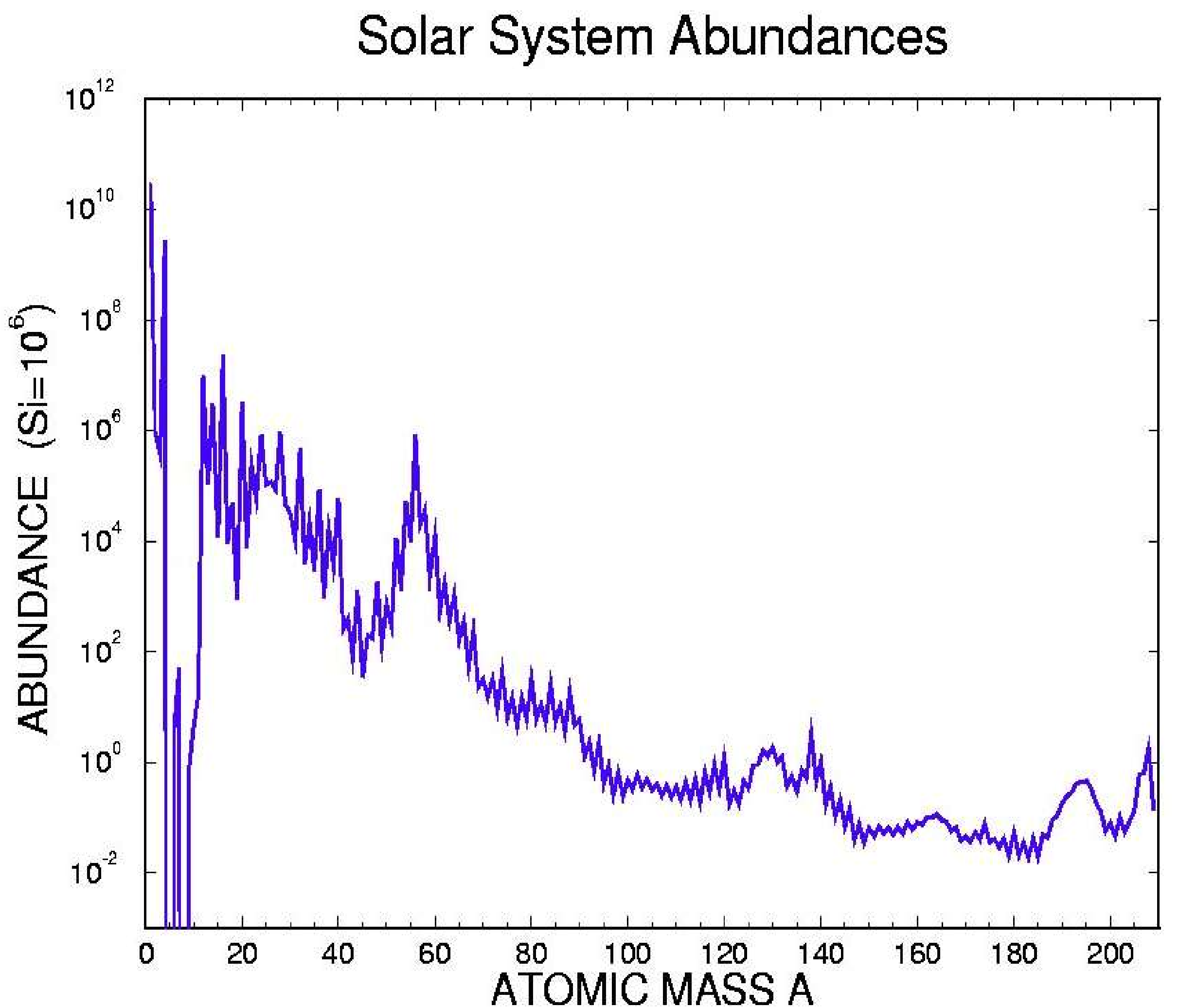
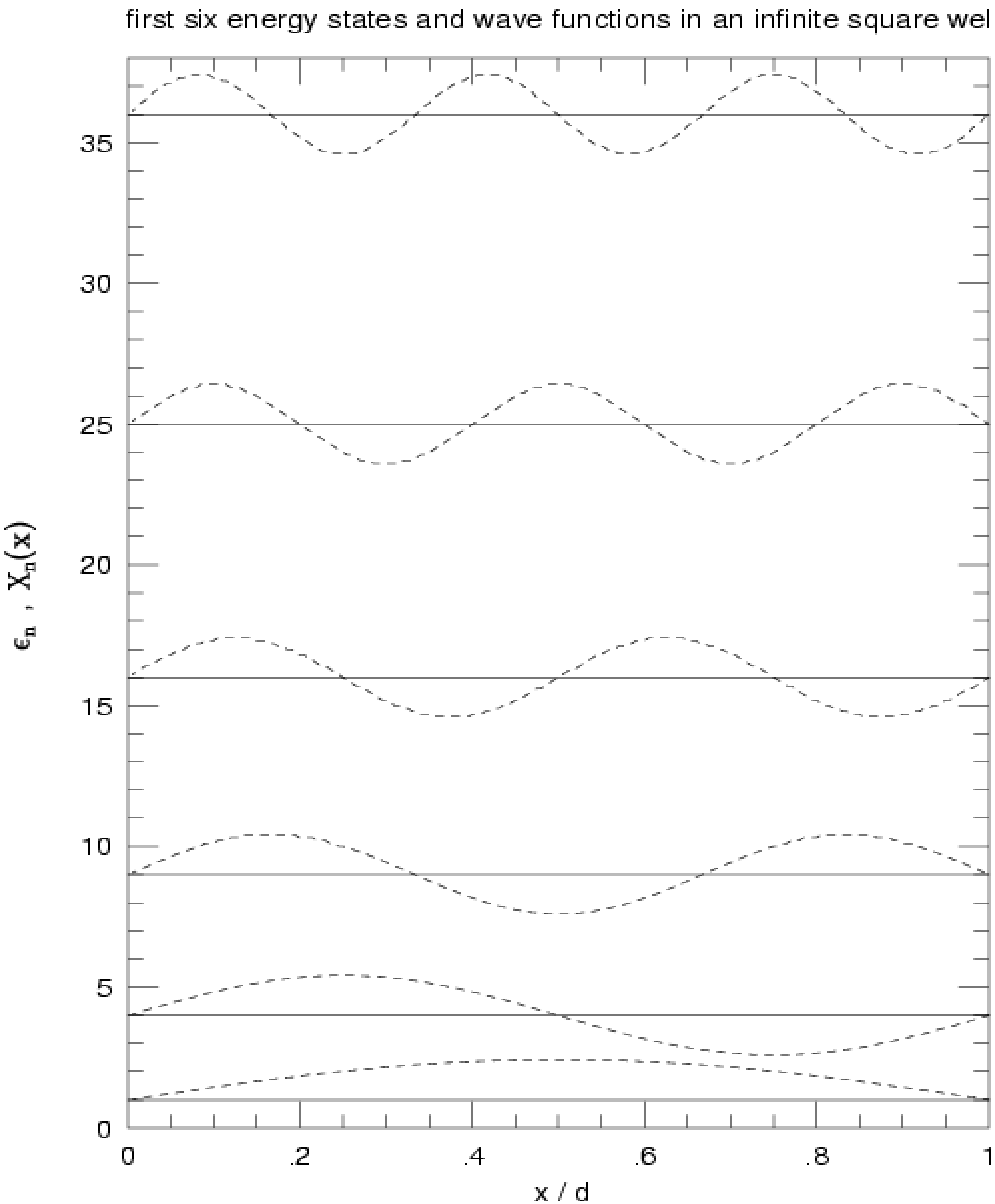
Nuclear Masses and their Relevance for (Nuclear) Burning in Astrophysical Plasmas

Friedrich-Karl Thielemann
Department of Physics and Astronomy
University of Basel



Statistical Mechanics of astrophysical plasmas/gases



a non-interacting gas can be represented by a 3D box in which it is contained (with inpenetrable walls)

energy eigenvalues

$$\varepsilon_{x,n_x} = \frac{\pi^2 \hbar^2}{2md^2} n_x^2$$

$$\varepsilon_{n_x,n_y,n_z} = \frac{\pi^2 \hbar^2}{2md^2} (n_x^2 + n_y^2 + n_z^2)$$

all these states can be occupied!

Total number of states and state density

$$\tilde{\Phi}(E) = g\frac{4\pi}{3}\frac{V}{h^3}(2m)^{3/2}E^{3/2}$$

$$\tilde{\omega}(E) = \frac{d\tilde{\Phi}(E)}{dE} = 2\pi g\frac{V}{h^3}(2m)^{3/2}E^{1/2}$$

total number of states in a given volume V=d^3 up to energy E, and state density at that energy

g measures degeneracy of state

$$\Phi(E) = \frac{4\pi}{3}\frac{g}{h^3}(2m)^{3/2}E^{3/2}$$

$$\omega(E) = 2\pi\frac{g}{h^3}(2m)^{3/2}E^{1/2}.$$

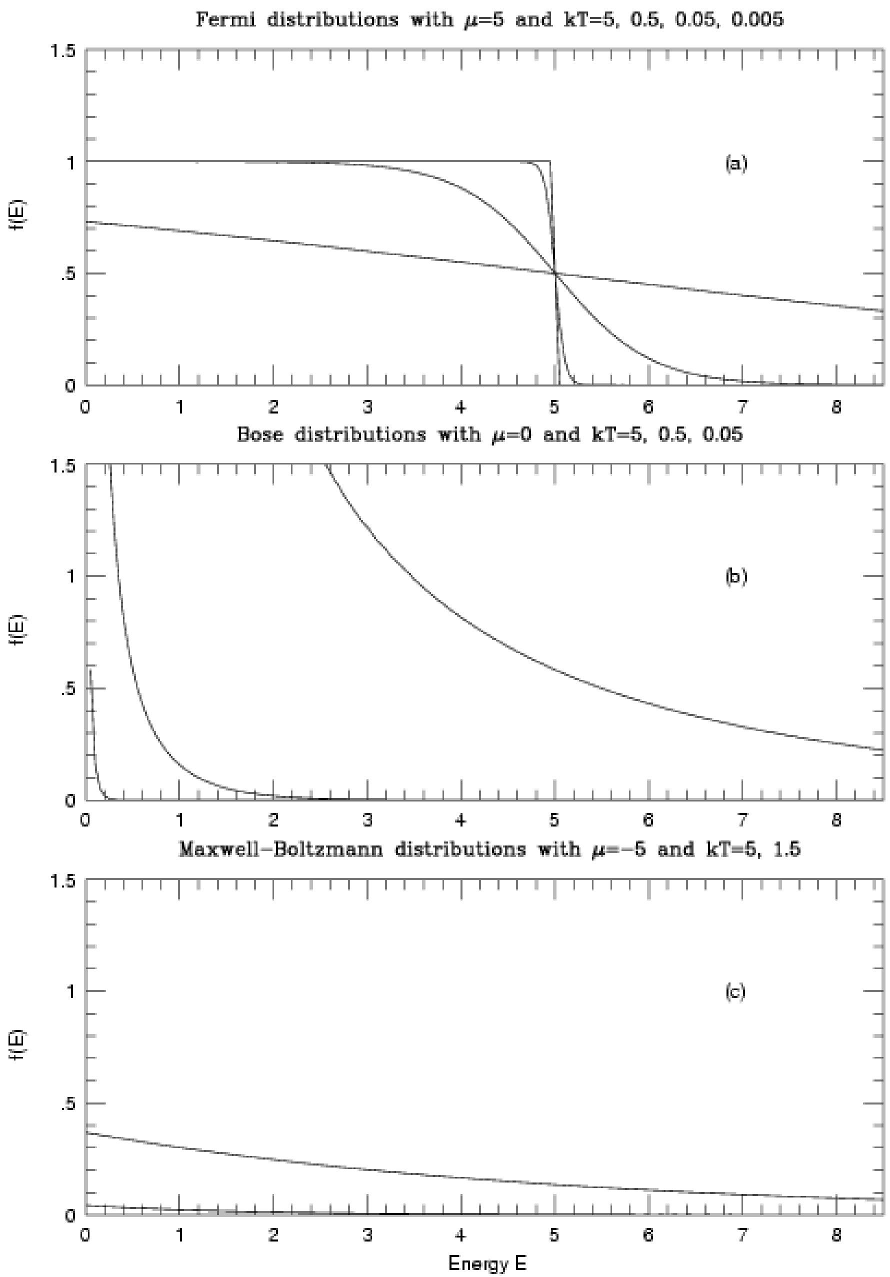
the same per volume

$$\Phi(p) = \frac{4\pi}{3}\frac{g}{h^3}p^3$$

$$\omega(p) = \frac{d\Phi(p)}{dp} = 4\pi\frac{g}{h^3}p^2$$

the same for momentum p with E=p^2/2m

Occupation probability for different statistics



$$f(p) = \begin{cases} \left[e^{(E(p)-\mu)/kT} + 1\right]^{-1} & \text{Fermions} \\ \left[e^{(E(p)-\mu)/kT} - 1\right]^{-1} & \text{Bosons} \\ e^{-(E(p)-\mu)/kT} & \text{Maxwell-Boltzmann} \end{cases}$$

f(p) measures the probability that a state at energy E or momentum p is occupied.

How is the chemical potential determined?

Thermodynamic Properties

$$n = \frac{N}{V} = \int_0^\infty \omega(p) f(p) dp$$

$$u = \frac{U}{V} = \int_0^\infty E\omega(p) f(p) dp$$

$$P = \frac{1}{3} \int_0^\infty p v \omega(p) f(p) dp.$$

if not already known (0 for photons), the chemical potential can be determined from the first equation, as we know the number density n of gas particles.

$$\bar{\mu} = \mu + mc^2 = kT \ln\left(\frac{nh^3}{g} \frac{1}{(2\pi mkT)^{3/2}}\right) + mc^2$$

chemical potential and dn for a Maxwell-Boltzmann gas

$$dn_j = n_j \frac{4\pi p_j^2}{(2\pi m_j kT)^{3/2}} \exp\left(-\frac{p_j^2}{2m_j kT}\right) dp_j$$

dn for a photon (Planck) gas

$$dn_\gamma = \frac{8\pi}{c^3} \frac{\nu^2 d\nu}{\exp(h\nu/kT) - 1} = \frac{1}{\pi^2 (c\hbar)^3} \frac{E_\gamma^2 dE_\gamma}{\exp(E_\gamma/kT) - 1}$$

Preview on chemical equilibria

a reaction involving particles 1 through 4 (with the C's being integer numbers) is in equilibrium, i.e. the forward and backward reactions occur on timescales shorter than the observing time. Then the following relation holds between the chemical potentials.

$$C_1 \text{ particle1} + C_2 \text{ particle2} \rightleftharpoons C_3\text{particle3} + C_4\text{particle4}$$

$$C_1\bar{\mu}_1 + C_2\bar{\mu}_2 = C_3\bar{\mu}_3 + C_4\bar{\mu}_4$$

$$\bar{\mu} = \mu + mc^2.$$

The chemical potential obtained from the total number density n provides information on energy/momentum distributions of particles. It is only determined up to a constant. If energy generation due to mass differences in reactions is involved, the above equation is correct, if the rest mass energy is added.

The above equation leads to solutions for the relative concentrations as a function of total (mass) density and temperature.

A sketch on nuclear reactions

$$\sigma = \frac{\text{number of reactions target}^{-1}\text{sec}^{-1}}{\text{flux of incoming projectiles}} = \frac{r/n_i}{n_j v}$$

$$\sigma = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)T_l$$

if one neglects spins of participating particles, the fusion cross section can be determined just by the sum of partial waves with transmission coefficients T_l for angular momentum l

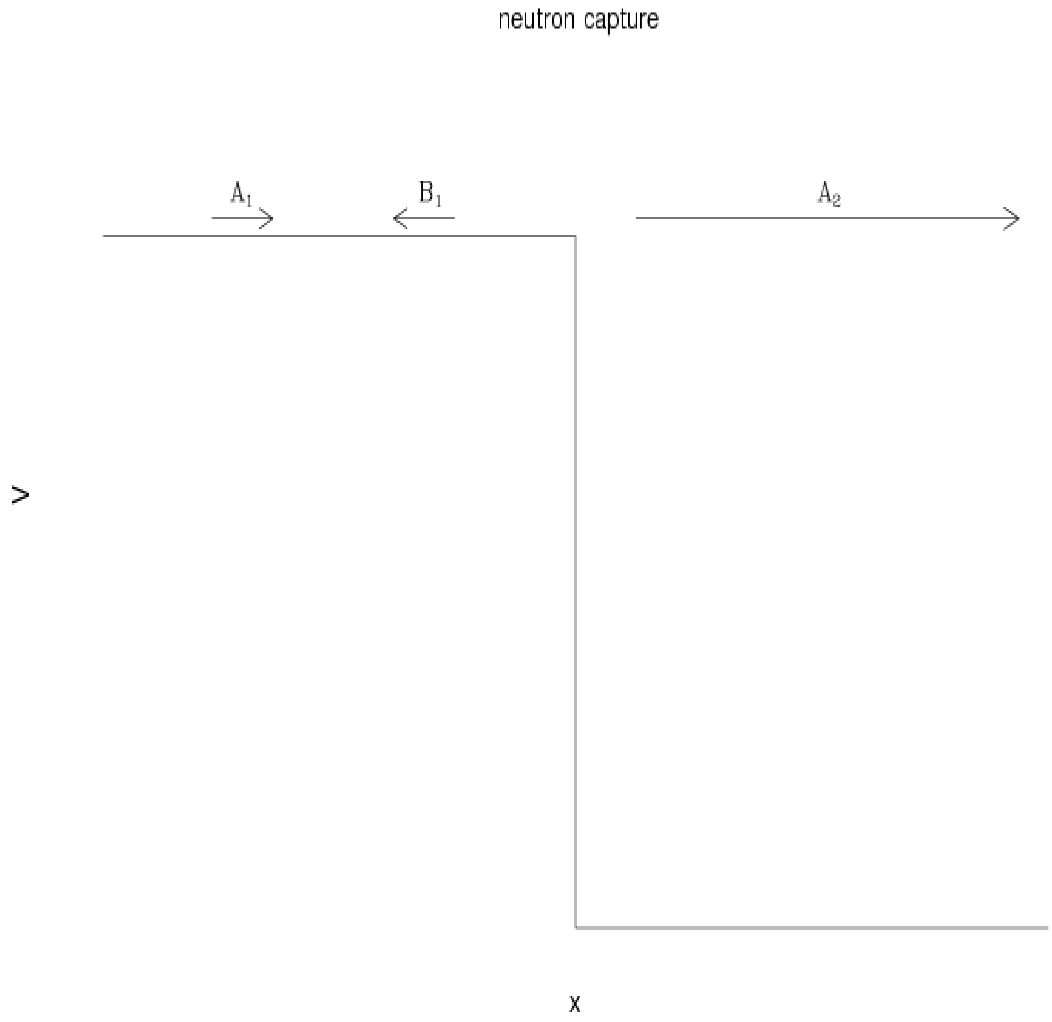
$$\sigma \approx \frac{\pi}{k^2}T_{l=0}$$

for low energies the fusion cross section is dominated by s-waves (l=0)

$$T = \frac{j_{fin}}{j_{in}} = \frac{k_{fin}|\phi_{fin}|^2}{k_{in}|\phi_{in}|^2}$$

transmission coefficient determined by ratio of penetrating to incoming flux.

Reactions with neutrons



"central collision", l=0

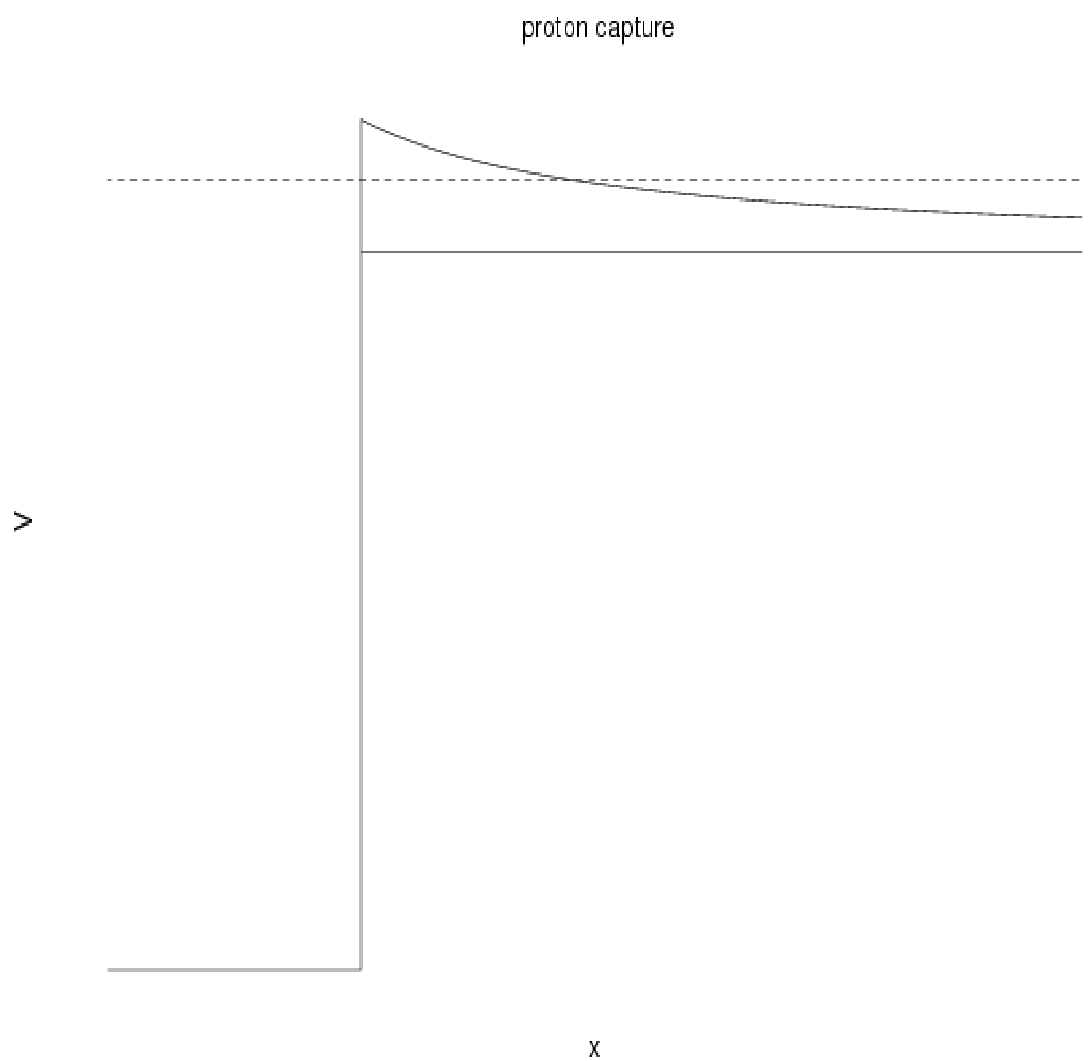
plane wave with momentum k_1 approaches nucleus, partially reflected and partially entering nucleus (inside nucleus momentum k_2).

$$T = \frac{k_2|A_2|^2}{k_1|A_1|^2} = \frac{4k_1k_2}{|k_1+k_2|^2}.$$

k_2 dominates over k_1 due to potential depth

$$T \approx \frac{4k_1}{k_2}$$

Cross sections with charged particles



$$T \approx e^{-\frac{2}{\hbar}\int_{x_1}^{x_2}\sqrt{2m(V(x)-E)}dx}$$

transmission coefficient
from WKB approximation

$$T = e^{-2\pi\eta}$$

$$\eta = \sqrt{\frac{m}{2E}}\frac{Z_1 Z_2 e^2}{\hbar},$$

Sommerfeld parameter.

for Coulomb barrier
penetration

cross sections for neutrons and charged particles

(i) neutrons $T_{n,0} \approx \frac{4k_1}{k_2}$

$$k_1 = \frac{\sqrt{2\mu E}}{\hbar} \qquad k_2 = \frac{\sqrt{2\mu(E+Q)}}{\hbar} \approx \text{const} \quad \text{for } E \ll Q$$

$$\Rightarrow \sigma = \frac{\pi}{k_1^2} \cdot 4\frac{k_1}{k_2} \propto \frac{1}{k_1}$$

$$\sigma \propto \frac{1}{\sqrt{E}} = \frac{1}{v}$$

declining as function of bombarding energy

(ii) charged particle captures $T_{c,0} = e^{-2\pi\eta}$

$$\sigma = \frac{\pi}{k^2} e^{-2\pi\eta} = \frac{\hbar^2 \pi}{2\mu E} e^{-2\pi\eta}$$

$$\eta = \sqrt{\frac{\mu}{2E}} \frac{Z_i Z_j e^2}{\hbar.}$$

increasing as function of energy by orders of magnitude due to Coulomb penetration

Introduction to reaction rates

$$\sigma = \frac{\text{number of reactions target}^{-1}\text{sec}^{-1}}{\text{flux of incoming projectiles}} = \frac{r/n_i}{n_j v}$$

$$r = \sigma v n_i n_j$$

reaction rate r (per volume and sec) for a fixed bombarding velocity/energy (like in an accelerator)

$$r_{i;j} = \int \sigma \cdot |\vec{v}_i - \vec{v}_j| dn_i dn_j$$

for thermal distributions in a hot plasma

e.g. Maxwell-Boltzmann (nuclei/nucleons) or Planck (photons)

$$dn_j = n_j \frac{4\pi p_j^2}{(2\pi m_j kT)^{3/2}} \exp(-\frac{p_j^2}{2m_j kT}) dp_j$$

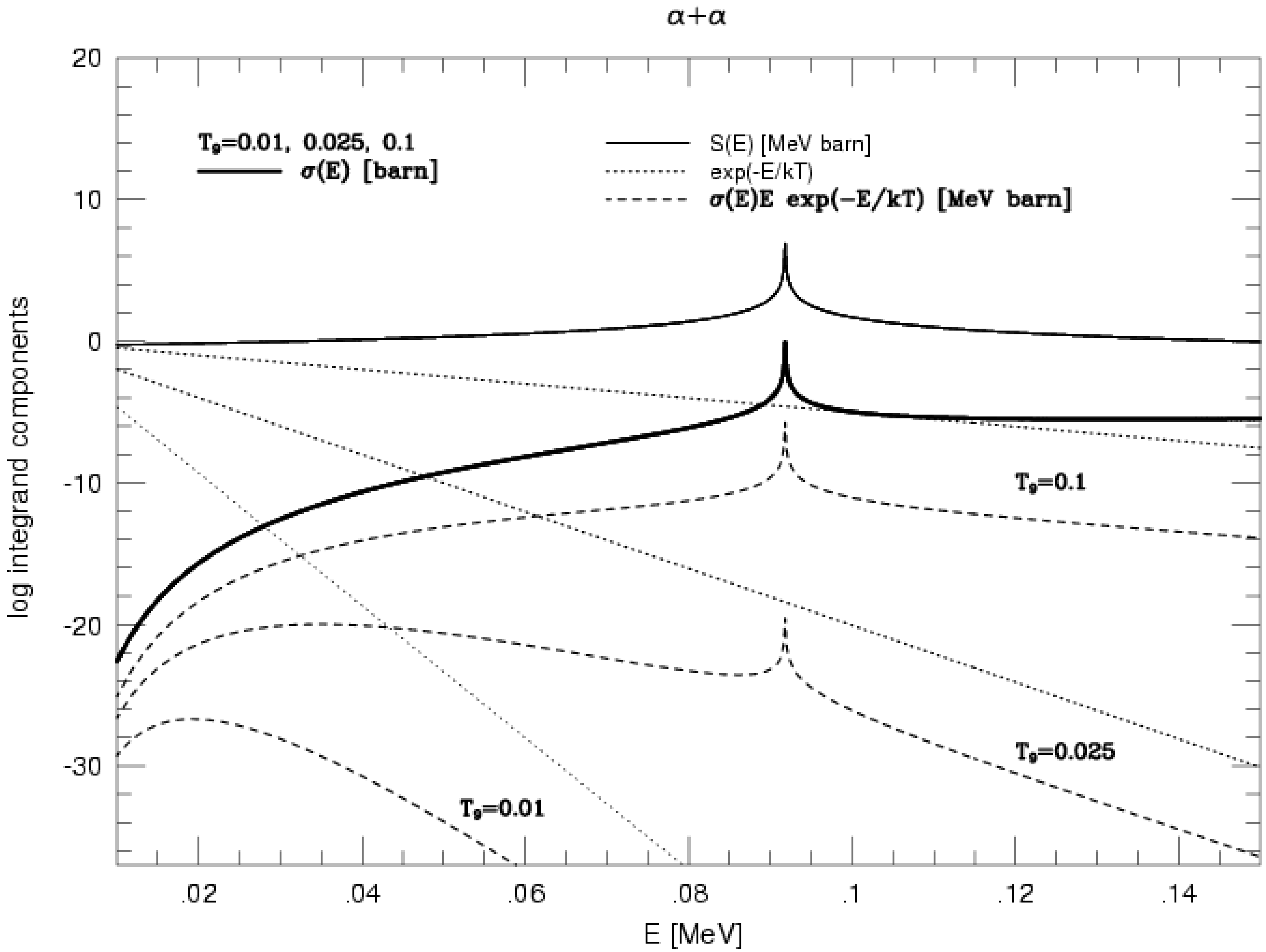
$$dn_\gamma = \frac{8\pi}{c^3} \frac{\nu^2 d\nu}{\exp(h\nu/kT) - 1} = \frac{1}{\pi^2 (c\hbar)^3} \frac{E_\gamma^2 dE_\gamma}{\exp(E_\gamma/kT) - 1}$$

for two MB-distributions for i and j one obtains after variable transformations

$$r_{i;j} = n_i n_j \langle \sigma v \rangle_{i;j}$$

$$\langle \sigma v \rangle (T) = \left(\frac{8}{\mu\pi} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E\sigma(E)\ \exp(-E/kT) dE$$

Temperature dependence of rates



for neutron captures close to constant (at higher temperatures, i.e. higher velocities, multiplied with 1/v dependence of cross section)

for charged particles the contribution to the integral is strongly rising with temperature

Reaction networks

reaction i+j->m+o i(j,o)m with reaction rate

$$r_{i;j} = \frac{1}{1+\delta_{ij}} n_i n_j \langle \sigma v \rangle$$

(avoiding double counting for reactions of identical particles)

$$\left(\frac{\partial n_i}{\partial t}\right)_\rho = \left(\frac{\partial n_j}{\partial t}\right)_\rho = -r_{i;j}$$

$$\left(\frac{\partial n_o}{\partial t}\right)_\rho = \left(\frac{\partial n_m}{\partial t}\right)_\rho = +r_{i;j}$$

resulting changes in number densities of participating nuclei (for constant mass densities!)

Introducing abundances Y and mass fractions X

$$\rho = \frac{1}{V} = \sum_i n_i m_i = \sum_i \frac{n_i}{N_A} m_i N_A$$

$$Y_i = \frac{n_i}{\rho N_A}$$

$$1 = \frac{\rho}{\rho} = \sum_i \frac{n_i}{\rho N_A} m_i N_A = \sum_i Y_i A_i = \sum_i X_i$$

Reaction networks

i(j,o)m

$$\dot{Y}_i = \frac{1}{\rho N_A}\left(\frac{\partial n_i}{\partial t}\right)_\rho = -\frac{r_{i;j}}{\rho N_A} = -\frac{1}{1+\delta_{ij}}\rho N_A \langle\sigma v\rangle_{i;j} Y_i Y_j$$

$$\dot{Y}_j = \frac{-1}{1+\delta_{ij}}\rho N_A \langle\sigma v\rangle_{i;j} Y_i Y_j$$

$$\dot{Y}_o = \frac{1}{1+\delta_{ij}}\rho N_A \langle\sigma v\rangle_{i;j} Y_i Y_j$$

$$\dot{Y}_m = \frac{1}{1+\delta_{ij}}\rho N_A \langle\sigma v\rangle_{i;j} Y_i Y_j.$$

decay i->m

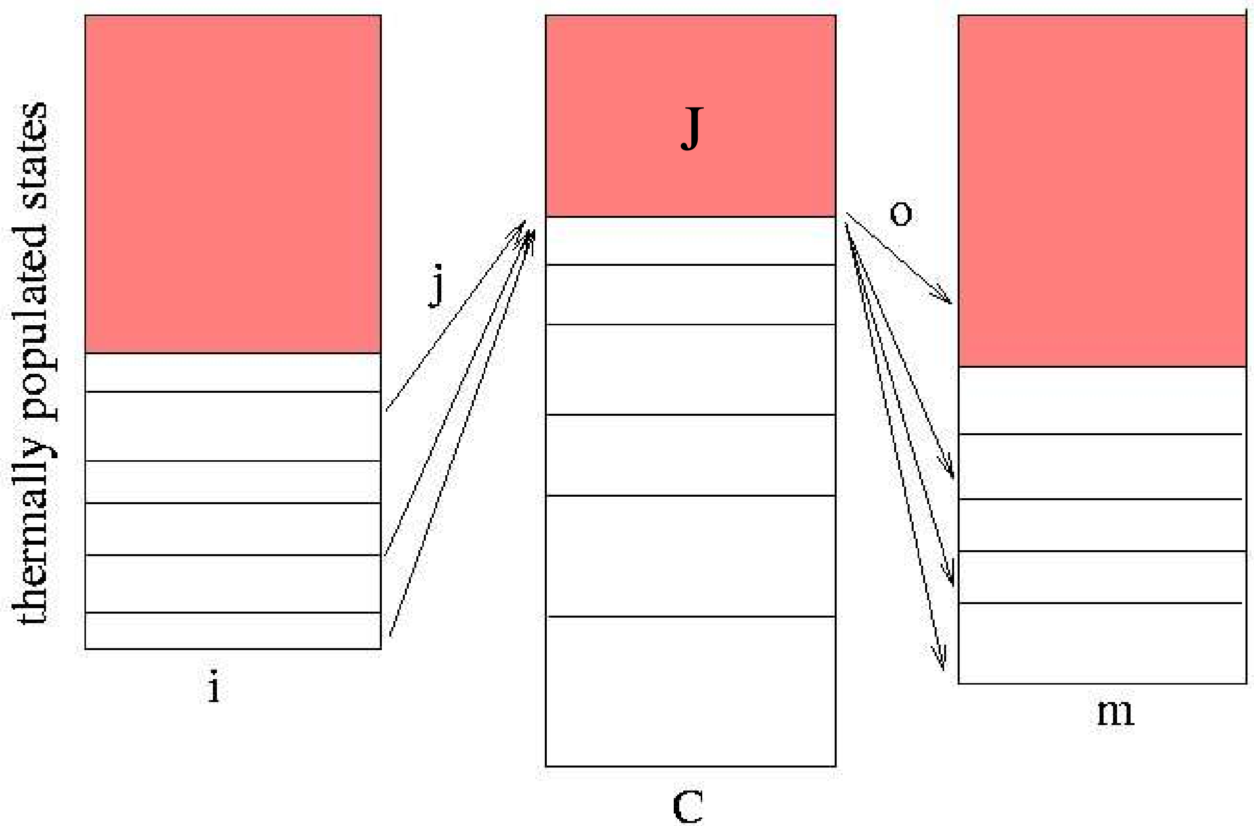
$$\dot{Y}_i = \left(\frac{\dot{n}_i}{\rho N_A}\right)_\rho = -\frac{r_i}{\rho N_A}$$

$$\Rightarrow \dot{Y}_i = -\lambda_i Y_i \qquad \dot{Y}_m = \lambda_i Y_i$$

general: N's count number of particles produced/distroyed in the reaction (positive/negative)

$$\dot{Y}_i = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} \frac{N^i_{j,k}}{1+\delta_{jk}} \rho N_A < \sigma v >_{j;k} Y_j Y_k.$$

General compound cross section



$$\sigma_i(j,o) = \frac{\pi}{k_j^2}\frac{(1+\delta_{ij})}{(2I_i+1)(2I_j+1)}\sum_{J,\pi}(2J+1)\frac{T_j(E,J,\pi)T_o(E,J,\pi)}{T_{tot}(E,J,\pi)}$$

including spin and parity dependence

www.nucastro.org
for statist. model
cross sections

Reverse rates

$$\sigma_m(o,j)_J = \frac{\pi}{k_o^2}\frac{(1+\delta_{om})(2J+1)}{(2I_m+1)(2I_o+1)}\frac{T_oT_j}{T_{tot}}$$

$$\sigma_i(j,o)_J = \frac{\pi}{k_j^2}\frac{(1+\delta_{ij})(2J+1)}{(2I_i+1)(2I_j+1)}\frac{T_jT_o}{T_{tot}}$$

$$k_o = \frac{p_o}{\hbar} = \frac{\sqrt{2\mu_{om}E_{om}}}{\hbar} \qquad k_j = \frac{p_j}{\hbar} = \frac{\sqrt{2\mu_{ij}E_{ij}}}{\hbar}$$

$$g_x = (2I_x+1) \qquad E_{ij} = E_{om} + Q_{o,j}.$$

$$\frac{\sigma_i(j,o)_J}{\sigma_m(o,j)_J} = \frac{1+\delta_{ij}}{1+\delta_{om}}\frac{g_og_m}{g_ig_j}\frac{k_o^2}{k_j^2}$$

going through a specific state J in the compound nucleus

but true for any state at that energy

$$\sigma_i(j,o;E_{ij}) = \frac{1+\delta_{ij}}{1+\delta_{om}}\frac{g_og_m}{g_ig_j}\frac{k_o^2}{k_j^2}\sigma_m(o,j;E_{om})$$

Reverse rates

$$\langle\sigma v\rangle_{i;j,o} = \frac{1+\delta_{ij}}{1+\delta_{om}} \left(\frac{8}{\mu_{ij}\pi}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E_{ij} \frac{g_o g_m}{g_i g_j} \frac{k_o^2}{k_j^2} \sigma_m(o,j;E_{om})$$

$$\times \ \exp(-E_{ij}/kT) dE_{ij}$$

$$= \frac{1+\delta_{ij}}{1+\delta_{om}} \frac{g_o g_m}{g_i g_j} (\frac{\mu_{om}}{\mu_{ij}})^{3/2} \ \exp(-Q_{o,j}/kT)$$

$$\times \left(\frac{8}{\mu_{om}\pi}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E_{om}\sigma_m(o,j;E_{om}) \ \exp(-E_{om}/kT) dE_{om}$$

$$\langle\sigma v\rangle_{i;j,o} = \frac{1+\delta_{ij}}{1+\delta_{om}} \frac{G_m g_o}{G_i g_j} (\frac{\mu_{om}}{\mu_{ij}})^{3/2} \ \exp(-Q_{o,j}/kT) \ \langle\sigma v\rangle_{m;o,j}$$

containing the Q-value of the reaction (nuclear mass differences)

Reverse photodisintegrations

$$r_{i\gamma} = n_i \frac{1}{\pi^2 c^2 \hbar^3} \int_0^\infty \frac{\sigma_i(\gamma, o; E_\gamma) E_\gamma^2}{\exp(E_\gamma/kT) - 1} dE_\gamma$$
$$= n_i \lambda_{i;\gamma,o}(T)$$
$$\lambda_{i;\gamma,o}(T) = \frac{1}{\pi^2 c^2 \hbar^3} \int_0^\infty \frac{\sigma_i(\gamma, o; E_\gamma) E_\gamma^2}{\exp(E_\gamma/kT) - 1} dE_\gamma.$$

photodisintegration rates only T-dependent!

$$k_\gamma = \frac{w}{c} = \frac{\hbar w}{\hbar c} = \frac{E_\gamma}{\hbar c} \qquad g_\gamma = 2$$

$$k_o = \frac{p}{\hbar} = \frac{\sqrt{2\mu_{om} E_{om}}}{\hbar} \qquad E_\gamma = E_{om} + Q_{o,\gamma}$$

$$\sigma_i(\gamma, o; E_\gamma) = \frac{g_o g_m}{(1 + \delta_{om}) g_i} c^2 \frac{\mu_{om} E_{om}}{E_\gamma^2} \sigma_m(o, \gamma; E_{om})$$

$$\lambda_{i;\gamma,o} = \frac{1}{\pi^2 c^2 \hbar^3} \int_0^\infty \frac{g_o g_m}{(1 + \delta_{om}) g_i} c^2 \frac{\mu_{om} E_{om}}{E_\gamma^2} \sigma_m(o, \gamma; E_{om}) E_\gamma^2$$
$$\times \exp(-E_\gamma/kT) dE_\gamma$$
$$= \frac{1}{\pi^2 \hbar^3} \frac{g_o g_m}{g_i} \mu_{om} \exp(-Q_{o,\gamma}/kT)$$
$$\times \int_0^\infty E_{om} \sigma_m(o, \gamma; E_{om}) \exp(-E_{om}/kT) dE_{om}$$

$$\lambda_{i;\gamma,o}(T) = \frac{g_o G_m}{(1 + \delta_{om}) G_i} \left(\frac{\mu_{om} kT}{2\pi\hbar^2}\right)^{3/2} \exp(-Q_{o,\gamma}/kT) \langle \sigma v \rangle_{m;o}$$

relation between photodisintegration rate and reverse capture rate

Reaction equilibria

reaction network for i(j,o)m

$$\dot{Y}_i = \dot{Y}_j = -\rho N_A \langle \sigma v \rangle_{i;j,o} Y_i Y_j + \rho N_A \langle \sigma v \rangle_{m;o,j} Y_o Y_m$$

$$\dot{Y}_m = \dot{Y}_o = -\dot{Y}_i$$

$$\dot{Y}_i = \dot{Y}_j = -\rho N_A \langle \sigma v \rangle_{i;j,\gamma} Y_i Y_j + \lambda_{m;\gamma,j} Y_m$$

$$\dot{Y}_m = -\dot{Y}_i.$$

in this case o is a photon

if forward and backward reaction are in equilibrium, we have for all indices

$$\dot{Y} = 0$$

this leads to the following abundance relations

$$\frac{Y_m}{Y_i} = \frac{Y_j}{Y_o} \frac{\langle \sigma v \rangle_{i;j,o}}{\langle \sigma v \rangle_{m;o,j}} = \frac{Y_j}{Y_o} \frac{g_o G_m}{g_j G_i} \left(\frac{m_o m_m}{m_i m_j}\right)^{3/2} \exp(Q_{j,o}/kT)$$

$$\frac{Y_m}{Y_i} = \frac{\rho N_A \langle \sigma v \rangle_{i;j,\gamma}}{\lambda_{m;\gamma,j}} Y_j = \rho N_A Y_j \frac{G_m}{g_j G_i} \left(\frac{m_m}{m_i m_j}\right)^{3/2} \left(\frac{2\pi\hbar^2}{kT}\right)^{3/2} \exp(Q_{j,\gamma}/kT)$$

The same results would have been obtained, if the equations for chemical equilibria would have been utilized which include the chemical potentials!!

Nuclear Statistical Equilibriuim (NSE)

$$\bar{\mu}(Z,N) + \bar{\mu}_n = \bar{\mu}(Z,N+1)$$
$$\bar{\mu}(Z,N) + \bar{\mu}_p = \bar{\mu}(Z+1,N)$$

i.e. neutron or proton captures on nucleus (Z,N) are in chemical equilibium with the reverse photodisintegrations.

If this is the case for all neutron and proton captures on all nuclei (hot enough to overcome all Coulomb barriers as well as having high energy photons...) this leads to

$$N \text{neutrons} + Z \text{ protons} \rightleftharpoons (Z,N)$$

$$N\bar{\mu}_n + Z\bar{\mu}_p = \bar{\mu}_{Z,N}.$$

with $$\bar{\mu}_i = kT \ln\left(\frac{\rho N_A Y_i}{G_i}\left(\frac{2\pi\hbar^2}{m_i kT}\right)^{3/2}\right) + m_i c^2$$

Solving NSE

$$kT\ln\left(\frac{\rho N_A Y(Z,N)}{G_{Z,N}}\left(\frac{2\pi\hbar^2}{m_{Z,N}kT}\right)^{3/2}\right)+m_{Z,N}c^2$$

$$=N\left[kT\ln\left(\frac{\rho N_A Y_n}{g_n}\left(\frac{2\pi\hbar^2}{m_n kT}\right)^{3/2}\right)+m_n c^2\right]$$

$$+Z\left[kT\ln\left(\frac{\rho N_A Y_p}{g_p}\left(\frac{2\pi\hbar^2}{m_p kT}\right)^{3/2}\right)+m_p c^2\right]$$

$$\times\ln\left(\frac{\rho N_A Y(Z,N)}{G_{Z,N}}\left(\frac{2\pi\hbar^2}{m_{Z,N}kT}\right)^{3/2}\right)$$

$$-N\ln\left(\frac{\rho N_A Y_n}{g_n}\left(\frac{2\pi\hbar^2}{m_n kT}\right)^{3/2}\right)-Z\ln\left(\frac{\rho N_A Y_p}{g_p}\left(\frac{2\pi\hbar^2}{m_p kT}\right)^{3/2}\right)$$

$$=\frac{1}{kT}(Nm_nc^2+Zm_pc^2-m_{Z,N}c^2)=B_{Z,N}/kT.$$

Solving NSE

with $A = N + Z \quad m_n \approx m_u \quad m_p \approx m_u \quad m_{Z,N} \approx A m_u$

this leads to

$$Y(Z,N) = G_{Z,N}(\rho N_A)^{A-1} \frac{A^{3/2}}{2^A} \left(\frac{2\pi\hbar^2}{m_u kT} \right)^{\frac{3}{2}(A-1)} \exp(B_{Z,N}/kT) Y_n^N Y_p^Z$$

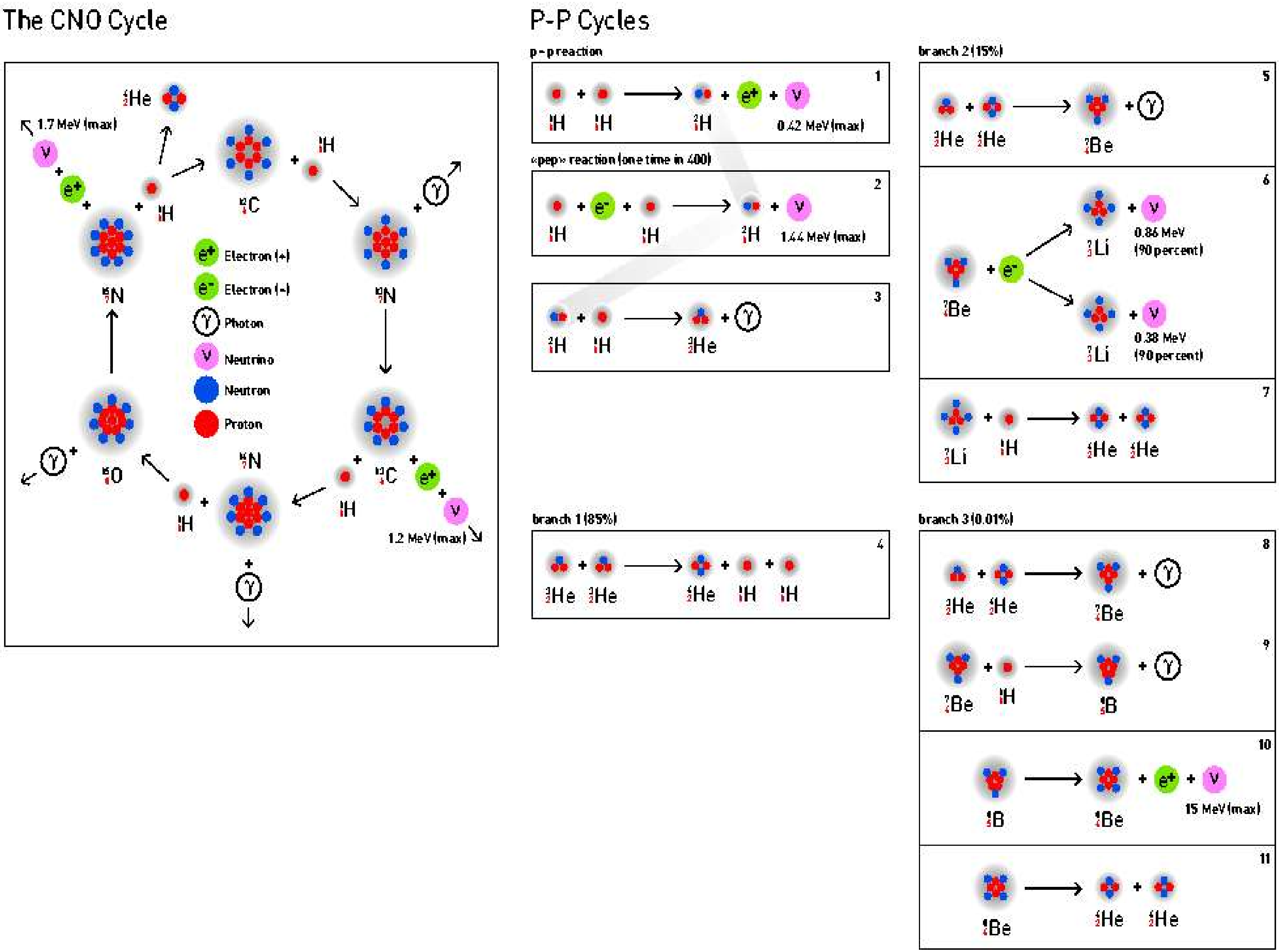
and can be solved via two equations (mass conservation and total proton to nucleon ratio Y_e) for neutron and proton abundances

$$\sum_i A_i Y_i = 1$$

$$\sum_i Z_i Y_i = Y_e$$

Stellar Burning Stages

Hydrogen Burning



Stellar Burning Stages

1. Hydrogen Burning — $T = (1\text{-}4)\times10^7$K
   - pp-cycles -> $^1H(p,e^+\nu)^2H$
   - CNO-cycle -> slowest reaction $^{14}N(p,\gamma)^{15}O$

2. Helium Burning — $T=(1\text{-}2)\times10^8$K
   - $^4He+^4He \Leftrightarrow {}^8Be$ $\quad$ $^8Be(\alpha,\gamma)^{12}C[(\alpha,\gamma)^{16}O]$
   - $^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)^{25}Mg$

3. Carbon Burning — $T=(6\text{-}8)\times10^8$K
   - $^{12}C(^{12}C,\alpha)^{20}Ne$ $\quad$ $^{23}Na(p,\alpha)^{20}Ne$
   - $^{12}C(^{12}C,p)^{23}Na$ $\quad$ $^{23}Na(p,\gamma)^{24}Mg$

Stellar Burning Stages

4. Neon Burning $T=(1.2\text{-}1.4)\times10^9K$

$^{20}Ne(\gamma,\alpha)^{16}O$

$^{20}Ne(\alpha,\gamma)^{24}Mg[(\alpha,\gamma)^{28}Si]$ $30kT = 4MeV$

5. Oxygen Burning $T=(1.5\text{-}2.2)\times10^9K$

$^{16}O(^{16}O,\alpha)^{28}Si$

$^{16}O(^{16}O,p)^{31}P$

$^{16}O(^{16}O,n)^{31}S(\beta^+)^{31}P$

$^{31}P(p,\alpha)^{28}Si$

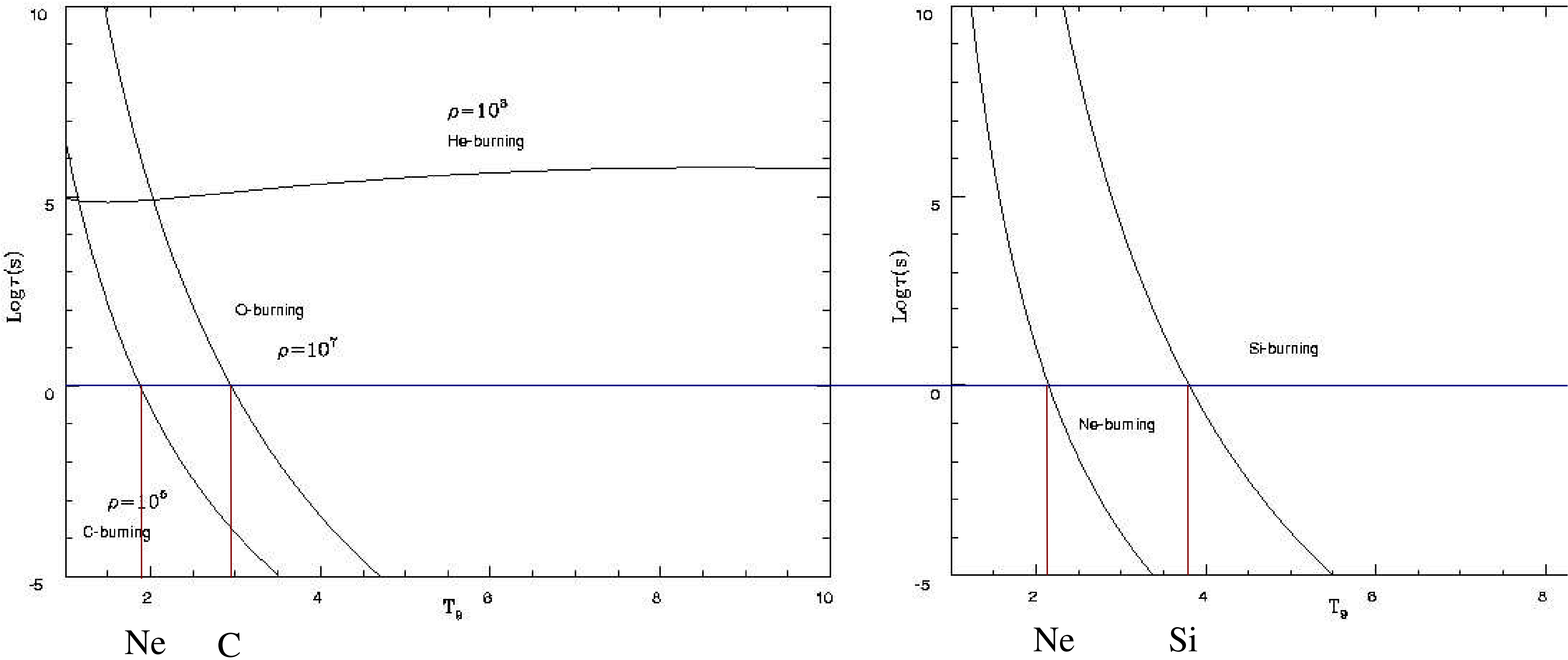
$^{31}P(p,\gamma)^{23}S$

6. "Silicon" Burning $T=(3\text{-}4)\times10^9K$

(all) photodisintegrations and capture reactions possible

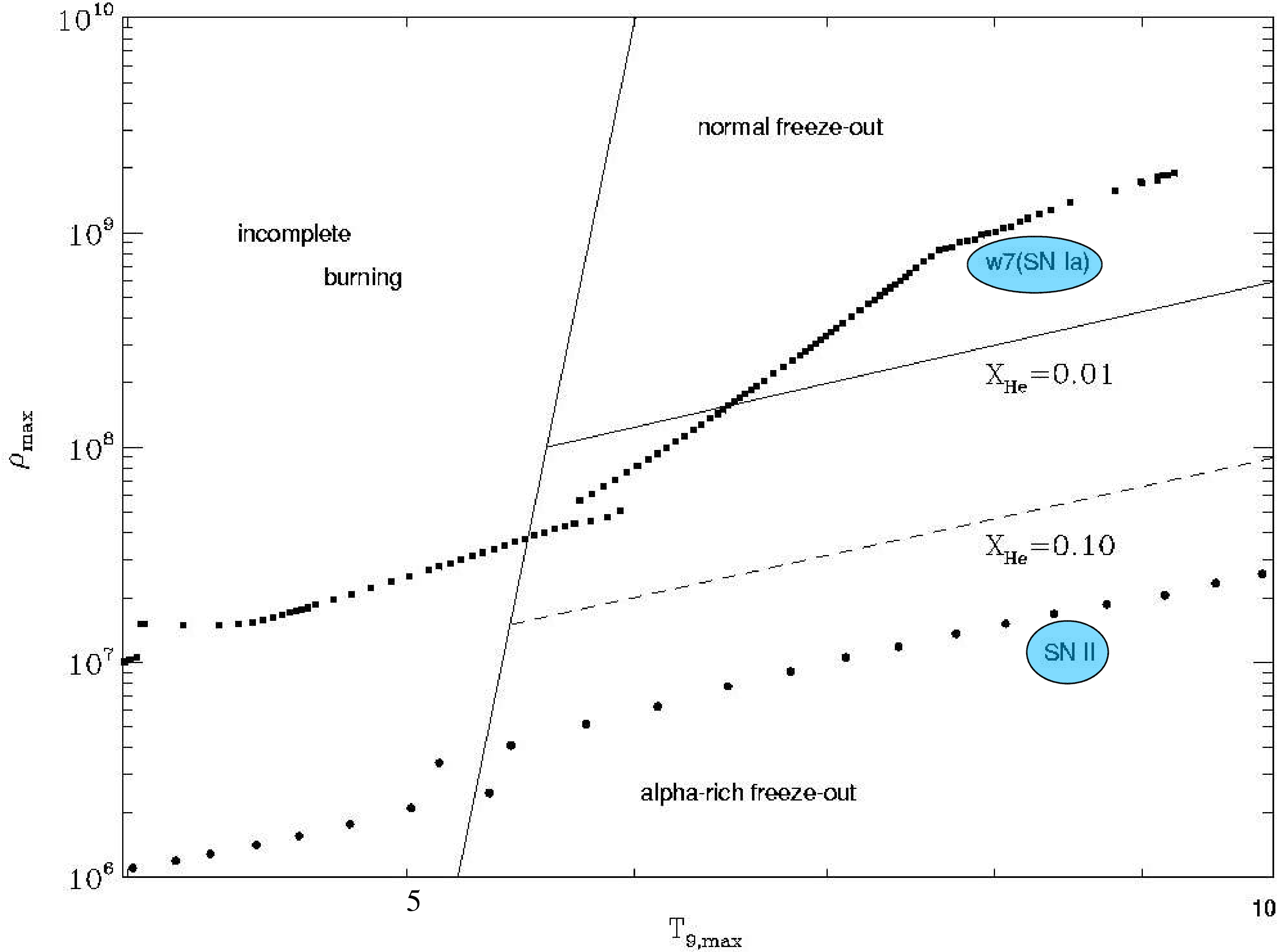
⇒ thermal (chemical) equilibrium

Explosive Burning

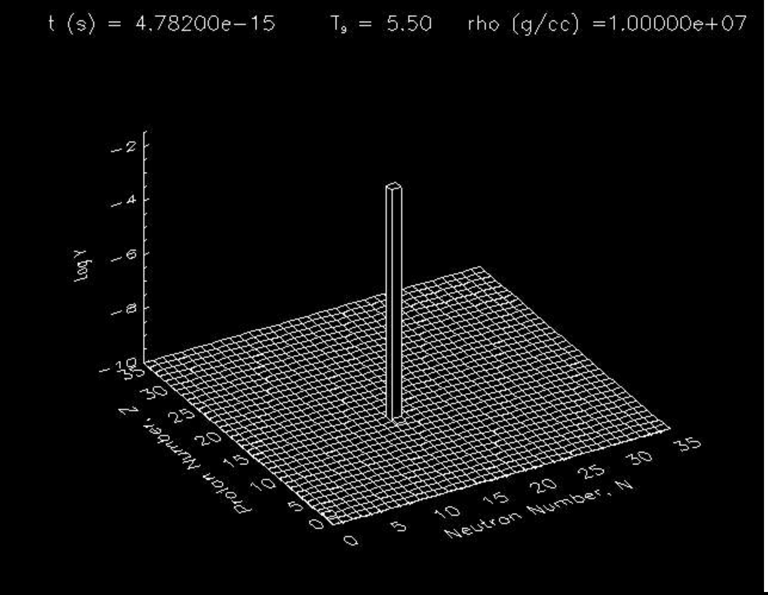


typical explosive burning process timescale order of seconds: fusion reactions (He, C, O) density dependent (He quadratic, C,O linear) photodisintegrations (Ne, Si) not density dependent

Explosive Si-Burning



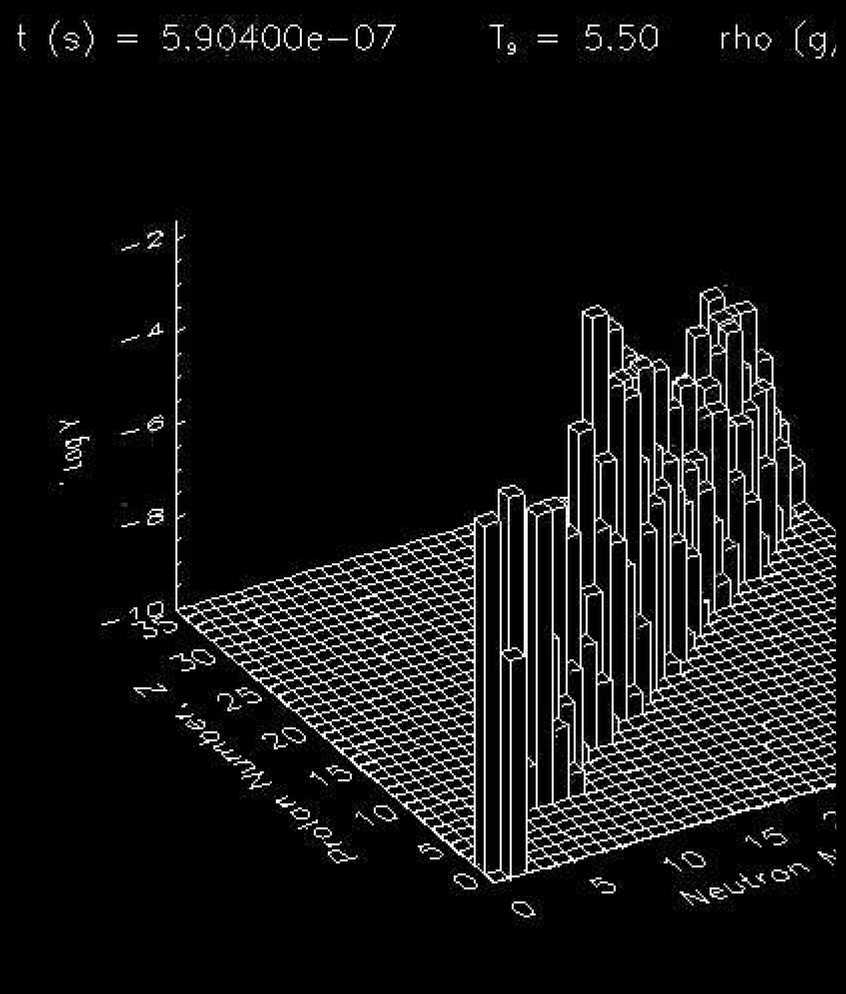
Explosive Burning above a critical temperature destroys (photodisintegrates) all nuclei and (re-)builds them up during the expansion. Dependent on density, the full NSE is maintained and leads to only Fe-group nuclei (normal freeze-out) or the reactions linking ^4He to C and beyond freeze out earlier (alpha-rich freeze-out).

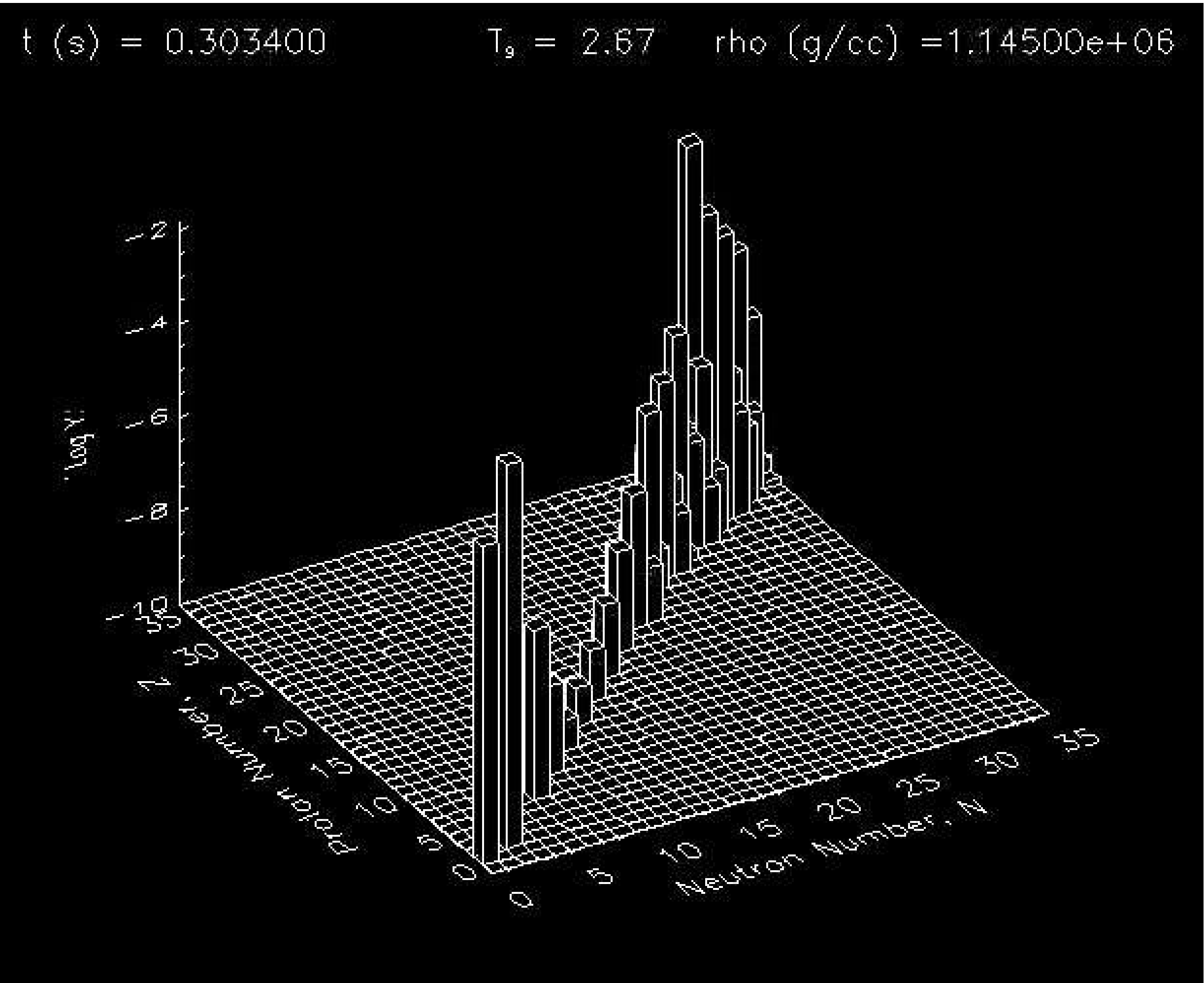


Explosive Si-burning

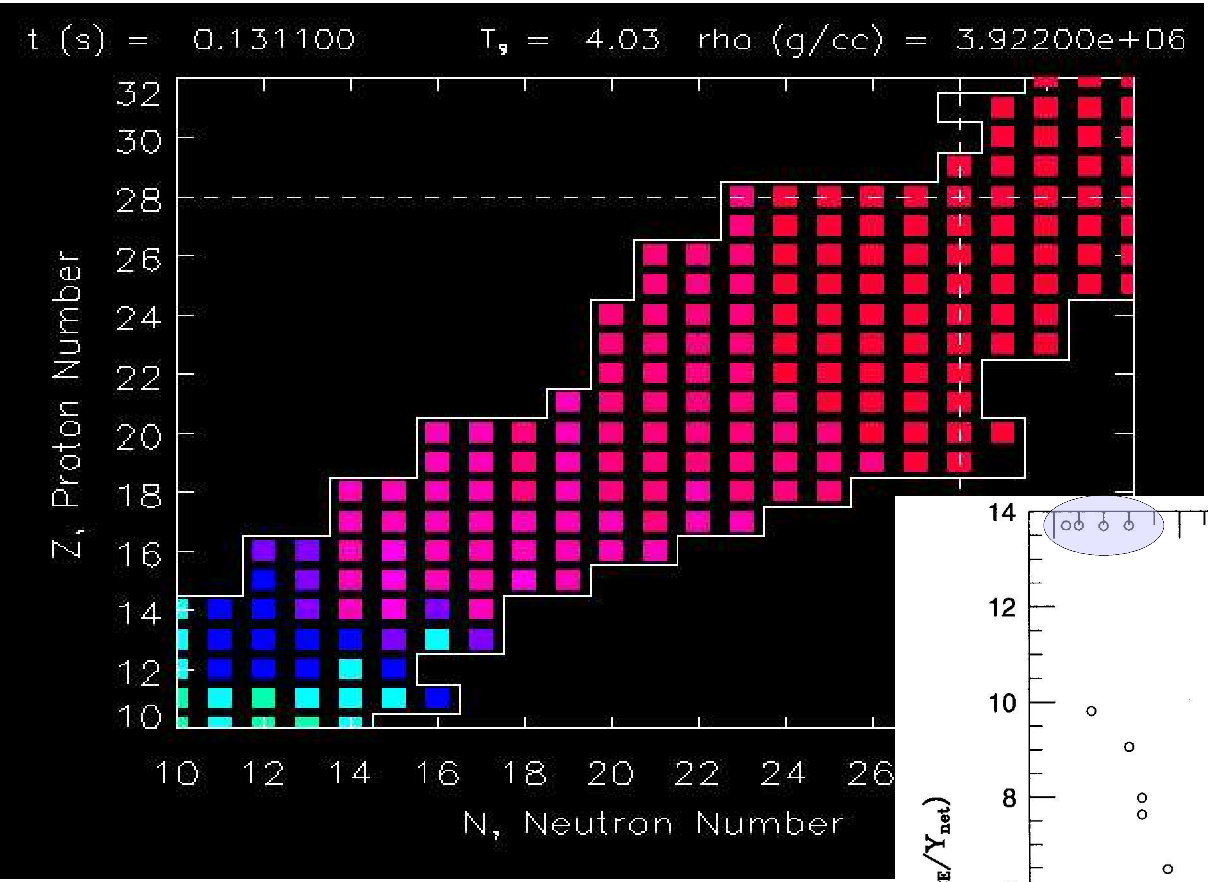
initially only ^{28}Si, fully burned, finally alpha-rich freeze-out

visualization: B.S. Meyer

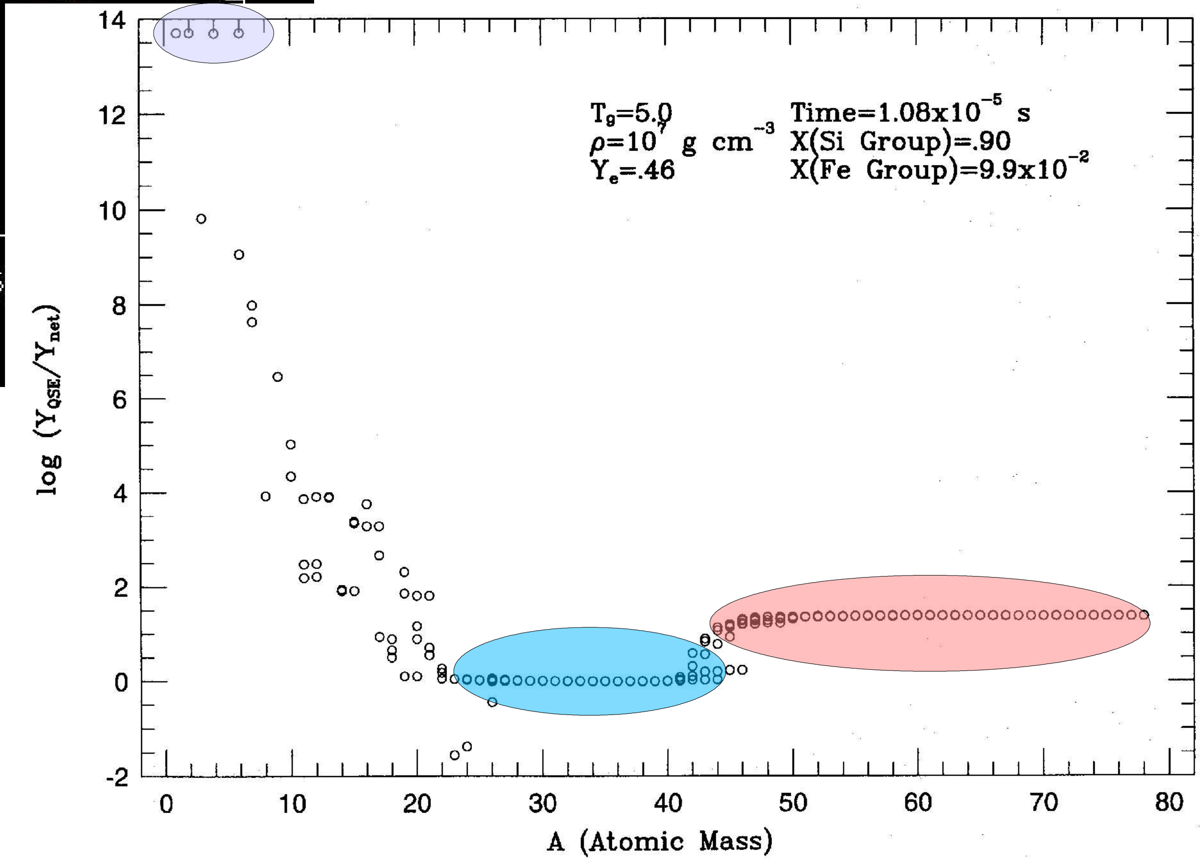




Quasi-Equilibrium (QSE)

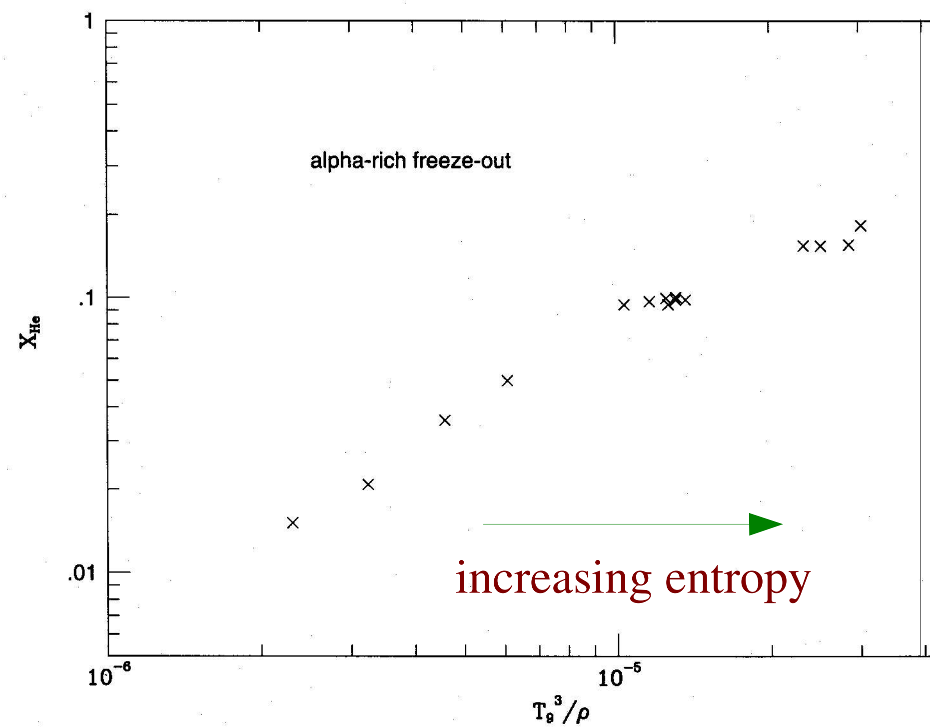


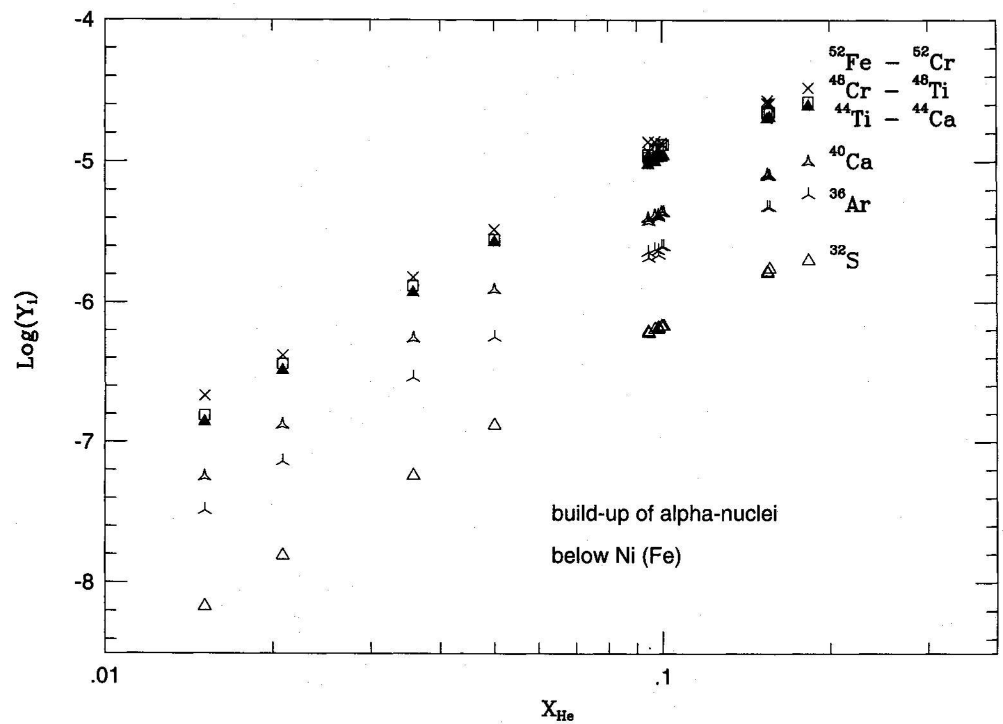
full NSE is not attained, but there exist equilibrium groups around ^{28}Si, ^{56}Ni and n,p,^{4}He, which are separated by slow reactions



Sample Calculations from
- B.S. Meyer and
- Hix and Thielemann

alpha-rich freeze-out





Thielemann et al. (1996)

increasing entropy

alpha-rich freeze-out occurs at high temperatures and/or low densities and is a function of entropy S in radiation-dominated matter

- it leads to the enhancement of "alpha-elements"
- and also to the extension of the Fe-group to higher masses (^{56}Ni to ^{64}Ge and for very high entropies up to A=80)

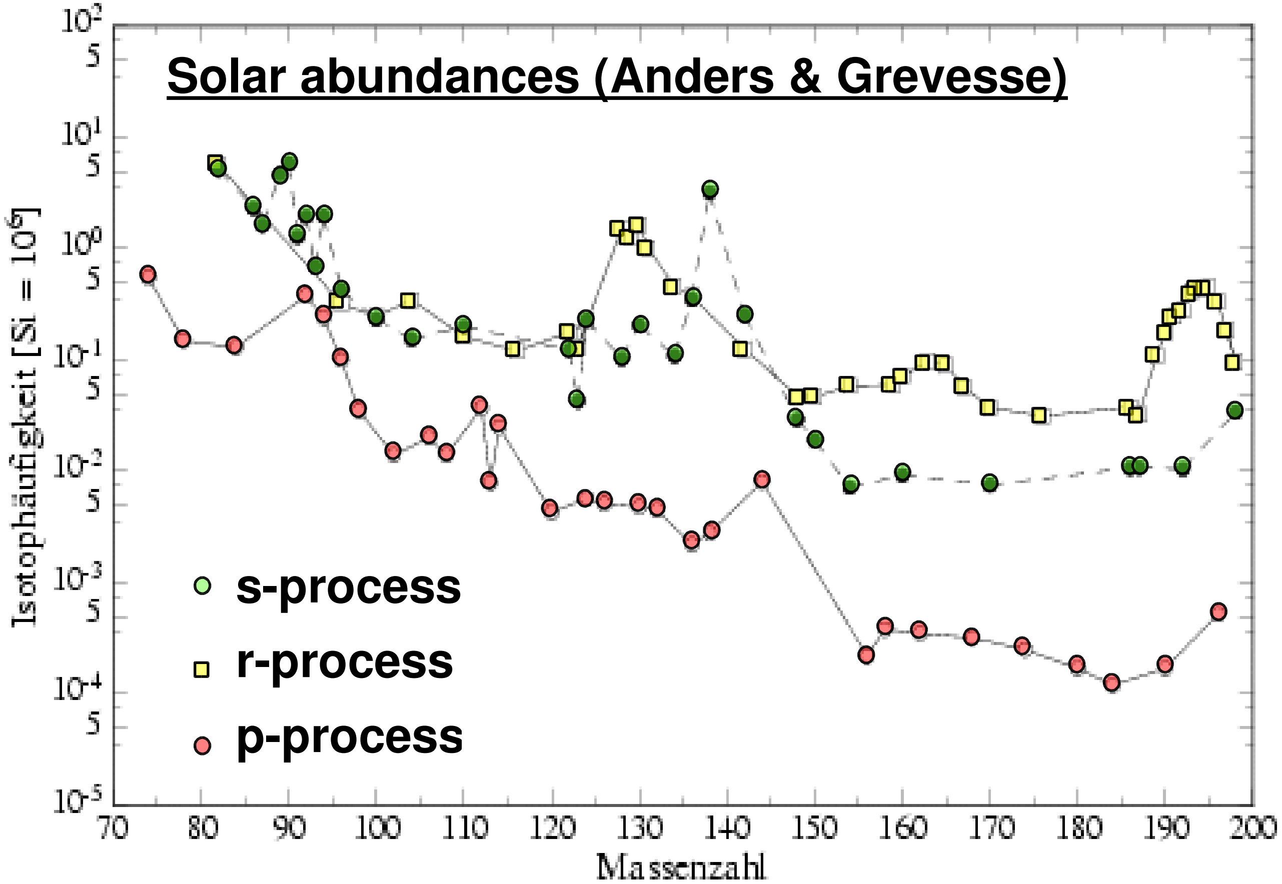
“Historical” Burning Processes (B^2FH)

- H-Burning
- He-Burning
- alpha-Process
- e-Process
- s-Process
- r-Process
- p-Process
- x-Process

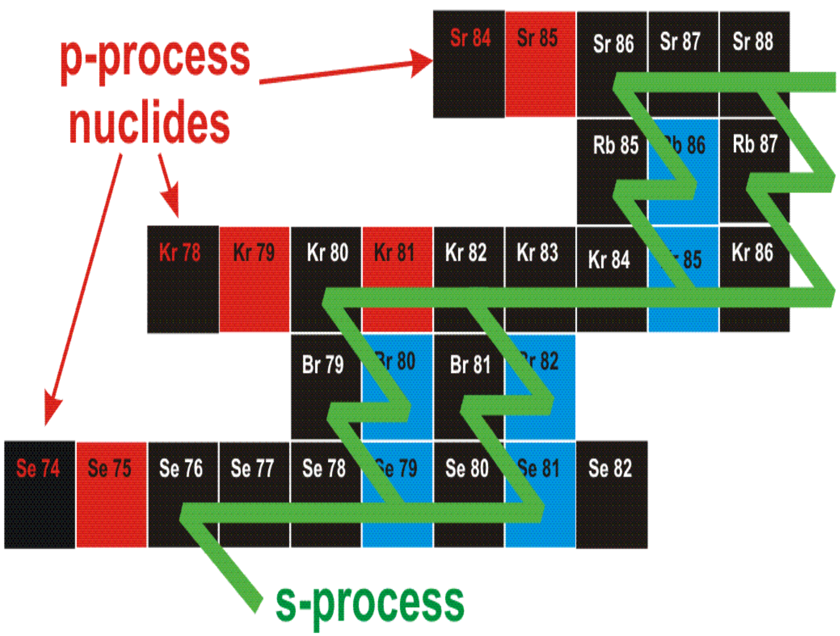
Present Understanding

- H-Burning
- He-Burning
- expl. C, Ne, O-Burning, incomplete Si-Burning
- explosive Si-Burning
- about 70% normal freeze-out with Y_e=0.42-47, about 30% alpha-rich freeze-out with Y_e=0.5
- s-Process (core and shell He-burning, neutrons from alpha-induced reactions on ^{22}Ne and ^{13}C)
- r-Process (see below)
- p-Process (see below)
- x-Process (light elements D, Li, Be, B [big bang, cosmic ray spallation and neutrino nucleosynthesis])

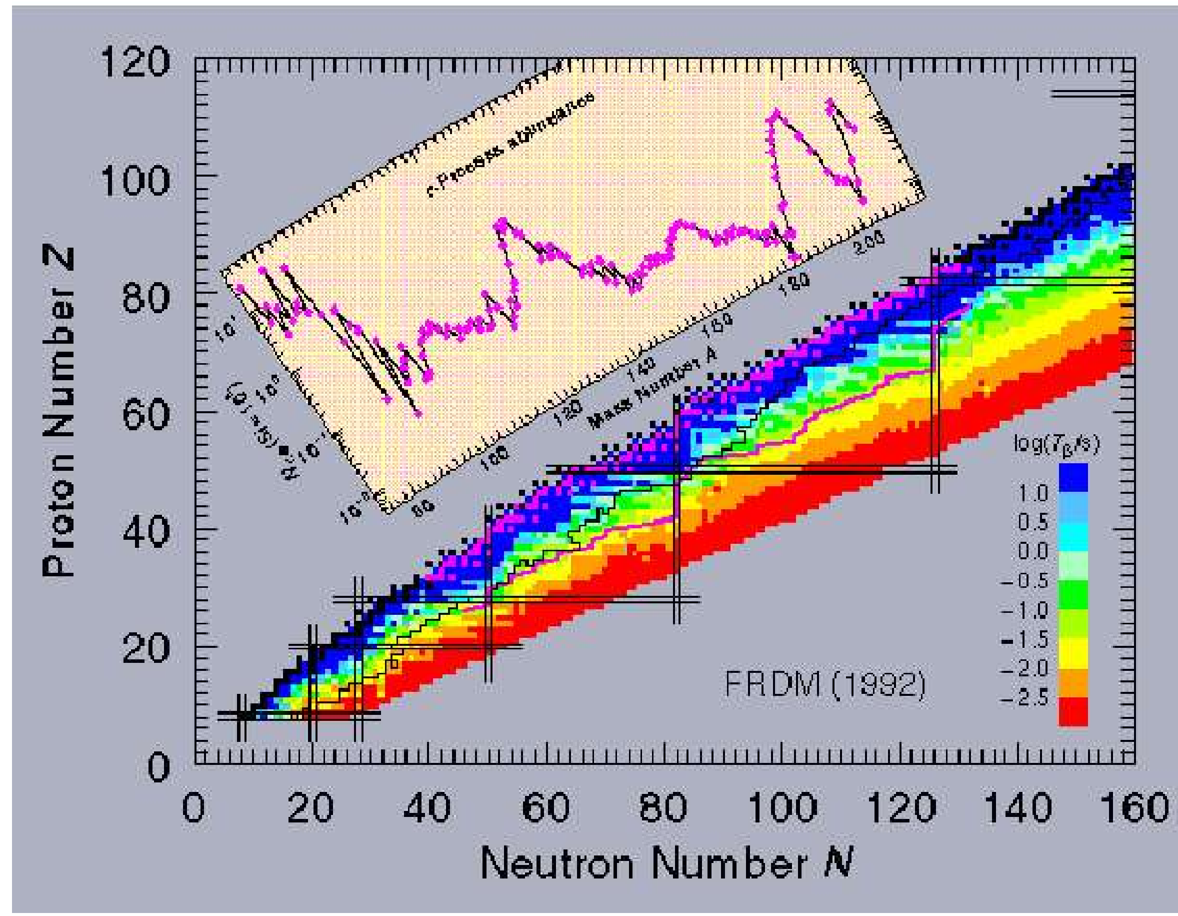
The Heavy Elements



s-, r- and p-Process



F. Käppeler



P. Möller

Processes in the Nuclear Chart