Nuclear Weak Processes of Astrophysical Interest

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Primosten June. 10, 2011

○ν-nucleus reactions

- **ν-^{12}C reactions and synthesis of light elements by supernova ν**
- **ν-^{13}C reactions; efffects of contamination of ^{13}C (1.1%) on ν-^{12}C reactions**
- **ν-induced reacions on ^{16}O**
- **^{40}Ar (ν, e$^-$) ^{40}K solar ν-reactions**
- **ν-^{56}Fe ▪ν-^{56}Ni and synthesis of Mn**

○ e-capture on Ni isotopes in steller environments

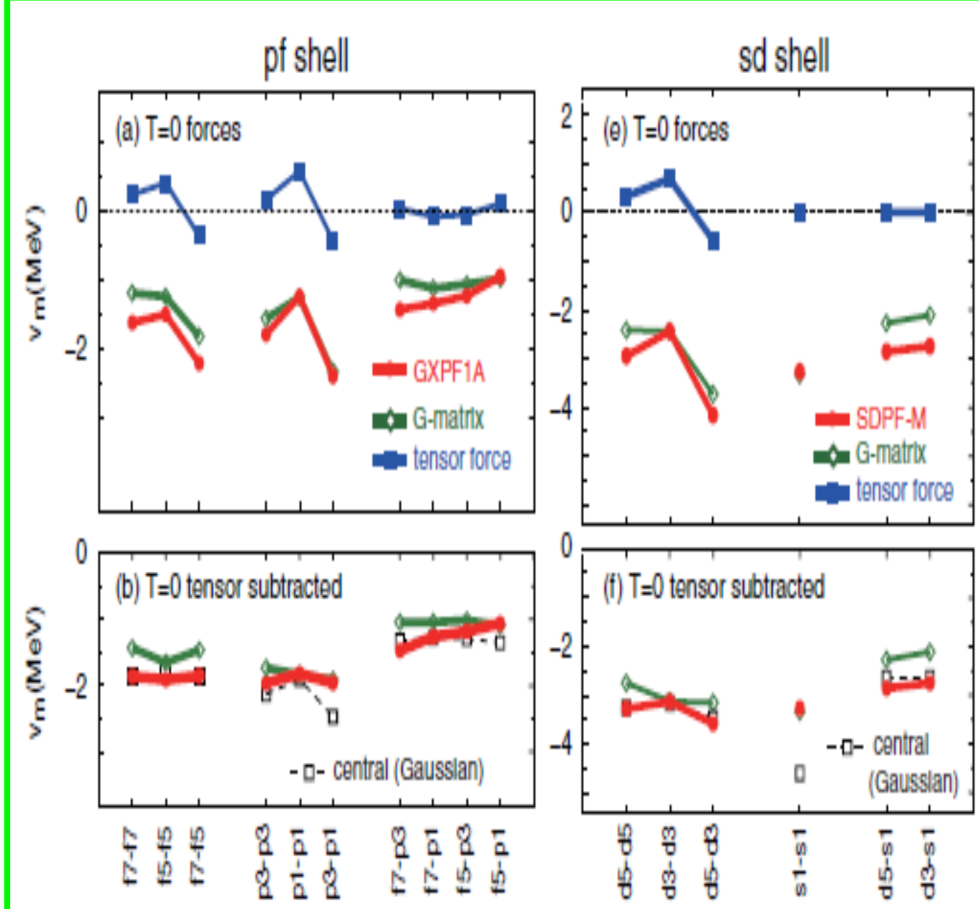
● New shell model Hamiltonians with proper tensor components, which give successful description of spin responses in nuclei

New shell model Hamiltonians → success in better description of spin modes in nuclei

- **Important roles of tensor force**
  → SFO (p, p-sd)
  (Suzuki-Fujimoto-Otsuka)
  - **Shell evolutions**
  - **GT transitions and magnetic moments**
- **Monopole-based universal interaction (VMU)**

Monopole terms of V_{NN}

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



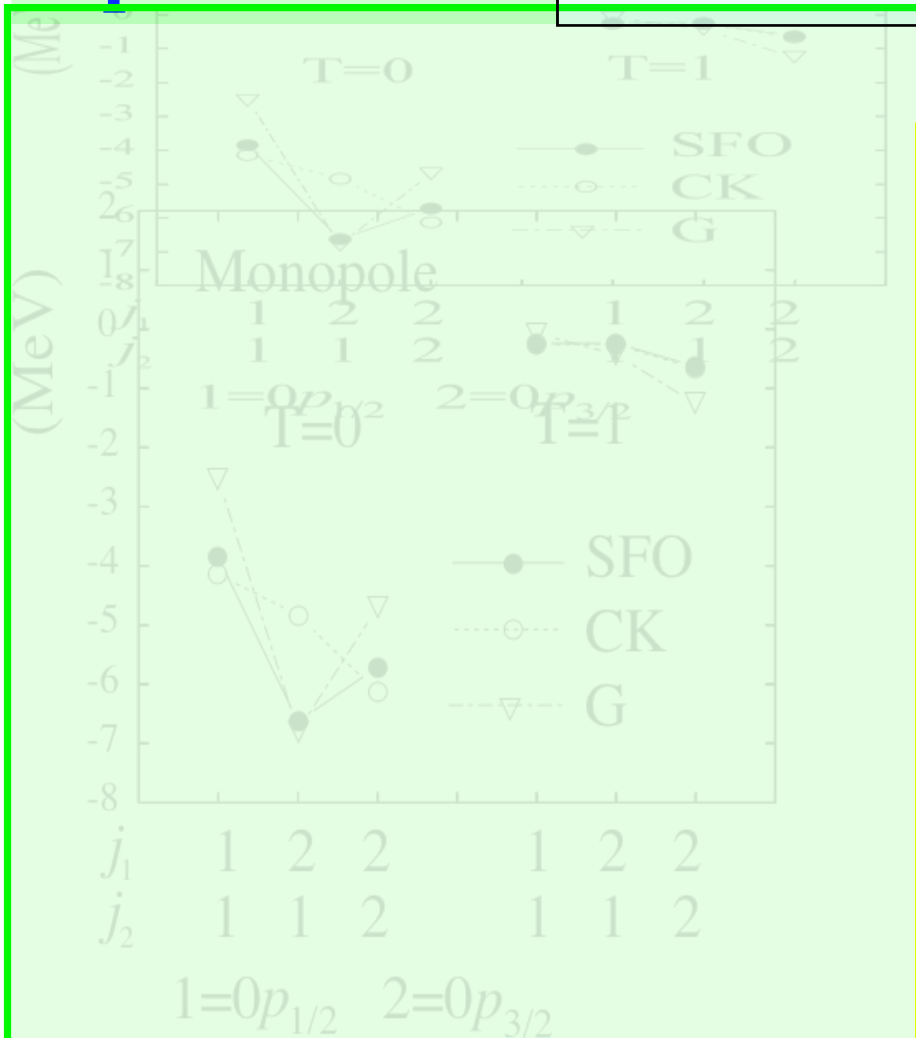
tensor force

SFO

p-sd shell

Suzuki, Fujimoto, Otsuka, PR C67 (2003)

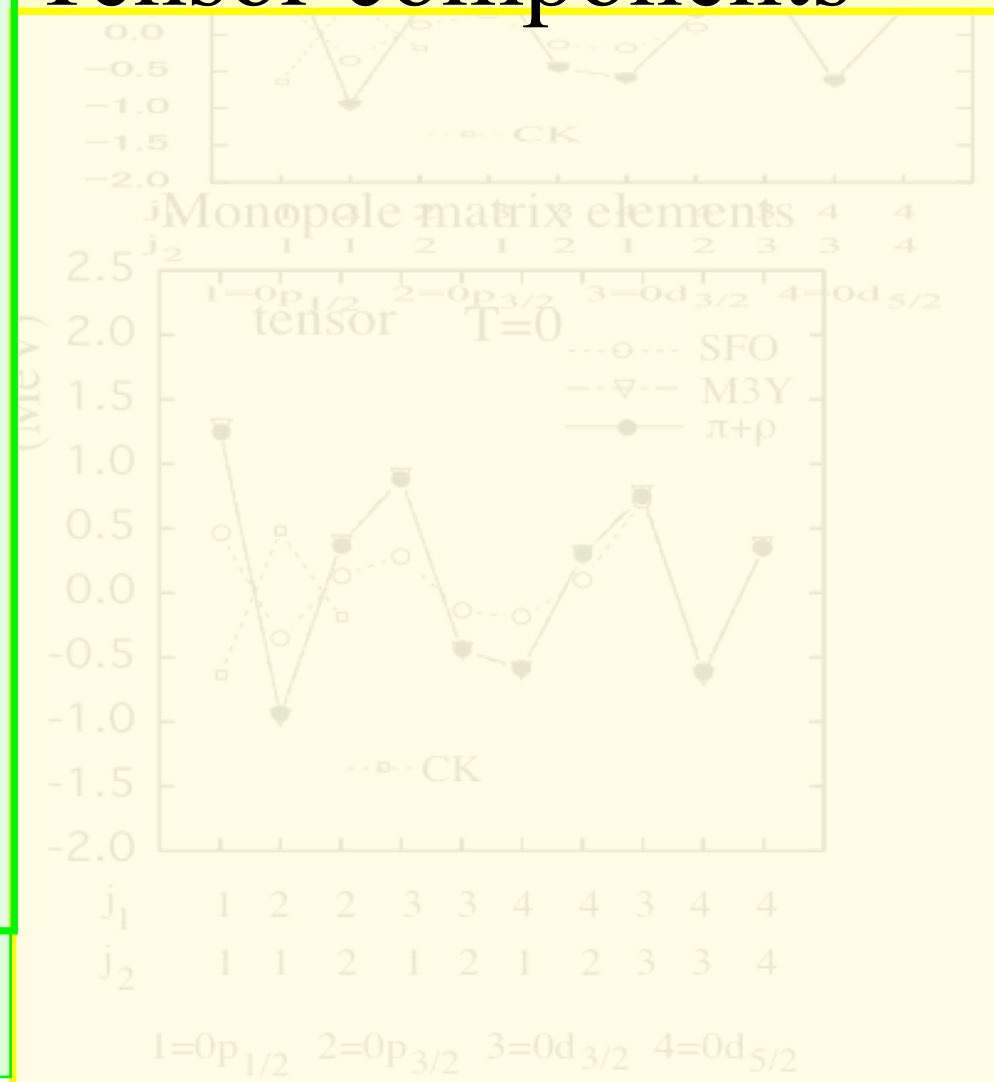
$$V = V_C\,(\text{central}) + V_T\,(\text{tensor}) +)V_{LS}\,(\text{LS}$$



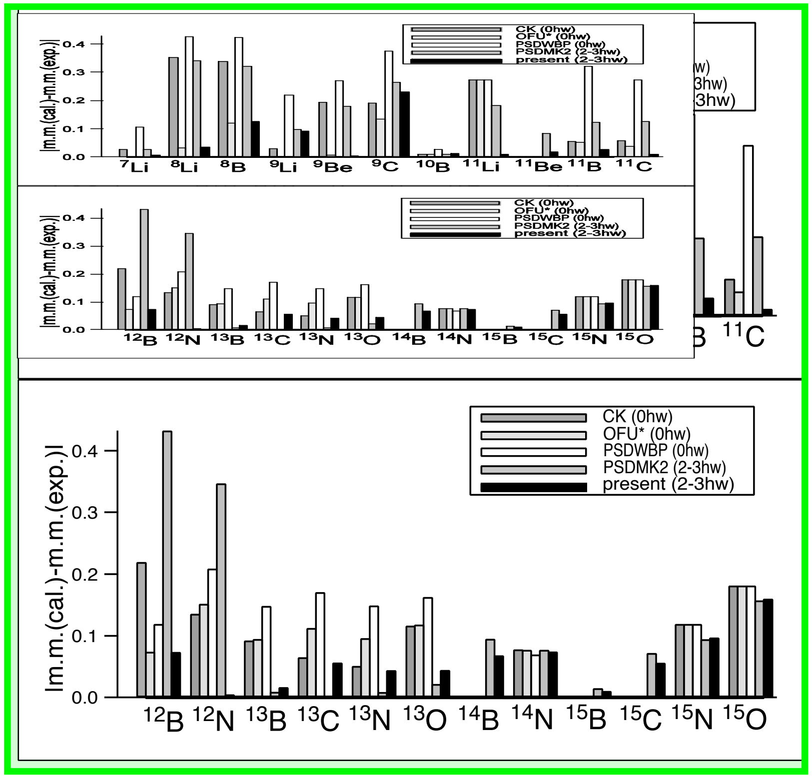
monopole T=0

CK →SFO p3／2-p1／2 -1.9 MeV

Tensor components



Magnetic moments of p-shell nuclei

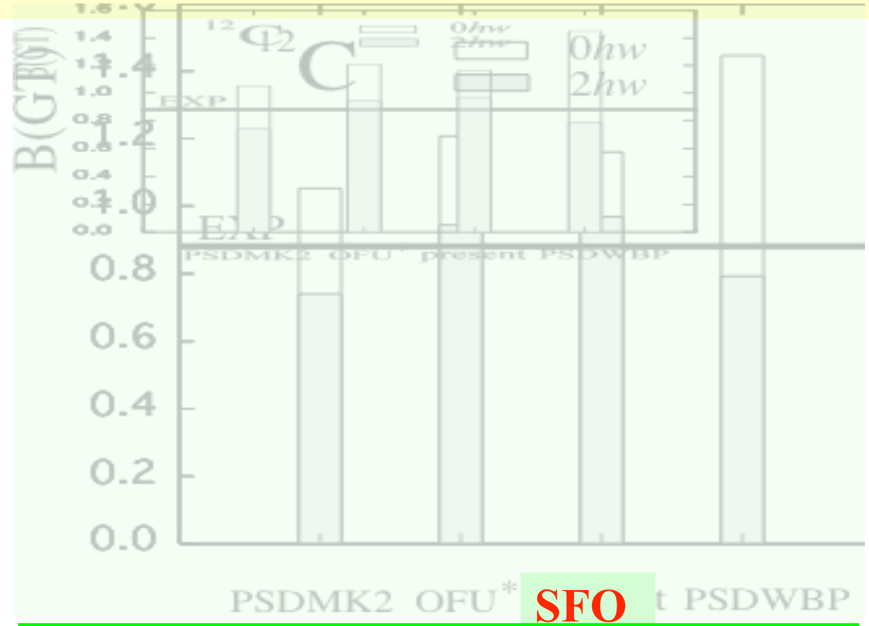


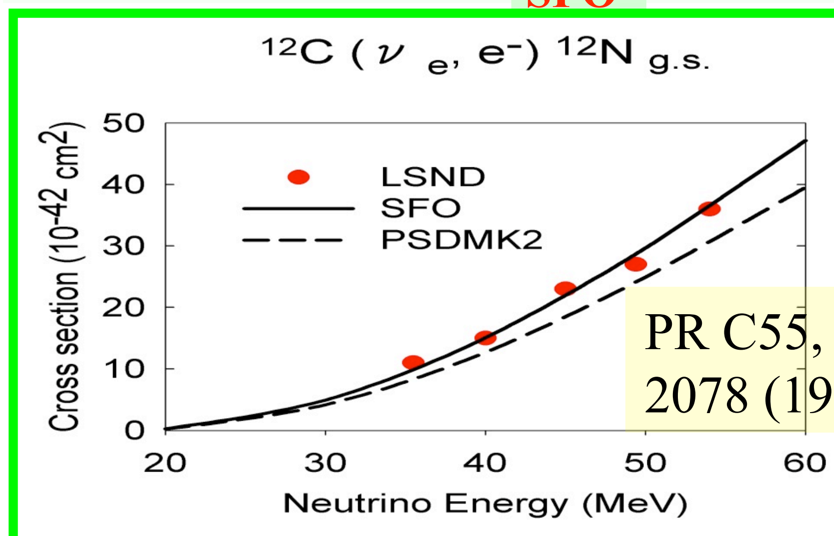
present = SFO **Suzuki, Fujimoto, Otsuka, PR C67 (2003)**

Space: up to 2-3 hw

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

B(GT) for ^{12}C $\rightarrow$ ^{12}N





PR C55, 2078 (1997)

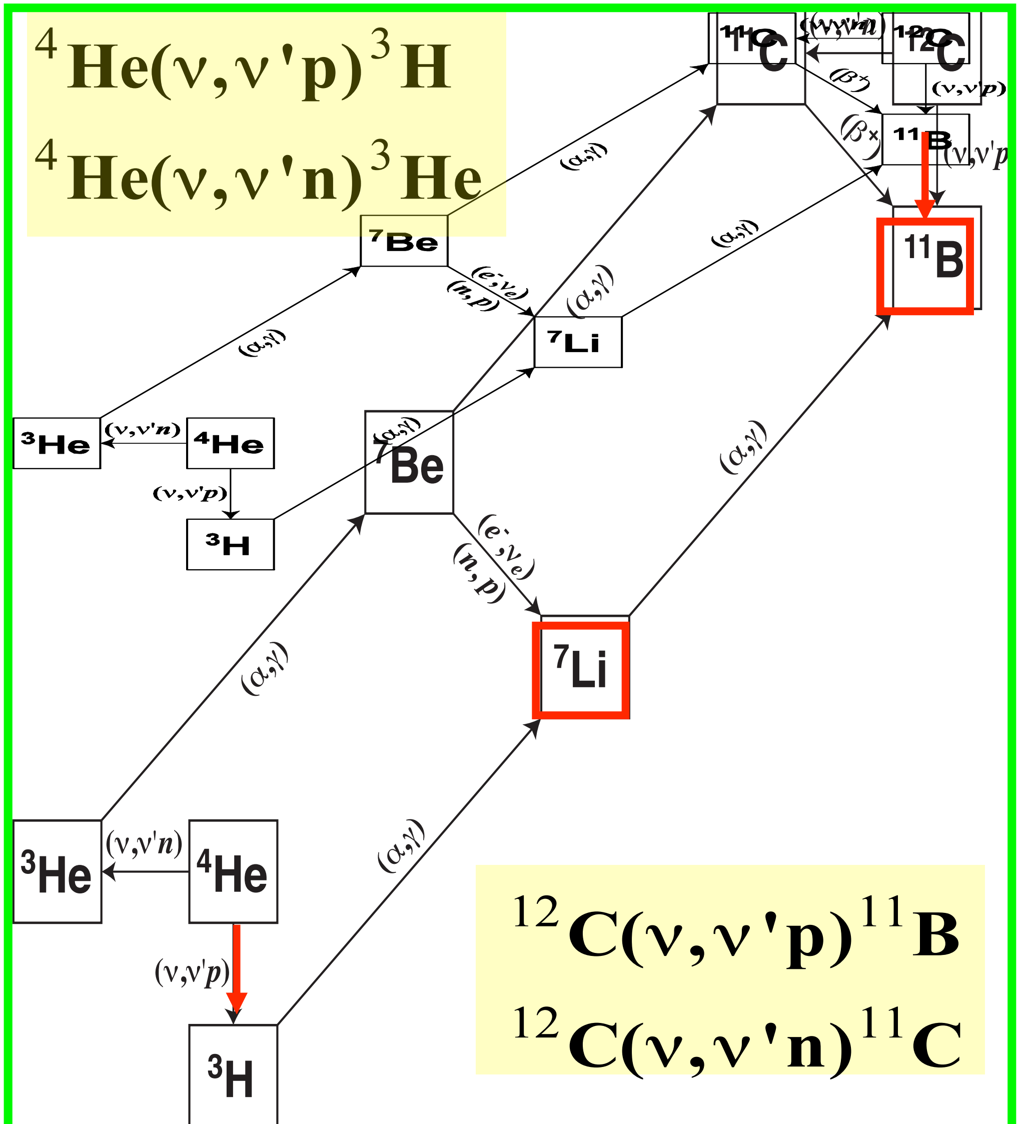
Suzuki, Chiba, Yoshida,Kajino, Otsuka, PR C74, 034307, (2006).

Nucleosynthesis processes of light elements

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

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

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



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

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

Cross sections for Supernova Neutrinos with temperature T

Effects of contamination of ^{13}C on inclusive ν-^{12}C reaction cross sections

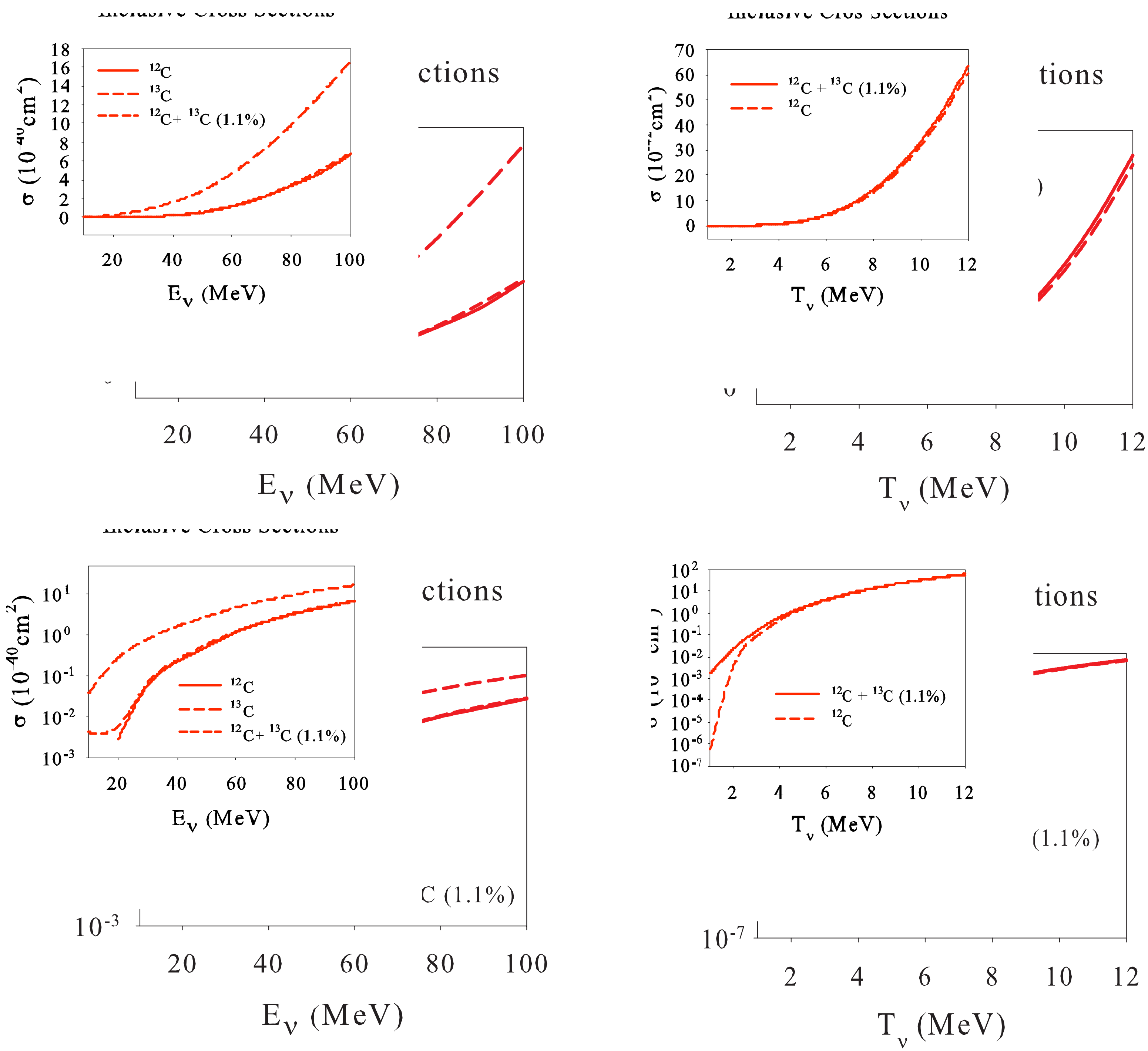
^{12}C 98.9%

^{13}C 1.1%

$^{12}C\ (\nu, e^-)\ ^{12}N_{g.s.}$ $\Delta M = 16.83$ MeV

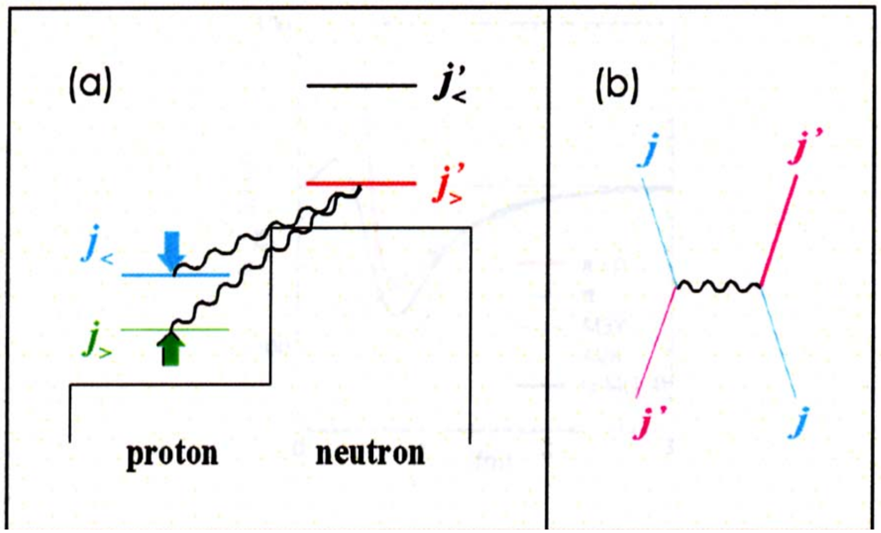
$^{12}C\ (\nu, e^-)\ ^{13}N_{g.s.}$ $\Delta M = 1.71$ MeV

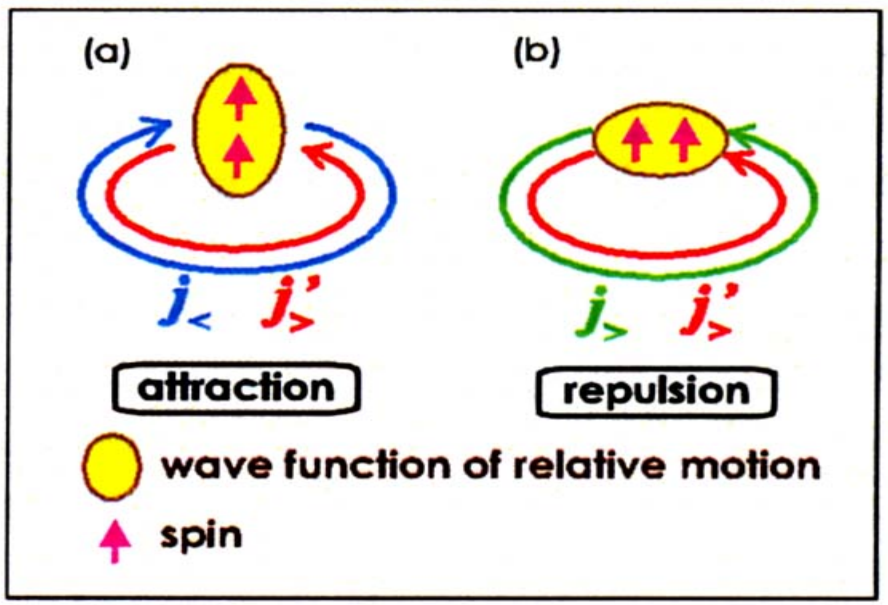
$\sigma(^{13}C) > \sigma(^{12}C)$


ctions
σ (10^-40 cm^2)
12C
13C
12C+ 13C (1.1%)
Eν (MeV)
tions
12C + 13C (1.1%)
12C
Tν (MeV)
C (1.1%)
(1.1%)
10^-3
10^-7

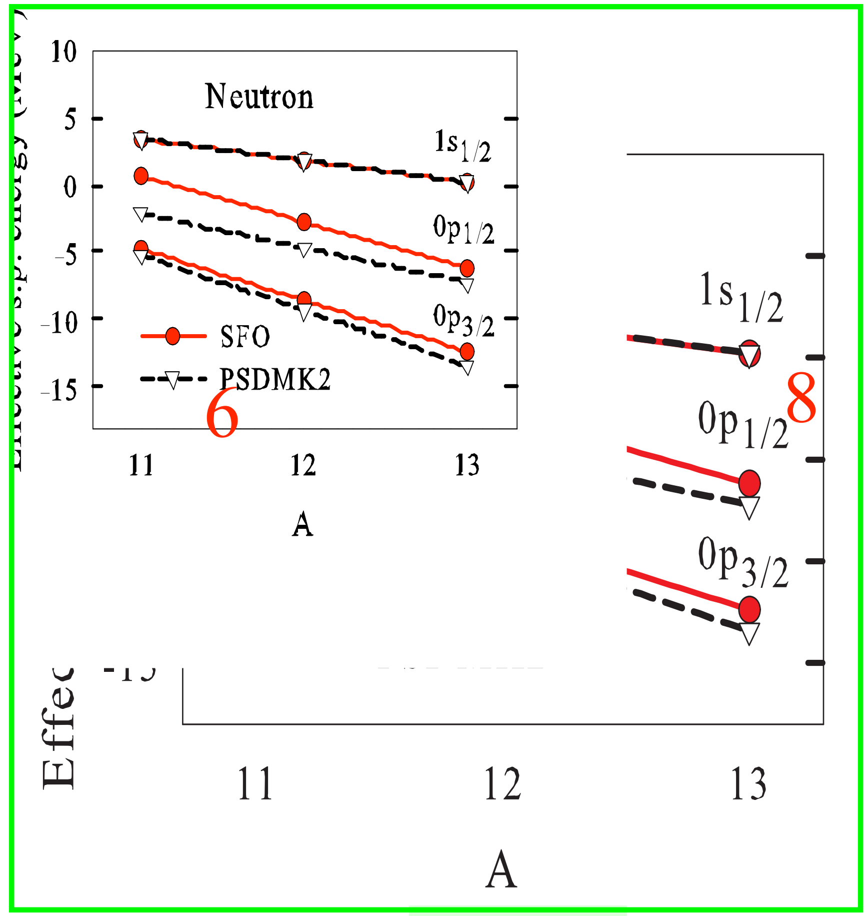
Tensor Force and Shell Evolution

Otsuka, Suzuki, Fujimoto, Grawe, Akaishi, PRL 69 (2005)





Shell evolution in N=8 isotone



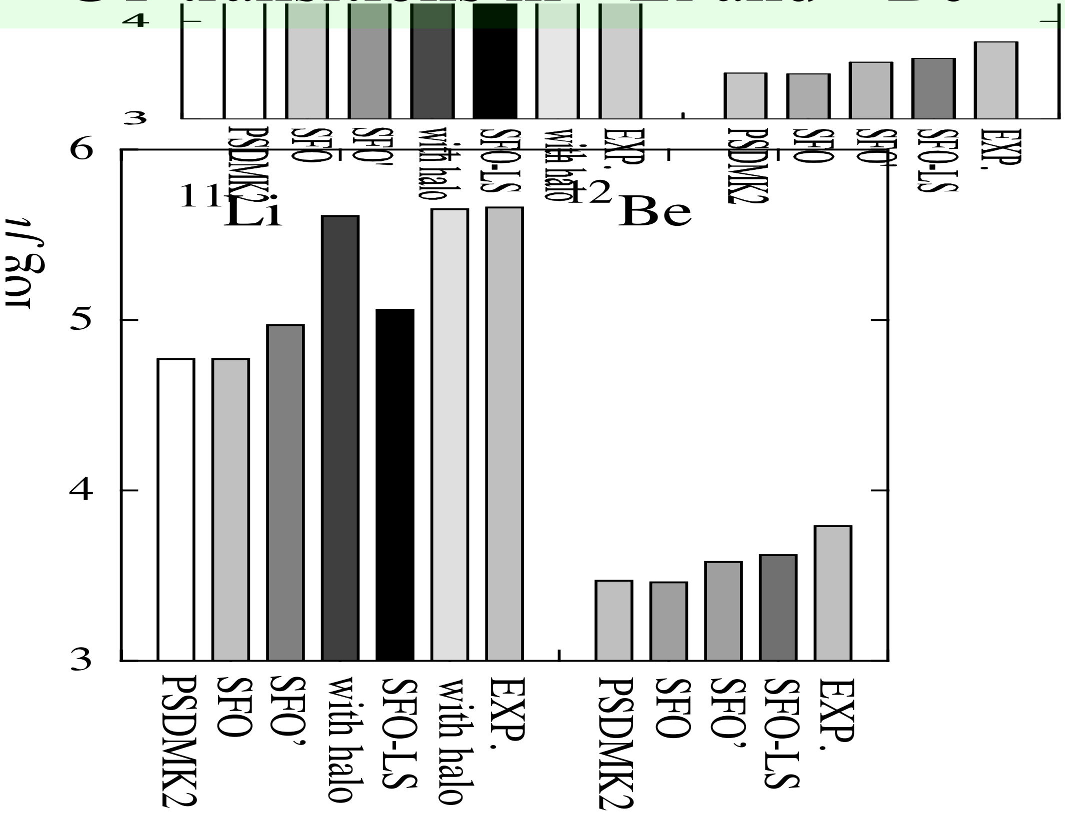
πp3/2

Large p-sd shell mixing

^{11}Li	PSDMK2	SFO	SFO’	(SFO-tls)
$P(p^7)$	88%	60%	**39%**	(28%)
^{12}Be				
$P(p^8)$	85%	59%	**44%**	(39%)

SFO’ :Δs1/2=-0.5 MeV

GT transitions in ^{11}Li and ^{12}Be

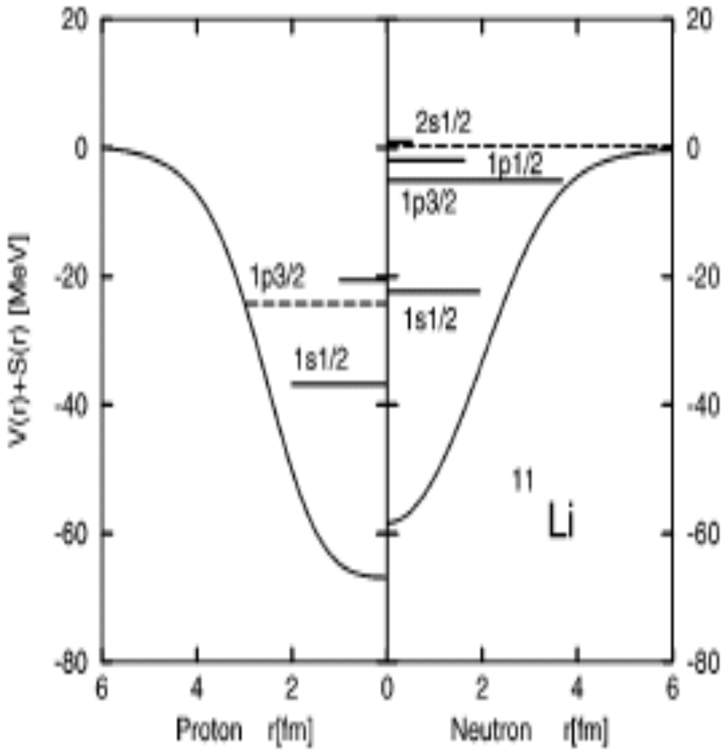


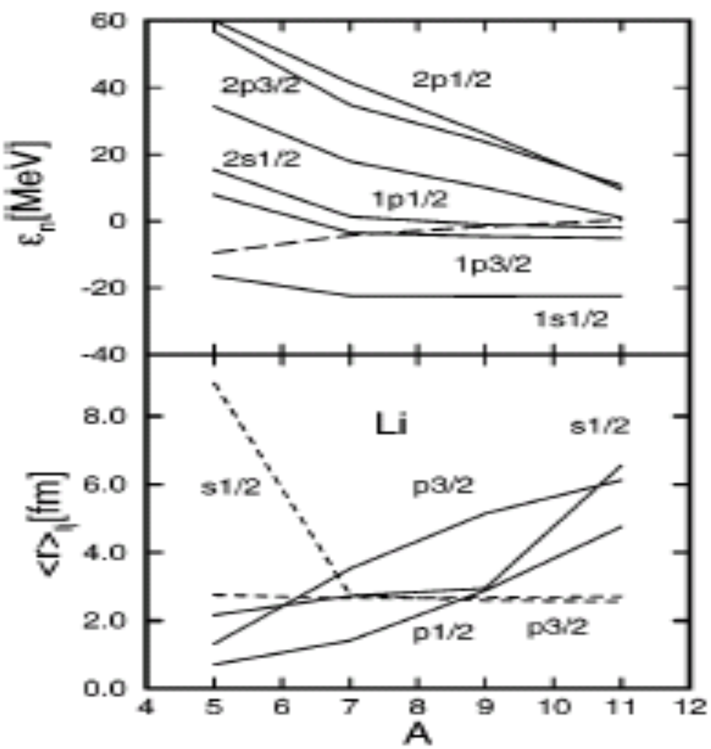
^{11}Li:
Importance of halo & sd-shell mixing

^{12}Be:
Importance of sd-shell mixing

Relativistic Hartree-Bogoliubov Description of the Neutron Halo in ^{11}Li

J. Meng and P. Ring
Physik-Department der Technischen Universität München, D-85748 Garching, Germany
(Received 4 June 1996)





•ν-induced reactions on ^{16}O

- **Modification of SFO**

Full inclusion of tensor force

·p-sd: tensor->π+ρ

LS -> σ+ρ+ω

$$V = V_C + V_T + V_{LS}$$

$$V_T = V_\pi + V_\rho$$

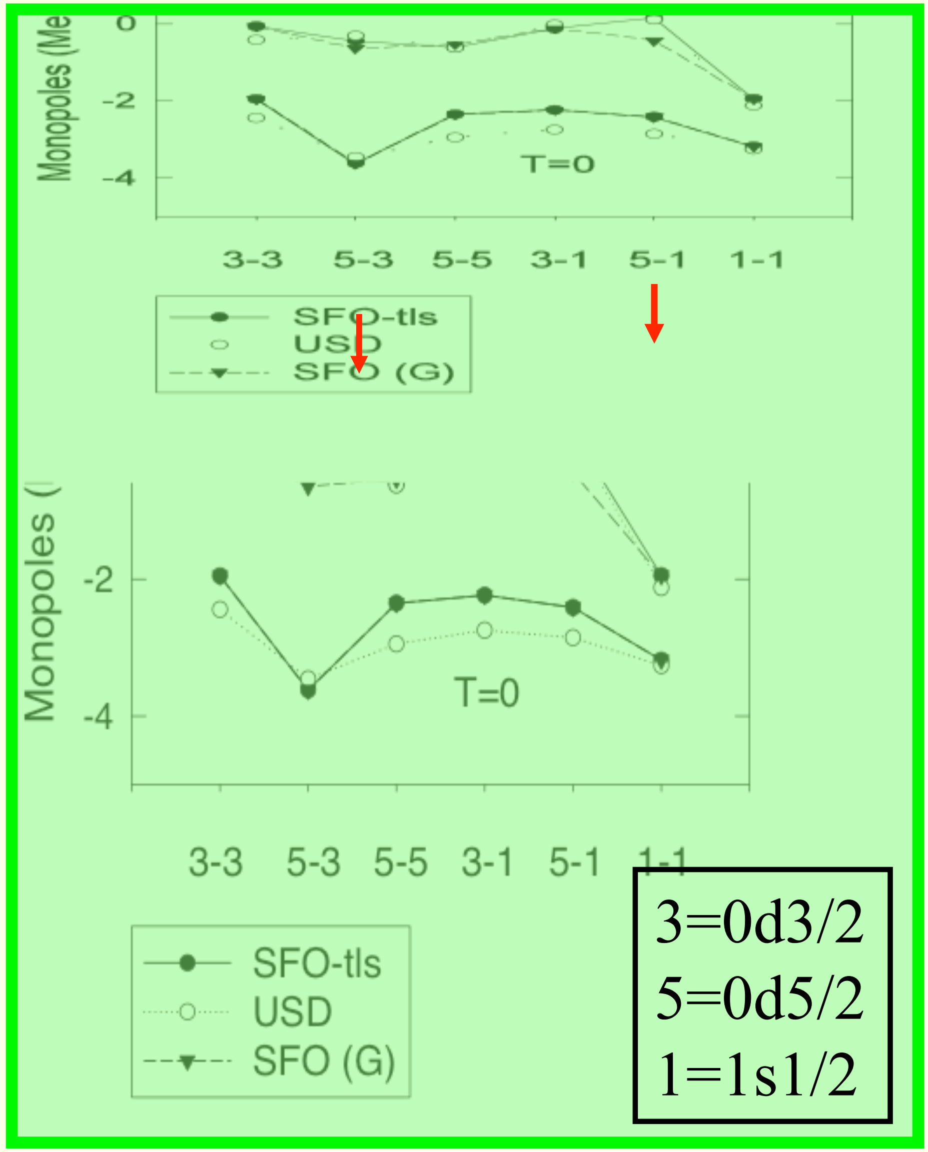
$$V_{LS} = V_{\sigma+\omega+\rho}$$

·sd: Kuo G-matrix

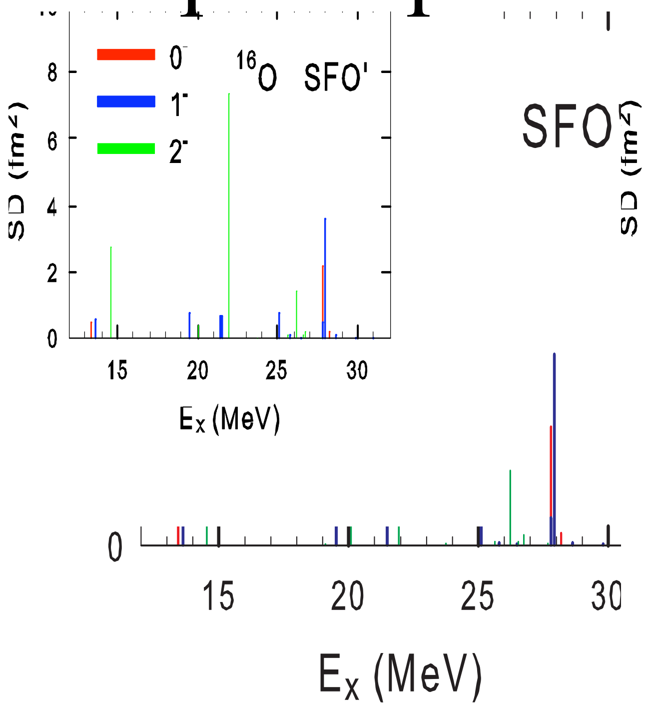
T=1 monopole terms

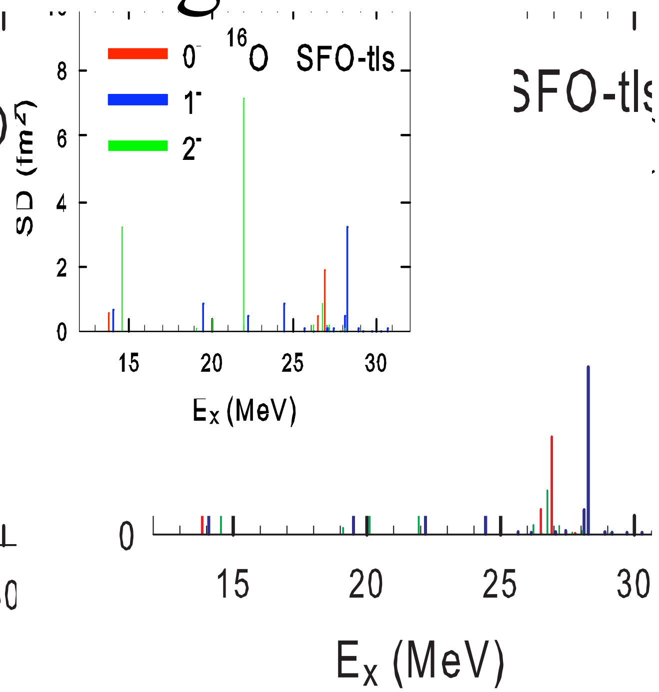
more repulsive

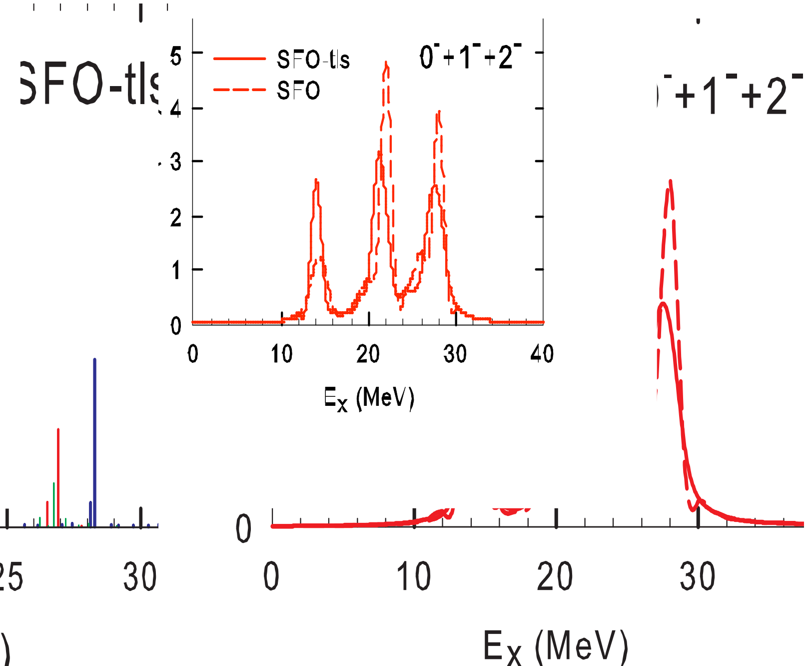
→ SFO-tls

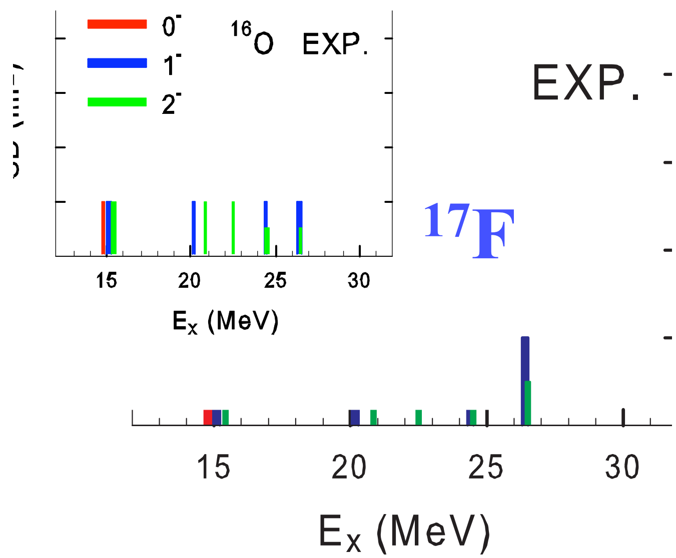


Spin-dipole strengths in ^{16}O



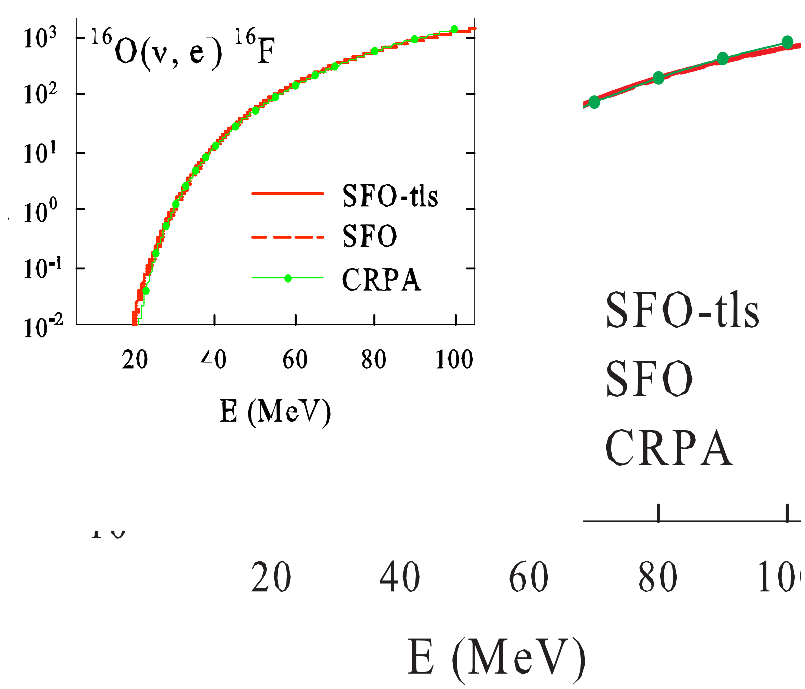


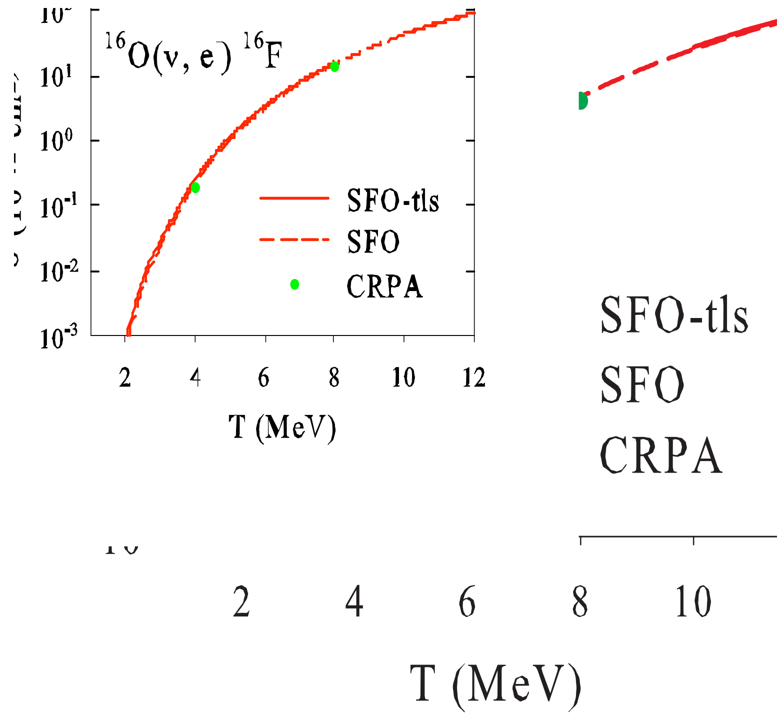


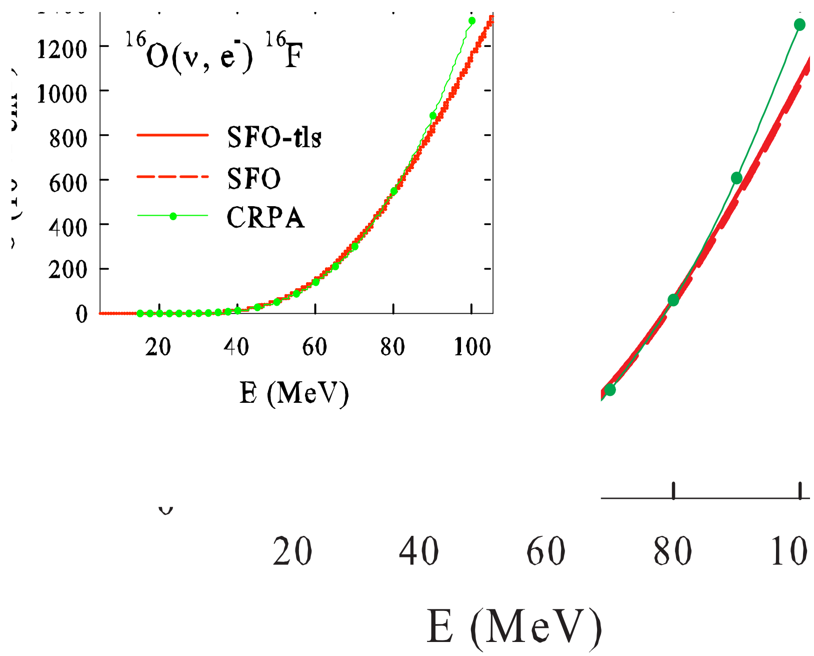


$$O(\lambda) = r[Y^1 \times \sigma]^\lambda t_-$$

^{17}F



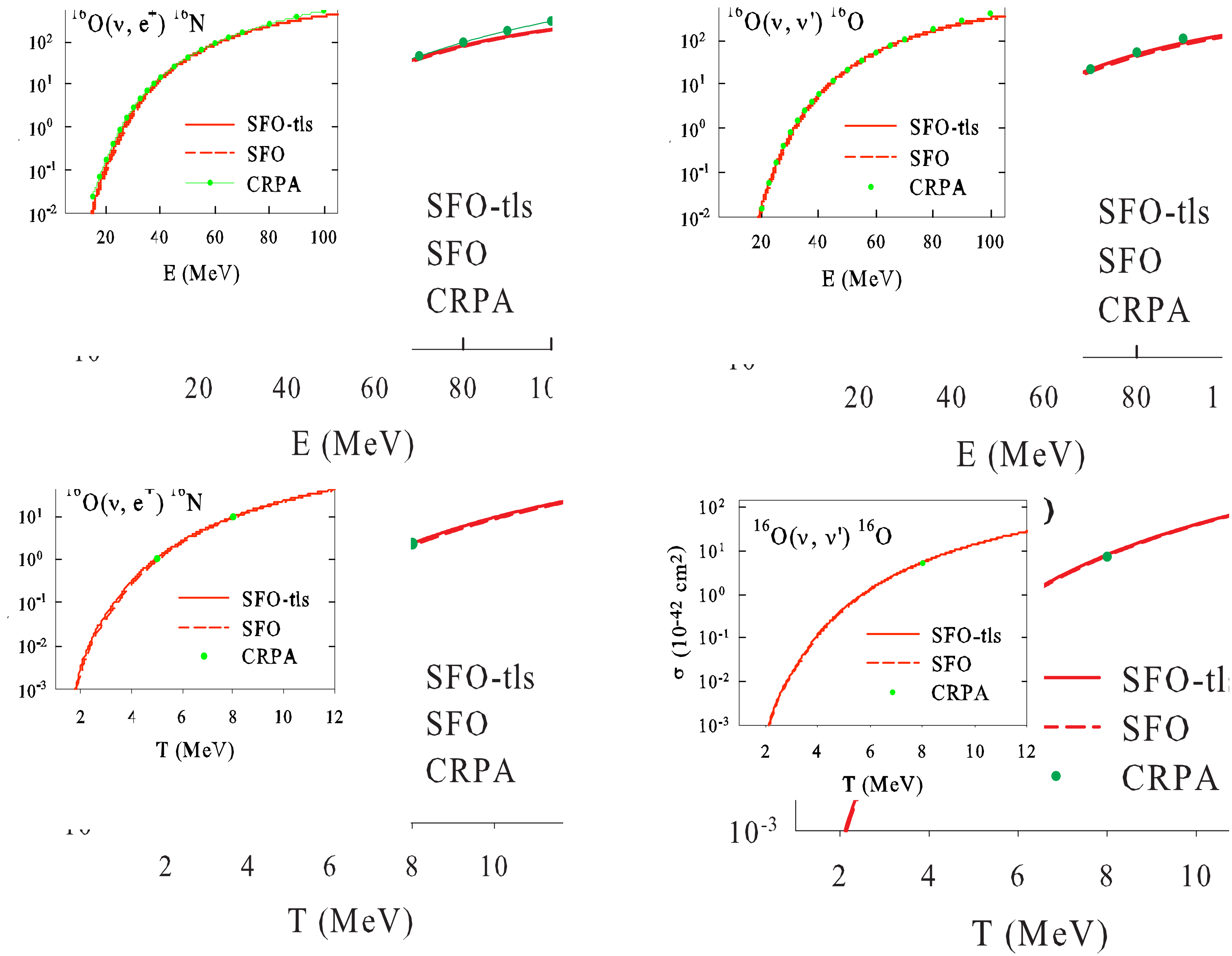




T= temperature of supernova ν

$g_A^{eff}/g_A=0.95$

CRPA: Kolbe, Langanke & Vogel,
PR D66 (2002)



T= temperature of supernova ν CRPA: Kolbe, Langanke & Vogel, PR D66 (2002)

VMU= Monopole based Universal Interaction

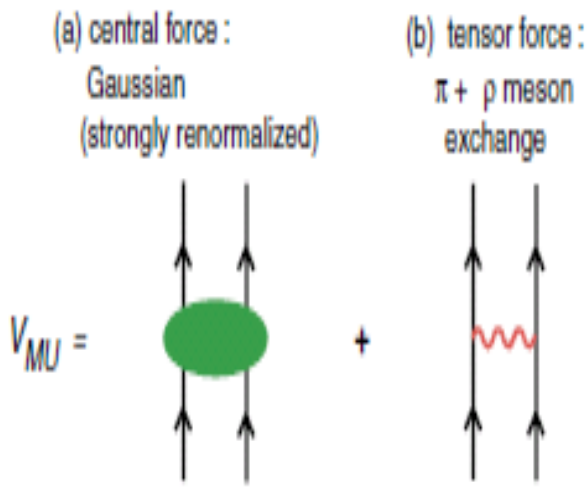
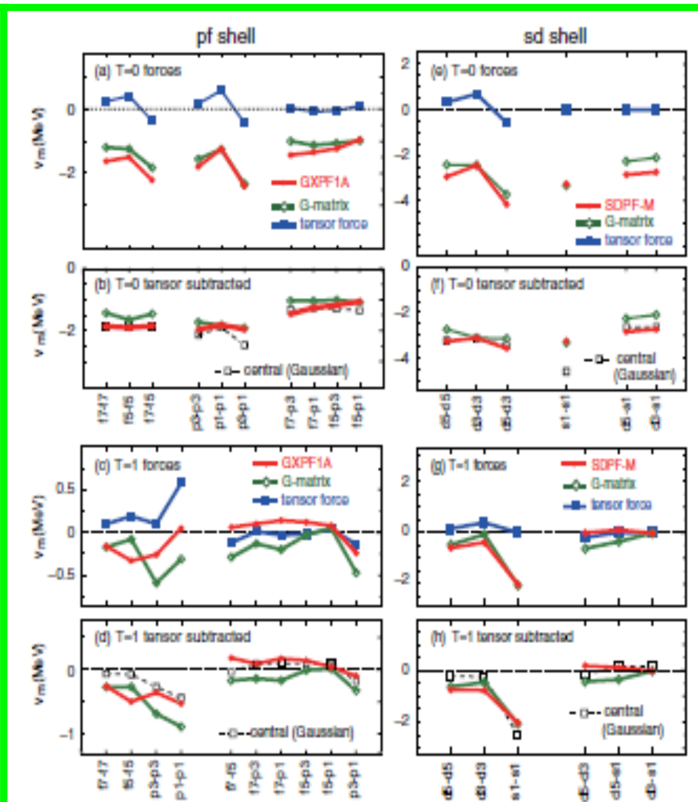
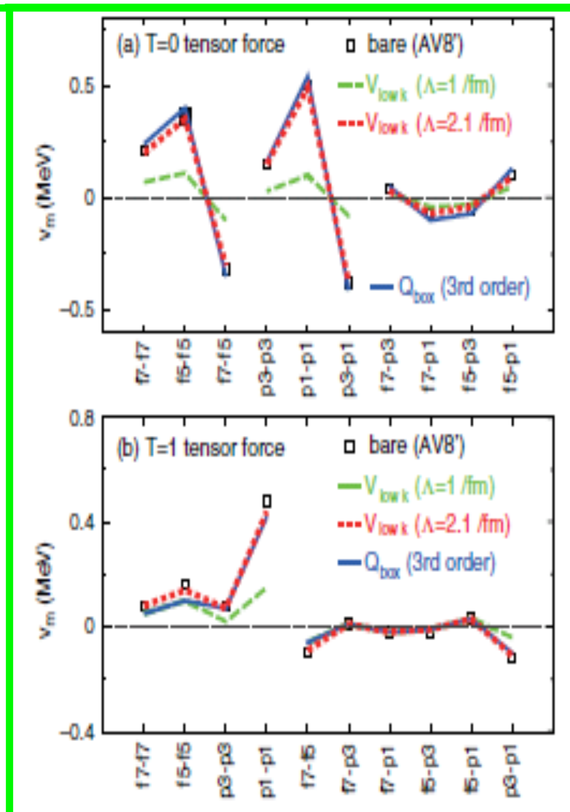
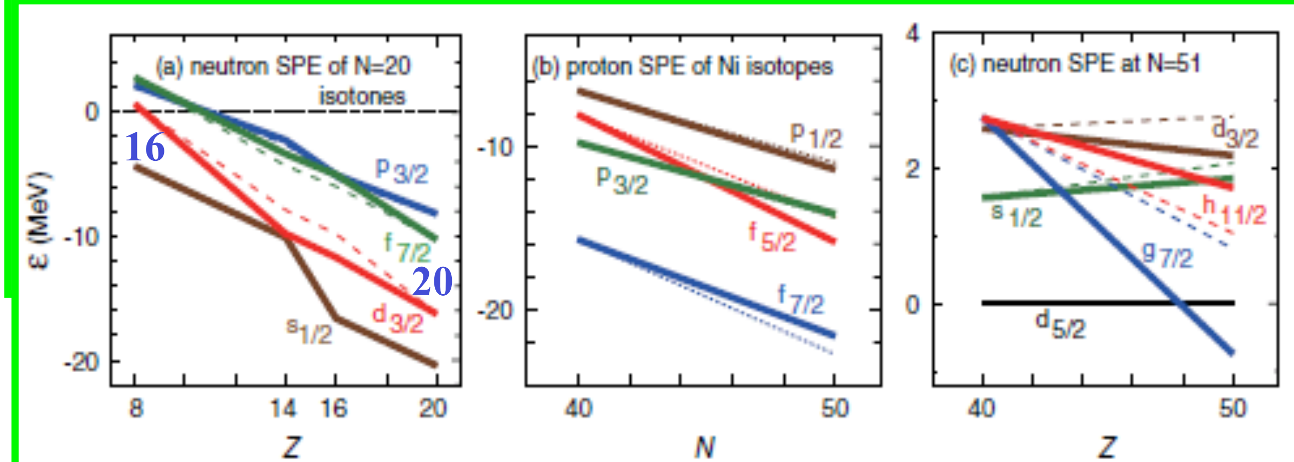


FIG. 2 (color online). Diagrams for the V_{MU} interaction.







Tensor:
bare≈renormalized

Otsuka, Suzuki, Honma, Utsuno, Tsunoda, Tsukiyama, Hjorth-Jensen
PRL 104 (2010) 012501

$^{40}Ar\ (\nu, e^-)\ ^{40}K$

SDPF-VMU

sd: SDPF-M (Utsuno et al.)

fp: GXPF1 (Honma et al.)

sd-pf: VMU

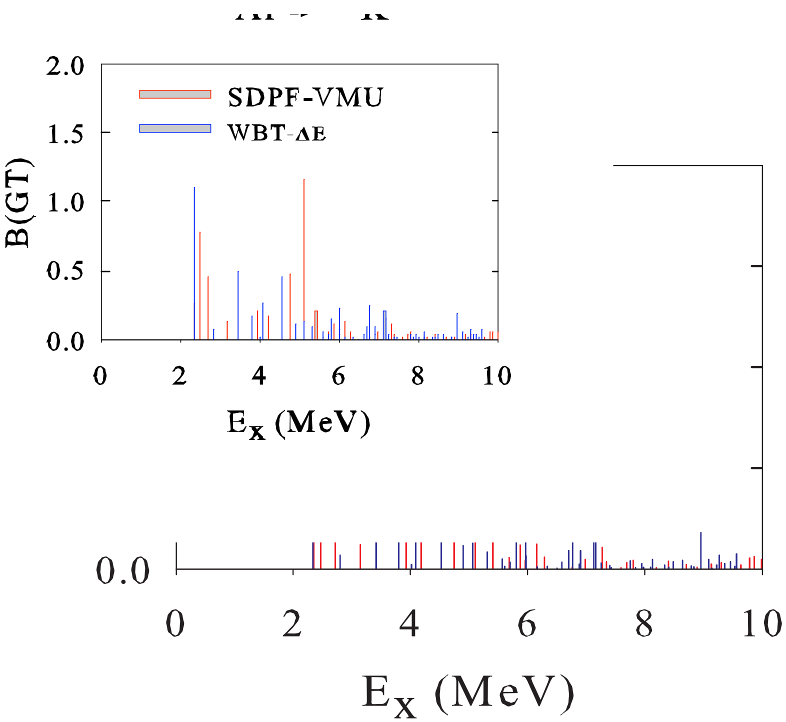
$(sd)^{-2}\ (fp)^2$: 2hw

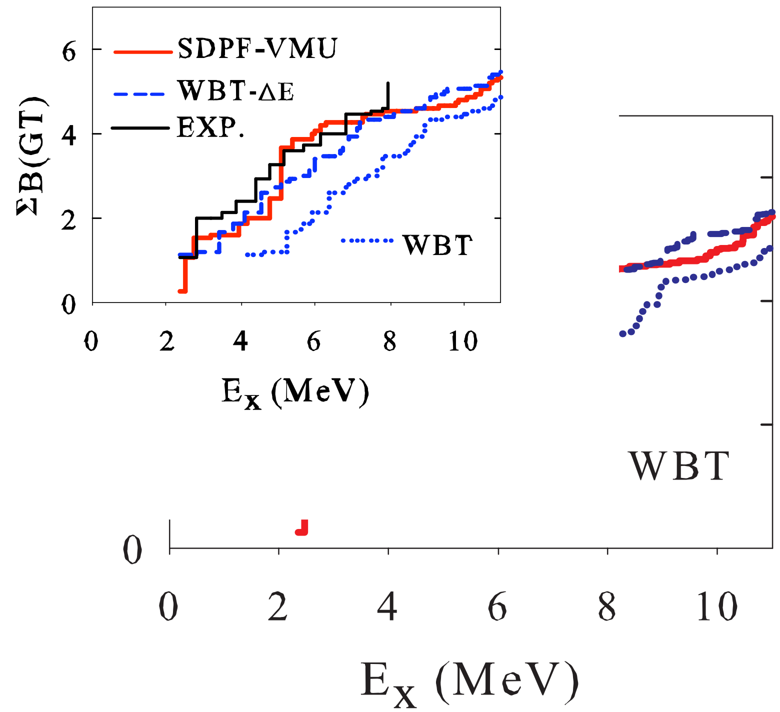
B(GT)

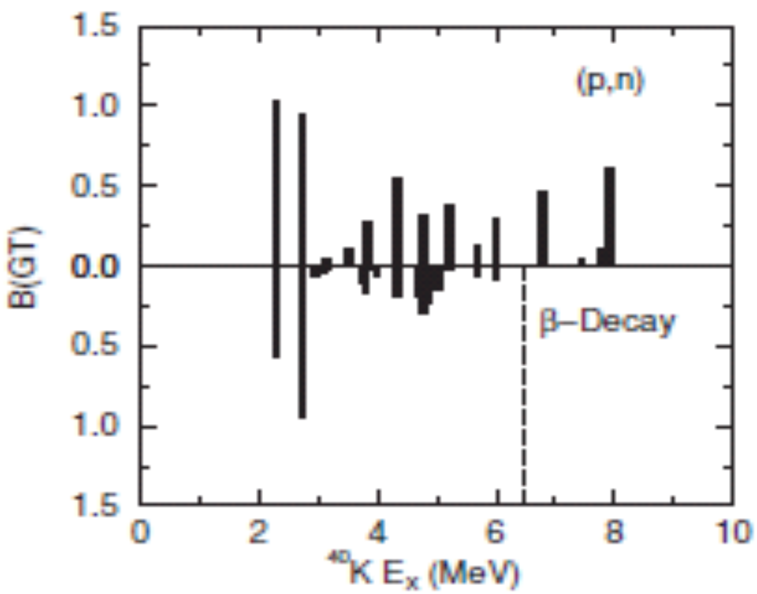
ν-^{40}Ar cross sections

Solar ν cross sections folded over ^{8}B ν spectrum

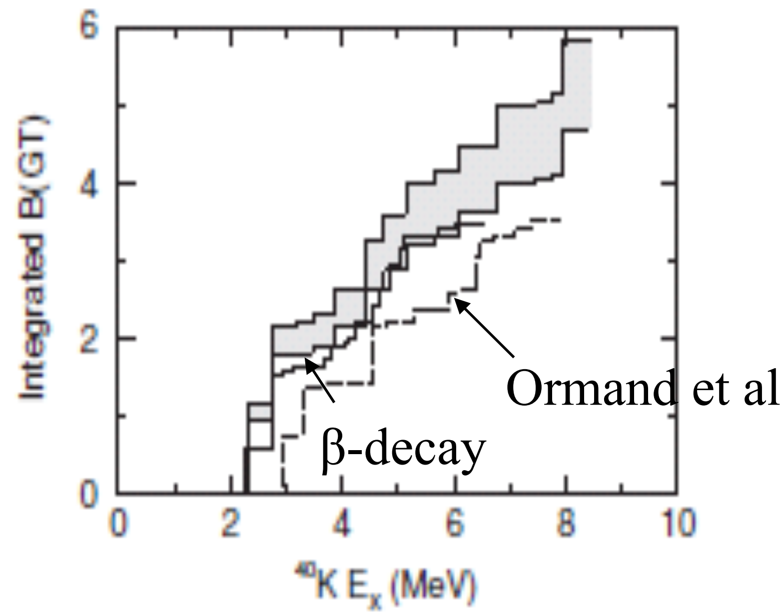
$B(GT) = \Sigma|\langle f||f_q \sigma t_-||i\rangle|^2$ $f_q = 0.775$ (Ormand et al.)

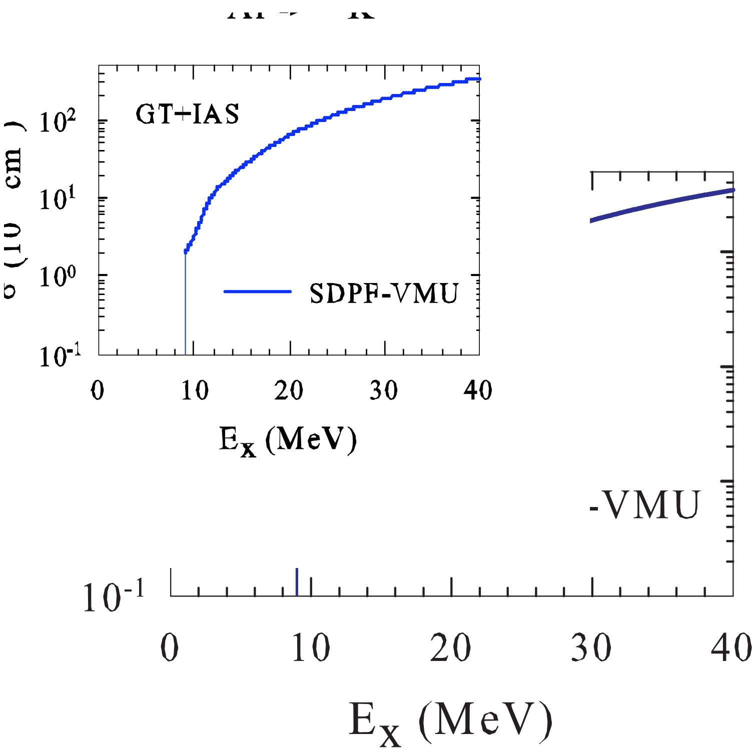






(p,n) Bhattacharya et al., PR C80 (2009)





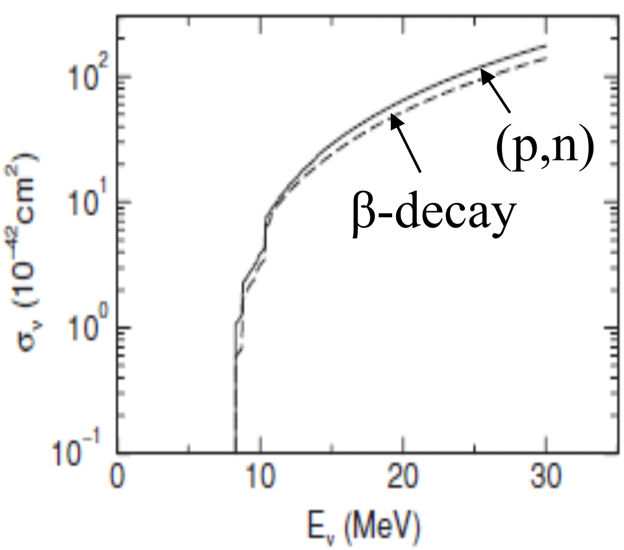
GT+IAS
$E_e > 5$ MeV : ICARUS

Solar ν cross sections
folded over ^{8}B ν spectrum

	GT	IAS	GT+IAS
SDPF-VMU:	10.36	1.94*	$12.3 \times 10^{-43} cm^2$
WBT-ΔE:	10.18	1.94	12.1
(WBT:	2.65	1.94	4.6)
Ormand et al,:	7.7^{++}	3.8^{+}	11.5

(PL B345, 343 (1995))

IAS: * $C0+L0 \approx [(q^2-\omega^2)/q^2]^2 \times C0$
$^{+}$ C0 only
GT: $E_1^5 + M1 + C_1^5 + L_1^5$
$^{++}$ E_1^5 only



(p,n) Bhattacharya et al., PR C80, 055501 (2009)

○ **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)

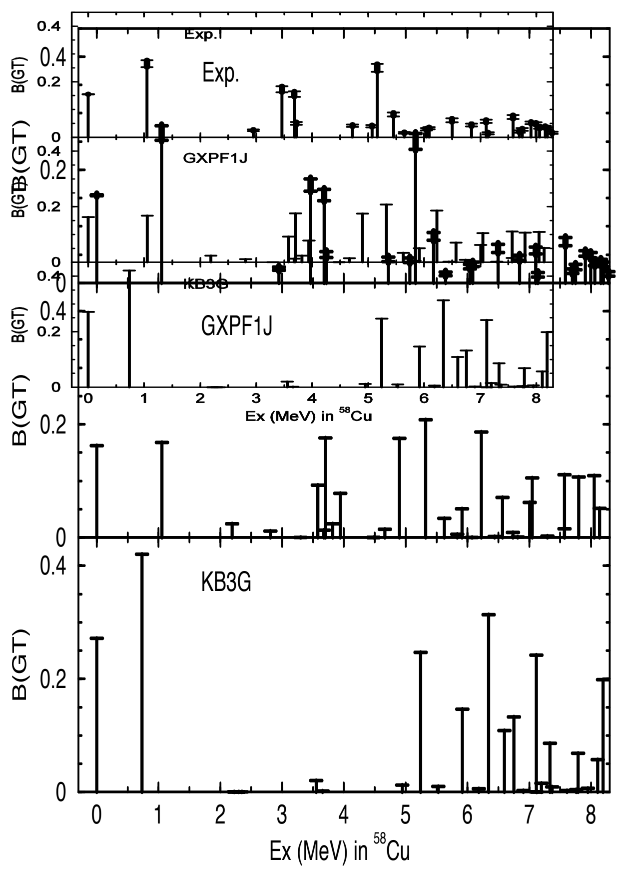
- ○ KB3G A = 47-52 KB + monopole corrections
- ○ GXPF1 A = 47-66

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

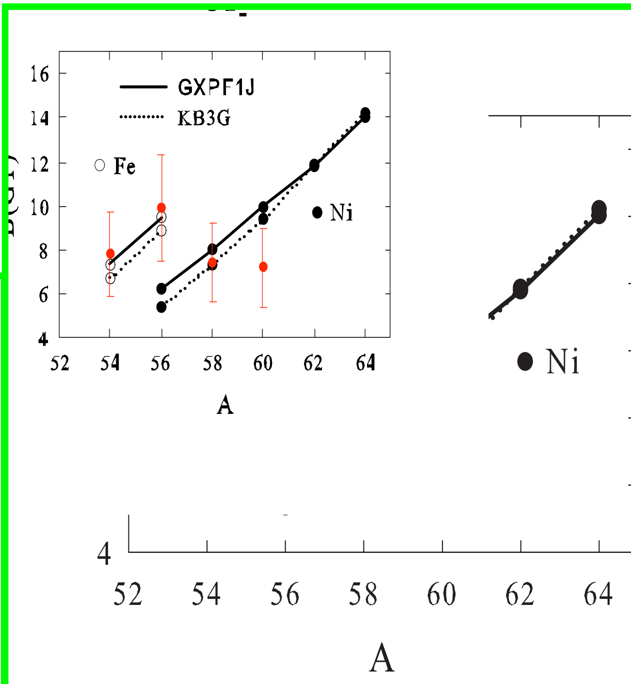
- **GT Strengths in Ni and Fe Isotopes and M1 strengths in fp-shell nuclei**

fp-shell
B(GT_) for 58Ni

Exp: Fujita et al.



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

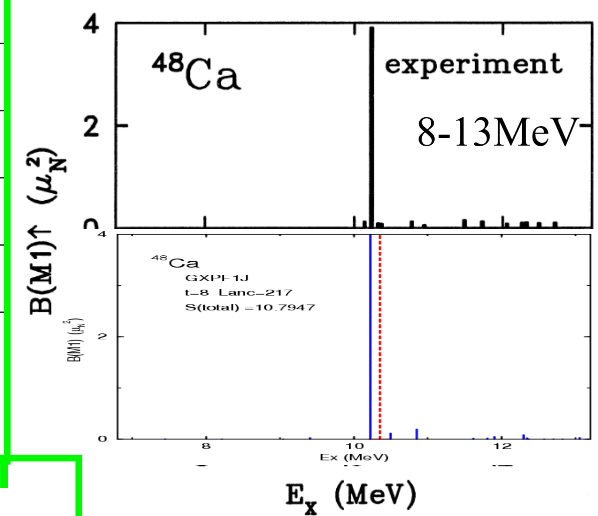


B(GT$_+$)

	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

M1 strength (GXPF1J)

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



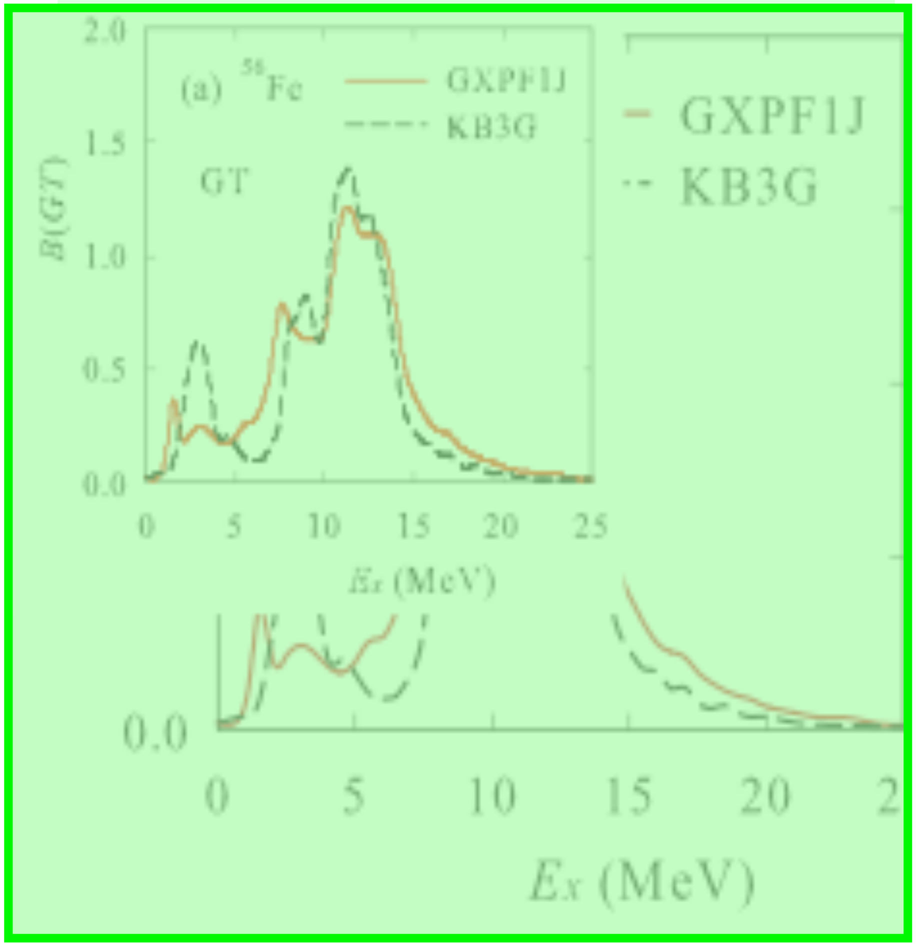
Honma

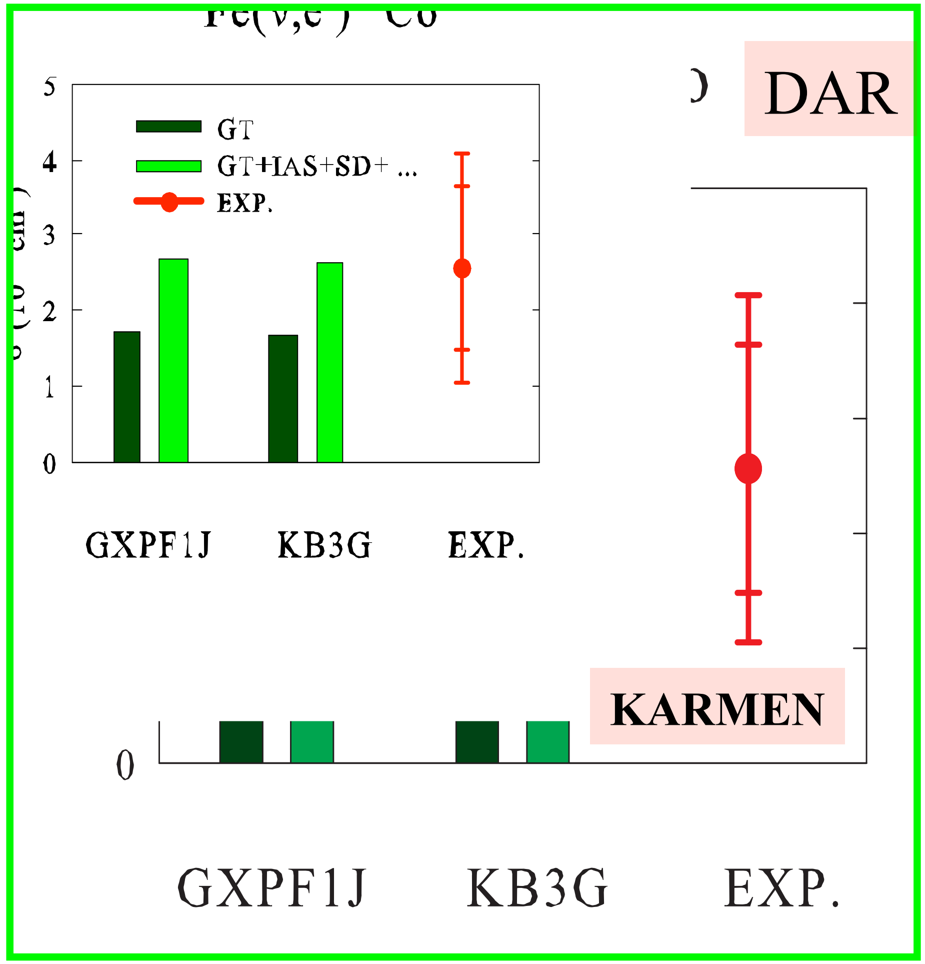
EXP: GT$_-$; Rapaport et al., NP A410, 371 (1983)
$0<E_x<13$-15 MeV
GT$_+$; Caurier et al., NP A653, 439 (1999)
$0<E_x<8$ MeV

$^{56}Fe(\nu_e, e^-)^{56}Co$

GXPF1J Honma et al.

cf. KB3 Caurier et al.





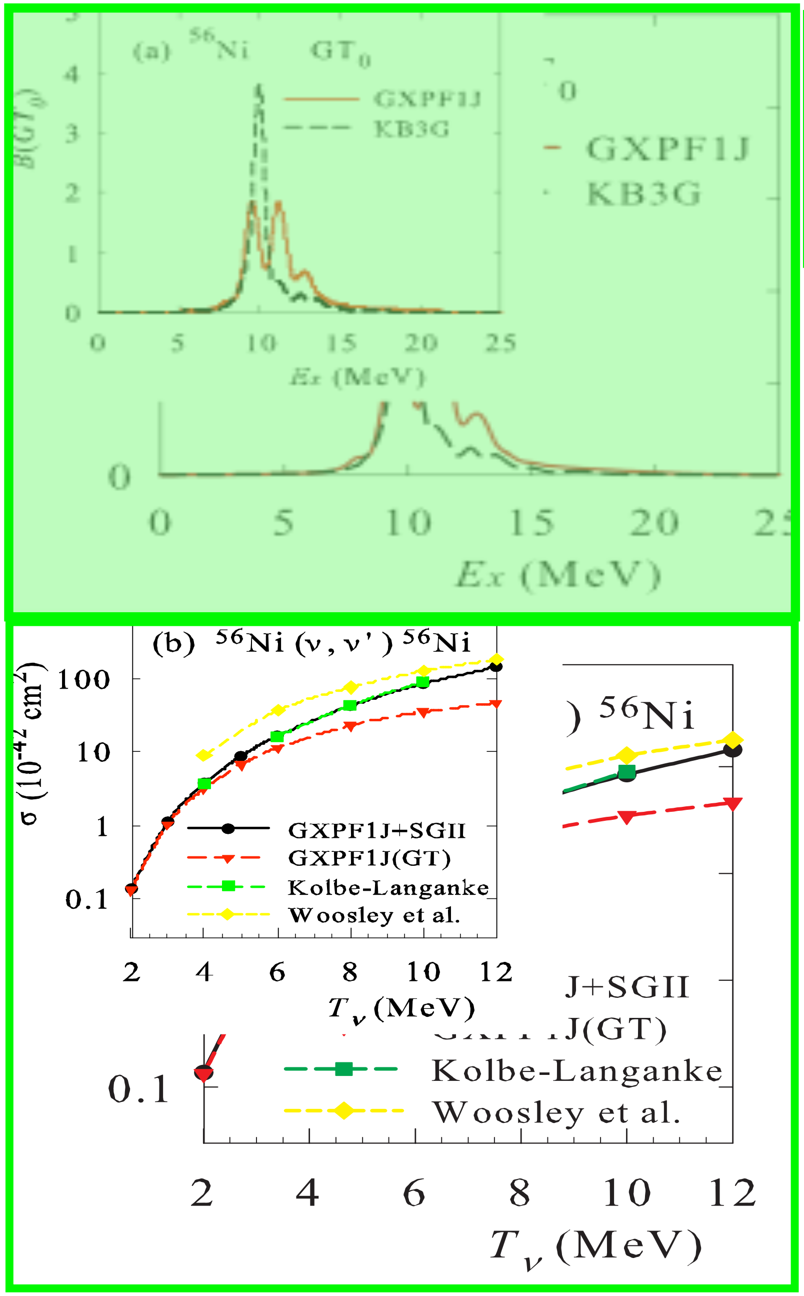
B(GT)=9.5

$B(GT)_{exp}$=9.9±2.4

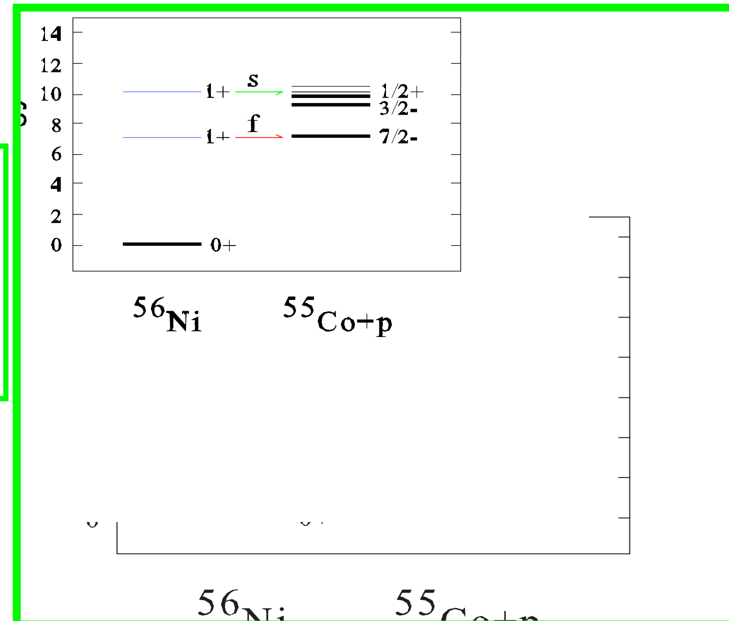
$B(GT)_{KB3G}$=9.0

SD + … : RPA (SGII)

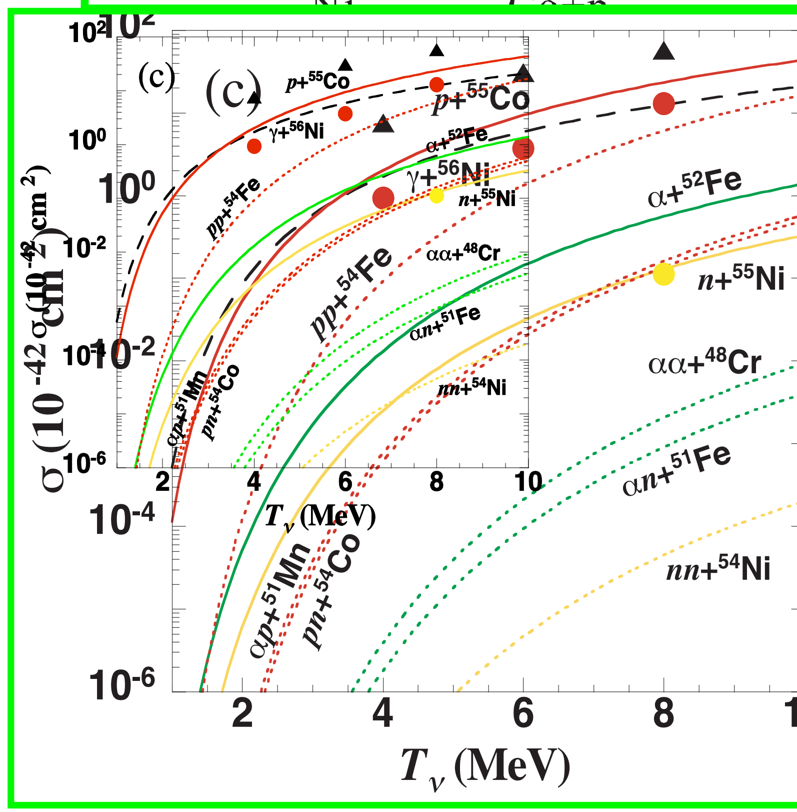
•Neutral current reaction on ^{56}Ni



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

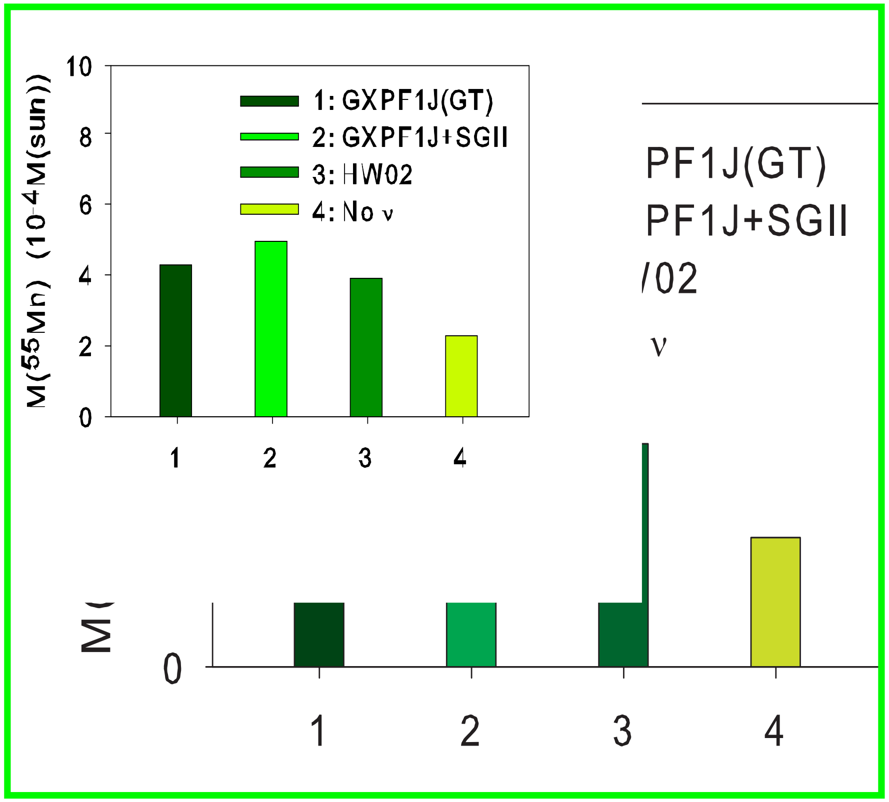


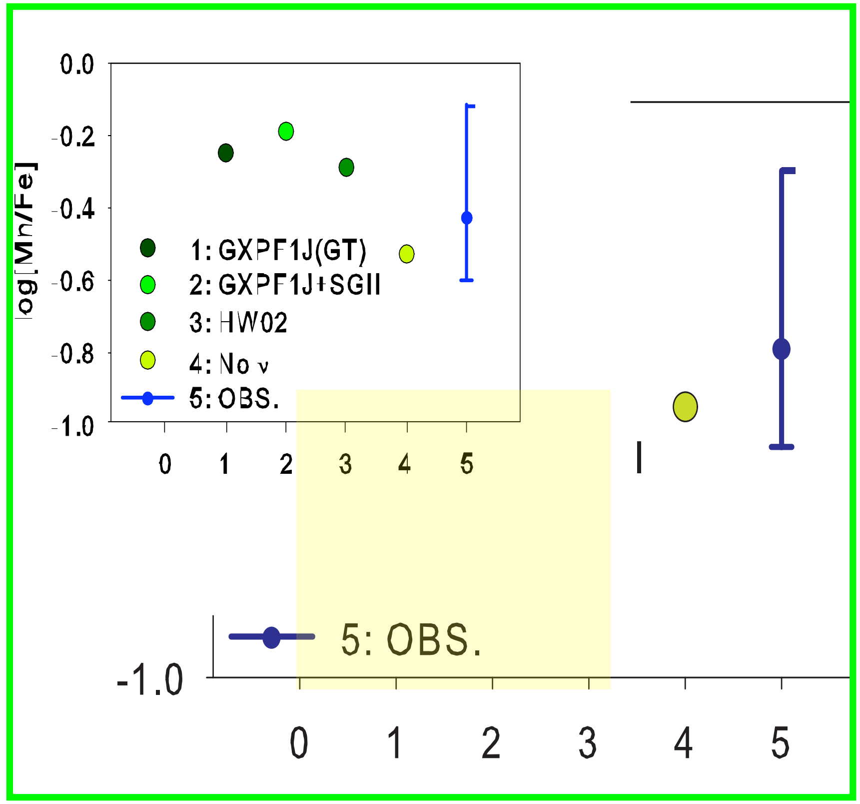
cf:
HW02
▲gamma
● p
○ n



Synthesis of Mn in Population III Star

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





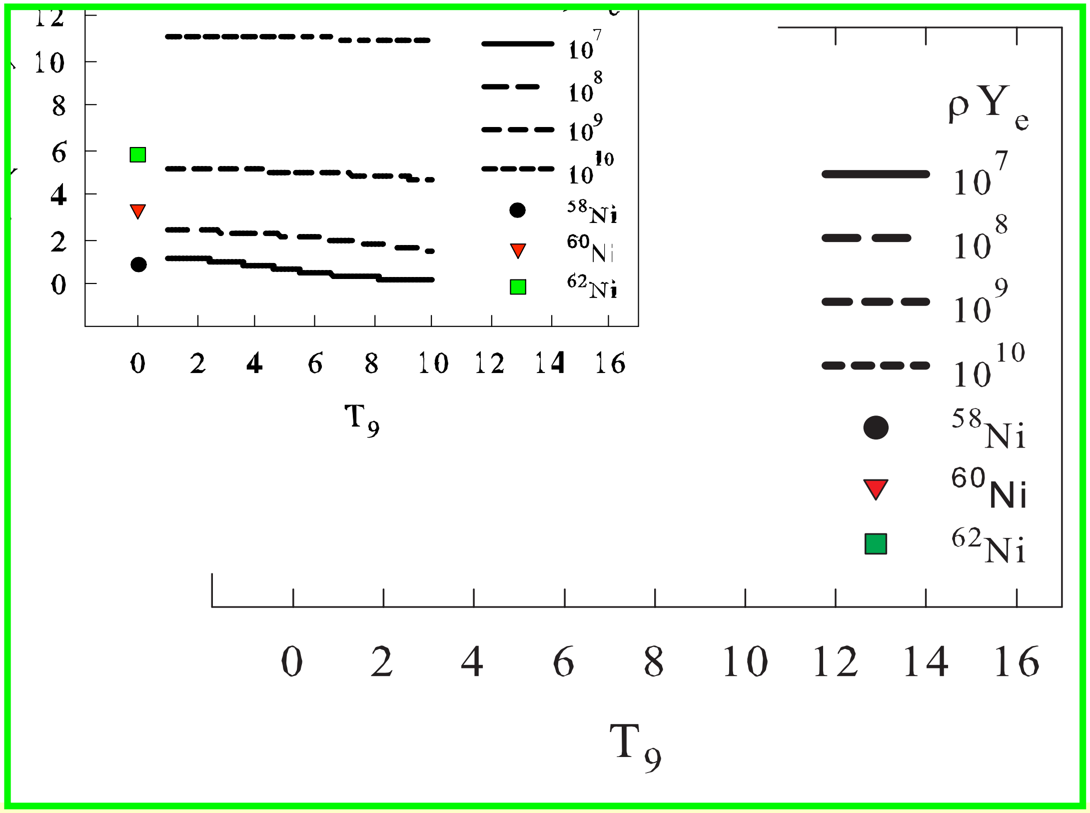
$^{54}Fe(p,\gamma)^{55}Co$

Yoshida, Umeda, Nomoto

Suzuki et al., PR C79 (2009)

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

•Electron-capture rate in steller environment



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

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

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

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

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

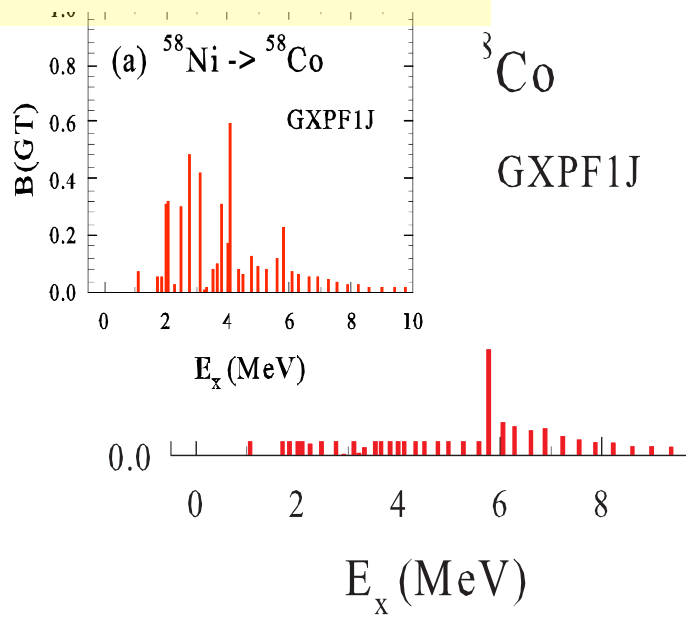
$$\lambda = \frac{\ln 2}{6146(s)} \sum_j B_j(GT) \int_{\omega_e}^{\infty} \omega p (Q_j + \omega)^2 F(Z,\omega) S_e(\omega) d\omega$$

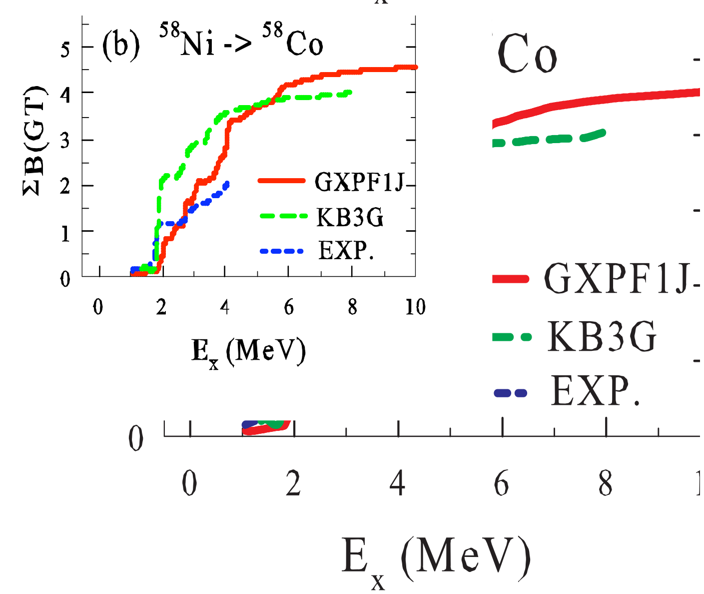
$$Q_j = (M_p c^2 - M_d c^2 - E_j)/m_e c^2$$

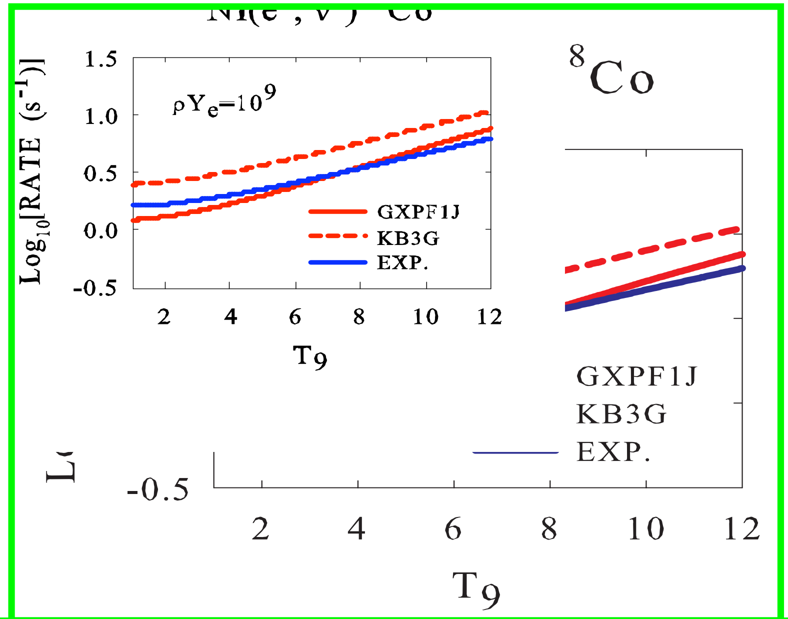
$$T = T_9 \times 10^9 K, \qquad S_e(E_e) = \frac{1}{\exp[(E_e - \mu_e)/kT] + 1}$$

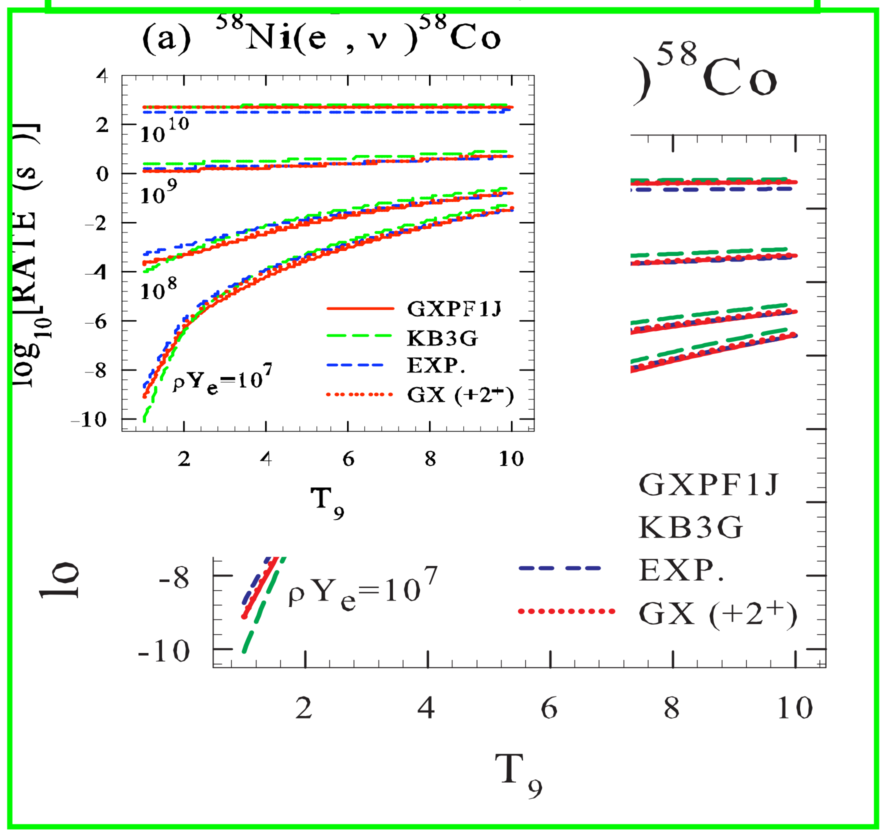
$$\rho Y_e = \frac{1}{\pi^2 N_A} \left(\frac{m_e c}{\hbar}\right)^3 \int_0^{\infty} (S_e - S_p) p^2 dp \qquad \mu_p = -\mu_e$$

$^{58}Ni \rightarrow {}^{58}Co$



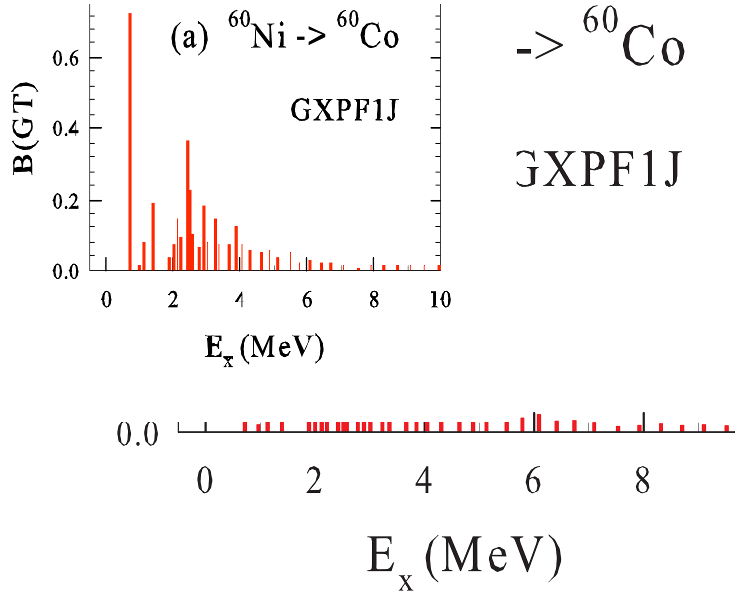


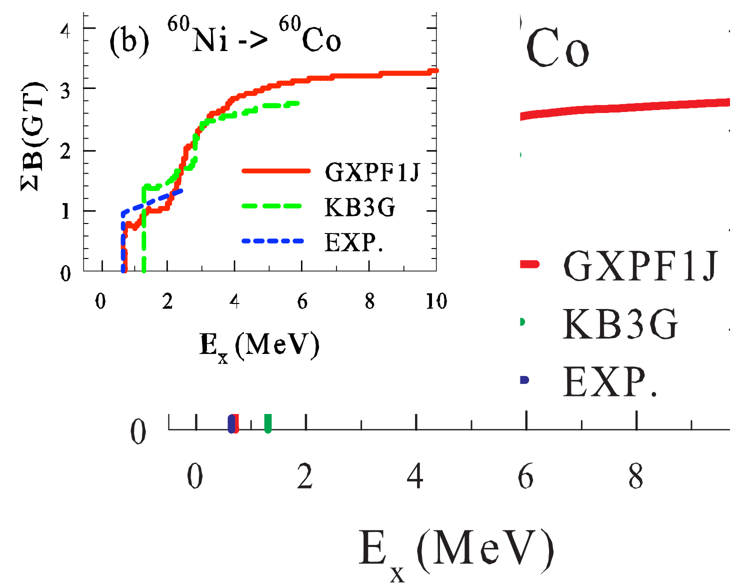


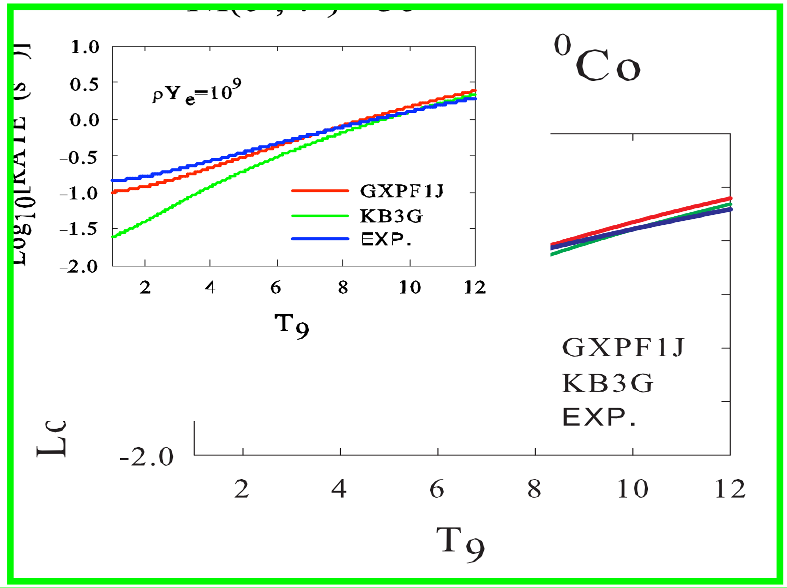


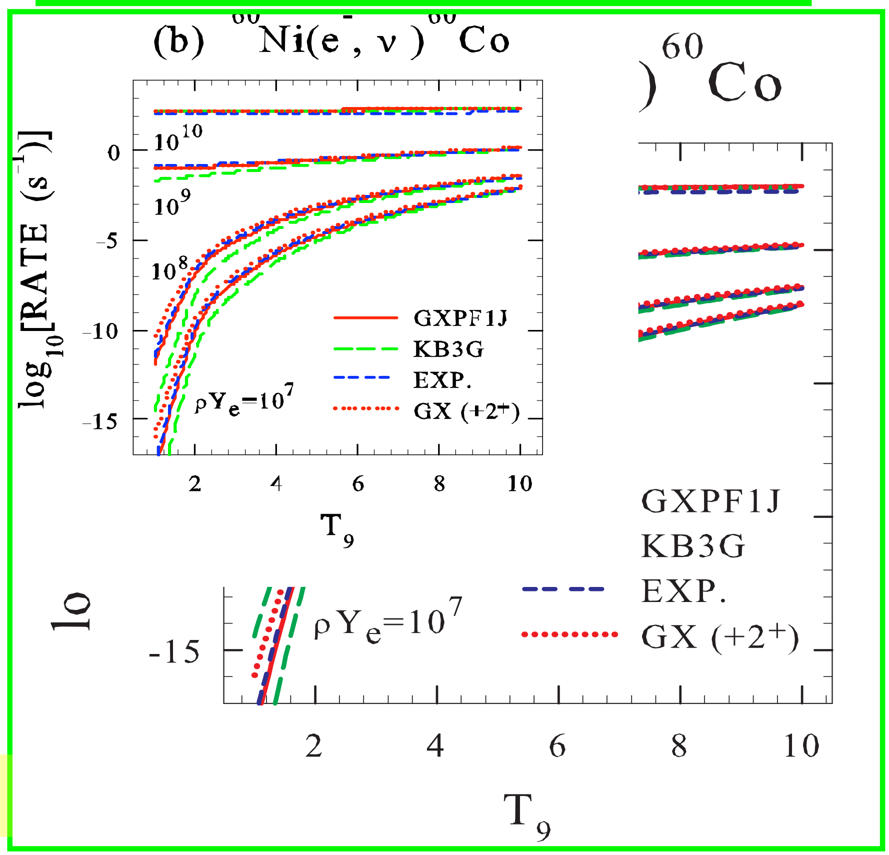
Exp: Hagemann et al., PL B579 (2004)

$^{60}Ni \rightarrow {}^{60}Co$









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

Summary

- **New shell model Hamiltonians with proper tensor interaction**
- **→ new ν-nucleus reaction cross sections in ^{12}C and ^{16}O**

  Enhancement of production rate of ^{7}Li, ^{11}B

  Cross sections in ^{16}O: shell model ~ CRPA

  Contamination effect of ^{13}C ~a few %

  sd-pf-VMU: ^{40}Ar (ν,e^{-}) ^{40}K for solar ν
- **ν-^{56}Fe cross sections (DAR), electron capture rates in ^{58}Ni and ^{60}Ni are well described by a new shell model Hamiltonian, GXPF1J.**

  ν-^{56}Ni → enhancement of production of Mn

Collaborators

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B. Balantekin (Wisconsin) for the ^{13}C problem

70   77   80   88   90   99   100

110   111   120 ….

VMU= Monopole based Universal Interaction

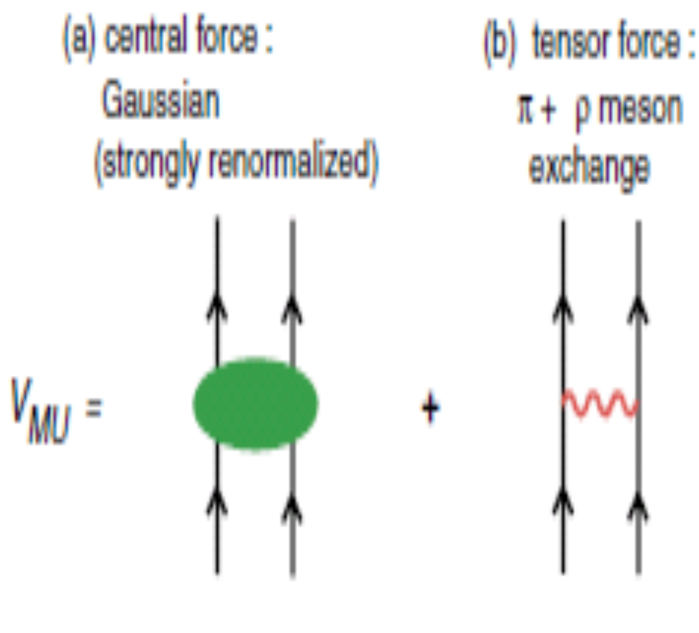


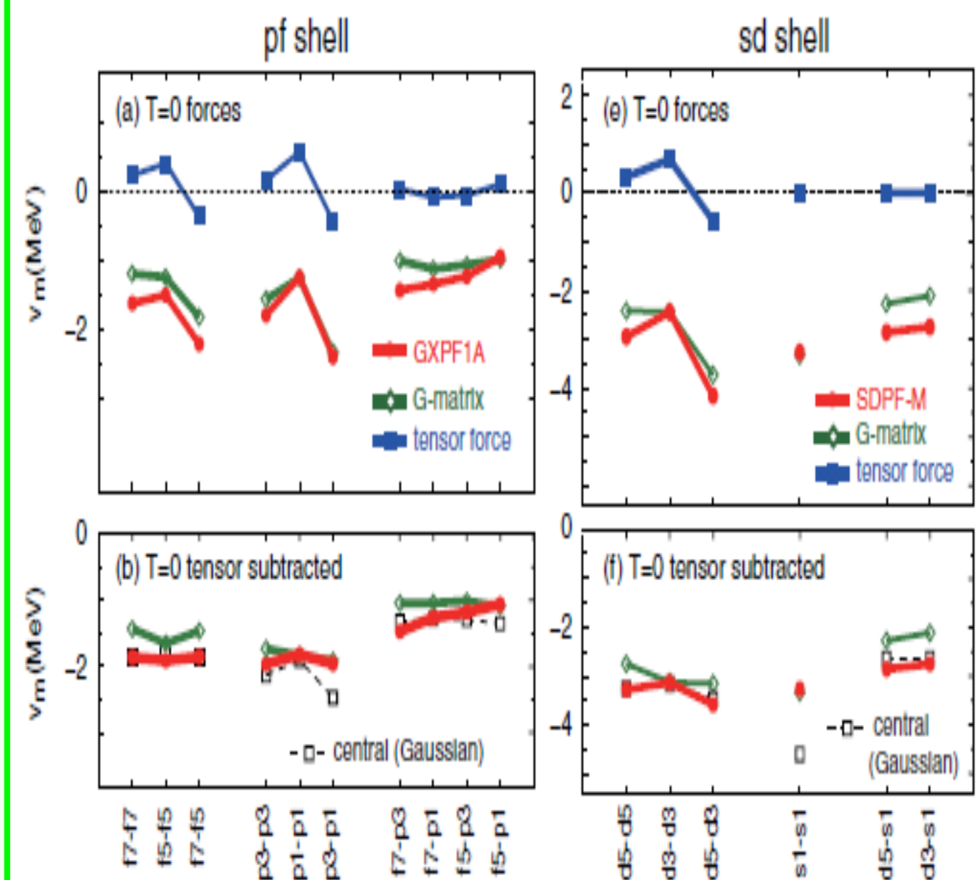
FIG. 2 (color online). Diagrams for the V_{MU} interaction.

- **Important roles of tensor force**

→ SFO (p, p-sd)
(Suzuki-Fujimoto-Otsuka)

Monopole terms in V_{nn}

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



tensor force