Fusion Reactions

Introduction

Fission, as we saw in the earlier lecture notes, is the splitting of one nucleus to form at least two smaller pieces. It proceeds because there is a loss of mass, and so a production of energy. In principle any heavy nucleus can be split, although some isotopes are better then others. There is however a lower limit to the mass of the nucleus for which fission reactions are possible. The diagram to the right is the same one that appeared in the lecture notes on atomic structure. It plots the binding energy per nucleon as a function of the mass number. This curve peaks at the location of iron, specifically the isotope ^{56}Fe.

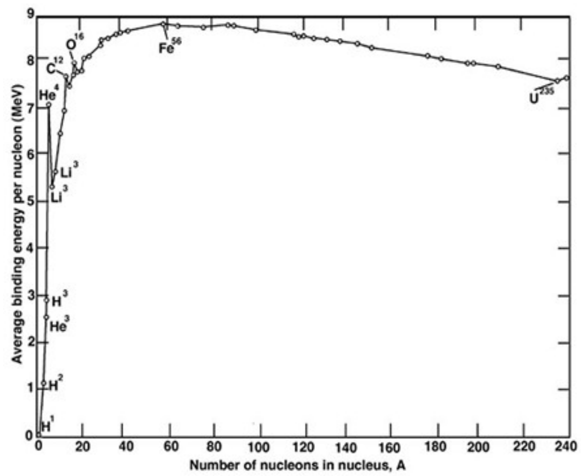

Fig 1: Binding energy per nucleon as a function of the number of nucleons

For isotopes lighter than ^{56}Fe fission would require the input of energy and the production of mass, which the exact opposite of the condition for a nuclear reaction to fuel the production of energy. For these light nuclei energy is produced (and mass destroyed) only if light nuclei are combined to produce a heavier nucleus. This is the nuclear reaction known as fusion.

An example of a fusion reaction

Starting with the lightest possible nucleus, that of the hydrogen atom, with only a single proton in its nucleus, it might at first be thought that a heavier nucleus would be produced consisting of two protons, that is $^{2}_{2}$He. However, the requirement to conserve momentum in a collision strongly discriminates against producing only a single particle. It is much more likely that two (or more) particles are produced. Because of the requirement to conserve momentum the fusion of two hydrogen nuclei produces a heavier nucleus, that of deuterium with both a proton and a neutron

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + ^{0}_{1}e^{+}$$

Note that in that reaction we have changed the nucleons. We started with two protons, but one of those protons has been changed into a neutron and a positron. The neutron has joined with the other proton to form the deuterium nucleus, and the positron is the second particle to be produced.

Energy production in fusion reactions

As was the case with fission reactions, fusion reactions produce energy only because the mass decreases as a result of the reaction. The calculation of the energy produced is identical. For the example above, the fusion of two protons

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + ^{0}_{1}e^{+}$$

the masses are given in the table to the right. The total mass of the reacting particles (2 protons) is 2.01455276 amu. After the reaction the product particles have a total mass of 2.0140979 amu. The is therefore a mass loss of 0.000454 amu, and an energy gain of 0. 000454 * 931.4 = 0.42 MeV.

Particle	**Mass (amu)**
Proton ($^{1}_{1}H$)	1.007276
Deuteron ($^{2}_{1}H$)	2.0136
Positron ($^{0}_{1}e^{+}$)	0.0005

Remember that this reaction is only one possible reaction out of many. There are dozens of possible product combinations, and for each one the energy released is calculated in the same way as for the one above.

Try one yourself

Another possible fusion reaction is

$$^{3}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{1}H + ^{1}_{1}H$$

In this reaction, how much energy is released? (Answer 12.9 MeV)

The problem in producing fusion reactions

The big problem in producing fusion is the need to bring two nuclei together. They are both positively charged, and so experience a mutual force of repulsion which gets stronger as they get closer together. Bearing in mind that we need to bring together to a distance comparable to their individual sizes (of the order of 10^{-15} m), this force of repulsion will become very strong long before the two nuclei approach to within this distance, and they fly apart again.

Fusion reactions in stars

For many years the fuel source for the Sun was a mystery. It has long been known that the energy output of the Sun is very high, about 4 x 10^{26} W. if we assume that this energy comes from the chemical burning of hydrogen (the main constituent of all stars), with an energy release of about 4 x 10^{-19} J (a few electron-volts) per reaction, then it is a simply calculation to calculate how many hydrogen atoms are used per second

$$\frac{\text{atoms}}{\text{second}}=\frac{\text{energy per second}}{\text{energy per atom}}=\frac{4\text{ x }10^{26}}{4\text{ x }10^{-19}}=10^{45}\text{ atoms per second}$$

That in turn tells us the mass loss per second, given that the mass of a hydrogen atom is about 1.67 x 10^{-27} kg

$$\frac{\text{mass}}{\text{second}}=\frac{\text{atoms}}{\text{second}}*\frac{\text{mass}}{\text{atom}}=1\text{ x }10^{45}*1.67\text{ x }10^{-27}=1.67\text{ x }10^{18}\text{ kg per second}$$

It has also been known for a long time that the mass of the Sun is about 2 x 10^{30} kg. At a rate of 1.67 x 10^{18} kg/s the Sun would exhaust its supply of hydrogen in about

$$\text{time}=\frac{\text{total mass}}{\text{mass loss rate}}=\frac{4\text{ x }10^{30}\text{ kg}}{1.67\text{ x }10^{18}\text{ kg/s}}=2.4\text{ x }10^{12}\text{ s}$$

which is only a few thousand years. Since the Sun is know to be much older than this (about 5 billion years) the initial assumption that the energy comes from the chemical burning of hydrogen has to be false. This problem wasn't solved until the discovery of the fusion of hydrogen onto helium. Fusion has the advantage that instead of producing just a few eV of energy per atom, the energy release is a few MeV per nucleus, a million times larger than the energy release from chemical processes. The same mass of hydrogen fuel will therefore last a million times longer, that is billions of years rather than thousands of years.

The extreme conditions for fusion to occur naturally in the interior of stars such as the Sun because of the extreme gravity that such a large mass generates. As a consequence the interior temperature of the Sun exceeds 10 million degrees Kelvin, and pressures exceed 100 billion atmospheres. For stars which are more massive than the Sun the interior pressure and temperature are even higher.

Fusion processes in the Sun

For stars comparable in mass to the Sun the interior temperatures and pressures are only sufficient for hydrogen to be used as a fuel. There are two possible process which can used to covert hydrogen to helium

1. the proton-proton chain[1,2]
2. the CNO cycle[3]

Of the two, the proton proton chain is the more important in the Sun, the latter for stars a little more massive.

If the details of these reactions are ignored, the overall result of each is the destruction of four hydrogen nuclei to form one helium nucleus and the release of about 26 MeV of energy.

$$4\ {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + 26\ \mathrm{MeV}$$

Fusion processes in massive stars

In the case of the Sun, and similar mass stars, the interior is not hot enough for the star any element other than hydrogen as it fuel. However, for stars which are more massive than the Sun the interiors are hotter, and pressures are higher. That means that these stars, once they have exhausted their supply of hydrogen can also use the helium that has been produced as a new nuclear fuel. The fusion of helium produces carbon, which can in turn be used as a fuel. There is a succession of nuclei which take their turn in fueling the star; carbon, oxygen, silicon, neon, and so on. But this sequence of nuclei has to come to an end. As was noted earlier (see figure 1) the plot of the binding energy per nucleon peaks at the element iron. Fusion of iron and heavier elements does not release energy, it actually requires the input of energy. The star cannot use iron as a fuel, and once the core of the star has been converted to iron the star dies in a violent explosion known as a supernova.

Aside from its role in providing the fuel to power stars, nuclear fusion is also responsible for the creation of nearly all the chemical elements in the universe. In the aftermath of the

---

1 http://csep10.phys.utk.edu/astr162/lect/energy/ppchain.html

2 http://www.fact-index.com/p/pr/proton_proton_chain.html

3 http://csep10.phys.utk.edu/astr162/lect/energy/cno.html

Big Bang the universe was composed of hydrogen, helium, and trace amounts of lithium. All of the heavier elements were absent in this early cosmos, they have been created since then as the result of nuclear fusion inside stars. Elements between lithium and iron can be created inside the most massive stars, and then dispersed throughout the universe as those stars come to the end of their lives and are destroyed in supernova explosions. The elements heavier than iron cannot be created in the same way. They had to be produced in the supernova explosions themselves. Fusions processes that create them require the input of energy, which is only present during these extremely violent events.

Fusion processes in the laboratory

Fusion in the laboratory bras proven very difficult to achieve. Replicating the conditions similar to those in the center of stars is a tremendous technical problem. The extremely high temperatures ($< 10^6$ K) and pressures (millions of atmospheres) are well above those normally encountered in terrestrial locations. That means building a very Sophisticated machine capable of heating a gas (hydrogen) to these temperatures. Furthermore, since we have no hope of producing the sort of pressures that are found at the centers of the stars, we have to aim for even higher temperatures, around 100 million Kelvin.

However as the gas hears up it rapidly loses energy again. One major process of heat loss is thermal radiation, similar to the way that an electric stove diner begins to glow as in heats up. Bur the stove element only reaches a temperature of a few handed degrees Kelvin, and for fusion we need to get to temperatures in excess of 100 million degrees Kelvin, more than 100,000 times larger. The rate at which an object radiates energy is described by Stefan's Law. The radiated power increases as T^4. That thousand-fold increase in temperature requires a $(100{,}000)^4 = 10^{20}$-fold increase in radiated power, and the lost energy has to be replaced in order to keep heating the gas. A number of approaches have beer tried in order to solve these tremendous technical difficulties in achieving such high temperatures.

- Magnetic confinement, in which the hour gas is contained within a region of space well away from the physical walls of the apparatus using a magnetic field.
- Inertial confinement, in which a gas is both heated and imploded by a sees of high crags light beans from a laser. As the gas is rapidly compressed its own inertia keeps it together long enough for the fusion process to commerce.

Despite large amounts of investment into research no commercial fusion reactor has yet been produced. The fundamental idea is and, but our technology is still lacking. Details of the leading approaches to achieving laser fusion can be found at the following official web sites:

- Joint European Torus (JET)

  - http://www.jet.efda.org/jet/
  - http://www.jet.efda.org/fusion-basics/conditions-for-a-fusion-reaction/
- ITER (International Thermonuclear Experimental Reactor)
  - http://www.iter.org/
- **Tokamak Fusion Test Reactor**
  - http://www.pppl.gov/projects/pages/tftr.html
- **National Ignition Facility**
  - https://lasers.llnl.gov/