Neutrino-nucleus reactions

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Launch09, Heidelberg, November 9, 2009

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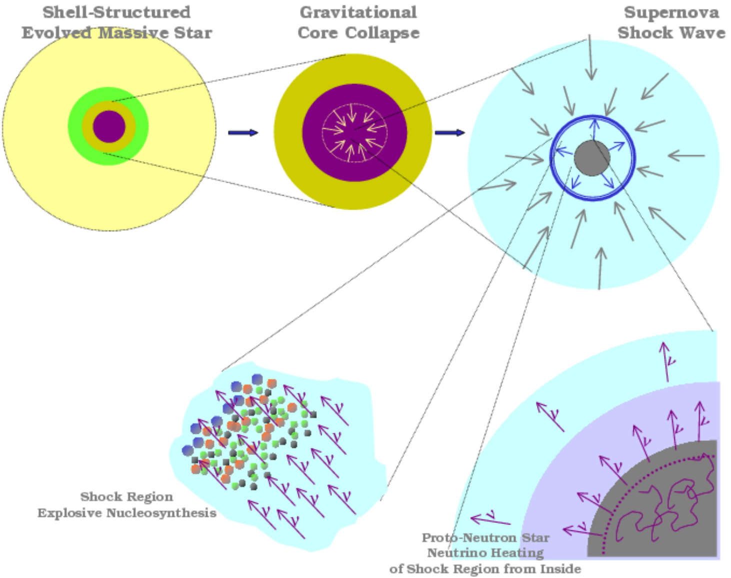
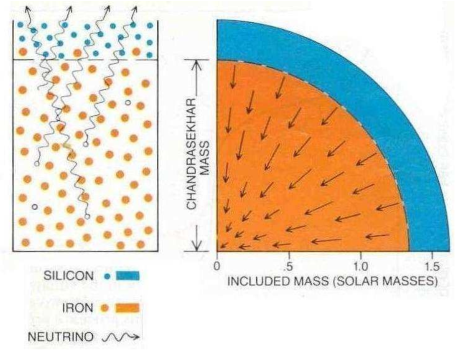
- Part I: Astrophysical needs
  - supernova neutrinos due to electron captures
  - inelastic neutrino-nucleus scattering
  - consequences for observation of neutrino-burst
  - explosive nucleosynthesis
  - neutrino nucleosynthesis
  - . . .
- Part II: Evaluation of neutrino-nucleus cross sections
  - energy scales and nuclear model requirements
  - examples and uncertainties
  - data?

Core-collapse supernova.



Electron captures in core collapse.

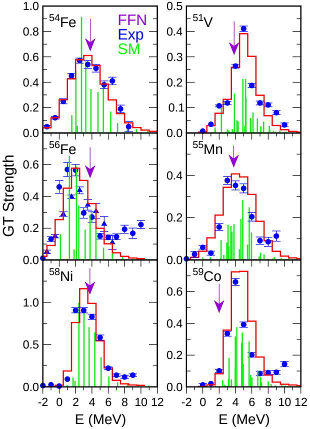


- $T = 0.5$–2.0 MeV, $\rho = 10^8$–10^{13} g cm^{-3}.
- The dynamical time scale set by electron captures: $e^- + (N, Z) \rightarrow (N + 1, Z - 1) + \nu_e$
- Evolution decreases number of electrons (Y_e) and Chandrasekhar mass ($M_{Ch} \approx 1.4(2Y_e)^2$ M$_\odot$)

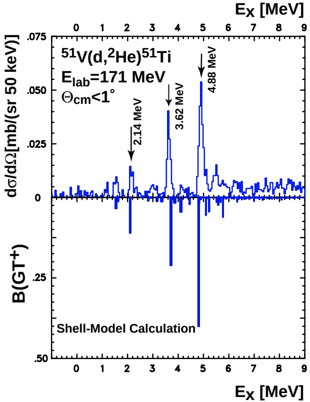
- Capture rates on individual nuclei computed by:
  - Shell Model ($A < 65$)
  - Shell Model Monte Carlo ($A > 65$)
  - RPA with parametrized occupation numbers ($A > 115$)

Gamow-Teller strength distributions in pf-shell nuclei.

(n,p) experiments, TRIUMF



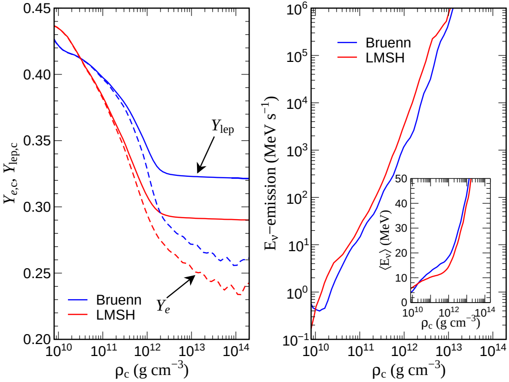
(d,^{2}He) experiments, KVI Groningen



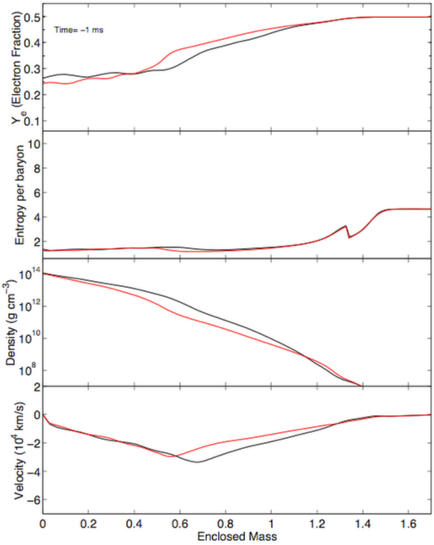
shell model results agree after overall quenching by $(0.77)^2$

Effect on improved rates on collapse simulations

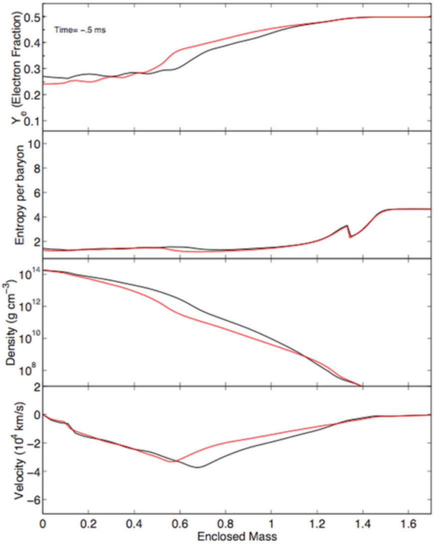
With Rampp & Janka (General Relativistic model)
15 $M_\odot$ presupernova model from A. Heger & S. Woosley



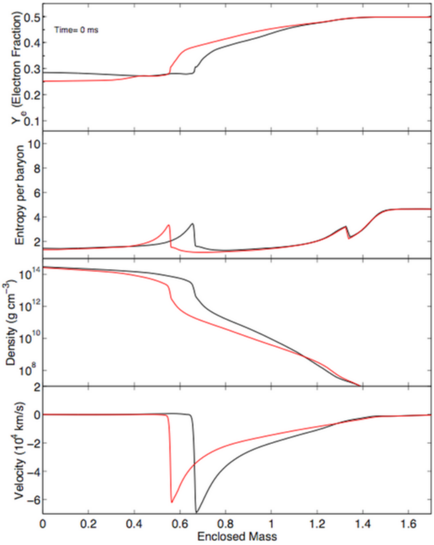
Bounce and shock wave evolution



Bounce and shock wave evolution



Bounce and shock wave evolution



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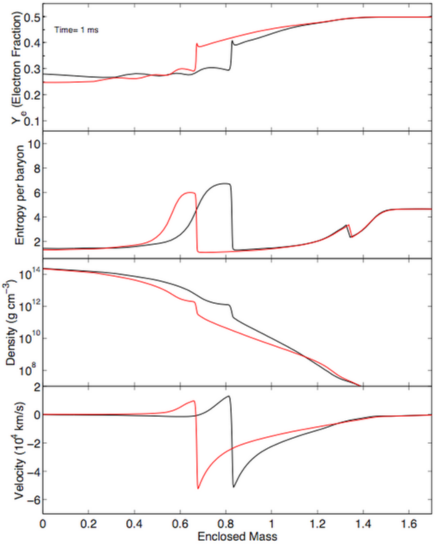
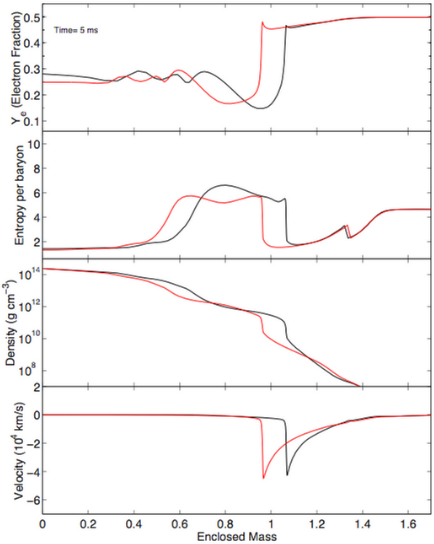
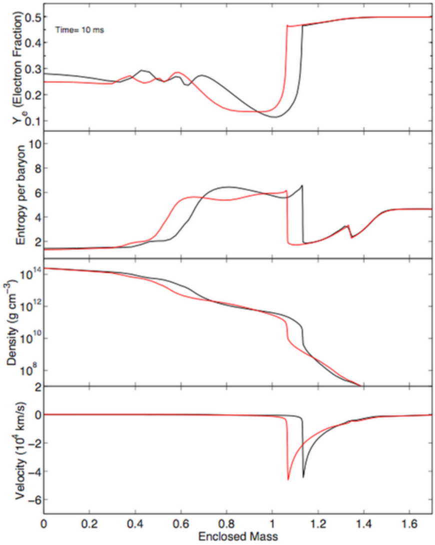


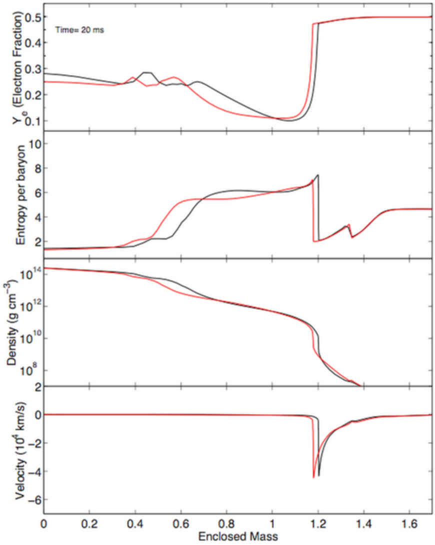
Bounce and shock wave evolution



Bounce and shock wave evolution



Bounce and shock wave evolution



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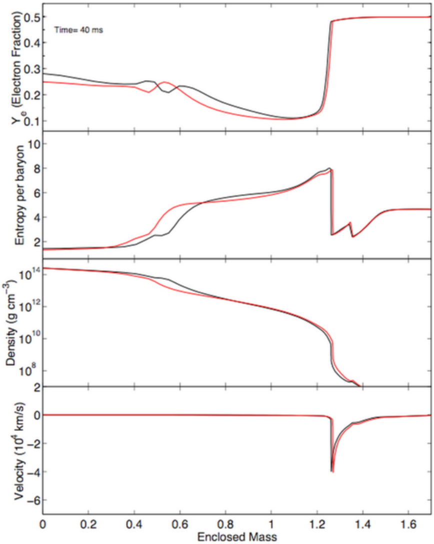
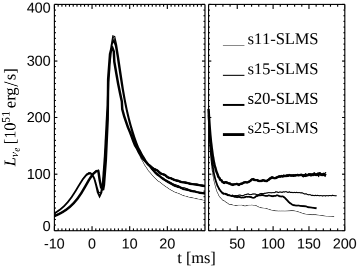


'Standard' neutrino burst

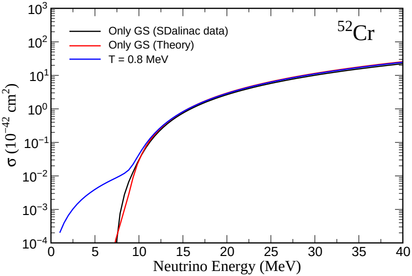


- shock dissociates matter into free protons and neutrons
- fast electron captures on free protons create ν_e neutrino burst
- 'standard' ν_e bursts
- future observation by supernova neutrino detectors
- 'standard neutrino candles'?

Inelastic ν-nucleus scattering in supernovae

Potential consequences:

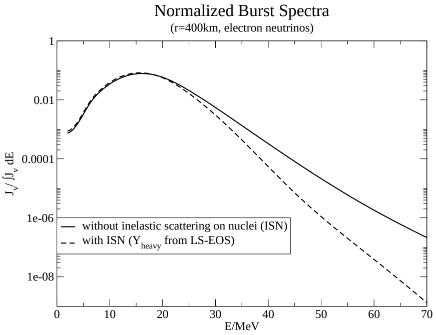
- thermalization of neutrinos during collapse
- preheating of matter before passing of shock
- nucleosynthesis, νp-process
- supernova neutrino signal



- neutrino cross sections from (e, e') data
- validation of shell model
- G.Martinez-Pinedo, P. v. Neumann-Cosel, A. Richter

Supernova neutrino signal

inelastic ν-nucleus scattering adds to the opacity for high-energy neutrinos



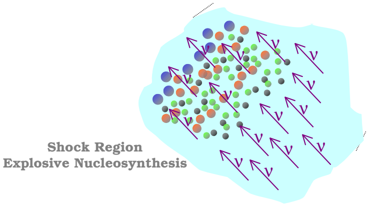
B. Müller, H.-Th. Janka, G. Martinez-Pinedo, A. Juodagalvis, J. Sampaio

Consequences for supernova neutrino detectors

Detector	Material	$\langle\sigma\rangle$ (10^{-42} cm^2) With $A(\nu,\nu')A^\star$	$\langle\sigma\rangle$ (10^{-42} cm^2) Without $A(\nu,\nu')A^\star$	Change
SNO	d	5.92	7.08	16%
MiniBoone	^{12}C	0.098	0.17	43%
	^{12}C (N_{gs})	0.089	0.15	41%
S-Kamiokande	^{16}O	0.013	0.031	58%
Icarus	^{40}Ar	17.1	21.5	20%
Minos	^{56}Fe	8.8	12.0	27%
OMNIS	^{208}Pb	147.2	201.2	27%

Change in supernova neutrino spectra reduce detection rates!

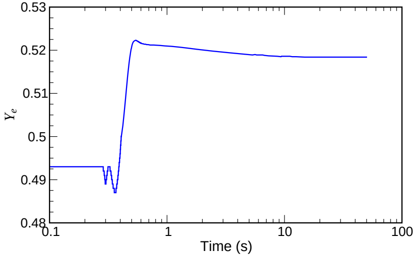
Explosive nucleosynthesis in supernova



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

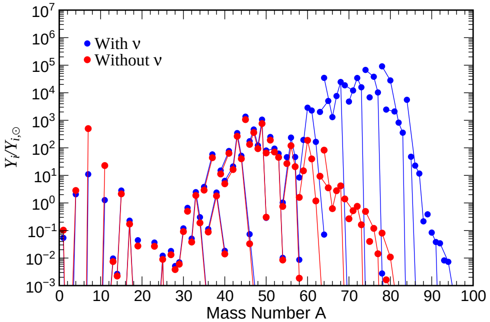
$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Y_e evolution of a mass element



The νp-process: basic idea

- Protonrich matter is ejected under the influence of neutrino reactions
- Nuclei form at distance where a substantial antineutrino flux is present

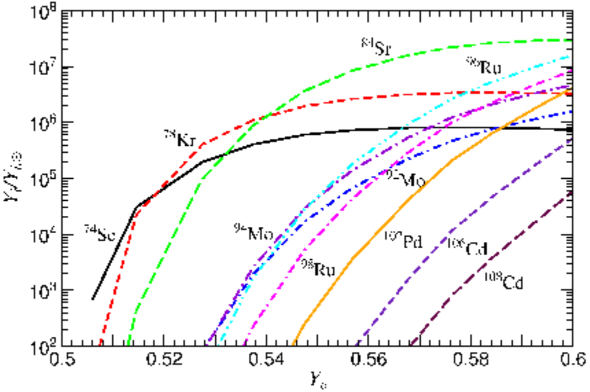


Antineutrinos help to bridge long waiting points via (n,p) reactions

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

C. Fröhlich, G. Martinez-Pinedo, et al., PRL 96 (2006) 142502

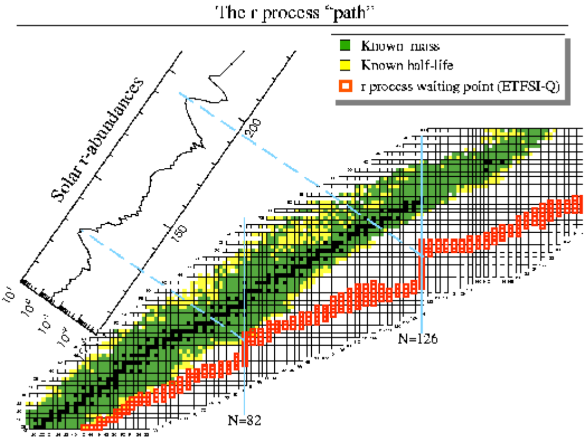
νp-process: abundance yields of medium-mass nuclei



Y_e: electron-to-nucleon ratio

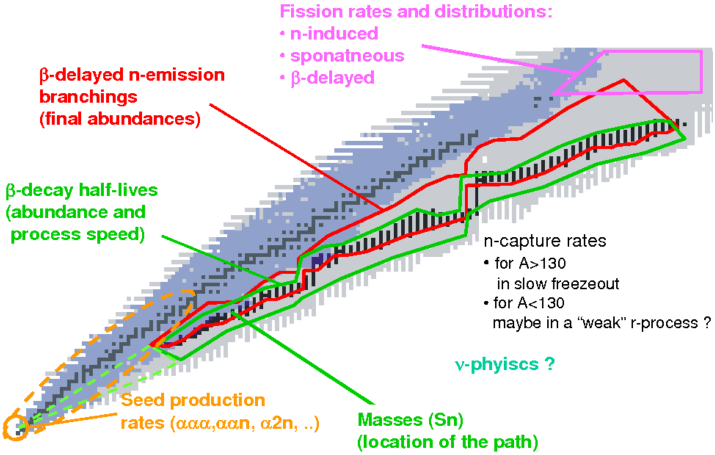
the larger Y_e, the more protons exist and can be transformed into neutrons by antineutrino capture

R-process nucleosynthesis



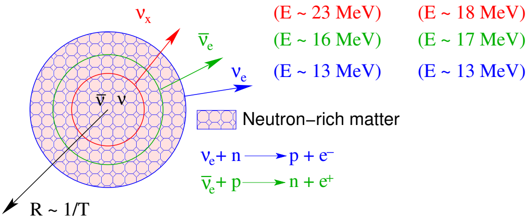
courtesy: K-L. Kratz

Which nuclear ingredients are needed?

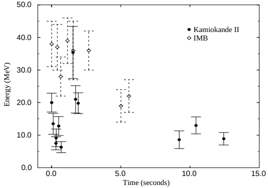


Neutrinos from supernovae

Raffelt *et al.*, astro-ph/0303226

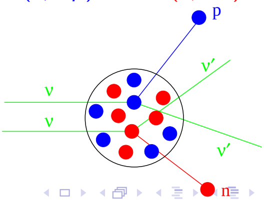


neutrino detection (SN1987A)



Neutrino nucleosynthesis

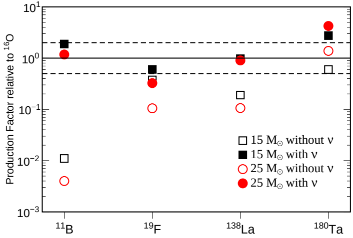
$^{12}\mathrm{C}(\nu,\nu' p)^{11}\mathrm{B}$ $^{12}\mathrm{C}(\nu,\nu' n)^{11}\mathrm{C}$

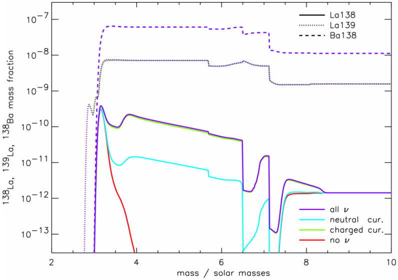


Neutrino nucleosynthesis

A. Heger *et al*, PLB 606 (2005) 258

Product	Parent	Reaction
^{11}B	^{12}C	$(\nu,\nu' n),(\nu,\nu' p)$
^{19}F	^{20}Ne	$(\nu,\nu' n),(\nu,\nu' p)$
^{138}La	^{138}Ba	(ν_e,e^-)
	^{139}La	$(\nu,\nu' n)$
^{180}Ta	^{180}Hf	(ν_e,e^-)
	^{181}Ta	$(\nu,\nu' n)$



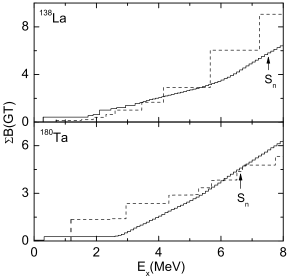


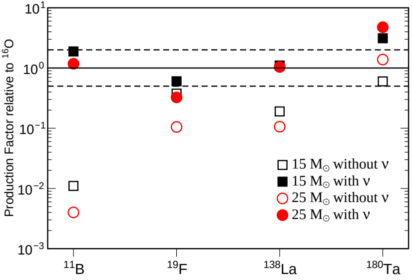
Importance of ^{138}La and ^{180}Ta nucleosynthesis

- ^{11}B and ^{19}F are produced by neutral-current reactions induced by ν_μ and ν_τ neutrinos and anti-neutrinos
- $\bar{\nu_e}$ neutrinos observed from SN1987a
- ^{138}La and ^{180}Ta are produced by charged-current reactions induced by ν_e neutrinos on ^{138}Ba and ^{180}Hf
- In summary, one has a sensitivity to ALL different neutrino spectra

However, neutrino cross sections based on theoretical models (RPA)

Measurement of GT strength for ^{138}Ba and ^{180}Hf





RCNP Osaka/ Darmstadt (A. Byelikov *et al.*)

Neutrino cross sections

Charged current: $(Z, A) + \nu_e \rightarrow (Z + 1, A) + e^-$

$$\sigma_{i,f}(E_\nu) = \frac{G_V^2}{\pi} p_e E_e F(Z+1, E_e)[B(F) + B(GT)]$$

Neutral current: $(Z, A) + \nu \rightarrow (Z, A)^* + \nu$

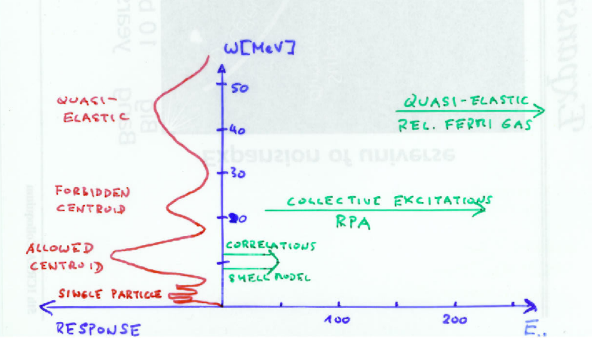
$$\sigma_{i,f}(E_\nu) = \frac{G_F}{\pi}(E_\nu - w)^2 B(GT_0)$$

with $w = E_f - E_i$
In general, multipoles beyond allowed transitions are necessary. See Donelly and Peccei, Phys. Repts. **50**, 1 (1979).

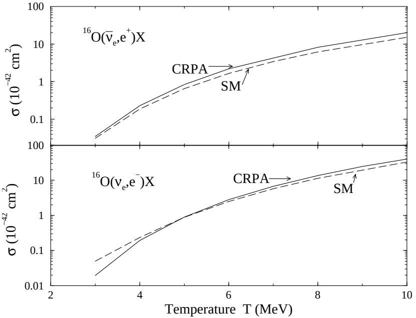
General considerations: Which multipoles?

- **Multipole operators O_λ**
  - $\sim \left(\frac{qR}{\hbar c}\right)^\lambda \quad ; q \approx E_\nu$
  - successively higher rank with increasing E_ν
- **Collective nuclear excitations:**
  - $[H, O_\lambda] \neq 0 \rightarrow$ strength is fragmented
  - centroid $E^\lambda_{coll} \sim \lambda\hbar\omega \sim \lambda\frac{41}{A^{1/3}}\mathrm{MeV}$
- **Phase space:**
  - $\sim p_{lep}E_{lep} \rightarrow$ high E_{lep} preferred
  - average nuclear excitation $\bar{\omega}$ lags behind with increasing E_ν
  - if $E_\nu >> \bar{\omega}$, σ sensitive to total strength

Remarks about response: Which models?

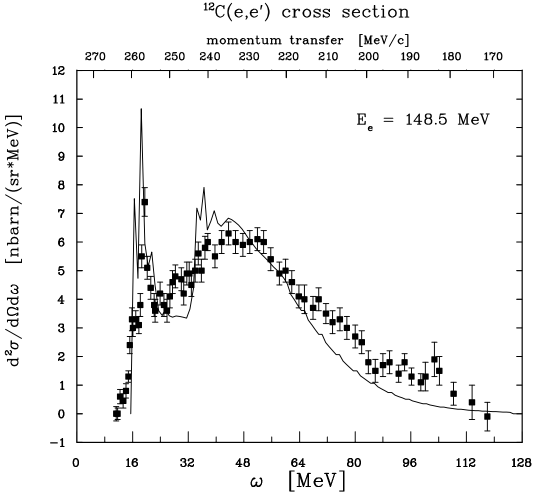


Shell Model versus RPA.



The RPA considers only (1p-1h) correlations; it is well suited to describe the centroid of giant resonances

Inelastic electron scattering: RPA description of response



Systematics of Fermi and Gamow-Teller centroids

ESTIMATE OF CHARGED-CURRENT CROSS SECTION

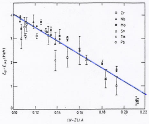
$$\sigma(E_\nu) = \frac{G_F^2 \cos^2\Theta_c}{\pi} k_e E_e F(Z+1, E_e) \left(|M_F|^2 + \left(g_A^{eff}\right)^2 |M_{GT}|^2 \right)$$

FERMI TRANSITIONS

- $|M_F|^2 = (N-Z)$ — ISOBARIC ANALOG
- $E_{IAS} \cong \left(\frac{1.728\, Z}{1.12\, A^{1/3} + 0.78} - 1.293 \right)$ MeV

GAMOW-TELLER TRANSITIONS

- $|M_{GT}|^2 = 3(N-Z)$ — VERY NEUTRON RICH, IKEDA SUM RULE
- $\langle E_{GT} \rangle - \langle E_{IAS} \rangle \approx A + B(N-Z)$

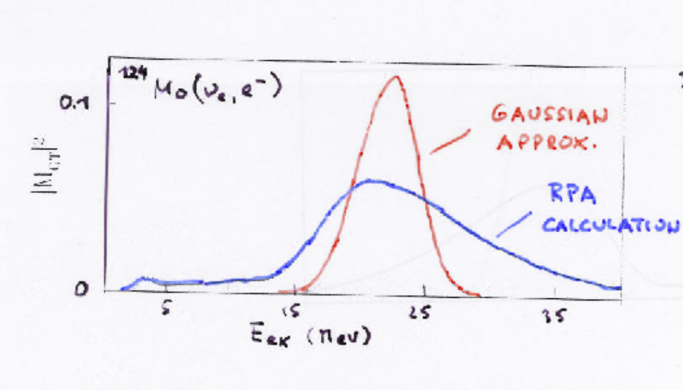


- DISTRIBUTION
  - a) δ-FUNCTION
  - b) GAUSSIAN AROUND $\langle E_{GT} \rangle$ WITH WIDTH ~ 5 MeV

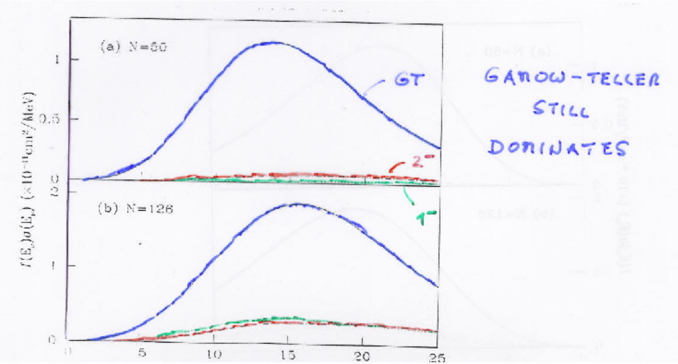
THE OPEN QUESTIONS:

- LOW LYING GT-STRENGTH
- FORBIDDEN TRANSITIONS

How well do we know charged-current cross sections?



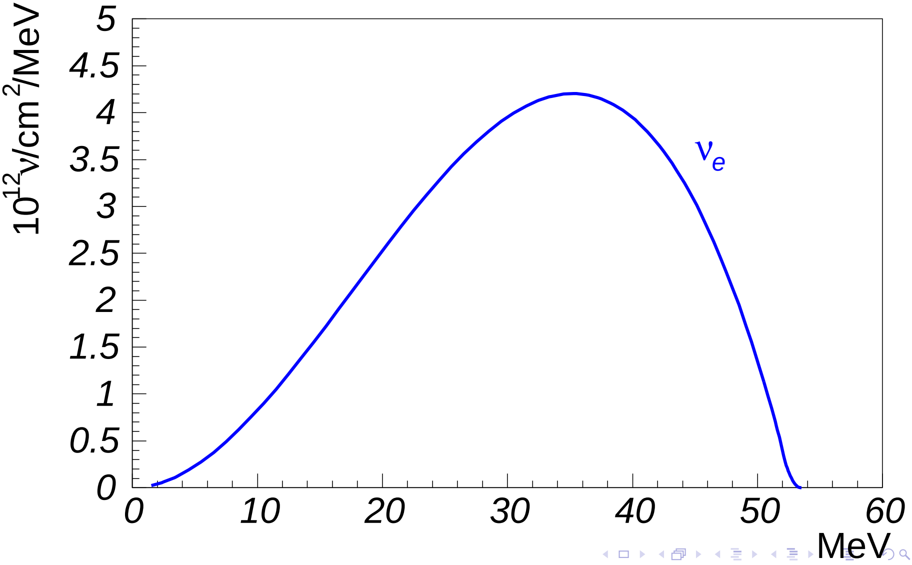
RPA vs simple Gaussian: $\sim$ factor 2 (Surmann+Engel)



for neutrino spectrum with $T = 4$ MeV

Influence of higher multipoles

Spectrum for muon decay: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

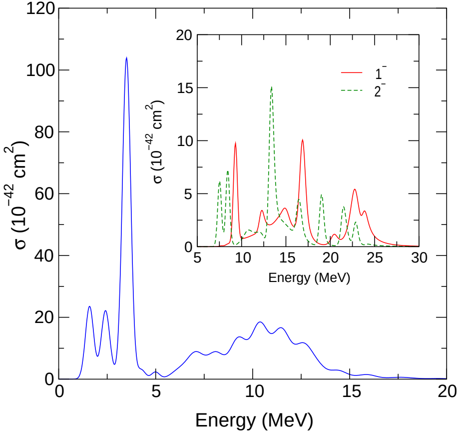


Influence of higher multipoles

$^{56}Fe(\nu_e, e^-)^{56}Co$ measured by KARMEN collaboration:

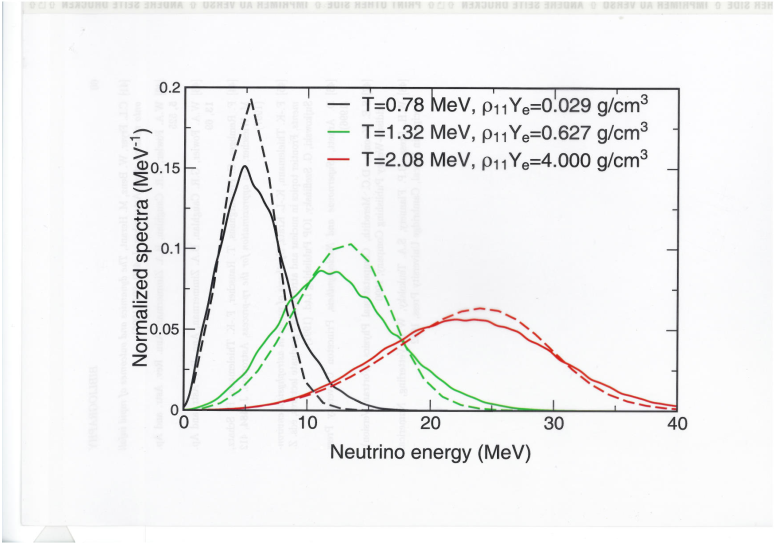
$\sigma_{exp} = 2.56 \pm 1.08(stat) \pm 0.43(syst) \times 10^{-40}\ cm^2$

$\sigma_{th} = 2.38 \times 10^{-40}\ cm^2$

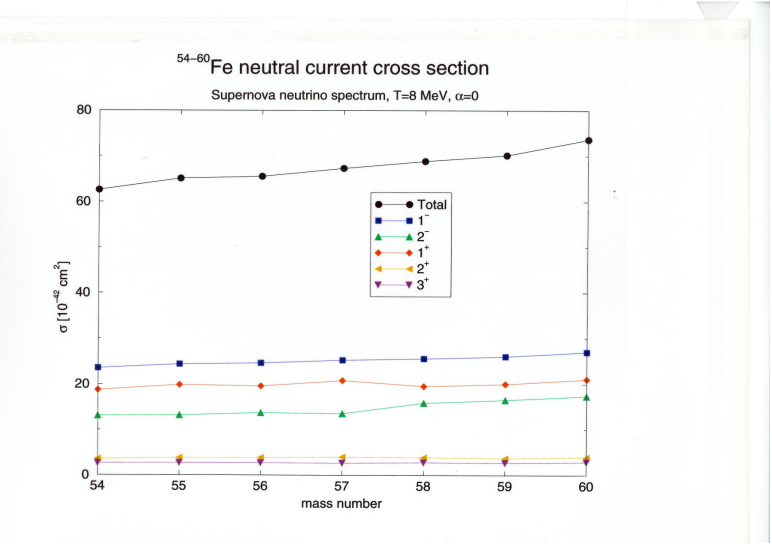


E. Kolbe, G. Martinez-Pinedo, Phys. Rev. C60 (1999) 052801

Typical supernova neutrino spectra



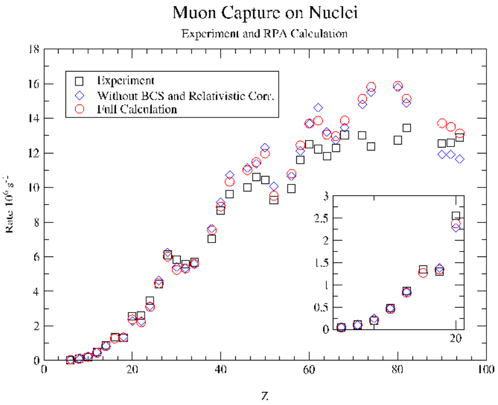
Multipole decomposition



J. Toivanen et al., Nucl. Phys. A694 (2001) 395

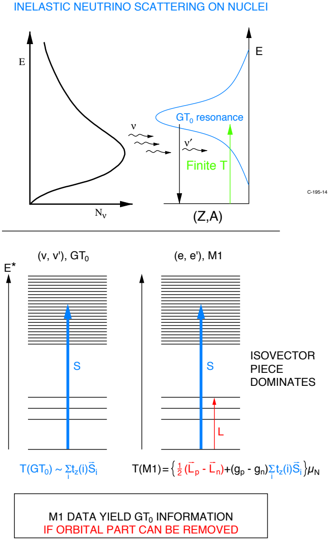
Muon capture

kinematics similar to capture of antineutrinos with a few 10 MeV

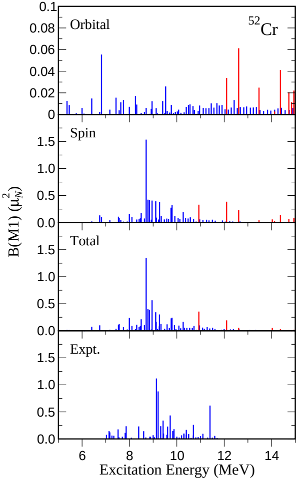


N.T. Zinner *et al.*, RPA calculations, Phys. Rev. C

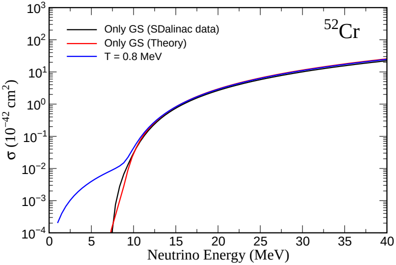
Determining inelastic neutrino-nucleus cross sections



Neutrino cross sections from electron scattering



- high-precision SDalinac data
- large-scale shell model

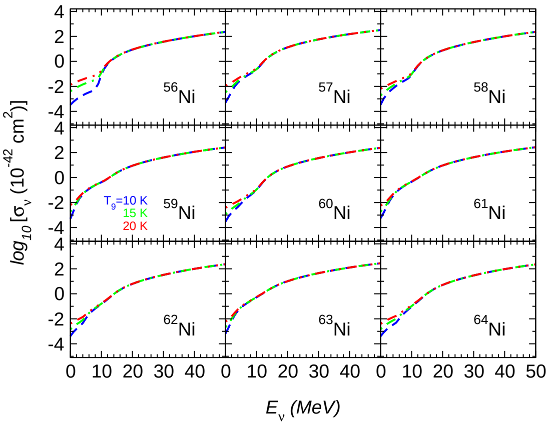


- neutrino cross sections from (e, e') data
- validation of shell model
- G.Martinez-Pinedo, P. v. Neumann-Cosel, A. Richter

Tables for neutrino-nucleus cross sections

- **Fuller-Meyer**: parametrized Gamow-Teller model (Gaussian), (ν_e, e^-)
  G.M. Fuller and B.S. Meyer, Astr. J. 453 (1995) 792: G. McLaughlin and G.M. Fuller, Astr. J. 455 (1995) 202
- **Borzov+Goriely**: Fermi liquid theory, (ν_e, e^-)
  I. Borzov and S. Goriely, Phys. Rev. C62 (2000)035501
- **Langanke-Kolbe**: RPA, neutronrich nuclei, (ν_e, e^-), (ν, ν')
  K. Langanke and E. Kolbe, ADNDT 79 (2001) 293; 82 (2002) 191
- **Juodagalvis**: diagonalization shell model + RPA, (ν, ν'), finite T
  A. Juodagalvis, K. Langanke, G. Martinez-Pinedo, W.R. Hix, D.J. Dean and J.M. Sampaio, Nucl. Phys. A747 (2005) 87

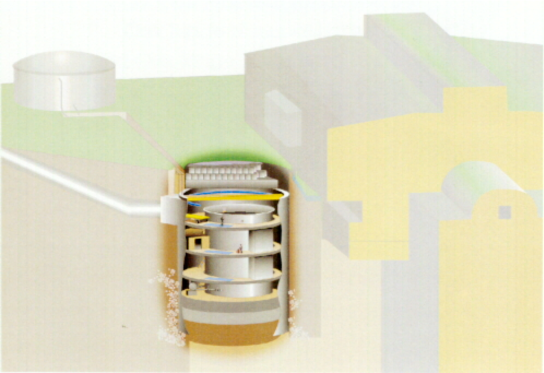
Inelastic neutrino-nucleus cross sections



- large-scale shell model (allowed transitions), finite-T effects
- random phase approximation (forbidden transitions)
- A. Juodagalvis, W.R. Hix, G. Martinez-Pinedo, J.M. Sampaio

Future: measurement of neutrino-nucleus cross sections?

Idea: dedicated neutrino detector at the European Spallation Source
G. Martinez-Pinedo



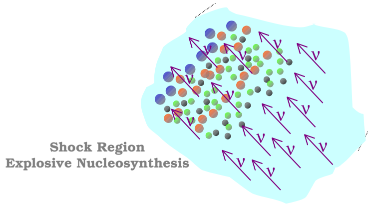
(Sketch of proposed Orland detector in Oak Ridge)

Summary

Improved nuclear ingredients for supernova simulations

- Electron capture rates on nuclei change collapse trajectory
- Neutrino-nucleus cross sections have impact on neutrino-burst signal
- Neutrino-nucleosynthesis might serve as neutrino thermometer

Explosive nucleosynthesis in supernova



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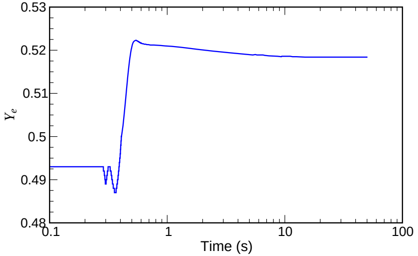
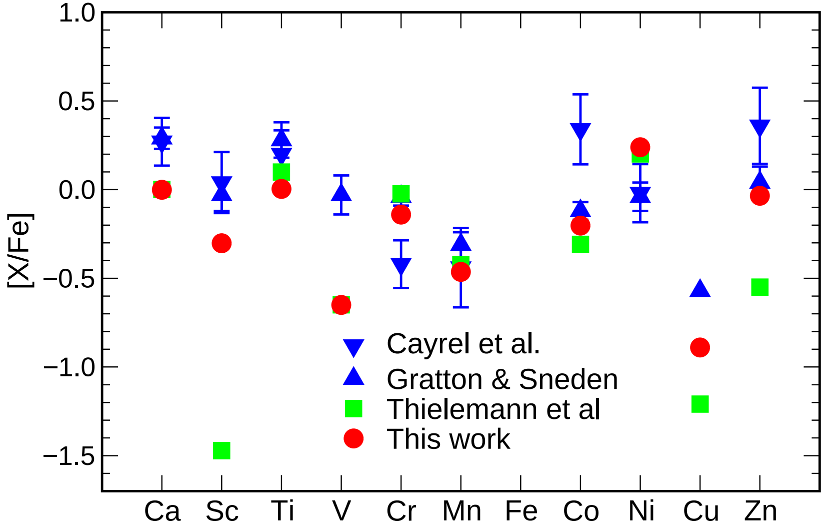
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

Y_e evolution of a mass element



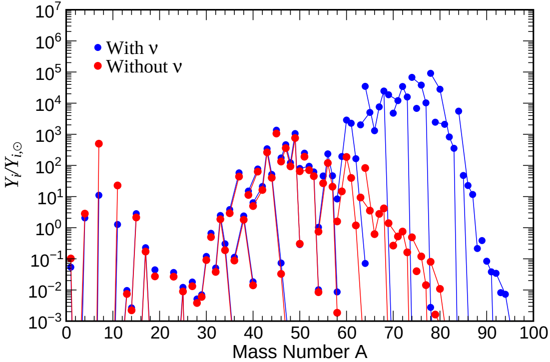
Comparison with observations.

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



Effect of neutrinos on nucleosynthesis.

G. Martínez-Pinedo, C. Fröhlich



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