Neutrino-Nucleus Reactions based on Recent Structure Studies

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NuInt12

Oct. 23, 2012

- New shell-model Hamiltonians and successful description of Gamow-Teller (GT) and spin-dipole (SD) strengths

SFO (p-shell): GT in ^{12}C, ^{14}C

Suzuki, Fujimoto, Otsuka, PR C69, (2003)

GXPF1J (fp-shell): GT in Ni isotopes

Honma, Otsuka, Mizusaki, Brown, PR C65 (2002); C69 (2004)

Suzuki, Honma et al., PR C79, (2009)

VMU (monopole-based universal interaction)

∗ important roles of tensor force

- ν-^{12}C and ν-^{13}C with SFO
- ν-^{56}Ni and e-captures on Ni isotopes with GXPF1J
- ^{40}Ar (ν, e^-) ^{40}K with VMU

Shell-model interactions

● Phenomenological interaction

single particle energies + fitted two-body matrix elements

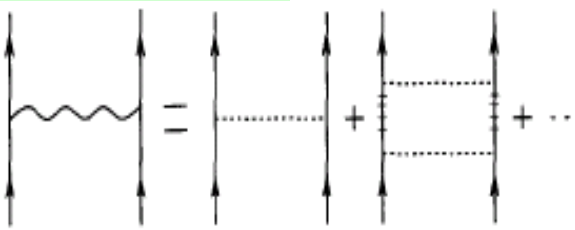
e.g. p-shell: Cohen-Kurath (1965), sd: USD (1988)

p-sd: Millener-Kurath (1975)

● Microscopic interaction derived from NN interaction

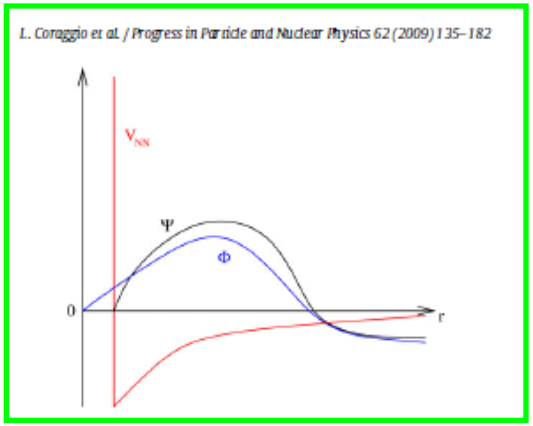
1. Renormalization of repulsive core part of NN interaction

G-matrix:



sum of ladders

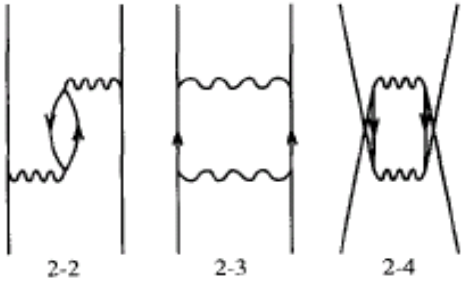
Hjorth-Jensen et al.,
Phys. Rep. 261, 125 (1995)



V_{low-k}: integrating out high momentum components of two-nucleon interaction

2. Effective interaction of truncated model space

core-polarization effects



+ 3rd order

Good energy levels except for a few cases:
e.g. closed-shell struture of ^{48}Ca can not be obtained
(3N forces can solve the problem)
Problems in saturation (binding energies)

- Improvements of G-matrix by monopole corrections

Poves, Zuker, Phys. Rep. 70, 235 (1981)

Monopole terms

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

Effective single-particle energy:

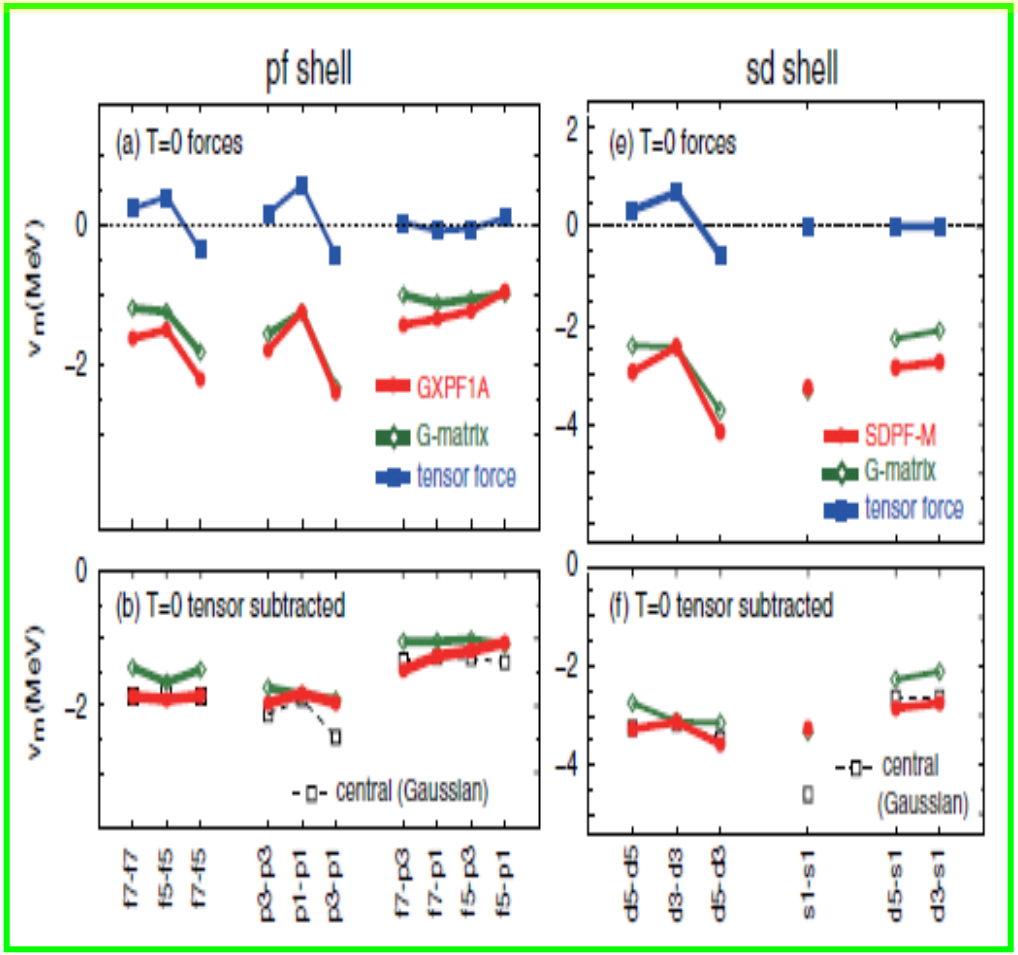
$$E_{eff}(\nu j) = \varepsilon(\nu j) + \sum_{j'} n(\nu j') V_M^{T=1}(j, j') + \sum_{j'} n(\pi j') V_M^{np}(j, j')$$

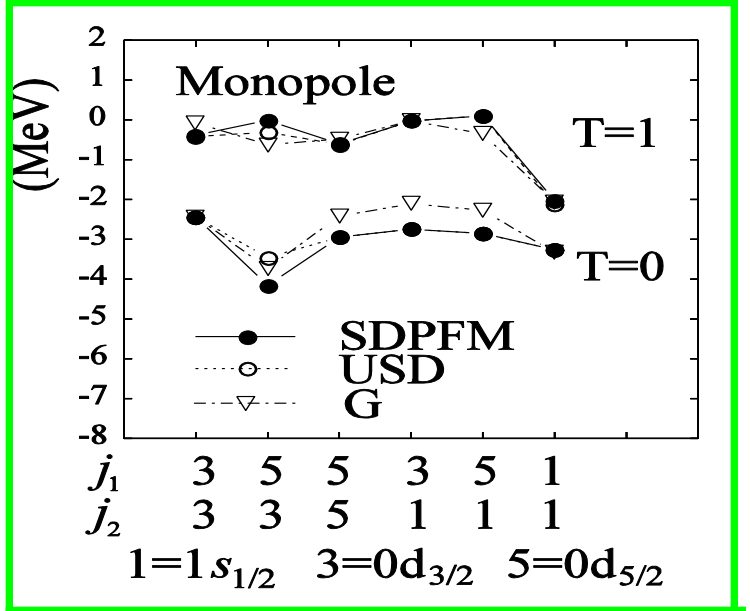
$\varepsilon(\nu j) =$ s.p.e for the core

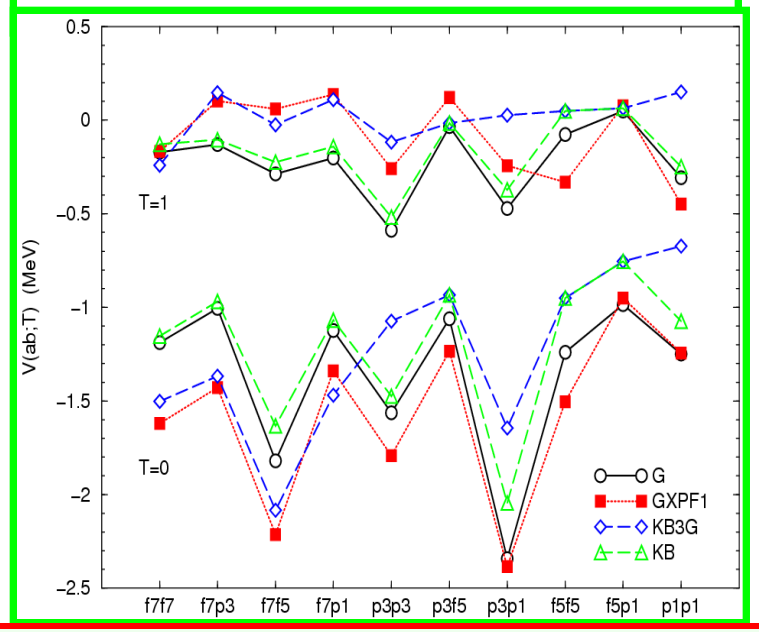
* New phenom. interactions with monopole corrections

sd-pf: SDPF-M (1999)* → successful descriptions of
pf: KB3 (2001)*, GXPF1 (2004)* energies and transitions

Monopoles:
G-matrix vs phenom. interactions







tensor force: $\pi + \rho$ -exchange

Three-body force

more repulsion than G in T=1
more attraction than G in T=0

● Important roles of tensor force

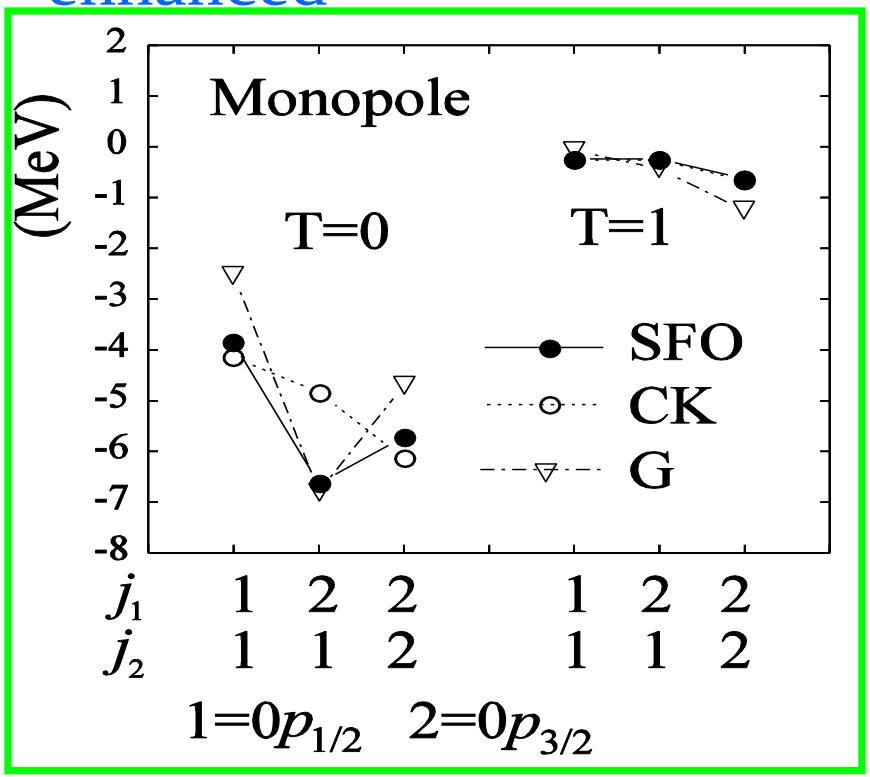
- SFO: p-shell p-sd space up to 2-3 hw excitations
  CK-MK (p: Cohen-Kurath, p-sd: MK, sd: G-matrix)

→ Enhancement of spin-isospin channel of monopole terms

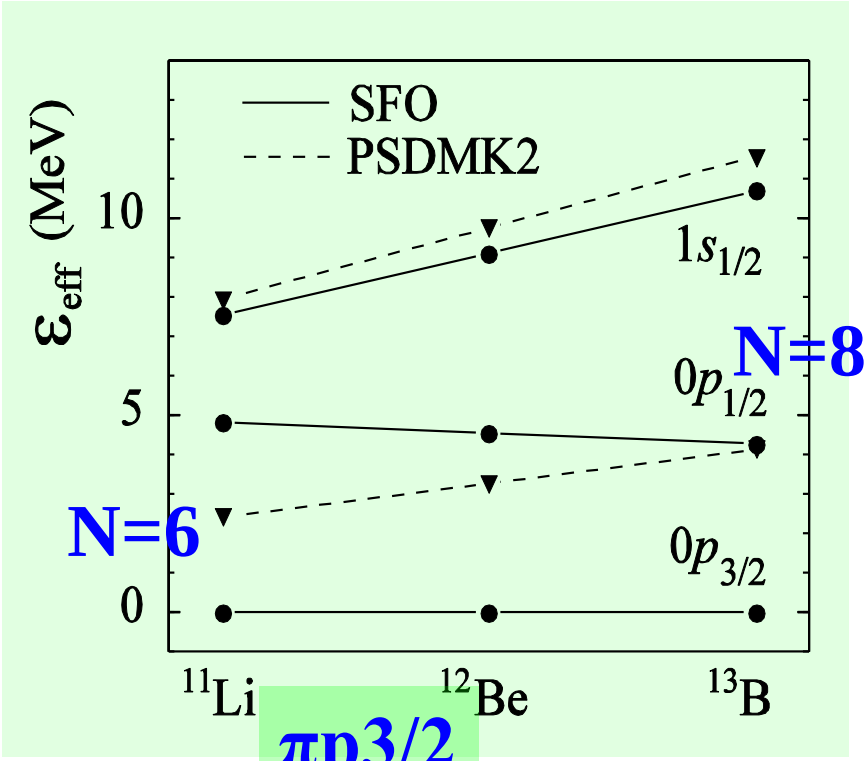
Monopole terms

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

p1/2-p3/2 (T=0) is enhanced



Shell evolution in N=8 isotones



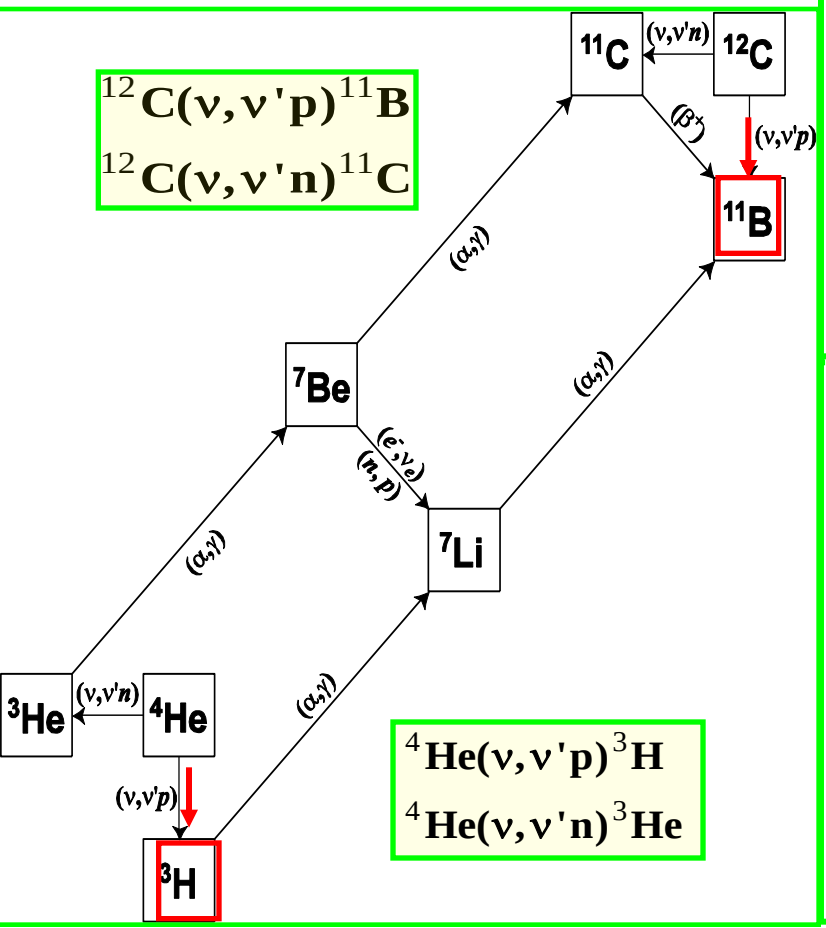
SFO p-sd shell

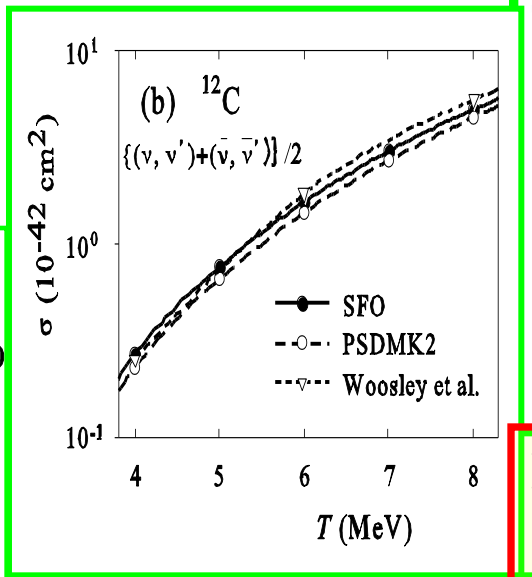
Suzuki, Fujimoto, Otsuka, PR C67, 044032 (2003)

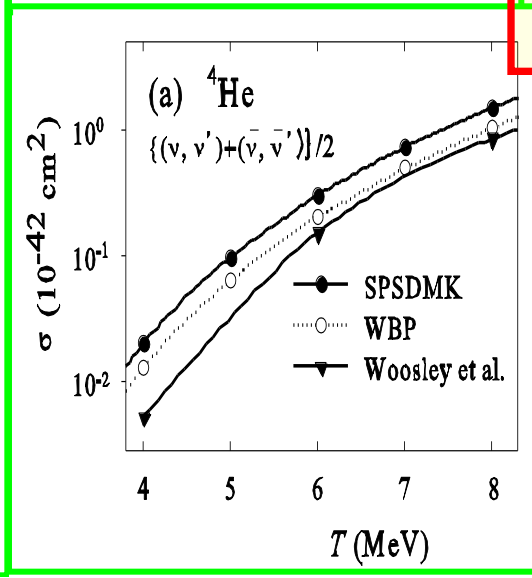
GT stengths in ^{12}C: reproduced with $g_A^{eff}/g_A=0.95$

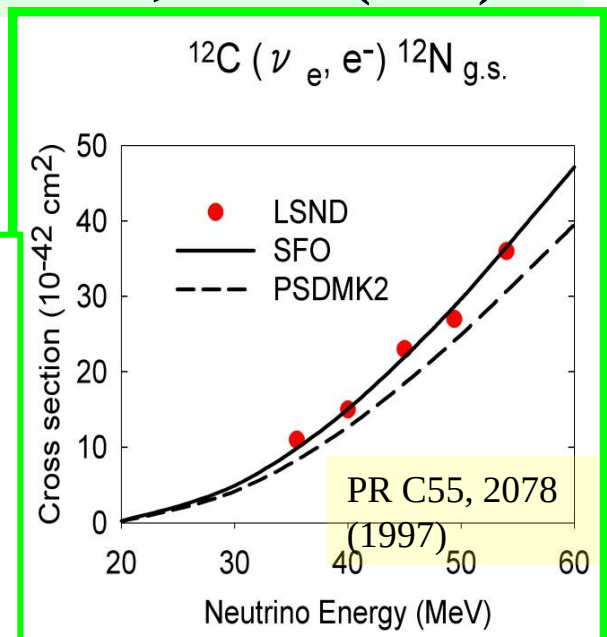
Nearly vanishing GT strength in ^{14}C

Nucleosynthesis processes of light elements



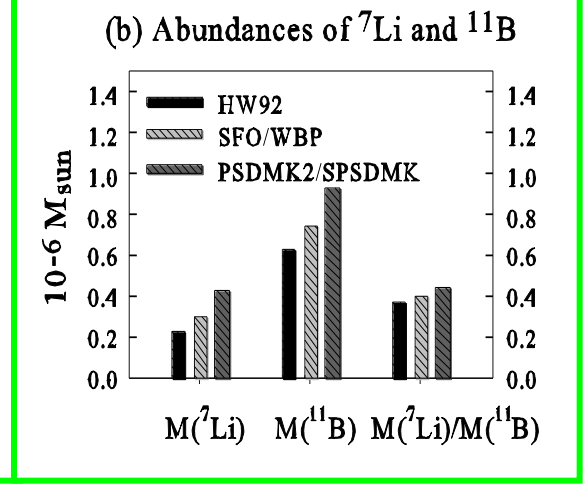






PR C55, 2078 (1997)

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



^{13}C: attractive target for very low energy ν: E_ν < 15 MeV

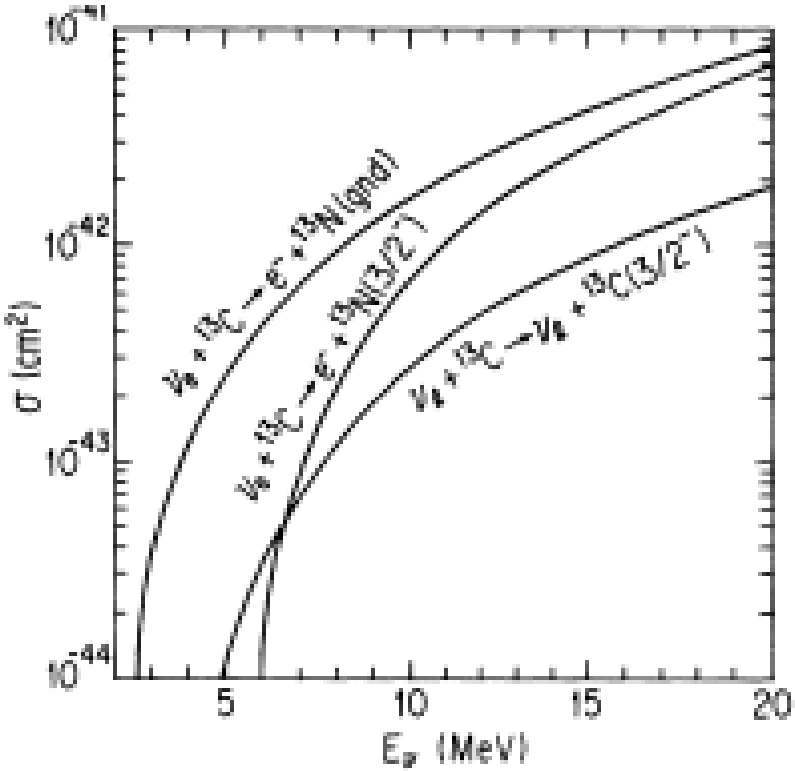
ν-^{12}C: E_ν > 15 MeV

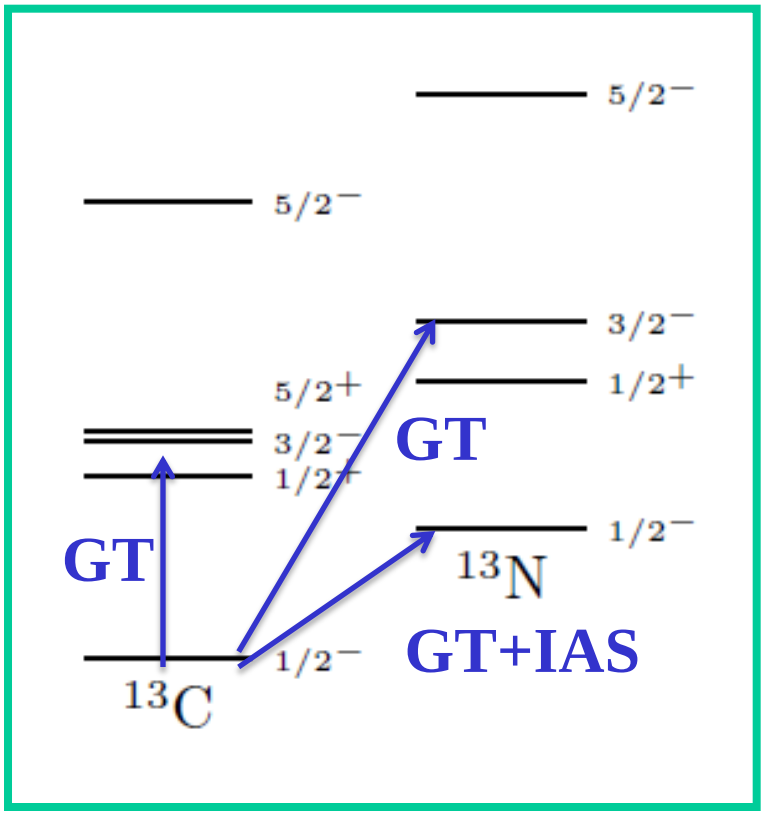
ν-induced reactions on ^{13}C

$$^{13}C(\nu_e, e^-)^{13}N$$

$$^{13}C(\nu_e, \nu_e')^{13}C$$

GT transitions





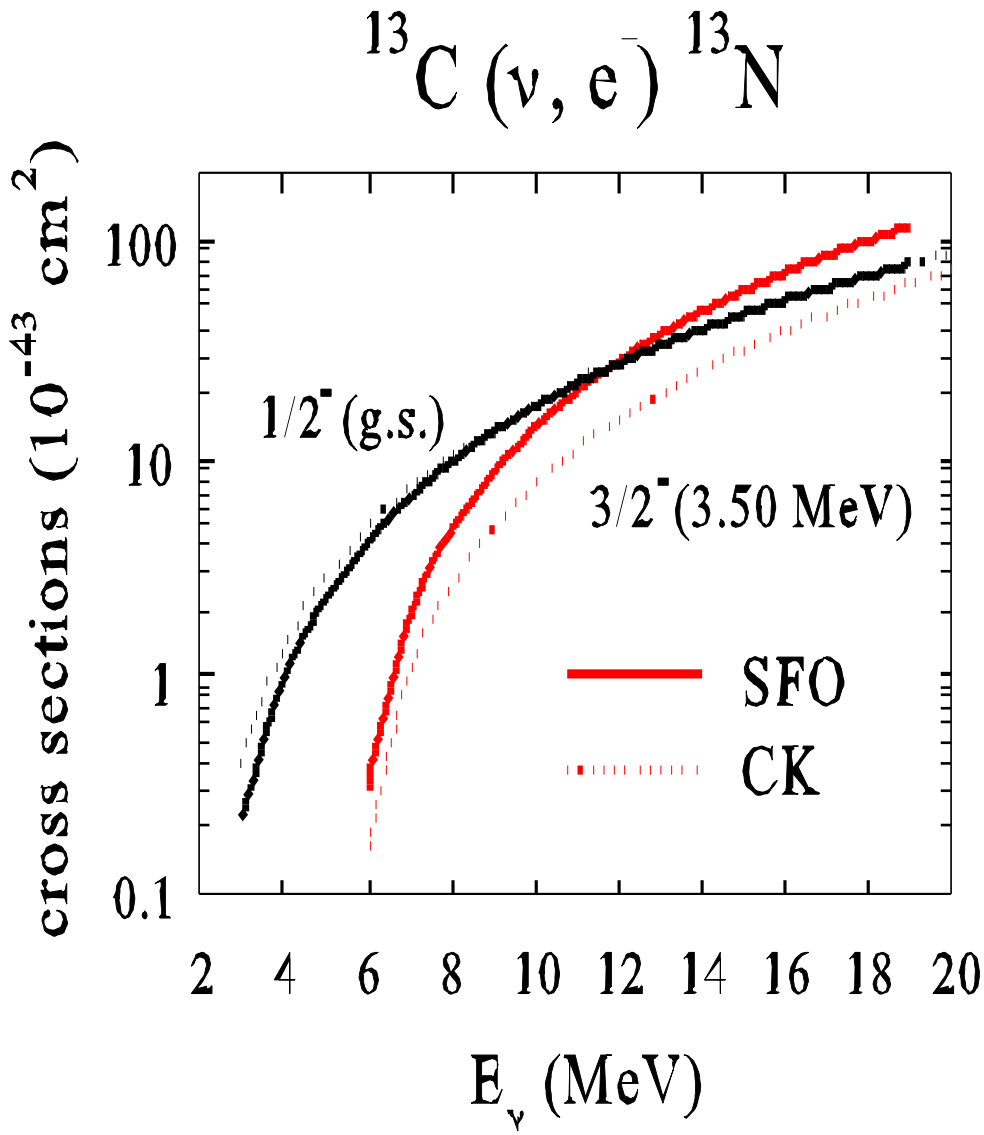
Fukugita et al., PR C41 (1990)

p-shell: Cohen-Kurath

g_A^{eff}/g_A =0.69

Detector for solar ν

p-sd shell: SFO



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

(ν_e, e^-) $[\frac{1}{2}^-$ (g.s.) $+ \frac{3}{2}^-$ (3.50MeV)$]$

CK: 1.07×10^{-42} cm^2

SFO: 1.34×10^{-42} cm^2

(ν, ν') $\frac{3}{2}^-$ (3.69MeV)

CK: 1.16×10^{-43} cm^2

SFO: 2.23×10^{-43} cm^2

Suzuki, Balantekin, Kajino, PR C (2012), in press.

○ New shell-model Hamiltonians in fp-shell:

GXPF1: Honma, Otsuka, Mizusaki, Brown, PR C65 (2002); C69 (2004)

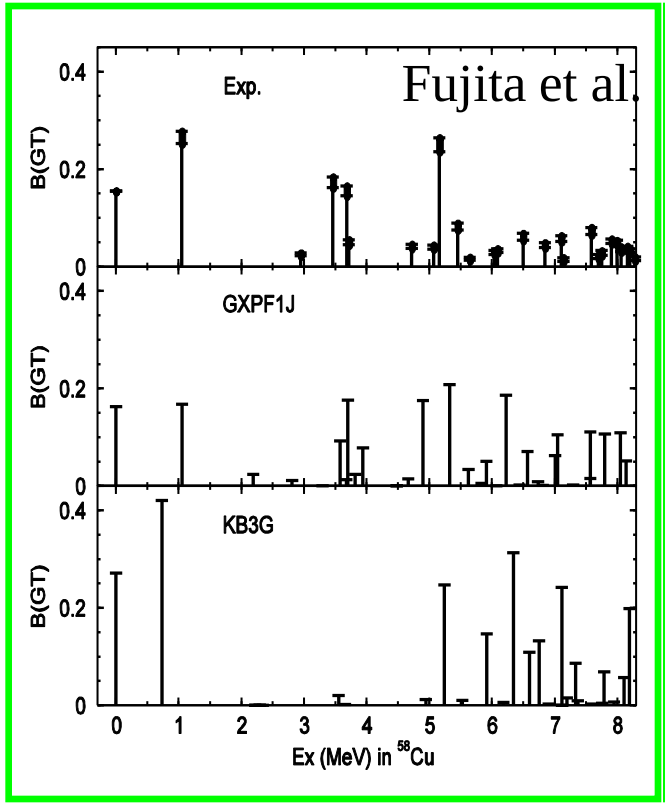
KB3: Caurier et al, Rev. Mod. Phys. 77, 427 (2005)

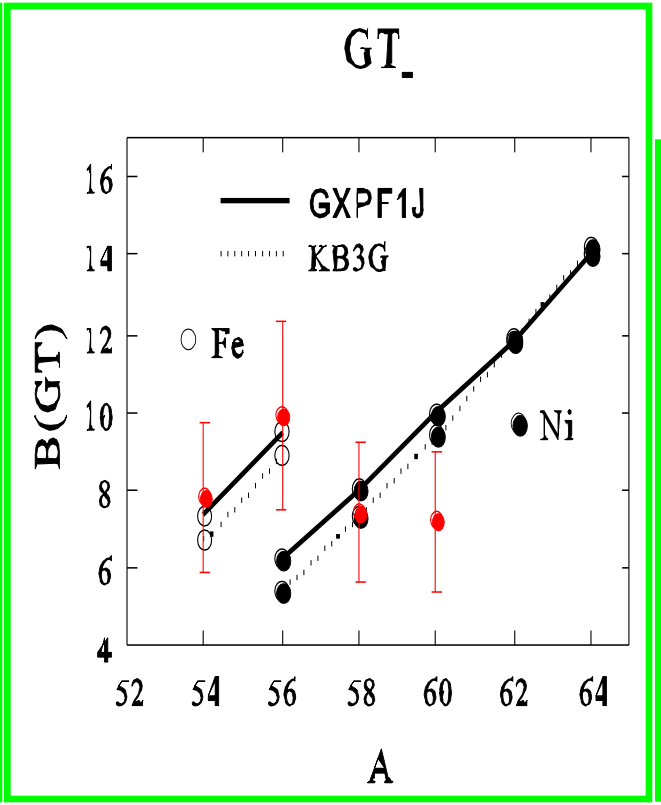
- ○ KB3G A = 47-52 KB + monopole corrections
- ○ GXPF1 A = 47-66

▪ **Spin properties of fp-shell nuclei are well described**

B(GT$_-$) for ^{58}Ni

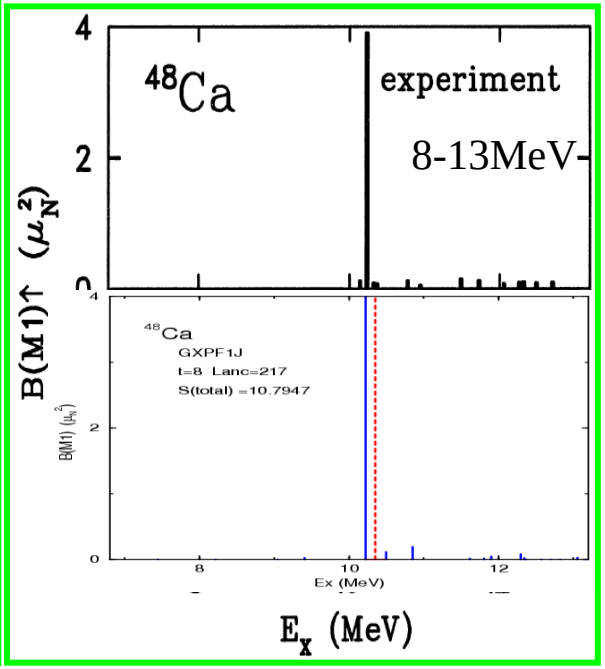
$g_A^{eff}/g_A^{free}=0.74$





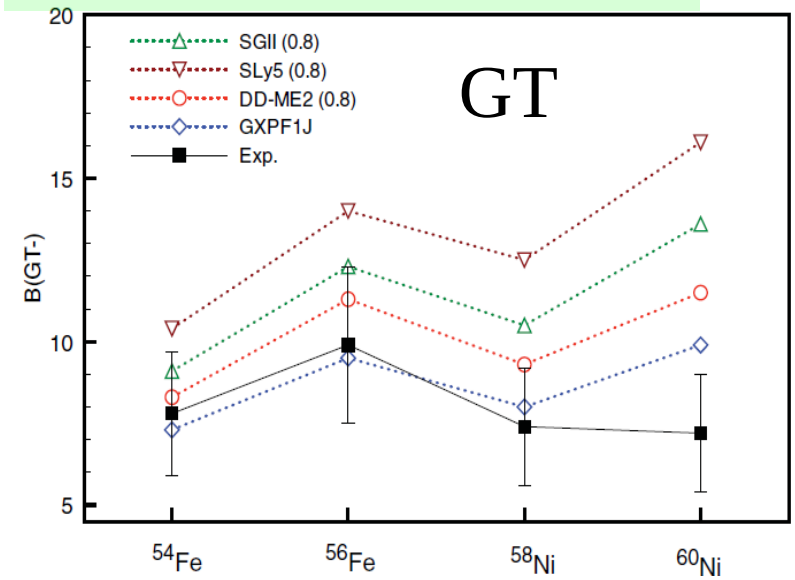
M1 strength (GXPF1J)

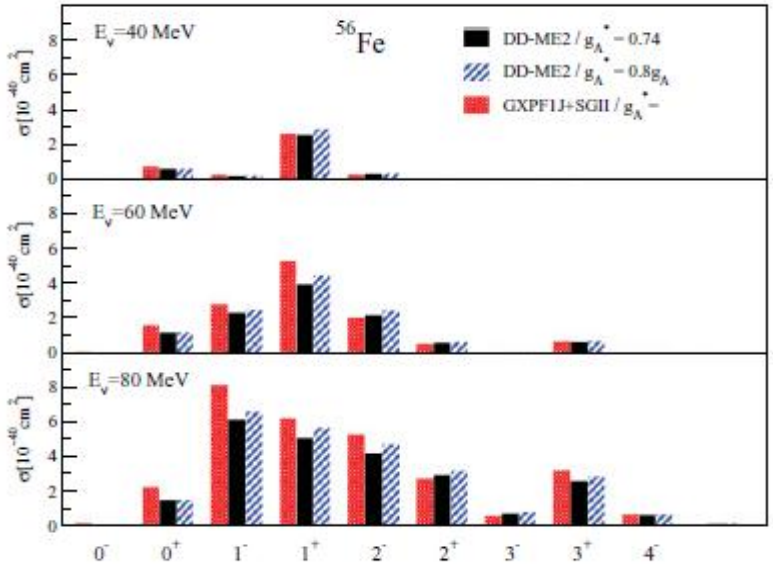
$g_S^{eff}/g_S=0.75\pm0.2$

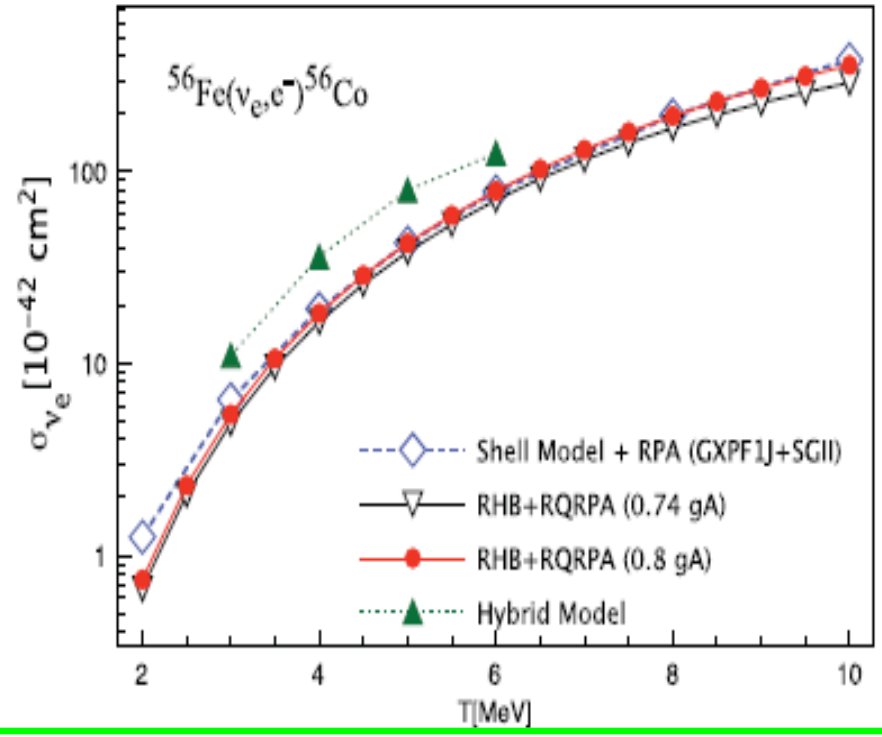


$^{56}Fe(\nu_e, e^-)^{56}Co$

RQRPA vs Shell-model







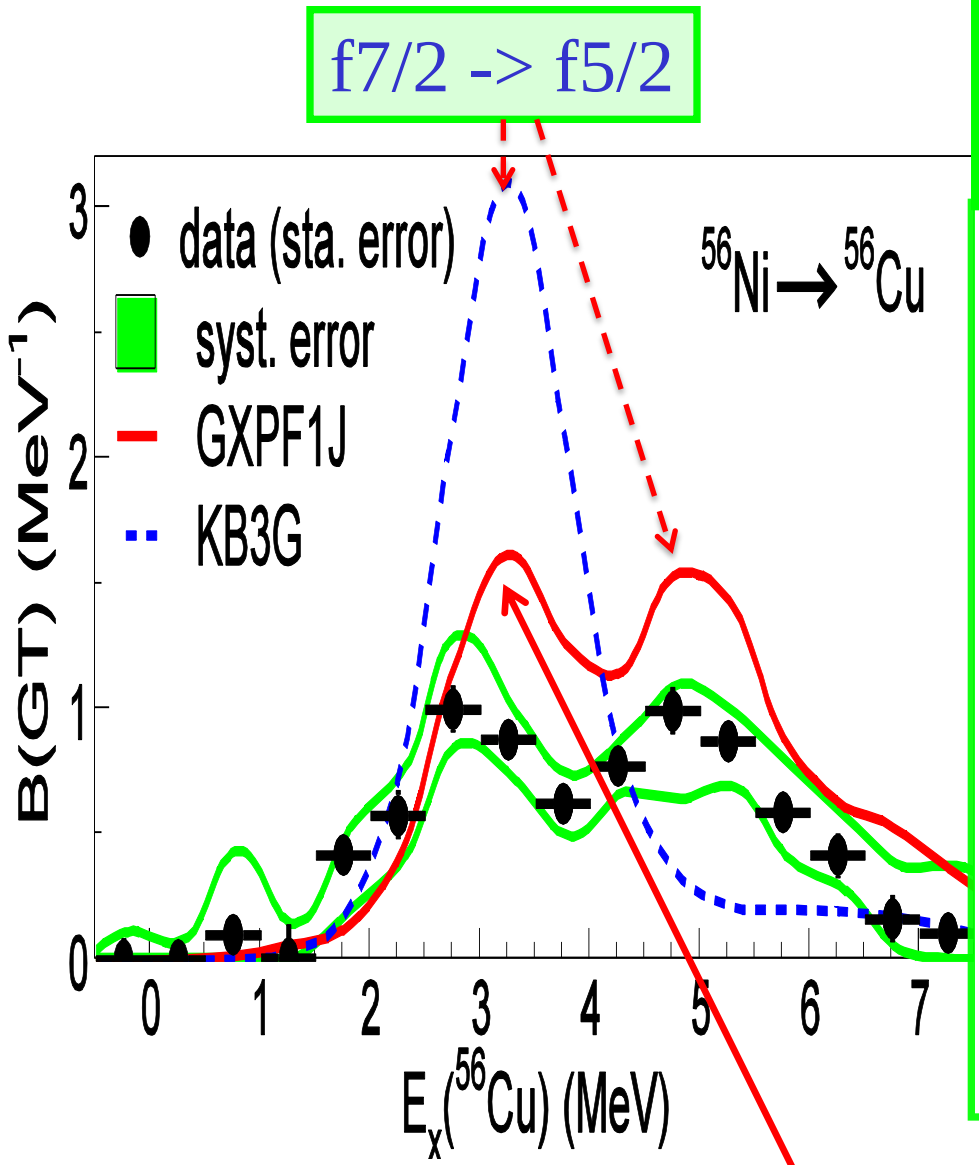
SM(GXPF1J)+RPA(SGII)	259 x10 $^{-42}$cm^2
RHB+RQRPA(DD-ME2)	263
RPA(Landau-Migdal force)	240
QRPA(SIII)	352
QRPA(G-matrix formalism)	174

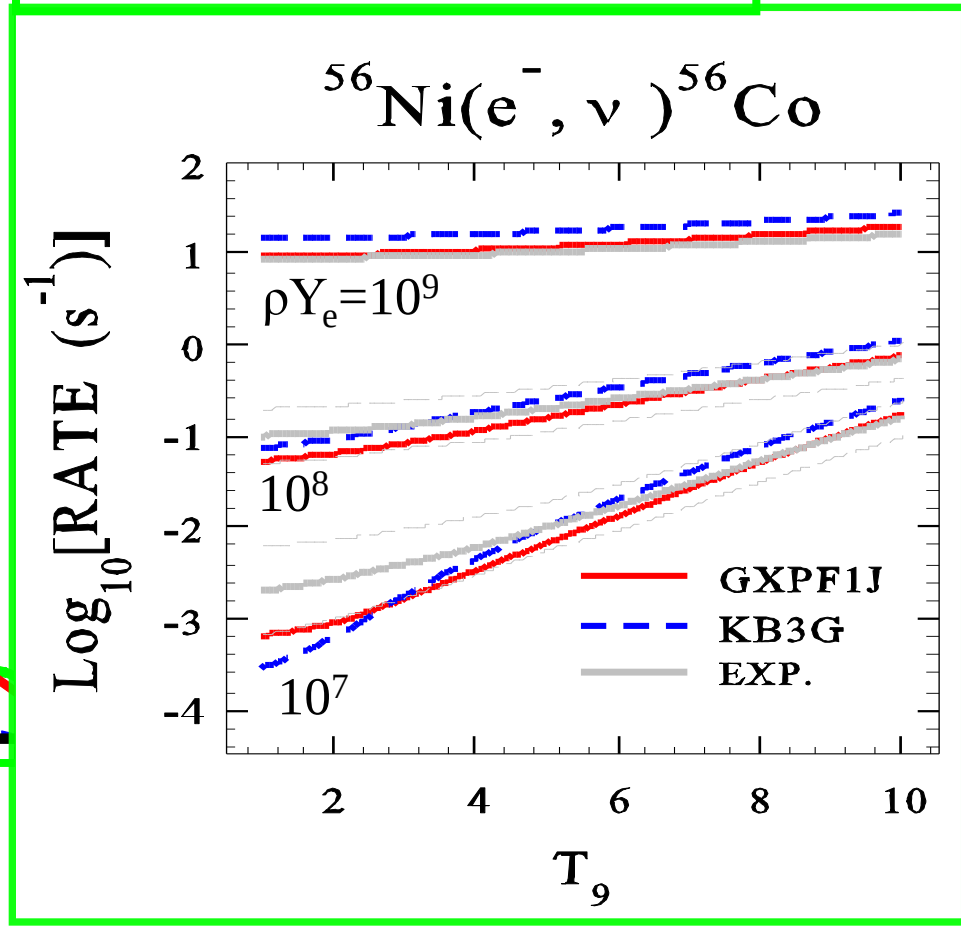
$\langle\sigma\rangle_{th} = (258 \pm 57) \times 10^{-42}$ cm^2.
$\langle\sigma\rangle_{exp} = (256 \pm 108 \pm 43) \times 10^{-42}$ cm^2.
KARMEN (DAR)

N. Paar,[1] T. Suzuki,[2] M. Honma,[3] T. Marketin,[1,4] and D. Vretenar[1]

PHYSICAL REVIEW C 84, 047305 (2011)

e-capture rates in stellar environments





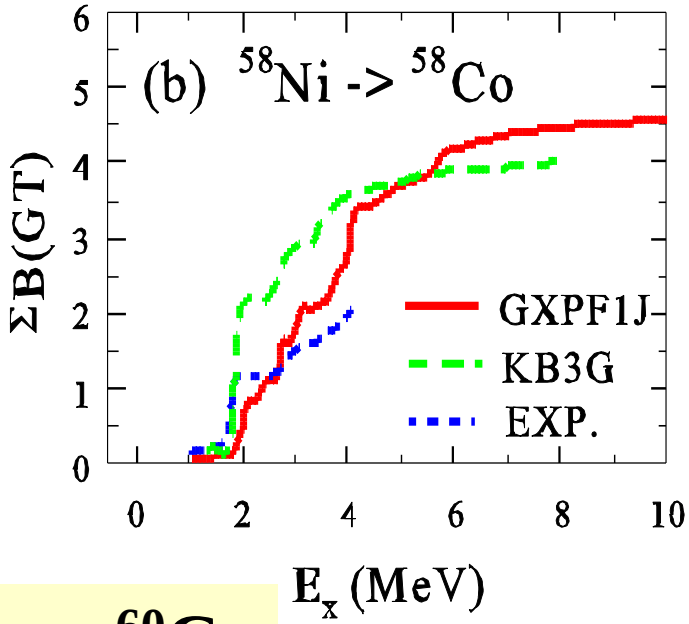
$$\rho Y_e = 10^7 - 10^{10}\ \mathrm{g/cm^3}$$

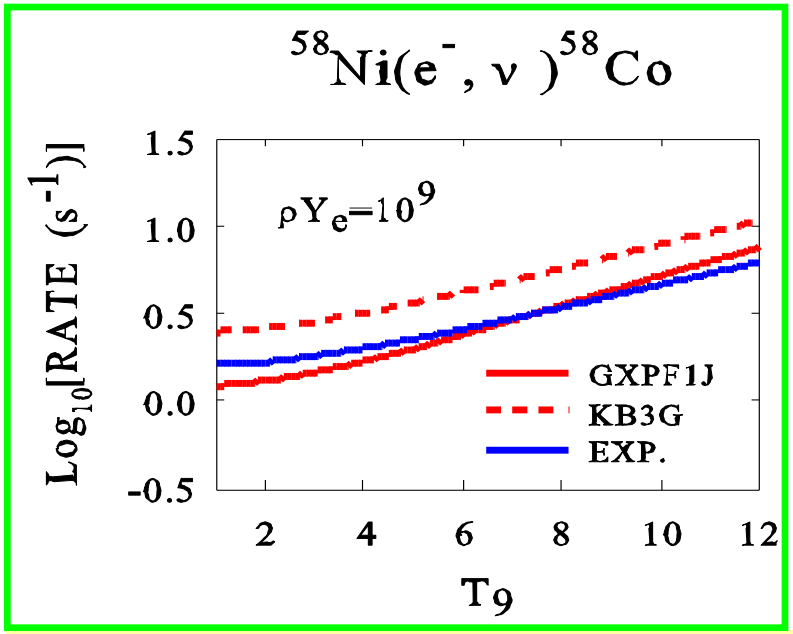
$$T = T_9 \times 10^9 \mathrm{K}$$

Sasano et al.

PRL 107, 202501 (2011)

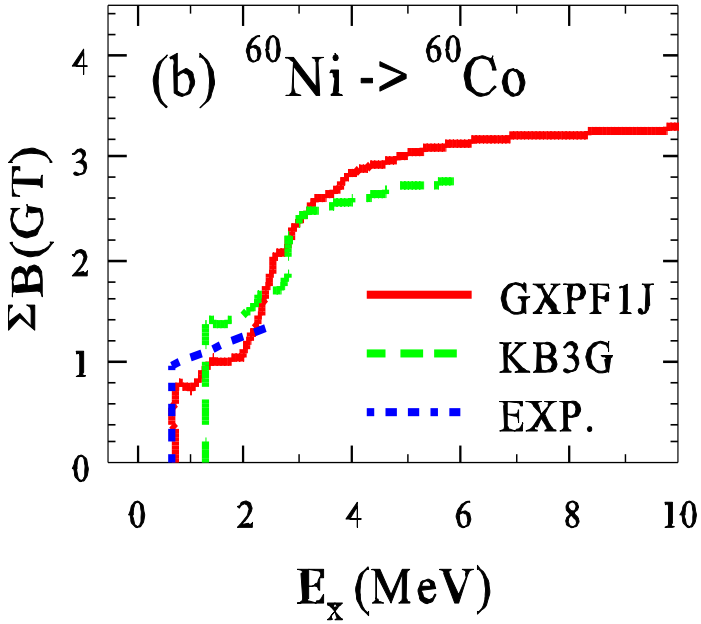
$^{58}Ni \rightarrow {}^{58}Co$

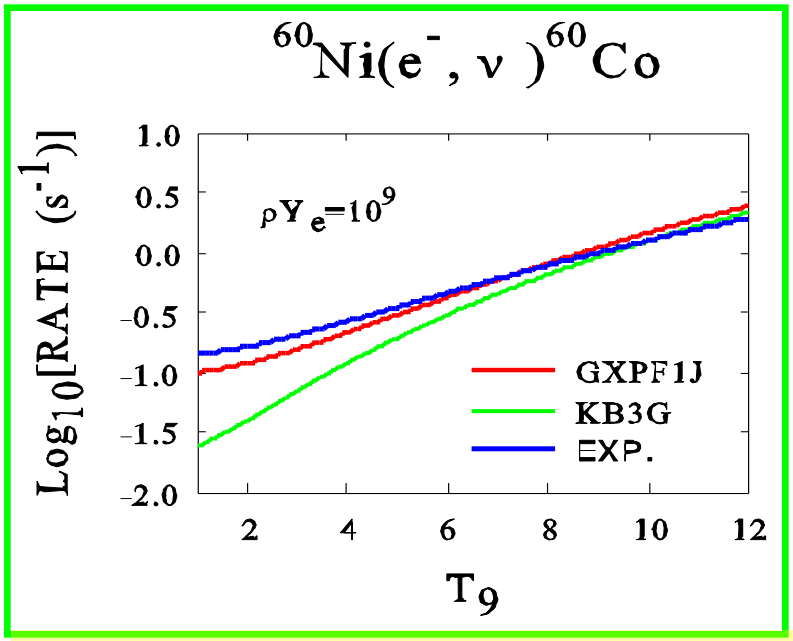




Exp: Hagemann et al., PL B579 (2004)

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





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

Type-Ia supernova explosion

Accretion of matter to white-dwarf from binary star

→ supernova explosion when white-dwarf mass is over Chandrasekhar limit

→ ^{56}Ni (N=Z)

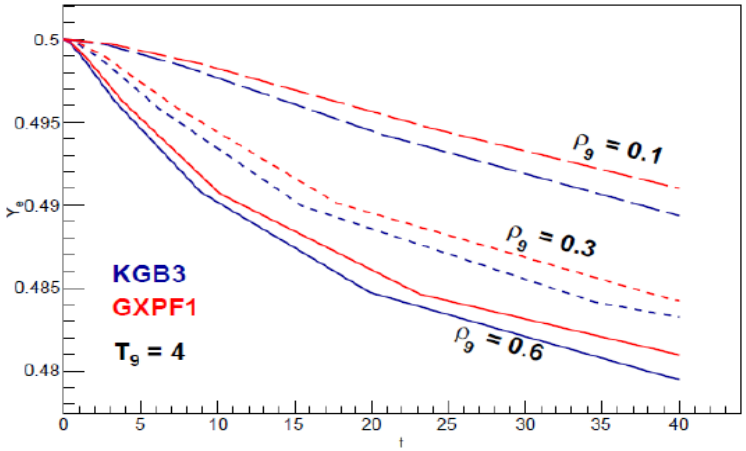
→ ^{56}Ni (e^-, ν) ^{56}Co Y_e =0.5 → Y_e < 0.5 (neutron-rich)

→ production of neutron-rich isotopes; more ^{58}Ni

Decrease of e-capture rate on ^{56}Ni → less production of ^{58}Ni.

NSE (Nuclear Statistical Equilibrium) calculation

GXPF1 計算ではKB3 計算に比べて、電子捕獲の強度が大幅に下がる（次ページ）ので、電子が減らない。



e-capture rates:

GXPF1J < KB3G

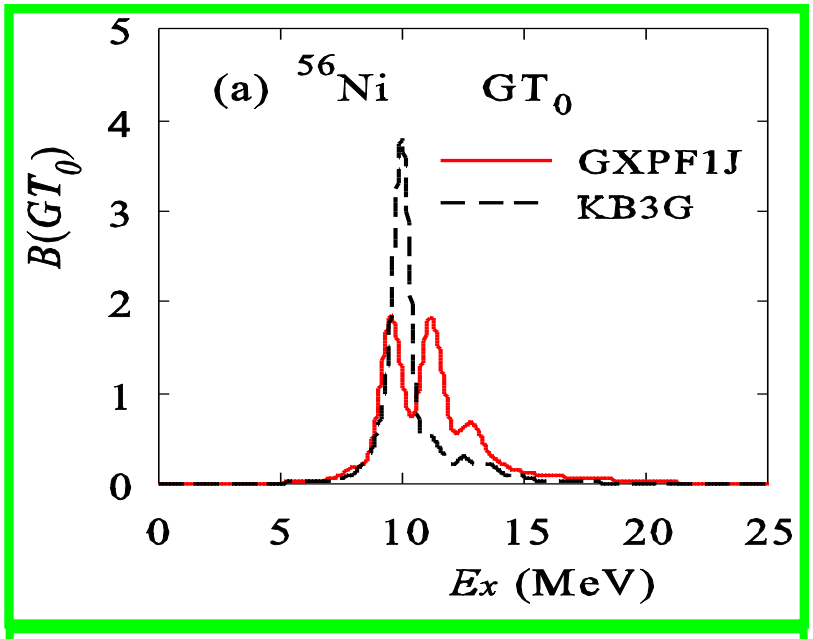
←→

Y_e (GXPF1J) > Y_e (KB3G)

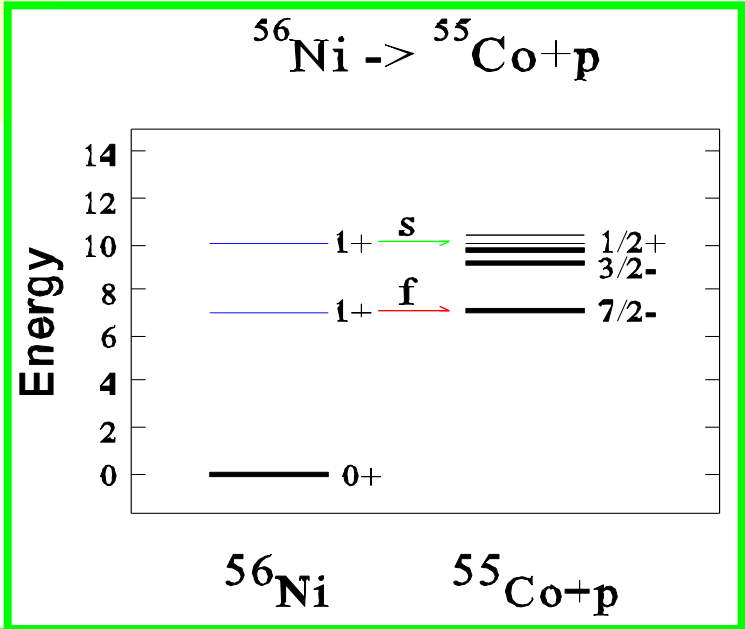
Problem of large 58Ni/56Ni ratio in previous calculations can be solved

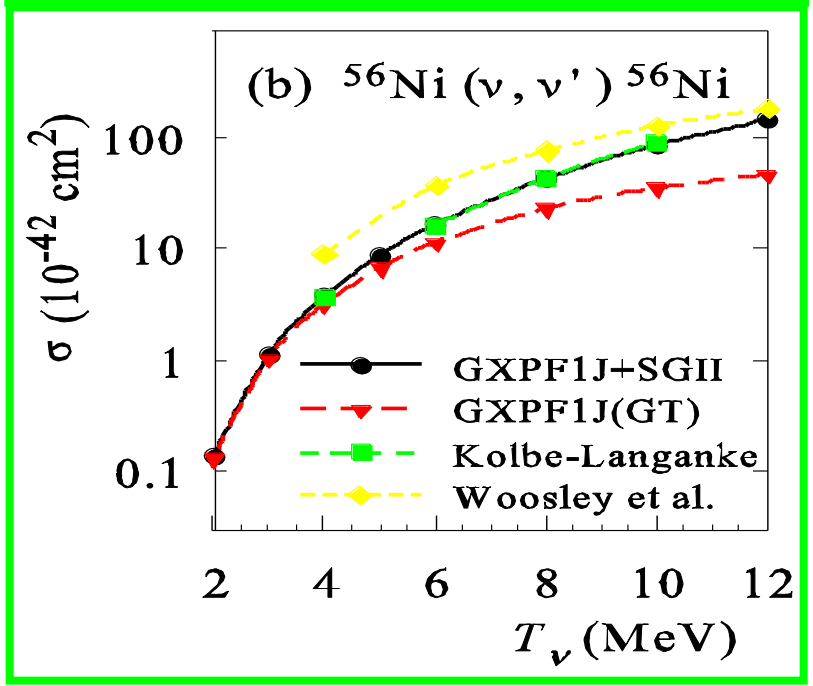
Famiano

●Neutral current reaction on ^{56}Ni

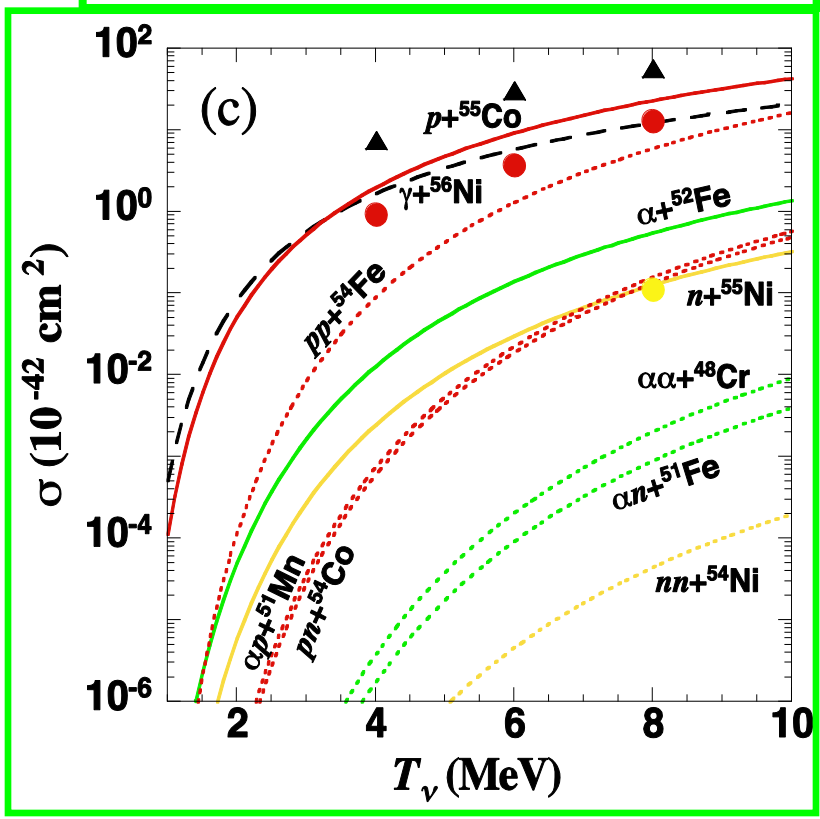


B(GT)=6.2 (GXPF1J)
B(GT)=5.4 (KB3G)



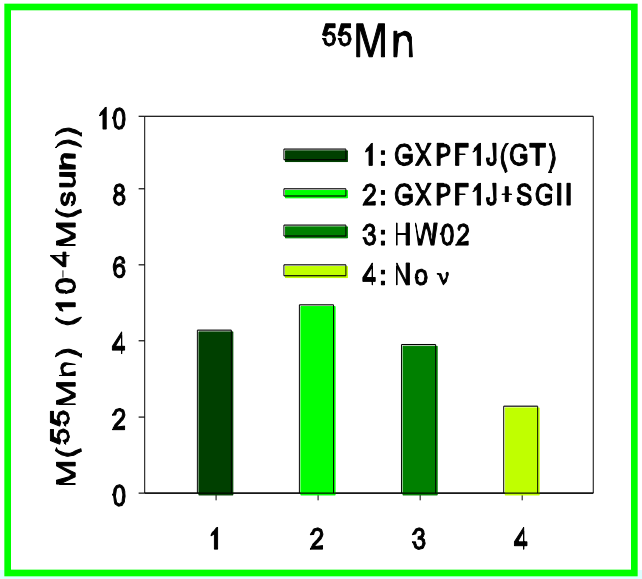


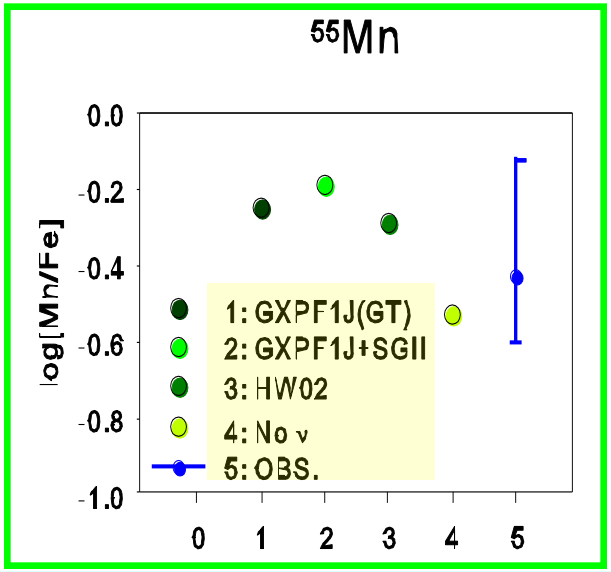
cf:
HW02
▲gamma
●p
●n



Synthesis of Mn in Population III Star

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

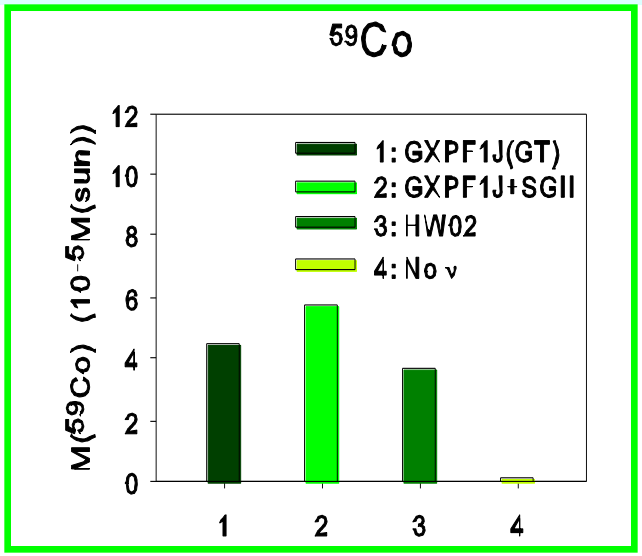


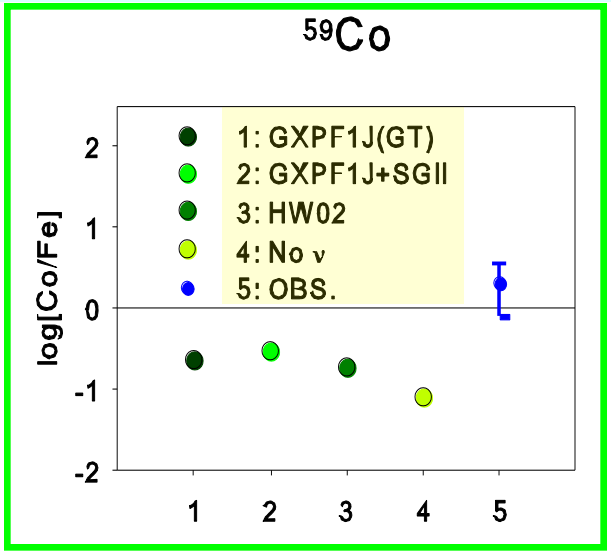


$^{54}Fe(p,\gamma)^{55}Co$

Yoshida, Umeda, Nomoto

$^{59}Co: \quad ^{58}Ni(p,\gamma)^{59}Cu(e^-,\nu)^{59}Ni(e^-,\nu)^{59}Co$





Suzuki et al., PR C79 (2009)

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

VMU= Monopole based Universal Interaction

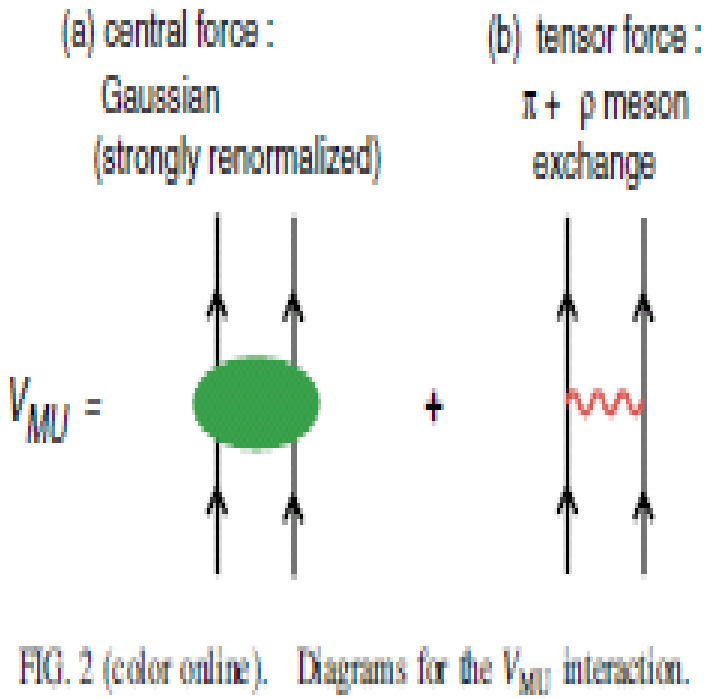


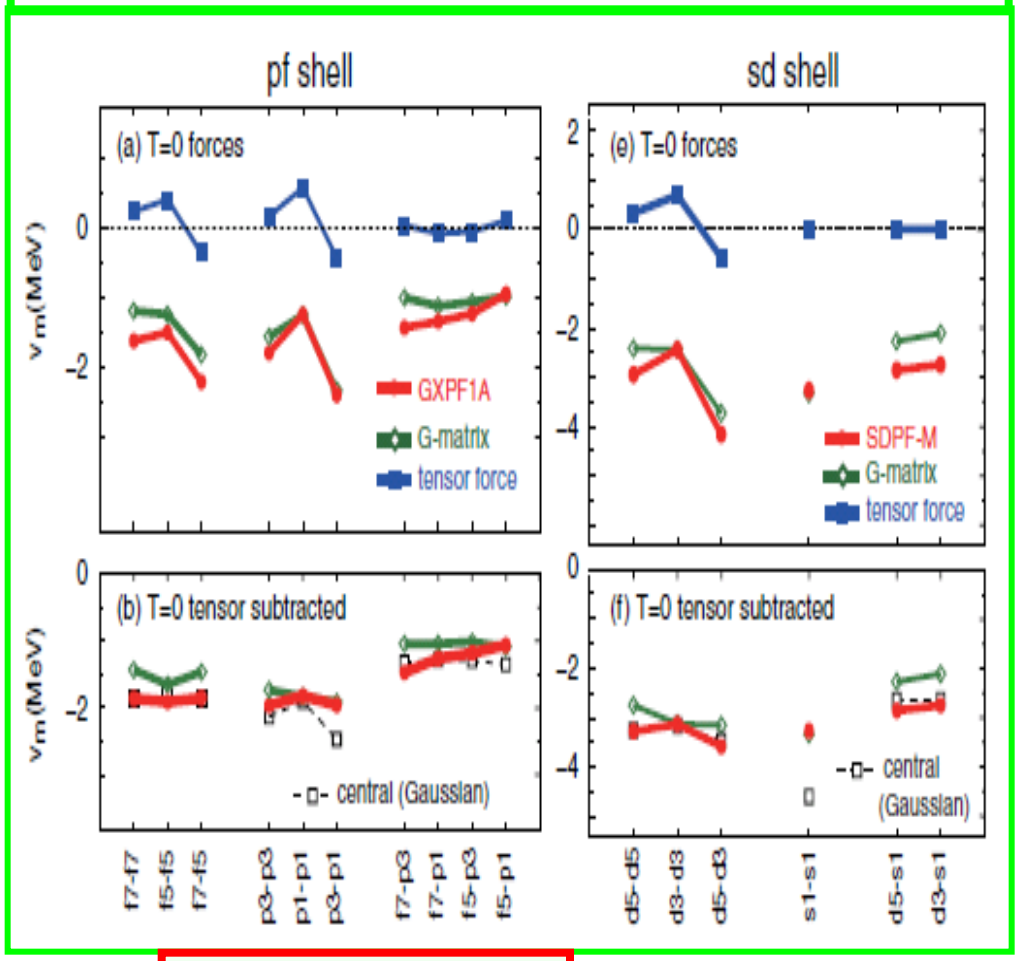
FIG. 2 (color online). Diagrams for the V_{MU} interaction.

- **Important roles of tensor force**

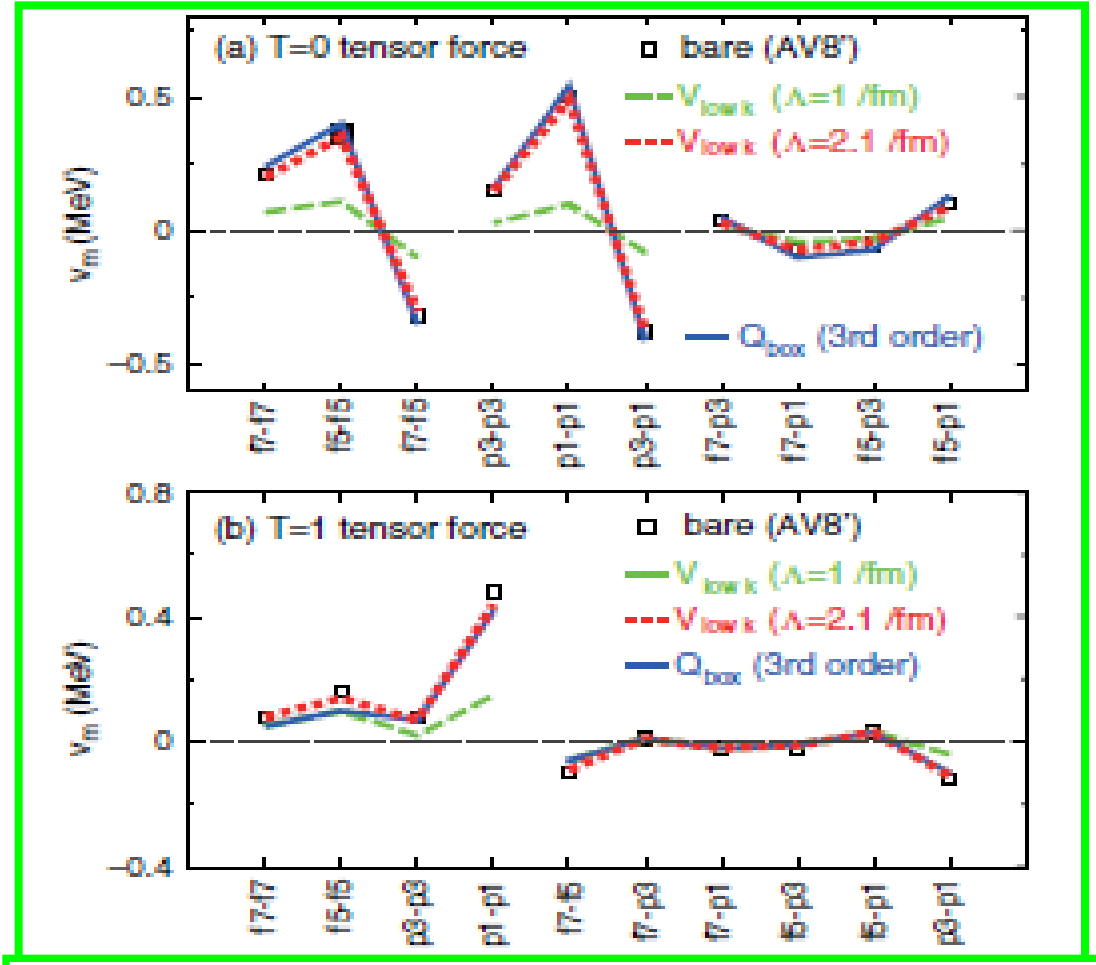
Otsuka, Suzuki, Honma, Utsuno, Tsunoda, Tsukiyama, Hjorth-Jensen PRL 104 (2010) 012501

Monopole terms in V_{nn}

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

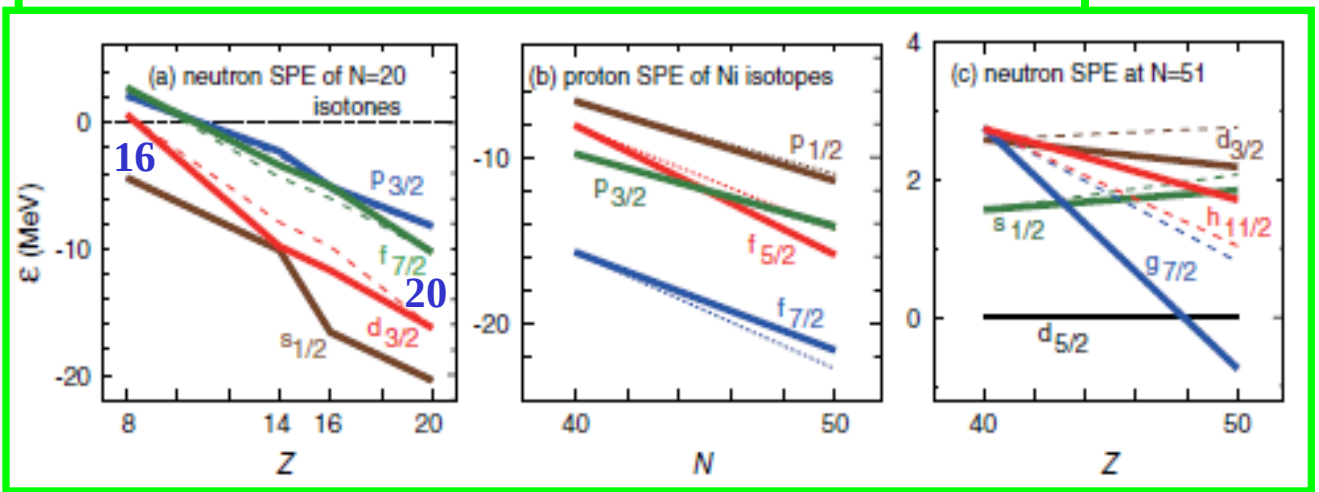


tensor force



Tensor:
bare≈renormalized

Tensor force →
proper shell evolutions
toward drip-lines



p-sd shell: VMU for p-sd,

Yuan, Suzuki, Otsuka, Xu, Tsunoda, PR C85, 064324 (2012) .

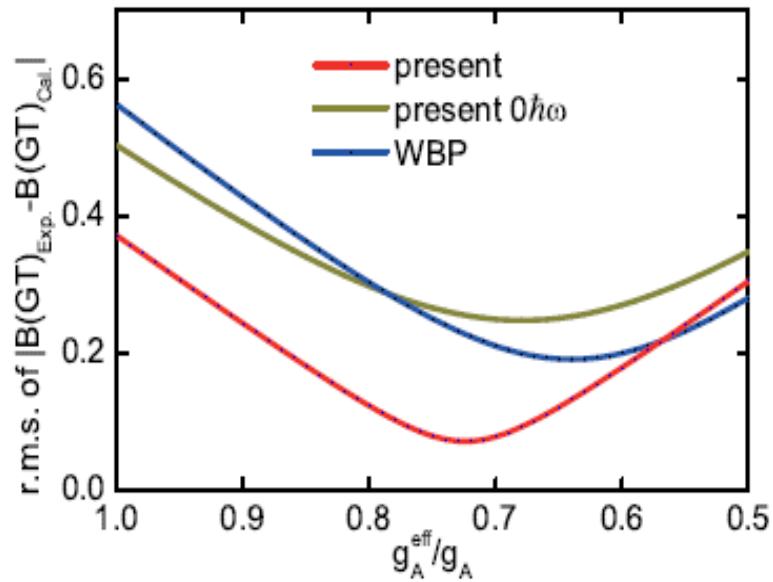
p: SFO

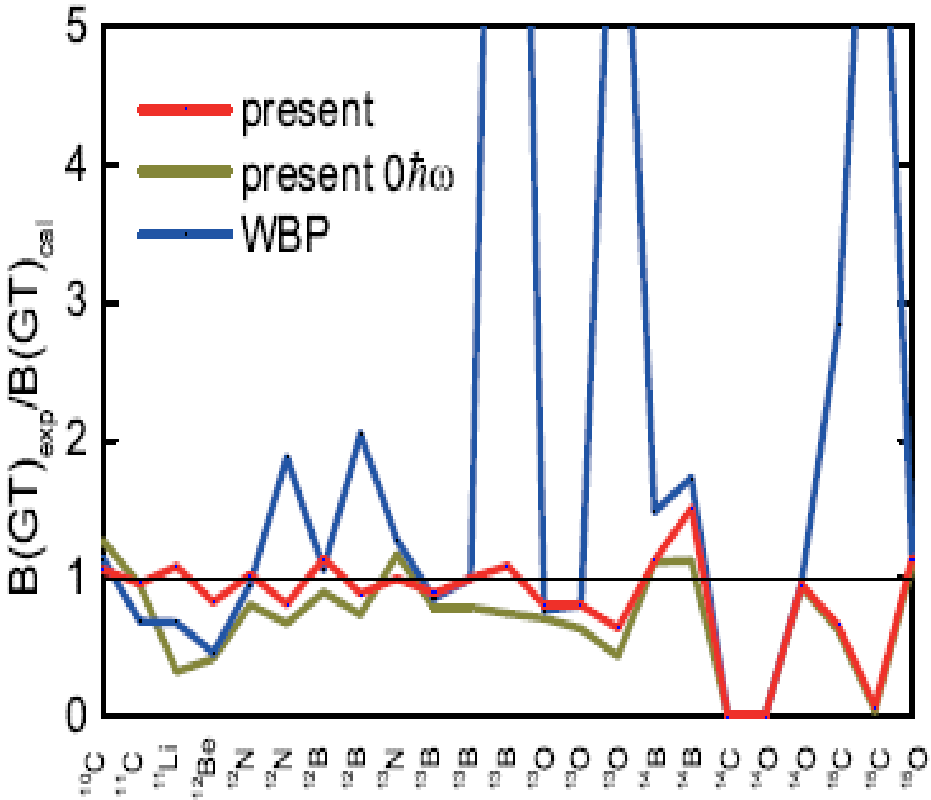
sd: SDPF-M (Utsuno)

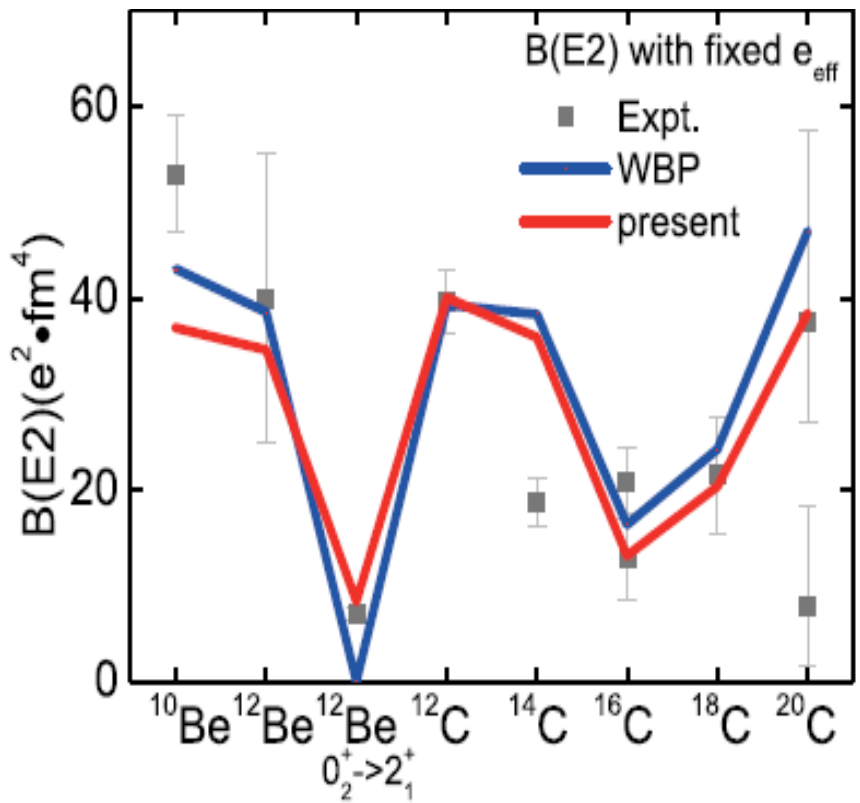
p-sd: VMU tensor = π+ρ,

2-body LS = σ+ρ+ω (M3Y)

central= renormalized VMU







^{40}Ar (ν, e$^-$) ^{40}K

SDPF-VMU-LS

sd: SDPF-M (Utsuno et al.)

fp: GXPF1 (Honma et al.)

sd-pf: VMU + LS

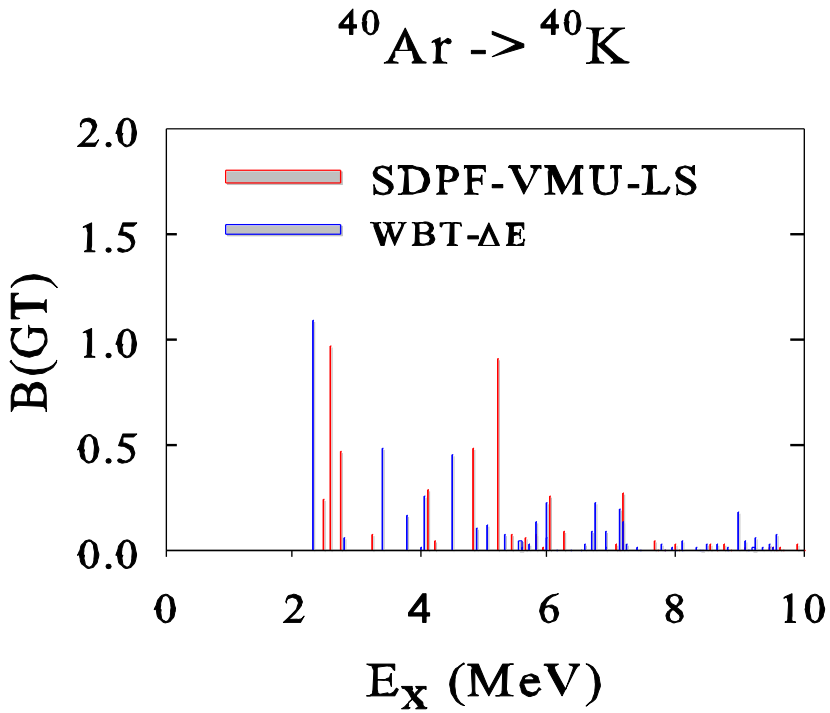
$(sd)^{-2}\ (fp)^2$: 2hw

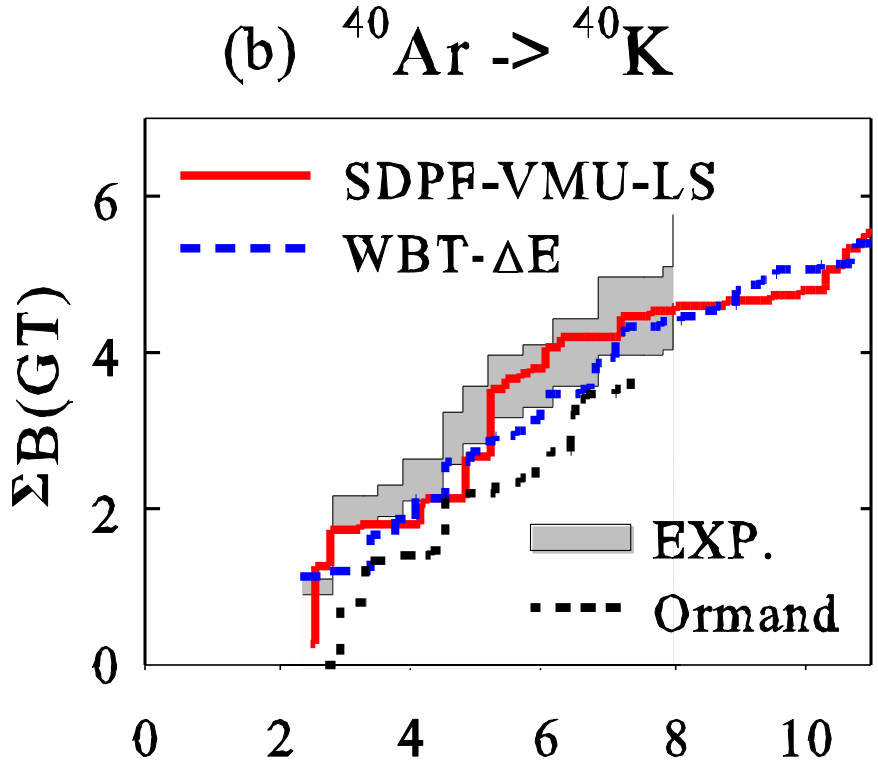
B(GT)

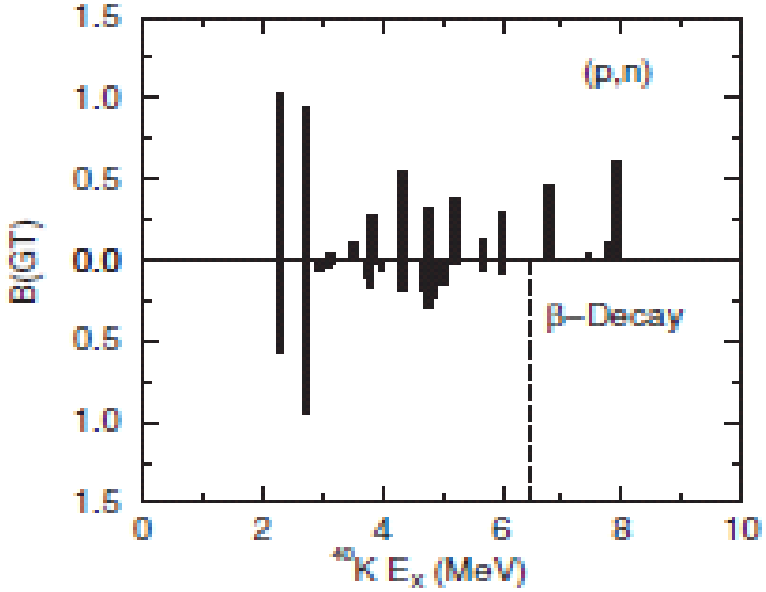
ν-^{40}Ar cross sections

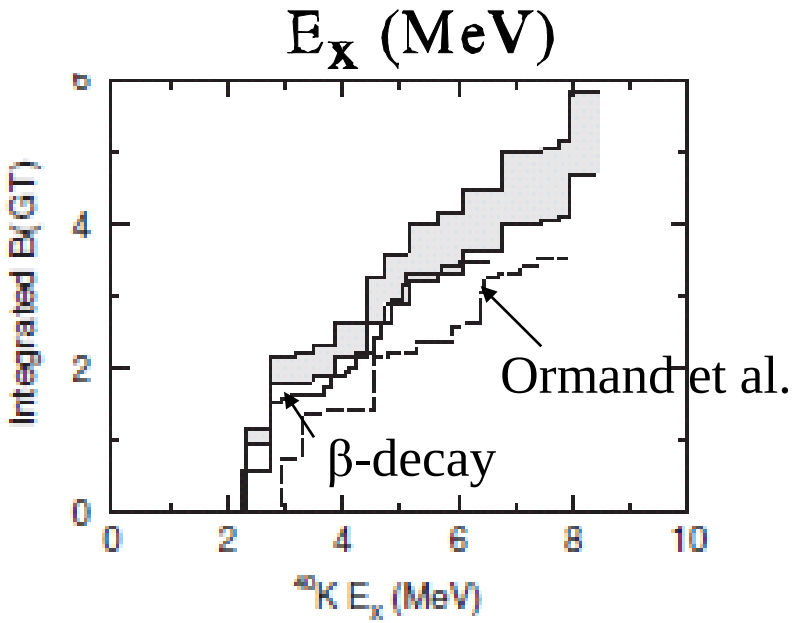
Solar ν cross sections folded over ^{8}B ν spectrum

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

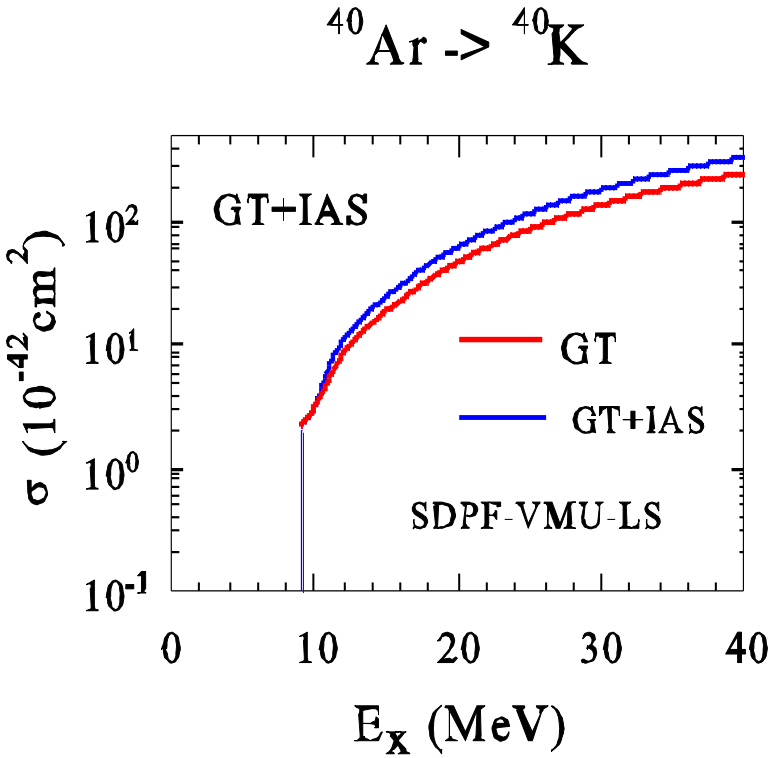






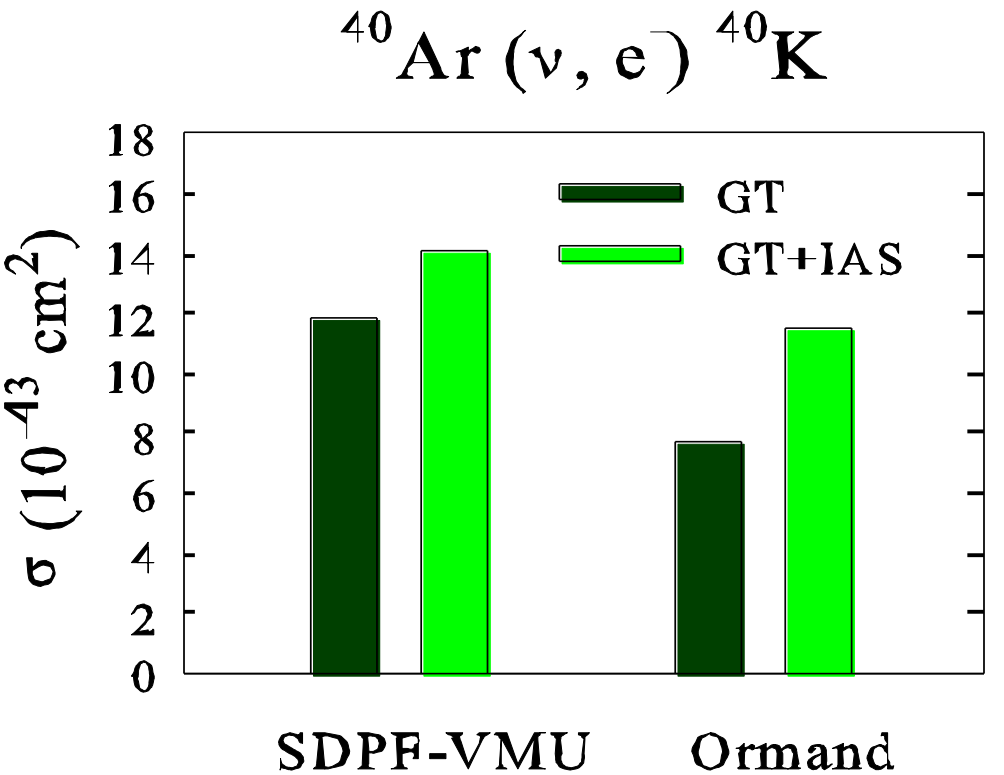


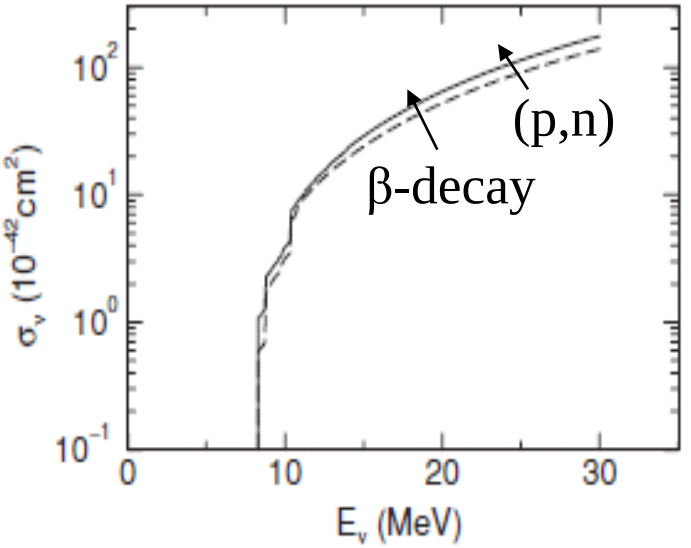
(p,n) Bhattacharya et al., PR C80 (2009)



GT+IAS
E_e > 5 MeV : ICARUS

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

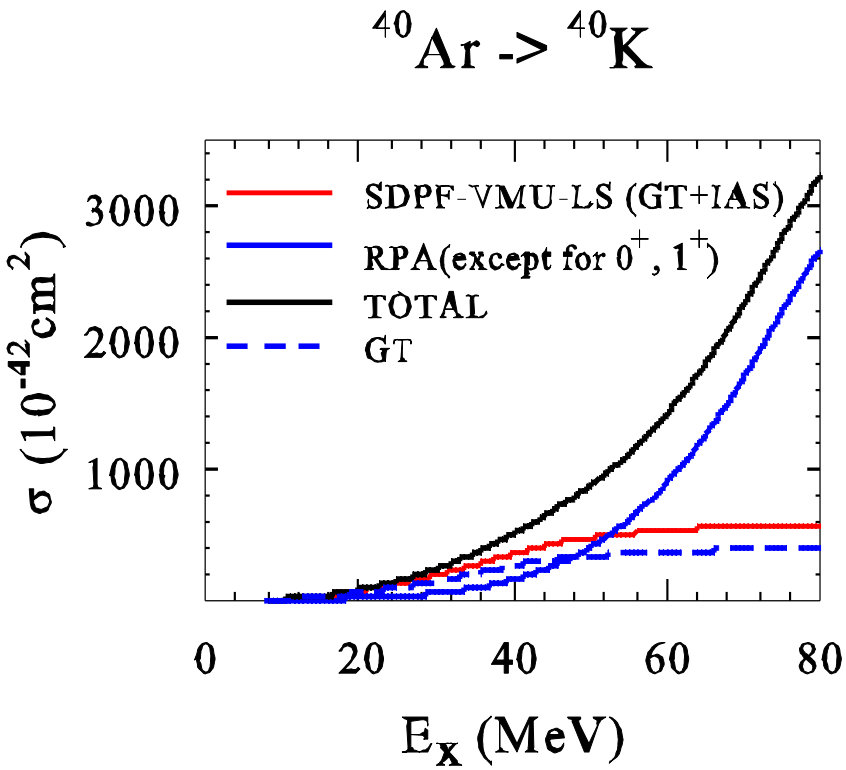




IAS: C0+L0 ≈$[(q^2-\omega^2)/q^2]^2 \times$ C ; $^+$ C0 only
GT: E_1^5 +M1+C_1^5+L_1^5 ; $^+$ E_1^5 only

$^+$Ormand et al, PL B345, 343 (1995)

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



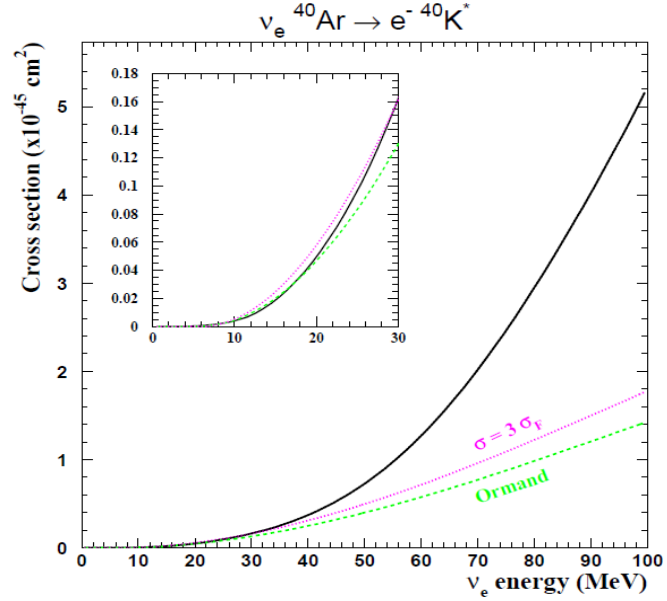
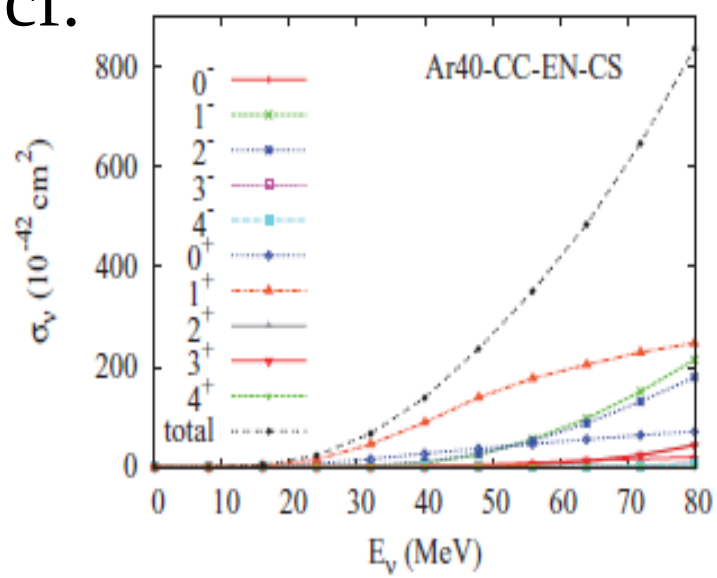
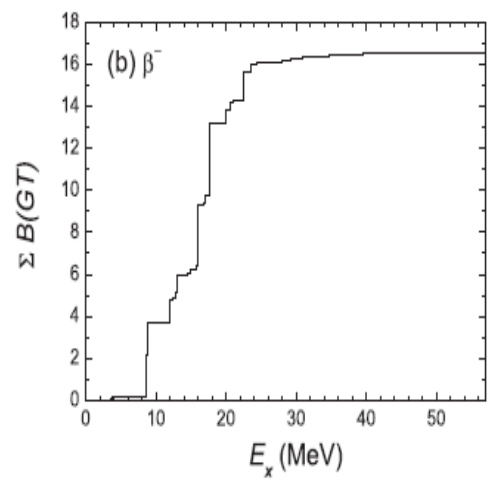


Figure 4: ν_e CC cross section as a function of the neutrino energy. The dashed line corresponds to the Ormand [21] cross section calculation, dotted line assumes that the total cross section of the absorption interaction is 3 times the cross section of the Fermi transition [16] and the solid line is the cross section used in this analysis calculated from RPA including all the transitions [20].

Pinedo, Kolbe, Langanke in Gil-Botella and Rubbia, arXiv:hep-ph/0307244v2

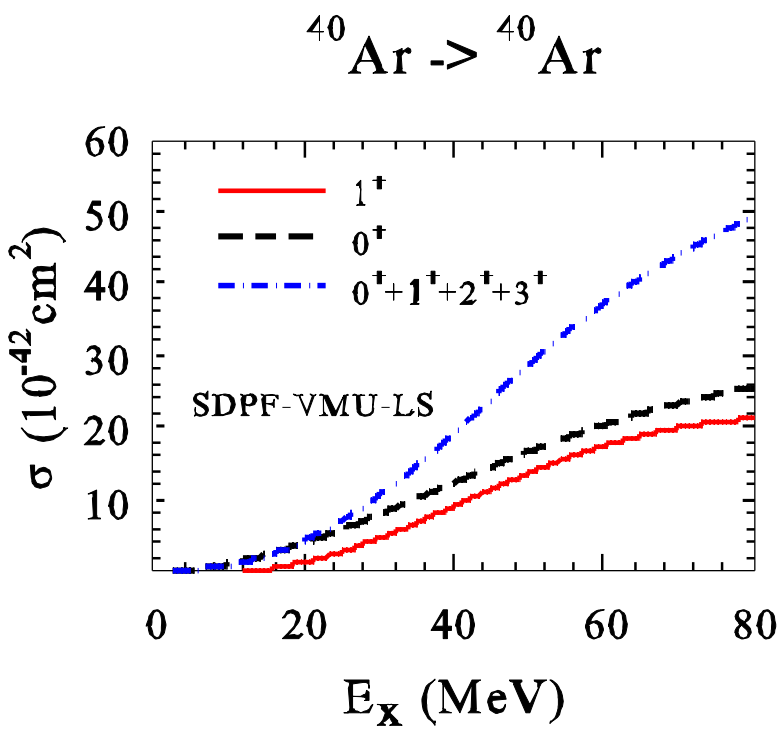
cf.





Cheoun, Ha and Kajino, PR C83, 028801 (2011)

Neutral-current reactions



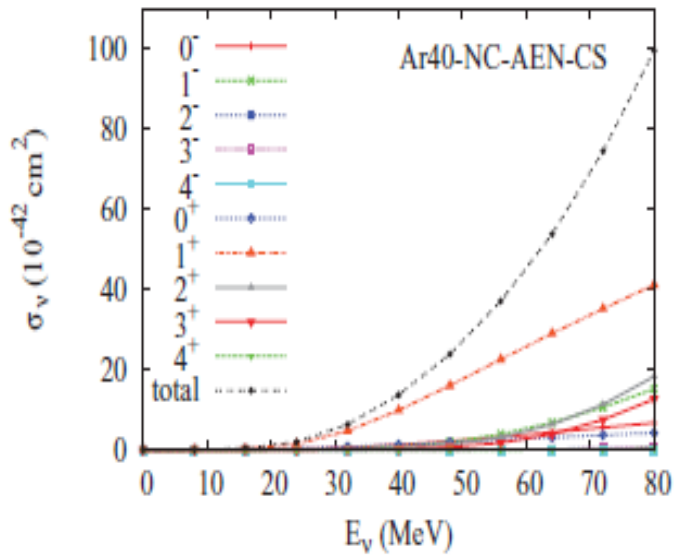
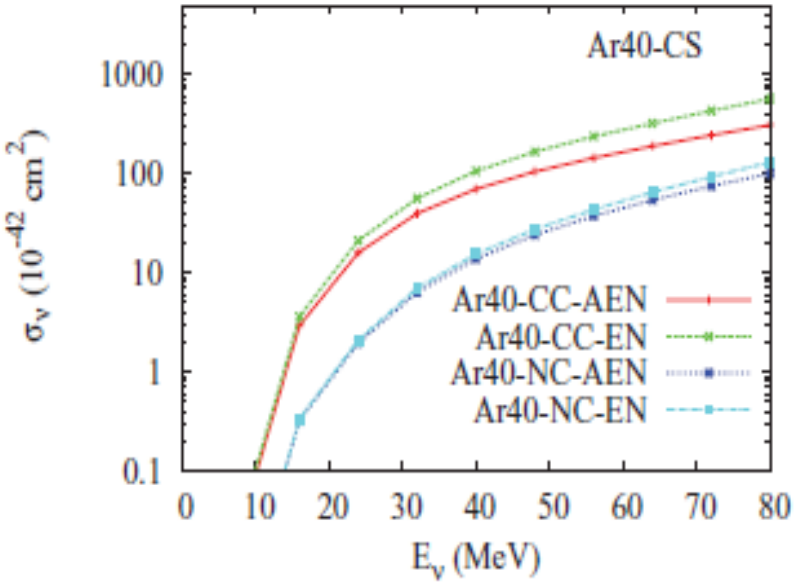
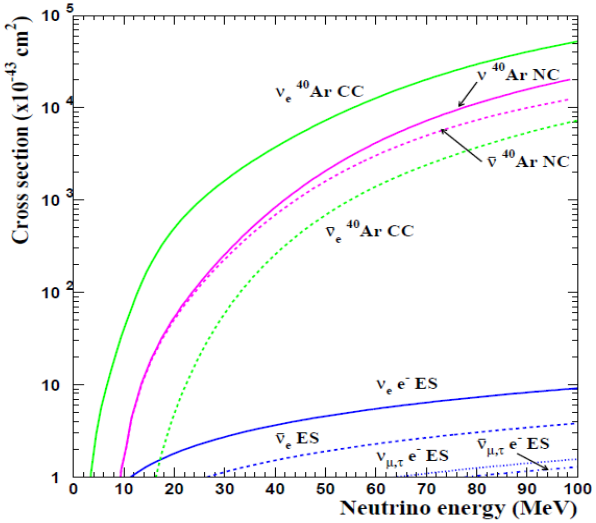


FIG. 4. (Color online) Cross sections by NC reaction ^{40}Ar($\bar{\nu}_e,\bar{\nu}'_e$)^{40}Ar* for SN neutrinos.

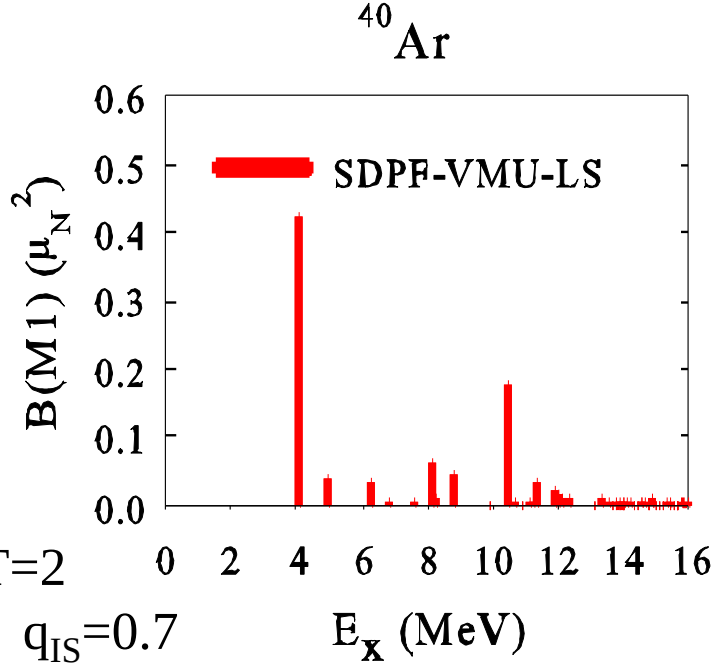
Cheoun, Ha and Kajino, PR C83, 028801 (2011)





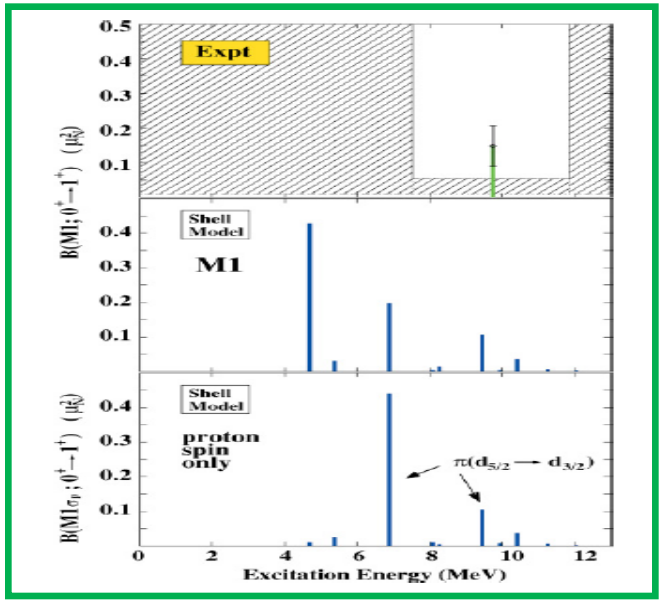
Martinez-Pinedo, Kolbe, Langanke

M1



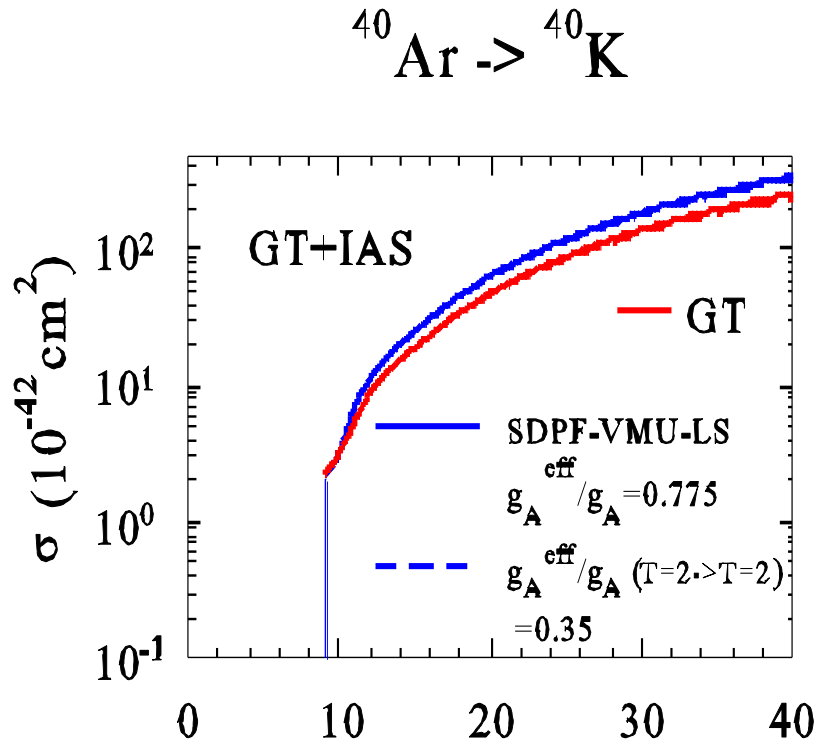
T=2 → T=2

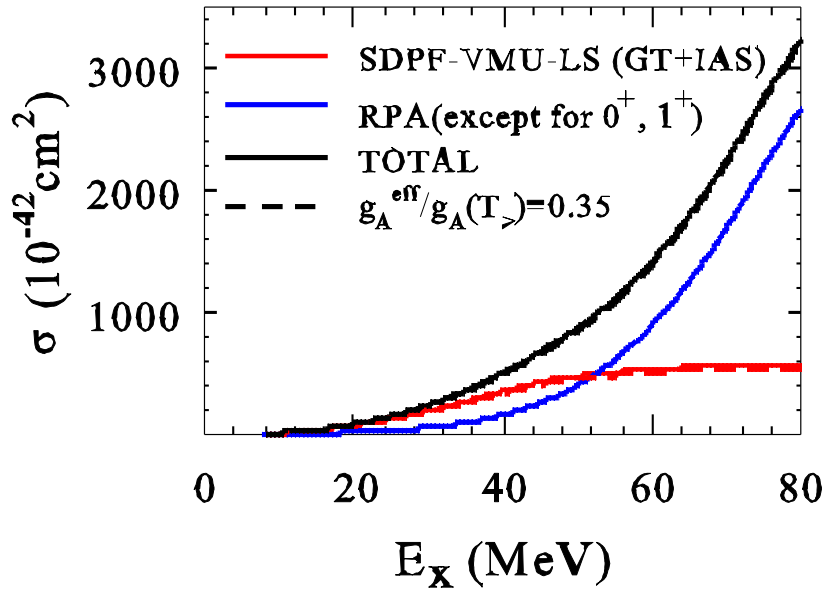
q_{IV}=0.35 q_{IS}=0.7



Exp. B(M1)=0.148(59) μ_N^2

Li et al, PR C73, 054306 (2006)





Summary

New ν –induced cross sections based on new shell-model Hamiltonians with proper tensor forces

- **New ν capture cross sections on ^{13}C by SFO in p-sd shell**
  Enhanced solar ν cross sections compared to Cohen-Kurath (p shell)

- **New ν-induced cross sections on ^{16}O by SFO-tls**
  Energies of spin-dipole states are well reproduced.
  Enhanced cross sections compared with SFO and CRPA

- **A new shell model Hamiltonian GXPF1J well describes the spin responses in fp-shell niclei → New GT strengths in Ni isotopes which reproduce recent experimental data, and more accurate evaluation of e-capture rates at stellar environments.**

- **New ν-nucleus reaction cross sections in ^{56}Ni → Enhancement of p-emission channel in ^{56}NI and production rates of Mn and Co in supernova explosions**

  Suzuki, Honma et al., PR C79, 061603(R) (2009)

- **sd-pf-VMU: GT strength consistent with (p, n) reaction → New cross section for ^{40}Ar (ν,e$^-$) ^{40}K induced by solar ν**

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