Study design

- **explain nuclear stability with reference to the forces in the nucleus including electrostatic forces, the strong nuclear force and the weak nuclear force**
- **model radioactive decay as random decay with a particular half-life, including mathematical modelling with reference to whole half-lives**
- **describe the properties of α, β-, β+ and γ radiation**
- **explain nuclear transformations using decay equations involving α, β-, β+ and γ radiation**
- **analyse decay series diagrams with reference to type of decay and stability of isotopes**
- **explain, qualitatively, nuclear energy as energy resulting from the conversion of mass**
- **explain fission chain reactions including:**
  the effect of mass and shape on criticality
  neutron absorption and moderation
- **compare the processes of nuclear fusion and nuclear fission**
- **explain, using a binding energy curve, why both fusion and fission are reactions that release energy**
- **investigate the viability of nuclear energy as an energy source for Australia.**

Nuclear radiation

Nuclear radiation is radiation emitted from the nucleus of an atom. There are many types of nuclear radiation, some that we experience every day and are harmless, and others that can have lasting effects.

Nuclear physics is a topic of great public interest and public fear. Public phobia about anything *nuclear* or anything *radioactive* is likened to the similar fears provoked by the advent of electricity and petrol powered vehicles some 100 years ago. Just as fears of electricity in homes and petrol in cars stemmed from ignorance, many of today's fears, about anything nuclear stems from a lack of knowledge about the nucleus and its processes.

Knowledge of the atomic nucleus began with the chance discovery of radioactivity in 1895 by Wilhelm Roentgen. He called this new type of ray, **X rays** – rays of unknown nature.

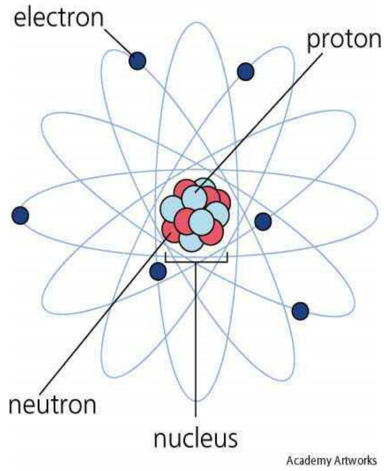
X rays pass more readily through flesh than through bone and produce an image on a film.

Today we know that X-rays are high-frequency electromagnetic waves, usually emitted by the de-excitation of the innermost orbital electrons of atoms.

Two months after Roentgen announced his discoveries Antoine Henri Becquerel tried to find out if other elements emitted X-rays. He discovered that Uranium produced rays. It was soon discovered that other elements (thorium, actinium and two new elements discovered by Marie and Pierre Curie-polonium and radium) also emitted similar rays. The emission of these rays was evidence of much more drastic changes in the atom than electron excitation. These rays were the result of changes occurring within the central atomic core – the nucleus.

A model for the structure of the atom

The current understanding of the structure of an atom was first devised by Ernest Rutherford in 1911.



The **nucleus** is at the centre of the atom and occupies 10^{-12} of the volume of the atom, yet it contains over 99% of its mass. Nuclear radii are of the order 10^{-15} m. The nucleus is positively charged and is made up of at least two types of particles, **protons** (positively charged) and **neutrons** (electrically neutral), collectively known as **nucleons**. Both protons and neutrons are part of a family known as **hadrons**. There are also many other types (~70) of hadrons.
The nucleus is held together by what is known as the **strong nuclear force**. The nucleus is surrounded by a cloud of negatively charged **electrons**, which move about the nucleus in definite energy states. Just as there are energy levels for the orbital electrons of an atom, there are energy levels within the nucleus.

Atomic number and mass number

The **atomic number** is the number of protons in an atom. Every atom has the same number of protons and electrons, because they need to be electrically neutral.

The electrons in an atom have almost no mass. So the mass of an atom is nearly all due to its protons and neutrons. The **mass number** = the number of protons and neutrons in an atom.

Shorthand for an atom

Mass number — $^{A}_{Z}\mathbf{X}$ — Element symbol

Atomic number

Isotopes, radioisotopes and ions

Isotopes

All atoms of a particular element will have the same number of protons but may have a different number of neutrons. For example, the nucleus of the hydrogen atom contains one proton, but some hydrogen nuclei contain a neutron in addition to the proton. And in rare instances, a hydrogen atom may contain two neutrons in addition to the proton. These are called **isotopes**. Isotopes have the same chemical properties but different physical properties.

The most common isotope of Hydrogen is $^{1}_{1}H$ The double mass hydrogen isotope $^{2}_{1}H$ is called *deuterium*. “Heavy water” is the name usually given to H_2O in which one or both of the H atoms have been replaced with deuterium atoms. Deuterium naturally occurs about 1 in 6000 Hydrogen atoms. The triple mass hydrogen isotope $^{3}_{1}H$, which is radioactive is called *tritium*, occurs naturally less than 1 in 10^{17} atoms.

All elements have a variety of isotopes. More than 2000 distinct isotopes, radioactive and stable, are known.

Radioisotopes
Most atoms are stable; however, some isotopes are unstable. An unstable nucleus may spontaneously lose energy by emitting a particle and change into a different element or isotope. Unstable atoms are radioactive and an individual radioactive isotope is known as a **radioisotope**. There are over 2000 known radioisotopes, most are artificially produced.

Ions
An **ion** is an atom with an overall charge. The charge can be positive or negative. Positive ions form when electrons are removed from a neutral atom and negative ions when electrons are added to a neutral atom.

Types of Nuclear Radiation

Alpha Radiation $^{4}_{2}\alpha$

Alpha particle radiation consists of two neutrons and two protons, as they are charged they are affected by both electric and magnetic fields. The speed of the α-particle depends very much on the source, but typically is about 10% of the speed of light.

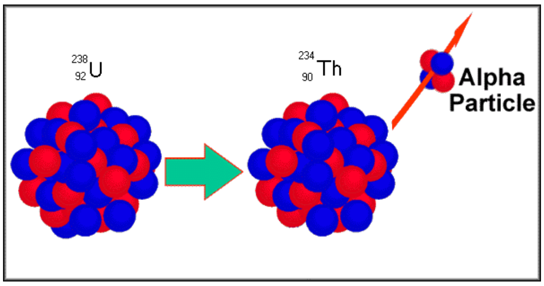
The capacity of the α-particle to penetrate materials is not very great, it usually penetrates no more than a few centimetres in air and is absorbed by a relatively small thickness of paper or human skin. However, because of their speed and size, they are capable of ionising a large number of atoms over a very short range of penetration.

This makes them relatively harmless for most sources that are about a metre or more away, as the radiation is easily absorbed by the air. Range in air at ordinary pressure is < 100 mm, they are almost completely absorbed by a sheet of paper. But if the radiation sources are close to sensitive organs α-article radiation is extremely dangerous.

When a nucleus emits an alpha particle, it loses two protons and two neutrons. Most alpha-emitters have high atomic numbers as the nucleus of these atoms are more unstable.

The symbols for an alpha particle are: $^{4}_{2}\alpha$, $^{4}_{2}He^{2+}$ α or α^{2+}

When an atom changes into a different element, it is said to have undergone a *nuclear transmutation*. The new element formed is called the *daughter nucleus*. In any nuclear reaction, including radioactive decay, atomic and mass numbers are conserved.



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

(<u>Investigation</u>: If you have access to an old watch that always glows in the dark. Take it into a completely dark room, wait for your eyes to adjust, and then examine the hands with a very strong magnifying glass. You should be able to see individual flashes, which together seem to be a steady

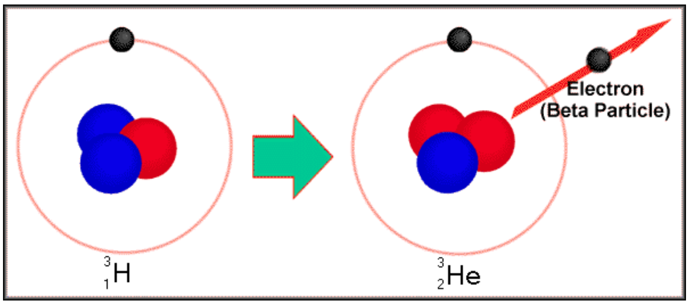
source of light to the unaided eye. Each flash occurs when an alpha particle ejected by a radium nucleus strikes a molecule of zinc sulphide).

Beta Radiation $^{0}_{-1}\beta$

Beta-particle radiation consists of fast moving electrons or positrons (anti-electron, positively charged). Every β-particle carries either one negative or one positive electronic charge ($\pm 1.6 \times 10^{-19}$ coulomb:-e, +e). They are affected by electric and magnetic fields. The speed depends on the source, but it can be up to 90% of the speed of light.

Beta particles can penetrate up to 1 m of air. They are stopped by a few millimetres of aluminium or perspex. Their ionising capacity is much less than that of α-radiation, but they are very dangerous if ingested.

Beta particles emanate from the nucleus of radioactive nuclei that has too many neutrons for stability. A neutron spontaneously decays into a proton, an electron, and an uncharged, low-mass particle (approximately 10^{-5} the mass of an electron), called an anti-neutrino $\bar{\upsilon}$. The electron and anti-neutrino are emitted to restore the nucleus to a more stable state.
The force responsible for beta emissions is called the *weak interaction* or *weak force*



The nuclear decay equation is $^{3}_{1}H \rightarrow ^{3}_{2}He + ^{0}_{-1}\beta + \bar{\upsilon}$ + energy.
Both the atomic and mass numbers are conserved.

Gamma Radiation γ

Just as there are energy levels for the orbital electrons of an atom, there are energy levels within the nucleus. Whereas electrons making transitions to lower orbits emit photons of light, similar changes of energy states within the nucleus result in the emission of gamma rays (high energy photons, outside the visible spectrum). As gamma radiation is part of the electromagnetic spectrum it travels at the speed of light (3×10^{8} m/s). Gamma radiation does not consist of charged particles; it is a form of very short wavelength electromagnetic energy.

Gamma radiation is very difficult to stop, it takes up to 30 mm of lead. Although the ionising capacity of gamma radiation is considerably smaller than that of beta radiation, their high penetration power means that they are dangerous even at a distance. They can penetrate our bodies and hit sensitive organs. They are particularly dangerous if ingested or inhaled.

Gamma rays are electromagnetic waves, similar in nature to light waves and x-rays. They have no charge and do not alter the mass number of the nucleus that emits them. Gamma radiation is often emitted at the same time as another form of radiation.

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

$$^{131}_{53}I \rightarrow ^{131}_{54}Xe + ^{0}_{-1}e + ^{0}_{0}\gamma$$

Gamma ray decay alone occurs when a nucleus is left in an energised or excited state following an alpha or beta decay. This excited state is known as the *metastable state* and it usually only lasts a very short time.

Decay Pathways

Nuclear reactions that transform atomic nuclei alter their identity and spontaneously emit radiation via processes of radioactive decay.

Types of Nuclear Decay

In 1889, Ernest Rutherford recognized and named two modes of radioactive decay, showing the occurrence of both processes in a decaying sample of natural uranium and its daughters. Rutherford named these types of radiation based on their penetrating power: heavier alpha and lighter beta radiation. Gamma rays, a third type of radiation, were discovered by P. Villard in 1900 but weren't recognized as electromagnetic radiation until 1914. Since gamma radiation is only the discharge of a high-energy photon from an over-excited nucleus, it does not change the identity of the atom from which it originates and therefore will not be discussed in depth here.

Because nuclear reactions involve the breaking of very powerful intra nuclear bonds, massive amounts of energy can be released. At such high energy levels, the matter can be converted directly to energy according to Einstein's famous Mass-Energy relationship $\boldsymbol{E = mc^2}$. The sum of mass and energy are conserved in nuclear decay. Therefore, a nuclear reaction will occur spontaneously when:

$$\Delta E = \Delta mc^2 < 0$$

$$\Delta E < 0 \text{ or } \Delta m < 0$$

When the mass of the products of a nuclear reaction weigh less than the reactants, the difference in mass has been converted to energy.

There are three types of nuclear reactions that are classified as beta decay processes. Beta decay processes have been observed in 97% of all known unstable nuclides and are thus the most common mechanism for radioactive decay by far. The first type (here referred to as *beta decay*) is when a negatively charged beta particle is emitted, whereas the second type (*positron emission*) emits a positively charged beta particle. In *electron capture*, an orbital electron is captured by the nucleus and absorbed in the reaction. All these modes of decay represent changes of one in the atomic number Z of the parent nucleus but no change in the mass number A. Alpha decay is different because both the atomic and mass number of the parent nucleus decrease. In this article, the term beta decay will refer to the first process described in which a true beta particle is the product of the nuclear reaction.

Beta Decay

Nuclides can be radioactive and undergo nuclear decay for many reasons. Beta decay can occur in nuclei that are rich in neutrons - that is - the nuclide contains more neutrons than stable isotopes of the same element. These "proton deficient" nuclides can sometimes be identified simply by noticing that their mass number A (the sum of neutrons and protons in the nucleus) is significantly more than twice that of the atomic number Z (number of protons in nucleus). In order to regain some stability, such a nucleus can decay by converting one of its extra neutrons into a proton, emitting an electron and an antineutrino(ν). The high energy electron emitted in this reaction is called a **beta particle** and is represented by ${}_{-1}^{0}e \text{ or } \beta^-$ in nuclear equations. Lighter atoms (Z < 60) are the most likely to undergo beta decay. The decay of a neutron to a proton, a beta particle, and an antineutrino is

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

Some examples of **beta decay** are

$$ {}_{2}^{6}He \rightarrow {}_{3}^{6}Li + {}_{-1}^{0}e + \nu $$

$$ {}_{11}^{24}Na \rightarrow {}_{12}^{24}Mg + {}_{-1}^{0}e + \nu $$

In order for beta decay to occur spontaneously according to Δm < 0, the mass of the parent *nucleus* (not atom) must have a mass greater than the sum of the masses of the daughter nucleus and the beta particle:

$$ m[{}^{A}Z] > m[{}^{A}(Z+1)] + m[{}^{0}_{-1}e^{-}] $$

(Parent nucleus) > (Daughter nucleus) + (electron)

The mass of the antineutrino is almost zero and can therefore be neglected.

Positron Emission

Nuclides that are imbalanced in their ratio of protons to neutrons undergo decay to correct the imbalance. Nuclei that are rich in protons relative to their number of neutrons can decay by conversion of a proton to a neutron, emitting a **positron** (${}_{1}^{0}e$) and a neutrino (ν). Positrons are the antiparticles of electrons, therefore a positron has the same mass as an electron but with the opposite (positive) charge. In positron emission, the atomic number Z *decreases* by 1 while the mass number A remains the same.

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

Some examples of **positron emission** are

$$ {}_{5}^{8}B \rightarrow {}_{4}^{8}Be + {}_{1}^{0}e + \nu $$

$$ {}_{25}^{50}Mg \rightarrow {}_{24}^{50}Cr + {}_{1}^{0}e + \nu $$

Positron emission is only one of the two types of decay that tends to happen in "neutron deficient" nuclides, therefore it is very important to establish the correct mass change criterion. Positron emission occurs spontaneously when

$$m[^{A}Z] > m[^{A}(Z\text{-}1)] + m[^{0}_{+1}e^{+}]$$

(Parent nucleus) > (Daughter nucleus) + (positron)

Electron Capture

As mentioned before, there are two ways in which neutron-deficient / proton-rich nuclei can decay. When the mass change Δm < 0 yet is insufficient to cause spontaneous positron emission, a neutron can form by an alternate process known as electron capture. An outside electron is pulled inside the nucleus and combined with a proton to make a neutron, emitting only a neutrino.

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

Some examples of **electron capture** are

$$^{231}_{92}U + ^{0}_{-1}e^{-} \rightarrow ^{231}_{91}Pa + \nu$$

$$^{81}_{36}Kr + ^{0}_{-1}e^{-} \rightarrow ^{81}_{35}Br + \nu$$

Electron capture happens most often in the heavier neutron-deficient elements where the mass change is smallest and positron emission isn't always possible. For Δm < 0, the following inequality applies:

$$m[^{A}Z] + m[^{0}_{-1}e^{-}] > m[^{A}(Z\text{-}1)]$$

(Parent nucleus) + (electron) > (Daughter nucleus)

Alpha Decay

In alpha decay, unstable, heavy nuclei (typically $Z>83$) reduce their mass number A by 4 and their atomic number Z by 2 with the emission of a helium nuclei ($^{4}_{2}He\ or\ ^{4}_{2}\alpha$), known as an **alpha particle**.

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He + energy$$

Some examples of **alpha decay** are

$$^{222}_{88}Ra \rightarrow ^{218}_{86}Rn + ^{4}_{2}He + energy$$

$$^{233}_{92}U \rightarrow ^{229}_{90}Rn + ^{4}_{2}He + energy$$

The mass of the parent atom must simply be greater than the sum of the masses of its daughter atom and the helium atom.

$$m[^{A}Z] > m[^{A-4}(Z-2)] + m[^{4}_{2}He^{2+}]$$

The change in mass then equals

$$\Delta m = m[^{A}(Z)] - m[^{A-4}(Z-2)] - m[^{4}_{2}He^{2+}]$$

Alpha decay is a form of spontaneous fission, a reaction in which a massive nuclei can lower its mass and atomic number by splitting. Other heavy unstable elements undergo fission reactions in which they split into nuclei of about equal size.

Summary: Characteristics of Radioactive Decay

Decay Type	Emitted Particle	ΔZ	ΔA	Occurrence
Alpha	$^{4}_{2}He^{2+}$	-2	-4	Z > 83
Beta	Energetic e^{-}, γ	+1	0	$A/Z > (A/Z)_{stable}$
PE	Energetic e^{+}, γ	-1	0	$A/Z < (A/Z)_{stable}$, light nuclei
EC	ν	-1	0	$A/Z < (A/Z)_{stable}$, heavy nuclei
γ	Photon	0	0	Any excited nucleus

Proton-deficient or neutron-deficient nuclei undergo nuclear decay reactions that serve to correct imbalanced neutron/proton ratios. Proton-deficient nuclei undergo **beta decay** - emitting a beta particle (electron) and an antineutrino to convert a neutron to a proton - thus raising the elements atomic number Z by one. Neutron-deficient nuclei can undergo **positron emission** or **electron capture** (depending on the mass change), either of which synthesizes a neutron - emitting a positron and a neutrino or absorbing an electron and emitting a neutrino respectively - thus lowering Z by one. Nuclei with Z > 83 which are unstable and too massive will correct by **alpha decay**, emitting an alpha particle (helium nucleus) and decreasing both mass and atomic number. Very proton-deficient or neutron-deficient nuclei can also simply eject an excess particle directly from the nucleus. These types of decay are called **proton** and **neutron emission**.

Ionising radiation

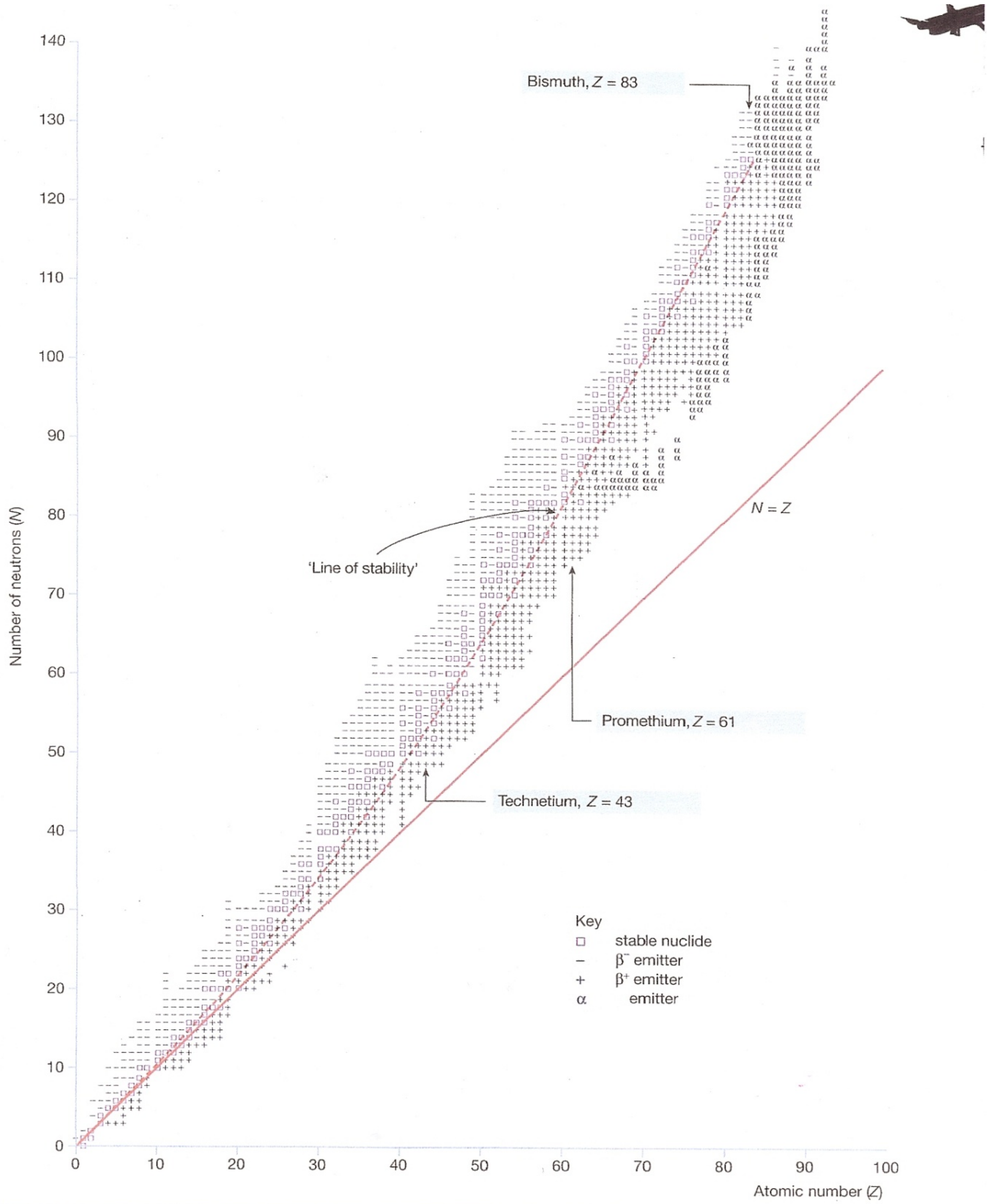
A property of ionising radiation is its ability to ionise atoms. That is, this type of radiation can cause an electrically neutral atom to lose an electron, the atom becomes charged, and we call it an ion. In the cells of living animals, ionising radiation can create ions that are chemically reactive, which can lead to the damage or destruction of cells. Short term harmful effects are called **somatic** effects and long term hereditary effects are called **genetic**.

Type of radiation emitted	Nature of the radiation	Nuclear Symbol	**Penetrating power, and what will block it** (more dense material, more radiation absorbed BUT smaller mass or charge of particle, more penetrating)	**Ionising power –** the ability to remove electrons to form positive ions
α Alpha	a helium nucleus of 2 protons and 2 neutrons, mass = 4, charge = +2	${}^{4}_{2}\alpha$ ${}^{4}_{2}He$	Low penetration, biggest mass and charge, stopped by a few cm of air or thin sheet of paper	Very high ionising power, the biggest mass and charge of the three radiations, the biggest 'punch'.
β Beta	High kinetic energy electrons, mass = 1/1850, charge = -1	${}^{0}_{-1}\beta$ ${}^{0}_{-1}e$	Moderate penetration, 'middle' values of charge and mass, most stopped by a few mm of aluminium	Moderate ionising power, with a smaller mass and charge than the alpha particle.
γ Gamma	Very high frequency electromagnetic radiation, mass = 0, charge = 0	${}^{0}_{0}\gamma$	Very highly penetrating, smallest mass and charge, most stopped by a thick layer of steel or concrete, but even a few cm of lead doesn't stop all of it.	The lowest ionising power of the three, gamma radiation carries no electric charge and has no mass, so not much of a 'punch' when colliding with an atom.

In subatomic world it is much more convenient to use unit of energy **electronvolt.**
1eV=1.6×10^(-19) J

Table **1.1** The properties of alpha, beta and gamma radiations

Property	α particle	β particle	γ ray
Mass	heavy	light	none
Charge	+2	−1	none
Typical energy	~5 MeV	~1 MeV	~0.1 MeV
Range in air	a few cm	1 or 2 m	many metres
Penetration in matter	~10^{-2} mm	a few mm	high
Ionising ability	high	reasonable	poor



Number of neutrons (N)
Atomic number (Z)
Bismuth, Z = 83
'Line of stability'
N = Z
Promethium, Z = 61
Technetium, Z = 43
Key
stable nuclide
β⁻ emitter
β⁺ emitter
α emitter

Measuring energy

An **electron-volt** (eV) is an extremely small quantity of energy. The electron volt is the amount of energy gained (or lost) by the charge of a single electron moving across an electric potential difference of one volt. It is a unit of energy given by E = V q and therefore equal to approximately 1.6×10^{-19} joules. MeV is a million electron-volts.

It is a useful measure of energy in nuclear physics because the energies from a single nucleus are so small.

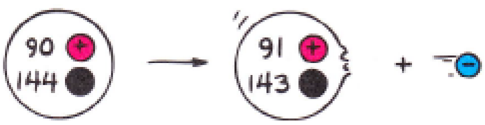
Property	α particle	β -particle	γ ray
Mass	heavy	light	none
Charge	+2	-1	none
Typical energy	~ 5 MeV	~ 1 MeV	~0.1 MeV
Range in air	100 mm	< 4 m	200 metres
Aluminium	0.2 mm	6 mm	500 mm
Lead	0.01 mm	0.4 mm	30 mm
Relative penetration power	1	100	10 000
Relative ionising power	10 000	100	1

Transmutations

When a nucleus emits an alpha or beta particle, a different element is formed. This changing of one chemical element to another is called **transmutation**. Consider uranium-238, the nucleus of which contains 92 protons and 146 neutrons. When an alpha particle is ejected, the nucleus is reduced by two protons and two neutrons. An element is defined by the number of protons in the nucleus, so the new element is thorium.

In equations such as this, the mass numbers and the atomic numbers balance.

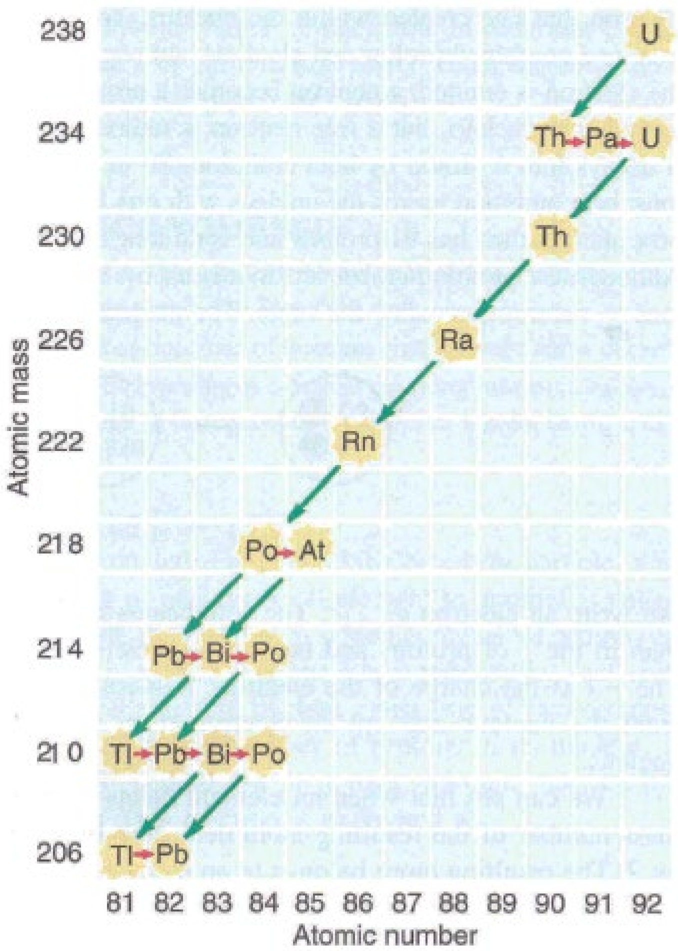
$$^{238}_{92}U \downarrow\ ^{234}_{90}Th + \ ^{4}_{2}He$$



Thorium-234, the product of this reaction, is also radioactive. When it decays, it emits a beta particle. (beta particle is an electron-not an orbital electron, but one created within the nucleus. When the electron is emitted, a neutron becomes a proton. The new nucleus now has 91 protons, so it is *protactinium*.

$$^{234}_{90}Th \rightarrow\ ^{234}_{91}Pa + \ ^{0}_{-1}e$$

Gamma emission results in no change in either the mass number or the atomic number, so are not shown in the diagram below. In some places there are multiple ways in which the atom may decay, these can be seen at the bottom of the diagram.



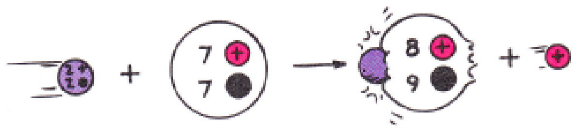
Artificial transmutation

Artificial radioisotopes are manufactured by bombarding stable nuclei with neutrons. This process is known as **artificial transmutation**.

An example is: ${}^{1}_{0}n + {}^{59}_{27}Co \rightarrow {}^{60}_{27}Co$.

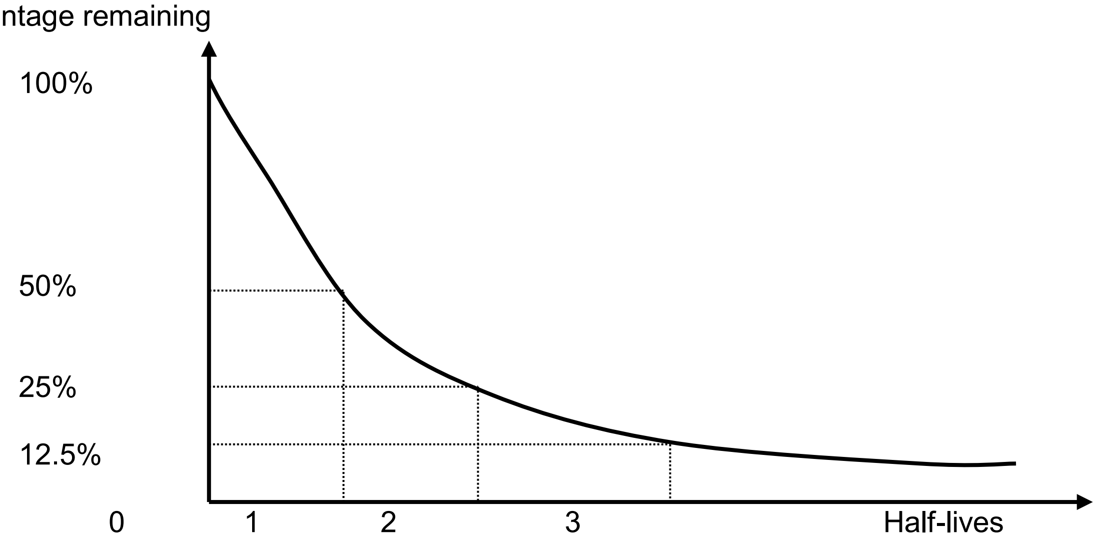
The artificial radioisotope cobalt-60 (half-life 5.27 years) is used extensively in the treatment of cancer. It decays by emitting a beta particle.

Rutherford (1919) was the first to succeed in transmuting a chemical element. He bombarded nitrogen nuclei with alpha particles and succeeded in transmuting nitrogen into oxygen:



Half-life of a radioisotope

A radioactive substance is one whose nuclei are unstable. At random instants the nuclei disintegrate with the emission of particles or rays or both. The average time taken for one-half of a given number of atoms to disintegrate is known as the half-life period ($T_{1/2}$) of that substance. After a further period T one half of the remaining nuclei will decay, and so on. The rate of disintegration varies widely; half-lives vary from a fraction of a second to 10^{10} years. In the case of the heavy radioactive elements radioactivity progressively leads to the formation of a series of other elements, each with its own half-life until a final stable element is reached that is not radioactive.



The decay process is random, these are average results, and it is impossible to predict what will happen to any individual nucleus. The decay is as exponential relationship.
Every isotope of every radioactive element has its own characteristic half-life. Uranium-238, for example, has a half-life of 4.5 billion years, while the shortest half-lives of elementary particles are on the order of 10^{-23} second, the time light would take to travel across the nucleus.

Isotope	Emission	Half-life	Application
Natural			
Polonium-214	α	0.00016 seconds	Nothing at this time
Carbon-14	β	5730 years	Carbon dating of fossils
Uranium-235	α	700 000 years	Nuclear fuel, rock dating
Uranium-238	α	4 500 million years	Nuclear fuel, rock dating
Artificial			
Technetium-99m	β	6 hours	Medical tracer
Sodium-24	β	15 hours	Medical tracer
Iodine-131	β	8 days	Medical tracer
Phosphorus-32	γ	14.3 days	Medical tracer
Cobalt-60	β	5.3 years	Radiation therapy
Americium-241	α	460 years	Smoke detectors
Plutonium-239	α	24 000 years	Nuclear fuel, rock dating

Activity

The strength of any given radioactive source is determined by its activity. The activity of the sample indicates the number of radioactive decays that are occurring in the sample each second. Activity is measured in Becquerels (Bq), where 1 Bq = 1 disintegration per second. The activity of any radioactive sample will decrease with time. Over a half-life, the activity of a sample will halve.

Carbon dating

While a plant or animal is alive, it is exchanging carbon with its surroundings, so that the carbon it contains will have the same proportion of ^{14}C as the biosphere. Once it dies, it ceases to acquire ^{14}C, but the ^{14}C that it contains will continue to decay, and so the proportion of radiocarbon in its remains will gradually reduce. Because ^{14}C decays at a known rate, the proportion of radiocarbon can be used to determine how long it has been since a given sample stopped exchanging carbon—the older the sample, the less ^{14}C will be left. The half-life of ^{14}C is 5730 years.

To calculate how old a material is the following formula can be used: $N = N_0 e^{(t/\tau)}$

Where N_0 is the number of atoms of the isotope in the original sample, N is the number of atoms left at time t, and τ is the mean life for the particular isotope.

The equation can be rearranged to the more convenient format of

$$t = \tau \ln(N_0 / N)$$

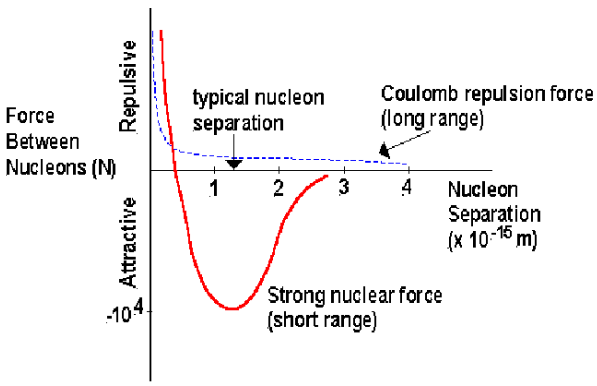
The **mean life** is the average amount of time that an element remains in its unstable state. It is also the amount of time it takes for the activity of a given sample to disintegrate to 1/e of the initial activity (this is the same as a half-life except instead of disintegrating to 1/2 it disintegrates to 1/e). The mean life and the half-life ($T_{1/2}$) are related by $T_{1/2} = \tau \ln(2)$,

therefore, the mean life of carbon-14 is $\tau = \dfrac{5730}{\ln(2)}$ = 8267 years.

Why atoms are radioactive

The positively charged and closely spaced protons in a nucleus have huge electrical forces of repulsion between them. Why don't they fly apart because of this huge repulsive force?

This is because there is an even larger force within the nucleus – the nuclear force. Both neutrons and protons are bound to each other by this attractive force. The principle part of the nuclear force, the part that holds the nucleus together, is called the *strong interaction*, *strong nuclear forc*e (or just *strong force*). This force acts only over a very short distance, ~ 10^{-15} m, and is close to zero at greater separations. The strong force is both attractive and repulsive depending on the distance, as seen from the graph. Electrical interaction, on the other hand, weakens as the inverse square of separation distance and is a relatively long range force. So as long as the protons are close together, as in small nuclei, the nuclear force easily overcomes the electrical force of repulsion. But for distant protons, like those on opposite edges of a large nucleus, the attractive nuclear force may be small in comparison to the repulsive electrical force. Hence the larger a nucleus the more unstable it is.

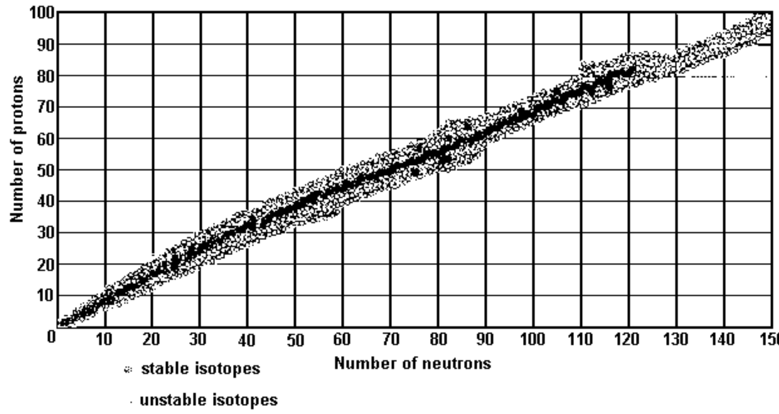


The presence of the neutrons also plays a large role in nuclear stability. In general terms extra neutrons increase stability. If the uranium nucleus were to have equal numbers of protons and neutrons, 92 neutrons and 92 protons, it would fly apart due to the electrical repulsion. Even so, the U-238 ($^{238}_{92}U$) nucleus is still unstable because of the electrical forces.

There is an electrical repulsion between *every* pair of protons in the nucleus, but there is not a substantial nuclear attractive force between every pair of protons in the nucleus (due to separation distance).

All nuclei having more than 82 protons are unstable. In this unstable environment, alpha and beta emissions take place. The force responsible for beta emissions is called the *weak interaction*. It acts on leptons as well as nucleons. When an electron is created in beta decay, another lighter particle called an *antineutrino* is also created and shoots out of the nucleus.

When an unstable nucleus undergoes radioactive decay, it may eject a particle. The two particles are alpha and beta particles, gamma radiation may also be emitted, but this is not a particle. The three decay processes all come from the nucleus; the electron cloud does not give of nuclear radiation, as it is not part of the nucleus.



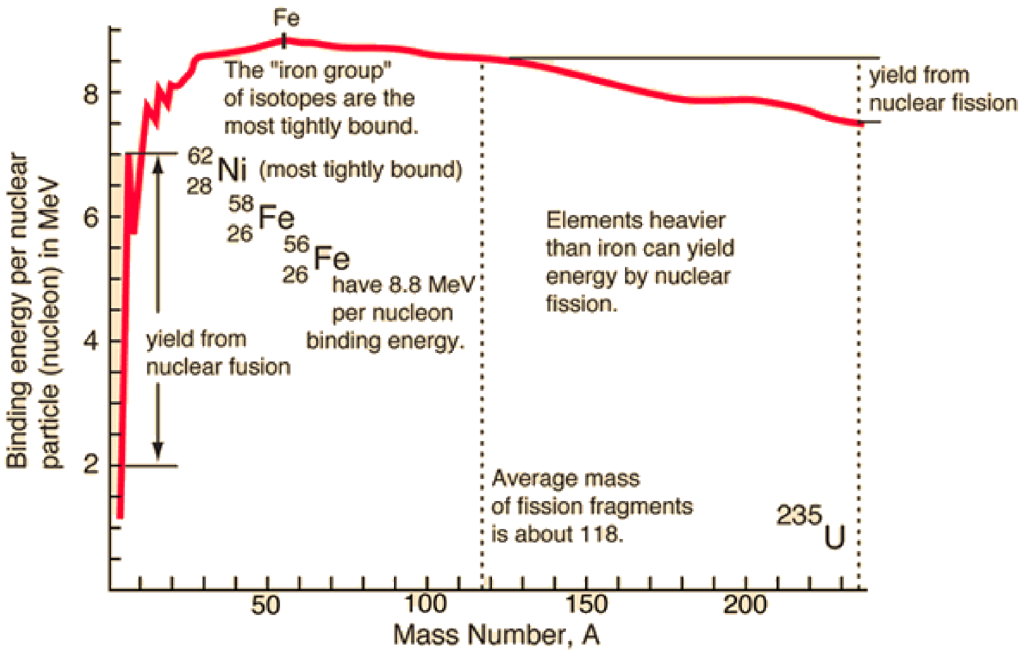
Binding energy

As technology improved, and more precise measurements could be made. Scientists noticed that the mass of a nucleus was always less than the mass of its constituent parts (the protons and neutrons). For example;
The mass of an alpha particle is 4.00153 u
Whereas the mass of the constituent parts is
Protons   2 × 1.00728 u
Neutrons 2 × 1.00866 u
Total   4.03188 u

Where u is the unified atomic mass unit, also known as Dalton (Da).
u = 1.66054 × 10^{-27} kg = 931.494 MeV/c^2. u is approximately the mass of one nucleon, numerically equivalent to 1 g/mol, and is defined as one twelfth of the mass of an unbound, neutral carbon-12 atom.

This difference in mass is a measure of the strength of the strong nuclear force that holds the nucleus together, this is known as the nuclear binding energy. The binding energy is different for each element, and each of their isotopes. The graph below shows the binding energy per nucleon for different mass numbers.

The binding energy can be calculated using Einstein's relationship
$E = mc^2$
Where E is the nuclear binding energy, m is the mass difference, and c is the speed of light.
Elements or isotopes with a high binding energy are more stable.

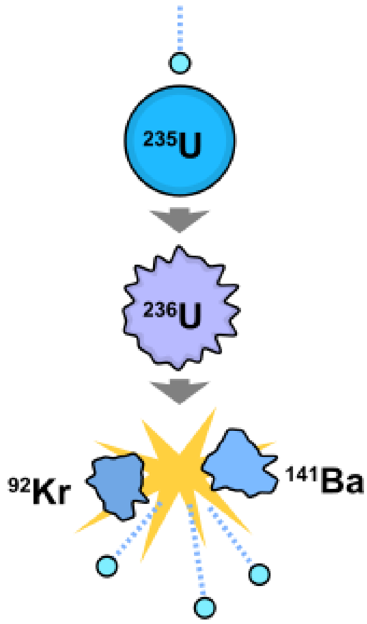


Nuclear fission – splitting the atom

In 1932 James Chadwick discovered the neutron, up until then scientists had been trying to split the atom by firing alpha particles at the nucleus. This did not work because the charged alpha particles were repelled by the nucleus. The uncharged neutrons changed this. In 1934 Enrico Fermi bombarded uranium nuclei with neutrons, the nuclei absorbed the neutrons and split in two. This is called **nuclear fission.**

Because the resulting fragments are not the same element as the original atom, fission is a form of nuclear transmutation. While alpha and beta decay also change the element this is not generally thought of as fission, as the speeds and masses of the resulting fragments are not comparable.

Nuclear fission is when an atomic nucleus splits into two or more pieces, this process is often triggered by the absorption of a neutron. Nuclides that are capable of undergoing nuclear fission are called fissile. Only uranium-235 and plutonium-239 are readily fissile. Uranium-238 and thorium-232 are slightly fissile.



When the nucleus splits it also releases more neutrons and a large amount of energy.

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{91}_{36}Kr + {}^{142}_{56}Ba + 3\,{}^{1}_{0}n + \text{energy}$$

Krypton-91 and barium-142 are known as the fission fragments. A uranium-235 nucleus can split in many different ways, up to 40 different pairs of fission products are possible most are beta emitters. These fission fragments make up the bulk of the high-level waste produced by nuclear reactors. On average uranium-235 produces ~ 2.5 neutrons per fission and plutonium-239, ~ 2.9 neutrons per fission. These neutrons can go on to trigger more fission reactions.

An enormous amount of energy is released during each fission reaction. In any fission reaction, the combined mass of the incident neutron and the target nucleus is always greater than the combined mass of the fission fragments and the released neutrons. This change in mass (only about 0.1% of the total mass) is what is converted into energy, using $E=mc^2$.

$${}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{92}^{236}U \rightarrow {}_{54}^{140}Xe + {}_{38}^{94}Sr + 2{}_{0}^{1}n + 160\ MeV$$

160 MeV = 2.6×10^{-11} J.

One kilogram of uranium-235 contains ~2.6×10^{24} nuclei. This means that the total energy available per kilogram = $2.6 \times 10^{24} \times 2.6 \times 10^{-11} = 6.8 \times 10^{13}$ J. It would require the combustion of 3×10^{6} kg of coal to release the same amount of energy.

Nuclear fusion – combining atoms

Nuclear fusion is the reverse process to fission. It is the process of fusing two atoms together and creating a larger atom. Massive amounts of energy are either being consumed or released during this process.
Nuclear fusion is the source of energy for stars. This is also how all the elements (up to iron for large stars) were made. During extreme events such as when a large star implodes, heavier elements can be created via fusion even though these transformations are not energetically favourable.
Nuclear Fusion is a nuclear reaction that requires massive amounts of energy to initiate, and massive amounts of energy to maintain as atoms repel each-other unless greatly heated. Nuclear fusion on earth, is a very hard reaction to perform and is only maintainable for a matter of seconds, as the energy needed to create the nuclear reaction is very high. It is estimated that to perform a successful you would require a heat that would not be containable in any material. And so, scientists must create environments with massive amounts of pressure and heat in order for the reaction to occur successfully. As a result, nuclear fusion does not have many uses on earth, at least not yet...