

Nuclear Physics Section 8 - Fusion

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Finally, we study the principles of nuclear fusion, and touch upon some modern developments.

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1 Principles of Nuclear Fusion

In nuclear fusion, light nuclei (to the left of the peak on the B/A against A plot) combine to form heavier nuclei, resulting in a positive Q-Value and hence a release of energy. Once again, we can explain why fusion does not happen all the time by invoking the Coulomb barrier. This time, of course, we want to bring positively charged nuclei together, and so the considerations are fairly straightforward. In order to bring two nuclei together so that they are touching (and hence so that the strong nuclear force comes into play), we must overcome a Coulomb potential of

$$V = k \frac{q_1 q_2}{r} = k \frac{Z_1 e Z_2 e}{r}, \quad (1)$$

where Z_1 and Z_2 are the atomic numbers of the two nuclei, and the separation, r , is equal to the sum of their radii. For example, to fuse two deuterium nuclei (deuterons) to form He-4, we would have

$$V = k \frac{(e^2)}{2 \times r_0 (2)^{1/3}} \approx 0.47 \text{ MeV} \quad (2)$$

From $E = k_B T$ this is equivalent to a temperature of over 10^{10} K! In practice, quite such high temperatures are not needed. Firstly, while a certain temperature gives an average kinetic energy of $k_B T$, there is a distribution of energies, and so some nuclei will have more. Secondly, quantum tunnelling allows for a non-zero probability of fusion even if the kinetic energy is below the Coulomb potential. Nevertheless, extremely high temperatures are still required (100s of millions of K for a viable fusion reactor); such a temperature is difficult to create, but is present in the core of stars due to the huge compressive gravitational forces.

2 Stellar fusion

In nature, fusion is much more important than fission, since it is the process that drives energy generation in stars. Those of you taking astrophysics modules will learn about this in far more detail there, but for this module we will look at the Hydrogen burning process, the dominant process in stars that fuses four protons to form a Helium-4 nucleus (also involving some Beta Decays). The first step is the fusion of two protons:



releasing 0.42 MeV, or a total of 1.442 MeV after the positron annihilates with an electron. This reaction is extremely rare, occurring on the order of once every few billion years (depending on the mass of the star). This limits the rate of fusion in stars. The deuteron formed in the first step then fuses with another proton:



releasing a further 4.493 MeV and a gamma ray. There are several possible routes to form He-4, including the most common (84%) fusion of two He-3 nuclei:



which releases 12.859 MeV.

3 Power from fusion

It has long been a goal to obtain useful amounts of energy from nuclear fusion here on Earth. This has several potential benefits over fission:

- The materials needed for fusion (light nuclei such as the deuteron) are more readily available, or can be easily created, compared with fissile materials such as U-235.
- A fusion reactor would produce much less radioactive waste.

Although the energy released in a fusion event is generally less than a fission event (i.e. the Q-Value is smaller), the energy released per unit mass of the reactants is larger. Therefore power from fusion is said to be more energy dense.

There is no question that fusion power is possible in principle, as we know it occurs in stars and fusion weapons, but it remains to be seen if the conditions for fusion can be generated on Earth in such a way as to generate stable and safe power at an acceptable cost. It turns out to be rather difficult to create the conditions for fusion without the gravitational field of a star to create the required pressure and hence temperature. (The idea of **cold fusion**, making fusion happen without these high temperature, is of course, complete nonsense.)

There have been several fusion reactions proposed as a power source. In order for the reaction to be sufficiently likely to occur it must, among other things:

- Only involve two reactants (probability for reactions between 3+ nuclei are very small).
- Produce two products.
- Conserve protons and neutrons (conversion is possible via the Weak Force, but too unlikely).

A particularly strong candidate is **deuterium-tritium (D+T) fusion**:



which releases 17.6 MeV. Notice that this does not produce radioactive products intrinsically (unlike fission), but the free neutron may go on to be absorbed by other materials, activating them. Deuterium is readily obtained from sea-water, while tritium can be produced by bombarding lithium with neutrons. This could be done using the neutrons created in the D-T fusion, known as **tritium breeding**.

To create the conditions for fusion, the reactants must be pushed together with sufficient energy to overcome the Coulomb barrier. There are two approaches to this which have been investigated in detail:

- Magnetic Confinement - The reactant mixture, once heated, becomes a plasma (i.e electrons are stripped from the nuclei to leave charged ions) and so can be directed using magnetic fields in a device such as a Tokamak.
- Inertial Confinement - The reactants are forced together using momentum imparted from a high energy laser beam.

In practice, the engineering challenges are immense, and no-one has yet demonstrated anything close

to a viable fusion reactor. On 5th December 2022, a major step forward was made when the United States Department of Energy managed to achieve 3.25 MJ of energy generation from only 2.05 MJ of laser energy used to inject energy to the target, resulting in 1.15 MJ of fusion energy output. However, this ignores the huge amount of energy required to run the laser, i.e. there was no viable way of generating power. Several private sector companies have attracted large amounts of investor funding in recent years, but whether this means that we are on the cusp of a new source of clean energy, or simply living through the hype before the next ‘fusion winter’ remains to be seen.