Spin-dependent Nuclear Weak Processes and Nucleosynthesis in Stars

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ERICE

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(1) ν-nucleus reactions in supernova explosions

- **Synthesis of ^{7}Li, ^{11}B, and ^{55}Mn by neutrino processes in stars**

(2) e-capture reactions in steller core-collapse processes

- **e-capture on Ni and Co isotopes in steller environments**

(3) Beta decay of N=126 isotones

- **Synthesis of elements in the r-process around its third peak**

● **Shell model calculations with the use of new shell model Hamiltonians in *p*-shell (SFO) and *fp*-shell (GXPF1), which give successful description of spin responses in nuclei**

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

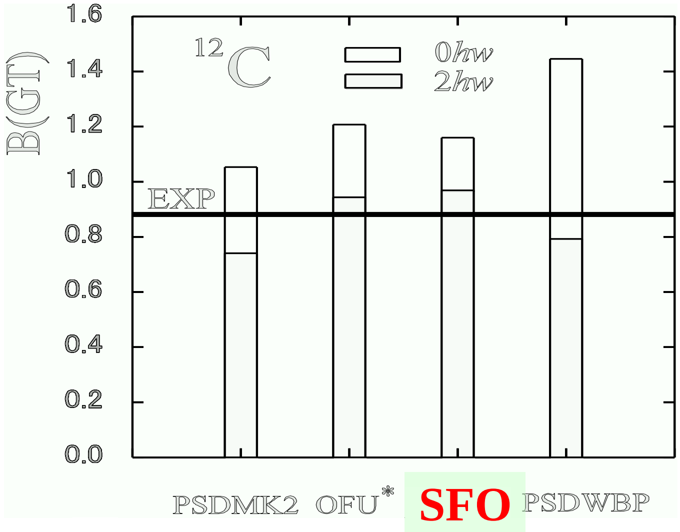
p-shell（p-sd） Cohen-Kurath+Millener-Kurath → SFO

Monopole terms in p1/2-p3/2 , T=0 enhanced：ΔV = -1.9 MeV

SFO: Suzuki, Fujimoto, Otsuka, PR C67, 044302 (2003)

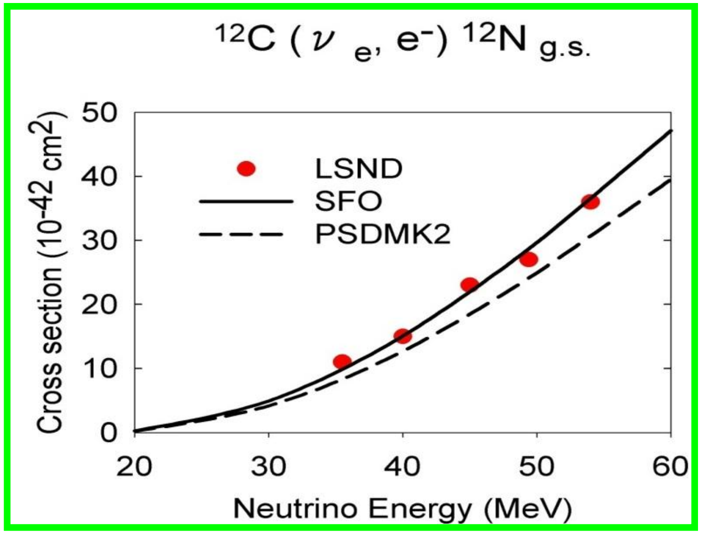
$$V_M^T(j_1 j_2) = \frac{\sum_J (2J+1) < j_1 j_2 ; JT \mid V \mid j_1 j_2 ; JT >}{\sum_J (2J+1)}$$

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



^{12}C -> ^{12}N

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



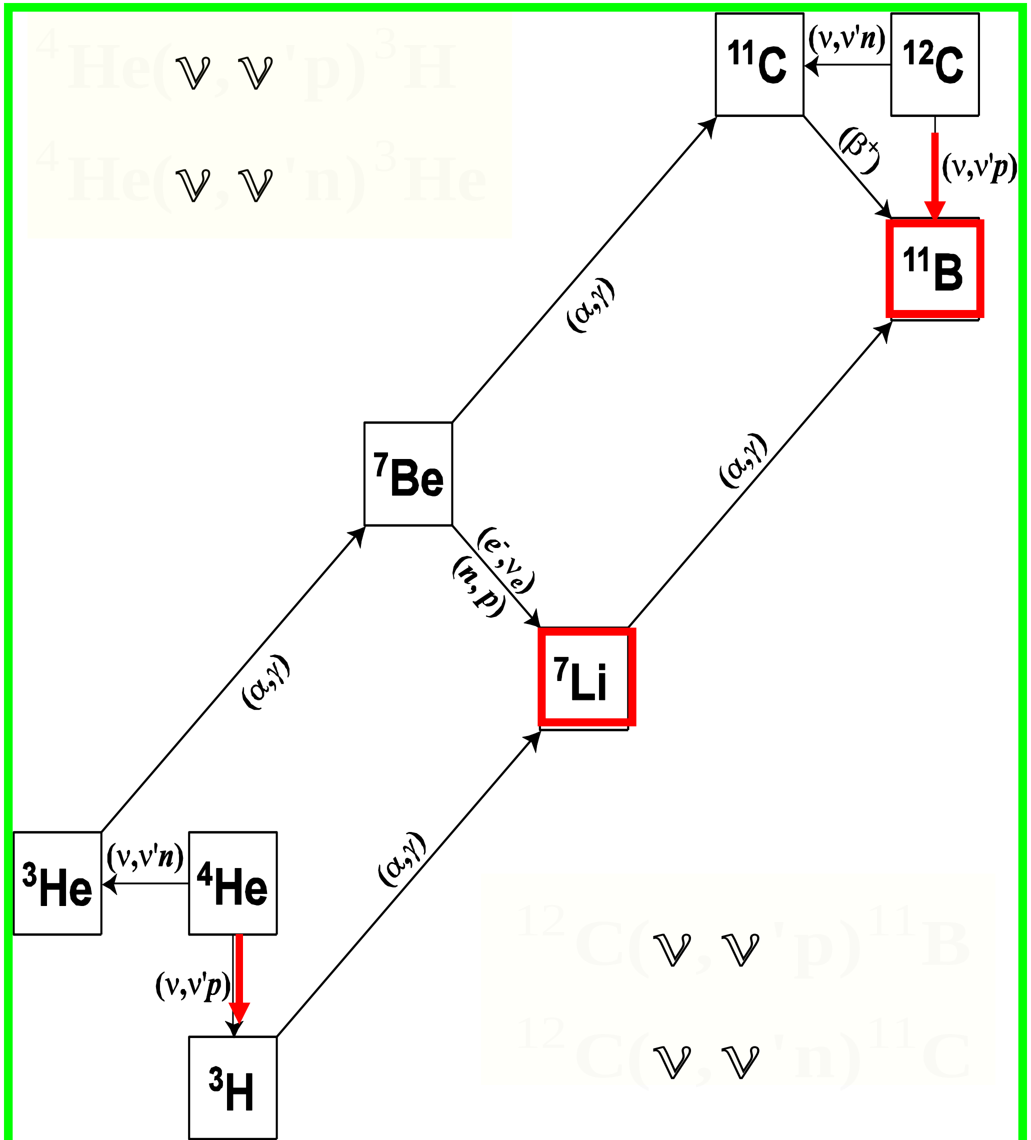
SFO*: g_A^{eff}/g_A=0.95
B(GT: ^{12}C)_cal = experiment

Space: up to 2-3 hw

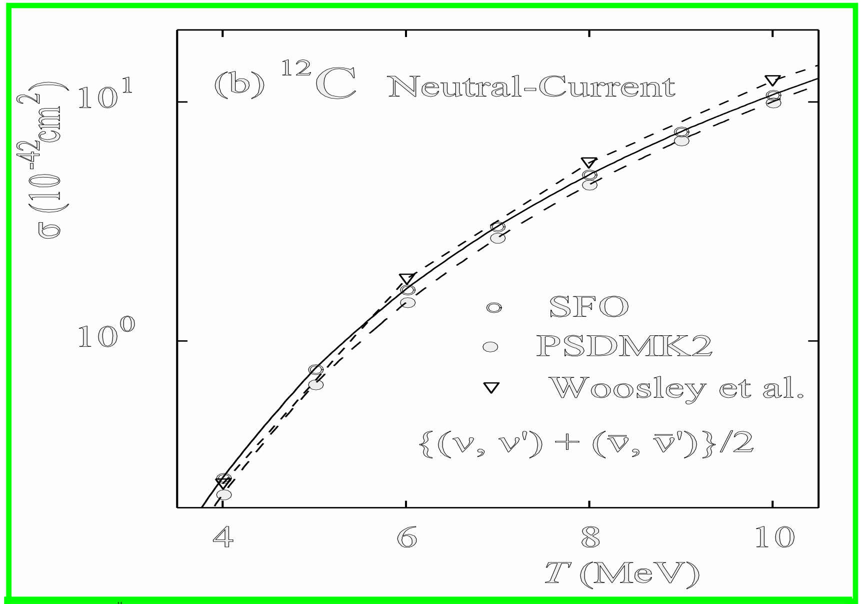
Suzuki, Chiba, Yoshida,Kajino, Otsuka, PR C74, 034307, (2006).

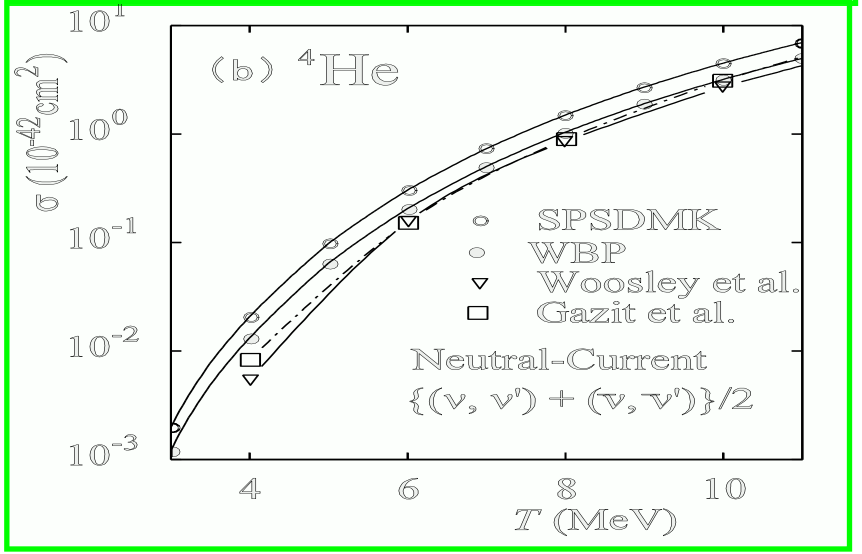
Nucleosynthesis processes of light elements

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



Cross sections for Supernova Neutrinos with temperature T





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

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

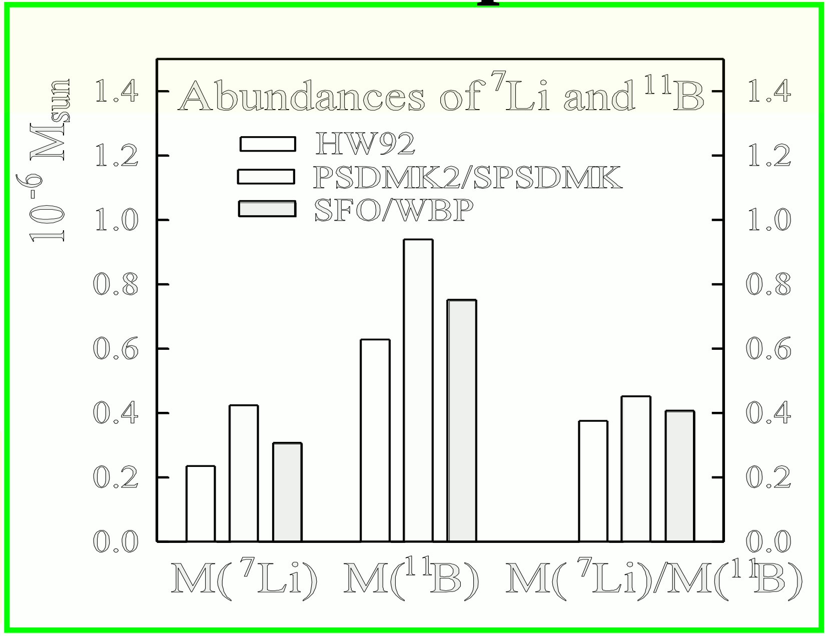
$T_{\nu_e}=3.2\ MeV,\ \ T_{\bar{\nu}_e}=5.0\ MeV,\ \ T_{\nu_\mu,\nu_\tau}=6.0\ MeV$

No oscillation case

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

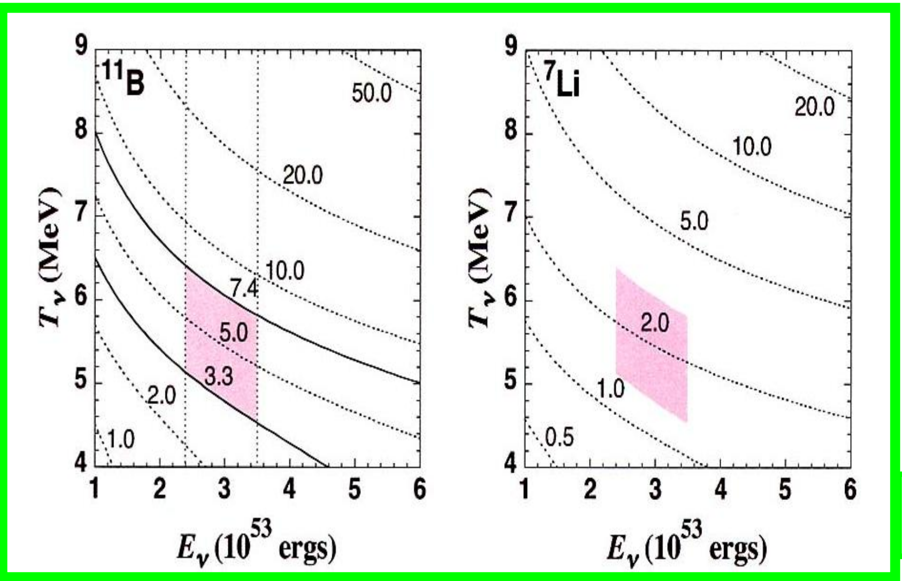
$\nu=\nu_{\mu,\tau},\bar{\nu}_{\mu,\tau}$

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



- Constraints on neutrino temperatures

SN contributions in GCE: $3.3\mathrm{x}10^{-7}\,\mathrm{M}_{\odot} \le \mathrm{M}(^{11}\mathrm{B}) \le 7.4\mathrm{x}10^{-7}\,\mathrm{M}_{\odot}$



WBP+SFO

$4.5\ \ \mathrm{MeV} \le \mathrm{T}_{\nu_{\mu,\tau}} \le 6.4\ \ \mathrm{MeV}$ WBP+SFO

$4.4\ \ \mathrm{MeV} \le \mathrm{T}_{\nu_{\mu,\tau}} \le 6.1\ \ \mathrm{MeV}$ SPSDMK+PSDMK2

cf. $4.8\ \ \mathrm{MeV} \le \mathrm{T}_{\nu_{\mu,\tau}} \le 6.6\ \ \mathrm{MeV}$

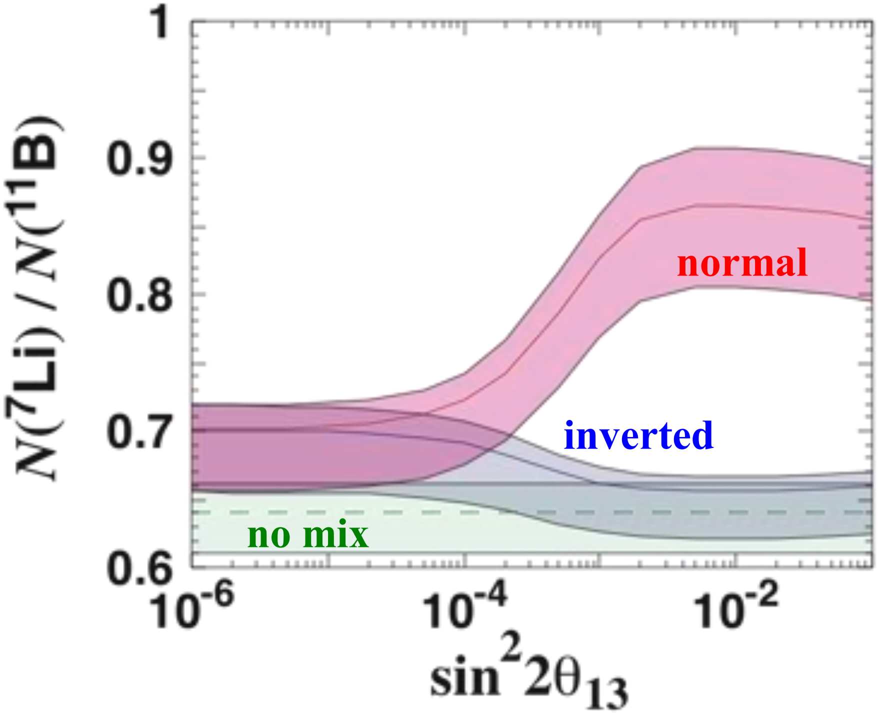
Yoshida, Kajino, Hartmann,
PRL 94 (2005)

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}.

Cf. Neutrino experiments

→ Constraining ***upper limit*** *of* θ_{13}

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**

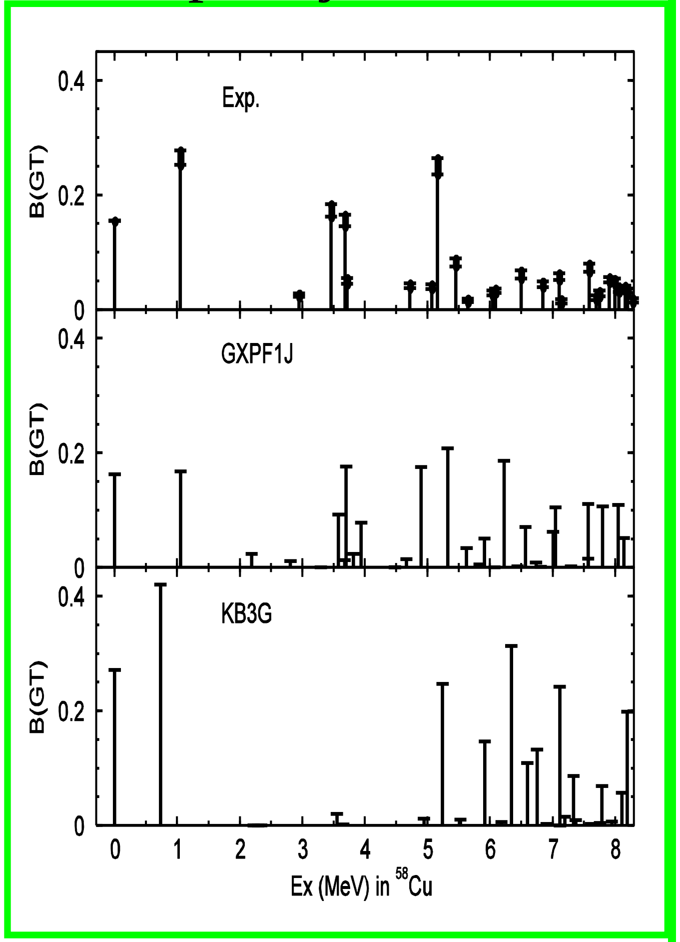
fp-shell
B(GT) for 58Ni

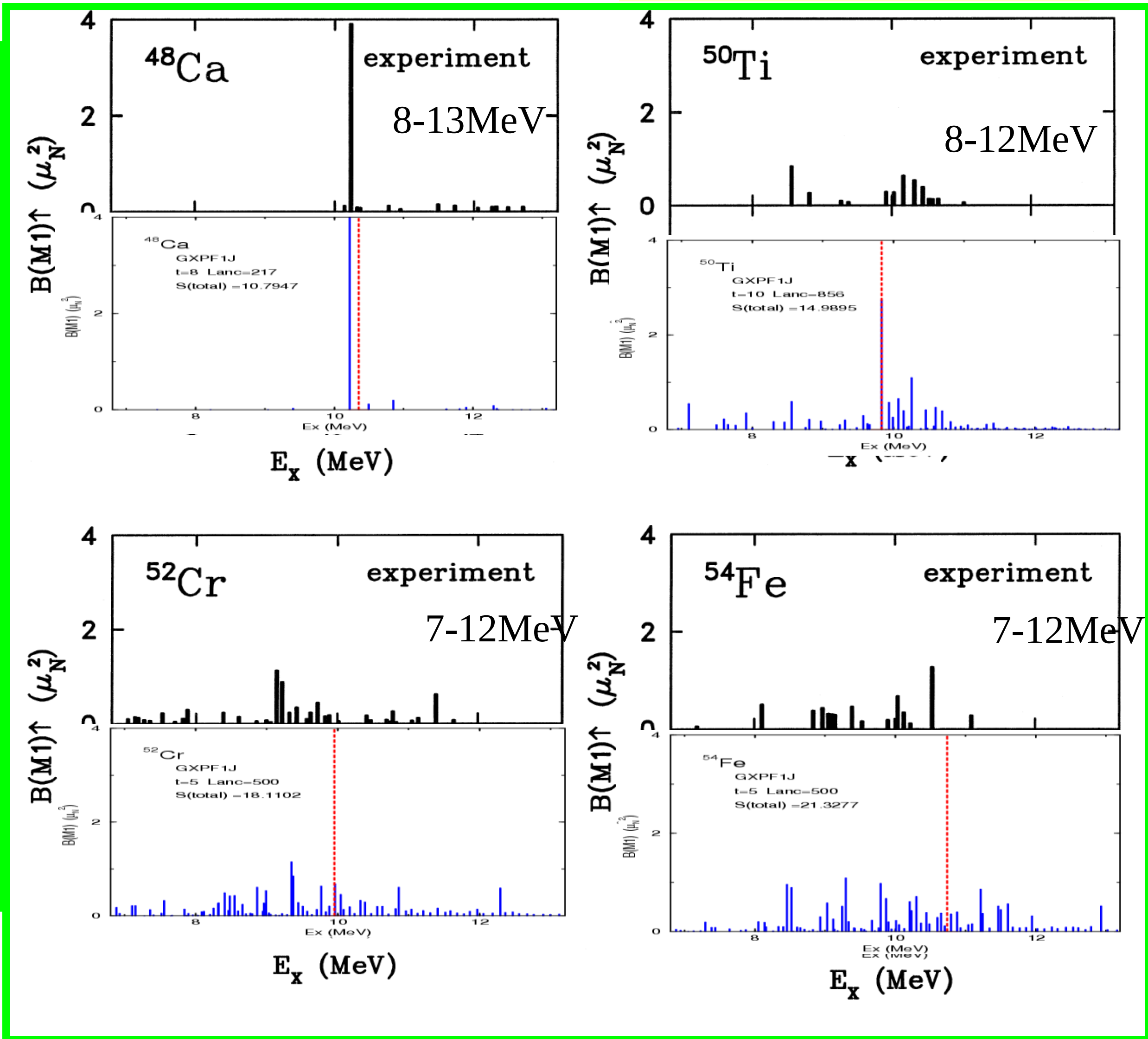
M1 strength (GXPF1J)

Honma

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

Exp: Fujita et al.



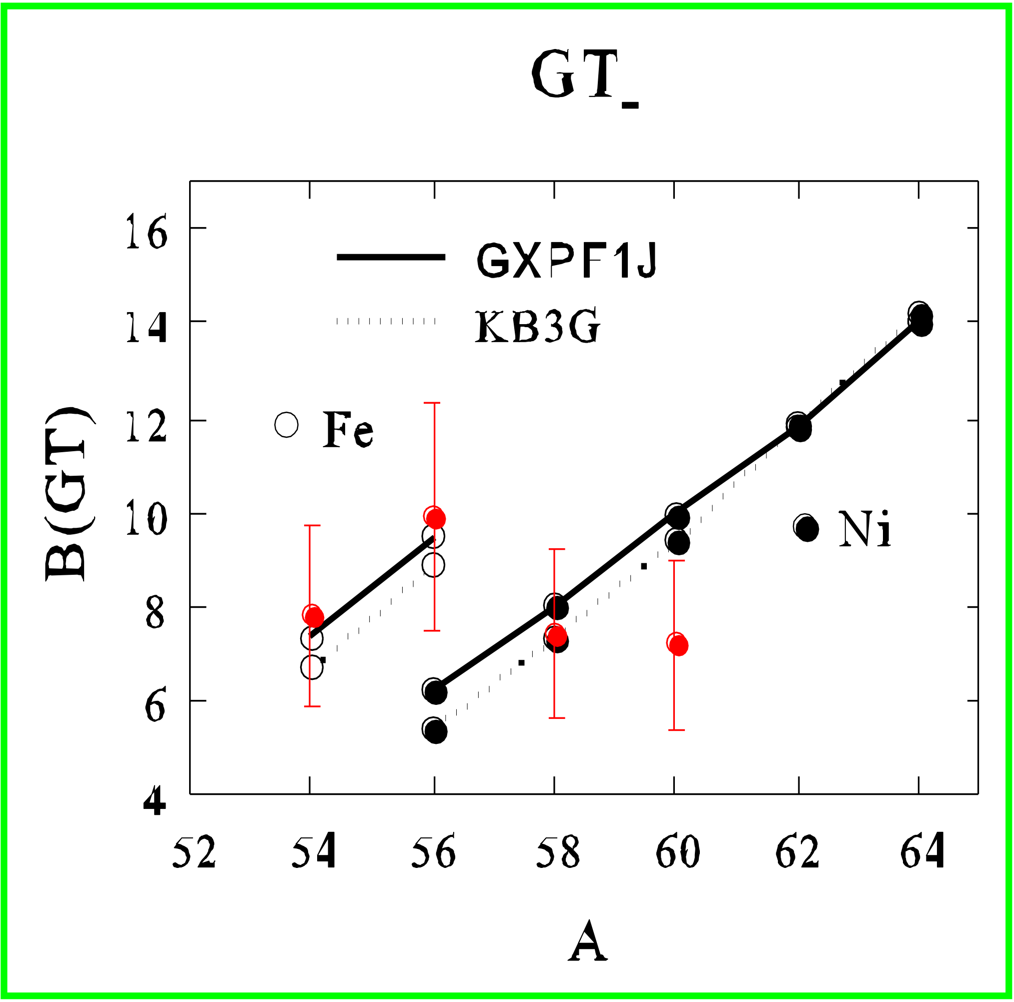

8-13MeV

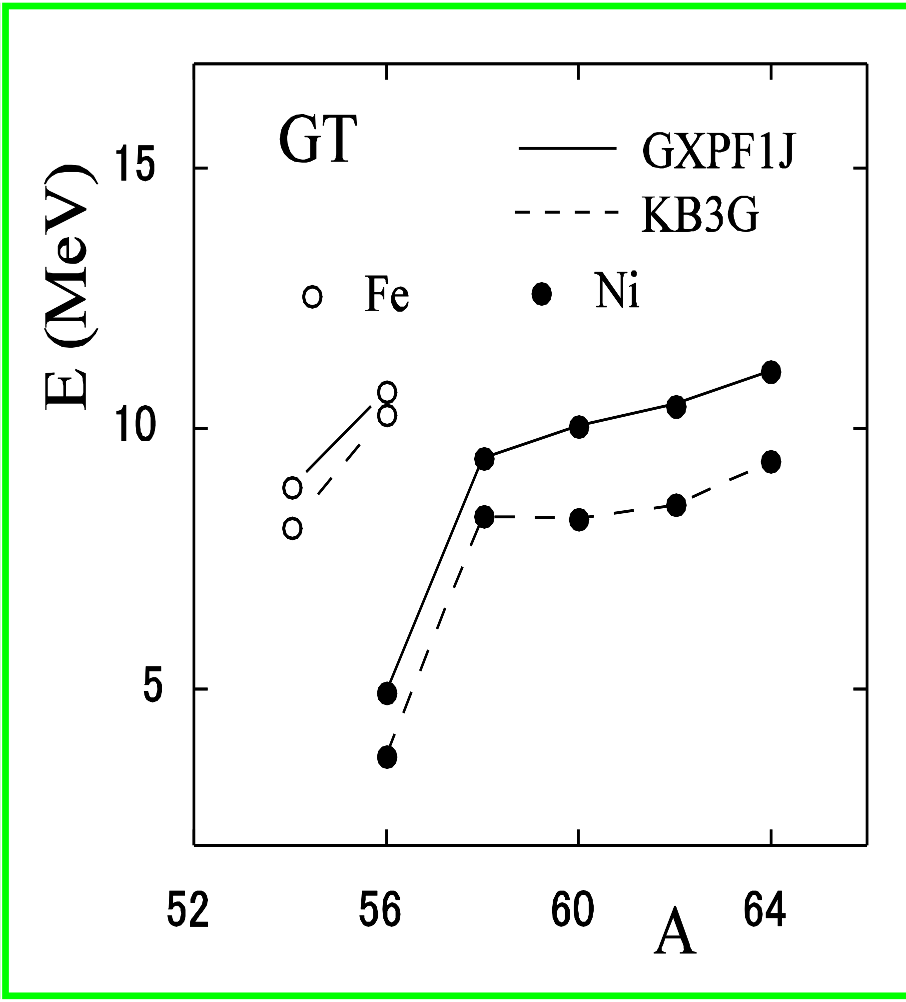
8-12MeV

7-12MeV

7-12MeV

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





B(GT_+)

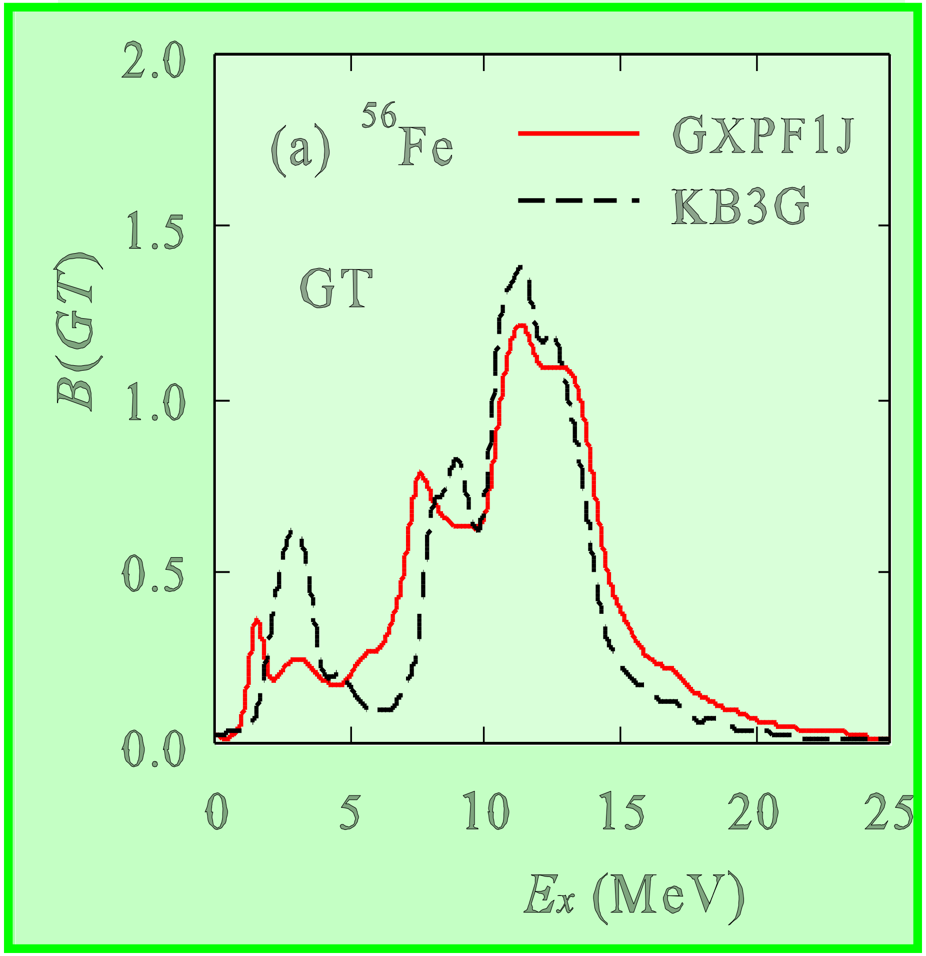
	GXPF1J	EXP.
54Fe	4.0	3.3+/-0.5
56Fe	2.9	2.8+/-0.3
58Ni	4.7	3.8+/-0.4
60Ni	3.4	3.1+/-0.1

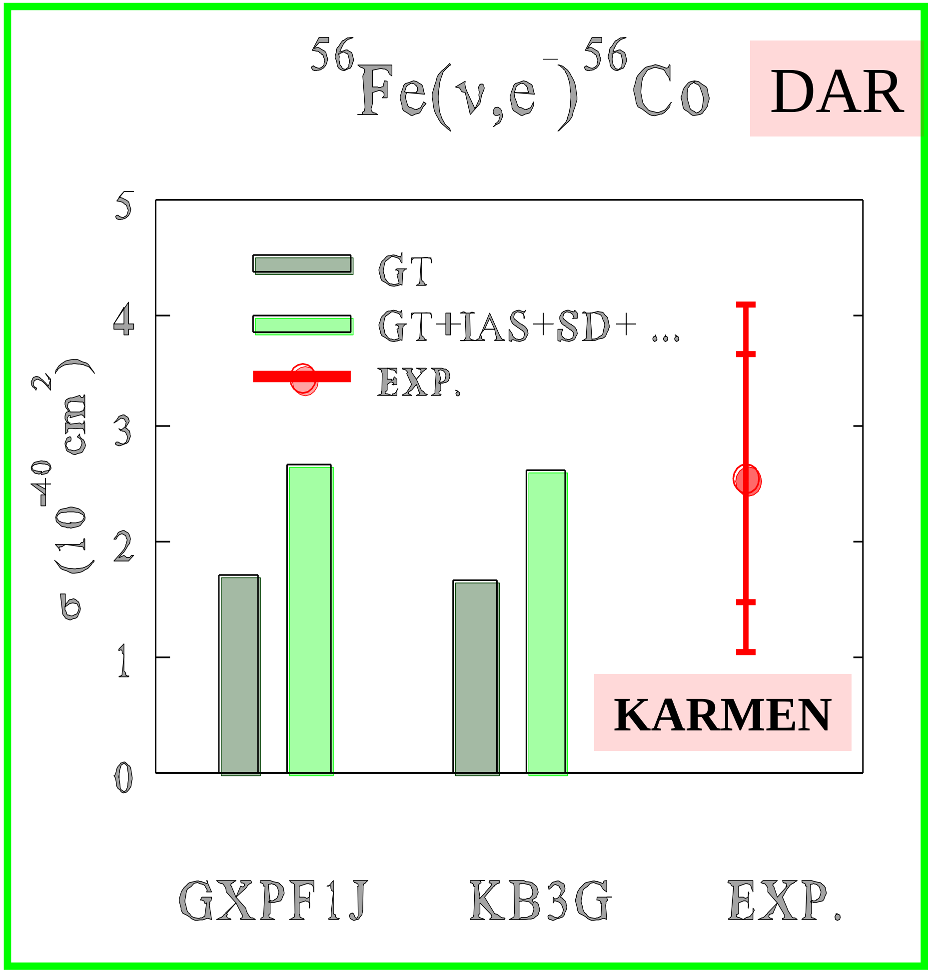
EXP: GT_-; Rapaport et al., NP A410, 371 (1983)
$0<E_x<13\text{-}15$ MeV
GT_+; Caurier et al., NP A653, 439 (1999)
$0<E_x<8$ MeV

^{56}Fe(ν_e, e$^-$)^{56}Co

GXPF1J Honma et al.

cf. KB3 Caurier et al.





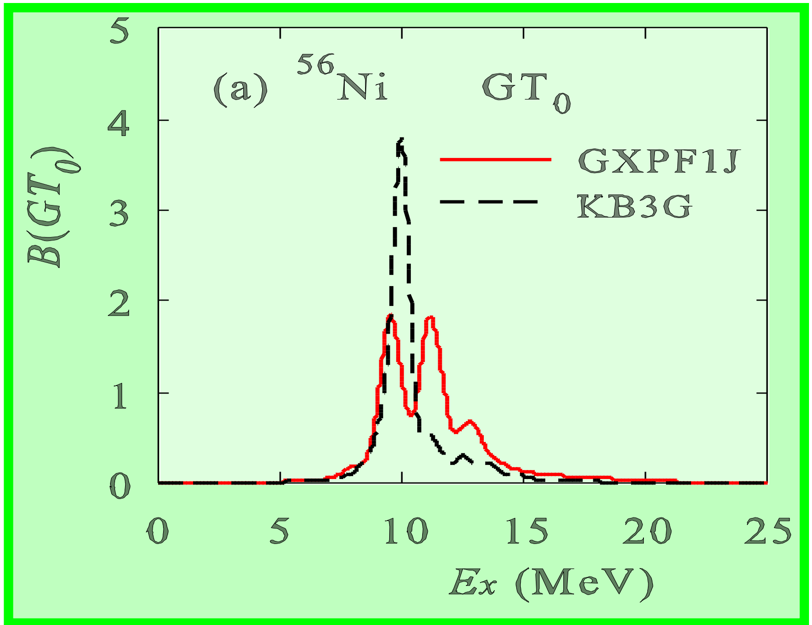
$B(GT)=9.5$

$B(GT)_{exp}=9.9\pm2.4$

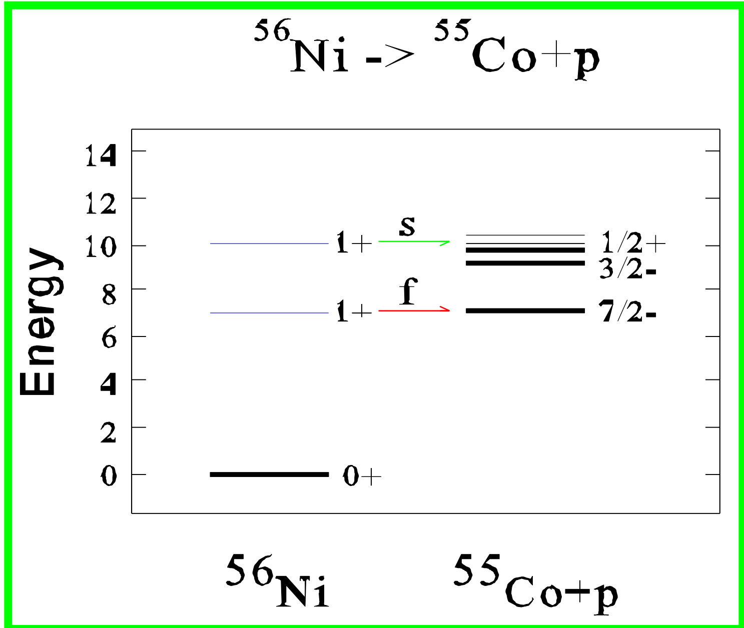
$B(GT)_{KB3G}=9.0$

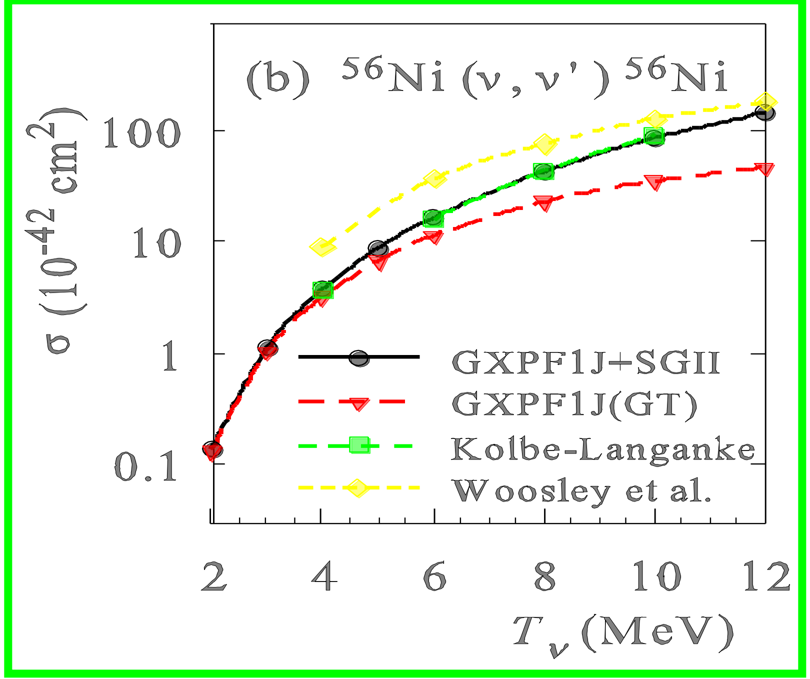
SD + … : RPA (SGII)

●Neutral current reaction on ^{56}Ni

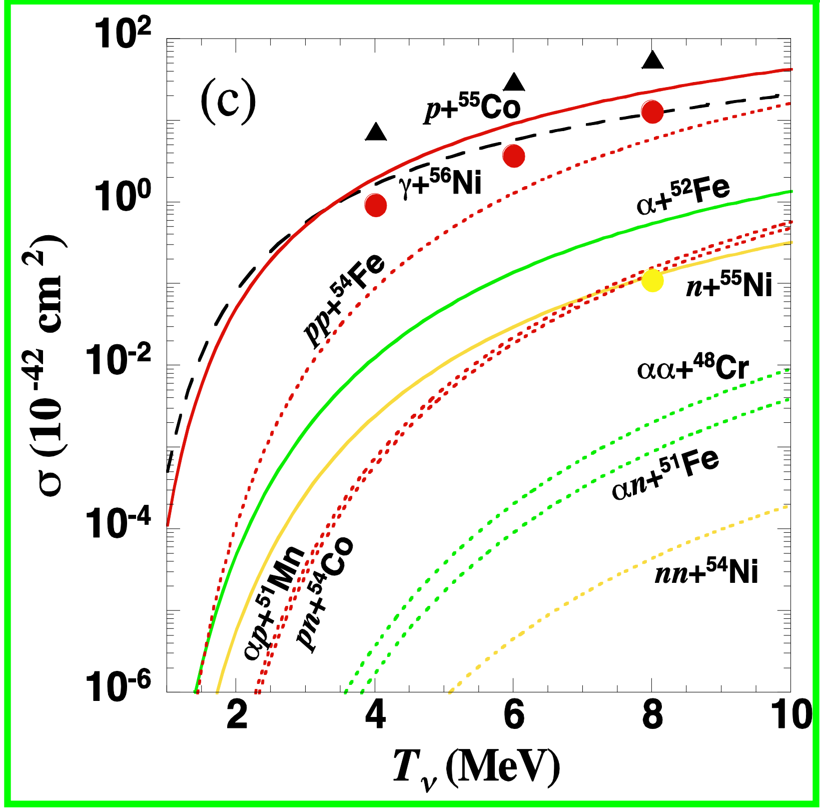


B(GT)=6.2
(GXPF1J)
B(GT)=5.4
(KB3G)



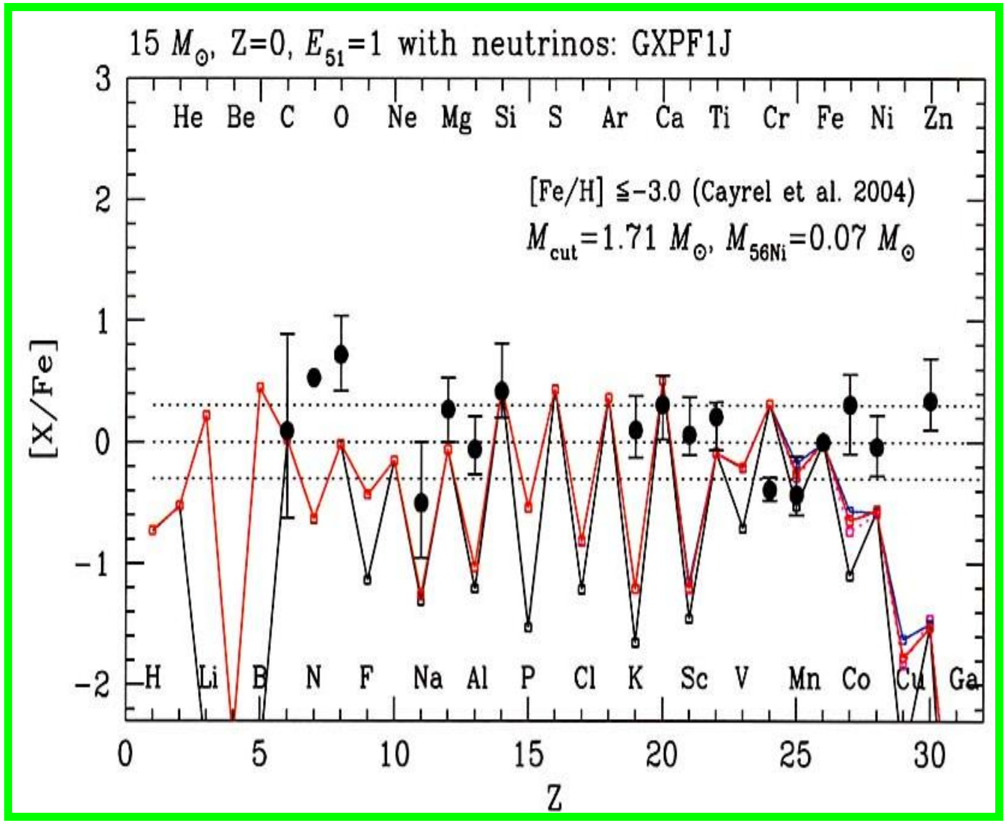


cf:
HW02
▲gamma
●p
●n



Synthesis of Mn in Population III Star

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



No ν

With ν(GXPF1J)

With ν x2

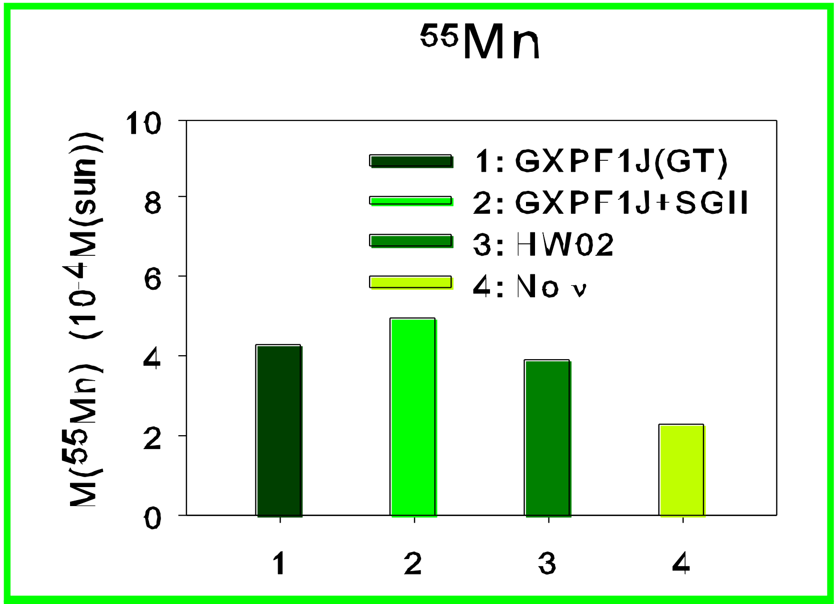
With ν(Woosley)

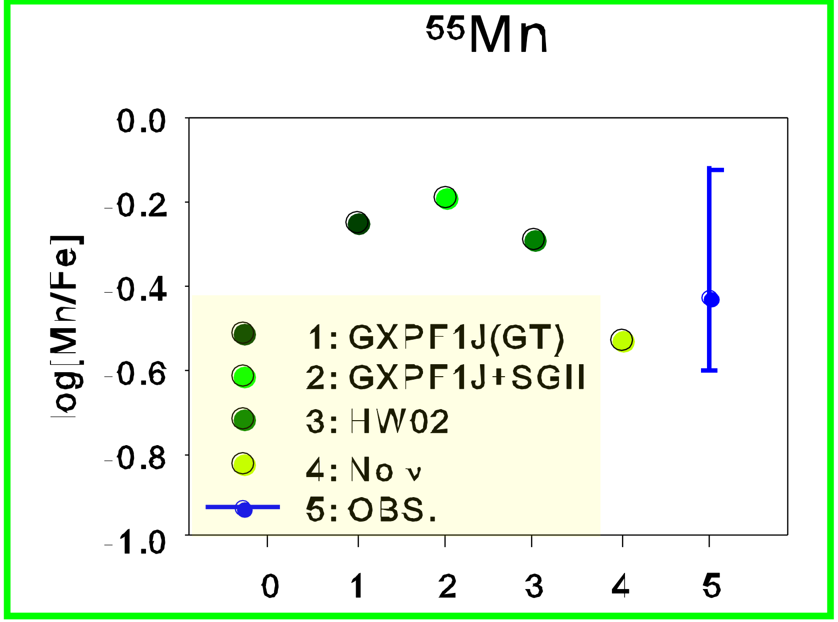
$$^{54}\text{Fe}(p,\gamma)^{55}\text{Co}$$

Yoshida, Umeda, Nomoto

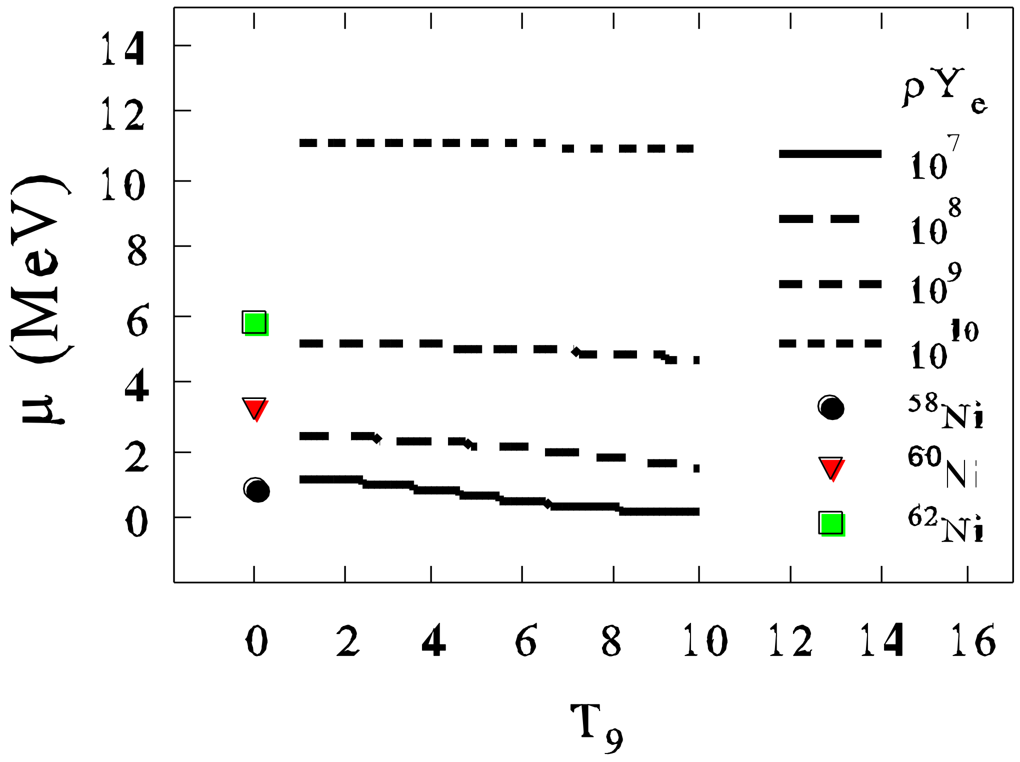
Suzuki et al.,
PR C79 (2009)

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





●Electron-capture rate in steller environment



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

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

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

$$\rho Y_e = 10^7 - 10^{10}\ \ \mathrm{mol/cm^3}$$

$$T = T_9 \times 10^9\,\mathrm{K}$$

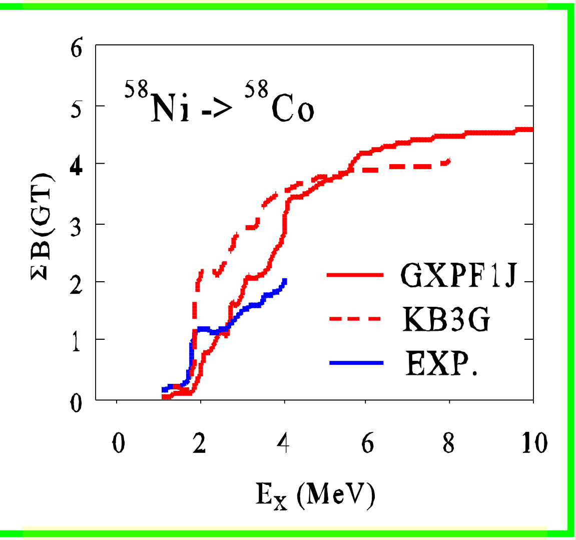
$$\lambda = \frac{ln2}{6146(s)}\sum_j B_j(GT)\int_{\omega_e}^{\infty} \omega p(Q_j + \omega)^2 F(Z,\omega) S_e(\omega) d\omega$$

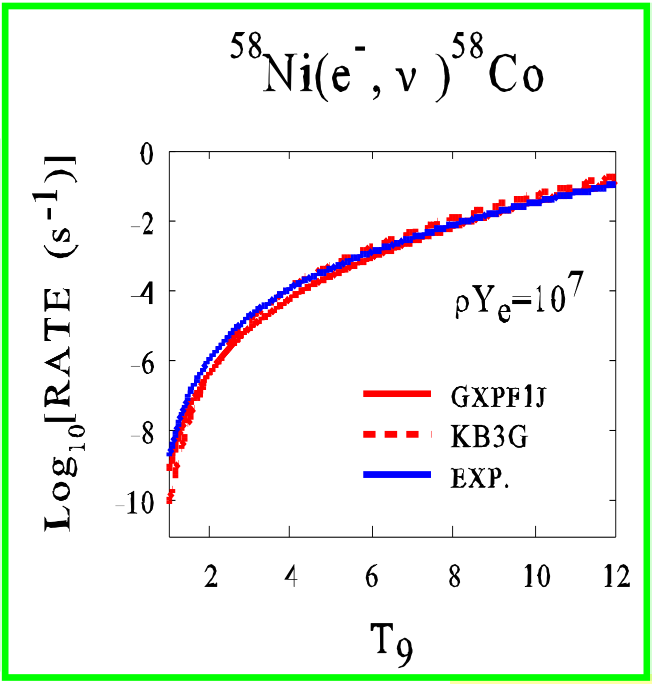
$$Q_j = (M_p c^2 - M_d c^2 - E_j)/m_e c^2$$

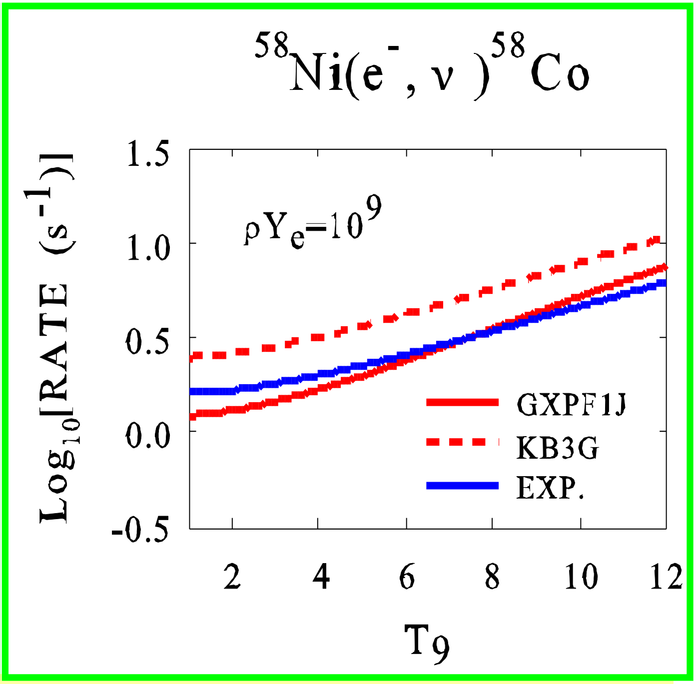
$$T = T_9 \times 10^9 K, \qquad S_e(E_e) = \frac{1}{exp[(E_e - \mu_e)/kT] + 1}$$

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

^{58}Ni → ^{58}Co

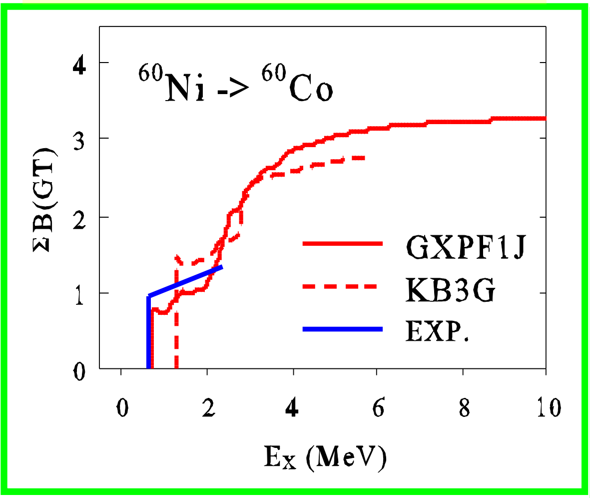




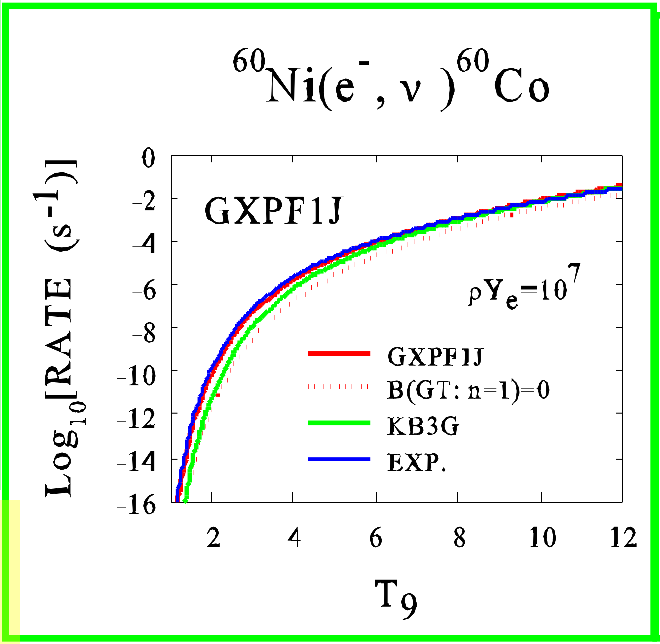


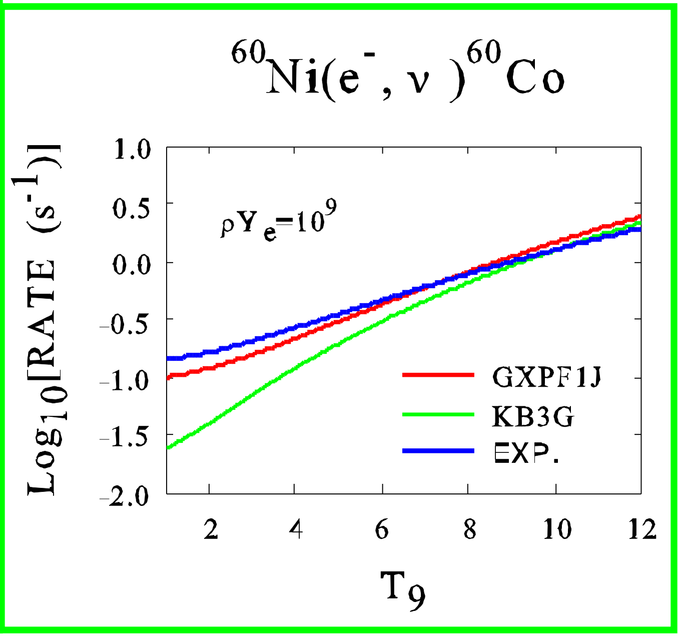
Exp: Hagemann et al., PL B579 (2004)

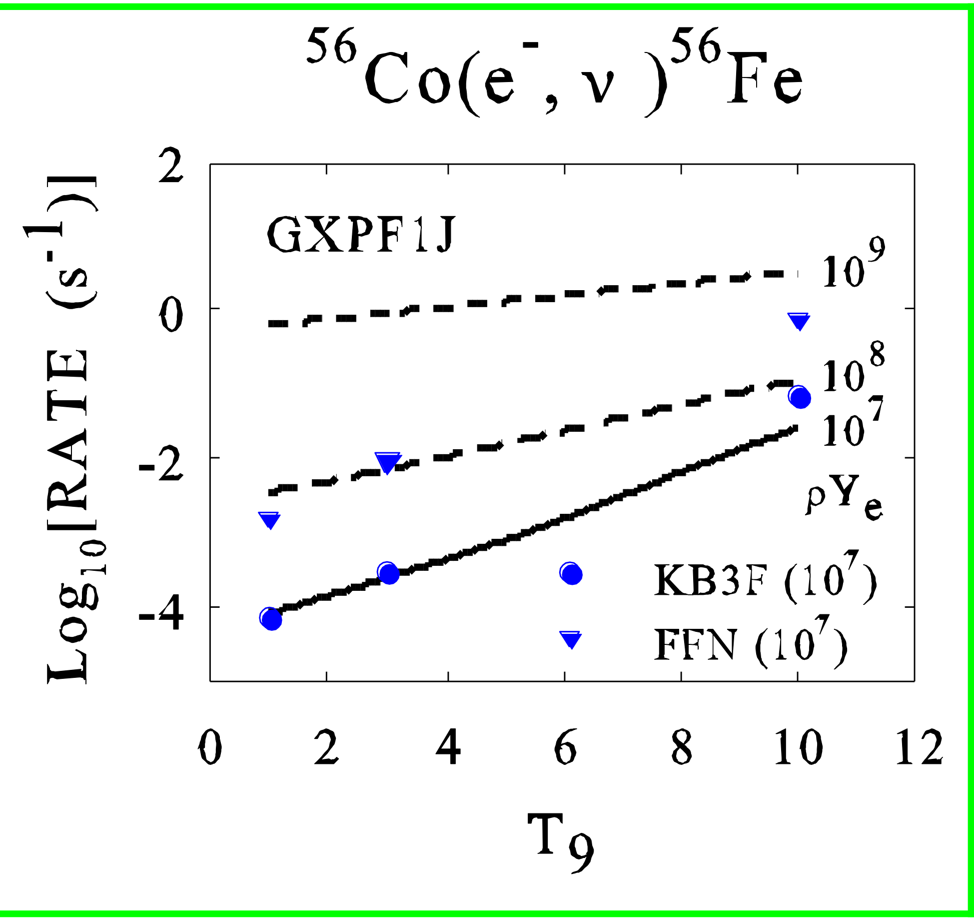
^{60}Ni → ^{60}Co

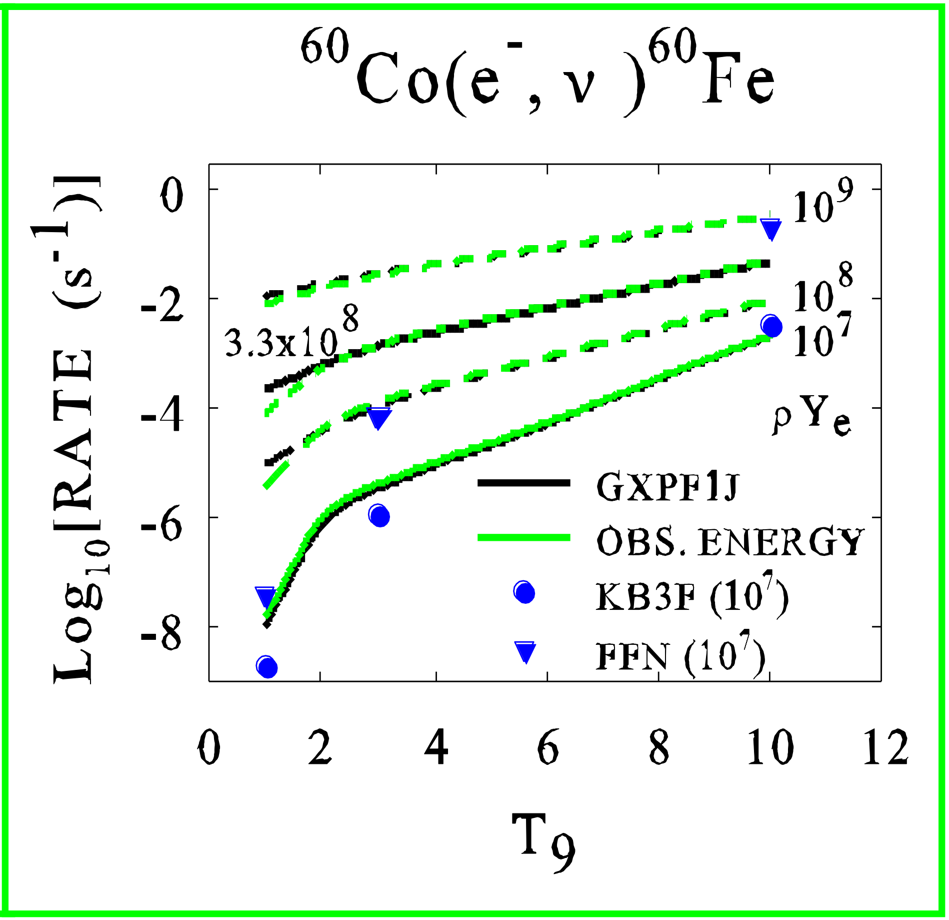


Exp: Anantaraman et al., PR C78 (2008)









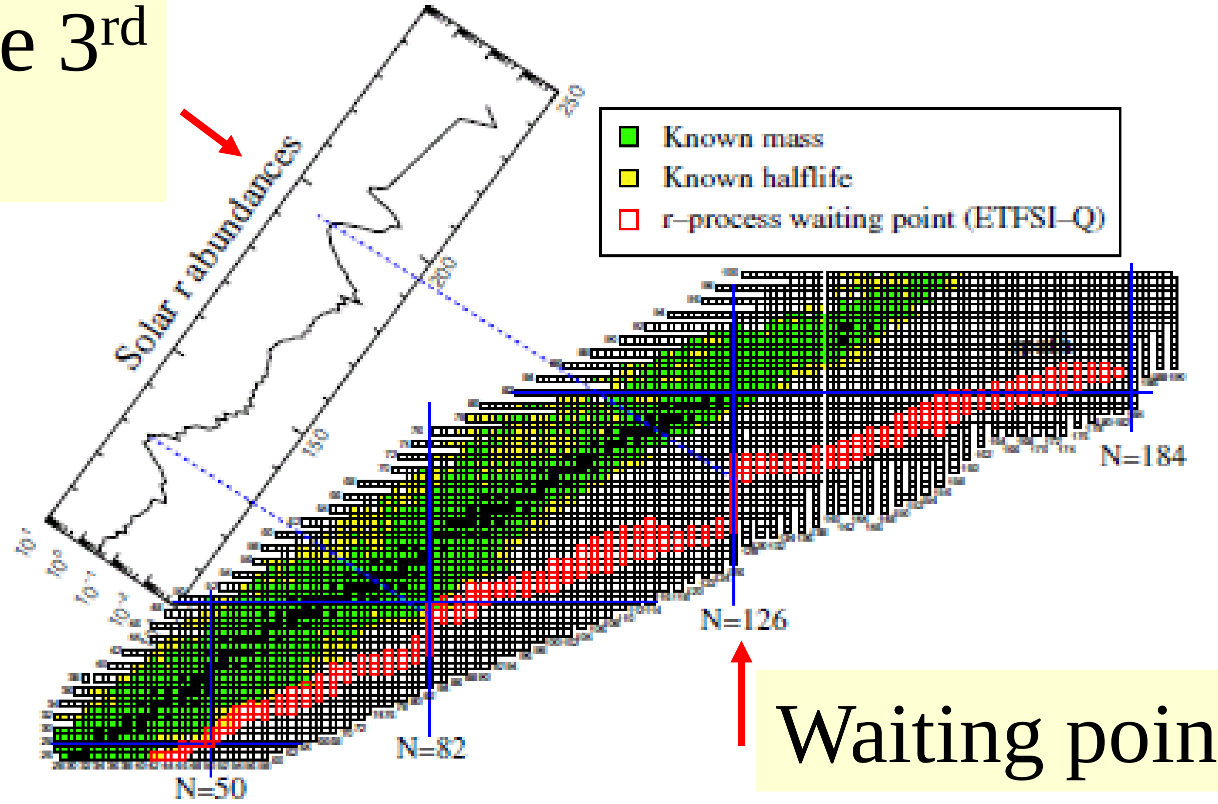
$\rho Y_e = 10^7$

- ● Langanke and Martinez-Pinedo, Atomic and Nucl. Data Tables (2001)
- ▼ FFN: Astrophys. J. Suppl. (1982)

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 ^{208}Pb

- **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

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

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

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

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

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

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

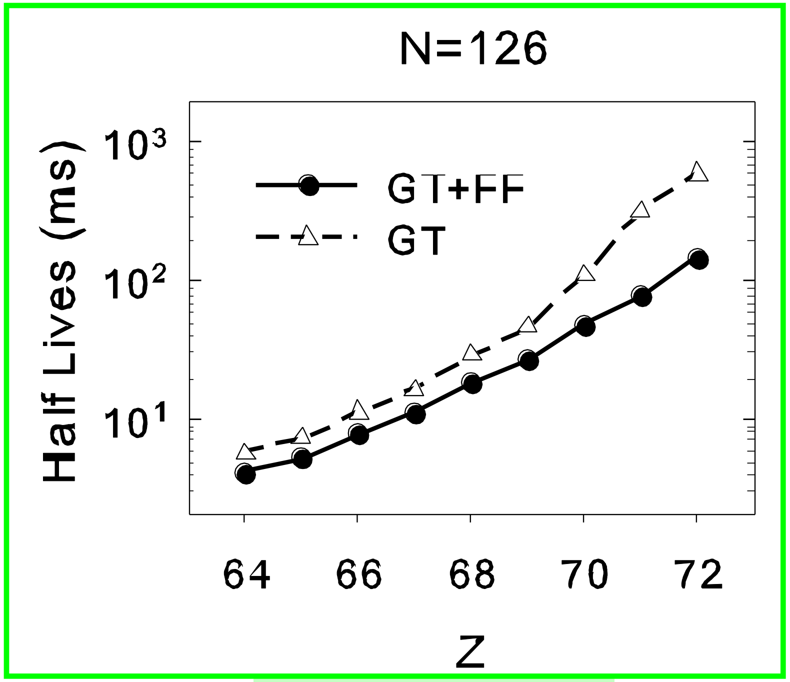
$$C(w) = K_0 + K_1 w + K_{-1}/w + K_2 w^2$$

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

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

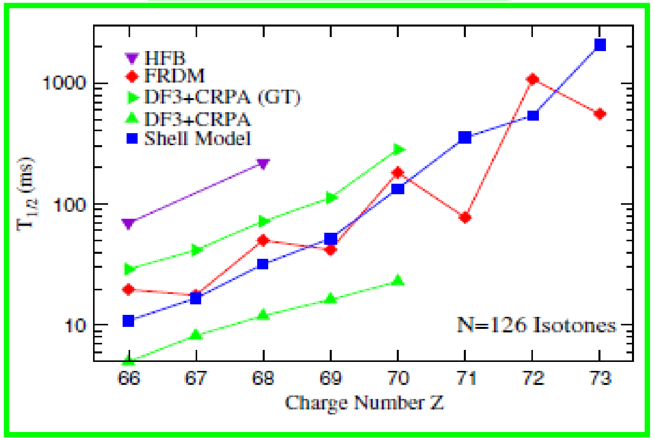
Warburton et al., Ann.Phys. 187 (1988)

Half-Lives of N=126 Isotones



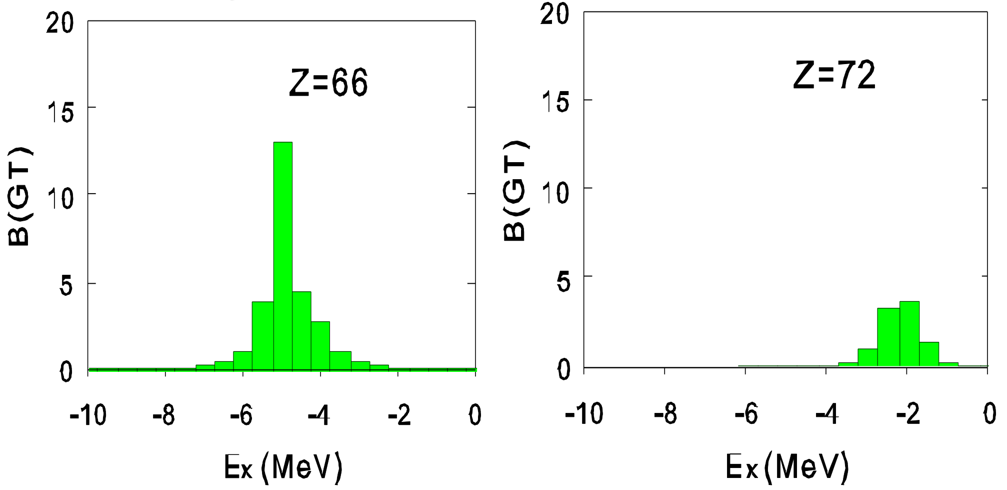
Q=g_A^{eff}/g_A=0.7

cf.



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

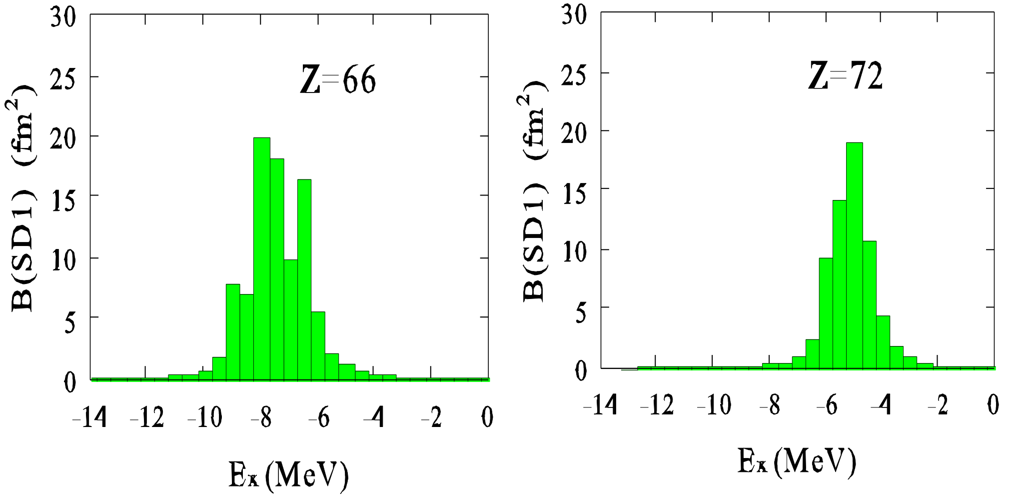
GT strengths



ΣB(GT)=14.6

ΣB(GT)=5.6

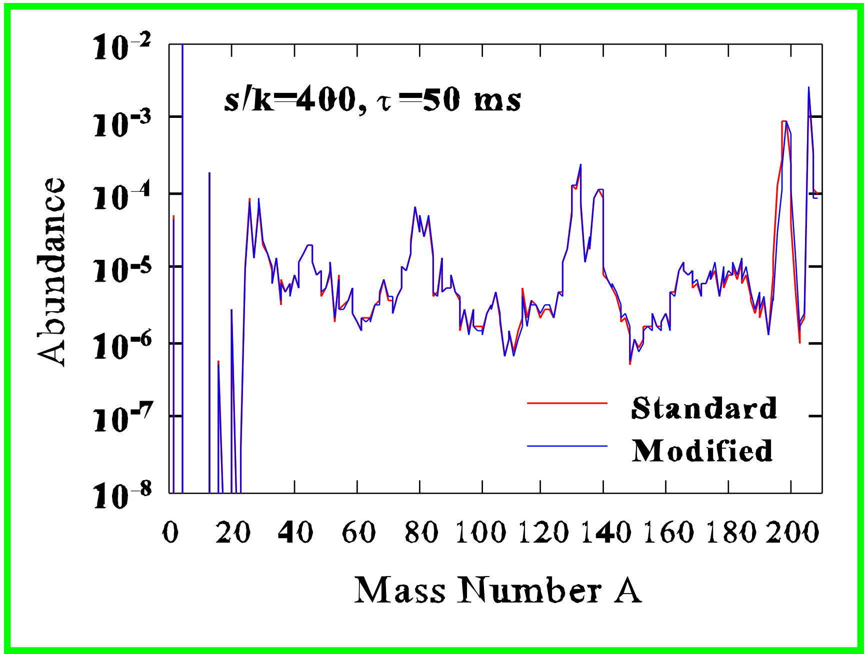
SD (1^-) strengths



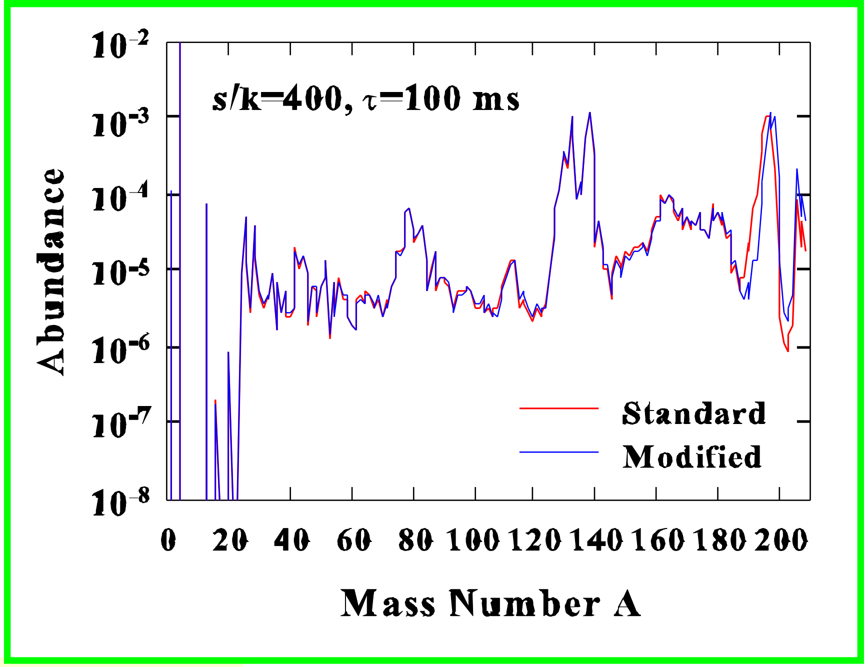
ΣSD1=49.2 fm^2

ΣSD1=35.1 fm^2

(a)



(b)



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

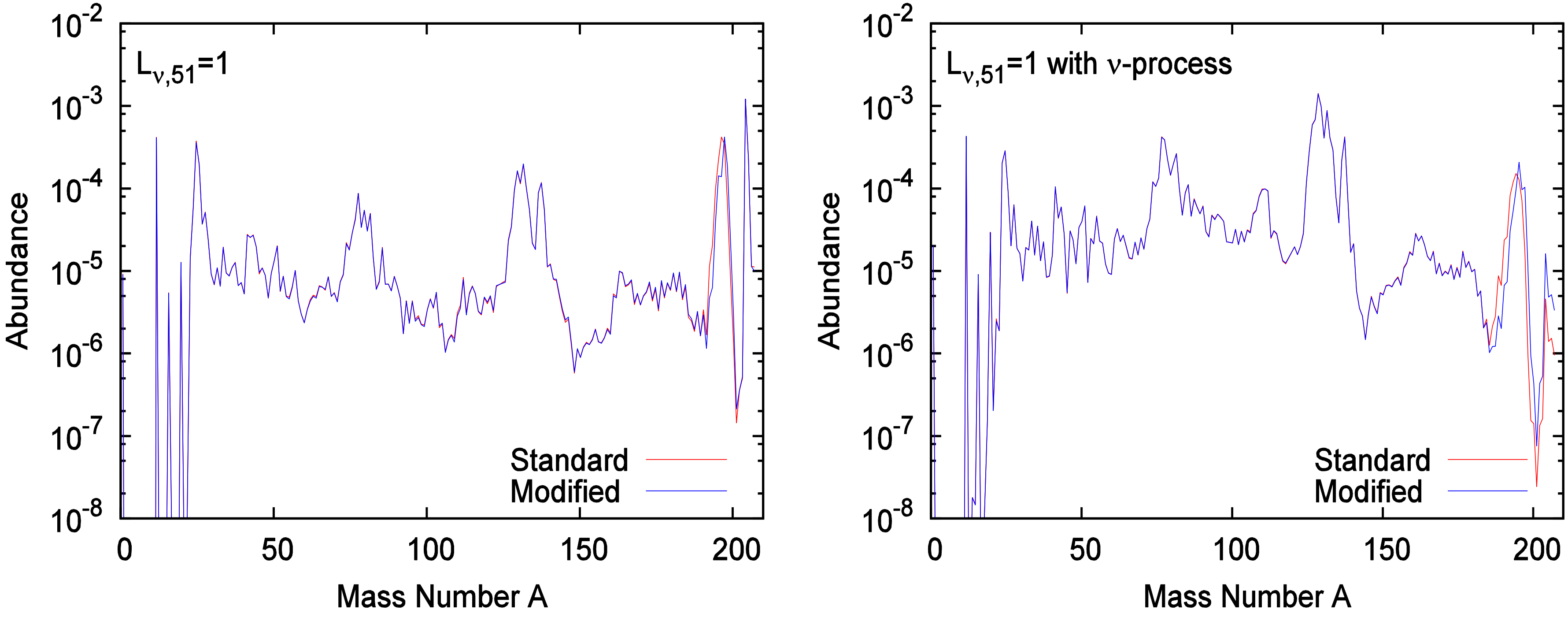
Half-lives:

🟥 Standard (Moller et al.)

🟩 Modified

neutrino processes: $n(\nu,e^-)p$, $\alpha(\nu,e^-p)^3He$ → less n

→ Y_e increses → suppression of the 3rd peak of the r-process (Meyer et al.)



ν luminosity: $L = 10^{51}$ergs/s/flavor

S/k =373

$T_{09}=5 \rightarrow T_{\alpha 9}=2$: $\tau = 0.027$s

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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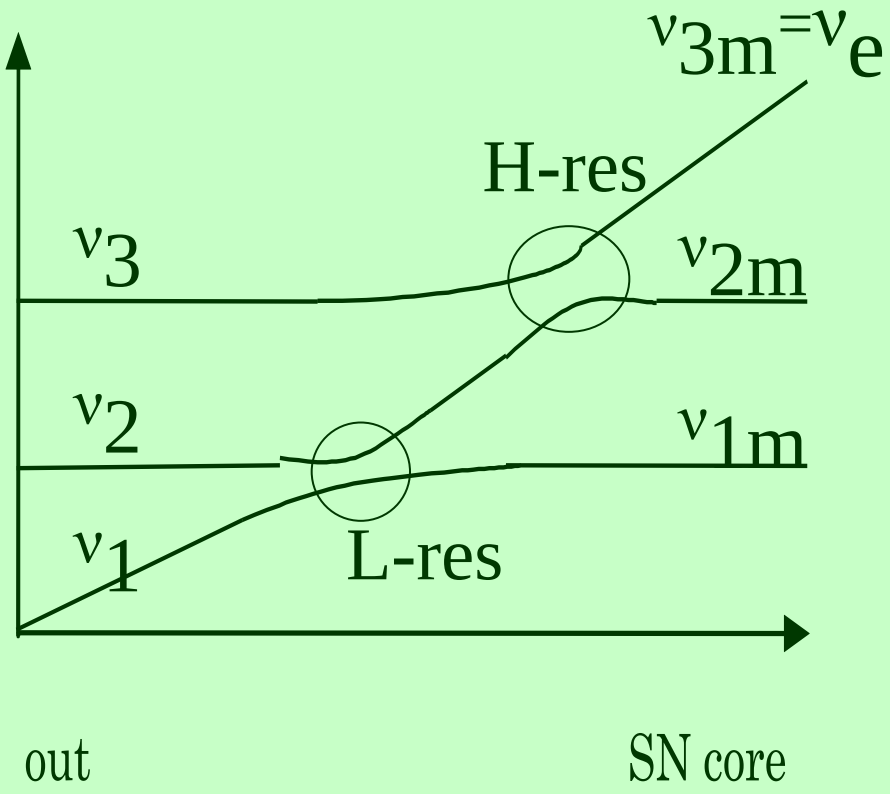
[f]JAEA
[g]ENSPS, Strasbourg

Normal



Inverted