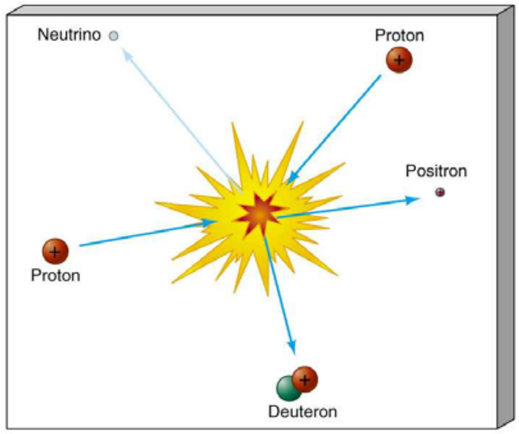
Nuclear Fusion



Stability

Most stars are neither expanding nor contracting. *At each layer* within the star the temperature, pressure, density, etc., are constant values.

The mutual gravitational attraction produces tremendous forces that tend to collapse the Sun toward its center. Yet it has been around for billions of years. The gravity is counter-balanced by pressure. To exert enough pressure to prevent the collapse due to gravity, the gases at the center of the Sun must be at a temperature of **15 million K**. At this temperature protons can fuse into helium nuclei.

Pressure ⟷ **Gravity**

Nuclear Physics

Key Words: **element, isotope, nucleon, proton, neutron**

Number of nucleons = A = Z + N

where Z is the number of protons
N is the number of neutrons

1 u = 1/12 C^{12} (atomic mass unit)

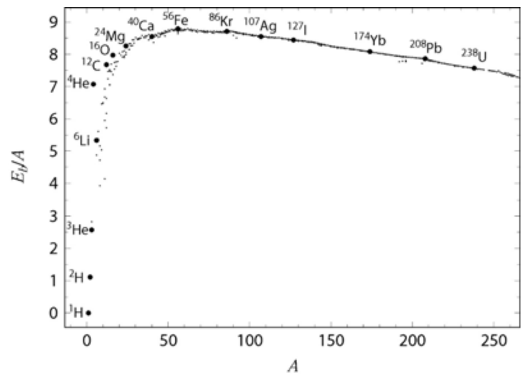
1 u = 1.660540 x 10^{-24} g → 931.5 MeV

Particle Masses

Particle	**g**	**u**		**MeV**
Proton	1.672623 x 10^{-24}	1.00727	→	938.27
Neutron	1.674929 x 10^{-24}	1.00866	→	939.56
Electron	9.109390 x 10^{-28}	0.00055	→	0.51

Binding Energy

Binding Energy is the energy released due to an accompanying loss in mass when nucleons are combined into atomic nuclei (i.e., **fusion**).



Binding Energy

For Example: 4H → He

$4\ m_H = 4 \times 1.007825 = 4.031280\ u$

$1\ m_{He} = 4.002603\ u$

$\Delta m = 0.028677\ u$

$= 26.71\ MeV$

$\Delta m / 4\ m_H = 0.028677 / 4.031280 = 0.0071 = 0.71\%$

Thermonuclear Reactions

Conservation of Mass and Energy
Conservation of Electric Charge
Conservation of Number of Nucleons
Conservation of Number of Leptons
(electrons & neutrinos)
[matter – antimatter]

Antimatter $e^- + e^+ \rightarrow 2\gamma$

Weak Force $p^+ + e^- \rightarrow n^o + \nu$

Thermonuclear Reactions

Symbols $^A_Z X$

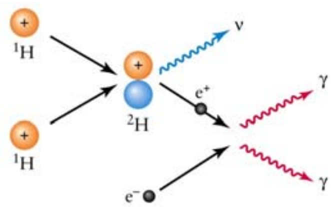
X: element

Z: number of protons (charge)

A: mass number = total number of protons and neutrons

Proton-Proton I

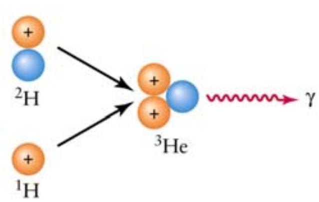
$$^{1}_{1}\mathrm{H} + ^{1}_{1}\mathrm{H} \rightarrow ^{2}_{1}\mathrm{H} + e^{+} + \nu$$



Proton-Proton I

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

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



Proton-Proton I

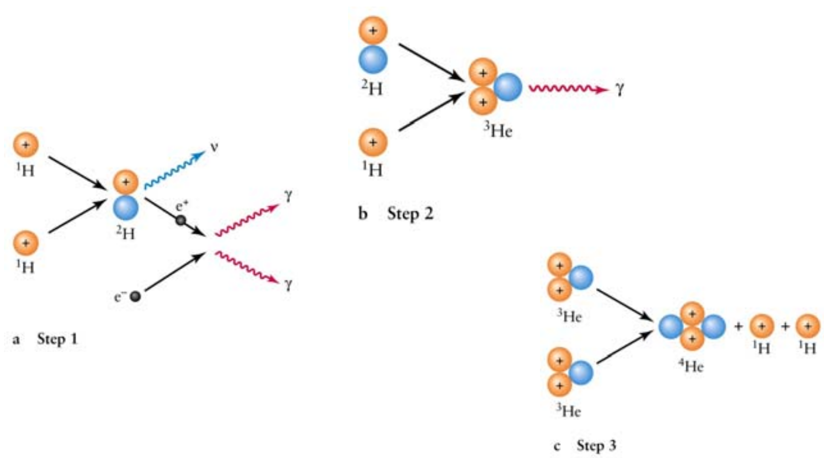
$$^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + e^{+} + \nu$$

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

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

69%

Diagram of PPI



Proton-Proton II

$$ {}^{3}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{7}_{4}\mathrm{Be} + \gamma $$

$$ {}^{7}_{4}\mathrm{Be} + e^{-} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu $$

$$ {}^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} \rightarrow 2\,{}^{4}_{2}\mathrm{He} $$

31% 99.7%

Proton-Proton III

$$ {}^{7}_{4}\mathrm{Be} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{8}_{5}\mathrm{B} + \gamma $$

$$ {}^{8}_{5}\mathrm{B} \rightarrow {}^{8}_{4}\mathrm{Be} + e^{+} + \nu $$

$$ {}^{8}_{4}\mathrm{Be} \rightarrow 2\,{}^{4}_{2}\mathrm{He} $$

0.3%

Example

Early Proposal for a Hydrogen Bomb:

$$5\,{}^{2}H \rightarrow {}^{3}He + {}^{4}He + {}^{1}H + 2n$$

${}^{2}H$	2.014102 u	${}^{3}He$	3.016029 u
${}^{1}H$	1.007825 u	${}^{4}He$	4.002603 u
n	1.008665 u		

There are 5 electrons on both sides of the reaction, so it is balanced.

Example

Early Proposal for a Hydrogen Bomb:

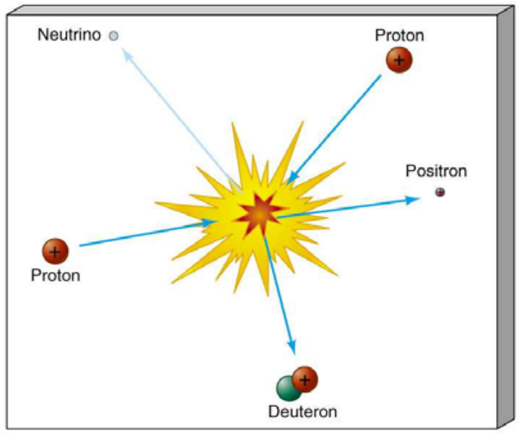
$$5\,{}^{2}H \rightarrow {}^{3}He + {}^{4}He + {}^{1}H + 2n$$

5 (2.014102)	= 10.070510 u
3.016029 + 4.002603 + 1.007825 + (2) 1.008665	= 10.043787 u

Mass Defect	= 0.026723 u

$Q = (0.026723\ u)\,(931.5\ MeV/c^2) = 24.9\ MeV/c^2$

Nuclear Fusion



Lifetimes

A simple relationship:

Assume the L has always been constant, and

Assume the entire all of the (appropriate) mass is fused, then

Lifetime $= \tau =$ Total Energy (J) / Luminosity (J/s)

$\tau = \mathbf{E_T / L} =$ time (s)

Solar Neutrinos

About 3% of the total energy generated by the Sun is carried away by neutrinos. Neutrinos rarely interact with matter, and they travel at about the speed of light. If we could devise a way to detect some of the 300 billion solar neutrinos that pass through each square meter of the Earth's surface every second, then we could obtain information directly about the center of the Sun.

Solar Neutrinos

But they are hard to detect. On very, very rare occasions, however, a neutrino of the highest energy of those emitted by the Sun will react with the isotope chlorine-37 to produce argon-37 and an electron.

Solar Neutrinos

The Davis Experiment had a tank of 400,000 liters of cleaning fluid 1.5 km beneath the surface of the Earth in a gold mine. Calculations showed that solar neutrinos should produce about **ten** atoms of argon-37 daily in this tank.

But only about one-third are measured as are predicted.

Theory versus Observations

The interior is cooler now than when the luminosity was generated a million years ago.

There are other types of subatomic particles (WIMPS – weakly interacting massive particles) which are carrying away heat.

There are three types of neutrinos, but only one type can interact in the Davis experiment. Possibly the neutrinos can transform themselves during the travel from the Sun to the Earth.