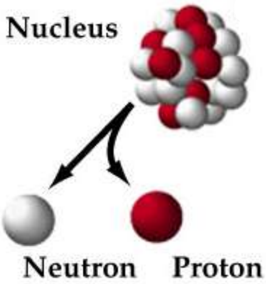
# NUCLEAR REACTIONS

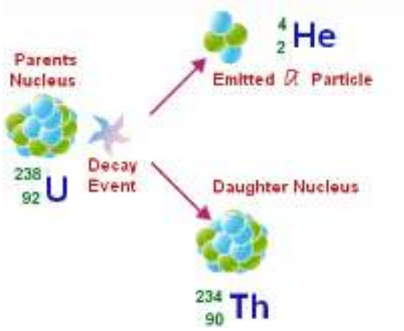


## NUCLEAR FORCES

The protons in a nucleus repel one another and would fly apart if there were not some other force to hold them together. This **nuclear force** is an attractive force that exists between nucleons (i.e between proton-proton, neutron-proton and neutron-neutron). This force only acts over a very short distance and a nucleus is unstable if it is too large (since the nucleons on opposite sides of the nucleus start to repel each other). Under these circumstances, a nucleus is could decay and energy be released.

## NATURAL RADIOACTIVITY

Although there are many types of particle that can be produced in nuclear reaction, there are three main types of radiation that can be emitted when large unstable nuclei decay naturally.

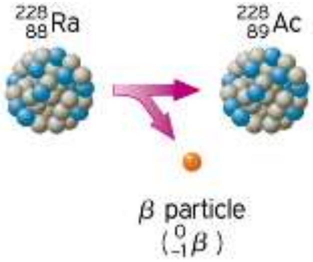


a) **Alpha particle (α)**

This is a helium nucleus ( $^4_2He$ or ) travelling at a high speed, often 0.1 times the speed of light.

e.g. $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^4_2He$

b) **Beta particle (β)**



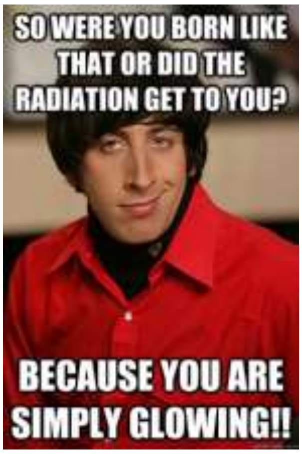
This is a high speed electron ( $^0_{-1}e$ or $\beta$ ), sometimes up to 0.99 times the speed of light.

e.g. $^{228}_{88}Ra \rightarrow {}^{228}_{89}Ac + {}^0_{-1}e$

(here a neutron decays into a proton and an electron)

c) **Gamma radiation (ɣ)**

This is a photon of very high energy (i.e. high frequency), which carries away excess energy after an alpha or beta decay.



## DETECTING RADIOACTIVE PARTICLES (for information only)

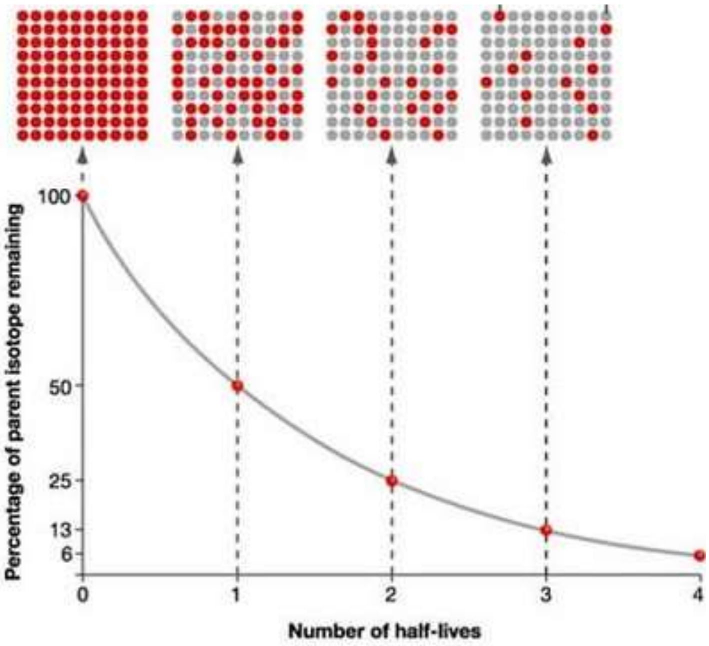
Radioactive particles can be detected using instruments such as a **Geiger counter** or observed in **cloud chambers** or other more modern detectors such as those installed at particle accelerators (e.g. the Large Hadron Collider) where artificial nuclear reactions produce a myriad of different particles.

Different particles behave differently due to their mass, charge and penetration potential.

| | **α - particle** | **β - particle** | **ϒ - ray (EM)** |
|---|---|---|---|
| **Mass** | 4 | 1/2000 | 0 |
| **Charge** | +2 | -1 (or +1 for a positron) | 0 |
| **Ionising ability** | high | medium | 0 |
| **Speed** | slow | fast | C (speed of light) |
| **Penetrating power** | low | medium | high |
| **Stopped by** | paper | aluminium | lead |

## HALF-LIFE (for information only)

In a sample of radioactive material, each individual nucleus could spontaneously decay at any time. As the nuclei decay the number of decays per second decreases. The time for the radioactivity of an isotope to fall to one half of the original value is called the half-life. Half-life of different elements varies from fractions of a millisecond to billions of years.



The property of half-life makes different radioactive substances particularly useful for dating (e.g. fossils and rocks) and medical applications.

## ARTIFICIAL NUCLEAR REACTIONS

It is possible to obtain almost any isotope of any element using particle accelerators. It was one such experiment in which our very own Rutherford famously “split the atom’. Nuclear power facilities also control the rate of chain reactions in an attempt to regulate the release of energy as required.

## CONSERVATION LAWS FOR NUCLEAR REACTIONS

The following properties are conserved in nuclear reactions:

- Mass number
- Atomic number
- Mass-Energy
- Momentum

**Example 1:** In London in 2006, Russian spy Alexander Litvinenko was quietly assassinated during a lunch meeting over sushi. He was poisoned with polonium 210, which decays by emitting an alpha particle.

Determine the other daughter product of this natural radioactive decay reaction.

**Answer:**

$^{210}_{84}Po \rightarrow ^{?}_{?}? + ^{4}_{2}He$ Remember mass number and atomic numbers are conserved.

Therefore unknown mass number = 210 – 4 = 206

and unknown atomic number = 84 – 2 = 82

Hence the other daughter product must be **lead 206**. $^{210}_{84}Po \rightarrow ^{206}_{82}Pb + ^{4}_{2}He$

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**Problems:** Write equations for the following reactions to answer the following questions:

a) Rubidium 87 has a half-life of 48.8 billion years. Its decay to strontium 87 is used for dating very old rocks. What sort of radioactive decay is this? (i.e. what other particle is emitted?)

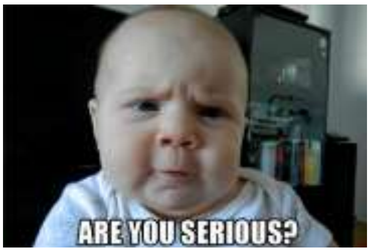
b) The Ministry of Health indicates that about half of the New Zealanders exposure to radiation is due to radon gas. Testing for radon gas is standard practice in places like the southwest of England. Radon 222 is dangerous because it emits an alpha particle during decay. What does Radon 222 form when it decays?

c) Einstein's famous E=mc$^2$ relationship was first confirmed by Cockroft and Watson who, in 1930, used high speed protons to bombard the nucleus of a metal to form two helium nuclei. What was the metal they used?

d) In 1932 Chadwick discovered a new particle in the nucleus by bombarding beryllium 9 with alpha particles. The reaction emitted a gamma ray and produced carbon 12. What was the other particle he discovered?

## MASS-ENERGY CONSERVATION IN NUCLEAR REACTIONS

Physicists can very accurately measure the mass of atoms and nuclear particles using a mass spectrograph. In doing so, they discovered that in nuclear reactions, **mass is not conserved** (even though the mass number is).



In some reactions mass was lost but kinetic energy was gained and in some reactions mass was gained but kinetic energy was lost.

Einstein had predicted this in his '"special theory of relativity" which said that mass could be changed to energy and energy could be changed into mass according to the equation:

$$\boxed{E = mc^2}$$

Where: E = (change in) energy, J

m = (change in) mass, kg

c = speed of light (ms$^{-1}$)

*NOTE: the speed of light is really fast, and in this equation it is squared, therefore even a very small change in mass will be associated with a very large change in energy.*

This means that although mass is not conserved in nuclear reactions,

**MASS – ENERGY IS CONSERVED**

Where the mass of the daughter products is less, these particles have more kinetic energy.
Where the mass of the daughter products is more, these particles have less kinetic energy.

**Example 1:** In Rutherford's famous experiment he bombarded nitrogen 14 to obtain an oxygen 17 nucleus and a proton ($i.e.\ {}^1_1H$).

a) What did he use to bombard the nitrogen?

b) Determine the change in rest mass during the reaction?

c) What is the change in energy in the reaction?

| Rest mass data (kg) | |
|---|---|
| Nitrogen 14 | $23.25069 \times 10^{-27}$ |
| Oxygen 17 | $28.22537 \times 10^{-27}$ |
| Alpha | $6.64466 \times 10^{-27}$ |
| Proton | $1.67262 \times 10^{-27}$ |
| Neutron | $1.67493 \times 10^{-27}$ |

**Answer:**

a) Mass number and atomic numbers are conserved.

$${}^?_?? + {}^{14}_7N \rightarrow {}^{17}_8O + {}^1_1H$$

Unknown mass number = 17 + 1 - 14 = 4

Unknown atomic number = 8 + 1 - 7 = 2

He must have bombarded the nitrogen with an alpha particle: ${}^4_2\alpha + {}^{14}_7N \rightarrow {}^{17}_8O + {}^1_1H$

b) $\Delta m = m_f - m_i$

$$= (28.22537 \times 10^{-27} + 1.67262 \times 10^{-27}) - (23.25069 \times 10^{-27} + 6.64466 \times 10^{-27})$$

$= \mathbf{2.64 \times 10^{-30}\ kg}$ (increase in mass since $m_{final} > m_{initial}$)

**c)** $E = mc^2 = 2.64 \times 10^{-30} \times (3.00 \times 10^8)^2$

$= \mathbf{2.376 \times 10^{-13}}$ **J** (Lost kinetic energy of particles)

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**Problem 1: Confirming E=mc²**

A lithium target is bombarded with hydrogen ions (i.e. protons) and alpha particles are produced.

$${}^1_1H + {}^7_3Li \rightarrow {}^4_2He + {}^4_2He$$

a) Calculate the total rest mass
   i. before the reaction;
   ii. after the reaction.

b) Calculate the difference in the total rest mass.

c) Find the energy associated with this difference in rest mass.

d) What happens to this energy?

| Rest mass data (kg) | |
|---|---|
| Li – 7 | $11.648 \times 10^{-27}$ |
| Proton | $1.67262 \times 10^{-27}$ |
| Alpha | $6.64466 \times 10^{-27}$ |

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**Problem 2: The Smoke Detector**

The main component of a household smoke detector is a tiny amount of Americium 241. Americium 241 can be formed from the decay of Plutonium 241.

This decay is shown by: ${}^{241}_{94}Pu \rightarrow {}^{241}_{95}Am + {}^b_aX + energy$

a) State the values of a and b.

b) Name the particle X

| Rest mass data (kg) | |
|---|---|
| Am – 241 | $4.00284 \times 10^{-25}$ |
| Np – 237 | $3.93628 \times 10^{-25}$ |
| Alpha | $6.64466 \times 10^{-27}$ |

Americium 241 found in smoke detectors undergoes alpha decay as shown in the following equation:

$${}^{241}_{95}Am \rightarrow {}^{237}_{93}Np + {}^4_2He + \gamma$$

c) Calculate the energy change in this reaction by first determining the change in rest mass.

## MASS DEFICIT AND BINDING ENERGY

Analysis of the nucleons of any isotope shows that the **mass of a nucleus is less than the mass of the individual components** that make up that nucleus. The difference between the mass of the components of a nucleus and the nucleus itself is called the **mass deficit.**

So how do we account for the mass deficit? Nucleons have a small mass when they are in a low energy state in a nucleus. Since mass has an energy equivalent, this mass deficit defines the **binding energy** of the nucleus. This is the amount of energy needed to pull the nucleus apart, or alternatively, the amount of energy released if the separate components where to form a nucleus.

**Example 1: Holding together the helium nucleus**

a) Use the rest mass data to calculate the mass deficit of a helium nucleus.
b) Therefore calculate the amount of energy necessary to separate the helium nucleus into its components.

Rest mass data (kg)

| | |
|---|---|
| Alpha | $6.64466 \times 10^{-27}$ |
| Proton | $1.67262 \times 10^{-27}$ |
| Neutron | $1.67493 \times 10^{-27}$ |

**Answer:**

a) Mass of components = $(2 \times 1.67262 \times 10^{-27}) + (2 \times 1.67493 \times 10^{-27}) = 6.69426 \times 10^{-27}$

Mass of nucleus = $6.64466 \times 10^{-27}$

Mass Deficit = mass of components – mass of nucleus = $6.69426 \times 10^{-27} - 6.64466 \times 10^{-27}$

**= $4.96 \times 10^{-29}$ kg**

b) Binding energy, $E = mc^2 = 4.96 \times 10^{-29} \times (3.00 \times 10^8)^2$

$= \mathbf{4.464 \times 10^{-12}}$ **J**

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**Problem 1: Uranium 235 and Iron 56**

a) Determine the amount of energy required to separate the components of the nucleus of uranium – 235 by:
   i. Identifying how many protons and how many neutrons are there in the nucleus of uranium – 235?
   ii. Calculating the total rest mass of these components.
   iii. Calculating the mass deficit for the nucleus of uranium – 235.
   iv. Calculating the total binding energy of uranium – 235?

Rest mass data (kg)

| | |
|---|---|
| $^{235}$U | $390.2480 \times 10^{-27}$ |
| $^{56}$Fe | $92.908 \times 10^{-27}$ |
| Proton | $1.67262 \times 10^{-27}$ |
| Neutron | $1.67493 \times 10^{-27}$ |

b) Calculate the binding energy of iron-56 and compare this to the binding energy of $^{235}$U.

## BINDING ENERGY PER NUCLEON AND STABILITY OF THE NUCLEUS

Because large nuclei have a much larger mass deficit than smaller nuclei, they have a large binding energy. However, we know that large nuclei are unstable because some of the nucleons are too far apart for the strong nuclear force to be effective.

The **stability of a nucleus depends on the binding energy per nucleon** rather than the total binding energy of the nucleus. The binding energy per nucleon is the amount of energy required to remove one nucleon from the nucleus. The higher the binding energy per nucleon, the more stable the nucleus.

Binding energy per nucleon is calculated by diving the total binding energy by the number of nucleons:

$$Binding\ energy\ per\ nucleon = \frac{total\ binding\ energy}{mass\ number}$$

Binding energy per nucleon is often stated eV or MeV (mega-electron volts) rather than J (Joules).

$$\frac{Binding\ energy\ (in\ joules)}{Charge\ on\ an\ electron} = Binding\ energy\ (in\ eV)$$

(One electron volt is the amount of energy it would take to accelerate and electron through a 1 V potential different.)

**Problem 1: Stability of Uranium and Iron**

a) Use the binding energy calculated in the previous problems to calculate the binding energy per nucleon (in eV) of:

   i. Uranium – 235. ii. Iron – 56.

b) Which of these nuclei is more stable?

**Problem 2: The carbon conundrum**

a) Calculate the binding energy per nucleon (in MeV) of

   i. A carbon 12 nucleus

   ii. A carbon 14 nucleus

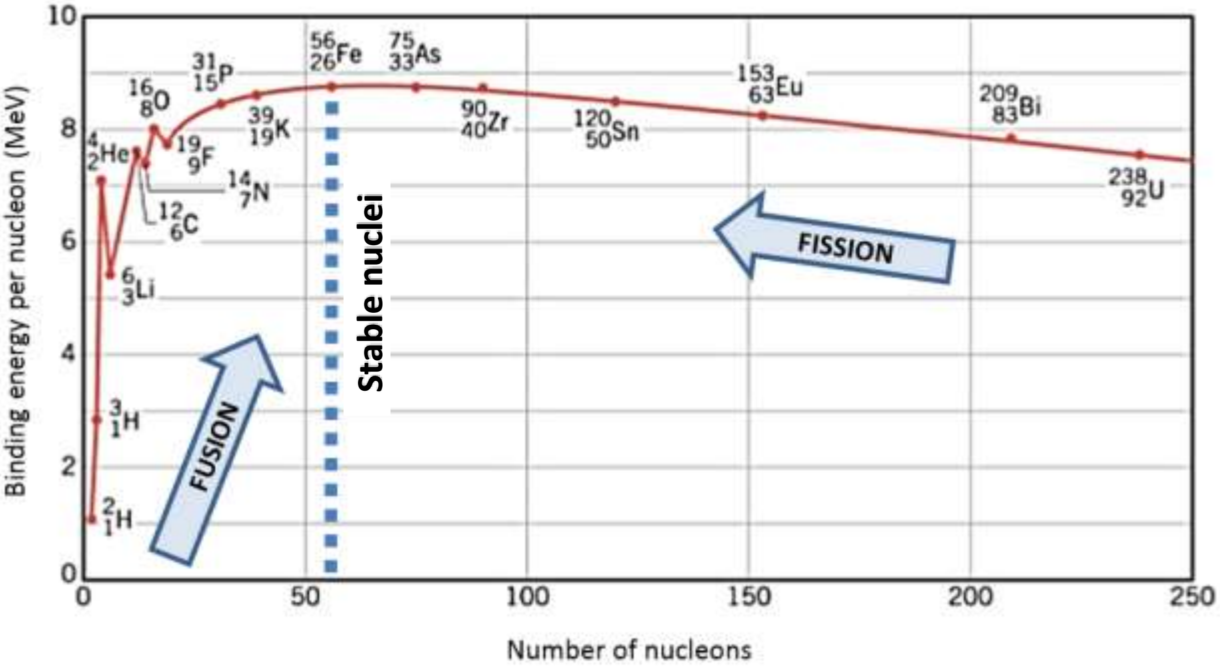
b) Which of these nuclei is the most stable?

| Rest mass data (kg) | |
|---|---|
| ${}^{1}_{1}H$ | $1.67262 \times 10^{-27}$ |
| ${}^{1}_{0}n$ | $1.67493 \times 10^{-27}$ |
| ${}^{14}C$ | $23.2454 \times 10^{-27}$ |
| ${}^{12}C$ | $19.9200 \times 10^{-27}$ |

## STABILITY AND NUCLEAR REACTIONS

Iron – 56 has the greatest binding energy per nucleon. This means that the nucleons are in a very low energy state, making it the most stable nucleus. Nuclear reactions normally result in nucleons moving towards a lower energy state, i.e. higher binding energies per nucleon.

When these reactions occur, mass of the nucleons decreases and energy is released. In order to reach a lower energy state, nuclei larger than iron get smaller, and small nuclei get bigger.



## FISSION RECTIONS

When large, unstable nuclei (on the right hand end of the binding energy curve) decay into smaller nuclei, normally of approximately equal size, these are called fission reactions.

The binding energy per nucleon of the products is greater since the nucleons are more tightly bound within the nucleus. The nucleons are in a lower energy state. The reactions all move to the left towards the more stable elements.

A particularly interesting example of this is when uranium – 235 is bombarded with neutrons as shown in the following equation:

$$^{235}_{92}U \ + \ ^{1}_{0}n \ \rightarrow \ ^{141}_{56}Ba + \, ^{92}_{36}Kr + 3 \, ^{1}_{0}n + \gamma$$

Energy is released by each reaction and a further 3 neutrons are also produced. These three neutrons can then go on to bombard three further uranium nuclei, thus setting up a chain reaction, which if left uncontrolled escalates very rapidly. This type of reaction is controlled in a nuclear power plant or in nuclear powered submarine etc, but is uncontrolled in fission nuclear bombs such as those in Japan in WWII.

(Other daughter products are also possible when $^{235}$U is bombarded with $^{1}$n.)

## NUCLEAR FUSION

Nuclear reactions where 2 small nuclei are pushed together to make a larger nuclei are called **fusion reactions.** These reactions occur in nuclei to the left of iron in the binding energy curve.

Very high pressures and temperatures are normally needed for these to occur (e.g. the sun) since the positive reactant nuclei need to collide with sufficient velocity and/or confining pressure to overcome the electro-static force. Where the binding energy curve has a very steep positive gradient, this shows that each reaction releases a significant amount of energy per nuclei formed.

*Just for interest:* *Due to the relative mass of hydrogen nuclei compared with uranium nuclei, and also the amount of energy released by a fission reaction (steep gradient) compared to a fusion reaction (shallow gradient), a small hydrogen bomb (H-bomb) will have a significantly greater impact with regards to energy released, compared to a uranium bomb with a much greater mass.*

Rest mass data (kg)

| | |
|---|---|
| $^{6}_{3}Li$ | 9.98835 x $10^{-27}$ |
| $^{4}_{2}He$ | 6.64466 x $10^{-27}$ |
| $^{3}_{1}H$ | 5.00784 x $10^{-27}$ |
| $^{2}_{1}H$ | 3.34330 x $10^{-27}$ |
| $^{1}_{1}H$ | 1.67262 x $10^{-27}$ |
| $^{1}_{0}n$ | 1.67493 x $10^{-27}$ |

**Problem 1:**

a) What nuclear process is described by the following equation?

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{140}_{55}Cs + ^{93}_{37}Rb + 3\,^{1}_{0}n + \gamma$$

b) Explain why is this type of reaction important? (two reasons)

**Problem 2:**

Describe the differences and similarities between nuclear fission and fusion.

**Problem 3:**

Write the equation for when 2 deuterium nuclei ($^{2}_{1}H$) combine to form an alpha particle.

a) Calculate the difference in total rest mass before and after the reaction.

b) Calculate the energy associated with this mass difference.

**Problem 4:** Three bottles of water and some rocks can, ***in theory***, provide enough energy for a family for one year. The water and rocks can be used to obtain raw materials for a thermonuclear reaction that can take place between the hydrogen isotopes deuterium ($^{2}_{1}H$) and tritium ($^{3}_{1}H$).

Tritium can be made from lithium, which can be extracted from the rocks.

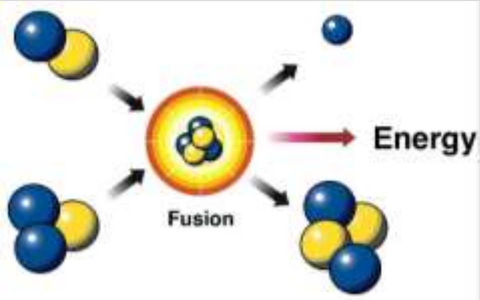
a) Calculate the total binding energy of a lithium – 6 nucleus.
b) Calculate the binding energy per nucleon (in MeV) of lithium – 6.
c) Describe how binding energy relates to the stability of a nuclei.

Deuterium can be extracted from the water. Thermonuclear reactors heat a mixture of $^{2}_{1}H$ and $^{3}_{1}H$ to 100 million degrees Celsius to produce the reaction illustrated adjacent.

The equation for this reaction is:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

d) Calculate the amount of energy produced in this reaction.



In 1989, Scientists Pons and Fleischmann gained overnight fame and notoriety for all the wrong reasons. They claimed to have discovered a method for “cold fusion”, thus opening the door for massive amounts of energy to be generated very cheaply and easily.

e) Explain why this is not possible and why it is necessary for the temperature to be very high for this fusion reaction to occur.