Nuclear Weak Processes in Stars

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New shell model Hamiltonians in *p*-shell (SFO) and *fp*-shell (GXPF1), and successful description of spin responses

- GT strengths in ^{12}C , Ni, Fe isotopes etc.

(1) ν-nucleus reactions

- Synthesis of ^{7}Li, ^{11}B, and ^{55}Mn in supernovae explosions

(2) e-capture reactions in Ni and Co isotopes in steller core-collapse environments

(3) Beta decay of N=126 isotones, and synthesis of elements in the r-process

1. New Shell-Model Hamiltonians in p-shell and Neutrino-Nucleus Reactions

	new		conventional
p-shell（p-sd）	**SFO, OFU**	**vs**	**CK+MK**

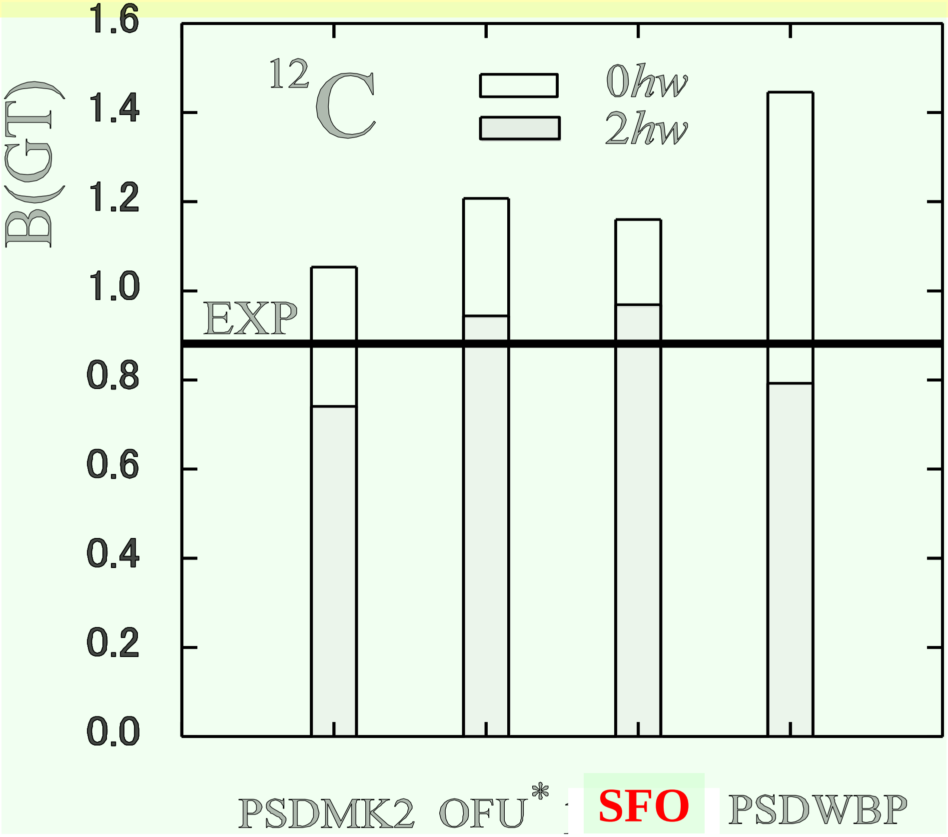
SFO: Suzuki, Fujimoto, Otsuka, PR C67, 044302 (2003)
OFU: Otsuka et al., PRL 87, 082502 (2001)
CK: Cohen-Kurath, Nucl. Phys. 73, 1 (1965)
MK: Millener-Kurath, Nucl. Phys. A255, 315 (1975)

Monopole terms in $p_{1/2}$-$p_{3/2}$, T=0 are enhanced：
$\Delta V = -(1.9 – 2.0)$ MeV

$$V_M^T(j_1 j_2) = \frac{\sum_J (2J+1) < j_1 j_2; JT \,|\, V \,|\, j_1 j_2; JT >}{\sum_J (2J+1)}$$

Systematic improvements in the description of magnetic moments, GT transitions in p-shell nuclei are obtained.

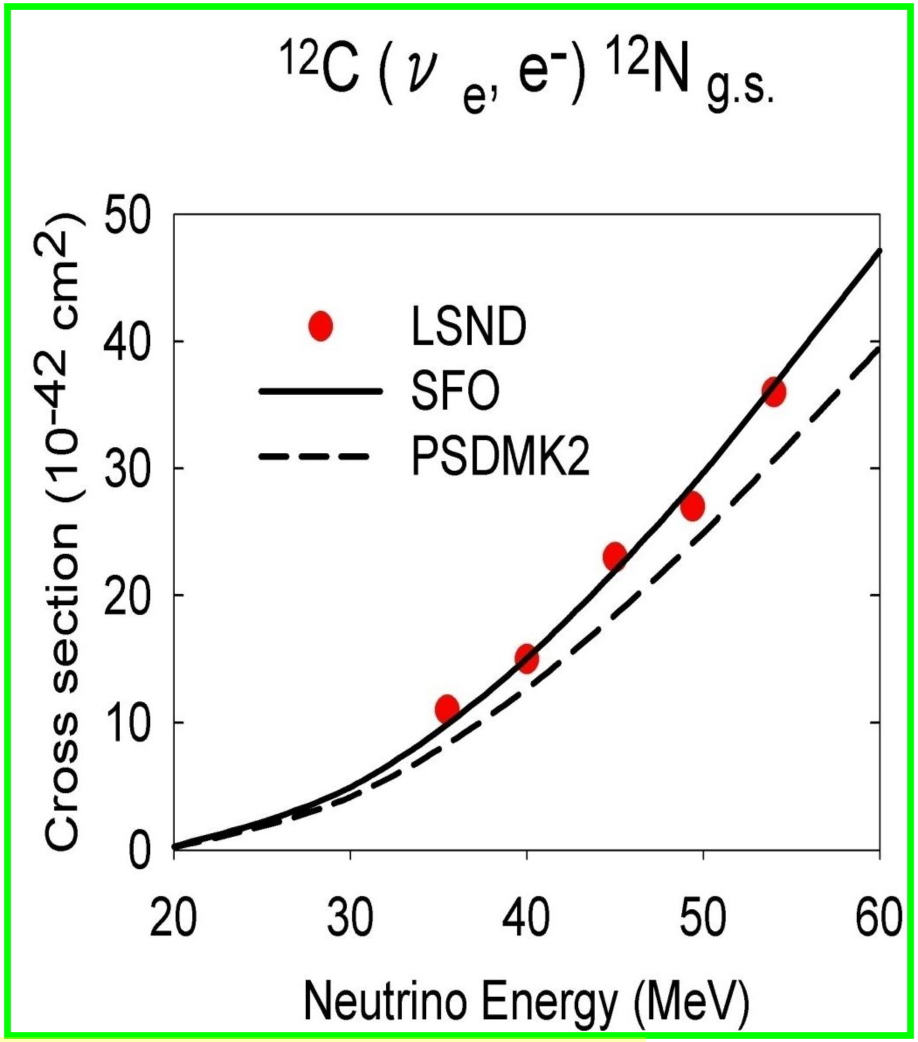
B(GT) values for ^{12}C -> ^{12}N



SFO **Suzuki, Fujimoto, Otsuka,**
PR C67 (2003)

Space: up to 2-3 hw

SFO*: g_A^{eff}/g_A=0.95
B(GT: ^{12}C)_cal = experiment



LSND
Athanassopoulos et al.
PR C55, 2078 (1997)

Suzuki, Chiba, Yoshida,Kajino,
Otsuka, PR C74, 034307, (2006).

Nucleosynthesis processes of light elements

Enhancement of ^{11}B and ^{7}Li in supernova explosions

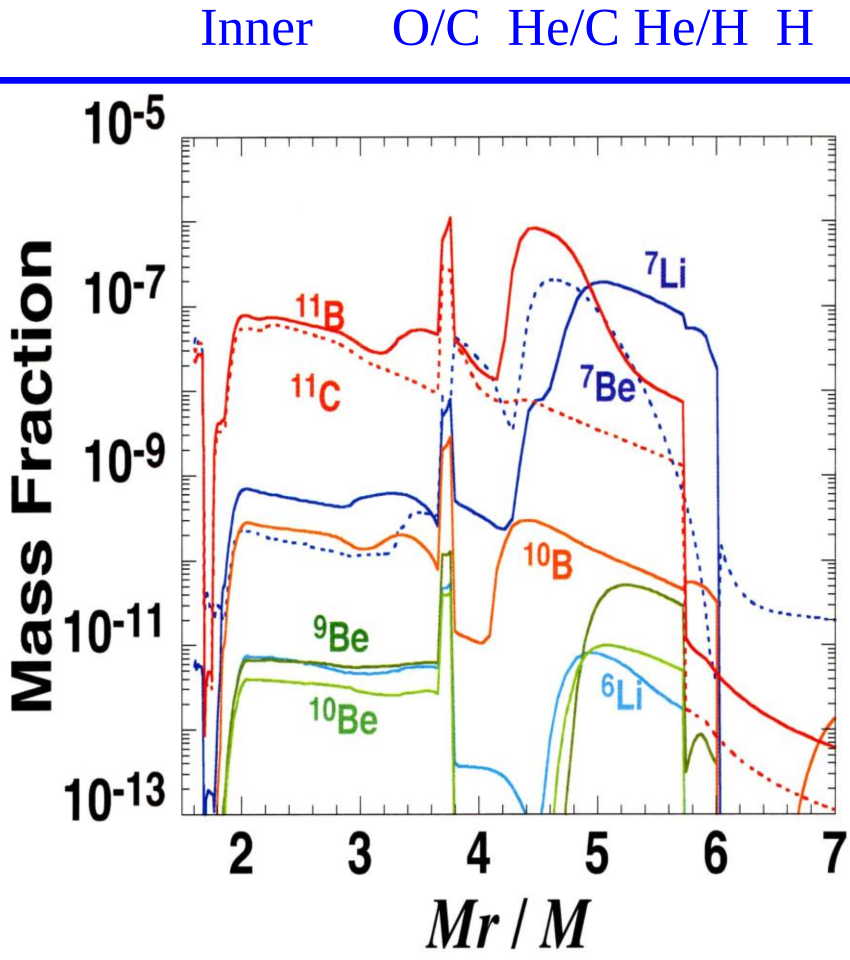
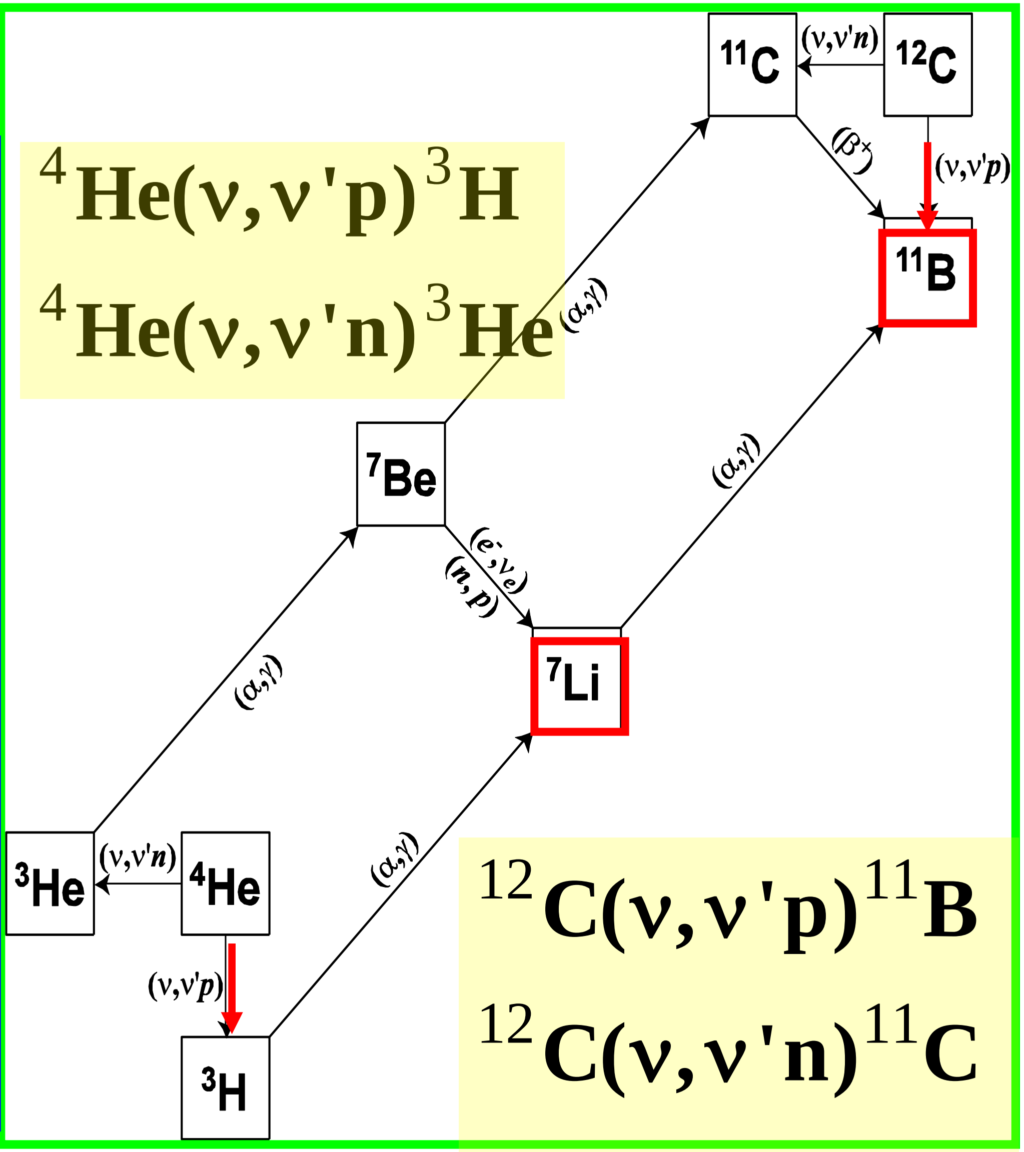


Fig. 4.— Mass fraction distribution of Model 1. The mass fractions of ^{7}Li and ^{7}Be, and ^{11}B and ^{11}C are separated.



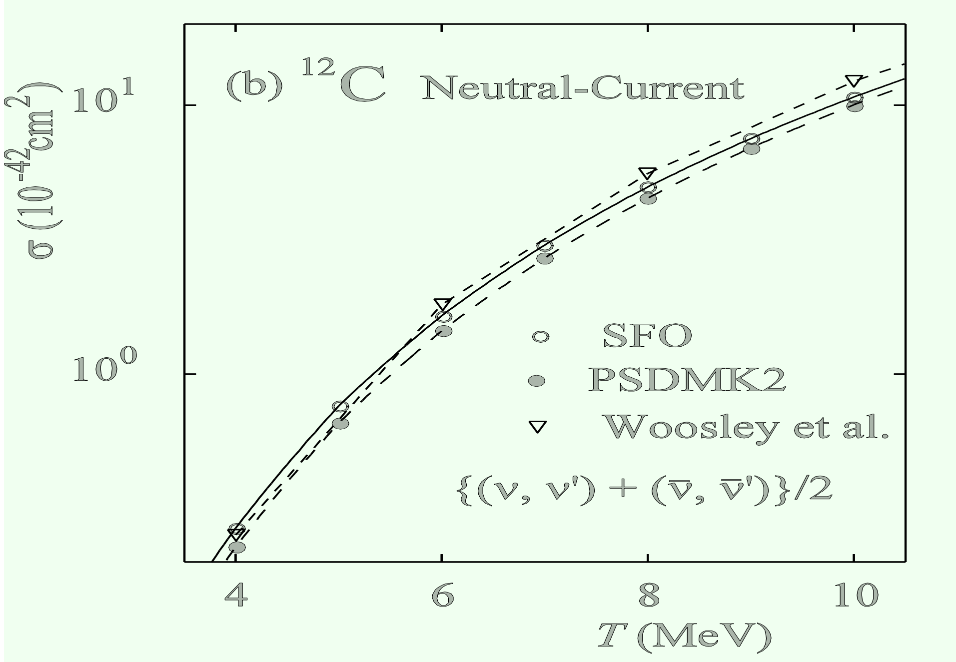
$$^{4}\mathrm{He}(\nu,\nu'p)^{3}\mathrm{H}$$

$$^{4}\mathrm{He}(\nu,\nu'n)^{3}\mathrm{He}$$

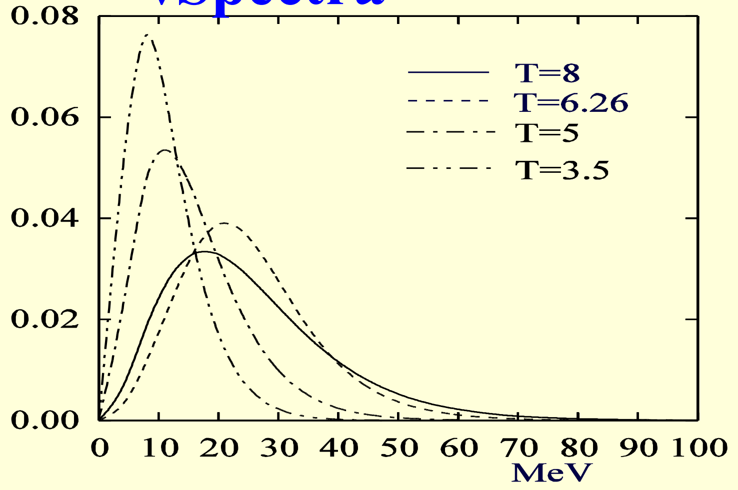
$$^{12}\mathrm{C}(\nu,\nu'p)^{11}\mathrm{B}$$

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

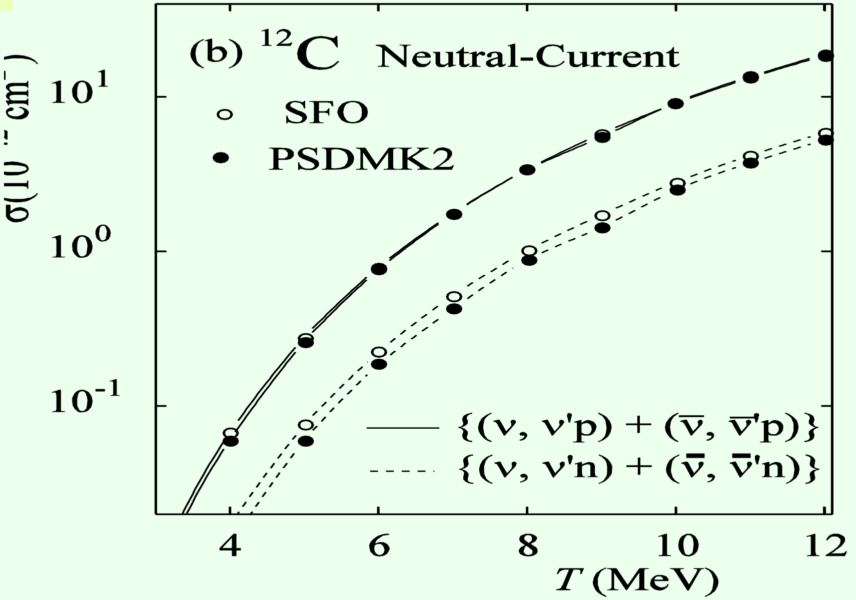
Cross sections for Supernova Neutrinos with temperature T

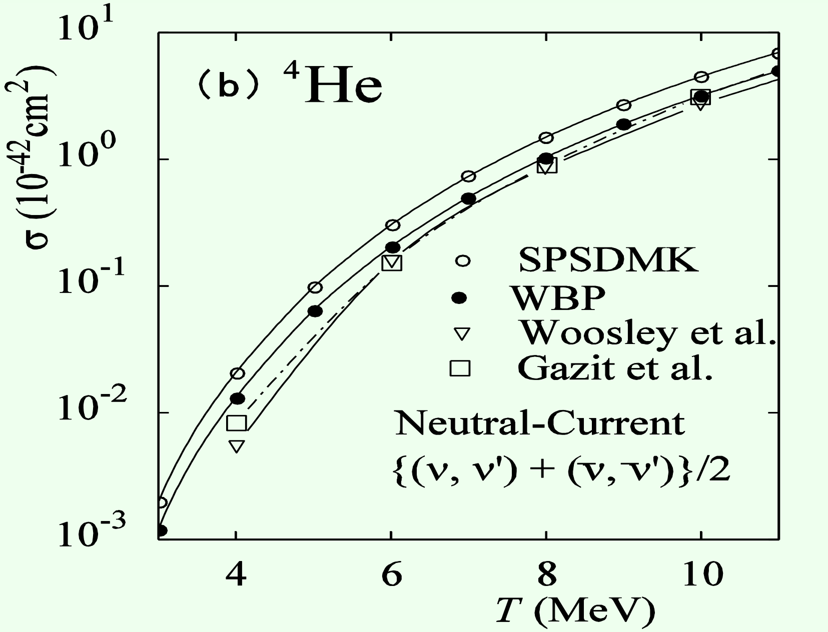


νSpectra



Proton and neutron emissions BR: Hauser-Feshbach model

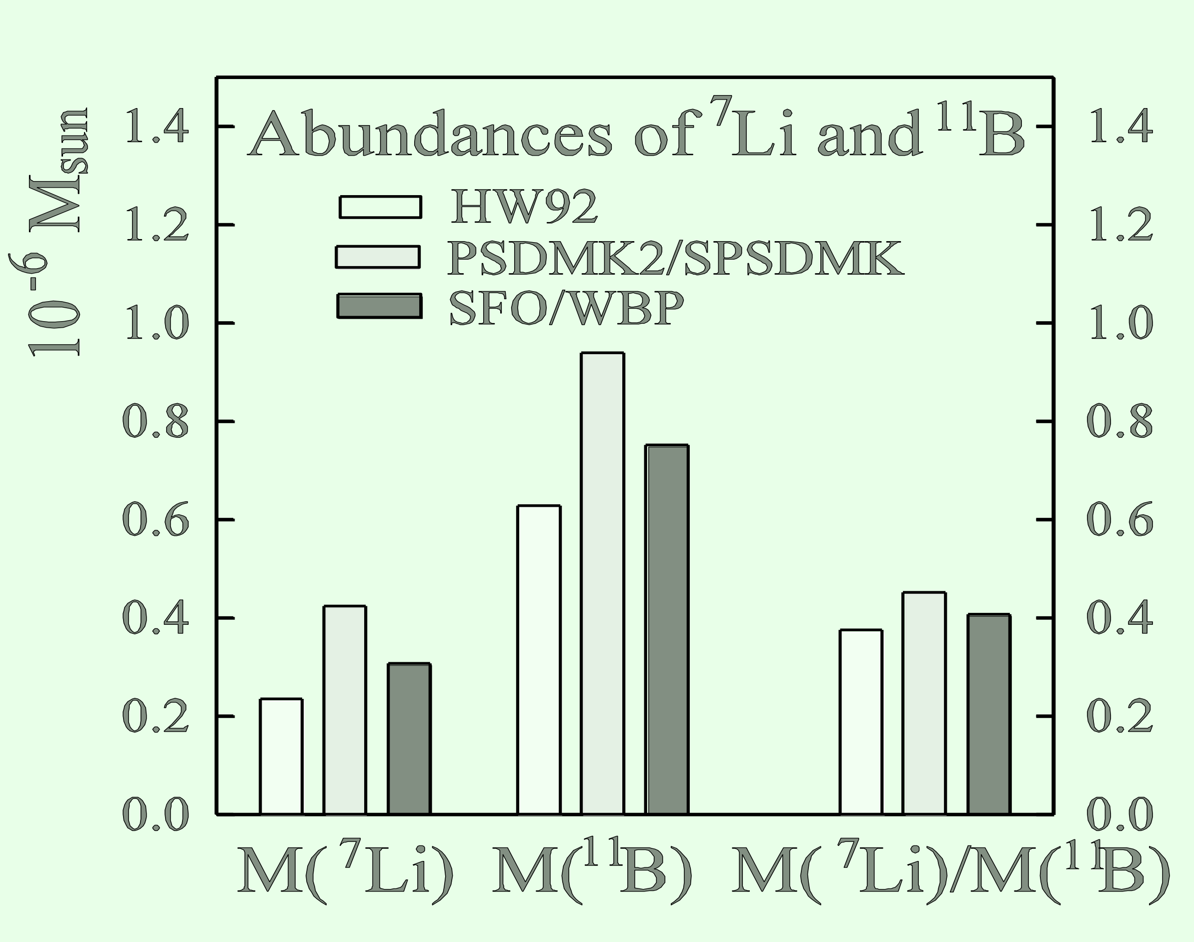




Abundances of ^{7}Li and ^{11}B produced in supernova explosion processes

$M = 16.2\ M_{\odot}$ (SN 1987A)

$$T_{\nu_e} = 3.2\ MeV,\quad T_{\bar{\nu}_e} = 5.0\ MeV,\quad T_{\nu_\mu,\nu_\tau} = 6.0\ MeV$$



No oscillation case

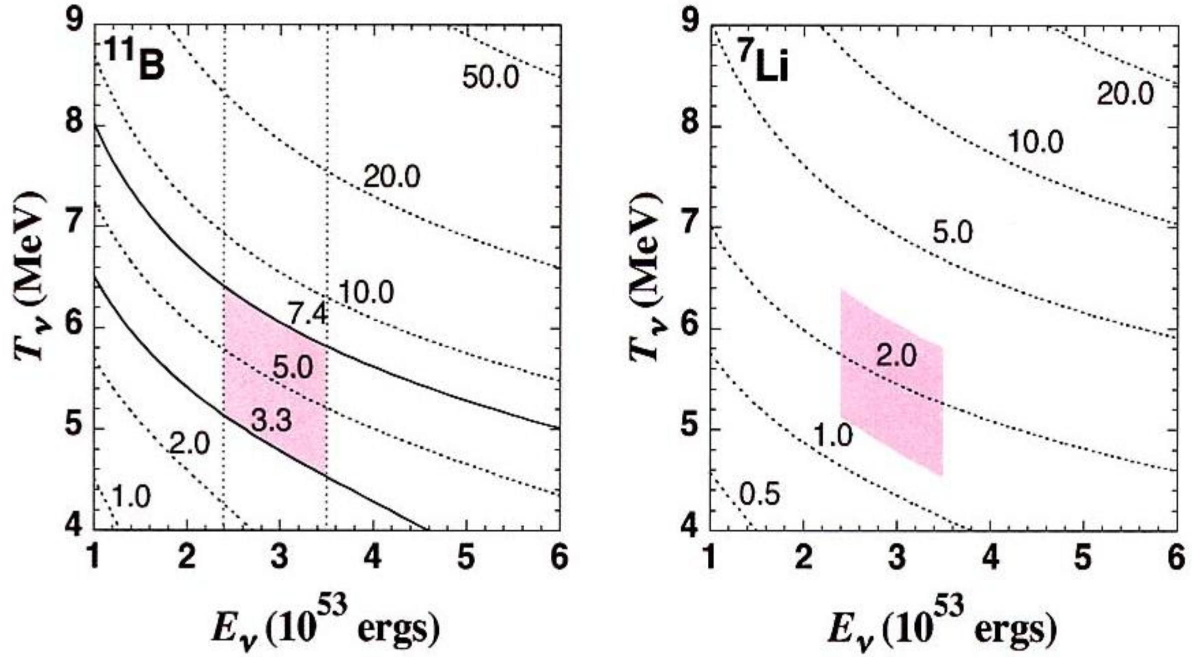
$$(\nu,\nu' p),(\nu,\nu' n)$$

$$\nu = \nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau}$$

Suzuki, Chiba, Yoshida, Kajino and Otsuka, PR C74, 034307 (2006)

Constraints on neutrino temperatures

SN contributions in GCE: $3.3\text{x}10^{-7}M_{\odot} \leq M(^{11}B) \leq 7.4\text{x}10^{-7}M_{\odot}$



WBP+SFO

$4.5\ \text{MeV} \leq T_{\nu_{\mu,\tau}} \leq 6.4\ \text{MeV}$ WBP+SFO $T_{\nu_e} = T_{\bar{\nu}_e} = 4\ \text{MeV}$

$4.4\ \text{MeV} \leq T_{\nu_{\mu,\tau}} \leq 6.1\ \text{MeV}$ SPSDMK+PSDMK2

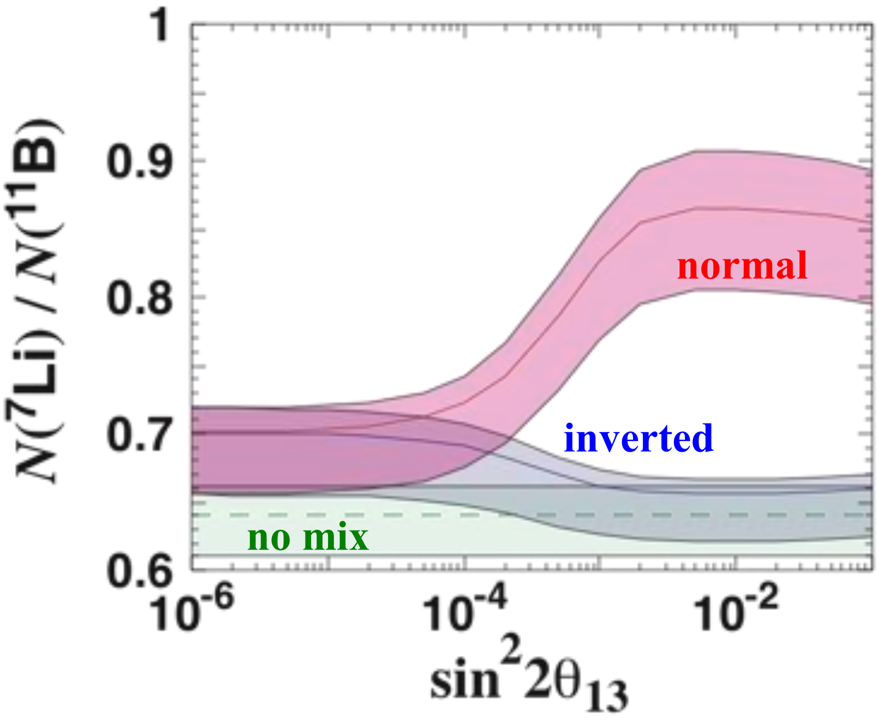
cf. $4.8\ \text{MeV} \leq T_{\nu_{\mu,\tau}} \leq 6.6\ \text{MeV}$ Yoshida, Kajino, Hartmann, PRL 94 (2005)

SN Nucleosynthesis with Neutrino Oscillations

- **^{7}B, ^{11}C** abundance → Increase by a factor of 2.5 and 1.4

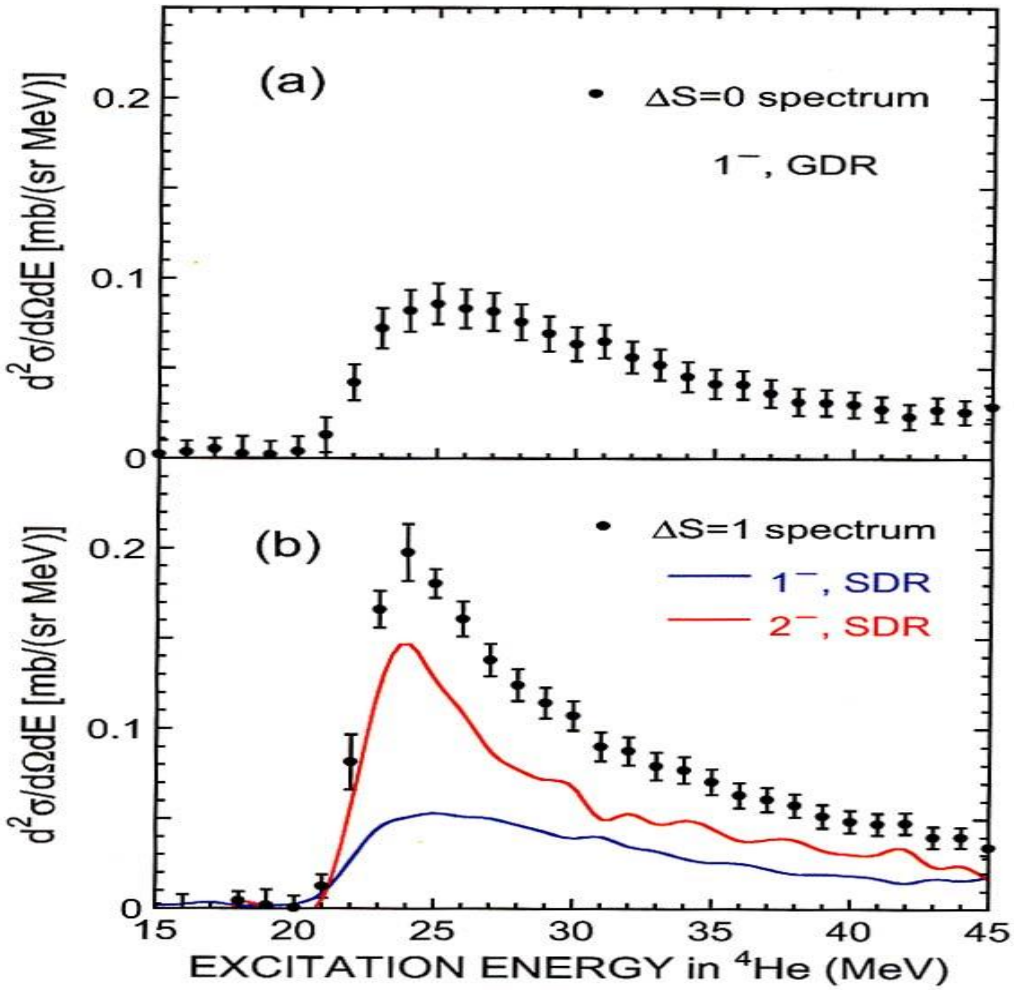
← Increase in the rates of charged-current reactions **^{4}He**(ν_e,e^-p)**^{3}He** and **^{12}C**(ν_e,e^-p)**^{11}C** in the He layer

N(7Li)/N(11B) → Good indicator for neutrino oscillation parameters



Possibility for constraining ***mass hierarchy*** and *lower limit of the mixing angle* θ_{13}.

Effects of the spreading of the SD strength in ^{4}He

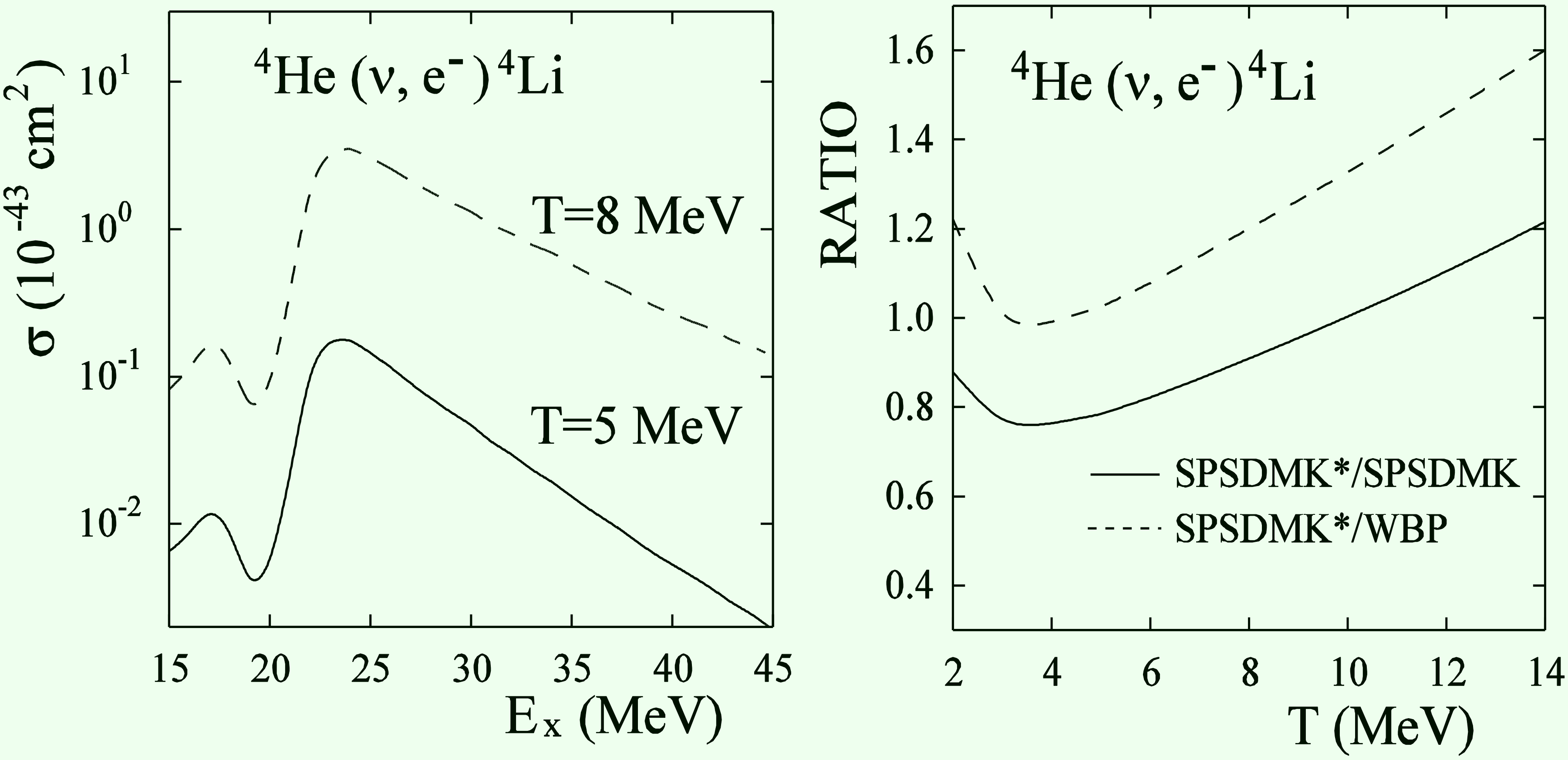


Nakayama et al.

FIG. 1: The ΔS=0 (a) and ΔS=1 (b) spectra deduced from the ^{4}He(^{7}Li,^{7}Be) reaction at E_L=455 MeV and at $\theta_L = 0°$. The ΔS=1 spectrum is decomposed into the 1^- and 2^- distributions by assuming that the 1^- SDR distributes in the same way as the 1^- GDR, and relative strength of the 1^- SDR to the 2^- SDR is evaluated with the SPSDMK calculated by T. SUzuki.

SPSDMK*
GDR+SDR1+SDR2

Total: + (0^-, 1^+, 2^+, 3^+, 3^- by shell model)



2. Neutrino Nucleus Reactions and Electron Capture Reactions in fp-shell Nuclei

New shell-model Hamiltonians in fp-shell:

GXPF1: Honma et al., PR C65 (2002); C69 (2004)

KB3: Caurier et al., Rev. Mod. Phys. 77, 427 (2005)

○	KB3G	A = 47-52	KB + monopole corrections
○	GXPF1	A = 47-66	

- Systematic reproduction of E(2+) and B(E2) in fp-shell nuclei
- Spin properties of fp-shell nuclei are well described

● **GT Strengths in Ni and Fe Isotopes and M1 strengths in fp-shell nuclei**

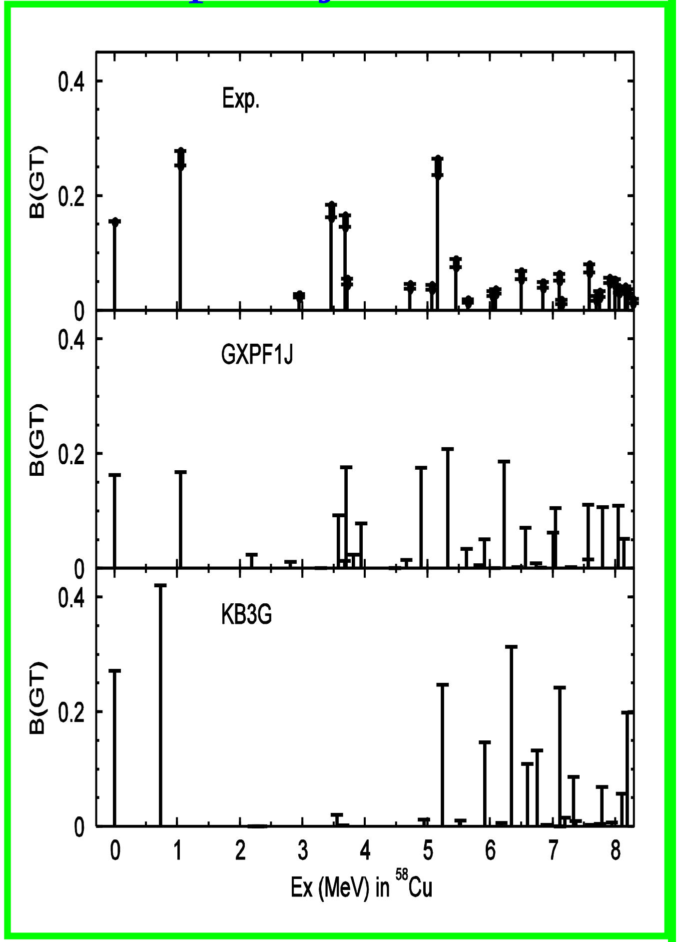
fp-shell
B(GT) for 58Ni

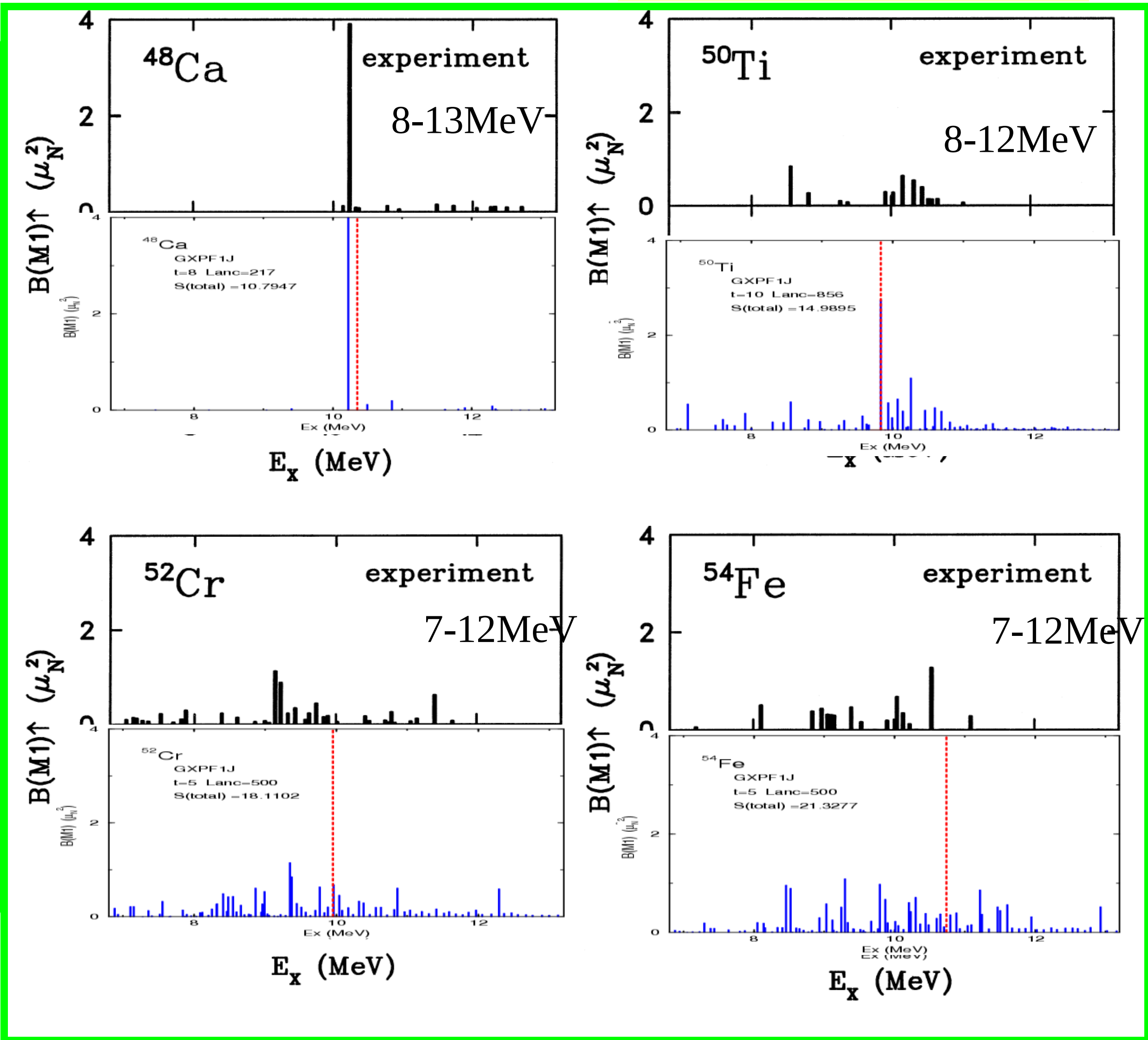
M1 strength (GXPF1J)

Honma

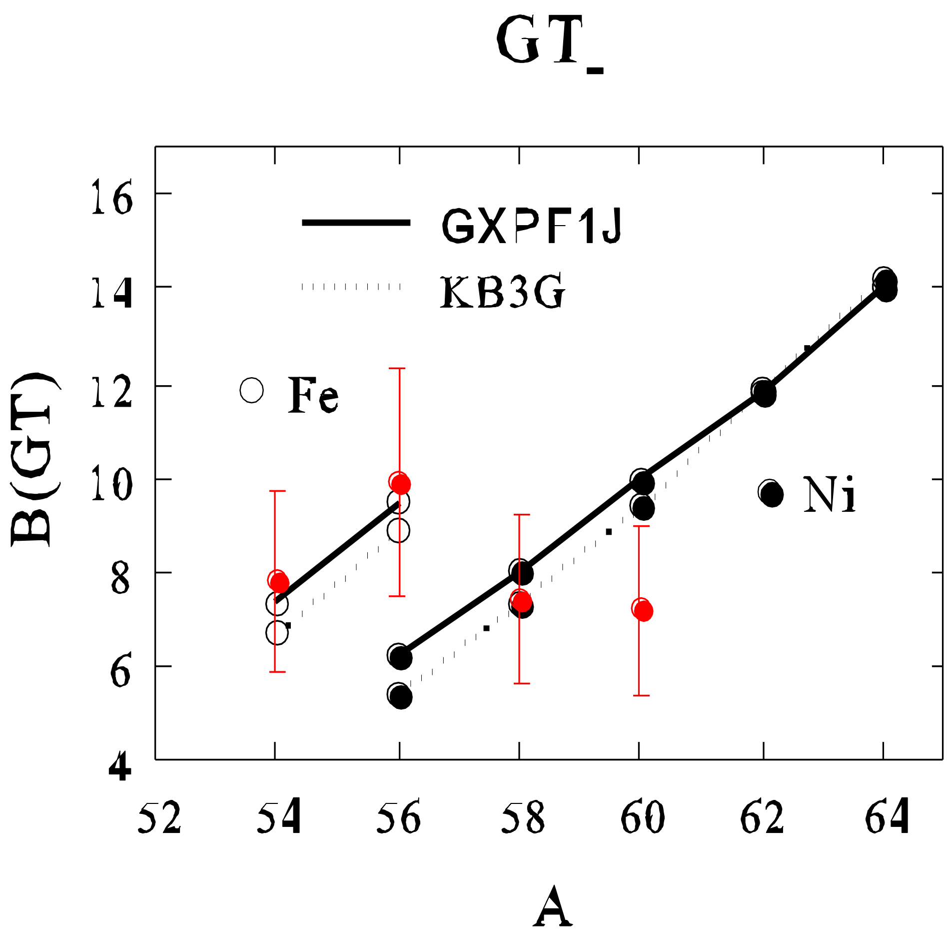
$g_S^{eff}/g_S=0.75\pm0.2$

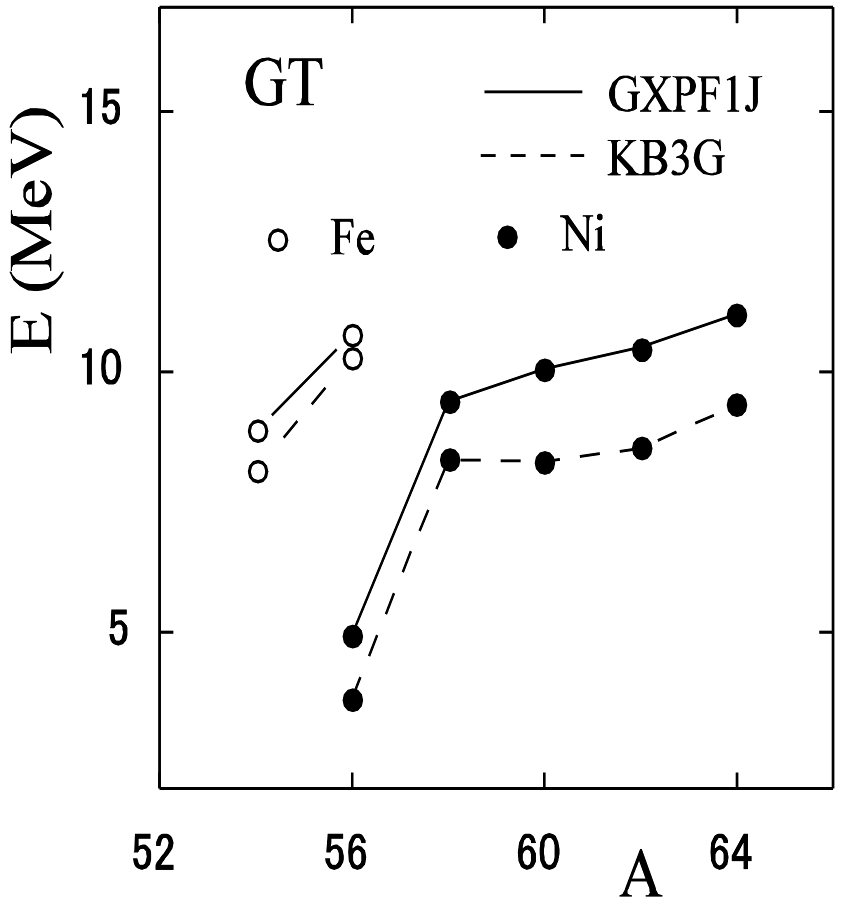
Exp: Fujita et al.





$g_A^{eff}/g_A^{free}=0.74$



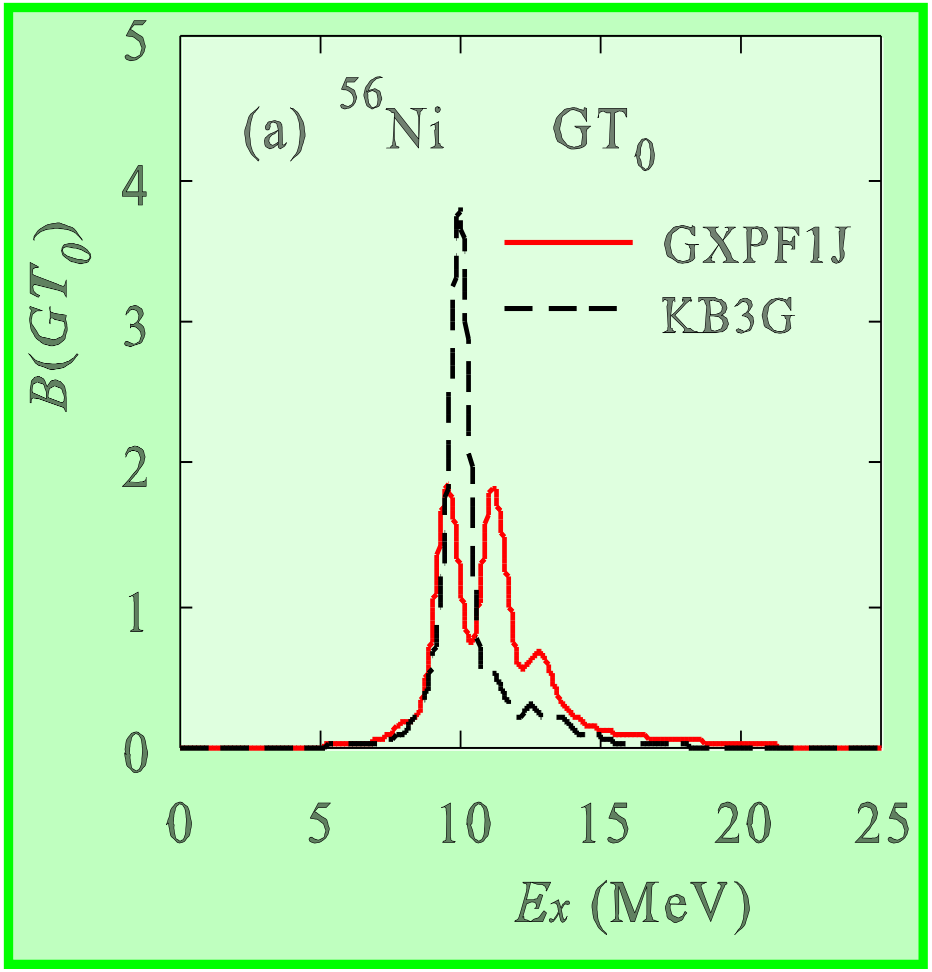


B(GT_+)

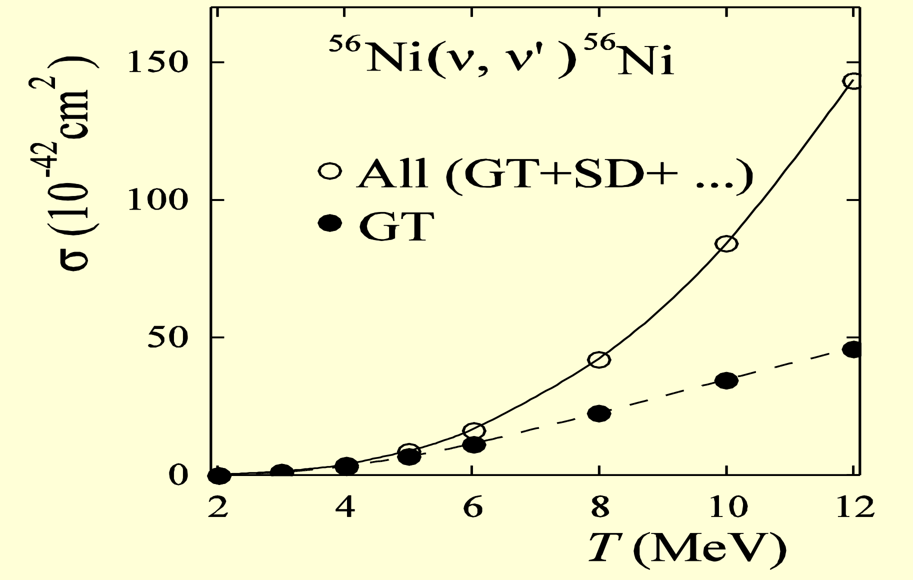
	GXPF1J	EXP.
54Fe	4.0	3.3+/-0.5
56Fe	2.9	2.8+/-0.3
58Ni	4.7	3.8+/-0.4
60Ni	3.4	3.1+/-0.1

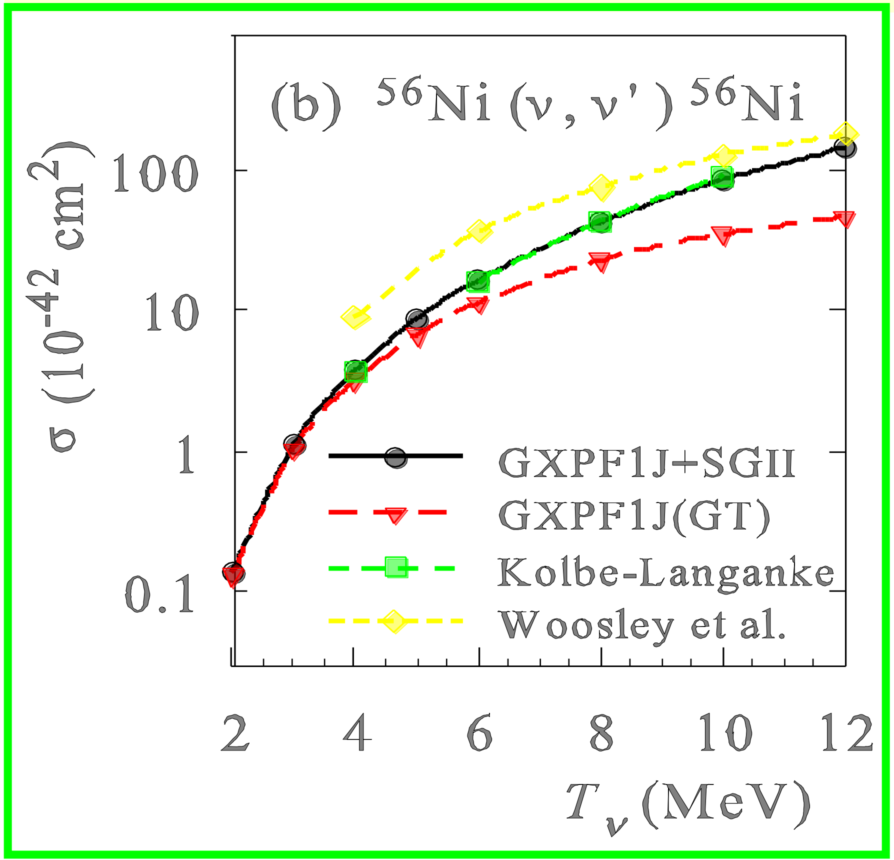
EXP: GT_-; Rapaport et al., NP A410, 371 (1983)
$0<E_x<13\text{-}15$ MeV
GT_+; Caurier et al., NP A653, 439 (1999)
$0<E_x<8$ MeV

Neutral current reaction on ^{56}Ni



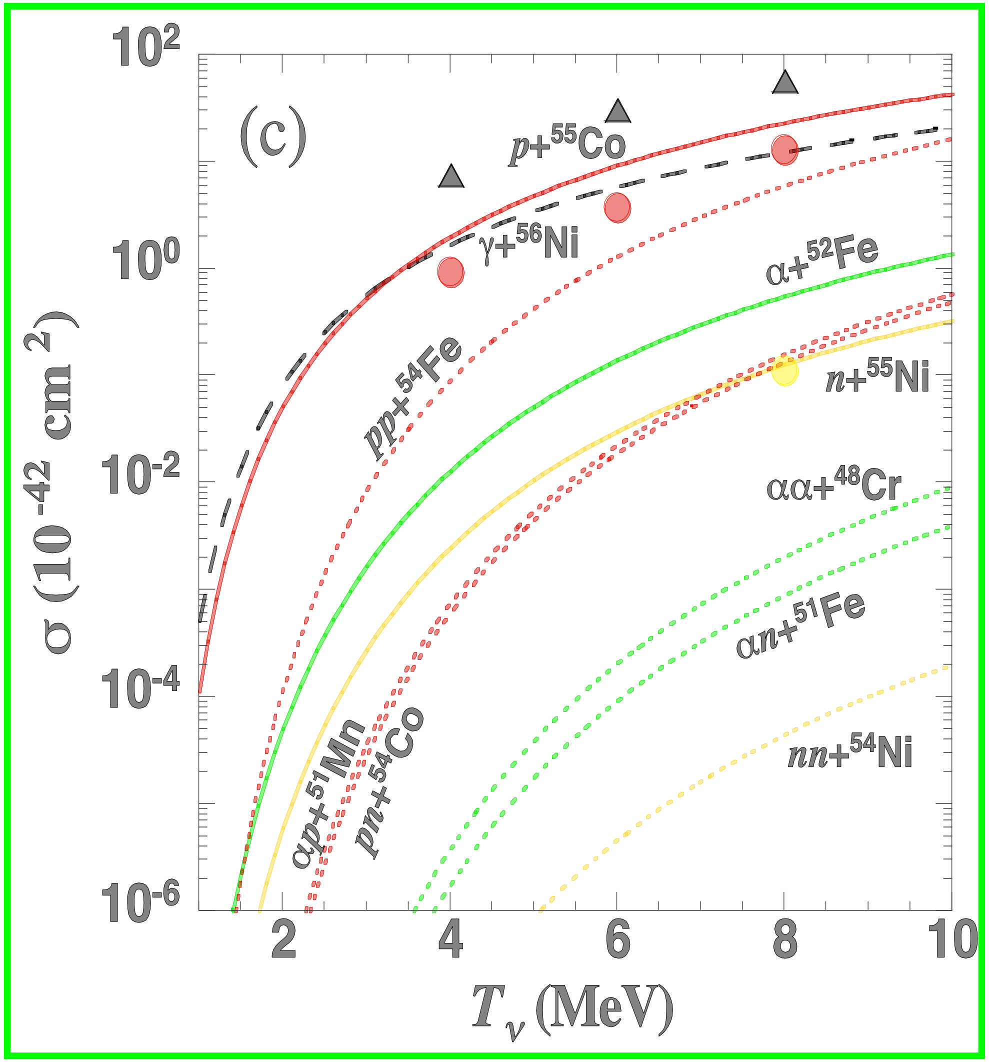
B(GT)=6.2 (5.4) GXPF1J (KB3G)
(7.5 : closed ^{56}Ni core)





Synthesis of Mn in Population III Star

$^{56}\mathrm{Ni}(\nu,\nu'p)^{55}\mathrm{Co}, \quad ^{55}\mathrm{Co}(e^-,\nu)^{55}\mathrm{Fe}(e^-,\nu)^{55}\mathrm{Mn}$

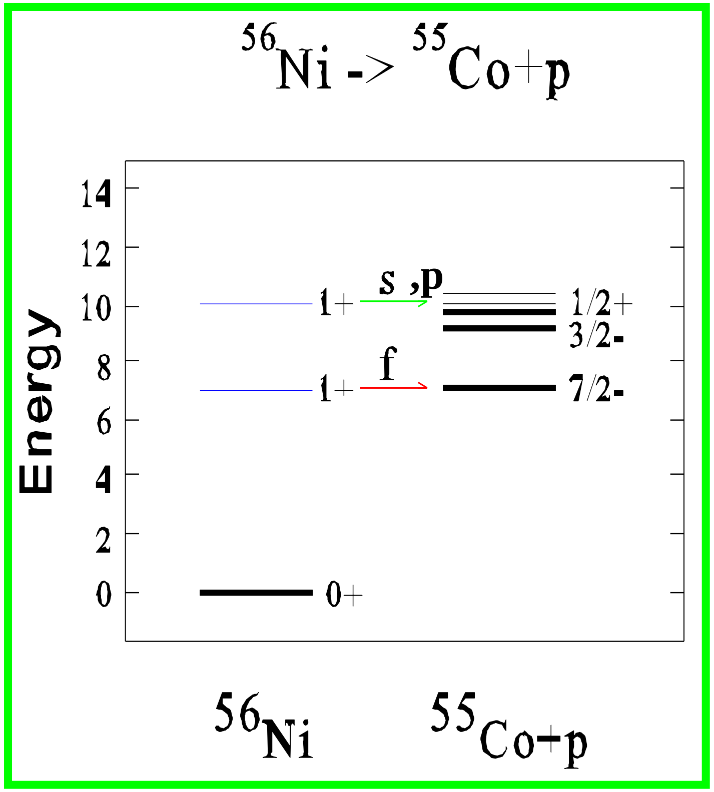


cf: HW02

▲ gamma

● p

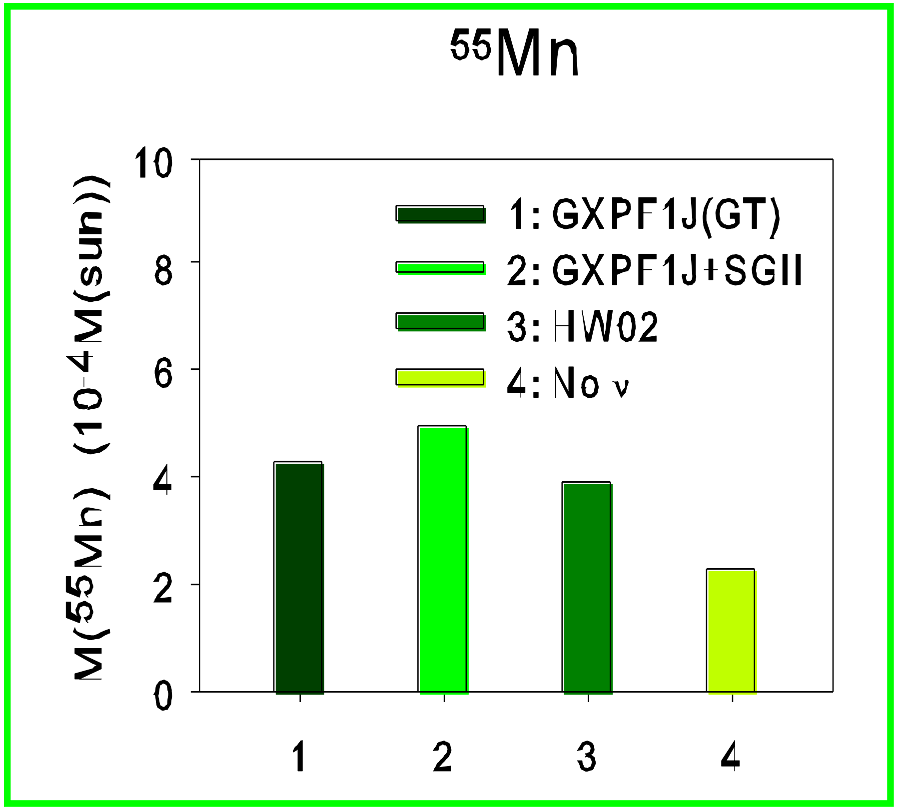
● n

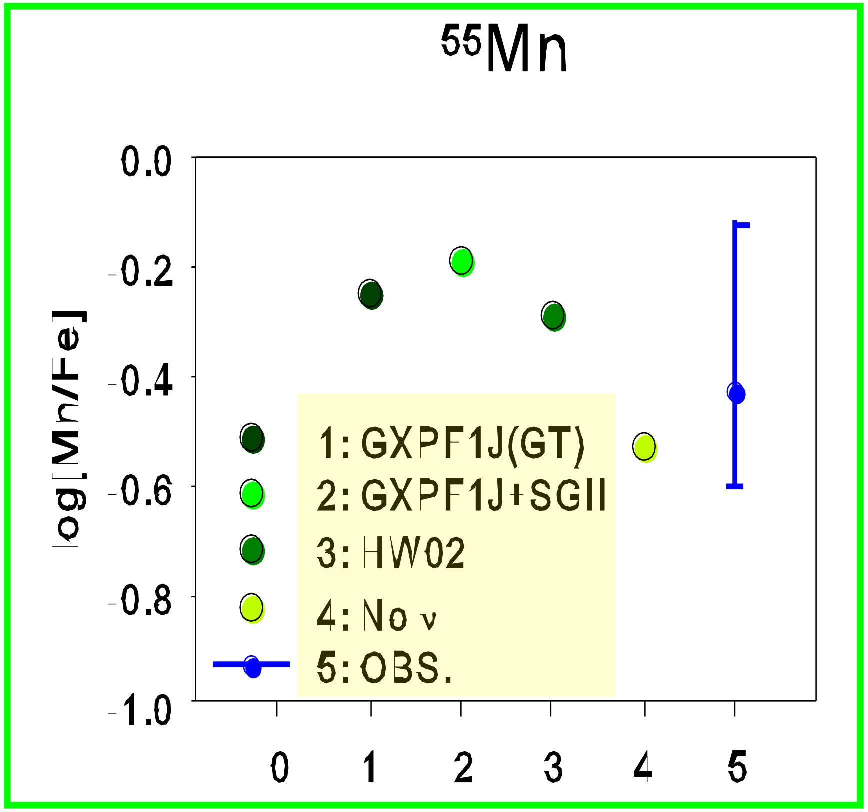


$^{54}\mathrm{Fe}(p,\gamma)^{55}\mathrm{Co}$

Synthesis of Mn in Population III Star

$$^{56}\mathrm{Ni}(\nu,\nu'p)^{55}\mathrm{Co}, \quad ^{55}\mathrm{Co}(e^-,\nu)^{55}\mathrm{Fe}(e^-,\nu)^{55}\mathrm{Mn}$$





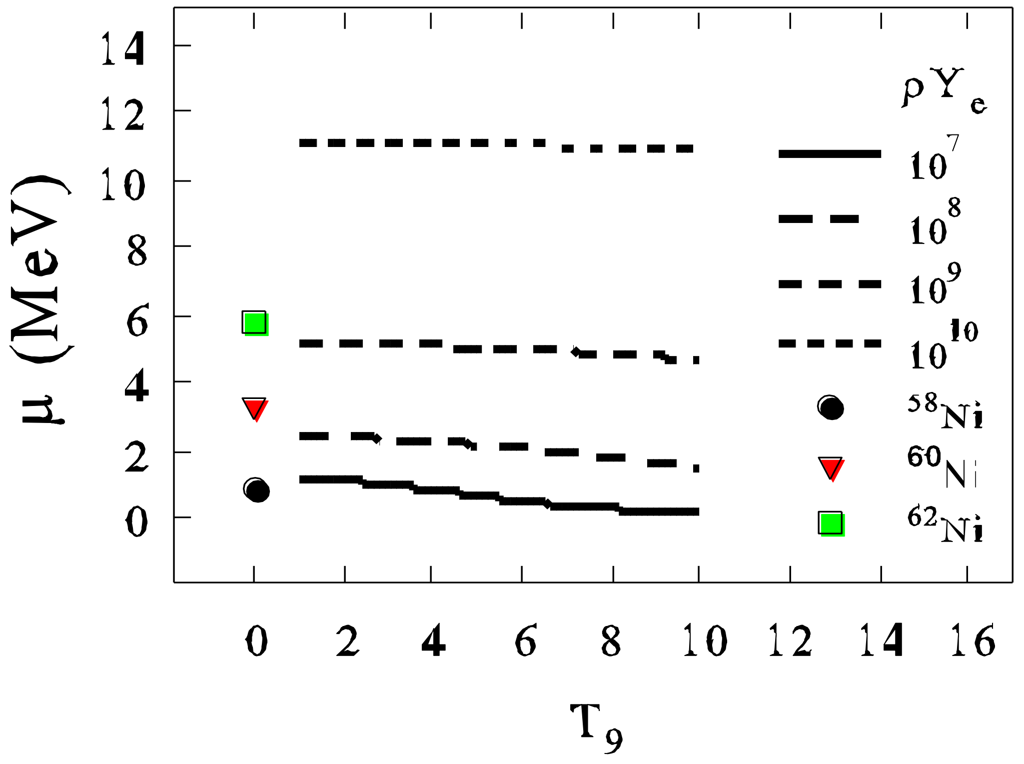
$$^{54}\mathrm{Fe}(p,\gamma)^{55}\mathrm{Co}$$

Yoshida, Umeda,
Nomoto

Suzuki et al.,
PR C79 (2009)

OBS: Cayrel et al.,
Astron. Astrophys.
416 (2004)

●Electron-capture rate in steller environment



$$e^- + {}_Z A \rightarrow \nu + {}_{Z-1}A$$

$$T = 0: \quad \mu + M({}_Z A) \geq M({}_{Z-1}A)$$

$$\mu \geq M({}_{Z-1}A) - M({}_Z A)$$

$\rho Y_e = 10^7$ □ 10^{10} mol/cm^3

$$T = T_9 \times 10^9\,K$$

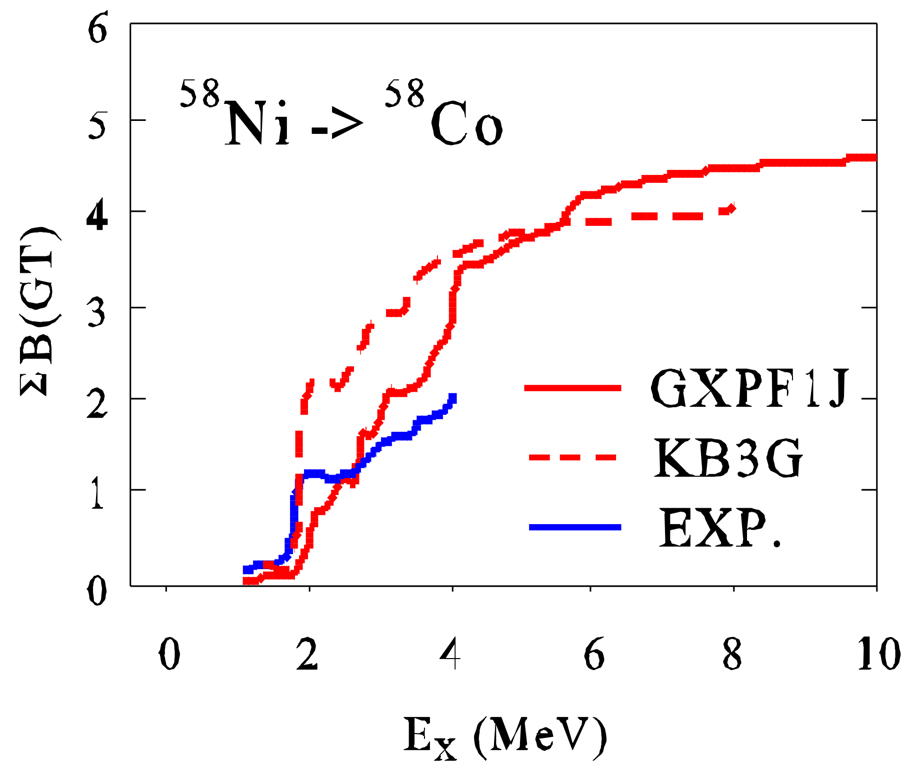
$$\lambda = \frac{\ln 2}{6146(s)} \sum_j B_j(GT) \int_{\omega_e}^{\infty} \omega p (Q_j + \omega)^2 F(Z,\omega) S_e(\omega) d\omega$$

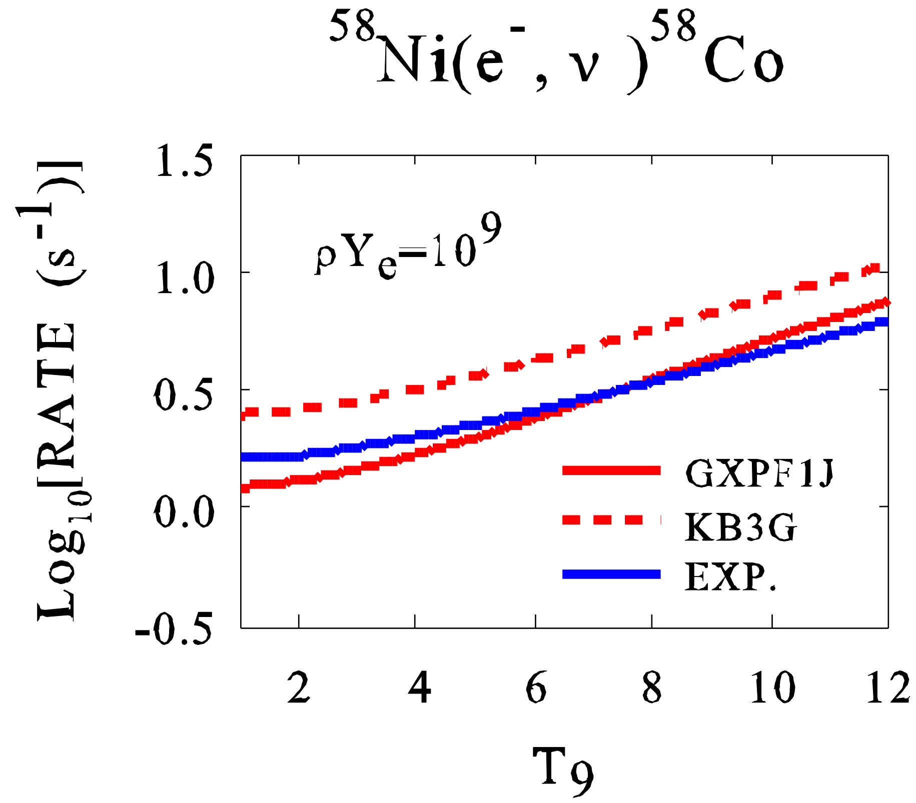
$$Q_j = (M_p c^2 - M_d c^2 - E_j) / m_e c^2$$

$$T = T_9 \times 10^9 K, \qquad S_e(E_e) = \frac{1}{\exp[(E_e - \mu_e)/kT] + 1}$$

$$\rho Y_e = \frac{1}{\pi^2 N_A} \left(\frac{m_e c}{\hbar}\right)^3 \int_0^\infty (S_e - S_p) p^2 dp \qquad \mu_p = -\mu_e$$

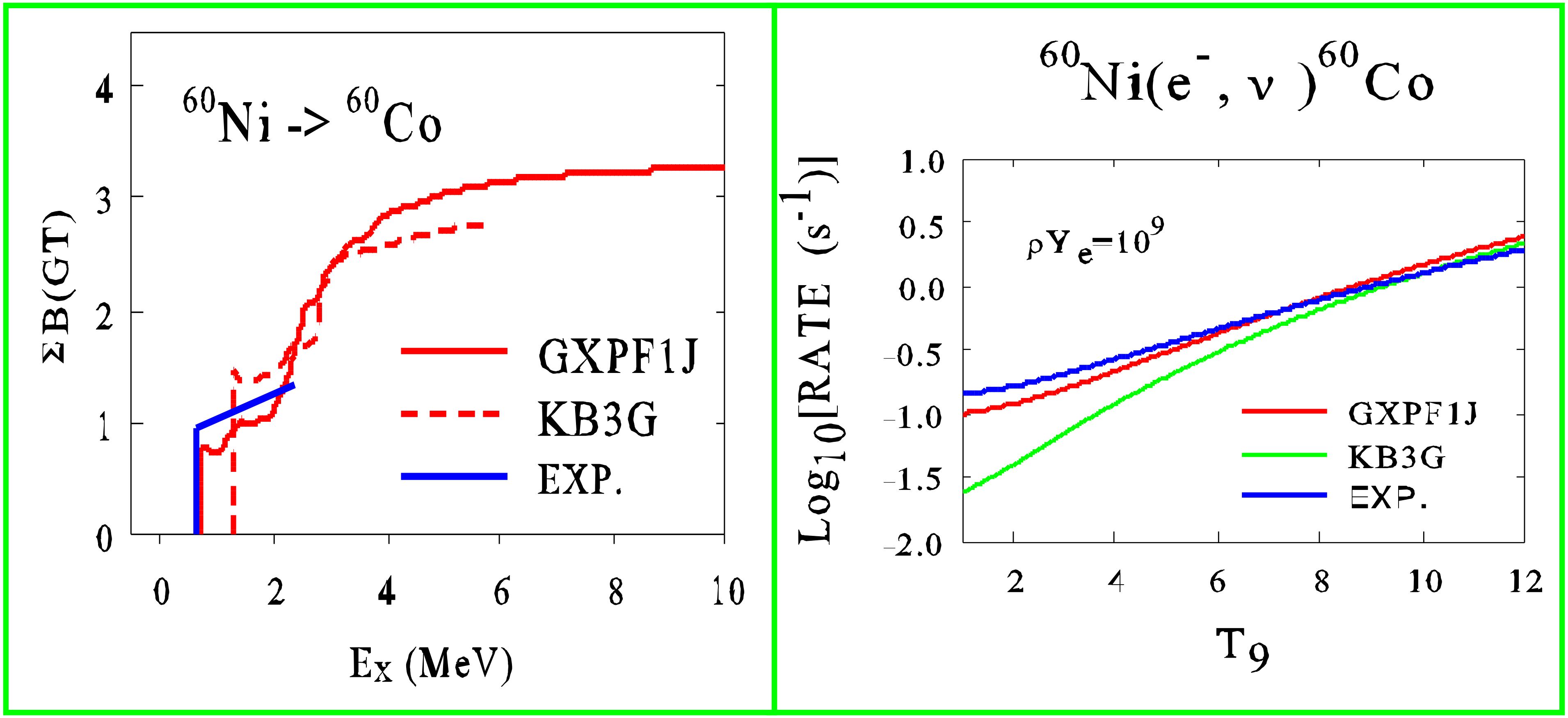
^{58}Ni -> ^{58}Co





Exp: Hagemann et al., PL B579 (2004)

^{60}Ni

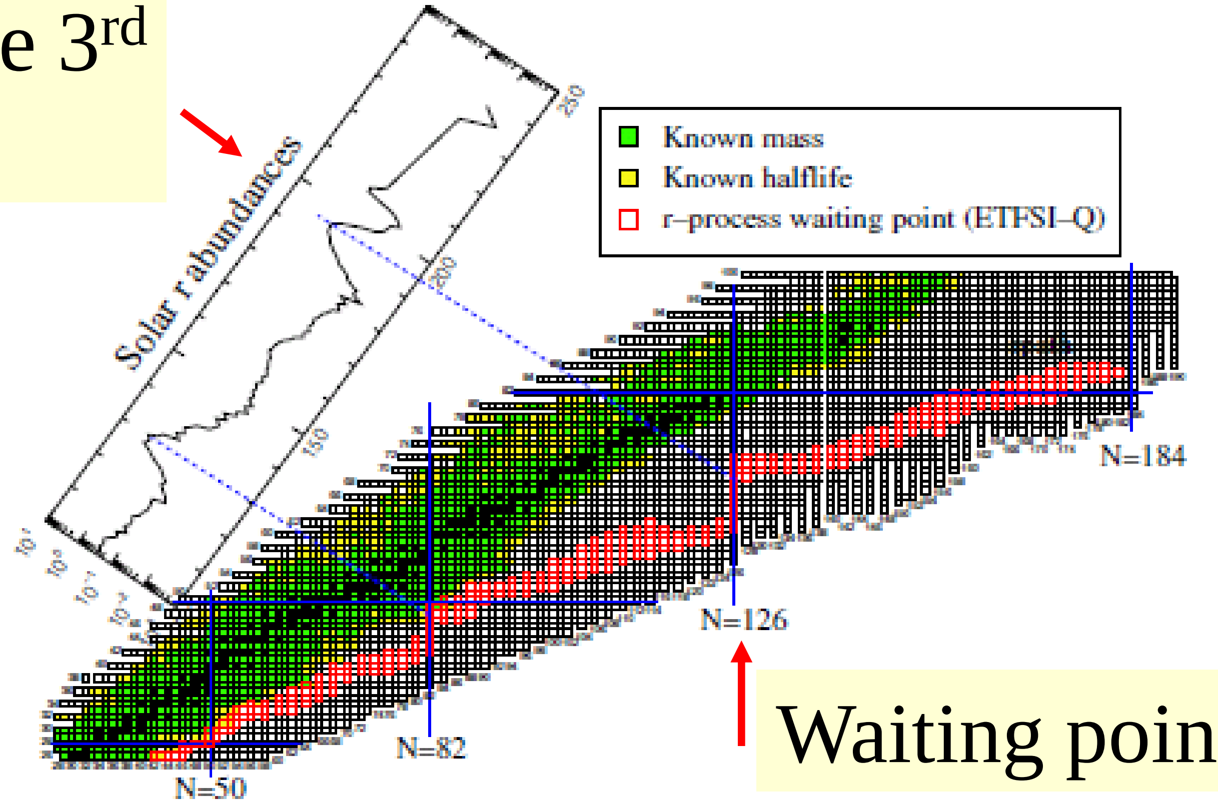


Exp:
Anantaraman et al.,
PR C78 (2008)

3. R-Process Nucleosynthesis and Beta Decays of N=126 Isotones

H Grawe *et al*

Focus on the 3rd peak region



Waiting point nuclei

Figure 18. The figure shows the range of r-process paths, defined by their waiting point nuclei. After decay to stability the abundance of the r-process progenitors produce the observed solar r-process abundance distribution. The r-process paths run generally through neutron-rich nuclei with experimentally unknown masses and half lives. In this calculation a mass formula based on the ETFSI model and special treatment of shell quenching [79] has been adopted (courtesy of Kratz and Schatz).

Beta Decays of N=126 Isotones

Z=64-72 (A=190-198): proton-hole states of 208Pb

- Shell-model calculations:

  Kuo-Herling G + mod. Steer et al., PR C78, 061302 (2008)
  Ryndstrom et al., NP A512, 217 (1990)

  Energy levels of Z=77-81 nuclei well described

- GT (1^+) + FF (first-forbidden: 0-, 1-, 2-) transitions

$$O(1^+) = g_A \sigma t_-$$

$$O(0^-) = g_A [\frac{\sigma \cdot p}{m} + \frac{\alpha Z}{2R} i\sigma \cdot r] t_-$$

$$O(1^-) = [g_V \frac{p}{m} - \frac{\alpha Z}{2R} (g_A \sigma x r - i g_V r] t_-$$

$$O(2^-) = i \frac{g_A}{\sqrt{3}} [\sigma x r]^2_\mu \sqrt{p_e^2 + q_\nu^2}\, t_-$$

$$\Lambda(s^{-1}) = \ln 2 / t = f / 8896(s)$$

$$f = \int_1^{w_0} C(w) F(Z,w) p w (w_0 - w)^2 dw$$

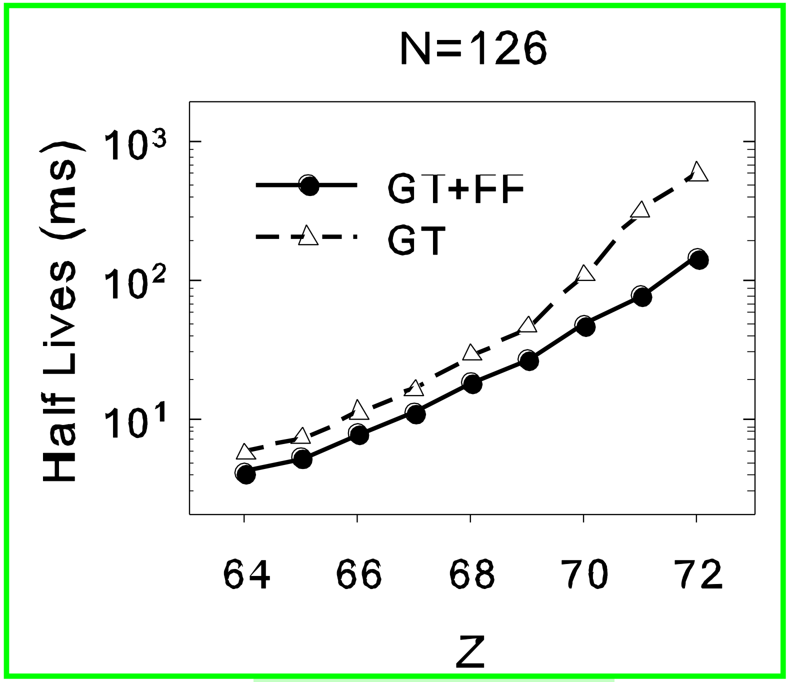
$$C(w) = K_0 + K_1 w + K_{-1} / w + K_2 w^2$$

$$K_N : \quad \vec{r}, \quad [\vec{r} \times \vec{\sigma}]^\lambda \quad (\lambda = 0,1,2)$$

$$\gamma_5, \quad \vec{\alpha}$$

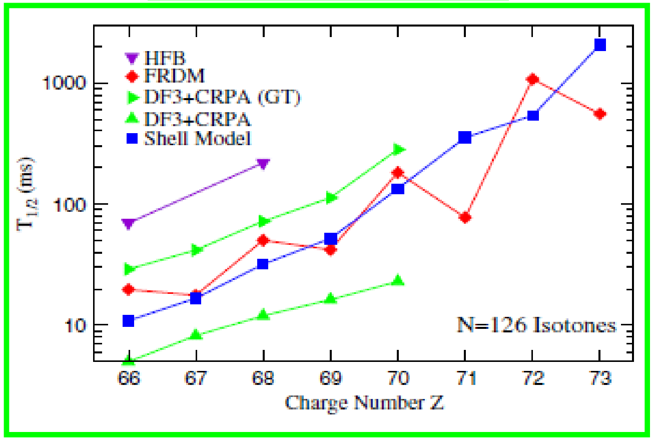
Warburton et al., Ann.Phys. 187 (1988)

Half-Lives of N=126 Isotones



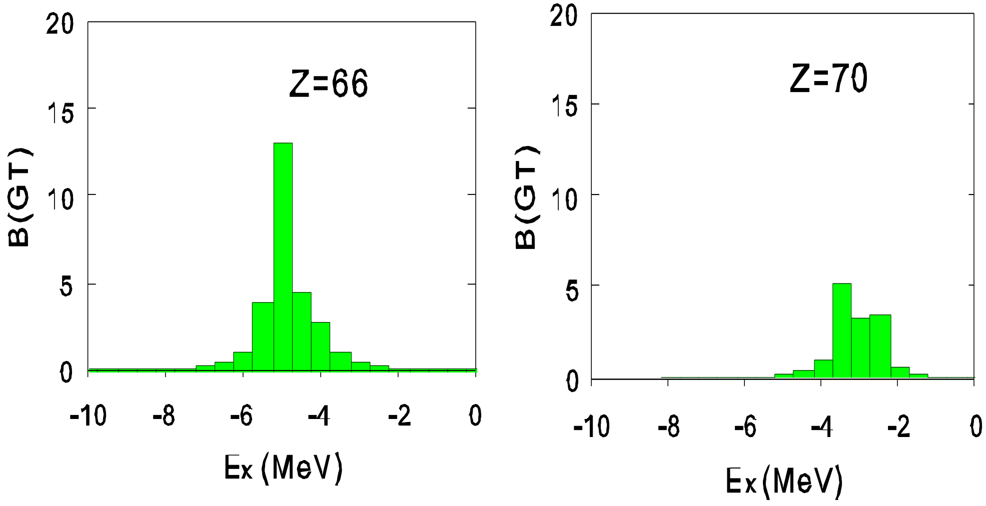
$Q=g_A^{eff}/g_A=0.7$

cf.

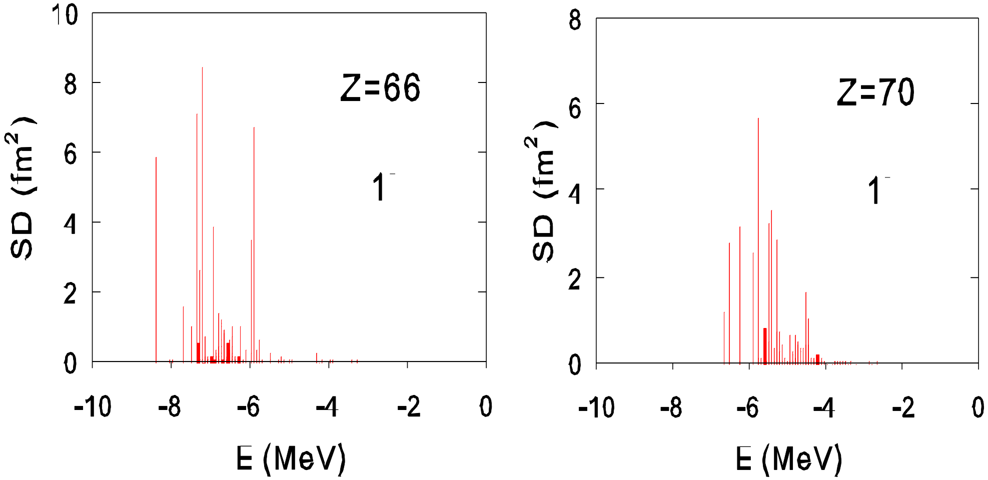


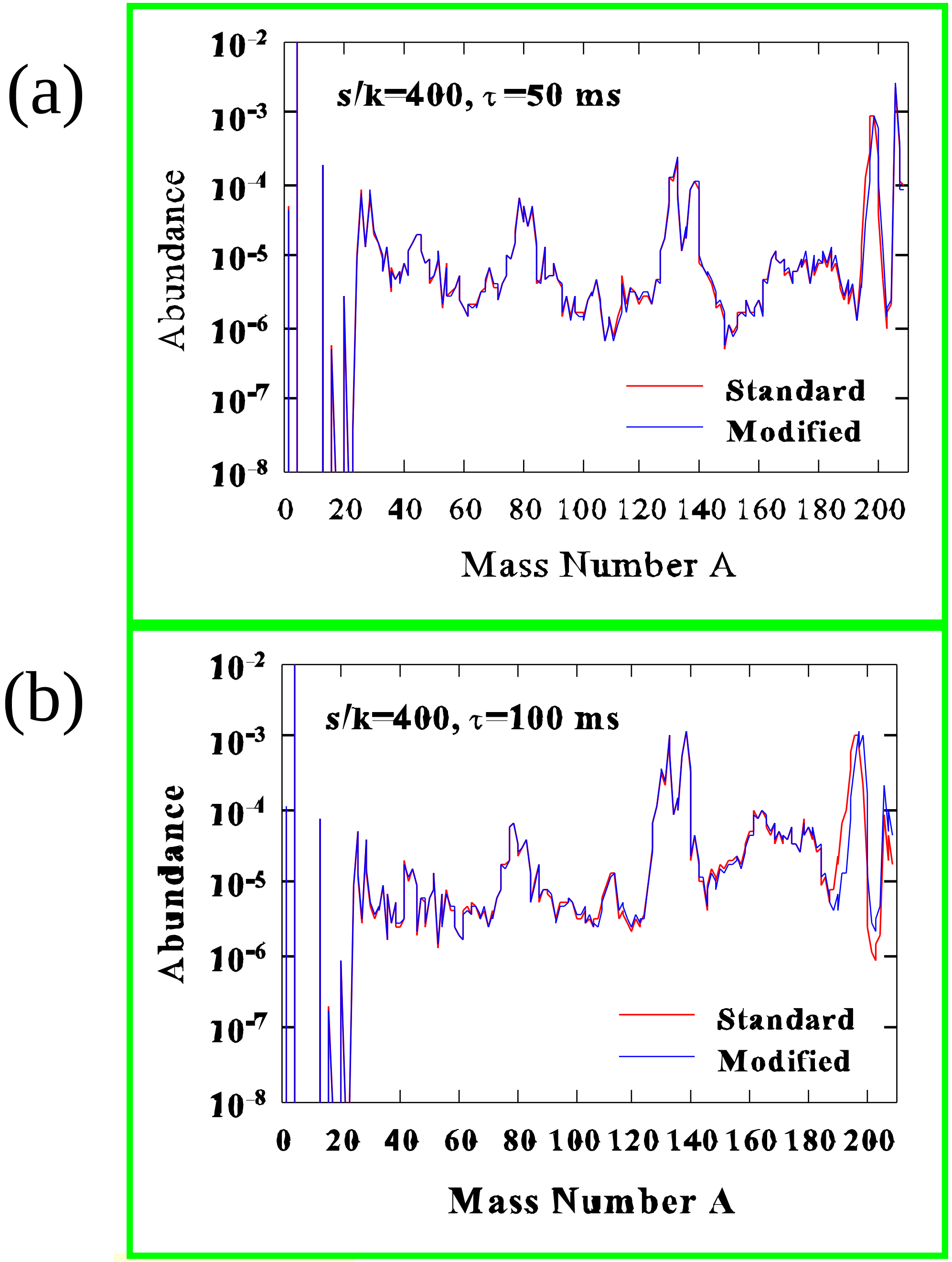
Grawe, Langanke, Martinez-Pinedo,
RPP 70, 1525 (2007)

GT strengths



SD (1^-) strengths





Yoshida

r-process nucleosynthesis

Constant Entropy Wind Model

$M_{NS}=2.0M_{sun}$

$R_{NS}=10$ km

$S=400\ k_B\ (\gamma, e^-, e^+)$

$dm/dt=1.1\times10^{-6}\ M_{sun}$

$T_9=(T_{09}-T_{\alpha 9})\exp(-t/\tau)+T_{\alpha 9}$

$T_{09}=9,\ \ T_{\alpha 9}=1$

$Y_{e\_ini}=0.40$

(a) $\tau= 0.05$ s

(b) $\tau=0.10$ s

Half-lives:

🟥 Standard (Moller et al.)

🟩 Modified

Summary

- **New shell model Hamiltonians → new ν-nucleus reaction cross sections → enhancement of production rate of ^{7}Li, ^{11}B and ^{55}Mn.**
- **Electron capture rates in ^{58}Ni and ^{60}Ni are well described by a new shell model Hamiltonian, GXPF1J.**
- **Capture rates in odd-odd Co isotopes (^{56}Co, ^{58}Co and ^{60}Co) evaluated by shell model calculations with GXPF1J remain smaller than FFN, while they are enhanced in ^{60}Co compared to those obtained by KB3.**
- **Shell model calculations for beta-decay half-lives including both GT and FF transitions lead to short half-lives for beta decays of N=126 isotones.**
- **→ A slight shift of the 3rd peak of the r-process element abundances toward larger mass number region.**

Collaborators

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