Weak interaction processes in stars

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GSI

Outline

1. Weak processes in core collapse supernovae
   - Electron capture during the collapse
   - Neutrino-nucleus reactions
2. Explosive nucleosynthesis
   - Proton-rich ejecta: The νp-process
   - neutron-rich ejecta: r-process
3. Conclusions

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   - Proton-rich ejecta: The νp-process
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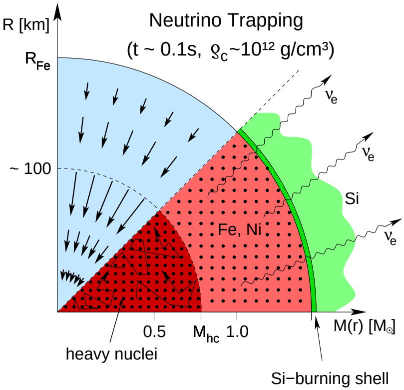
Electron capture during the collapse



Important processes:

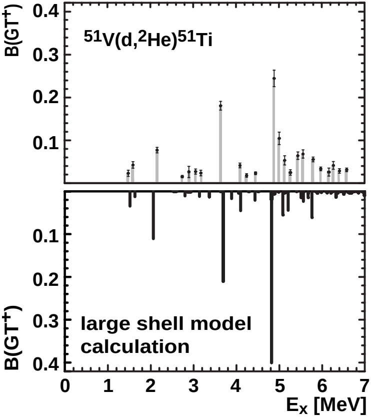
- Neutrino transport (Boltzmann equation):
  $\nu + A \rightleftarrows \nu + A$ (trapping)
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)

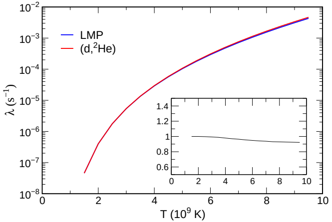
  cross sections $\sim E_\nu^2$
- electron capture on protons:
  $e^- + p \rightleftarrows n + \nu_e$
- electron capture on nuclei:
  $e^- + A(Z,N) \rightleftarrows A(Z-1,N+1) + \nu_e$
- Traditional treatment suppresses electron capture on nuclei for $N = 40$.

- Gamow-Teller strength can be determined by charge exchange reactions
- Theory is needed to account for finite temperature effects (excited states).

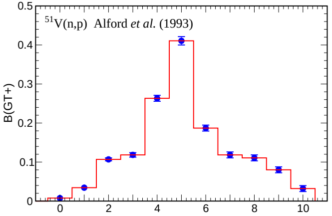
KVI results using $(d, {}^2\mathrm{He})$

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





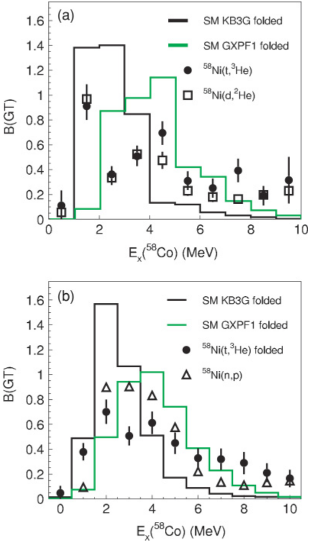
Old (n, p) data

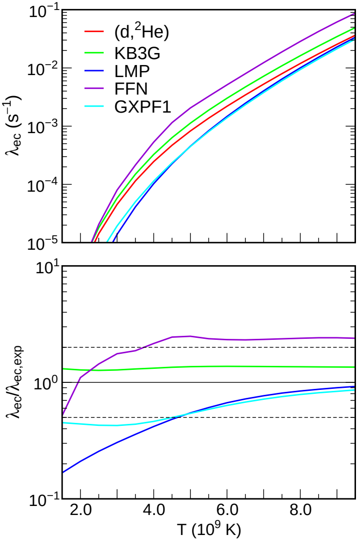


GT strength in ^{48}Sc, ^{50}V, ^{58}Ni, ^{64}Ni also measured.

NSCL results using $(t, {}^3\text{He})$

A. L. Cole, *et al.*, PRC **74**, 034333 (2006)

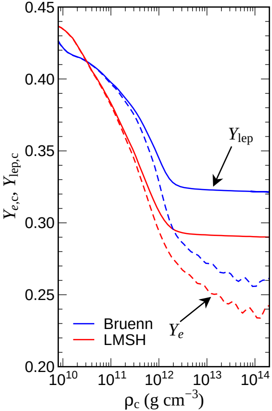


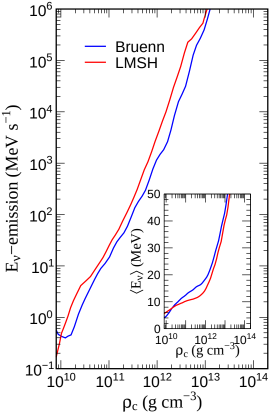


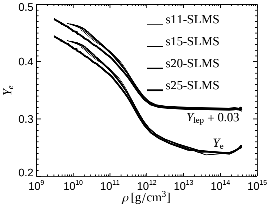
Extension to unstable nuclei requires measurements in inverse kinematics

Effects Realistic calculation

Marek et al, in preparation



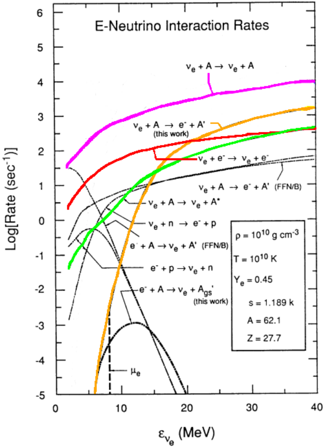




- Electron capture on nuclei dominates over capture on protons
- All models converge to a “norm” stellar core at the moment of shock formation.

Neutrino interactions during the collapse

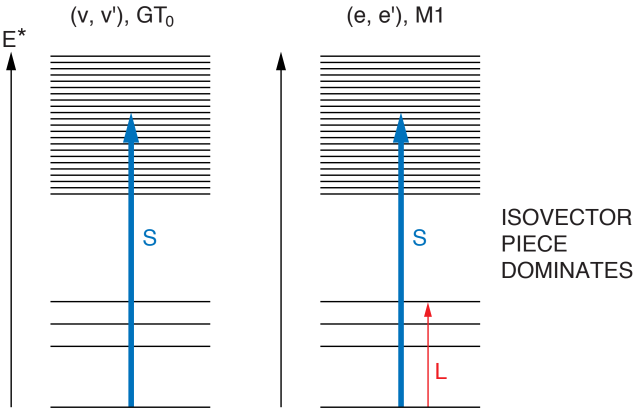
Bruenn and Haxton (1991)
Based on results for ^{56}Fe



- Elastic scattering:
  $\nu + A \rightleftarrows \nu + A$ (trapping)
- Absorption:
  $\nu_e + (N, Z) \rightleftarrows e^- + (N-1, Z+1)$
- ν-e scattering:
  $\nu + e^- \rightleftarrows \nu + e^-$ (thermalization)
- Inelastic ν-nuclei scattering:
  $\nu + A \rightleftarrows \nu + A^*$

Inelastic Neutrino-nucleus interactions had not been included in collapse simulations.

Neutrino scattering from (e, e')



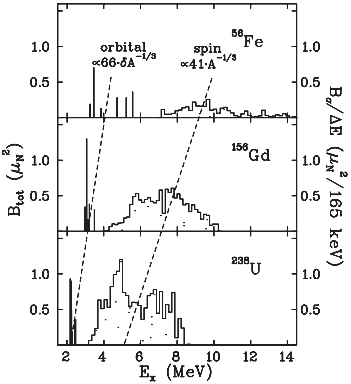
$$T(GT_0) \sim \sum_i t_z(i)\vec{S}_i \qquad T(M1) = \left\{ \frac{1}{2}(\vec{L}_p - \vec{L}_n) + (g_p - g_n)\sum_i t_z(i)\vec{S}_i \right\}\mu_N$$

M1 data give GT_0 information

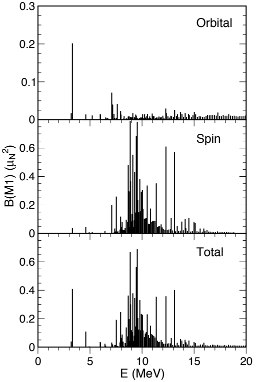
if Orbital contribution can be removed

Neutrino scattering from (e, e')

M1 DATA
(A. Richter)



DECOMPOSITION OF
M1 STRENGTH
(SHELL MODEL)

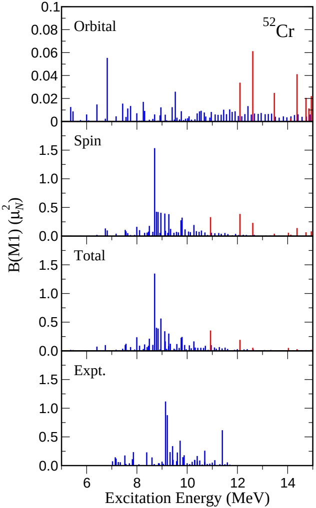


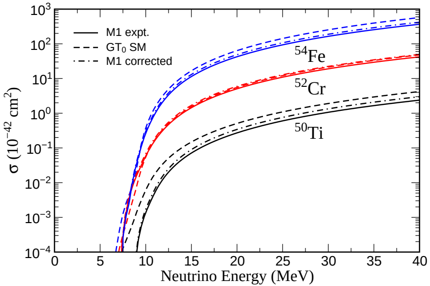
Usually orbital and spin parts well separated.

Spherical nuclei: Orbital part strongly suppressed.

Neutrino Scattering from (e, e')

K. Langanke *et al*, PRL **93**, 202501 (2004)

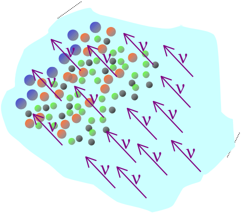


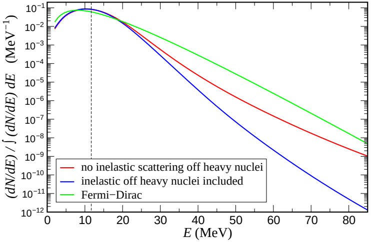


$M1$ data can be used to constrain supernovae inelastic neutrino cross sections.

Influence on neutrino spectra

- A future detection of a close by supernova could bring information about supernova dynamics.
- We have done detailed simulations and shown that the spectrum of the initial ν_e burst is affected by the inclusion of inelastic neutrino scattering with nuclei (B. Müller *et al*).
- At later times (relevant for nucleosynthesis) spectra is unchanged as all nuclei are dissociated.





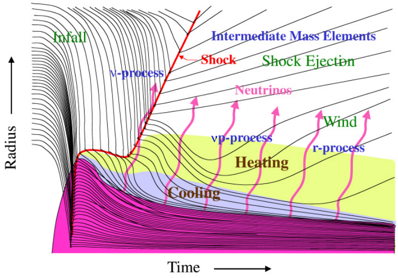
Material	$\langle\sigma\rangle$ (10^{-42} cm^2) With INNS	Without INNS	Change
e	0.106	0.110	3%
d	4.92	5.36	8%
^{12}C	0.050	0.080	37%
^{16}O	0.0053	0.0128	58%
^{40}Ar	13.4	15.1	11%
^{56}Fe	6.2	7.5	17%
^{208}Pb	103.3	124.5	17%

Effect of weak interactions

- Current simulations show that early ejecta (1 s) 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 (C. Fröhlich, *et al.* 2006, J. Pruet, *et al.* 2005).
- Neutrinos are responsible for the production of nuclei with $A > 64$ (νp-process).
- Later ejecta becomes neutron rich (r-process)

Main processes:

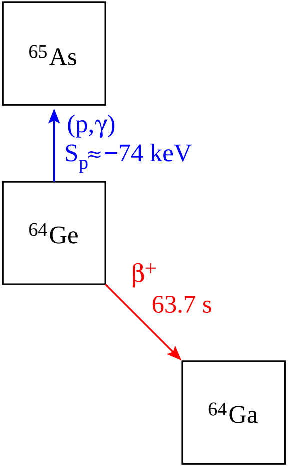
$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$



Proton-rich ejecta: The νp-process

- Once matter reaches temperatures around $T_9 \sim 3$ (250 keV) the composition in proton-rich ejecta is given by protons, alpha particles and $N = Z$ nuclei with $A \lesssim 64$.
- Can nuclei with $A > 64$ be produced?
- Problem with the short time scales for explosive nucleosynthesis in supernovae ($\sim$ seconds).
- Antineutrino absorption can speed up matter flow.

$$\bar{\nu}_e + p \to e^+ + n \quad (\text{time} \sim \text{seconds})$$



Proton-rich ejecta: The νp-process

- Once matter reaches temperatures around $T_9 \sim 3$ (250 keV) the composition in proton-rich ejecta is given by protons, alpha particles and $N = Z$ nuclei with $A \leq 64$.
- Can nuclei with $A > 64$ be produced?
- Problem with the short time scales for explosive nucleosynthesis in supernovae ($\sim$ seconds).
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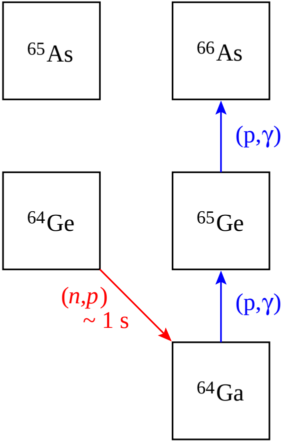
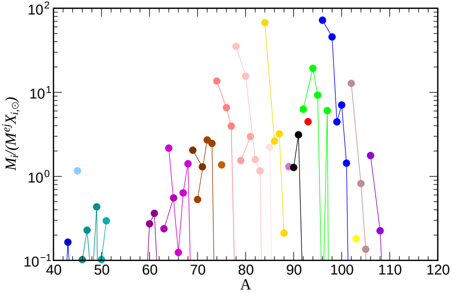
$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (\text{time} \sim \text{seconds})$$



The νp-process
C. Fröhlich, *et al.*, PRL **96**, 142502 (2006)

Production factors

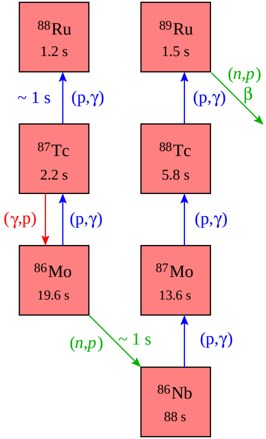
The νp-process offers the possibility of producing light p-process nuclei that are normally underproduced in standard p-process models.
Integrated abundances (Trajectories from by H-Th. Janka, Pruet *et al.*, 2006)



Nucleosynthesis sensitive to:

- Thermal history of matter and antineutrino flux.
- Masses, (p,γ), (n,p), (n,γ), neutrino spallation (?).

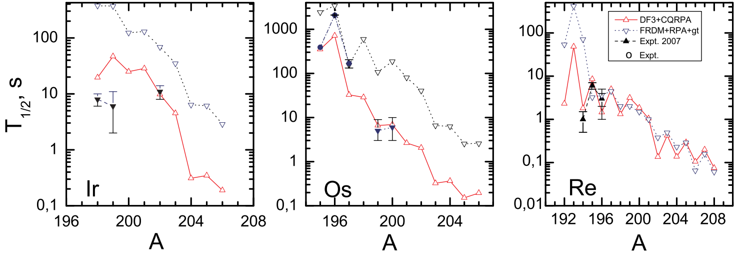
Nucleosynthesis fluxes

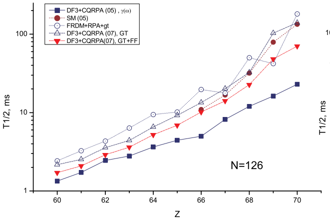


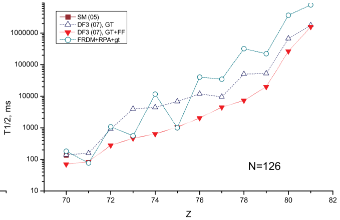
In the matter flow there are several branching points where (p, γ) and (n, p) reactions compete. Masses are needed to determine the dominating reaction.

Beta-decay half-lives (N=126)

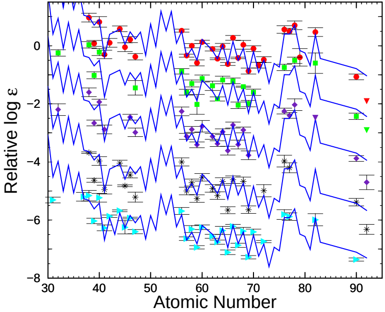
The N=126 nuclei are not yet accessible experimentally. However, in a recent experiment at the FRS (GSI) several nuclei were produced approaching the $N = 126$ (Kurtukian-Nieto *et al*, 2007) (Talk J. Benlliure)





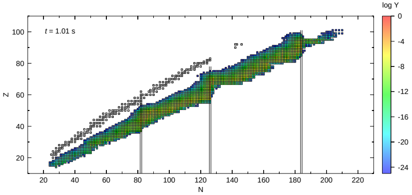


Metal poor stars and fission



J. Cowan *et al.* PoS(NIC-IX)014
Cowan & Sneden, Nature **440**, 1151 (2006)

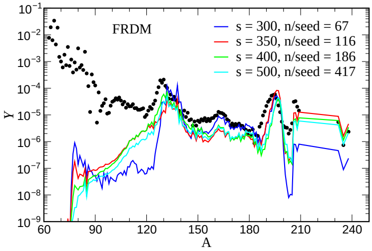
Can fission explain the robust r-process pattern for $Z > 56$?

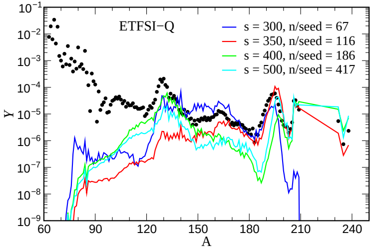


We need detailed knowledge of

- Fission rates (neutron-induced, beta-delayed, spontaneous, neutrino-induced)
- Fission yield distribution (computed by GSI ABLA code).

Fission and N=82 shell structure

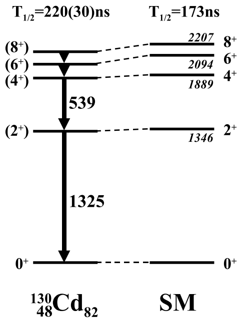




Differences are due to different shell structure at $N = 82$

- Neutron-induced fission dominates always by more 90%.
- Neutrino-induced fission plays a negligible role.

A recent RISING/GSI experiment (Talk by A. Jungclaus) has observed the decay of the 8^+ seniority isomer in ^{130}Cd.



Conclusions

- Weak interaction processes dominate the dynamics of the collapse, in particular electron capture on nuclei. To extend the experimental knowledge of Gamow-Teller distributions to unstable nuclei experiments in inverse kinematics will be needed.
- Neutrino-nucleus interactions are important for the determination of the ν_e-burst spectrum. They influence the detectability of neutrinos on Earth.
- Neutrino matter interactions play an important role during explosive nucleosynthesis. They determine the proton or neutron richness of matter and the subsequent nucleosynthesis.
- Supernovae Proton rich ejecta constitute the site of a novel nucleosynthesis process: The νp-process.
- Fission in the r-process is sensitive to the shell structure at $N = 82$ that will become accessible to future radioactive beam facilities.