

Radioactivity and the nucleus

Nothing in life is to be feared; it is only to be understood. Now is the time to understand more, so that we may fear less.

Marie Curie

REMEMBER

Before beginning this chapter, you should be able to:

- recall that all matter is made up of atoms
- explain the arrangement of particles in an atom, in particular that atoms have a central nucleus containing protons and neutrons.

KEY IDEAS

After completing this chapter, you should be able to:

- use equations to model the random radioactive decay processes of substances with a particular half-life
- describe the origin and properties of α , β^- , β^+ and γ radiation
- explain nuclear transformations and decay chains
- distinguish between the two types of forces holding the nucleus together: the strong nuclear force and the weak nuclear force
- explain nuclear energy as energy resulting from the conversion of mass into energy using $E = mc^2$
- compare the processes of nuclear fusion and nuclear fission
- use a binding energy curve to explain why both fusion and fission are reactions that produce energy.

Marie Curie (1867–1934), Polish-French physicist who won two Nobel Prizes: in 1903 for Physics and 1911 for Chemistry

Natural nuclear radiation

The ideas and events described in this chapter all started from a single chance discovery: Wilhelm Röntgen's discovery of X-rays in 1895. Röntgen's discovery led to a deep understanding of the nature of matter and to technological innovations of impressive and at times catastrophic impact. The timeline below describes many of the discoveries that have happened since then.

This chapter covers the events of the early years of the timeline, when radioactivity was discovered and the structure of the atom determined.

TABLE 7.1 Nuclear timeline

1895	Röntgen accidentally discovers X-rays while investigating the flow of electricity in a gas contained in a tube.
1896	Becquerel discovers natural radioactivity while investigating phosphorescent minerals, such as uranium salts, to see if they also give off X-rays when exposed to sunlight.
1897	Joseph Thomson discovers the electron. He later proposes a 'plum pudding' model of the atom, which suggests the atom is a slightly positive sphere with raisin-like, negatively charged electrons inside.
1898	Marie and Pierre Curie separate out radioactive elements in minerals, in the process discovering two new elements: radium and polonium.
1899	Rutherford shows that there is more than one type of radiation; he identifies α and β rays
1900	Pierre Curie shows that β rays are negatively charged particles by deflecting them in a magnetic field. He later deflects α rays with a stronger field, showing that they are positively charged particles. Villard discovers gamma rays. Becquerel shows that β particles have the same charge-to-mass ratio as electrons.
1901	Becquerel chemically removes all the β -emitting elements from a uranium sample and puts it aside. Some months later he finds the sample is emitting β particles.
1902	Rutherford repeats Becquerel's work, but he examines the count on a daily basis. He concludes that radioactive decay is a random process leading to an exponential decay curve, with each radioactive nucleus having its own half-life.
1903	Rutherford and Soddy propose a 'spontaneous disintegration theory'.
1906	Rutherford measures the charge-to-mass ratio of α particles. It is half that of the hydrogen ion. Boltwood discovers two forms of thorium with different radioactive properties. Soddy proposes the name 'isotope'.
1908	Rutherford and Geiger measure the charge on α particles. They are doubly charged helium atoms.
1909	Rutherford and Royds fire α particles into a vacuum. After some time they confirm the presence of helium from the spectrum. Geiger and Marsden fire α particles at thin gold leaf and observe that some are scattered back. Rutherford proposes a nuclear model of the atom.
1913	Geiger and Marsden experimentally confirm Rutherford's nuclear model.
1919	Rutherford changes nitrogen into oxygen with α particles.

1920	Chadwick confirms that the nuclear charge is the atomic number.
1920	Rutherford proposes a particle described as a 'neutral doublet' in the nucleus to explain β decay and atomic mass.
1920s	Aston discovers that the masses of atoms are close to exact integers, based on oxygen set at 16, but the difference is measurable. This leads to the concept of nuclear binding energy.
1927	Paul Dirac develops theory of the electron which suggests the possibility of anti-matter.
1930	Bothe and Becker bombard beryllium with α particles to produce an unknown form of radiation.
1931	Urey discovers deuterium, known as heavy hydrogen, with one proton and one neutron.
1932	Chadwick shows that the radiation discovered by Bothe and Becker is a neutral particle of mass approximate to that of the proton, to be called the neutron.
1932	<p>Carl Anderson discovers the anti-electron (or positron), the first antiparticle, in cosmic rays. (The positron's existence was proposed by Paul Dirac in 1927 and Ettore Majorana in 1928)</p> <p>Cockcroft and Walton fire high energy protons at lithium, producing two α particles.</p> <p>Anderson discovers a positively charged electron.</p> <p>Mark Oliphant discovers tritium, an isotope of hydrogen with two neutrons, and helium-3, with only one neutron. He also discovers fusion when he fires a deuterium nucleus at a deuterium target.</p>
1934	Enrico Fermi postulates the existence of the neutrino (Italian for 'little neutral one'), a neutral-charge partner to the electron to ensure energy is conserved in β decay. The theory is confirmed in 1959.
1935	Fermi discovers fission when he fires neutrons at uranium. Radioactive products with unexpected half-lives were found, but he thought that they might have atomic numbers greater than 92.
1939	<p>Hahn and Strassmann repeat Fermi's experiment and chemically analyse the products, finding barium (atomic number 56).</p> <p>Meitner and Frisch call the process 'fission.' They find that thorium and protactinium also split, as well as evidence of bromine, molybdenum, rubidium, antimony, iodine and caesium. They estimate that 200 MeV is released from a single uranium-235 nucleus.</p> <p>Von Halban and Joliot discover that a fission reaction produces two or three high-speed neutrons. The possibility of a self-sustaining or chain reaction is realised.</p>
1945	When uranium-238 accepts a neutron, it becomes uranium-239, which β decays to neptunium-239, which β decays to plutonium-239.
2007	Calcium-48 ions are fired at californium-249 atoms to produce the element with atomic number 118.

Nuclear radiation is an everyday occurrence for all people. We are exposed to a small amount of natural nuclear radiation all the time. There are two types of natural nuclear radiation: terrestrial radiation from the Earth and cosmic radiation from space. This radiation does not cause us permanent damage. There is evidence to suggest that living things have adapted to this background radiation.

Terrestrial radiation

When the Earth was formed, it contained a large number of radioactive nuclei. Some of these nuclei are still emitting radiation from the Earth's crust and atmosphere. This low-level radiation surrounds us. Moreover, our bodies are made from atoms that originally came from the Earth and atmosphere, so we are even emitting some radiation ourselves!

Cosmic radiation

Cosmic radiation comes to us from space. The atmosphere absorbs much of this radiation. This means we receive much less cosmic radiation than we would if we were on the surface of the Moon, which doesn't have an atmosphere. Because of the effect of the atmosphere, people living at higher altitudes receive higher doses of cosmic rays than those living at sea level. People flying in planes receive even more, although these levels are still quite safe.

The latitude at which you live also has a slight effect on the amount of cosmic radiation you receive. Cosmic radiation is affected by the Earth's magnetic field, and its intensity increases as you move towards the poles.

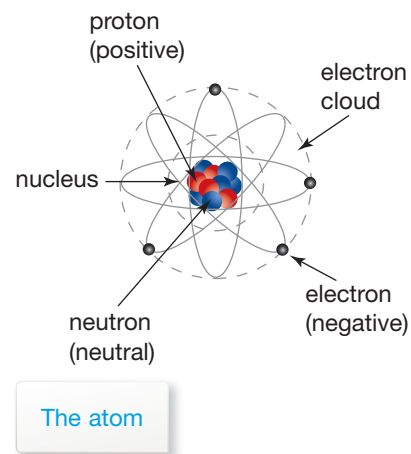
What is nuclear radiation?

Nuclear radiation, as the name suggests, is radiation emitted from the nucleus of an atom. In order to explain the mechanisms that release such radiation, it is important to understand a little about the structure of the atom, and the terminology that is associated with it.

All matter is made up of atoms. Each atom consists of a tightly packed, positively charged centre, called the **nucleus**, which is surrounded by a 'cloud' of small, negatively charged particles known as **electrons**. The particles in the nucleus are known collectively as **nucleons**, but there are two different types. Both types have roughly the same mass. The positively charged nucleus are **protons**, and the neutral (chargeless) ones are **neutrons**. Protons and neutrons are about 2000 times heavier than the electrons that surround the nucleus.

Scientists name atoms according to the number of protons in the nucleus. For example, all atoms with six protons are called carbon, all atoms with 11 protons are called sodium, and all atoms with 92 protons are called uranium. A substance consisting of atoms that all have the same name is called an **element**. Each element's name has its own shorthand symbol that scientists use. Carbon has the symbol 'C', sodium 'Na' and uranium 'U'. It is very important that the upper or lower case of the letters used in the symbols is kept the same. The names of all the elements, and their symbols, can be found in the periodic table on page xxx.

Strangely enough, not all atoms of the same name (and therefore the same number of protons) have the same number of neutrons. For instance, it is possible to find carbon atoms with six, seven and eight neutrons in the nucleus along with the six protons that make it carbon. These different forms of an element are called **isotopes**. To avoid confusion about which isotope is being referred to, scientists have a few standard ways of writing them. The number of nucleons, or **mass number**, of the particular isotope is used. The isotope of carbon with



The **nucleus** is the solid centre of an atom. Most of the mass of an atom is concentrated in the nucleus.

An **electron** is a negatively charged particle found around the nucleus of an atom.

The collective name for the particles found in the nucleus of an atom is **nucleon**.

A **proton** is a positively charged particle in the nucleus of an atom.

A **neutron** is a nucleon with no charge.

A substance is an **element** if it consists only of atoms of the same name.

Atoms containing the same number of protons but different numbers of neutrons are called **isotopes** of an element.

Mass number describes the total number of nucleons in an atom.

The number of protons in a nucleus is called the **atomic number** of the atom.

six protons and six neutrons is written as carbon-12 or ^{12}C , while the isotope of carbon with eight neutrons is written as carbon-14 or ^{14}C . Sometimes the number of protons, or **atomic number**, is written directly underneath the mass number, although this is not necessary (for example, $^{14}_6\text{C}$).

Sample problem 7.1

Write the name of the isotope of an atom with 90 protons and 144 neutrons.

Solution: From the periodic table on page xxx it can be seen that all atoms with 90 protons are called thorium, which has the symbol Th. The mass number (or number of nucleons) of this isotope is $90 + 144 = 234$. Therefore the isotope is thorium-234, or ^{234}Th .

Revision question 7.1

How many protons and neutrons are there in one atom of each of the following isotopes?

- (a) Hydrogen-2, also known as deuterium
- (b) Americium-241
- (c) Europium-64

A **radioisotope** is an unstable isotope.

Not all atomic nuclei (the plural of nucleus) are particularly stable. In some instances one isotope of an atom may be stable while another is not. This is why nuclear radiation is released. It is the atom's way of becoming more stable. Isotopes that are not stable are called **radioisotopes**. Many radioisotopes are found in nature; many more are produced artificially.

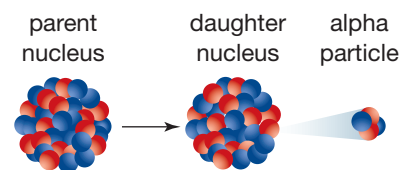
Types of nuclear radiation

Unstable isotopes can emit various types of radiation while 'striving' to become more stable. There are three naturally occurring forms of nuclear radiation: α , β and γ (pronounced *alpha*, *beta* and *gamma*). Each type of radiation was named with a different Greek letter because, when the different types of radiation were discovered, scientists did not know what they consisted of. The emissions are described as decay processes because the nucleus changes into a different nucleus and the change is irreversible.

Alpha decay

During α decay an unstable nucleus ejects a relatively large particle known as an **α particle**. This actually consists of two protons and two neutrons, and so may be called a helium nucleus. The remainder of the original nucleus, known as the **daughter nucleus**, is now more stable.

The number of protons in the nucleus determines the elemental name of the atom. The daughter nucleus is therefore of a different element. For example, uranium-238 decays by emitting an α particle. The uranium-238 atom contains 92 protons and 146 neutrons ($238 - 92 = 146$). It emits an α particle, with two protons and two neutrons. The original nucleus is left with four less nucleons: 90 protons ($92 - 2 = 90$) and 144 neutrons ($146 - 2 = 144$). As the daughter nucleus now has 90 protons, it is called thorium and has the symbol Th. This particular isotope of thorium has



Alpha decay: a nucleus ejects a helium nucleus.

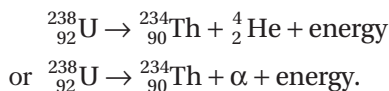
An **α particle** is a relatively slow-moving decay product consisting of two protons and two neutrons. It is equivalent to a helium nucleus and so can be written as ^4_2He . α particles carry a positive charge.

The nucleus remaining after an atom undergoes radioactive decay is called a **daughter nucleus**. The daughter nucleus is more stable than the original nucleus.

A **decay equation** is a representation of a decay reaction. It shows the changes occurring in nuclei and lists the products of the decay reaction.

$^{234}_{90}\text{Th}$ has 90 protons and 144 neutrons (234 nucleons) and is more correctly written as thorium-234.

The information in the previous paragraph can be written much more effectively in symbols. This is called the **decay equation**:



The ejected α particle is relatively slow and heavy compared with other forms of nuclear radiation. The particle travels at 5–7% of the speed of light: roughly 2×10^7 metres each second. Every object that moves has a form of energy known as kinetic energy, or energy of motion. Because the α particle is moving, it has kinetic energy. That energy is written into the decay equation.

In addition to having energy, the α particle has an overall charge of +2 because it contains two protons. This charge means the particle can be deflected by electric or magnetic fields — properties that helped scientists determine what an α particle consisted of.

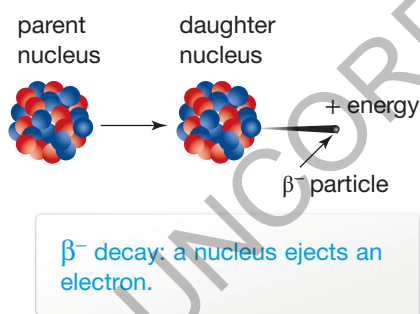
Energy

The main unit of energy used in this text is the joule (J). The joule is a very convenient unit when dealing with large amounts of energy. However, the energy of a moving α particle is comparatively small. Often it is more convenient in this area of physics to use electron volts (eV).

An electron volt is the amount of energy an electron or a proton gains when accelerated across a voltage drop of 1 volt. Because the amount of charge on an electron and a proton is $1.602\,176 \times 10^{-19}$ coulombs, 1 electron volt is equivalent to $1.602\,176 \times 10^{-19}$ joules. The symbol ‘MeV’ means one million electron volts and is equal to $1.602\,176 \times 10^{-13}$ joules. Because the numbers are easier to deal with, the MeV is the unit of preference when working with nuclei.

Energies of nuclear radiation are usually from 0.1 to 10 MeV (megaelectron volts).

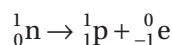
Beta decay



Two types of β decay are possible. The β^- particle is a fast moving electron that is ejected from an unstable nucleus. The β^+ particle is a positively charged particle with the same mass as an electron, and is called a **positron**. Positrons are mostly produced in the atmosphere by cosmic radiation, but some nuclei do decay by β^+ emission.

In β^- decay an electron is emitted from inside the nucleus. Since nuclei do not contain any electrons, this might seem strange, but it is in fact true! There is no change whatsoever to the electrons in the shells surrounding the nucleus.

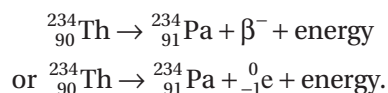
Some very interesting changes take place inside a nucleus to enable it to emit an electron. One of the neutrons in the nucleus transforms into a proton and an electron. The proton remains in the nucleus and the electron is emitted and called a β^- particle:



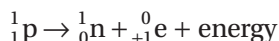
The resulting daughter nucleus has the same number of nucleons as the parent, but one less neutron and one more proton.

An example of β^- decay is the decay of thorium-234. This isotope is the result of the α decay of uranium-238. The nucleus is more stable than it was before the emission of the α particle, but could become more stable by emitting

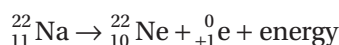
a β^- particle. During this second decay, the mass number of the nucleus is unchanged (234). The number of protons, however, increases by one when a neutron changes into a proton and an electron. There are now 91 ($90 + 1$) protons in the nucleus, so the atom must be called protactinium-234. The decay equation is written as:



In β^+ decay, the positron is also emitted from inside the nucleus. In this case, strange as it may seem, the proton changes into a neutron and a positron with the neutron staying in the nucleus.



The resulting nucleus has one less proton, but the same number of nucleons. An example of β^+ decay is sodium-22 decaying to neon-22:



Beta particles are very light when compared to alpha particles. They travel at a large range of speeds — from that of an alpha particle up to 99 per cent of the speed of light. Just like α particles, β particles are deflected by electric and magnetic fields.

Sample problem 7.2

Write down the complete decay equation in each case:



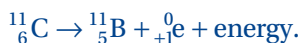
Solution: In [1] the number of particles in the nucleus has decreased by 4, while the number of protons has decreased by 2. This implies that an α particle, or helium nucleus, has been released. The full equation is:



Equation [2] cannot show an α emission, as the mass number remains constant. The atomic number has increased, indicating that a proton has been formed, and therefore β^- decay has occurred. The equation becomes:



In equation [3], the mass number stays the same, but there is one less proton, so it must be β^+ decay. The equation becomes:



Revision question 7.2

Write the equations for:

- (a) the alpha decay of americium-241
- (b) the β^- decay of platinum-197
- (c) the β^+ decay of magnesium-23.

PHYSICS IN FOCUS

In 1928, Paul Dirac developed a mathematical theory to explain the properties of the electron: its mass, charge, role in beta decay and its energy inside the atom. The calculated values for these properties exactly fitted their measured values, but Dirac's equations suggested there may be two solutions — a negatively charged electron and a positively charged electron with the same mass, but opposite charge. Indeed, he raised the possibility of there being another form of matter, which he called 'antimatter'.

In 1932, Carl Anderson discovered the positron when he was researching cosmic rays, which are high-energy charged particles that originate from outside the solar system. Their progressive impacts with atoms as they pass through the atmosphere generates a shower of particles detectable at the Earth's surface. β^+ decay was subsequently discovered.

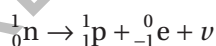
Neutrinos

Alpha particles are emitted with particular energies that are unique to the host nucleus, whereas beta particles are emitted with any energy up to a maximum. When examining decay reactions, scientists found that not all of the energy was accounted for. The possible explanations were:

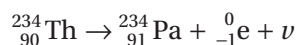
- the Law of Conservation of Energy, one of the foundations of physics, did not apply in nuclear processes
- a second particle, as yet undetected, was emitted. This idea was proposed by Wolfgang Pauli, who said the particle must have no charge, as all the charge was accounted for, and have negligible mass.

Enrico Fermi named the particle 'neutrino', from the Italian for 'little neutral one'. Fermi incorporated Pauli's suggestion into a theory of β decay that not only built on Dirac's work but also derived a mathematical relationship between the half-life of a particular decay and the maximum energy of the emitted β particle. This relationship matched the experimental data, which was convincing evidence for the existence of the neutrino, although it was not actually detected until 1956.

The neutrino has the symbol ν , which is the Greek letter nu. The complete β^- decay process is:



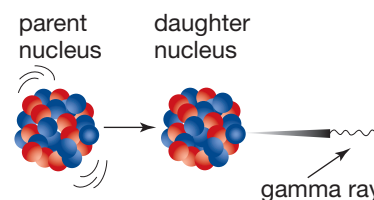
The word 'energy' in β decay equations should be replaced by ν . For example:



Gamma decay

This form of radioactive decay is quite different from either α or β decay. During γ decay a small packet of electromagnetic energy called a **γ ray**, or photon, is emitted, rather than a particle.

(See page xxx for more information about electromagnetic waves.) Gamma emission occurs after another form of nuclear decay has taken place. Following a decay, the arrangement of protons and neutrons in the nucleus may not be ideal, and the nucleus may need to release some extra energy to become more stable. Before the release of this energy, the nucleus is known as 'excited'. An **excited nucleus** is



Gamma decay: an excited nucleus ejects a photon.

A **γ ray** is the packet of electromagnetic energy released when a nucleus remains unstable after α or β decay. γ rays travel at the speed of light and carry no charge.

An **excited nucleus** is one that does not have an ideal arrangement of protons and neutrons in its nucleus. An excited nucleus emits γ radiation to become more stable.

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Investigation 7.1: Radioactive decay

Analyse the radioactive decay of a source.

A **half-life** is the time taken for half of a group of unstable nuclei to decay.

A **decay curve** is a graph of the number of nuclei remaining in a substance versus time elapsed. The half-life of a substance can be determined by looking at the time that corresponds to half of the substance remaining.

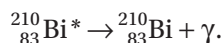
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The Law of Radioactive Decay app

denoted by an asterisk (*) after the symbol for the element. The excess energy is emitted as a γ ray.

One example of γ decay occurs after lead-210 emits a β^- particle and becomes bismuth-210. The excited daughter nucleus goes on to emit a γ ray:



This γ ray is a packet of excess energy. It has no mass and no charge and is not deflected by electric or magnetic fields. Because it is a photon, or packet of electromagnetic energy, it travels at the speed of light.

Half-life

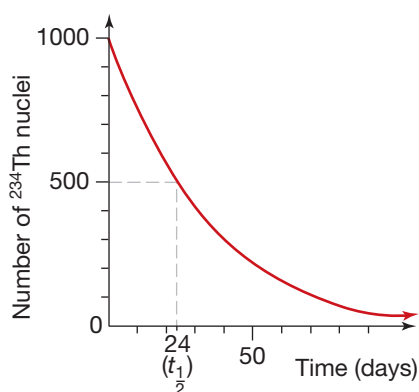
It is not possible to predict exactly when a given unstable nucleus will decay. However, we can predict what proportion of a certain number of nuclei will decay in a given time. It is rather like tossing a coin. We can't be sure that a given toss will result in a tail, but we can predict that, from 1000 tosses, about 500 will result in tails. Scientists know that it will take 24 days for half of a group of unstable thorium-234 nuclei to decay to protactinium-234. The time taken for half a group of unstable nuclei to decay is called the **half-life**. Half-lives vary according to the isotope that is decaying. They range from microseconds to thousands of millions of years.

Mathematicians and scientists often use graphs with the same basic shape as the one in the graph below. It shows what is known as a **decay curve**. This type of curve often appears in science. It is called exponential decay.

TABLE 7.2 Table of half-lives

Element	Decay mode	Half-life
Indium-115	Beta minus	6×10^{14} years
Potassium-40	Beta minus	1.3×10^9 years
Uranium-235	Alpha	7.1×10^8 years
Actinium-227	Alpha	22 years
Thorium-227	Alpha	18 days
Carbon-11	Beta plus	20 minutes
Thallium-207	Beta minus	4.8 minutes
Magnesium-23	Beta plus	11 seconds
Polonium-212	Alpha	3×10^{-7} seconds

Graph showing decay of 1000 thorium-234 nuclei. The time taken for half of the original nuclei (500 nuclei) to remain is called the half-life. It can be seen from this graph that the half-life is 24 days. After the fourth half-life (at time = 96 days) it can be predicted that one-sixteenth of the thorium-234 (about 62 or 63 nuclei) would remain undecayed.



Looking at the graph at left, in the first few days the number of atoms decaying every day is quite high, but towards the end the number is quite low. If there was a Geiger counter near the source at the beginning, it would be clicking quickly, but near the end you would wait minutes for the next click. In fact, a graph of the count rate (the number of clicks per second) will have exactly the same shape and will show the same half-life. The number of decays per second of a radioactive source is a measure of its activity and is measured in Becquerel (Bq).

TABLE 7.3 Activities of some everyday items

Item	Activity (Bq)
1 adult human	3000
1 kg coffee	1000
1 kg granite	1000
1 kg coal ash (used in cement)	2000
1 kg superphosphate fertiliser	5000

Sample problem 7.3

Technetium-99 is often used for medical diagnosis. It has a half-life of 6 hours. A patient has a small amount of the isotope injected into the bloodstream. What fraction of the original amount will remain after:

- (a) 12 hours
(b) 48 hours?

Solution:

- (a) The half-life of technetium-99 is 6 hours, so 12 hours is the same as two half-lives. After the first half-life, half the original nuclei remain. After the second half-life, half of this amount, or one-quarter of the original amount, remain undecayed.
- (b) 48 hours is 8 lots of 6 hours, so the amount of technetium-99 has reduced by $\left(\frac{1}{2}\right)^8$, which equals $\frac{1}{256}$ or 0.004.

Revision question 7.3

Cobalt-60 is radioactive with a half-life of 5.27 years. It is produced from cobalt-59 by bombardment with neutrons at a nuclear reactor. It emits a low-energy beta particle followed by two high-energy gamma rays. It is used in the sterilisation of medical equipment, in radiotherapy and in industrial applications. A cobalt-60 source will need to be replaced when its activity decreases to $\frac{1}{16}$ of its initial value. How long will this take?

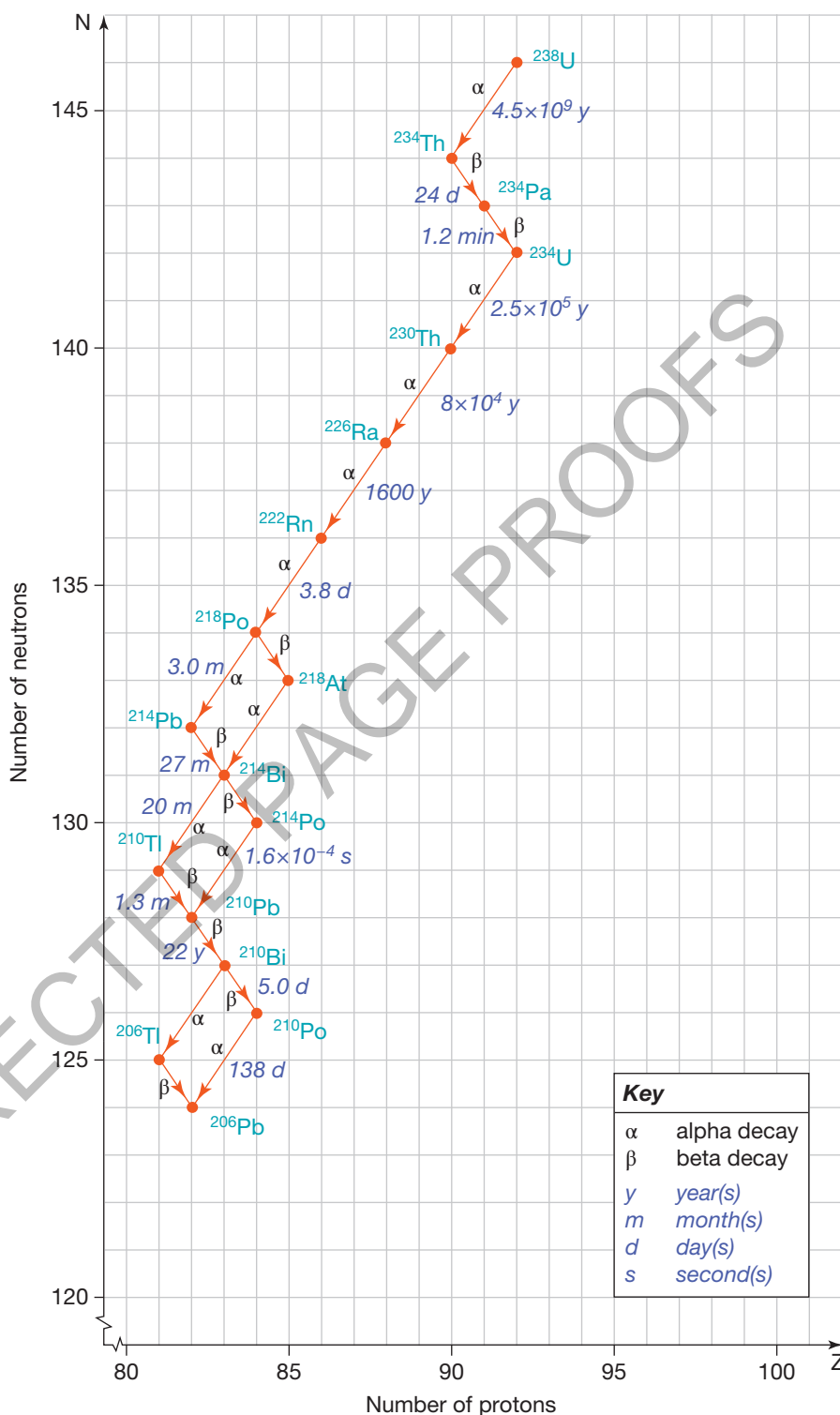
Radioactive series

In its 'quest' to become stable, an isotope may have to pass through many stages. As a radioactive isotope decays, the daughter nucleus is often radioactive itself. When this isotope decays, the resulting nucleus may also be radioactive. This sequence of radioisotopes is called a **decay chain** or decay series.

Uranium-238 undergoes 14 radioactive decays before it finally becomes the stable isotope lead-206. Two other decay chains, one starting with uranium-235 and another with thorium-232, also end with a stable isotope of lead. Another decay chain once passed through uranium-233, but this chain is almost extinct in nature now due to its shorter half-lives.

Not all naturally occurring radioisotopes are part of a decay series. There are about 10 with atomic numbers less than that of lead, for example potassium-40. How can there be radioisotopes isolated in the periodic table? A look at the half-lives of potassium-40 and indium-115 reveals the answer (see table 7.2, page 107). Their half-lives are so long, greater than the age of the Earth, that they are still decaying from when they were formed in a supernova explosion billions of years ago.

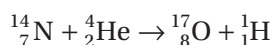
A **decay chain**, also known as a decay series, is the sequence of stages a radioisotope passes through to become more stable. At each stage, a more stable isotope forms. The chain ends when a stable isotope forms.



Nuclear transformations

Alpha and beta decay are natural examples of nuclear transformations. The numbers of protons and neutrons in the nucleus change during these processes. Artificial nuclear transformations are also possible. These are done either to investigate the structure of the nucleus or to produce specific radioisotopes for use in medicine or industry. The first artificial transformation was

made by Ernest Rutherford, who fired alpha particles at nitrogen atoms to produce an isotope of oxygen.



This result raised the intriguing possibility of achieving the alchemist's dream of changing lead into gold. Although prohibitively expensive, it appears to be theoretically possible.

The building of particle accelerators in the early 1930s enabled charged particles such as protons to be fired at atoms as well as alpha particles, but with the advantage that their energy could be pre-set. The limitation of both these particles is that since they are positively charged, they have to be travelling at very high speed to overcome the repulsion of the positively charged nucleus. This problem was overcome with the discovery of the neutron in 1932. The neutron, which has no net charge, can enter the nucleus at any speed. Both protons and neutrons are used today to produce radioisotopes. Particle accelerators firing positive ions produce neutron-deficient radioisotopes such as thallium-201 ($t_{1/2} = 73$ days), which is used to show damaged heart tissue, and zinc-65 ($t_{1/2} = 244$ days), which is used as a tracer to monitor the flow of heavy metals in mining effluent. Neutrons from nuclear reactors produce neutron-rich radioisotopes such as iridium-192 ($t_{1/2} = 74$ days), which is used to locate weaknesses in metal pipes, and iodine-131 ($t_{1/2} = 8.0$ days), which is used in the diagnosis and treatment of thyroid conditions.

Particle accelerators are also used to produce new elements with atomic numbers greater than that of uranium. The hunt is on for a new stable element. In 2007, calcium-48 ions were fired at californium-249 atoms to produce the element with atomic number 118. Only three atoms were produced, and as the half-life of this isotope is 0.89 ms, they don't exist any more.

PHYSICS IN FOCUS

What's in the nucleus?

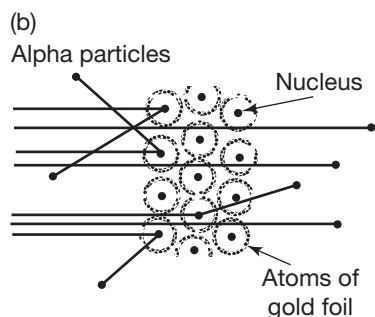
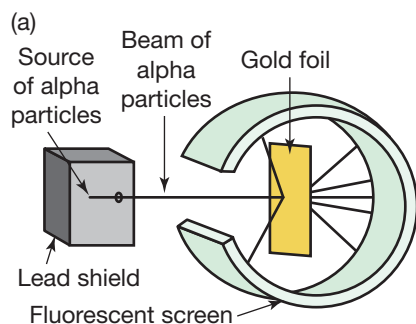
Early experiments with radioactivity produced the nuclear model of the atom with nearly all its mass in a small, positively charged, central core called the nucleus, with negatively charged electrons moving like planets around it. The number of protons in the nucleus was the element's atomic number, but the mass of the protons was about half the mass of the atom, so there must be something else inside the nucleus.

Beta particles were emitted from the nucleus, so Ernest Rutherford suggested that the additional mass came from proton-electron pairs, called a 'neutral doublet'. He was predicting the existence of a neutron about 12 years before it was discovered by Chadwick.

Discovering the structure of the atom

The nuclear timeline on page xxx shows that Ernest Rutherford was one of the central players in the investigation of radioactivity. By 1908, Rutherford and his team had determined that alpha particles were doubly charged helium ions and that they were moving very fast — at about 5% of the speed of light. They quickly realised that these particles would be ideal 'bullets' to investigate the structure of the atom.

Two of Rutherford's younger colleagues, Hans Geiger and Ernest Marsden, fired alpha particles at a very thin foil of gold, about 400 atoms thick, and measured their angle of deflection. Nearly all of the particles either went straight through or suffered a very small deflection, but about 1 in every 8000 came back.



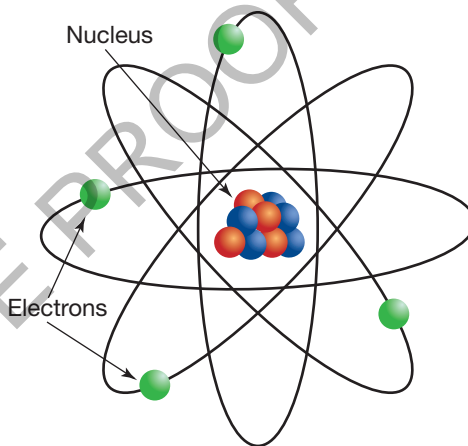
Geiger and Marsden's gold foil experiment

The positively charged α particle was repelled and deflected by the electrostatic interaction with the positive charges in the atom. Rutherford believed that for an α particle to be turned around, these positive charges would need to be concentrated in a very small volume, which he called the 'nucleus'. He calculated that the radius of such a nucleus would be about 10^{-14} m, and the radius of an atom was about 10^{-10} m.

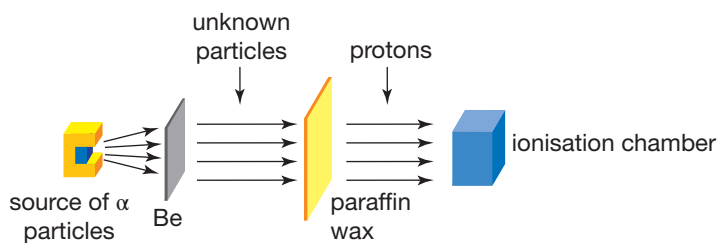
Rutherford's nuclear model of the atom had nearly all the mass of the atom in the central nucleus and the much lighter electrons 'orbiting' around it.

However, this model was incomplete because it did not fully explain the mass of an atom. At the time it was known that an alpha particle, that is a helium ion, had exactly twice the positive charge of a hydrogen ion, so presumably contained two protons, but was almost exactly four times as heavy. There were a number of explanations for this anomaly. One was that the extra mass was made up of proton-electron pairs, which would effectively have zero charge; another was that there was an as yet unknown neutral particle in the nucleus.

It was only in the 1930s that this neutral particle, called the 'neutron', was discovered. In 1930, Walter Bothe and Herbert Becker fired alpha particles at beryllium and detected what they thought was gamma radiation. The husband-and-wife team Frédéric Joliot and Irène Joliot-Curie (daughter of Marie Curie) placed hydrogen-rich paraffin wax in front of this 'gamma radiation' and observed the ejection of protons. While they explored the possibility of very high energy radiation, James Chadwick showed that this was virtually impossible; instead, he demonstrated that a single neutron was ejected when the alpha particle entered the beryllium nucleus, which in turn knocked on a proton in a simple billiard-ball-like collision.



Rutherford's model of the atom



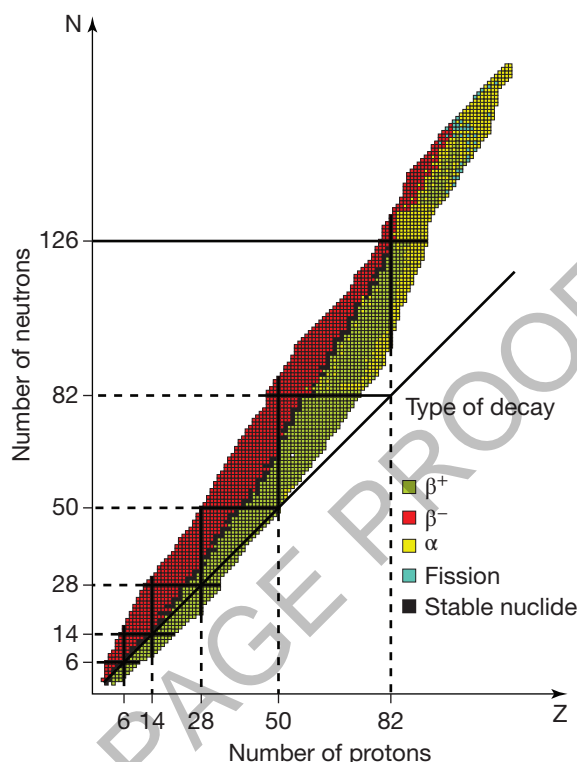
Discovery of the neutron

The discovery of the neutron now provided an explanation for the existence of isotopes: atoms with the same atomic number but different atomic mass due to different numbers of neutrons.

The stability of nuclei

The stability of any nucleus depends on the number of protons and neutrons. For small nuclei to be stable, the number of protons must roughly equal the number of neutrons. As the number of protons increases, however, more neutrons are needed to maintain stability.

The complex nature of the figure below indicates that there is more to the question of stability than a simple ratio.

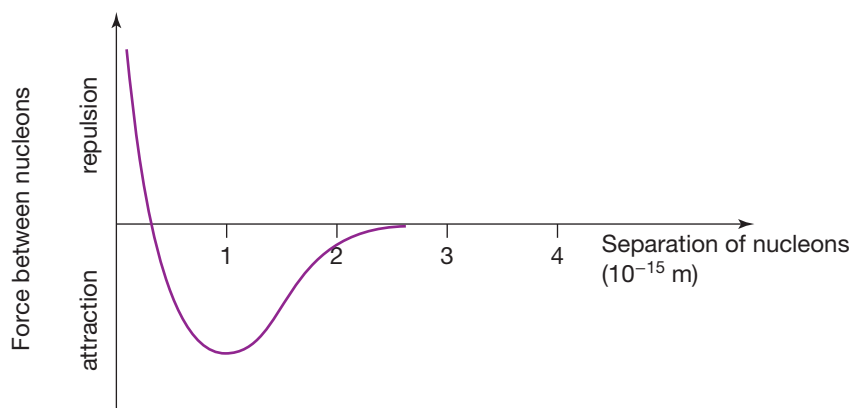


This graph shows which nuclei are stable (black) and which are unstable (oth.).

What holds the nucleus together?

The force that holds electrons around a nucleus is called an electrostatic force. Electrostatic forces increase as charges move closer together. Electrostatic attraction exists between unlike charges; electrostatic repulsion exists between like charges. So, it seems strange that the positive charges inside a nucleus don't repel each other so strongly that the nucleus splits apart. In fact, two protons do repel each other when they are brought together, but in the nucleus they are so close to each other that the force of repulsion is overcome by an even stronger force — the **strong nuclear force**. While the strong nuclear force is, as its name suggests, a very strong force, it is able to act over only incredibly small distances. Inside a nucleus, the nucleons are sufficiently close that the pull of the strong nuclear force is much greater than the push of the protons repelling each other, and therefore the nucleus remains intact.

The **strong nuclear force** is the force that holds nucleons together in a nucleus of an atom. It acts over only very short distances.



The graph shows how the strong nuclear force between two nucleons varies with the separation of the nucleons.

AS A MATTER OF FACT

The forces that hold the nucleus together are much stronger than the forces that hold electrons to the nucleus. This means that changes to the nucleus can release much more energy than changes to the electrons; therefore, nuclear reactions are much more powerful than chemical reactions. Nuclear changes in a baseball-sized lump of uranium-235 can release a similar amount of energy to the chemical changes in 20 000 tonnes of TNT!

What makes the nucleus change?

The **weak nuclear force** explains the transformation of neutrons into protons and vice versa.

The **weak nuclear force** is the force used to explain the transformation of neutrons into protons and vice versa. It is the mechanism underlying beta decay, fission, which is the splitting of heavy nuclei, and fusion, which is the joining of light nuclei. The strength of the weak nuclear force is about one millionth that of the strong force, and it acts over a distance of 0.1% of the diameter of a proton, which is one thousandth that of the strong force!

TABLE 7.4 Types of forces, their relative strengths and ranges

Force	Strength	Range	Type
Strong nuclear	1	10^{-15} m (diameter of a nucleus)	Attractive
Electric and magnetic	$\frac{1}{137}$	Infinite	Attractive or repulsive
Weak nuclear	$\frac{1}{1000000}$	10^{-18} m (fraction of proton diameter)	Attractive
Gravity	$\frac{1}{10^{38}}$	Infinite	Attractive

Binding energy

The **binding energy** of a nucleus is the energy that is required to split a nucleus into individual nucleons.

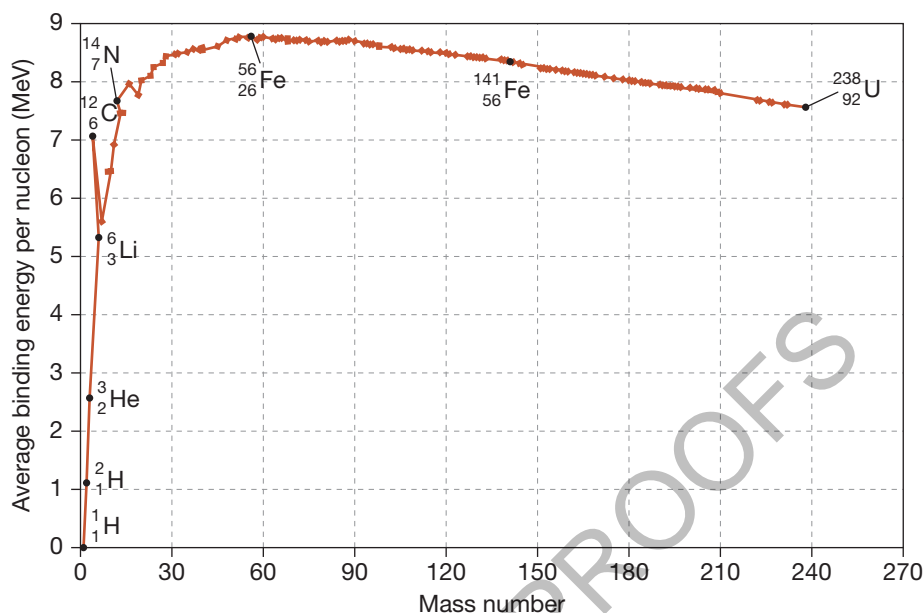
The amount of energy needed to overcome the strong nuclear force and pull apart a nucleus is known as the **binding energy**. This is the amount of energy that has to be added to a nucleus to split it into its individual nucleons: that is, to reverse the binding process. For example, it would take 2.23 MeV of energy to split a 'heavy' hydrogen nucleus into a separate proton and neutron.

Each isotope has its own specific binding energy. Nuclei with high binding energies are very stable as it takes a lot of energy to split them. Nuclei with lower binding energies are easier to split. Of course, it is difficult to supply sufficient energy to cause a nucleus to split totally apart. It is much more common for a nucleus to eject a small fragment, such as an α or β particle, to become more stable.

To compare the binding energies of various nuclei, and therefore their stability, it is easiest to look at the average binding energy per nucleon. The average binding energy per nucleon is calculated by dividing the total binding energy of a nucleus by the number of nucleons in the nucleus.

It can be seen from the figure below that iron has the highest binding energy per nucleon. This means it is the most stable of all nuclei. In order to become more stable, other nuclei tend to release some of their energy. Releasing this energy would decrease the amount of energy they contained, and therefore increase the amount of energy that must be added to split them apart.

This graph of binding energy versus mass number shows that iron has the most stable nucleus.



Nuclear energy

The binding energy is not only the amount of energy required to separate a nucleus into its component parts, but it is also the amount of energy released when those parts are brought together to form the nucleus. That is, when a proton and a neutron collide to form a 'heavy' hydrogen nucleus, 2.23 MeV of energy is released.

The curve of the binding energy graph above indicates that if two nuclei with low mass numbers could be joined together to produce a nucleus higher up the graph, then a lot of energy would be released. Similarly, if a nucleus with a very high mass number could split into two fragments higher up the graph, then once again a lot of energy would be released. These two possibilities were realised in the 1930s. The released energy can be calculated from Einstein's equation $E = mc^2$, where m is the difference between the total nuclear mass before and after the event, and c is the speed of light.

The joining together of two nuclei is called **nuclear fusion**, and the splitting of a single nucleus is called **nuclear fission**.

Nuclear fission

In 1934, Enrico Fermi investigated the effect of firing neutrons at uranium. The products had half-lives different from that of uranium. He thought that he had made new elements with atomic numbers greater than 92. Others repeating the experiment got different half-lives. In 1939, Otto Hahn and Fritz Strassmann chemically analysed the samples and found barium, which has atomic number 56, indicating that the nuclei had split.

Lise Meitner and Otto Frisch called this process 'fission' and showed that neutrons could also initiate fission in thorium and protactinium. Further chemical analysis revealed a range of possible fission reactions, each with a different combination of **fission fragments** including bromine, molybdenum or rubidium (which have atomic numbers around 40), and antimony, caesium or iodine (which have atomic numbers in the 50s). Cloud chamber photographs showing two heavy nuclei flying off in opposite directions confirmed that fission had occurred. Meitner and Frisch also calculated from typical binding energies that the fission of one uranium-235 nucleus would produce about 200 MeV of energy, mainly as kinetic energy of the fission fragments. This is a huge amount of energy to be released by one nucleus, as can be seen

Nuclear fusion is the process of joining together two nuclei to form a larger, more stable nucleus.

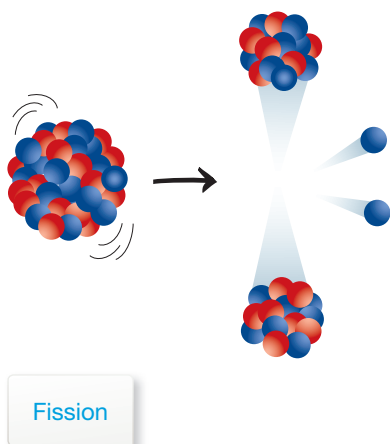
Nuclear fission is the process of splitting a large nucleus to form two smaller, more stable nuclei.

eBookplus

Weblink

Fission animation

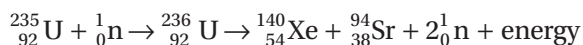
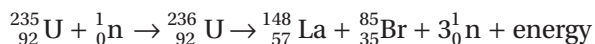
Fission fragments are the products from a nucleus that undergoes fission. The fission fragments are smaller than the original nucleus.



when it is compared to the burning of coal in power plants. Each atom of carbon used in coal burning releases only 10 eV of energy — about 20 million times less than the energy released in the fission of uranium-235.

Also in 1939, Frederic Joliot and his team confirmed that two or three fast neutrons were emitted with each fission reaction. This allowed for the possibility of a chain reaction, which could potentially release enormous amounts of energy.

Some possible equations for the fission of uranium-235 set off by the absorption of a neutron are:

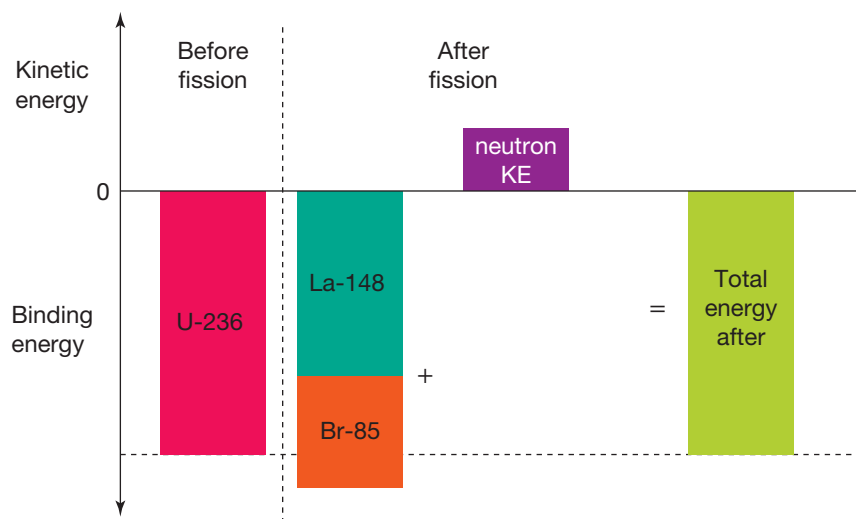


The data in the previous graph on binding energies and Einstein's equation $E = mc^2$ can be used to calculate the amount of energy released in each of the fission reactions above.

TABLE 7.5 Masses and binding energies of atoms

Nucleus	Symbol	Mass (kg)	Total binding energy (MeV)
Uranium-236	${}_{92}^{236}\text{U}$	$3.919\,629 \times 10^{-25}$	1790.415 039
Lanthanum-148	${}_{57}^{148}\text{La}$	$2.456\,472 \times 10^{-25}$	1213.125 122
Bromine-85	${}_{35}^{85}\text{Br}$	$1.410\,057 \times 10^{-25}$	737.290 649
Barium-141	${}_{56}^{141}\text{Ba}$	$2.339\,939 \times 10^{-25}$	1173.974 609
Krypton-92	${}_{36}^{92}\text{Kr}$	$1.526\,470 \times 10^{-25}$	783.185 242
Xenon-140	${}_{54}^{140}\text{Xe}$	$2.323\,453 \times 10^{-25}$	1160.734 009
Strontium-94	${}_{38}^{94}\text{Sr}$	$1.559\,501 \times 10^{-25}$	807.816 711
Neutron	${}_0^1\text{n}$	$1.674\,924 \times 10^{-27}$	

Speed of light, c , = $2.997\,924\,58 \times 10^8$ m/s. 1 MeV = $1.602\,176 \times 10^{-13}$ joules.



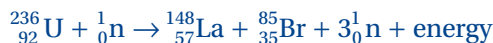
Graph of energies in a fission reaction. The sum of the binding energies of La-148 and Br-85 is greater than the binding energy of U-236. The difference is released as kinetic energy of the neutrons and the fission fragments. The total energy after fission is the same as the energy before.

Sample problem 7.4

Answer the following questions about the fission of uranium-236 producing lanthanum-148 and bromine-85. Use table 7.4 for data on masses and binding energies.

- What is the difference between the binding energy of the uranium-236 nucleus and the sum of the binding energies of the two fission fragments?
- What is the difference between the mass of the uranium-236 nucleus and the sum of the masses of the all fission fragments, including neutrons?
- Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV.

Solution: From above, we know that the equation for this fission is:



Binding energy of uranium-236 = 1790.415 039 MeV

Sum of binding energies of fragments = 1213.125 122 + 737.290 649 MeV
= 1950.415 771 MeV

Energy difference = 1950.415 771 – 1790.415 039 MeV
= 160.000 732 MeV

Mass of uranium-236 = $3.919\,629 \times 10^{-25}$ kg

Sum of masses of fragments = $2.456\,472 \times 10^{-25} + 1.410\,057 \times 10^{-25} + 3$
 $\times 1.674\,924 \times 10^{-27}$ kg
= $3.916\,777 \times 10^{-25}$ kg

Mass difference = $0.002\,852 \times 10^{-25}$ kg

Energy difference in joules = mc^2
= $0.002\,852 \times 10^{-25} \times (2.997\,924\,58 \times 10^8)^2$
= $2.563\,250 \times 10^{-11}$ J

Energy difference in MeV = $2.563\,250 \times 10^{-11} \div 1.602\,176 \times 10^{-13}$
= 159.985 545 MeV

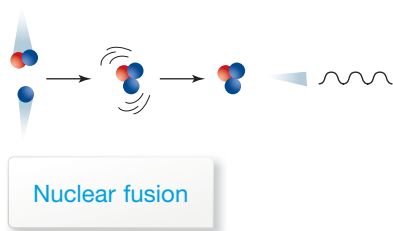
The two answers are effectively identical. The slight difference in the two answers is due to rounding errors, because of the different powers of 10 in the data values.

Revision question 7.4

Now answer the questions from sample problem 7.4 for the fission of U-236 to Ba-141 and Kr-92. Also answer the questions for the fission to Xe-140 and Sr-94.

Nuclear fusion

Nuclear fusion is the process of joining two smaller nuclei together to form a larger more stable nucleus. This was first observed by Australian physicist Mark Oliphant in 1932 when he was working with Ernest Rutherford. He was searching for other isotopes of hydrogen and helium. Heavy hydrogen (one proton and one neutron) was already known, but Oliphant discovered tritium (one proton and two neutrons) and helium-3 (with only one neutron). In his investigation he fired a fast heavy hydrogen nucleus at a heavy hydrogen target to produce a nucleus of tritium plus an extra neutron. This fusion reaction was to become the basis of the hydrogen bomb, but Oliphant was only interested in the structure of the nucleus and did not realise the energy implications. For fusion to occur more extensively, high temperatures and pressures are needed, such as those that exist inside the Sun or in a fission bomb explosion.



The Sun's core has a temperature of more than 15 million K, just perfect for fusion to occur! Inside the Sun, hydrogen nuclei fuse together to form helium. As helium is more stable than hydrogen, the excess nuclear energy is released. This energy is emitted from the nuclei as γ radiation, and is eventually received on Earth as light and heat.

Fusion reactions also take place in other stars. Stars that are bigger than the Sun have such severe conditions that larger, more stable nuclei such as silicon and magnesium can be produced from the fusion of smaller nuclei. A star about 30 times more massive than the Sun would be needed to produce conditions that would enable the formation of iron by fusing smaller nuclei.

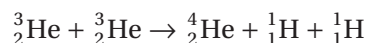
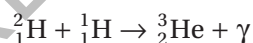
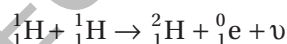
Our Sun

The chain of events occurring in the Sun is quite complex. The major component of the Sun is ${}^1_1\text{H}$; that is, nuclei consisting of only one proton and no neutrons. When collisions occur between ${}^1_1\text{H}$ nuclei, they fuse together in an unusual way. One of the protons is changed into a neutron (in much the same way as a neutron is changed into a proton and an electron during β^- decay). This forms a ${}^2_1\text{H}$ nucleus. The by-products of this process are a positron and a neutrino.

Positrons are produced when some artificially produced isotopes undergo radioactive decay. Positrons are the opposite of electrons; they have the same mass, but carry a positive charge. When a positron and an electron collide, they immediately annihilate each other. The only thing that remains of either is a gamma ray. Neutrinos are produced when protons change into neutrons and vice versa. They have no charge, are considered massless and travel at close to the speed of light. Fifty trillion neutrinos from the Sun pass through the human body every second.

When a ${}^1_1\text{H}$ nucleus and a ${}^2_1\text{H}$ nucleus collide, they form a more stable ${}^3_2\text{He}$ nucleus, and release the extra energy as a γ ray. If two ${}^3_2\text{He}$ nuclei collide, they complete the process of turning hydrogen into helium. The collision results in the formation of a ${}^4_2\text{He}$ nucleus and two ${}^1_1\text{H}$ nuclei. Again, energy is released. The energy released during nuclear reactions inside the Sun provides energy for life on Earth.

This is the sequence of nuclear equations that occur in the Sun to convert hydrogen to helium:



AS A MATTER OF FACT

All the atoms that make up your body (and the rest of the atoms in the Earth) were originally produced in a star. Fusion in stars caused all the atoms to be formed. Those nuclei with atomic numbers up to that of iron were produced in regular stars. However, when large stars stop producing energy from fusion of elements up to iron, they implode, or collapse in on themselves. This causes conditions in which even large atoms will fuse together to produce very heavy elements such as gold, lead and uranium. (This is not energetically favourable, but does occur in very extreme circumstances.) If these stars later explode as supernovas, they spread the elements they have made out into space. The Earth was formed from a cloud consisting of the remnants of an old supernova.

The binding energy can be used to determine the amount of energy released in a fusion reaction.

Sample problem 7.5

In the final reaction above, two helium-3 nuclei collide to produce a helium-4 nucleus and two hydrogen-1 nuclei, that is, two protons. Use the data in the table below to calculate:

- the difference between the binding energy of the helium-4 nucleus and sum of the binding energies of the two helium-3 nuclei
- the difference between the sum of masses of the helium-4 nucleus and the two protons, and mass of two helium-3 nuclei
- the energy equivalent of this mass difference in joules and MeV.

Particle	Symbol	Mass (kg)	Total binding energy (MeV)
Helium-3	${}^3_2\text{He}$	$5.022\,664 \times 10^{-27}$	7.718 058
Helium-4	${}^4_2\text{He}$	$6.665\,892 \times 10^{-27}$	28.295 673
Proton	${}^1_1\text{p}$ or ${}^1_1\text{H}$	$1.678\,256 \times 10^{-27}$	

- Solution:**
- Binding energy of helium-4 nucleus = 28.295 673 MeV

Binding energy of two helium-3 nuclei = $2 \times 7.718\,058 = 15.436\,116$ MeV

Difference = $28.295\,673 - 15.436\,116 = 12.859\,557$ MeV
 - Mass before fusion = $2 \times 5.022\,664 \times 10^{-27} = 10.045\,328 \times 10^{-27}$ kg

Mass after fusion = $6.665\,892 \times 10^{-27} + (2 \times 1.678\,256 \times 10^{-27})$

$= 10.022\,404 \times 10^{-27}$ kg

Mass difference = $0.022\,924 \times 10^{-27}$ kg
 - Energy equivalent (in joules) = mc^2

$= 0.022\,924 \times 10^{-27} \times (2.997\,924\,58 \times 10^8)^2$

$= 2.060\,306 \times 10^{-12}$ joules

Energy equivalent (in MeV) = $2.060\,306 \times 10^{-12} \text{ J} \div 1.602\,176 \times 10^{-13} \text{ (MeV/J)}$

$= 12.859\,426$ MeV

PHYSICS IN FOCUS

Lise Meitner (1878–1968)

Lise Meitner was the physicist who coined the term ‘fission’ and, along with her nephew Otto Frisch, explained the splitting of uranium nuclei into barium and lanthanum.

Born in Vienna, Lise was fascinated by the world around her from an early age. A talented student, she wanted to understand the things she observed in nature. Having decided that she would like to pursue her interest in physics and mathematics, Lise engaged a private tutor to prepare her for the university entrance exams, as schools that taught such subjects would not accept girls at that time. She was the second woman to be granted a Doctorate in Physics from the University of Vienna, conferred in 1906.

Lise then moved to the Institute of Experimental Physics in Berlin to work with Otto Hahn. Initially, this proved difficult. Lise was forced to work in a converted workshop as females were not permitted to use the facilities available to male students. As

the place of women in the institute became more accepted, Lise was given positions of responsibility, finally being made a professor in 1926. During her time at the institute, Lise made many important contributions to atomic and particle physics, including the co-discovery with Otto Hahn of the radioactive element protactinium.

In 1938 Berlin became a dangerous place for Jews, and Lise moved to Sweden. It was there she and Otto Frisch interpreted the results of experiments conducted by Otto Hahn and Fritz Strassman to come up with the first explanation of the fission process. In doing so, Lise was the first person to use Einstein’s theory of mass–energy equivalence to calculate the energy released during fission.

Her international reputation led to an invitation to join the Manhattan Project in 1941 and work on the development of the atomic bomb. Lise objected to the project and declined the offer. She continued to work in Sweden until moving to England in 1960, finally retiring at the age of 82.

Chapter review

Summary

- Nuclear radiation is emitted from the nucleus of unstable atoms (radioisotopes) that are striving to become more stable.
- There are four types of radiation: α , β^- , β^+ and γ radiation.
- α particles are released during α decay. α particles are slow-moving particles that are equivalent to a helium nucleus and can be represented as ${}^4_2\text{He}$. After α decay, the mass number of the daughter nucleus is four less than that of the parent nucleus and the atomic number is two less.
- β^- particles are released in β^- decay. β^- particles are high-speed electrons released from the nucleus when a neutron transforms into a proton and an electron. After β^- decay, the mass number of the daughter nucleus is the same as that of the parent nucleus, but the atomic number is one more than that of the parent nucleus.
- β^+ particles are released in β^+ decay. β^+ particles are high-speed positrons emitted from the nucleus when a proton transforms into a neutron. The atomic number of the daughter nucleus is one less than the parent nucleus; the mass number remains the same.
- γ radiation is electromagnetic radiation that is emitted when an excited nucleus becomes more stable. γ rays are emitted during α and β decay.
- In all nuclear transformations, atomic and mass numbers are conserved.
- Half-life is the time for half of a group of unstable nuclei to decay. It is different for every isotope. The shorter the half-life of an isotope, the greater the activity; that is, the greater the number of decays per second. Activity decreases over time as less and less of the isotope remains. Activity is measured in becquerel (Bq).
- Isotopes may pass through a sequence of decays in order to become stable. Such a sequence is called a decay chain, or decay series.
- The force that holds nucleons together in a nucleus of an atom is called a strong nuclear force. It acts over a very short distance and is strong enough to overcome the electrostatic force of repulsion that exists between the protons of a nucleus.
- The nuclei of different atoms have varying degrees of stability. The binding energy of a nucleus is the energy required to completely separate a nucleus into individual nucleons. Therefore the binding energy is a measure of the stability of a nucleus. Iron is the most stable of all nuclei.

- In order for a nucleus to become more stable, it emits energy called nuclear energy. The amount of energy released is related to the size of the difference between the mass of a nucleus and the mass of the individual nucleons.
- Fusion reactions generally occur between nuclei smaller than iron. Fusion occurs in our sun, where it converts hydrogen nuclei into helium nuclei and releases large amounts of energy.
- Fission reactions occur when a nucleus is split into smaller, more stable fission fragments.

Questions

Structure of the atom

- How many protons and neutrons are in the following atoms?

(a) ${}^{66}_{30}\text{Zn}$	(c) ${}^{45}_{20}\text{Ca}$
(b) ${}^{230}_{90}\text{Th}$	(d) ${}^{31}_{14}\text{Si}$
- Write the symbols for isotopes containing the following nucleons:

(a) two neutrons and two protons
(b) seven protons and 13 nucleons
(c) 91 protons and 143 neutrons.
- Write the elemental name and the number of protons and neutrons in each of the following:

(a) Au-197	(b) ${}^{210}_{83}\text{Bi}$	(c) ${}^{210}_{82}\text{Pb}$.
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- Explain why it is possible to have two atoms of different elements with the same number of nucleons.

Radioactive decay and nuclear transformations

- From where in an atom are α and β particles and γ rays emitted?
- In each of the following, determine the type of decay that has occurred:

(a) ${}^{14}_6\text{C} \rightarrow {}^{14}_7\text{N} + \text{X} + \text{energy}$
(b) ${}^{90}_{38}\text{Sr} \rightarrow {}^{90}_{39}\text{Y} + \text{X} + \text{energy}$
(c) ${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + \text{X} + \text{energy}$
- Write a decay equation to show the α decay of:

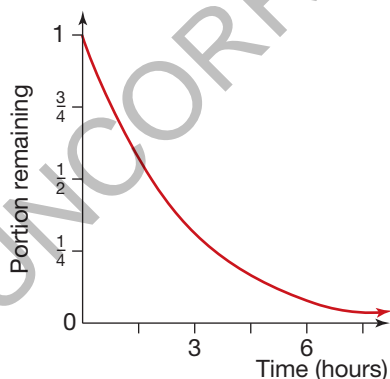
(a) radium-226
(b) polonium-214
(c) americium-241.
- Write a decay equation to show the β^- decay of:

(a) cobalt-60
(b) strontium-90
(c) phosphorus-32.

9. Write a decay equation to show the γ decay of excited magnesium-24.
10. Complete the following general decay equations:
 - (a) α decay: ${}^Z_X \rightarrow {}^?_?D + ? + \text{energy}$
 - (b) β^- decay: ${}^Z_X \rightarrow {}^?_?E + ? + \text{energy}$
 - (c) γ decay: ${}^Z_X^* \rightarrow ? + ?$
 - (d) ${}^{27}_{13}\text{Al} + {}^2_1\text{H} \rightarrow ? + {}^1_0\text{n}$
 - (e) ${}^{22}_{11}\text{Na} + {}^4_2\text{He} \rightarrow ? + {}^1_1\text{H}$
11. Draw a small decay chain graph, similar to that given for uranium-238 on page xxx, for the β^- decay of yttrium-90. (*Hint*: There is only one decay.)
12. How is β^- decay of a nucleus possible when a nucleus does not contain electrons?
13. How many α particles are released by one atom of uranium-238 as it becomes lead-206? How many β particles are released? (*Hint*: Look at the change in the proton number and the change in the nucleon number.) Check your answer by using the figure on page xxx.
14. Repeat question 13 for the following decay series.
 - (a) Uranium-235 to lead-207
 - (b) Thorium-232 to lead-208
15. In a decay chain, radium-226 emits two α particles, then one β^- particle. What is the element at the end of this sequence and what is its atomic mass?
16. Bismuth-212 has two possible decay modes: an α decay followed by a β^- decay, or a β^- decay followed by an α decay. The first mode happens about 36% of the time. Will the two modes produce different final results? Explain.

Half-life

17. What is the half-life of the substance represented in the graph below?



18. Sketch a decay curve for technetium, which has a half-life of 6 hours.
19. Assume the half-life of carbon-14 is 5730 years. If you had 1 g of carbon-14, how many years would it take for one-eighth of it to remain?
20. The artificial isotope ${}^{15}_8\text{O}$ is used in medical diagnosis. It has a half-life of 120 seconds. If a

doctor requires 1 μg of the isotope at exactly 2 pm, how many grams must be delivered to the room 30 minutes earlier? (*Hint*: How much will be needed at 1:58 pm? How much will be needed at 1:56 pm? At 1:54 pm? Can you see a pattern?)

21. Americium-241 is an alpha emitter with a half-life of 432.2 years. It is used in smoke detectors because when the smoke absorbs the α particles, the current drops and the alarm is triggered. The label on the smoke detector says it contains 0.20 micrograms of americium-241 with an activity of 27.0 kBq.
 - (a) Determine the activity of the americium-241 after 0, 1, 2, 3 and 4 half-lives.
 - (b) Plot the data and draw a smooth graph (assuming the half-life is 400 years).
 - (c) Use your graph to estimate the activity after:
 - (i) 100 years
 - (ii) 50 years.
 - (d) What is the implication of your answers to part (c) for the lifetime of the smoke detector?
 - (e) Write down the decay equation for americium-241 and do an internet search to determine the decay chain.
22. The activity of a radioactive sample drops from 8.0 kBq to 1.0 kBq in 6.0 hours. What is its half-life?
23. Cobalt-60 has a half-life of 5.3 years. If a sample has an activity of 250 GBq (2.5×10^{11} disintegrations per second), what will the activity be in 21.2 years?

The nucleus

24. Explain how individual nucleons are held together in a nucleus, given that like charges repel.
25. (a) Define the terms 'fusion' and 'fission'.
(b) Which of these reactions occurs in our Sun?
26. Explain why *splitting* uranium-235 nuclei releases energy, but *joining* hydrogen atoms also releases energy.
27. Use the graph of binding energy per nucleon (see the figure on page XXX) to estimate the amount of energy released when a uranium-235 nucleus is split into barium-141 and krypton-92. Think carefully about the number of significant figures in your answer. How well does your answer agree with the measured value of 200 MeV?
28. Why is energy released in the process of fusing two small nuclei together?
29. How can a neutron produce an ion?

Nuclear fission and fusion

30. Why are neutrons good at initiating nuclear reactions?
31. In what form does the energy released from a nuclear fusion reaction appear?

Use the following table to help answer questions 32, 33 and 34.

Nucleus	Symbol	Mass (kg)	Total binding energy (MeV)
Plutonium-240	${}^{240}_{94}\text{Pu}$	$3.986\,187 \times 10^{-25}$	1813.454 956
Strontium-90	${}^{90}_{38}\text{Sr}$	$1.492\,953 \times 10^{-25}$	782.631 470
Barium-147	${}^{147}_{56}\text{Ba}$	$2.439\,896 \times 10^{-25}$	1204.158 203
Uranium-234	${}^{234}_{92}\text{U}$	$3.886\,341 \times 10^{-25}$	1778.572 388
Zirconium-95	${}^{95}_{40}\text{Zr}$	$1.575\,985 \times 10^{-25}$	821.139 160
Tellurium-136	${}^{136}_{52}\text{Te}$	$2.257\,006 \times 10^{-25}$	1131.440 918
Neutron	${}_0^1\text{n}$	$1.674\,924 \times 10^{-27}$	
Proton	${}_1^1\text{p}$ or ${}_1^1\text{H}$	$1.678\,256 \times 10^{-27}$	
Hydrogen-2	${}_1^2\text{H}$ or ${}_1^2\text{D}$	$3.344\,494 \times 10^{-27}$	2.224 573
Hydrogen-3	${}_1^3\text{H}$ or ${}_1^3\text{T}$	$5.008\,267 \times 10^{-27}$	8.481 821
Helium-4	${}_2^4\text{He}$	$6.665\,892 \times 10^{-27}$	28.295 673
Lithium-6	${}_3^6\text{Li}$	$9.988\,344 \times 10^{-27}$	31.994 564

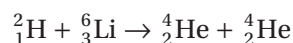
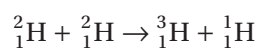
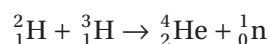
- 32.** A plutonium-239 nucleus absorbs a neutron to become plutonium-240, which splits to form strontium-90, barium-147 and 3 neutrons.

- What is the difference between the binding energy of the plutonium-240 nucleus and the sum of the binding energies of the two fission fragments?
- What is the difference between the mass of the plutonium-240 nucleus and the sum of the masses of all the fission fragments, including neutrons?
- Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV.

- 33.** A uranium-233 nucleus absorbs a neutron to become uranium-234, which splits to form zirconium-95, tellurium-136 and 3 neutrons

- What is the difference between the binding energy of the uranium-234 nucleus and the sum of the binding energies of the two fission fragments?
- What is the difference between the mass of the uranium-234 nucleus and the sum of the masses of all the fission fragments, including neutrons?
- Use $E = mc^2$ to calculate the energy equivalent of this mass difference in joules and MeV.

- 34.** A fusion reactor could not feasibly use the same reactions as the Sun. A reactor on Earth would have to use a different reaction, preferably a one-step reaction with only two reactants. Three possible reactions for a terrestrial fusion reactor are displayed below; there are many others.



Using data from the table above, calculate:

- the difference between the binding energy of the products and the sum of the binding energies of the reactants
- the difference between the sum of masses of the products and of the reactants
- the energy equivalent of this mass difference in joules and MeV.