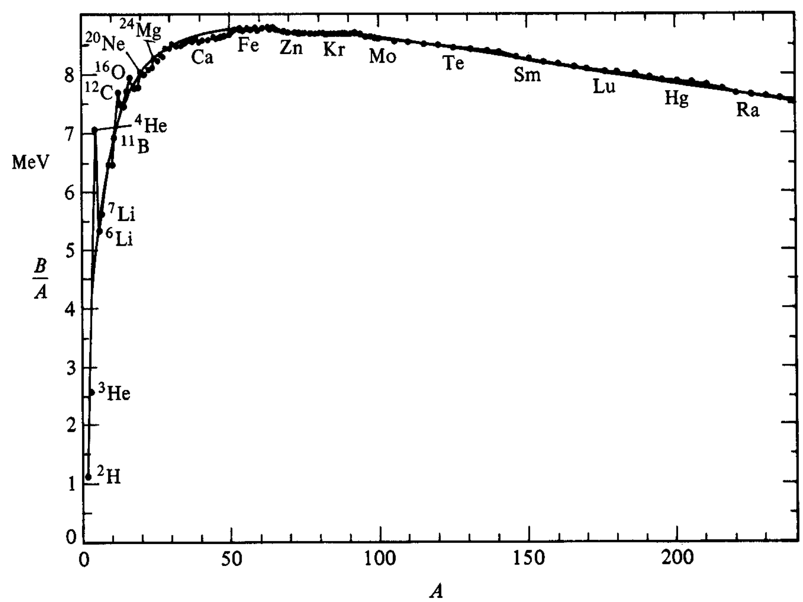
Nuclear and Particle Physics - Lecture 25
Nuclear Fusion

1 Introduction

We have seen from the binding energy per nucleon curve that nuclei at A above ${}^{56}_{26}\mathrm{Fe}$ can split and release energy e.g. through alpha decay or more generally through fission. However, it is also the case that nuclei below the maximum can combine and release energy, a process called fusion.

2 Fusion reactions

The binding energy per nucleon curve is shown below, showing all nuclei below $A \approx 56$ are lower than the maximum.



Therefore, energy will be released through fusion. The generic fusion process is

$$ {}^{A_X}_{Z_X}X + {}^{A_Y}_{Z_Y}Y \rightarrow {}^{A_X+A_Y}_{Z_X+Z_Y}F $$

To extract energy then the final nucleus has to have less total mass than the initial two nuclei. This means F must actually be in an excited state. The released energy will therefore come out when it decays. For example, it can gamma decay to release the extra energy

$$ {}^{A_X}_{Z_X}X + {}^{A_Y}_{Z_Y}Y \rightarrow {}^{A_X+A_Y}_{Z_X+Z_Y}F^* \rightarrow {}^{A_X+A_Y}_{Z_X+Z_Y}F + \gamma $$

We often don't need to consider F^* explicitly and indeed, often no coherent nucleus can be considered to be made.

The simplest case of such a reaction is the creation of a deuteron ($d = {}^2_1\mathrm{H}$) from a proton and neutron

$$ p + n \rightarrow d + \gamma $$

where, for $E_p \approx E_n \approx 0$, the emitted photon energy is $E_\gamma = Q = (m_p + m_n - m_d)c^2 = 2.2$ MeV. This is clearly an electromagnetic reaction and so in general does not have such a large cross section as a strong reaction.

Other possibilities for the energy to be released are to emit protons or neutrons in a strong interaction, e.g. An example of this is the so-called "D-T" reaction of a deuteron and tritium ($t = {}^3_1\mathrm{H}$) to make helium and a neutron

$$d + t \rightarrow {}^4_2\mathrm{He} + n$$

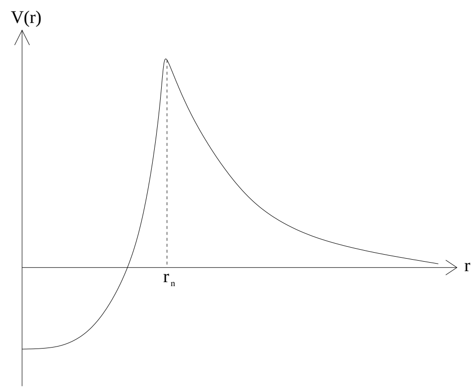
It is also possible to emit weakly interacting particles; the most important reaction of this type (as we will see in the next lecture) is

$$p + p \rightarrow d + e^+ + \nu_e$$

but, being weak, the cross section is very small compared with the previous reactions.

3 Coulomb barrier

We already saw the deuteron is the only bound state of two nucleons. In particular, there is no nn bound state as the equivalent wavefunctions do not satisfy the Pauli exclusion principle. It turns out that there are no bound states made purely of neutrons even for $A > 2$ so in fusion, we will always consider combining nuclei containing some protons. This means they have positive charge and so in almost all cases there will be a Coulomb repulsive force to be overcome before the nuclei can be brought close enough together that the attractive nuclear force can take effect. This is effectively the same issue as for fission, but in reverse.



The barrier can in principle be overcome in two ways, either by having high enough energy for the two incoming particles or by tunnelling. However, the latter gives such a small cross section that it is not done in practice. The barrier height is of order

$$\frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 r_0 A^{1/3}} = a_c \frac{Z_1 Z_2}{A^{1/3}} = 0.72 \text{ MeV } \frac{Z_1 Z_2}{A^{1/3}}$$

Clearly, we have accelerators which can speed up charged particles up to TeV, i.e. well beyond the Coloumb barrier height, so it is straightforward to do experiments on these reactions. However, for practical applications, this is not a feasible way to go and instead very high temperatures are used. This gives the nuclei a range of kinetic energies as per the Maxwell-Boltzman distribution so there are some at the higher end with enough energy to overcome the barrier. For a barrier of order 1 MeV, the temperature corresponding to this energy is $\sim 10^{10}$ K. Hence, even allowing a mean well below this and using the high energy tail still means extremely high temperatures are needed. Any matter is always a plasma at these temperatures as it is well above any atomic binding energies. Often the plasma is also compressed to very high pressures to increase the reaction rate. The technique of using such temperatures and pressures to overcome the Coulomb barrier is called thermonuclear fusion.

4 Helium

Let's look at the binding energy per nucleon plot again in more detail. A clear feature is the large value for $^4_2$He, particularly compared with the values just above it. $^4_2$He is doubly magic and stands out as being much more strongly bound, with a value of $B_E/A \approx 7.1$ MeV, than its neighbours. It is, in fact, more strongly bound than all the higher nuclei until $^{12}_6$C. Indeed there are no $A = 5$ or $A = 8$ stable nuclei because $^4_2$He is so stable. $^5_2$He and $^5_3$Li very rapidly decay by nucleon emission

$$^5_2\mathrm{He} \to\ ^4_2\mathrm{He} + n, \qquad ^5_3\mathrm{Li} \to\ ^4_2\mathrm{He} + p$$

with lifetimes of order 10^{-21} s, while $^8_4$Be spontaneously fissions to two $^4_2$He nuclei with a lifetime of order 10^{-16} s. If $^4_2$He had a lower binding energy, these reactions would not be energetically possible.

The maximum value of the binding energy per nucleon is around 8.7 MeV for nuclei close to iron. If we create $^4_2$He in fusion as a first step to building up to iron, we already get over 80% of the maximum possible energy release. Also, the next step would require combining $^4_2$He nuclei into the next nucleus with a higher binding energy, which is $^{12}_6$C. This requires three $^4_2$He nuclei and is very hard to do; reacting three nuclei at once is almost impossible and we have already seen the most obvious intermediate nucleus, $^8_4$Be, decays very rapidly. Even if these problems can be overcome, this reaction only yields another 0.6 MeV per nucleon.

Hence, all practical applications of fusion concentrate on combining hydrogen isotopes into $^4_2$He. This also has the advantages that the Coulomb barriers are smaller for these nuclei and that hydrogen and deuterium are readily available. Deuterium occurs naturally in 0.015% of water which is not a large fraction but water is clearly plentiful so the supply is enormous. Also, unlike uranium, deuterium is relatively easy to separate from hydrogen as the masses differ by a factor of two, not 1%. The most obvious reaction to make helium would be using two deuterons

$$d + d \to\ ^4_2\mathrm{He} + \gamma, \qquad Q = 23.8\ \mathrm{MeV}$$

but although the energy release is large, this is an EM reaction with a correspondingly low cross section. The more common reactions are

$$d + d \to\ ^3_2\mathrm{He} + n, \qquad Q = 3.3\ \mathrm{MeV}$$

and

$$d + d \to\ ^3_1\mathrm{H} + p, \qquad Q = 4.0\ \mathrm{MeV}$$

This final reaction produces tritium, which is the third isotope of hydrogen. Tritium beta decays to $^3_2$He with a lifetime of 17.7 years so none is found naturally and it has to be manufactured. This can be done from the above or by using lithium reactions

$$^6_3\mathrm{Li} + n \to\ ^4_2\mathrm{He} + t, \qquad ^7_3\mathrm{Li} + n \to\ ^4_2\mathrm{He} + t + n$$

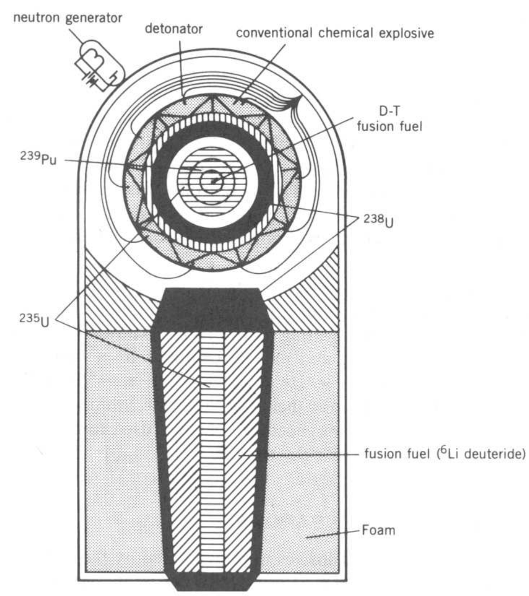
As previously mentioned, tritium also reacts with a deuteron (the D-T reaction) to produce helium through a strong interaction

$$d + t \to\ ^4_2\mathrm{He} + n, \qquad Q = 17.6\ \mathrm{MeV}$$

This releases a lot of energy as the helium is strongly bound and happens to have a large cross section, making it good for practical applications. The main disadvantage is that tritium is needed, which firstly must be manufactured and secondly must be replenished as it decays. Also, the neutron produced takes more than half the energy and extracting that for power uses is not straightforward.

5 The hydrogen bomb

The simplest conceptual use of fusion reactions is in the hydrogen bomb, called the "H bomb" to distinguish it from the fission "A bomb". A diagram of a D-T reacting H bomb is shown below

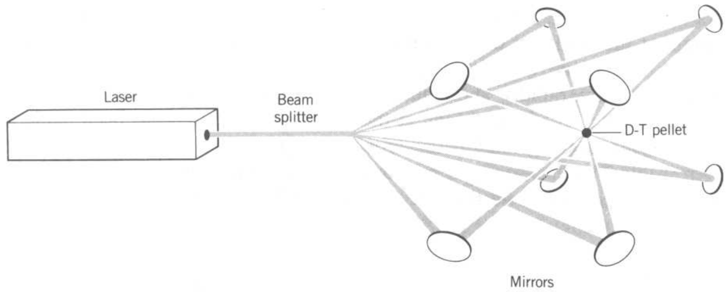


To start the reaction, the temperature must be made high enough. This is done using a fission A bomb (which itself is started from conventional explosives). This generates enough heat and pressure (from the vapourised material surrounding the fusion material) for the fusion reaction to proceed. The fusion reaction clearly generates heat itself and so is self-sustaining for the short period until the material is blown apart. The diagram shows the main part of the fusion fuel in this case is lithium deuteride, ${}^{6}_{3}\mathrm{LiD}$, where D is deuterium, which is chemically similar to the salt lithium hydride, but with deuterium rather than hydrogen. The neutrons emitted from the fission reaction actually convert the lithium to tritium as shown above as part of the explosion, hence providing the fuel for the fusion reaction and reducing the need for tritium manufacture beforehand.

H bombs can be made much more powerful than fission bombs due to the more efficient use of the fuel. Yields of around 1000 times those obtained from fission bombs can be produced from a bomb which is small and light enough to easily be carried in an aeroplane.

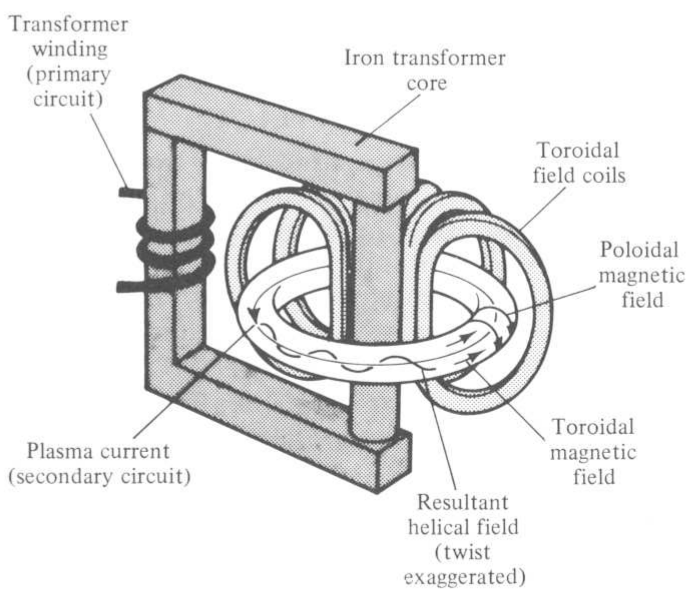
6 Fusion reactors

Again, like fission, there is a more peaceful application of fusion as a power source for energy generators. However, unlike for fission, this has never been achieved in a sustainable, power-neutral, efficient way. The benefits would be large, as the deuterium fuel is plentiful and there are no radioactive daughter products, unlike for fission, which result in long-lasting radiactive waste. The main challenges are not in understanding the nuclear physics involved, but in the technology of how to produce the very high temperatures and pressures needed. This is obviously a very active area of research. One approach is to use lasers to rapidly implode capsules of D-T mixture using the photon pressure from the intense lasers.



The lasers have to be extremely fast and powerful, which themselves require significant power input, so achieving a net power output is difficult.

An alternative approach is to try to store the plasma at the temperature and pressure required while the reaction proceeds. Since the plasma would vapourise any solid material it touched, then a magnetic containment system is used, where magnetic fields are shaped such that the charged plasma particles spiral round in the field and cannot emerge and touch the vessel walls.



It is assumed that any future reactor will be likely to use tritium and hence it needs to be able to manufacture this in such a way as to replenish its fuel supply. By surrounding the reactor with ${}^{7}_{3}\mathrm{Li}$, the neutron capture reaction mentioned previously can be used to produce tritium from the emitted neutrons of the D-T reaction. Since a further neutron is re-emitted in the lithium reaction, then it is feasible to believe enough neutrons are available to make the tritium at a rate at least equal to the rate it is used as fuel.