Fusion

D. Craig, WTAMU

2006–03–27

Light nuclei and binding energy

For light nuclei, energy can be released by combining them, since BE/nucleon is more for heavier nuclei on that side of the curve.

This is the mechanism of nuclear **fusion.**

Fusion in the Sun and other stars

$$\begin{aligned}
{}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} &\rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{1}\mathrm{e}^{+} + \nu && (1)\\
{}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} &\rightarrow {}^{3}_{2}\mathrm{He} + \gamma \text{ then:} && (2)\\
{}^{1}_{1}\mathrm{H} + {}^{3}_{2}\mathrm{He} &\rightarrow {}^{2}_{4}\mathrm{He} + {}^{0}_{1}\mathrm{e}^{+} + \nu && (3)\\
{}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} &\rightarrow {}^{2}_{4}\mathrm{He} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} && (4)
\end{aligned}$$

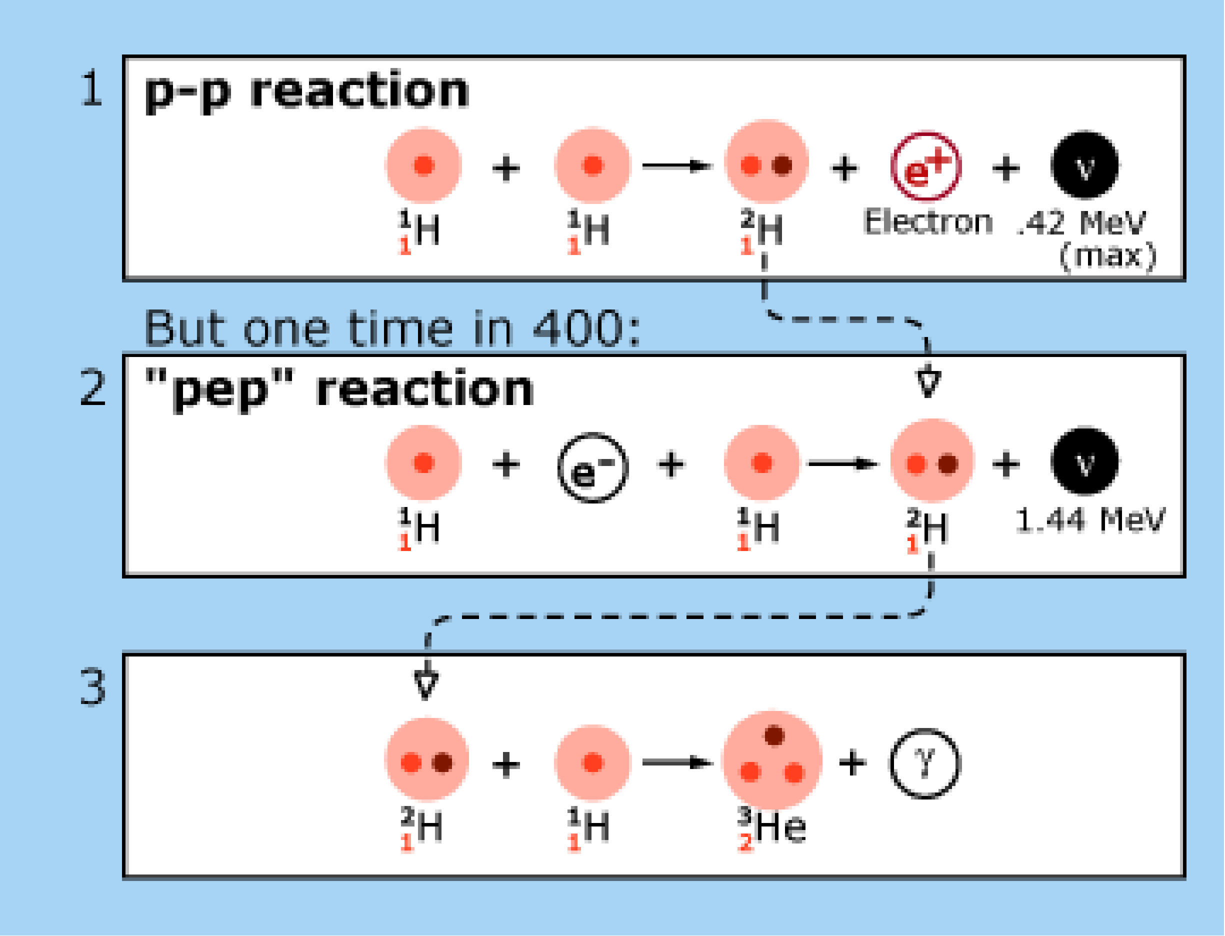
This is the **proton-proton cycle,** all steps are exothermic. It proceeds at $\mathrm{T} = 1.5 \times 10^{7}$ K and high pressure and proton density in the Sun's interior. The is the most "generic" reaction cycle, using only H, He.

In larger stars, the main energy production is via the **CNO bi-cycle**, in which ${}^{12}_{6}\mathrm{C}$ acts as a catalyst.

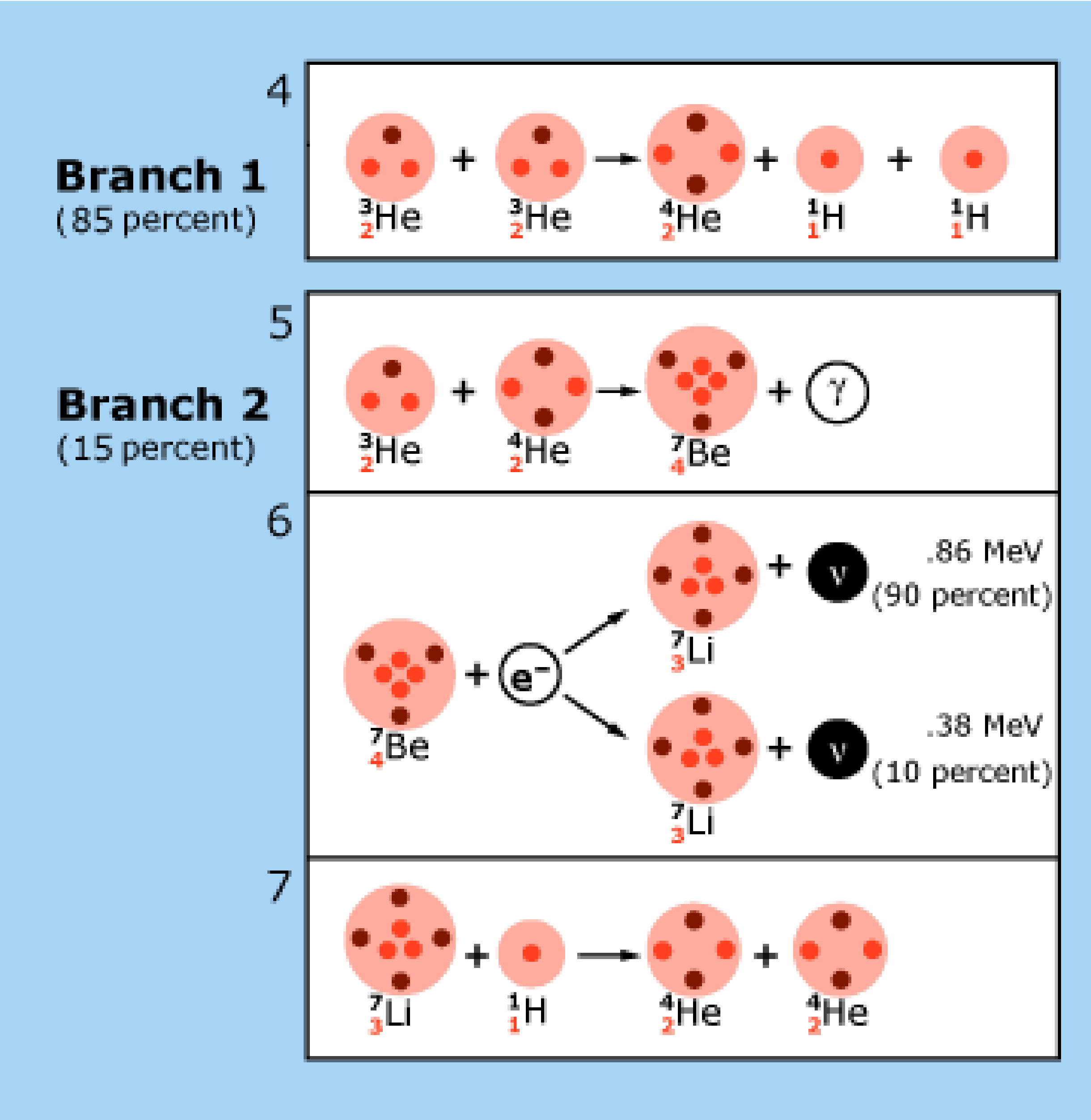
There is a nice overview at the Nobel Prize website:

`http://nobelprize.org/physics/articles/fusion/index.html`

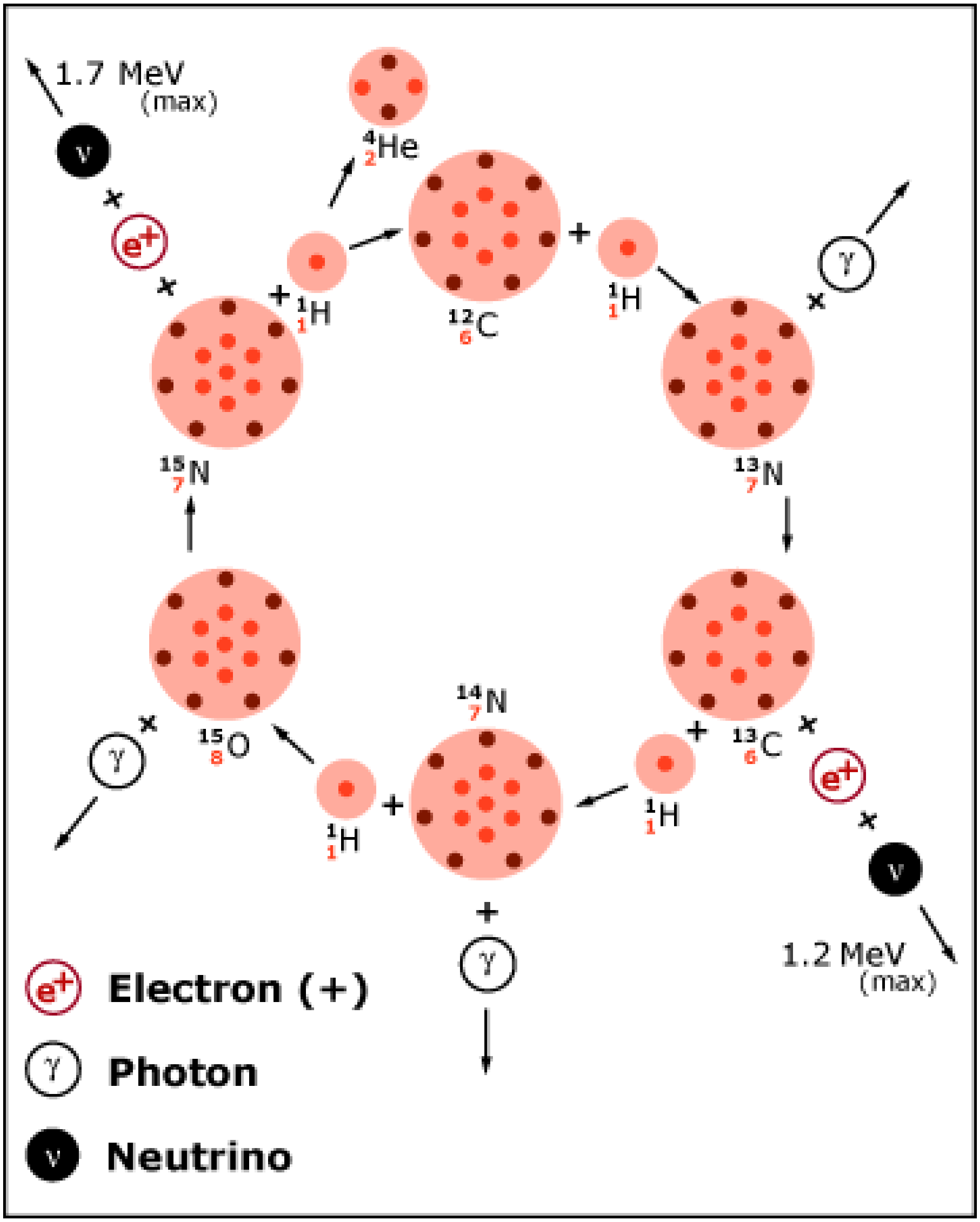
following figures from there.


1
p-p reaction
^1_1H + ^1_1H → ^2_1H + e^+ + ν
Electron
.42 MeV (max)
But one time in 400:
2
"pep" reaction
^1_1H + e^- + ^1_1H → ^2_1H + ν
1.44 MeV
3
^2_1H + ^1_1H → ^3_2He + γ

The ${}^3_2$He can react several ways:



The CNO cycle:



Reactions for controlled nuclear fusion

Most promising involve deuterium and tritium:

$$
\begin{aligned}
{}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} &\rightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \qquad && Q = 3.27 \text{ MeV} \\
{}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} &\rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \qquad && Q = 4.03 \text{ MeV} \\
{}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} &\rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} \qquad && Q = 17.59 \text{ MeV}
\end{aligned}
$$

Deuterium readily available from seawater, tritium has a short half-life, and must be manufactured, or possibly obtained from the Moon, where the solar wind is trapped on surface grains.

Ignition temperature

At attainable pressures, high T is required to overcome the Coulomb barrier for fusion. $T \approx 4 \times 10^8$ K is required for D-D fusion. This is the **critical ignition temperature.** The energy is $E \approx k_B T = 35$ keV for D-D fusion, but only $T = 4.5 \times 10^7$ K or 4 keV for D-T fusion.

In a hot plasma at this temperature, ion-ion collison produce **bremsstrahlung radiation** by charge acceleration. This is an energy loss mechanism.

Ion density and confinement time

For a net energy yield, fusion reactions must happen often enough to release energy exceeding the energy required to heat the plasma.

This requires they be confined for a time τ at a density n given by **Lawson's criterion:**

$$n\tau \geq 10^{14}\ \text{s/cm}^3\ \text{D-T}$$
$$n\tau \geq 10^{16}\ \text{s/cm}^3\ \text{D-D}$$

Requirements for a power reactor

- Plasma temperature must be very high.
- Ion density must be high for a high collision rate.
- Confinement time must be long. Probability of fusion/collision goes up with τ.

How to confine a plasma at 10^8 K for about 1 s?