

**ADVANCED GCE UNIT
PHYSICS B (ADVANCING PHYSICS)**

Advances in Physics
INSERT

FRIDAY 26 JANUARY 2007

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Morning

Time: 1 hour 30 minutes



INSTRUCTIONS TO CANDIDATES

- This insert contains the article required to answer the questions in Section A.

This document consists of **8** printed pages.

Taming nuclear fusion

The energy crisis and the population explosion

5 The world's population has been growing exponentially for some time, and the rate of exponential growth suddenly increased significantly in the middle of the last century. Even if the annual energy consumption per capita – the total global energy consumption divided by the total population – does not increase from the current value of about 68 GJ per person per year, it is clear that fossil fuel resources, currently estimated at 4×10^{22} J, are going to run out.

10 Nuclear fusion has received much attention since the 1950s. It offers the prospect of using a raw material which is abundant here on Earth, produces no greenhouse gases and leaves much less radioactive waste than nuclear fission. Unfortunately, at any stage since fusion research started, it seems as if the final product has always needed another thirty years to bring it to fruition. However, with the promising results from the JET fusion experiments, real success may be in sight.

Sliding down the fusion hill

15 In 1929, using the famous $E = mc^2$ relationship, Robert Atkinson and Fritz Houtermans suggested that the Sun's energy output could be produced by the fusion of hydrogen nuclei. This can be explained in terms of binding energies, shown in Fig. 1.

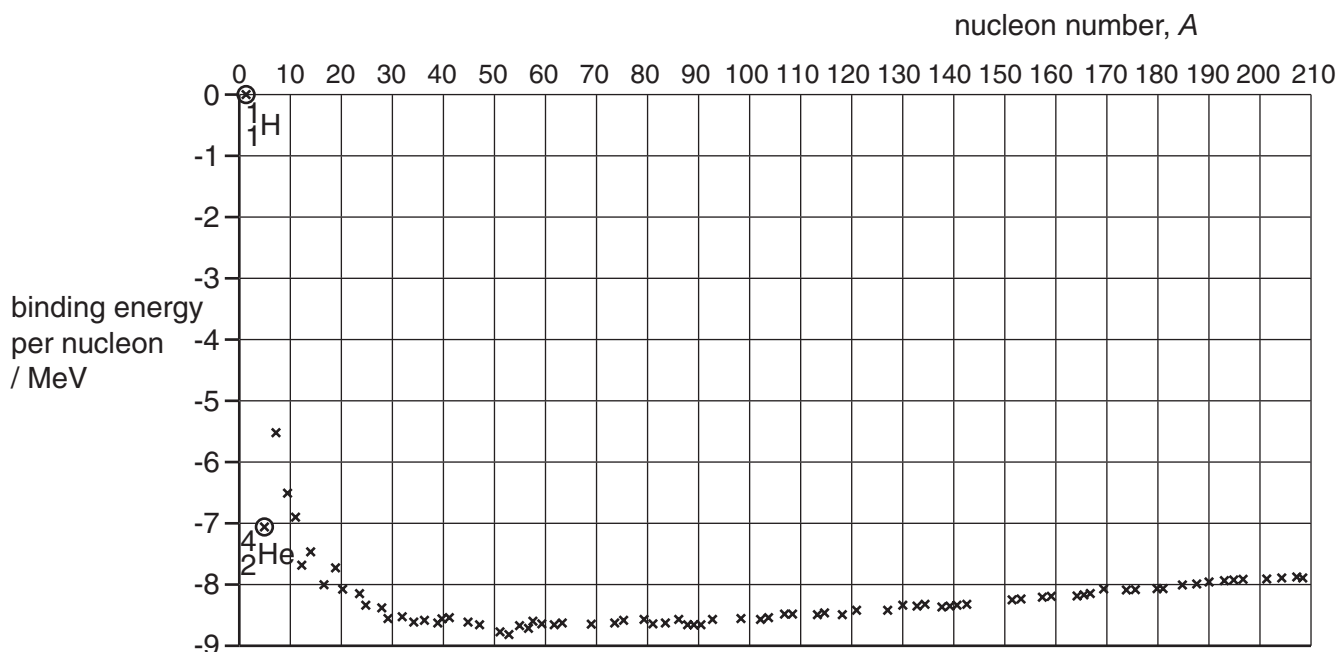
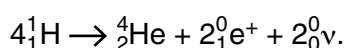


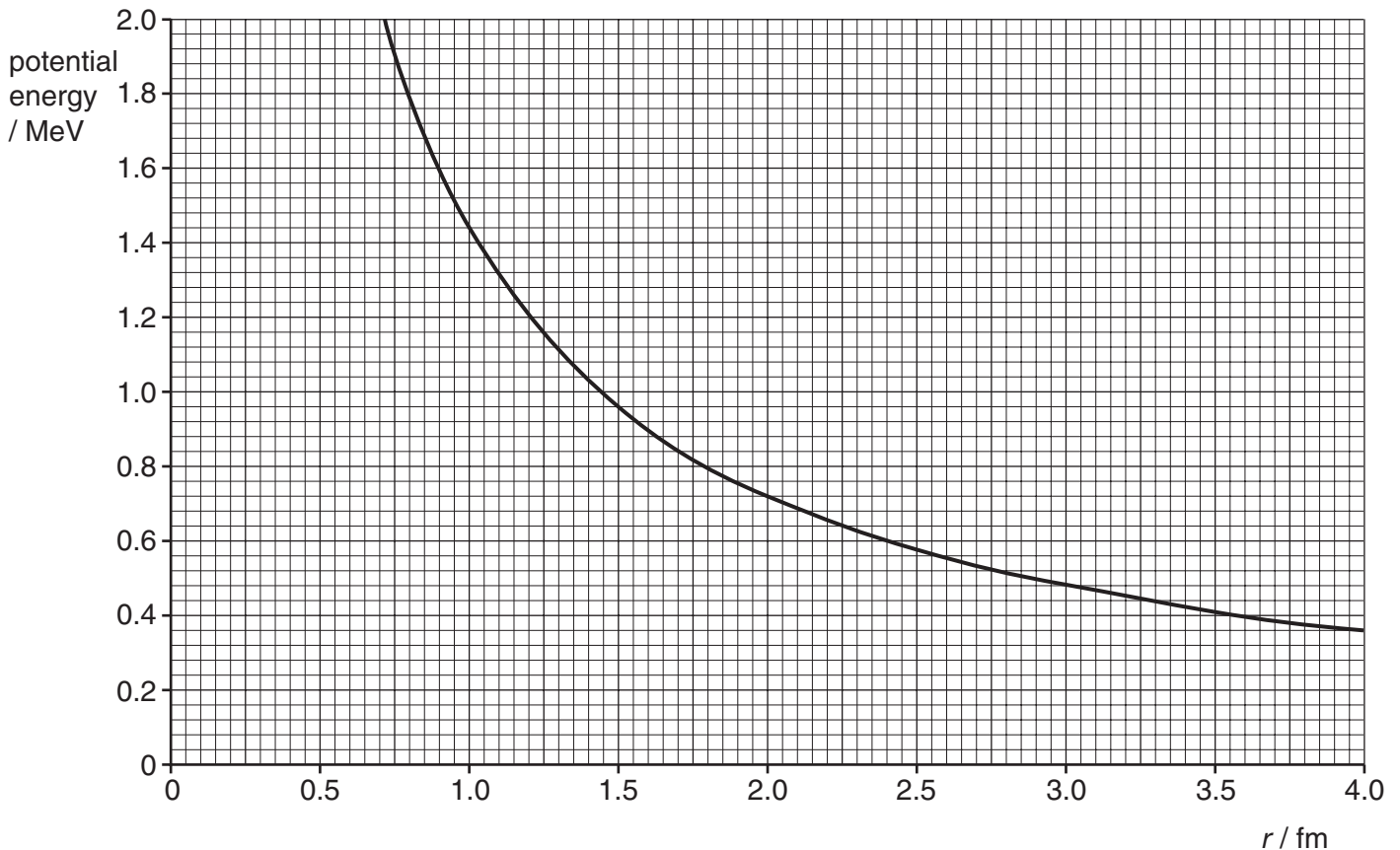
Fig. 1

20 The most tightly bound nucleus has the most negative binding energy per nucleon. This occurs where the nucleon number A is about 50. This corresponds to values typical of iron and its neighbours in the Periodic Table. For nucleon numbers up to 20 there is a sharp drop in binding energy per nucleon from hydrogen, with zero binding energy, through the next few elements. By analogy with gravitational potential energy, this steep region of the graph could be called the 'fusion hill'. There is a particularly big drop from hydrogen to helium, so significant amounts of energy are released by a series of nuclear reactions which turn protons into helium nuclei,

25 summarised by the equation



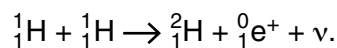
Unfortunately, you need to get protons very close together if nuclear fusion is to happen. This is because the strong nuclear force is a very short range force which becomes stronger than electrostatic forces of repulsion only for separations less than 1 fm (1×10^{-15} m). At this distance, the electrical potential energy of a pair of protons is considerable, as Fig. 2 shows.



The electrical potential energy of two extremely close protons

Fig. 2

The proportion of protons in the Sun's core at 15 million K with enough energy to approach this close is so tiny that fusion would be extremely unlikely to occur. However, quantum mechanics does allow a finite probability for protons of lower energy to get as close as this. There is a small probability that two protons, heading directly towards each other, can 'tunnel' into contact from a substantially larger distance. They then have a further small probability of converting into a deuteron through the reaction

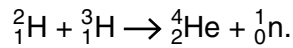


The combination of these two small probabilities and the enormous number of protons in the Sun means not only that fusion in the Sun can take place, but also that it has been proceeding at a steady rate for about 5 billion years, rather than happening within a very short time.

The Sun and the hydrogen bomb

Fusion in the Sun is slow, even though the Sun is very massive. To achieve fusion on Earth using more modest numbers of nuclei, it is essential that a more rapid process is used.

Different nuclear reactions have different threshold energies, and proton-proton fusion is not the easiest reaction to accomplish. Most attention in fusion research has focused on fusion between deuterium (hydrogen-2) and tritium (hydrogen-3) to form helium-4 and a neutron



To get deuterium and tritium to react, it is not only necessary to reach high temperatures and pressures, but also to sustain these for long enough for fusion to take place. The conditions that
 50 are needed were summed up by John Lawson in 1957 in what is now called the Lawson criterion: any fusion process needs to have a minimum value of the product of the number density (the number of nuclei per cubic metre) and the confinement time (the time for which the reactants are kept together). The numerical value of the product also depends on the temperature, but at a temperature of one hundred million K, the Lawson criterion for the deuterium-tritium reaction is

55 $(\text{number density}) \times (\text{confinement time}) > 10^{20} \text{ m}^{-3} \text{ s}.$

The only method that has successfully tapped fusion energy on Earth is the hydrogen bomb, developed by Edward Teller in the USA and Andrei Sakharov in the former Soviet Union. The high temperature, number density and confinement time were provided by a nuclear fission bomb, of the type which destroyed Hiroshima. The deuterium-tritium reactants were compressed by
 60 implosion from the fission bomb, keeping the reactants together until fusion occurred.

Research into harnessing this reaction to generate electricity has had to tackle the triple problem of the Lawson Criterion: the temperature must be very high, the deuterium and tritium nuclei must be packed closely together, and this arrangement must be maintained for long enough for the process to take place. The most promising research involves heating the deuterium-tritium
 65 mixture to produce a plasma of nuclei and electrons, and then compressing the plasma in the centre of a large torus (a doughnut shape) as shown in Fig. 3.

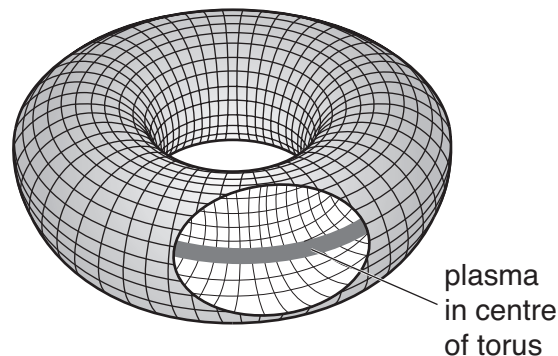


Fig. 3. a torus, cut away to show the central tube of plasma

Tokamaks

Tokamaks, from the Russian for 'toroidal magnetic chamber', were first developed by Andrei Sakharov, and remain the most promising design. This is the design that was used in the
 70 successful **JET** (Joint European Torus) experiment at Culham, near Oxford.

The entire torus, about 100m^3 in volume, contains only about one-tenth of a gram of plasma in the experiments at JET, and so would be only at a few times atmospheric pressure, even at the working temperature of 100 million K. Just as with a hot gas, random movement will cause it to expand into the available space, and it must be squeezed into a tiny region, and also heated. To
 75 compress this plasma until fusion occurs, and to prevent it hitting the relatively cool walls of the torus, it is essential to compress it into the centre of the torus, as shown in Fig. 3.

The plasma is kept in the centre of the torus by a combination of magnetic fields. This is no easy task. It has been compared with trying to make a container for jelly from rubber bands. The entire structure is a gigantic transformer built around a massive iron core, with the plasma ions in the
 80 centre of the torus acting as the charge carriers in a single-turn secondary coil, as shown in Fig. 4.

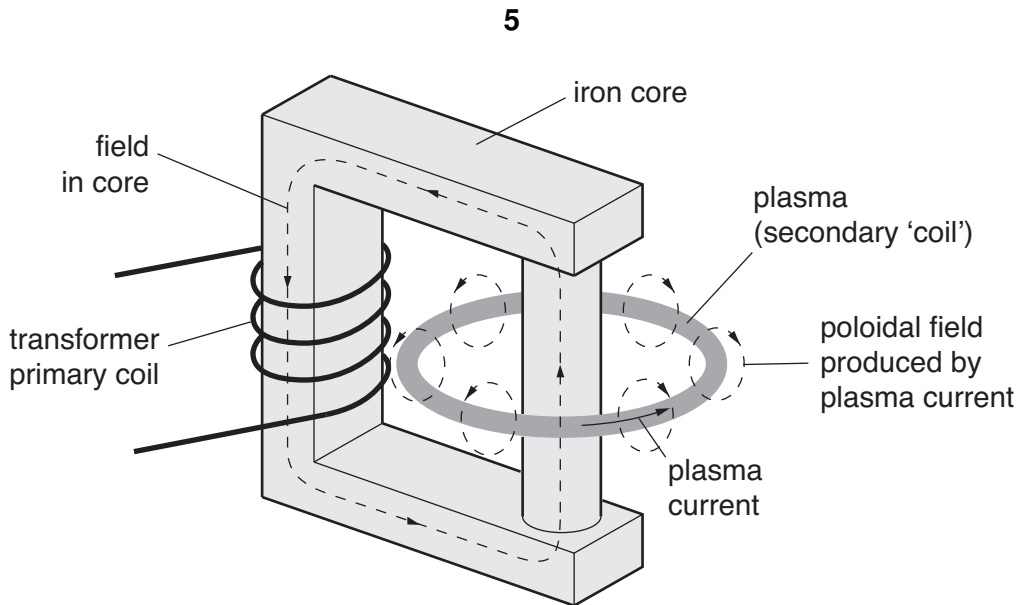


Fig. 4

The moving ions generate magnetic flux, in a pattern described as poloidal, which is shown in Fig. 4. This poloidal field compresses or 'pinches' the ions into the centre of the torus in the same way as two conductors, carrying electric current in the same direction, experience attractive forces (Fig 5).

85



Currents in the same direction attract one another

Fig. 5

Although the poloidal field compresses the plasma, the arrangement is not stable. To increase stability, toroidal field coils are added. These toroidal coils produce flux through the torus in the same direction as the plasma current, as shown in Fig. 6.

The combination of the toroidal and poloidal field give rise to a field pattern in the shape of a helix, like the thread of a screw, as shown in Fig. 7. The Lorentz force ($F = qvB$) forces the moving particles to spiral around these helical field lines.

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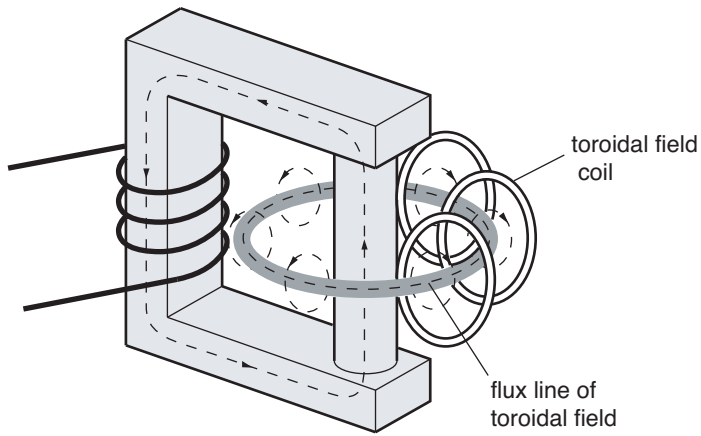


Fig. 6

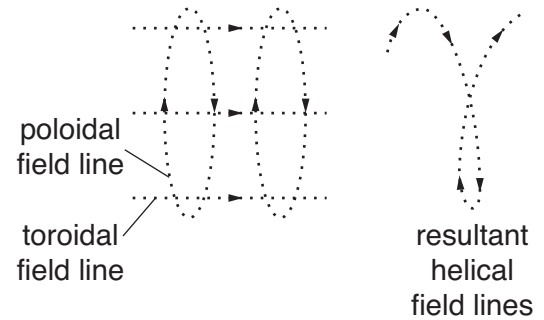


Fig. 7

As the Tokamak is a transformer, the primary current cannot be constant. However, to get the positive ions continuing in the direction shown in Fig. 4, there should not be an alternating flux in the core. This means that JET and other tokamaks operate in pulses.

95 Reaching 100 000 000 K

In JET, the plasma is heated in three ways.

The first method takes advantage of the high electric current formed by the plasma, which heats the plasma just like the current in a wire heats the wire. A relatively low induced voltage, of the order of one volt, produces a high electric current, about 3 million amps, which heats the plasma at a rate of a few megawatts.

The second method uses electromagnetic radiation. This radiation can be absorbed by the moving electrons and positive ions in the plasma, which have resonant frequencies in the radio frequency range.

The third method is to use neutral beam heating. A beam of fast-moving deuterium ${}^2_1\text{H}$ atoms is injected into the plasma. The atoms give up their energy as they collide with the background plasma ions. It is not possible to accelerate neutral particles to the speeds needed to raise the temperature of the plasma to the values required. ${}^2_1\text{H}^+$ ions are produced and accelerated to about 60 keV. An ion beam cannot be injected directly into the plasma, as strong magnetic fields would deflect the ions from their paths. The ion beam, travelling at high speed, is neutralised before entering the plasma. Should some of these neutral atoms, on collision with ions in the plasma, become ionised again, then they will merely add to the plasma rather than contaminating it.

After JET

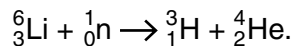
JET is the only operational machine to produce fusion from D-T (deuterium-tritium) reactions. Such fusion reactions have been maintained in JET for around five seconds. In 1997 JET produced a peak of 16.1 MW fusion power, with average fusion power of over 10 MW sustained for over 0.5 seconds.

These positive results show that fusion power is a real possibility in the not-too-distant future. The next step is a larger tokamak called ITER (International Thermonuclear Experimental Reactor). This has been designed and should be built in the next decade. It should demonstrate much more powerful fusion reactions for 5–10 minutes and give clear indications of the way that commercial fusion reactors could be constructed.

The perfect solution to the energy problem?

To date, most criticism of fusion research has concentrated on the probability of success. Now that eventual success seems more likely, we seem to be provided with an ideal form of power production, free from greenhouse gases. However, various pressure groups have voiced their concerns about it.

One area of concern is the use of tritium as a reactant. As a radioactive gas, any leakage could be hazardous to people nearby. Of more concern is the large number of neutrons produced in the deuterium-tritium reaction. These neutrons are essential, because the tritium needed in the reaction has a short half-life and does not occur naturally. Tritium has to be produced, and the best way to do this is to absorb the neutrons in lithium through the reaction



The flow of neutrons from the reactor is intense, much larger than from a fission reactor. This is because the energy output per kilogram of reactants in fusion is about five times greater than that for fission, but the neutron output per kilogram is about fifty times greater. This means that a fusion reactor would generate ten times as many neutrons as a fission reactor of the same power output. As neutrons have a high quality factor of 10 – they give 10 times the equivalent radiation dose of beta particles or gamma rays – they are extremely hazardous. Furthermore, bombarding the construction materials of the project with neutrons will make them radioactive, so it is not true that nuclear fusion produces no radioactive waste. The construction materials need to be chosen to ensure that radioactive isotopes produced by neutron absorption have relatively short half-lives, but this may require a compromise between radioactive and mechanical properties.

Both of these problems – the possibility of tritium leaks, and the large number of neutrons produced – could be solved by changing the reaction to deuterium-deuterium fusion. This also removes the need for lithium to produce the tritium. Unfortunately, the reaction ${}^2_1\text{H} + {}^2_1\text{H} \rightarrow {}^4_2\text{He}$ has a higher energy threshold than deuterium-tritium fusion, so it is necessary to get successful fusion with the easier reaction first. If deuterium-deuterium fusion could be achieved, then we might have an ideal method of generating power – provided that no unforeseen problems arise.

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