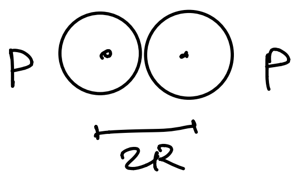
Fusione Nucleare



$$U(2R) = \frac{\alpha Z^2}{r} = \frac{\alpha}{2}\frac{1}{r_0} = 550\,\text{keV}$$

$r_0 \simeq 1$ fm

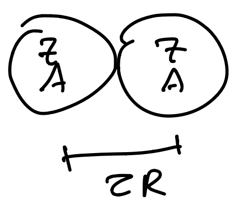
rendimento energetico.

$$M + M \longrightarrow X + Q$$

$$\eta = \frac{Q}{2M}$$

vogliamo $Q > 0$ e η grande $\Rightarrow$ fusione rilevante per nuclei leggeri

$${}^A_Z X + {}^A_Z X \longrightarrow$$



$$U(2R) = \frac{e^2}{4\pi\varepsilon_0}\frac{ZZ}{2R} = \frac{\alpha Z^2}{2 r_0 A^{1/3}} = \frac{\alpha}{2}\frac{1}{r_0}\frac{Z^2}{A^{1/3}}$$

nuclei leggeri: $A = 2Z$ $\quad Z^2 = \frac{A^2}{4}$

$$U(2R) = \frac{\alpha}{2}\frac{1}{r_0}\frac{1}{4}A^{5/3} = 0.145\,A^{5/3}\ \text{MeV}$$

Helio $A = 4$, $Z = 2$ $\quad U(2R) = 1.45$ MeV

$E = 1.45\ \text{MeV} = KT$ $\quad$ K: Boltzman

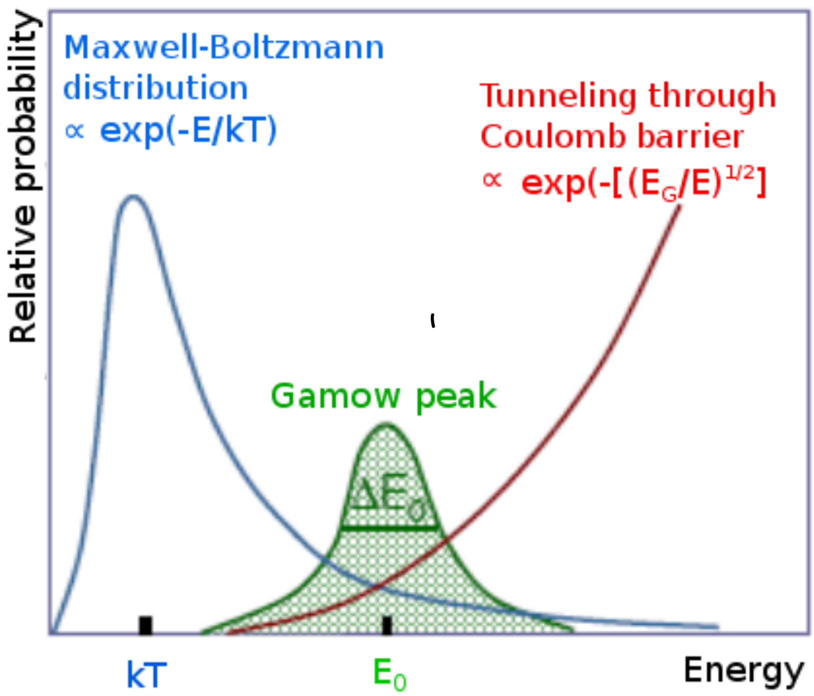
$K = 8.6 \times 10^{-5}$ eV/K

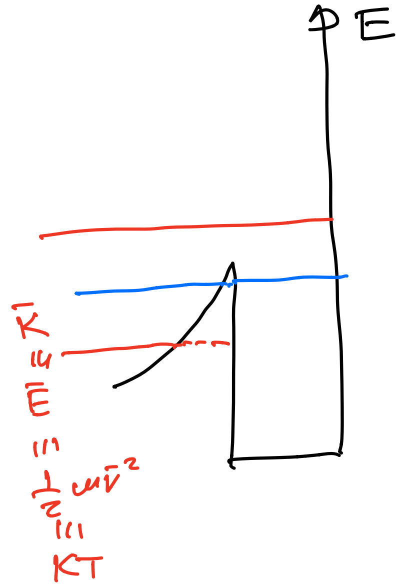
$$T = \frac{1.45\ \text{MeV}}{8.6\times 10^{-5}\ \text{eV/K}} \simeq 1.6 \times 10^{9}\ \text{K}$$

$$\bar{E} = \frac{3}{2} kT = \frac{1}{2} m \bar{v}^2 \Rightarrow \bar{v} = \sqrt{\frac{3kT}{m}}$$

$$\frac{dn}{dv} = \frac{v^2}{(2kT/m)^{3/2}} e^{-\frac{1}{2}\frac{mv^2}{kT}}$$

Distribuzione di Maxwell-Boltzmann





Fusione nelle stelle

produzione energetica principale

$$4p \longrightarrow He + \underbrace{26\ MeV}_{Q}$$

$$\eta = \frac{Q}{M} = \frac{26\ MeV}{3.7\ GeV} \simeq 7 \times 10^{-3}$$

Temperatura del Sole $\quad T = 1.5 \times 10^{7}\ K.$

$$\bar{E} = \frac{3}{2} kT \simeq 190\ keV.$$

$U(2R)$ $\quad p+p: \quad 550\ keV.$

effetto tunnel fondamentale.

1) $p + p \longrightarrow {}^2_1H + e^+ + \nu_e$ $Q = 0.42$ MeV.

Interazione debole

$\sigma = 10^{-55}\ cm^2 \simeq 10^{-31}\ b$

$\frac{dN_r}{dt} \propto \frac{dN_p}{dt} \cdot \sigma$

$\tau_{SS} \simeq 5 \times 10^9\ yr$ Circa metà della vita del sole.

2) $p + \underbrace{{}^2_1H}_{\text{deutone}} \longrightarrow {}^3_2He + \gamma$ $Q = 5.49$ MeV

deutone
nucleo di deuterio

al passare del tempo densità di ${}^3_2He \nearrow$

3) ${}^3_2He + {}^3_2He \longrightarrow {}^4_2He + p + p$ $Q = 12.86$ MeV

In totale $3p + 3p \longrightarrow {}^4_2He + 2p + (2e^+ +)\ 2\nu_e + 2\gamma$

$$4p \longrightarrow {}^4_2He + Q$$

$Q = 4m_p - m_\alpha - 2m_e = 24.7$ MeV

$\langle E_\nu \rangle \simeq 0.3$ MeV

$Q' = Q - 2\langle E_\nu \rangle \simeq 24.7 - 0.6 = 24.1$ MeV

$e^+ + e^- \longrightarrow 2\gamma$

$\langle E_\gamma \rangle \simeq 1$ MeV

$Q_{netto} = 24.7 - \underbrace{2 \times 0.3\ MeV}_{\nu_e} + 2 \times 1\ MeV \simeq 26$ MeV.

$$p + p \rightarrow {}^{2}H + e^{-} + \upsilon_e \qquad\qquad p + p + e^{-} \rightarrow {}^{2}H + \upsilon_e + 0.42 MeV$$

99.77% 0.23%

$${}^{2}H + p \rightarrow {}^{3}He + \gamma + 5.49 MeV$$

$${}^{3}He + {}^{3}He \rightarrow \alpha + 2p + 12.86 MeV \qquad\qquad {}^{3}He + p \rightarrow \alpha + e^{+} + \upsilon_e$$

84.92% $\approx 10^{-5}\%$

$${}^{3}He + \alpha \rightarrow {}^{7}Be + \gamma + 1.59 MeV$$

15.08%

$$p + p \longrightarrow {}^{4}_{2}He$$

$t \rightarrow \infty$. finire H nella stella.

H esaurisce.

$${}^{4}_{2}He + {}^{4}_{2}He \longrightarrow {}^{8}_{4}Be \qquad Q \simeq -0.099 \text{ MeV}.$$

Be instebile $\quad {}^{8}_{4}Be \rightarrow {}^{4}_{2}He + {}^{4}_{2}He$

$$\tau \simeq 0.7 \times 10^{-16} \text{ s}$$

$${}^{8}_{4}Be + {}^{4}_{2}He \longrightarrow {}^{12}_{6}C^{*} \longrightarrow {}^{12}_{6}C + \gamma$$

$${}^{4}_{2}He + {}^{12}_{6}C \rightarrow {}^{16}_{8}O + \gamma \qquad Q = 7 \text{ MeV}$$

$${}^{4}_{2}He + {}^{16}_{8}O \rightarrow {}^{20}_{10}Ne + \gamma$$

$${}^{12}_{6}C + {}^{12}_{6}C \longrightarrow {}^{20}_{10}Ne + {}^{4}_{2}He$$

$${}^{24}_{12}Mg$$

Finche $\frac{\partial \bar{B}}{\partial A} > 0$ fino al Ferro.