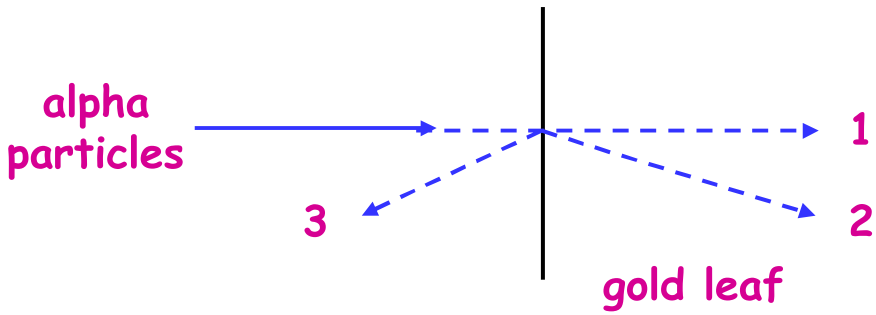
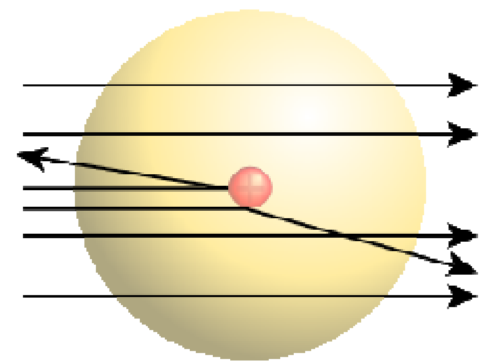
Higher Physics – Unit 3

3.4 Nuclear Reactions

Rutherford's Experiment

Alpha (α) particles in a vacuum are fired at a very thin gold leaf.





Results

1. most alpha particles passed straight through
2. some were slightly deflected
3. a few were reflected

Conclusions

- Most of the **atom** is **empty space** (since most alpha particles passed straight through).
- The **diameter** of the **nucleus** is much **smaller** than the **diameter** of the **atom**.
- Most of the **mass** and all the **positive charge** is in the **nucleus**. (repels positive alpha particles).

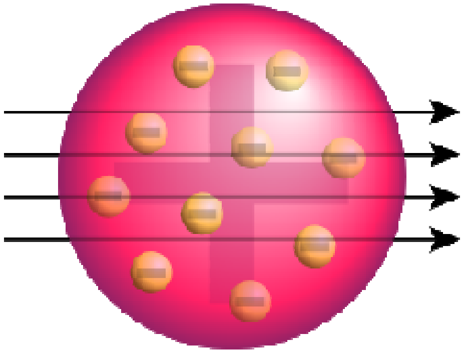
Ernest Rutherford

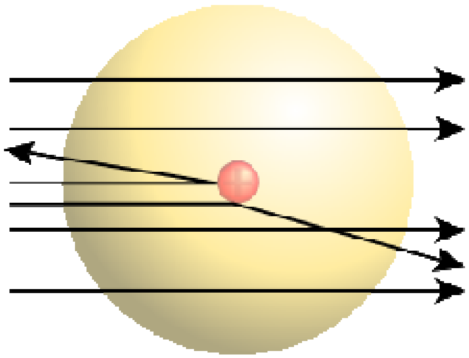
(1871-1937)

Born: New Zealand

The Rutherford Experiment was done by Hans Geiger and Ernest Marsden in 1909 under the direction of Ernest Rutherford at the Physical Laboratories of the University of Manchester.

This experiment led to the downfall of the plum pudding model of the atom.





Nuclear Symbols

The atomic number (Z) is the number of protons in the nucleus.

This is equal to the number of orbiting electrons.

The number of protons and neutrons (called nucleons) in the nucleus is the mass number (A).

The chemical symbol (X) represents the element.

This is written as:

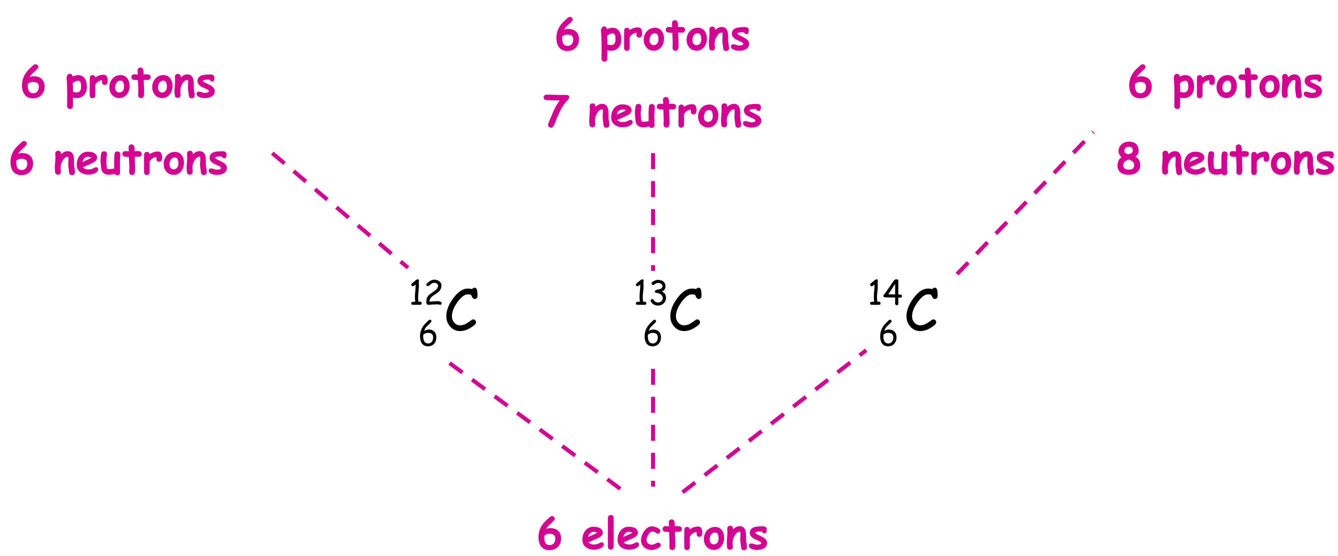
$$^{A}_{Z}X$$

Isotopes

An **isotope** is a **different form** of the same **element**.

All isotopes of an element have the **same number** of **protons** but each has a **different number** of **neutrons**.

Consider isotopes of carbon.



Most isotopes occur in nature and are stable, however a few are unstable.

Radioisotopes

An **unstable isotope** may **emit** a form of **nuclear radiation** to become stable.

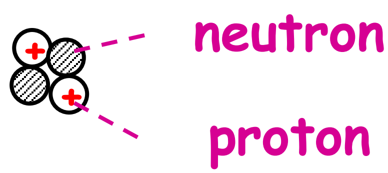
This is called **radioactive decay**.

The isotopes of elements that undergo radioactive decay are called **radioisotopes**.

Radioactive Decay

Alpha Emission

An alpha (α) particle consists of 2 protons and 2 neutrons.



An alpha particle is a helium nucleus.

The symbol for an alpha particle is $^{4}_{2}\alpha$ or $^{4}_{2}He$.

If uranium 235 were to emit an alpha particle we get:

$$^{235}_{92}Ur \rightarrow \, ^{231}_{90}Th + \, ^{4}_{2}\alpha$$

Beta Emission

Beta (β) particles are **high energy electrons**.

The **symbol** for a high energy electron is $^{0}_{-1}e$ or $^{0}_{-1}\beta$.

If lead 211 were to emit a beta particle we get:

$$^{211}_{82}Pb \rightarrow \, ^{211}_{83}Bi + \, ^{0}_{-1}e$$

Gamma Emission

Gamma rays (γ) are **high frequency electromagnetic waves**.

It has **no charge**, **no mass** and travels at the **speed of light**.

Its symbol is ${}^{0}_{0}\gamma$.

If uranium 239 gives off a gamma ray we get:

$$ {}^{239}_{92}\text{Ur} \rightarrow {}^{239}_{92}\text{Ur} + {}^{0}_{0}\gamma $$

The energy given off is released as a photon.

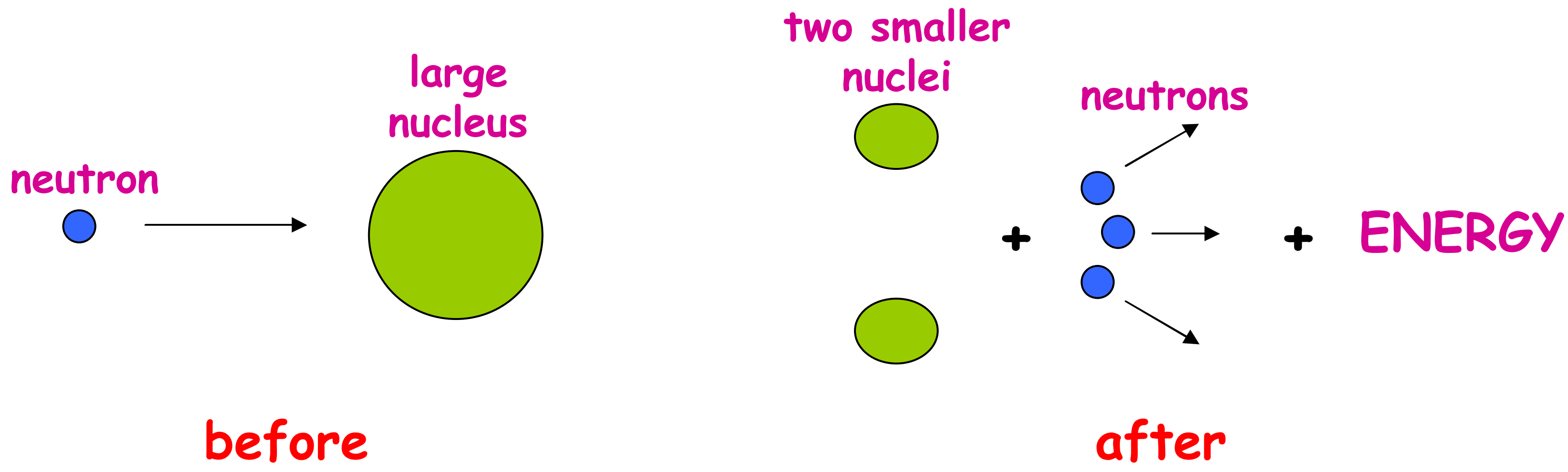
Nuclear Reactions

There are **two types** of **nuclear reaction**:

- nuclear **fission**
- nuclear **fusion**

Nuclear Fission

Nuclear **fission** is when a large **nucleus splits** into **two smaller nuclei** and **releases energy**.



This diagram shows **induced fission** by **neutron bombardment**. A chain reaction occurs releasing large amounts of energy.

It may be **controlled** (nuclear reactor) or **uncontrolled** (nuclear bomb).

Natural fission is usually **spontaneous** and involves giving off an **alpha** or **beta particle**.

The total **mass before** fission is **greater** than the total **mass after** fission.

The **mass lost** and **energy released** are related by Einstein's equation:

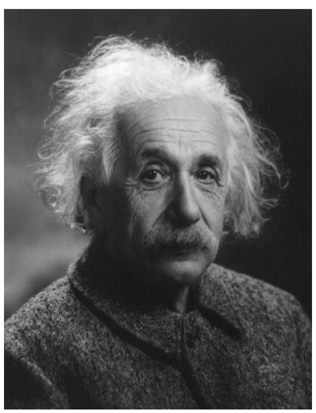
$$E = mc^2$$

energy produced (J)

mass lost (kg)

speed of light (3×10^8 ms^{-1})

5-metre tall sculpture of Einstein's 1905 $E = mc^2$ formula in Germany.



(1879 – 1955)

Born: Germany

Mass-energy equivalence says that when a body has mass, it has energy (even when its not moving).

The c^2 is the conversion factor required to change units of mass into units of energy.

Example 1

A plutonium nucleus undergoes fission as shown.

$$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{137}_{52}Te + ^{100}_{42}Mo + 3\,^{1}_{0}n$$

The masses of the various nuclei are

Nuclei	**Mass (kg)**
$^{239}_{94}Pu$	3.967×10^{-25}
$^{137}_{52}Te$	2.274×10^{-25}
$^{100}_{42}Mo$	1.658×10^{-25}
$^{1}_{0}n$	0.017×10^{-25}

Calculate the amount of energy released by this fission reaction.

Total mass before:

$$m = 3.967 \times 10^{-25} + 0.017 \times 10^{-25}$$
$$m = 3.984 \times 10^{-25}\ kg$$

Total mass after:

$$m = 2.274 \times 10^{-25} + 1.658 \times 10^{-25} + 3 \times \left(0.017 \times 10^{-25}\right)$$
$$m = 3.983 \times 10^{-25}\ kg$$

Mass lost:

$$m = 3.984 \times 10^{-25} - 3.983 \times 10^{-25}$$
$$m = 1.0 \times 10^{-28}\ kg$$

Energy released:

$$m = 1.0 \times 10^{-28}\ kg$$
$$c = 3 \times 10^{8}\ ms^{-1}$$
$$E = ?$$

$$E = m c^2$$
$$= \left(1 \times 10^{-28}\right) \times \left(3 \times 10^{8}\right)^2$$
$$E = 9 \times 10^{-12}\ J$$

Example 2

Determine the value of y in the following fission reaction, and hence the isotope formed.

$$ {}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{98}_{42}Mo + {}^{136}_{y}\square + 2\,{}^{1}_{0}n + 4\,{}^{0}_{-1}e $$

The sum of atomic numbers on the LHS must equal the sum of atomic numbers on RHS.

$$Z_{LHS} = 92$$

$$\begin{aligned} Z_{RHS} &= 42 + y + (-4) \\ &= 42 - 4 + y \\ &= 38 + y \end{aligned}$$

$$\begin{aligned} Z_{LHS} &= Z_{RHS} \\ 92 &= 38 + y \\ y &= 54 \end{aligned}$$

The isotope is: ${}^{136}_{54}Xe$

Example 3

Uranium 238 emits an alpha particle.

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

Calculate the energy released in this fission using the following data.

Nuclei	**Mass (kg)**
$^{238}_{92}U$	3.9508×10^{-25}
$^{234}_{90}Th$	3.8843×10^{-25}
$^{4}_{2}He$	6.6425×10^{-27}

Total mass before:

$$m = 3.9508 \times 10^{-25} \text{ kg}$$

Total mass after:

$$m = 3.8843 \times 10^{-25} + 6.6425 \times 10^{-27}$$

$$m = 3.950725 \times 10^{-25} \text{ kg}$$

Mass lost:

$$m = 3.9508 \times 10^{-25} \text{ - } 3.950725 \times 10^{-27}$$

$$m = 7.5 \times 10^{-30} \text{ kg}$$

Energy released:

$$m = 7.5 \times 10^{-30} \text{ kg}$$

$$c = 3 \times 10^{8} \text{ ms}^{-1}$$

$$E = ?$$

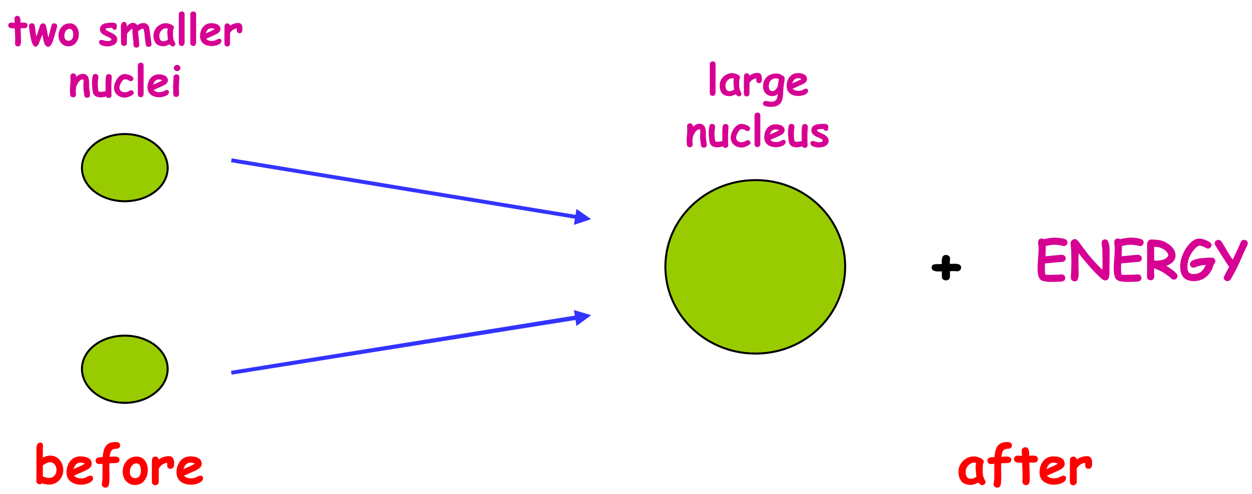
$$E = m c^2$$

$$= \left(7.5 \times 10^{-30}\right) \times \left(3 \times 10^{8}\right)^2$$

$$\underline{\underline{E = 6.8 \times 10^{-13} \text{ J}}}$$

Nuclear Fusion

Nuclear **fusion** is when **two small nuclei combine** to form **one larger nucleus** and **release energy**.



The total **mass before** fusion is **greater** than the total **mass after** fusion.

The **mass lost** and **energy released** are related by Einstein's equation:

$$E = m c^2$$

Example 1

Calculate the energy released in these fusion reaction.

$$^{1}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He$$

Nuclei	**Mass (kg)**
$^{1}_{1}H$	1.672×10^{-27}
$^{2}_{1}H$	3.342×10^{-27}
$^{3}_{2}He$	5.004×10^{-27}

Total mass before

$$m = 5.014 \times 10^{-27}\ kg$$

Total mass after

$$m = 5.004 \times 10^{-27}\ kg$$

Mass lost

$$m = 1 \times 10^{-29}\ kg$$

Energy released:

$$m = 1 \times 10^{-29}\ kg$$

$$c = 3 \times 10^{8}\ ms^{-1}$$

$$E = ?$$

$$E = m c^2$$

$$= \left(1 \times 10^{-29}\right) \times \left(3 \times 10^{8}\right)^2$$

$$E = 9 \times 10^{-13}\ J$$