Nuclear Fusion

Nuclear Fusion is the process stars employ to convert mass to energy. While the details of the reactions can get confusing, the basic idea is well, pretty basic: $E=mc^2$. Stars spend most of their lives fusing isotopes of hydrogen into heavier isotopes of hydrogen and helium. As they do so, mass is converted into energy--both thermal energy (the reaction products move very fast) and energy in photons of light (like gamma rays).

In order to study the specific fusion reactions in stars like Earth's Sun, we first need to know something about units of energy. The SI Unit for energy is the Joule, but it's often more convenient to use a smaller unit of energy for individual fusion reactions. The unit of choice is the electron-Volt (eV). An electron-Volt is the energy an electron gains if it crosses an electric potential difference of 1 Volt. This is equivalent to 1.60×10^{-19} J. That is:

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

Sometimes you'll see energies written in MeV or millions of electron-Volts.

We also need to know something about mass units. The SI unit for mass is the kilogram, but on the nuclear level we often use a unit called an atomic mass unit: *amu* or *u* for short. One u is defined as 1/12 the mass of a carbon-12 atom and is equivalent to 1.660539×10^{-27} kg.

Since Einstein showed that mass and energy are equivalent, most nuclear scientists simply give masses of tiny particles in terms of their energies. For example, the mass of a single electron is 9.109383×10^{-31} kg. If we use this in Einstein's famous equation:

$$E=mc^2$$
$$E = (9.109383 \times 10^{-31} \text{ kg})*(299{,}792{,}458 \text{ m/s})^2 = 8.18711 \times 10^{-14} \text{ J}$$

Dividing the energy in Joules by 1.60×10^{-19} J/eV we get about 510,000 eV or 0.51 MeV

Isn't 0.51 MeV much easier to write and work with than 9.1×10^{-31} kg ?!

Now you try converting some masses to energy equivalents in MeV. First convert to Joules using $E=mc^2$, then to electron-Volts, then to MeV. (You can use 3.00×10^8 m/s for c.)

Proton
$m = 1.672\ 622 \times 10^{-27}$ kg

Neutron
$m = 1.674\ 927 \times 10^{-27}$ kg

One more thing...since many masses are given in terms of atomic mass units for element isotopes, we need to know the conversion factor from u to MeV.

1 u = 1.6605 x 10^{-27} kg = 931.5 MeV

Finally, back to fusion...as we stated earlier, stars spend most of their lives fusing hydrogen into heavier isotopes. For example:

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

What's going on here? Well let's discuss the symbols and numbers. For any nuclear reaction, the top numbers must balance left and right as well as the bottom numbers. Across the bottom are numbers representing the electric charge of each piece and across the top are numbers representing the total number of nucleons (particles of the nucleus, so protons + neutrons). The reactants are the most common isotopes in the universe-hydrogen. The ${}^{2}_{1}H$ is an isotope of hydrogen with 1 proton and an extra neutron (2 nucleons) and is sometime referred to as deuterium or a deuteron. The last particle is an anti-electron or positron which as the same mass as an electron but opposite charge. The positron has no nucleon number since it's not made up of protons or neutrons.

Atomic Number (z)	**Element**	**Symbol**	**Mass (u)**
0	(electron)	${}^{0}_{-1}e$	0.000 549
0	(positron)	${}^{0}_{+1}e$	0.000 549
0	(neutron)	${}^{1}_{0}n$	1.008 665
1	Hydrogen-1	${}^{1}_{1}H$	1.007 825
1	Hydrogen-2, Deuterium	${}^{2}_{1}H$	2.014 102
1	Hydrogen-3, Tritium	${}^{3}_{1}H$	3.016 049
2	Helium-3	${}^{3}_{2}He$	3.016 029
2	Helium-4	${}^{4}_{2}He$	4.002 603

Using the information in the table above and the reaction equation, determine the amount of mass difference from one side of the equation to the other in u and then convert to MeV. This is the energy liberated in this particular nuclear fusion reaction. Show all your work and check your answer with someone else.

The Proton-Proton Chain

In stars with similar mass to the Sun, a series of fusion reactions result in fusing four Hydrogen-1 nuclei into one Helium-4 nucleus. It's hard enough to get two protons to fuse because they are both positively charged and repel--getting four to do so at once is highly improbable. Through a series of reactions called the proton-proton chain (or p-p chain) four hydrogen do fuse into a helium. One such set of reaction is listed below. For the last two, calculate the energy liberated in units of MeV--show all your calculations.

1. $^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + ^{0}_{+1}e$ (you already did this one on the previous page)

2. $^{2}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{2}He + ^{0}_{0}\gamma$ (the last particle is a gamma photon--no mass)

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

Physicists and engineers are trying to build nuclear fusion reactors on Earth, but it is very challenging. If you want to know more, check out the National Ignition Facility (NIF) https://lasers.llnl.gov and the International Thermonuclear Experimental Reactor (ITER) https://www.iter.org .