Atomic and Nuclear Physics

Topic 7.3 Nuclear Reactions

Nuclear Reactions

- Rutherford conducted experiments bombarding nitrogen gas with alpha particles from bismuth-214.
- He discovered that fast-moving particles were produced that could travel further in the gas than did the alpha particles.
- Furthermore, the "new" particles were deflected by a magnetic field in the way one would expect positively charged particles to be deflected.
- Rutherford concluded that the particles released in the collision were protons.

Nuclear Reactions

- Since the number of protons in a nucleus defines an element, a change in this number literally changes the element.
- This change of one element to another through the bombardment of a nucleus is known as artificial transmutation.
- Rutherford used the cloud chamber to test his two theories of artificial transmutation.
- He realised that if a proton was simply being chipped off the nitrogen nucleus, then the cloud chamber should show four distinct tracks:
  - one for the alpha particle before the collision
  - and one each for the alpha particle, proton, and recoiling transmuted nucleus after the collision.

Nuclear Reactions

- However, if the alpha particle was absorbed by the nitrogen nucleus, then the alpha particle track should disappear, leaving only three tracks, that of the alpha particle before the collision, and the tracks of the proton and recoiling nucleus after the collision.

- In 1925, P M. S. Blackett, an associate of Rutherford's, settled the issue when he discovered only three tracks, proving the alpha particle is indeed absorbed upon colliding with the nitrogen nucleus.

Nuclear Reactions

- The collision between an alpha particle and nitrogen can be represented by the following equation:

$$\boxed{{}^{4}_{2}\alpha + {}^{14}_{7}\mathrm{N} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}}$$

- Note the equation is balanced by equating the mass numbers and the atomic numbers from the right and left-hand sides.
- The equation shows that when nitrogen is bombarded by an alpha particle, it is transmuted into oxygen, releasing a proton in the process.
- The proton is represented as a hydrogen nucleus, that is, a hydrogen atom with no electron.
- It carries a positive charge equal in magnitude to the charge on an electron.

Nuclear Reactions

- Artificial transmutation does not happen only with alpha particle bombardment.

- In fact, neutrons, protons, and deuterons ($^{2}_{1}H$) can also be used to produce artificial nuclear reactions.

- The key to understanding these reactions, and making predictions about the products of such reactions is being able to balance nuclear equations.

Example:

- To begin this type of problem, write out the reaction equation, with all known particles and isotopes. Be sure to include mass and atomic numbers for each particle or isotope.
- Let X represent the unknown nucleus.

$$\boxed{{}^{16}_{8}\mathrm{O} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{A}_{Z}\mathrm{X} + {}^{2}_{1}\mathrm{H}}$$

- Now add the mass numbers on the left side of the equation, and the known mass numbers on the right side of the equation.
- The total number of nucleons on the left is 17, while there are only 2 nucleons on the right, so the mass number of the unknown nucleus must be 15

- Now use the same process to determine the atomic number of the unknown nucleus.
- Since the atomic numbers on the left side of the equation equal 8, the atomic numbers on the right side of the equation must also equal 8.
- Therefore, the unknown atomic number must be 7.
- The element with atomic number 7 is nitrogen, so the resulting nucleus is:

$${}^{15}_{7}\mathrm{N}$$

Einstein’s Mass-Energy Equivalence Relationship

- In 1905, while developing his special theory of relativity, Einstein made the startling suggestion that energy and mass are equivalent.
- He predicted that if the energy of a body changes by an amount E, its mass changes by an amount m given by the equation

$$E = mc^2$$

where c is the speed of light.

- Everyday examples of energy gain are much too small to produce detectable changes of mass.
- The changes of mass accompanying energy changes in chemical reactions are not much greater and cannot be used to prove Einstein's equation.

Einstein’s Mass-Energy Equivalence Relationship

- However, radioactive decay, which is a spontaneous nuclear reaction, is more helpful.

- Thus for a radium atom, the combined mass of the alpha particle it emits and the radon atom to which it decays is, by atomic standards, appreciably less than the mass of the original radium atom.

- Atomic masses can now be measured to a very high degree of accuracy by mass spectrographs.

Einstein’s Mass-Energy Equivalence Relationship

- Mass appears as energy and the two can be regarded as equivalent.

- In nuclear physics mass is measured in **unified atomic mass units** (u)

  1 u = one twelfth of the mass of the carbon-12 atom

  $1\ \mathrm{u} = 1.661 \times 10^{-27}\ \mathrm{kg}$.

- It can readily be shown using $E = mc^2$ that

  931 MeV has mass 1u

Einstein’s Mass-Energy Equivalence Relationship

- A unit of energy may therefore be considered to be a unit of mass, and in tables of physical constants the masses of various atomic particles are often given in MeV as well as in kg and u.
- For example, the electron has a rest mass of about 0.5 MeV
- If the principle of conservation of energy is to hold for nuclear reactions it is clear that mass and energy must be regarded as equivalent.
- The implication of $E = mc^2$ is that any reaction producing an appreciable mass decrease is a possible source of energy.
- Shortly we will consider two types of nuclear reaction in this category.

Mass Defect and Binding Energy

- The mass of a nucleus is found to be less than the sum of the masses of the constituent protons and neutrons.

- This is explained as being due to the binding of the nucleons together into a nucleus and the **mass defect** represents the energy which would be released in forming the nucleus from its component particles.

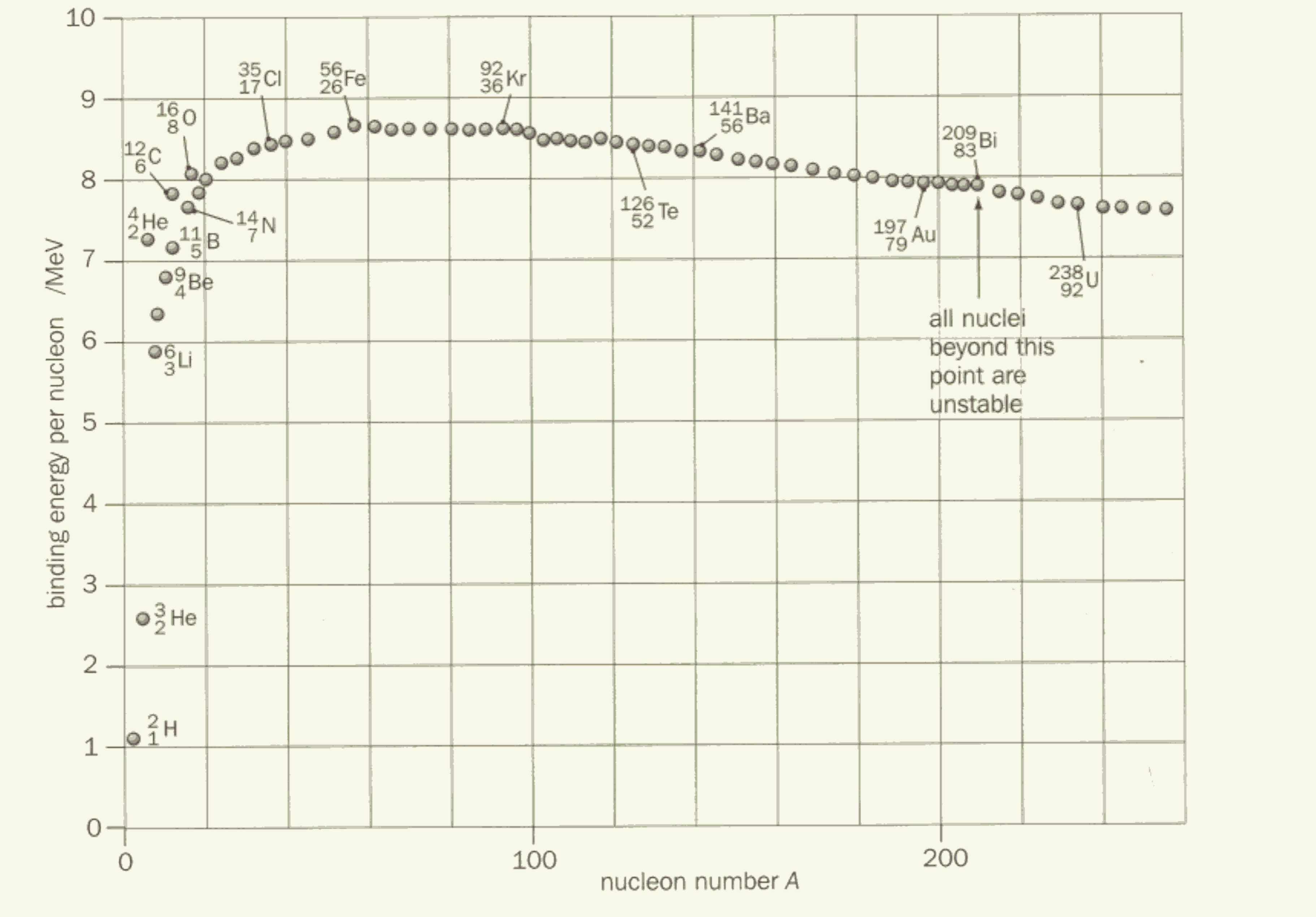
- The energy equivalent is called the **binding energy** of the nucleus.

- It would also be the energy needed to split the nucleus into its individual nucleons if this were possible.

Mass Defect and Binding Energy

- The binding energy, derived in a similar manner for other nuclides, is found to increase as the mass (nucleon) number increases.
- For neon, $^{20}_{10}\mathrm{Ne}$, it is 160 MeV
- If the binding energy of a nucleus is divided by its mass number, the **binding energy per nucleon** is obtained.
- The next graph shows how this quantity varies with mass number; in most cases it is about 8 MeV

Binding Energy per nucleon graph



Binding Energy per nucleon graph

- Nuclides in the middle of the graph have the highest binding energy per nucleon and are thus the most stable since they need most energy to disintegrate.

- The smaller values for higher and lower mass numbers imply that potential sources of nuclear energy are reactions involving the disintegration of a heavy nucleus or the fusing of particles to form a nucleus of high nucleon number.

- In both cases nuclei are produced having a greater binding energy per nucleon and there is consequently a mass transfer during their formation.

α-decay

Thorium-228 decays by α-emission:

$$ {}^{228}_{90}\mathrm{Th} \Rightarrow {}^{224}_{88}\mathrm{Ra} + {}^{4}_{2}\alpha $$

Mass of thorium-228 nucleus = 227.97929 u

Mass of radium-224 nucleus + α-particle
= 223.97189 u + 4.00151 u = 227.97340 u

∴ Mass difference = 227.97929 u – 227.97340 u
= 0.00589 u
= 5.49 MeV (as 1 u = 931.5 MeV)

What happens to this energy? It appears mostly as the kinetic energy of the α-particle. The radium nucleus also recoils slightly (and so momentum is conserved).

β-decay

Aluminium-29 decays by β-emission:

$$^{29}_{13}\mathrm{Al} \rightarrow {}^{29}_{14}\mathrm{Si} + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}$$

Mass of aluminium-29 nucleus = 28.97330 u

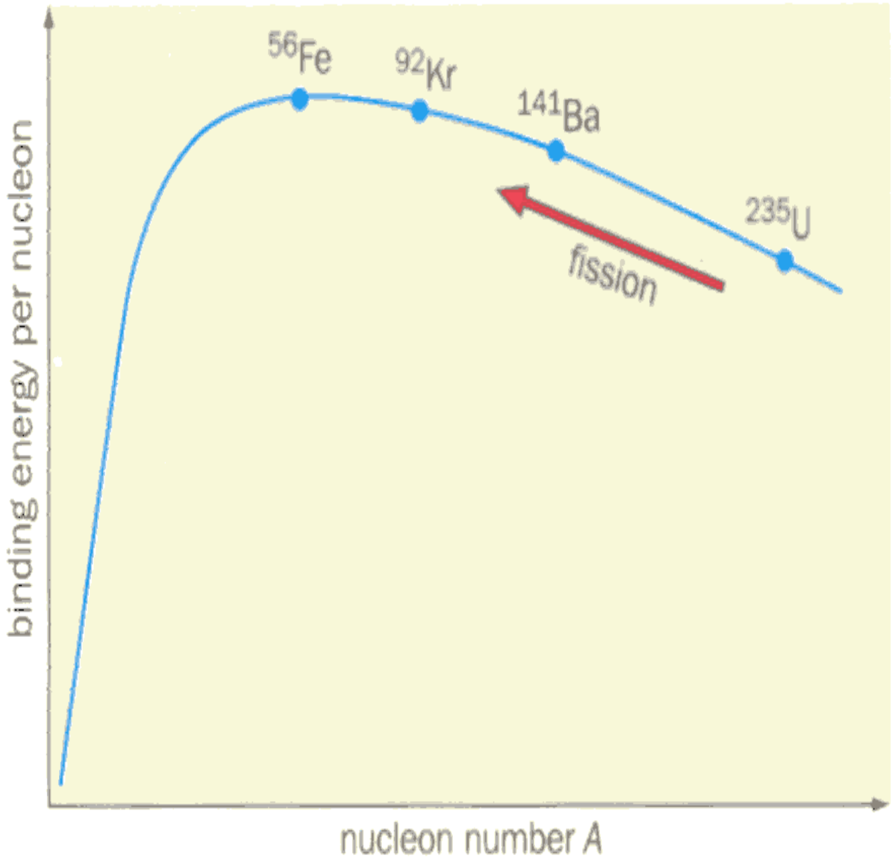
Mass of silicon-29 nucleus + β-particle + antineutrino
= 28.96880 u + 0.000549 u + 0 = 28.969349 u

$\therefore$ Mass difference = 28.97330 u – 28.969349 u
= 0.003951 u
= $\underline{3.68\ \text{MeV}}$ (as 1 u = 931.5 MeV)

Again this energy becomes the kinetic energy of the decay products.

Fission

- Fission means splitting up. In a fission reaction a large nucleus (A > 200) splits in two.
- Look again at the binding energy per nucleon curve
- If a nucleus with A>200 splits in half, the two fragments have a higher binding energy per nucleon than the parent.
- This means that the fragments are more stable than the parent.
- The excess energy is released by the reaction.



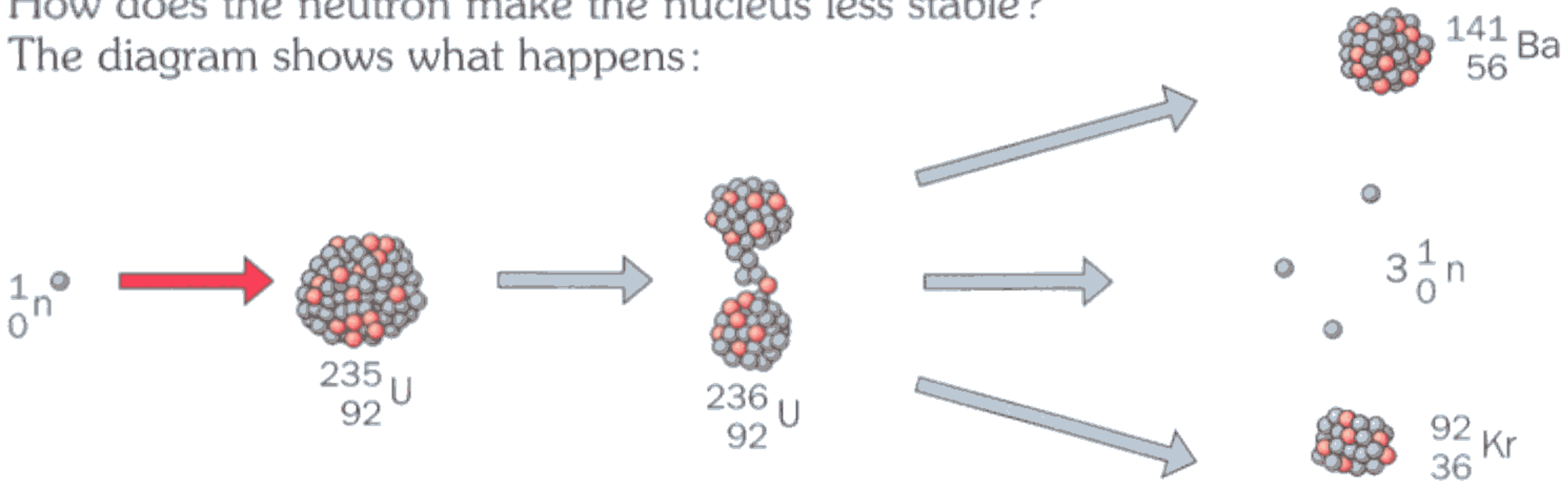
Fission

- Spontaneous fission is very rare. Uranium is the largest nucleus found on Earth.
- Its isotopes will sometimes fission naturally. Bombarding the nucleus with neutrons can trigger a fission reaction.

For example:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{236}_{92}\text{U} \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n} + \text{energy}$$

How does the neutron make the nucleus less stable?
The diagram shows what happens:

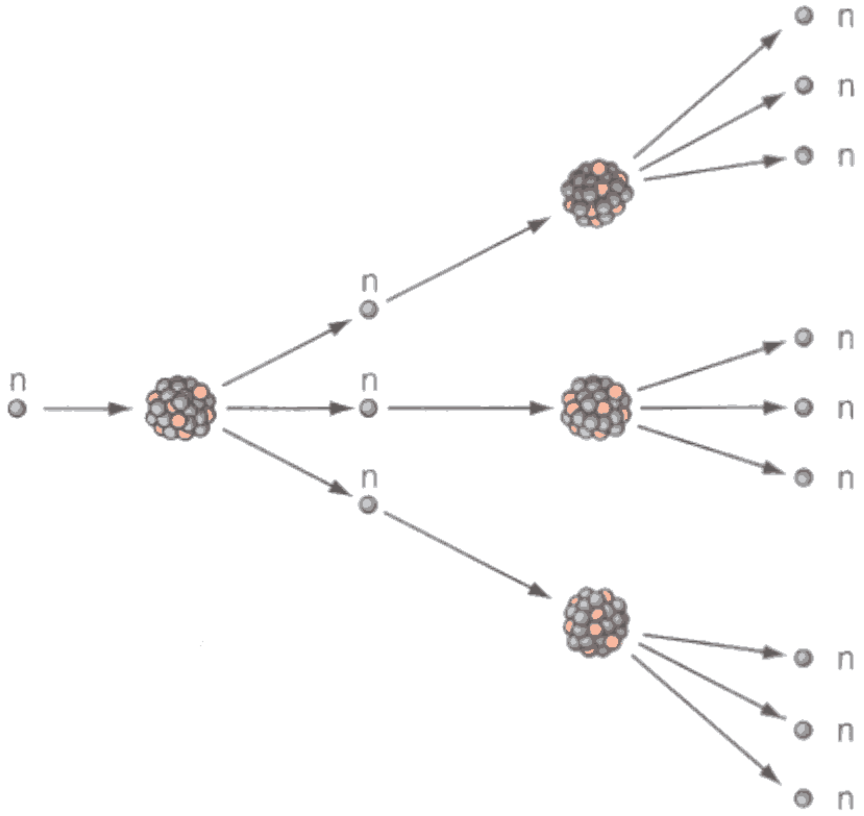


Fission

- The strong forces that hold the nucleus together only act over a very short distance.
- When a uranium nucleus absorbs a neutron it knocks the nucleus out of shape.
- If the nucleus deforms enough, the electrostatic repulsion between the protons in each half becomes greater than the strong force. It then splits in two.
- The nucleus splits randomly.
- In the diagram, the fission fragments are shown as isotopes of barium and krypton.
- This is just one of the many possible combinations.
- Fission of a uranium nucleus gives out about 200MeV of energy.

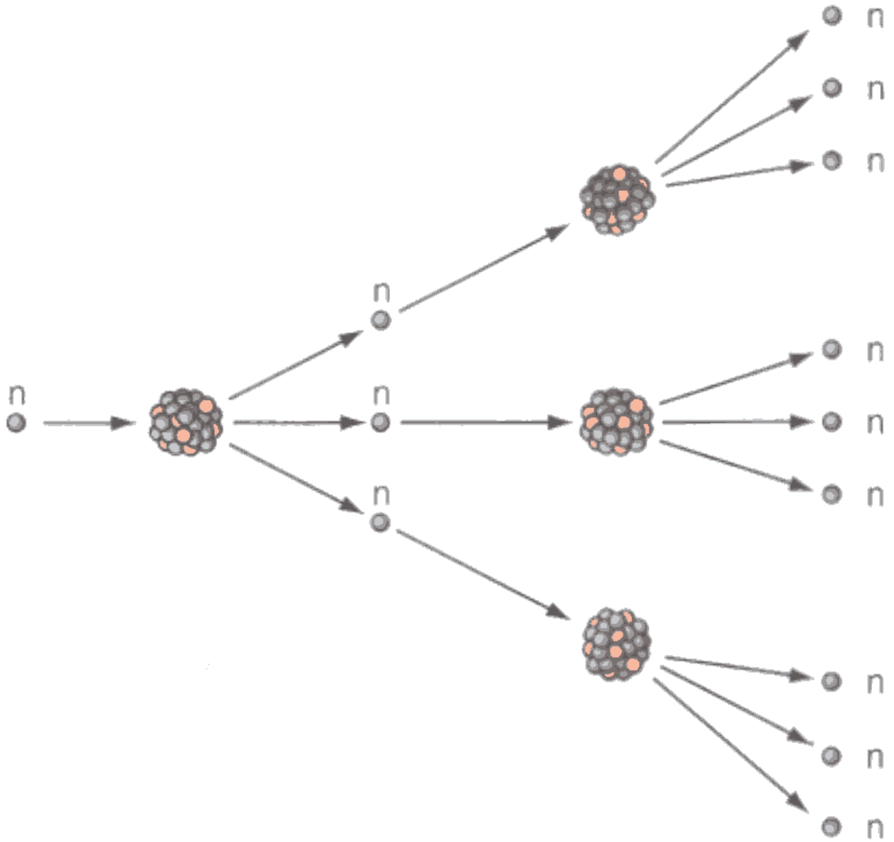
Chain reactions

- When the uranium nucleus splits, a number of neutrons are also ejected.
- If each ejected neutron causes another uranium nucleus to undergo fission, we get a chain reaction.



Chain reactions

- The number of fissions increases rapidly and a huge amount of energy is released.
- Uncontrolled chain reactions are used in nuclear bombs
- The energy they unleash is devastating.

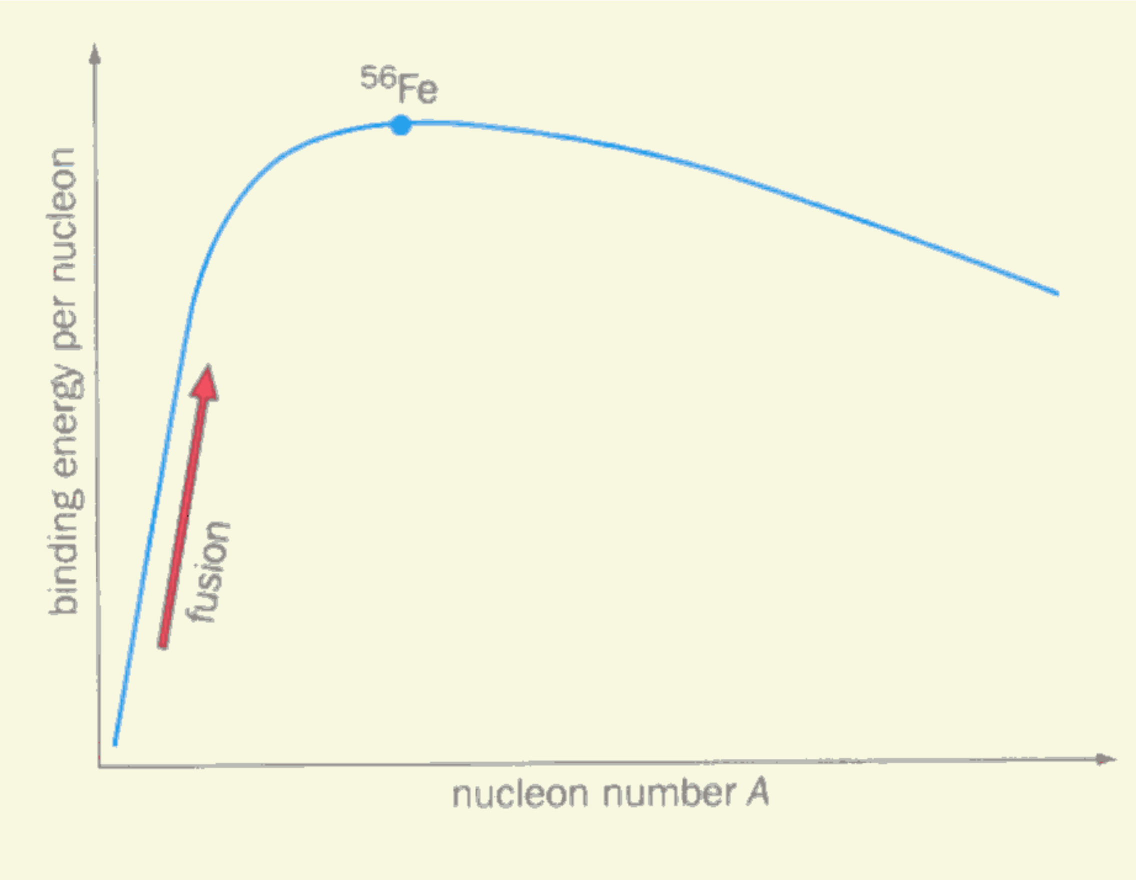


- Nuclear power stations use the heat released in carefully controlled fission reactions to generate electricity.
- They use control rods to absorb some of the neutrons.

Fusion

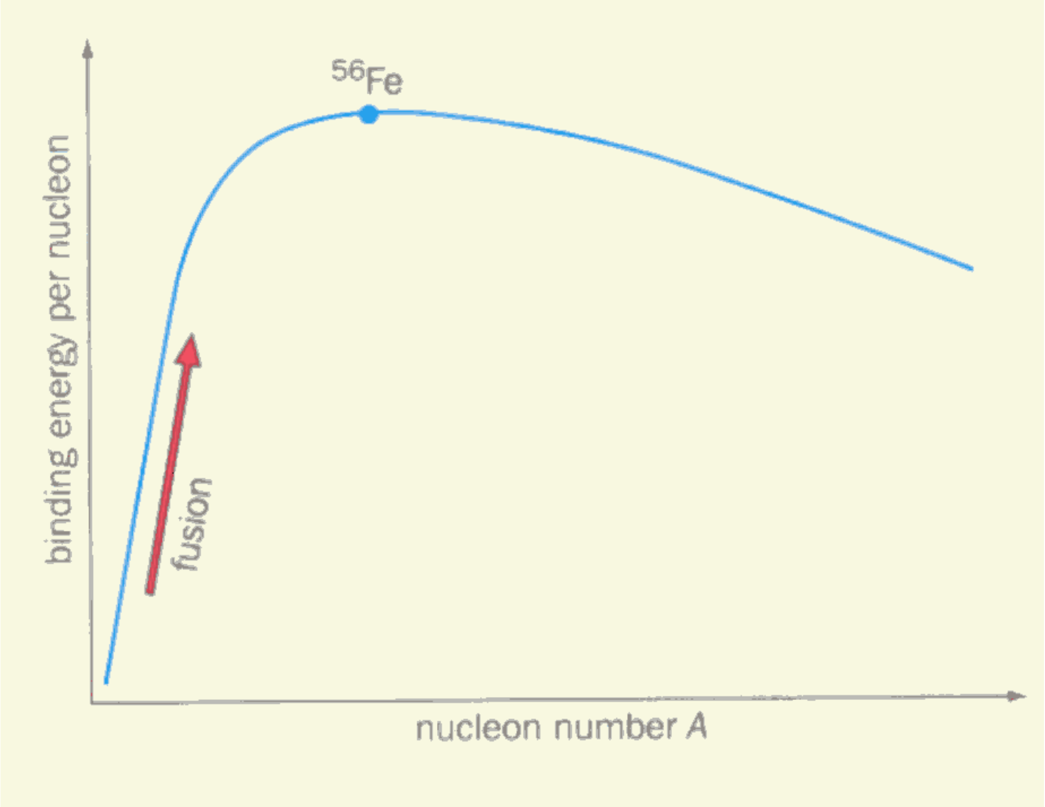
- Fusion means joining together.
- In a fusion reaction two light nuclei join together to make a heavier nucleus.

- Fusion gives out more energy per kilogram of fuel than fission.
- Can you see why from the graph?

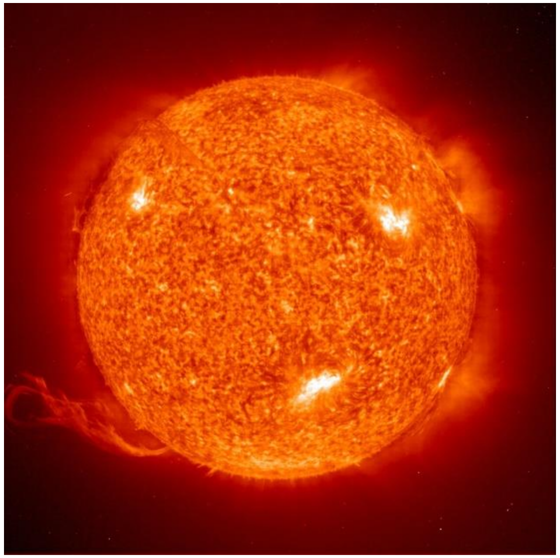


Fusion

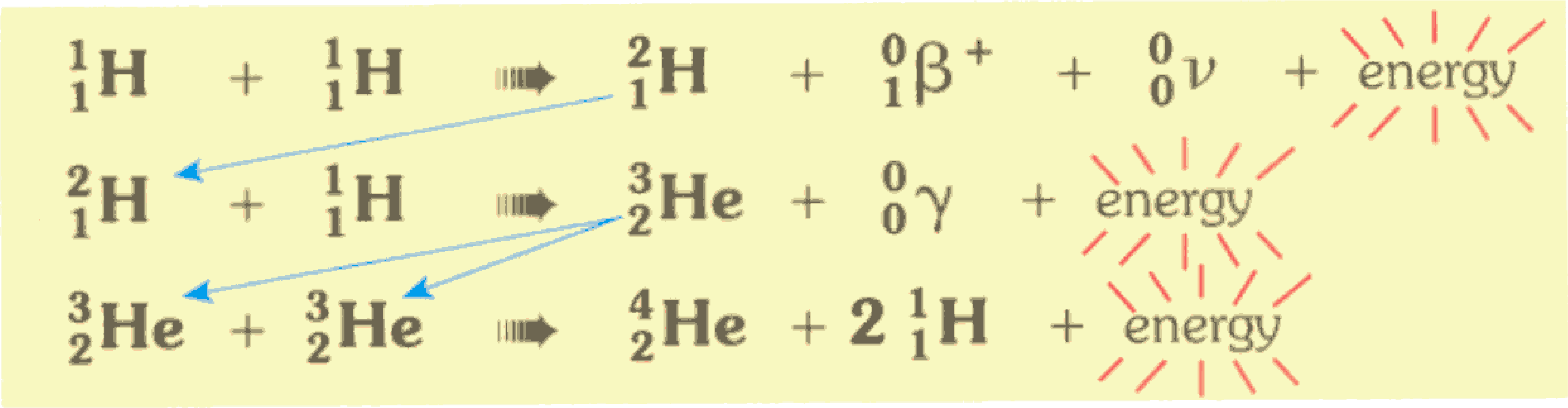
- The increases in binding energy per nucleon are much larger for fusion than for fission reactions, because the graph increases more steeply for light nuclei.
- So fusion gives out more energy **per nucleon** involved in the reaction than fission.



Fusion



- The stars are powered by fusion reactions.
- Each second, in our Sun, more than 560 million tonnes of hydrogen fuse together to make helium.
- One series of reactions for this is shown here:

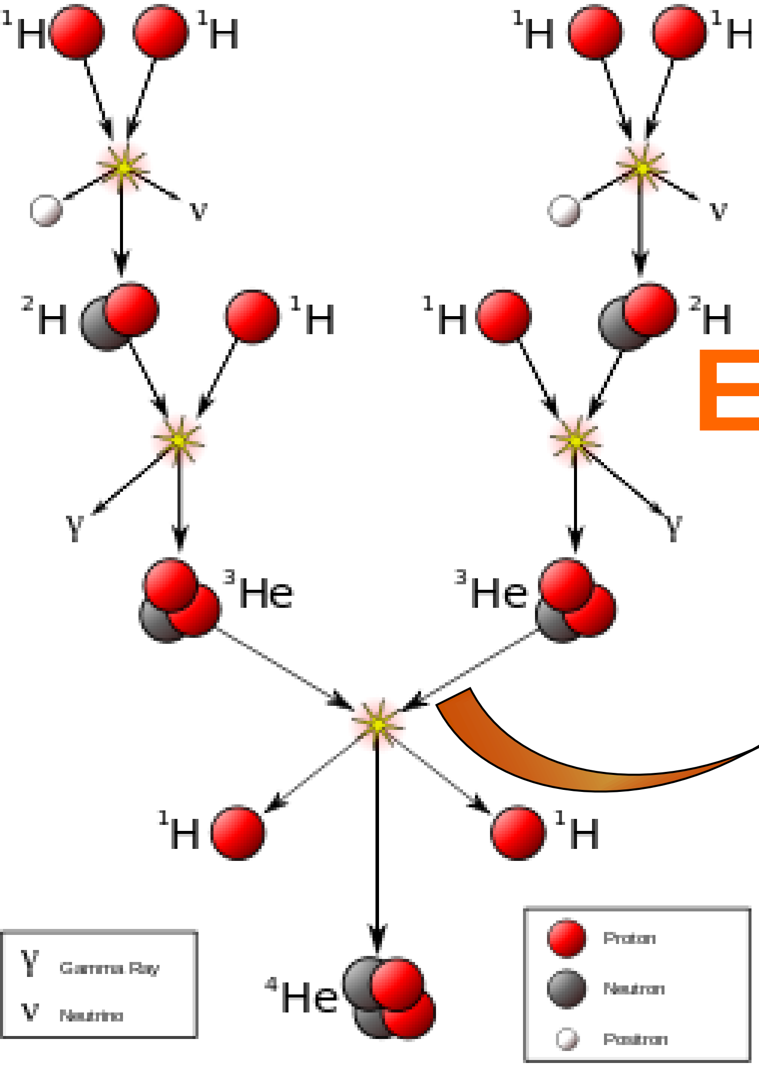


$$^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{1}\beta^{+} + {}^{0}_{0}\nu + \text{energy}$$

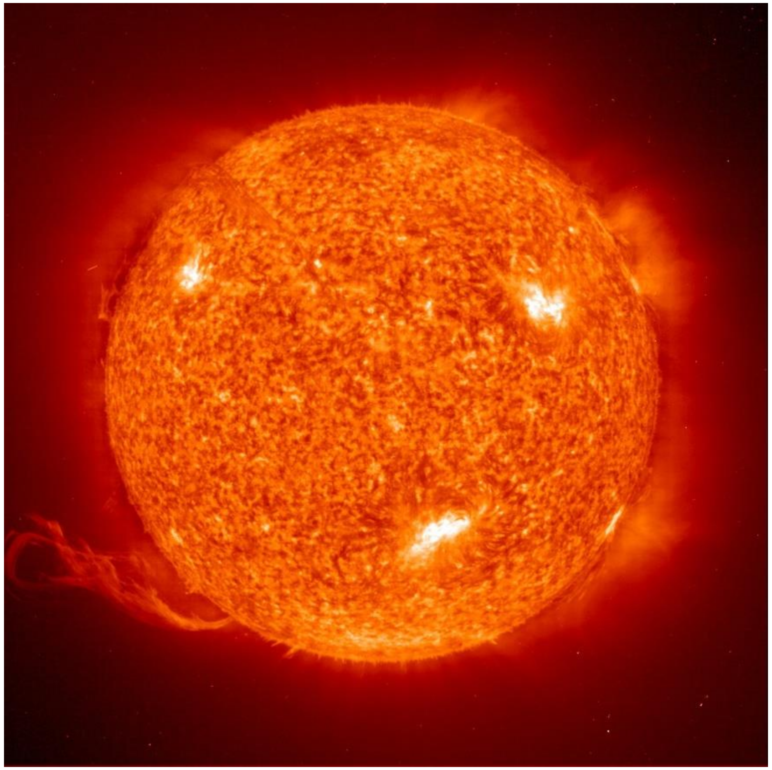
$$^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{0}\gamma + \text{energy}$$

$$^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H} + \text{energy}$$

Fusion



Energy



Fusion

- The energy released is radiated by the Sun at a rate of 3.90 x 10^{20} MW.
- This is the power output of a million million million large power stations!

- Not surprisingly scientists are keen to develop fusion as a source of power.
- One possible reaction is the fusion of deuterium and tritium.
- These are isotopes of hydrogen

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

Fusion

- Fusion has a number of advantages over fission:
  - greater power output per kilogram,
  - the raw materials are cheap and readily available,
  - no radioactive elements are produced directly,
  - irradiation by the neutrons leads to radioactivity in the reactor materials but these have relatively short half lives and only need to be stored safely for a short time.

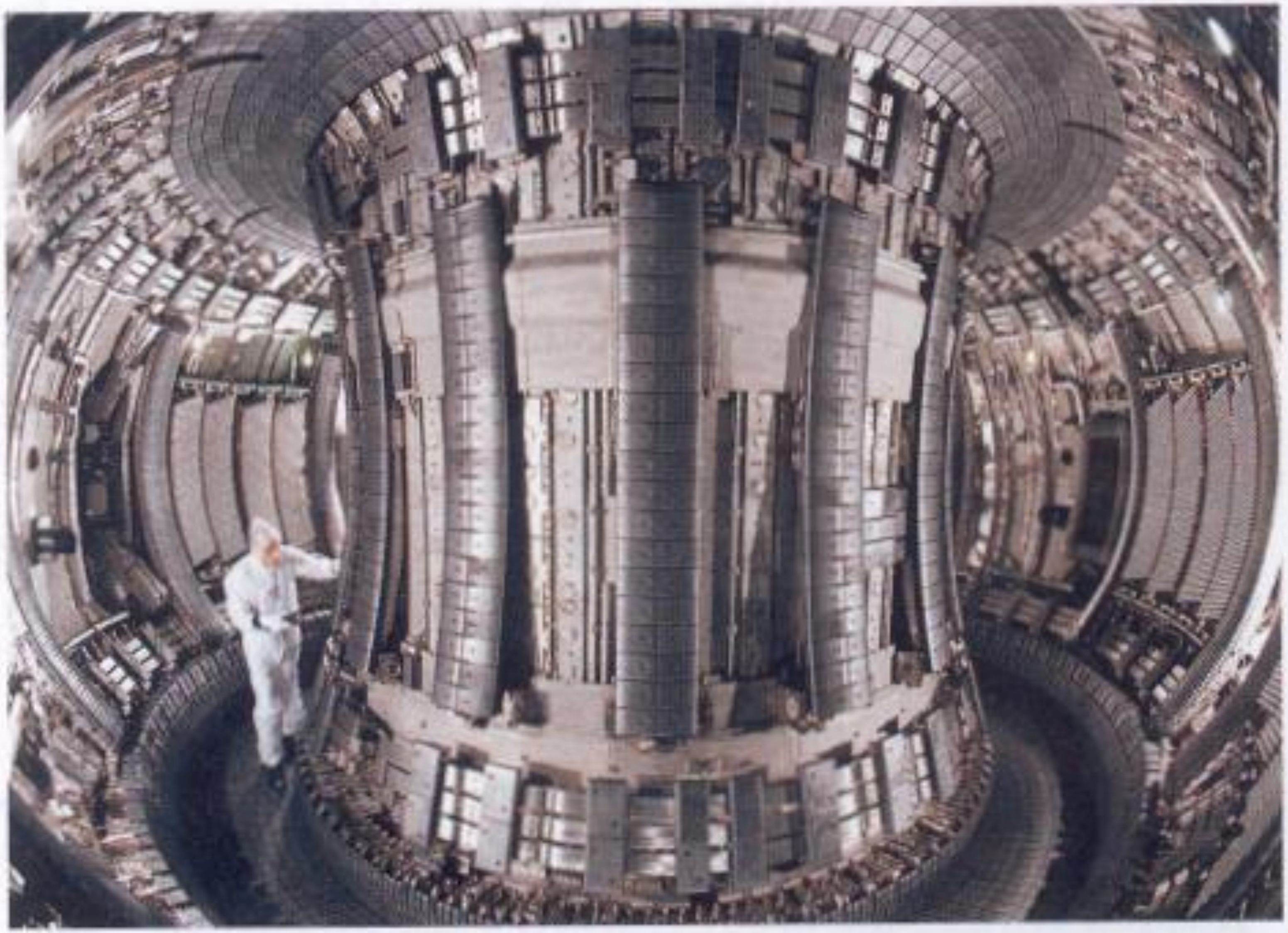
So why don't we use fusion in nuclear power stations?

Fusion on Earth

- The JET (Joint European Torus) project was set up to carry out research into fusion power.
- It has yet to generate a self-sustaining fusion reaction.
- The main problem is getting two nuclei close enough for long enough for them to fuse.
- The enormous temperatures and pressures in the Sun's core provide the right conditions.
- On Earth temperatures of over 100 million kelvin are needed.
- At this temperature all matter exists as an ionised gas or plasma.

Fusion on Earth

- Another problem is containment.
- What can you use to hold something this hot?
- JET uses magnetic fields in a doughnut shaped chamber called a torus to keep the plasma away from the container walls.
- Unfortunately generating high temperatures and strong magnetic fields uses up more energy than the fusion reaction produces!
- We are still some years off a fusion power station.



A scientist working inside JET's 6 m diameter torus