- *Candidates should be able to :*
  - **Select** and **use** Einstein's mass-energy equation : $\boxed{\Delta E = \Delta mc^2}$
  - Define **binding energy** and **binding energy per nucleon**.
  - Use and interpret the **binding energy per nucleon against nucleon number graph**.
  - Determine the binding energy of nuclei using the masses of nuclei and $\Delta E = \Delta mc^2$.
  - **Describe** the process of **induced nuclear fission**.
  - **Describe** and **explain** the process of **nuclear chain reaction**.
  - **Describe** the basic construction of a **fission reactor** and **explain** the role of the **fuel rods**, **control rods** and the **moderator**.
  - **Describe** the use of nuclear fission as an energy source.
  - **Describe** the **peaceful** and **destructive** uses of nuclear fission.
  - **Describe** the **environmental effects of nuclear waste**.
  - **Describe** the process of nuclear fusion.
  - **Describe** the conditions in the core of stars.

MASS DEFECT

- All atoms are **lighter** than the **sum of the masses** of their constituent protons, neutrons and electrons.

The difference in mass is called the **MASS DEFECT (Δm)** and it is in the nucleus that it is most apparent.

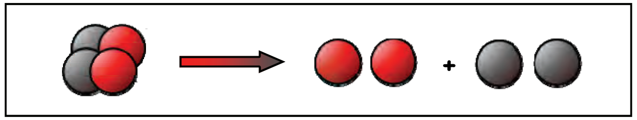
The **MASS DEFECT (Δm)** of a nucleus is the difference between the total mass of all its separate nucleons and the mass of the nucleus itself.

$$\Delta m = m(\text{separate nucleons}) - m(\text{nucleus})$$

*Because the nuclear masses are very small, they are measured in a Unit called the **ATOMIC MASS UNIT (u)**, rather than in kilograms.*

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

The **helium nucleus** consists of **2 protons + 2 neutrons**.



m(2p + 2n) = (2 x 1.00728) + (2 x 1.00867) u = **4.03190 u**.

m(He nucleus) = **4.00151 u**.

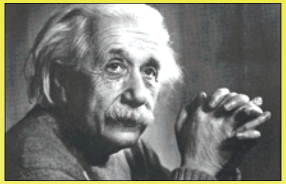
Mass defect, **Δm** = m(separate nucleons) - m(nucleus)

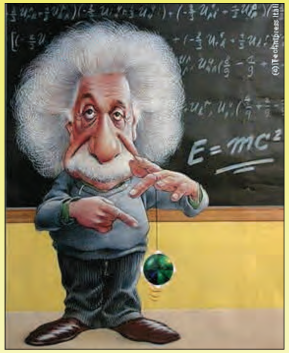
$\Delta m = 4.03190 - 4.00151 = \boxed{0.03039\ u}$

$= 0.03039 \times 1.6605 \times 10^{-27}$

$= \boxed{5.046 \times 10^{-29}\ kg}$

MASS-ENERGY EQUIVALENCE AND EINSTEIN'S EQUATION





- As we have seen from our calculation with the helium nucleus, when a nucleus is separated into its constituent nucleons, there is an **increase in mass**. The question is, **"where does this extra mass come from?"**.

  The answer is that the energy which is needed to pull the nucleons apart against the **strong nuclear forces** which bind them together, is in effect converted into mass.

  It was **Albert Einstein** who suggested that **mass and energy are equivalent**, that is to say, they are interchangeable quantities.

  He expressed this idea mathematically in the very famous equation shown below :

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

Where **ΔE** is the energy change(in **J**) equivalent to a mass change **Δm** (in **kg**) and **c** is the speed of light in a vacuum **(3.00×10^8 m s^{-1})**.

- In Einstein's equation, mass is in **KILOGRAM (kg)** and energy in **JOULE(J)**, but when we are working with nuclei these units are far too large and we are more likely to use the **ATOMIC MASS UNIT (u)** and the **ELECTRON-VOLT (eV)** instead.

ENERGY EQUIVALENT OF 1 ATOMIC MASS UNIT

1 u = 1.6605×10^{-27} kg. / c = 2.9979×10^8 m s^{-1}. / 1 eV = 1.6022×10^{-19} J.

$$\Delta E = \Delta mc^2 = 1.6605 \times 10^{-27} \times (2.9979 \times 10^8)^2 = \mathbf{1.4924 \times 10^{-10}\ J}.$$

$$\Delta E = \frac{1.4924 \times 10^{-10}\ \text{J}}{1.6022 \times 10^{-19}\ \text{J eV}^{-1}} = \mathbf{931.5 \times 10^6\ eV} = \mathbf{931.5\ MeV}.$$

$$\boxed{1\ \text{u} = 931.5\ \text{MeV}}$$

WORKED EXAMPLE

The **carbon-12** nucleus contains **6 protons** and **6 neutrons**. Given that :

mass of carbon-12 nucleus = **$19.926483 \times 10^{-27}$ kg.**
mass of a proton = **1.672623×10^{-27} kg.**
mass of a neutron = **1.674929×10^{-27} kg.**
1 u = **1.6605 x 10-27 kg.**
1 u = **931.5 MeV.**

Calculate : **(a)** The **mass defect (Δm)** **(i)** in **kg**, **(ii)** in **u**.
(b) The **energy in MeV** needed to split the nucleus into its constituent protons and neutrons.

(a) (i) Δm = **m(6p + 6n) - m(C-12 nucleus)**
=
= ☐ **kg**

(ii) Δm = $\dfrac{}{1.6605 \times 10^{-27}}$ = ☐ **u.**

(b) ΔE = **Δm x 931.5 MeV u^{-1}.**
= ☐ **MeV.**

- **PRACTICE QUESTIONS (1)**

1 Using the mass values below, calculate the **energy released** when a helium nucleus is formed from the combination of two protons and two neutrons.

Proton mass = 1.672623×10^{-27} kg
Neutron mass = 1.674929×10^{-27} kg
Helium nucleus mass = 6.644661×10^{-27} kg

2 Using the masses below, explain why the **fusion** reaction $^{4}_{2}He + ^{4}_{2}He \rightarrow ^{8}_{4}Be$ is unlikely to occur unless energy is supplied.

Helium nucleus mass = 4.001506 u
Beryllium nucleus mass = 8.003111 u

3 An **electron** and its antiparticle, the **positron**, collide. They annihilate one another, so that all of their mass is converted into energy.

(a) Use the equation, $\Delta E = \Delta m\, c^2$ to calculate the **energy released in joule**.
(electron mass = positron mass = 9.1×10^{-31} kg).

(b) Calculate the **energy released in MeV**. (1 MeV = 10^6 eV).

4 A gold nucleus contains **79** protons and **118** neutrons. Given the data shown below, calculate :
(a) The **mass defect in u**.
(b) The **energy in MeV** required to split the nucleus into its constituent protons and neutrons.

Mass of **gold nucleus** = **196.923180 u.**

Mass of a **proton** = **1.007276 u.**

Mass of a **neutron** = **1.008665 u.**

1u = 931.5 MeV.

BINDING ENERGY AND BINDING ENERGY PER NUCLEON

- Imagine a nucleus being dismantled by pulling each nucleon apart from its neighbour. To do this, work has to be done against the **strong nuclear force** which holds the nucleons together and each separated nucleon has **increased potential energy** as a result.

The **BINDING ENERGY** of a nucleus is defined as the work that must be done to separate the nucleus into its constituent protons and neutrons.

* The **binding energy** of a nucleus is the energy equivalent of the **mass defect** of the nucleus.

- When a nucleus forms from separate protons and neutrons, the strong nuclear force does work in pulling the nucleons together. An amount of energy equal to the binding energy of the nucleus, is released as a result.

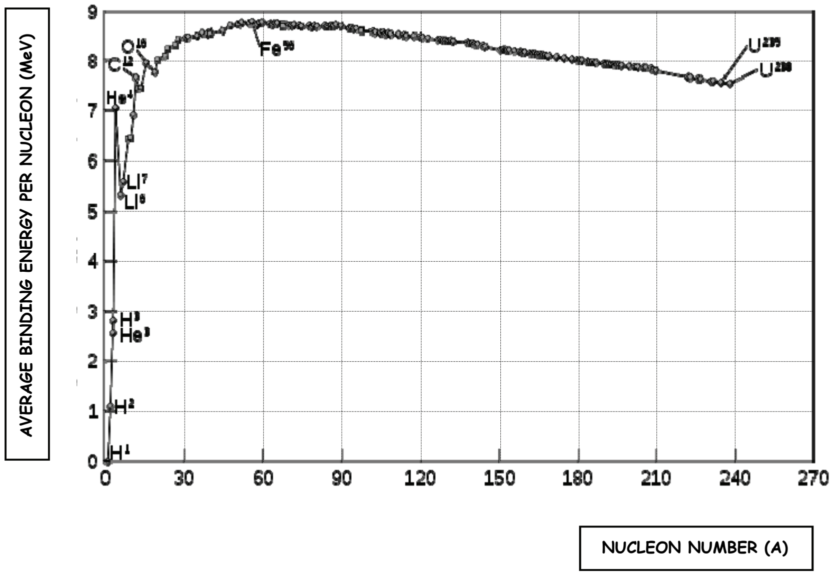
- The **total binding energy** of a nucleus gives us some information about the **stability** of the nucleus, but a more useful indicator of nuclear stability is The **binding energy per nucleon.**

The **BINDING ENERGY PER NUCLEON** is the average energy needed to remove each nucleon from a nucleus.

$$\text{BE per nucleon} = \frac{\text{total BE}}{A}$$

Calculate the **binding energy per nucleon** for the **carbon-12** nucleus we considered on page 2.

- Shown below is a graph of **BINDING ENERGY PER NUCLEON** against **NUCLEON NUMBER (A)** for all known nuclides.

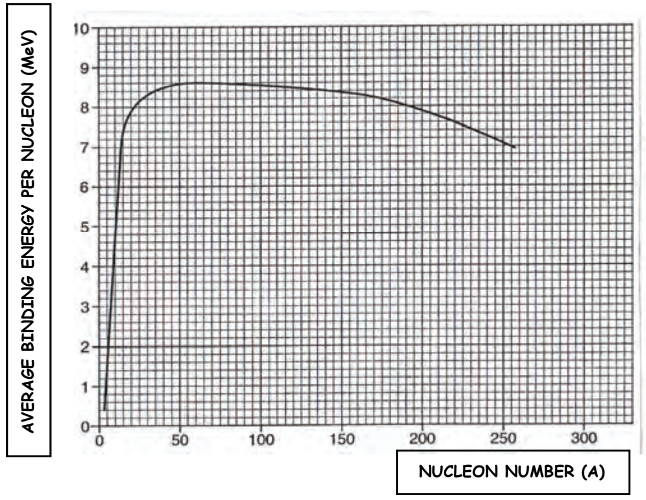


POINTS TO NOTE

- The **binding energy per nucleon** is typically about **8 MeV**.
- The **lighter nuclei,** hydrogen, helium-3, lithium etc. have **low binding energy per nucleon.**
- **Helium-4** is a distinct spike on the curve, having a higher binding energy per nucleon than predicted by its nucleon number.
- The **most stable nucleus, iron-56,** has the **highest binding energy per nucleon at 8.79 MeV.**

USING BE/A GRAPH TO ESTIMATE ENERGY RELEASED IN FISSION

The graph below shows the variation of **binding energy per nucleon** with **nucleon number (A).**



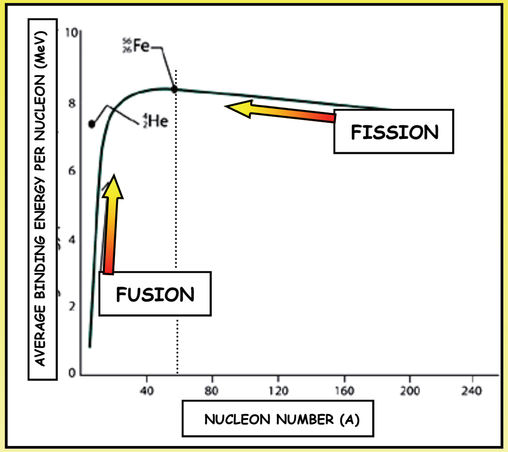
Use the graph to calculate a value for the energy which would be released from the fission of **uranium-235** into a **lanthanum-146** nucleus and a **bromine-87** nucleus.

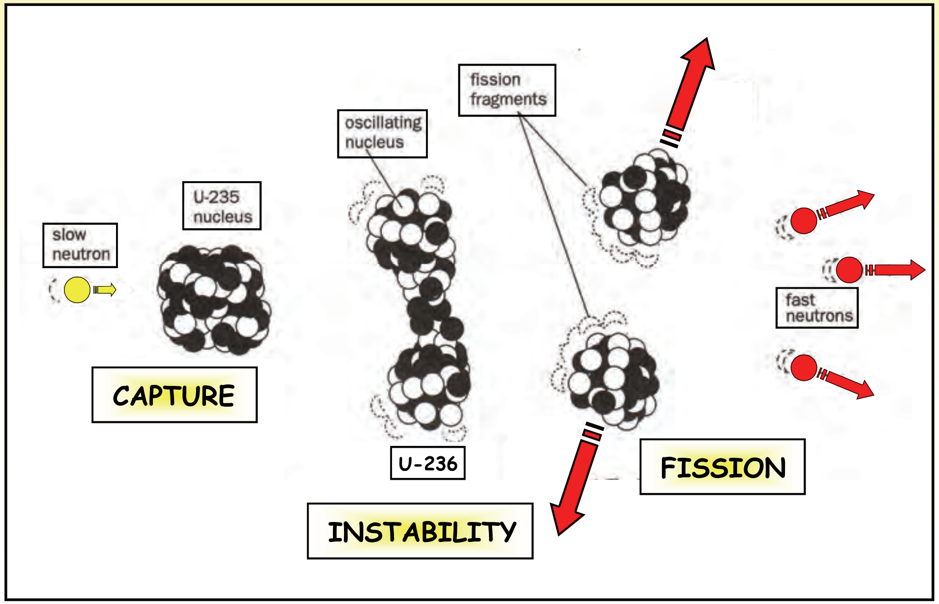
INDUCED NUCLEAR FISSION

- The differences between values of binding energy per nucleon suggests a means of extracting energy from nuclear reactions.

- If heavy nuclei can be split, lighter nuclei will be formed, and the difference in binding energy per nucleon is released in the process **(nuclear fission)**.

- Similarly, if two very light nuclei can be fused together, the resulting nucleus will be more stable, and again the difference in binding energy will be released **(nuclear fusion)**.



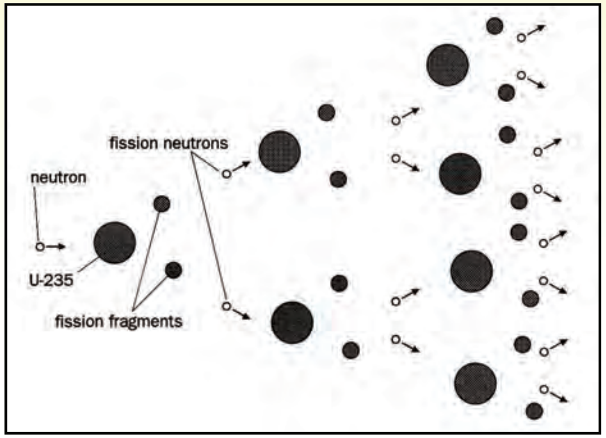


- The diagram shows how fission of a **uranium-235** nucleus occurs when it captures a slow-moving neutron and so becomes **U-236**. The absorption of the neutron **deforms** the nucleus which then starts to oscillate until it eventually acquires a **dumbbell shape**. At this point, the **electrostatic repulsion** between the protons in the two halves becomes **greater than** the **short-range strong force** between all the nucleons and the nucleus splits.

- There are many possible fission fragment combinations and a relatively large amount of energy **(≈ 200 MeV)** is released by each fission event. **Several neutrons (typically 3) are also ejected at high speeds.**

- The **mass of the U-235 nucleus plus the captured neutron is greater than the mass of the fission fragments plus the ejected fission Neutrons** and it is this mass difference which results in the release of energy, which appears as **kinetic energy of the fragments and neutrons.** The fission fragments have **greater binding energy** and are therefore **more stable** than the U-235 nucleus. The **energy released is equal to the change in total binding energy.**

- If the **fast, high-energy** fission neutrons are somehow slowed down so that they are captured by U-235 nuclei, they can then cause further fission, which in turn leads to further fission and so on. This is called a **fission chain reaction** (shown in the diagram below) and as each fission event occurs in a tiny fraction of a second, a huge amount of energy can be released in a very short time.



- The equation shown below is that for a typical nuclear fission reaction. A **U-235 nucleus** is split into a **barium nucleus**, a **krypton nucleus** and **three fission neutrons**, with the **release of energy**.

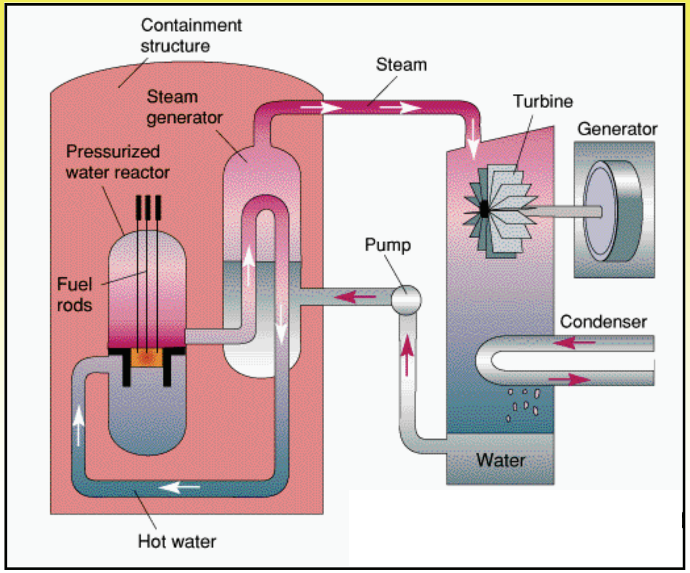
$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n + \text{energy released}$$

The energy released **(ΔE)** can be calculated using $\Delta E = \Delta mc^2$, where **Δm** is the difference between the total mass **before** and **after** fission.

- If the masses are in **kg**, **ΔE** will be in **JOULE (J)**.
- If the masses are in **u**, **ΔE** is calculated using :

$$\Delta E = \Delta m \times 931.5 \text{ MeV}.$$

NUCLEAR FISSION REACTOR



GENERAL INTRODUCTION

- In a nuclear reactor, energy released from fission is extracted and used to produce steam which drive turbines to run generators which produce electricity.

- In order to harness the energy from fission, the chain reaction has to be perfectly controlled (i.e. **CRITICAL**).

  A **CRITICAL** chain reaction is one in which **the rate at which neutrons are produced by fissions = the rate at which neutrons are lost** (By (1) further fissions, (2) absorption without fission, and (3) leaving the fissile material).

  If the rate of fission neutron production is **greater than** that at which they are lost, the chain reaction is said to be **SUPERCRITICAL** (this is what happens in nuclear fission bombs).

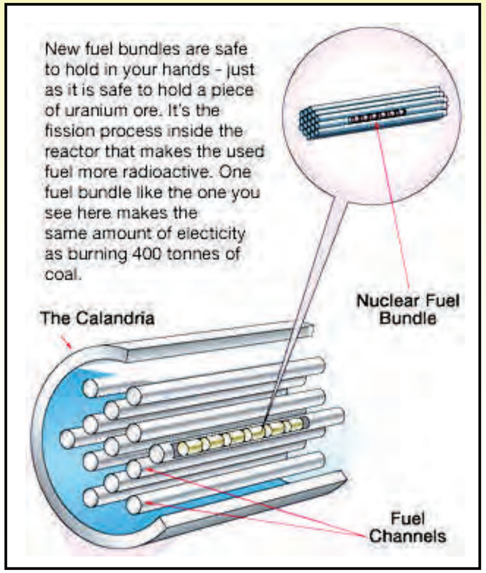
  If the rate of fission neutron production is **less than** that at which they are lost, the chain reaction **dies out**.

FUEL RODS

Uranium is a naturally-occurring metal which is mined in several parts of the world. Unfortunately it only contains **0.7 %** of the fissile isotope **U-235**, the rest being the non-fissioning **U-238**.

The uranium used in reactors is **artificially enriched** to increase the concentration of U-235 to about **3 %**.

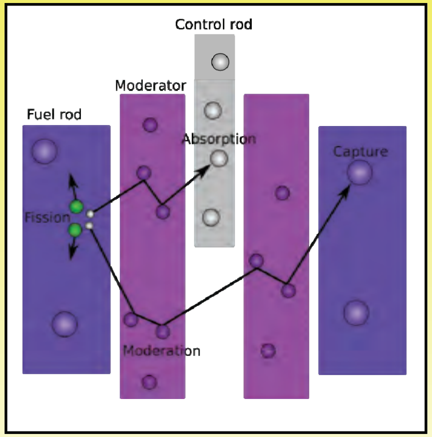
The fuel is contained in cylindrical, stainless steel rods which are inserted into tubes in the reactor core. Once the uranium in a rod has been used up, it can easily be removed and replaced.


New fuel bundles are safe to hold in your hands - just as it is safe to hold a piece of uranium ore. It's the fission process inside the reactor that makes the used fuel more radioactive. One fuel bundle like the one you see here makes the same amount of electicity as burning 400 tonnes of coal.

MODERATOR

- The neutrons released by each fission are travelling **too fast** to be captured by the U-235 nuclei and so cause further fission. They must therefore be **slowed down** by absorbing most of their kinetic energy.

The **moderator** is a material which is incorporated into the reactor core in order to reduce the high speeds of the fission neutrons to **'thermal'** speeds and so enable them to cause further fission.



Successive elastic collisions of the neutrons with the nuclei of the moderator material allows energy to be transferred to the material and so the neutrons are slowed down.

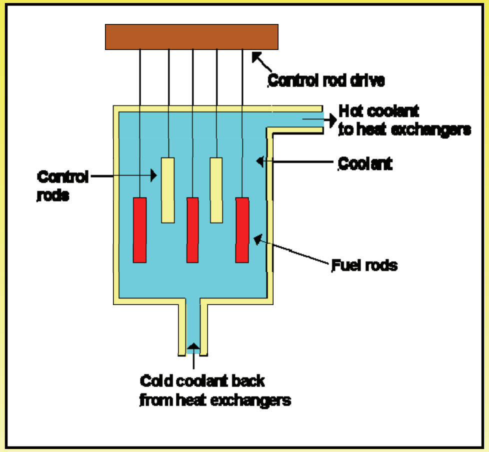
Since in an **elastic collision**, energy is transferred most effectively if the two bodies are of **equal mass**, the nuclei of the moderator need to be of a size **comparable to that of a neutron**.

Additional to this, the moderator material needs to have a **low neutron absorbing capability**. Otherwise fission neutrons would be removed from the reaction.

The **pressurised water reactor (PWR)** employs **water** as both the moderator and coolant. **Graphite** is used in the **Magnox** and **advanced gas cooled (AGR)** reactors.

CONTROL RODS

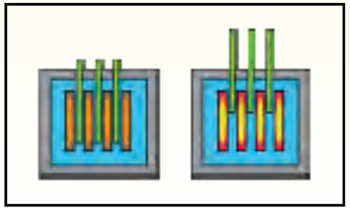
- As we already know, the reaction rate must be **CRITICAL** (i.e. on average each fission neutron must go on to cause a further fission). Anything less means that the **reaction ceases** and anything more causes the **reaction to go out of control**.



- A minimum mass of uranium, called the **critical mass**, is needed to set up a chain reaction. So if the uranium mass is too small, the fission neutrons will escape from the surface before they can cause further fissions.

  Each individual fuel rod is **below** the critical mass and their narrow, cylindrical shape means that fission neutrons escape into the moderator where they are slowed down sufficiently to enable them to cause fission in the next rod.

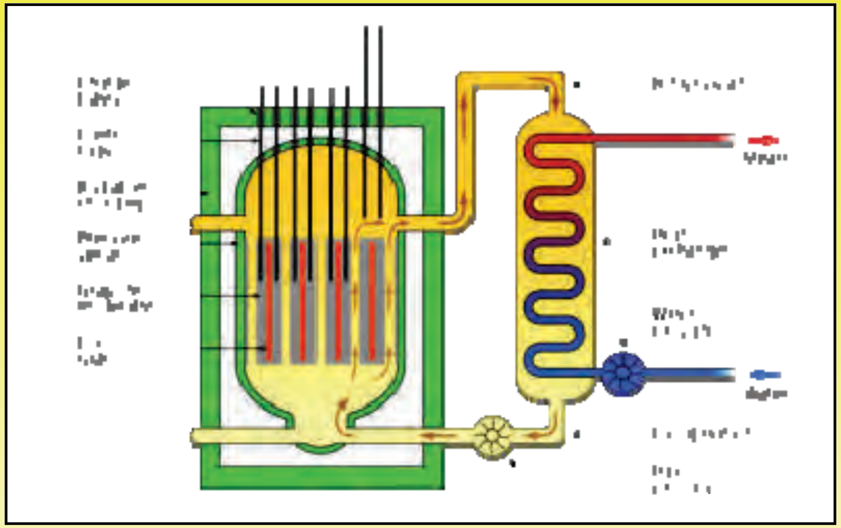
- The control rods are made of **neutron-absorbing** materials, such as **boron** and **cadmium** and they are used to control the number of neutrons available to cause fission. This control is achieved by **raising** or **lowering** the control rods into the reactor core.



Lowering the rods **increases** the number of neutrons which are absorbed and so **reduces** the reaction rate, whereas raising them has the opposite effect.

The reactor can be **shut down** completely by lowering the rods **fully** into the core.

COOLANT



- The energy released in the fission reaction is almost entirely kinetic energy of the fission fragments and the neutrons. This kinetic energy **increases the internal energy** of all the components of the reactor, resulting in a **temperature rise**. To extract this heat energy, a **coolant** is pumped around the reactor core and this fluid gets heated through contact with the reactor components. It then passes to a **heat exchanger** where its heat energy is passed on to water to create steam.

- The **coolant** used must have the following properties :
    - **High specific heat capacity.**
    - **Non-corrosiveness.**
    - **Stability at the high reactor temperatures.**

  Common coolants are **carbon dioxide** and **water**. In the **pressurised water reactor (PWR)** the water is pressurised so as to remain liquid at the high reactor temperatures.

- The coolant becomes **radioactive** as it passes through the core, so it must be **fully contained**. Loss of coolant could eventually result in meltdown (the core overheats and melts). This is because even if the reactor is quickly shut down, the core temperature will continue to rise as a result of radioactive decay of the fission fragments.

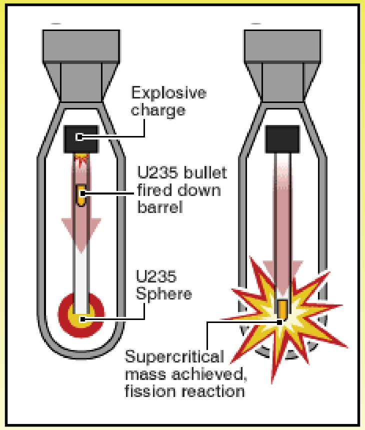
SHIELDING AND SAFETY

- The core of the reactor is contained within a **steel pressure vessel** which contains the highly pressurised coolant. A **5 metre thick concrete shield** surrounds the reactor and this stops harmful radiation and neutrons from escaping and the whole system is housed in a **steel and concrete containment building** which is designed to prevent the escape of any radiation even in the extreme event of core meltdown.

DESTRUCTIVE USE OF NUCLEAR FISSION

- The **fission bomb (A-bomb)** uses an uncontrolled chain reaction to unleash an immense amount of destructive energy. The first A-bomb used in warfare was dropped by the USA on **August 6th 1945**. Called **'Little Boy'**, it produced an explosion that devastated the Japanese city of **Hiroshima,** killing 130, 000 people in little over a minute.

  In this bomb, a mass of uranium about the size of a baseball produced an explosion equivalent to the instantaneous detonation of **15 kilotons of TNT!**



  Little Boy was a **'gun-type'** fission bomb in which a small bullet of uranium was fired into a larger 'target' piece of uranium and, upon impact, the two pieces fused together forming a **supercritical mass**. Neutrons were simultaneously directed at this mass and this initiated the uncontrolled chain reaction leading to the explosion.
  A barometric-pressure sensor was used to determine the optimum detonation altitude and so ensure maximum destruction.

ENVIRONMENTAL EFFECTS OF NUCLEAR WASTE

- The nuclear industry, and nuclear reactors in particular produce large quantities of hazardous material. The management of nuclear waste is one of the most controversial issues surrounding the production of electrical energy from nuclear power.

  After some years in the reactor, the proportion of U-235 in the fuel rods will have decreased to the point at which a chain reaction can no longer be sustained. The fuel is removed and must be re-processed, a hazardous operation in which plutonium-239 and other useful isotopes are extracted. The remaining radioactive material must be stored for later disposal

- Radioactive waste is categorised according to its activity as **high, medium** or **low level** waste.

- **<u>High-level radioactive waste</u>** (such as spent fuel rods) contains many different radioisotopes, including fission fragments as well as unused U-235, U-238 and Pu-239.

  The spent fuel rods are handled remotely and stored in cooling ponds (because they continue to release heat as a result of radioactive decay) for up to a year. The unused U and Pu is then removed and stored for further possible use.

  The high-level radioactve waste is sealed inside glass blocks which are placed in thick, steel containers, encased in concrete and buried underground. Although this packaging of the nuclear waste is both safe and effective, the problem is that the radioisotopes contained have long half-lives and remain hazardous for thousands of years. We don't know for how long the packaging will remain intact.

- **<u>Intermediate-level waste</u>** consists mainly of empty fuel rods, contaminated reactor components and chemical sludges used in the treatment of nuclear fuel.

  This type of nuclear waste is very much less radioactive than the spent fuel rods.

  This waste is encased in cement inside stainless steel drums which are then stored in concrete vaults or underground.

- **<u>Low-level waste</u>** is only slightly radioactive and includes items such as packaging, laboratory instruments and protective clothing.

  It is disposed of by compacting, placing in steel containers and either given a shallow land burial or dumped at sea.

  Liquid wastes, such as cooling pond water, are cleaned and then discharged into the sea.

NUCLEAR FUSION

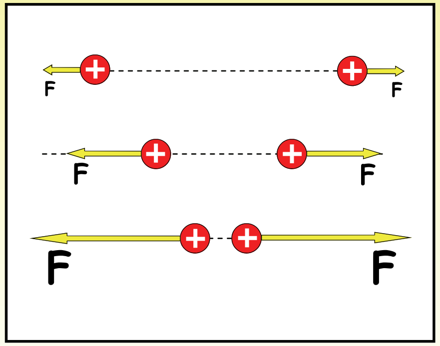
- If you look back to the **binding energy per nucleon versus nucleon number** graph shown on page **4**, you will see that the binding energy per nucleon of light nuclei (such as **hydrogen**, **deuterium**, **tritium and helium-3**) is **much less** than that of larger nuclei.

  Thus, if two light nuclei could be forced to fuse into a single larger nucleus, the difference in the binding energy could be released. This forms the basis of the process of **nuclear fusion**.

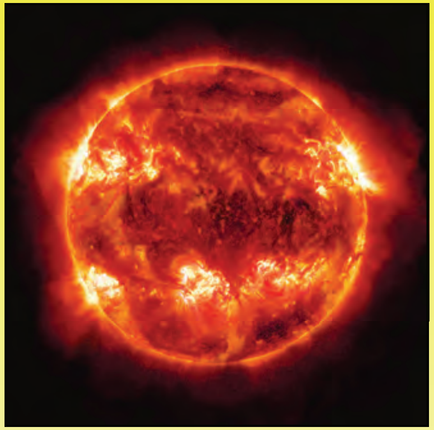
  In nuclear fusion, the **mass of the resulting larger nucleus < the sum of the masses of the fusing nuclei** and it is this mass difference which is Converted into energy.

- In order for two light nuclei to fuse, they must be brought **close enough for the strong force to come into action** and overcome the electrostatic repulsion force due to the positive charges of the nuclei.

  The problem is that the repulsion force **increases dramatically** as the two nuclei come closer.



For two hydrogen nuclei to have enough Kinetic energy to overcome the electrostatic repulsion forces and so fuse, the hydrogen needs to be at an **enormously high temperature**.

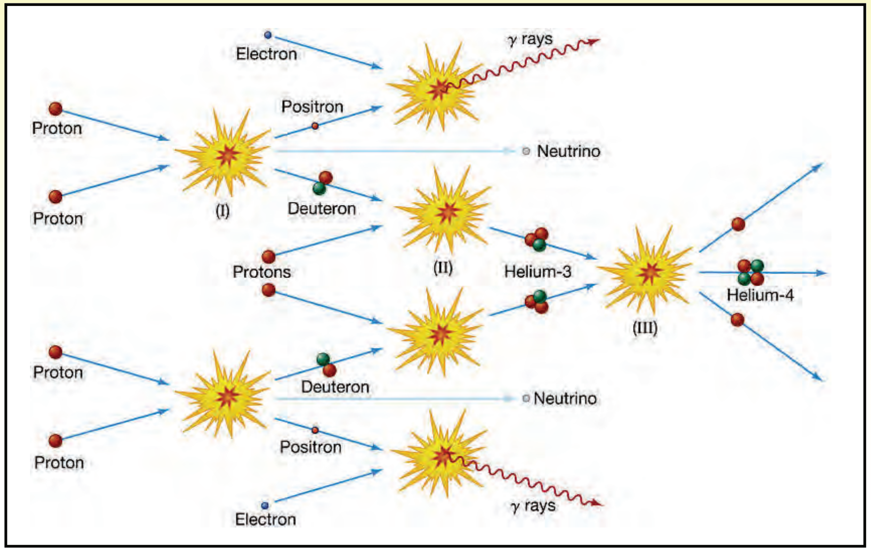


This is exactly the case in the Sun's core and that of all stars, where the temperature is in excess of **20 million °C** and matter exists as a 'soup' of **free nuclei and negatively charged electrons**. This mixture is called a **plasma**.

The density of this plasma is greater than **100 000 kg m^{-3}** (due to compression by the **enormous gravitational forces** produced by Such massive bodies), and under these conditions, the nuclei collide with enough kinetic energy to fuse, releasing more energy to sustain the reaction.

- The two main series of fusion reactions occurring in the Sun are :

1. THE HYDROGEN CYCLE



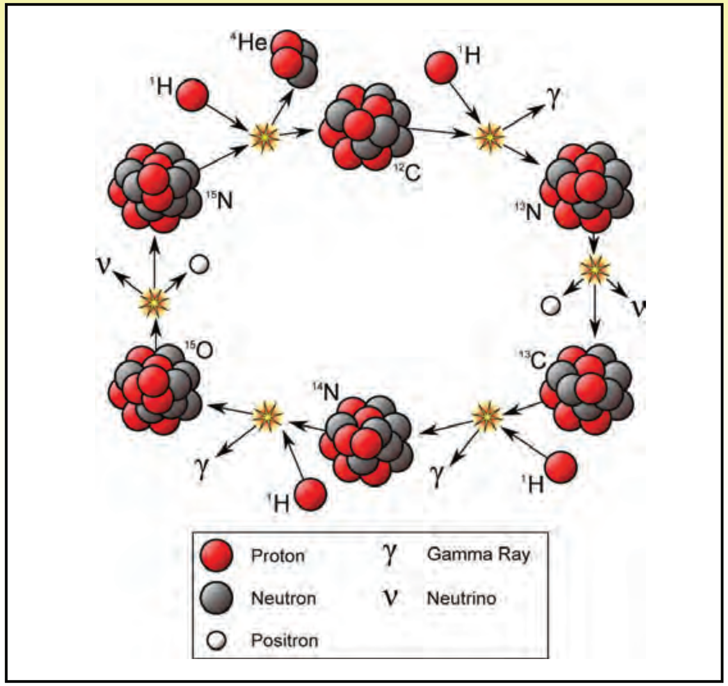
- In **STEP I** - Two **hydrogen nuclei (protons)** fuse to produce a **deuterium nucleus**. A **positron** and a **neutrino** are emitted.

- In **STEP II** - The **deuterium nucleus** fuses with another **proton** to produce a **helium-3 nucleus.**

- In **STEP III** - Two **helium-3 nuclei** fuse to produce a **helium-4 nucleus** and **two protons.**

2. THE CARBON CYCLE

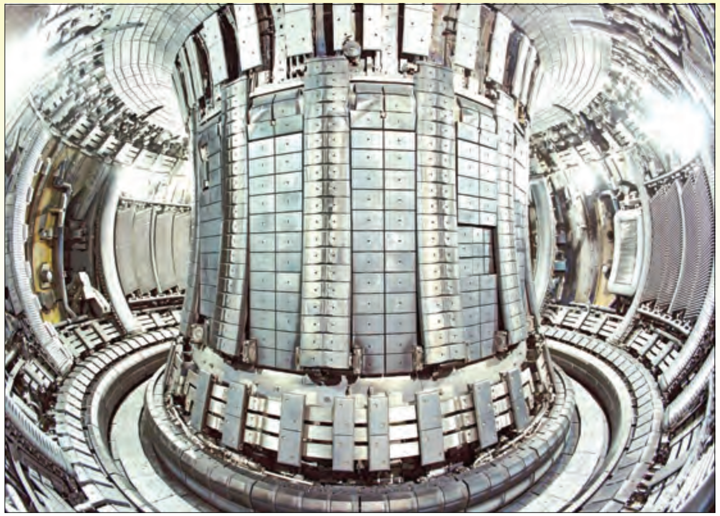
- The Sun consists mainly of **hydrogen** and **helium,** but about 1% of its mass is made up of heavier elements which allow the fusion of protons to helium-4 by alternative fusion reaction sequences. The most important of these sequences **starts and ends with carbon-12** and is aptly named the **CARBON CYCLE** (shown diagrammatically below).



NUCLEAR FUSION ON EARTH

- The conditions for fusion in the core of stars can be created on Earth, when a nuclear fission bomb is detonated. The high temperature and high pressure generated by such an explosion can be made to cause a fusion reaction in light nuclei. The resulting **hydrogen bomb** is a truly awesome weapon, delivering the explosive power of **millions of tons** of dynamite from a few kilograms of plutonium and a few grams of lithium, deuterium and tritium. Creating these conditions for a **controlled fusion reaction,** in order to harness the energy for peaceful purposes, is a far more difficult proposition.

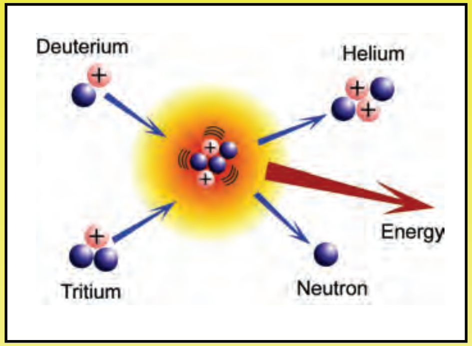
- A major problem in controlled fusion is that of confining the extremely hot **($T \approx 10^8$ to 10^9 K)** deuterium-tritium plasma. This means that the plasma cannot be allowed to come into contact with the walls of the containing vessel, since this would instantly cool it and so cause the reaction to stop. One of the most promising methods for confining the plasma is the use of **magnetic fields.** Since the plasma consists entirely of charged particles, magnetic fields will exert forces on them and it is hoped that the field shape can be controlled to enable the plasma to be contained within a toroidal fusion chamber. The photograph below shows the plasma-containing chamber of the **JET prototype fusion reactor.**



- The most promising fusion reaction is that between **deuterium (D) and tritium (T).**

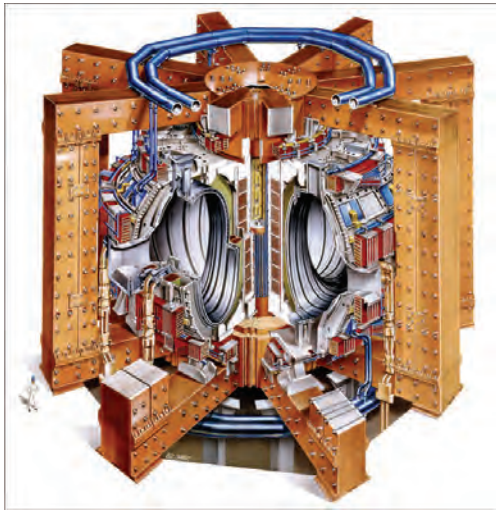
  DT fusion is preferred over **DD fusion** because :

  - It occurs at a **lower temperature.**
  - It **releases a lot more energy.**



- The **reaction equation for DT fusion** is :

$${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n + \text{energy}$$



The JET prototype fusion reactor.

1 (a) **(i)** State what is meant by **nuclear binding energy**.

(ii) Fig 1. shows the **binding energy per nucleon** for five nuclides, plotted against **nucleon number**.

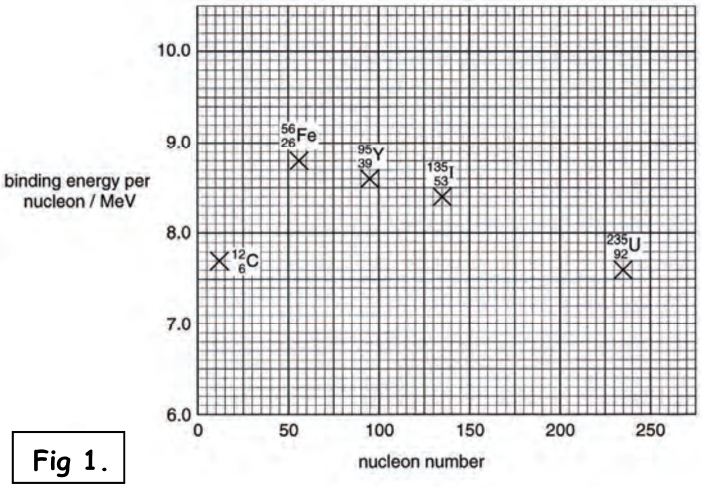


Fig 1.

Fe-56 has the highest binding energy per nucleon. **C-12** and **U-235** have less binding energy per nucleon. Explain how these values relate to the possibility of **fission** or **fusion** of the nuclides **Fe-56, C-12 and U-235.**

(b) **(i)** A **U-235** ${}^{235}_{92}U$ nucleus inside a nuclear reactor can absorb a **thermal neutron. State** what is meant by a **thermal neutron.**

(ii) Write a **nuclear equation** for this reaction.

(iii) The resulting nucleus undergoes fission. **iodine-135** ${}^{135}_{53}I$ and **yttrium-95** ${}^{95}_{39}Y$ are produced.

Write a **nuclear equation** for this reaction.

(iv) Use data from **Fig 1.** to deduce how much energy in **MeV** is released when one nucleus of **U-235** undergoes these reactions.

(OCR A2 Physics - Module 2825 - June 2005)

2 This question is about **nuclear fusion inside the Sun**.

(a) Describe the conditions inside the Sun and explain how they favour nuclear fusion. Your account should explain why the material inside the Sun is in the **plasma state** and how the **plasma is confined**.

(b) One process by which hydrogen nuclei fuse is called the **carbon cycle**. The following equations represent the reactions which make up this cycle.

$$^{12}_{6}C + ^{1}_{1}H \longrightarrow ^{13}_{7}N$$
$$^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{1}e$$
$$^{13}_{6}C + ^{1}_{1}H \longrightarrow ^{14}_{7}N$$
$$^{14}_{7}N + ^{1}_{1}H \longrightarrow ^{15}_{8}O$$
$$^{15}_{8}O \longrightarrow ^{15}_{7}N + ^{0}_{1}e$$
$$^{15}_{7}N + ^{1}_{1}H \longrightarrow ^{12}_{6}C + ^{4}_{2}He$$

(i) Why is it called the **carbon cycle?**

(ii) Summarise the carbon cycle by reducing the six equations above to a single equation, in its simplest form.

(iii) The binding energy per nucleon of He-4 is **7.1 MeV**.

Show that the **energy released in joules** when one He-4 nucleus is formed is about **4.5 x 10^{-12} J**. By referring to your answer to **(b) (ii)**, give one reason why this is only an approximation.

(c) It is estimated that **8 x 10^{37}** helium nuclei are formed per second inside the Sun. Assuming that this is the only energy-generating process, calculate the **total power emitted by the Sun**.

(OCR A2 Physics - Module 2825 - June 2004)

3 A **tin-120 atom** has a mass of **119.902 u**. It contains **50** protons.

(a) How many **neutrons** and **electrons** does it contain?

(b) Given the masses of the constituent particles shown below, calculate the **mass defect (Δm)**.

Mass of a **proton** = **1.007276 u.**
Mass of a **neutron** = **1.008665 u.**
Mass of an **electron** = **0.000550 u.**

(c) Calculate the **binding energy** of the atom in **MeV**. Given that **1u = 931.5 MeV**.

(d) Calculate the **binding energy per nucleon** in **MeV**.

4 **(a)** Use the binding energy per nucleon against nucleon number graph shown on **page 4** to show that the total binding energy of a single U-235 nucleus is ≈ **2.8 x 10^{-10} J**.

(b) A typical **nuclear fission reaction** is shown on **page 6**.

(i) Explain why the energy released in this reaction as **kinetic energy of the fragments** is only a small fraction of the energy calculated in **(a)**.

(ii) Assuming that the actual fraction is **1/6**, calculate the **energy released per kilogram of U-235**.

(c) One sequence of reactions involving isotopes of hydrogen can be summarised by the single reaction equation :

$$^{1}_{1}H \longrightarrow ^{4}_{2}He + 2^{0}_{1}e$$

(i) Again use the graph on **page 4**, to find the **total energy released** in this reaction.

(ii) Calculate the **energy released per kilogram of H-1** used.

(d) Comment on your answers to **(b) (ii)** and **(c) (ii)**.