Module 6 Particles & Medical Physics

Module 6: Particles and medical physics

In this module, learners will learn about capacitors, electric field, electromagnetism, nuclear physics, particle physics and medical imaging.

Module 6 Particles & Medical Physics

Unit 4 Nuclear & Particle Physics

6.4 Nuclear and particle physics

This section provides knowledge and understanding of the atom, nucleus, fundamental particles, radioactivity, fission and fusion.

Nuclear power stations provide a significant fraction of the energy needs of many countries. They are expensive; governments have to make difficult decisions when building new ones. The building of nuclear power stations can be used to evaluate the benefits and risks to society (HSW9). Ethical, environmental and decision making issues may also be discussed (HSW10 and HSW12). The development of the atomic model also addresses issues of scientific development and validation (HSW7,11).

Module 5 – Newtonian world and astrophysics

5.1 Thermal physics

5.2 Circular motion

5.3 Oscillations

5.4 Gravitational fields

5.5 Astrophysics and cosmology

Module 6 – Particles and medical physics

6.1 Capacitors

6.2 Electric fields

6.3 Electromagnetism

You are here! → 6.4 Nuclear and particle physics

6.5 Medical imaging

6.4 Nuclear & Particle Physics

- 6.4.1 The Nuclear Atom
- 6.4.2 Fundamental Particles
- 6.4.3 Radioactivity
- 6.4.4 Nuclear Fission & Fusion

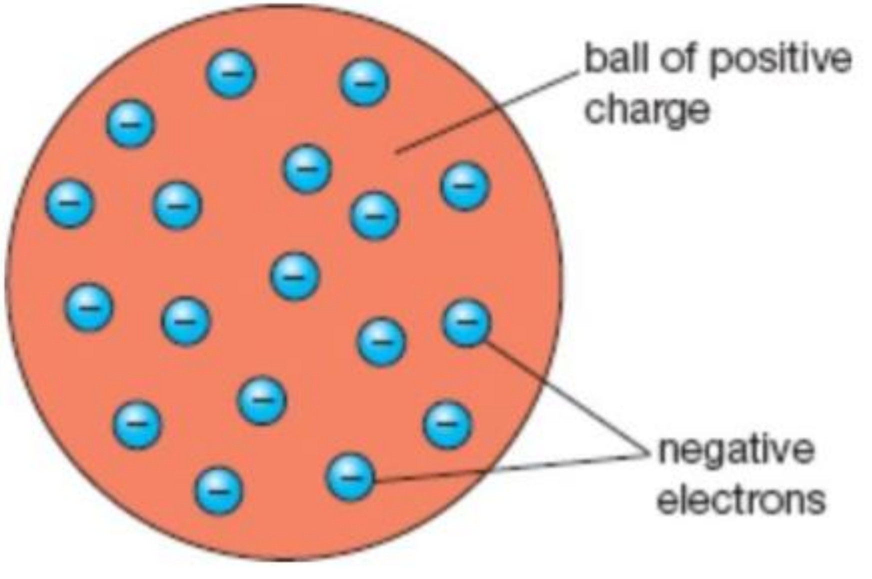
6.4.1 The Nuclear Atom

6.4.1 The nuclear atom	
	Learning outcomes
	Learners should be able to demonstrate and apply their knowledge and understanding of:
(a)	alpha-particle scattering experiment; evidence of a small charged nucleus
(b)	simple nuclear model of the atom; protons, neutrons and electrons
(c)	relative sizes of atom and nucleus
(d)	proton number; nucleon number; isotopes; notation $^{A}_{Z}X$ for the representation of nuclei
(e)	strong nuclear force; short-range nature of the force; attractive to about 3 fm and repulsive below about 0.5 fm
(f)	radius of nuclei; $R = r_0A^{1/3}$ where r_0 is a constant and A is the nucleon number
(g)	mean densities of atoms and nuclei.

How have the models of the atom changed?

Thomson's Plum Pudding Model

- J. J. Thomson produced this model in late 1800s.
  - A neutral atom with negative electrons (the plums) contained in a sea of positive charge (the dough).



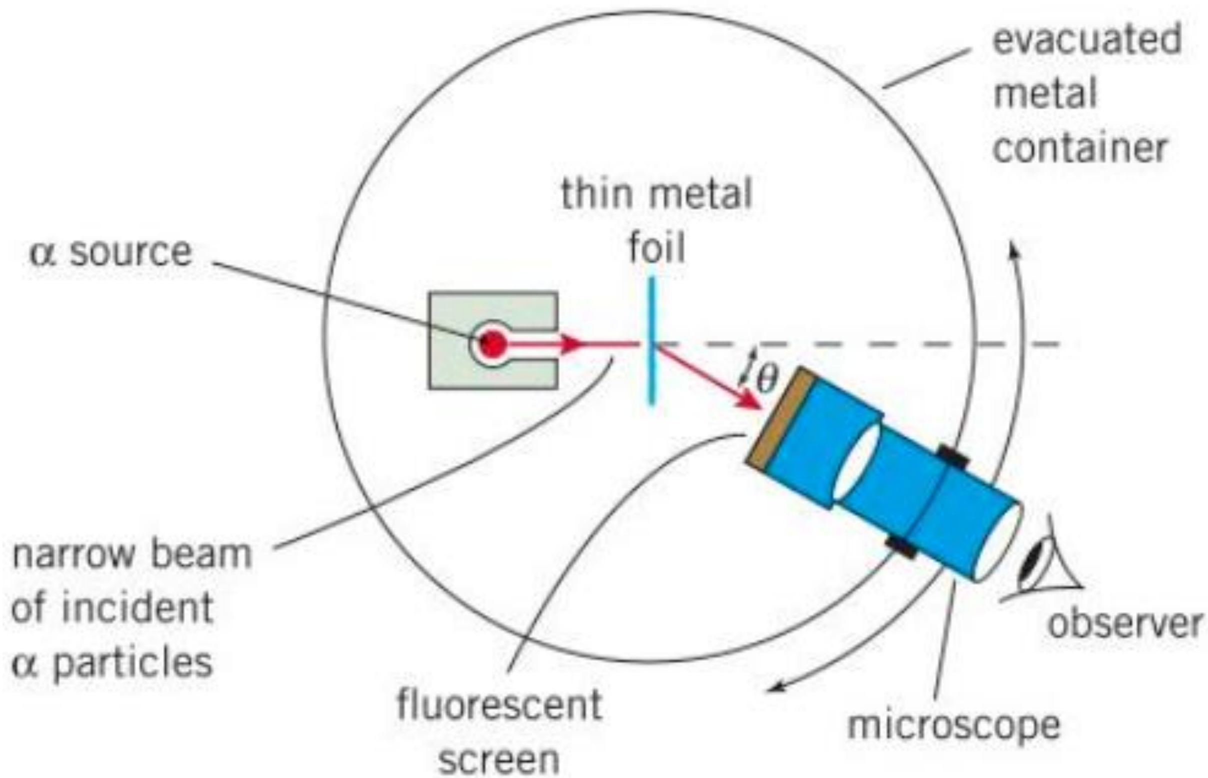
Rutherford’s Nuclear Model

- Rutherford, Geiger & Marsden (1911) showed that the positive charge is actually contained within a tiny volume in the centre of an atom.
  - They called this the nucleus.

Rutherford’s alpha-scattering experiment

- Alpha particles are fired onto a gold foil a few atoms thick.

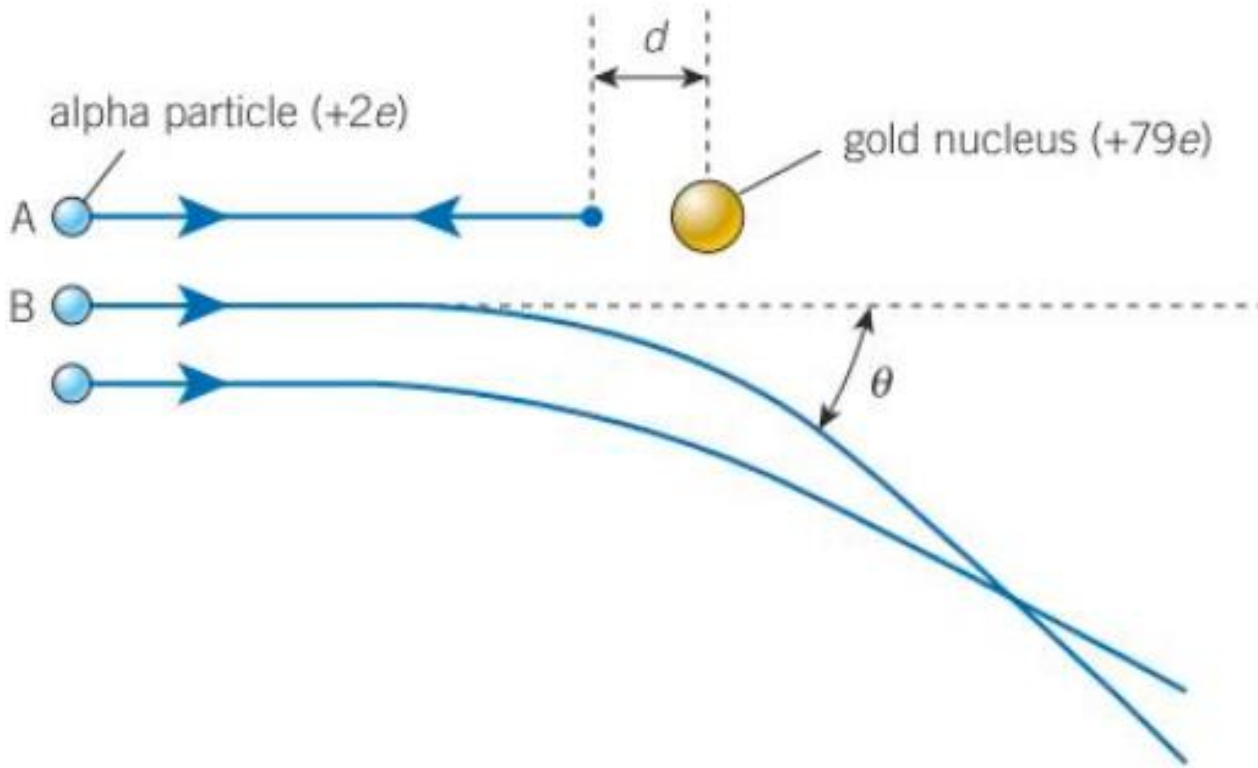
- A detector placed at different angles counts the scattered particles & measures their deflection angle.



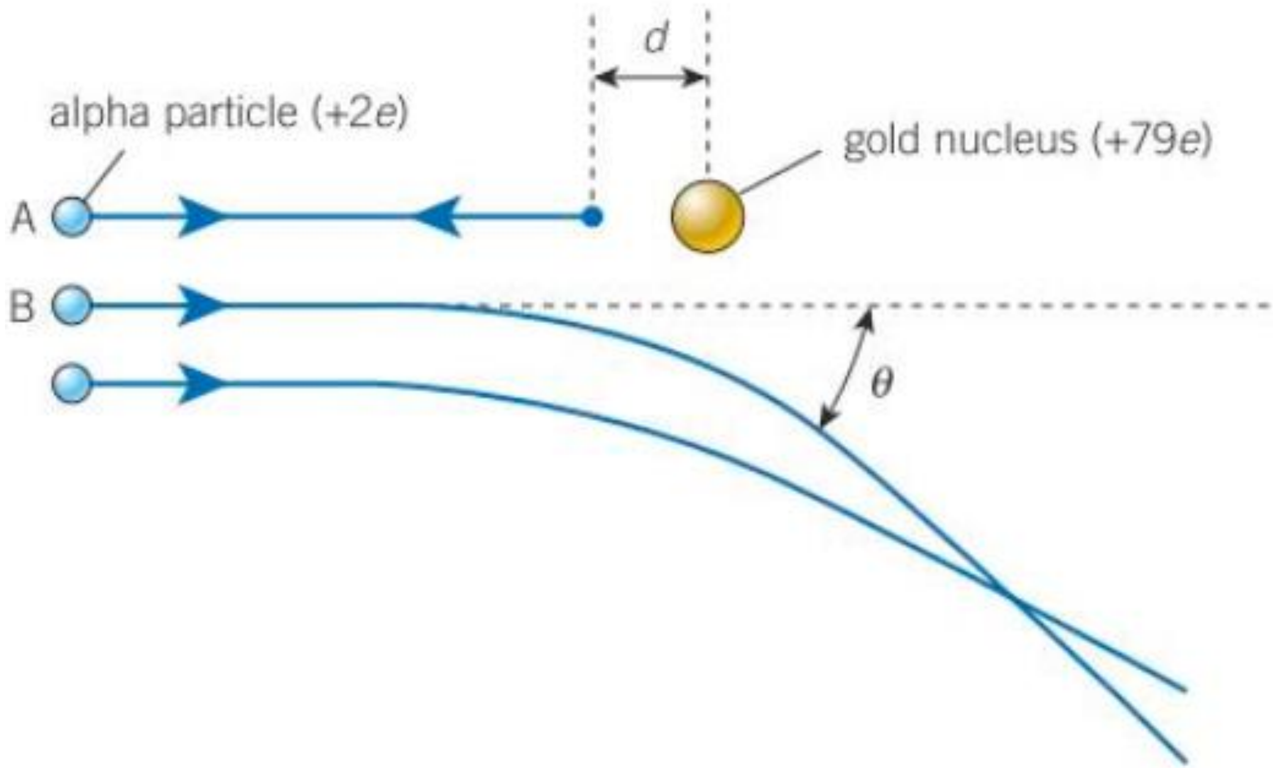
Results

- Most (1999 in 2000) alpha particles passed straight through the gold foil with no deflection.
- A few alpha particles (1 in 10000) were deflected at angles over 90^{o}.

- These observations do not support Thomson's model.
- They do support a model where the atom is largely empty space with a small region of positive charge & mass concentrated in the centre.



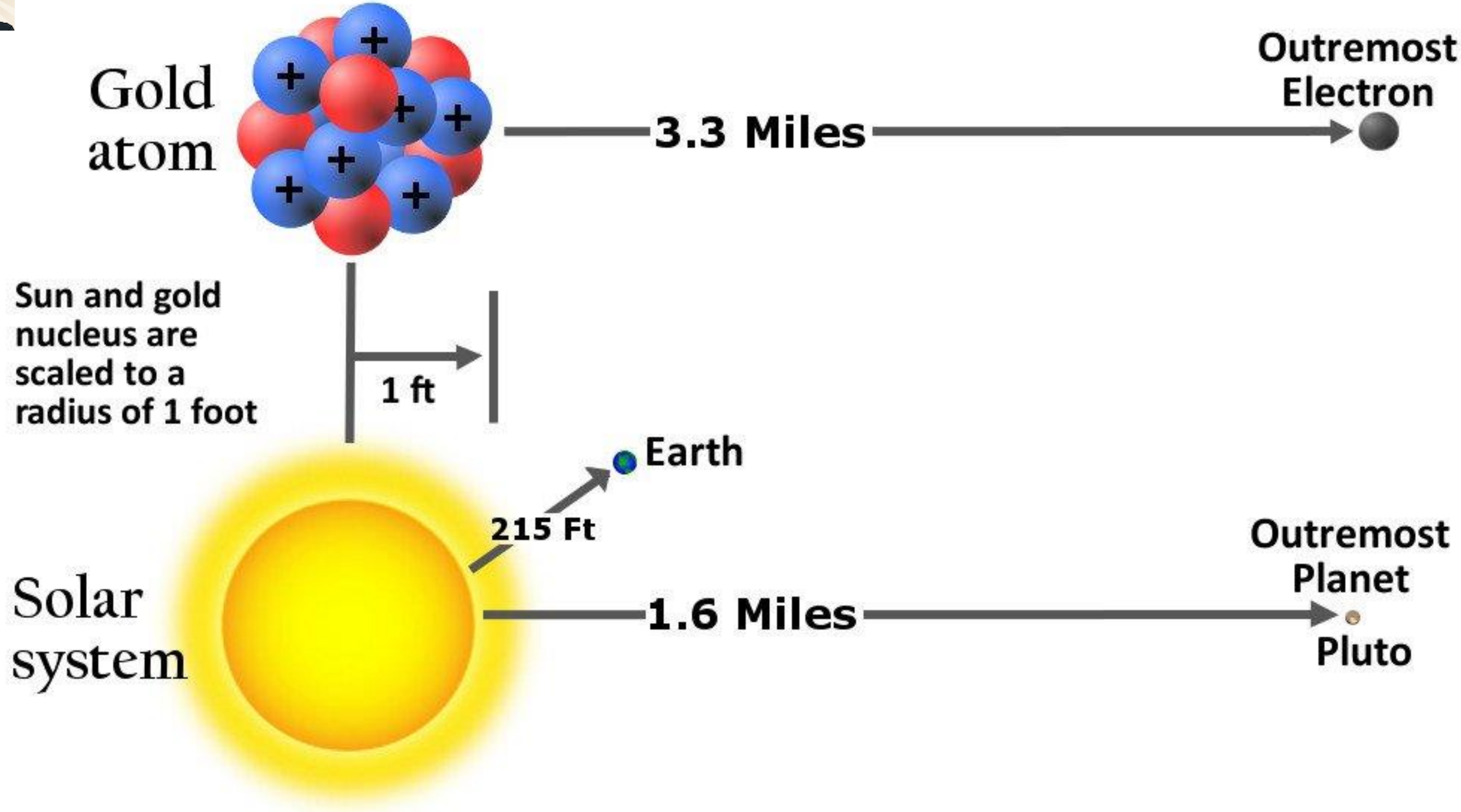
- Particle A makes a head on collision & is deflected back where it came from.
- Particle B makes an oblique collision and is scattered through angle θ.



- Distance d is the closest an alpha particle will get to the gold nucleus.
  - Can be calculated from the electrical potential energy of a +2e particle and a +79e particle equalling the initial kinetic energy of the +2e alpha particle to begin with.

Nuclear size

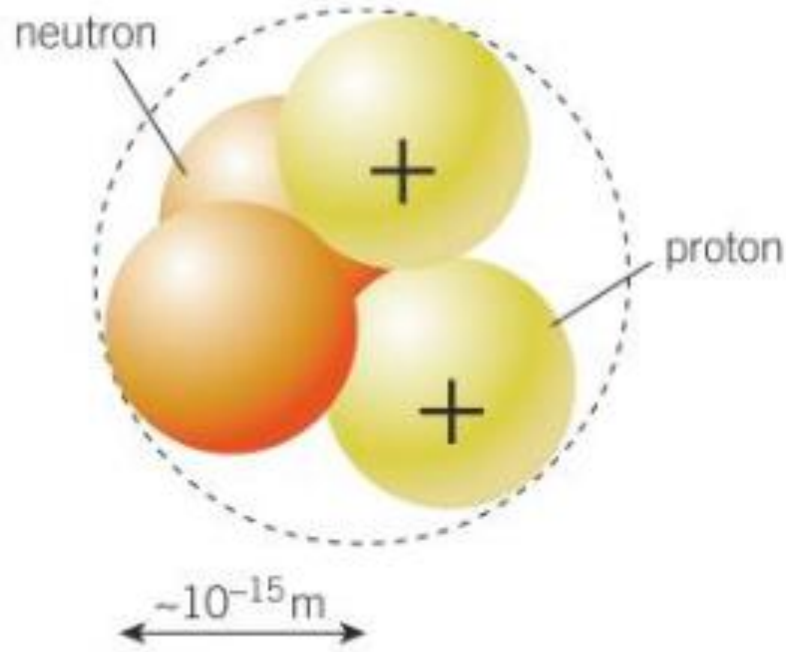
- Distance d gives us an upper limit for the radius of a gold nucleus.
  - Roughly 10^{-15}m
- If most atoms have a radius of about 10^{-10}m then the nucleus is 10^5 times smaller than the atom.
- On that scale, a nucleus the size of a 1mm diameter full stop would have electrons 100m away.



- To scale, a gold atom's outer electrons are twice the distance as Pluto is from our sun.

OK, so what's in a nucleus?

The Nucleus



Nucleon = a proton or neutron

- Since Chadwick's discovery of the neutron, we now know that the nucleus contains positive protons and neutral neutrons.
- Neutral atoms have the same number of protons as electrons

Atomic Symbols

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

Where:

X = the chemical symbol for the element

A = the nucleon number (mass number)

Number of Protons plus Neutrons

Z = the proton number (atomic number)

Number of Protons

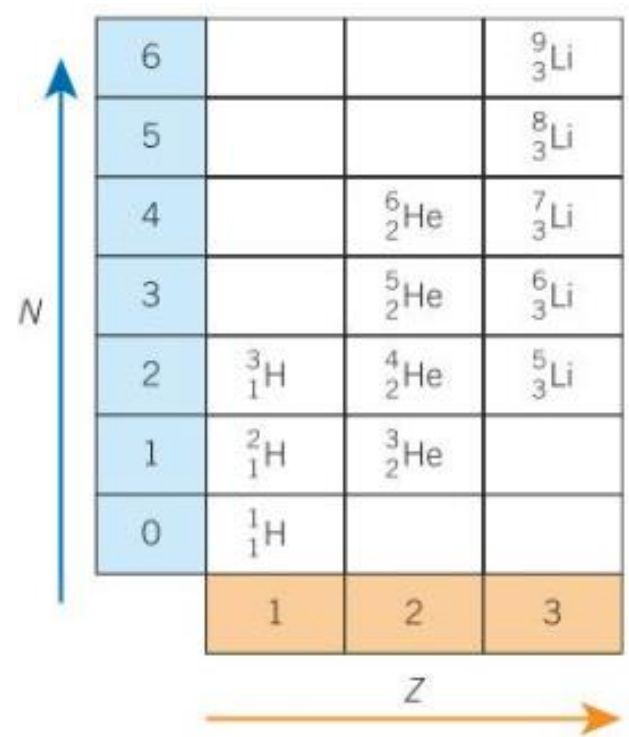
The number of neutrons = A-Z

Isotopes

$$^{12}_{6}C \qquad\qquad ^{14}_{6}C$$

- Nuclei of the same element, with the same number of protons but a different number of neutrons.

- Isotopes of an element undergo identical reactions.



Atomic Mass Units (u)

- One atomic mass unit is 1/12th of the mass of a neutral ^{12}C Carbon atom.
  - So $1u = 1.661 \times 10^{-27}$ kg

Particle	electron	proton	neutron	helium-4 nucleus	carbon-12 nucleus	iron-56 nucleus	uranium-235 nucleus
Mass / u	0.00055	1.00728	1.00867	4.00151	11.99671	55.79066	234.99343

Nuclear Size

- The radius of a nucleus depends on its nucleon number, A.
- Various experiments show the nuclear radius to be:

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

- Where r_0 is the radius of a single proton ($r = 1.2 \times 10^{-15}$ m)

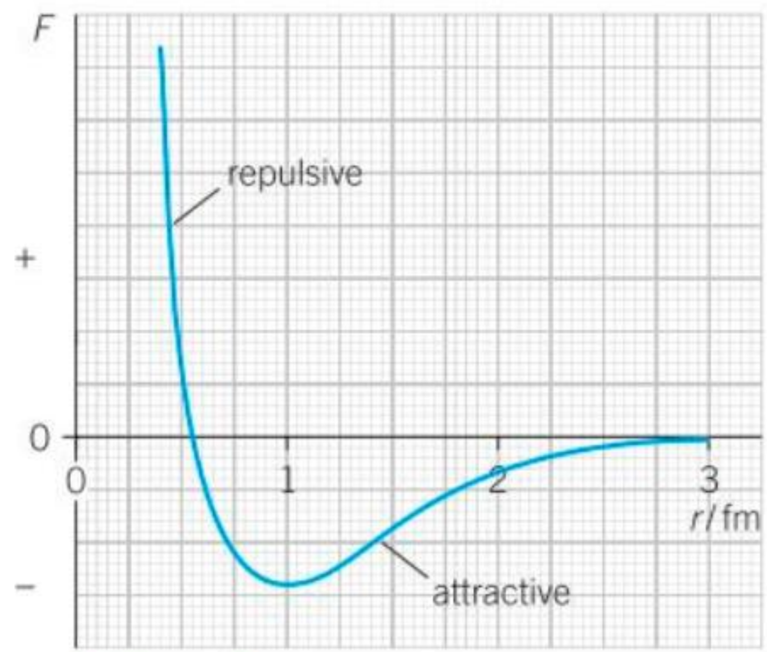
Nuclear Density

- Given that almost the entire mass of an atom is contained in its nucleus, the nuclear density is huge.

- The density of a nucleus is about 10^{17}kgm^{-3}.
- Whereas the density of ordinary matter is about 10^{3}kgm^{-3}.

The Strong Nuclear Force

- Protons in a nucleus are held together in close proximity to each other.
- Coulomb’s Law shows how strong the repulsive force between them is.
- 230N is a huge repulsive force for protons.
- It will equal the Strong Nuclear Force required to hold the protons together.
- This Strong Nuclear Force acts over very short distances as shown by the graph.



6.4.1 The Nuclear Atom (review)

6.4.1 The nuclear atom

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) alpha-particle scattering experiment; evidence of a small charged nucleus

(b) simple nuclear model of the atom; protons, neutrons and electrons

(c) relative sizes of atom and nucleus

(d) proton number; nucleon number; isotopes; notation $^{A}_{Z}X$ for the representation of nuclei

(e) strong nuclear force; short-range nature of the force; attractive to about 3 fm and repulsive below about 0.5 fm

(f) radius of nuclei; $R = r_0 A^{1/3}$ where r_0 is a constant and A is the nucleon number

(g) mean densities of atoms and nuclei.

6.4.2 Fundamental Particles

6.4.2 Fundamental particles

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) particles and antiparticles; electron–positron, proton–antiproton, neutron–antineutron and neutrino–antineutrino

(b) particle and its corresponding antiparticle have same mass; electron and positron have opposite charge; proton and antiproton have opposite charge

(c) classification of hadrons; proton and neutron as examples of hadrons; all hadrons are subject to the strong nuclear force

(d) classification of leptons; electron and neutrino as examples of leptons; all leptons are subject to the weak nuclear force

(e) simple quark model of hadrons in terms of up (u), down (d) and strange (s) quarks and their respective anti-quarks

(f) quark model of the proton (uud) and the neutron (udd)

(g) charges of the up (u), down (d), strange (s), anti-up ($\bar{u}$), anti-down ($\bar{d}$) and the anti-strange ($\bar{s}$) quarks as fractions of the elementary charge *e*

(h) beta-minus (β^-) decay; beta-plus (β^+) decay

(i) β^- decay in terms of a quark model;

$$d \rightarrow u + {}^{0}_{-1}e + \bar{\nu}$$

(j) β^+ decay in terms of a quark model;

$$u \rightarrow d + {}^{0}_{+1}e + \nu$$

(k) balancing of quark transformation equations in terms of charge

(l) decay of particles in terms of the quark model.

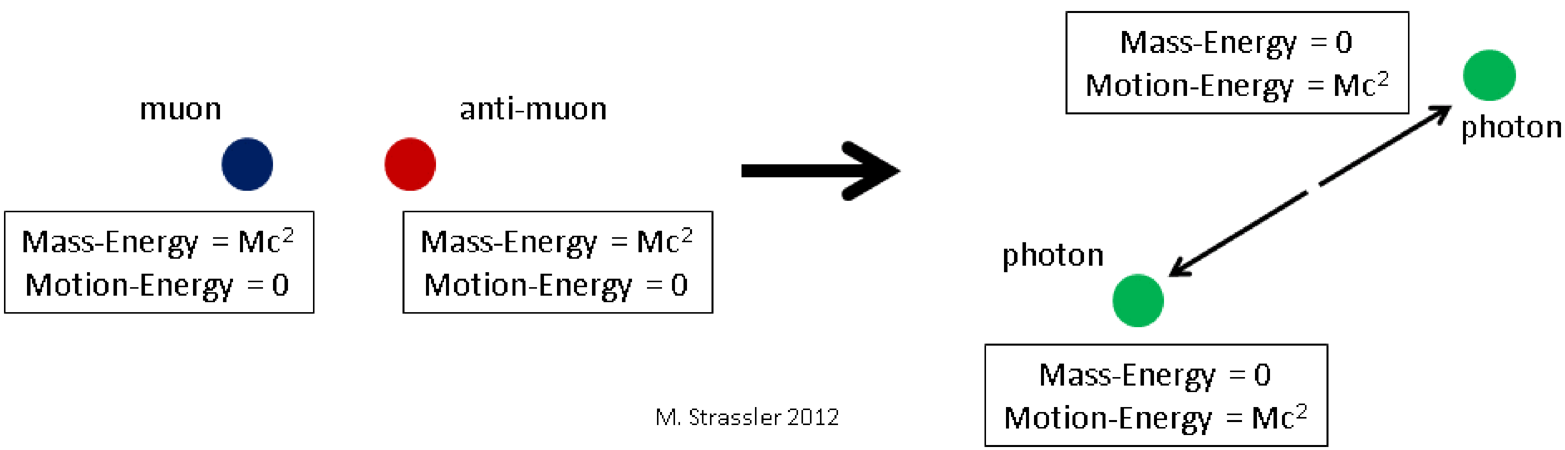
What’s the matter?

What is everything made of?

- Matter/Antimatter
- Held in place by 4 fundamental forces
- Classifying the particles

Matter & Antimatter

- Every particle has a corresponding antiparticle.
  - Antiparticles have the same mass but opposite charge to the particle.
  - Antiparticles are symbolised by a bar over the symbol for the particle (electron – e, positron – ē).
  - Whenever particles & their antiparticles meet they annihilate each other, producing a high-energy pair of photons.



Fundamental Forces

- These explain how the various particles behave:

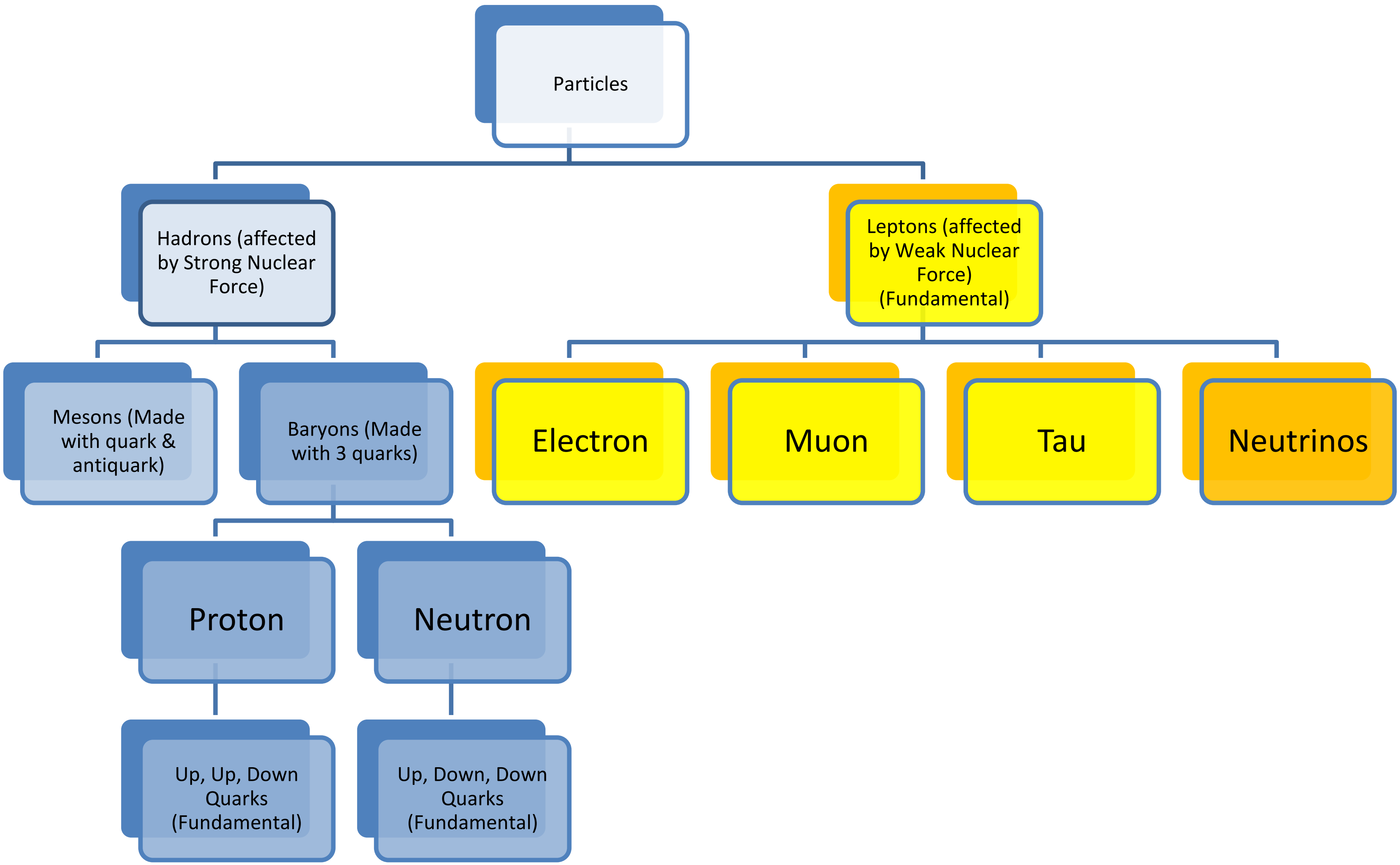
Fundamental force	Effect	Relative strength	Range
strong nuclear	experienced by nucleons	1	$\sim 10^{-15}$ m
electromagnetic	experienced by static and moving charged particles	10^{-3}	infinite
weak nuclear	responsible for beta-decay	10^{-6}	$\sim 10^{-18}$ m
gravitational	experienced by all particles with mass	10^{-40}	infinite

Fundamental Particles

- Particles with no internal structure.
  - Cannot be broken down into constituent parts.

- Everyday matter
  - Atoms
    - Protons
      - 3 quarks (Fundamental)
    - Neutrons
      - 3 quarks (Fundamental)
    - Electrons (Fundamental)

Classifying the Particles



Quarks (Fundamental)

- Six types (plus antiquarks)
- All have charges that are fractions of e.

Quarks			Anti-quarks		
Name	Symbol	Charge Q/e	Name	Symbol	Charge Q/e
up	u	$+\frac{2}{3}$	anti-up	$\bar{u}$	$-\frac{2}{3}$
down	d	$-\frac{1}{3}$	anti-down	$\bar{d}$	$+\frac{1}{3}$
charm	c	$+\frac{2}{3}$	anti-charm	$\bar{c}$	$-\frac{2}{3}$
strange	s	$-\frac{1}{3}$	anti-strange	$\bar{s}$	$+\frac{1}{3}$
top	t	$+\frac{2}{3}$	anti-top	$\bar{t}$	$-\frac{2}{3}$
bottom	b	$-\frac{1}{3}$	anti-bottom	$\bar{b}$	$+\frac{1}{3}$

- Each hadron has a charge equal to the sum of the charges of its quarks.

Hadrons

- Affected by the strong nuclear force.
- Need to know:
  - Proton
    - Made of Up, Up & Down Quarks
    - Charge: 2/3 + 2/3 – 1/3 = 1
  - Neutron
    - Made of Up, Down & Down Quarks
    - Charge: 2/3 – 1/3 – 1/3 = 0

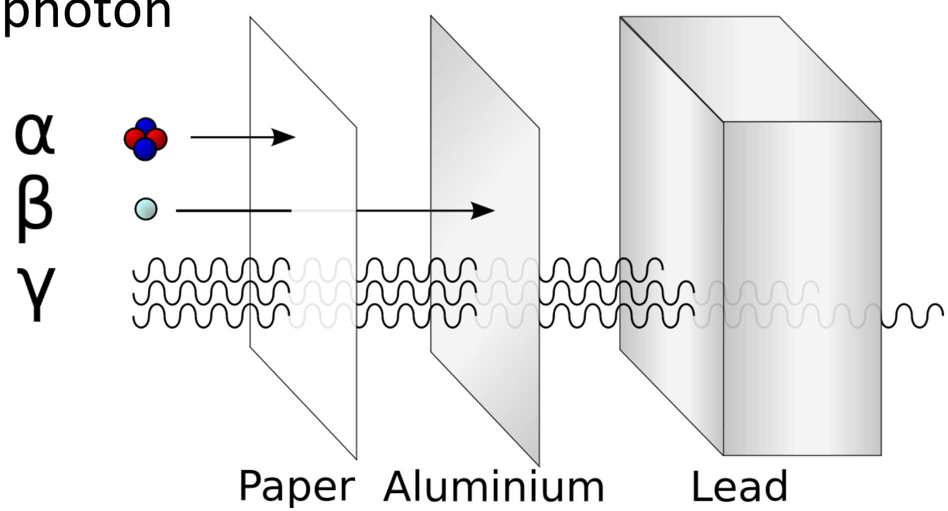
Neutrinos

- Fundamental leptons
- No charge
- Almost no mass
- Rarely interact with matter
- May be passing straight through us and Earth.
- Predicted to explain beta decay conservation laws.
- Three types:
  - Electron Neutrino, v_e
  - Muon Neutrino, v_μ
  - Tau Neutrino, v_τ

Can we explain beta decay in terms of quarks?

Decay

- From GCSE, unstable nuclei emit:
  - Alpha (α) radiation
    - A helium nucleus
  - Beta (β) radiation
    - An electron or positron
  - Gamma (γ) radiation
    - A high energy gamma photon



Beta Minus (β^-) Decay

- A neutron in an unstable nucleus decays into:
  - A proton
  - An electron
  - An electron antineutrino

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

  - See how the nucleon number (A), proton number (Z) and mass are all conserved.

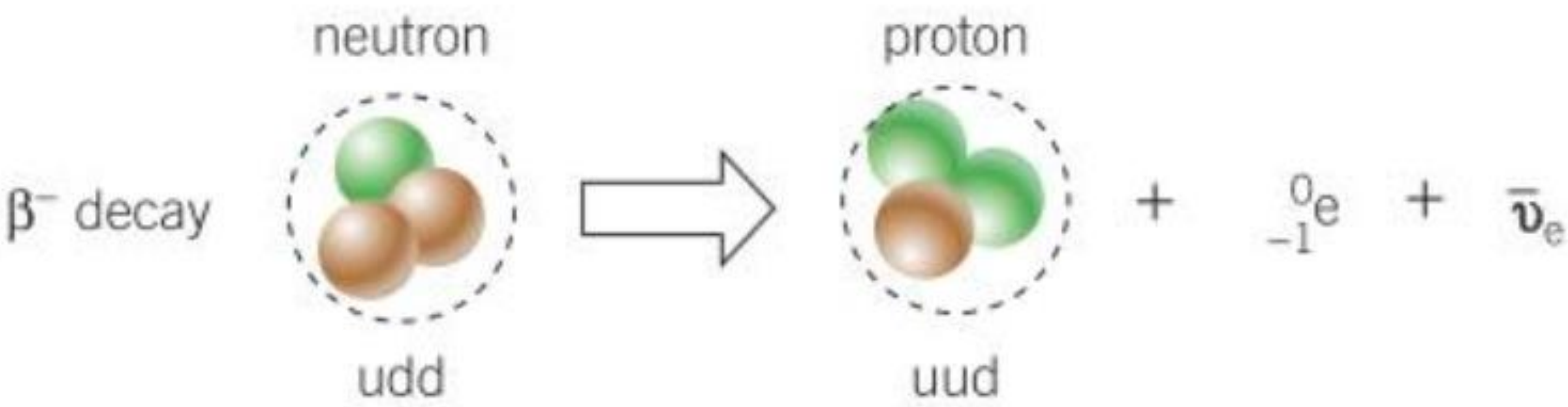
Beta Plus (β^{+}) Decay

- A neutron in an unstable nucleus decays into:
  - A proton
  - A positron
  - An electron neutrino

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

  - Again, the nucleon number (A), proton number (Z) and mass are all conserved.

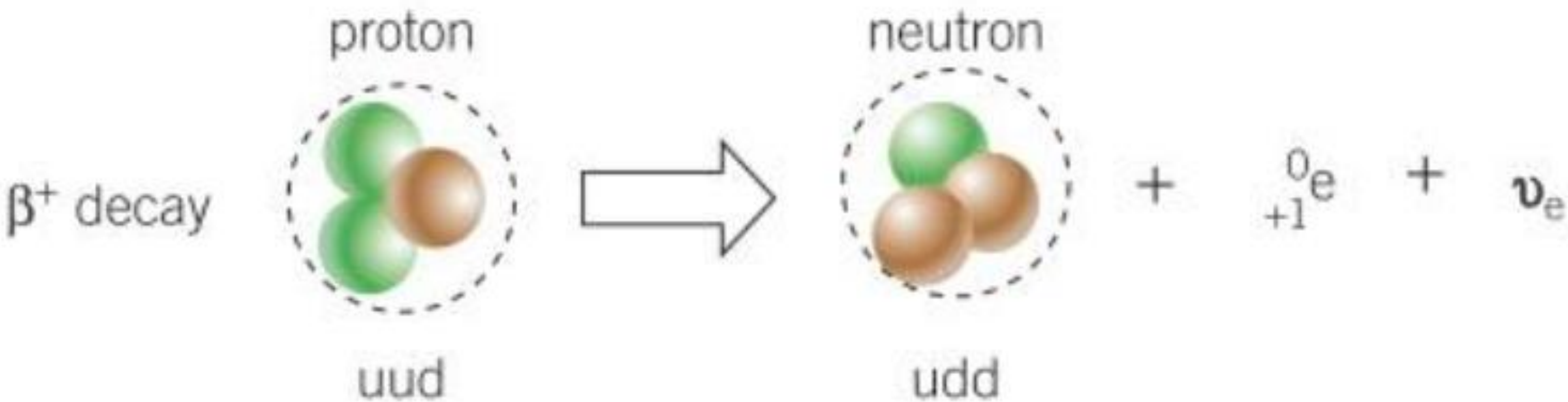
β^- decay in terms of quarks



$$d \rightarrow u + {}^{0}_{-1}e + \bar{\nu}_e$$

The charge on the left-hand side is $-\frac{1}{3}e$ and the total charge on the right-hand side is $\frac{2}{3}e + (-1)e = -\frac{1}{3}e$. The decay equation is balanced in terms of charge.

β^+ decay in terms of quarks



$$u \rightarrow d + {}^{0}_{+1}e + \nu_e$$

The total charge on both sides of the equation is $+\frac{2}{3}e$. As expected, charge has been conserved in this decay too.

6.4.2 Fundamental Particles (review)

6.4.2 Fundamental particles

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) particles and antiparticles; electron–positron, proton–antiproton, neutron–antineutron and neutrino–antineutrino

(b) particle and its corresponding antiparticle have same mass; electron and positron have opposite charge; proton and antiproton have opposite charge

(c) classification of hadrons; proton and neutron as examples of hadrons; all hadrons are subject to the strong nuclear force

(d) classification of leptons; electron and neutrino as examples of leptons; all leptons are subject to the weak nuclear force

(e) simple quark model of hadrons in terms of up (u), down (d) and strange (s) quarks and their respective anti-quarks

(f) quark model of the proton (uud) and the neutron (udd)

(g) charges of the up (u), down (d), strange (s), anti-up ($\bar{u}$), anti-down ($\bar{d}$) and the anti-strange ($\bar{s}$) quarks as fractions of the elementary charge *e*

(h) beta-minus (β^-) decay; beta-plus (β^+) decay

(i) β^- decay in terms of a quark model;

$$d \rightarrow u + {}^{0}_{-1}e + \bar{\nu}$$

(j) β^+ decay in terms of a quark model;

$$u \rightarrow d + {}^{0}_{+1}e + \nu$$

(k) balancing of quark transformation equations in terms of charge

(l) decay of particles in terms of the quark model.

6.4.3 Radioactivity

6.4.3 Radioactivity

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) radioactive decay; spontaneous and random nature of decay

(b) **(i)** α-particles, β-particles and γ-rays; nature, penetration and range of these radiations

(ii) techniques and procedures used to investigate the absorption of α-particles, β-particles and γ-rays by appropriate materials

(c) nuclear decay equations for alpha, beta-minus and beta-plus decays; balancing nuclear transformation equations

(d) activity of a source; decay constant λ of an isotope; $A = \lambda N$

(e) **(i)** half-life of an isotope; $\lambda t_{1/2} = \ln(2)$

(ii) techniques and procedures used to determine the half-life of an isotope such as protactinium.

(f) **(i)** the equations $A = A_0 e^{-\lambda t}$ and $N = N_0 e^{-\lambda t}$, where A is the activity and N is the number of undecayed nuclei

(ii) simulation of radioactive decay using dice

(g) graphical methods and spreadsheet modelling of the equation $\frac{\Delta N}{\Delta t} = -\lambda N$ for radioactive decay

(h) radioactive dating, e.g. carbon-dating.

What are the 3 types of radiation?

Radiation

- Radiation is emitted from unstable atomic nuclei.
  - First discovered by Henri Becquerel by accident.
  - Three types:
    - Alpha, α
    - Beta, β
    - Gamma, γ

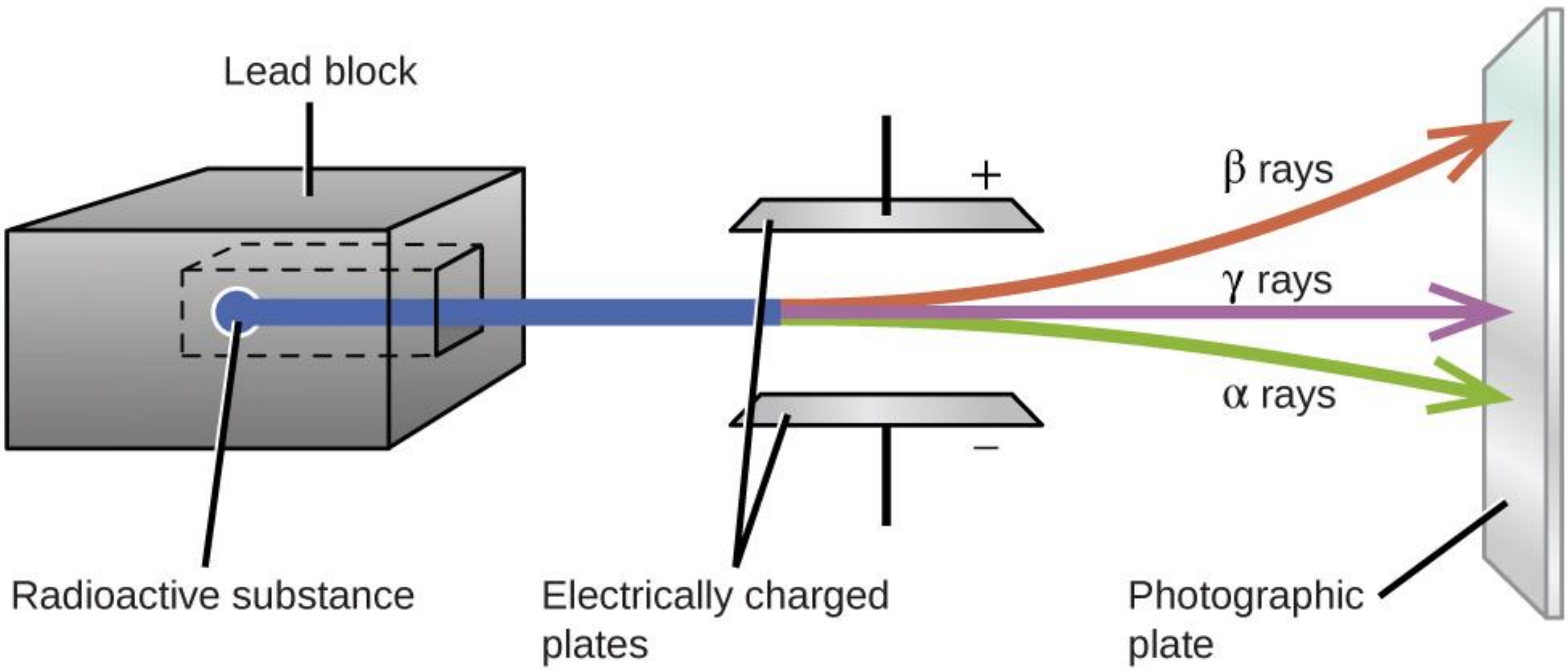
Easy as A, B, C

- Alpha radiation
  - A helium nucleus (2 protons & 2 neutrons)
  - Charge of +2*e* (where *e* is the elementary charge)
- Beta radiation
  - Fast moving electrons (β^-) or positrons (β^+)
  - Charge of -e or +e.
- Gamma radiation
  - High energy photons ($\lambda < 10^{-13}$m)
  - No charge, travel at light speed

The effect of electric & magnetic fields

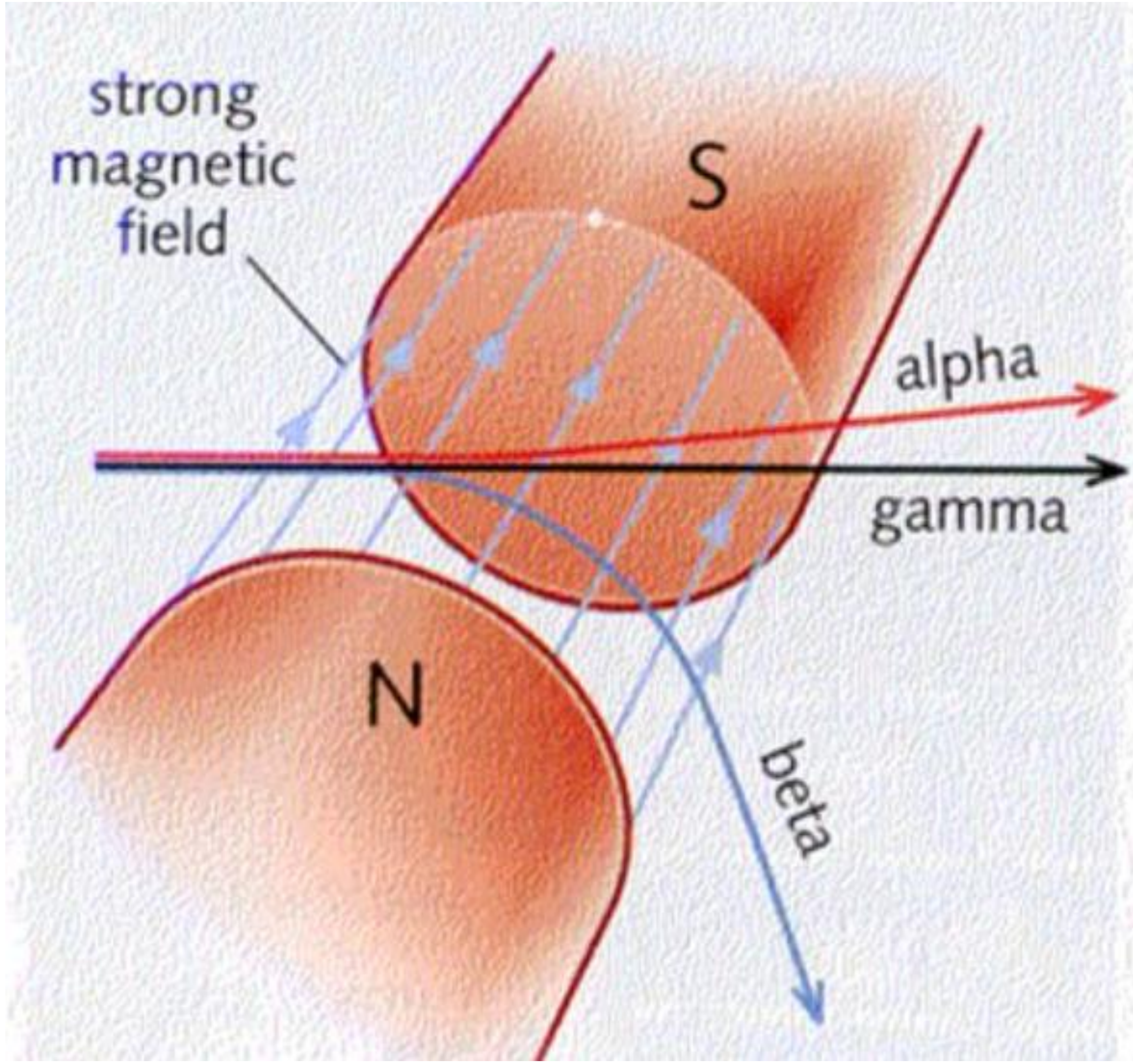
- We can distinguish between these 3 particles by their deflection as they move through an electric or magnetic field.

- Can you explain:
  - The direction of deflection?
    - Positive α deflected towards the negative plate & vice versa.
  - The magnitude of deflection?
    - Higher mass α deflected less than low mass β.



- Similar deflections are seen when travelling through magnetic fields.

- Flemming's left hand rule will show direction of deflection.



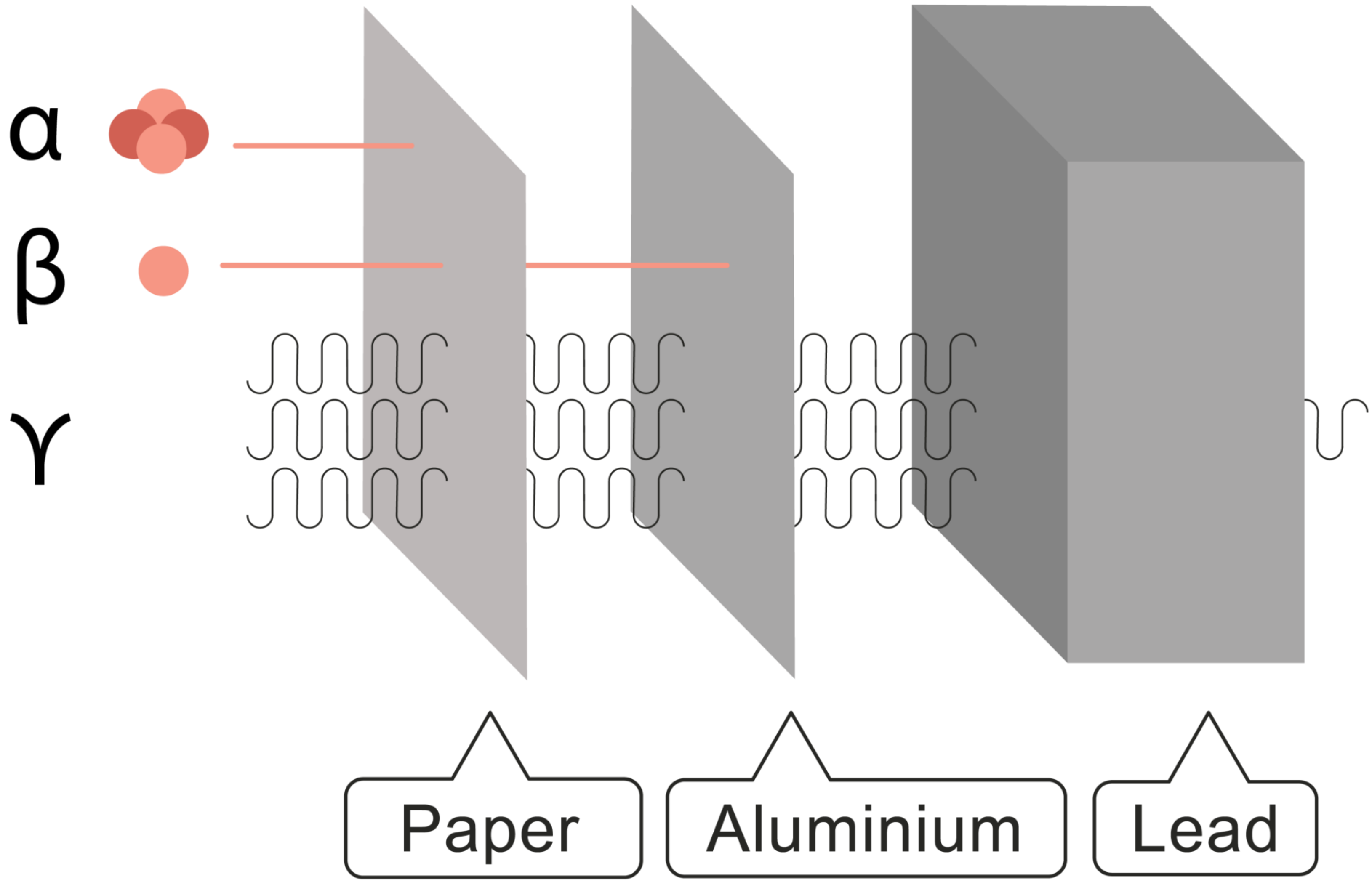
Absorption

- Alpha, Beta & Gamma radiation are ionising.
- They cause ions to be formed when the radiation collides with matter particles.

- Alpha particles are very positively charged so they interact with (ionise) matter very easily.

- Beta particles are less charged so can travel further.

- Gamma rays are the least ionising and travel furthest.


α
β
γ
Paper
Aluminium
Lead

Experiments with radiation

- Ionising radiation can destroy or damage living cells.
- Sources are stored in lead-lined boxes for safety.
- When using sources handle with long armed tongs to keep them as far from the body as possible.

- Take a background count first and subtract this from any measurement you make.

Nuclear Decay

- Radioactive elements have unstable nuclei that decay (emit radiation).
- The original unstable nucleus is the parent nucleus which decays into the new nucleus called the daughter nucleus.
- This process is called transmutation.

Conservation of Mass Number & Atomic Number

- When a nucleus decays its mass number and atomic number are reduced by the values of the radiation type:

Radiation	Symbol	Charge	Mass /u
Alpha	${}^{4}_{2}He \text{ or } \alpha$	+2e	4.002
Beta-minus	${}^{0}_{-1}e \text{ or } \beta^{-} \text{or } e^{-}$	-e	0.001
Beta-plus	${}^{0}_{1}e \text{ or } \beta^{+} \text{or } e^{+}$	+e	0.001
Gamma	${}^{0}_{0}\gamma$	0	0.000

Alpha Decay

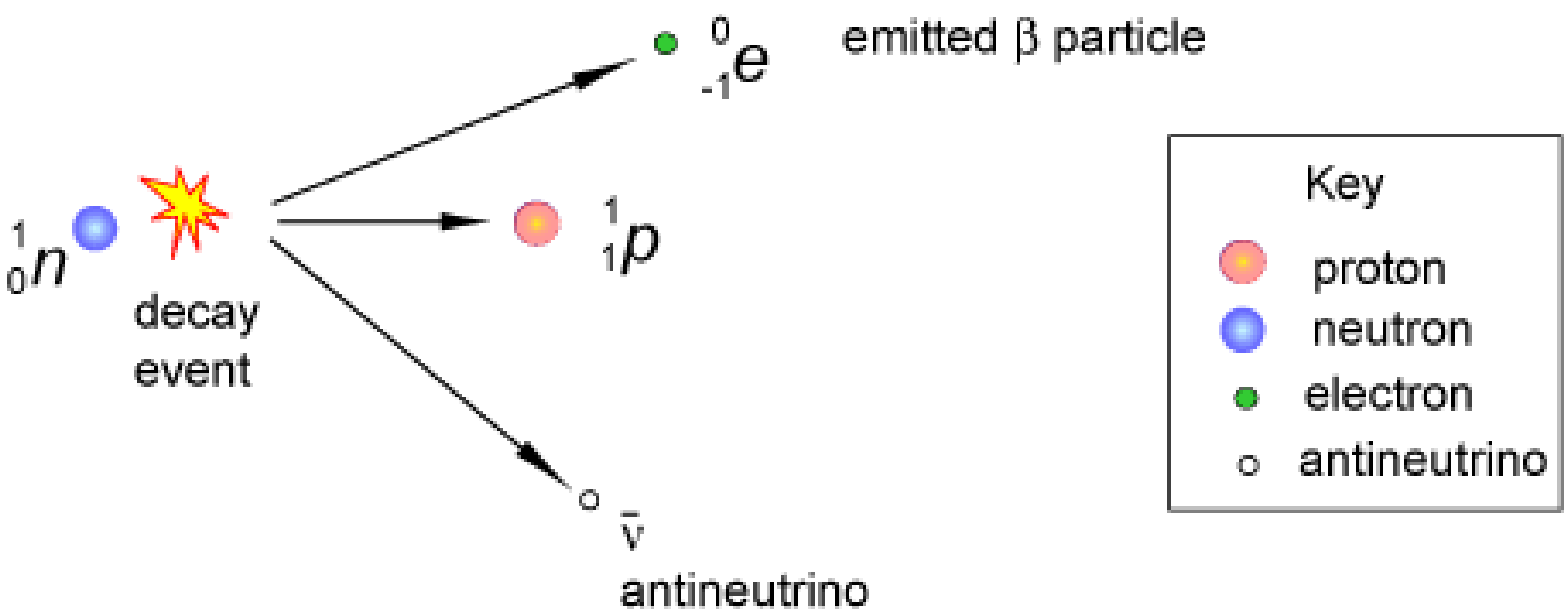
- Emitting an alpha particle (2P, 2N) causes the nucleon number to reduce by 4 and the atomic number by 2.
  - So the element will have been transmuted.
  - What element will radium-226 transmute into via alpha decay?

$$^{226}_{88}Ra \rightarrow \, ^{222}_{86}Rn + \, ^{4}_{2}He$$

Beta Decay

- Nuclei can be unstable by having too many neutrons.
- One of them can decay into a proton, an electron and an electron-antineutrino.
  - The proton stays in the nucleus and the electron & antineutrino are emitted.
    - The neutrino is uncharged and very nearly massless.
    - It was proposed to account for the apparent low energy of the emitted electrons.

Beta Decay of a Neutron



Beta-minus Decay

- Emitting a beta-minus particle causes the nucleon number to remain constant and the atomic number to increase by 1.

$$^{90}_{38}Sr \rightarrow \ ^{90}_{39}Y + \ ^{0}_{-1}e + \overline{v}_e$$

Beta-plus Decay

- Emitting a beta-plus particle causes the nucleon number to remain constant and the atomic number to decrease by 1.

$$^{37}_{19}K \rightarrow \, ^{37}_{18}Ar + \, ^{0}_{1}e + v_e$$

Gamma Decay

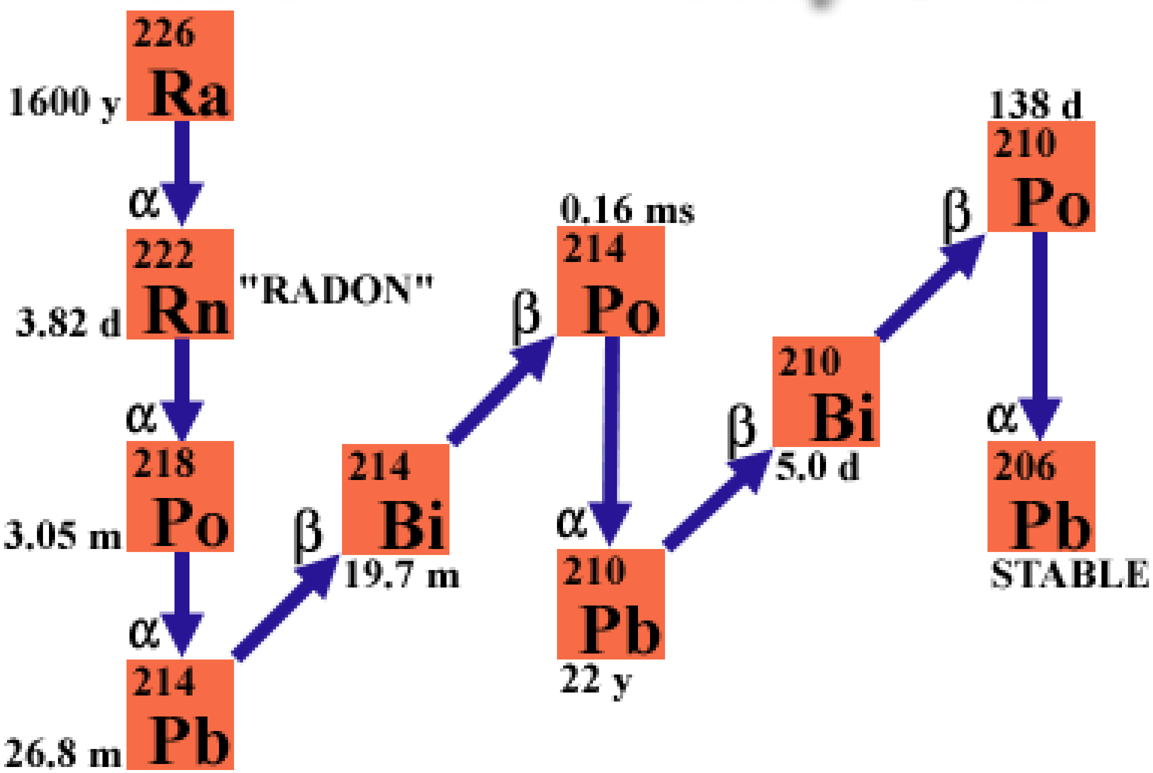
- A nucleus with a surplus of energy following alpha or beta decay will emit photons in the gamma spectrum.
- The nucleus will not change following gamma emission.

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z}X + \gamma $$

Decay Chains

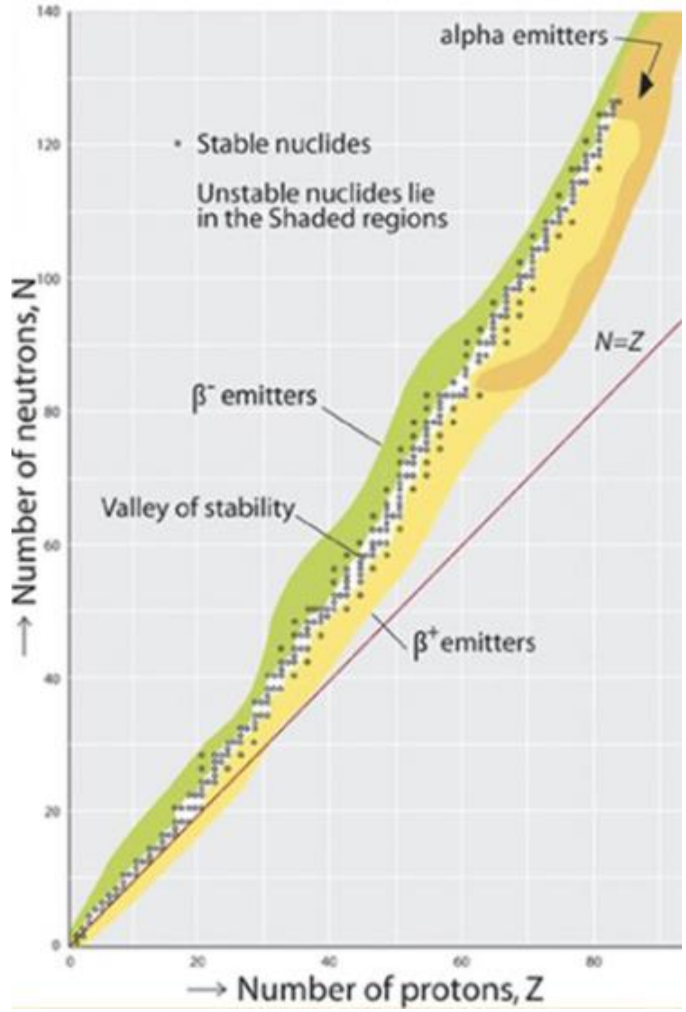
- Nuclei don’t always just decay once then become stable.
- The daughter nuclei may still not be stable and so will undergo further decay.
- This can happen a number of times.

Radium-226 Decay Chain



Can we predict the stable nuclei?

- The stable nuclei lie on a very narrow stability band.



What do we mean by activity & half life?

Radioactivity

- Nuclear decay is:
  - Random
    - Unpredictable
    - Each unstable nucleus has an equal chance decaying
  - Spontaneous
    - Unaffected by other nearby nuclei, pressure, temperature or other external factors

- We can simulate random spontaneous activity using popcorn. Can you think how?

Activity

- What is meant by the activity of an unstable isotope?
  - The rate at which nuclei decay, or the number of emissions per second.
  - Measured in becquerels, Bq.
  - An activity of 4Bq is 4 decays per second.
- This is different from the count rate from a Geiger-Muller tube since emissions happen in all directions and only a fraction of these will be detected.

Half Life

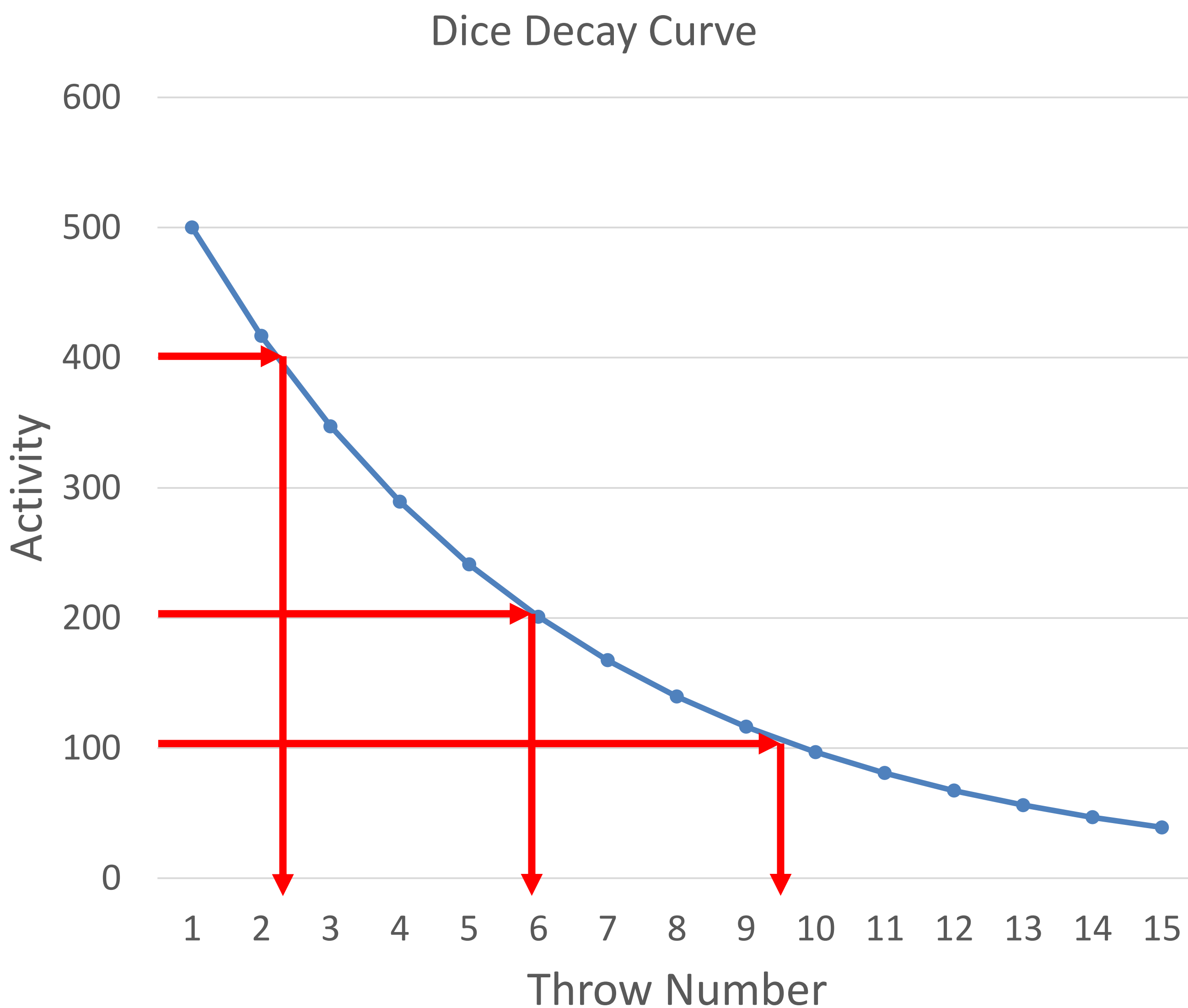
- The average time taken for half of the number of active nuclei to decay.
- This shows that nuclear decay is exponential.

  - Half lives can range from fractions of a second (Be: $8\text{x}10^{-17}$s) to billions of years (Th: $1.4\text{x}10^{10}$yr)

What is the half life of dice?

- Imagine throwing 500 dice.
  - These represent active nuclei.
- Imagine removing all the dice showing a 6.
  - These represent nuclei that have just decayed.
- Imagine rethrowing the remaining dice and repeating.

- Record the results and plot a graph of active nuclei remaining (activity) over number of throws (time).
- Use the graph to show the half life is just under 4 throws.



Throws	Activity	Decays
1	500	83
2	417	69
3	347	58
4	289	48
5	241	40
6	201	33
7	167	28
8	140	23
9	116	19
10	97	16
11	81	13
12	67	11
13	56	9
14	47	8
15	39	6

Decay Constant

- With a large sample of unstable nuclei, N, and a small period of time, Δt:
  - The number of decaying nuclei, ΔN, will be proportional to N and Δt.

$$\Delta N \propto N\Delta t$$

  - The rate of decay is therefore proportional to N.

$$\frac{\Delta N}{\Delta t} \propto N$$

  - The Activity, A, is defined as:

$$A = \frac{\Delta N}{\Delta t} = \lambda N$$

    - Where λ is the decay constant

$$A = \lambda N$$

- What are the units of the decay constant?

S^{-1}

(number of decays per second/number undecayed)

- The decay constant is defined as:
  - The probability of a decay per unit time.

Calculating Half Life

- How did we measure the half life of plutonium 239 to be 24000 years?
  - Record results over a long time?
  - A more mathematical approach?

- We actually just need to know the activity and the number of nuclei present.
  - We can get these from a GM tube and the mass.

Exponential Decay

- We can calculate the number of undecayed nuclei, N, using this equation:

$$N = N_0 e^{-\lambda t}$$

You do not need to know where this equation comes from.

Where:

N = the current number of undecayed nuclei

N_0 = the original number of nuclei at time = 0

λ = the decay constant

t = time elapsed (seconds)

$$N = N_0 e^{-\lambda t}$$

- So the number of undecayed nuclei, N, decreases exponentially over time.

- Since activity, A, is proportional to N:

$$A = A_0 e^{-\lambda t}$$

Where:

A = the current activity of undecayed nuclei

A_0 = the original activity of nuclei at time = 0

Decay Constant v Half Life

- The decay constant, λ, and half life, $t_{½}$, are inversely related to each other as follows:

$$\lambda t_{1/2} = \ln 2$$

- So as half life increases, decay constant will decrease.
  - P.494 has the derivation of this equation if you want it.

Other equations:

- We can also calculate the number of undecayed nuclei if you know how many half lives have elapsed (n):

$$N = (0.5)^n N_0$$

Where:

$$n = \frac{t}{t_{1/2}}$$

How can we model radioactivity?

Using iterative models

- Iterative models to show the number of undecayed nuclei over time are useful if using a computer spreadsheet.

- Let's compare an iterative modelling method with the actual number of undecayed nuclei over time as predicted by:

$$N = N_0 e^{-\lambda t}$$

Start with the decay equation: $A = \frac{\Delta N}{\Delta t} = \lambda N$

- Rearrange it to show the number of nuclei decaying in a set timeframe:

$$\Delta N = (\lambda \Delta t) N$$

- Set up your spreadsheet to show the iterations of undecayed nuclei with each timeframe.

For example

$N_0 = 1000$

$t_{½} = 1.00s$

$\lambda = 0.693s_{-1}$

$\Delta t = 0.10s$

E16

	A	B	C
1		Iterative modelling method using: $\Delta N = (\lambda \Delta t)N$	Actual numbers using: $N = N_0 e^{-\lambda t}$
2	Time /s	N	N
3	0.00	1000	1000
4	0.10	930.7	933.0
5	0.20	866.2	870.6
6	0.30	806.2	812.3
7	0.40	750.3	757.9
8	0.50	698.3	707.2
9	0.60	649.9	659.8
10	0.70	604.9	615.6
11	0.80	563.0	574.4
12	0.90	523.9	536.0
13	1.00	487.6	500.1
14	1.10	453.8	466.6
15	1.20	422.4	435.4

=0.9307*B3

=C$3*EXP(-0.693*A4)

The iterative model follows the actual values fairly closely.

Can you really take radioactive material out on a date?

Radioactive Dating

- Atmospheric CO_2 contains a mixture of the stable C-12 isotope and the unstable C-14 version.
- C-14 has a half life of 5700 years and is a beta minus emitter.
- The ratio of C-14 to C-12 in the atmosphere remains constant at 1.3×10^{-12} due to the constant replacement in the upper atmosphere.
- All living things contain carbon in the same ratio.
- Once it dies, it stops taking in new carbon (eating or photosynthesis) but the C-14 it has continues to decay.
- The ratio of C-14 to C-12 will therefore reduce over time.
- We can calculate the time of death (and so the age) of a once living item from the ratio of C-14 to C-12.

So, how do we do this?

- At GCSE this was easy. We just multiplied the half life (5700yrs) by number of half lives elapsed.

- At A Level we use the equations:

$$\lambda t_{1/2} = \ln 2$$

$$A = A_0 e^{-\lambda t}$$

Method:

- Step 1
  - Calculate the decay constant for C-14

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

- Step 2
  - Rearrange the activity equation to find the age of the object:

$$A = A_0 e^{-\lambda t} \rightarrow \frac{A}{A_0} = e^{-\lambda t}$$

$$\rightarrow \ln\left(\frac{A}{A_0}\right) = -\lambda t \rightarrow \ln\left(\frac{A}{A_0}\right)\Big/_{-\lambda} = t$$

Limitations to Dating

- We assume the ratio of C-14 to C-12 has remained constant over the long periods of time.
  - Increased use of fossil fuels may have reduced this ratio recently.

- The activity of C-14 in living organisms is so low it is almost at background levels.

- Carbon dating cannot be used for geological samples of rocks/meteors because its half life is not long enough.
  - Ru-87 is used instead with a half life of 49 billion years.

6.4.3 Radioactivity (review)

6.4.3 Radioactivity

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) radioactive decay; spontaneous and random nature of decay

(b) **(i)** α-particles, β-particles and γ-rays; nature, penetration and range of these radiations

(ii) techniques and procedures used to investigate the absorption of α-particles, β-particles and γ-rays by appropriate materials

(c) nuclear decay equations for alpha, beta-minus and beta-plus decays; balancing nuclear transformation equations

(d) activity of a source; decay constant λ of an isotope; $A = \lambda N$

(e) **(i)** half-life of an isotope; $\lambda t_{1/2} = \ln(2)$

(ii) techniques and procedures used to determine the half-life of an isotope such as protactinium.

(f) **(i)** the equations $A = A_0 e^{-\lambda t}$ and $N = N_0 e^{-\lambda t}$, where A is the activity and N is the number of undecayed nuclei

(ii) simulation of radioactive decay using dice

(g) graphical methods and spreadsheet modelling of the equation $\frac{\Delta N}{\Delta t} = -\lambda N$ for radioactive decay

(h) radioactive dating, e.g. carbon-dating.

6.4.4 Nuclear Fission & Fusion

6.4.4 Nuclear fission and fusion

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) Einstein's mass–energy equation; $\Delta E = \Delta mc^2$

(b) energy released (or absorbed) in simple nuclear reactions

(c) creation and annihilation of particle–antiparticle pairs

(d) mass defect; binding energy; binding energy per nucleon

(e) binding energy per nucleon against nucleon number curve; energy changes in reactions

(f) binding energy of nuclei using $\Delta E = \Delta mc^2$ and masses of nuclei

(g) induced nuclear fission; chain reaction

(h) basic structure of a fission reactor; components – fuel rods, control rods and moderator

(i) environmental impact of nuclear waste

(j) nuclear fusion; fusion reactions and temperature

(k) balancing nuclear transformation equations.

How can mass be energy and energy be mass?

$E=mc^2$

- Einstein proposed the idea that mass and energy are equivalent in 1905.

- This equation has 2 interpretations:
  - Mass is a form of energy
    - As shown by the annihilation of an electron-positron pair. Their combined mass is transformed into 2 gamma photons.
  - Energy has mass
    - Raising the kinetic energy of an object by accelerating it has an upper limit. As speed increases, so does mass and therefore it becomes harder to accelerate.

Examples

- You gain mass as you sit in an accelerating car.
- A mug of coffee loses mass as it cools.
- An unstable nucleus loses mass as it emits gamma photons.

What is the minimum energy of the 2 gamma photons produced as a result of electron-positron annihilation?

$E = mc^2 = 2m_e c^2 = 2 \times 9.11 \times 10^{-31} \times (3.00 \times 10^8)^2$

$E = 1.64 \times 10^{-13}$ J

The energy of each photon will have half this value.

If the photons have kinetic energy as well then the total energy will be greater than this.

Pair production

- Pair production is the opposite effect:
  - Where the energy in a single photon is used to create a particle-antiparticle pair.

- The minimum energy of the photon must be enough to produce the particle pair.

Particle accelerators

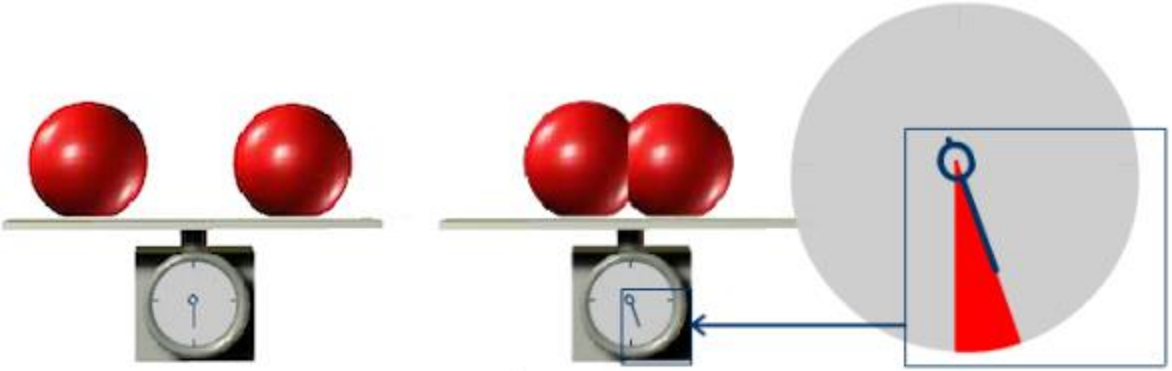
- The LHC at CERN in Geneva is used to accelerate particles such as protons to speeds close to the speed of light and collide them together.

- Their kinetic energy is used to produce other particle-antiparticle pairs which can then be detected.

Splitting nuclei

- A deuterium (^2_1H) nucleus contains a proton and a neutron.
  - These are held together by the strong nuclear force.
  - To separate them we must do work on them.
  - By doing work we're transferring energy to them.
  - According to Einstein, energy and mass are equivalent.

  - So separated particles have more mass than when joined!!



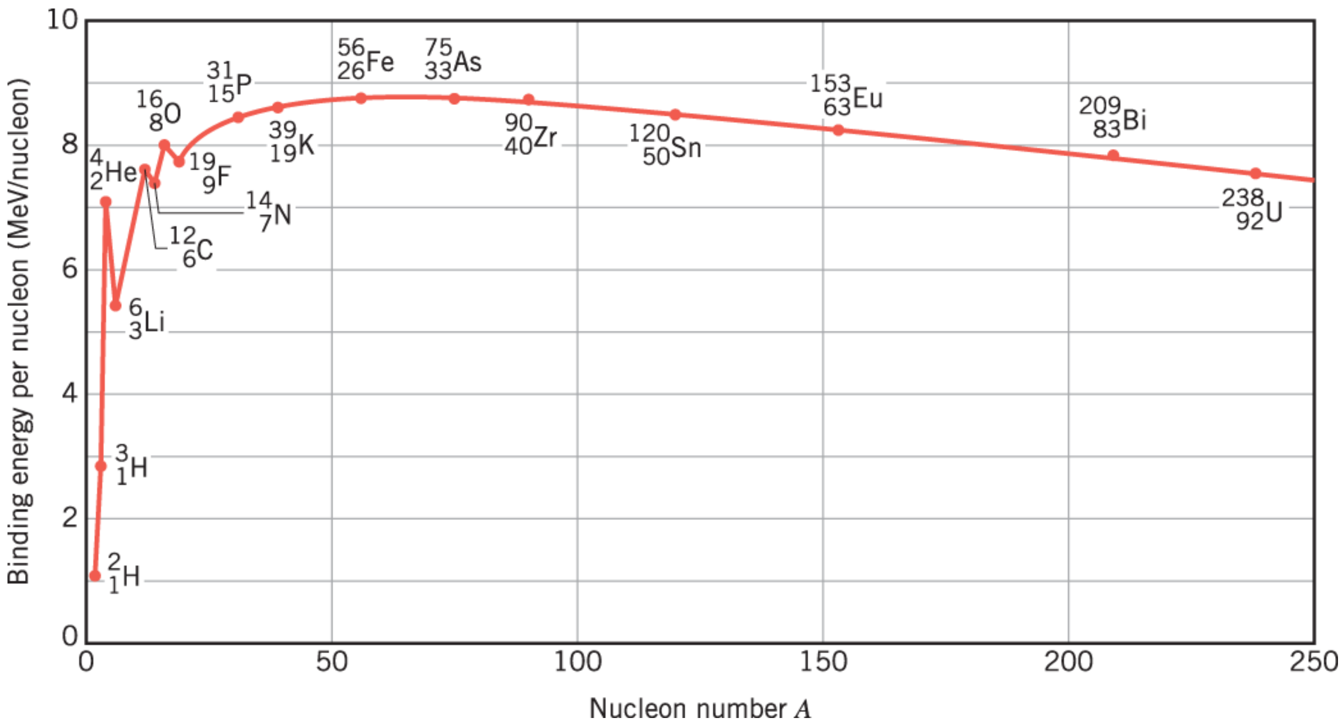
Mass Defect & Binding Energy

- The difference in mass in the deuterium example is called the mass defect.
  - The difference between the mass of completely separated nucleons from a nucleus and the mass of the nucleus itself.
- Converting this mass into energy using $E=mc^2$ gives us the binding energy for the nucleus.

$$\text{Binding Energy} = \text{Mass Defect} \times c^2$$

Careful!!

- Binding energies are not the same for all nuclei.



Remember an eV is the energy transferred when moving an electron against 1 volt.

W = QV

W = 1.60×10^{-19} J

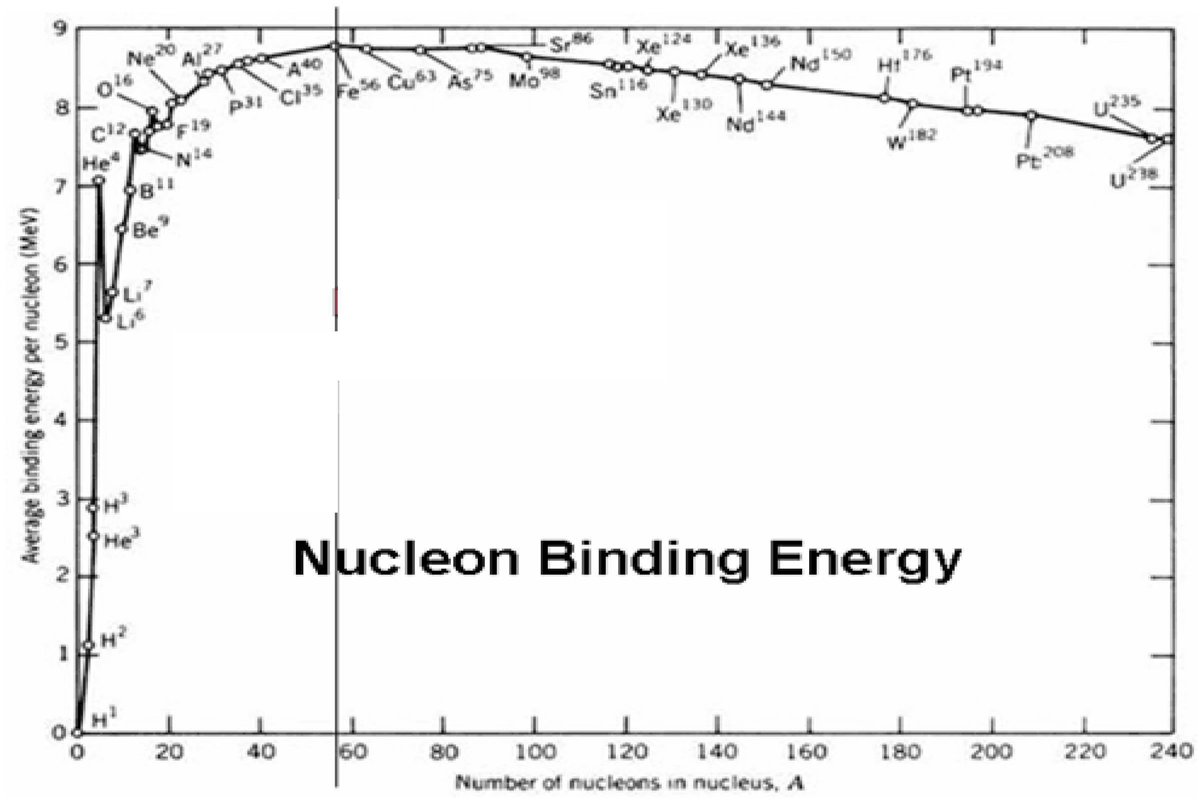
Careful also!!

- The values in the graph above show binding energies per nucleon.
  - These are average binding energies for all nucleons in a nucleus.
  - Allows comparisons between different nuclei.

- Binding energies hold nuclei together not atoms!!

Fission or Fusion?

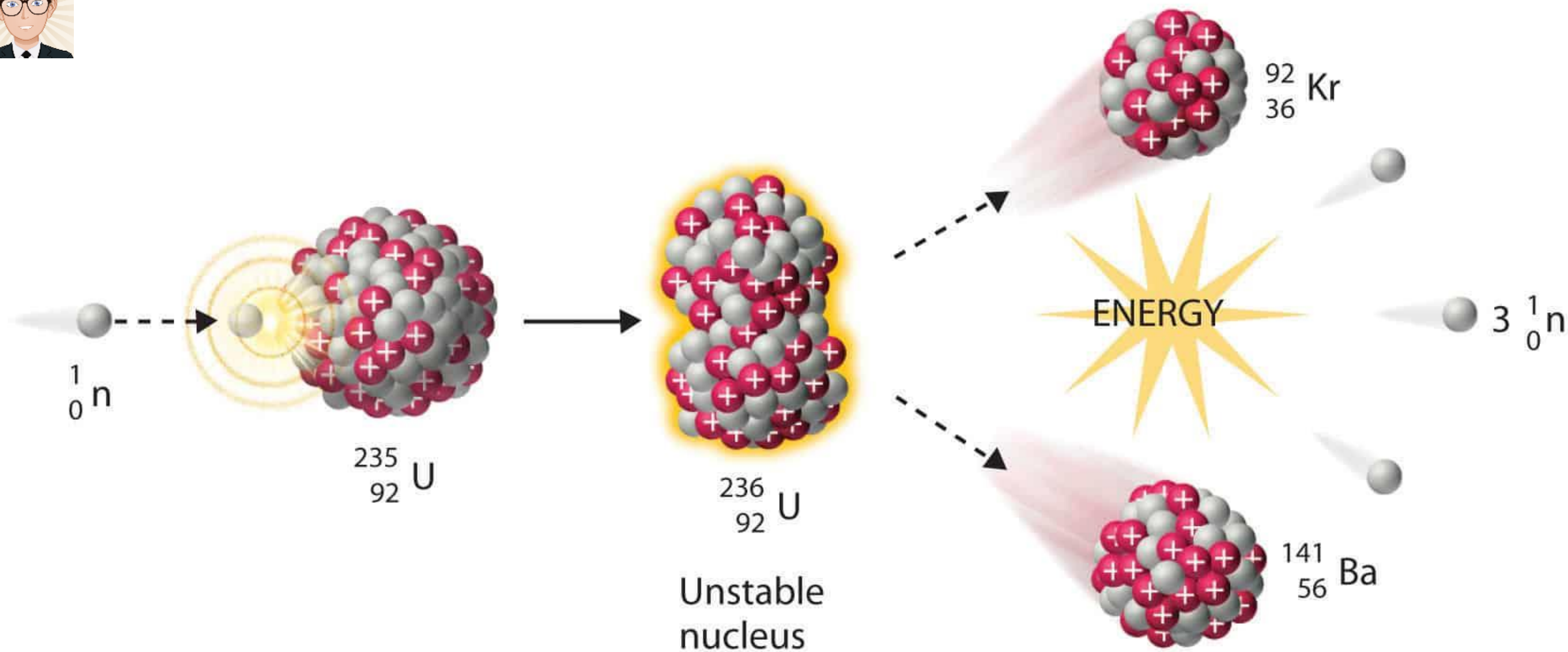
- Fusion reactions:
  - Small nuclei fuse to form larger nuclei with higher total binding energies.
- Fission reactions:
  - Large nuclei split into smaller nuclei with higher total binding energies.



Fission and Fusion – what gives?

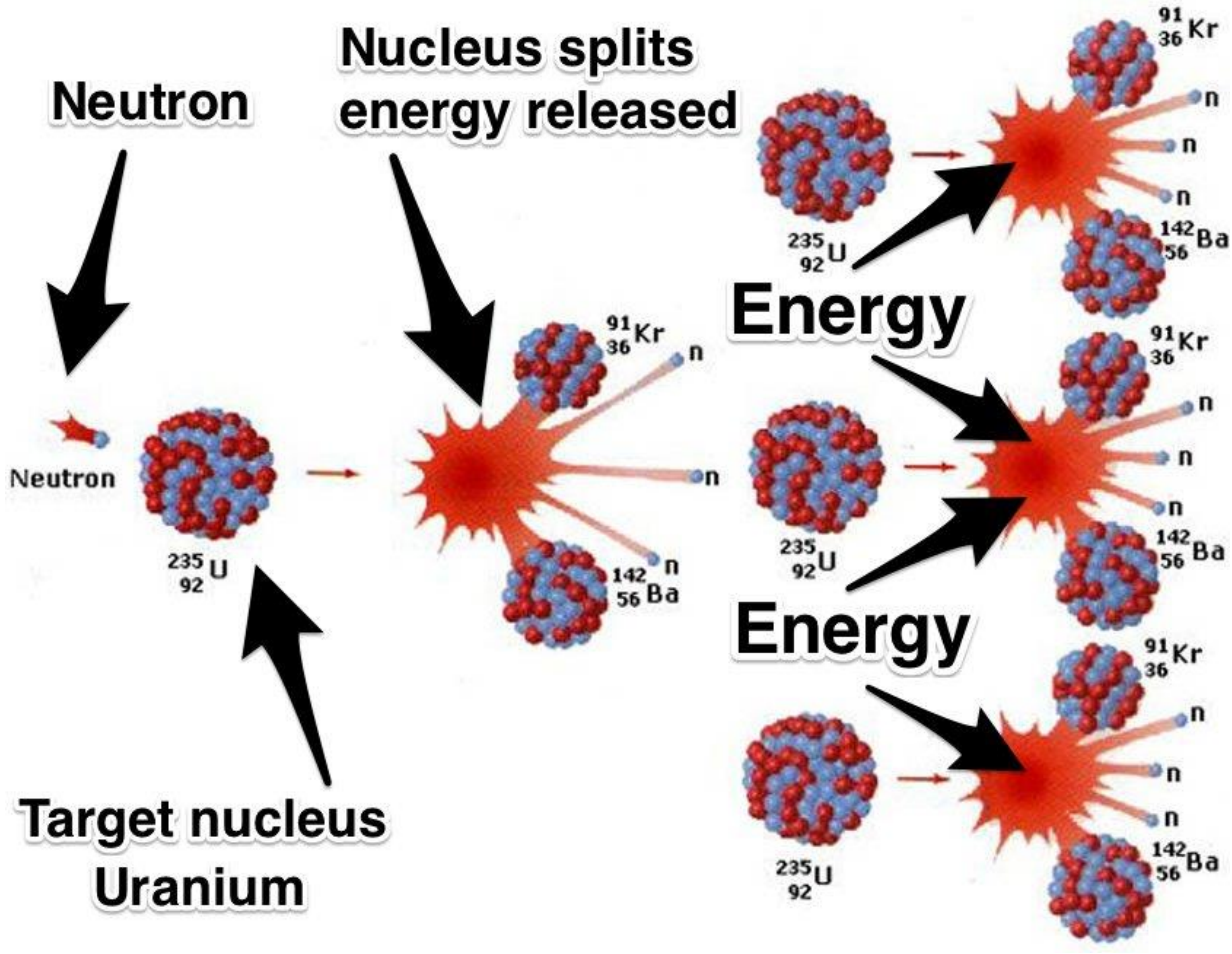
Nuclear Fission

- Fission (splitting) of large nuclei into smaller ones can release enough energy to run 20% of UK’s electrical power stations, or to destroy entire countries with nuclear bombs.



- The energy released from U-235 fission comes from:
  - Difference in binding energies of nuclei before & after fission.
- This energy is in the form of:
  - Kinetic energy of particles produced.
  - Energy of photons emitted.

What happens next – Chain Reactions



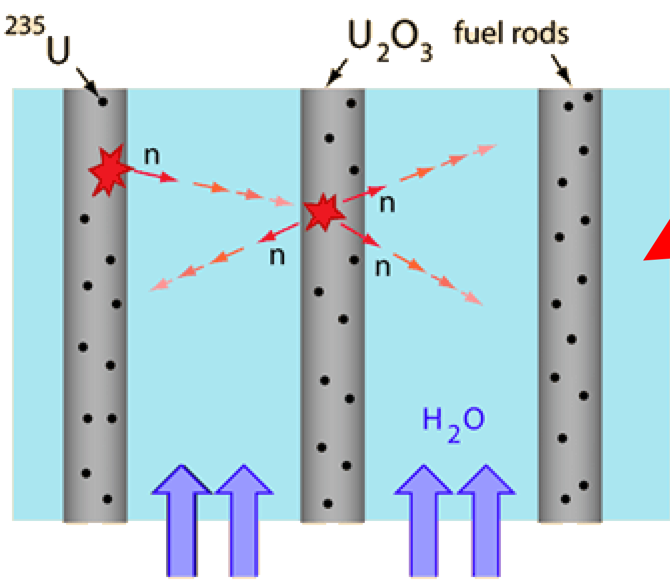
Use p. 512 -513 to explain how a fission reactor works.

Include:

Fuel rods

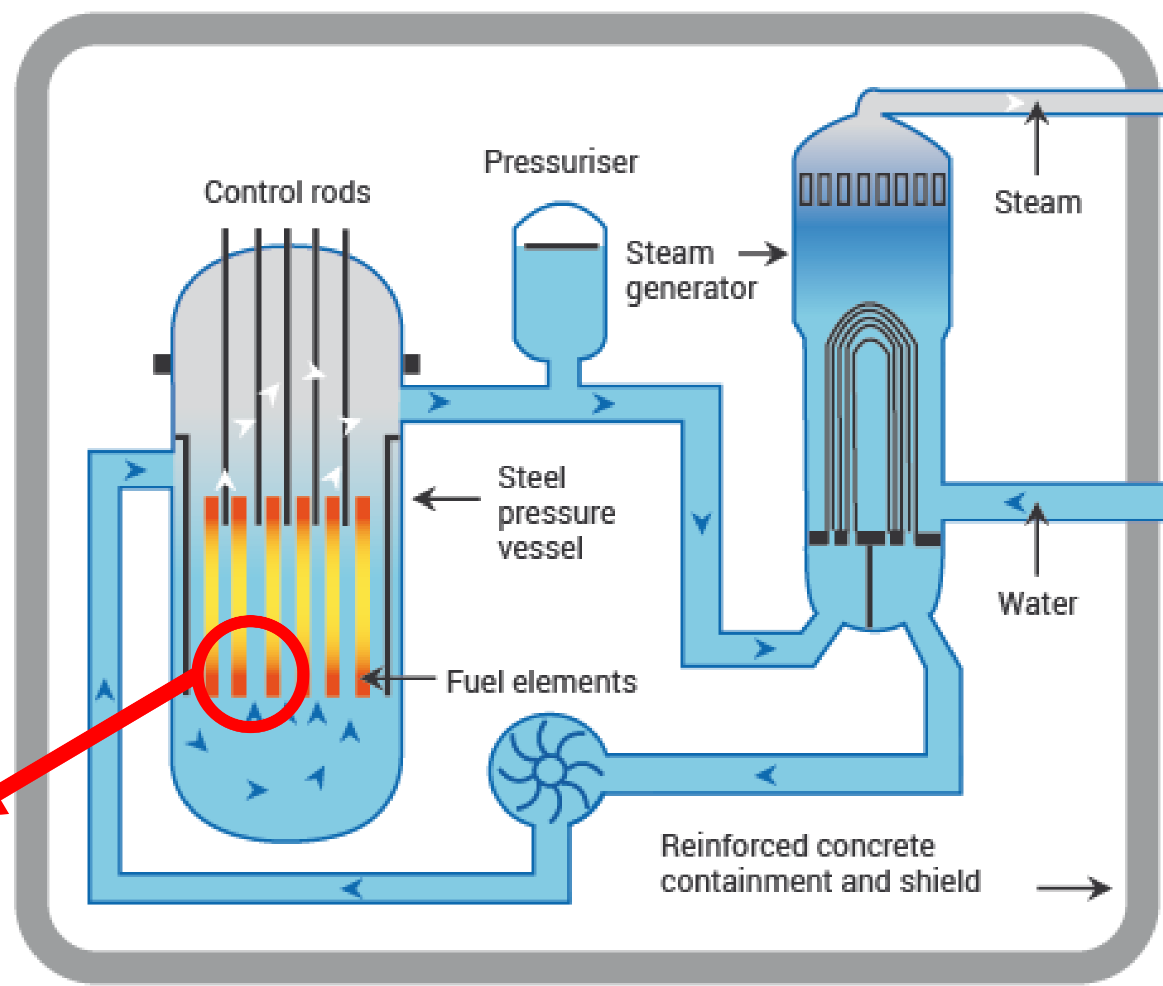
Control rods

Moderator



Water as coolant and moderator flows between fuel rods.

A Pressurized Water Reactor (PWR)



Environmental issues

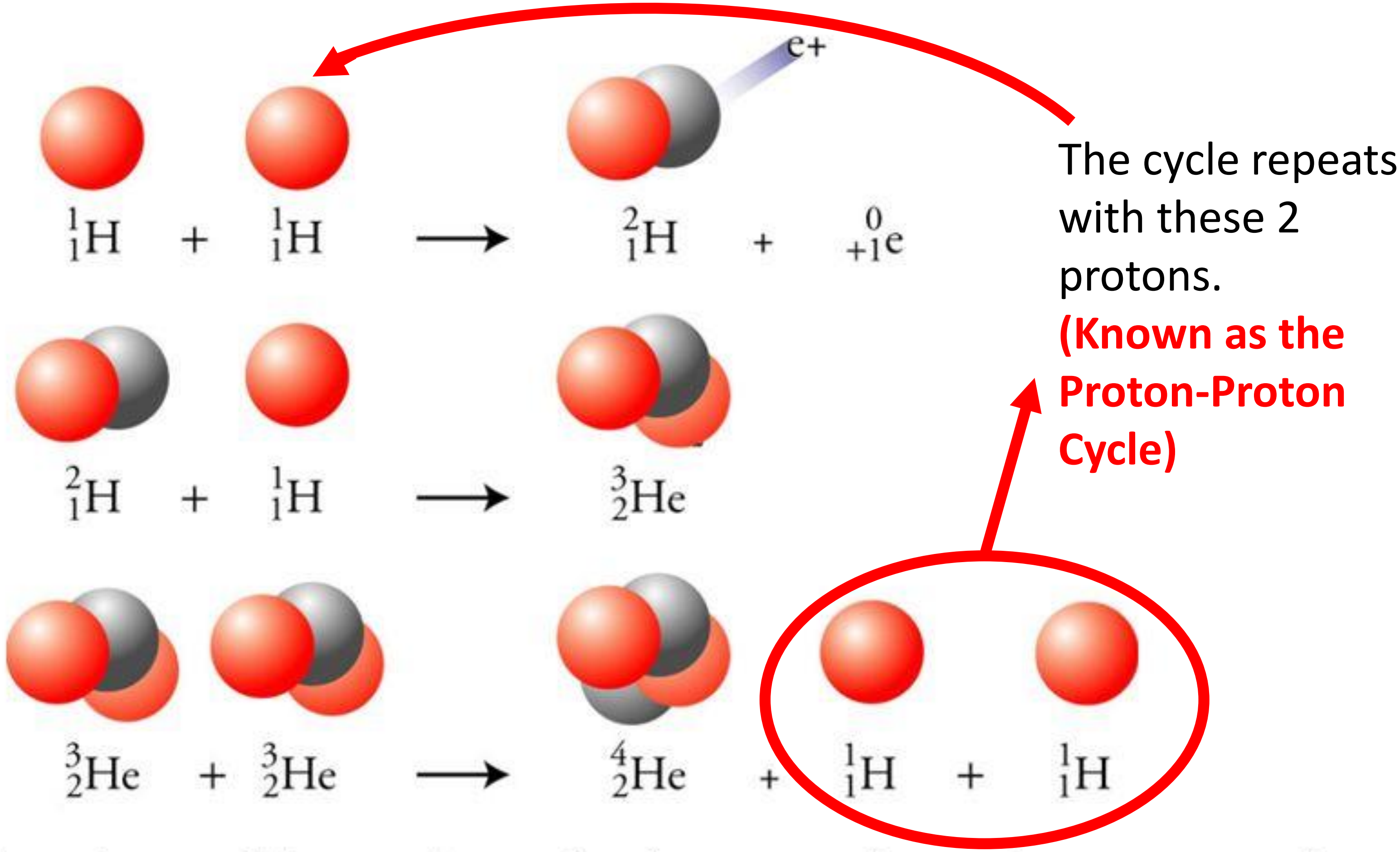
- The uranium oxide fuel rods contain different isotopes:
  - U-238 (99%), U-235 (1%)
  - U-235 is the fuel source.
  - U-238 will absorb neutrons as well which decays into plutonium-239.
- Pu-239 is radioactive waste with a half life of 24000 yrs.
  - This waste is buried deep underground in secure containers in geologically stable sites.

Nuclear Fusion

- If nuclei can be pushed close enough together the strong nuclear force can overcome the massive electrostatic repulsion and they fuse, releasing the binding energy as they lose mass.

- This happens inside stars.

Nuclear Fusion in the Sun



- Energy is released from these fusion reactions that we receive as **LIGHT** and **HEAT**!
- **NOTE**: **3** hydrogen-1 atoms required (total), yet only **2** produced
  - **The Sun is running out of fuel (hydrogen-1 atoms)!**

Can we use fusion to generate electricity?

- Not yet.
  - Temperatures have to be high to force nuclei together.
  - Which then creates problems containing the reactions.

- Small scale fusion has been achieved using lasers to heat & compress deuterium & tritium.

6.4.4 Nuclear Fission & Fusion (review)

6.4.4 Nuclear fission and fusion

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) Einstein's mass–energy equation; $\Delta E = \Delta mc^2$

(b) energy released (or absorbed) in simple nuclear reactions

(c) creation and annihilation of particle–antiparticle pairs

(d) mass defect; binding energy; binding energy per nucleon

(e) binding energy per nucleon against nucleon number curve; energy changes in reactions

(f) binding energy of nuclei using $\Delta E = \Delta mc^2$ and masses of nuclei

(g) induced nuclear fission; chain reaction

(h) basic structure of a fission reactor; components – fuel rods, control rods and moderator

(i) environmental impact of nuclear waste

(j) nuclear fusion; fusion reactions and temperature

(k) balancing nuclear transformation equations.

Module 5 – Newtonian world and astrophysics

5.1 Thermal physics

5.2 Circular motion

5.3 Oscillations

5.4 Gravitational fields

5.5 Astrophysics and cosmology

Module 6 – Particles and medical physics

6.1 Capacitors

6.2 Electric fields

6.3 Electromagnetism

Complete! → 6.4 Nuclear and particle physics

6.5 Medical imaging