Nucleosynthesis issues and massive stars

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- supernova: general picture
- the quest for nuclear input
- explosive nucleosynthesis
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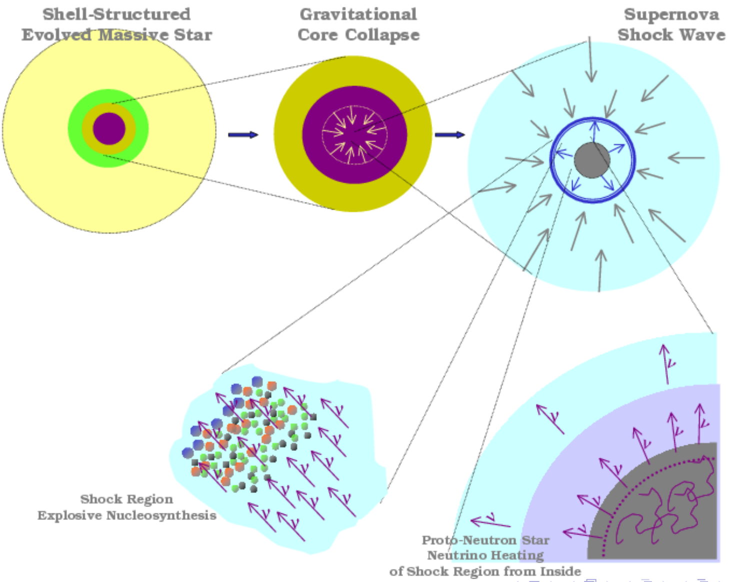
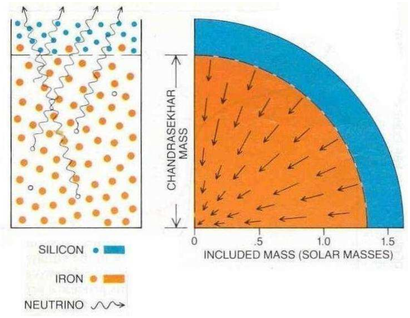
Core-collapse supernova.



Presupernova evolution.

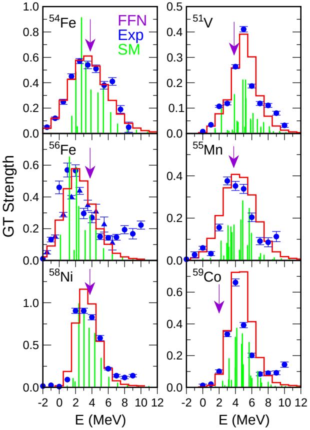


- $T = 0.1$–1.0 MeV, $\rho = 10^7$–10^{10} g cm^{-3}.
- Composition of iron group nuclei (A=45-65)
- The dynamical time scale set by electron captures: $e^- + (N, Z) \rightarrow (N+1, Z-1) + \nu_e$
- Evolution decreases number of electrons (Y_e) and Chandrasekhar mass ($M_{Ch} \approx 1.4(2Y_e)^2$ $M_\odot$)

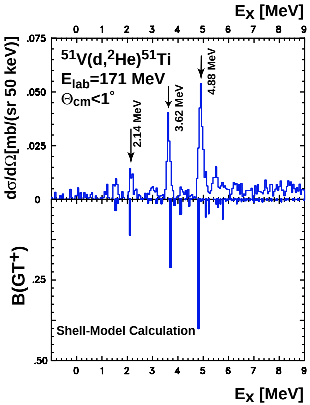
- Capture rates on individual nuclei computed by:
  - Shell Model ($A < 65$)
  - Shell Model Monte Carlo ($A > 65$)

Gamow-Teller strength distributions.

(n,p) experiments, TRIUMF

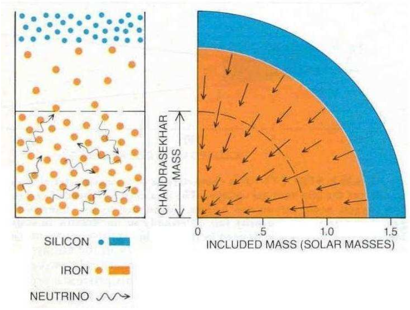


(d,^{2}He) experiments, KVI Groningen



shell model results agree after overall quenching by $(0.77)^2$

Collapse phase.



Important processes:

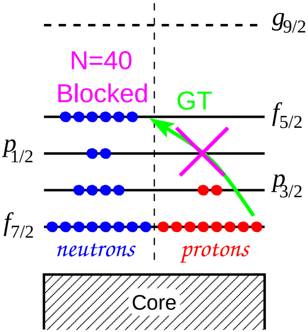
- $T > 1.0$ MeV, $\rho > 10^{10}$ g cm^{-3}.
- electron capture on protons
  $e^- + p \to n + \nu_e$
- Neutrino transport (exact solution Boltzmann equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

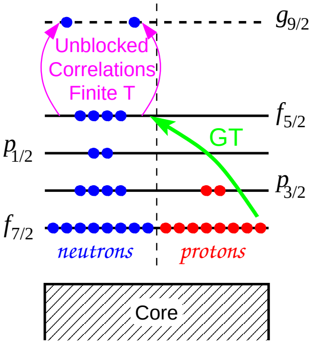
  cross sections $\sim E_\nu^2$

What is the role of electron capture on nuclei?

$$e^- + (N, Z) \to (N + 1, Z - 1) + \nu_e$$

Pauli blocking of Gamow-Teller transition

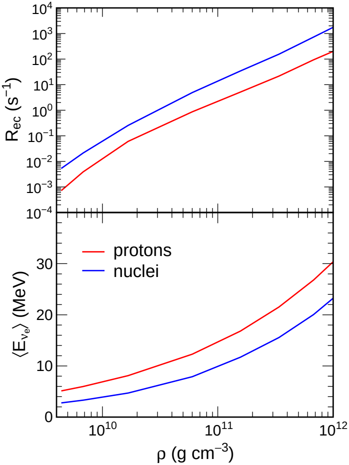




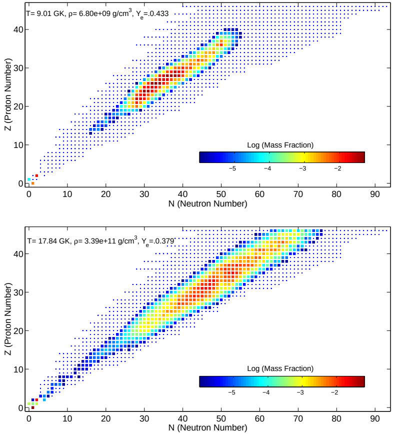
- Unblocking mechanism: correlations and finite temperature
- calculation of rate in SMMC + RPA model

Electron capture: nuclei vs protons

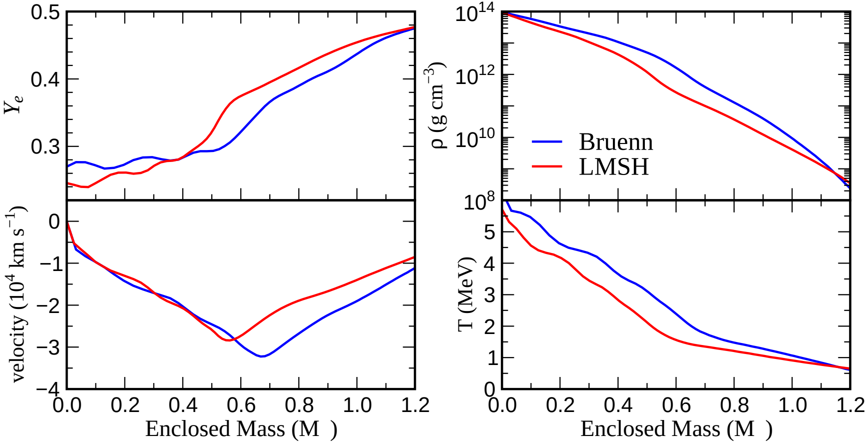
Capture rate and average energy



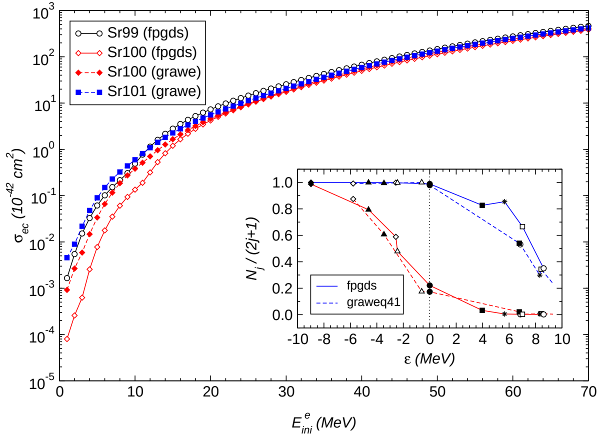
Mass abundances



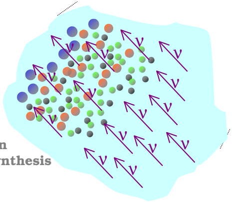
Consequences



Capture rates and single-particle energies



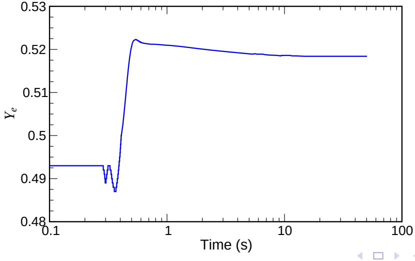
Explosive nucleosynthesis in supernova



- Consistent treatment of supernova dynamics coupled with a nuclear network.
- Essential neutrino reactions in the shock heated region

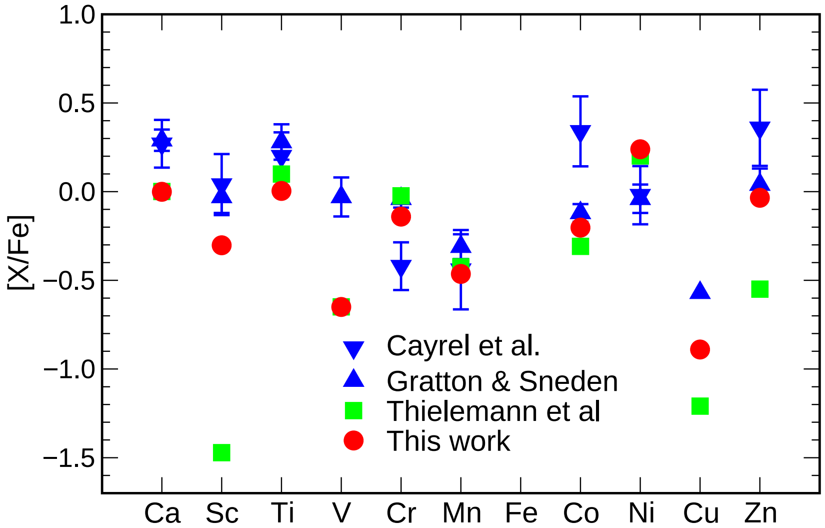
$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Y_e evolution of a mass element



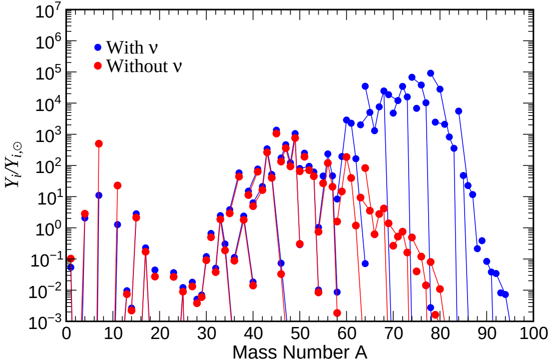
Comparison with observations.

Carla Fröhlich *et al.*, astro-ph/0410208



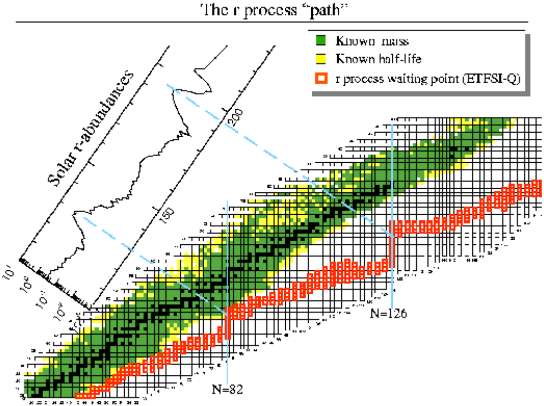
Effect of neutrinos on nucleosynthesis.

G. Martínez-Pinedo, C. Fröhlich, F.-K. Thielemann



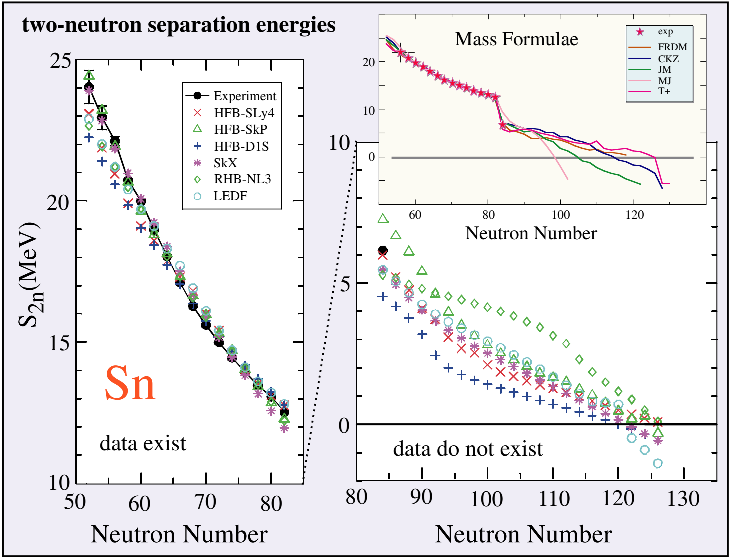
- Without neutrinos flow stops at ^{64}Ge ($t_{1/2} = 64$ s)
- With neutrinos:
  $\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + {}^{64}\text{Ge} \rightarrow {}^{64}\text{Ga} + p; \quad {}^{64}\text{Ga} + p \rightarrow {}^{65}\text{Ge}; \ldots$

r-process

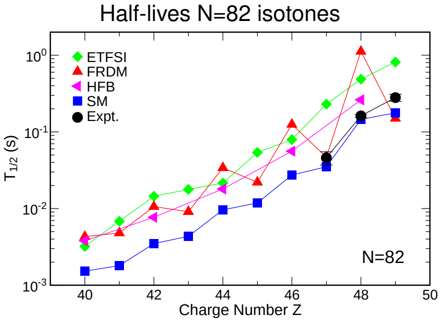


$T \approx 100$ keV $\quad n \gtrsim 10^{20}$ cm^{-3} implies $\tau_n \ll \tau_\beta$
$(n,\gamma) \rightleftarrows (\gamma,n)$ implies $S_n \approx 2$ MeV

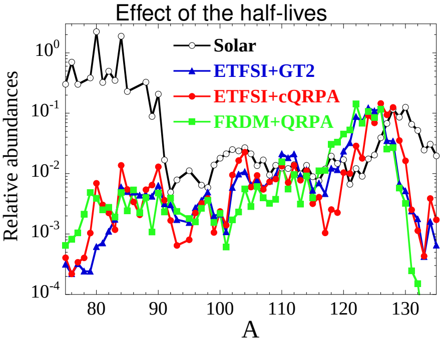
Masses for r-process nuclei



Half-lives for r-process nuclei

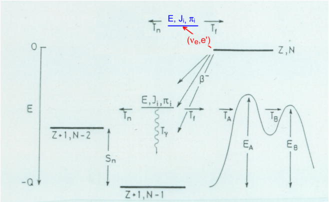


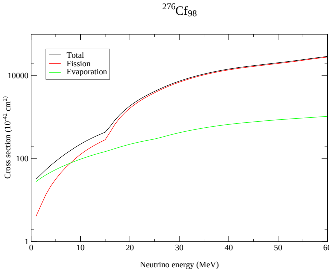
^{130}Cd decay (K.-L. Kratz *et al*)



Peak position depends on the half-lives used

Neutrino induced fission for r-process



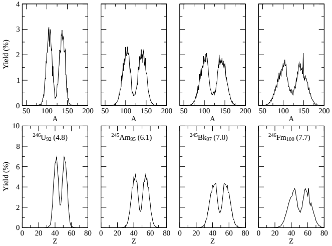


- Competition between neutron decay and fission.
- Fission relatively enhanced with increasing neutrino energy.

R-process fission fragment distributions.

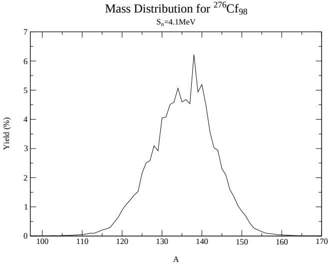
A. Kelić, K.-H. Schmidt, N. Zinner

^{245}Am, decay to stability



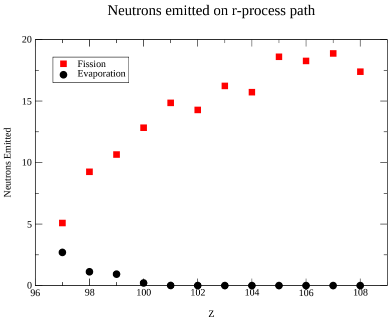
Fission fragment distribution

^{296}Cf, on r-process path



Fission fragment distribution

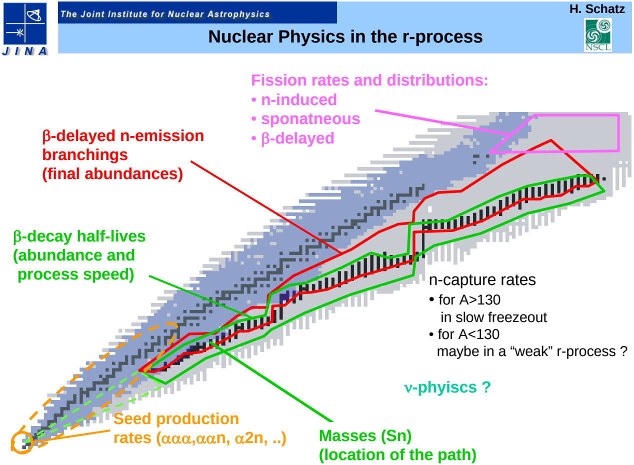
R-process: neutron emission.



Number of emitted neutrons

- Also relevant for beta-induced fission
- Postprocessing of abundance distribution after neutron freeze-out

r-process needs



Summary and outlook

Improved nuclear ingredients are required for supernova simulations

- Electron capture rates on nuclei
- Neutrino-nucleus cross sections
- Equation of state; matter composition

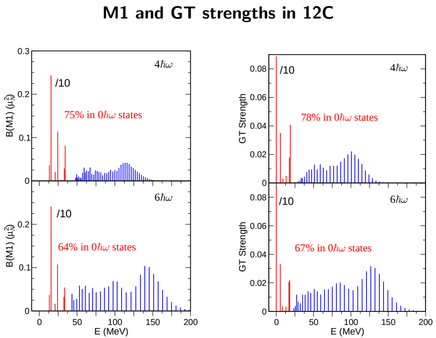
Improved nuclear ingredients are required for r-process

- Masses $\rightarrow$ r-process path
- Half-lives, β-delayed n-emission $\rightarrow$ abundances
- Neutron capture rates $\rightarrow$ after freeze-out, abundances
- Fission rates and mass fragment distributions
- Neutrino-induced rates?

Answer from radioactive ion-beam facilities

GT strength in multi-shell calculations

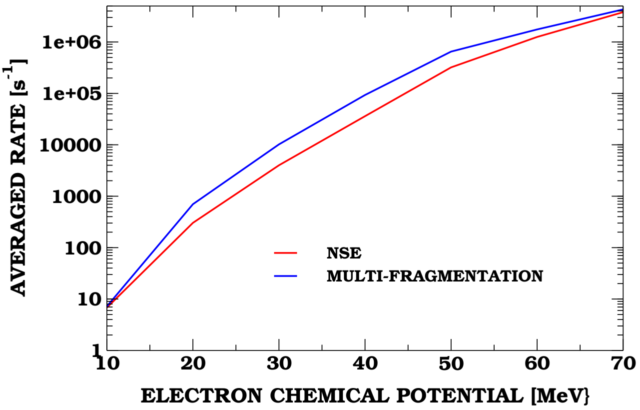
- No-core shell model calculation of ^{12}C
- Gamow-Teller strength shifted to higher excitation energies



E. Caurier, G. Martinez-Pinedo, F. Nowacki

Composition dependence of the electron capture

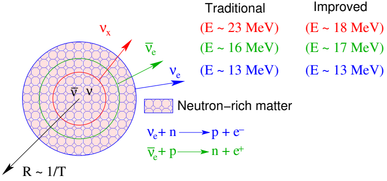
- NSE (Strong and electromagnetic reactions in equilibrium)
- Multifragmentation model: developed from heavy-ion collisions (A. Botvina, I. Mishustin & W. Trautmann).



Neutrino nucleosynthesis

Neutrinos interact with abundant nuclear species

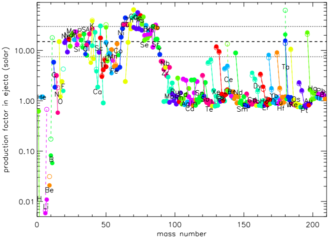
- Neutral current (ν, ν'): nucleus excited to particle unbound states which decay by particle emission
- Charged current (ν_e, e^-) and $(\bar{\nu}_e, e^+)$.

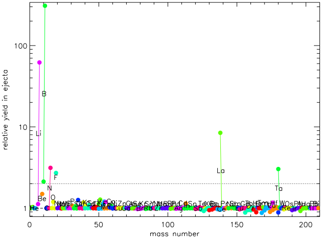


Product	Parent	Reaction
^{7}Li	^{4}He	$(\nu, \nu' n)^3$He$(\alpha, \gamma)^7$Be(n,p)
		$(\nu, \nu' p)^3$H(α, γ)
^{11}B	^{12}C	$(\nu, \nu' n), (\nu, \nu' p)$
^{15}N	^{16}O	$(\nu, \nu' n), (\nu, \nu' p)$
^{19}F	^{20}Ne	$(\nu, \nu' n), (\nu, \nu' p)$
^{138}La	^{138}Ba	(ν, e^-)
	^{139}La	$(\nu, \nu' n)$
^{180}Ta	^{180}Hf	(ν, e^-)
	^{181}Ta	$(\nu, \nu' n)$

Results of neutrino nucleosynthesis

A. Heger *et al*, Phys. Lett. B606 (2005) 258





Production of ^{138}La

Produced by $^{139}\mathrm{La}(\gamma, n)$,$^{138}\mathrm{Ba}(\nu_e, e^-)$