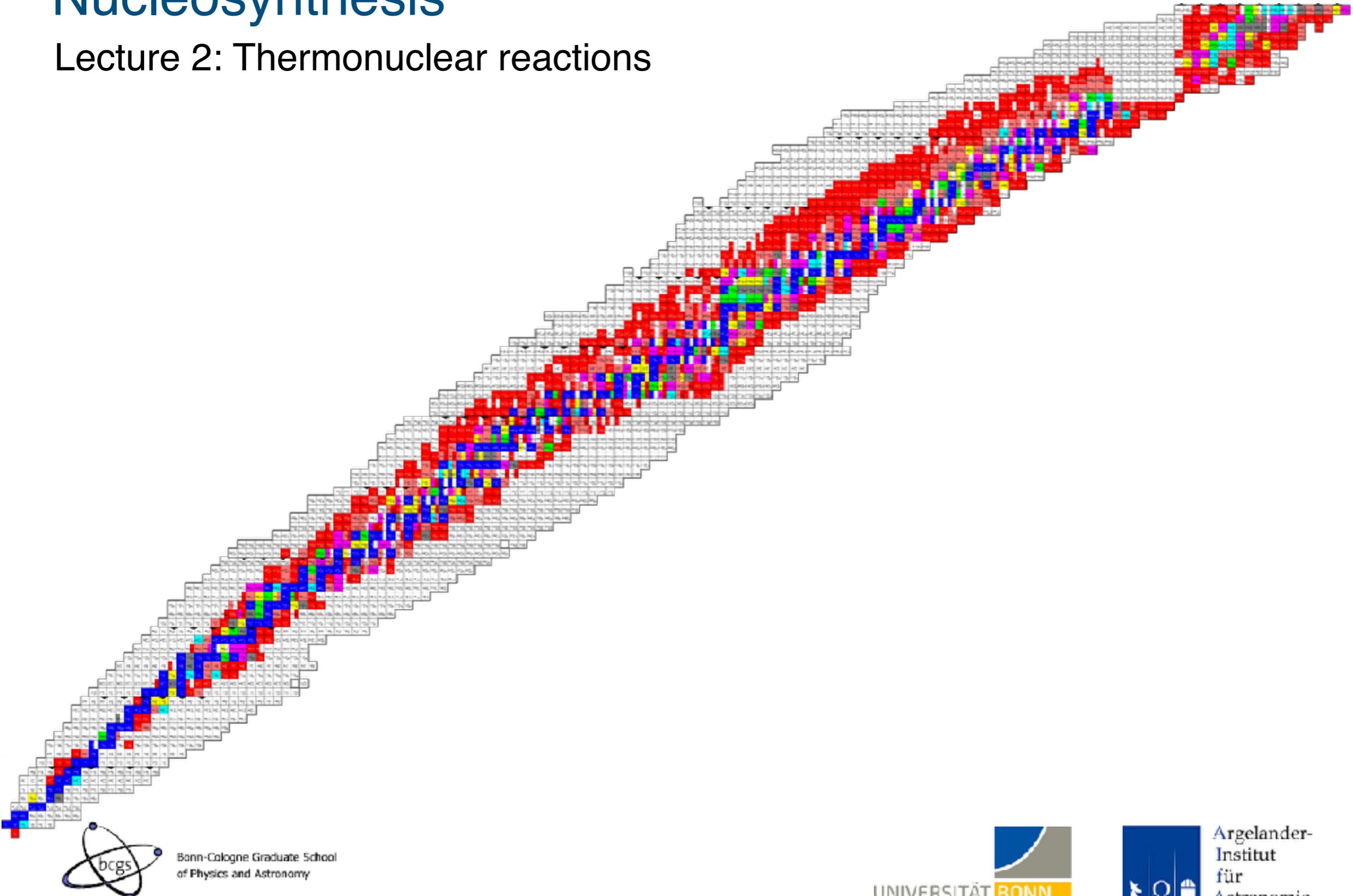


Nucleosynthesis

Lecture 2: Thermonuclear reactions



Bonn-Cologne Graduate School
of Physics and Astronomy



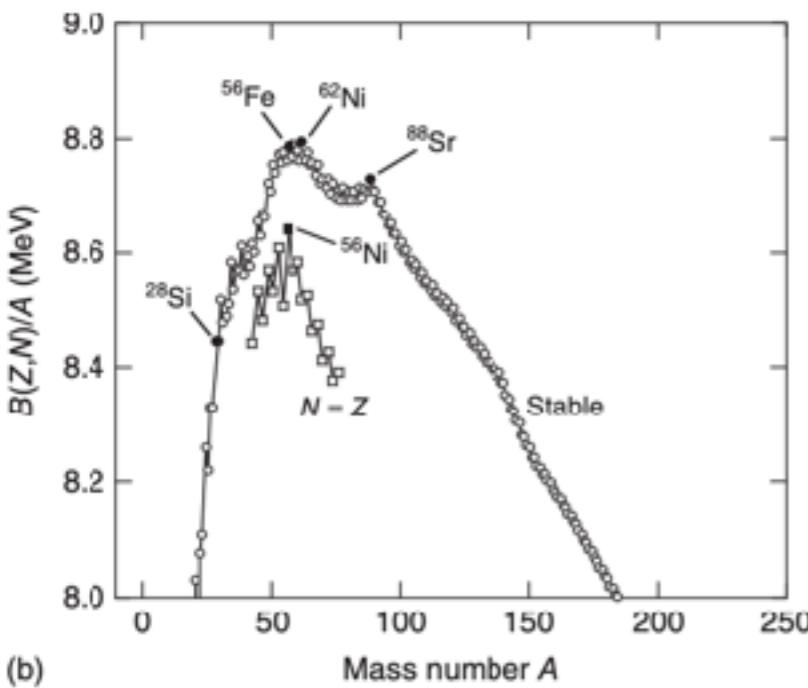
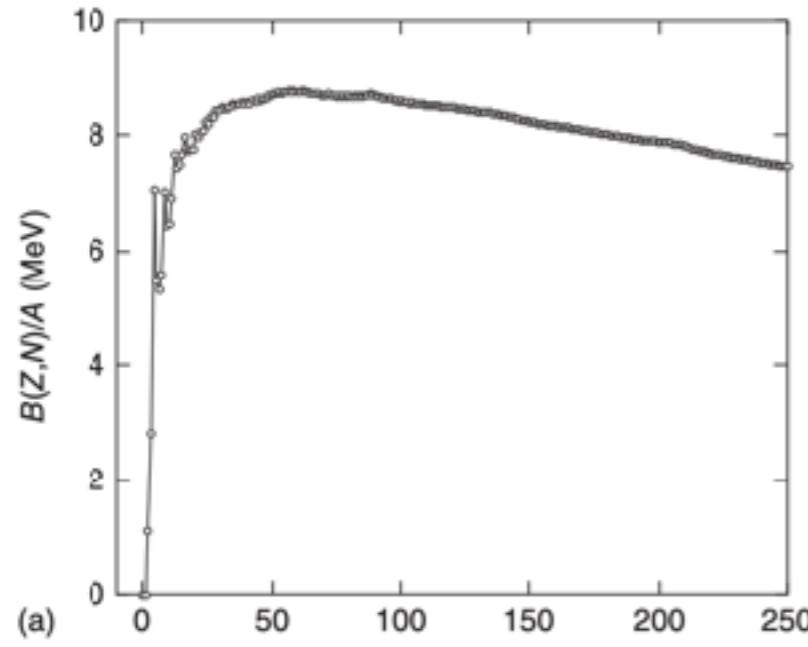
Overview

| | |
|--|-----------------|
| • Lecture 1: Introduction & overview | April 18 |
| • Lecture 2: Thermonuclear reactions | April 25 |
| • Lecture 3: Big-bang nucleosynthesis | May 2 |
| • Lecture 4: Thermonuclear reactions inside stars – I (H-burning) | May 7 |
| • Lecture 5: Thermonuclear reactions inside stars – II (advanced burning) | May 16 |
| • Lecture 6: Neutron-capture and supernovae – I | May 23 |
| • Lecture 7: Neutron-capture and supernovae – II | June 6 |
| • Lecture 8: Thermonuclear supernovae | June 13 |
| • Lecture 9: Li, Be and B | July 4 |
| • Lecture 10: Galactic chemical evolution and relation to astrobiology | July 11 |
| | |
| Paper presentations I | June 21 |
| Paper presentations II | June 27 |

Why does the Sun shine?

Answer: the Sun shines because *it is massive*

However, it can shine for billions of years only if nuclear reactions take place in its interior



Solar luminosity:

$$L_{\odot} = 3.9 \times 10^{33} \text{ ergs s}^{-1}$$

Total rest-mass energy of the Sun

$$M_{\odot}c^2 \simeq 2 \times 10^{54} \text{ ergs}$$

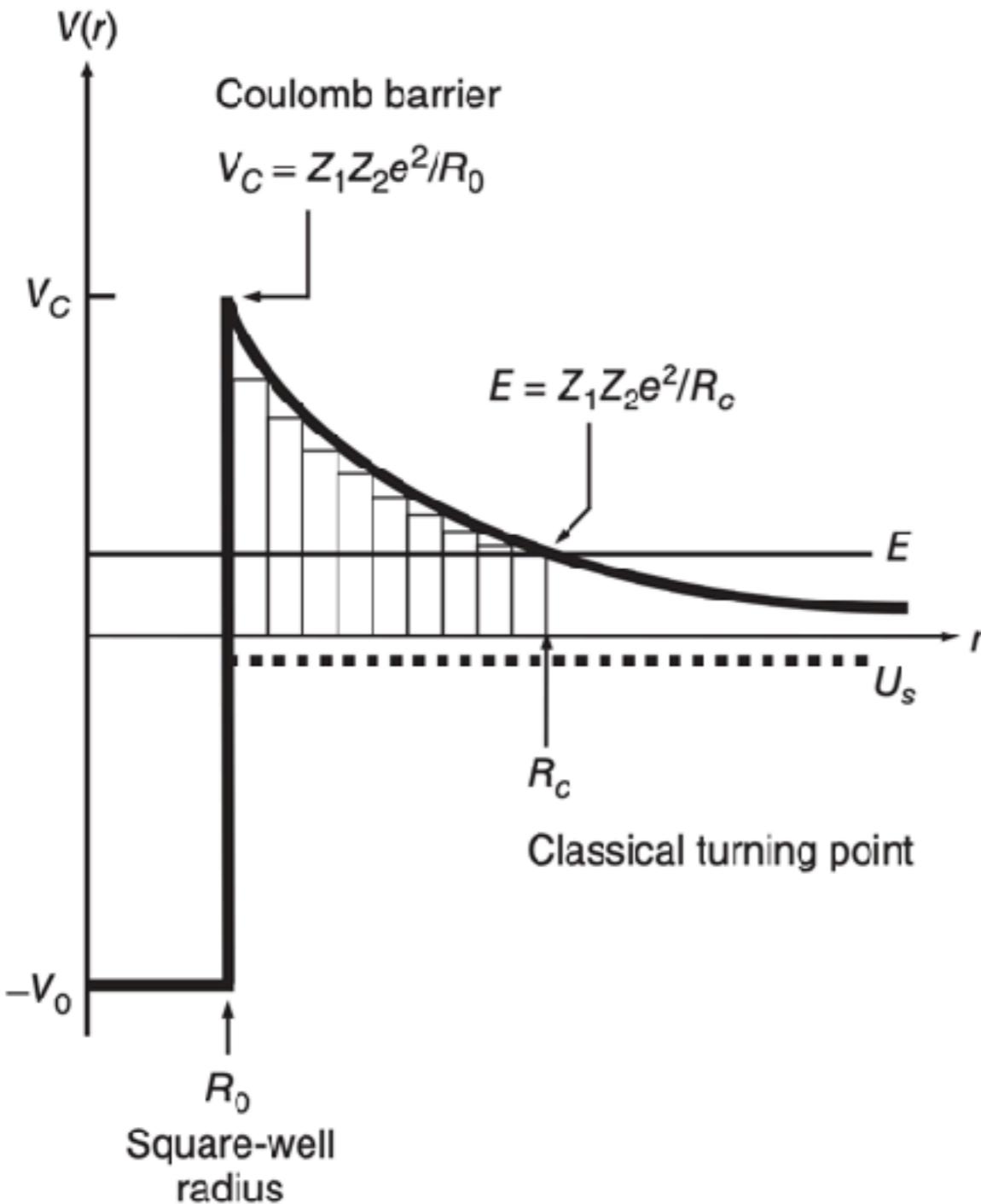
If the entire mass is converted to energy at present luminosity then the Sun can keep on shining for

$$M_{\odot}c^2/L_{\odot} \simeq 1.6 \times 10^{13} \text{ years}$$

However, this is not realistic, since only a fraction of the mass can be converted to energy.

Since different elements have different binding energies, fusion is the most likely energy source

Occurrence of nuclear reactions



Characteristic length-scale of nuclear forces

$$R_0 \simeq A^{1/3} 1.44 \text{ fm}$$

Reactions can occur “classically” when

$$E_{\text{particle}} \geq V(R_0) \simeq Z_1 Z_2 \text{ MeV}$$

For the centre of the Sun:

$$E_{\text{particle}} = kT_c \simeq k10^7 \text{ K} \simeq 1 \text{ keV} \ll 1 \text{ MeV}$$

Probability for “classical” interaction
 $\exp(-1000) \simeq 10^{-434}$

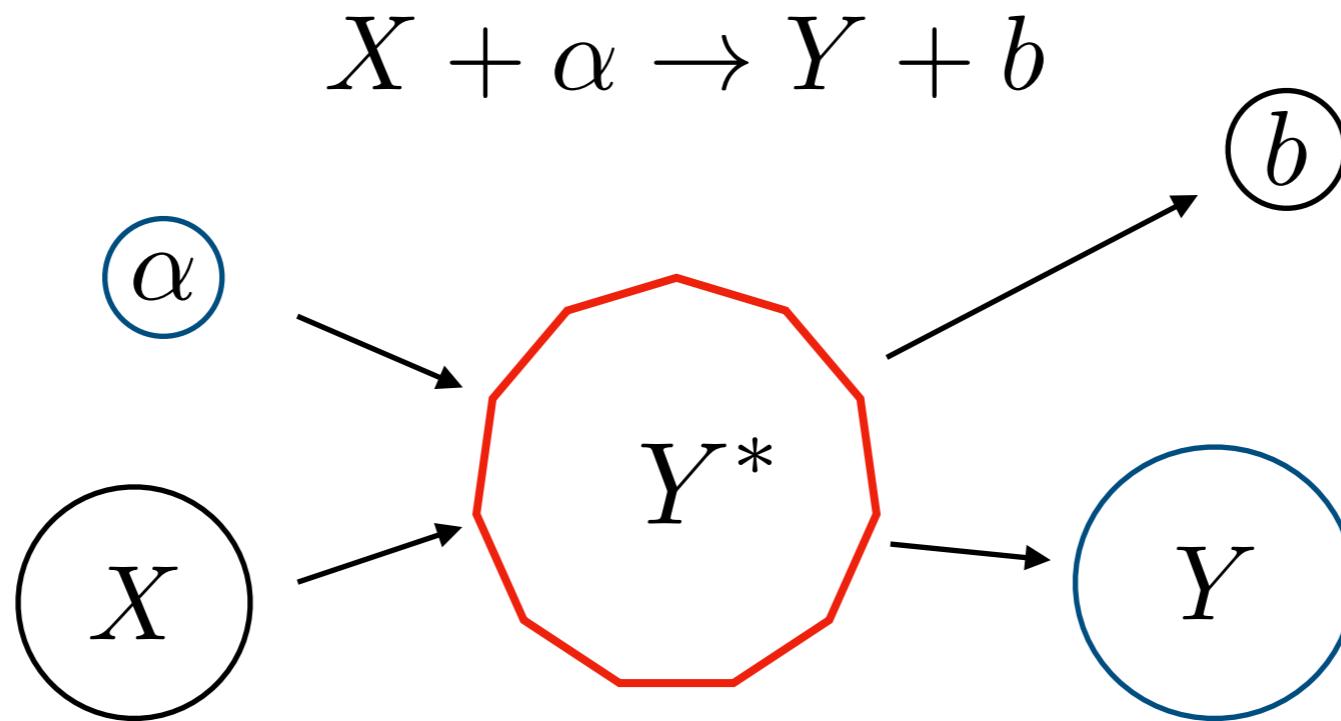
Reactions take place at relatively low temperatures because of the “tunnelling effect” discovered by Gamow.
 Allows penetration at radii larger than classical capture radius.

Capture probability:

$$P_0 \propto E^{-1/2} \exp(-2\pi\eta); \eta = \frac{\mu}{2} \frac{Z_1 Z_2 e^2}{\hbar E^{1/2}}$$

Probability for “quantum” interaction
 $P_0 \simeq 10^{-20}$

Energetics of nuclear reactions



Alternative notation: $X(\alpha, b)Y$

Conservation of relativistic energy

$$E_{\alpha X} + (M_\alpha + M_X)c^2 = E_{Yb} + (M_b + M_Y)c^2$$

Conservation of charge; nuclear masses can be replaced by atomic masses

$$E_{\alpha X} + (M_{\alpha'} + M_{X'})c^2 = E_{Yb} + (M_{b'} + M_{Y'})c^2$$

Conservation of number of nuclei

$$M_{\alpha'}c^2 \rightarrow \Delta M_{\alpha'}c^2 = (M_{\alpha'} - A \times 1 \text{ amu})c^2$$

Energetics of nuclear reactions

Table 1.1 Experimental values of the atomic mass excess (M.E.), binding energy per nucleon (B/A), and relative atomic mass (M) for light nuclides in the $A \leq 20$ mass region.

| A | Element | M.E. (keV) | B/A (keV) | M (u) |
|----|---------|-------------|-------------|----------------|
| 1 | n | 8071.3171 | 0.0 | 1.0086649158 |
| | H | 7288.97059 | 0.0 | 1.00782503223 |
| 2 | H | 13135.72174 | 1112.283 | 2.01410177812 |
| 3 | H | 14949.8061 | 2827.266 | 3.0160492779 |
| | He | 14931.2155 | 2572.681 | 3.0160293201 |
| 4 | He | 2424.91561 | 7073.915 | 4.00260325413 |
| 6 | Li | 14086.8789 | 5332.331 | 6.0151228874 |
| 7 | Li | 14907.105 | 5606.439 | 7.016003437 |
| | Be | 15769.00 | 5371.548 | 7.01692872 |
| 8 | Li | 20945.80 | 5159.712 | 8.02248625 |
| | Be | 4941.67 | 7062.435 | 8.00530510 |
| | B | 22921.6 | 4717.15 | 8.0246073 |
| 9 | Li | 24954.90 | 5037.768 | 9.02679019 |
| | Be | 11348.45 | 6462.668 | 9.01218307 |
| 10 | Be | 12607.49 | 6497.630 | 10.01353470 |
| | B | 12050.7 | 6475.07 | 10.0129369 |
| 11 | Be | 20177.17 | 5952.540 | 11.02166108 |
| | B | 8667.9 | 6927.72 | 11.0093054 |
| | C | 10650.3 | 6676.37 | 11.0114336 |
| 12 | B | 13369.4 | 6631.22 | 12.0143527 |
| | C | 0.0 | 7680.144 | 12.0000000 |
| 13 | B | 16562.1 | 6496.41 | 13.0177802 |
| | C | 3125.00875 | 7469.849 | 13.00335483507 |
| | N | 5345.48 | 7238.863 | 13.00573861 |
| 14 | C | 3019.893 | 7520.319 | 14.003241988 |
| | N | 2863.41669 | 7475.614 | 14.00307400443 |
| | O | 8007.46 | 7052.301 | 14.00859636 |
| 15 | C | 9873.1 | 7100.17 | 15.0105993 |
| | N | 101.4387 | 7699.460 | 15.0001088989 |
| | O | 2855.6 | 7463.69 | 15.0030656 |
| 16 | N | 5683.9 | 7373.80 | 16.0061019 |
| | O | -4737.00137 | 7976.206 | 15.99491461957 |
| 17 | N | 7870.0 | 7286.2 | 17.008449 |
| | O | -808.7636 | 7750.728 | 16.9991317565 |
| | F | 1951.70 | 7542.328 | 17.00209524 |
| 18 | N | 13113.0 | 7038.6 | 18.014078 |
| | O | -782.8156 | 7767.097 | 17.9991596129 |
| | F | 873.1 | 7631.638 | 18.0009373 |
| 19 | O | 3332.9 | 7566.49 | 19.0035780 |
| | F | -1487.4443 | 7779.018 | 18.9984031627 |
| | Ne | 1752.05 | 7567.342 | 19.00188091 |
| 20 | F | -17.463 | 7720.134 | 19.99998125 |
| | Ne | -7041.9306 | 8032.240 | 19.9924401762 |
| | Na | 6850.6 | 7298.50 | 20.0073544 |

$$Q \equiv E_{Y'b'} - E_{\alpha'X'}$$

$$= (\Delta M_{\alpha'} + \Delta M_{X'} - \Delta M_{Y'} - \Delta M_{b'})c^2$$

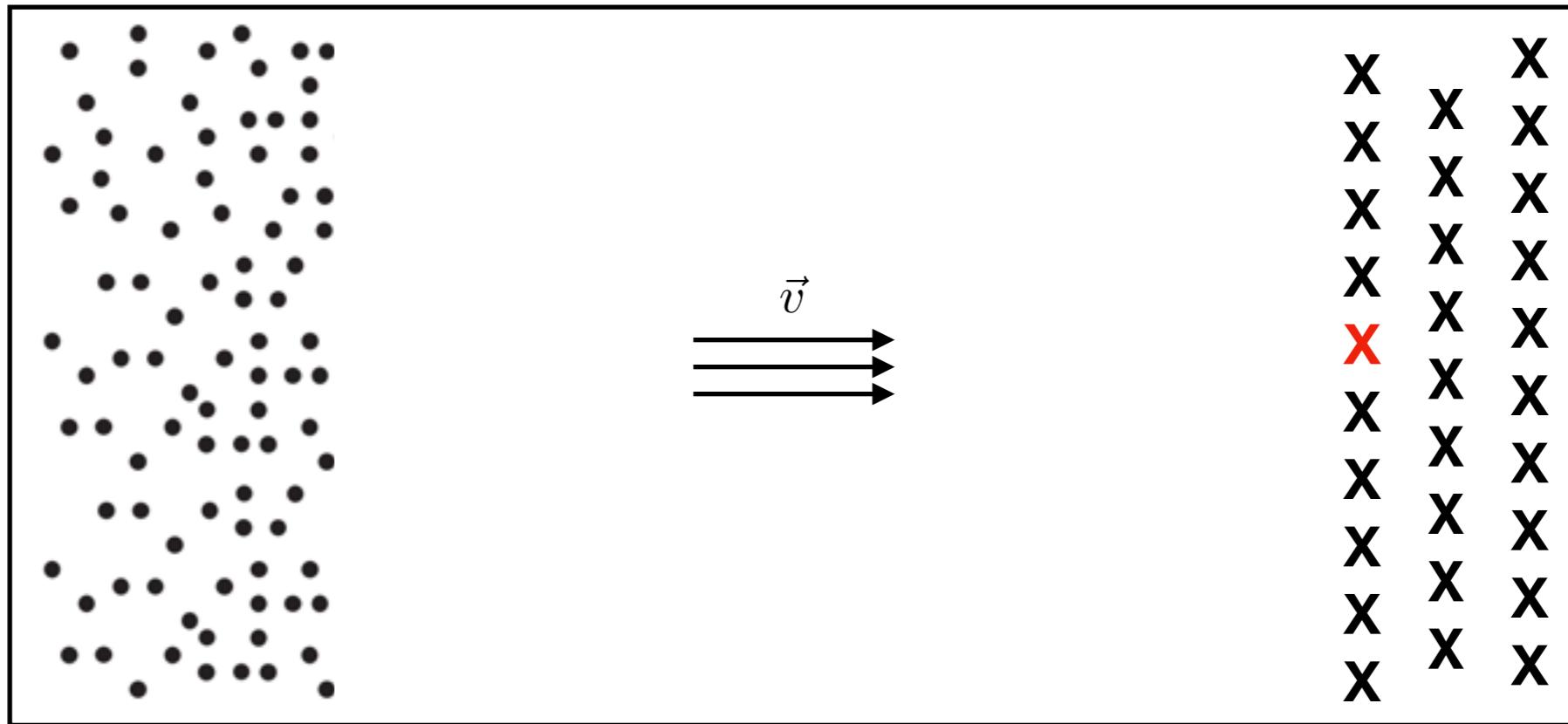
Exothermic reaction $Q > 0$

Endothermic reaction $Q < 0$

Binding energy: energy required to disassemble the nucleus to its constituent neutrons and protons

$$\text{B.E.} = [m_p \times Z + m_n \times (A - Z) - M_X]c^2$$

Rate of nuclear reactions



$$\text{cross section} \equiv \frac{\text{number of reactions/target nucleus/unit time}}{\text{number of incident particles/unit area/unit time}}$$

- The cross section, σ of a reaction, as defined here, has units of area, and can be thought of as the area around a nucleus X , over which an incoming particle can be captured (although this picture is not accurate).
- σ can vary with velocity, i.e. energy

From definition: $\frac{\text{number of reactions}}{\text{unit time unit volume}} = \text{cross section} \times \text{velocity} \times N_\alpha N_X \Rightarrow r_{\alpha X} = \sigma_{\alpha X}(v)vN_\alpha N_X$

Rate of nuclear reactions

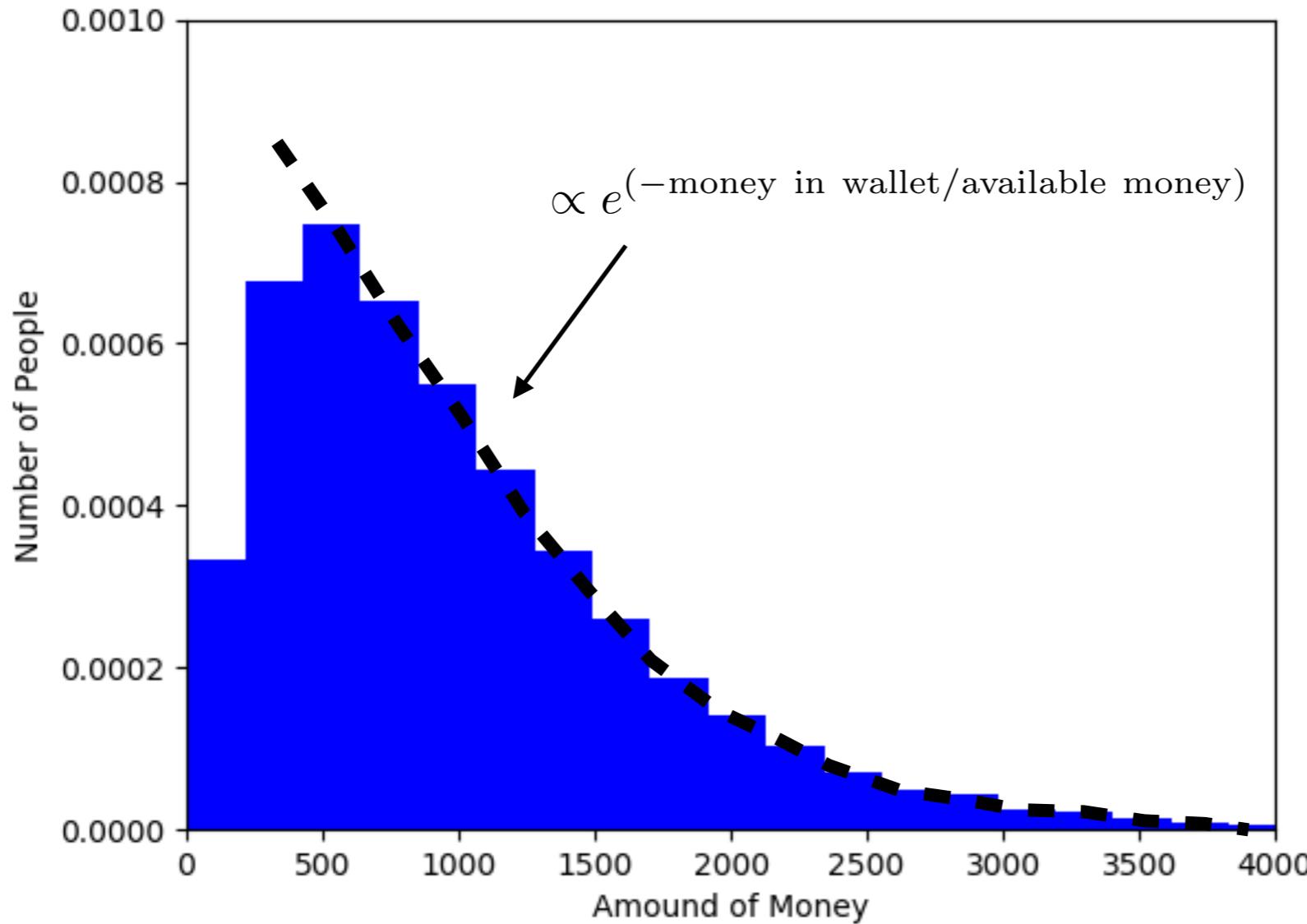
strong force: $^{15}\text{N}(\text{p}, \alpha)^{12}\text{C}$ $\sigma \simeq 0.5 \text{ b}$ at $E_p = 2 \text{ MeV}$

el. mag. force: $^3\text{He}(\alpha, \gamma)^7\text{Be}$ $\sigma \simeq 10^{-6} \text{ b}$ at $E_\alpha = 2 \text{ MeV}$

weak force: $\text{p}(\text{p}, e^+ \nu)D$ $\sigma \simeq 10^{-20} \text{ b}$ at $E_p = 2 \text{ MeV}$

Thermal equilibrium

10000 people have 1000 EUR each. They can exchange freely and spend as much as they like among each other. The total amount of money is conserved



Rate of nuclear reactions

In a mixture of gases in thermal equilibrium, there exists a spectrum of *relative velocities* between the particles of type α and X , just as α and X *individually* have well defined velocity spectra

$$r_{\alpha X} = N_\alpha N_X \int_0^\infty v \sigma(v) \phi(v) dv = N_\alpha N_X \langle \sigma u \rangle \quad \text{with} \quad \int \phi(v) dv = 1$$

More generally, $r_{\alpha X} = (1 + \delta_{\alpha X})^{-1} N_\alpha N_X \langle \sigma v \rangle$
so the entire *problem reduces to determining* $\langle \sigma v \rangle$

Nuclei inside stars, with the exception of neutron stars, are always non-degenerate, therefore the spectrum of relative velocities follows the Maxwell-Boltzmann distribution

$$r_{\alpha X} = (1 + \delta_{\alpha X})^{-1} N_\alpha N_X 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} \int_0^\infty v^3 \sigma(v) \exp\left(-\frac{\mu v^2}{2kT}\right) dv$$

Lifetime of nucleus X

$$\left(\frac{\partial N_X}{\partial t} \right)_\alpha \equiv -\frac{N_X}{\tau_\alpha(X)}$$

Combined with the definition for the nuclear reaction rate, it follows that

$$\tau_\alpha(X) = (1 + \delta)^{-1} \frac{N_X}{r_{\alpha X}} = (\langle \sigma v \rangle N_\alpha)^{-1} \quad \text{for multiple reactions involving } X: \frac{1}{\tau(X)} = \sum \frac{1}{\tau_i(X)}$$

Rate of nuclear reactions

Evaluation of the integral

$$r_{\alpha X} = (1 + \delta_{\alpha X})^{-1} N_\alpha N_X 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} \int_0^\infty v^3 \sigma(v) \exp \left(-\frac{\mu v^2}{2kT} \right) dv$$

Step 1: Evaluate $\sigma(v)$

Depends on quantum interactions, coulomb barrier, nuclear properties...impossible to evaluate analytically, but we can do some tricks

$\sigma(v) = \text{Penetration Probability} \times \text{Size (De Broglie)} \times \text{Nuclear Properties} \times \text{constant factor}$



$$\exp \left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar u} \right)$$

$$\frac{1}{E}$$

Astrophysical Factor := $S(E)$

i. e. we can “hide” all unknown nuclear terms and constants inside $S(E)$

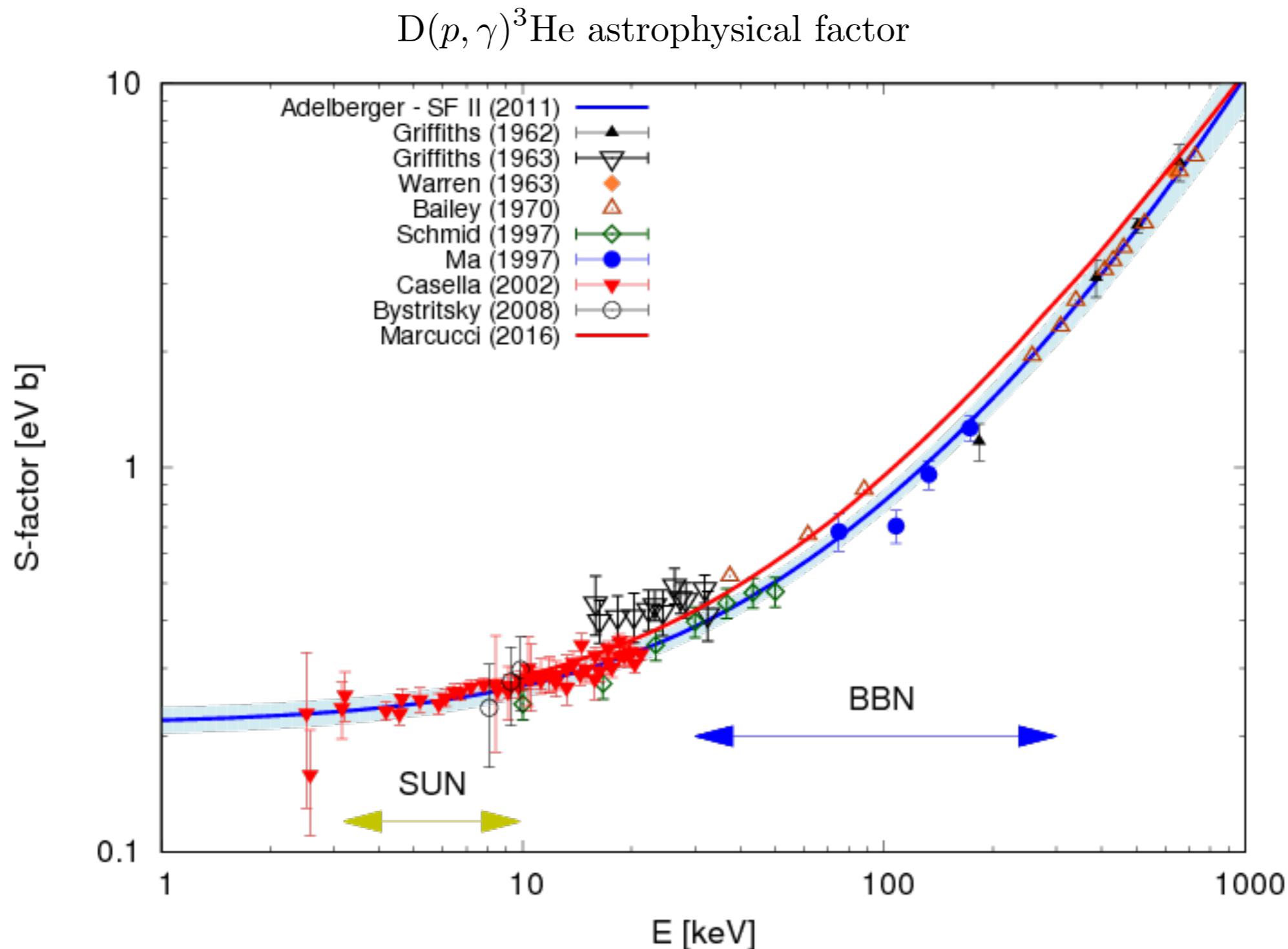
$$\sigma(E) \equiv S(E) E^{-1} \exp(-bE^{-1/2}); b = 31.28 Z_1 Z_2 A^{1/2}$$

The energy difference between nuclear states is usually larger than the energy range of nuclear reactions inside stars.

This means that in many cases $S(E)$ can be fixed to a constant when evaluating astrophysical rates

Rate of nuclear reactions

Often $S(E)$ is measured only at high energies in the lab and extrapolated down to astrophysical energies. Only recently direct measurements at low energies are becoming possible (still for a limited number of reactions)



Rate of nuclear reactions

Evaluation of the integral

$$r_{\alpha X} = (1 + \delta_{\alpha X})^{-1} N_\alpha N_X 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} \int_0^\infty v^3 \sigma(v) \exp \left(-\frac{\mu v^2}{2kT} \right) dv$$

Step 2: Replace $\sigma(v)$; $v \rightarrow E$

$$r_{\alpha X} = \frac{N_\alpha N_X}{1 + \delta_{\alpha X}} 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} \overline{\sigma v} \left[\left(\frac{8}{\mu\pi} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp \left(-\frac{E}{kT} - bE^{-1/3} \right) dE \right]$$

Step 3: For non-resonant reactions, assume $S(E) \simeq \text{const} = S_0$

$$J = \int_0^\infty \exp(-E/kT - bE^{-1/2}) dE$$

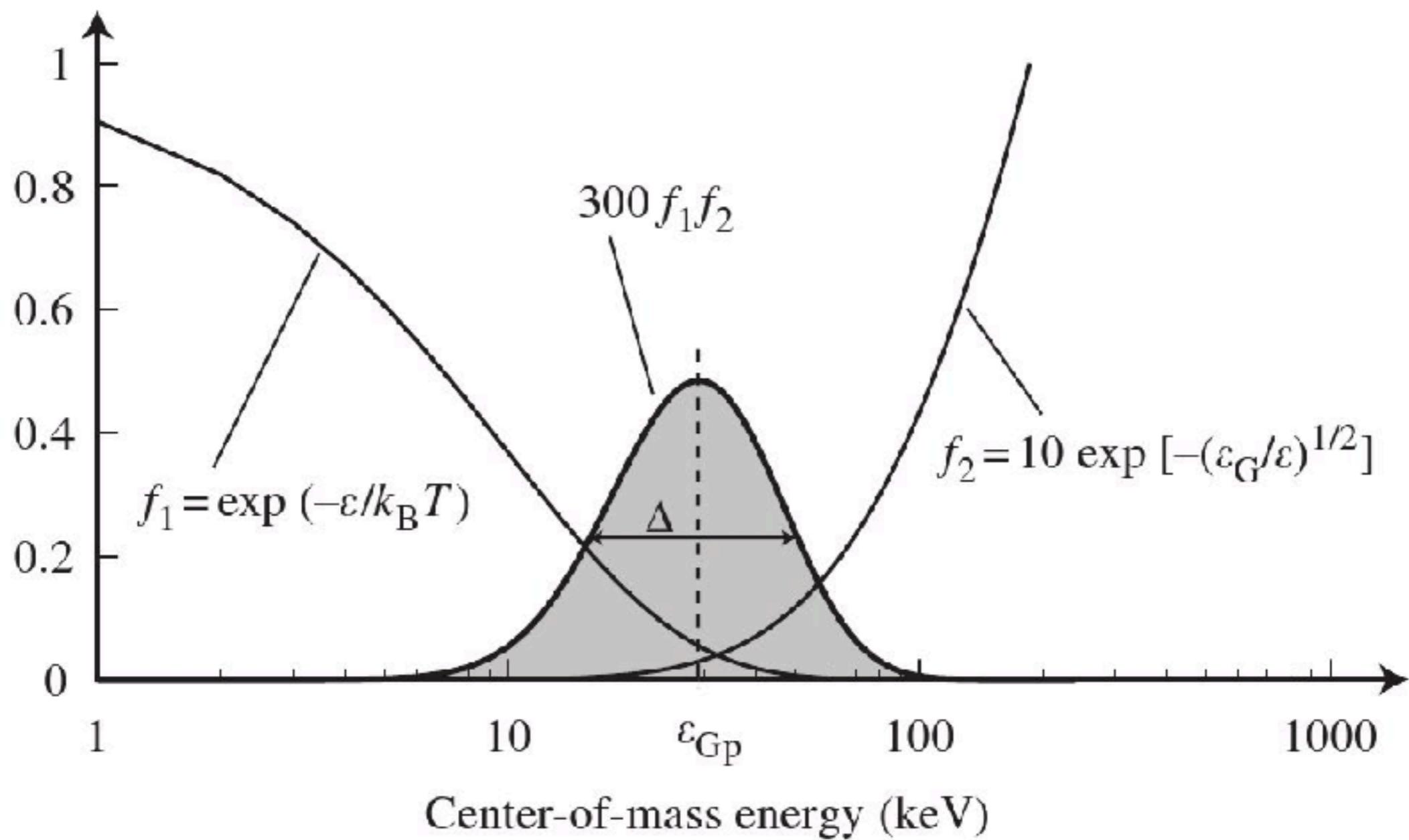
The integrand is significant only around a small range of energies ΔE around maximum, $f'(E) = 0$

$$E_0 = (0.5bkT)^{2/3} = \left[\left(\frac{\mu}{2} \right)^{1/2} \pi \frac{Z_1 Z_k e^2 k T}{\hbar} \right]^{2/3}$$

Rate of nuclear reactions

The Gamow Peak

$$E_0 = (0.5bkT)^{2/3} = \left[\left(\frac{\mu}{2} \right)^{1/2} \pi \frac{Z_1 Z_k e^2 k T}{\hbar} \right]^{2/3}$$



Rate of nuclear reactions

Evaluation of the integral

$$r_{\alpha X} = (1 + \delta_{\alpha X})^{-1} N_\alpha N_X 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} \int_0^\infty v^3 \sigma(v) \exp \left(-\frac{\mu v^2}{2kT} \right) dv$$

Step 4 (final!): Approximate Gamow peak with a Gaussian

$$\tau = 3 \frac{E_0}{kT}; f(E) = f_0 + f'_0(E - E_0) + 0.5 f''_0(E/E_0)^2 + \dots = -\tau - 0.25\tau(E/E_0 - 1)^2 + \dots$$

$$\xi = (E/E_0 - 1)\sqrt{\tau}/2 \Rightarrow J \simeq \frac{2/3}{k} T \tau^{1/2} e^{-\tau} \int_{-\infty}^{\infty} e^{-xi} d\xi$$

$$J \simeq \frac{2}{3} k T \pi^{1/2} \tau^{1/2} e^{-\tau}$$

$$\langle \sigma v \rangle \simeq \frac{4}{3} \left(\frac{2}{\mu} \right)^{1/2} \frac{1}{(kT)^{1/2}} S_0 \tau^{1/2} e^{-\tau}$$

$$r_{\alpha X} \simeq \frac{2.62 \times 10^{29} (A_\alpha + A_X)}{(1 + \delta_{\alpha X}) Z_\alpha Z_X} \rho^2 \frac{X_\alpha X_X}{(A_\alpha A_X)^2} S_0 (\text{keV barn}) \tau^2 e^r; r = 42.48 \left(\frac{Z_\alpha^2 Z_X^2 A_\alpha A_X}{T/(10^6 \text{ K})(A_\alpha + A_X)} \right)^{1/3}$$

Rate of nuclear reactions

$$r_{\alpha X} \simeq \frac{2.62 \times 10^{29} (A_\alpha + A_X)}{(1 + \delta_{\alpha X}) Z_\alpha Z_X} \rho^2 \frac{X_\alpha X_X}{(A_\alpha A_X)^2} S_0 (\text{keV barn}) \tau^2 e^r; r = 42.48 \left(\frac{Z_\alpha^2 Z_X^2 A_\alpha A_X}{T/(10^6 \text{ K})(A_\alpha + A_X)} \right)^{1/3}$$

Some Important properties

Effective width of Gamow peak: $\Delta = \frac{4}{\sqrt{3}} (E_0 kT)^{1/2}$

Height of Gamow peak: $I_{\max} = \exp(-3E_0/kT)$

Temperature dependence of nuclear reactions

$$\langle \sigma v \rangle = \langle \sigma v \rangle_0 \left(\frac{T}{T_0} \right)^\nu, \quad \nu = \frac{\partial \ln \langle \sigma v \rangle}{\partial \ln T} = \frac{\tau}{3} - \frac{2}{3}$$

| $(T = 1.5 \cdot 10^7 \text{ K})$ | $\Delta/2$ | $\Delta \cdot I_{\max}$ |
|----------------------------------|------------|---------------------------|
| p + p | 3.2 keV | $7.0 \cdot 10^{-6}$ keV |
| p + ^{14}N | 6.8 keV | $2.5 \cdot 10^{-26}$ keV |
| $\alpha + ^{12}\text{C}$ | 9.8 keV | $5.9 \cdot 10^{-56}$ keV |
| $^{16}\text{O} + ^{16}\text{O}$ | 20.2 keV | $2.5 \cdot 10^{-237}$ keV |

| $(T = 1.5 \cdot 10^7 \text{ K})$ | $\langle \sigma v \rangle \sim$ | E_C |
|----------------------------------|---------------------------------|-----------|
| p + p | $T^{3.9}$ | 0.55 MeV |
| p + ^{14}N | T^{20} | 2.27 MeV |
| $\alpha + ^{12}\text{C}$ | T^{42} | 3.43 MeV |
| $^{16}\text{O} + ^{16}\text{O}$ | T^{182} | 14.07 MeV |

- the thermonuclear reaction rate is one of the most strongly varying function treated in physics!
- need of efficient thermostat for regulation
- burning stages in stars are well separated, only few elements interact at a given time

Rate of nuclear reactions

Errors introduced from assumptions

1. S_0 is not constant; a more accurate treatment would be to assume that it's slowly changing around Gamow peak

$$S(E) = S(E_0) + \left(\frac{dS}{dE} \right)_{E_0} (E - E_0)$$

Fix: error is reduced by replacing $S_0 = S(E_0) \rightarrow S(E_0 + \frac{5}{6}kT)$

2. Error introduced by replacing area with a gaussian function: correction factor depends on τ , $F(\tau)$
3. Interaction potential is not a pure two-body central potential. Most important modification comes from electron shielding which can lower the effective potential and increase the rate. For reactions inside stars, free electrons cluster around nuclei in spherical shells with radius equal to Debye-Hückel radius

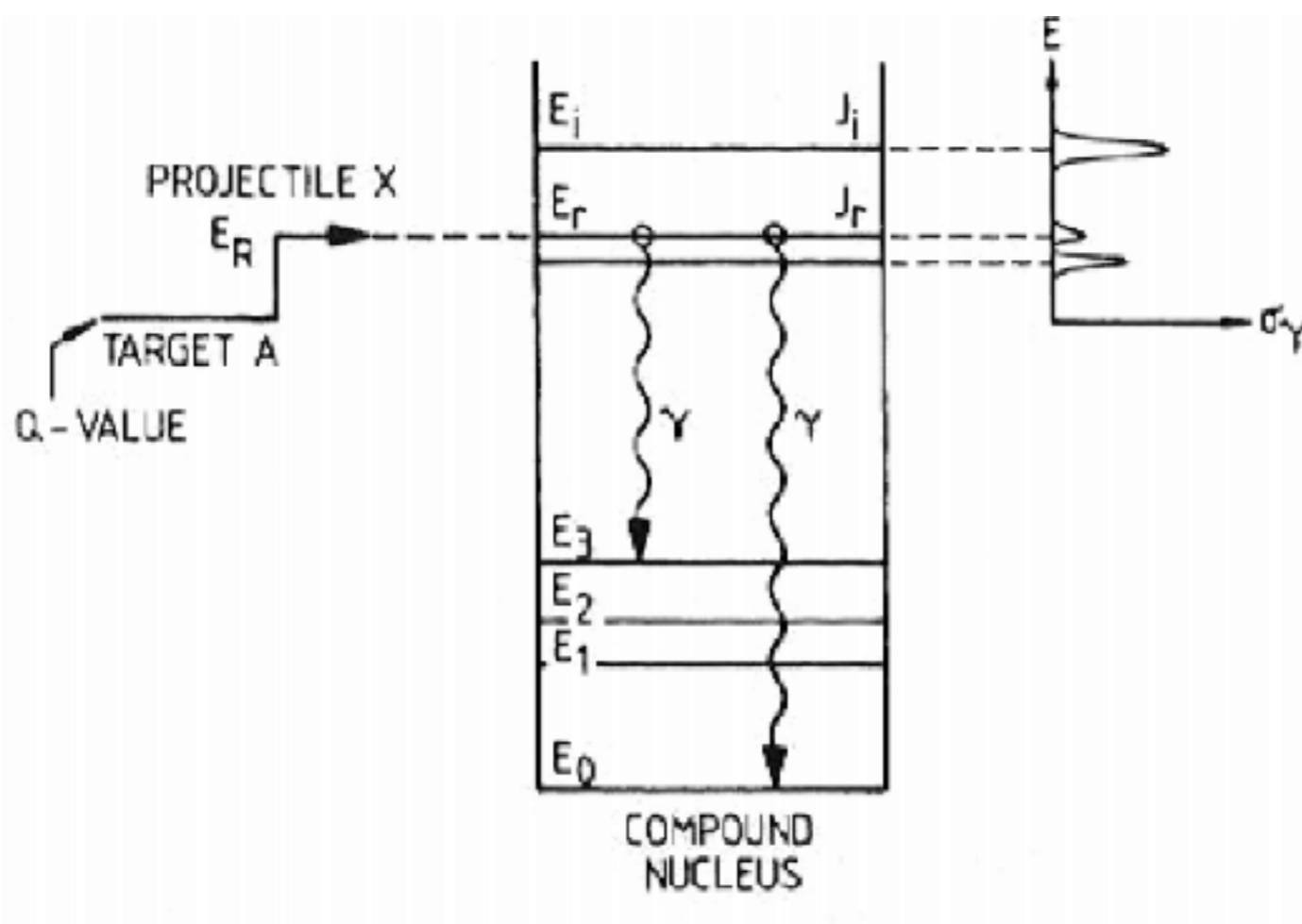
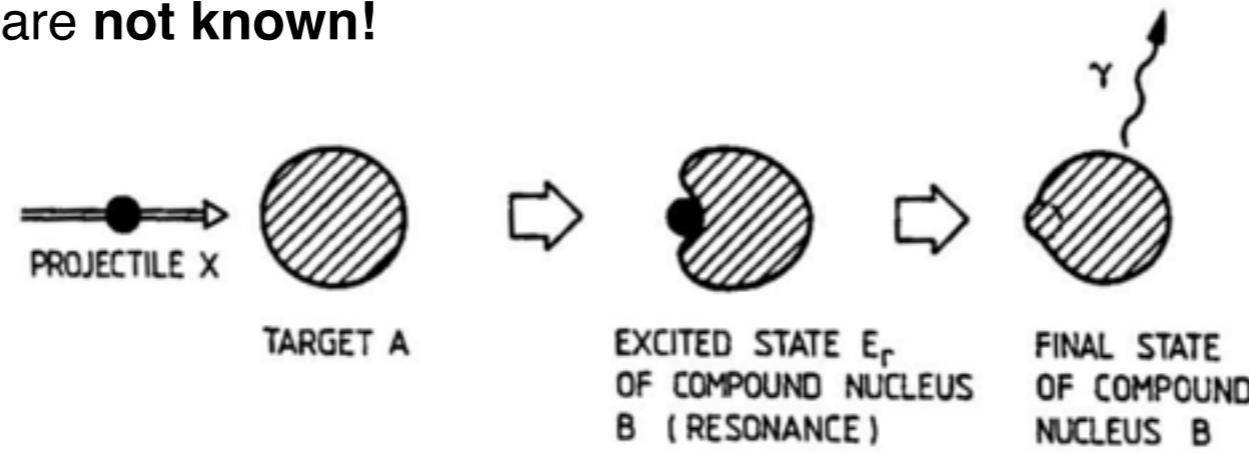
$$R_D = \left(\frac{kT}{4\pi e^2 \rho N_A \zeta} \right)^{1/2} \quad \text{with } \zeta = \sum_i (Z_i^2 + Z_i) \frac{X_i}{A_i}$$

Important for low temperatures and high densities!

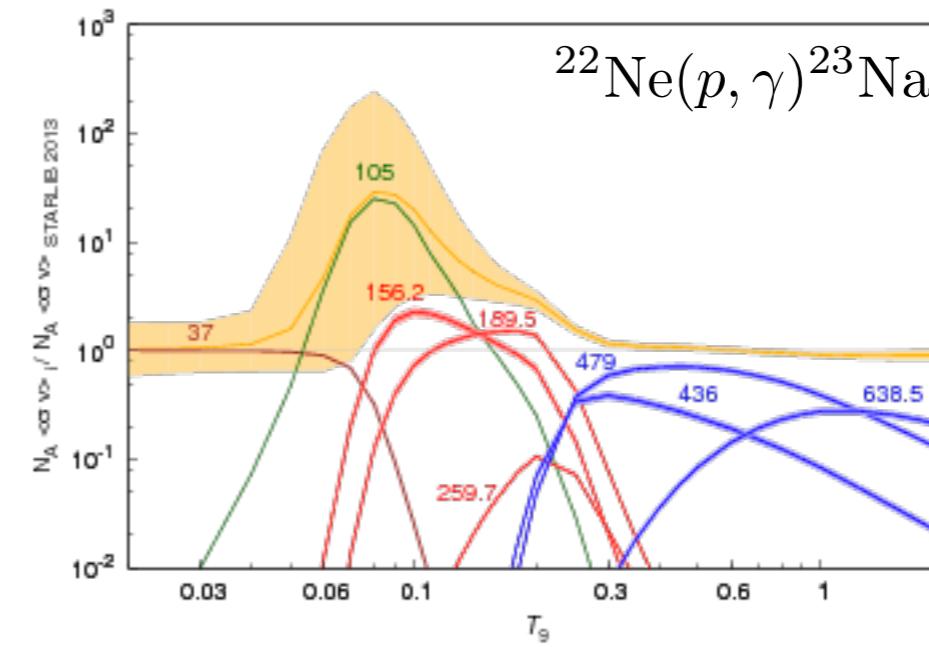
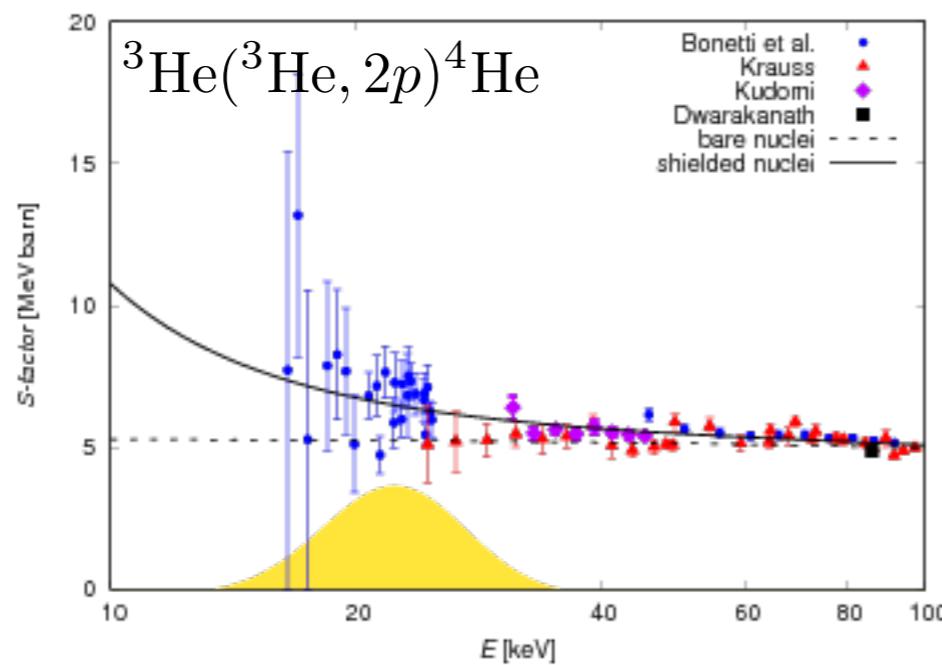
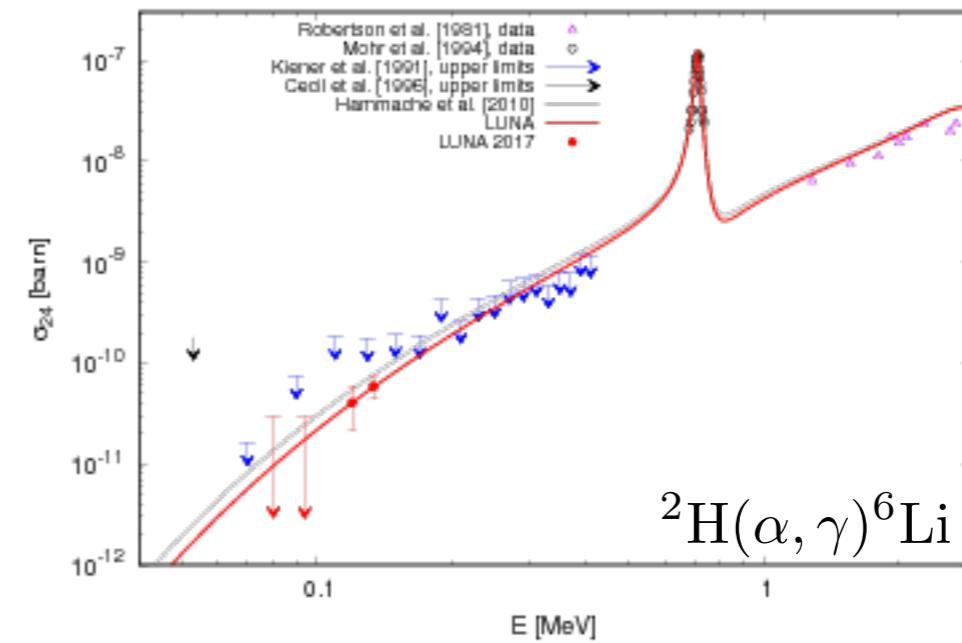
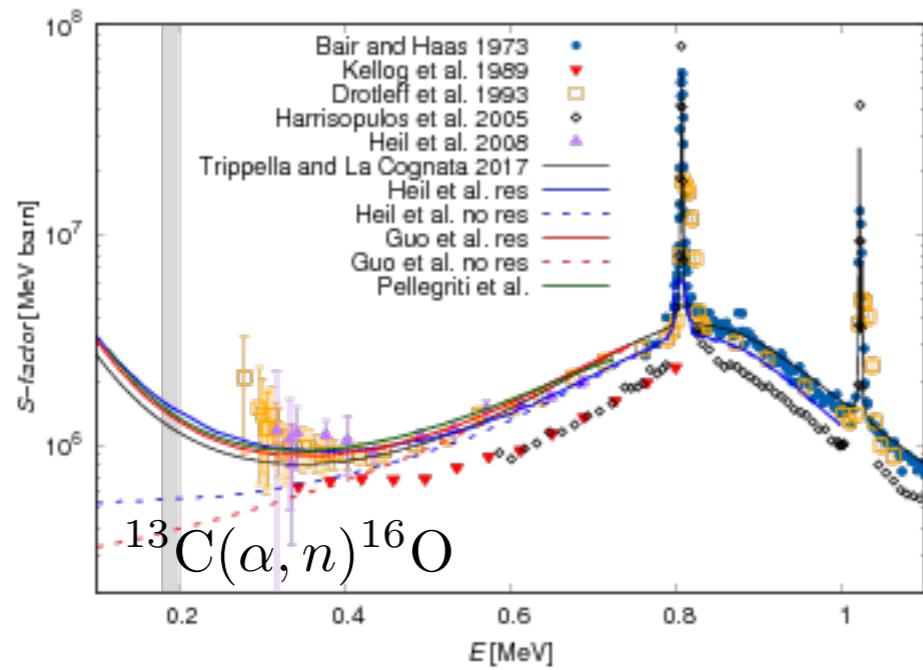
see CLAYTON for details

Rate of nuclear reactions

4. Nuclear resonances can introduce strong local maxima that dominate in the reaction rate. Some resonances are predicted by theory (e.g. nuclear-shell model) while others are inferred experimentally, but some are **not known!**



Rate of nuclear reactions



Energy generation rate

Once all reaction rates are known, the abundance changes due to nuclear burning can be calculated

$$\frac{dX_i}{dt} = A_i \frac{m_u}{\rho} \left(- \sum r_{\text{reactions that destroy } i} + \sum r_{\text{reactions that create } i} \right)$$

Energy generation rate:

$$\epsilon_{\alpha X} = \frac{Q_{\alpha X}}{m_u^2} \frac{X_\alpha X_X}{A_\alpha A_X} \rho \langle \sigma v \rangle_{\alpha X} \simeq \epsilon_0 X_\alpha X_X \rho T^\nu$$

Summary

Take Home Message

1. Thermonuclear fusion generates energy at high temperatures, providing an efficient energy source for the Sun and converting light elements to heavier (up to iron)
2. Reactions only possible due to QM tunnelling
3. Cross-section of a reaction depends on the nature of the interaction
4. Astrophysical factor often constant within energy range relevant to stars
5. Rates depend strongly on Coulomb barrier, extremely temperature-dependent
6. Burning stages inside stars are well separated in temperature
7. Rate modified by electron cloud, nuclear resonances
8. Resonances not often known

Extra Slides

The nuclear shell model

Inspired by atomic model in which the Schrödinger equation is solved in a spherically-symmetric coulomb potential, yielding discrete electron orbits (shells) characterised by certain quantum numbers for the energy (n), angular momentum (l) and spin (s).

Rules for building up the shells follow from Pauli's exclusion principle for fermions: no more than two electrons can occupy a given (n,l) state.

For nucleus, there are several complications: two types of particles (neutrons, protons), nature of the interaction is not known, interacting particles closely packed...

Nuclear shell model: Assume that each nucleon moves in a static potential

Usual assumption: Empirical Wood-Saxon central potential + strong spin-orbit coupling term (non-EM)

$$V(r) = -V_0/[1 + \exp[(r - R)/a]] + V(\vec{l} \times \vec{s})$$

Solving the Schrödinger equation in 3D yields the allowed wave functions and energy levels for each nucleon

The nuclear shell model

Properties of the solution

Each nucleon is characterised by an energy level $n(>0)$, an angular momentum $I(>0)$, a spin s , and total angular momentum j

These combine via j-j coupling to form the total spin of the nucleus, I .

Parity

$$\prod = (-1)^{\sum l}$$

Energy splitting proportional to $\langle \vec{l} \cdot \vec{s} \rangle = 0.5(2l + 1)$

Shells are filled according to Pauli's exclusion principle, for each nucleon type

$$l = 1, 2, 3, 4, 5, \dots : s, p, d, f, g, \dots$$

$$j = l \pm s$$

Number of identical particles that can occupy a state: **2j+1**

Nuclear shell model

Important Properties

Nuclei with filled major shells of protons or neutrons (or both), exhibit an energetically favourable configuration

Magic Numbers: masses, particle separation, energies, quadrupole moments

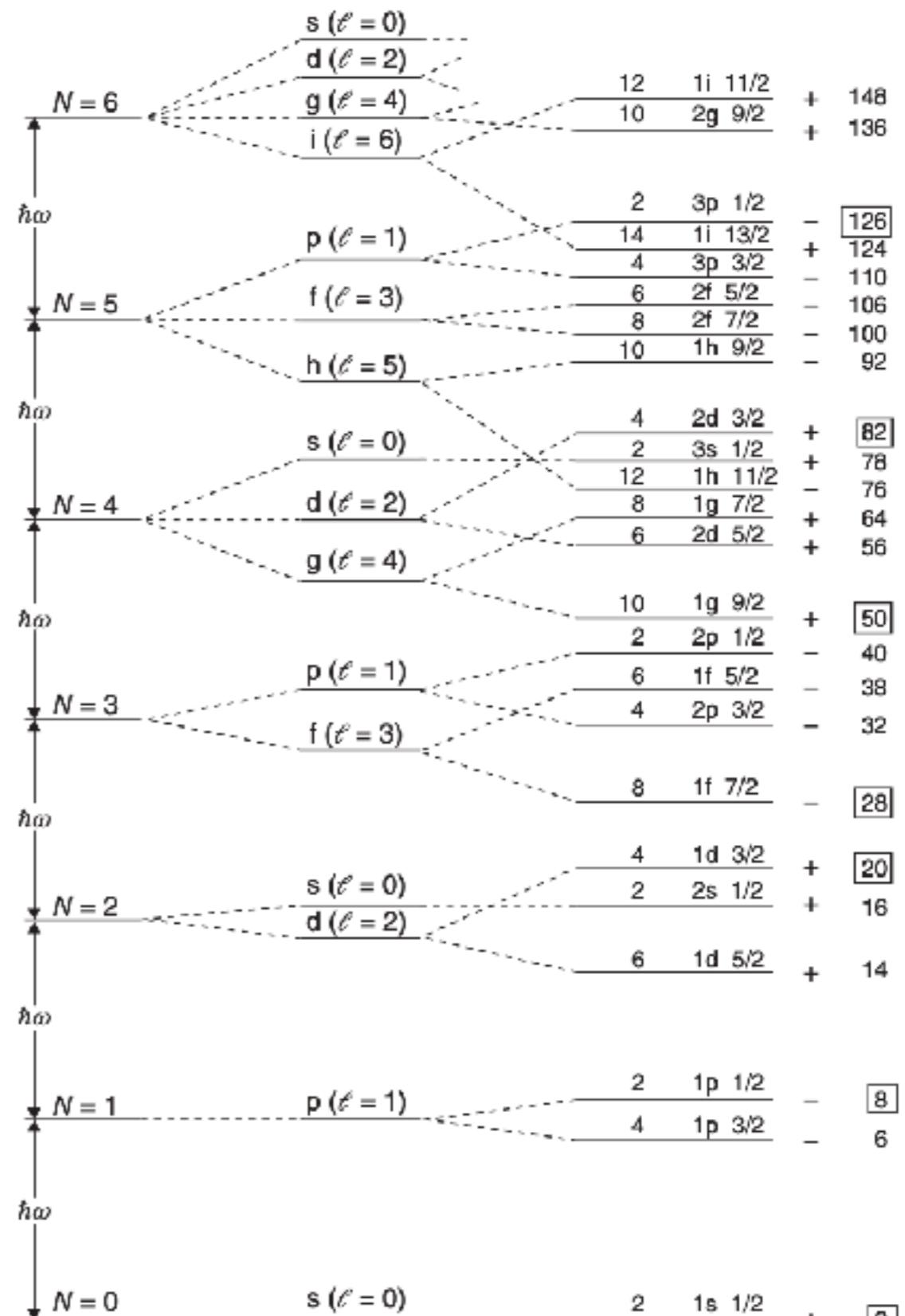
Nuclei with completely filled sub shells have $I=0$,
 $\Gamma=1$

For a single nucleon outside a closed shell,
ground-state spin and parity are determined by the
lowest-energy state available to the nucleon
Same holds for a single “hole” in a sub-shell

Partially-filled shells are more complicated.
Experimentally, the ground states of doubly even nuclei have $J=0$, $\Pi=1$

Energetically favourable for pairs of p,n to couple to $J=0$

Predictions of model, not always correct



Harmonic oscillator

$$\ell = N, N-2, \dots$$

→

$$N_i = 2^{j+1} - n\ell_j$$

$$\Pi = (-1)^f \sum N_i$$

(a)

(b)

(c)

(d)

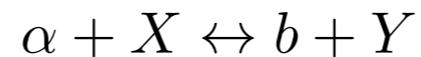
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Reactions in statistical equilibrium

At very high temperatures ($>5 \times 10^9$ K) nuclear statistical equilibrium (NSE) is achieved, i.e. the rates of all strong and electroweak reactions are exactly balanced by their reverse reactions, $dX_i/dt = 0$



In NSE abundances are determined by a “nuclear Saha equation” which depends only on nuclear properties, the temperature T and the density ρ

$$X_i(A_i, Z_i, T, \rho) = \frac{A}{N_A \rho} G(A, Z, T) \left(\frac{2\pi k T M(A_i, Z_i)}{h^2} \right)^{3/2} \exp \left[\frac{\mu(A_i, Z_i) + B(A_i, Z_i)}{kT} \right]$$

where A_i is the atomic number, Z_i is the charge, T is the temperature, ρ is the mass density, N_A is the Avogadro number, $G(A, Z, T)$ is the temperature-dependent partition function, $M(A_i, Z_i)$ is the mass of the nucleus, $B(A_i, Z_i)$ is the binding energy and $\mu(A_i, Z_i)$ is the chemical potential

$$\mu(A_i, Z_i) = Z_i \mu_p + N_i \mu_n = Z_i \mu_p + (A_i - Z_i) \mu_n$$

Considering conservation of baryon number, and conservation of charge

$$\sum_i X_i = 1; \quad Y_e = \sum_i \frac{Z_i}{A_i} X_i$$

Considering conservation of baryon number, and conservation of charge, each triplet (T, ρ, Y_e) yields a unique solution for (X_i, μ_p, μ_n)

Reactions in statistical equilibrium

