Neutrino-Nucleus Reactions based on Recent Shell-Model Interactions

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NDM12

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- 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)
  - SFO-tls (p-sd shell): SD in ^{16}O
    - Suzuki, Otsuka, PR C78, (2008)
  - 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-^{16}O with SFO-tls
- ν-^{56}Ni and e-captures on Ni isotopes with GXPF1J
- ^{40}Ar (ν, e$^-$) ^{40}K by solar ν with VMU

Shell-model interactions

- Phenomenological interaction

single particle energies + fitted two-body matrix elements

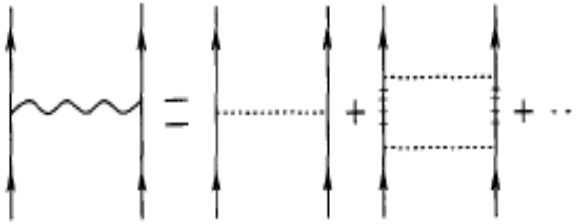
e.g. p-shell: Cohen-Kurath (1965), sd: USD (1988)

p-sd: Millener-Kurath (1975)

- Microscopic interaction derived from NN interaction

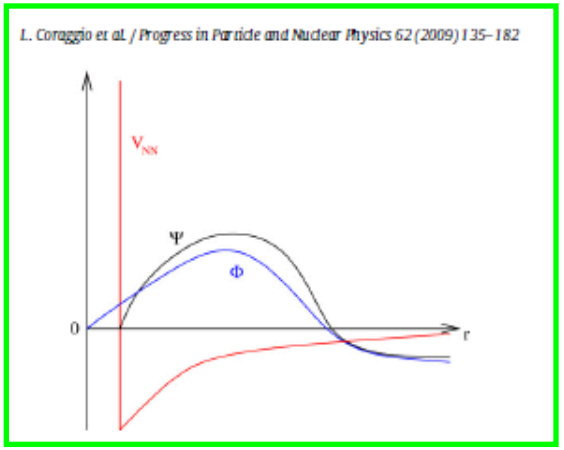
1. Renormalization of repulsive core part of NN interaction

G-matrix:



sum of ladders

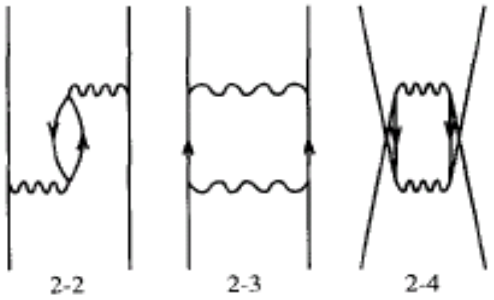
Hjorth-Jensen et al.,
Phys. Rep. 261, 125 (1995)



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

2. Effective interaction of truncated model space

core-polarization effects



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:

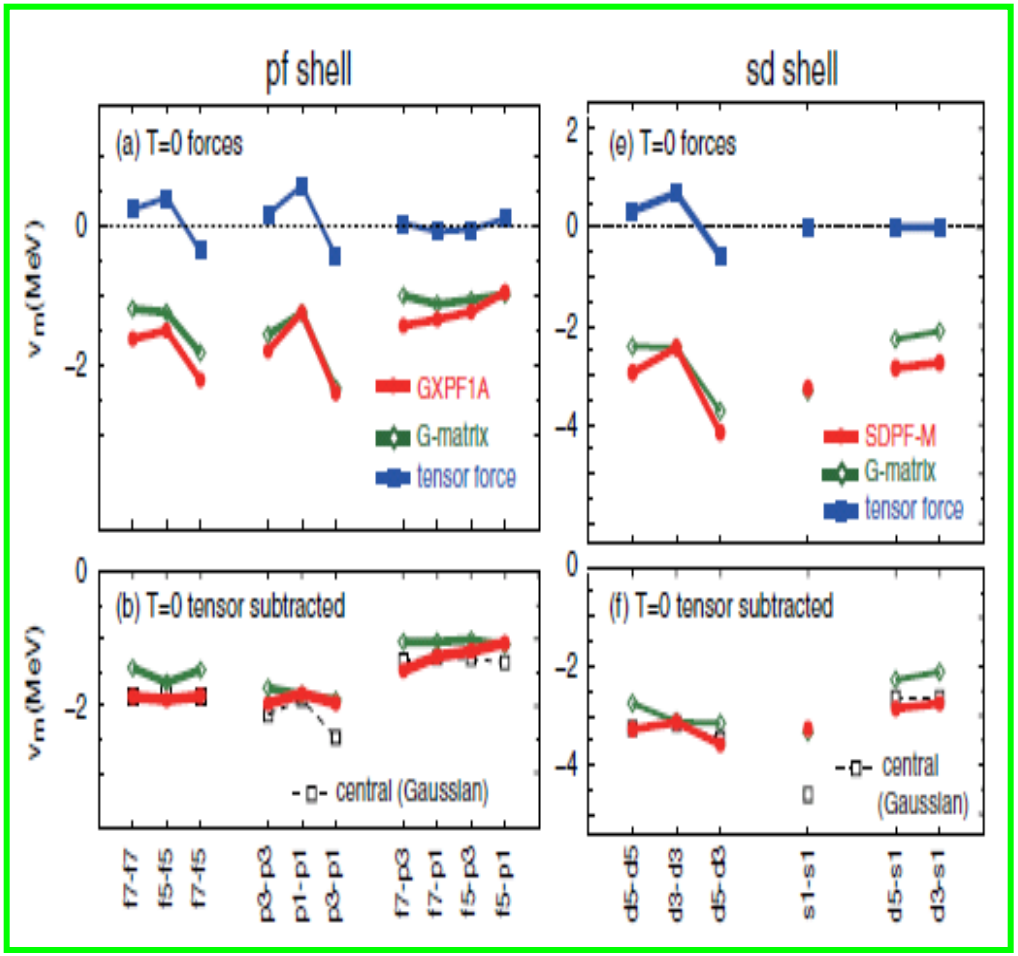
$$E_{eff}(\nu j) = \varepsilon(\nu j) + \sum_{j'} n(\nu j') V_M^{T=1}(j, j') + \sum_{j'} n(\pi j') V_M^{np}(j, j')$$

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

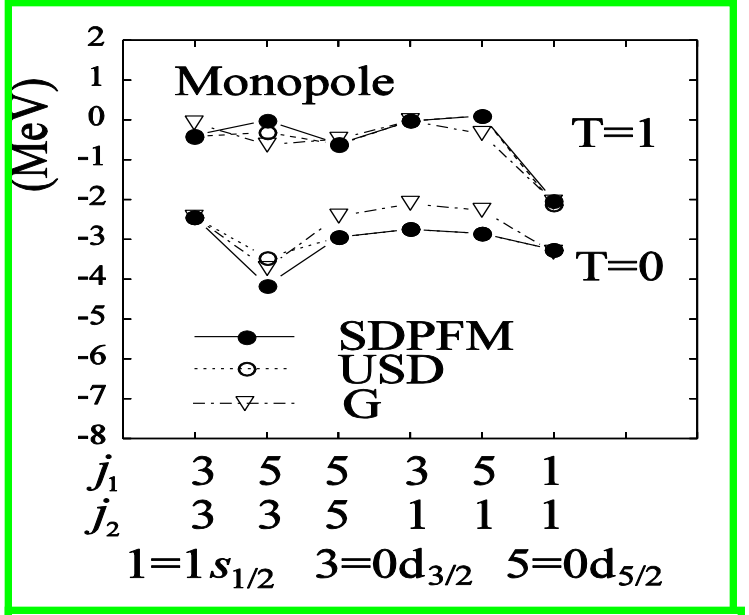
* New phenom. interactions with monopole corrections

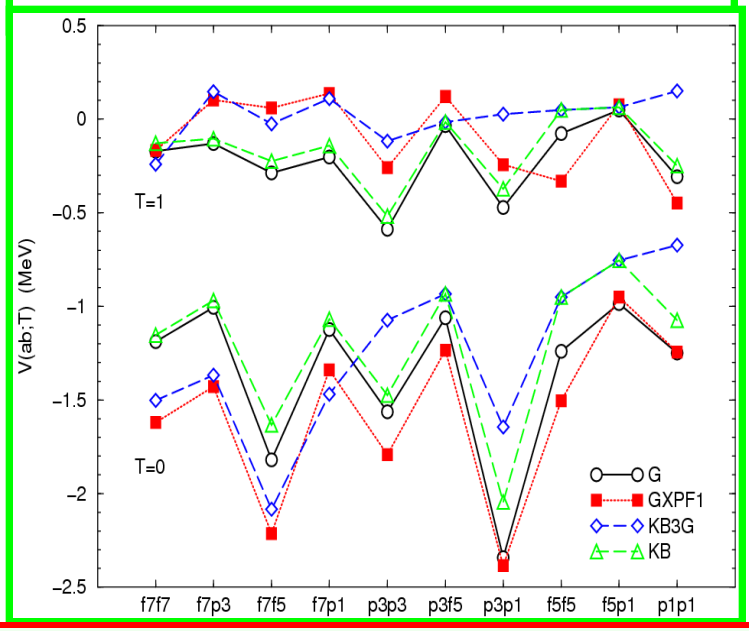
sd-pf: SDPF-M (1999)* → successful descriptions of
pf: KB3 (2001)*, GXPF1 (2004)* energies and transitions

G-matrix vs phenom. interactions



tensor force





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

● Important roles of tensor force

○ Phenomenological Hamiltonians

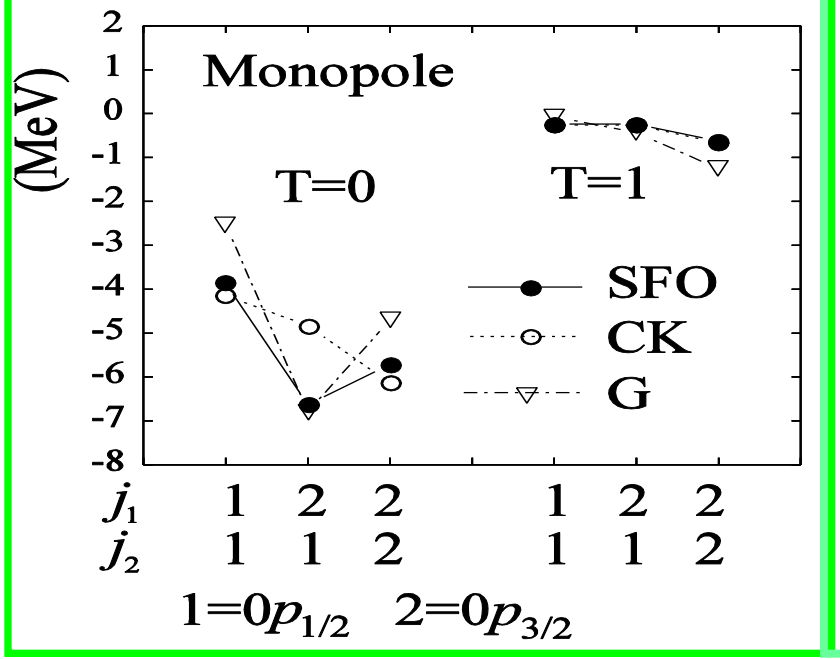
- SFO: p-shell p-sd space up to 2-3 hw excitations
  CK-MK (p: Cohen-Kurath, p-sd: MK, sd: G-matrix)

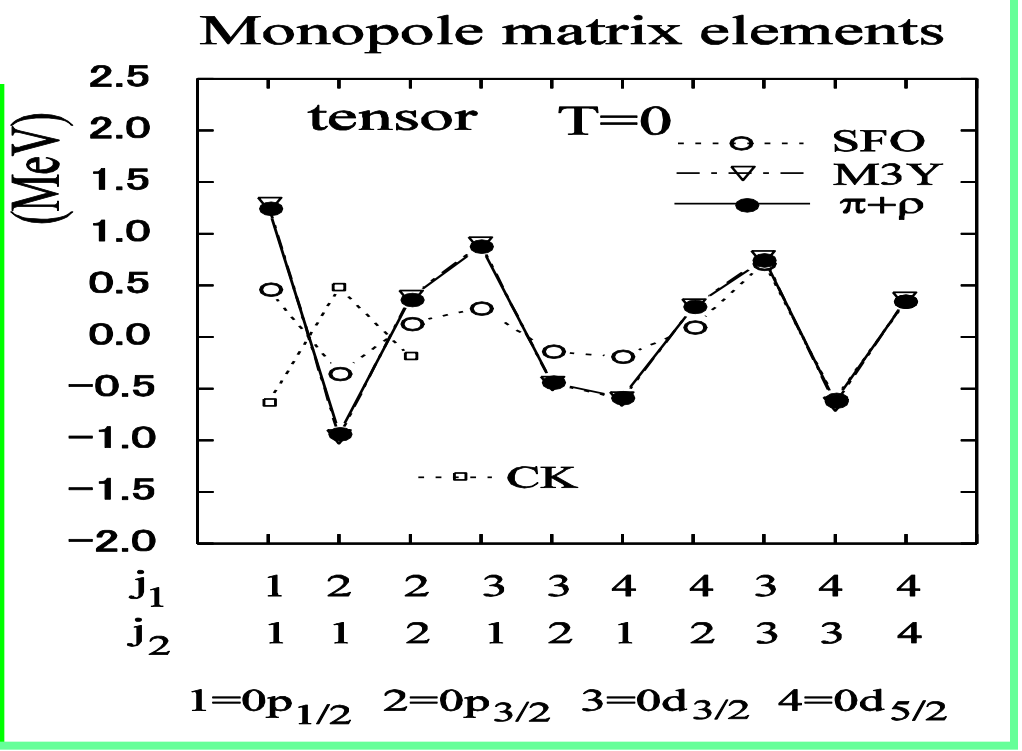
→ Enhancement of spin-isospin channel of monopole terms

Monopole terms

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

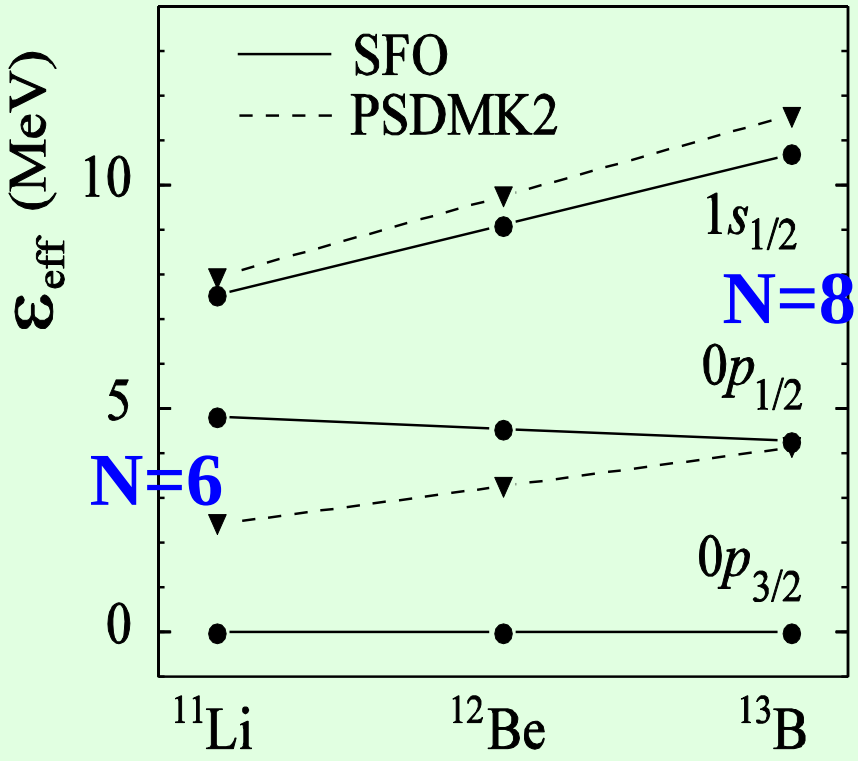
p1/2-p3/2 (T=0) is enhanced





Shell evolution in

N=8 isotones

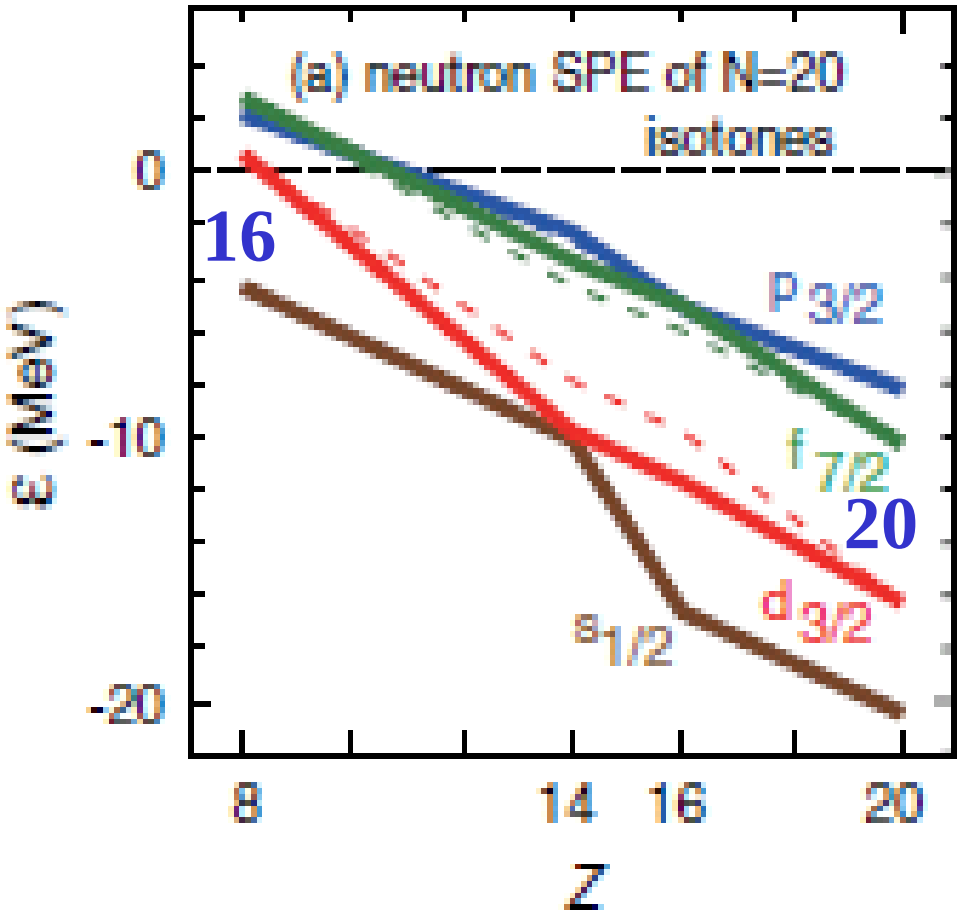


πp3/2

Change of magic number

N=8 → N=6

N=20 isotones



N=20 → N=16

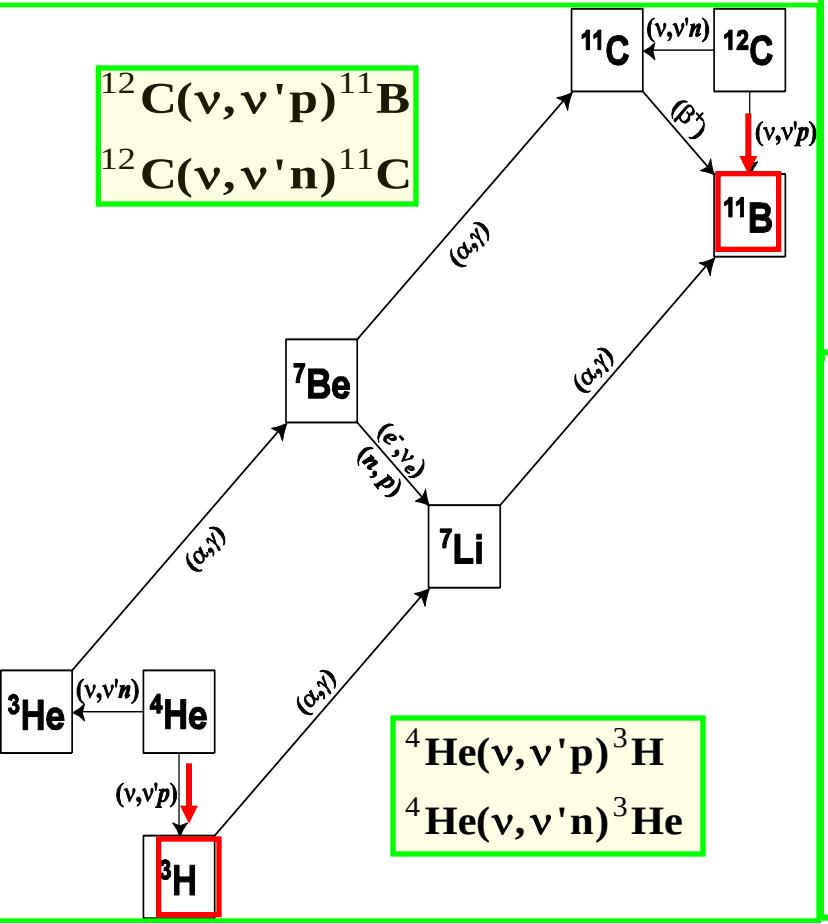
SFO p-sd shell

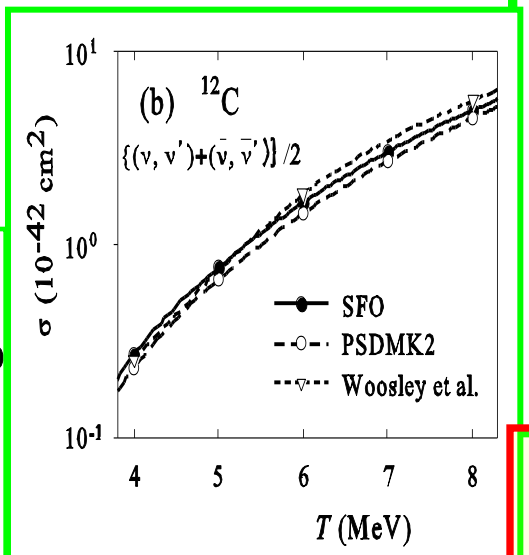
Suzuki, Fujimoto, Otsuka, PR C67, 044032 (2003)

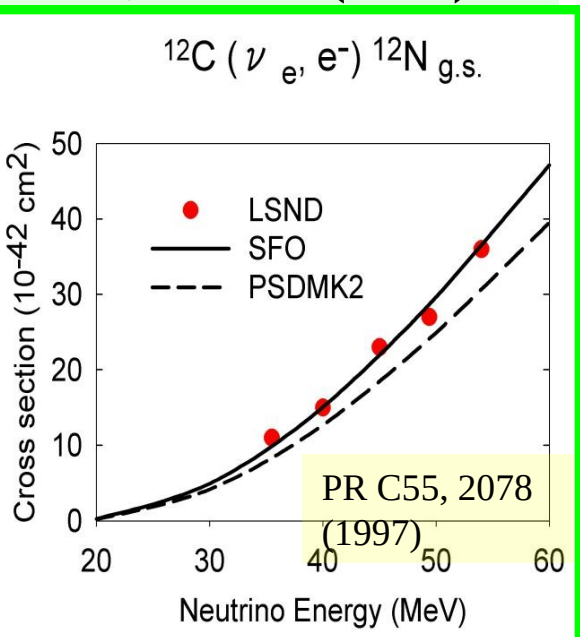
GT stengths in ^{12}C: reproduced with $g_A^{eff}/g_A=0.95$

Nearly vanishing GT strength in ^{14}C

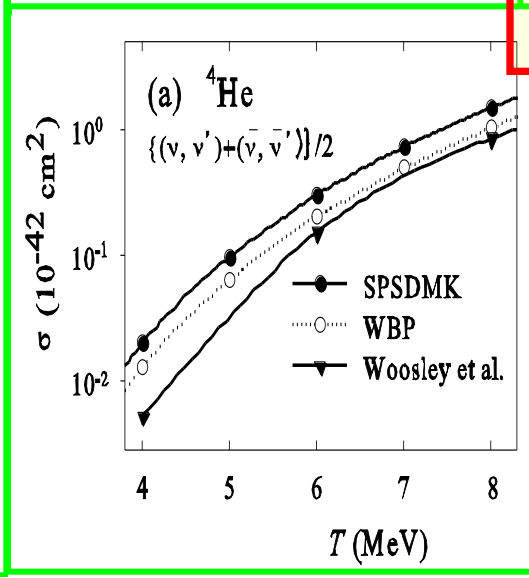
Nucleosynthesis processes of light elements

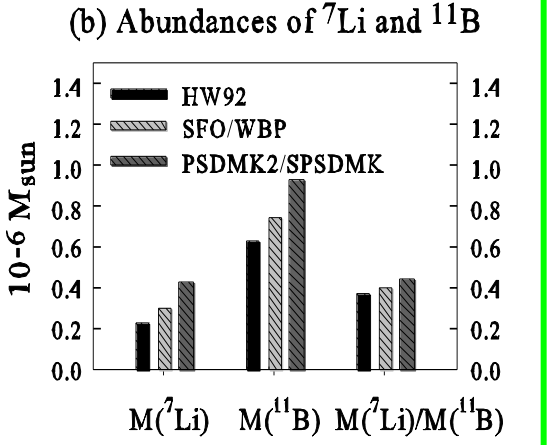






Enhancement of ^{11}B and ^{7}Li abundances in supernova explosions



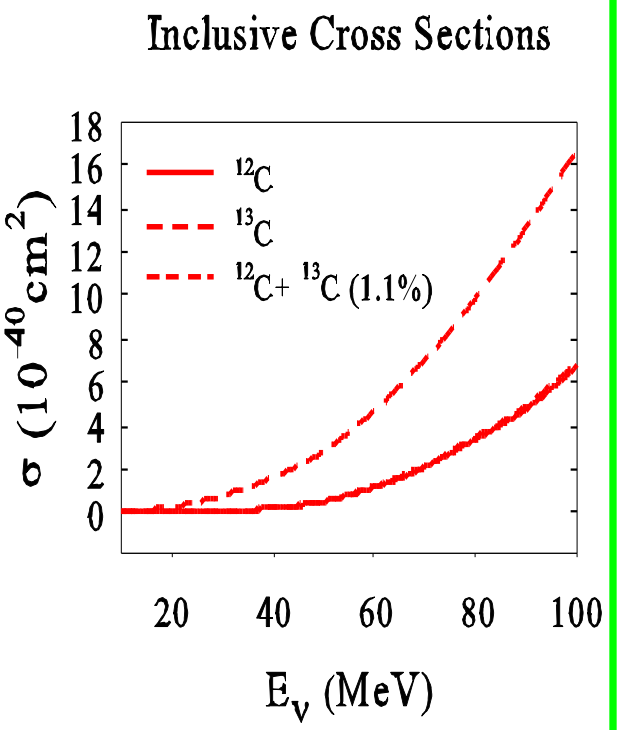


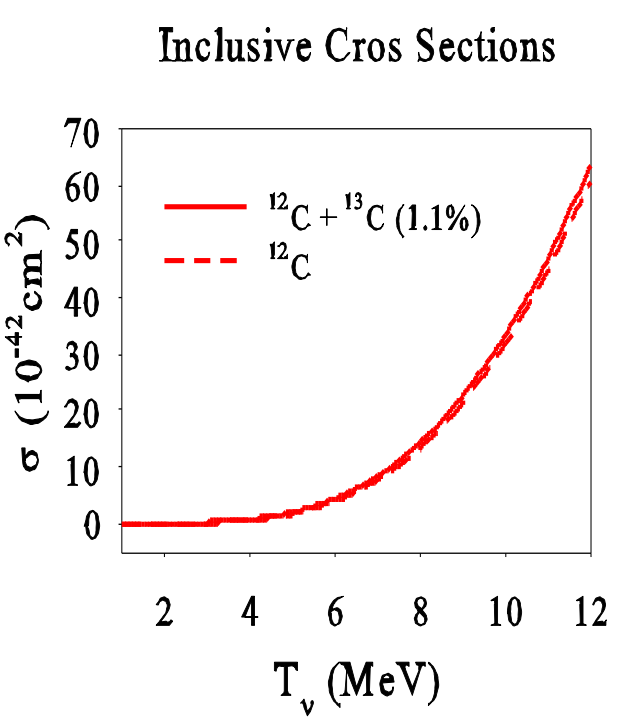
Effects of contamination of ^{13}C on inclusive ν-^{12}C reaction cross sections

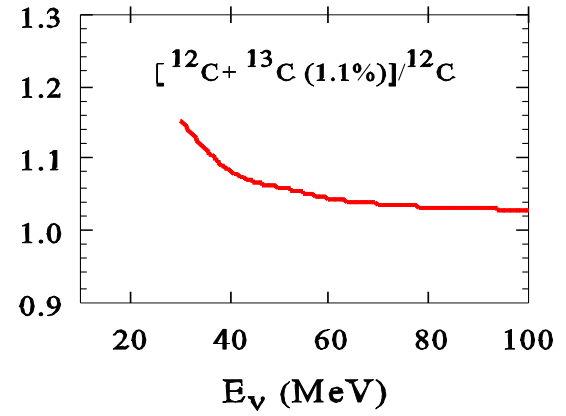
^{12}C 98.9% ^{13}C 1.1%

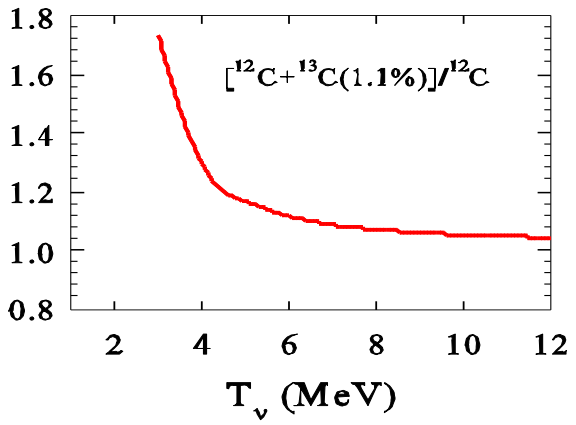
^{12}C (ν, e^-) ^{12}Ng.s. ΔM =16.83 MeV

^{13}C (ν, e^-) ^{13}Ng.s. ΔM = 1.71 MeV → $\sigma(^{13}C) > \sigma(^{12}C)$









Below E_ν = 15 MeV: pure ν-^{13}C reactions

No contamination from ν-^{12}C reactions

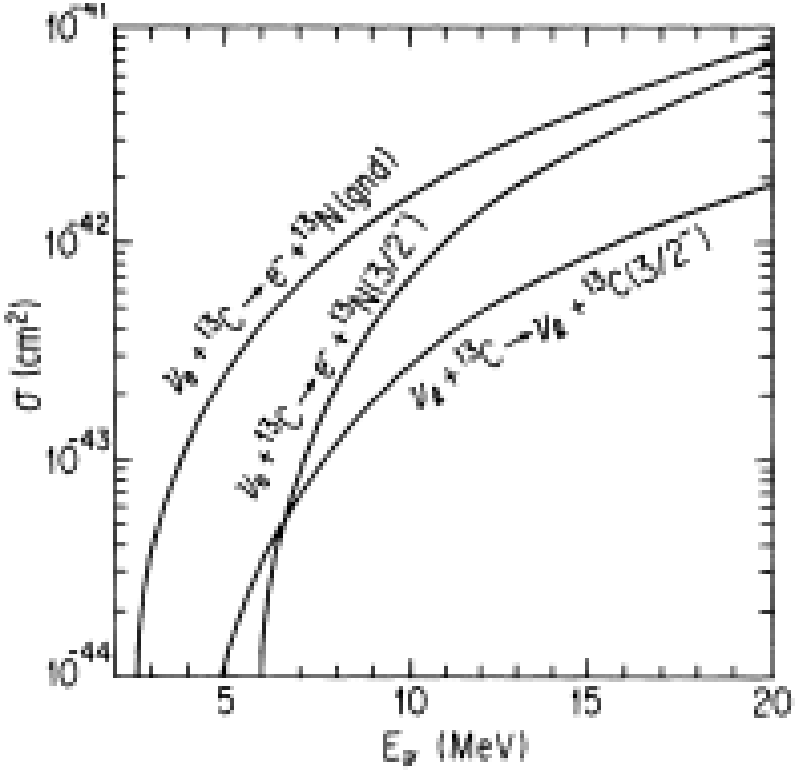
^{13}C: attractive target for very low energy ν

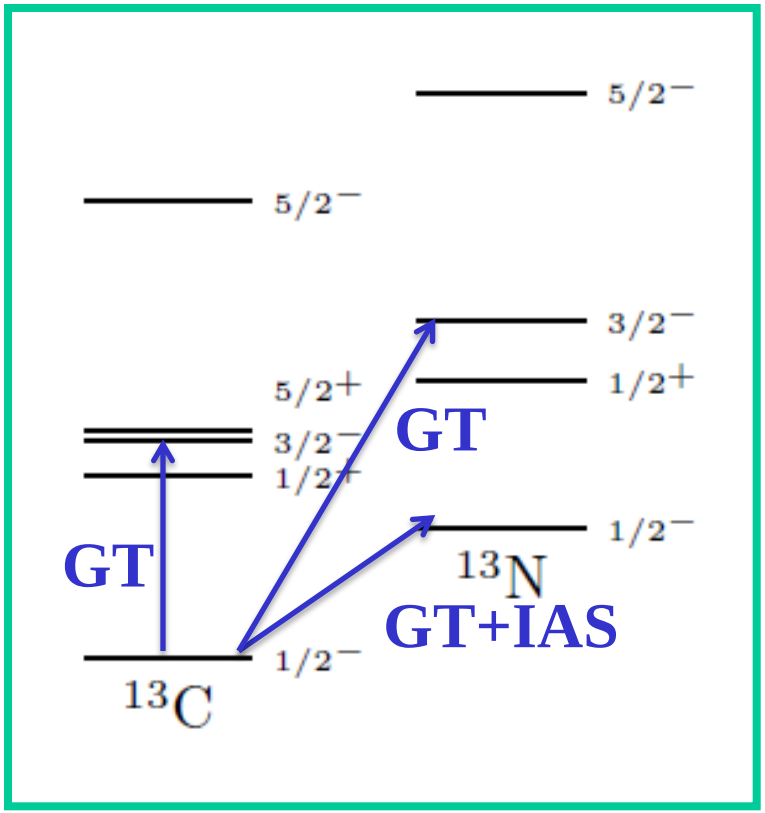
ν-induced reactions on ^{13}C

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

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

GT transitions

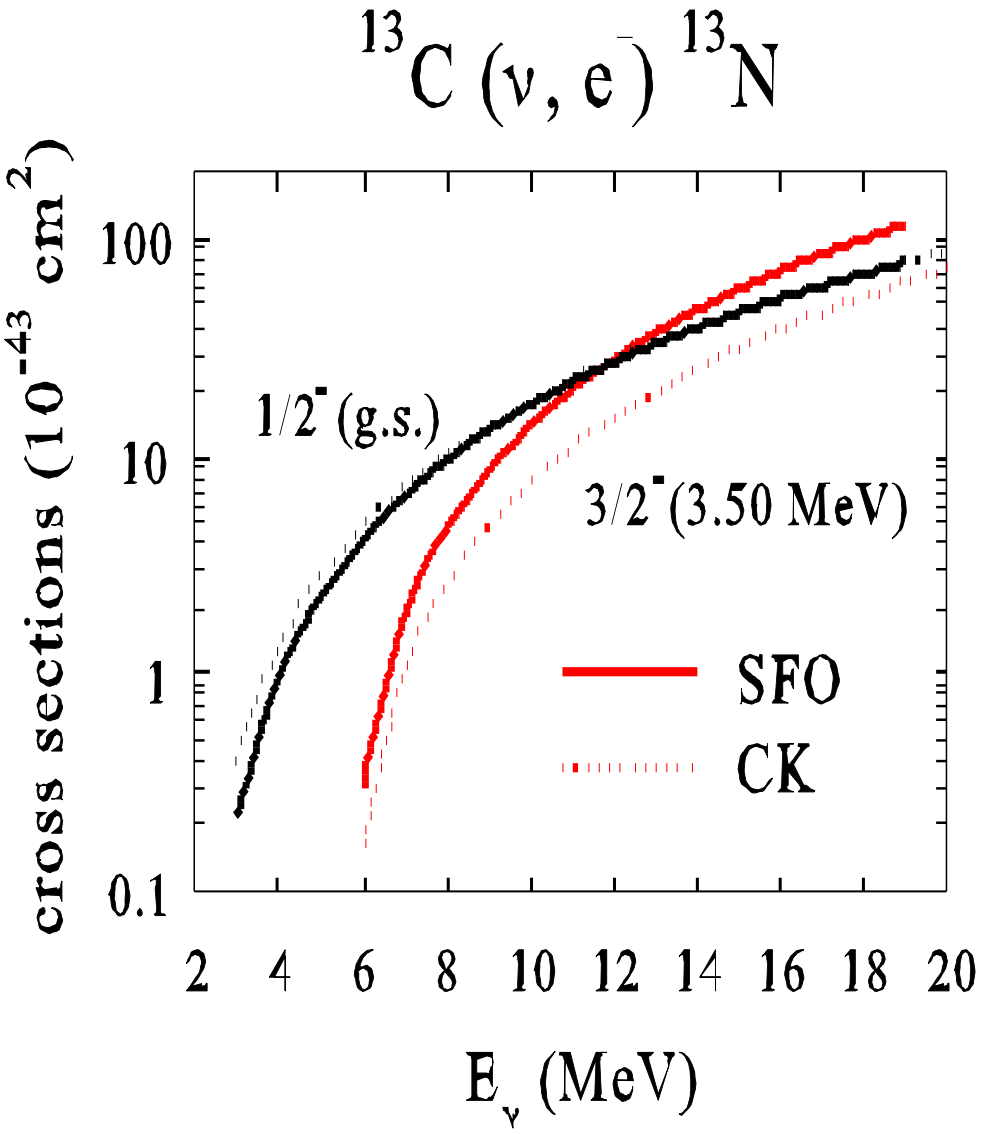




Fukugita et al., PR C41 (1990)
p-shell: Cohen-Kurath
$g_A^{eff}/g_A = 0.69$

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.

ν-induced reactions on ^{16}O

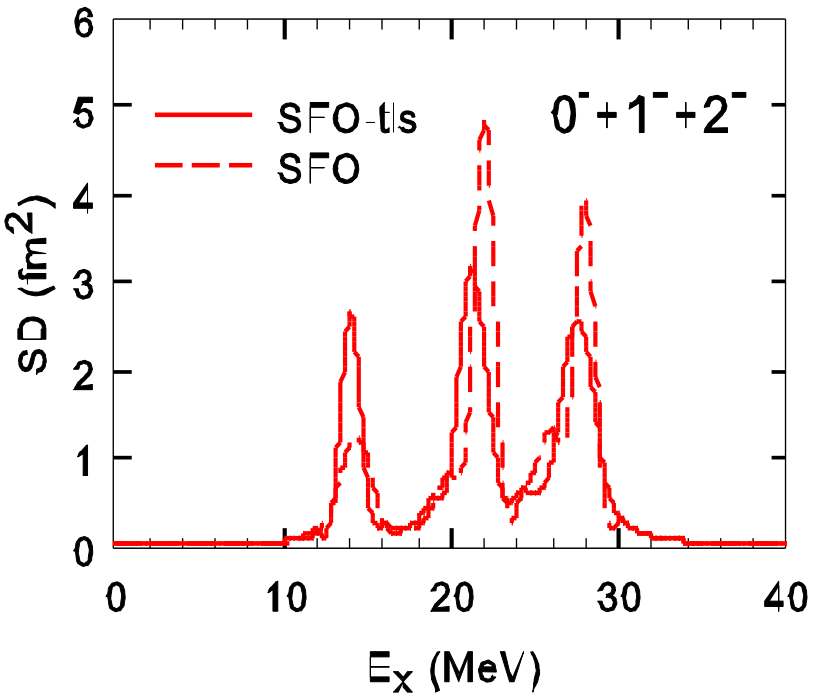
- **Modification of SFO → SFO-tls**

Full inclusion of tensor force

- **p-sd: tensor->π+ρ**

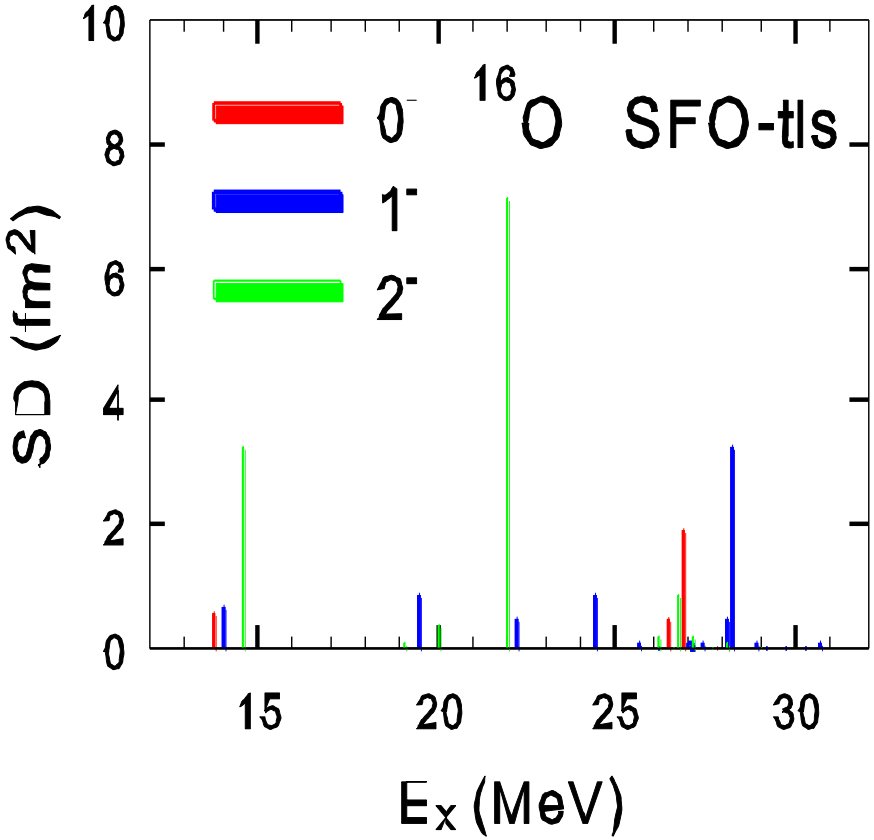
LS -> σ+ρ+ω

$$V = V_C + V_T + V_{LS}$$
$$V_T = V_\pi + V_\rho$$
$$V_{LS} = V_{\sigma+\omega+\rho}$$



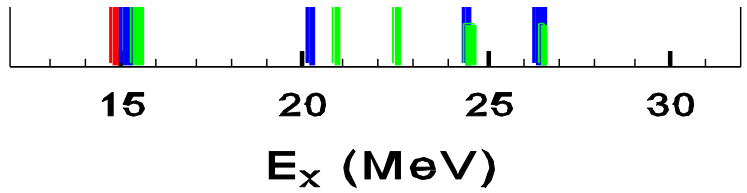
Spin-dipole strength in ^{16}O

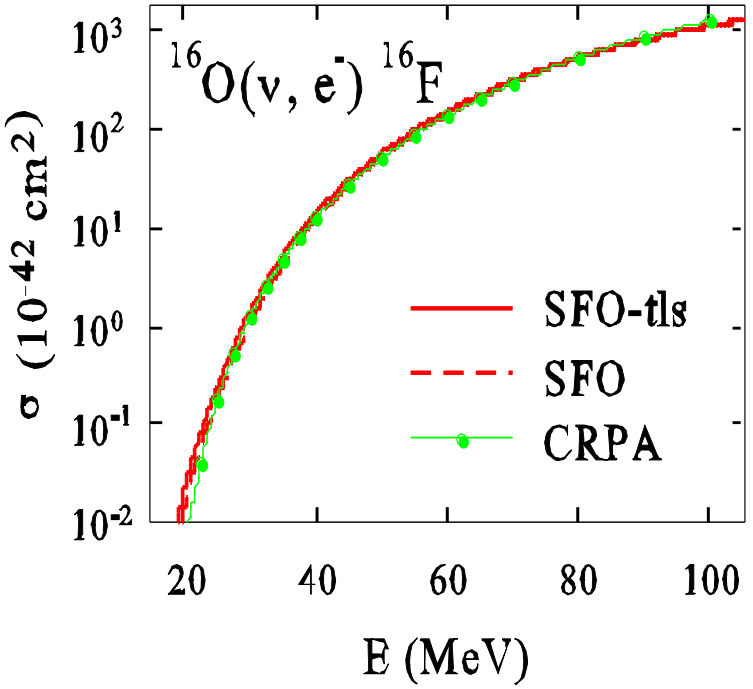
$$O(\lambda) = r[Y^1 \times \sigma]^\lambda t_-$$

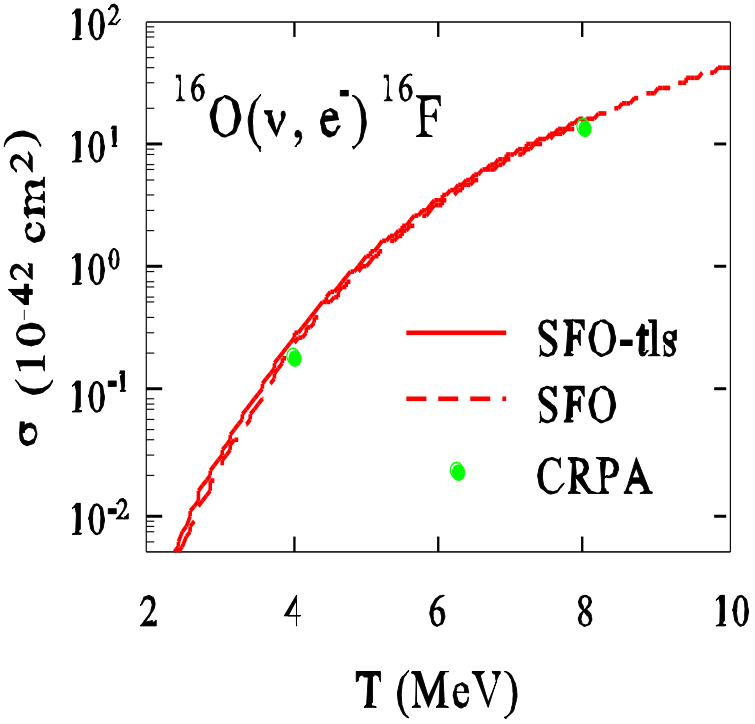


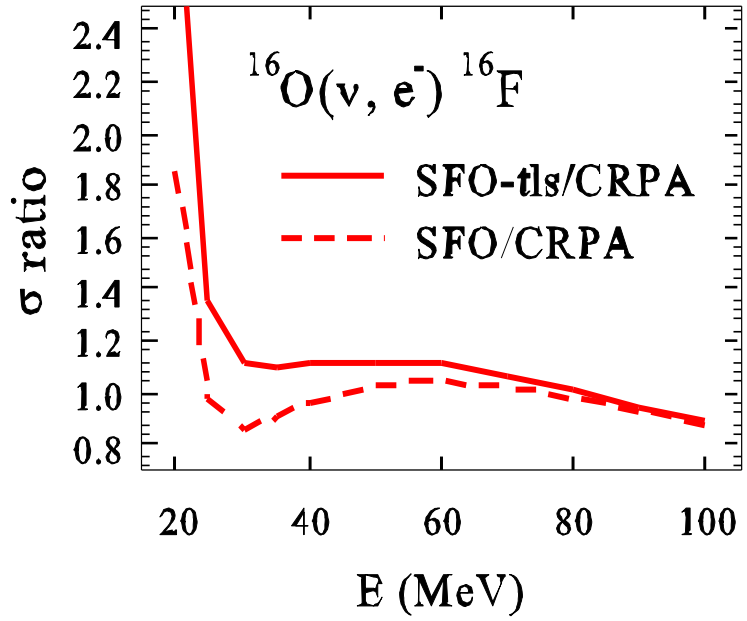
exp.

^{17}F









T= temperature of supernova ν

T	σ(SFO-tls)/σ(CRPA):
4	1.41
8	1.17

g_A^{eff}/g_A=0.95

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

New shell-model Hamiltonians in fp-shell:

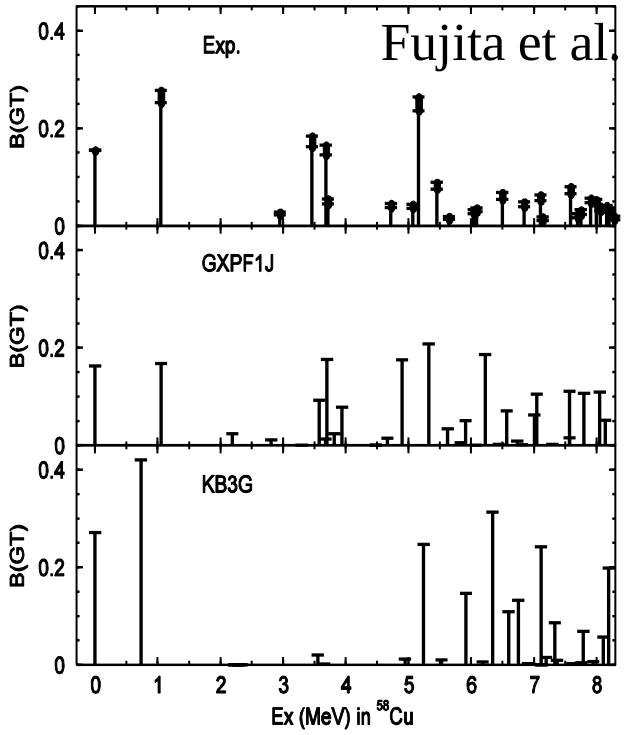
GXPF1: Honma, Otsuka, Mizusaki, Brown, PR C65 (2002); C69 (2004)

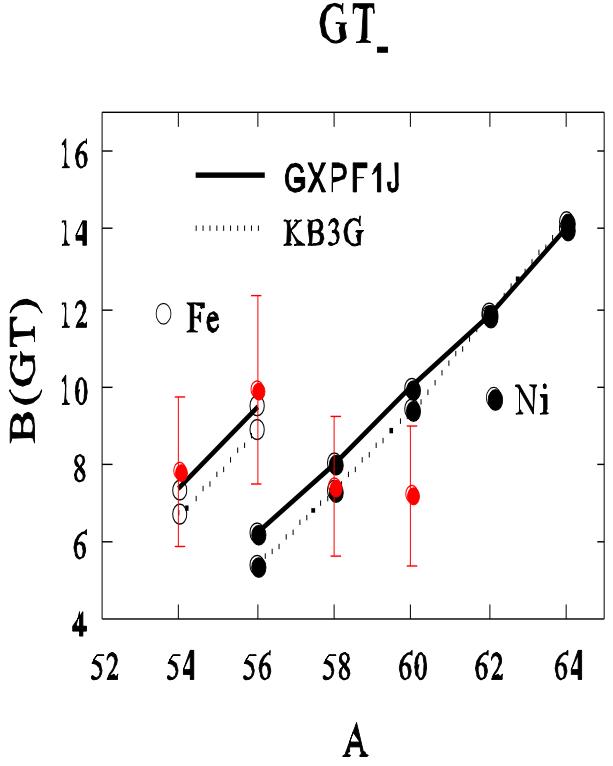
KB3: Caurier et al, Rev. Mod. Phys. 77, 427 (2005)

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

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

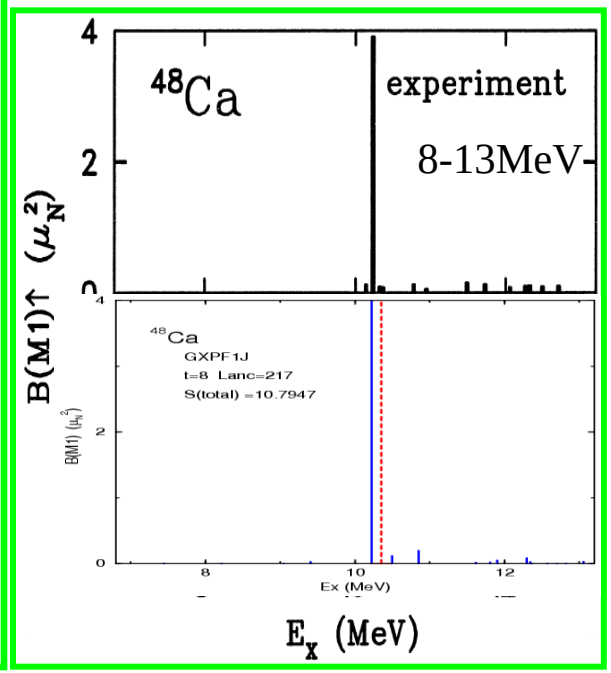
B(GT$_-$) for ^{58}Ni $g_A^{eff}/g_A^{free}=0.74$

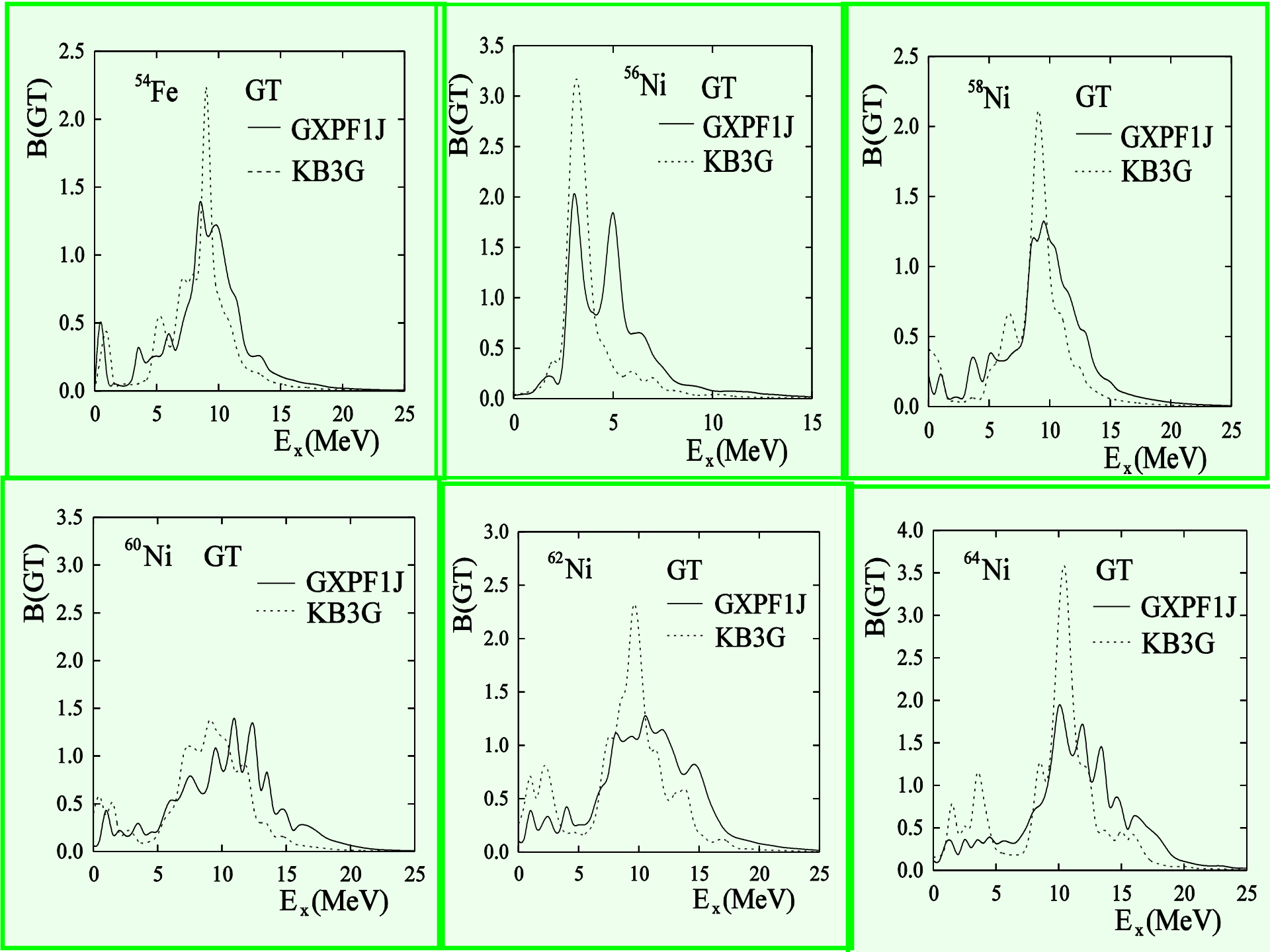




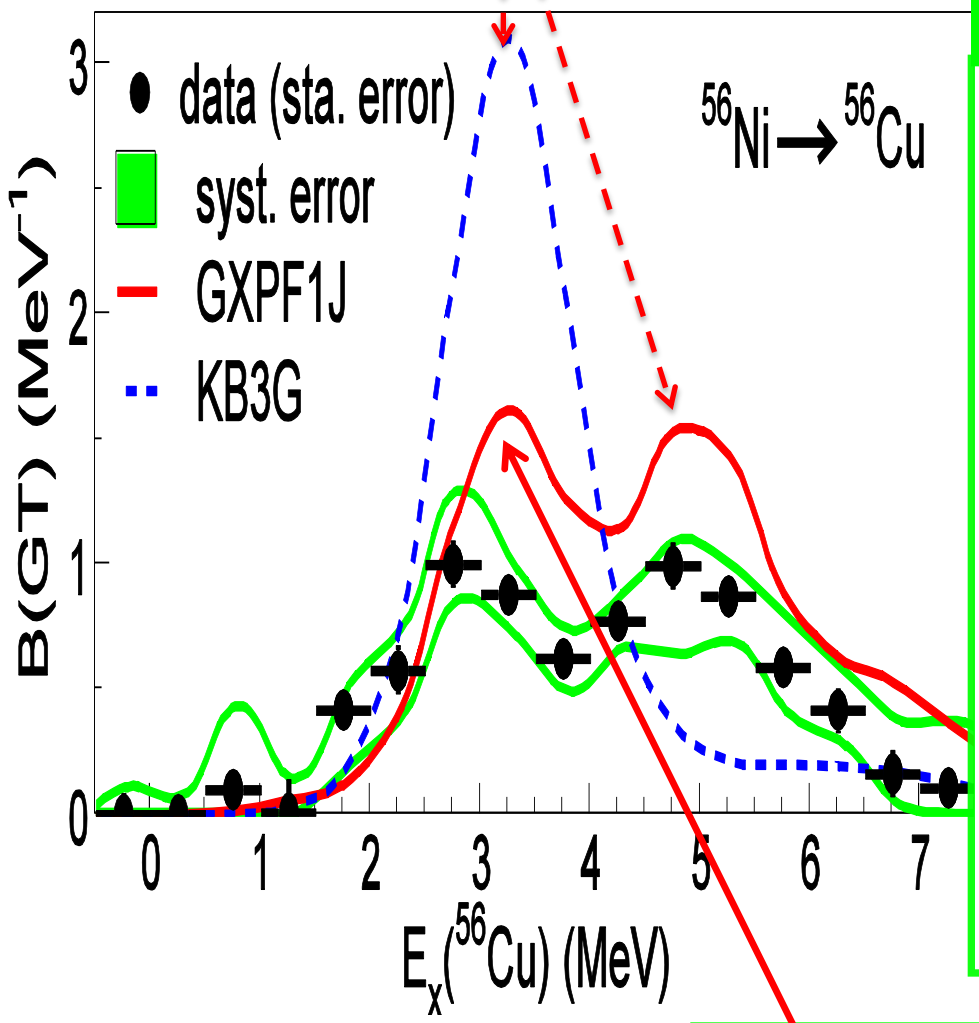
M1 strength (GXPF1J)

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




^{54}Fe GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
^{56}Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
^{58}Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
^{60}Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
^{62}Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)
^{64}Ni GT
GXPF1J
KB3G
B(GT)
E_x(MeV)

f7/2 -> f5/2



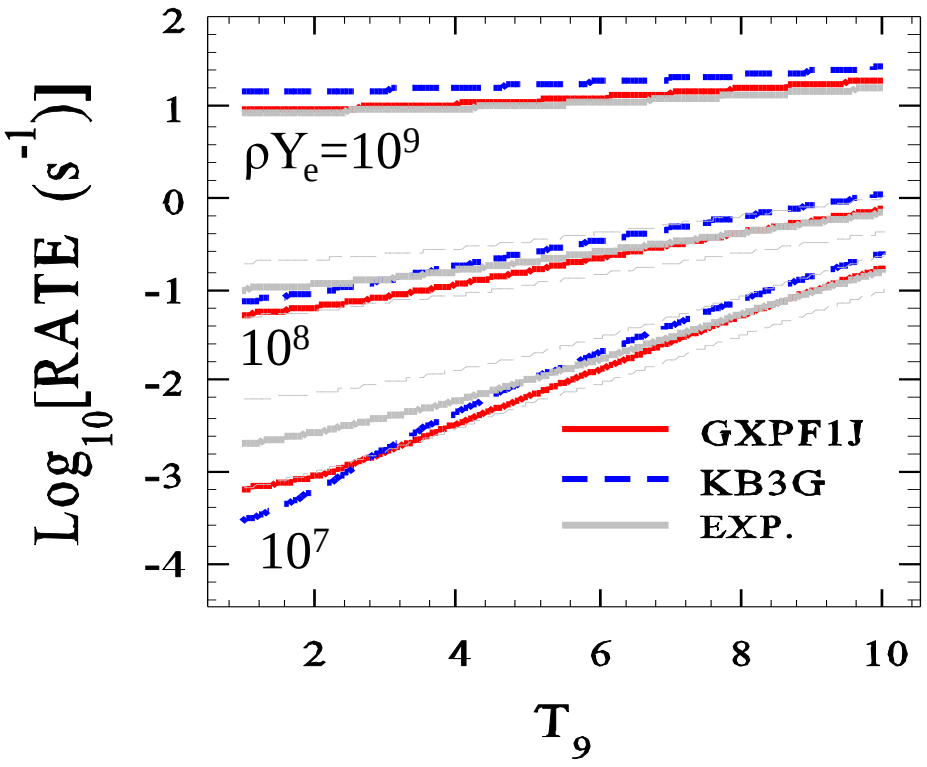
f7/2 -> f7/2

f7/2 -> f5/2

Sasano et al.

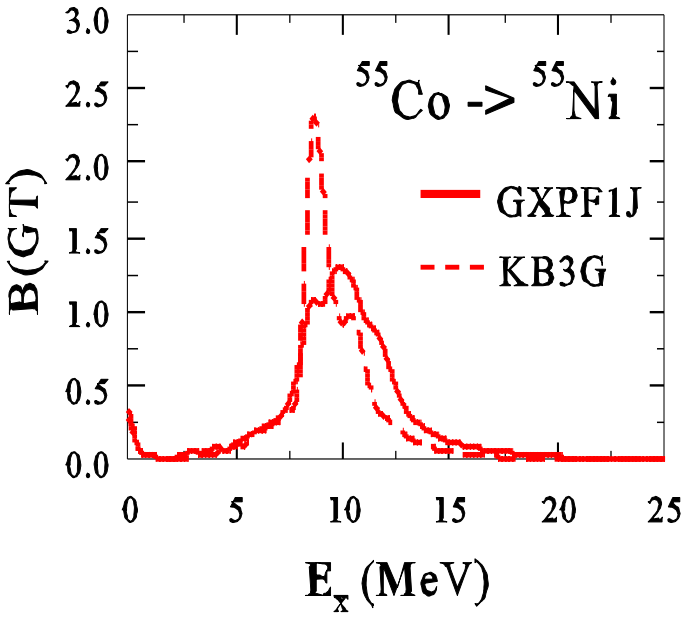
PRL 107, 202501 (2011)

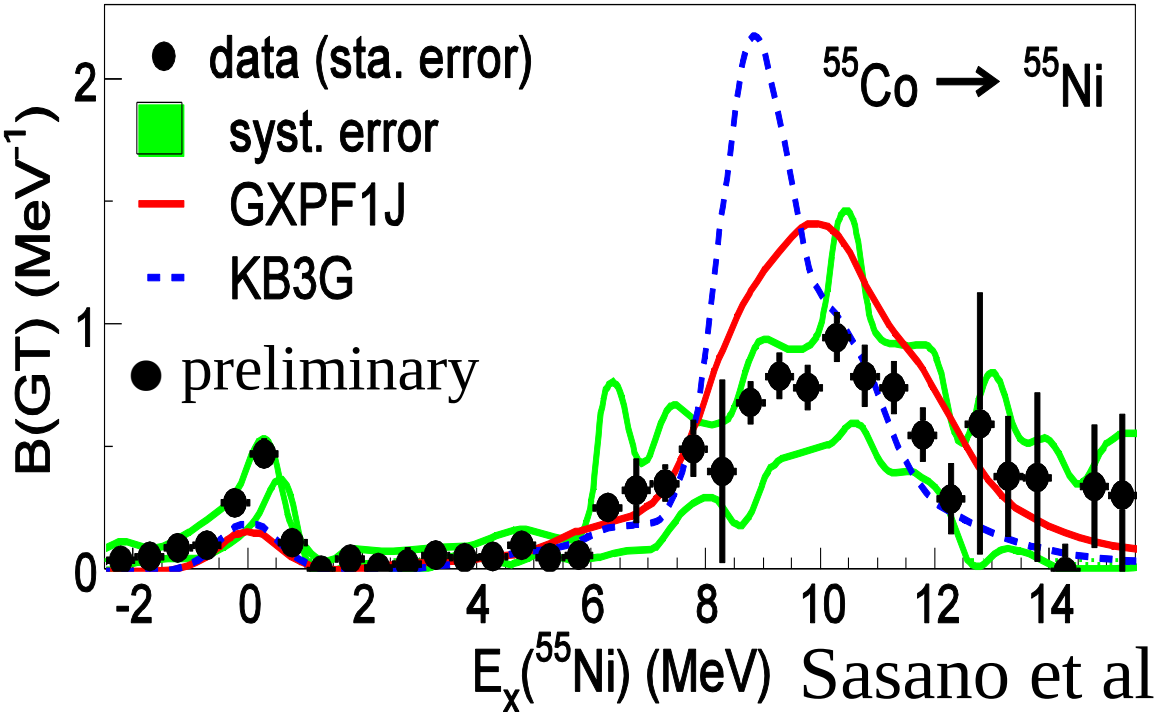
e-capture rates in stellar environments

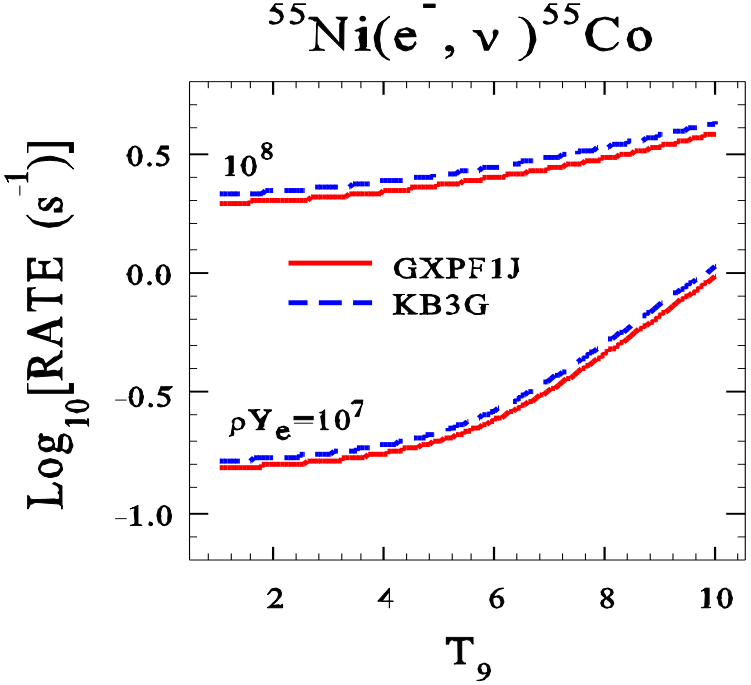


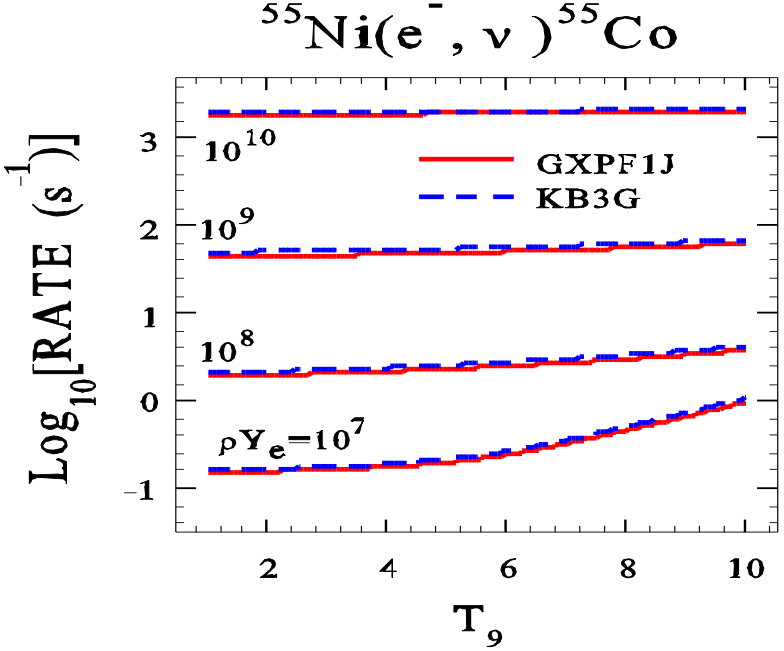
$\rho Y_e = 10^7 - 10^{10}\ \mathrm{g/cm^3}$

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

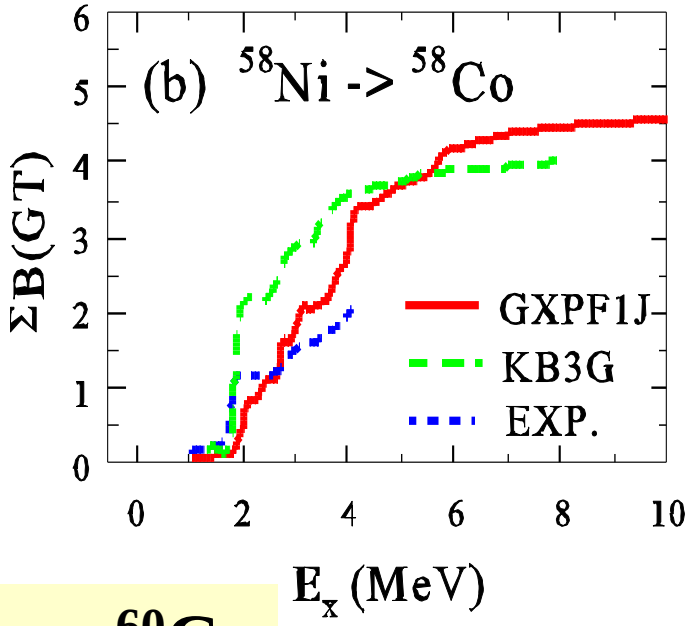

^{55}Co -> ^{55}Ni
GXPF1J
KB3G
B(GT)
E_x (MeV)

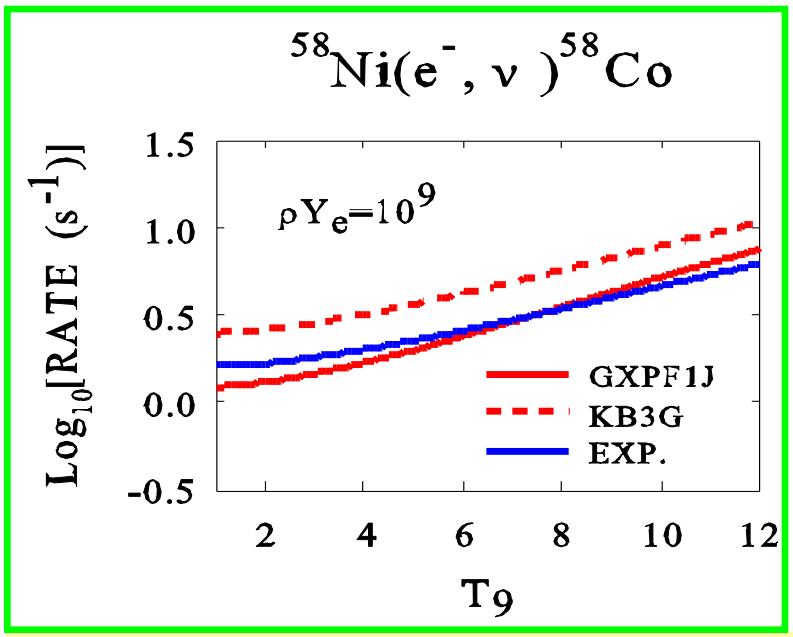

data (sta. error)
syst. error
GXPF1J
KB3G
preliminary
^{55}Co → ^{55}Ni
B(GT) (MeV^{-1})
E_x(^{55}Ni) (MeV)
Sasano et al.


^{55}Ni(e$^-$, ν)^{55}Co
10^8
GXPF1J
KB3G
ρY$_e$=10^7
Log$_{10}$[RATE (s^{-1})]
T$_9$


^{55}Ni(e$^-$, ν)^{55}Co
10^{10}
10^9
10^8
ρY$_e$=10^7
GXPF1J
KB3G
Log$_{10}$[RATE (s^{-1})]
T$_9$

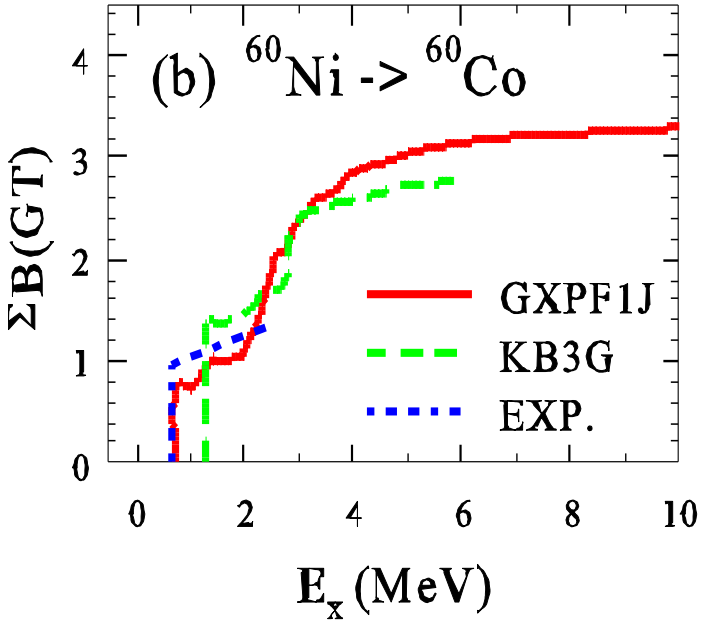
$^{58}Ni \rightarrow {}^{58}Co$

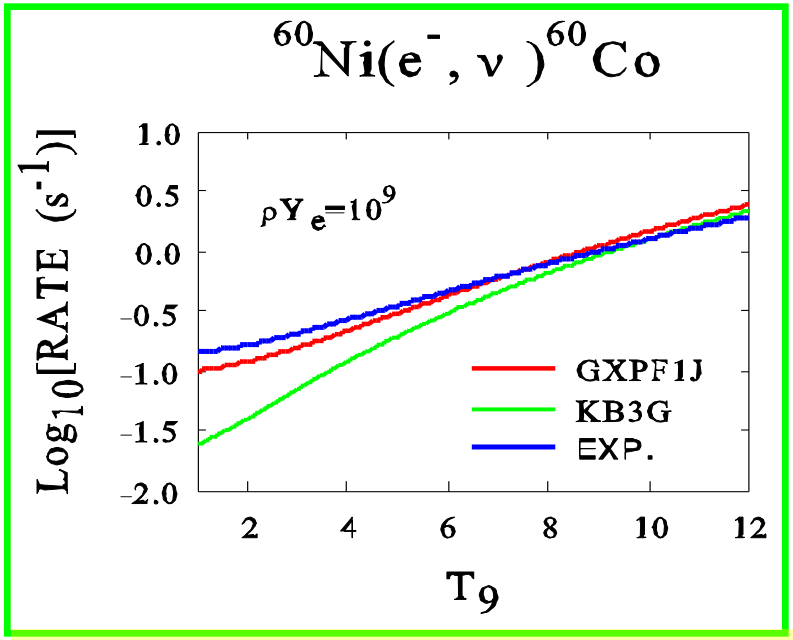




Exp: Hagemann et al., PL B579 (2004)

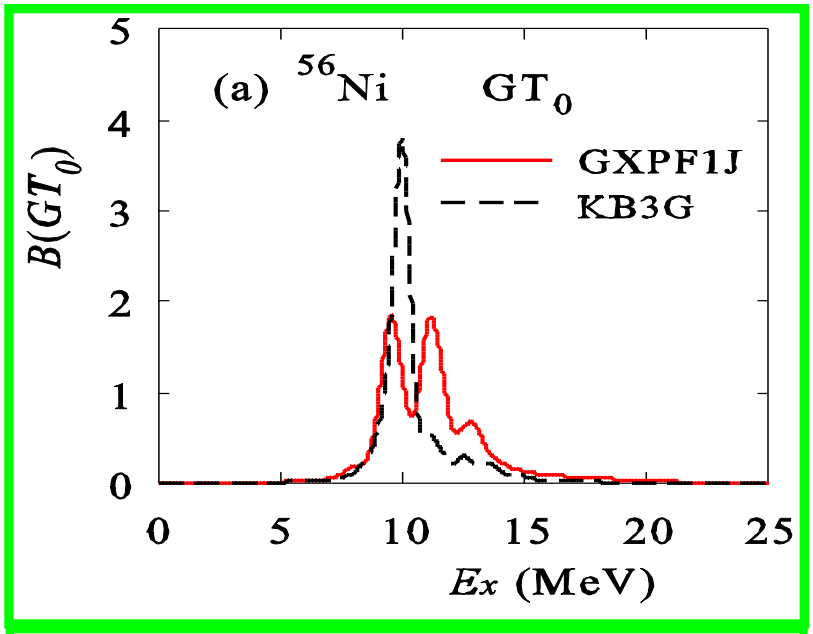
$^{60}Ni \rightarrow {}^{60}Co$



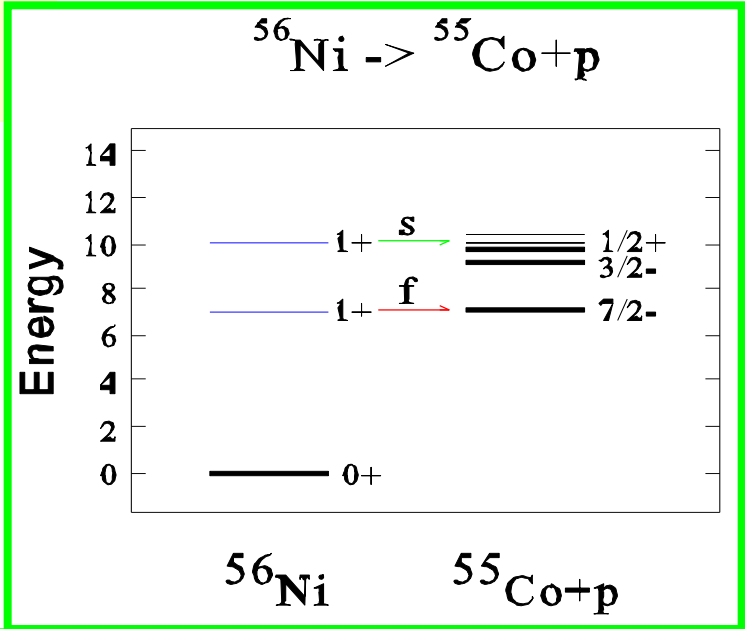


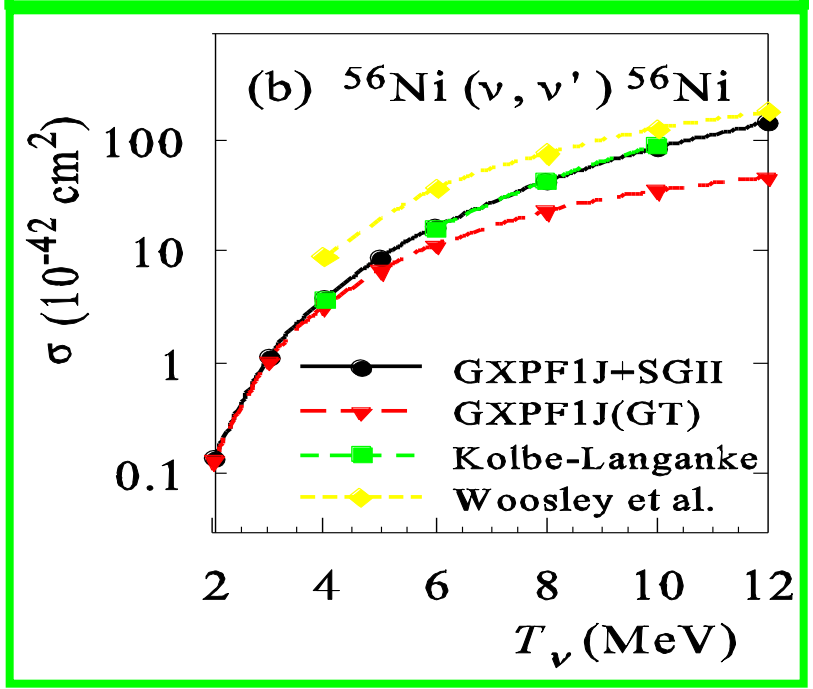
Exp: Anantaraman et al., PR C78 (2008)

●Neutral current reaction on ^{56}Ni

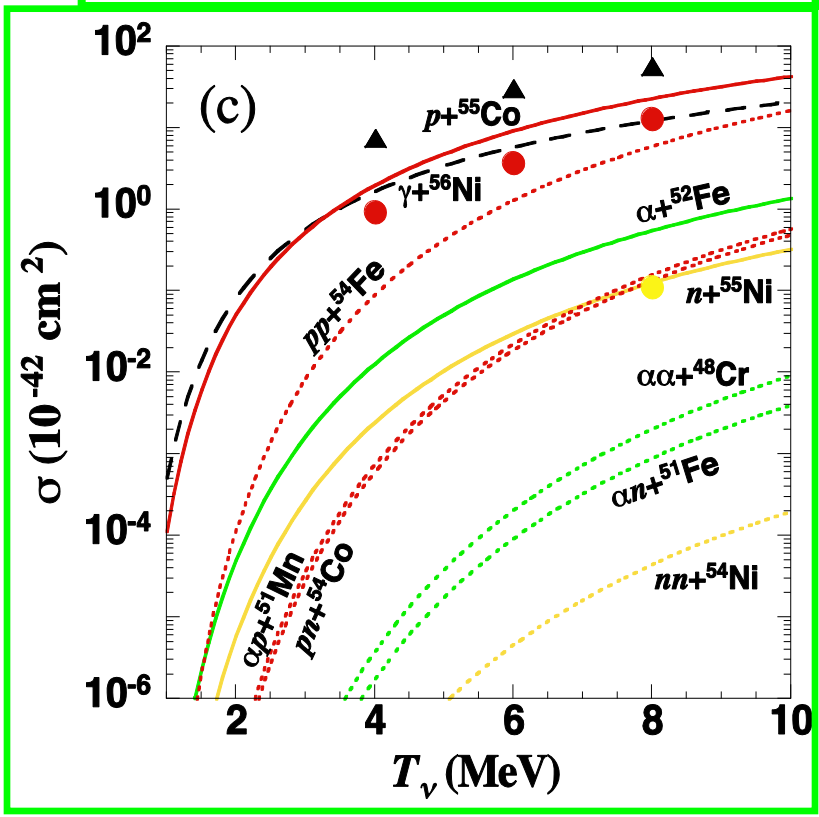


B(GT)=6.2 (GXPF1J)
B(GT)=5.4 (KB3G)



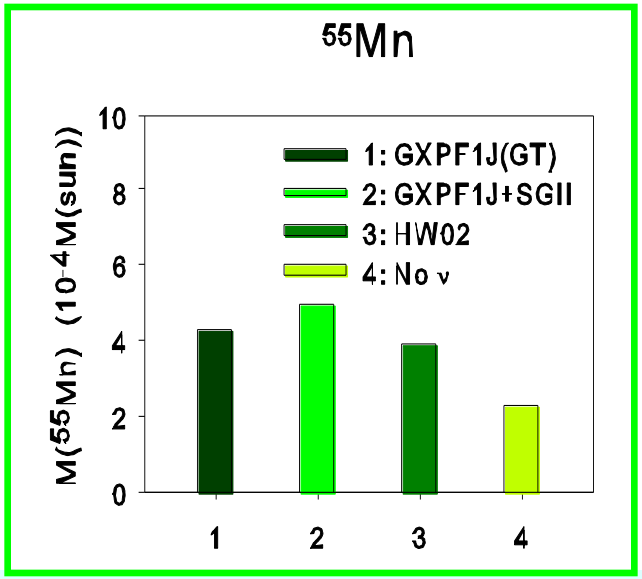


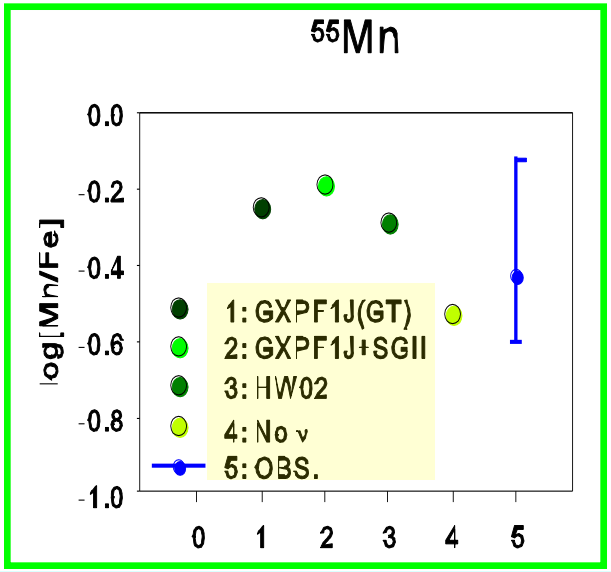
cf:
HW02
▲gamma
●p
●n



Synthesis of Mn in Population III Star

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

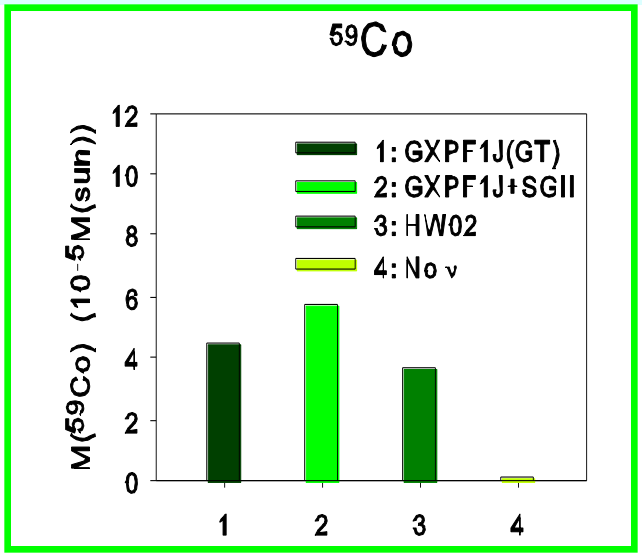


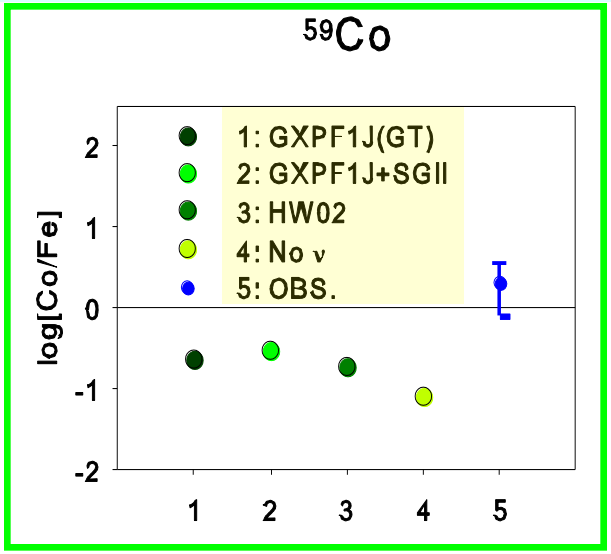


$^{54}\mathrm{Fe}(\mathrm{p},\gamma)^{55}\mathrm{Co}$

Yoshida, Umeda, Nomoto

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





Suzuki et al., PR C79 (2009)

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

VMU= Monopole based Universal Interaction

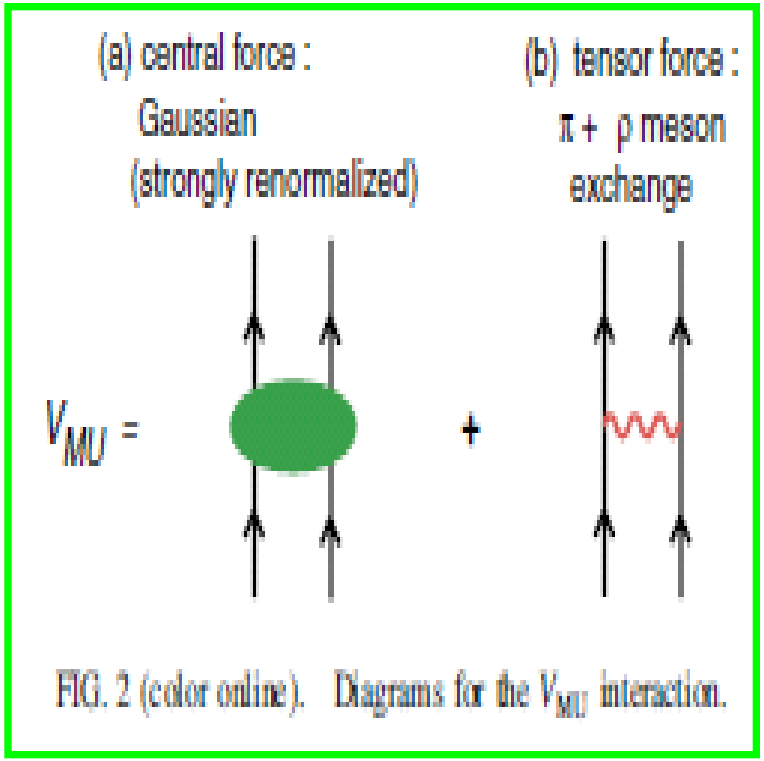


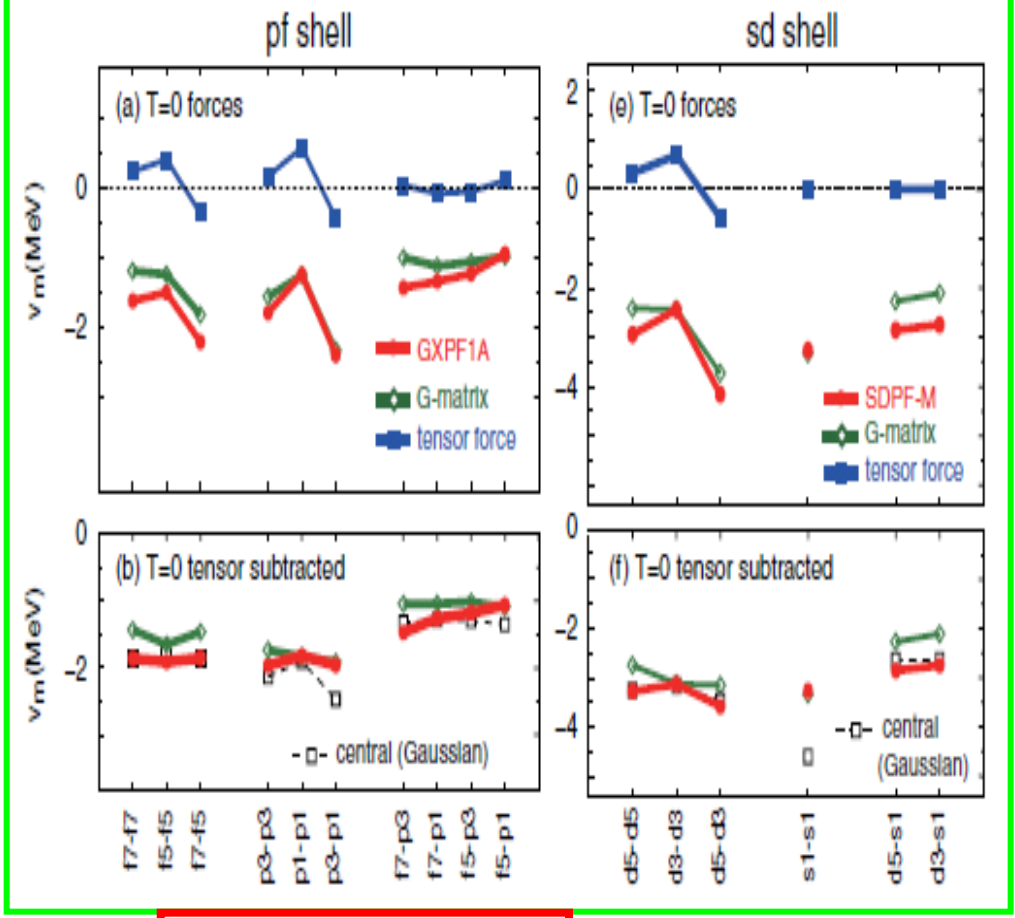
FIG. 2 (color online). Diagrams for the V_{MU} interaction.

- **Important roles of tensor force**

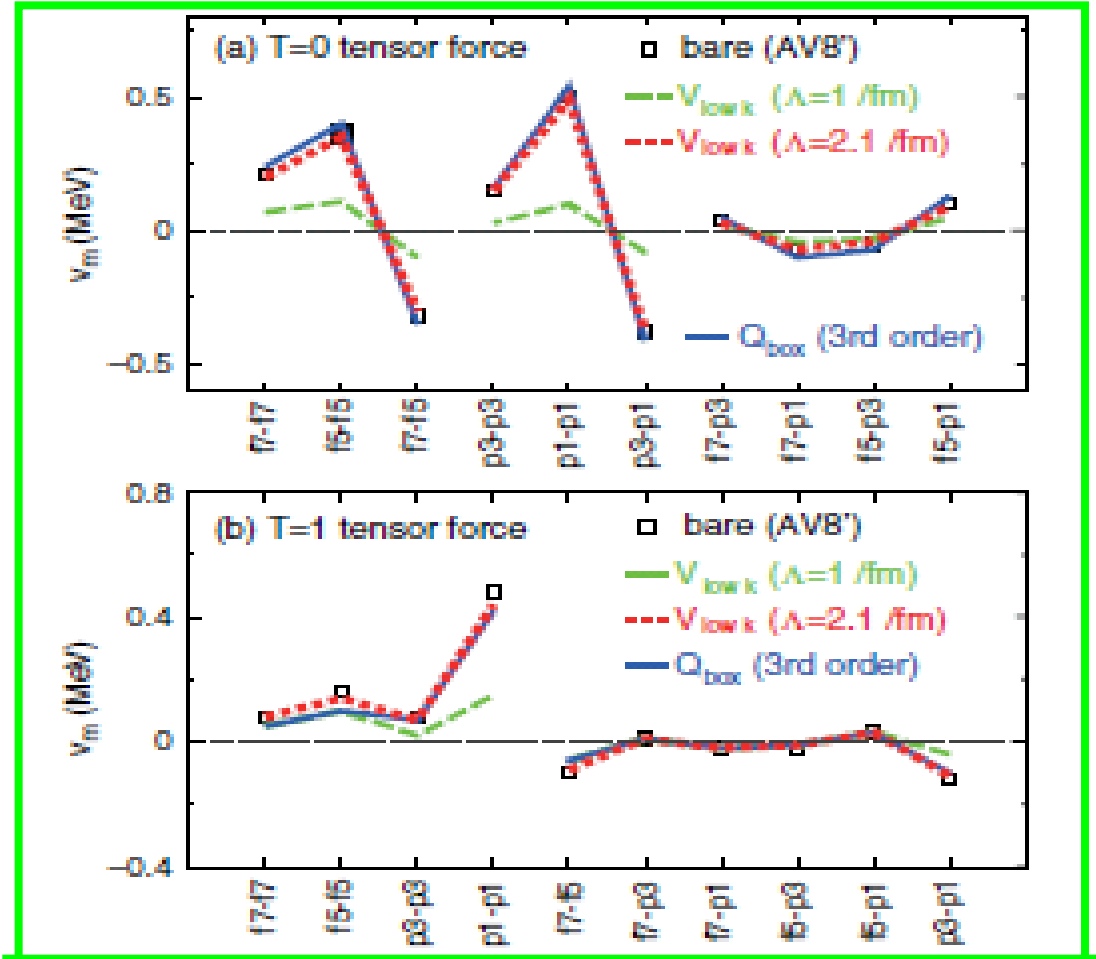
Otsuka, Suzuki, Honma, Utsuno, Tsunoda, Tsukiyama, Hjorth-Jensen
PRL 104 (2010) 012501

Monopole terms in V_{nn}

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

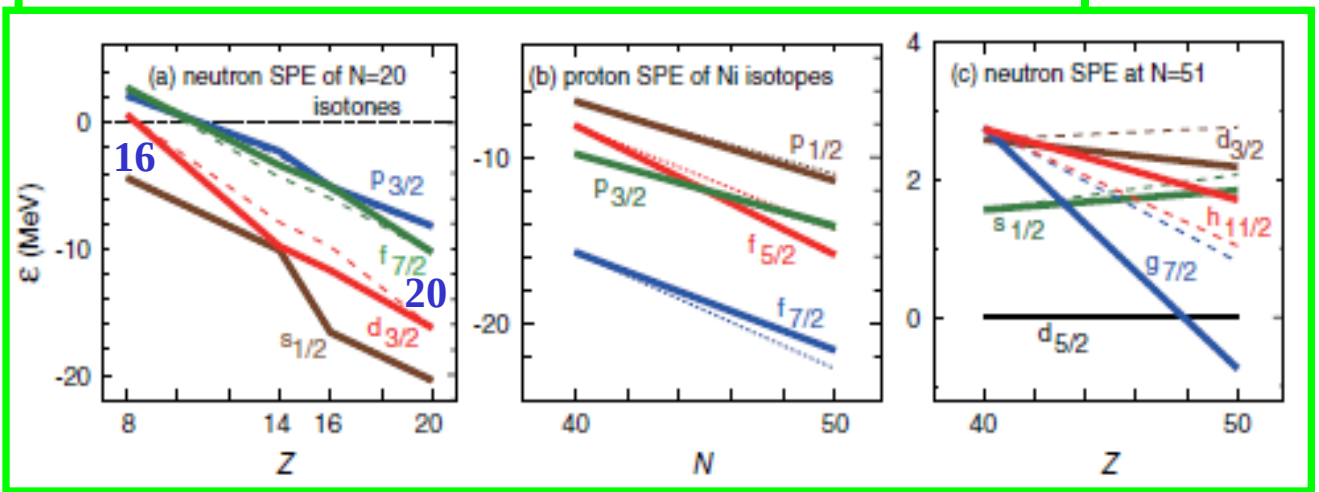


tensor force



Tensor:
bare≈renormalized

Tensor force →
proper shell evolutions
toward drip-lines



^{40}Ar (ν, e^-) ^{40}K

SDPF-VMU

sd: SDPF-M (Utsuno et al.)

fp: GXPF1 (Honma et al.)

sd-pf: VMU

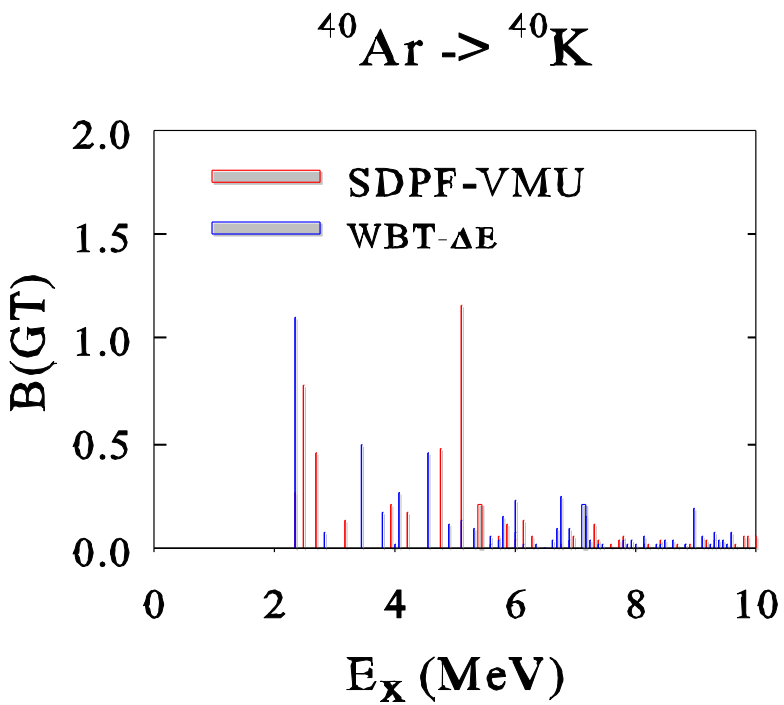
$(sd)^{-2}\ (fp)^2$: 2hw

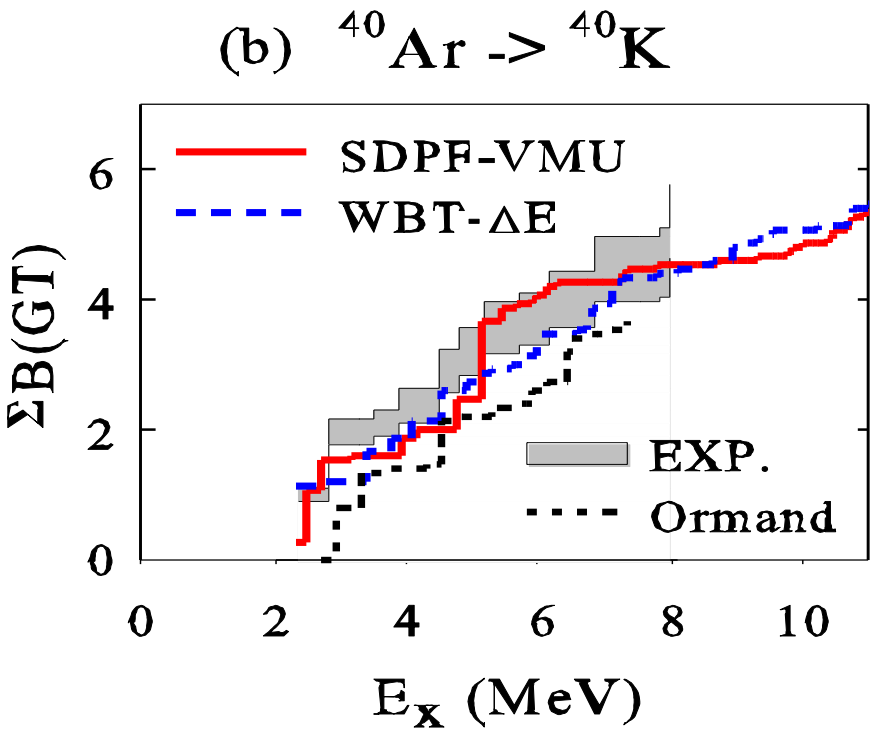
B(GT)

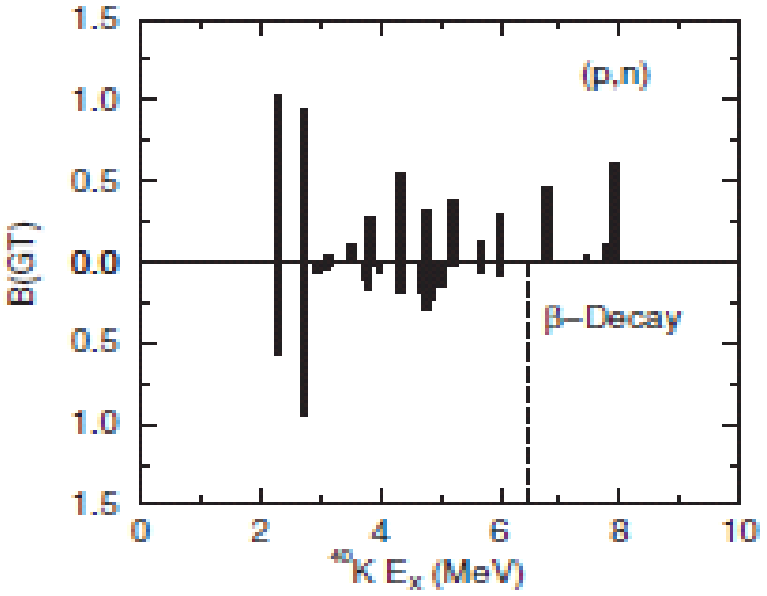
ν-^{40}Ar cross sections

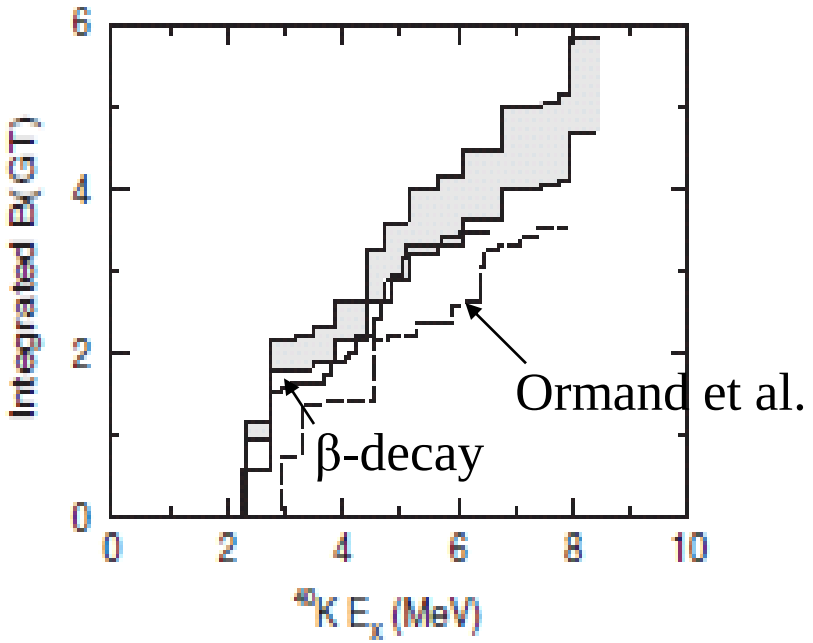
Solar ν cross sections folded over ^{8}B ν spectrum

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

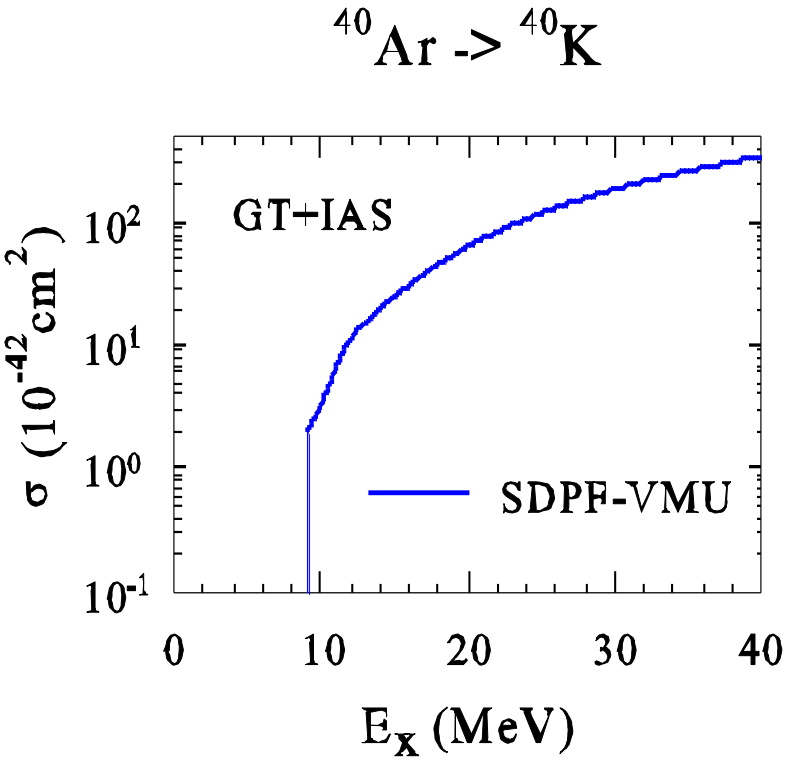






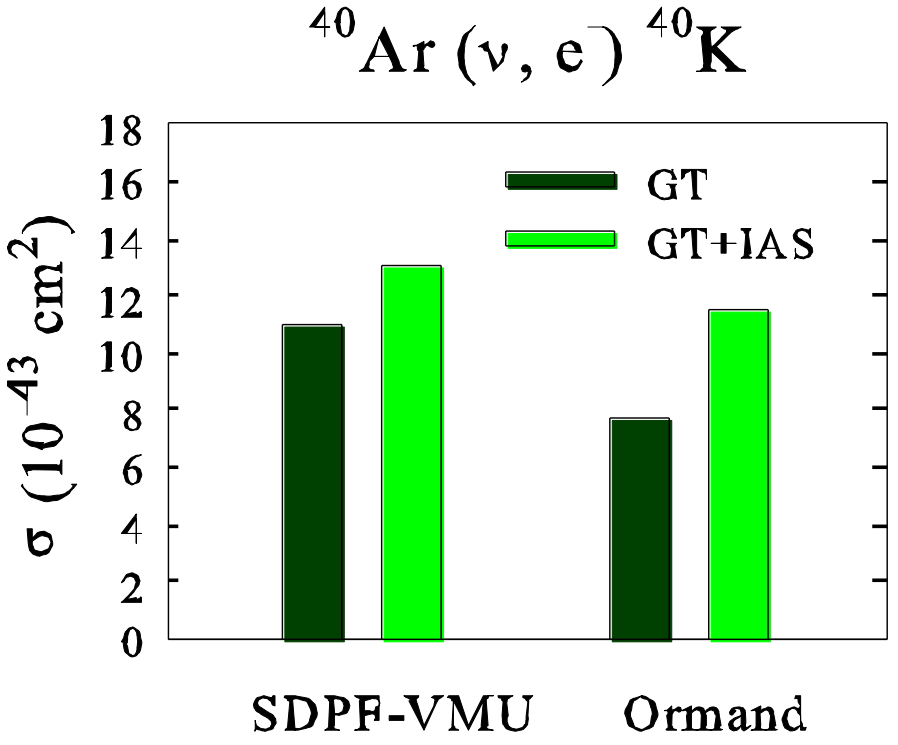


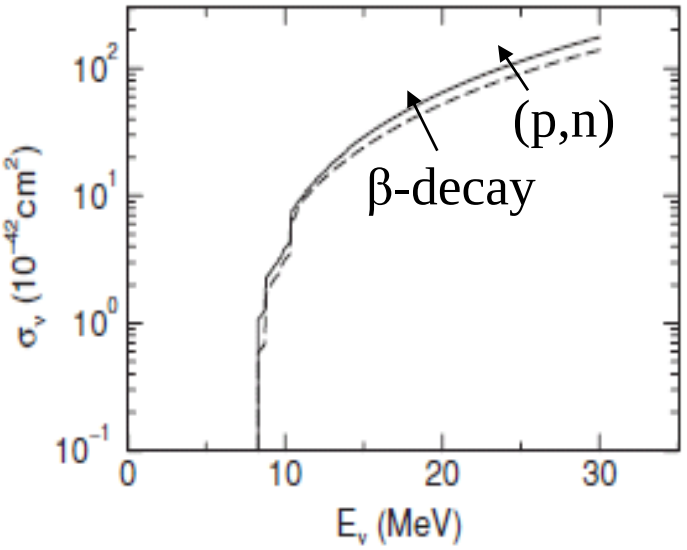
(p,n) Bhattacharya et al., PR C80 (2009)



GT+IAS
E_e > 5 MeV : ICARUS

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

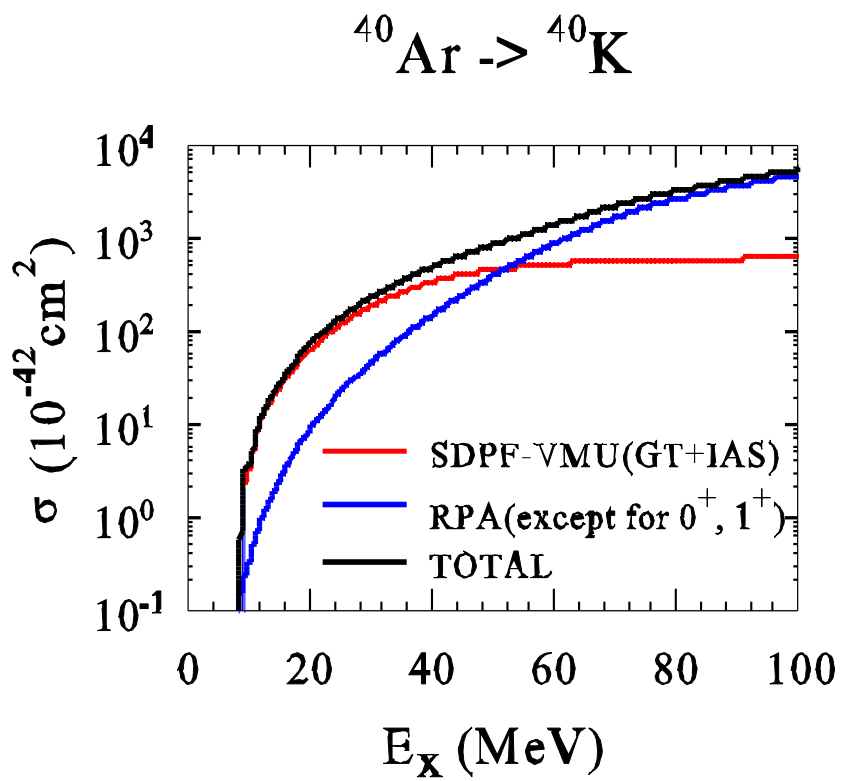


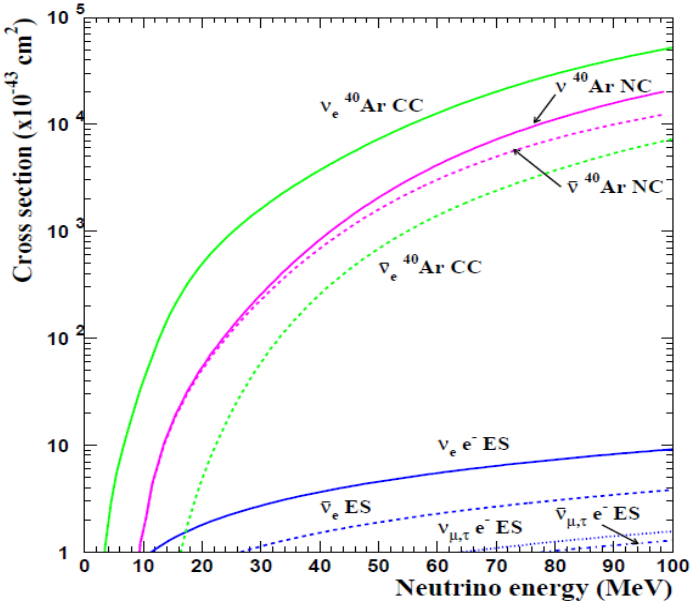


IAS: C0+L0 ≈$[(q^2-\omega^2)/q^2]^2 \times$ C ; $^+$ C0 only
GT: E_1^5 +M1+C_1^5+L_1^5 ; $^+$ E_1^5 only

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

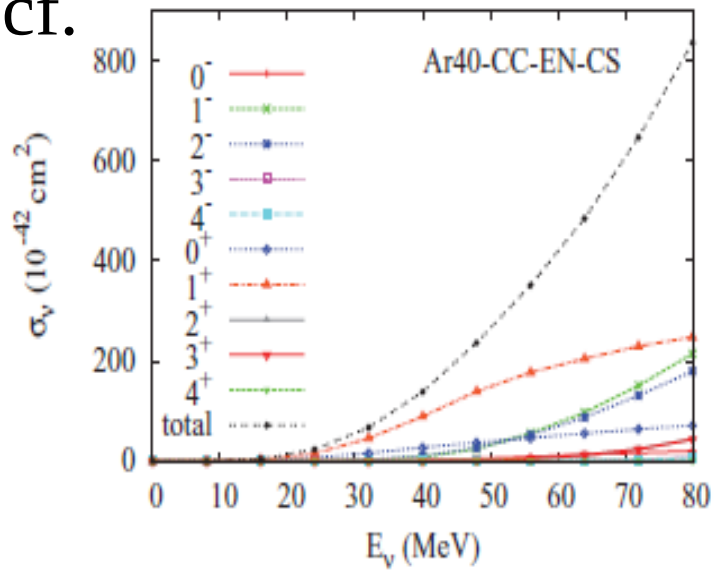
(p,n) Bhattacharya et al., PR C80, 055501 (2009)

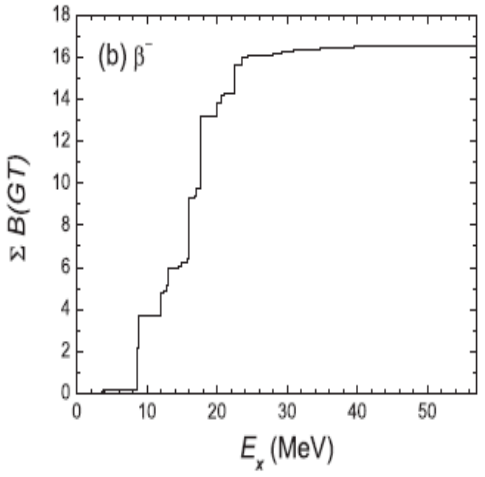




Pinedo, Kolbe, Langanke in Gil-Botella and Rubbia, arXiv:hep-ph/0307244v2

cf.





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

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**
- **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**

Collaborators

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