Nuclear Fusion

Nuclear Data

name of atom	symbol	# of e^-	name of nucleus	symbol	mass (u)	stable?
neutron	^1n	0	neutron	n	1.008 664	no; $\tau = 10$ min 14 sec
hydrogen	^{1}H	1	proton	p	1.007 276	yes
deuterium	^{2}H	1	deuteron	d	2.013 553	yes
tritium	^{3}H	1	triton	t	3.015 500	no; $\tau = 12.3$ years
helium-3	^{3}He	2	helion	h	3.014 932	yes
helium-4	^{4}He	2	alpha particle	α	4.001 506	yes

electron mass: 0.000 548 580 u

neutrino mass: less than 10^{-8} u

Unit Conversions $E_0 = mc^2$

$$\begin{aligned} 1 \text{ u} &= 1.660\,538 \times 10^{-27} \text{ kg} \\ &= 931.494 \text{ MeV}/c^2 \\ 1 \text{ J} &= 1 \text{ kg m/s}^2 \\ 1 \text{ eV} &= 1.602 \times 10^{-19} \text{ J} \end{aligned}$$

Decay reactions

$$\begin{aligned} n &\rightarrow p + e^- + \bar{\nu}_e \\ t &\rightarrow h + e^- + \bar{\nu}_e \end{aligned}$$

Zeroth generation fusion reaction — the Sun

The net reaction that occurs in the sun is to fuse four protons into one α particle

$$4p \rightarrow \alpha + 2e^+ + 2\nu_e + 2\gamma.$$

The mass before the reaction is that of four protons, 4.029 104 u. After the reaction, ignoring the neutrino masses, the mass left is 4.002 603 u, which means that 0.026 501 u was "lost."

Where did it go? The mass was converted to energy, and appeared as kinetic energy (energy of motion) of the products of the reaction. The helium nucleus and the electrons remain in the sun and keep it hot, while the neutrinos and photons (light) escape the sun, with the light warming the Earth.

Because an α particle is composed of two protons and two neutrons, what must happen is that two of the protons "transform" into neutrons. How do they do this? The weak nuclear force acts as a magician, and makes the change. However, there are some rules that must be followed, one of which is to conserve electric charge. In order to do this, a positron (anti-electron) must also be created. In addition, something called "lepton number" must also remain the same. For this reason, a neutrino (specifically, an electron neutrino) must be created. The fundamental reaction is

$$p \rightarrow n + e^+ + \nu_e.$$

Note that this is the same as the neutron decay reaction above, with the change that the positron and the neutrino have moved on the other side of the reaction, and in the process have changed into their anti-particles. This is a rule of nuclear reactions: particles can change sides but must be replaced by their anti-particles.

First generation

To be a useful reaction on Earth, however, it would be nice if it contained only one reaction, rather than the several in the proton-proton chain or the CNO cycle. Two possibilities are two use deuterium

$$d + d \rightarrow \begin{cases} n + h & (3.269 \text{ MeV}) \\ p + t & (4.033 \text{ MeV}) \end{cases}$$

or deuterium and tritium

$$d + t \rightarrow \alpha + n \quad (17.59 \text{ MeV})$$

Obviously, the *d*-*t* reaction released more energy, and so is more attractive, but the main problem is that it releases an energetic neutron. The energy from this neutron must be extractable, but it is not so simple. In addition, the neutrons tend to make the walls of the machine radioactive.

Second generation

One reaction that does not release neutrons is between a deuteron and a helion, the nuclei of deuterium and helium-3 (^{3}He)

$$d + h \rightarrow \alpha + p \quad (18.35 \text{ MeV})$$

The problem with this reaction is that the helion is doubly charged (2 protons and 1 neutron), which means that it and the deuteron repel each other *twice* as strongly as two deuterons, making it less likely that they will get close enough to "fuse."

Third generation

Finally, we are led to the most difficult type of reaction, but one that might be commercially viable if enough ^{3}He can be found—on the Moon, for example. The reaction is

$$h + h \rightarrow \alpha + 2p$$

Can you calculate the reaction energy? Again, the major problem is the helion charges, which means they repel each other quite strongly.