

# Weak interaction processes in stars

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# Outline

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

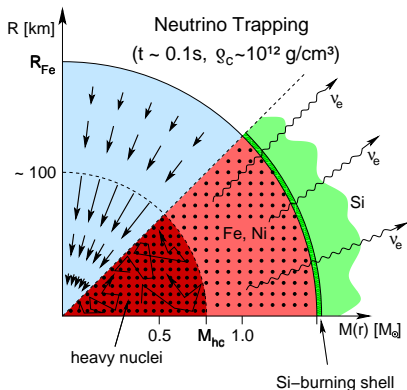
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# Electron capture during the collapse



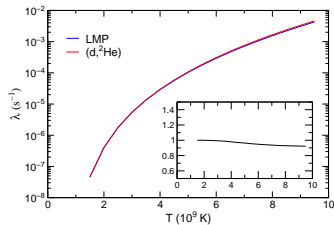
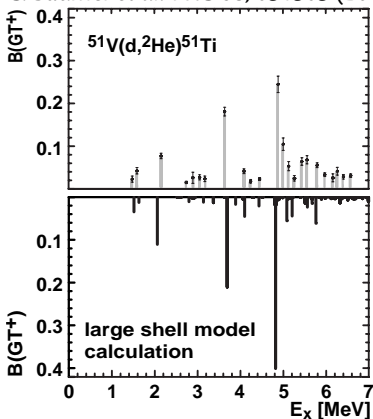
## Important processes:

- Neutrino transport (Boltzmann equation):  
 $\nu + A \rightleftharpoons \nu + A$  (trapping)  
 $\nu + e^- \rightleftharpoons \nu + e^-$  (thermalization)  
 cross sections  $\sim E_{\nu}^2$
- electron capture on protons:  
 $e^- + p \rightleftharpoons n + \nu_e$
- electron capture on nuclei:  
 $e^- + A(Z, N) \rightleftharpoons A(Z-1, N+1) + \nu_e$
- Traditional treatment suppresses electron capture on nuclei for  $N = 40$ .

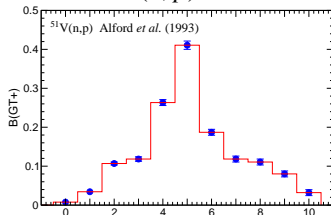
- Gamow-Teller strength can be determined by charge exchange reactions
- Theory is needed to account for finite temperature effects (excited states).

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

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



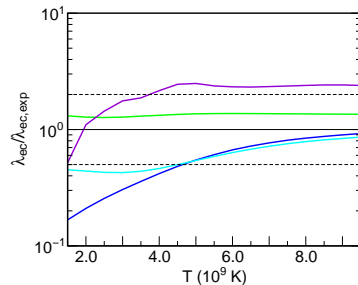
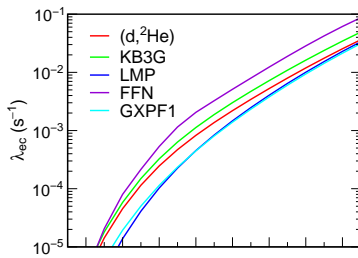
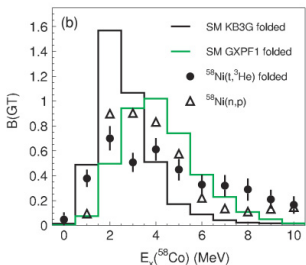
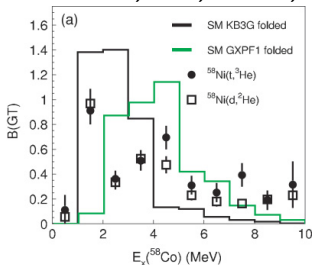
Old ( $n, p$ ) data



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

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

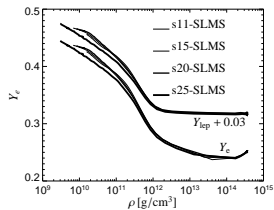
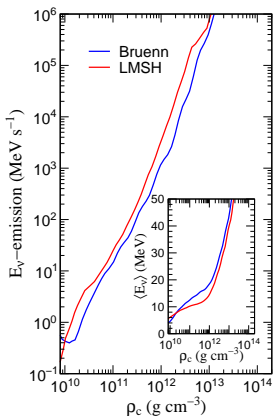
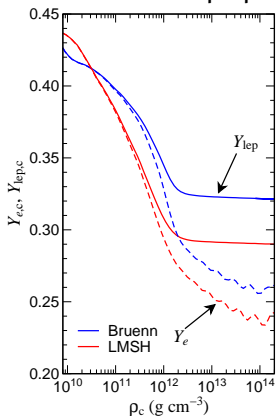
A. L. Cole, et al., PRC 74, 034333 (2006)



Extension to unstable nuclei requires measurements in inverse kinematics

# Effects Realistic calculation

Marek et al, in preparation

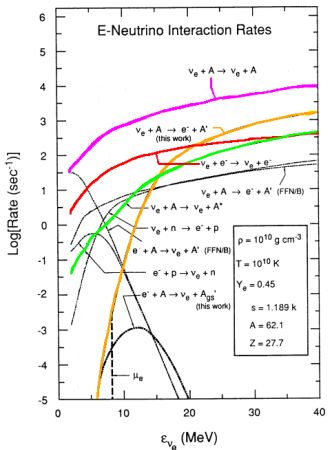


- Electron capture on nuclei dominates over capture on protons
- All models converge to a “norm” stellar core at the moment of shock formation.

# Neutrino interactions during the collapse

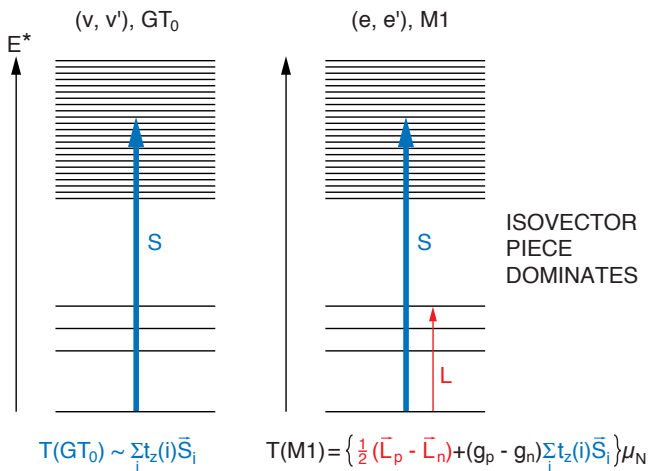
Bruenn and Haxton (1991)

Based on results for  $^{56}\text{Fe}$



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

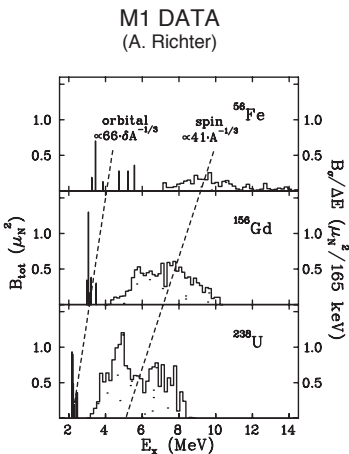
Inelastic Neutrino-nucleus interactions had not been included in collapse simulations.

Neutrino scattering from  $(e, e')$ 

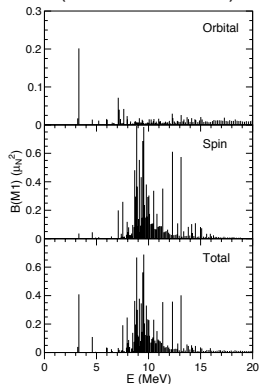
M1 data give  $GT_0$  information

if Orbital contribution can be removed

# Neutrino scattering from $(e, e')$



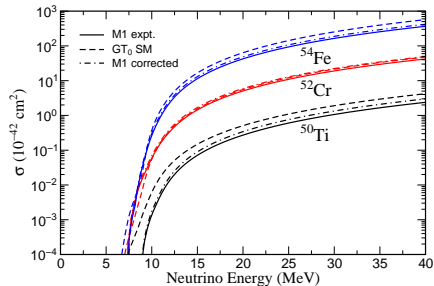
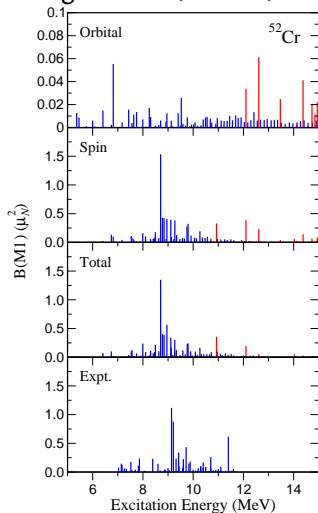
## DECOMPOSITION OF M1 STRENGTH (SHELL MODEL)



Usually orbital and spin parts well separated.  
Spherical nuclei: Orbital part strongly suppressed.

# Neutrino Scattering from $(e, e')$

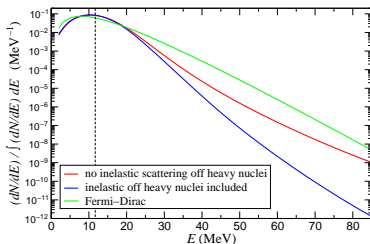
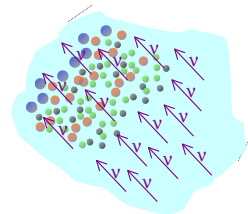
K. Langanke *et al*, PRL **93**, 202501 (2004)



*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  $\nu_e$  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.

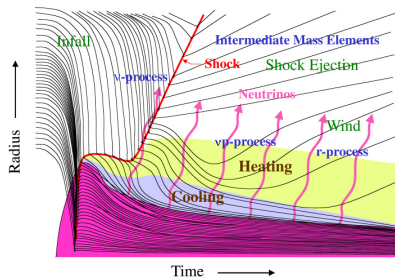
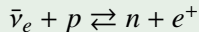
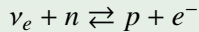


Material	$\langle \sigma \rangle$ ( $10^{-42} \text{ cm}^2$ )		Change
	With INNS	Without INNS	
e	0.106	0.110	3%
d	4.92	5.36	8%
$^{12}\text{C}$	0.050	0.080	37%
$^{16}\text{O}$	0.0053	0.0128	58%
$^{40}\text{Ar}$	13.4	15.1	11%
$^{56}\text{Fe}$	6.2	7.5	17%
$^{208}\text{Pb}$	103.3	124.5	17%

# Effect of weak interactions

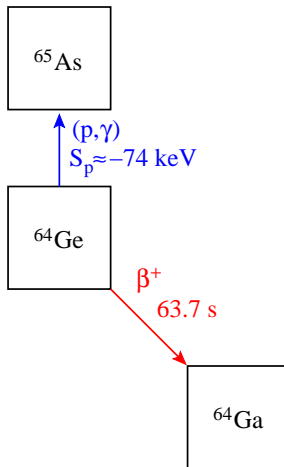
- Current simulations show that early ejecta (1 s) is proton-rich
- This occurs whenever:  
 $\epsilon_{\bar{\nu}} - \epsilon_{\nu} < 4(m_n - m_p)$ .
- Proton-rich ejecta could be the mayor contributors to  $^{45}\text{Sc}$ ,  $^{49}\text{Ti}$ , and  $^{64}\text{Zn}$  (C. Fröhlich, *et al.* 2006, J. Pruet, *et al.* 2005).
- Neutrinos are responsible for the production of nuclei with  $A > 64$  ( $\nu p$ -process).
- Later ejecta becomes neutron rich (r-process)

## Main processes:



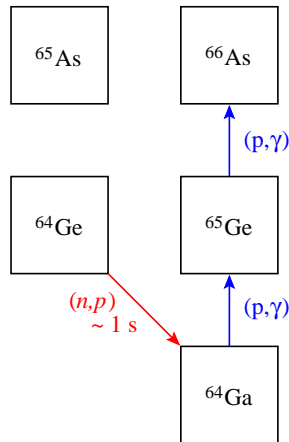
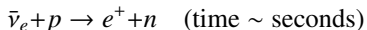
## Proton-rich ejecta: The $\nu p$ -process

- 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).
- Antineutrino absorption can speed up matter flow.



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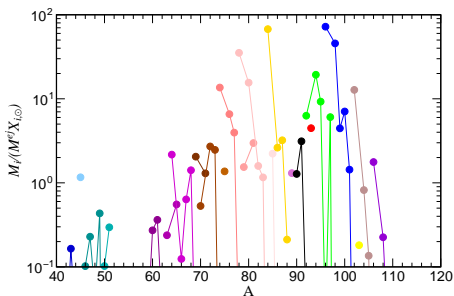
The  $\nu p$ -process

C. Fröhlich, *et al.*, PRL **96**, 142502 (2006)

## Production factors

The  $\nu p$ -process offers the possibility of producing light p-process nuclei that are normally underproduced in standard p-process models.

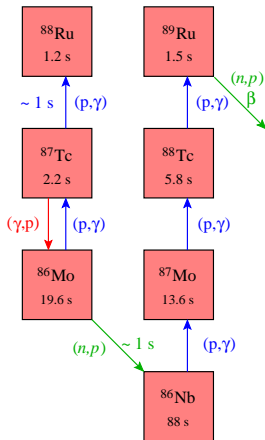
Integrated abundances (Trajectories from by H-Th. Janka, Pruet *et al.*, 2006)



Nucleosynthesis sensitive to:

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

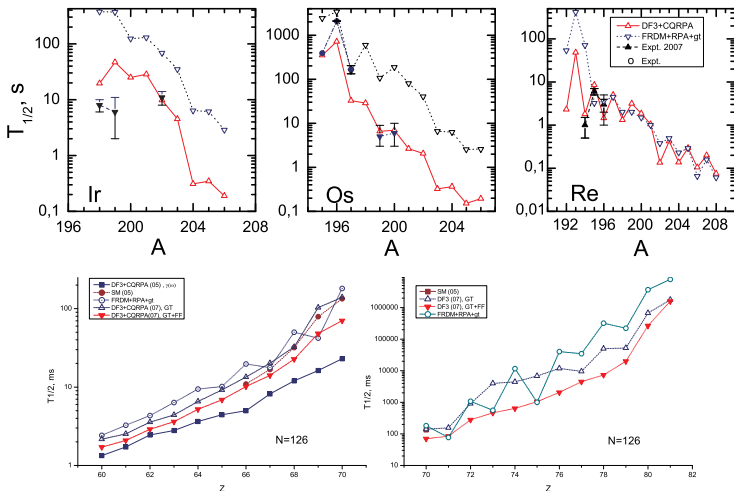
# Nucleosynthesis fluxes



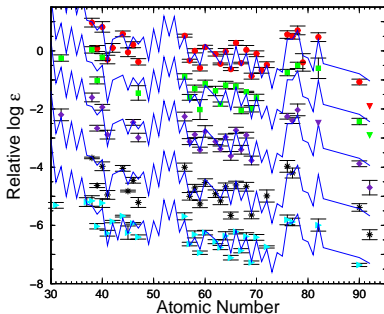
In the matter flow there are several branching points where  $(p, \gamma)$  and  $(n, p)$  reactions compete. Masses are needed to determine the dominating reaction.

# 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)

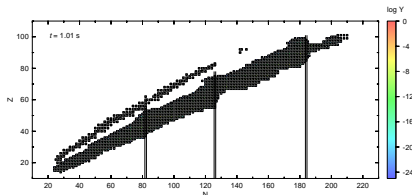


# Metal poor stars and fission



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

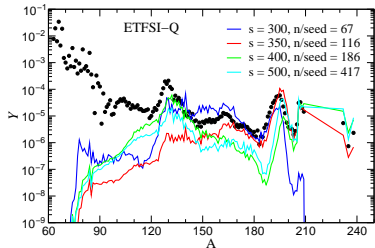
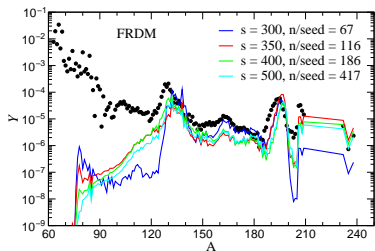
Can fission explain the robust r-process pattern for  $Z > 56$ ?



We need detailed knowledge of

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

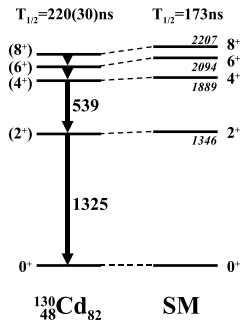
# Fission and N=82 shell structure



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  $^{130}\text{Cd}$ .



## 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  $\nu_e$ -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  $\nu p$ -process.
- Fission in the r-process is sensitive to the shell structure at  $N = 82$  that will become accessible to future radioactive beam facilities.