A2 Level Physics

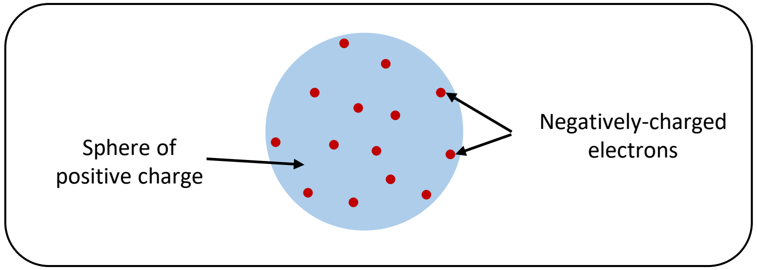
Chapter 20 – Nuclear and Particle Physics

20.1.1 The Nuclear Atom

Notes

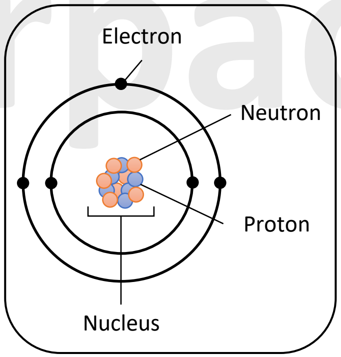
The Atom

In the late 18th century J.J. Thomson suggested that every atom contains one or more negatively charged electrons. Thomson proposed a model of the atom know as the Plum Pudding model. He considered the atom to be a sphere with an uniform positive charge spread across its volume and negatively charged electrons embedded within it. As plums in a plum pudding.



The "plum pudding" model of the atom

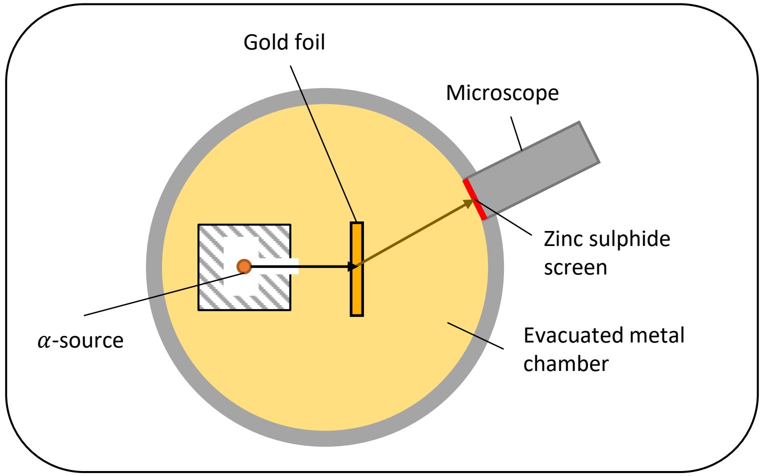
Ernest Rutherford was the first to argue that atoms' charge and density were not evenly distributed and challenged the Plum Pudding model. Rutherford had his own concept of the atom, in which the atom is made up of a large, positively charged nucleus in the centre, surrounded by much lighter, negatively charged electrons. Nobody proposed the nucleus concept before Rutherford.



Rutherford tested Thomson's theory by performing the Rutherford Alpha-Particle Scattering Experiment.

He assumed that if the positive charge was evenly distributed throughout each atom, an a-particle beam directed towards a thin metal foil would only be slightly scattered, but he was astounded by what he discovered.

Rutherford's Alpha-Particle Scattering Experiment



In an evacuated container, a narrow, mono-energetic beam of alpha (α) particles (positively charged helium nuclei, i.e. 2p + 2n) were aimed towards an extremely thin gold foil. A zinc sulphide screen was used to detect the scattered α-particles which created a dot of light when they struck the screen. The pinpoints of light were then examined using a microscope that could be rotated at a constant distance from the foil.

For different angles of deflection ranging from 0° to almost 180°, Rutherford and his students counted the number of α-particles reaching the detector over a fixed time interval.

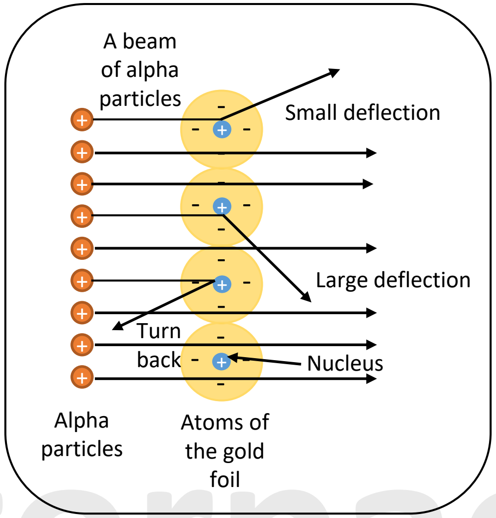
Their findings showed that:

- Majority of α's passed directly through the foil with no deflection.
- Some α's were deflected through small angles.
- A small number of α's were deflected at angles greater that $90°$ and a very small number of α's experienced 'back scattering' (i.e. being reflected back towards the source).

Rutherford's Alpha-Particle Scattering Experiment

Rutherford came to the following conclusions:

- **Most alpha particles passed directly through** the atom, implying that it is **mostly empty space**.
- **Some** positively charged alpha particles are **repelled and deflected by a large angle**, indicating that the nucleus must have a **large positive charge**.



- Only a **few alpha particles** are deflected by an **angle greater than 90°**, implying that the **nucleus must be very small**. (In reality the nuclear radius is of the order of $10^{-15}m$ while the radius of the atom is of the order of $10^{-10}m$).
- Since the fast alpha particles (with high momentum) are deflected by the nucleus, the **nucleus must contain the majority of the mass**. To put it another way, the fast alpha particles must collide with something more massive than themselves in order to be deflected by the nucleus.

Therefore Rutherford's scattering experiment shows that **atoms must have a small, positively charged nucleus** containing the majority of the atom's mass.

The path of some a-particles as they pass through the gold foil is shown in the diagram.

Rutherford's Alpha-Particle Scattering Experiment

The electrostatic repulsion force between an a-particle and a nucleus can be calculated using:

$$F = \frac{Q_\alpha Q_N}{4\pi\varepsilon_0 r^2}$$

The closer an a-particle is moving to the nucleus (i.e. the smaller r is), the stronger the force, F is and hence the greater the deflection will be.

Points to note about the alpha-scattering experiment

- The metal foil needs to be very thin to avoid the a's being deflected more than once.
- The a-particle source used had to have a long half-life since radioactive decay would cause later readings to be lower than early ones.
- The equipment had to be in a vacuum since the a's would hardly travel 5 to 10 cm before colliding with air molecules and stopping.
- The a-particles all had the same energy, otherwise slow a's would be deflected more than faster ones on the same initial path.

Nuclear Model of the Atom

The atom is represented in the nuclear model as a central, positively-charged nucleus containing protons and neutrons, with negatively-charged electrons orbiting the nucleus in circular orbits.

Since protons and neutrons are found in the nucleus, they are referred to as nucleons.

In the table below, the properties of each of the particles contained in the atom are listed:

Particle	Location	Charge	Mass/kg
Electron	Orbiting the nucleus	$-1.6 \times 10^{-19} C$	9.11×10^{-31}
Proton	Inside the nucleus	$+1.6 \times 10^{-19} C$	1.673×10^{-27}
Neutron	Inside the nucleus	0	1.675×10^{-27}

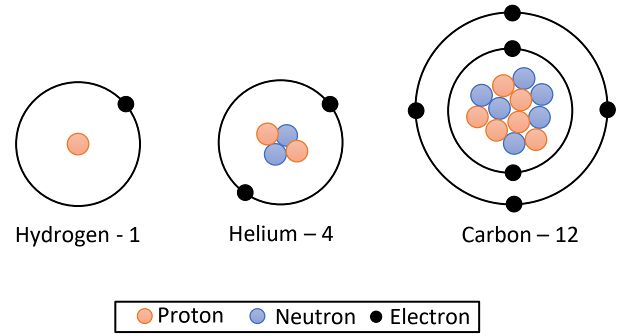
Since the masses of these sub-atomic particles are so small, they are measured using a very small unit called the atomic mass unit (u):

$$\mathbf{1u = 1.6605 \times 10^{-27} kg}$$

- $Proton\ mass \approx neutron\ mass = 1u$
- $Electron\ mass \approx \frac{1}{1800} u$

Nuclear Model of the Atom

Some atoms are shown in the diagram below:



Atoms are extremely small. Each atom has a diameter of roughly a tenth of a nanometre ($1 \times 10^{-10} m$). To put it in perspective, to make a 1 millimetre long line, you'd need to line up about 4 million copper atoms side by side.

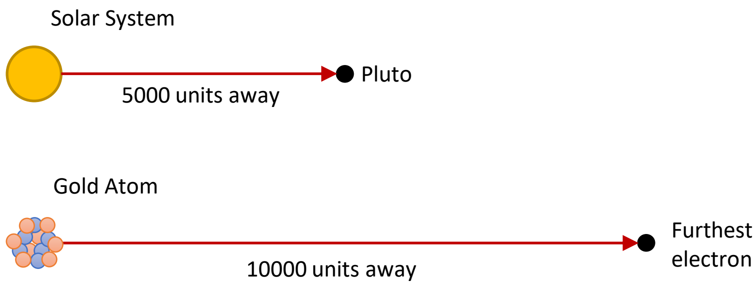
The nucleus is even smaller.

Regardless of the fact that the protons and neutrons have a mass 2000 times that of electrons, the nucleus only makes up a small part of the atom. The electrons orbit at relatively vast distances.

The nucleus is only $\frac{1}{10000}$ the size of the whole atom – while the rest of the atom is empty space.

Nuclear Model of the Atom

If the Solar System (including Pluto) were shrunk to the size of a gold nucleus, the Sun would be the size of a gold nucleus. With this new scale, Pluto would only be half as far away as gold's furthest electron.



Summary of orders of magnitude:

- $Proton\ radius \approx neutron\ radius \approx 10^{-15}m$
- $radius\ of\ nucleus \approx 10^{-15}m\ to\ 10^{-14}m$
- $radius\ of\ atom \approx 10^{-10}m$
- $radius\ of\ molecule \approx 10^{-10}m\ to\ 10^{-6}m$

Nuclear Model of the Atom

Go to the next page.

Terminology and Notation

The nuclei of different atoms are identified by the number of protons and neutrons they contain. These differences are described using the terminology below.

The proton (or atomic) number (Z) is the number of protons contained in the nucleus of an atom.

The nucleon (or mass) number (A) is the total number of nucleons (i.e. protons + neutrons) in the nucleus of an atom.

Neutron number = Nucleon number (A) – Proton Number (Z)

Each nucleus is referred to as a nuclide, and its proton number (Z) and nucleon number (A) are used to characterise it.

The following is the standard notation for representing nuclides:

$$^{A}_{Z}X$$

Where:

A = nucleon number

Z = proton number

X = element symbol

Examples:

- $^{1}_{1}H$: Hydrogen (1p + 0n)
- $^{12}_{6}C$: Carbon (6p + 6n)
- $^{40}_{20}Ca$: Calcium (20p + 20n)

Isotopes

Isotopes are atoms of the same element having the same proton number (Z), but a different nucleon number (A)

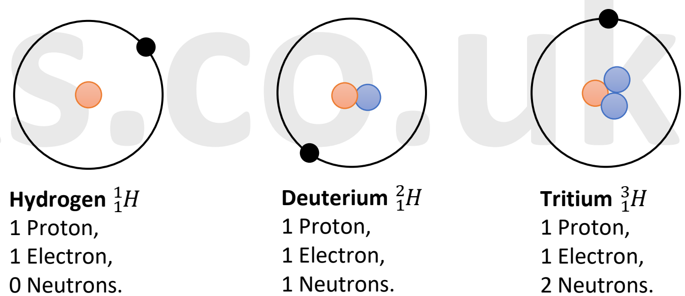
In other words,

Isotopes are atoms that have the same number of protons but a different number of neutrons.

Since ISOTOPES have the same number of protons, they have the same electron arrangement and, as a result, the same chemical properties, but their physical properties differ due to differences in atomic mass.

Example:

Hydrogen

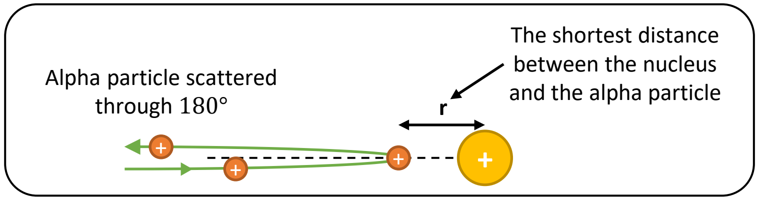


There are several isotopes for each element. Although there are only about 90 naturally occurring elements, there are approximately 1500 identified isotopes. Only about 300 occur in nature, and some are radioactive. The remaining ones are entirely man-made and radioactive.

Nuclear Radius (AQA Only)

Closest approach of Alpha particle (Rutherford's Scattering)

Rutherford's scattering experiment can be used to estimate the radius of an atomic nucleus. An alpha particle that 'bounces back' and is deflected through 180 degrees will come to a stop a short distance from the nucleus — see image below:



The alpha particle does this at the point where all the kinetic energy of the alpha particle has been converted to electric potential energy (pack 18.1 Electric fields). When this has been achieved the alpha particle has reached its distance of closest approach and comes to a stop. At this point:

$$Initial\ KE = E_P = V_E q = \frac{Q_{nucleus} q_{alpha}}{4\pi\varepsilon_0 r}$$

Where:

- Initial E_k is in J
- E_P = electric potential energy, J
- $Q_{nucleus}$ = charge on nucleus, C
- q_{alpha} = charge on alpha particle, C
- ε_0 = the permittivity of free space ($= 8.85 \times 10^{-12}\ Fm^{-1}$)
- r = distance closest approach, m

In order to get distance of closest approach and therefore an estimate for the nuclear radius, rearrange the above formula for r:

$$\therefore r = \frac{Q_{nucleus} q_{alpha}}{4\pi\varepsilon_0\ E_P}$$

Nuclear Radius (AQA Only)

Closest approach of Alpha particle (Rutherford's Scattering)

This is energy conservation, and if you know the alpha particle's initial KE, you can use it to calculate how close the particle can get to the nucleus.

To determine the charge of a nucleus you must first determine the atom's proton number, Z – which indicates how many protons are present in the nucleus. A proton has a charge of $+e$ (where e is the magnitude of the charge on an electron $(1.60 \times 10^{-19} C)$), thus the charge of a nucleus must be $+Ze$.

The nuclear radius is estimated using the distance of closest approach, which offers a maximum value. However, electron diffraction (which we will discuss next) provides a far more precise nuclear radii measurements.

Worked Example

A gold nucleus is struck by an alpha particle with an initial KE of $6.0\ MeV$. Estimate the gold nucleus's radius by determining the alpha particle's point of closet approach. $(Z_{gold} = 79)$ $(\mathrm{Z_{alpha}} = 2)$.

Initial particle energy = $6.0\ MeV = 6.0 \times 10^6\ eV$

Convert energy into joules: $6.0 \times 10^6 \times 1.60 \times 10^{-19} = 9.6 \times 10^{-13} J$

So initial $E_k = E_{elec} = \frac{Q_{nucleus} q_{alpha}}{4\pi\varepsilon_0 r} = 9.6 \times 10^{-13} J = 9.6 \times 10^{-13} J$ at closet approach.

Rearrange to get $r = \frac{(79e)(2e)}{4\pi\varepsilon_0 (9.6\times10^{-13})} = \frac{(79\times1.60\times10^{-19})(2\times1.60\times10^{-19})}{4\pi\times8.85\times10^{-12}\times9.6\times10^{-13}}$

$$= 3.788 \times 10^{-14}$$
$$= 3.8 \times 10^{-14}\ m(to\ 2s.f.)$$

Therefore nuclear radius $\approx 3.8 \times 10^{-14} m$

Nuclear Radius (AQA Only)

Closest approach of Alpha particle (Electron Diffraction)

Electrons are type of particle called a lepton. The strong nuclear force has no effect on leptons (whereas neutrons and alpha particles do). As a result, electron diffraction is a reliable method for determining the radius of the nucleus.

Electrons accelerated to near the speed of light have wave-like properties such as the ability to diffract and have a de Broglie wavelength equal to:

$$\lambda \approx \frac{hc}{E}$$

Where:

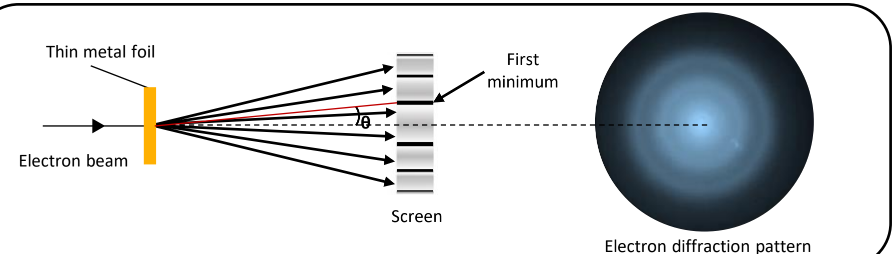
λ = de Broglie wavelength of the electron, m

h = the Planck constant $(= 6.63 \times 10^{-34} Js)$

c = speed of light in a vacuum $(= 3.00 \times 10^{8} ms^{-1})$

E = energy of the electron, J

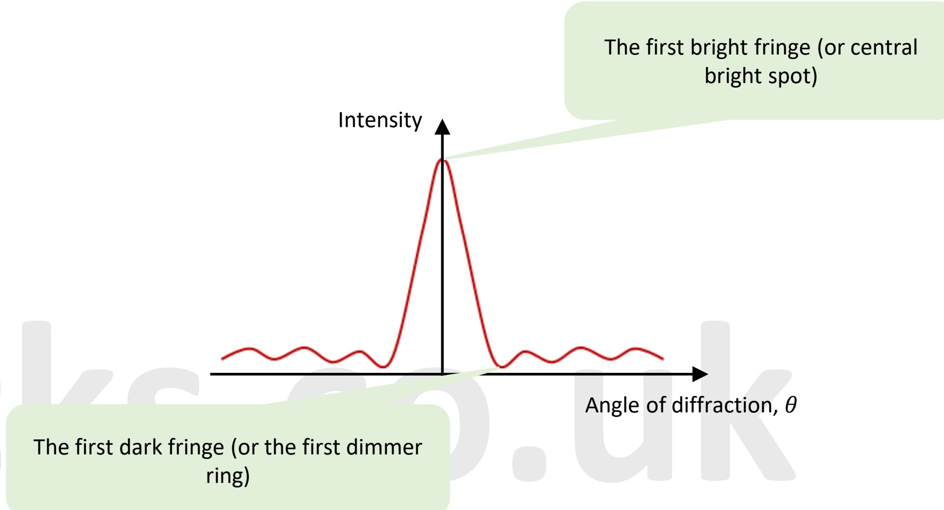
To investigate the nuclear radius, the wavelength must be very small $\left(\sim 10^{-15} m\right)$, which means the electrons will have a very high energy. Therefore if a beam of high-energy electrons is directed onto a thin film of material in front of a screen, a diffraction pattern (or bright and dark fringes) forms a central bright spot with dimmer concentric circles around it on the screen.



Nuclear Radius (AQA Only)

Closest approach of Alpha particle (Electron Diffraction)

Then a graph of intensity against diffraction angle can be used to determine the diffraction angle of the first minimum based on this diffraction pattern.



The diffraction pattern has a bright central maximum (circle) that contains the majority of the incident electrons (shown by the central peak on the graph), which is surrounded by dimmer rings.

From the graph you can see as the angle of diffraction increases, the intensity of the maxima decreases.

The intensity will never reach zero, but it will come very close to zero.

Nuclear Radius (AQA Only)

Closest approach of Alpha particle (Electron Diffraction)

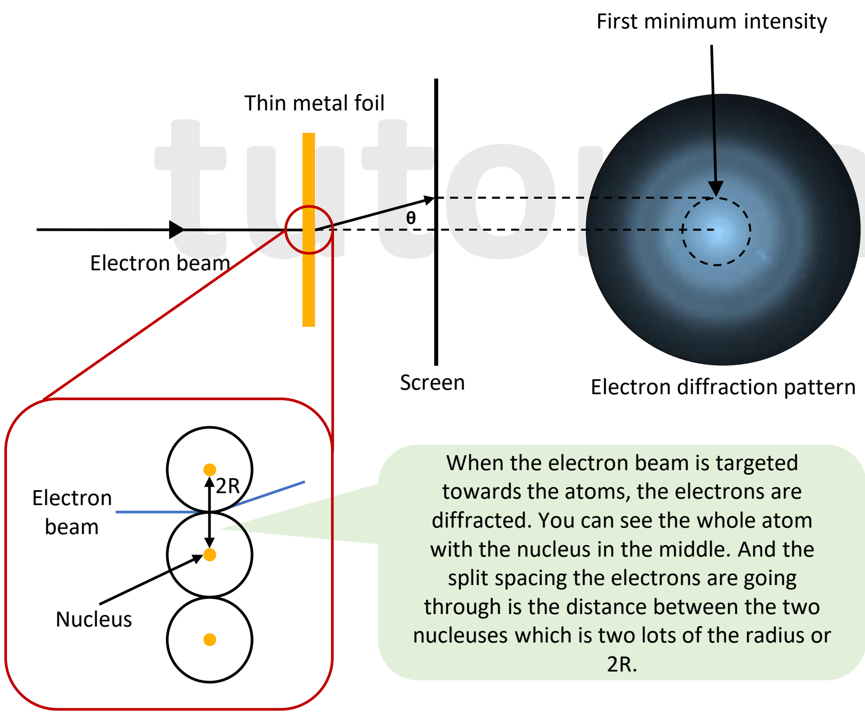
Once the diffraction angle of the first minimum has been determined, the size of the atomic nucleus, R, can be calculated using:

$$sin\theta \cong \frac{1.22\lambda}{2R}$$

Where:

θ = scattering angle

R = the radius of the nucleus the electrons have been scattered by.



Nuclear Radius (AQA Only)

Closest approach of Alpha particle (Electron Diffraction)

Worked Example

A thin piece of foil is hit by a $350MeV$ electron beam, which causes a diffraction pattern to appear on a fluorescent screen. The first minimum of the diffraction pattern is at an angle of $35°$ from the straight-through position. Estimate the radius of the nuclei the electrons were diffracted by.

$$E = 350MeV = 350 \times 10^{6} \times 1.60 \times 10^{-19} = 5.60 \times 10^{-11} J$$

$$\lambda \cong \frac{hc}{E} = \frac{(6.63 \times 10^{-34}) \times (3.00 \times 10^{8})}{5.60 \times 10^{-11}} = 3.55 \ldots \times 10^{-15} m$$

So $R \cong \frac{1.22\lambda}{2sin\theta} = \frac{1.22 \times 3.55 \ldots 10^{-15}}{2sin30°} = 4.333 \ldots \times 10^{-15}$
$= 4.33 \times 10^{-15} m \ (to\ 3s.f.)$

Nuclear Reactions and Equations

A nuclear reaction occurs when a nucleus changes its composition or releases energy. This can occur when:

- A nucleus that is unstable releases a, or-radiation (Radioactive decay)
- Splitting a large nucleus into two smaller nuclei (Fission)
- A nucleus fuses with another nucleus (Fusion)
- Another particle collides with a nucleus (Bombardment)

The following conservation law applies when dealing with nuclear reactions:

1) Conservation of mass/energy

This means that the number of protons and neutrons on both sides of a nuclear reaction equation are the same (i.e. A and Z are balanced across the equation).

2) Conservation of momentum

3) Conservation of electric charge

This indicates that on both sides of a nuclear reaction equation, the overall charge of all nuclei and particles is the same.

Nuclear Decay

1) Alpha (α)-decay

When an unstable nucleus decays by emitting an a-particle, it is called a-particle decay (i.e. a helium nucleus). It loses 2 protons and 2 neutrons, reducing its atomic number (A) by 4 and its proton number (Z) by 2.

Alpha decay occurs only in very big atoms (with more than 82 protons), such as uranium. These atoms' nuclei are simply too large for the strong nuclear force to keep them stable. In order to make themselves more stable the atom emits an alpha particle from the nucleus.

The nuclear equation that describes the a-particle emission of a parent nuclide into a daughter nuclide is:

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

Parent nuclide

Daughter nuclide

α-particle

Appears as K.E. of daughter and α-particle

A and Z are balanced throughout the equation (i.e. there is mass and charge conservation)

If Uranium – 235 emits an α-particle then the Uranium-235 would decay to Thorium – 231.

The equation for this a-decay can be seen below:

$$^{235}_{92}U \rightarrow ^{231}_{90}Th + ^{4}_{2}He + (Energy)$$

A and Z are balanced across the equation and mass and charge are conserved.

Nuclear Decay

2) Beta Minus (β^-)-decay

When an unstable atom decays by emitting a β^- - particle (i.e. a high speed electron), one of the nucleus' neutrons changes into a proton (which remains in the nucleus) plus an electron (which is emitted as a β^- - particle) plus another particle, called an antineutrino.

Isotopes that are "neutron rich" (i.e. have too many neutrons compared to protons in their nucleus) undergo beta decay. When a nucleus ejects a beta particle, one of the nucleus' neutrons becomes a proton. The number of protons increases by one, while the number of nucleons remains unchanged.

The nuclear equation for a parent nuclide decaying into a daughter nuclide by β^- - particle emission is:

$$^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}e + {}_{0}^{0}\overline{v} + (Energy)$$

Parent nuclide — Daughter nuclide — β^- - particle — Antineutrino

A and Z are balanced across the equation (i.e. there is mass and charge conservation).

Carbon – 14 will decay to Nitrogen – 14 if it emits an β^- - particle.

The equation for this β-decay can be seen below:

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}_{-1}^{0}e + {}_{0}^{0}\overline{v} + (Energy)$$

A and Z are balanced across the equation thus mass and charge are conserved.

Nuclear Decay

3) Beta Plus (β^+, e^+)-decay

When an unstable atom decays by emitting a β^+ - particle (i.e. a positron (the opposite of an electron)), one of the protons in the nucleus changes into a neutron (which remains in the nucleus) plus a positron (which is emitted as a β^+ - particle) plus another particle, called a neutrino.

The nuclear equation for a parent nuclide decaying into a daughter nuclide by β^+ - particle emission is:

$$^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + {}_{+1}^{0}e + {}_{0}^{0}v + (Energy)$$

Parent nuclide — Daughter nuclide — β^+ - particle — Neutrino

There is mass and charge conservation and A and Z are balanced across the equation.

If Polonium-15 emits an β^+ - particle it will decay to Silicon-14 and release a positron (e^+, β^+) and a neutrino.

The equation for this a-decay can be seen below:

$$^{30}_{15}Po \rightarrow {}^{30}_{14}Si + {}_{+1}^{0}e + {}_{0}^{0}v + (Energy)$$

A and Z are balanced across the equation and mass and charge are conserved.

Nuclear Decay

4) Gamma Emission

The nucleus often has excess energy and often in an excited state after alpha and beta decay. This energy is lost by emitting a gamma ray. The nuclear constituents do not change during gamma emission; the nucleus just loses energy.

Electron capture is another way of emitting gamma radiation. This occurs when a proton-rich nucleus captures and absorbs one of its own orbiting electrons, converting a proton to a neutron. In the process, a neutrino is released.

Electron capture has the same effect on the nucleon and proton numbers as beta-plus decay: both increase the number of neutrons and reduce the number of protons in the nucleus by one. As a result, the nucleus becomes unstable and releases gamma radiation.

Example:

Beryllium-7 decays to lithium-7 by electron capture:

$$^{7}_{4}Be + {}^{0}_{-1}\beta \rightarrow {}^{7}_{3}Li + {}^{0}_{0}v_e + \gamma$$

Beryllium-7

β^- - particle / electron

$Lithium - 7$

Neutrino

Gamma radiation

The number of nucleons remains constant, but the number of protons reduces by 1.

A and Z are balanced across the equation and mass and charge are conserved.

Energy Level Diagrams for Nuclear Reactions (AQA Only)

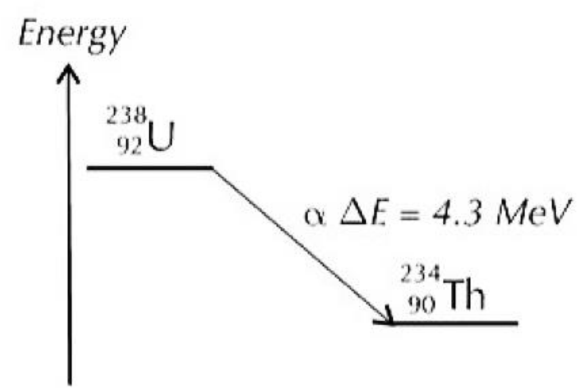
Nuclei energy transitions during radioactive decay can be shown using energy level diagrams in the same way that electron energy transitions can.

A vertical energy axis is commonly used in energy level diagrams to represent the relative energy of each level – the lower the axis, the lower the nucleus' energy. The energy levels themselves are drawn as horizontal lines.

On the energy levels, the element is usually written in nuclide notation. An arrow between the energy levels shows the decay and energy change. The type of decay and the change in nucleus energy, ΔE, are labelled on this arrow. The amount of energy released by the decay is equal to this change in energy.

Example:

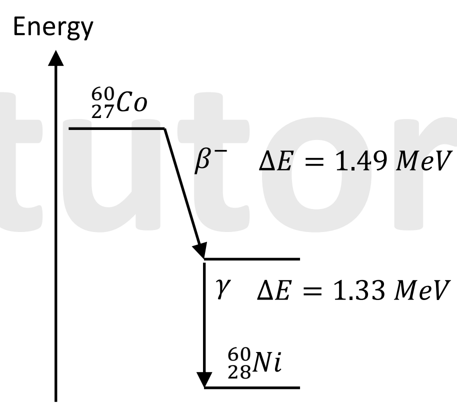
The alpha decay of uranium-238 nucleus into thorium-234 is represented by the energy diagram below. This decay results in a 4.3MeV energy loss for the nucleus.



Energy Level Diagrams for Nuclear Reactions (AQA Only)

The energy diagram below shows one potential beta-minus and gamma decay pathway for cobalt-60 to nickel-60. The diagram's order of decays demonstrates that the beta-minus decay took place before the gamma decay.

The cobalt is converts into nickel by the beta-minus decay – but the nucleus is excited and unstable at this energy level. Once it has released a gamma ray, it de-excites. You don't need to write the nuclide notation for the nickel isotope twice, writing it on one of the levels is sufficient.



This diagram can be used to calculate the total energy required to transition from cobalt-60 to nickel-60:

$$1.49 + 1.33 = 2.82\ MeV$$

The strong nuclear force (Strong Interaction)

All nuclei contain positively charged protons and uncharged neutrons, except for hydrogen, which has only one proton.

The protons repel each other with an electrostatic force which is directly proportional to the product of their charges and inversely proportional to the square of their separation.

We already know that matter stays together, and that nuclei do not blow apart. As a result, the repulsion force must be balanced by an attraction force between nucleons. So, what is the force that keeps the nuclei together? Is it possible that it's the gravitational pull that exists between all large particles?

Calculating the magnitudes of the Electrostatics repulsion force (F_E) and the gravitational attraction force (F_g) between two protons at their typical separation distance in a nucleus can help us find out if this is true.

The following are the two equations that we must use:

$$F_E = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2}$$

$$F_g = \frac{G m_1 m_2}{r^2}$$

- F_E = electrostatic repulsion force on the object in N
- Q_1 and Q_2 = charges of the two objects in C
- ε_0 = "epsilon-nought", the permittivity of free space $(= 8.85 \times 10^{-12} Fm^{-1})$ in farads per metre (Fm^{-1})
- F_g = gravitational attraction force magnitude in N
- G = gravitational constant in Nm^2kg^{-2}
- m_1 = mass of the first object in kg
- m_2 = mass of the second object in kg
- r = distance between the two objects in m

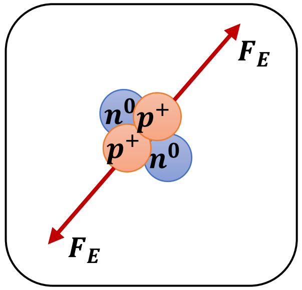
The strong nuclear force (Strong Interaction)

Is it possible that the gravitational force is keeping nuclei together?

Consider the two protons in a helium nucleus. Calculate the following using the information provided below:

a) The electrostatic repulsion force (F_E).

b) The gravitational attraction force (F_g).



- The two protons are $1.0 \times 10^{-15} m$ apart.
- Charge on proton, $e = +1.6 \times 10^{-19} C$
- Mass of proton, $m_p = 1.67 \times 10^{-27} kg$
- $\frac{1}{4\pi\varepsilon_0} = 9.0 \times 10^9 \ mF^{-1}$
- $G = 6.67 \times 10^{-11} \ Nm^2kg^{-2}$

Electrostatic force:

$$F_E = \frac{Q_1Q_2}{4\pi\varepsilon_0 r^2} = \frac{(1.6\times10^{-19} \ C)(1.6\times10^{-19} \ C)}{4\pi(8.85\times10^{-12} Fm^{-1})(1.0\times10^{-15} \ m)^2}$$
$$F_E = 230.2 \ N$$

The gravitational attraction force:

$$F_g = \frac{Gm_1m_2}{r^2} = \frac{(6.67 \times 10^{-11} \ Nm^2kg^{-2})(1.67 \times 10^{-27} \ kg)^2}{(1.0 \times 10^{-15} \ m)^2}$$
$$F_g = 1.86 \times 10^{-34} \ N$$

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The strong nuclear force (Strong Interaction)

According to the calculation of the electrostatic repulsion and gravitational forces between two adjacent protons, the gravitational force is far too weak to be the force that holds nucleons together.

So, in order to hold nucleons together, there must be another force acting between them. This force is called the strong nuclear force often known as the strong interaction (F_S) and has the following properties:

- **It has a very short range**

Strong nuclear force has no effect outside the nucleus since it does not extend far beyond adjacent nucleons (i.e. $F_S \approx 0$ at separations $(r) > about \ 3.0 \times 10^{-15} m$).

- **It is independent of charge**

Strong nuclear force acts between all nucleons (i.e. proton-proton, proton-neutron and neutron-neutron).

- **It is attractive**

Until the separation (r) becomes $< about \ 5.0 \times 10^{-16} m$.

Then it gets progressively more repulsive. The nucleons would otherwise collapse in on themselves.

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The strong nuclear force (Strong Interaction)

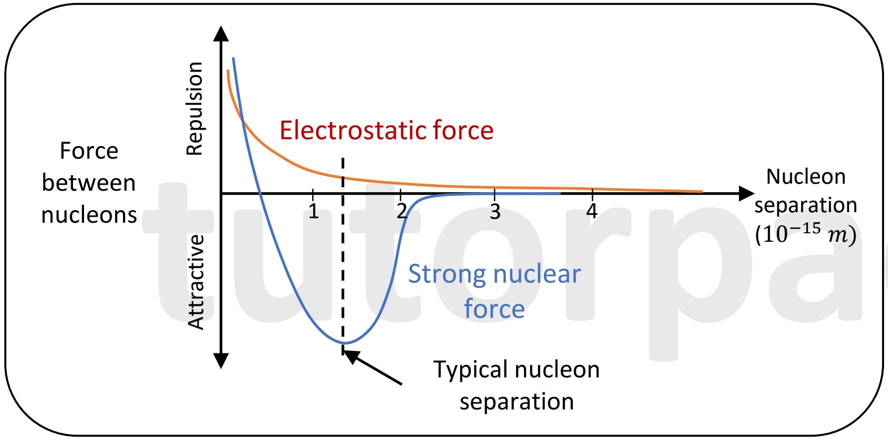
The graph opposite shows how the strong force (F_S) changes as nucleon separation (r) increases.

Note:

F_S is repulsive for r less than $5.0 \times 10^{-16} m$ (or $0.5 fm$)

F_S is attractive for r between $5.0 \times 10^{-16} m$ and $3.0 \times 10^{-15} m$ (or $3 fm$)

F_S = zero for r greater than $3.0 \times 10^{-15} m$



The vector sum of the strong nuclear force and the repulsive electrostatic force is the resultant force on any nucleon. In the case of a neutron, which has no charge, it is simply the strong force.

F_S can be hundreds of times larger than the electrostatic force.

The strong nuclear force (Strong Interaction)

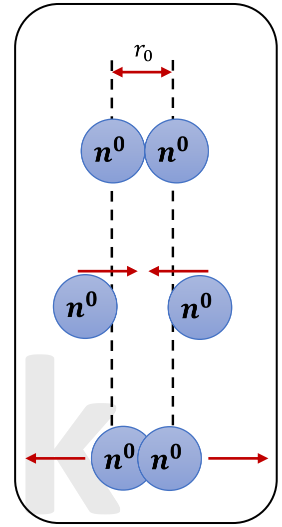
The equilibrium separation (r_0) is the distance between two nucleons at which their resultant force is zero, indicating that they are in equilibrium.

Since there is no electrostatic repulsion between two nearby neutrons, the resultant force is just the strong force.

If the neutrons are moved further apart than their equilibrium separation (r_0) there is a strong attraction force that pulls them back together.

A strong repulsive force will push the neutrons back to their equilibrium separation if they are moved closer than r_0.

The resultant force between two adjacent protons is the vector sum of the attractive strong nuclear force and repulsive electrostatic force.



Since the strong nuclear force is so much stronger than the electrostatic repulsion force, it dominates, and the protons' equilibrium separation is nearly identical to that of a neutron-neutron pair.

Nuclear Stability (AQA Only)

We know, the nucleus is held together by the strong nuclear force, whereas the electromagnetic force pushes the protons apart. It's a sensitive balance, and a nucleus can easily become unstable.

If the nucleus has any of the following, it will be unstable, i.e.:

- There are too many nucleons altogether – i.e. it's too heavy.
- There are too many neutrons.
- There aren't enough neutrons.
- There is too much energy.

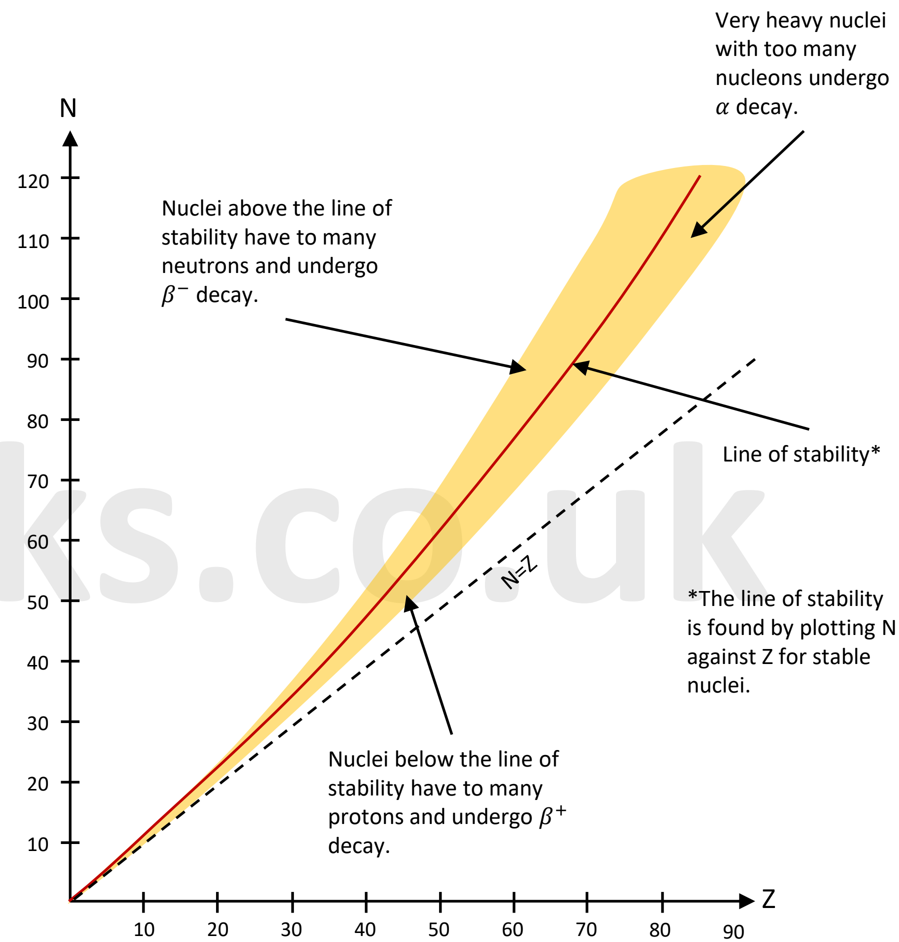
Alpha and beta decay, as well as gamma emission, are all types of decay or 'decay modes' that an unstable nucleus can go through to become more stable.

Plotting number of neutrons (N) against proton number (Z) yields a stability graph, as shown opposite.

From the graph you can see that:

- For proton numbers (Z) up to 20, $N = Z$ is a straight line.
- The line slopes upwards for all nuclei with $Z > 20$ because stable nuclei contain more neutrons than protons.
- Neutron-rich nuclei are unstable nuclei that are above the stability curve.
- Unstable nuclei below the stability curve are called neutron-poor.

Nuclear Stability (AQA Only)



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Radius of a Nuclei

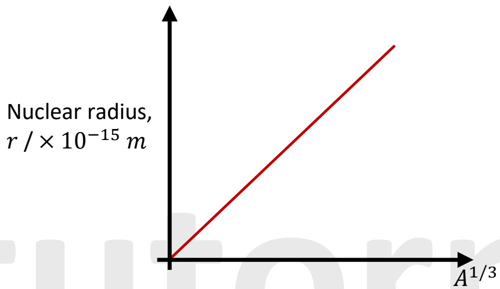
Analysis of experimentally obtained data shows that the radii (R) of a nuclei is related to their nucleon number (A) by the following equation:

$$R = r_0 A^{\frac{1}{3}}$$

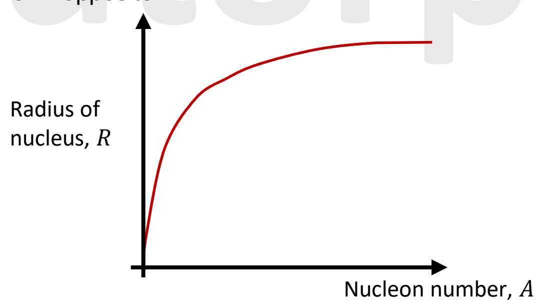
Where r_0 is the radius of a single nucleon. This is a constant of approx. $1.4\ fm\ (= 1.4 \times 10^{-15} m)$.

Therefore, the radius of a nucleus is proportional to the cube root of the number of nucleons it contains.

As a result, plotting R against $A^{\frac{1}{3}}$ for a range of nuclei produces a straight line through the origin, as shown opposite.



If you plot R against A for a range of nuclei, you'll get an increasing exponential graph like the one shown opposite.



To summarise, the more nucleons that are added to a nucleus, the bigger it gets.

Worked example:

Calculate the radius of a carbon nucleus containing 14 nucleons.

$$R = r_0 A^{\frac{1}{3}}$$

$$R = \left(1.4 \times 10^{-15}\right) \times (14)^{\frac{1}{3}}$$

$$R = 3.374 \times 10^{-15} m = 3.4\ fm\ (to\ 2s.f.)$$

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Nuclear Density

The density (ρ) of a nucleus can be determined by imagining the nucleus as a sphere with radius (R), mass (M), containing (A) nucleons of mass (m) each (remember protons and neutrons have almost the same mass).

We know:

$$mass = volume \times density$$

If we assume the nucleus to be a sphere then:

Volume of a radius, $V = \frac{4}{3}\pi R^3$

Radius of a nucleus (R) is, $\mathrm{R} = r_0 A^{\frac{1}{3}}$

And mass of the nucleus (M) is, $M = Am$

$$Am = \frac{4}{3}\pi r_0^3 A \times \rho$$

From which:

$$\rho = \frac{3m}{4\pi r_0^3}$$

As shown by the equation above, the density of a nucleus is independent of the number of nucleons it contains, hence all nuclei have the same density.

Let's plug in some numbers to calculate the density:

Given that:

Nucleon radius $(r_0) = 1.2 \times 10^{-15} m$ and

Nucleon mass $(m) = 1.67 \times 10^{-27} kg$.

Nuclear density (ρ) is given by:

$$\rho = \frac{3 \times (1.67 \times 10^{-27})}{4 \times \pi \times (1.2 \times 10^{-15})^3} = 1.8 \times 10^{17} kgm^{-3}$$

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Nuclear Density

This is roughly 10 million million times the densest metal's density. The fact that atoms are nearly entirely empty space accounts for such a high figure.

About 99.8% of the mass of a uranium atom is stored in the nucleus, which takes up the tiniest fraction of the atom's volume, with the remainder being empty space occupied by 92 electrons.

Please see '20.1.2 The Nuclear Atom worked examples' pack for exam style questions.

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