Outcome
On completion of this area of study, you should be able to explain and model relevant physics ideas to describe the sources and uses of nuclear reactions and radioactivity and their effects on living things, the environment and in industry.

By the end of this chapter should be able to describe
• The origin, nature and properties of $\alpha$, $\beta$ and $\gamma$ radiation
• The detection of $\alpha$, $\beta$ and $\gamma$ radiation
• stable, unstable, natural and artificial isotopes
• production of artificial radioisotopes
• the half-life of a radioactive isotope
• radiation doses from internal and external sources
• effects of $\alpha$, $\beta$ and $\gamma$ radiation on humans and other organisms
• nuclear transformations and decay series.
1.1 Atoms, isotopes and radioisotopes

Atoms

In order to understand radioactivity, it is necessary to be familiar with the structure of the atom. The central part of an atom, the nucleus, consists of particles known as protons and neutrons. Collectively, these particles are called nucleons, and are almost identical in mass and size. They have very different electrical properties.

- Protons have a positive charge
- Neutrons are electrically neutral and have no charge.

The nucleus contains nearly all of the mass of the atom, but accounts for less than a million millionth ($10^{-12}$) of its volume. Most of an atom is empty space that is only occupied by negatively charged particles called electrons. These are much smaller and lighter than protons or neutrons and they orbit the nucleus of the atom at high speed.

A particular atom can be identified by using the following format:
Isotopes

All atoms of a particular element will have the same number of protons, but may have a different number of neutrons. For example, lithium

Isotopes are chemically identical to each other. They react and bond with other atoms in precisely the same way. The number of neutrons in the nucleus does not influence the way in which an atom interacts with other atoms.

When referring to a particular nucleus, we talk about a nuclide.

Radioisotopes

Most of the atoms that make up the world around us are stable. Their nuclei have not altered in the billions of years since they were formed and, on their own, they will not change in the years to come.

However, there are also naturally occurring isotopes that are unstable. An unstable nucleus may spontaneously lose energy by emitting a particle and so change into a different element or isotope. Unstable atoms are radioactive and an individual radioactive isotope is known as a radioisotope.

Most of the elements found on Earth have naturally occurring radioisotopes; there are about 200 of these in all. As well as these, about 2000 radioisotopes have been manufactured. During the 20th century, an enormous number of radioisotopes were produced in a process known as artificial transmutation.
Artificial transmutation: how radioisotopes are manufactured

Natural radioisotopes were used in the early days of research into radiation. Today, most of the radioisotopes that are used in industrial and medical applications are synthesised by artificial transmutation.

One of the ways that artificial radioisotopes are manufactured is by neutron absorption. (In Australia, this is done at the Lucas Heights reactor near Sydney.)

A stable isotope is placed inside a nuclear reactor and bombarded with neutrons. When a neutron collides with a nucleus of the stable isotope, the neutron is absorbed into the nucleus. This creates an unstable isotope of the sample element.

The heaviest stable isotope in the universe is $^{209}_{83}$Bi, Bismuth. Every isotope of every element with more than 83 protons, i.e. beyond bismuth in the periodic table, is radioactive.

**Worked example 1.1A**

Use the periodic table in Figure 1.6 to determine:

a) the symbol for element $^{42}_{95}$X

b) the number of protons, nucleons and neutrons in this isotope.

Now complete Questions 1 to 10 of Section 1.1
1.2 Radioactivity and how it is detected

About 100 years ago, Ernest Rutherford and Paul Villard discovered that there were three different types of emission from radioactive substances.

They named these **alpha**, **beta** and **gamma radiation**. Further experiments showed that the alpha and beta emissions were actually *particles* expelled from the nucleus.

Gamma radiation was found to be high-energy *electromagnetic radiation*, also emanating from the nucleus.

*When these radioactive decays occur, the original atom spontaneously changes into an atom of a different element.*

**Alpha decay** \( \frac{4}{2} \alpha \)

When a heavy nucleus undergoes radioactive decay, it may eject an alpha particle. An alpha particle is a *positively* charged chunk of matter.

It consists of two protons and two neutrons that have been ejected from the nucleus of a radioactive atom.

An alpha particle is identical to a **helium nucleus** and can also be written as \( \frac{4}{2} \alpha, \alpha^{2+}, \frac{4}{2} He^{2+}, \) or simply \( \alpha \).

**EXAMPLE**

Uranium-238 is radioactive and may decay by emitting an alpha particle from its nucleus.

This can be represented in a nuclear equation in which the changes occurring in the nuclei can be seen.

\[
^{238}_{92}U \rightarrow ^{234}_{90}Th + \frac{4}{2}\alpha + \text{energy}
\]

or

\[
^{238}_{92}U \rightarrow ^{234}_{90}Th
\]

In the decay process, the *parent nucleus* \(^{238}_{92}U\) has spontaneously emitted an alpha particle (\(\alpha\)) and has changed into a completely different element, \(^{234}_{90}Th\). Thorium-234 is called the *daughter nucleus*. The energy released is mostly kinetic energy carried by the fast-moving alpha particle.

*When an atom changes into a different element*, it is said to have undergone a **nuclear transmutation**. In nuclear transmutations, electric charge is conserved (92 = 90 + 2). The number of nucleons is also conserved (238 = 234 + 4).
Beta decay $\_{-1}^0\beta$

Beta particles are electrons, but they are electrons that have originated from the nucleus of a radioactive atom, not from the electron cloud. A beta particle can be written as $\_\beta e$, $\beta^-$, or $\_1^0\beta$. The atomic number of -1 indicates that it has a single negative charge, and the mass number of zero indicates that its mass is far less than that of a proton or a neutron.

Beta decay occurs in nuclei in which there is an imbalance of neutrons to protons. Typically, if a light nucleus has too many neutrons to be stable, a neutron will spontaneously change into a proton, and an electron and an uncharged massless particle called an antineutrino are ejected to restore the nucleus to a more stable state.

Consider

The nuclear equation for this decay is:

$$\_{\beta}^{14}C \rightarrow \_{\gamma}^{14}N + \_\beta e + \nu$$

The transformation taking place inside the nucleus is:

$$\_n \rightarrow \_p + \_0e + \sigma$$

Once again, notice that in all these equations the atomic and mass numbers are conserved. (The antineutrino has no charge and has so little mass that both its atomic and mass numbers are zero.)

Gamma decay $\gamma$

Generally, after a radioisotope has emitted an alpha or beta particle, the daughter nucleus holds an excess of energy. The protons and neutrons in the daughter nucleus then rearrange slightly and off-load this excess energy by releasing gamma radiation (high-frequency electromagnetic radiation). Symbol is $\gamma^\circ$. Being a form of light, gamma rays travel at the speed of light.

A common example of a gamma ray emitter is iodine-131. Iodine-131 decays by beta and gamma emission to form xenon-131 as shown below.

The equation for this decay is:

$$\_{\beta}^{131}I \rightarrow \_{\gamma}^{131}Xe + \_0e + \gamma$$

or

$$\_{\beta\gamma}^{131}I \rightarrow \_{\gamma}^{131}Xe$$

Since gamma rays carry no charge and have almost no mass, they have no effect when balancing the atomic or mass numbers in a nuclear equation.

The table below shows the 272 stable nuclides, as well as some radionuclides and decay modes.
From this table of stable isotopes and radioisotopes, it is evident that for larger nuclei there is a distinct imbalance between the number of protons and neutrons. The 'line of stability' of the stable nuclides can be seen as a line that curves away from the $N$ $Z$ line. Notice that every element, up to and including bismuth, has stable isotopes, except for technetium and promethium. Also notice that every isotope of every element beyond bismuth is radioactive.
Why radioactive nuclei are unstable

Inside the nucleus there are two completely different forces acting. The first is an electric force of repulsion between the protons. The second is the nuclear force, a strong force of attraction between nucleons, which acts only over a very short range.

In a stable nucleus, there is a delicate balance between the repulsive electric force and the attractive nuclear force.

For example,

Bismuth-209, the heaviest stable isotope, has 83 protons and 126 neutrons, and the forces between the nucleons balance to make the nucleus stable.

Bismuth-211. It has two extra neutrons and this upsets the balance between forces. The nucleus of $^{211}\text{Bi}$ is unstable and it ejects an alpha particle in an attempt to attain nuclear stability.

From the 'line of stability' above

Small nuclei with atomic numbers up to about 20, the ratio of neutrons to protons is close to one.

As the nuclei become bigger, so too does the ratio of neutrons to protons.

Zirconium (Z 40) has a neutron to proton ratio of about 1.25, while for mercury (Z 80) the ratio is close to 1.66.

This indicates that for higher numbers of protons, nuclei must have even more neutrons to remain stable. These neutrons dilute the repelling forces that act between the extra protons. Elements with more protons than bismuth (Z 83) simply have too much repulsive charge and additional neutrons are unable to stabilise their nuclei. All of these atoms are radioactive.

How radiation is detected

Our bodies cannot detect alpha, beta or gamma radiation. Therefore a number of devices have been developed to detect and measure radiation.

A common detector is the Geiger counter. These are used to audibly monitor the amount of radiation the count is heard as a 'click'. People who work where there is a risk of continuing exposure to low- level radiation usually pin a small radiation-monitoring device to their clothing, which will monitor their dosage over a short period (i.e. Monthly) and make sure they don't acquire more than their yearly dose.

Film badges are used by doctors, radiologists, dentists and technicians who work with radiation, to monitor their exposure levels.

Now complete Questions 1 to 10 of Section 1.2
1.3 Properties of alpha, beta and gamma radiation

Alpha particles, beta particles and gamma rays all originate from the same place (the nucleus) and have enough energy to dislodge electrons from the atoms and molecules that they smash into. This property is what makes radiation dangerous, but it also enables it to be detected.

*The properties of alpha, beta and gamma radiation are distinctly different from each other.*

**Alpha particles**

Alpha particles, $\alpha$, consist of two protons and two neutrons so it is relatively heavy and slow moving. It is emitted from the nucleus at speeds of up to $20 \,000 \text{ km s}^{-1} \ (2.0 \times 10^7 \text{ m s}^{-1})$; just less than 10% of the speed of light ($3 \times 10^8 \text{ m s}^{-1}$).

**Beta particles**

Beta particles, $\beta$, are fast-moving electrons, created when a neutron decays into three particles: a proton; an electron (beta-particle) and antineutrino. Beta particles are much lighter than alpha particles, and so they leave the nucleus with higher speeds up to 90% of the speed of light.

**Gamma rays**

Gamma rays, $\gamma$, being electromagnetic radiation with a very high $10^8 \text{ m s}^{-1}$ or $300 \,000 \text{ km s}^{-1}$. They have no electric charge. Their high energy and uncharged nature make them a very penetrating form of radiation. Gamma rays can travel an almost unlimited distance through air and even a few centimetres of lead or a metre of concrete would not completely absorb a beam of gamma rays.

**The ionising abilities of alpha, beta and gamma radiation**

When an *alpha particle* travels through air, its slow speed and double positive charge causes it to interact with just about every atom that it encounters. The alpha particle dislodges electrons from many thousands of these atoms, turning them into ions. Each interaction slows it down a little, and eventually it will be able to pick up some loose electrons to become a helium atom. This takes place within a centimetre or two in air. As a consequence, the air becomes quite ionised, and the alpha particles are said to have a **high ionising ability**. Since the alpha particles don’t get very far in the air, they have a **poor penetrating ability**.

*Beta particles* have a negative charge and are repelled by the electron clouds of the atoms they interact with. This means that when a beta particle travels through matter, it experiences a large number of glancing collisions and loses less energy per collision than an alpha particle. As a result, beta particles are **less ionising** but will be **more penetrating**.
**Gamma rays** have no charge and move at the speed of light, and so are the most highly penetrating form of radiation. Gamma rays interact with matter infrequently, in the unlikely event when they collide directly with a nucleus or electron. Gamma rays pass through matter very easily so they have a **poor ionising ability** but a **high penetrating ability**.

**The energy of α, β and γ radiation**

The energy of moving objects such as cars and tennis balls is measured in joules. However, alpha, beta and gamma radiations have such small amounts of energy that the joule is inappropriate. The energy of radioactive emissions is usually expressed in **electronvolts** (eV). An **electronvolt** is the energy that an electron would gain if it were accelerated by a voltage of 1 volt.

---

Alpha and beta particles are ejected from unstable nuclei with a wide range of energies.

**Alpha particles** typically have energies of 5–10 million electronvolts (5–10 MeV).

**Beta particles** are usually ejected with energies up to a few million electronvolts. For example, sodium-24 emits beta particles with a maximum energy of 1.4 MeV. This is equivalent to 2.24 \(10^{-13}\) J.

**Gamma rays** normally have less than a million electronvolts of energy. They may even have energy as low as 100 000 electronvolts. Increasing the energy of a gamma ray does not increase its speed; it increases the frequency of the radiation.

**Example:**

Calculate the energy of these particles in MeV:

a) an alpha particle with energy \(1.4 \times 10^{-12}\) J

b) a beta particle with energy \(6.7 \times 10^{-14}\) J

c) a gamma ray with energy \(8.0 \times 10^{-14}\) J
Summary

(a) Alpha particle

(b) Beta particle

(c) Gamma ray

Figure 1.19 The relative speeds of alpha, beta and gamma radiation. (a) Alpha particles are the slowest of the radioactive emissions. Typically they are emitted from the nucleus at up to 10% of the speed of light. (b) Beta particles are emitted from the nucleus at speeds up to 90% of the speed of light. (c) Gamma radiation, being high-energy light, travels at the speed of light (3.0 × 10^8 m s^-1).

Figure 1.20 Gamma rays can pass through human tissue and sheets of aluminium quite readily. A 5 cm thick sheet of lead is needed to stop 97% of the gamma rays in a beam. By comparison, alpha particles are not capable of penetrating through a sheet of paper or beyond the skin of a person.

Table 1.1 The properties of alpha, beta and gamma radiations

<table>
<thead>
<tr>
<th>Property</th>
<th>α particle</th>
<th>β particle</th>
<th>γ ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>heavy</td>
<td>light</td>
<td>none</td>
</tr>
<tr>
<td>Charge</td>
<td>+2</td>
<td>-1</td>
<td>none</td>
</tr>
<tr>
<td>Typical energy</td>
<td>~5 MeV</td>
<td>~1 MeV</td>
<td>~0.1 MeV</td>
</tr>
<tr>
<td>Range in air</td>
<td>a few cm</td>
<td>1 or 2 m</td>
<td>many metres</td>
</tr>
<tr>
<td>Penetration in matter</td>
<td>~10^-2 mm</td>
<td>a few mm</td>
<td>high</td>
</tr>
<tr>
<td>Ionising ability</td>
<td>high</td>
<td>reasonable</td>
<td>poor</td>
</tr>
</tbody>
</table>

Now complete Questions 1 to 10 of Section 1.3
Discussion

Each year, dozens of people in Australia die as a result of domestic fires. Evidence has shown that the installation of a smoke detector can reduce the risk of dying in a house fire by about 60%. For this reason, new houses are required to contain at least one smoke detector. Domestic smoke detectors contain a small radioactive source. The radiotrace commonly used is americium-241, an artificial isotope which is produced in the core of a nuclear reactor. Americium-241 emits alpha particles and low-energy gamma rays. The penetrating ability of the alpha particles is so poor that they are stopped by the case of the detector. Some gamma rays will escape into the room, but they have such low energy (~60 keV) that exposure to them is insignificant when compared with the level of background radiation. As well as this, the detectors are usually located in the ceiling, some distance from people, and this distance further reduces the intensity of the radiation.

A smoke detector contains a pair of oppositely charged low-voltage metal electrodes. When the alpha particles pass between these electrodes, they ionize the air molecules that are present. These ions are then attracted to the electrodes. However, when smoke (or steam) is present, the ions attach themselves to the smoke particles. The flow of charges to the electrodes reduces greatly because these charged smoke (or steam) particles are much bigger and so much less mobile than the ionized air molecules. It is this reduction in the flow of charges reaching the electrodes that triggers the alarm.

Monitoring the thickness of sheet metal

Beta particles can be used to monitor the thickness of rolled sheets of metal and plastic during manufacture. A beta particle source is placed under the newly rolled sheet and a detector is placed on the other side. If the sheet is being made too thick, fewer beta particles will penetrate and the detector count will fall. This information is instantaneously fed back to the rollers and the pressure is increased until the correct reading is achieved, and hence the right thickness is attained.

Would alpha particles or gamma rays be appropriate for this task? Alpha particles have a very poor penetrating ability, so none of them would pass through the metal. Gamma rays usually have a high penetrating ability and so a thin metal sheet would not stop them. Workers would also need to be shielded from gamma radiation. You can see that the penetrating properties of beta rays make them ideal for this job. The thickness of photographic film and coatings on metal surfaces are also monitored in this way.
1.4 Half-Life and activity of Radioisotopes

Different radioisotopes will emit radiation and decay at very different rates. For Example, Consider Polonium and Radium.

(a) The emissions from polonium-218 only last for a relatively short time. Its activity decreases very rapidly.
(b) The emissions from a sample of radium-226 remain steady for a very long time. Its activity does not change significantly.

To explain this, you need to know that radionuclides are unstable but to different degrees. Consider again the sample of polonium-218. If the sample initially contains 100 million undecayed polonium-218 nuclei

During one half-life, the number of nuclei of the radioisotope sample decreases by half (i.e. by 50%). After two half-lives, only one-quarter (25%) of the original radioisotope nuclei will remain.

The decay rate of a radioisotope is measured in terms of its half-life \( t_{1/2} \). The HALF-LIFE of a radioisotope is the time that it takes for half of the nuclei of the sample radioisotope to decay spontaneously.

The half-life of polonium-218 is 3 minutes.

It is important to appreciate that although the behaviour of a large sample of nuclei can be predicted, it is impossible to predict when any one particular nucleus will decay. The decay of the individual nuclei in a sample is random. It is rather like throwing dice. If 60 dice are thrown, on
average, 10 will roll up ‘6’. You just don’t know which ones!

Figure 1.25 The amount of the original isotope halves as each half-life passes. This is an exponential relationship and the mathematical relationship that describes it is shown.

The half-lives of some common radioisotopes are shown in Table 1.2. The half-life of a radioisotope is a factor in its application.

For example, most medical applications using a radioisotope as a tracer require a short half-life. This is so that radioactivity does not remain in the body any longer than necessary.

However, the radioisotope used in a smoke detector is chosen because of its long half-life. The detector can continue to function for a very long time, as long as the battery is replaced each year.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Emission</th>
<th>Half-life</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polonium-214</td>
<td>α</td>
<td>0.00016 s</td>
<td>Nothing at this time.</td>
</tr>
<tr>
<td>Strontium-90</td>
<td>β</td>
<td>28.8 y</td>
<td>Cancer therapy</td>
</tr>
<tr>
<td>Radium-226</td>
<td>α</td>
<td>1630 y</td>
<td>Once used in luminous paints</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>β</td>
<td>5730 y</td>
<td>Carbon dating of fossils</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>α</td>
<td>700 000 y</td>
<td>Nuclear fuel, rock dating</td>
</tr>
<tr>
<td>Uranium-238</td>
<td>α</td>
<td>4.5 billion y</td>
<td>Nuclear fuel, rock dating</td>
</tr>
<tr>
<td>Thorium-232</td>
<td>α</td>
<td>14 billion y</td>
<td>Fossil dating, nuclear fuel</td>
</tr>
<tr>
<td>Artificial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technetium-99m</td>
<td>γ</td>
<td>6 h</td>
<td>Medical tracer</td>
</tr>
<tr>
<td>Sodium-24</td>
<td>γ</td>
<td>15 h</td>
<td>Medical tracer</td>
</tr>
<tr>
<td>Iodine-131</td>
<td>γ</td>
<td>8 d</td>
<td>Medical tracer</td>
</tr>
<tr>
<td>Phosphorus-32</td>
<td>β</td>
<td>14.3 d</td>
<td>Medical tracer</td>
</tr>
<tr>
<td>Cobalt-60</td>
<td>γ</td>
<td>5.3 y</td>
<td>Radiation therapy</td>
</tr>
<tr>
<td>Americium-241</td>
<td>α</td>
<td>460 y</td>
<td>Smoke detectors</td>
</tr>
<tr>
<td>Plutonium-239</td>
<td>α</td>
<td>24 000 y</td>
<td>Nuclear fuel, rock dating</td>
</tr>
</tbody>
</table>

Activity

A Geiger counter records the number of radioactive decays occurring in a sample each second. This is the activity of the sample.

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

where \( n \) = no. of half-lives

\( N_0 \) = original amount

\( N \) = final amount
Over time, the activity of any sample of a radioisotope will decrease.

This is because more and more of the radioactive nuclei have decayed and will no longer emit radiation. So after one half-life, the activity of any sample will be reduced by half. If the sample of polonium-218, discussed previously, has an initial activity of 2000 Bq, then after one half-life (i.e. 3 minutes) its activity will be 1000 Bq. After 6 minutes, the activity of the sample will have reduced to 500 Bq and so on.

*Short-lived radioisotopes have an initially high activity. Their nuclei decay at a fast rate and so the sample lasts only for a short time. High-activity samples are extremely dangerous and must be handled with great caution.*

**Decay series**

Generally, when a radionuclide decays, its daughter nucleus is not completely stable, and is itself radioactive. This daughter will then decay to a grand-daughter nucleus, which may also be radioactive, and so on. Eventually a stable isotope is reached and the sequence ends. This is known as a decay series.

Four naturally occurring decay series remain active. These are:

- The uranium series in which uranium-238 eventually becomes lead-206
- The actinium series in which uranium-235 eventually becomes lead-207
- The thorium series in which thorium-232 eventually becomes lead-208
- The neptunium series in which neptunium-237 eventually becomes bismuth-209. (Since neptunium-237 has a relatively short half-life, it is no longer present in the crust of the Earth, but the rest of its decay series is still continuing.)

Geologists analyse the proportions of the radioactive elements in a sample of rock to gain a reasonable estimate of the rock’s age. This technique is known as rock dating.
Worked example 1.4A

A sample of the radioisotope thorium-234 contains $8.0 \times 10^{12}$ nuclei. The half-life of $^{234}$Th is 24 days. How many thorium-234 atoms will remain in the sample after:

a) 24 days?
b) 48 days?
c) 96 days?

Worked example 1.4B

In 2 hours, the activity of a sample of a radioactive element falls from 240 Bq to 30 Bq. What is the half-life of this element?
1.5 Radiation dose and its effect on humans

Ionising radiation

The term radiation is widely used and widely misunderstood. There are many different forms of radiation and the degree of danger that they present depends on their ability to interact with atoms. Some radiation has enough energy to interact with atoms, removing their outer-shell electrons and creating ions. For this reason, these radiations are known as ionising radiations. As was discussed in Section 1.3, alpha particles, beta particles and gamma rays are all ionising.

<table>
<thead>
<tr>
<th>Table 1.3 Summary of the different ionising and non-ionising types of radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionising radiation [high energy]</td>
</tr>
<tr>
<td>Non-ionising radiation [low energy]</td>
</tr>
</tbody>
</table>

The background level of ionising radiation to which we are continually exposed is not a significant health problem. However, exposure to above-average levels of ionising radiation is dangerous.

Measuring radiation exposure

1. Absorbed dose

When a person is exposed to high-energy radiation, the energy of the radiation acts to break apart molecules and ionise atoms in the person’s body cells. The severity of this exposure depends on the amount of radiation energy that has been absorbed by the individual’s body. This quantity is known as the absorbed dose. The absorbed dose is the radiation energy that has been absorbed per kilogram of the target material.

\[
\text{ABSORBED DOSE} = \frac{\text{energy absorbed by tissue}}{\text{mass of tissue}}
\]

\[
\text{ABSORBED DOSE is measured in joules/kilogram (J kg}^{-1}\text{) or grays (Gy), i.e. } 1 \text{ Gy} = 1 \text{ J kg}^{-1}.
\]

To illustrate this, if a 25 kg child absorbed 150 J of radiation energy, then the absorbed dose would be 6 Gy. This is a massive dose and would be enough to kill the child within a few weeks. However, an adult, being much larger, would be less severely affected by this radiation. If a 75 kg adult absorbed 150 J of radiation energy, the absorbed dose would be just 2 Gy. This dose would give the adult a severe case of radiation sickness but would probably not be fatal. You can think of dose in the same way as one administers medicine. The small mass of a child means that taking just half a tablet might be equivalent to an adult taking two tablets.
2 Dose equivalent

Different forms of radiation have different abilities to ionise, and so cause different amounts of damage as they pass through human tissue.

This means a weighting of the biological impact of the radiation is needed. This is called the quality factor. A list of quality factors is shown in Table 1.4.

A measure of radiation dose that takes into account the absorbed dose and the type of radiation will give a more accurate picture of the actual effect of the radiation on a person. This is the dose equivalent. Dose equivalent is measured in sieverts (Sv).

\[ \text{Dose equivalent} = \text{absorbed dose} \times \text{quality factor} \]

Dose equivalent is measured in sieverts (Sv).

For example, an absorbed dose of just 1 Gy of alpha radiation is biologically equally as damaging as an absorbed dose of 20 Gy of beta radiation.

<table>
<thead>
<tr>
<th>Radiation source</th>
<th>Average annual dose (μSv)</th>
<th>Local variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic radiation</td>
<td>300</td>
<td>Plus 200 μSv for each round-the-world flight. Plus 20 μSv for each 10° of latitude. Plus 150 μSv if you live 1000 m above sea level.</td>
</tr>
<tr>
<td>Rocks, air and water</td>
<td>1350</td>
<td>Plus 1350 μSv if you live underground. Plus 1350 μSv if your house is made of granite. Minus 140 μSv if you live in a weatherboard house.</td>
</tr>
<tr>
<td>Radioactive foods and drinks</td>
<td>350</td>
<td>Plus 1000 μSv if you have eaten food affected by the Chernobyl fallout.</td>
</tr>
<tr>
<td>Manufactured radiation</td>
<td>60</td>
<td>Plus 60 μSv if you live near a coal-burning power station. Plus 30 μSv from nuclear testing in the Pacific. Plus 20 μSv if you watch 20 hours of TV on a CRT television set each week.</td>
</tr>
<tr>
<td>Medical exposures</td>
<td>–</td>
<td>Plus 30 μSv for a chest X-ray. Plus 300 μSv for a pelvic X-ray. Plus 1000 μSv if you have had a 'barium milkshake' ulcer examination. Plus 40 000 000 μSv for a course of radiotherapy using cobalt-60.</td>
</tr>
</tbody>
</table>
Worked example 1.5A

A 10 g cancer tumour absorbs 0.0020 J of energy from an applied radiation source.

a) What is the absorbed dose for this tumour?
b) Calculate the dose equivalent if the source is an alpha emitter.
c) Calculate the dose equivalent if the source is a gamma emitter
d) Which radiation source is more damaging to the cells in the tumour?

3 Effective dose

The different organs of the body have different sensitivities to radiation doses. For example, if a person's lung was exposed to a dose of 10 mSv, it would be more than twice as likely that cancers would develop than if the same 10 mSv dose was delivered to the liver. The weightings assigned by the International Commission of Radiological Protection (ICRP) to the various organs in shown in Table 1.7.

<table>
<thead>
<tr>
<th>Body part</th>
<th>Weighting, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ovaries/testes</td>
<td>0.20</td>
</tr>
<tr>
<td>Bone marrow</td>
<td>0.12</td>
</tr>
<tr>
<td>Colon</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Stomach</td>
<td>0.12</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.05</td>
</tr>
<tr>
<td>Breast</td>
<td>0.05</td>
</tr>
<tr>
<td>Liver</td>
<td>0.05</td>
</tr>
<tr>
<td>Oesophagus</td>
<td>0.05</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.05</td>
</tr>
<tr>
<td>Rest of body</td>
<td>0.07</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
</tr>
</tbody>
</table>
The effects of radiation

When ionising radiation passes through human tissue, it may ionise atoms and molecules in the body cells, which can lead to the development of cancerous cells. If at all possible, exposure to ionising radiation should be avoided. When alpha, beta or gamma radiation passes through a body cell, it may turn one of the molecules in the cell into an ion pair; for example, if the radiation ionises a water molecule, then a hydrogen ion and a hydroxide ion will be formed. These ions are highly reactive and can attack the DNA that forms the chromosomes in the nucleus of the cell. This can cause the cell to either die or divide and reproduce at an abnormally rapid rate. When the latter occurs, a cancerous tumour may form.

Exposure to ionising radiation can lead to both somatic and genetic effects.

**Somatic**

Depending on the radiation dose, somatic effects can vary from feelings of nausea to severe illness and even death.

**Genetic**

If a person's reproductive cells are damaged by radiation, genetic abnormalities may arise in future generations.