Electron Capture in Core Collapse Supernovae

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How to determine the evolution

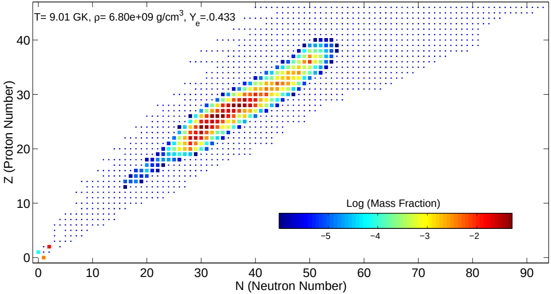
- Composition is a function of temperature, density and Y_e (Reaction network, NSE, EoS)
- Weak interactions are not in equilibrium. Change of Y_e has to be computed explicitly ($Y_i = n_i/n$):

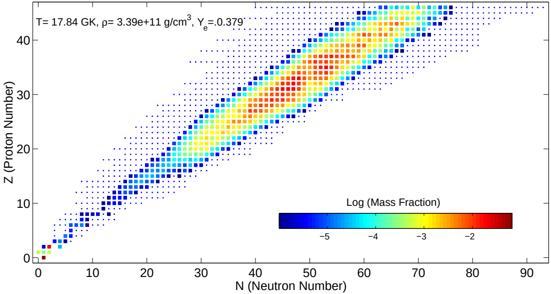
$$Y_e = \sum_i Y_i Z_i$$

$$\dot{Y}_e = -\sum_i \lambda_i^{ec} Y_i + \sum_i \lambda_i^{\beta^-} Y_i$$

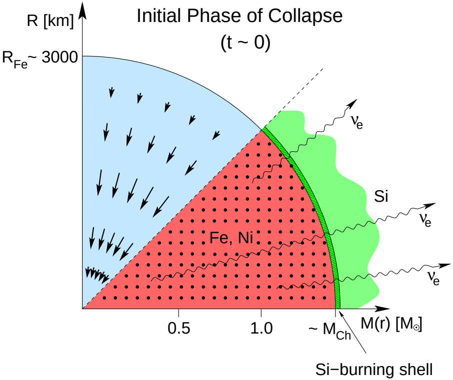
- Sytem is degenerate: $\mu_e \approx 1.11(\rho_7 Y_e)^{1/3}$ MeV

Composition



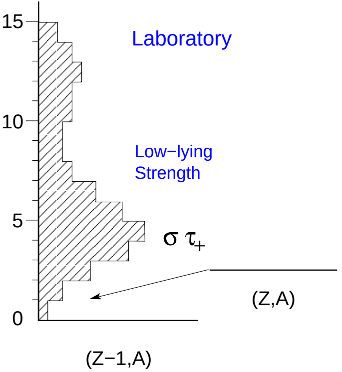


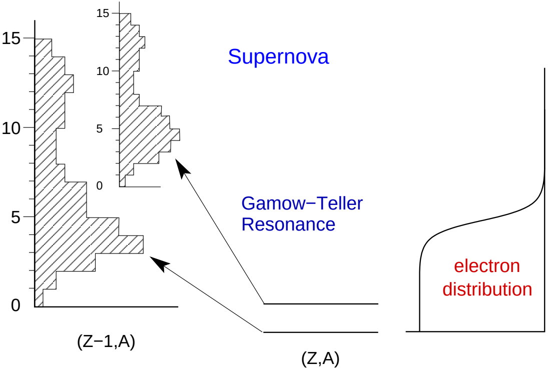
Presupernova evolution



- $T = 0.1–0.8$ MeV, $\rho = 10^7–10^{10}$ g cm^{-3}. Composition of iron group nuclei.
- Important processes:
  - electron capture: $e^- + (N, Z) \rightarrow (N + 1, Z - 1) + \nu_e$
  - β^- decay: $(N, Z) \rightarrow (N - 1, Z + 1) + e^- + \bar{\nu}_e$
- Dominated by allowed transitions (Fermi and Gamow-Teller)
- Evolution decreases number of electrons (Y_e) and Chandrasekar mass ($M_{ch} \approx 1.4(2Y_e)^2\ M_\odot$)

Laboratory vs. stellar electron capture

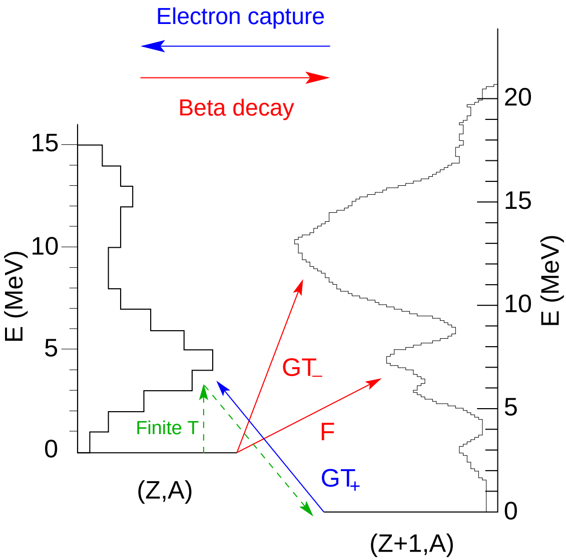




Capture of K-shell electrons to tail of GT strength distribution. Parent nucleus in the ground state

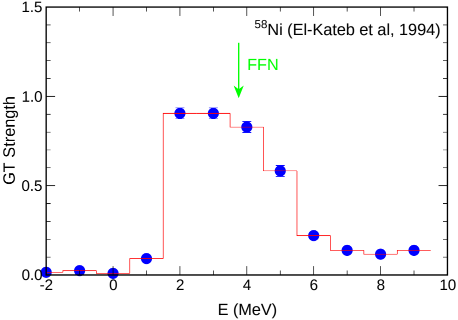
Capture of electrons from the high energy tail of the FD distribution. Capture to states with large GT matrix elements (GT resonance). Thermal ensemble of initial states.

Beta-decay

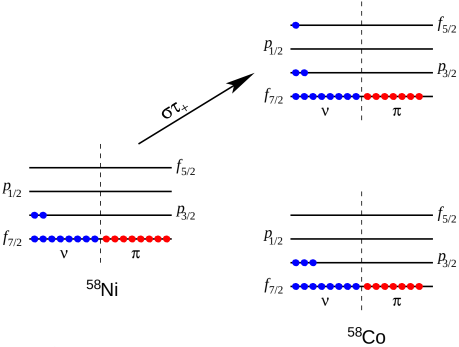

Electron capture
Beta decay
15
10
5
0
E (MeV)
20
15
10
5
0
E (MeV)
GT_
F
GT+
Finite T
(Z,A)
(Z+1,A)

Independent Particle Model

GT$_+$ strength in ^{58}Ni measured in (n, p).

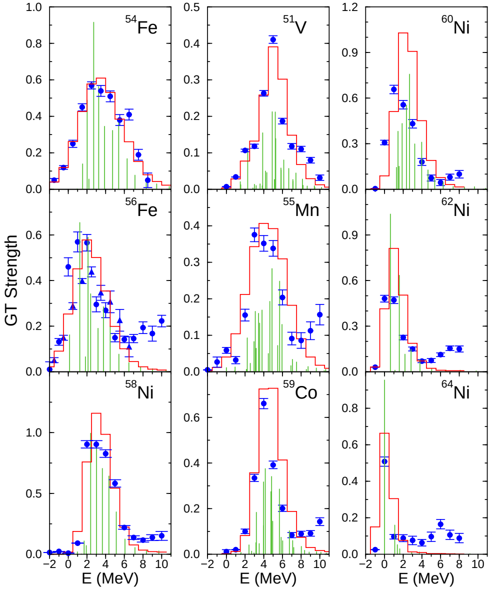


Independent particle model.



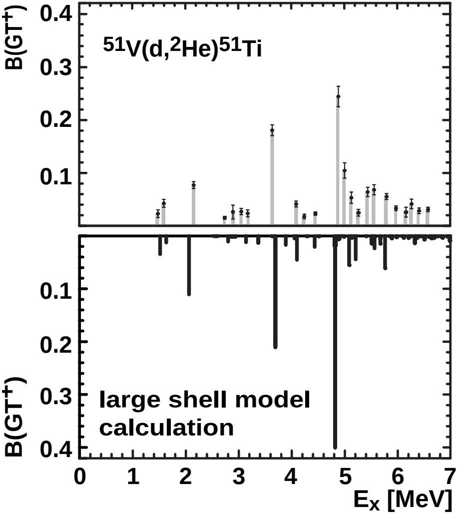
The IPM allows for a single transition ($f_{7/2} \to f_{5/2}$. It does not reproduce correctly the fragmentation of GT strength (correlations).

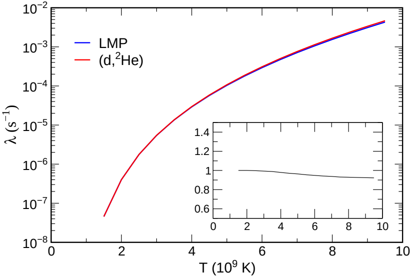
Strength distributions



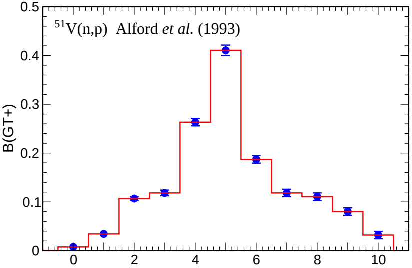
Shell-Model vs experiment (^{51}V)

C. Baümer *et al.* PRC **68**, 031303 (2003)



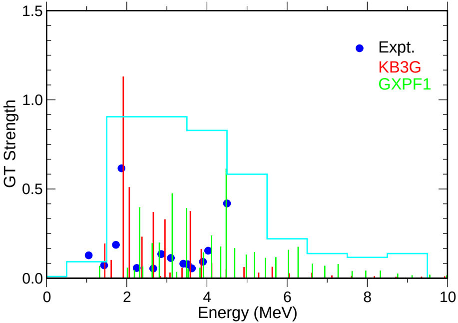


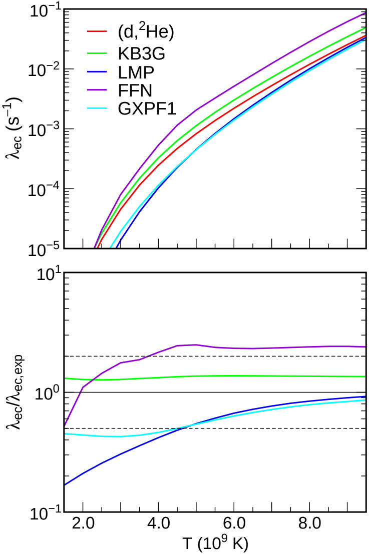
Old (n,p) data



Shell-Model vs experiment (^{58}Ni)

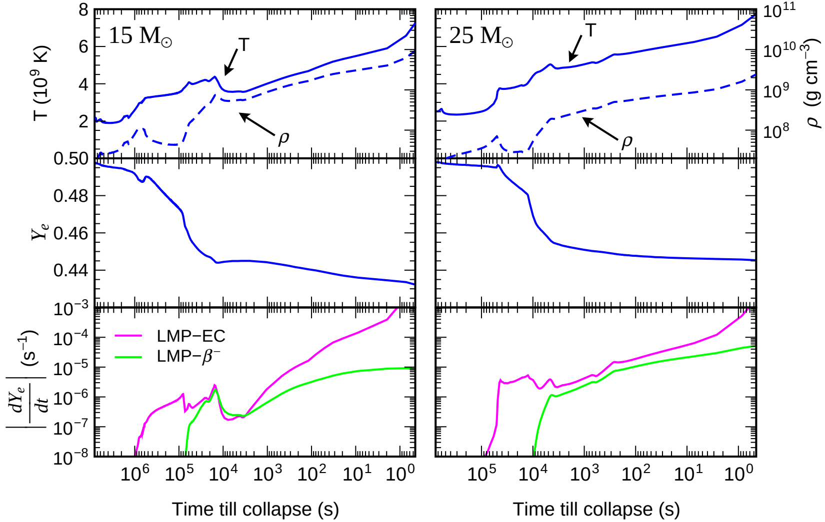
M. Hagemann, *et al.*, PLB **579**, 251 (2004)



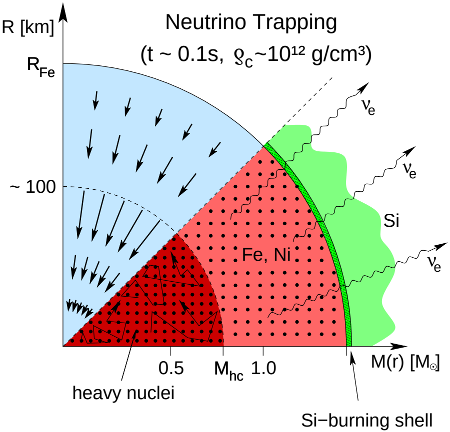


Consequences weak rates

(A. Heger *et al.*, 2001)



Collapse phase

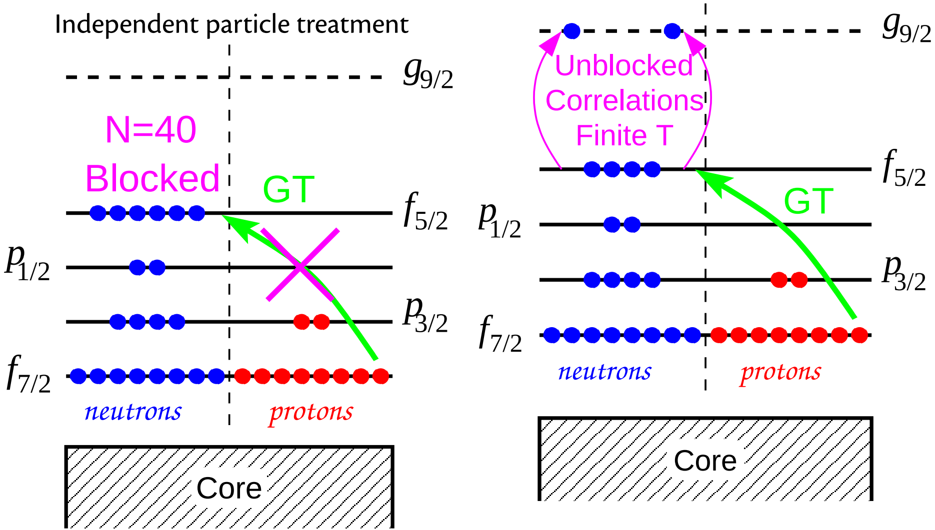


Important processes:

- Neutrino transport (Boltzmann equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

  cross sections $\sim E_\nu^2$
- electron capture on protons:
  $e^- + p \rightleftarrows n + \nu_e$
- electron capture on nuclei:
  $e^- + A(Z,N) \rightleftarrows A(Z-1,N+1) + \nu_e$
- Standard description suppresses electron capture on nuclei for $N = 40$.

(Un)blocking electron capture at N=40

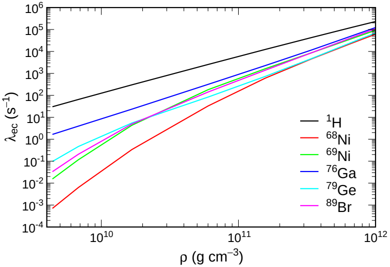


Model used

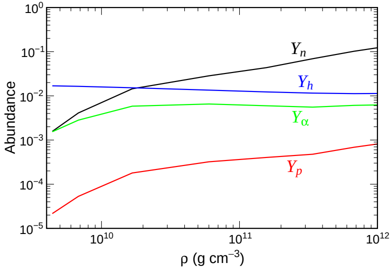
- Nucleus seats in a finite temperature environment ($T \sim 2$ MeV). Shell-Model Monte Carlo (SMMC) is well suited for a finite temperature description of the nucleus.
- Electron energies are relatively large ($\mu_e \sim 20$–30 MeV) so that forbidden transitions and finite momenta transfer should be taken in account. Possible via RPA calculations.
- NSE abundances used to compute average rates for a pool of nuclei with $A = 45$–112 (LMSH rate set).

Electron capture: nuclei vs protons

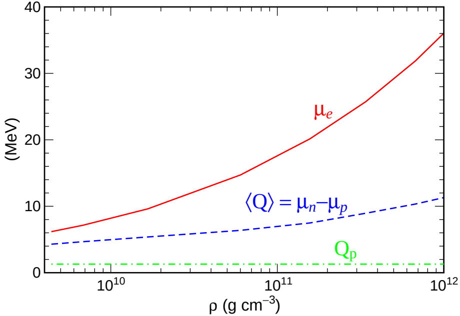
Electron capture rates



Abundances

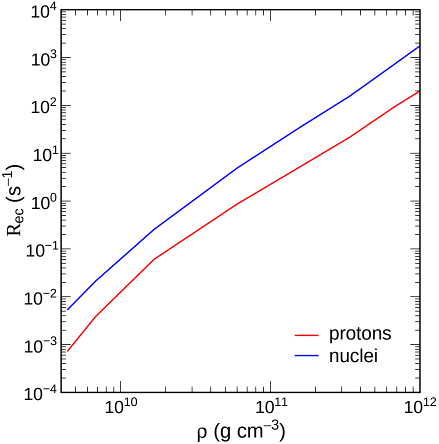


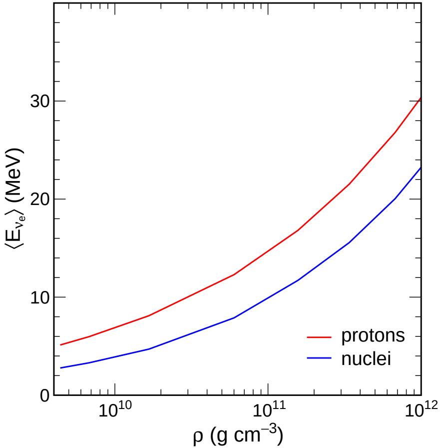
Energetics



$$R_h = \sum_i Y_i \lambda_i = Y_h \langle \lambda_h \rangle$$
$$R_p = Y_p \lambda_p, \quad Y_i = n_i/n$$

Reaction rates

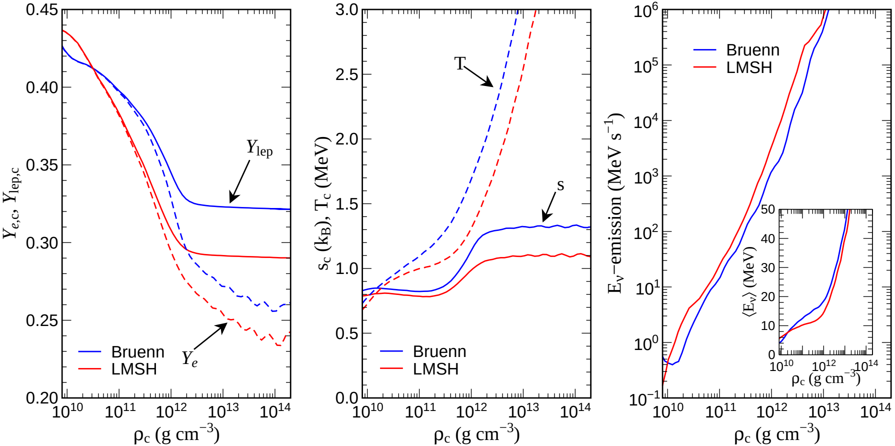




Electron capture on nuclei dominates over capture on protons

Realistic calculation

With Marek, Rampp, Janka & Buras (Approx. General Relativistic model)
15 $M_\odot$ presupernova model from A. Heger & S. Woosley



Screening of electron capture rates

- Correction to nuclear binding energy (DeWitt, Graboske, and Cooper 1973; Hix and Thielemann 1996, Bravo and García-Senz 1999). Q-value increases by 0.5–2.0 MeV.
- Correction to electron energy (Itoh *et al.* 2002). Chemical potential reduced by 0.1–1.0 MeV.
- Net effect is a reduction of a factor 2–3 in the electron capture rate (independent of the value of the rate).

Screening in a consistent calculation

With Marek, Rampp, Janka & Buras.