CHAPTER 17

Applications of nuclear physics and the standard model of matter

An understanding of the nucleus has led to large science projects and many applications

Introduction

This chapter will focus on the practical applications of nuclear reactions and alpha, beta and gamma radioisotopes. Later, the development and the basic features of the standard model of matter, including quarks, will complete the module 'From Quanta to Quarks'.

17.1 An application of nuclear fission reactions—a typical fission reactor

■ *Explain the basic principles of a fission reactor*

Chapter 16 described the principle and conditions needed for a controlled nuclear fission reaction. Such a reaction can be used primarily to produce energy or act as a rich source of neutrons to initiate nuclear transmutation reactions. The diagram in Figure 17.1 shows how a nuclear power plant is designed to utilise the energy produced by the controlled fission reaction to produce electricity.

As shown in Figure 17.1, a typical nuclear power plant consists of three parts:

1. The **reactor core**, where the fission reaction takes place. It contains fuel rods and control rods embedded in the moderator. The control rods are able to be moved up or down freely in order to control the rate of the fission reaction. This was described in Chapter 16.
2. The **heat exchanger**. This is where the heated coolant circulates out of the nuclear reactor core (also known as the **primary coolant**) and heats water to make steam, which is in turn used to operate the generator to produce electricity. The primary coolant then circulates back into the reactor core to carry away more energy and the cycle repeats. The primary coolant from the nuclear core forms a closed loop, and thus does not mix with the steam. This design minimises the transfer of nuclear waste from the reactor to the generator, reducing the chance of the nuclear waste leaking out into the environment.

NOTE: Recall that examples of materials that may be used as primary coolant include molten sodium or molten sodium chloride.

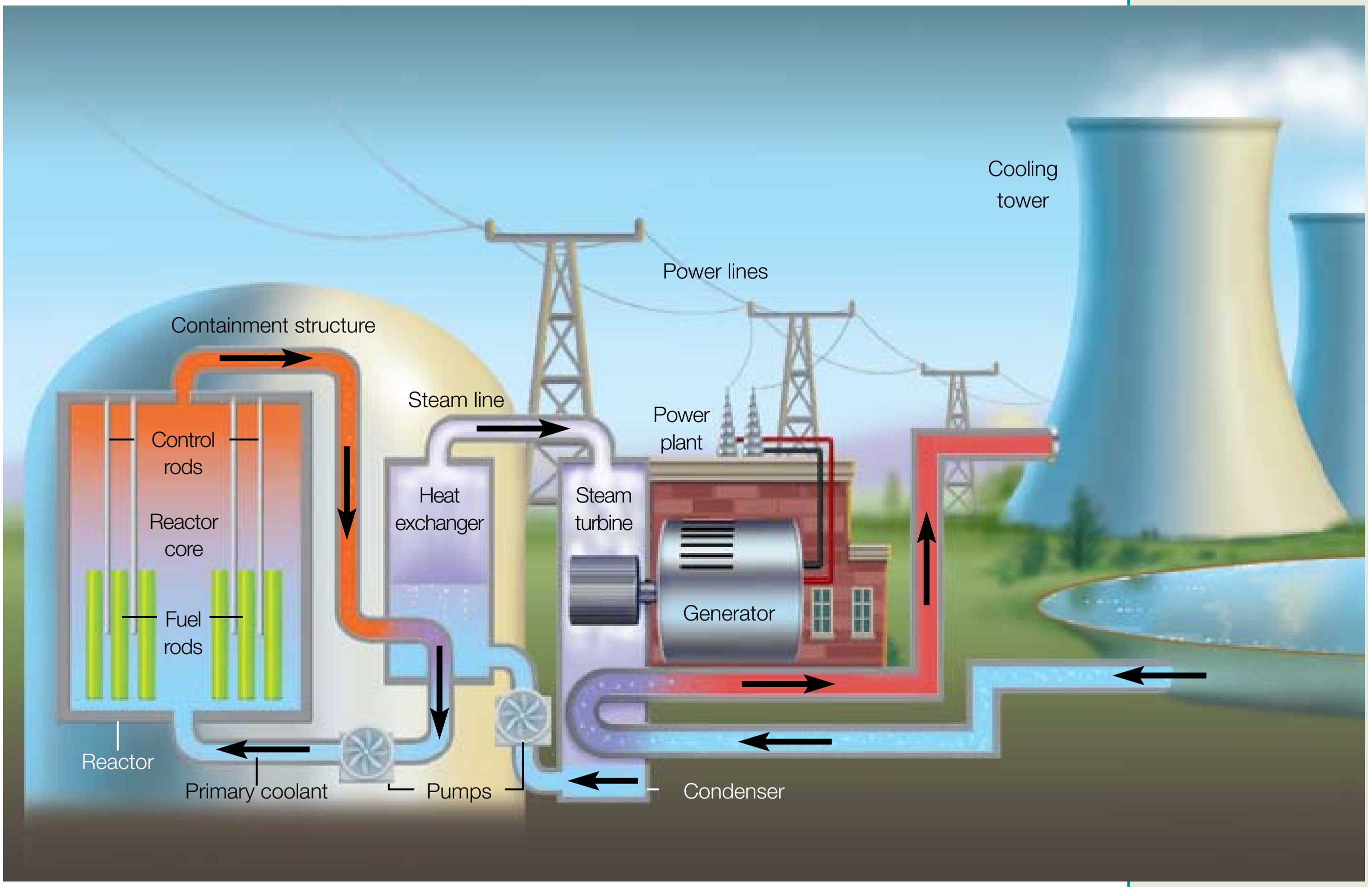


Figure 17.1 A nuclear power station

3. The **generator** and the **secondary coolant**. The steam is used to turn the turbine of the generator. After that, the steam is cooled and condensed to warm water by using a secondary coolant before it is recirculated back into the heat exchanger so that more steam is produced. The secondary coolant is usually just cool water taken directly from a natural source, such as a river, and after it is used, it is discharged back into the environment. To prevent thermal pollution caused by discharging this slightly warm water into the environment, a cooling pond may be used.

NOTE: Thermal pollution is caused by discharging warm or hot water directly into a local waterway, causing a rise in the temperature of the water, resulting in a reduction in the level of dissolved oxygen in the water and impaired reproductive cycle of aquatic species. The reduction in the level of dissolved oxygen in the waterway may lead to the death of many aquatic species.

Some countries have employed fission technology (see Fig. 17.1) as their main source of electricity supply. However, currently in Australia, we do not use fission technology for power; rather, we use it as a source of neutrons in the nuclear reactor at Lucas Heights, Sydney. In such a reactor, the design is simpler as no heat exchanger or generator is required. Coolant is still required to carry away the excess heat from the reactor core in order to prevent the meltdown of the core. Transmutation reactions using neutrons take place inside the core, as this is where neutrons are produced.

17.2 Radioisotopes and their applications

- *Describe some medical and industrial applications of radioisotopes*

Uses of radioisotopes

SECONDARY SOURCE INVESTIGATION

PFAs

H4, H5

PHYSICS SKILLS

H12.3A, B, C, D
H12.4F
H14.1A, C, E, F, G, H

- *Identify data sources and gather, process and analyse information to describe the use of:*
  - *a named isotope in medicine*
  - *a named isotope in agriculture*
  - *a named isotope in engineering*

Chapter 16 discussed the phenomenon of alpha, beta and gamma decay: the way in which the decay occurs and the products of the decay, using some simple examples. The physical properties of alpha, beta and gamma radiation are summarised in Table 17.1.

Table 17.1 Properties of alpha, beta and gamma radiation

Name	Identity	Charge	Mass (u)	Energy	Ionisation power	Penetration power
Alpha	Helium nucleus $^{4}_{2}He$	+ 2	4.03	Low	High	**Low** ■ Travels for 7 cm in air ■ Blocked by a layer of skin or a thin piece of paper
Beta	Fast-moving electron ($^{0}_{-1}e$)	−1	5.48×10^{-4} (approx. $\frac{1}{1825}$)	Medium	Medium	**Medium** ■ Travels for 1 m in air ■ Blocked by a thin layer of metal sheet
Gamma	Highest frequency EMR (γ)	0	0	High	Low	**High** ■ Penetrates through thin metal sheets ■ Blocked by thick lead sheets or concrete wall

Isotopes of the elements that undergo alpha, beta or gamma decay are known as **radioisotopes**. Radioisotopes have extensive applications in many areas. The syllabus requires you to identify the uses of the radioisotopes in medicine, industry, agriculture and engineering. Many of the radioisotopes used commercially are required in large quantities, therefore are usually artificially manufactured using a nuclear reactor—more than 500 radioisotopes are produced at Lucas Heights, Sydney. However, a few exceptional ones are made in a particle accelerator. (Particle accelerators are discussed later in this chapter.)

Some examples of the uses of radioisotopes in various fields are described here. You are encouraged to conduct your own research, using the Internet and library resources, either to further extend these examples or initiate your own. Key words are: ‘uses of radioisotopes’, ‘radioisotopes’, ‘nuclear medicine’, ‘radioisotopes in industries’, and so on.

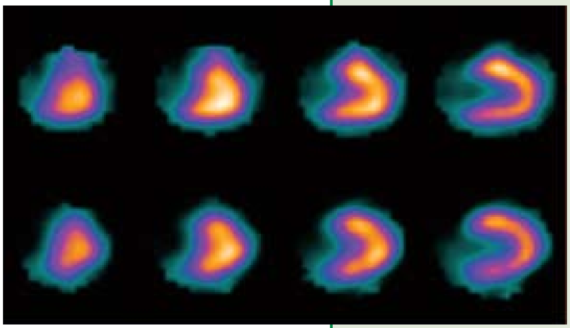
Medical use

Technetium-99m

Technetium-99m is a pure gamma emitter and has a very short half-life of six hours.

The fission of uranium produces molybdenum-99 ($^{99}_{42}Mo$), which is then extracted and packed into small glass tubes. $^{99}_{42}Mo$ undergoes continuous beta decay to form technetium-99m:

$$^{99}_{42}Mo \rightarrow {}^{99m}_{43}Tc + {}^{0}_{-1}e + \overline{v}$$



A nuclear scan image using Tc-99m

When needed, technetium-99m is then extracted at the site of use by passing saline through the glass tube. The reason for this complicated production method is that molybdenum has a much longer half-life (67 hours) compared to technetium, thus allowing adequate time for the transportation from Lucas Heights to various hospitals around the country. When technetium-99m is extracted at the hospitals, it needs to be used almost immediately because of its short half-life.

NOTE: Half-life is defined as the time needed for half the amount of a given radioisotope to decay or the time for the intensity of its radiation to decrease by a half.

Use of the radioisotope

Technetium-99m is one of the most commonly used radioisotopes in medicine. It is used as a diagnostic tracer to detect abnormal blood circulations, abnormal lung functions, bone pathologies and many more. For example, when technetium-99m is used to examine the circulatory system, it is made to attach to a biological molecule such as albumin (a blood protein) and is injected into the bloodstream. These molecules are then allowed to circulate and distribute evenly in the bloodstream. The gamma radiation from the technetium-99m, and therefore the distribution of the radioisotopes, is detected by a gamma camera. An abnormal increase in or absence of scintillation (detection) at certain areas could result from either haemorrhage or clots respectively.

Properties related to its use

- Very short half-life of six hours, so technetium-99m does not last long when injected into the human body, making it relatively safe to use.
- Technetium-99m is a gamma emitter: only gamma radiation, but not alpha or beta radiation, are penetrative enough so that it can be detected outside the body. Gamma radiation also causes the least amount of ionisation, making it safer to use compared to the same dosage of alpha or beta radiation inside the body.
- Technetium-99m is also relatively cheap to produce.

NOTE: Gamma radiation causes the least amount of ionisation compared to alpha and beta radiation, and therefore is the safest to use inside the body. The impression that alpha and beta radiation are safer to use compared to gamma radiation is related to the fact that they have low penetration power; therefore, when they are emitted from an external source, they are often blocked by air, cloth and skin and are unable to do harm.

Cobalt-60

Cobalt-60 is a co-emitter of beta and gamma radiation and has a half-life of 5.3 years. Cobalt-60 is produced in the nuclear reactor by neutron bombardment. Naturally occurring cobalt-59 atoms are placed inside the nuclear reactor for many weeks to capture neutrons in order to produce cobalt-60.

$$^{59}_{27}Co + {}^{1}_{0}n \rightarrow {}^{60}_{27}Co + energy$$

Use of the radioisotope

To kill cancer cells such as in radiotherapy. Gamma radiation produced by Cobalt-60 destroys the cancer cells. Unfortunately, it also destroys the surrounding healthy tissues which can be an unavoidable side effect of the therapy.

Properties related to its use

- Cobalt-60 is a gamma emitter and only gamma rays are penetrative enough to reach the deep cancer tissues. Also gamma radiation is energetic enough to destroy the cancer cells.
- It has a moderate half-life, meaning that it can last long enough for economical use but at the same time, not so long that the radiation it emits is too weak to kill the cancer cells.

NOTE: Usually the longer the half-life, the lower the intensity of the radiation emission.

Industrial use

Strontium-90

Strontium-90 is a beta emitter that has a half-life of 28 years. Strontium-90 is produced via the fission of uranium as one of the daughter isotopes.

Use of the radioisotope

Strontium-90 is used in industries as a thickness gauge to monitor and control the thickness of sheets as they are being manufactured. Some examples include paper sheet and metal sheet production. A schematic diagram of how a radioisotope can be used as a thickness gauge is shown in Figure 17.2. The thickness gauge works by directing the beta radiation emitted by strontium-90 to pass through the sheet as it is being produced (rolled). The sheet absorbs the radiation partially and the remainder penetrates through to reach the detector. The amount of the radiation being absorbed by the sheet depends on its thickness. The detector measures the strength of the radiation received and feeds this data back to the rollers, instructing the rollers to adjust the pressure in order to keep the thickness of the sheet constant. For instance, a sheet that is too thick will absorb too much of the radiation, resulting in the detector measuring less radiation than normal. This information is fed back to the rollers so that they will roll with more pressure to reduce the thickness of the sheet.

Properties related to its use

- As a beta emitter, strontium-90 is quite safe to use (compared to gamma emitters, as beta radiation is not as penetrative); only minimal safety precautions are required.
- Strontium-90 has a long half-life of 28 years. This means the radioisotope does not have to be replaced constantly, making it more economical. Also, a long half-life means a lower emission intensity. This results in a larger proportion of the radiation being absorbed by the sheet, making any changes in absorption more noticeable, thus increasing the sensitivity of the device.

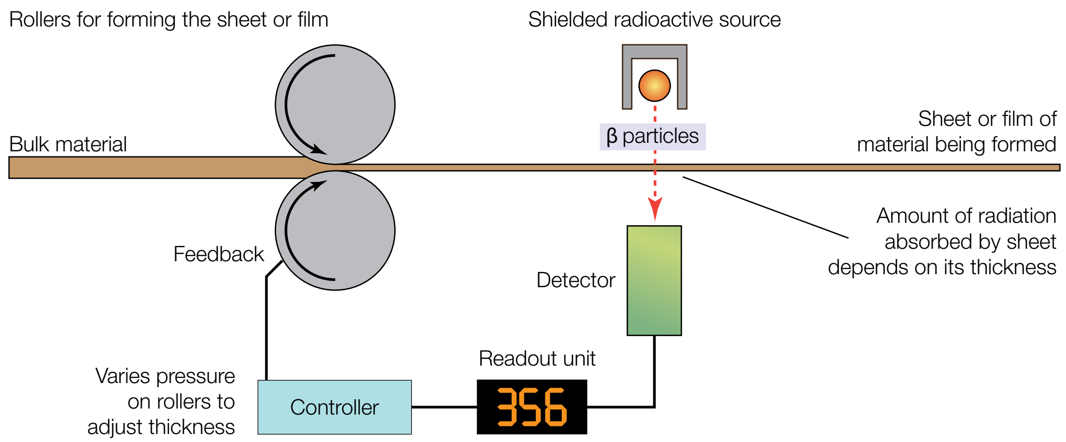


Figure 17.2 Thickness gauges using radioactive sources are widely used in industry to monitor and control the thickness of materials produced, ranging from paper to plastics to steel

Americium-241

Americium-241 is a co alpha and gamma emitter with a half-life of 432 years.

NOTE: Americium-241 is also a transuranic element.

Use of the radioisotope

Americium-241 can be used in smoke detectors. Inside the smoke detector, americium-241 constantly releases alpha particles in between the electrodes in the detector to set up a current flow. When there is an increased level of smoke particles, these particles migrate into the interior of the detector to disrupt the movement of the alpha particles. Consequently, the current flow decreases, which in turn triggers the alarm.

A smoke detector

Properties related to the use

Alpha radiation can be stopped very easily, so its movement can be disrupted readily by the smoke particles. This forms the functional basis of the detector. The low penetration power of the alpha radiation also makes americium-241 safe to use.

Agricultural use

Phosphorus-32

Phosphorus-32 is a beta emitter with a half-life of 14 days. It can be produced by neutron bombardment of the naturally occurring phosphorus-31.

Use of the radioisotope

Phosphorus-32 can be used as a biological tracer to study natural processes such nutritional uptake by plants in the natural environment and in agricultural settings. For example, phosphorous-32 can be introduced into plants or crops as radioactive phosphate ions ($^{32}PO_4^{3-}$). (Phosphate is an essential nutrient for the growth of plants and crops.) The plants or the crops process the radioactive phosphate in the same way as they handle normal phosphate. The only difference is that the radioactive phosphate continues to emit beta radiation. By tracing the radiation, biochemical processes such as nutritional uptake, transportation and storage can be studied. The efficacy of phosphorous based fertiliser can also be studied in a similar way.

Properties related to its use

The fact that phosphorous-32 can be easily introduced into biological systems and be traced makes it ideal for this use. Compounds formed by phosphorous-32 have the same chemical properties compared to those formed by non-radioactive phosphorous (phosphorous-31) so they are indistinguishable by plants.

Cobalt-60

Use of the radioisotope

Cobalt-60 can be used in agricultural settings to irradiate crops after they have been harvested. Cobalt-60 produces gamma radiation that is energetic enough to kill the micro-organisms living on the crops. This enables the crops to be preserved longer; an example is irradiation of wheat.

Properties related to its use

Just as with cancer cells, gamma rays are damaging enough to kill those micro-organisms.

Engineering use

Sodium-24

Sodium-24 is a co-emitter of gamma and beta radiation. It has a half-life of 15 hours. Sodium-24 is produced in the nuclear reactor by neutron bombardment of the naturally occurring sodium-23, similar to the production of cobalt-60.

Use of the radioisotope
Sodium-24 is used in detecting leakage from underground water pipes. It is introduced into the water pipes as a compound such as ${}^{24}_{11}NaCl$, and undergoes continuous decay to give off gamma and beta radiation. The radiation (mainly gamma) is then detected at ground level, with any abnormal distributions or increased level of the radiation detected indicating a leakage.

Properties related to its use
- Sodium-24 is a co-emitter of gamma and beta radiation. The gamma radiation is penetrative enough to reach the surface so that it can be detected.
- It has a short half-life of 15 hours, which is long enough for the process of detecting the leakages but does not stay in the water system long enough to cause harm to the end users.

Many other gamma emitters are commonly used for detecting flaws in welding, ships and aircraft, similar to how X-rays may be used to detect breakage in bones.

17.3 Neutron scattering and probing

Describe how neutron scattering is used as a probe by referring to the properties of neutrons

Apart from using neutrons to initiate nuclear fission reactions and artificial transmutation, neutrons can also be used to study the internal structure of matter. In 1994, Bertram Brockhouse (1918–2003) and Clifford Shull (1905–2001) shared the Nobel Prize for their pioneering work on the development of neutron scattering.

Definition

Neutron scattering or probing is the method that utilises the wave characteristics of neutrons to study the internal structure and properties of matter.

The principle used by neutron scattering is very similar to that of electron microscopes and Braggs' X-ray diffraction technique. When conducting neutron scattering, high flux neutrons are required; hence, the investigation needs to be carried out near or inside a nuclear reactor. The reason for using a large number of neutrons is that neutrons do not have any charge and therefore they are very hard to manipulate.

ANALOGY: Using neutrons to probe an object is like pouring a bucket of paint onto an object—very little control exists. Therefore more paint is required than if the object is painted precisely using a paintbrush.

These high flux neutrons are first made to pass through certain crystals such as sodium chloride, so that they all possess the same amount of kinetic energy. The neutrons are then directed to bombard the material that is to be analysed. These neutrons will collide with the atoms that make up this material, or more correctly, their nuclei, and subsequently lose a specific amount of energy according to the nature of the collisions. Side-on collisions compared to head-on collisions will result in the neutrons losing less of their kinetic energy, and their occurrences are determined by the arrangement of the atoms that make up this material. Furthermore, collisions between neutrons and small elements will result in a significant amount of energy loss from the neutrons (to the atoms), whereas colliding with large elements will cause neutrons to bounce off without losing much energy at all.

ANALOGY: When a tennis ball is used to hit another tennis ball (representing an atom), the first ball loses a significant amount of its kinetic energy to the second one, causing the first tennis ball to slow down and the second one to start to move. On the other hand, when a tennis ball is made to hit a wall (a large element), it bounces back almost with the same speed, hence kinetic energy.

Therefore, after the neutrons have interacted with the material, they will be scattered and returned with various levels of energy, hence momentum. Recall that any small particles, like these neutrons, also exhibit wave characteristics, with $\lambda = \frac{h}{mv}$, where mv is the momentum of the neutrons. Hence, the scattered neutron waves will return with different wavelengths, which in turn will generate a specific interference pattern. Lastly, by analysing the interference pattern, the nature of the neutron waves, and therefore the nature of their initial interaction with the material, can be determined. From this, the internal structure and the composition of the sample material can also be deduced.

The advantages of using neutron scattering

First, neutrons are not charged, therefore they do not interact with the electrons around the nucleus. If they do not hit the nucleus of any atoms, they will pass through these atoms, thus making them extremely penetrative. Consequently, neutron scattering is able to analyse the entire depth of the sample material. This is an advantage compared to an electron microscope, which can only analyse the surface of matter or thin specimens because of the extensive interactions between the electrons used by the electron microscope and electrons around the atoms of the sample specimen. A similar, but less extensive, problem is encountered with the use of X-rays for X-ray diffraction.

Second, neutrons are good for probing the nucleus. This is related to the fact that neutrons are not charged, therefore they are able to penetrate through the electron cloud to reach the nucleus. Compared to the smaller electrons and the even smaller X-ray photons, neutrons and the nuclei usually have a comparable size, which makes the interaction more efficient.

Finally, neutrons are very useful for probing small elements and proton-rich materials. In these materials, the relative low amount of electrons leads to poor results when they are imaged using an electron microscope or X-ray scattering, since both work on the electrons in the material. The fact that neutrons work on the nuclei will circumvent the problem. Small elements and proton-rich materials make up organic matter, such as living tissues or viruses. Therefore neutron scattering or probing has an important role in analysing these materials.

Some applications of neutron scattering

1. Finding structural faults in welds and metals.
2. Developing magnetic material for computer data storage. Neutrons are neutral, therefore when they are used for probing magnetic materials, they will not be influenced or interfered with by the magnetic field.
3. Developing new superconductor materials, again due to their neutral charge.
4. Identification and study of viruses, which are rich in small elements and protons, and therefore can be analysed efficiently using neutron probing.

Neutron scattering is an expensive process. It is also difficult to use, as neutrons are very difficult to control. Also, the actual investigation needs to be carried out near or inside a nuclear reactor, making neutron scattering an uncommon process.

The Manhattan Project

SECONDARY SOURCE INVESTIGATION

PFAs

H1, H4, H5

PHYSICS SKILLS

H12.3A, B, D
H12.4F
H14.1B, D, F, G, H

'Assess'

Gather, process and analyse information to assess the significance of the Manhattan Project to society

The Manhattan Project was the code name used by the US army to describe the project to develop atomic bombs during World War II. The project got its name from the Manhattan district of the US, where much of the early work was done in developing the atomic bombs.

The key chronological events and impacts of the project are summarised below. You are encouraged to conduct your own research, using internet and library resources, by typing in 'Manhattan Project', to expand your knowledge of the project and appreciate its significance.

- In 1938, German scientists discovered nuclear fission.
- Later in the year, refugees from the Nazis including Leo Szilard, Edward Teller and Eugene Wigner raised the possibility that Germany was utilising nuclear fission technology to develop nuclear weapons.
- In 1939, Leo Szilard, Edward Teller and Eugene Wigner convinced Albert Einstein to write the famous letter to the US President Franklin D. Roosevelt to advocate the development of atomic bombs. President Roosevelt set up an advisory committee on uranium in October 1939, headed by L. J. Briggs, director of the National Bureau of Standards. This marked the starting point of the Manhattan Project.
- In March 1940, it was confirmed that uranium-235 was able to undergo fission, whereas uranium-238 was not.
- In 1941, plutonium-239 was also identified as capable of undergoing fission but at a faster rate compared to uranium-235.
- On 7 December 1941, Japanese forces attacked Pearl Harbor and the US entered the war. This accelerated the development of the project and the War Department was given joint responsibility for it.
- In December, 1942, Fermi successfully carried out the first ever controlled fission reaction in a basement of the University of Chicago (see Chapter 16). This gave a huge boost to the project.
- Unlike Fermi's reaction pile, the atomic bombs needed high concentrations of fissionable material in order to produce very rapid fission reactions for the explosion. Between 1942 and 1943, two huge industrial plants were constructed to provide fissionable material for the bombs; one was at Oak Ridge, Tennessee, and the other was at Hanford Engineer Works, Washington.
- At Oak Ridge, the concentration of uranium-235 was taking place. The uranium-235 was concentrated from its natural composition of 0.07% to 95% by two methods:
  – *Gaseous diffusion separation*: Uranium (containing both uranium-238 and uranium-235) was first reacted to form uranium hexafluoride (UF_6) gas. The gas was then allowed to pass through a series of membranes. The heavier $^{238}UF_6$ would diffuse slightly slower compared to the lighter $^{235}UF_6$. This difference in speed of migration as the gas mixtures were passing through the membranes allowed separation.
  – *Electromagnetic separation*: Uranium was ionised and was then allowed to pass through a uniform magnetic field, perpendicular to the field lines. As shown in Chapter 10, when a charged particle passes through a magnetic field perpendicularly, it will describe an arc of a circle. The radius of the circle can be described by the equation, $r = \frac{mv}{qB}$. (Why?) The fact that the uranium-238 had a slightly higher mass compared to uranium-235 would result in a slightly larger radius as the uranium ions were passing through the magnetic field. This allowed the separation to be made.

Manhattan Project officials, including Dr Oppenheimer (white hat), inspect the detonation site of the Trinity atomic bomb test, 16 July 1945.

The Hiroshima Peace Memorial, Genbaku Dome, believed to be the exact spot where the atomic bomb exploded during World War II: it has been preserved as a reminder of the destruction

- At Hanford, production of plutonium-239 by transuranic reactions was taking place: uranium-238 was converted to form plutonium-239 by neutron bombardment as described in Chapter 16 (page 283).
- Also during 1942 and 1945, under the leadership of Robert Julius Oppenheimer, the actual weapon design was taking place simultaneously at Los Alamos, New Mexico. The weapon designed focused on how to assemble the fissionable materials into a bomb as well as the construction of a deliverable weapon.
- By 1945, enough concentrated uranium-235 was produced so that it could be packed into a gun-barrel-type atomic bomb. The gun-barrel-type atomic bomb consisted of two pieces of uranium, both sub-critical in mass, which would be brought together quickly upon explosion to achieve a super-critical mass. On the other hand, plutonium-239 bomb was made into an implosion-type of bomb. The implosion-type atomic bomb utilised many sub-critical mass pieces of plutonium, which needed to be brought together even more quickly upon explosion to reach a super-critical mass. Note that with both designs, an initiating neutron was required to start off the fission reaction.
- In 16 July 1945, a test explosion was performed near Alamogordo, New Mexico. This bomb produced energy equivalent to 15 000 to 20 000 tons of TNT.
- On 6 August 1945, the uranium-235 bomb was dropped on Hiroshima and three days later the plutonium-239 was dropped on Nagasaki. The next day, Japan surrendered.
- The two bombs together killed 100 000 people and caused a similar number of people to be wounded. The radioactivity produced by the bombs (mainly beta emitters) was spread by the wind and remained a threat to lives many decades after the bombs were dropped.
- After the war, many scientists discovered that the Germans were not close to developing atomic bombs. Einstein particularly regretted the letter he wrote to the US president to advocate the development of the nuclear weapon.

Impacts of the Manhattan Project

The Manhattan Project can be seen to have both positive and negative impacts. You can choose to emphasise the positive or negative impacts, or present a balanced view.

Positive impacts

1. The project ended World War II promptly; three days after dropping the two atomic bombs, Japan surrendered. Some people argued that the use of the atomic bombs, although they killed many people, also saved many other people's lives by ending the war quickly, avoiding a long process of invasion with even more casualties.
2. The project facilitated the development of technologies to produce fissionable fuels. The method of gas diffusion and electromagnetic separation, as well as the method for producing plutonium-239 are still used today to produce fissionable materials for nuclear reactors and nuclear power stations.
3. The project accelerated the development of nuclear technologies, which gave us the ability to manipulate nuclear power. The best scientists in the world gathered to work for the project, which led to a rapid and accelerated advancement of nuclear technologies during World War II. Without the Manhattan Project, our ability to control nuclear power would now be much less developed.
4. It was argued that the existence of nuclear weapons prevented a war between the USSR and NATO (North Atlantic Treaty Organization). The fact that both possessed nuclear weapons meant both were afraid to enter into another war—they knew the damage that nuclear weapons could cause.

Negative impacts

1. The project was expensive. It cost US$2 billion dollars for the project in 1945—which would be much more if translated to today's currency.
2. One hundred thousand people were killed when the two bombs were dropped and many more were wounded. The bombs also left behind radiation, so that even many decades later, Japanese people were still dying from radiation-related diseases, such as leukemia.
3. Just as for the Manhattan Project, governments are putting more and more money into nuclear research because it seems to countries that lack nuclear weapons that they are more vulnerable. This huge amount of money could be used for social welfare and medical research instead. Many countries' nuclear policies still remain controversial.
4. Nuclear weapons are so powerful that humans now have the power to destroy themselves. A world war involving nuclear weapons would effectively end the human race and much life on Earth.

17.4 Particle accelerators

- ***Identify ways by which physicists continue to develop their understanding of matter, using accelerators as a probe to investigate the structure of matter***

The term **particle accelerator** is a collective name for a series of devices that are designed to use electric fields and/or magnetic fields to accelerate charged particles to very high speeds before smashing the particles against a target. This can subsequently cause transmutation or breaking up of the particles as a result of the 'smashing'. The latter forms the basis by which sub-atomic and fundamental particles were discovered. The fundamental particles are discussed in the next section.

NOTE: Only charged particles can be influenced by electric and magnetic fields, therefore, particle accelerators work well for particles like protons, electrons and various ions. They do not work for neutrons!

There are many different types of particle accelerators. Some examples include:

- circular particle accelerators: cyclotrons, synchrocyclotrons, synchrotrons and betatrons
- linear accelerators

Most particle accelerators, except the linear accelerator, are circular. Although these particle accelerators are designed to utilise the electric fields and/or magnetic fields in different ways to accelerate charged particles, they share a similar functional principle. The cyclotron will be examined in detail in order to illustrate the basic functional principle.

Cyclotron

A cyclotron consists of two D-shaped hollow metal cases, called 'Dees', which are mounted between the poles of two powerful magnets. The size of the Dees can range from just over a hundred metres to hundreds of metres. A schematic drawing of a cyclotron is shown in Figure 17.3 (a).

Figure 17.3 (b) shows a simplified diagram of the same cyclotron when viewed from the top. The charged particle (source) that is to be accelerated is placed in between the two Dees, a little bit off the centre (of the particle accelerator). The

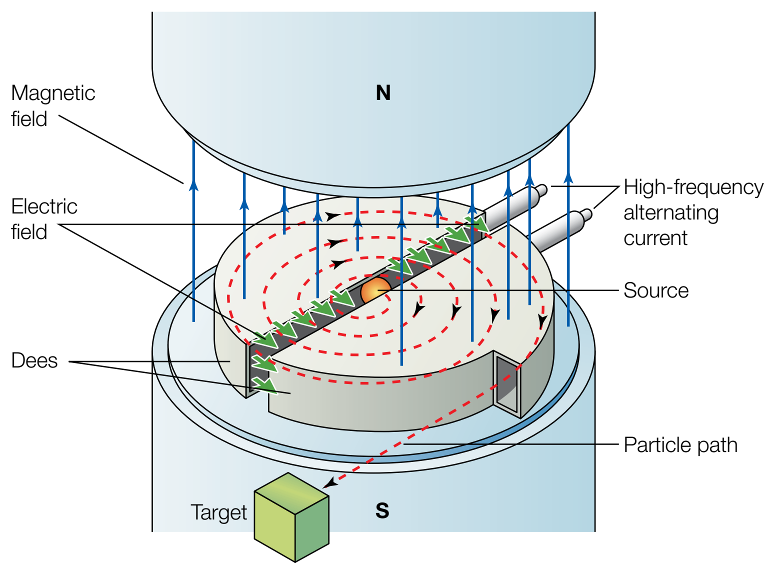


Figure 17.3 (a) A cyclotron

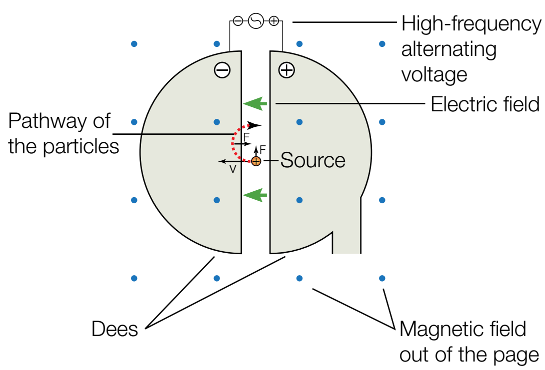


Figure 17.3 (b) Top view of a cyclotron

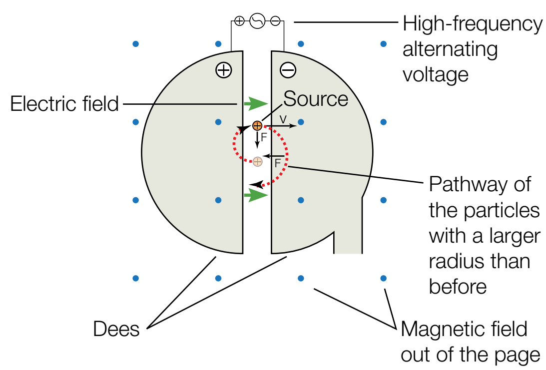


Figure 17.3 (c) Top view, after the charged particle has exited the Dees on the left

electric field produced in between the Dees as a result of the alternating voltage that supplies the Dees will accelerate the particle to increase its linear velocity and the particle enters the Dee to the left, shown in Figure 17.3 (a).

As the particle travels inside the hollow Dee, it experiences no more electric force (the electric field inside a hollow conductor is zero) and is acted upon by the force due to the uniform magnetic field running perpendicularly through the Dees. Under the influence of the magnetic force, the particle subsequently bends to describe an arc of a circle inside this Dee and then exits. At this point, the polarity of the Dees is reversed by the AC voltage, so that the particle is again accelerated when it is in between the two Dees. This is shown in Figure 17.3 (c).

Subsequently, the particle enters the Dee to the right with an increased linear velocity and is again bent by the magnetic field. As this process repeats, the particle will continue to describe a circular pathway inside the Dees and is accelerated by the electric field every time it passes in between the Dees. Thus the particle's velocity increases continuously, which is accompanied by an ever-increasing radius of its pathway, as shown in Figure 17.3 (a).

NOTE: As $r = \frac{mv}{qB}$, as v increases, r increases.

Once the particle has reached a desirable velocity, it is then allowed to exit the particle accelerator, resuming a linear motion to collide with a target. This high-velocity collision will either:

- smash the particle apart for analysis
- create transmutation

Other circular particle accelerators

A synchrocyclotron operates similarly to a cyclotron, the only difference being the synchrocyclotron takes into account the effect of mass dilation as the particle speeds up, which can delay the particle's motion and its arrival at the opposite Dees. By taking into consideration mass dilation, the particle can be accelerated to a higher velocity.

A synchrotron on the other hand utilises a variable magnetic field (compared to a constant magnetic field used by the cyclotron and synchrocyclotron), such that the increase in velocity of the particle is coupled with a proportional increase in the applied magnetic field, so that the radius of the pathway described by the particle is kept constant. This helps to reduce the size of the device.

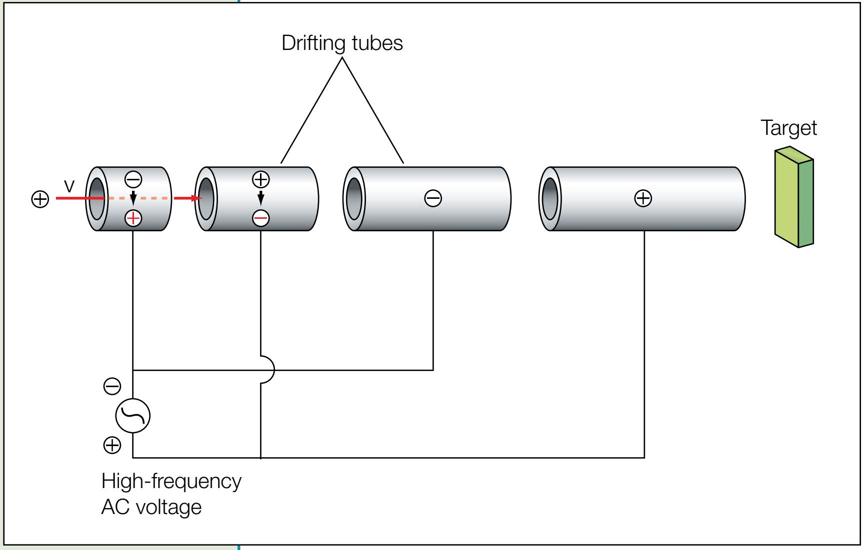
Betatrons have specific designs that cater for accelerating electrons or positrons.

Linear accelerator

A linear accelerator consists of many hollow tubes, called drifting tubes, that are aligned in a line. The drifting tubes are made progressively longer and their total length can reach a few kilometres. Each second tube is connected to one of the terminals of a high-frequency AC power supply—so the polarities of the tubes alternate. As shown in Figure 17.4, to accelerate a positively charged particle, the first tube is made negative. This attracts the particle and accelerates it through the tube. Upon its arrival at the second tube, the polarities of the tubes are reversed, such that the first tube (which was negative before) is now positive and the second tube is now negative. As a result, the positively charged particle is repelled by the positive tube behind it and is attracted to the negative tube in front of it, so that it is further accelerated. As the whole process repeats, the particle will increase its velocity as it travels through all of the tubes of the accelerator. Finally, the particle exits the last tube to strike the target.

Note that the length of the tubes is made progressively longer in order to accommodate the increase in velocity of the charged particle, so that the particle will always arrive in between the tubes at a constant time interval, which must be in synchrony with the timing of the polarity change.

Figure 17.4 A linear accelerator



NOTE: As the particle speeds up, it is able to travel greater distance in a given time.

The standard model of matter

17.5

■ *Discuss the key features and components of the standard model of matter, including quarks and leptons*

The standard model of matter was initially developed in an attempt to describe all matters and forces in the Universe using fundamental particles. The standard model of matter can be summarised by a flow chart shown in Figure 17.5.

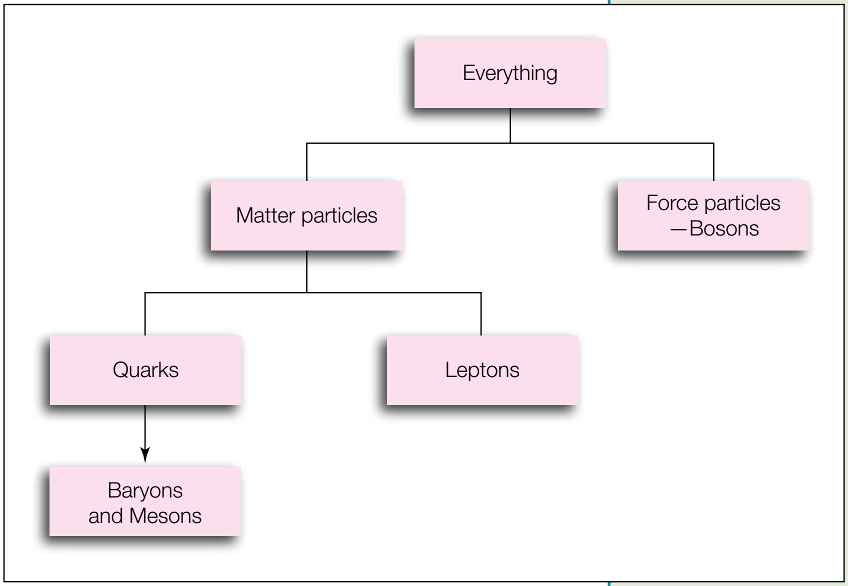


Figure 17.5 The standard model of matter

Quarks

In 1964, two physicists, Murray Gell-Mann and George Zweig, proposed the existence of particles with charges that were sub-multiples of electron charges, termed **quarks**. Later the quarks were recognised as fundamental particles—the smallest particles that could not be broken down further. In simple terms, there are six 'flavours' of quarks as well as six corresponding anti-quarks. The names, symbols and charges of the six flavours of quarks are summarised in Table 17.2. Although the six anti-quarks are not shown, their existence should be emphasised. For instance, an anti-up quark has the symbol $\bar{u}$ and a charge of $-\frac{2}{3}$ while an anti-down quark has the symbol $\bar{d}$ and a charge of $+\frac{1}{3}$. There are also other differences between quarks and anti-quarks at a quantum mechanical level but these are beyond the scope of this course.

Table 17.2 The six 'flavours' of quarks

Generation	Quarks	Symbols	Charges
1	Up	u	$+\frac{2}{3}$
	Down	d	$-\frac{1}{3}$
2	Charm	c	$+\frac{2}{3}$
	Strange	s	$-\frac{1}{3}$
3	Top	t	$+\frac{2}{3}$
	Bottom	b	$-\frac{1}{3}$

Hadrons

Although quarks can be identified as fundamental particles through the use of particle accelerators, they usually do not exist by themselves as they are unstable. Quarks usually exist in more stable forms by combining with one or two other quarks. The combination of quarks is known as **hadrons**. All hadrons have integral charges. There are two types of hadrons: **baryons** (three-quark combinations) and **mesons** (two-quark combinations).

Baryons

Baryons make up everyday matter as they form the nucleons. Protons consist of two up quarks and one down quark, hence a charge of $2 \times (+\frac{2}{3}) + (-\frac{1}{3})$, which gives a value + 1. Neutrons on the other hand consist of one up quark and two down quarks, giving an overall charge of 0, that is, $(+\frac{2}{3}) + 2 \times (-\frac{1}{3})$.

All quarks, thus all baryons, act through strong nuclear force. This is the reason for the strong nuclear force to act equally between proton–proton, proton–neutron and neutron–neutron, since all are made from different numbers of the same quarks.

Mesons

A meson consists of a quark and an anti-quark. One example is positive peon (π^+), which is made from an up quark $(+\frac{2}{3})$ and an anti-down quark $(+\frac{1}{3})$, giving it an overall charge of −1. Mesons are generally unstable therefore short-lived; this makes them hard to detect or identify.

Leptons

Leptons are another type of fundamental particle that have either very little or no mass. There are six ‘flavours’ of leptons, also grouped into three generations. Within each generation, an electrically charged lepton is coupled with its corresponding neutrino. This is summarised in Table 17.3.

Also note that, just like quarks, for every lepton there is a corresponding anti-lepton. For example, there exist anti-electrons, termed **positrons**, which have the symbol of e^+. Positrons are quantum mechanically differently to electrons but more noticeably, they carry a charge of +1. The existence of anti-electrons—positrons—is discussed in Chapter 16 (recall that they occur along with β^- decay). All leptons interact through weak nuclear force and the charged leptons also interact through electromagnetic force.

Table 17.3 The six ‘flavours’ of leptons

Generation	Leptons	Symbols	Charges
1	Electron	e^-	− 1
	Electron-neutrino	υ_e	0
2	Muon	μ^-	− 1
	Muon-neutrino	υ_μ	0
3	Tau	τ^-	− 1
	Tau-neutrino	υ_τ	0

A word about 'generation'

Note that in Tables 17.2 and 17.3, the category 'generation' is used. The first generation particles are ones that make up ordinary matter. For instance, the generation 1 quarks make up the nucleons, whereas generation 1 leptons include the electrons and the electron-neutrinos that are released during ordinary β^- decays. The second generation particles are less stable and quickly decay to form the first generation particles; the third generation particles are even less stable and decay rapidly to form the second generation particles. The fact the second and third generation particles are unstable and short-lived means they cannot constitute everyday matter and are harder to detect. Also, as the generation number increases, the mass of the particles also increases.

Bosons—the force particles

As discussed in Chapter 16, there are four fundamental forces in the Universe. Using the standard model of matter, these four forces are thought to act through the exchange of force particles, called **bosons**:

1. Electromagnetic force acts through photons.
2. Strong nuclear force acts through gluons.
3. Weak nuclear force acts through weakons.
4. Gravity was thought to act through gravitons, however, although gravitons had been hypothesised, unlike the other force particles, their existence has not been proved. They were included in the standard model of matter for the sake of completeness.

The way that force particles are thought to convey attraction forces (between matter) is by having the matter pulling on the force particles as they are exchanged, whereas repulsion forces are conveyed by having the force particles being pushed away as they are exchanged.

Conclusion

The concept of the standard model of matter and the existence of quarks, leptons and bosons is an area of physics that has existed for more than 40 years. We may also consider this model as a further advancement in our understanding of the atom. Scientists have come a long way from the most 'primitive' model of the atom suggested by Thompson, to the idea of the quanta and Bohr's, and eventually to the more sophisticated quantum mechanics, based upon which de Broglie, Wolfgang and Heisenberg further advanced the model of the atom.

CHAPTER REVISION QUESTIONS

1. For a typical nuclear power station:
   (a) Describe two features of the use of the primary coolant.
   (b) Describe the role of the heat exchanger.
   (c) Describe the role of the secondary coolant and the cooling pond.
   (d) Explain what type of energy transformation is taking place in the nuclear reactor.
2. Describe the function of the nuclear reactor at Lucas Heights, Sydney.

SR

Answers to chapter revision questions

3. Radioisotopes have extensively applications in:
(a) medicine
(b) industries
(c) agriculture
(d) engineering
For each of the above fields:
(i) Choose a radioisotope and describe how it can be used in this field.
(ii) Discuss the properties of the radioisotope that make it suitable for this particular use.
(iii) Describe the production of this radioisotope.

4. (a) Describe the use of neutrons for probing the internal structure of matter.
(b) Why are neutrons particularly useful for probing organic matter and materials with magnetic properties?

5. Regarding the Manhattan Project:
(a) What were the events that led to the initiation of the project?
(b) What were the methods developed for preparing fuels required for the atomic bombs?
(c) Why did the bomb design have to be carried out at the same time as the nuclear fuel preparation and what could be some of the implications of proceeding with both simultaneously?
(d) Evaluate the social impacts of the project.

6. (a) Describe the functional principle of a cyclotron that allows it to accelerate a charged particle to high speeds.
(b) Will such a particle accelerator work for a sodium ion? Explain your answer.
(c) Within this cyclotron, a proton is accelerated to a radius of 100 m. If the cyclotron was able to provide a magnetic field strength of 5.00×10^{-3} T, determine the speed of this proton.

7. (a) What are quarks?
(b) There are six ‘flavours’ of quarks, plus their corresponding anti-quarks. What are they?
(c) What are leptons?
(d) There are six ‘flavours’ of leptons, along with their corresponding anti-leptons. What are they?
(e) What are the four classes of bosons and what are their roles?