly high radiation levels. They thought it was a mistake but they soon realised that they were the first people in England to detect that the radioactive plume had crossed the English Channel. They beat all the Government's sophisticated monitoring equipment. What a buzz!

Most school Geiger counters have sockets for output to external devices. Can you design a simple interface that will enable you to connect the Geiger counter to one of the ports of a computer? *Hint:* you could use the parallel port and write a program that reads when the appropriate pin goes 'high' and increments a counter. This will be no easy task! You will need expert help but you could probably sell it to your school.

Questions

1 Each of the devices mentioned has different strengths and weaknesses. Make a list to compare each device.

2 **(a)** List radiation detectors that make use of **(i)** ionising ability; **(ii)** the photoelectric effect. **(b)** Both the cloud chamber and the bubble chamber show the tracks of radioactive emissions. Explain the basic difference in the way they work.

28.4 NUCLEAR STABILITY AND RADIOACTIVE DECAY

Transmutations

For centuries, medieval researchers sought in vain for a material that could turn ordinary metals such as lead into the precious metal gold — a process they called **transmutation** (Latin *trans* = 'across', *mutare* = 'change'). These people were called *alchemists* (Greek *chyma* = 'to fuse a metal'). They developed numerous techniques that are still used in laboratories today, such as distillation, crystallisation, sublimation and fusion. They derived many useful compounds in the process, such as caustic soda, red lead, tin oxide and various alloys; but they used many substances not commonly found in laboratories today: hair, skull, brains, bile, blood, milk, urine and horn. No wonder they didn't turn lead into gold. But it wasn't the chemicals that caused them to fail; it was their underlying theory of matter. The alchemists believed in Aristotle's four-element theory (earth, wind, fire and water). Until this was overthrown, science couldn't progress.

Little did they know that in nature many atoms transmute from one form to another in the normal course of events. When atoms transmute they are said to be radioactive and particles are emitted by the nucleus. These particles can be alpha, beta or a neutron. In many cases a gamma ray is also emitted. The question that bothered physicists was why some nuclei were radioactive (e.g. uranium) and why some were stable (lead) and stayed unchanged indefinitely. The answer lies in the way the nucleus is structured.

Nuclear forces

The nucleus is made up of protons and neutrons. However, the protons are positively charged and because they are almost touching, the electrostatic repulsive force is enormous. But why don't they fly apart? The answer lies in the role of the neutrons. The neutrons serve two purposes — first, to add some distance between the protons to reduce the repulsive force and, second, to act as a nuclear 'glue'. This gluing force is called the '**strong force**'. As the number of protons increases, the number of neutrons must also increase. This 'strong force' binds adjacent nucleons together. It is a very short-ranged force because, unlike the electrostatic force that decreases as the inverse square of the distance, the 'strong force' decreases rapidly. When nucleons are just a few diameters apart, the 'strong force' is nearly zero.

For the smaller nuclei, the number of neutrons required for stability is about the same as the number of protons present (that is, a n/p ratio of 1:1). For example, the most stable isotope of oxygen is ${}^{16}_{8}O$. It has eight protons and eight neutrons. Similarly, ordinary carbon is ${}^{12}_{6}C$ (6p, 6n). But as the number of protons increases, the number of neutrons required for stability increases more — the n/p ratio becomes greater than 1:1. For example, stable zinc is ${}^{66}_{30}Zn$, which has thirty protons and thirty-six neutrons so the n/p ratio is 1.17. Table 28.1 lists some common examples. Note that the n/p ratio starts at 1.00 and has increased to 1.59 for uranium. Figure 28.6 shows a plot of neutron number against proton number. There are no completely stable nuclides above a proton number (Z) of 82.

Table 28.1 SOME N/P RATIOS

STABLE NUCLIDE	PROTONS (Z)	NEUTRONS (N)	n/p RATIO
${}^{16}_{8}O$	8	8	1.00
${}^{65}_{30}Zn$	30	35	1.17
${}^{207}_{82}Pb$	82	125	1.52
${}^{238}_{92}U$	92	146	1.59

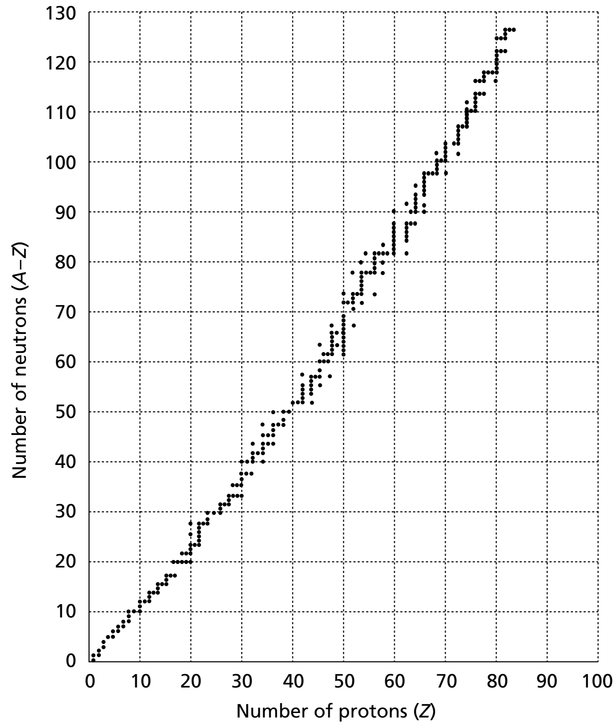


Figure 28.6
Graph of a proton (or atomic) number *Z*, versus a neutron number *N*, for naturally occurring isotopes.

The particle ‘zoo’

The 1930s were to witness a new burst of radioactivity research even greater than the two previous bursts in 1895 (Curie, Thompson, Becquerel) and 1912 (Rutherford, Bohr). In 1932 Chadwick discovered the neutron and, very soon afterwards, American physicist Carl Anderson discovered another fundamental particle, the positive electron or **positron**. The existence of the positron had been predicted by Paul Dirac several years earlier. This was a major development in physics. Further discussion of the positron and other fundamental particles is reserved for the following chapter. The important particles discussed so far are shown in Table 28.2.

Table 28.2 SYMBOLS OF ATOMIC PARTICLES

PARTICLE	SYMBOL
Alpha particle (α)	^4_2He
Proton	^1_1H or ^1_1p
Neutron	^1_0n
Electron (β particle)	$^0_{-1}e$
Positron	$^0_{+1}e$
Gamma ray	γ

Radioactive decay

The world is made up of stable nuclei — all atoms don’t just disintegrate in front of us. But there are some atoms that are radioactive and decay or disintegrate into other types of atoms. Some nuclei, such as Pa-221, may only last for 6 microseconds whereas lead-206 will last for billions of years and is said to be infinitely stable. Between these two extremes are nuclei that may exist for seconds, hours, days or years before decaying. Lead-214 will, on average, last for 27 minutes before giving off β and γ particles.

When the original unstable 'parent' nucleus decays it produces a daughter nucleus and at least one other particle. The reaction can be written like the normal chemical equation:

Parent nucleus → daughter nucleus + particle(s)

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

In all cases it can be seen that:

- **The sum of the atomic masses on the left of the equation must be the same as the sum of the atomic masses on the right**.
  In the case above the 234 + 4 = 238, so this rule is obeyed.
- **The total charge on the left-hand side of the equation must equal the total charge on the right-hand side**.
  Charge refers to the nuclear charge and that of its emitted particles. A proton has a charge of +1; an electron (β particle) has a charge of −1. In the case above, the left-hand side shows 92 protons, so the charge is +92 or simply 92. The sum of the nuclear charges on the right is 90 + 2 = 92; so the rule is obeyed.
  Another important rule is:
- **The number of protons (atomic number) determines the name and symbol of the element**.
  A mistake students often make when trying to work out the symbol for the daughter nucleus is to use the atomic *mass* and not the atomic *number*.

Example

Balance the following radioactive decay:

$^{226}_{88}Ra \rightarrow ^{4}_{2}He + ?$

Solution

Step 1: The atomic masses (the top numbers) have to be equal to 226 on both sides; the daughter nucleus must have an atomic mass of 226 − 4 = 222.
Step 2: The nuclear charges (the bottom numbers) have to be equal to 88: the daughter must have a charge of 88 − 2 = 86.
Step 3: The nuclear charge (atomic number) determines the name of the element; $Z = 86$ refers to *radon*.
Note: the top number (222) is *not* used to find the name of the atom.
Step 4: Write equation: $^{226}_{88}Ra \rightarrow ^{4}_{2}He + ^{222}_{86}Rn$.

Questions

3 State the number of neutrons and protons in the following: **(a)** $^{226}_{88}Ra$; **(b)** $^{1}_{1}H$; **(c)** $^{239}_{93}Np$.

4 What element is represented by X in each of the following: **(a)** $^{226}_{88}X$; **(b)** $^{1}_{1}X$; **(c)** $^{247}_{97}X$; **(d)** $^{82}_{38}X$?

5 Balance the following equations:

(a) $^{214}_{83}Bi \rightarrow ^{0}_{-1}e + ?$

(b) $^{239}_{93}Np \rightarrow ^{0}_{+1}e + ?$

(c) $^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ?$

(d) $^{45}_{20}Ca \rightarrow ^{0}_{-1}e + ?$

(e) $^{58}_{29}Cu \rightarrow ^{0}_{+1}e + ?$

(f) $^{234}_{94}Pu \rightarrow ^{4}_{2}He + ?$

TYPES OF DECAY 28.5

There are three main ways that nuclei decay naturally. They are alpha decay, beta decay and positron decay.

These types of decay are associated with three unstable states of a nuclide:

- too many neutrons (beta decay)
- too many protons (positron decay)
- too many protons and neutrons — too much mass (alpha decay).

Alpha decay

Atoms heavier than uranium-238 do not occur naturally. We can produce them artificially but they have too many neutrons and protons to be stable; in other words, they have too much mass for the nuclear 'glue' to work. Such atoms decay by alpha emission and the parent nucleus loses two protons and two neutrons as a fast moving, energetic alpha particle. The alpha particles emitted have discrete kinetic energies, usually up to 10 MeV.

$$^{A}_{Z}X \rightarrow \, ^{A-4}_{Z-2}Y + \, ^{4}_{2}He + \text{energy } (\gamma)$$

$$^{236}_{91}Pa \rightarrow \, ^{232}_{89}Ac + \, ^{4}_{2}He + \gamma$$

Alpha decay occurs because the 'strong nuclear force' is unable to hold large nuclei together. Because the strong nuclear force is a short-range force, it acts only between neighbouring nucleons. But the repulsive electrostatic force can act across the whole nucleus. For very large nuclei, the large number of protons means that the total repulsive force is great compared with the attractive strong nuclear force, which cannot hold the nucleus together. The only way to achieve stability is to shed some protons and neutrons. This occurs in packets of 2 p and 2 n, that is, the helium nucleus $^{4}_{2}He$, known as an alpha (α) particle.

Beta decay

There are two types of beta particles: beta minus (the electron) and beta plus (the positron). Each type is associated with a different type of instability in a nuclide. From now on, *beta decay* will refer to the electron (β–) and *positron decay* will be used for β+.

Beta decay occurs when there is a surplus of neutrons.

A beta particle is an electron that has come from the nucleus. The symbol $^{0}_{-1}e$ stands for an electron whose charge is –1 (i.e. $Z = -1$) and negligible atomic mass ($A = 0$). When a parent nucleus emits a beta particle, the daughter nuclide produced has the same mass number as the parent:

$$^{A}_{Z}X \rightarrow \, ^{A}_{Z+1}Y + \, ^{0}_{-1}e + \text{energy } (\gamma)$$

Two examples of beta decay are:

$$^{239}_{92}U \rightarrow \, ^{239}_{93}Np + \, ^{0}_{-1}e$$

$$^{234}_{91}Pa \rightarrow \, ^{234}_{92}U + \, ^{0}_{-1}e$$

It can be seen that the number of nucleons has not changed but the daughter has one more proton than the parent. It is as if one of the neutrons has changed into a proton and in the process (to conserve charge) has given off an electron. In fact, neutrons actually do decay in this manner. Outside the nucleus, neutrons only last for about 11 seconds before this reaction occurs.

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

In the 1920s, accurate measurements of the masses of reactants and products in beta decay showed that the masses were not equal. Some mass appeared to be lost. Physicists were troubled at the prospect of the law of conservation of mass being violated. In 1930, Wolfgang Pauli proposed an alternative solution: the missing mass was being carried off by a particle of zero charge and negligible mass that made it difficult to detect. The Italian physicist Enrico Fermi (1901–54) suggested the name **neutrino** meaning 'little neutral one'. The symbol for the neutrino is the Greek letter *nu* (ν). A bar is place over the symbol ($\bar{\nu}$) to indicate that in beta decay an antineutrino is formed. An **antineutrino** is an **antiparticle** to the normal neutrino — more on that in Chapter 29. For the moment, you do not have to include the neutrino in your equations (unless your teacher says so). Neutrinos are flooding through your head right now but nothing much stops them. In fact, it has been estimated that you would need a lead block 90 light years thick to stop about 50% of them.

Positron decay

When a nuclide has a surplus of protons it undergoes positron decay:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + \text{energy } (\gamma)$$
$$^{239}_{93}Np \rightarrow {}^{239}_{92}U + {}^{0}_{+1}e$$

A positron is a positive electron ${}^{0}_{+1}e$, or e^{+}. It has the same mass as an electron (A = 0) but it has the opposite charge, so its atomic number is said to be Z = +1, the same as its charge. It is sometimes called a 'beta plus' (β+) to distinguish it from ordinary beta radiation, which is then called beta minus (β^{-}). In this book we will use the terms *beta radiation* meaning an electron and *positron radiation* as its opposite or antiparticle. In positron decay, the number of nucleons (the top number) does not change. But as the number of protons decreases, it appears that a proton has been changed into a neutron and a positron ejected. When a positron and an electron collide they annihilate each other and give out a burst of gamma rays, which travel in opposite directions, a process made use of in positron emission tomography (PET). This is discussed in Chapter 33 on Medical Physics.

English physicist Paul Dirac predicted the existence of the positron in the late 1920s and American physicist Carl Anderson was awarded the Nobel prize in 1936 for his discovery of it in a cosmic ray shower. In fact, it is now believed that all particles have antiparticles, protons and antiprotons for example.

Predicting the type of decay

The graph of proton number versus neutron number is repeated in more detail in Figure 28.7. From it you can see what type of decay will occur in unstable nuclides.

- Beta decay will occur in those nuclides that are *above* the line of stability.
- Positron decay will occur in those nuclides that are *below* the line of stability.

Beta decay is typical in nuclides with a higher proportion of neutrons than in the stable isotopes of the same element. The opposite is true for positron decay, so that nuclides that undergo these two forms of decay lie on either side of the band of stable nuclides.

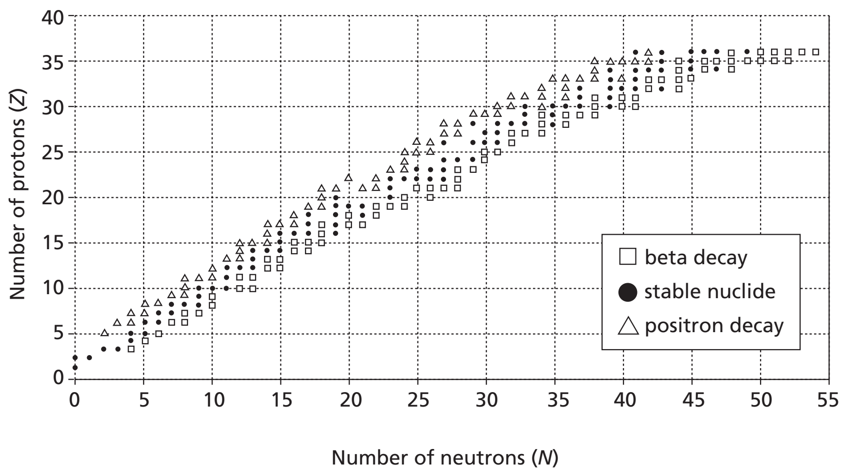


Figure 28.7
Predicting the type of decay from the stability graph. The band of stable nuclei is shown by the black dots. Note that in this graph the number of neutrons is on the x-axis.

Gamma decay

In pure gamma decay there is no change to the numbers of protons or neutrons and therefore no transmutation. It is a release of energy in the form of electromagnetic radiation of a particular wavelength and frequency.

Remember, a gamma ray is an electromagnetic radiation that originates from within the nucleus. An X-ray, on the other hand, is an electromagnetic radiation originating from the electron cloud surrounding the nucleus.

Questions

6 Complete the following equations:

(a) $^{32}_{15}\text{P} \rightarrow {}^{0}_{-1}\text{e} + ?$

(b) $^{234}_{90}\text{Th} \rightarrow ? + {}^{234}_{91}\text{Pa}$

(c) $^{22}_{11}\text{Na} \rightarrow ? + {}^{0}_{+1}\text{e}$

(d) $^{1}_{0}\text{n} \rightarrow ? + {}^{1}_{1}\text{H}$

(e) $^{1}_{1}\text{H} + {}^{0}_{-1}\text{e} \rightarrow ?$

7 What are the parent nuclei for each of the following daughter nuclei produced by alpha decay: **(a)** $^{206}_{81}\text{Tl}$; **(b)** thallium-210; **(c)** Po-218; **(d)** Pb-206?

8 Write equations for the beta decay of **(a)** C-14; **(b)** Na-24; **(c)** P-32.

9 Write equations for the positron decay of **(a)** ^{22}Na; **(b)** ^{18}F; **(c)** ^{19}Ne; **(d)** ^{199}Pb.

HALF-LIFE 28.6

Radioactive decay is a random event, just as a car accident is a statistically random event. There is no means of predicting whether a particular driver will be involved in a crash. However, it is possible to say statistically how many crashes will happen in Australia each year. The more cars, the more accidents.

In a similar way, it is quite impossible to predict when a particular nucleus will decay but it is possible to predict the number of nuclei that will decay in a given time from a particular source. Likewise, if you throw 100 coins into the air, you can reliably predict that about 50 will come down heads and 50 tails; but you can't say what a particular coin will do.

For example, N-13 decays to C-12 by positron emission:

$$^{13}_{7}\text{N} \rightarrow {}^{12}_{6}\text{C} + {}^{0}_{+1}\text{e}$$

If we had 10 000 N-13 atoms, about 12 of them would decay in 1 second (12 s^{-1}). We say the **decay rate** or **activity** (A) is 12 disintegrations per second (dps) or $A = 12\ s^{-1}$. So after 1 second there would be 9988 left. After another second about 12 more N-13 atoms would decay and there would be 9976 left. But as the number of N-13 atoms decreases so too does the decay rate. After 10 minutes, there would be about 5000 N-13 atoms left (i.e. half the starting number) and the decay rate would be 6 disintegrations per second. When another 10 minutes had elapsed, there would be about 2500 atoms of N-13 left and the decay rate would be down to 3 dps. The period of 10 minutes in which it takes half the N-13 atoms to decay is called the **half-life** ($t_{1/2}$). It also represents the time taken for the decay rate to fall to half its original rate. The SI unit for activity is **Becquerel** (Bq), so 1 Bq = 1 disintegration per second (1 dps or 1 s^{-1}). In less active substances, the activity may be expressed as disintegrations per minute (dpm).

Table 28.3 summarises the data. The decay is shown graphically in Figure 28.8.

Table 28.3 DECAY OF NITROGEN-13 ISOTOPE

TIME ELAPSED (t) (MINUTES)	NUMBER OF N-13 ATOMS REMAINING (N)	DECAY RATE (A) (Bq)
0	10 000	12
10	5000	6
20	2500	3
30	1250	1.5
40	625	0.75

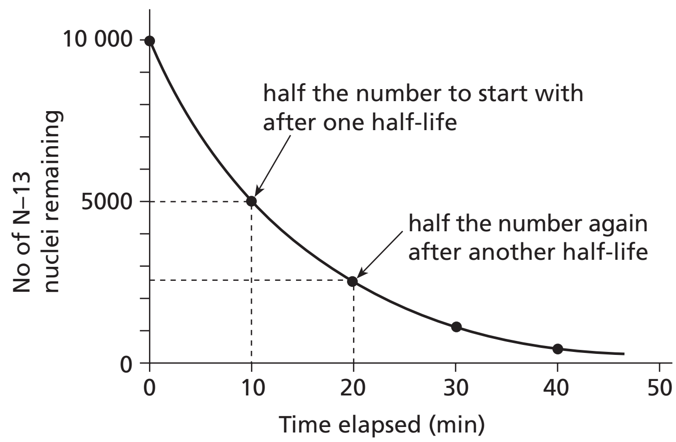


Figure 28.8
Graph of nitrogen-13 decay.

Half-lives can be very short or very long (Table 28.4).

Table 28.4 HALF-LIFE OF SOME ISOTOPES

NUCLIDE	DECAY	HALF-LIFE
^{206}Pb	stable	infinite
^{234}U	α	4.51 billion years
^{234}Th	β, γ	24.1 days
^{222}Rn	α	3.82 days
^{218}Po	α	3.05 min
^{214}Po	α	1.64×10^{-4} s
^{1}H proton	γ	10^{37} years

NOVEL CHALLENGE

Other things in nature have a half-life. For example, $t_{1/2}$ for human protein is 80 days, for rat muscle it is 21 days, and for rat blood 6 days. In non-mammals half-life values are much lower because they have lower temperatures. How is this different from nuclear half-lives?

The half-life of a radioactive isotope is the time taken for half the radioactive atoms in a sample to decay.

If N_0 = number of parent nuclei at start, and N = number of atoms at end of the time period:

- after 1 half-life: $N = N_0 \times \frac{1}{2}$
- after '*n*' half-lives: $N = N_0 (\frac{1}{2})^n$.

Example:

Iodine-131 has a half-life of 8 days and undergoes beta decay according to the equation: ${}^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}\text{e}$. If a milk sample contains 3×10^{18} atoms at a particular time, calculate **(a)** the number remaining after 60 days; **(b)** the time that would have to elapse for there to be 1 million atoms left.

Solution

(a) Number of half-lives elapsed $(n) = \frac{60}{8} = 7.5$.

$$N = N_0 \left(\frac{1}{2}\right)^n = 3 \times 10^{18} \left(\frac{1}{2}\right)^{7.5} = 1.6 \times 10^{16} \text{ atoms}$$

Note: one way to do this on your calculator is to enter: [3] [EXP] [1] [8] [×] [.] [5] [x^y] [7] [.] [5] [=]

(b)

$$N = N_0 \left(\frac{1}{2}\right)^n$$

$$1 \times 10^6 = 3 \times 10^{18} \left(\frac{1}{2}\right)^n$$

$$\frac{1 \times 10^6}{3 \times 10^{18}} = \left(\frac{1}{2}\right)^n$$

$$3.333 \times 10^{-13} = \left(\frac{1}{2}\right)^n$$

$$\log 3.333 \times 10^{-13} = \log \left(\frac{1}{2}\right)^n = n \log \left(\frac{1}{2}\right)$$

$$-12.48 = n \times -0.301$$

$$n = \frac{-12.48}{-0.301} = 41.46 \text{ half-lives}$$

$$= 41.46 \times 8 \text{ days}$$

$$= 332 \text{ days}$$

Note: instead of specifying N and N_0 as meaning the number of atoms, it could also mean the mass of the nuclide in a specimen. The formula still works.

Decay series

Sometimes a radioactive isotope decays into another isotope that is also radioactive. Sometimes the daughter decays into another isotope, which decays further and so on. This successive chain of decays is called a decay series. A good example is shown in Figure 28.9 in which U-238 decays by alpha emission to Th-234, which in turn decays by beta emission and so on until the stable isotope Pb-206 is reached. In an alpha decay ${}^{4}_{2}\text{He}$ is lost so the atomic mass decreases by 4 and the atomic number decreases by 2. This appears as a diagonal arrow. Beta emission (in which $n \rightarrow p$) has no effect on atomic mass so it appears as an arrow to the right. Positron emission appears as an arrow to the left.

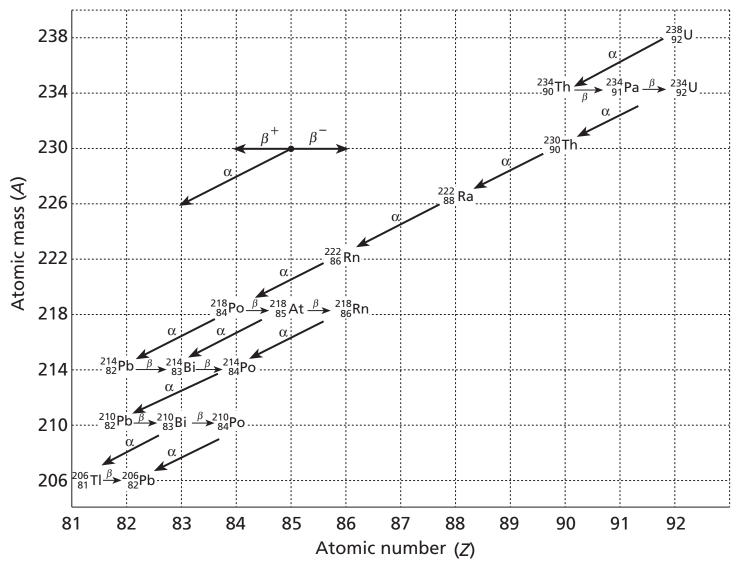


Figure 28.9

In the uranium–lead decay series, note that there are several paths the sequence can take. For example, Po-218 can decay by alpha emission to Pb-204 or by beta emission to At-218 and so on. The series ends at the stable lead isotope Pb-206. Other radioactive series also exist.

28.7 LAWS OF RADIOACTIVE DECAY

Several laws and mathematical relationships have been developed for radioactivity. It was Rutherford in 1919 who first suggested that radioactive decay was an exponential process. His work underpins most of the laws we have today.

Activity

The rate at which a radioactive nuclide decays is called its **activity** (*A*). The SI unit for activity is the **becquerel** (Bq), which represents one disintegration per second (dis s^{-1} or dps). For example, a sample in which 12 atoms decay in one second is said to have an activity of 12 disintegrations per second (dps); that is A = 12 Bq. If you use a Geiger counter to measure activity in the classroom, you would most likely measure the number of disintegrations over a longer period of time, say, 1 minute, and calculate the activity by dividing the 'count' (disintegrations) by the time elapsed in seconds; this would give activity in Bq. You could also express activity as the number of disintegrations per minute (dis min^{-1} or dpm).

The activity law

In an earlier example, the rate of decay of a nitrogen-13 atom was discussed:

$$^{13}_{7}N \rightarrow {}^{12}_{6}C + {}^{0}_{+1}e$$

At the start of the experiment, the sodium was undergoing 12 disintegrations per second (12 Bq); after 10 minutes its activity had dropped to 6 Bq and after a further 10 minutes it had dropped to just 3 Bq (Table 28.5).

Table 28.5 DECAY OF N-13 NUCLIDES

TIME ELAPSED (MINUTES)	NUMBER OF RADIOACTIVE ATOMS REMAINING, *N*	ACTIVITY (Bq)
0	10 000	12
10	5 000	6
20	2 500	3

Inspection of the data shows that the activity is directly proportional to the number of radioactive atoms remaining in the sample:

$$A \propto N$$

or, by replacing the proportional sign with an equal sign and a constant, $A = \lambda N$. The constant, λ, is called the **disintegration constant**. It has the same unit as the unit of the activity. If activity is in Bq (i.e. s^{-1}), then the disintegration constant will also have the same unit (s^{-1}).

Example 1

Calculate the disintegration constant for the above data.

Solution

$$A = \lambda N$$

$$\lambda = \frac{A}{N} = \frac{12\ s^{-1}}{10\ 000} = 1.2 \times 10^{-3}\ s^{-1}$$

Example 2

The disintegration constant of Ra-226 is $4.3 \times 10^{-4}\ y^{-1}$. Calculate the number of atoms in a sample of radium-226 that has an activity of 3 kBq.

Solution

The disintegration constant is given in y^{-1} and has to be converted to s^{-1} because activity is measured in s^{-1}:

$$\lambda = \frac{4.3 \times 10^{-4}}{1\ \text{year}} = \frac{4.3 \times 10^{-4}}{365 \times 24 \times 60 \times 60\ \text{seconds}} = 1.36 \times 10^{-11}\ s^{-1}$$

$$N = \frac{A}{\lambda} = \frac{3 \times 10^{3}}{1.36 \times 10^{-11}} = 2.2 \times 10^{14}\ \text{atoms}$$

Exponential decay law

In maths, you may have learnt the general exponential decay law: $N = N_0\, e^{-kt}$, where e is the base of the natural logarithm, k is the rate constant, and t is time elapsed. In radioactive decay, the formula becomes:

$$N = N_0\, e^{-\lambda t} \text{ or } A = A_0\, e^{-\lambda t}$$

where the Greek letter *lambda* (λ) is the disintegration constant. The relationship between the disintegration constant and half-life is derived in the following manner:

$$N = N_0\, e^{-\lambda t} \quad \text{or} \quad \frac{N}{N_0} = e^{-\lambda t}$$

Take the natural logarithm ($\log_e$ or ln) of both sides:

$$\ln\left(\frac{N}{N_0}\right) = -\lambda t$$

Half-life is defined as the time that one-half of the radioactive atoms in a sample will decay; that is, when:

$$N = \tfrac{1}{2}N_0 \text{ and } t \text{ is replaced by } t_{\frac{1}{2}},$$

hence

$$\ln\left(\frac{\frac{1}{2}N_0}{N_0}\right) = -\lambda t_{\frac{1}{2}} \quad \text{or} \quad \ln \tfrac{1}{2} = -\lambda t_{\frac{1}{2}}$$

$$\ln 2 = \lambda t_{\frac{1}{2}}$$

$$t_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$$

$$t_{\frac{1}{2}} = \frac{0.693}{\lambda}$$

$$\text{or disintegration constant } (\lambda) = \frac{0.693}{t_{\frac{1}{2}}}.$$

Example

The half-life of Ra-226 is 1620 years. Calculate its disintegration constant, λ.

Solution

The disintegration constant for Ra-226 is calculated by:

$$\lambda = \frac{0.693}{1620}$$

$$= 4.3 \times 10^{-4}\ \text{y}^{-1}$$

Questions

10 $^{124}_{55}$Cs has a half-life of 31 s. **(a)** Calculate its decay constant in s^{-1} and min^{-1}; **(b)** if there was 20.0 g of Cs-124 to start with, state how much will be left (in grams) after **(i)** 62 s, **(ii)** 124 s, **(iii)** 10 minutes.

11 **(a)** $^{68}_{32}$Ge has a half-life of 9.0 minutes. How many minutes will it take for the germanium in a 1.00 g sample to decay to 1.00 mg?
(b) If its activity at a particular time is 3.55 kBq, how many minutes will elapse before its activity is 250 Bq?

12 A sample of $^{13}_{7}$N ($t_{\frac{1}{2}}$ = 10.0 minutes) contains 6.90×10^{16} atoms of N-13. **(a)** Calculate its decay constant; **(b)** state its initial activity; **(c)** state its activity after **(i)** 1 hour, **(ii)** 6 hours; **(d)** state after how long will its activity be 1 Bq.

SR Activity 28.3 'ACTIVITIES' ACTIVITY

1 *Spreadsheet decay* If you have access to a computer and spreadsheet, see if the following challenges you.

- Imagine you had a Tc-99m isotope ($t_{\frac{1}{2}}$ = 6 hours) with an initial activity, A_0, of 1000 Bq. Develop cell formulas that will calculate the activity, A, of the sample every hour for 24 hours. *Hint:* appropriate formulas are: $A = A_0(\frac{1}{2})^n$ or $A = A_0e^{-\lambda t}$.
- Set up a column that will calculate the number of nuclei remaining, N. *Hint:* use $A = \lambda N$.
- Set up a column that will calculate the natural logarithm of activity, ln A.
- Plot A vs t, N vs t and ln A vs t. Are they what you would expect?
- Print out a page of the results, including the graphs.

2 *Random programming* If you are sufficiently familiar with computer programming, write a program that will simulate the decay of a collection of radioactive nuclei. Use whatever language you like (e.g. BASIC, Pascal, C++).

- Start with 1000 nuclei (N_0).
- Use a random number generator to determine if any nuclei will decay. *Hint:* generate a random number between 0 and 10; if number >5 = will decay; <5 = will not decay.
- Subtract 1 if 'decay'; determine number of nuclei remaining, N.
- Draw a graph of N vs t.
- Hand in a printout of the code and the output.

ANALYSIS OF EXPERIMENTAL DATA 28.8

The meticulous and often dangerous collection of data on rates of decay helped scientists to uncover the structure of the nucleus and develop an understanding of radioactivity. This goes on today, even in school laboratories.
The exponential decay law is written:

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

Because A is proportional to N, we can rewrite this as:

$$A = A_0 e^{-\lambda t}$$

If we take natural logs of both sides:

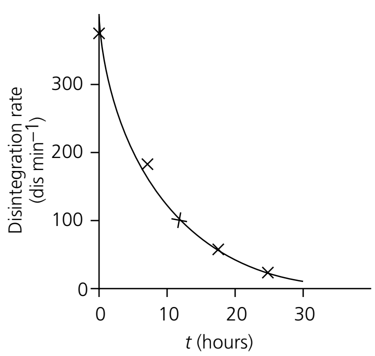
$$\ln A = \ln A_0 - \lambda t$$

This can be arranged to give:

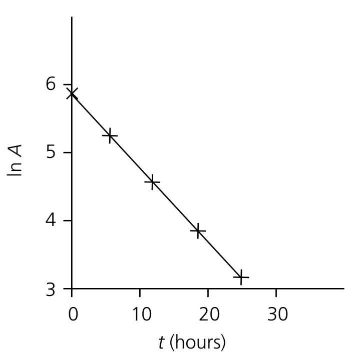
$$\frac{\ln A - \ln A_0}{t} = -\lambda$$

Figure 28.10
A–t time curve is exponential **(a)** whereas ln *A–t* is a straight line.

(a)



(b)



Graphing

As the rate of radioactive decay is exponential, a graph of activity vs time should show an exponential curve (Figure 28.10**(a)**), whereas a graph of the log of activity (ln A) vs time should be a straight line (Figure 28.10**(b)**).

The slope of the ln A vs t graph is equal to $\frac{\ln A - \ln A_0}{t}$, which is equal to $-\lambda$ according to the previous equation.

Example
A sample of radioactive actinium Ac-288 has an initial activity of 363 disintegrations per minute and its activity is measured in a laboratory every six hours. The results are shown in Table 28.6.

Table 28.6 DECAY OF Ac-288 NUCLIDES

TIME ELAPSED (h)	ACTIVITY (DISINTEGRATIONS/MIN)	ln *A*
0	363.0	5.89
6	184.0	5.21
12	93.2	4.53
18	47.3	3.85
24	24.0	3.18

Plot a graph of ln A vs t and calculate the half-life.

Solution

Refer to Figure 28.10**(b)**.

$$\text{Slope} = \frac{3.18 - 5.89}{24}$$
$$= -0.113\ \text{h}^{-1}$$
$$\lambda = -\text{slope} = +0.113\ \text{h}^{-1}$$
$$t_{\frac{1}{2}} = \frac{0.693}{\lambda} = \frac{0.693}{0.113\ \text{h}^{-1}} = 6.13\ \text{hours}$$

Notes:

- The unit of time for the 'disintegration constant' will automatically be the same as the unit for 'time elapsed'. In this case *hour* was the unit of time.
- The unit of time used for 'activity' does *not* have to be the same as the unit for 'time elapsed'. You may recall that in the exponential decay law formula, 'activity' appeared on both sides of the equation and the time unit would cancel out. *Minutes* were chosen in this experiment to get more accurate results.
- You may ask why all the data collection was necessary when only a starting and final activity are necessary in the formula. In experimental determination of half-life, many data are collected and plotted to improve accuracy. It is just good scientific practice.

Questions

13 Phosphorus-32 is a positron emitter that gives the stable isotope Si-30. The activity of a sample was measured every minute in order to measure its half-life. The results are shown in Table 28.7.

Table 28.7

t (min)	0	1	2	3	4	5	6	7	8	10	12
A (Bq)	5000	3840	2915	2220	1723	1293	977	745	617	361	209

Plot ln *A* against time and determine its half-life.

14 The radioactive isotope Kr-88 undergoes gamma decay. The activity of the isotope was measured every 30 minutes as shown in Table 28.8.

Table 28.8

t (min)	0	30	60	90	120
A (Bq)	88	78	69	61	52

(a) Plot ln *A* vs *t*.
(b) Determine the disintegration constant (s^{-1}).
(c) Determine the half-life.

Radioactive dating

The universe is believed to be somewhere between 8 billion and 15 billion years old. Our Earth has been around for over 4 billion (4×10^9) years of that. Grains of the mineral zircon from gneiss rocks have been measured as being 3.962 billion years old, with a three million year margin of error. The estimate is based on the belief that small amounts of radioactive uranium-238 were trapped in the zircon at the time of crystallisation. Since then the uranium has gradually been decaying, eventually into stable lead. The age calculation is done by measuring the amounts of lead and uranium trapped in the rock and by knowing the half-life of U-238, the age *t* can be calculated.

The age of any object made from previously living material such as wood can be estimated using radiocarbon dating. All living plants take in and excrete carbon dioxide. The vast majority of the C atoms is present as the isotope C-12 but a very small fraction (about $1.3 \times 10^{-10}\%$) is the radioactive isotope C-14. The ratio has remained constant for thousands of years because even though C-14 decays (with a half-life of 5730 years), more is being made by the cosmic radiation from space bombarding nitrogen in the atmosphere:

$$^{14}_{7}\text{N} + {}^{1}_{0}\text{n} \rightarrow {}^{14}_{6}\text{C} + {}^{1}_{1}\text{H}$$

When plants and animals die they stop exchanging C-14 with the atmosphere so the C-14 decays without being replaced. So the C-14:C-12 ratio drops. After 5730 years, it would be half the normal ratio. If the ratio can be determined, then the time that has elapsed since death can be established.

Questions

15 A piece of wood from a giant redwood tree has a C-14 ratio only one-quarter of that found in living tissue. How old is the wood?

16 For hundreds of years the Shroud of Turin has been claimed to be the burial garment of Jesus. Recently, a sample was analysed and found to have a C-14 count of 92% of that found in living tissue. **(a)** How old is the shroud? **(b)** What is controversial about the answer? **(c)** If it really was from Jesus's time, what would be the amount of C-14 as a percentage of the C-14 in living tissue?

TRANSMUTATIONS BY NUCLEAR REACTION 28.9

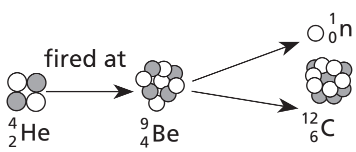
A nuclear reaction happens when there is a change in the structure of the nucleus. Nuclear reactions can be classified as either:

- natural radioactive decay, or
- artificial nuclear reactions.

The radioactive decay processes already discussed are examples of spontaneous nuclear reactions. They occur naturally. No external influence is required.

Other nuclear reactions can be induced artificially by bombarding a nucleus with a projectile, such as a proton, an electron, an alpha particle or other heavy nuclei such as ^{14}N, ^{16}O, etc. (Figure 28.11).

Figure 28.11
Bombardment of a nucleus by alpha particle 'bullets'.



Alpha bombardment

In 1919, after the proton had been discovered, Rutherford designed a series of experiments to probe further into the production of the proton. He bombarded nitrogen gas with 'bullets' of alpha particles:

$$^{4}_{2}\text{He} + {}^{14}_{7}\text{N} \rightarrow {}^{17}_{8}\text{O} + {}^{1}_{1}\text{p}$$

The equation shows that the **transmutation** of nitrogen into oxygen had occurred. When fast, high energy alpha particles are used, neutrons are sometimes formed. For example, if we bombard beryllium nuclei with alpha particles we produce carbon nuclei and fast moving neutrons:

$$^{4}_{2}\text{He} + {}^{9}_{4}\text{Be} \rightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n} \quad \text{See Figure 28.11.}$$

Deuteron bombardment: turning lead into gold?

Although it is almost impossible to turn lead into gold, **deuterons** ($^{2}_{1}H$) can be used to make gold from mercury or platinum:

$$^{2}_{1}H + ^{199}_{80}Hg \rightarrow ^{197}_{79}Au + ^{4}_{2}He$$
$$^{2}_{1}H + ^{196}_{78}Pt \rightarrow ^{197}_{79}Au + ^{1}_{0}n$$

For both of these reactions, the deuterons must be given high enough speed by a suitable accelerator so that they can enter the nuclei of the target atoms. It costs a lot to use an accelerator, so it is cheaper to go and mine the gold. Bad luck!

Neutron bombardment

The bombarding 'bullets' can also be whole nuclei or single particles, such as neutrons, electrons or protons.

One of the common ways of producing transmutation is by using neutrons. Because they carry no charge, neutrons can enter the nuclei of the target atoms more easily than charged particles can. The target is said to have 'captured' the neutron. By the same token, free neutrons are a serious health hazard because of their penetrating power. The good news is that free neutrons have a short half-life — about 11 minutes before they decay into a proton and an electron.

Some examples of transmutations caused by neutron bombardment and capture:

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$$
$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U$$
$$^{59}_{27}Co + ^{1}_{0}n \rightarrow ^{60}_{27}Co$$

The Co-60 produced in the last reaction decays spontaneously by β and γ emission. Cobalt-60 is used as the gamma source for school radioactive specimens. By completely encasing the radioactive sample in plastic, the β particles are absorbed whereas the γ rays can penetrate through.

28.10 NUCLEAR FISSION AND FUSION

Artificial nuclear reactions can also be classified as either nuclear **fusion** or nuclear **fission**.

In nuclear fusion, the colliding particle unites with the parent and fuses (Latin *fusus* = 'melted', 'unite') into a single nucleus with a higher mass. Sometimes other small particles (n, p) are given off.

In nuclear fission, the lighter colliding particle makes the heavy parent more unstable and it fragments or fissions (Latin *fissus* = 'cleaved', 'split') into smaller nuclei and other particles.

Nuclear fusion

The alpha bombardment of nitrogen carried out by Rutherford in 1919 can be classed as a fusion reaction (Figure 28.12**(a)**):

$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}p$$

Another example of fusion is that occurring in the upper atmosphere and forms the basis of C-14 dating, as described earlier (Figure 28.12**(b)**):

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}H$$

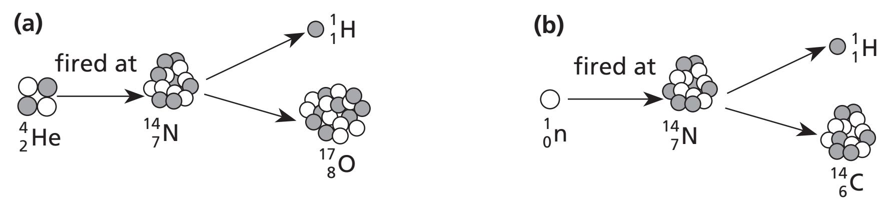


Figure 28.12
Nuclear fusion reactions.

In 1932 J. D. Cockcroft artificially accelerated protons and bombarded a lithium target. The following nuclear fusion reaction took place:

$$^{1}_{1}H + ^{7}_{3}Li \rightarrow ^{8}_{4}Be$$

Nuclear fission

The German scientists Otto Hahn and Fritz Strassman made an amazing discovery in 1938. When U-235 was bombarded with neutrons, sometimes smaller nuclei were produced, which were approximately half the size of the original, for example $^{136}_{56}Ba$ and $^{84}_{36}Kr$. They were baffled by this but Lisa Meitner and Otto Frisch (two Jewish physicists who escaped Nazi Germany in 1938 and were working in Scandanavia) quickly realised what happened. The U-235 nucleus absorbed the neutron to form a U-236 nucleus. Then, like a drop of water, it split into two roughly equal pieces (see Figure 28.13). They called it 'nuclear fission' because it reminded them of biological fission (cell division).

A tremendous amount of energy is released because the mass of U-235 is considerably greater than that of the fission fragments. In early 1940 when Germany was already at war, Hitler banned the sale of uranium from the Czech mines he had overrun. American physicists were alarmed that the Germans might be developing a bomb so the Allies began their own research in the USA (the 'Manhattan Project'), which culminated in the nuclear destruction of the two Japanese cities Hiroshima and Nagasaki, thus ending the Second World War.

To make this fission work, more neutrons must be released than are consumed so as to produce a **chain reaction**. The released neutrons go on to react with other U nuclei and so on. Figure 28.14 shows a four generation chain reaction.

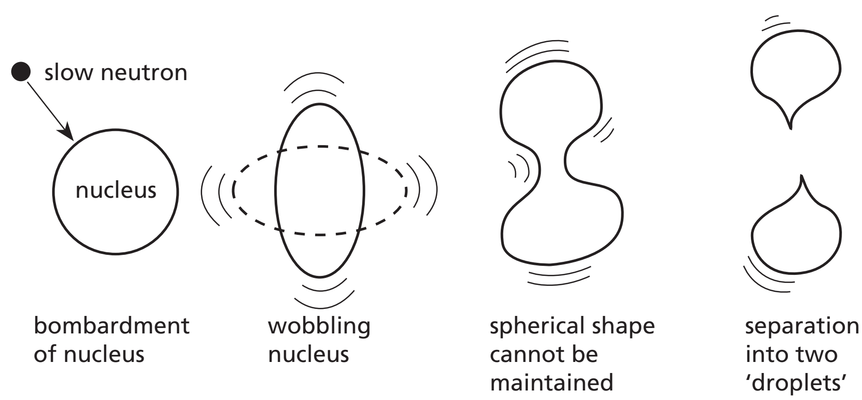


Figure 28.13
Liquid drop model of nuclear fission.

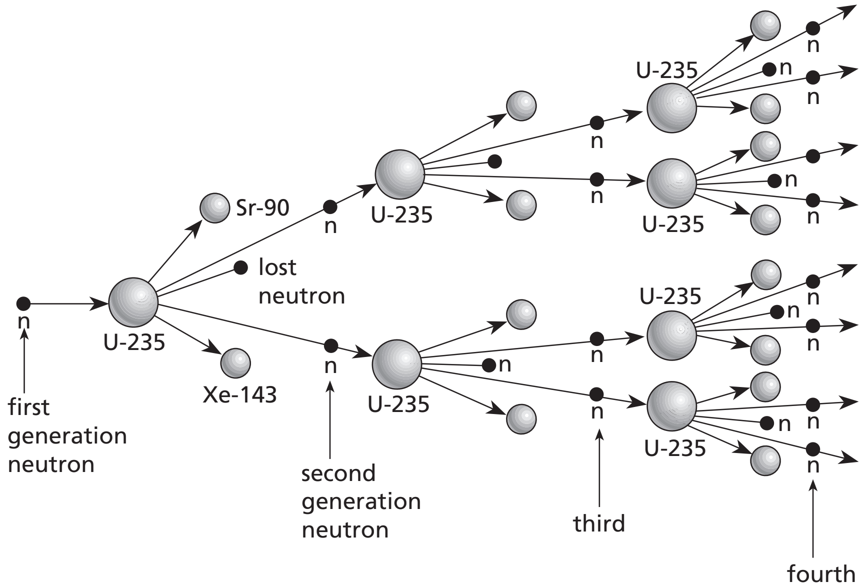


Figure 28.14
A chain reaction.

PHYSICS FACT

If you held a 10 kg lump of U-238 in your hand it would feel slightly warm. But if you found two separate 10 kg lumps of U-238 and brought them together you'd be blown apart and a crater 50 m deep would form.

In each generation the number of fissioning nuclei increases even though some neutrons do not go on to strike another U-235 atom. These are said to be 'lost'. In a nuclear reaction, a chain reaction is kept under control by absorbing excess neutrons with 'control rods' of substances such as cadmium.

Mass and energy in nuclear reactions

In 1905, long before the discovery of nuclear reactions, **Albert Einstein** (1879–1955), a German scientist who moved to the USA in 1933, published his now-famous special theory of relativity. This theory (discussed in Chapter 30) proposed that mass and energy are not separate quantities; rather, they are different forms of one another. The equation relating the two is:

$$E = mc^2$$

where:
m = change in mass or **mass defect** (kg) in a reaction
E = energy released or absorbed (J)
c = speed of light (3×10^8 m s^{-1}).

Example 1

If 1.0 g of a substance is converted completely into energy, how much energy is produced?

Solution

$$E = mc^2$$
$$E = 1.0 \times 10^{-3} \text{ kg} \times (3 \times 10^8)^2$$
$$= 9 \times 10^{13} \text{ J}$$

NOVEL CHALLENGE

Example 1 shows that, when 1 g of a substance is converted completely to energy, 9×10^{13} J is released. By comparison, the chemical energy released when 1 g of the explosive TNT is reacted is 4000 J, and when 1 g of petrol is burnt 30 000 J is released.

Comment on the following: '1 kg of uranium fuel releases 9×10^{16} J'.

Example 2

For the following U-235 fission reaction, calculate the energy released **(a)** per fission; **(b)** per kilogram of U-235 reacted.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{94}_{38}Sr + ^{139}_{54}Xe + 3^{1}_{0}n + \text{energy}$$

NOVEL CHALLENGE

The time it takes to hear a nuclear explosion was worked out by the Rand Corporation in 1968 (in the USA). The formula is: $t = 5.8 \times 10^{-19} R^{10} W^{-3}$ where t is the time in seconds to hear the explosion, W = the equivalent amount of TNT explosive in megatonnes, and R = the distance from the explosion in metres. Calculate how much time would elapse before you could hear a 1000 megatonne bomb at 500 m.

Solution (see Appendix 8 for masses.)

(a)
- Mass of reactants, m_r

U-235	235.043 94 u
neutron	1.008 665 u
total m_r	236.052 61 u

- Mass of products, m_p

Sr-94	93.9154 u
Xe-139	138.9184 u
3 neutrons	3 × 1.008 665 u
total m_p	235.859 8 u

- Mass defect, $\Delta m = |m_p - m_r| = 235.859\ 795\text{ u} - 236.052\ 61\text{ u} = 0.192\ 81\text{ u}$
- 1 u of mass = 1.66×10^{-27} kg
- Mass defect = $0.192\ 81 \times 1.66 \times 10^{-27} = 3.2 \times 10^{-28}$ kg

$$\begin{aligned} E &= mc^2 \\ &= 3.2 \times 10^{-28} \times (3 \times 10^8)^2 \\ &= 2.88 \times 10^{-11}\text{ J} \end{aligned}$$

(b) Mass of one U-235 atom = $235\text{ u} \times 1.66 \times 10^{-27}\text{ kg/u} = 3.90 \times 10^{-25}$ kg.

$$\text{Energy released by 1 kg} = 2.88 \times 10^{-11}\text{ J} \times \frac{1\text{ kg}}{3.90 \times 10^{-25}\text{ kg}} = 7.38 \times 10^{13}\text{ J.}$$

Questions

17 Calculate the energy released in the following fission reaction in **(a)** J per fission; **(b)** J per kg of U-235: ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{90}_{38}\text{Sr} + {}^{135}_{54}\text{Xe} + 11{}^{1}_{0}\text{n}$ + energy.

18 Which one of the following fusion reactions releases the most energy per fusion event?

(a) ${}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n}$.
(b) ${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + {}^{1}_{0}\text{n}$.
(c) ${}^{2}_{1}\text{H} + {}^{3}_{2}\text{He} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{1}\text{p}$.

In equation **(c)**, be careful to use the mass of the proton (${}^{1}_{1}\text{p}$), not the mass of a hydrogen atom (${}^{1}_{1}\text{H}$).

THE NUCLEUS AS A SOURCE OF POWER 28.11

One issue that has created more debate and social upheaval than any other is nuclear power. People want cheap electricity but they don't want nuclear power stations; they want good export income but they don't want to mine and sell uranium; and they want to be safe from foreign invaders but they don't want the atomic bomb. Common fears are:

- that a reactor might blow up like a uranium bomb
- that a reactor will suffer **meltdown**, the melting of the fuel core because of the heat generated by the fission process
- that radioactive gases will escape into the atmosphere, as did occur at Chernobyl
- that radioactive wastes have to be stored for millions of years
- that terrorists will steal uranium to make a bomb.

These are all real fears. They could all happen but to be able to debate these issues properly, you need to understand how the power of a nucleus can be tapped.

Chain reactions

A chain reaction is one in which the products of the reaction initiate further reactions. There are two types:

- controlled chain reactions — nuclear fission reactors
- uncontrolled chain reactions — the nuclear bomb.

Either way, the underlying nuclear reaction is similar to the one you saw before:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{90}_{38}Sr + ^{143}_{54}Xe + 3^{1}_{0}n + \text{energy}$$

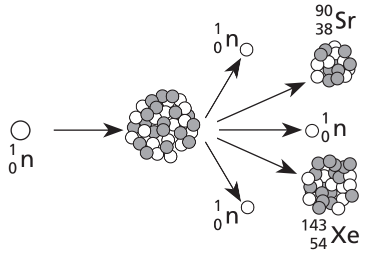


Figure 28.15
The nuclear fission of uranium-235.

Not only are Sr-90 and Xe-143 produced (Figure 28.15), but many different pairs of nuclei are produced, one usually bigger than the other. Examples of pairs are: $^{92}_{36}Kr$ and $^{141}_{56}Ba$; $^{85}_{35}Br$ and $^{148}_{57}La$; $^{94}_{38}Sr$ and $^{139}_{54}Xe$. There are hundreds of different combinations but you will notice that the sum of atomic numbers (the lower numbers) add up to 92 for each pair. But when the mass of the products is less than the mass of the reactants you know that the missing mass has been converted to energy. With the right technology this energy can be harnessed.

PHYSICS FACT

In 1903 Rutherford knew that energy was being slowly released by nuclear decay, and said that if you could speed it up you'd have a bomb. In 1914, writer H. G. Wells wrote the book *The World Set Free* where he described a world 42 years into the future (1956) where a nuclear bomb destroyed cities. He was most perceptive and way ahead of anyone else with his thinking.

28.12 NUCLEAR FISSION REACTORS

The first attempt to harness nuclear energy was in 1942 following a complex program of research involving the coordinated efforts of almost 100 000 scientists and technicians, headed by Enrico Fermi. It was a fission reactor built from 60 tonnes of uranium and about 400 tonnes of graphite blocks in a squash court under the stands of the football stadium at the University of Chicago.

There are basically two types of nuclear fission power reactors — the **thermal reactor** and the more modern but uncommon and far more complex **fast-breeder** reactor. Do we have either in Australia? You bet! Read on.

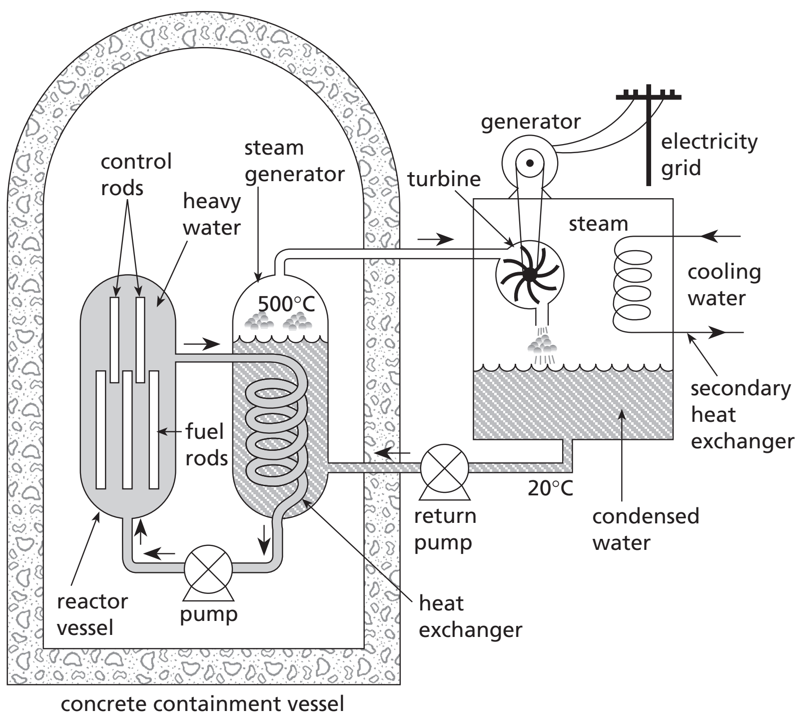


Figure 28.16
Schematic diagram of a typical pressurised water reactor in a thermal nuclear power station.

PHYSICS FACT

In 1950 Ford Motor Co. in the US proposed a nuclear-powered car called the 'Nucleon'. It was never built. Imagine your day trip to the beach. Stop off at the hospital on your way home for a bone marrow transplant.

The Australian Nuclear Science and Technology Organisation (ANSTO) has had a reactor working at its base in Lucas Heights, Sydney, since 1960 and is being replaced. This reactor is called HIFAR — 'High Flux Atomic Reactor'. The reactor is not used to generate electricity; rather, it is used to produce radioisotopes for medicine and industry and for nuclear research. There are no power reactors in Australia but there are hundreds in other countries throughout the world. One of the best sources for further information about the nuclear industry is the Uranium Information Centre's website at the address http://www.uic.com.au where dozens of briefing papers can be found.

Fuel

The fuel has to be a nuclide that undergoes nuclear fission, can sustain a chain reaction and release energy. U-235 is such a fuel. Uranium is mined as a low-grade ore (about 0.3% uranium) and after crushing, chemical treatment and concentration, it appears as uranium oxide (U_2O_3) or 'yellow cake'. This concentrate contains two isotopes, U-238 (99.3%) and U-235 (0.7%). To have a self-sustaining chain reaction, this nuclear fuel usually is **enriched** so that it has about 5% of the U-235 isotope. At Lucas Heights, they enrich theirs to a very high 50% U-235.

The rods are spread to allow the fuel to be cooled and the neutrons to be slowed down to thermal energies for maximum effect in the fission process. But some neutrons will leak away and be lost from the reactor core so the amount of uranium must be sufficiently large to compensate for the loss of neutrons. The minimum mass of uranium needed is called the **critical mass**. It is in the order of a few kilograms.

Moderator

To have a self-sustaining chain reaction, on average at least *one* neutron produced in each fission 'event' must go on to produce another fission. The average number that go on to produce further fissions is called the **multiplication factor**, f. If $f < 1$, the reaction will die out and is called **subcritical**. If, on the other hand, $f > 1$, the reaction is called **supercritical** and an uncontrolled 'run-away' explosion will take place, that is, a nuclear bomb. The aim is to have $f = 1$. Even though 2.4 neutrons are produced on average per fission event in a power reactor, 1.4 of them will be lost, leaving the one neutron to continue the reaction.

The neutrons released in fission of ^{235}U nucleus are very energetic; they have about 2 MeV of energy and are therefore fast-moving. Fast-moving neutrons are unlikely to interact and combine with a nucleus to initiate fission. Slower-moving neutrons are much more likely to be captured by a nucleus. It is important to slow down the fast neutrons from about 20 000 km s^{-1} to 2 km s^{-1}. These slow neutrons are called **thermal neutrons**. This reduction in speed is achieved by placing a **moderator** around the reactor core. To be effective, the moderator must have a mass very similar to the mass of a neutron, so that a neutron can lose maximum energy, in a single collision. The moderator must not absorb neutrons. Carbon (graphite), water, heavy water (D_2O), or liquid sodium are a few suitable moderators. In the Chernobyl accident, the graphite moderator actually caught fire.

Control rods

A reaction is started by placing a neutron source inside the core alongside the fuel rods. After the reaction starts, control is achieved by use of control rods containing neutron-absorbing material such as cadmium or boron steel. These substances have large nuclei so they can easily absorb the neutrons. For example, at Lucas Heights in Sydney, cadmium rods enclosed in a stainless steel coat are used. If the core is not reactive enough, the control rods are raised, which increases the neutron flux, thus accelerating the reaction. If the core becomes too reactive, the control rods are lowered. In 1942, Enrico Fermi had an assistant standing beside the rope that supported the control rods. He was armed with an axe and had orders to chop the rope if the reactor started to run away. The axe was never used, but is now in a museum.

Coolant

The **coolant** is a liquid that circulates through the reactor core to remove excess heat energy and stop it from overheating. Water is a good coolant but heavy water (deuterium oxide, D_2O) is normally used so that it can also act as a moderator.

As the coolant comes in contact with the fuel rods it too becomes radioactive so it cannot be allowed to escape to the atmosphere or down the drain. Instead the hot radioactive coolant is passed through a heat exchanger, where the heat is transferred to a secondary loop. Here, water is converted to steam to drive turbines and produce electricity.

Other forms of reactor use gas (for example, helium) as a coolant. In some cases where a coolant that does not slow down neutrons is required, molten sodium is used to cool the reactor core.

In the worst case scenario of a meltdown accident, the core would get so hot it would melt its way through the floor of the building and into the ground. It was often said that it would 'melt its way through to China', hence the title of the movie *The China Syndrome*. But as soon as the core hit the underground water table it would erupt like a volcano.

Reactor shielding

When in operation, reactor cores emit high levels of radiation harmful to humans. Consequently, the core must be isolated from other areas of the reactor to ensure human safety. This is achieved by use of a shield made from high density materials such as concrete and steel. To prevent any release into the atmosphere the buildings are usually airtight. However, the building at Chernobyl and at others of this design throughout the old Russian republic did not have a containment building. That's why the gases escaped so easily.

Reactor output

The power output of a reactor is measured in megawatts (MW), that is, 1 million joules per second (1 MJ s^{-1}). However, fission reactors have an efficiency of about 32% so they must generate 3000 MW of thermal energy to produce 1000 MW of electrical energy. Research reactors like the type at Lucas Heights only produce about 10 MW.

Fast breeder reactors: FBRs

Fast reactors depend on the fission of ^{239}Pu by fast neutrons. The fuel used is a 10% Pu-239 and 90% U-238 mixture usually extracted as a by-product from a normal thermal fission reactor. Because fast neutrons are used, no moderator is required and the core can be much more compact and operate at a higher temperature, so usually liquid sodium is used as a coolant. Fast neutrons strike U-238, causing a series of beta decays, which result in the production of Pu-239. Thus this reactor produces more of the fissionable Pu-239 material than it started with, hence the name 'breeder'. The problem with FBRs is that the Pu-239 is extremely toxic and has a very long half-life. Secondly, liquid sodium reacts violently with water or air so the engineers must be very careful with the design specifications and control systems.

Uncontrolled fission: the atomic bomb

Fission weapons are relatively uncomplicated. Scientists working on the uranium bomb that was dropped on Hiroshima didn't even test it beforehand. The fission or *atomic* bomb consists of a cannon-like tube with a chemical explosive at one end and two subcritical masses of U-235. To allow safe transportation, the two pieces of fuel must be below critical mass and when detonation is to take place, the two subcritical pieces of almost pure U-235 are fired together. In the bomb dropped on Nagasaki, a ball of subcritical Pu-239 lumps formed the

PHYSICS FACT

Before the two bombs were dropped on Japan at the end of the Second World War, 'Trinity' tests were undertaken.
A plutonium bomb was exploded in the New Mexico desert (USA) on 16 July 1945. A crater 350 m diameter was formed and windows 300 km away were shattered. Three weeks later similar bombs were ready for deployment in Japan. 'Little Boy' was dropped on Hiroshima on 6 August 1945. It was 3 m long, 75 cm diameter, weighed 4.1 tonnes and had an explosive power equivalent to 12 700 tonnes of TNT. It was released at an altitude of 9500 m and at 2100 m the explosive charge detonated, making the uranium go 'critical'. By 580 m, 43 seconds had elapsed and the whole thing exploded in a few millionths of a second. 'Fat Man' was dropped on Nagasaki on 9 August 1945. It was 3.5 m long, 1.5 m diameter and weighed 4.5 tonnes. It was equivalent to 22 350 tonnes of TNT. Japan surrendered the next day.

core. Around the outside of this ball was a layer of chemical explosive, which compressed the plutonium and made it go critical (Figure 28.17).

A nuclear power plant can't explode like a nuclear bomb because the concentration of U-235 is too low. In a reactor, the concentration is only about 3% whereas in a bomb it is enriched to about 90%.

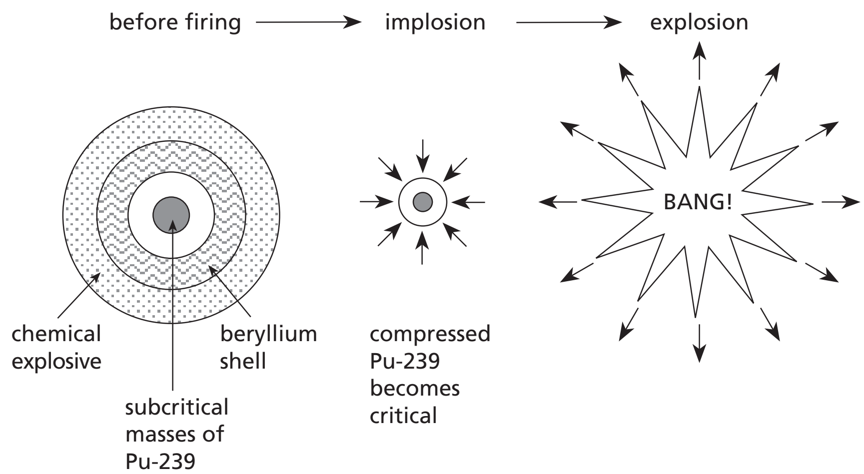


Figure 28.17
An atomic explosion.

Activity 28.4 CRITICAL EVALUATION

SR

1. Enrico Fermi found out in 1939 that uranium could be split into two fragments to release huge amounts of energy. He said it was lucky that nuclear fission had not been discovered five years earlier. What did he mean by this and what possible consequences could have arisen?
2. Students often say that moral questions about the use of physics for weapons should not be discussed in class. Develop some points for and against this comment.

NUCLEAR WASTE PRODUCTS 28.13

The biggest problem for supporters of nuclear power generation is what to do with the wastes and how to convince the public that the wastes can be disposed of safely.

Types of waste

Radioactive waste may be gas, liquid or solid. It is usual to classify it into one of three levels, depending on how radioactive it is:

Low-level waste This waste consists primarily of protective clothing, used wrappers, worn out or damaged plant, and water from showers where protective clothing is washed. It is usually just above the limit that regulations define as radioactive.

Medium-level waste This waste consists of irradiated fuel containers, reactor components and old sealed sources returned from hospitals and industry.

High-level waste This waste comes from fuel reprocessing and contains most of the fission products from the spent fuel and remains quite hot. It contains small amounts of U-235, U-238, Pu-239 and Sr-90.

Disposal

Disposal involves the confinement, isolation and sometimes cooling of the wastes so that they are harmless to the environment. Unlike coal- or oil-fired power plants, which spread their gaseous waste and residues over large areas, nuclear waste is small in volume. The unfortunate part is that the waste is so dangerous.

Unlike many other wastes, nuclear waste will decay in time to become harmless, depending on its half-life. Sr-90 has a half-life of 28 years; Pu-239, 24 400 years. After about 1000 years, however, the wastes have decayed to about the same activity as the original ore body — about 100 gigabecquerel (10^{11} Bq). Some people say 'Why not put it in a rocket and send it to the Sun?' The amount of energy and money required makes this commercially non-viable.

Storage

There are several thousand cubic metres of waste being stored at about 50 different sites throughout Australia. Half is low-level waste. Throughout the world, research continues into safe disposal sites, such as a long way underground, under the sea bed or fusing it with clay to make ceramic beads (e.g. Synroc). At present, ANSTO has accumulated 1600 highly radioactive, highly enriched spent fuel rods at Lucas Heights and is storing them underground in concrete wells until they can convince the United States to take them back for reprocessing. Because only 5% of the original uranium-235 is used up, reprocessing will recover the remaining 95% for reuse. ANSTO has only been able to get rid of some spent fuel rods to Scotland in 1963 and 450 to South Carolina in 1987. Greenpeace accuses ANSTO of not having a decent disposal option for this waste, which is growing at the rate of 36 rods per year and even more when (if?) the new reactor gets built. The idea of burying it is a problem, says Greenpeace, as one cost estimate of a permanent repository is US$17 billion.

NOVEL CHALLENGE

A letter-writer to the *Courier Mail* suggested that we could deflect an approaching asteroid with a nuclear bomb. Propose several reasons why this would not be appropriate.

PHYSICS FACT

An old engineering proverb goes: 'Faster, better, cheaper. Choose two of the above'.
Is this only funny to engineers?

NEI Activity 28.5 NOTHING IS FOOLPROOF FROM FOOLS

The International Atomic Energy Agency (IAEA) argues that nuclear materials, properly handled, are very safe. They suggest that only 17 nuclear accidents have occurred worldwide since 1945 with a total of only 59 deaths (by comparison with about 60 road deaths per week Australia-wide).

Nuclear accidents can be classified as follows:

Radiation accidents (not involving a nuclear reactor) The most publicised have been in Morocco (1984), where eight people died after one person took some radiography isotope home for his mantlepiece; and in Goiania, South America (1986), where people took glowing Cs-137 home in their pockets from a radiotherapy unit — 4 dead, 249 contaminated.

Nuclear power reactor accidents Examples are at Three Mile Island, USA (1979) — partial melting of the core; and at Chernobyl (1986) — 100 000 people evacuated after the graphite moderator caught fire.

Either

1 Write a two-page report about a nuclear accident (including one of the above, if you like).

  (a) Describe what went wrong from a nuclear physics viewpoint.

  (b) Describe the long-term environmental effects.

  (c) Discuss whether the benefits of nuclear technology outweigh the environmental effects.

or

2 Design a public survey to discover what people in your local community know about the issues involved in nuclear energy. Conduct a small survey and analyse the results. Submit a full report: introduction, methodology, results, analysis, conclusion.

NOVEL CHALLENGE

Poet W. H. Auden wrote in his poem *Marginalia*:

No tyrant ever fears
His geologists or his engineers.

What do you suspect he meant by this? What evidence would he need to substantiate this claim?

NUCLEAR FUSION 28.14

Nuclear fusion is the process in which two small nuclei join together to produce a larger nucleus and a release of energy.

The dream of producing a sustainable and controlled nuclear fusion on Earth is one that scientists have had for fifty years. Nuclear fusion powers the Sun and it powers the hydrogen bomb but trying to get it working in a controlled fashion here on Earth is a difficult task. For two small nuclei to fuse, we have to overcome their massive electrostatic repulsions. It normally takes more energy to do this than could ever be released, so very careful selection of nuclei is needed.

The first release of energy from a fusion reaction was in 1932, when Cockcroft and Watson demonstrated the following reaction:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6 \text{ MeV}$$

The energy comes from the high binding energy per nucleon of the very stable helium nucleus compared with the smaller binding energy per nucleon of deuterium $^{2}_{1}H$ and tritium $^{3}_{1}H$. Other fusion reactions that form helium nuclei include:

- $^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n + 3.3$ MeV
- $^{2}_{1}H + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}p + 18.3$ MeV

Since some mass has had to be converted to energy, this will be accompanied by an equivalent mass decrease. The energy is normally given off in the form of gamma rays.

High temperature fusion

The British physicist Sir Arthur Eddington (1882–1944) first suggested in 1920 that the Sun might produce all of its energy by nuclear fusion. In 1930 Dr Hans Bethe, an American scientist, gave a clear indication of how this process could work.

At the core of the Sun the temperature is about 100 million °C. The temperature and pressure are high enough to enable hydrogen atoms to fuse together to form helium atoms. As the gamma rays that are produced move outward through the Sun they heat the surrounding gas. At the Sun's surface the temperature is about 6000°C. Although the reaction occurs in a number of steps, the process can be represented as:

$$4^{1}_{1}H \rightarrow ^{4}_{2}He + 2^{\ 0}_{+1}e + \gamma + \text{neutrino } (\nu)$$

The energy produced is 26.72 MeV when the four hydrogen atoms react. About 26.2 MeV is carried off by the gamma rays and about 0.5 MeV by the neutrinos. Every second, 4 million tonnes of hydrogen is converted to helium in the Sun, providing the energy that makes life on Earth possible.

NOVEL CHALLENGE

Two new heavy nuclides have been prepared recently. Work out what they are from these incomplete equations: $^{249}_{98}Cf + ^{12}_{6}C \rightarrow 4^{1}_{0}n + ?$; and $^{242}_{94}Pu + ^{22}_{10}Ne \rightarrow 4^{1}_{0}n + ?$

Fusion reactors

High temperatures and pressures like those found inside the Sun are needed to sustain nuclear fusion. There are two major problems associated with this:

- How do we reach this high temperature and maintain it?
- How do we contain the fuel, since most containers would melt well before 100 million degrees C is reached?

For the construction of fusion power reactors the reactions mentioned earlier involving deuterium and tritium seem to be promising. There is a vast supply of deuterium available in ordinary water, particularly in sea water. Therefore, there is no scarcity of fuel for fusion reactors.

In order for the particles to come close enough to fuse together, the deuterium or tritium atoms must have very high kinetic energy (high speed), sufficient to overcome the Coulomb repulsion. Such high speed can be achieved by heating the gas to a temperature of 100 million °C. At such high temperatures, gas contains electrons and positive ions and is called 'plasma' (Figure 28.18).

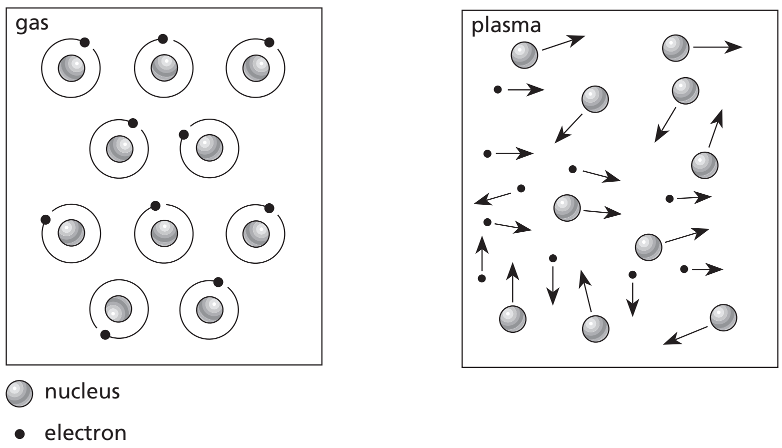
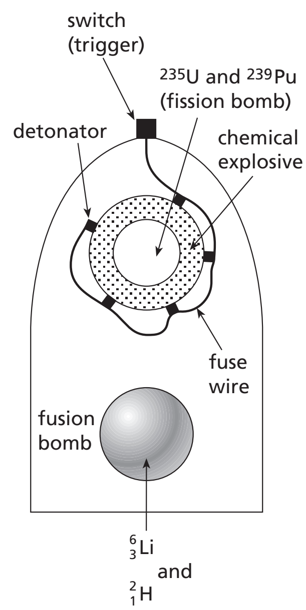


Figure 28.18
In gas, the electrons orbit the nuclei. In plasma, the electrons are separated from the nuclei.

Figure 28.19
The H-bomb is ignited by a fission bomb.



Uncontrolled fusion

The energy of fusion has been harnessed for destructive purposes in the form of the **hydrogen bomb** (Figure 28.19). This type of bomb is technically more advanced than the fission bomb and potentially more devastating.

To obtain the high temperatures and pressures required for fusion, the H-bomb begins with a fission explosion. The fission neutrons combine with Li-6 to form tritium, and when the temperature is hot enough, the tritium atoms fuse with the deuterium atoms in an uncontrolled fusion reaction. The H-bomb has never been detonated in anger. The first successful detonation was in 1952 in the United States when it was said that the explosion was 'brighter than a thousand suns'. (See Photo 28.2.)

NEI Activity 28.6 NUCLEAR UNCLEAR

1. Prepare a table showing the similarities and differences of a thermal fission reactor, a research reactor (e.g. ANSTO's HIFAR), an FBR, a fusion reactor and a coal-fired power station. Some headings you could use are: fuel, moderator, control rods, power output, wastes, but there are others.
2. Use an encyclopedia to find the meaning of: yellowcake, Synroc, Candu reactor, trefoil symbol, tokamak.

Questions

19 Greenpeace has said that having ships take spent fuel rods back to the United States through the waters of the South Pacific would be like 'floating Chernobyls'. What do they mean?

20 Australia mines uranium for sale overseas but won't allow nuclear power reactors to be built here. It seems hypocritical — but is it? The government says that by being a part of the nuclear community we have control over what happens to the uranium. Prepare a short statement with your argument for or against this policy.

Photo 28.2
The first fusion bomb (known as 'Mike') was exploded on 31 October 1952. During Operation Ivy, Mike yielded 10.4 megatonnes (TNT equivalent) and was reported to be 'brighter than a thousand suns'.

BIOLOGICAL EFFECTS OF RADIATION 28.15

Nuclear radiation is everywhere. It has been a part of the natural environment since the Earth was formed some 4 billion years ago. We cannot feel it but in high doses its effects can be devastating. When ionising radiation (α, β, γ, X-rays and neutrons) passes through tissue, it can interfere with the DNA, causing it to split up. When the DNA replicates (makes copies of itself) it can get 'confused' and produce defective cells. All people who deal with ionising radiation should be aware of the consequences.

However, not all radiation effects are the same. Different types of radiation have different ionising and penetrating powers. Hence, the effects on human tissue will also be different. You could ask: would you rather be hit by a truck moving at 10 km/h, a motorbike going at 100 km/h or a bullet going at 1000 km/h? All three do damage but in different ways. Alpha radiation is made up of heavy, relatively slow moving particles but is more intensely ionising over a very short distance than beta, gamma or X-rays. Even though it cannot penetrate the outer layers of the skin, it can be inhaled as a dust or get into open cuts in the skin. Then it is very dangerous as it can move around in the blood and migrate to the brain and lungs — a deadly result.

Beta particles have a lower risk as they can be stopped by a few millimetres of tissue and are not very strongly ionising. Nevertheless they can cause skin burns. Because gamma and X-rays are highly penetrating, they can pass deep into the body and cause great damage. For example, when you have an X-ray, the radiation passes right through you to the photographic film behind. Gamma is like the bullet.

In summary, radiation may result in:

- the death of the cell
- prevention of cell division
- permanent modification to the cell.

Questions

21 Find out how cobalt-60 actually kills cells. Why doesn't irradiation of the patient make the patient radioactive?

22 Prepare a case for or against the use of radioactive sources in school physics laboratories.

MEASURING RADIATION — DOSIMETRY 28.16

Because there are so many different factors affecting the radiation dose, there are several different ways of measuring it.

Absorbed dose (D)

When ionising radiation interacts with matter, some of its energy is transferred to the absorbing material, such as the tissues of the body. Radiation that deposits one joule of energy per kilogram of tissue is called the **absorbed dose**. It has the units J kg^{-1} or 1 **gray** (Gy).

For example, if a 50 kg person absorbed 100 J of radiation energy, this absorbed dose would be 100 J/50 kg = 2 J kg^{-1} or 2 Gy. This could make you very sick but would probably not be fatal. If a 20 kg child absorbed the same energy, the dose would be 100 J/20 kg = 5 Gy, which would probably be fatal.

Dose equivalent (H)

The amount of damage 1 Gy of absorbed dose can do depends on the nature of the radiation. For example, alpha particles are 20 times more damaging to tissue than X-rays, gamma rays or beta particles. To quantify the potential damage of radiation, physicists use weighting to reflect the biological impact. These weightings are called **quality factors** (QF) and are shown in Table 28.9.

Table 28.9

RADIATION	QUALITY FACTOR (QF)
heavy nuclei	20
fusion fragments	20
alpha	20
neutrons <10 keV (slow)	5
10 keV – 100 keV	10
100 keV – 2 MeV (fast)	20
2 MeV – 20 MeV	10
>20 MeV	5
protons	5
beta	1
gamma photons	1
X-ray photons	1

A measure of the radiaion dose that combines the amount of radiation (in J/kg) with the quality factor (QF) is called the 'dose equivalent' and is measured in a unit called **sievert** (Sv).

Dose equivalent = absorbed dose × quality factor
or $H = D \times QF$

For example, if an absorbed dose of 2 Gy was from an alpha source, the dose equivalent would be 2 Gy times a QF of 20 = 40 Sv. This is a big dose and would probably be fatal (>6.5 Sv is lethal). It is common to use millisievert (mSv) or microsievert (μSv). In Australia, the average annual background radiation dose is about 2 mSv.

28.17 RADIATION RISKS TO YOUR HEALTH

Radiation is all around us. It comes from the ground, from space (cosmic radiation) and can be from artificial sources such as medical X-rays and nuclear bomb testing such as the French did in the Pacific Ocean. Non!

The effective 'whole body' *dose limits* established by the International Commission for Radiological Protection for artificial sources are:

- radiation workers: 20 mSv (100 mSv averaged over 5 years and maximum of 50 mSv in any one year)
- members of the public: 1 mSv annual average over lifetime; maximum of 5 mSv in any one year; pregnant woman (abdomen) 13 mSv/3 months; foetus 1 mSv/9 months.

The effects of ionising radiation on the body are summarised in Table 28.10.

INVESTIGATING

No new nuclear reactors have been built in the USA since 1972 and the number operating has dropped from 146 to 143 over recent years.
How does this compare with the UK, France and Indonesia?

Table 28.10 EFFECTS OF IONISING RADIATION ON THE BODY

EXPOSURE (Sv)	EFFECT
High (3–6 Sv)	severe sickness with up to 100% deaths for 4.5 Sv and over
Medium (1–3 Sv)	slight to moderate sickness; recovery complete within 3 months; delayed effects may shorten life by a few percent
Low (0–1 Sv)	No sickness; person unaware of any biological changes

Activity 28.7 WHAT'S YOUR POISON?

You can work out your total annual radiation dose by summing the various sources. What does your annual dose come to? Is this dangerous? See Table 28.11.

Table 28.11

SOURCE	AVERAGE ANNUAL DOSE (μSv)	LOCAL VARIATIONS
Cosmic radiation	300	+200 μSv per 100 m of altitude
		+ 20 μSv per 10° of latitude
		+ 20 μSv per hour of flying time
		+1000 μSv per day in a space station
Rocks	600	−150 μSv if you live in a wooden house
Food and drink	300	Nil
Air (breathing)	700	Nil
Manufactured source	100	+ 30 μSv for nuclear testing
		+ 20 μSv if you watch TV and use the computer for about 15 hrs/week
Medical	0	See medical treatment, Table 28.12
Your total	2000	

Table 28.12 MEDICAL TREATMENT

PROCEDURE		DOSE (μSv)
X-rays:	Chest	30
	Leg	20
	Dental	140
	Head	70
	Intestine	3 000
	Mammography	400
CAT scan:	Head	1 800
	Abdomen	7 200
Radiopharmaceutical drugs:		
	Bone scan	5 000
	Thyroid scan	2 000
	Lung scan	800
	Brain scan	1 200
	Heart scan	17 000
	Tumour therapy	22 000
	Thyroid therapy	8 000 000
Your total dose due to medical treatment:		

1 Calculate the annual dose for an airline pilot who lives in a wooden house in Brisbane (latitude 28°) at an altitude of 100 m and makes 200 return flights to Sydney in a year. He had a chest X-ray after swallowing a fish hook and a mouth X-ray for an impacted wisdom tooth.

2 Why is altitude a factor in determining dose? Is this related to airline flights being listed as a hazard?

For further information see Chapter 33, 'Medical Physics'.

INVESTIGATING

The international symbol for nuclear disarmament made up of the semaphore (flag) signals for N and D is shown in the following figure.

What part of the symbol is N and which part is D?

PHYSICS FACT

Radon gas (from bricks and other earthy materials) causes between 7000 and 30 000 of the 130 000 lung cancer deaths in the USA per year (Environmental Protection Agency estimate, 2001).

NOVEL CHALLENGE

A person receives a dose of 0.3 mGy of slow neutrons, 6 mGy of gamma rays and 0.1 mGy of fast neutrons. How many millisieverts is this?

28.18 APPLICATIONS OF NUCLEAR TECHNOLOGY

Uses of nuclear technology include more than just nuclear power and radioactive dating. Here are some other uses:

Food and medical equipment irradiation Within a year of Roentgen's discovery of X-rays in 1895, physicists were proposing that food be irradiated to kill off microbes. By 1921 patents had been given for irradiation of meat to destroy parasites. Later, in 1931, it was being used to kill off bacteria and preserve food indefinitely.

Gamma radiation and high energy X-rays can be used to prolong the shelf-life of foods by slowing the ripening process and stopping the sprouting of vegetables like potatoes and onions. Although the food does not become radioactive, irradiation can cause physical and chemical changes in the food. When molecules are split by nuclear radiation, the fragments are called **radiolytic** products (Greek *lysis* = 'to split'). Although 50 years of research has shown irradiation to be useful and generally safe, there is concern that these radiolytic substances could be carcinogenic (cancer-forming).

To date, in Australia and New Zealand, only herbs and spices and some tropical fruits have been approved to be irradiated (for sanitary reasons) and to a maximum dose of 1 kGy. The tropical fruits include breadfruit, carambola (star fruit), custard apple, lychee, longan (dragon's eye lychee), mango, mangosteen, papaya and rambutan. Food that has been irradiated must be labelled with a statement that says it has been treated with ionising radiation.

Medical equipment has been sterilised with gamma rays for years. If you look on a syringe packet it will probably say that it has been gamma irradiated and sealed with the gas ethylene oxide inside.

PHYSICS FACT

ANSTO scientists measured the U/Pb ratio in Gold Coast beach sand. They found it was Precambrian sand from the Antarctic 600 million years old.

INVESTIGATING

In the nuclear power plant accident at Tokaimura, one worker — Mr Hisashi Ouchi — received 18 Sv of radiation and spent 3 months in hospital. Normally, anything greater than 5 Sv is fatal.
So how come he survived?

Questions

23 **(a)** List the arguments for and against food irradiation.
(b) Do you think Australians should be allowed to eat irradiated foods? Give reasons.
(c) How can we easily check that irradiated foods do not have any residual radioactivity?
(d) List the arguments for and against the irradiation of medical products.
(e) Do you think medical supplies should be irradiated by the manufacturers before they are placed on the market? Won't they become radioactive?
(f) How is this different from the food irradiation argument?

Industrial radiography Gamma rays can be used to examine the interior of solid objects such as the welds in natural gas pipelines (Figure 28.20).

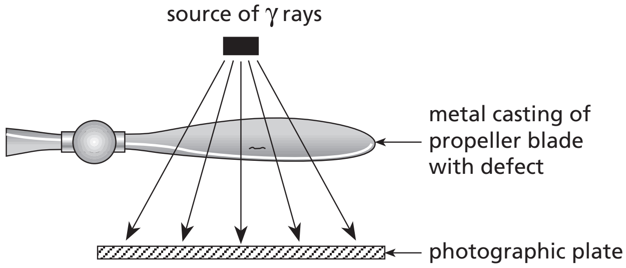


Figure 28.20 Detection of flaws inside metal parts.

Neutron radiography Slow neutrons are fired at an object and, depending on the presence of elements like hydrogen, cadmium and boron, a clear image of the internal structure can be obtained in much the same way that X-ray images are taken. These atoms are strong absorbers of slow neutrons and are remarkable in the detail they can show. Common uses are to detect flaws in gas turbine blades, corrosion of aircraft components and the presence of explosives in luggage.

Gauging Radiation has its intensity reduced by matter placed between the source and a detector. By measuring the radiation through a plastic film, its thickness can be monitored as it comes out of the rollers and adjusted to maintain a thickness of incredible uniformity (Figure 28.21). In Australia, the thickness of paper, felt, steel and glass are areas where radioactive gauging is also used.

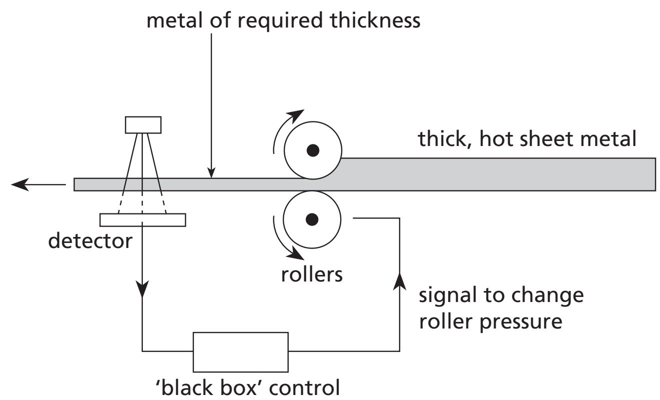


Figure 28.21
Use of radiation to monitor the thickness of sheet metal.

PHYSICS FACT

British nuclear physicist James Chadwick was a slum boy from Manchester. He did his postdoctoral research under Rutherford and later went to Berlin. When the Second World War broke out, he was taken prisoner by the Germans. While in the prisoner of war camp, he ordered special toothpaste from the Berlin Auer Company which had radioactive thorium in it to make teeth glow. He extracted the thorium and used it to continue his nuclear experiments while in the POW camp. In 1932 Chadwick discovered the neutron. That's what you call persistence.

Neutron activation analysis (NAA) This is used in forensic science to match soil and hair from crime scenes to suspects. Australia has become a world leader in this field.

Neutron transmutation doped silicon (NTDS) This is a process used to produce the 'doped' silicon for silicon chips in the computer industry. Bombardment of silicon with neutrons produces phosphorus:

$$^{28}_{14}Si + 3^{1}_{0}n \rightarrow ^{31}_{15}P + ^{0}_{-1}e$$

By controlling the intensity of the radiation, a transmutation of 1 in every 10^8 atoms can be achieved — just the right amount for N-type semiconductors. This is a big income earner for ANSTO and for Australia.

Medical applications These are among the most important uses of radiation and radioactivity. They are discussed in Chapter 33.

EI Activity 28.8 SMOKE DETECTORS

Smoke alarms in homes operate on the principle of ionisation. A radioactive source of americium-241, with a half-life of over 7000 years, emits alpha particles that ionise air particles in a chamber. When smoke enters the chamber, the ionisation changes and an alarm sounds.

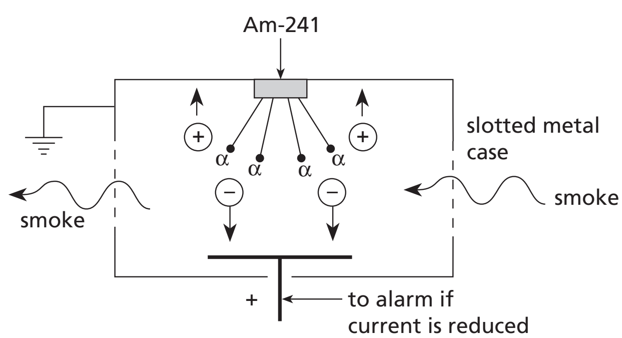


Figure 28.22
A smoke detector.

1 Examine a smoke detector and, by unscrewing the cover, look at the components. Can you identify the ionisation chamber? Don't open it! Blow some smoke from a candle into it — did the alarm sound? How long did it take?

2 Hold a Geiger counter near it. Can you detect radiation? If not, why?

3 Is there any warning about the Am-241? Is it clear to a non-physics student that it is dangerous? Are there sufficient instructions about how to dispose of it once it stops working?

4 If you replaced the battery regularly, would the detector be good for thousands of years? Explain.

Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Review — applying principles and problem solving

***24** What element is represented by X in each of the following: **(a)** $^{233}_{92}X$; **(b)** $^{2}_{1}X$; **(c)** $^{226}_{88}X$; **(d)** $^{32}_{15}X$?

***25** What elements are formed by the radioactive decay as shown in each of the following?
(a) $^{24}_{11}Na(\beta^-)$. **(b)** $^{22}_{11}Na(\beta^+)$. **(c)** $^{210}_{84}Po(\alpha)$. **(d)** $^{32}_{15}P(\beta^-)$.

***26** Complete the following nuclear reactions:
(a) $^{234}_{91}Pa \rightarrow {}^{234}_{92}U + ?$
(b) $^{?}_{?}Rn \rightarrow {}^{218}_{84}Po + \alpha$.

***27** A certain nuclide, represented by $^{b}_{a}X$, ejects an α-particle followed by an emission of a β-particle. Use Y and Z as daughter symbols and write two nuclear equations to represent the process.

***28** Complete the following nuclear equations:
(a) $^{11}_{5}B + {}^{4}_{2}He \rightarrow {}^{14}_{7}N + ?$
(b) $^{23}_{11}Na + {}^{1}_{0}n \rightarrow ?$
(c) $^{27}_{13}Al + {}^{2}_{1}H \rightarrow {}^{4}_{2}He + ?$
(d) $? + {}^{4}_{2}He \rightarrow {}^{42}_{20}Ca + {}^{1}_{1}H$
(e) $? + {}^{1}_{0}n \rightarrow {}^{27}_{12}Mg + {}^{1}_{1}H$
(f) $? + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$

***29** The fission fragment Sr-96 undergoes four successive β^- emissions before a stable nucleus is formed. What is the stable nucleus formed?

***30** For the isotope carbon-14:
(a) write the equation for its beta-minus decay;
(b) determine the mass loss per atom of carbon-14 in kg;
(c) determine the energy change for this process.

****31** Indium-116 decays by beta-minus decay to tin-116. The atomic masses are 115.905 53 u for indium-116 and 115.901 79 u for tin-116. **(a)** Write the equation for the beta-minus decay of indium-116. **(b)** Determine the mass loss in kg per atom of indium-116. **(c)** Determine the energy change for this process.

****32** Can C-14 dating be used to measure the age of stone walls and tablets of ancient civilisations?

****33** Carbon-14 was used to date a medieval linen sample. Calculate how old it was if it had a C-14 : C-12 ratio that was only 1.56% of the expected living tissue ratio.

****34** Some rocks in your neighbourhood show that their percentage of uranium-236 is 67% of what you expected. If $t_{\frac{1}{2}}$ for U-236 is 2.39×10^7 years, calculate the age of the rocks.

****35** The half-life of a cobalt-60 source used for food irradiation is 5.26 years.
(a) If the original activity of a working sample is 500 GBq, what is the activity after 2.63 years?
(b) If it is not safe to dispose of it until its activity is less than one-thousandth of its original activity, calculate how many half-lives this is.

****36** Iridium-192 is used in the treatment of early cancer of the breast. It has a half-life of 74 days. If initially there is 3.6 mg of the isotope present, what time will elapse before it has been reduced to **(a)** 0.90 mg; **(b)** 0.25 mg?

****37** Iodine-131, used for destroying malignant tumours of the thyroid, has a half-life of 8.07 days. **(a)** What is its disintegration constant? **(b)** If the activity of I-131 is 5×10^{10} Bq, how many iodine atoms are present? **(c)** How many days will elapse before its activity is 1 MBq?

****38** Immediately after a ${}^{238}_{92}U$ nucleus decays to ${}^{234}_{90}Th + {}^{4}_{2}He$, the daughter thorium nucleus still has 92 electrons circling it. Since thorium normally holds only 90 electrons, what do you suppose happens to the two extra ones?

****39** Design an experiment to measure how much liquid is in a can without opening it. *Hint:* alpha radiation would not be suitable for this experiment. Why not?

****40** The activity of a sample of a beta-emitting phosphorus nuclide was measured and the count was corrected for background radiation. The results were as shown in Table 28.13.

Table 28.13 A RADIOACTIVITY COUNT

TIME ELAPSED (h)	ACTIVITY (min^{-1})
0.0	36 506
0.5	31 501
0.75	29 268
1.0	27 106
2.0	20 244
5.0	8 256
10.0	1 913
13.0	800
18.0	181

Plot ln *A* vs *t* for these data and determine the half-life of the phosphorus.

****41** One of the long-term effects from a nuclear explosion is the radioactive fallout. If all 3.0×10^6 radioactive fission nuclei were spread evenly among the human population (5 billion), how many radioactive nuclei would each human breathe in? Why is this not a realistic calculation?

****42** The following is a problem regularly faced by scientists and engineers in the nuclear industry. You have to dispose of some low-level nuclear waste and you must choose from three types of storage containers (Table 28.14).

Table 28.14 NUCLEAR WASTE MANAGEMENT

CONTAINER	COST OF ONE BOX ($)	VOLUME OF ONE BOX (m^3)	LIFE OF ONE BOX (y)
Steel and lead box	500	2	10
Steel and plastic box	1000	2	100
Carbon fibre box	2400	2	1000

You have to dispose of 30 m^3 of waste by burying it in boxes until its activity reaches the low level of 600 Bq/kg of waste. Initially the 'hot' waste has an activity of 10 500 Bq/kg and has a half-life of 12 years.

(a) How many years have to pass before the activity falls to 600 Bq/kg?
(b) How many containers do you need?
(c) Which container would you choose? Why?
(d) What is the total cost of your containers?
(e) Would the operation have any other costs?
(f) If the containers leaked, who would you blame?

Extension — complex, challenging and novel

****43** For the reaction: $4\,^{1}_{1}H \rightarrow \,^{4}_{2}He + 2\,^{0}_{+1}e$:

(a) calculate the energy released when four $^{1}_{1}H$ nuclei fuse;

(b) calculate the energy released when 1 kg of $^{1}_{1}H$ fuses.

****44** **(a)** Which one of the following produces the most energy per kilogram of reactant?

(i) $^{239}_{94}Pu + \,^{1}_{0}n \rightarrow \,^{137}_{52}Te + \,^{100}_{42}Mo + 3\,^{1}_{0}n$ (See Appendix 7 for masses.)

(ii) $2\,^{2}_{1}H \rightarrow \,^{4}_{2}He$

(b) State whether the above reactions are fusion or fission.

*****45** In the carbon cycle that occurs on the Sun, He-4 is built from four protons and C-12. First, C-12 absorbs a proton to form a nucleus, X_1. Then X_1 decays by positron emission to X_2, which then absorbs a proton to become X_3, which itself absorbs a proton to become X_4. X_4 then decays to X_5 by positron decay and X_5 reacts via: $X_5(p,\alpha)X_6$.

(a) Determine the formulas of X_1 to X_6 by writing out complete balanced nuclear equations.

(b) Sum the six reactions and write a balanced net reaction.

*****46** The Sun radiates 3.9×10^{23} J of energy into space every second.

(a) Calculate how much mass is lost per second on the Sun.

(b) If the Sun has a mass of 2×10^{30} kg, calculate how many years will elapse before the Sun has lost 50% of its mass.

*****47** Nuclear fission of U-235 releases about 3.5×10^{-11} J per fission event. Calculate this as J per kg of U-235 reacted and calculate how many times greater it is than the combustion of methane, which releases 50 MJ per kg.

*****48** The Earth receives 1.8×10^{14} kJ per second of solar energy. **(a)** What mass of solar material is converted to energy over a 24 hour period to provide the daily amount of solar energy to the Earth? **(b)** If coal releases 32 kJ of energy per gram, what mass of coal would have to be burnt to provide this same amount of energy?

*****49** An unstable isotope disintegrates by beta decay to form a stable product. In an experiment to determine its half-life, the following data were collected at the same time each school day (Table 28.15). *Note:* better results are obtained by measuring the time taken for a certain count. In this case 2000 counts were made. Background radiation = 13 counts per minute.

Table 28.15 DECAY DATA FOR QUESTION 49

DAY	TIME FOR 2000 COUNTS
Mon	1 min 16 s
Tue	1 min 39 s
Wed	2 min 10 s
Thurs	2 min 51 s
Fri	3 min 40 s
Mon	8 min 28 s
Tue	10 min 15 s
Wed	13 min 48 s
Thurs	17 min 33 s
Fri	22 min 59 s

(a) Calculate the observed activity and then the actual activities by subtracting background activity.

(b) Calculate the half-life by a graphical method. *Hint:* watch the 'time elapsed'; there are some days when no data were taken (who'd go to school at the weekend?).

*****50** Radioactive gold-198, which has a half-life of 2.7 days, is routinely used by ANSTO for detecting movement of substances through the environment. It was once suspected that the high concentration of aluminium in the brains of Alzheimer's patients was from using aluminium saucepans for cooking. Devise a procedure using Au-198 to measure the movement of saucepan metal into the brains of Alzheimer's patients.

*****51** A 70 kg patient receives a 10 second dose of gamma radiation from a 3.7×10^{13} Bq cobalt-60 source. The gamma rays have an energy of 1.25 MeV (1 MeV = 1.6×10^{-13} J). Only 2% of the radiation reaches the patient and only 50% of that is absorbed; the rest just passes through. Show that the effective dose is 0.011 Gy.

*****52** In a fast breeder reactor, U-238 is bombarded with a nuclear particle and turns into U-239, which promptly decays into Pu-239 by several steps. Deduce the full set of reactions for the FBR.