Stellar Structure

Reading assignment

THURSDAY 10/29: Chapter 10.5 (first 4 pages) + 10.6

Homework Assignment #4 due by:

TUESDAY 11/10 before beginning of class

MIDTERM EXAM: THURSDAY Nov. 12

Energy balance (conservation of energy):

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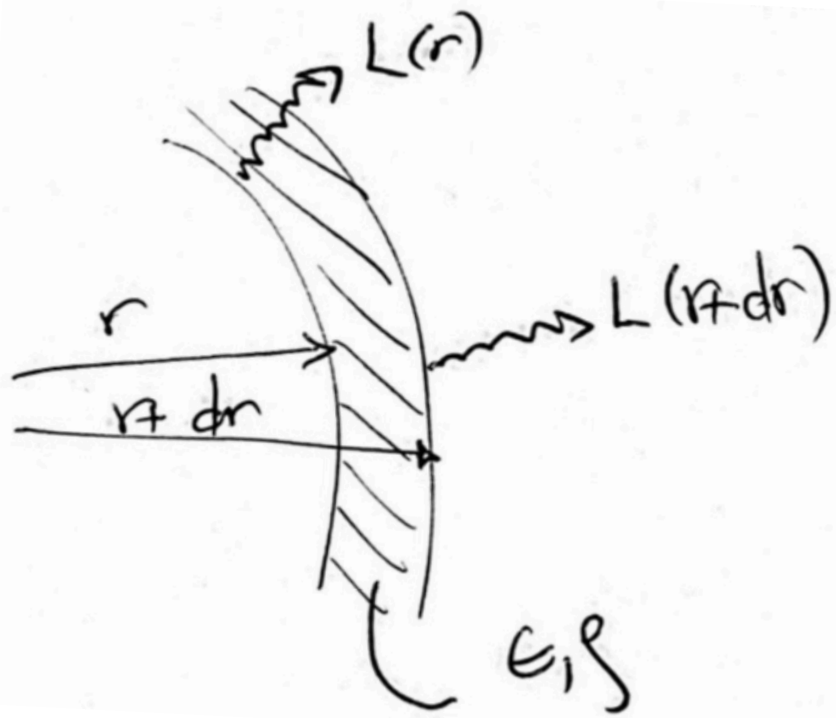

For a static stellar structure

$$L = \int_V \epsilon\rho \, dV = \int_0^R 4\pi r^2 \, dr \, \epsilon\rho$$

total luminosity of the star

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balance of energy in the shell at radius r

$$\Rightarrow \boxed{\frac{dL(r)}{dr} = \epsilon(r)\,\rho(r)\,4\pi r^2}$$

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$$\Rightarrow \boxed{\begin{array}{l} \dfrac{dL(r)}{dM(r)} = \epsilon(r) \\ M(r) = \int_0^r 4\pi r^2 \rho\, dr \end{array}}$$

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NOTE: This equality does not have to be maintained all the time. The star would contract and the virial theorem ensures that half of the gravitational potential energy goes into kinetic energy, and the other half is radiated away, until the star settles into a new configuration. Re-configuration is a slow process.

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$$\frac{dQ}{dt} = \frac{dU}{dt} + P\frac{dV}{dt}$$

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4B) important equation in the computation of stellar models during evolutionary change

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4B) important equation in the computation of stellar models during evolutionary change

$E_{nuclear}$+$E_{gravity}$; $E_{gravity}>0$ if star contracting, <0 if expanding; note dependence on time

NOTE: Eq. 4B does not determine the luminosity of a star. The actual rate of flow of energy is determined by the mechanism of energy transport, which is determined by the temperature gradient dT/dr of the star.

Thermonuclear reaction rates: $\epsilon = \epsilon(\rho, T, \{X_Z\})$

There is enough energy in the nuclei of atoms to provide a source of energy for stellar luminosity. For reactions to occur, the nuclei of atoms must collide; however, all nuclei are positively charged, meaning a Coulomb potential energy barrier must be overcome before contact can occur.

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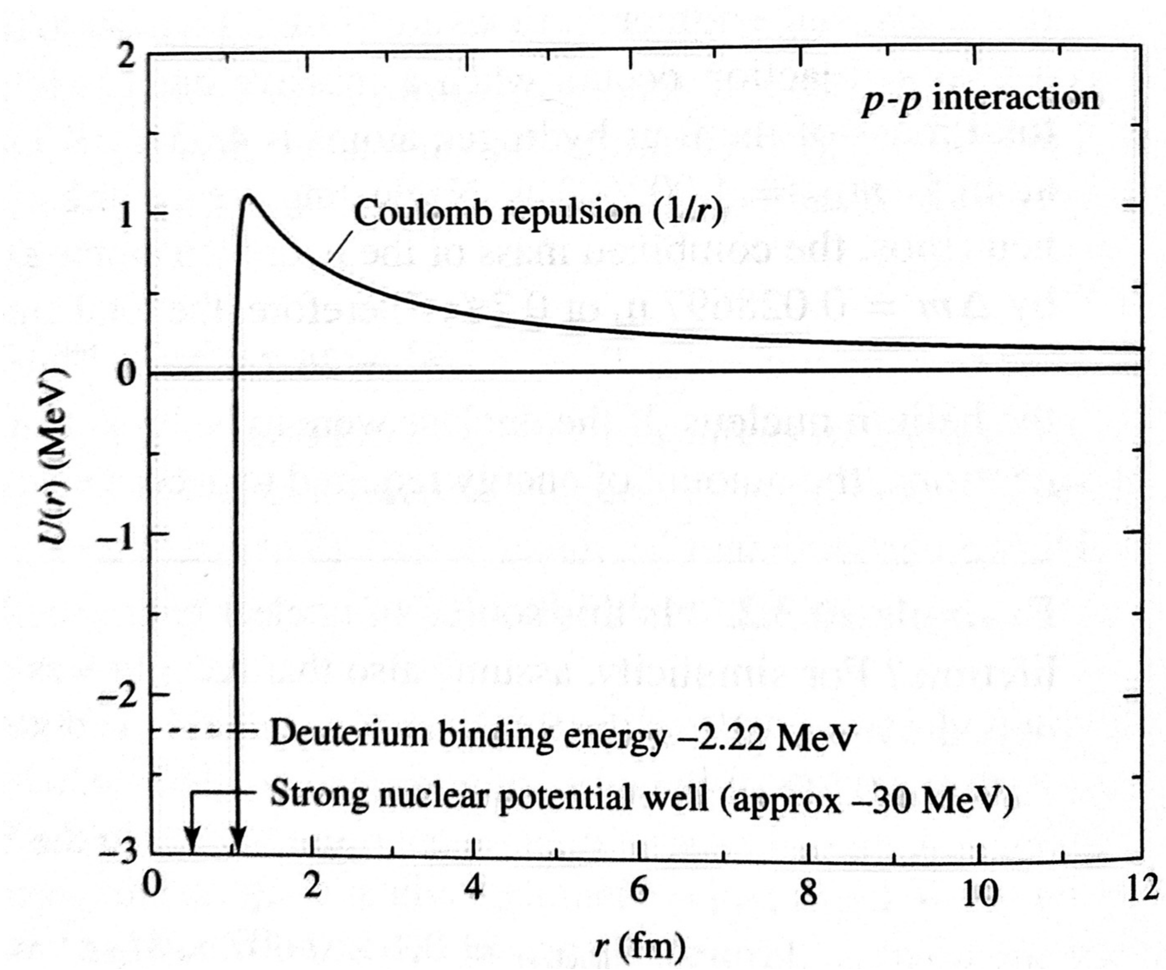

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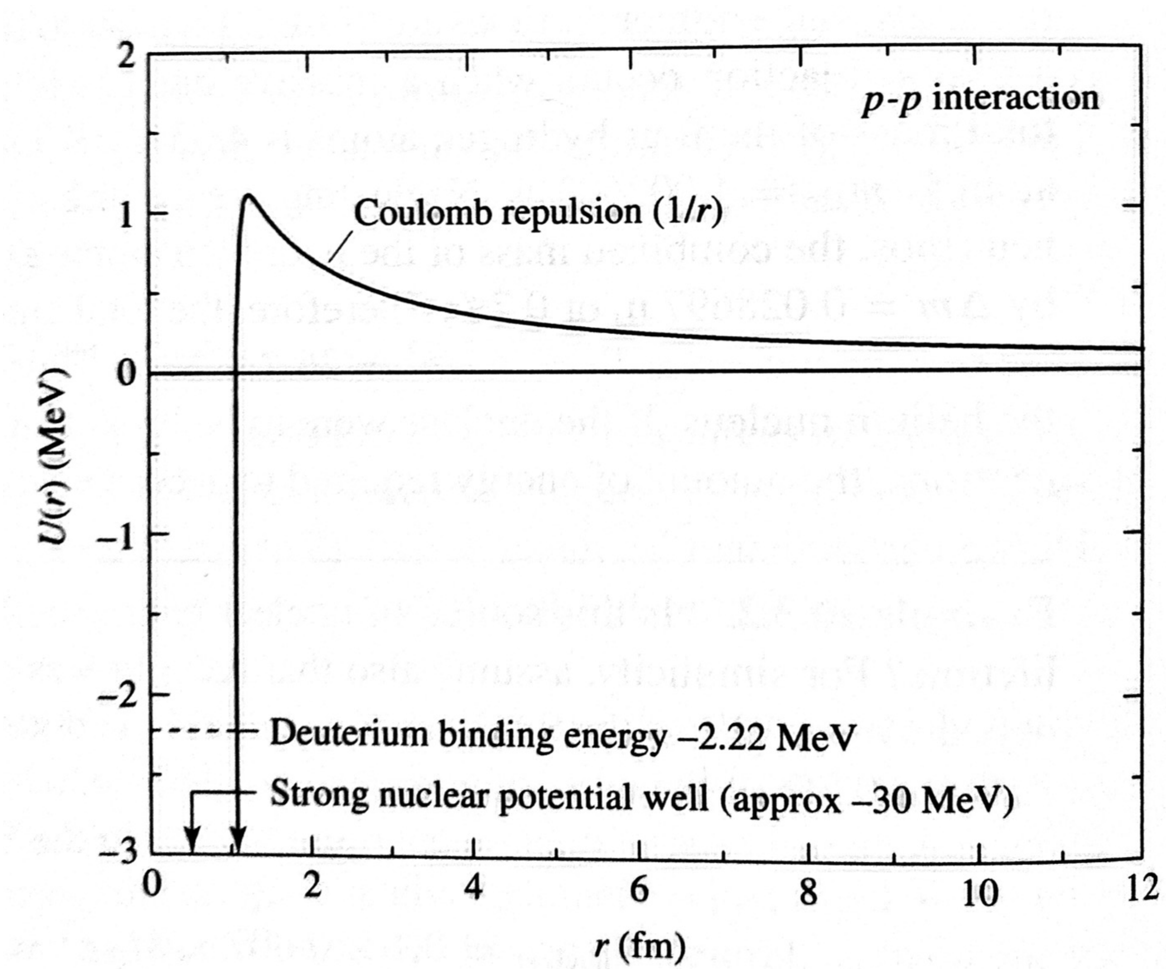

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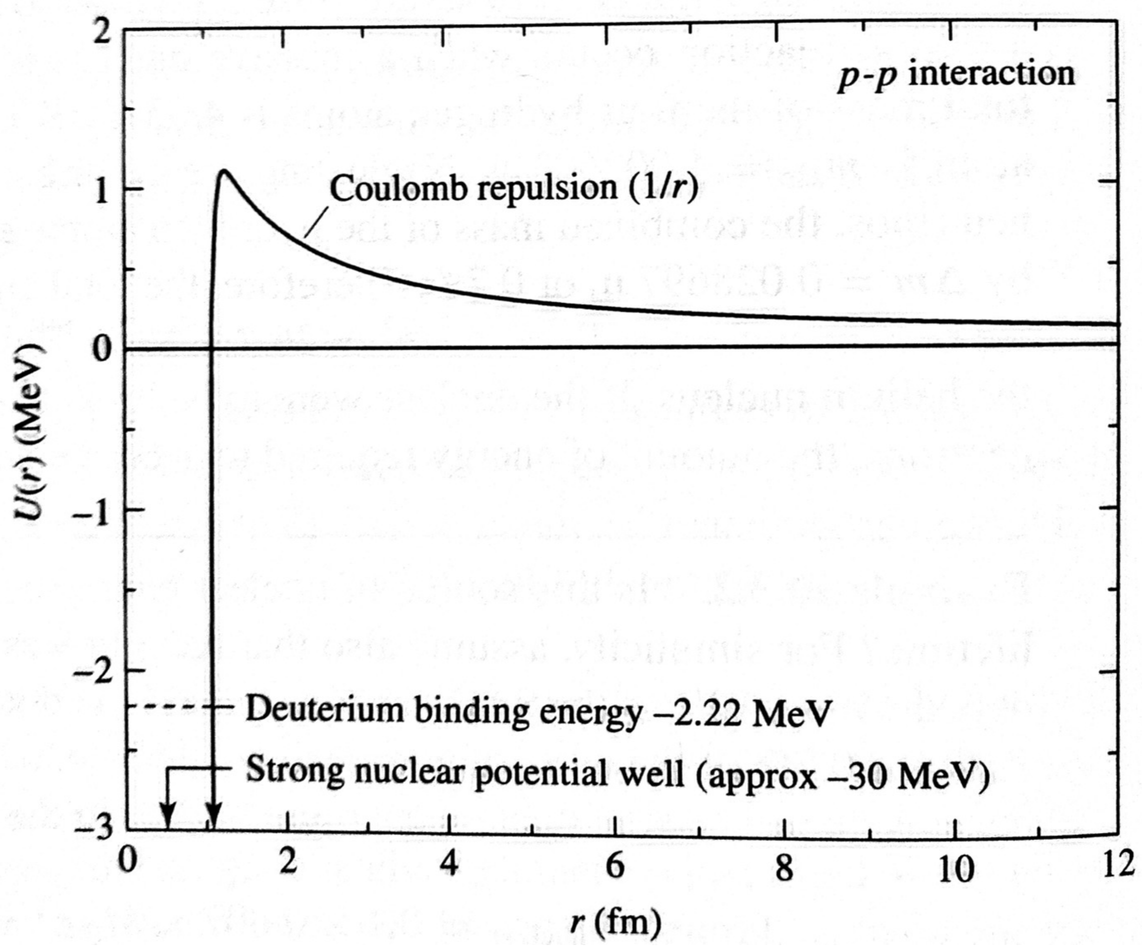

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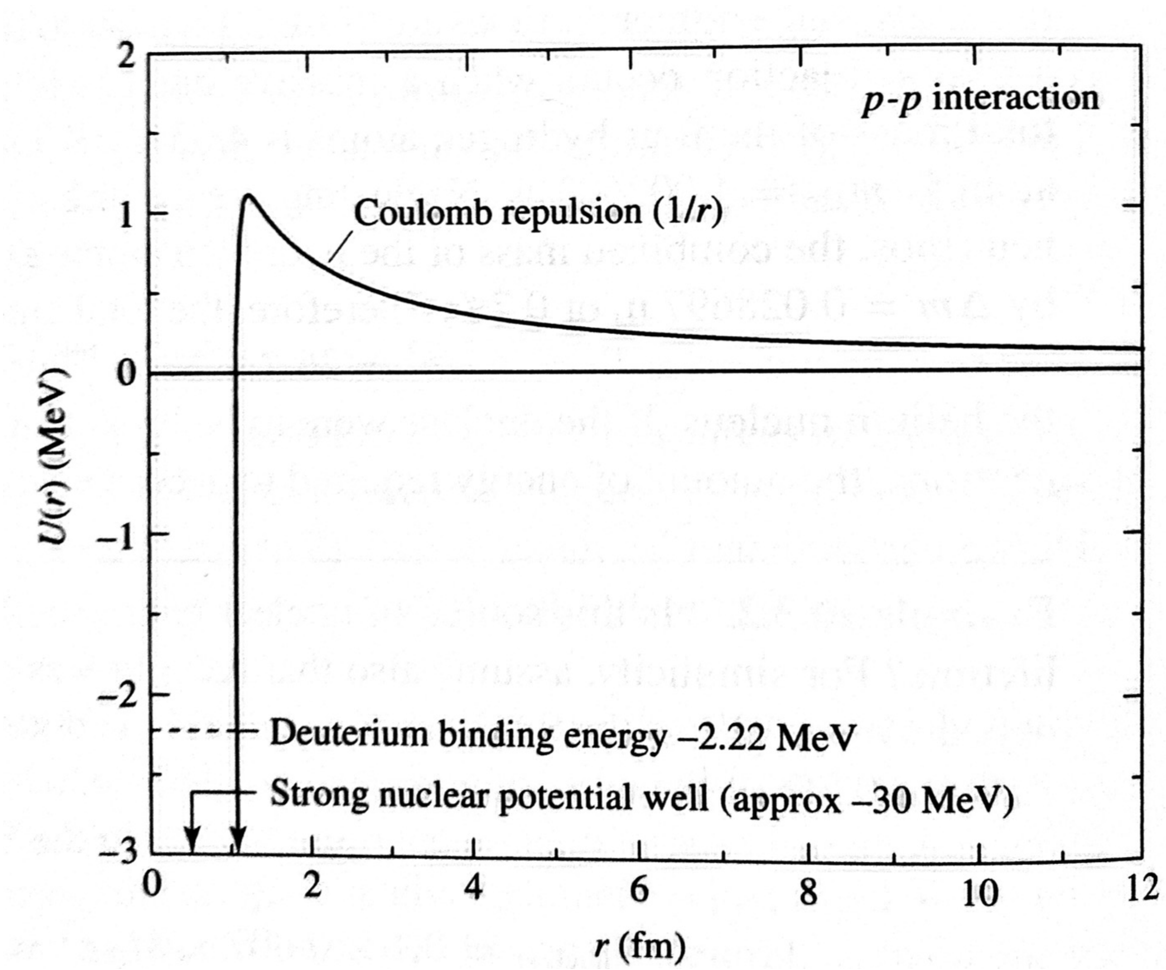

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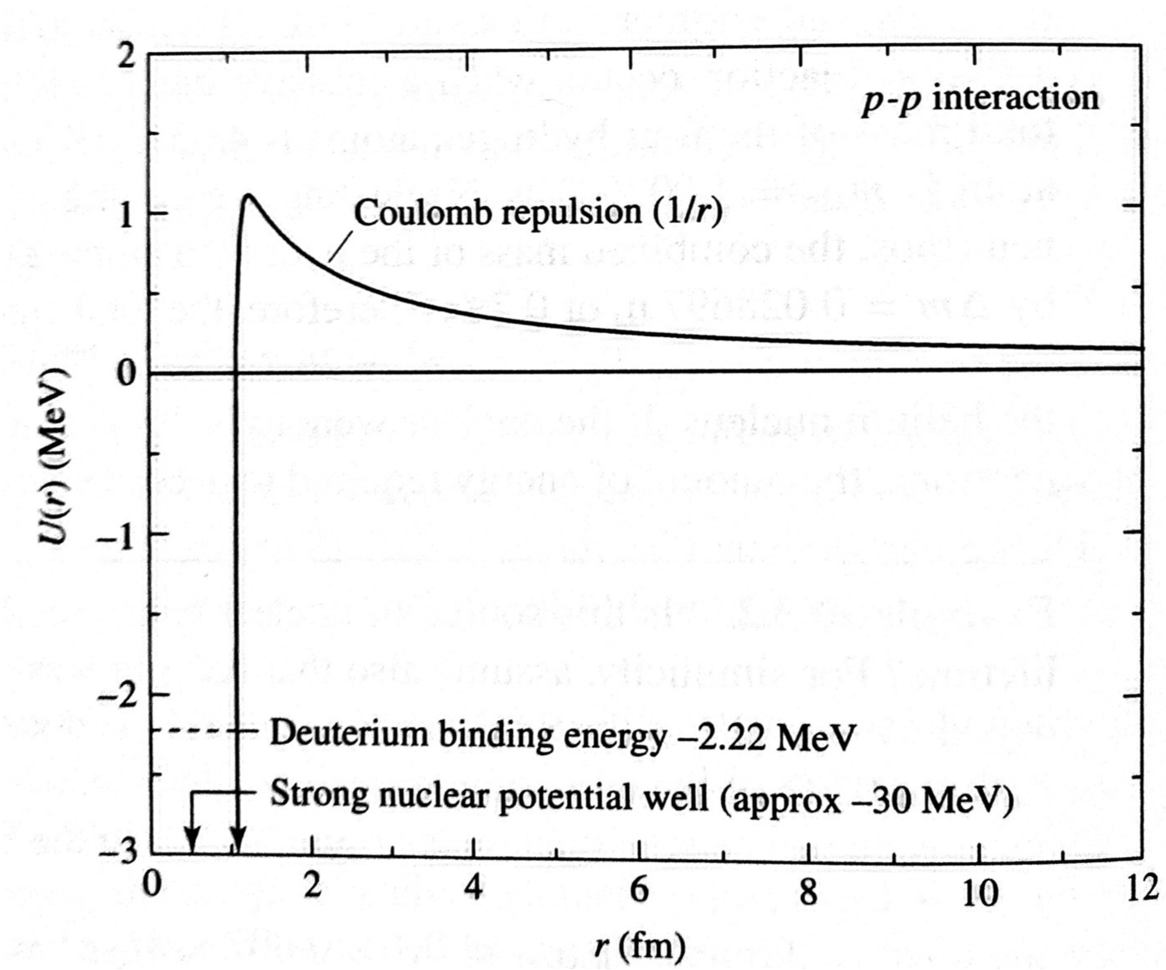

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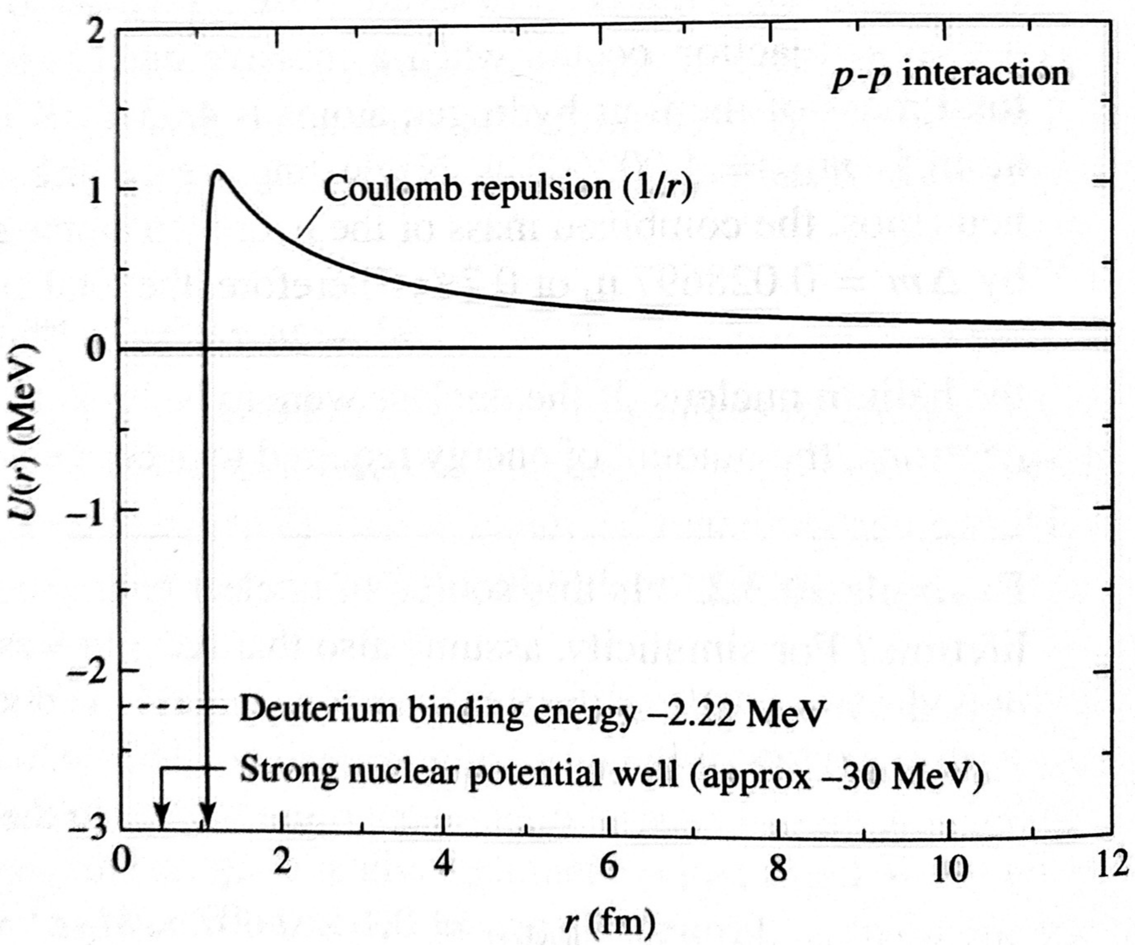

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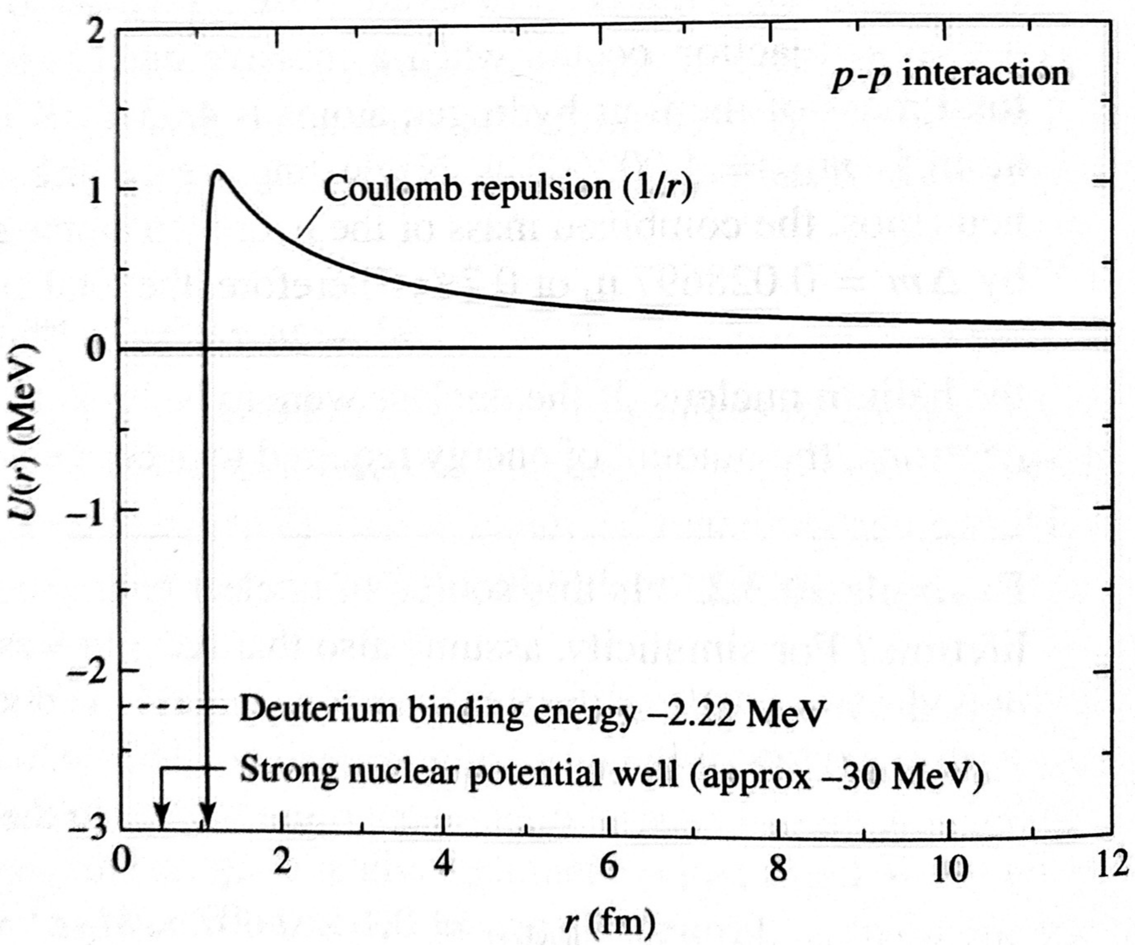

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For $Z_1 = Z_2 = 1$ (proton-proton)

$r \simeq 1$ fm $= 10^{-15}$ m

$\epsilon_0 = 8.854188 \times 10^{-12}$ F/m

$e = 1.60218 \times 10^{-19}$ C

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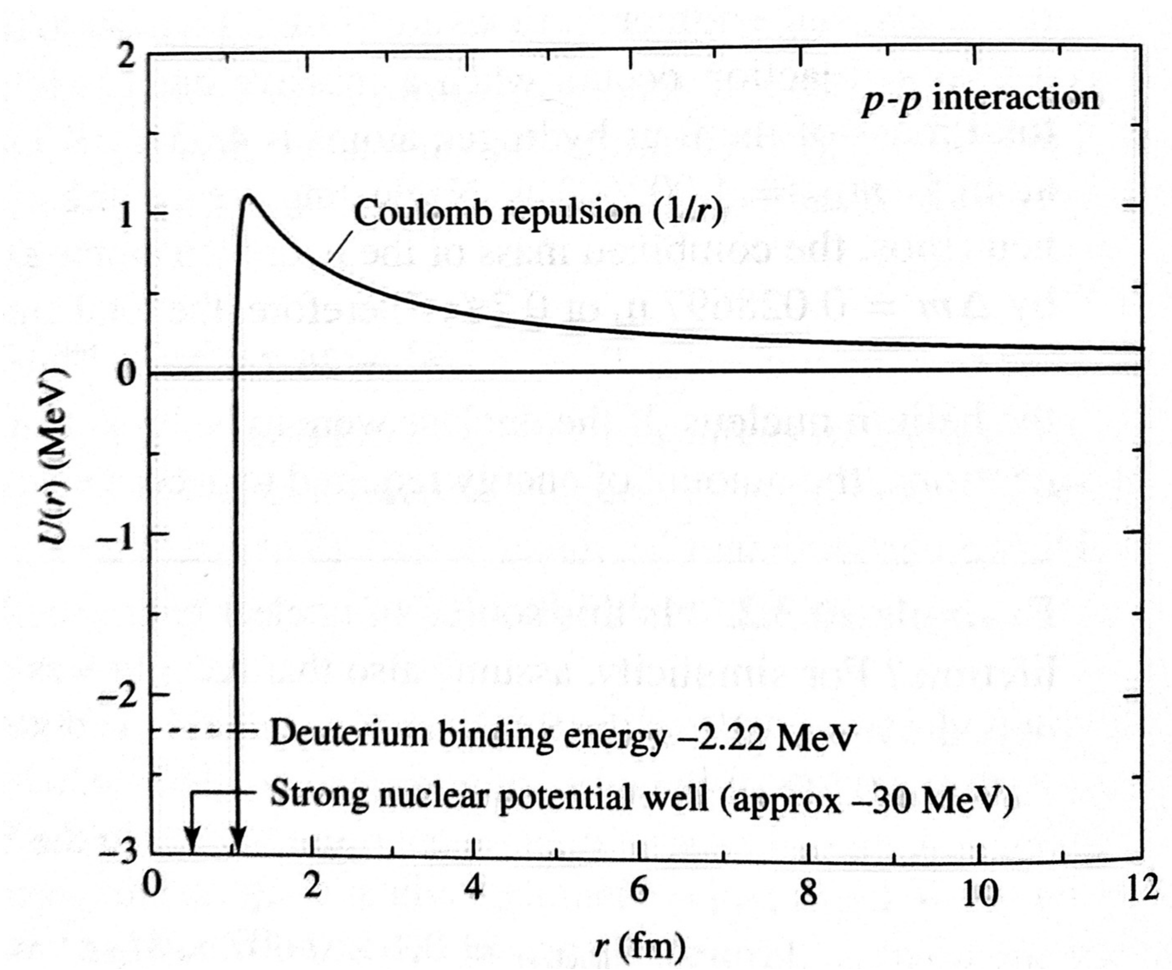

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$T_{classical}$ = 10^{10} K!!! >>> 10^7 K temperature of Sun in core, i.e., classical physics is unable to explain nuclear fusion in the Sun!!!

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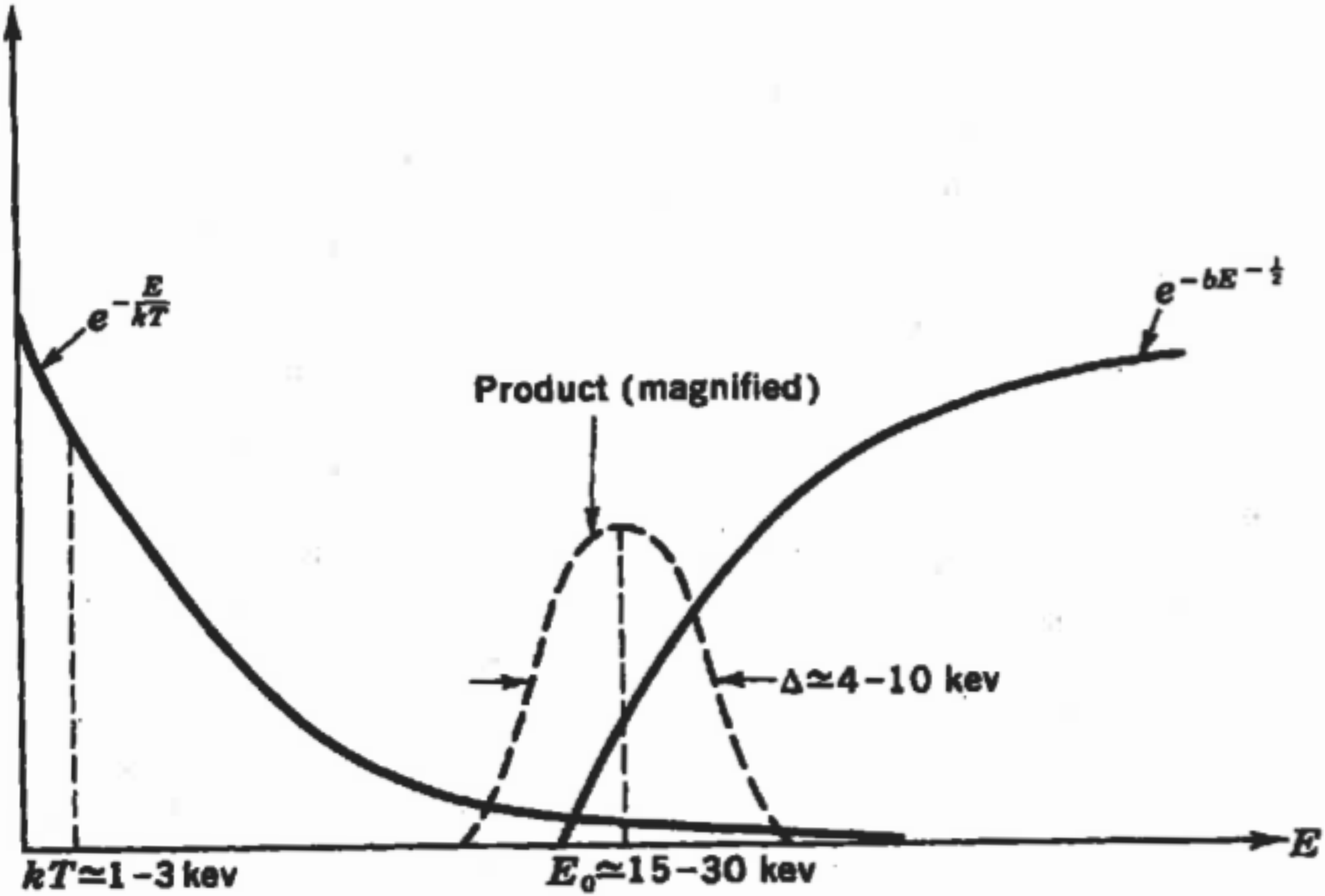
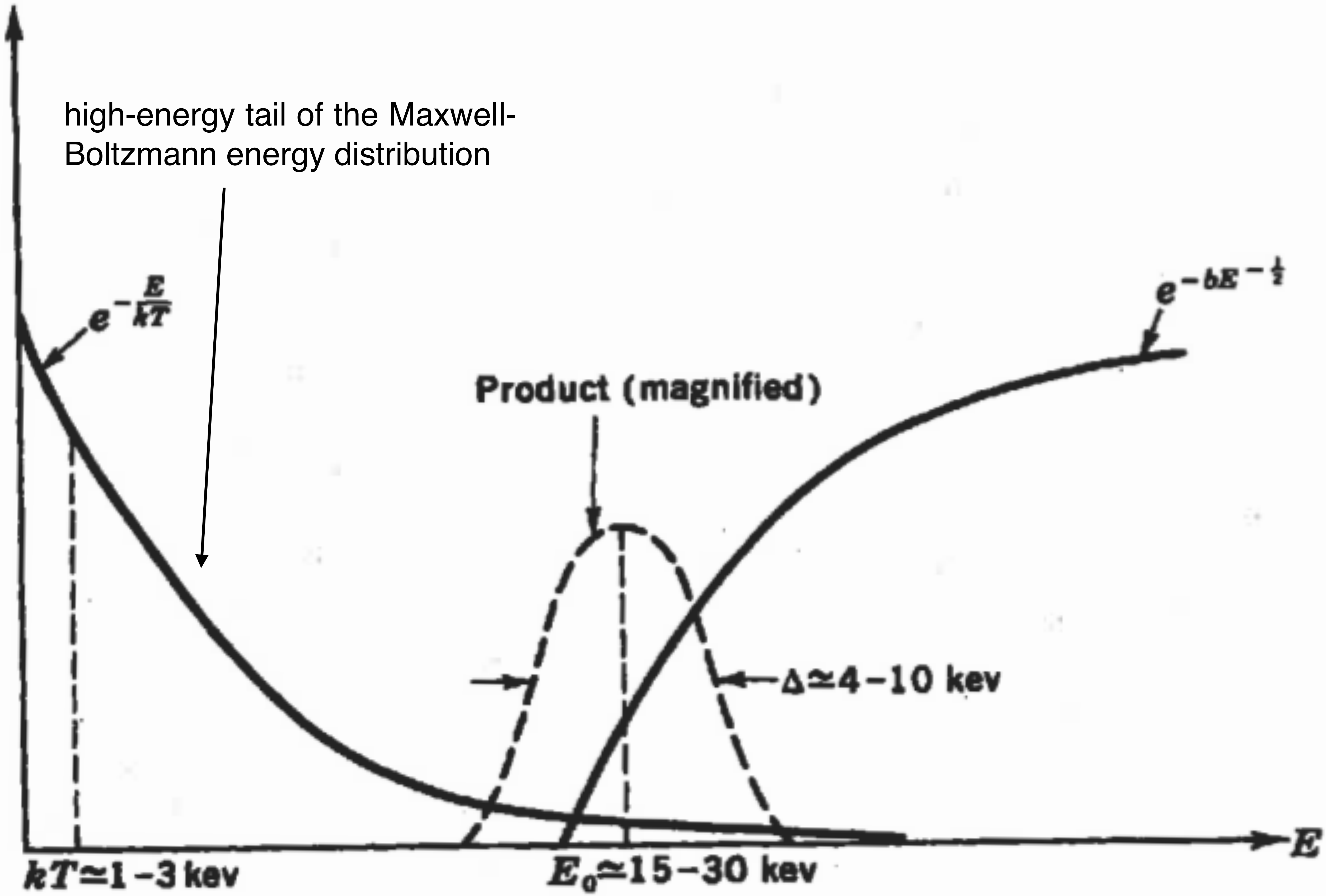
$$T_{quantum} = \frac{Z_1^2 Z_2^2 e^4 \mu_m}{12 \pi^2 \epsilon_0^2 h^2 K}, \quad w/ \ \mu_m = \frac{m_1 \cdot m_2}{m_1 + m_2}$$

If $p + p \longrightarrow T_{quantum} \simeq 10^7\,K$



$e^{-\frac{E}{kT}}$
$e^{-bE^{-\frac{1}{2}}}$
Product (magnified)
$\Delta \simeq 4-10$ kev
E
$kT \simeq 1-3$ kev
$E_0 \simeq 15-30$ kev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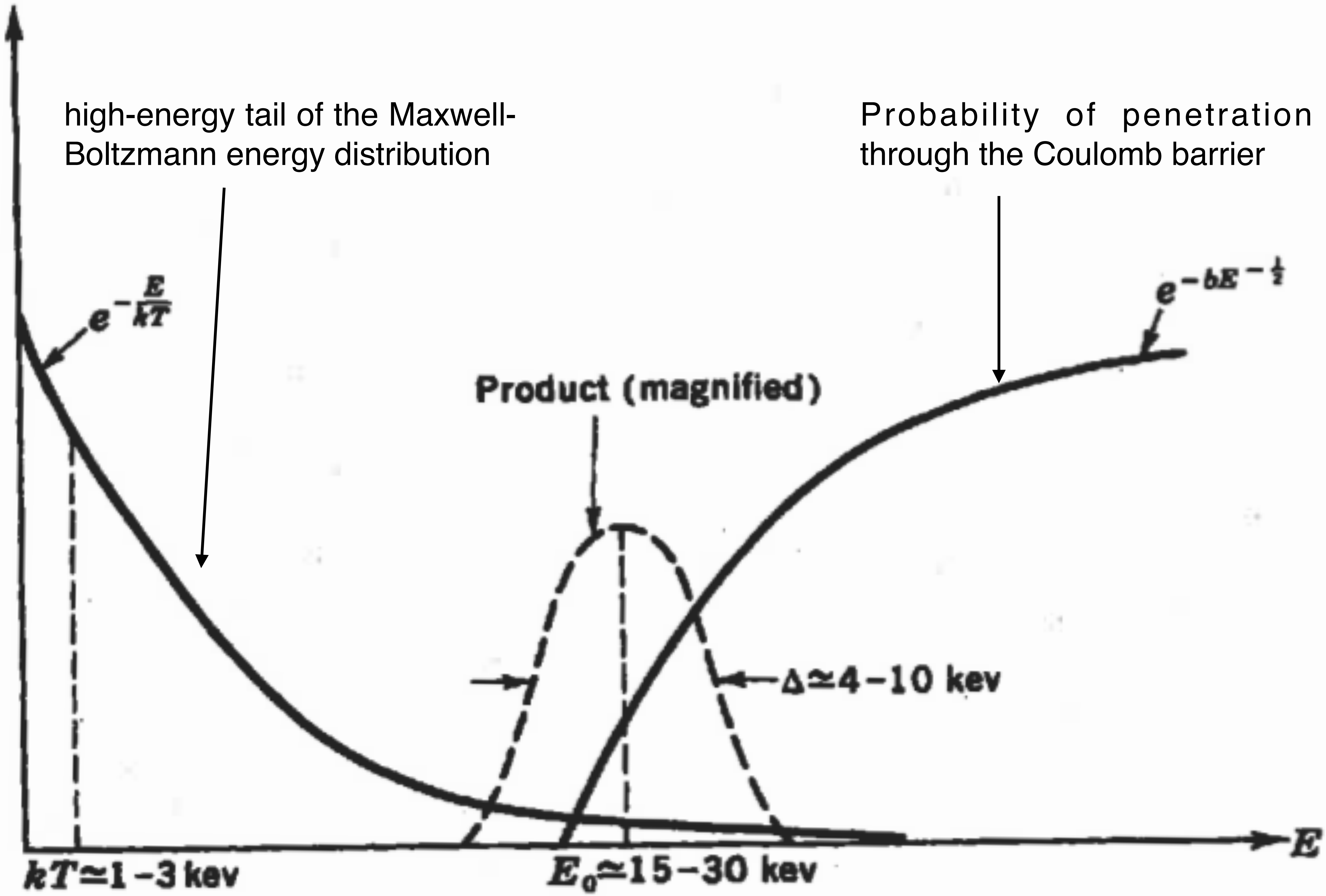

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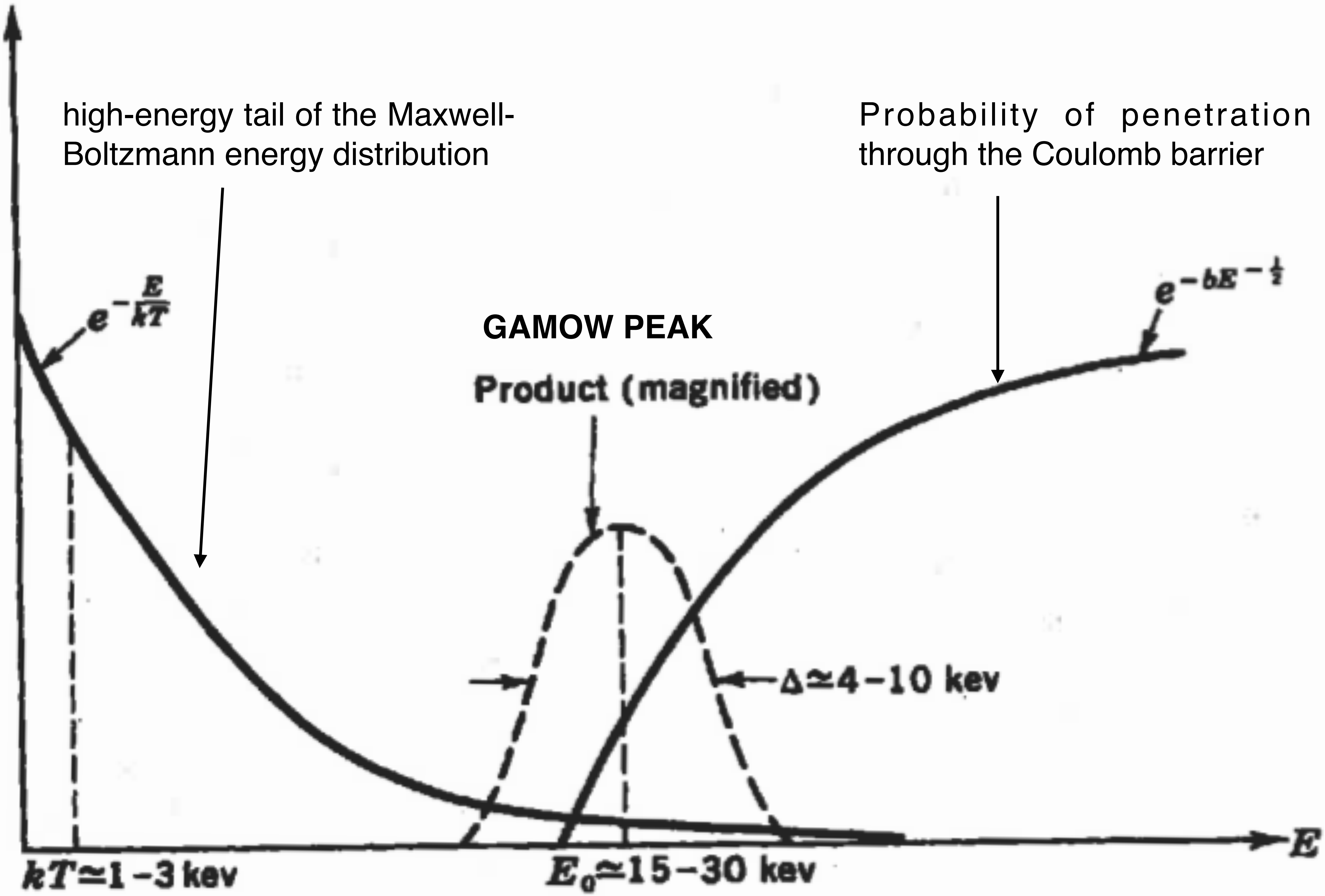
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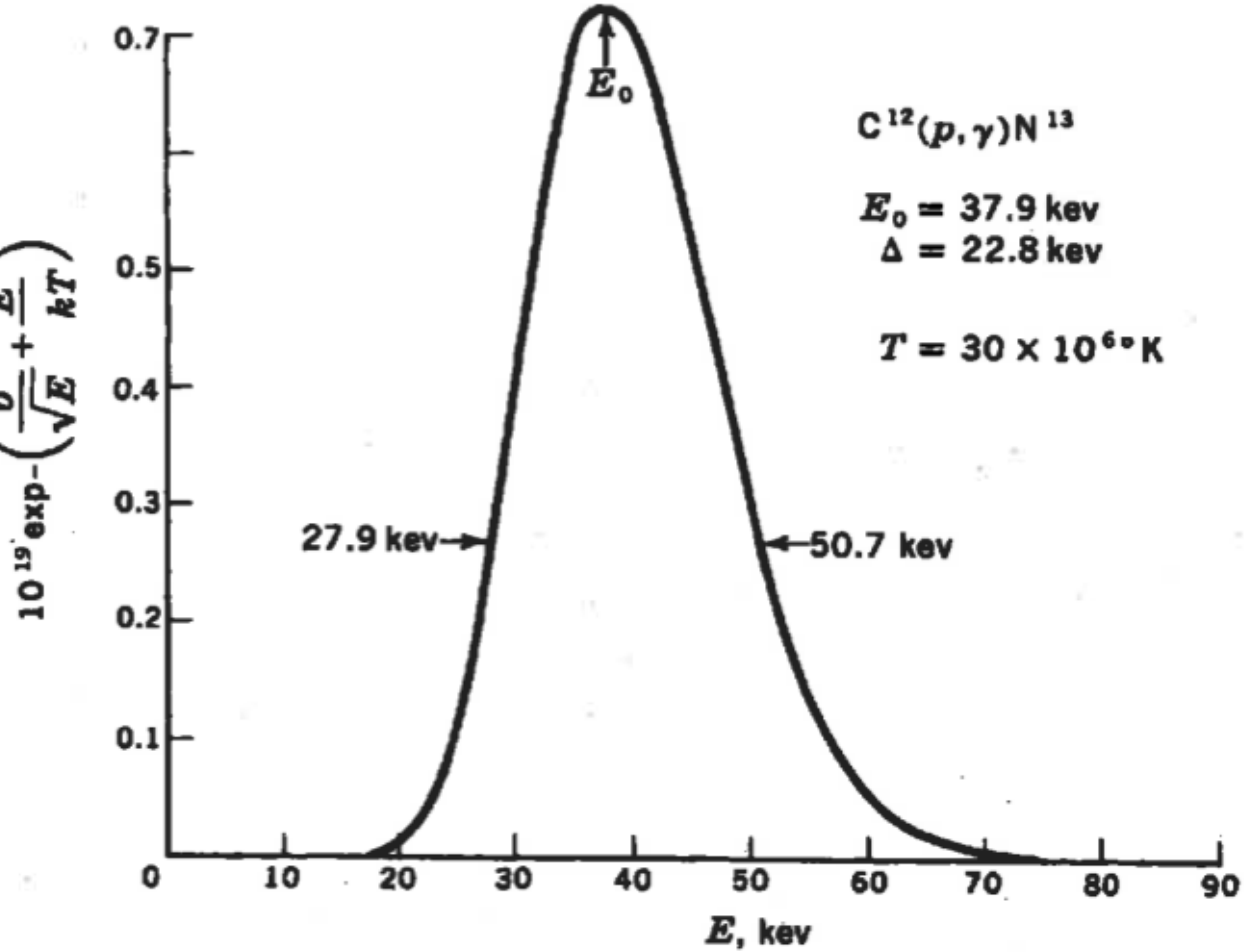

$C^{12}(p,\gamma)N^{13}$
$E_0 = 37.9$ kev
$\Delta = 22.8$ kev
$T = 30 \times 10^{6}$ °K
E_0
27.9 kev
50.7 kev
$10^{19} \exp-\left(\frac{b}{\sqrt{E}} + \frac{E}{kT}\right)$
0.7
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
70
80
90
E, kev

We can write the reaction rate r_{ix} (number of reactions per second per unit of volume) equation in the form of a power law centered at a particular temperature

$$r_{ix} \simeq \underbrace{r_0}_{\text{constant}} \underbrace{X_i X_x}_{\text{mass fractions of the two particles}} \rho^{\alpha'} T^{\beta}$$

$\alpha' \simeq 2$ (for a 2-body collision)

$\beta \simeq 1 \div 40+$

$$\Rightarrow \underbrace{\epsilon_{ix}}_{\text{energy liberated per second per Kg of material}} = \left(\frac{\overbrace{\varepsilon_0}^{\text{energy released per reaction}}}{\underbrace{\rho}_{\text{mass density}}}\right) r_{ix}$$

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The total nuclear energy generation rate is the sum over all reactions happening in the stellar interiors ϵ_{ix}

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Because the exponent is large, the major reactions are those for which $Z_1 Z_2$ is as small as possible. However, the major two-particle combinations (involving protons p_s and ^{4}He) have unstable ground states.

$$p + p \rightarrow He^2 \text{ (unstable)} \rightarrow p + p$$

$$p + He^4 \rightarrow Li^5 \text{ (unstable)} \rightarrow p + He^4$$

$$He^4 + He^4 \rightarrow Be^8 \text{ (unstable)} \rightarrow He^4 + He^4$$

The first thermonuclear reaction to proceed is $H^1 + D^2 \rightarrow He^3 + \gamma$

This converts deuterium D into ^{3}He during pre-main sequence contraction, hence the D is quickly exhausted, and its effect is to slow the contraction somewhat during the D-burning phase.

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Reactions converting H into He: p-p chains, CNO cycle

Proton-proton Reactions

$$H^1 + H^1 \longrightarrow He^2 \longrightarrow D^2 + e^+ + \nu_e \quad + \text{ 0.42 MeV of kinetic energy of } e^+ \text{ \& } \nu$$

$p \rightarrow n + e^+ + \nu_e$

(β^+ decay, ie: decay of p through weak interaction decay)

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

w/ 1.02 MeV

$\Downarrow$

total of 1.442 MeV

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NOTE: The 1.442 Mev is converted to local heat, of which <E>=0.262 MeV are carried away by the neutrinos.
Therefore, the average heat input from each reaction is 1.442 - 0.262 = 1.18 MeV.

PP I chain (~69% of times in the Sun)

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(C) $He^3 + He^3 \longrightarrow He^4 + 2H^1$

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slowest step because it involves the beta+ decay

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PP I chain (~69% of times in the Sun)

Many reactions proceed at a negligible rate, either because the cross sections are too small or the product of the abundances are too small.
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A and B happen twice: 4^{1}H (from 2A) + 2^{1}H (from 2B) —> ^{4}He + 2^{1}H

PP II chain (~31% of times in the Sun)

A + B

C_{II} $He^3 + He^4 \longrightarrow Be^7 + \gamma$

D_{II} $Be^7 + e^- \longrightarrow Li^7 + \nu\,(0.8\,\mathrm{MeV})$

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A + B + C_{II}

D_{III} $Be^7 + H^1 \longrightarrow B^8 + \gamma$

E_{III} $B^8 \longrightarrow Be^8 + e^+ + \nu_e\,(7.2\,\text{MeV average})$

β^+ decay

F_{III} $Be^8 \longrightarrow He^4 + He^4$

unstable

NOTE: PPI, PPII, PPIII have the same total energy released, but different amount of it is carried away by the neutrinos. For PPI is 2% (2x0.262/26.73); for PPII is 4% (0.262+0.8/26.73); and for PPIII is 27.9% (0.262+7.2/26.73).

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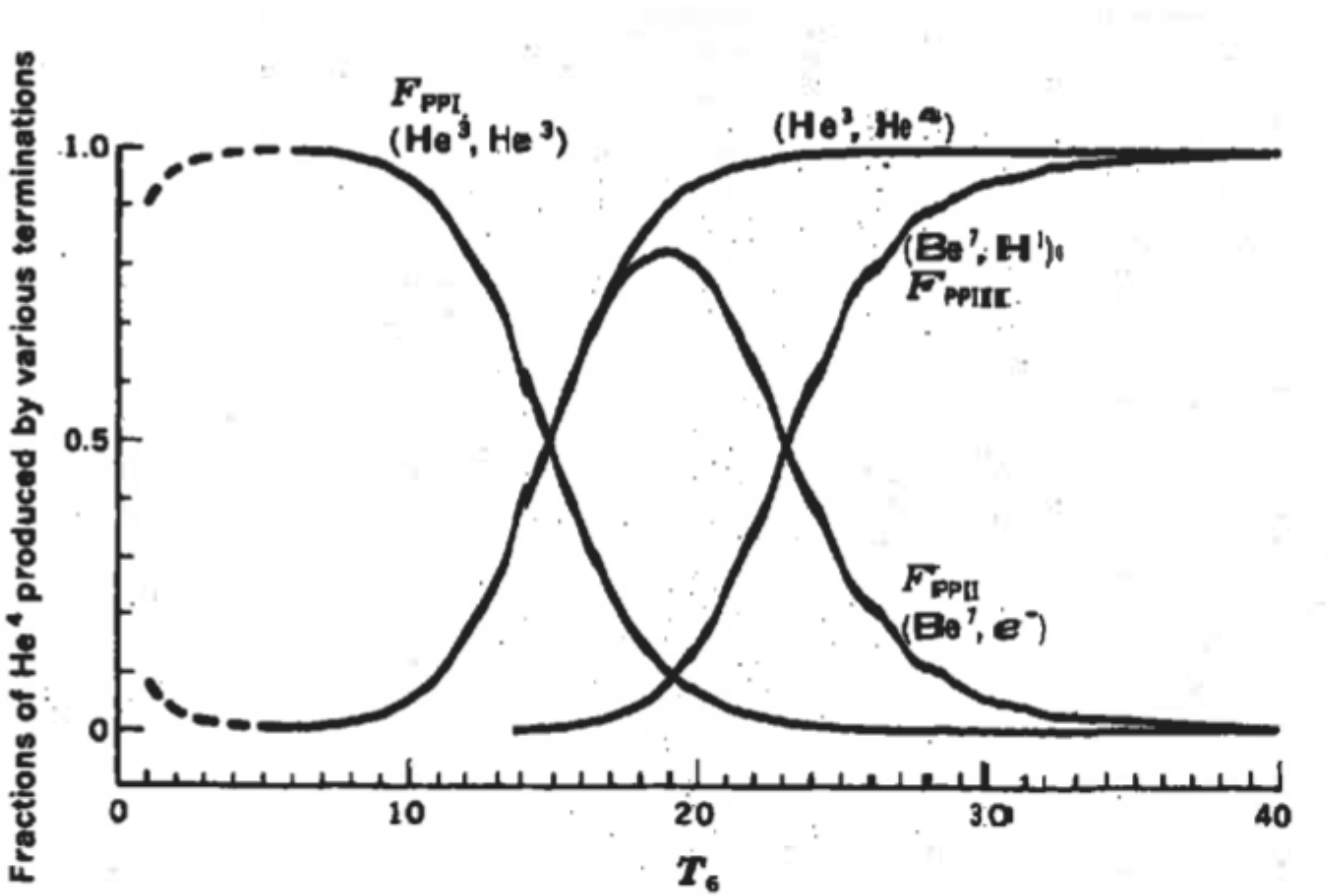

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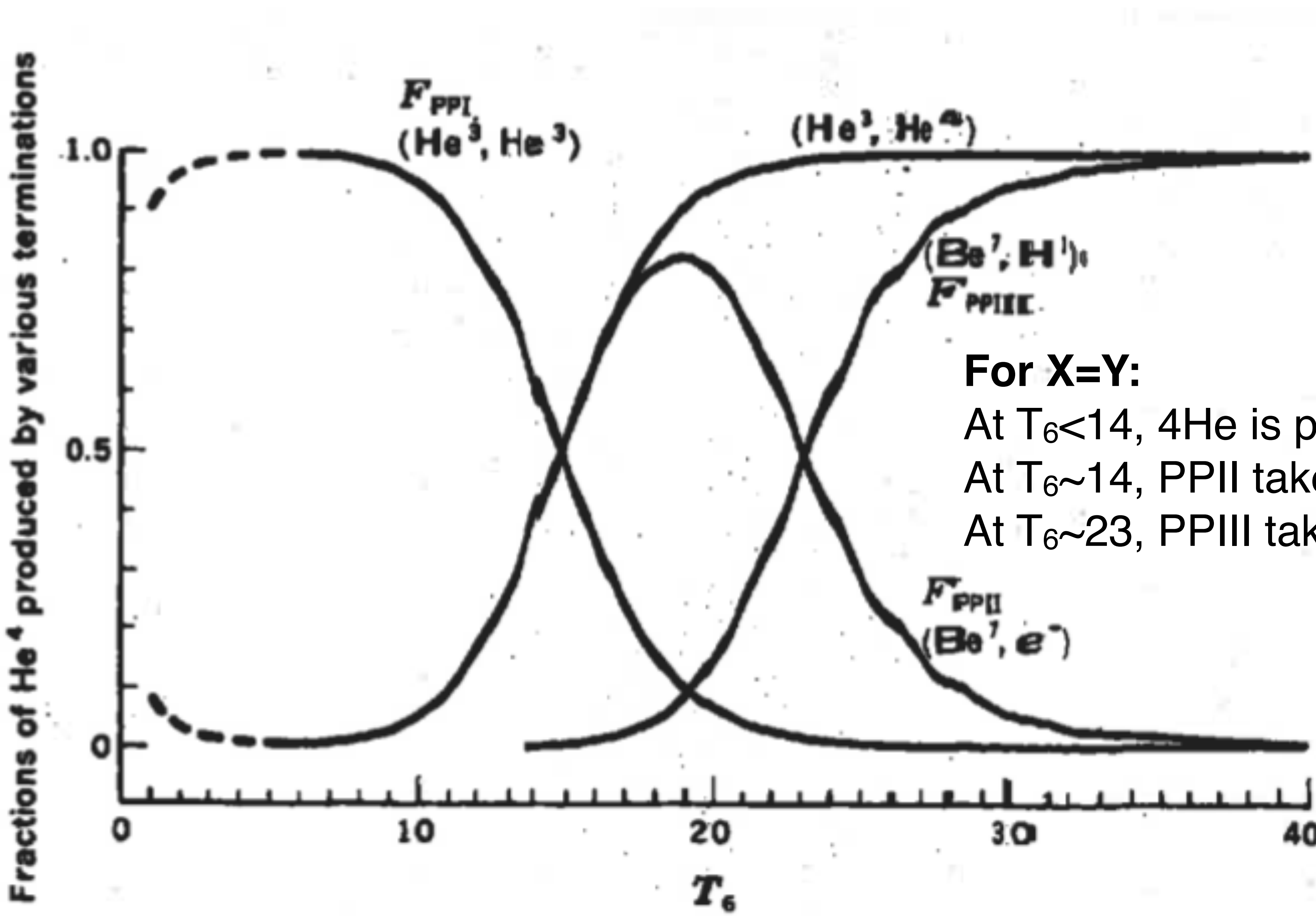

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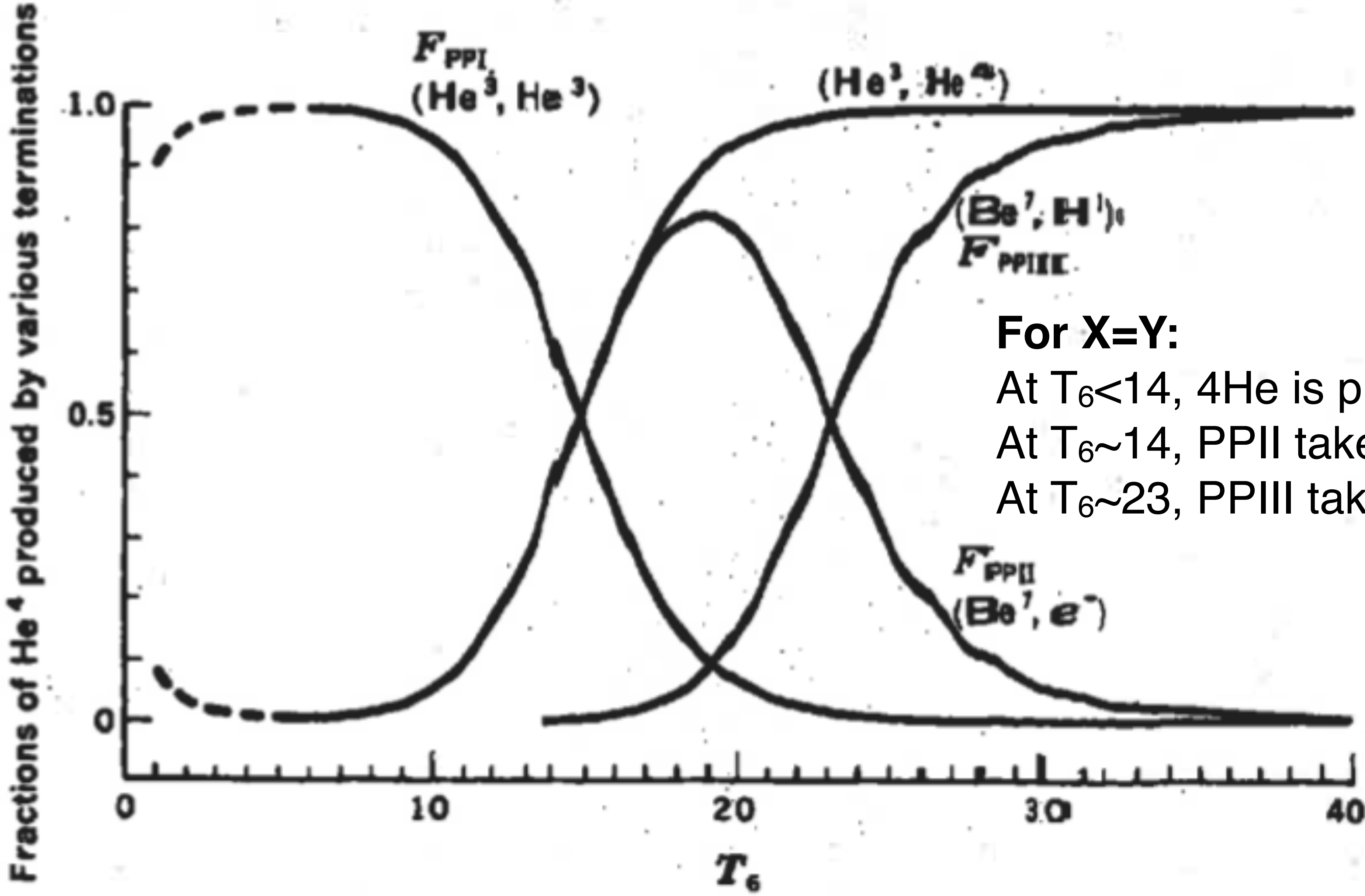

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NOTE: **X=0.74, Y=0.28 and $T_{Sun,6}$=16**

NOTE: The following is the major source of solar neutrinos of sufficiently high energy to be absorbed efficiently

$$B^8 \longrightarrow Be^8 + e^+ + \nu_e$$

$$Be^7 + e^- \longrightarrow Li^7 + \nu_e$$

$$\phi_\nu(Be^7) = (1.2 \pm 0.5)\, 10^{10} \ \#/cm^2 s$$ neutrino flux

$$\phi_\nu(B^8) = (2.25 \mp 1)\, 10^{7} \ \#/cm^2 s$$

$$\phi_\nu(Be^7) = 500\, \phi_\nu(B^8)$$

BUT those from ^{8}B are more capable of producing detection in experiments on Earth

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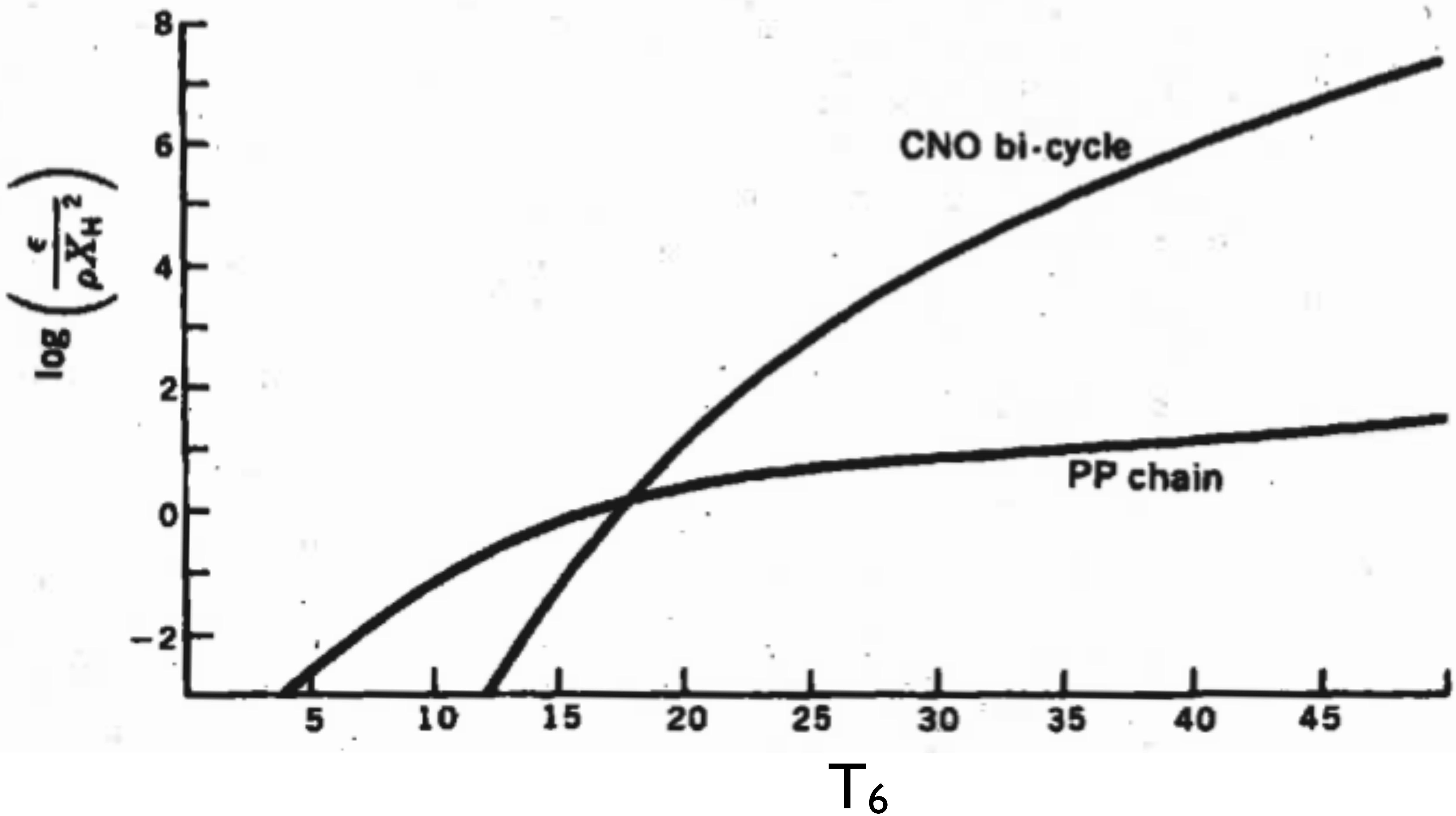
$T_6 \sim 25$ is the characteristic temperature of most CNO burning (upper main sequence stars)

In most H-burning stars, the PP chains and the CNO bi-cycle operate simultaneously. Which of the two dominates the energy generation depends on the relative abundance of H and CN nuclei and on the temperature.

For Solar Z=0.02, the CNO cycle takes over the PP chains at T_6~18.



Low-mass stars, with smaller central T, are dominated by the PP chains during the H burning evolutions, whereas more massive stars, with higher central T, convert H into He with the CNO cycle.

$$P = \frac{\rho K T}{\mu m_H}$$

When H is converted into He, the mean molecular weight of the gas increases, hence if T and the mass density remain the same, the pressure of the gas decreases, and the star would no longer be in hydrostatic equilibrium and contraction would begin. The contraction raises both the T and mass density, compensating the increase of the mean molecular weight.

H-burning in stars is found to occur as the central source of energy for main-sequence stars, and as a shell source in later stages of stellar evolution.

He Burning, a.k.a., 3-alpha reaction

The present ratio $^4He/H \sim 0.1$ (in number) is the result of H-burning in early cosmological stages followed by ~13 Gyr of star formation, death, and remixing.
There are no stable nuclei with A=5 and A=8, forbidding the fusion of two ^4He into an A=8 nucleus.
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$$\epsilon_{3\alpha} \propto \rho^2 Y T_8^{41}$$

Very dramatic temperature dependence: even small increase in T will produce a large increase in the amount of energy generated per second. In a stellar center supported by e$^-$ degeneracy, the onset of the He burning is accompanied by an explosive reaction, the Helium Flash.

Nucleosynthesis during the He burning

"C" burning : $C^{12} + He^{4} \longrightarrow O^{16} + \gamma$

"O" " : $O^{16} + He^{4} \longrightarrow Ne^{20} + \gamma$

"Ne" " : $Ne^{20} + He^{4} \longrightarrow Mg^{24} + \gamma$

$\vdots$

Continued successive alpha-particle captures can occur in principle, but the increasing Coulomb barrier severely limits the number of alpha-particle captures at temperatures low enough for some ^{4}He still to remain.

^{12}C and ^{16}O are produced in significant amounts by stars of moderate mass. The final product is almost entirely ^{16}O for M>10 M_{Sun} stars. ^{20}Ne is produced appreciably only at high temperatures, i.e., for massive stars M>>20 M_{Sun} (during ^{4}He burning in a star with M=15 M_{Sun}, the final weight of ^{20}Ne at the center is only 1%).

He burning happens in giant stars and in horizontal branch stars (in the HR diagram).

The product of nucleosynthesis during He burning is quite uncertain, and causes a corresponding uncertainties in the subsequent evolution of the star. If ^{12}C is a substantial remnant, the next nuclear burning phase will be from interactions of ^{12}C with itself. If little ^{12}C is produced, that burning phase will be omitted, and the star wil progress directly from He to ^{16}O burning.

Advanced burning stages

When the burning ceases to provide sufficient power to the star, gravitational contraction begins again. From the virial theorem, T of the He-exhausted region rises during contraction, until T and density are high enough for the next nuclear burning stage, or electron degeneracy halting contraction.

Stars with $M>0.7\ M_{Sun}$ can contract until T is large enough for carbon to interact with itself, while less massive stars settle into degenerate white-dwarf configurations.

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\begin{aligned}
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\bullet\ & Ne^{20} + \alpha \\
& Mg^{23} + n \\
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$T \sim 6\text{-}7 \times 10^8 K$

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By the end of C burning, the initial 12C nuclei have been converted into ^{16}O, ^{20}Ne, ^{23}Na, ^{24}Mg, ^{28}Si (through also alpha-capture by ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg)

NOTE: Reactions between ^{12}C and ^{16}O are not important, since the larger Coulomb barrier makes the rate too slow to be important at the C-burning temperatures, while ^{12}C is completely exhausted when T gets large enough.

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NOTE: Photo-disintegration of ^{20}Ne happens at the same temperature. The major final nucleus synthesized appears to be ^{28}Si. Neutrino losses will be high during the O-burning phases, so much that most of the generated energy is radiated as neutrino luminosity. Because of this, O-burning happens at T>10^{9}K to replace the heavy neutrino losses.

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At $T>1.3\times10^9$K, the rate of ^{20}Ne photo-disintegration becomes greater than the rate of ^{20}Ne production ($^{16}O+{}^4He \longrightarrow {}^{20}Ne$ + photons) ==> ^{20}Ne is effectively disintegrated. The liberate ^4He is likely capture by the remaining ^{20}Ne: $^{20}Ne + {}^{20}Ne \longrightarrow {}^{16}O + {}^{24}Mg$.
[what ^{20}Ne is observed in nature was produced by C burning in a shell surrounding an even more advanced core]

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At the conclusion of O burning, the gas continues to heat up. Subsequent nuclear reactions are primarily of a re-arrangement type, i.e.: a particle is photo-ejected from one nucleus and capture by another ==> converting nuclear particles to their most stable forms.

Binding energy: $E_b = \Delta m c^2 = \left[Z m_p + (A - Z) m_H - m_{nucleus} \right] c^2$

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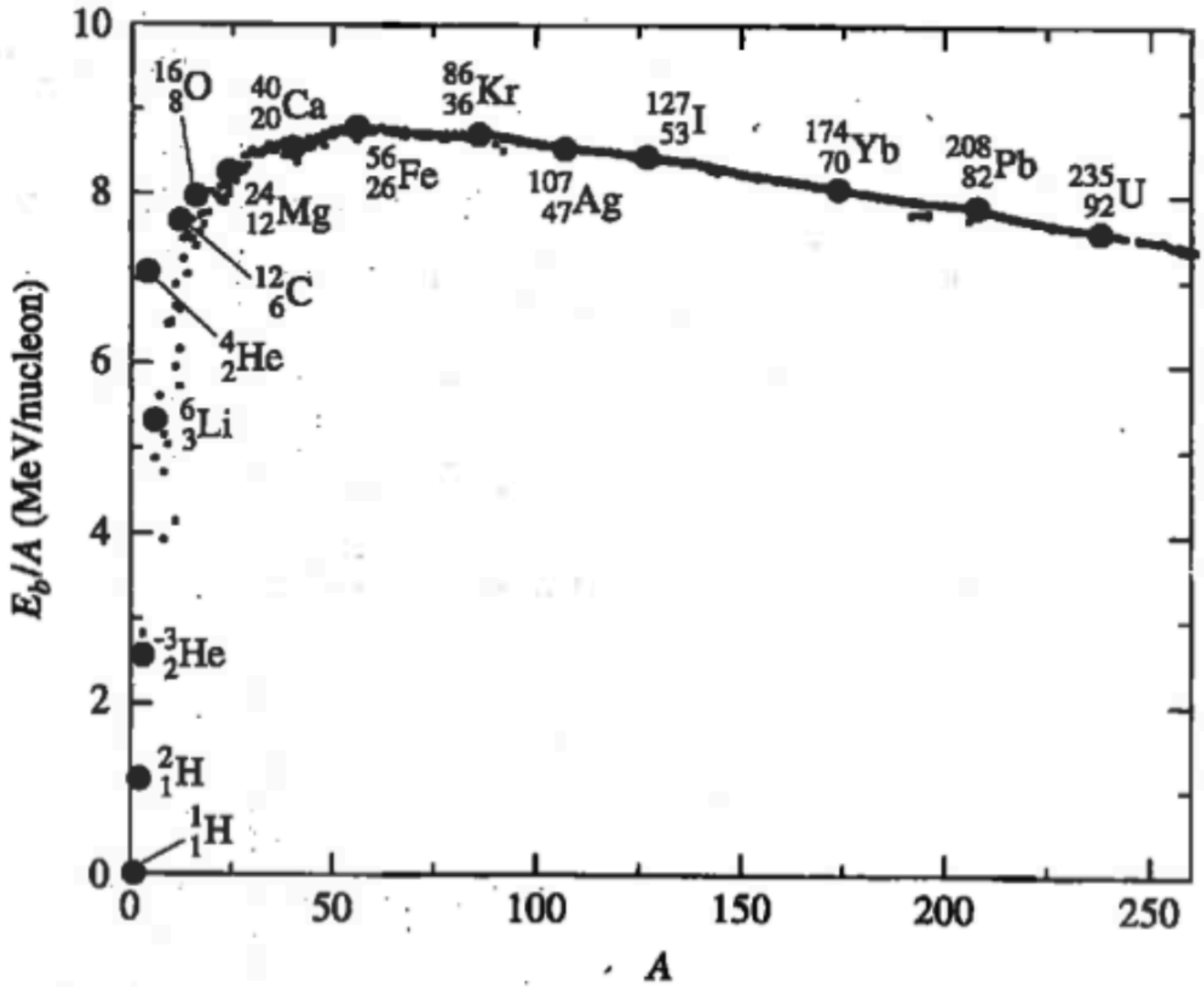
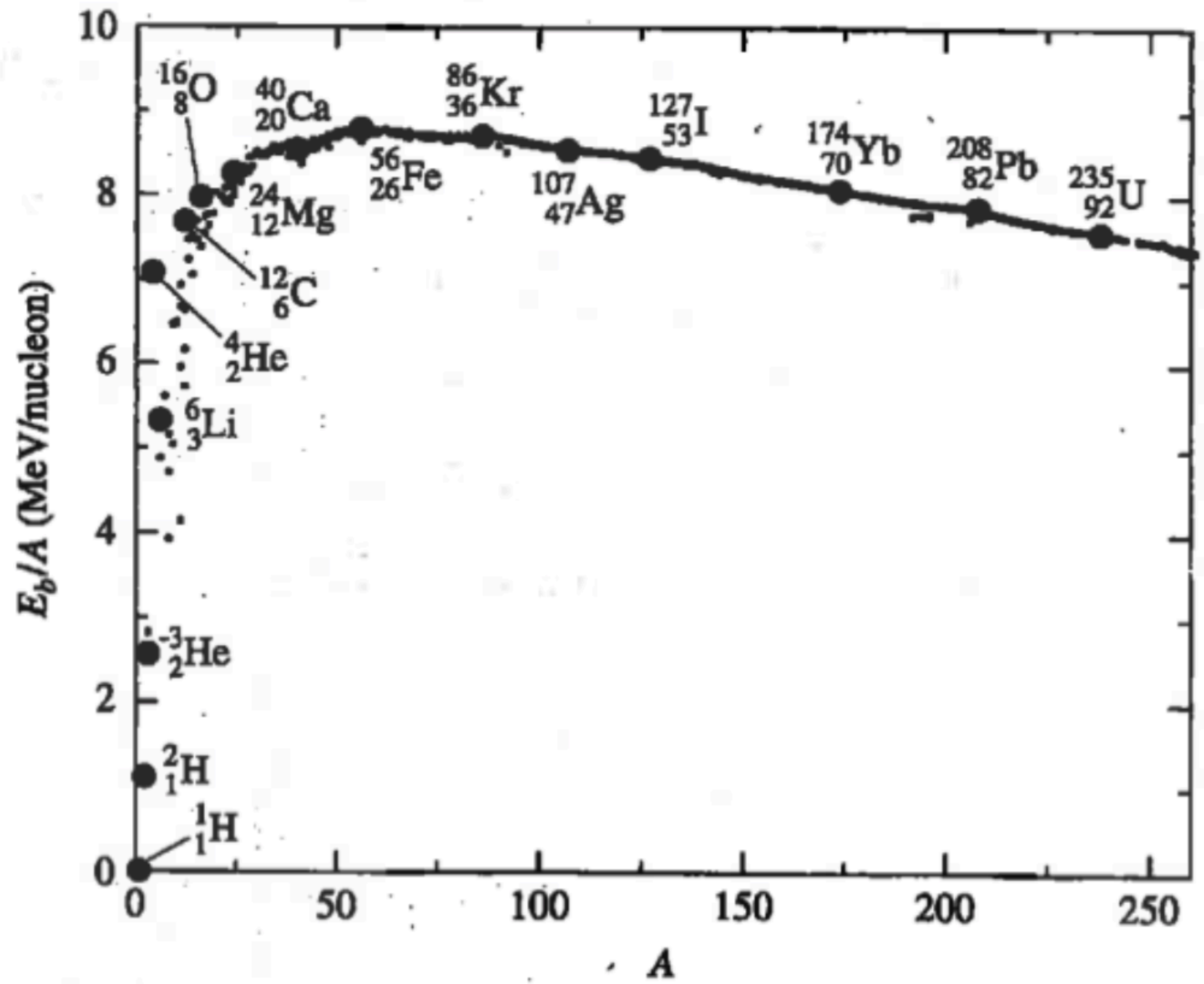


^4He, ^{12}C, ^{16}O are unusually stable nuclei relative to other of similar mass, and are the most abundant elements in the universe, along with H.



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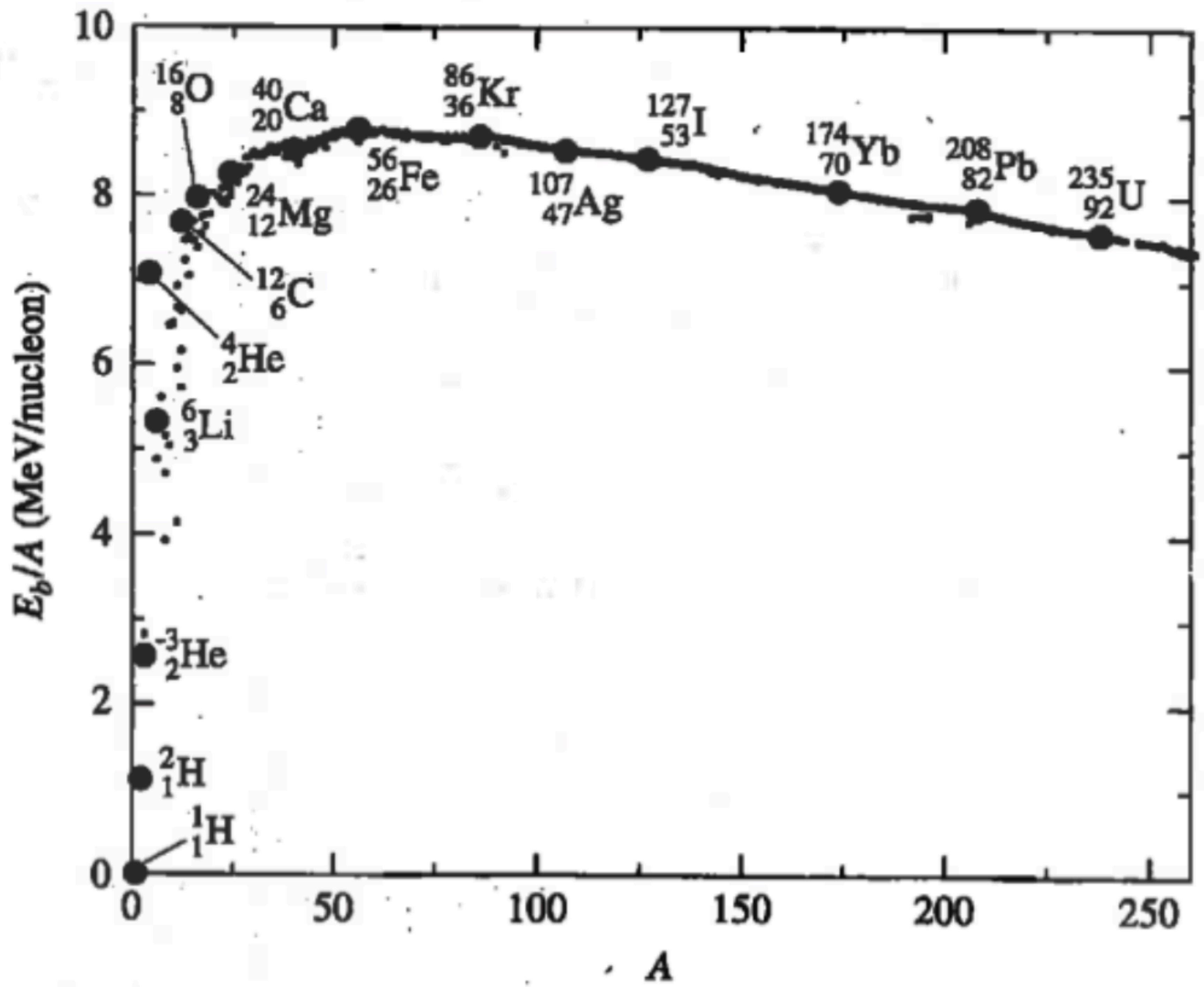
There is a maximum in E_b/A at ^{56}Fe —> the re-arrangement attempts to convert O-burning remnants into nuclei in the vicinity of ^{56}Fe. The timescale of this is controlled primarily by the photo-disintegration of ^{28}Si.



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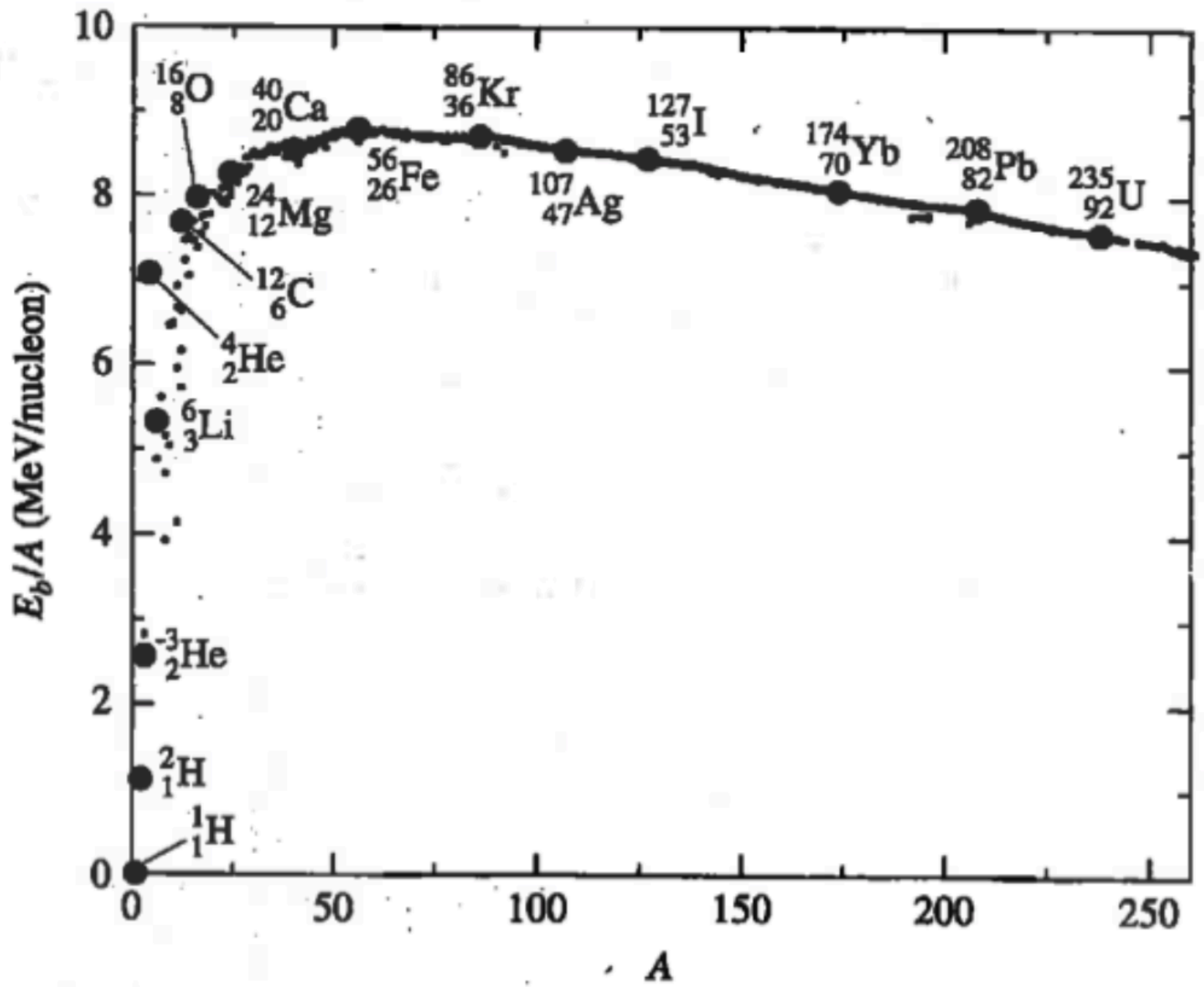

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The most abundant nuclear species in the universe are ^{1}H, ^{4}He, ^{16}O, ^{12}C, ^{20}Ne, ^{14}N, ^{24}Mg, ^{28}Si, and ^{56}Fe, the result of the dominant nuclear reaction processes occurring in stars.

From stellar spectra, the atmospheres of most stars are made of H ($X=0.70$) and metals $Z<0.03$. The first nuclear reactions (when the stars are on the main sequence) convert H—>He (pp chains, CNO cycle). Since most stars have similar compositions, the structures of stars vary smoothly with mass.

As M increases, P_C and T_C increase.

For stars or low mass, the pp chain will dominate since less energy is required to initiate these reactions than the reactions of the CNO cycle. For high-mass stars, the CNO cycle will likely dominate because of its very strong temperature dependence.

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Stars with $M>90\ M_{Sun}$ become subject to thermal oscillations in the center that may produce significant variations in the nuclear energy generation rates over timescales as short as 8 hours!

Stellar Structure

Reading assignment
TUESDAY 11/3: 10.6+13.1

Homework Assignment #4 due by:
TUESDAY 11/10 before beginning of class

MIDTERM EXAM: THURSDAY Nov. 12