Astrophysical challenges to nuclear structure

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April 4–7, 2006

Outline

1. Electron-capture in core collapse supernovae
   - Presupernova phase
   - Collapse phase
2. Nucleosynthesis in proton-rich supernova ejecta
   - Effect of neutrinos
   - The νp-process
3. r-process
   - Beta decays
   - Fission in the r-process

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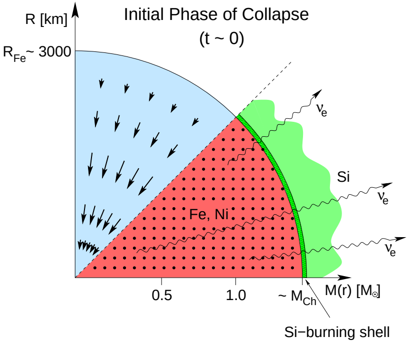
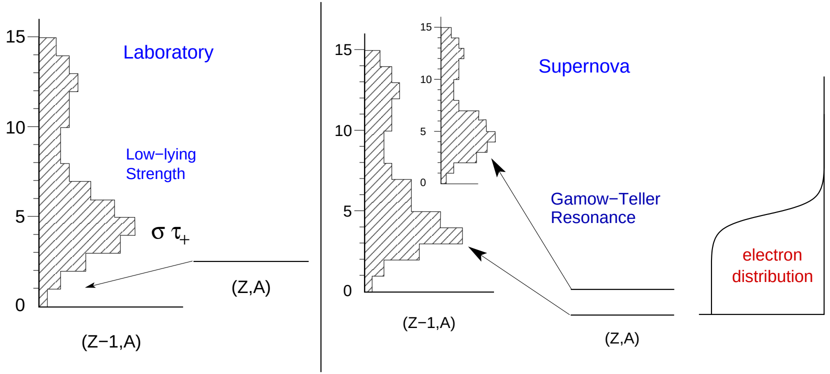
Presupernova evolution



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

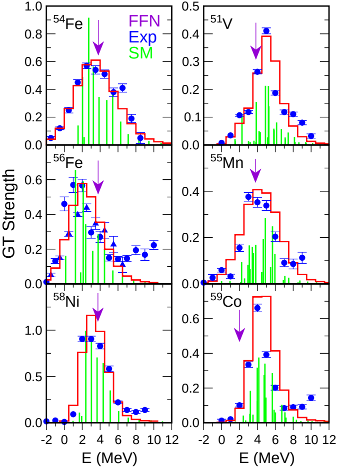
Laboratory vs. stellar electron capture

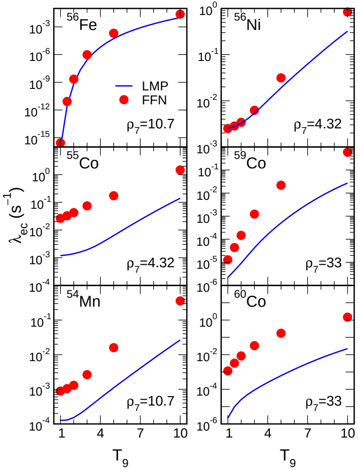


Capture of K-shell electrons to tail of GT strength distribution. Parent nucleus in the ground state

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.

Comparison with (n, p) data

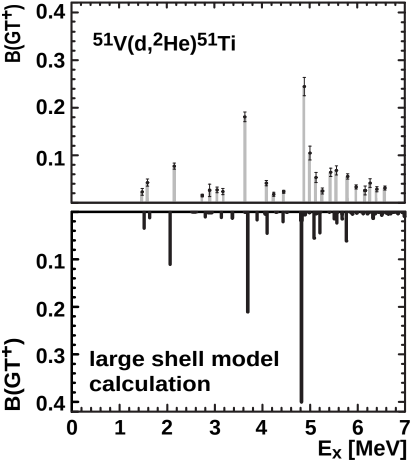


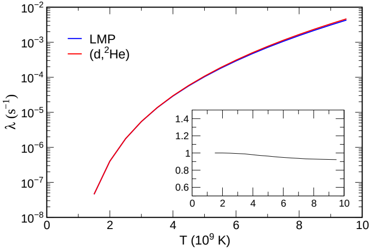


Systematic differences translate in different properties of the iron core at the onset of the collapse.

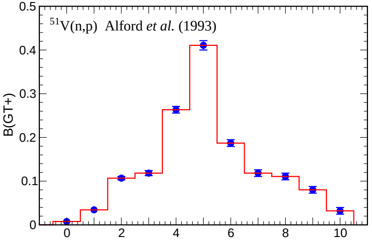
Shell-Model vs experiment (^{51}V)

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



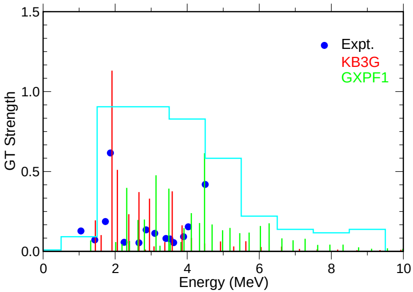


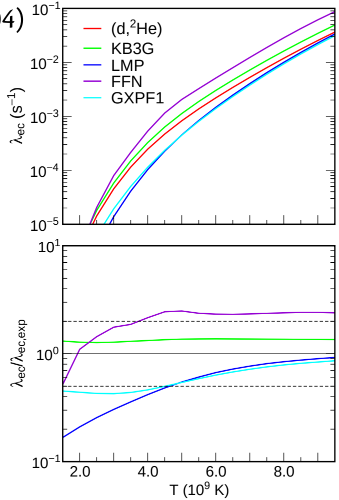
Old (n, p) data



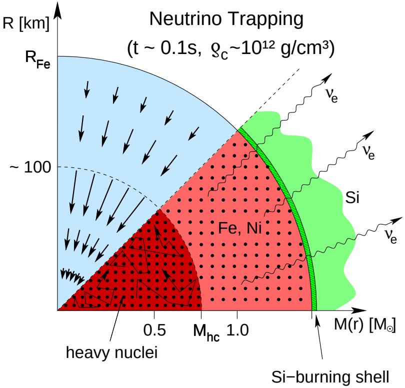
Shell-Model vs experiment (^{58}Ni)

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





Collapse phase

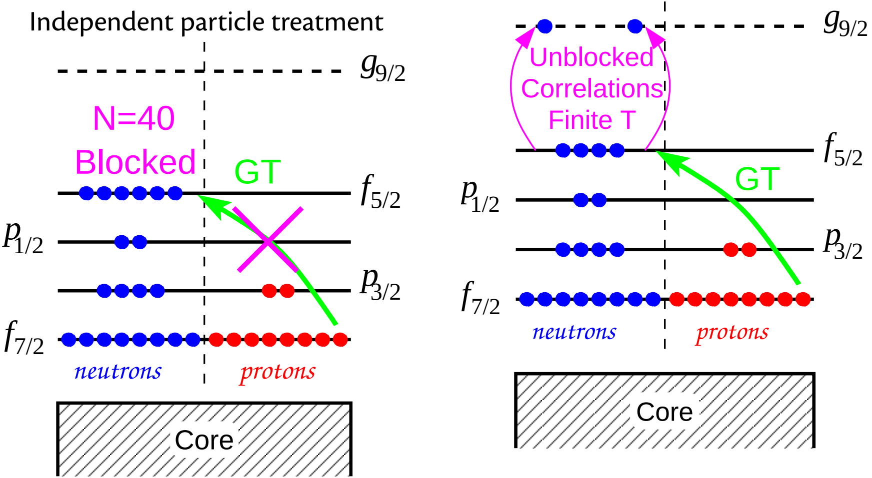


Important processes:

- 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 $N = 40$.

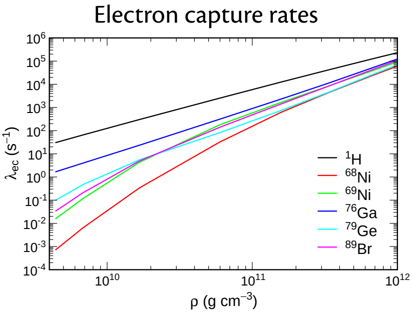
(Un)blocking electron capture at N=40

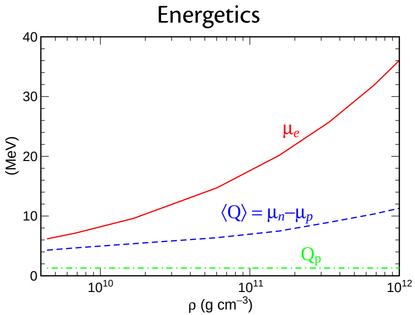


Model used

- 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).

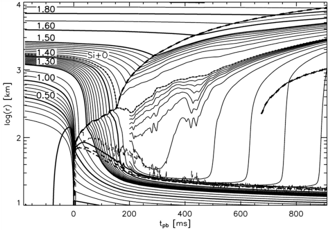
Electron capture rates





Effect of weak interactions

Pruet *et al.*, ApJ **623**, 325 (2005)

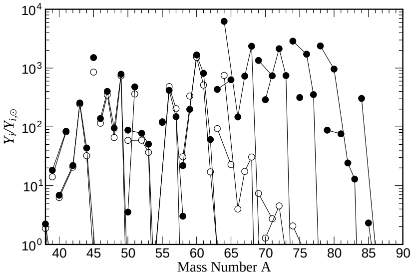


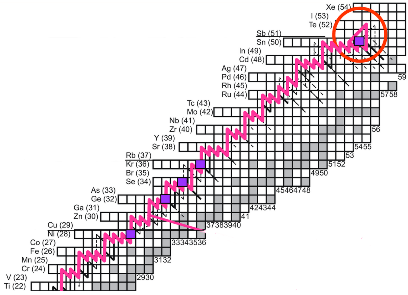
Main processes:

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

- Current simulations show that early ejecta is proton-rich
- This occurs whenever: $\epsilon_{\bar{\nu}} - \epsilon_{\nu} < 4(m_n - m_p)$.
- Proton-rich ejecta could be the mayor contributors to ^{45}Sc, ^{49}Ti, and ^{64}Zn.
- Neutrinos are responsible for the production of nuclei with $A > 64$ (νp-process).

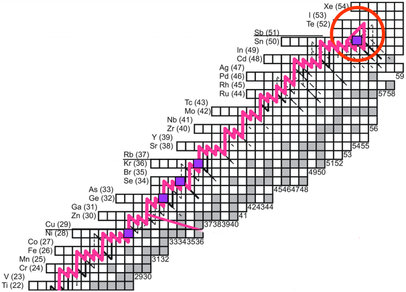
Effect of neutrinos





The basics of the νp-process

- Proton rich matter is ejected under the influence of neutrino interactions.
- Nuclei form at distances where a substantial antineutrino flux is present.



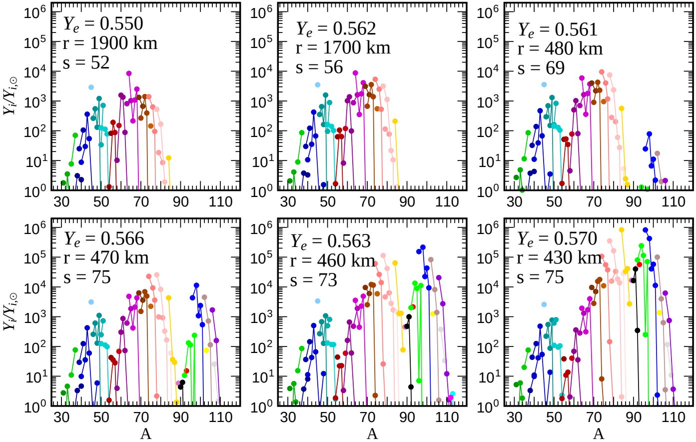
Antineutrinos help in bridging long waiting points via (n, p) reactions

$$\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + {}^{64}\mathrm{Ge} \rightarrow {}^{64}\mathrm{Ga} + p; \quad {}^{64}\mathrm{Ga} + p \rightarrow {}^{65}\mathrm{Ge}; \ldots$$

C. Fröhlich, *et al.*, PRL (April 14 issue).

Sensitivity

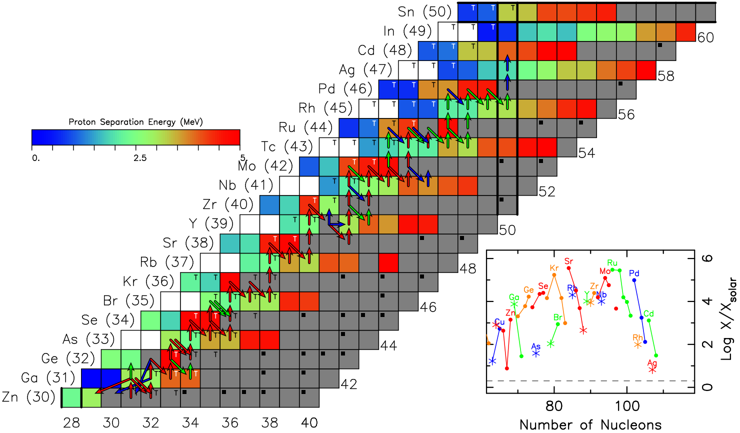
Trajectories provided by H.-Th. Janka.



Sensitivity to Y_e, entropy and radius.

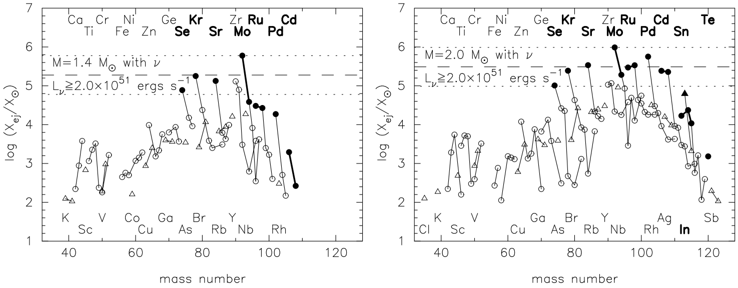
Nucleosynthesis fluxes

From Pruet *et al*, astro-ph/0511194



Production of light p nuclei

S. Wanajo, astro-ph/0602488

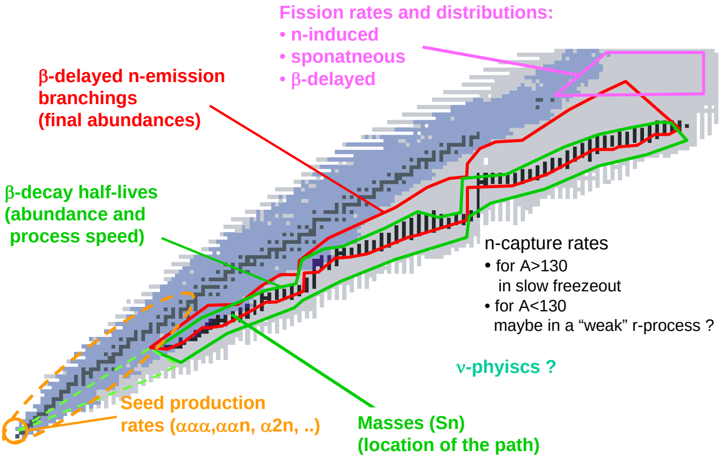


- ^{92}Mo is produced in slightly neutron rich ejecta, $Y_e \approx 0.47$–0.49 (Fuller & Meyer 1995, Hoffman *et al.* 1996).
- The rest is produced in proton-rich ejecta.

νp-process needs

- Evolution of the proto-neutron star neutrino spectra and luminosities.
- Cross sections for (p,γ), (n,p), (n,γ).
- Antineutrino charge-current reactions.
- Neutral-current neutrino reactions.

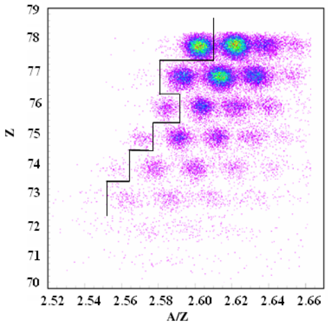
r-process needs

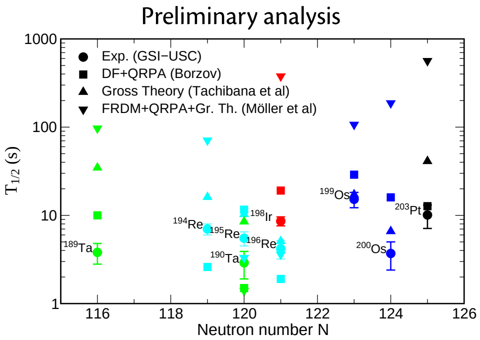


Beta decays for N=126

T. Kurtukian-Nieto (U. Santiago Compostela), FRS-GSI

30 new neutron-rich nuclei identified



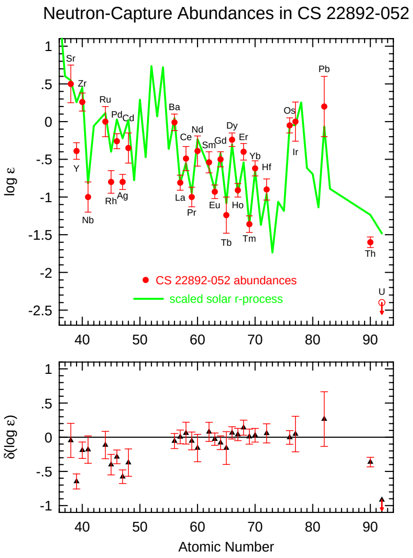


Fission and the r-process

Fission types:

- Neutron-induced fission.
- Beta-delayed fission.
- Neutrino-induced fission.

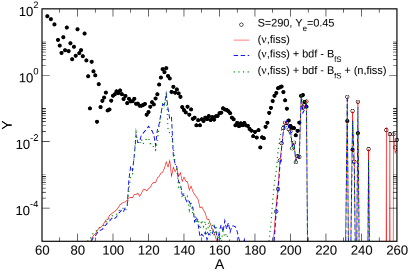
r-process calculations (Darko Mocelj) assuming adiabatic expansion with a constant velocity.



Some results

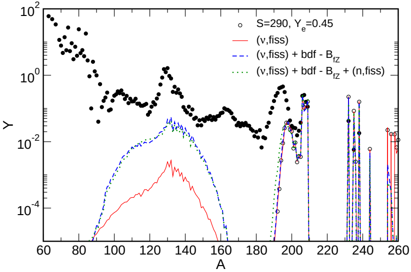
Myers & Swiatecki Barriers

Schematical fragment distribution



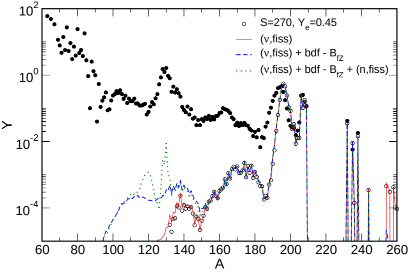
Sierk barriers

Realistic fragment distribution



Some results

Lower entropy



Expansion velocity dependence