

THERMONUCLEAR ENERGY

- Only energy source capable of producing observed stellar luminosities for known time scales is **thermonuclear fusion** -

the coalescence of light elements to form heavier nuclei, releasing energy in the process.

- How likely is it for two protons to coalesce?

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- **Average thermal energy** of particles

$$E_{\text{th}} = 3 kT / 2 \\ = 4 \times 10^{-16} \text{ J} \quad \text{for } T \sim 2 \times 10^7 \text{ K (core temp)}$$

- **But Coulomb potential** between 2 protons separated by $r = 10^{-15} \text{ m}$ is much bigger...

$$E_{\text{pot}} = \frac{q_1 q_2}{4\pi\epsilon_0 r} = 2.3 \times 10^{-13} \text{ J}$$

with

$$q_1 = q_2 = 1.6 \times 10^{-19} \text{ C}$$

$$\epsilon_0 = 8.85 \times 10^{-12} \text{ J}^{-1} \text{ m}^{-1} \text{ C}^2$$

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There is, however, a **finite probability** of overcoming this huge potential barrier.

At $T \sim 2 \times 10^7$ K, about 10^{-8} of all protons have sufficient energy. The strong nuclear force takes over to build 2 protons into a nucleus of deuterium.

The term **thermonuclear** arises because the necessary velocities are of **thermal** origin.

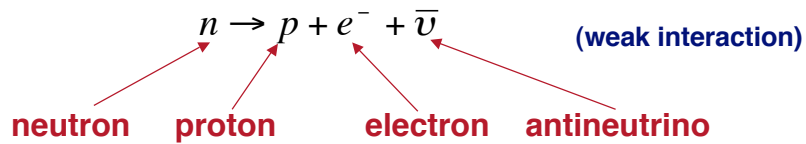
Basic particle interactions in nuclear reactions

Conservation laws

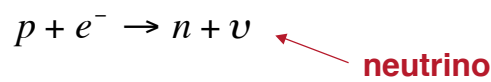
- **mass - energy** $E = mc^2 = m_0c^2 / \sqrt{1 - v^2/c^2}$
- **total electric charge**
- **number of particles and antiparticles**
- **difference between number of leptons and antileptons (eg electrons, neutrinos)**
- **difference between number of baryons and antibaryons (eg protons, neutrons)**

Most common nuclear reactions in stars involve:

(1) **Beta decay**: exergonic, spontaneous



also inverse beta decay



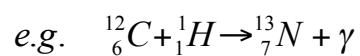
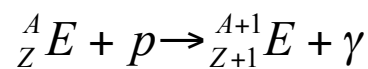
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(2) **Positron decay**: endergonic, requires threshold input energy
(since mass of neutron and positron > mass of proton)



(3) **(p, γ) process**: proton reacts with nucleus of charge Z and mass A to produce a more massive particle ($A+1$) with charge ($Z+1$):



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(4) **(α, γ) process**: similar to (p, γ) process but with α - particle (${}^4\text{He}$ nucleus) added to nucleus

also: **(γ, α) process** where photon liberates an α - particle

Important in nuclei with even numbers of p and n - very stable nuclei

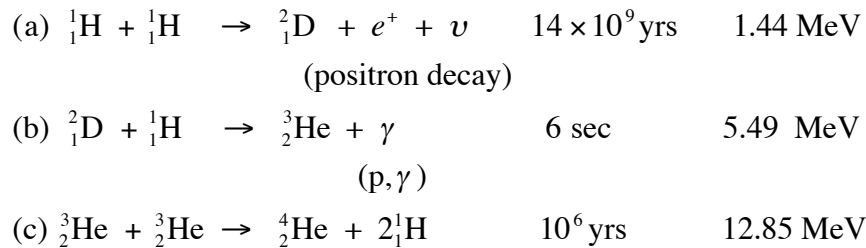
(5) **(n, γ) and (γ, n) processes**: as above with neutrons

The first nuclear reaction in stars

- These occur when core temp $T \sim 10^6$ K (this is not a critical temperature, rather the temp at which reactions proceed at a certain rate).
- The first reactions involve elements like ${}^2\text{D}$, ${}^6,{}^7\text{Li}$ at $T \sim n \times 10^6$ K with $1 \leq n < 10$
- These elements are readily destroyed, even from the surfaces of stars (since stars are fully convective at the early stages).

HYDROGEN NUCLEAR REACTIONS

1. PROTON - PROTON CHAIN

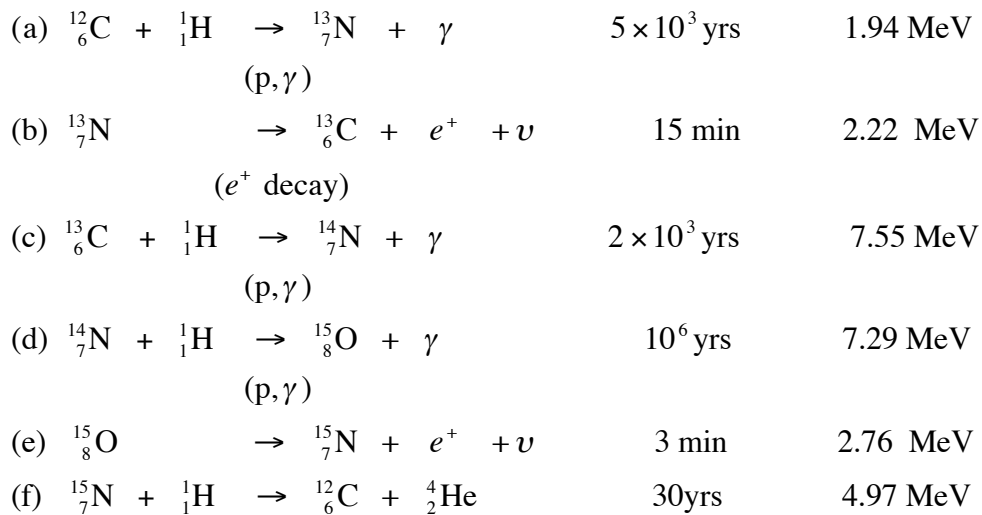


Steps (a) and (b) repeated before (c) can occur. Reaction rate $\epsilon \sim T^4$. Dominant in Sun, G, K stars. $\epsilon \sim 26\text{MeV}$

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2. CARBON - NITROGEN - OXYGEN (CNO) CYCLE

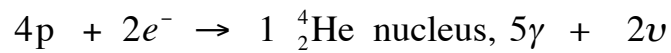


Reaction rate $\epsilon \sim T^{15}$; dominant in O, B, A stars, total $\epsilon \sim 25\text{MeV}$

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In both cases, net result is the same



Since CNO cycle requires ^{12}C as a catalyst, it can only occur in stars with sufficient heavy element abundance

=> ineffective in pop II stars .

Rough calculation of energy conversion:



Hence $0.028 \text{ amu} = 4.6 \times 10^{-29} \text{ kg}$

converted (by $E = mc^2$) to an energy of

$$E \sim 4 \times 10^{-12} \text{ J} \sim \underline{25 \text{ MeV}} \quad (\text{since } 1\text{eV} = 1.6 \times 10^{-19} \text{ J})$$

This result compares well with more detailed summations of the individual reactions, namely 26.3 MeV (pp chain) and 25.0 MeV (CNO cycle). If you sum up the energy released in each part of these reaction chains, the values are ~1MeV greater, but the neutrinos escape with that extra energy.

NB: for each H nucleus, 0.007 amu ~ 0.007 of H is lost as energy.