Roles of Tensor and Three-Body Forces on Shell Evolution and Spin Degrees-of-Freedom in Nuclei

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GSI May 3, 2012

- **Important roles of tensor forces for shell evolution and spin-dependent transitions**
- **Need for repulsion in T=1 monopoles**

○ **Phenomenological shell model interactions**

SFO: tensor in p-shell ; p-shell nuclei

GT strength in ^{12}C, ^{14}C

SFO-tls: tensor in p-sd; spin-dipole strength in ^{16}O

+repulsion in sd-shell (T=1); n-rich C isotopes

○ **Monopole-based-universal interaction (VMU)**

GT strength in ^{40}Ar and ν-induced reactions on ^{40}Ar

- **Three-body forces → repulsion**

○ **Microscopic 2+3-body forces**

G + FM-3N (Δ excitaions by 2π exchanges)

Structure of n-rich isotopes

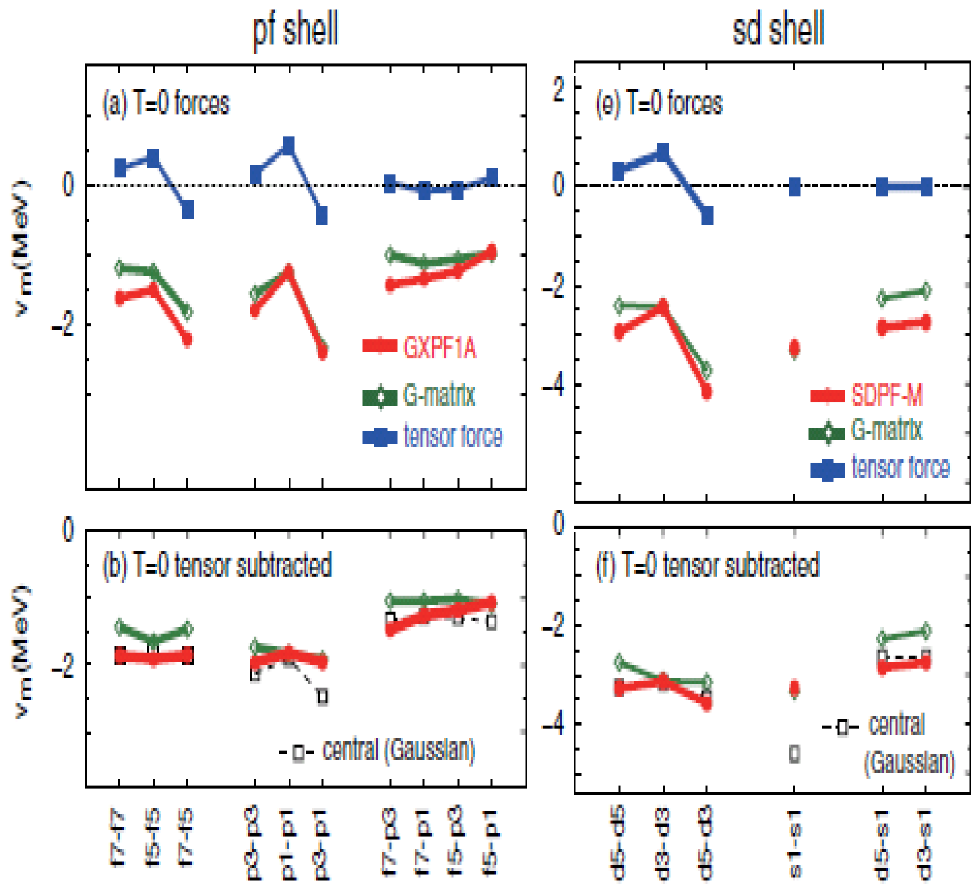
M1 strength in ^{48}Ca

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 in V_{nn}

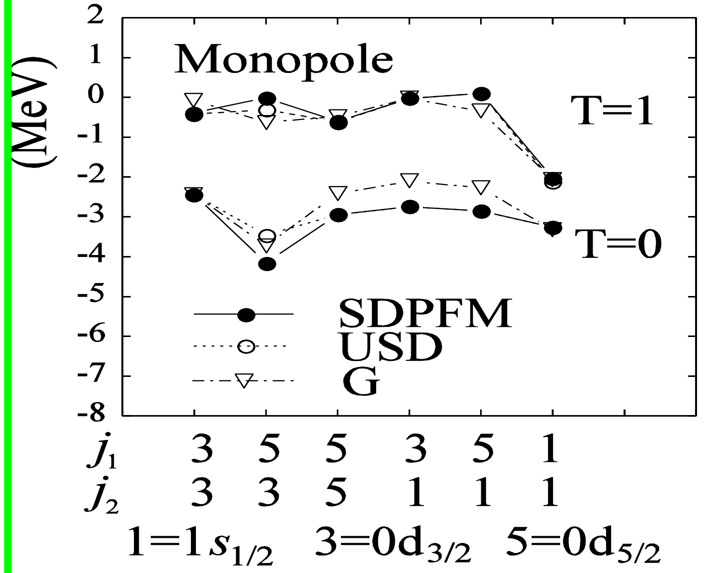
$$V_M^T(j_1 j_2) = \frac{\sum_J (2J+1) < j_1 j_2; JT \mid V \mid j_1 j_2; JT >}{\sum_J (2J+1)}$$

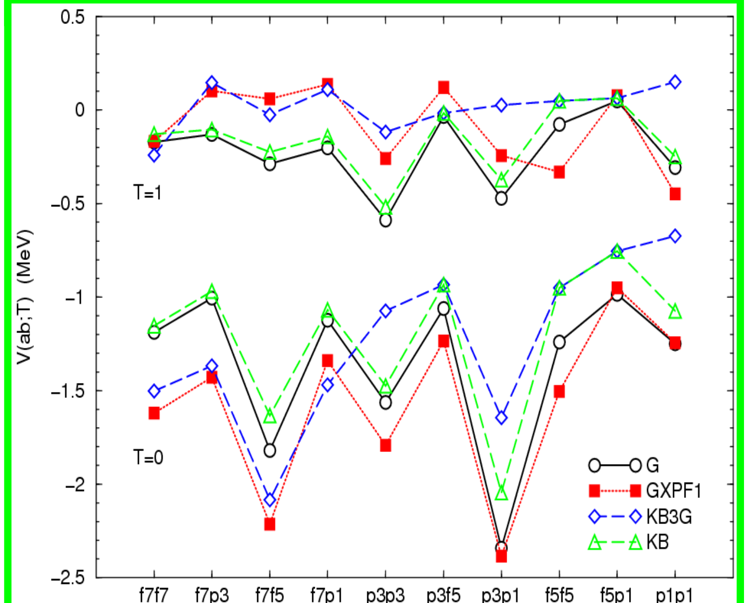


tensor force

- **Tensor force + repulsive corrections in T=1 monopoles**
  → SFO-tls
  - **Structure of neutron-rich C isotopes**
  - **Exotic M1 transitions in ^{17}C**

- **3 body forces induced by Δ excitations**
  → repulsion in T=1 monopoles



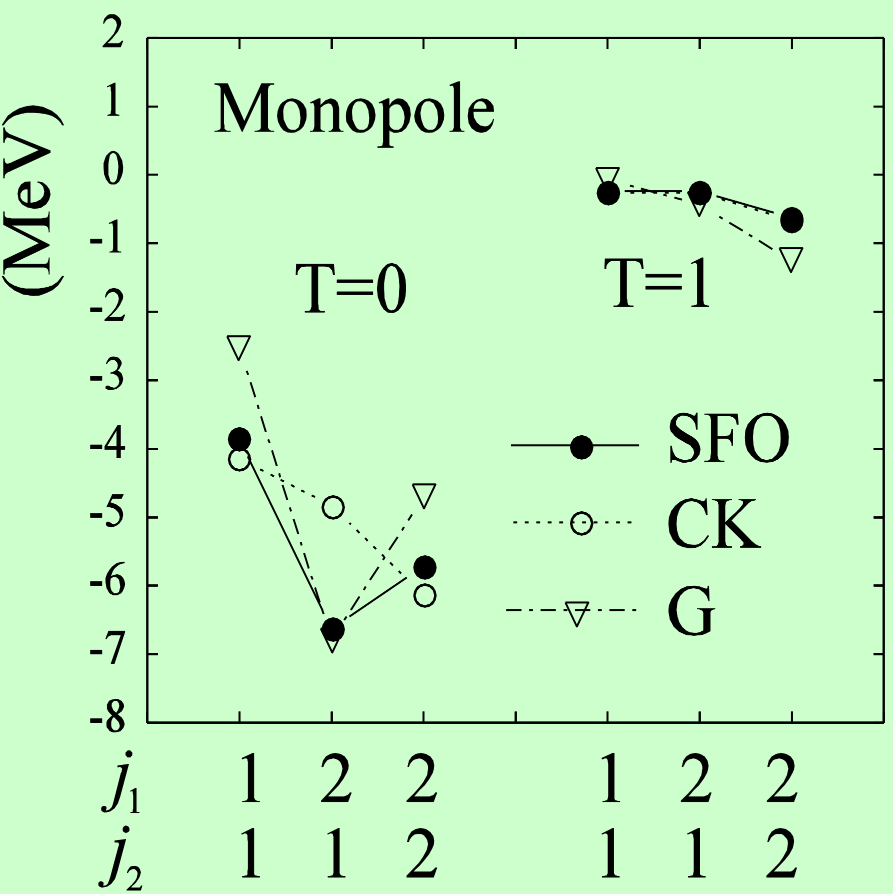


more repulsion than G in T=1
more attraction than G in T=0

SFO
p-sd shell

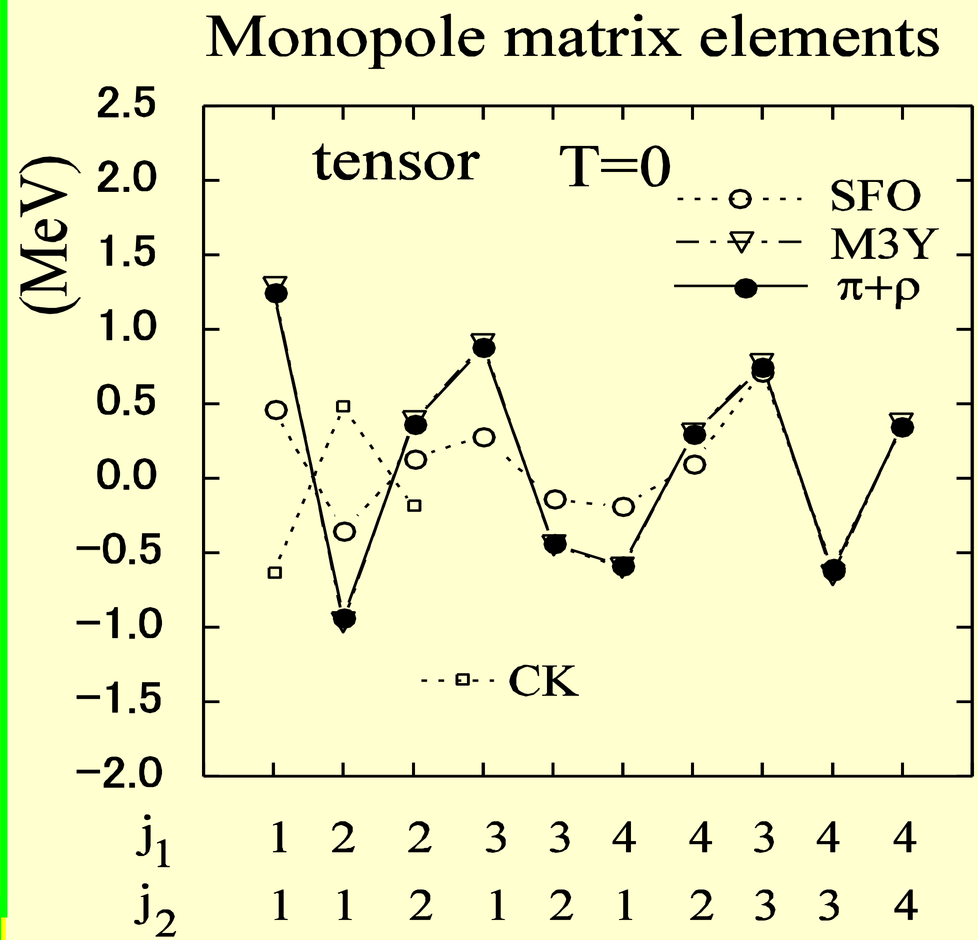
Suzuki, Fujimoto, Otsuka, PR C67 (2003)

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



$1=0p_{1/2}$ $2=0p_{3/2}$

Tensor components

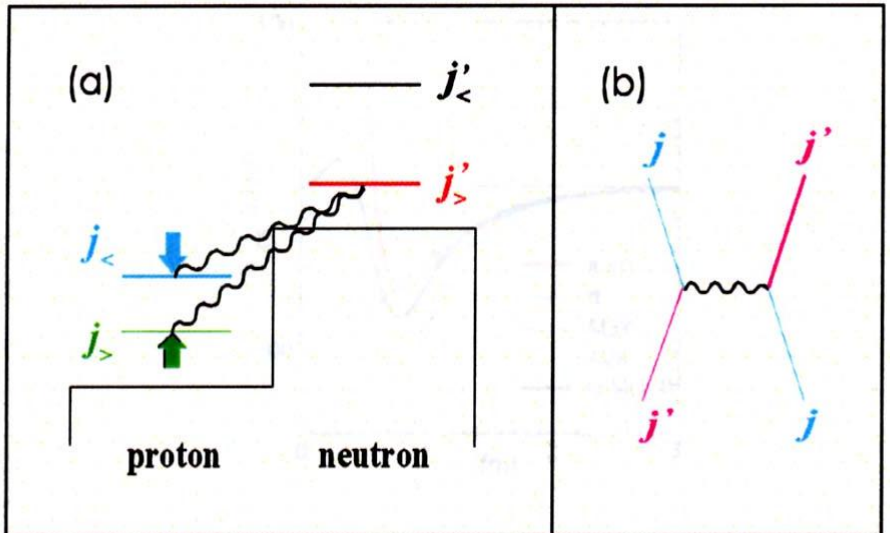


$1=0p_{1/2}$ $2=0p_{3/2}$ $3=0d_{3/2}$ $4=0d_{5/2}$

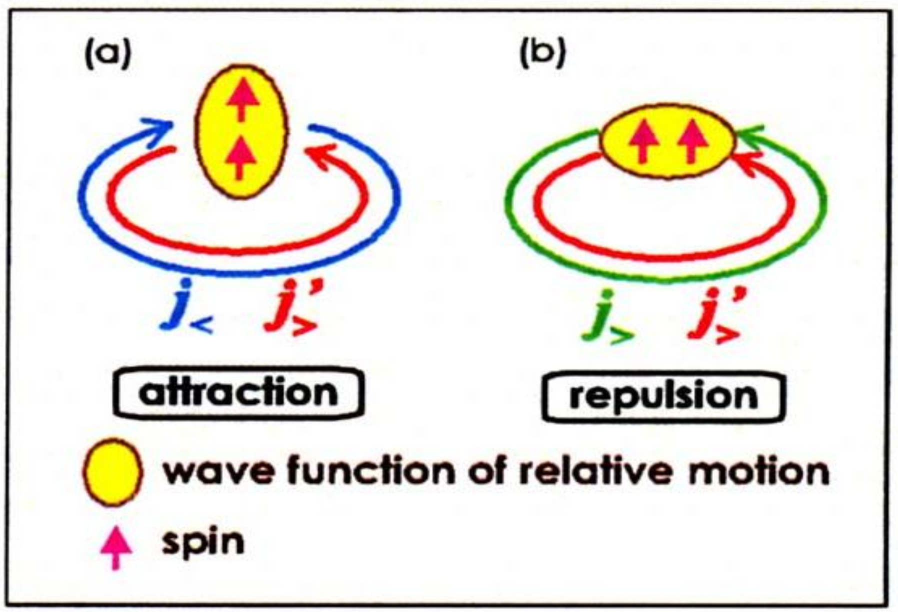
	monopole	T=0
CK →SFO	p3／2 - p1／2	-1.9 MeV

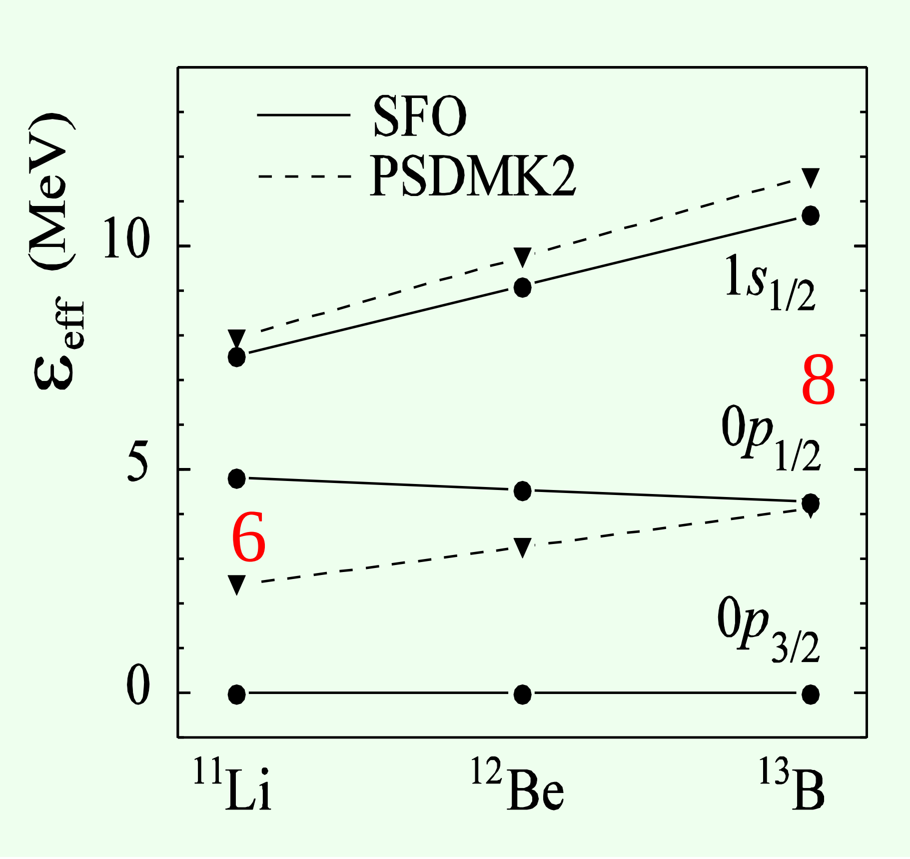
Effects of Tensor Force on Shell Evolution

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



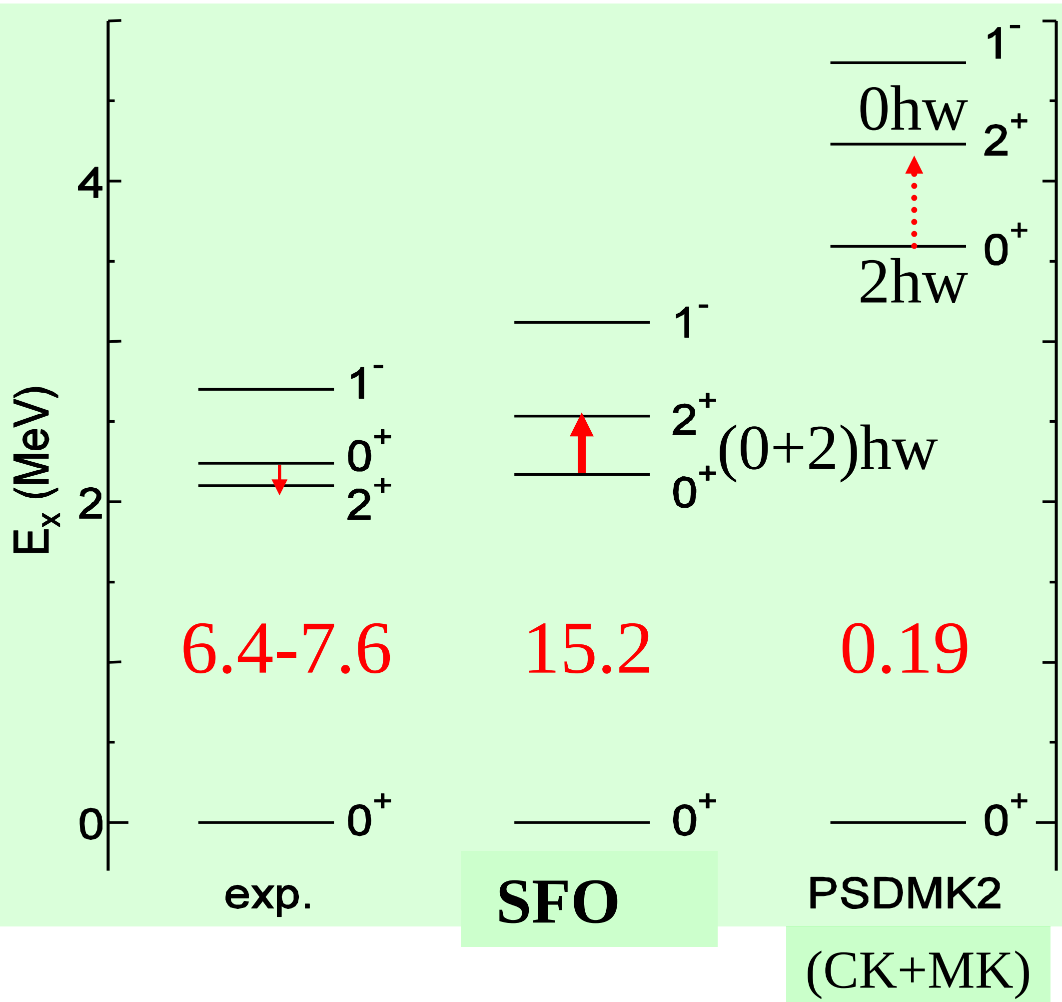
Shell evolution in N=8 isotone





πp3/2

Levels and E2 transitions in ^{12}Be



B(E2: $0_2^+ \to 2^+$)

exp: Shimoura et al.

(e_p=1.2, e_n=0.3)

Levels of ^{12}O and mirror symmetry

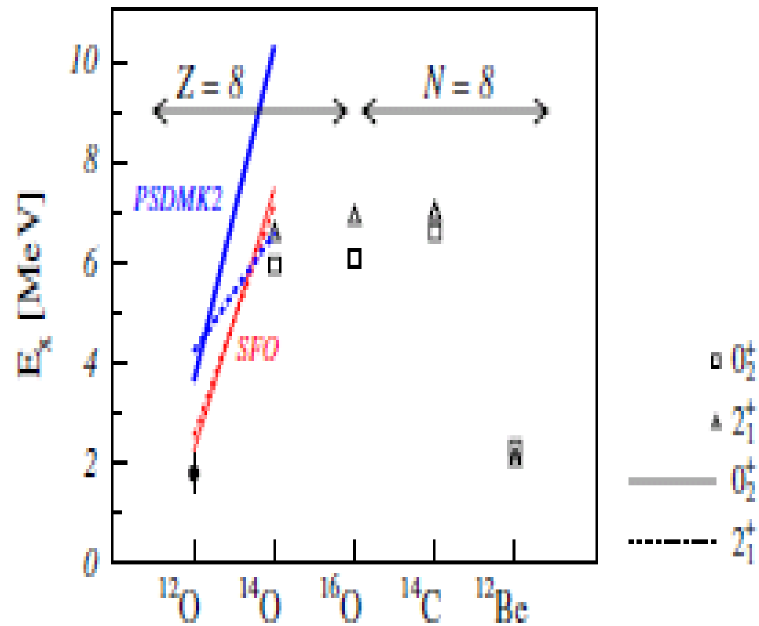
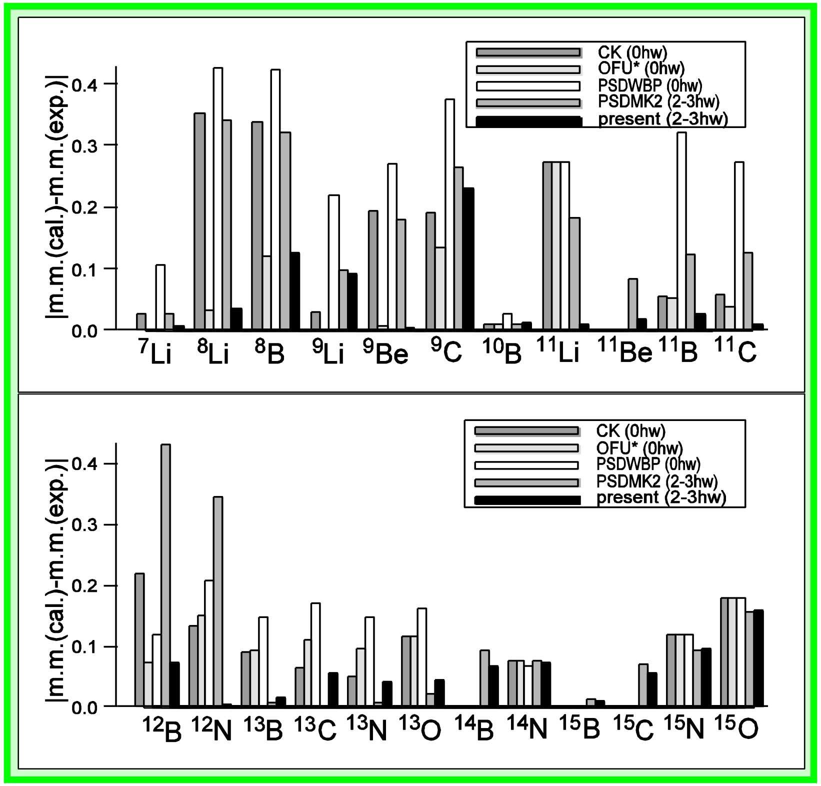


FIG. 4 (color online). Plot of E_x of the 2_1^+ and 0_2^+ states in the $Z = 8$ ^{12,14,16}O isotopes and $N = 8$ ^{12}Be and ^{14}C isotones. The shell-model predictions with the SFO (red, thin lines) and PSDMK2 (blue, bold lines) interactions [13] are shown together. The present result is denoted by the filled circle.

D. Suzuki, PRL 103 (2009) 152503

Magnetic moments of p-shell nuclei

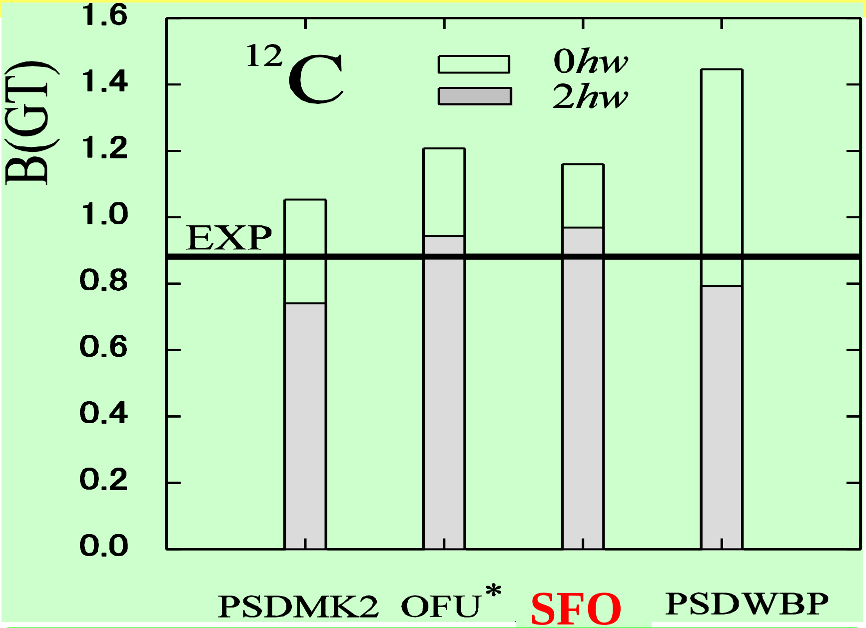


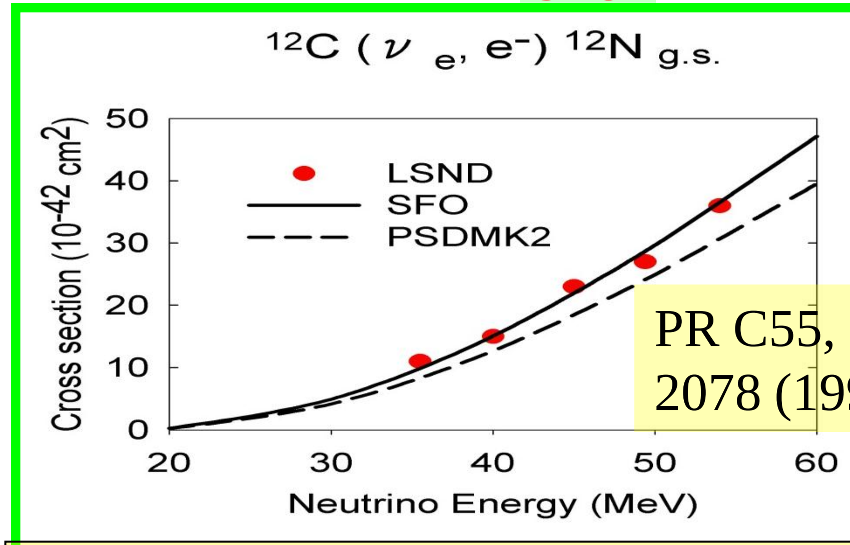
present = SFO **Suzuki, Fujimoto, Otsuka, PR C67 (2003)**

Space: up to 2-3 hw

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

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

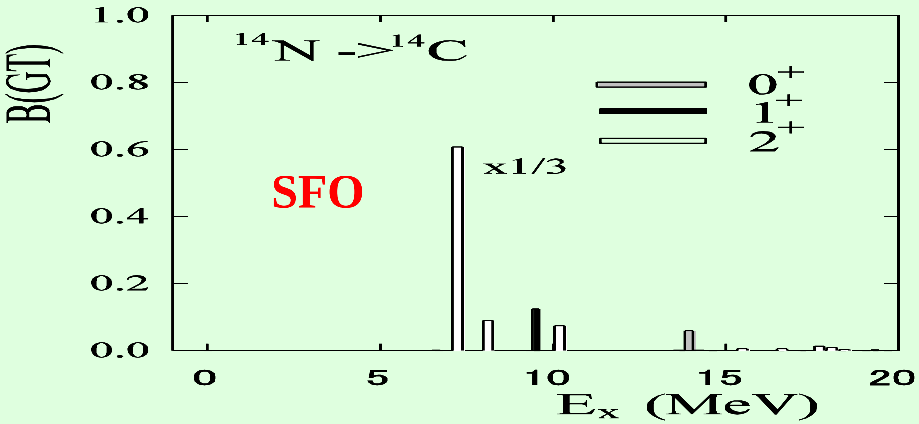




PR C55, 2078 (1997)

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

B(GT) for ^{14}N -> ^{14}C



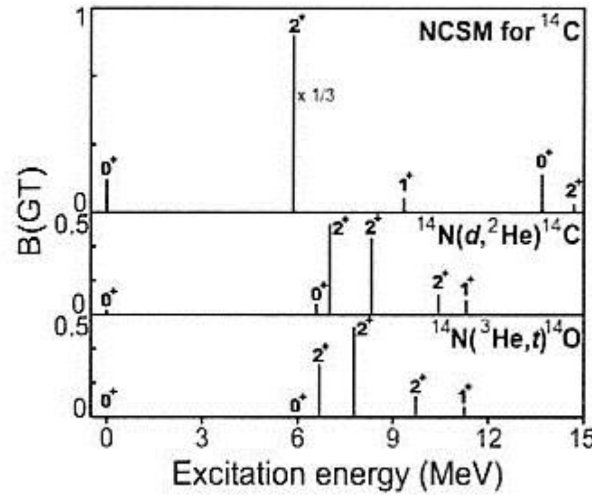


FIG. 3. Experimental B(GT) distributions, compared to the theoretical result of Aroua *et al.* [14], where the B(GT) to the 2^+ state was scaled down by a factor of 3.

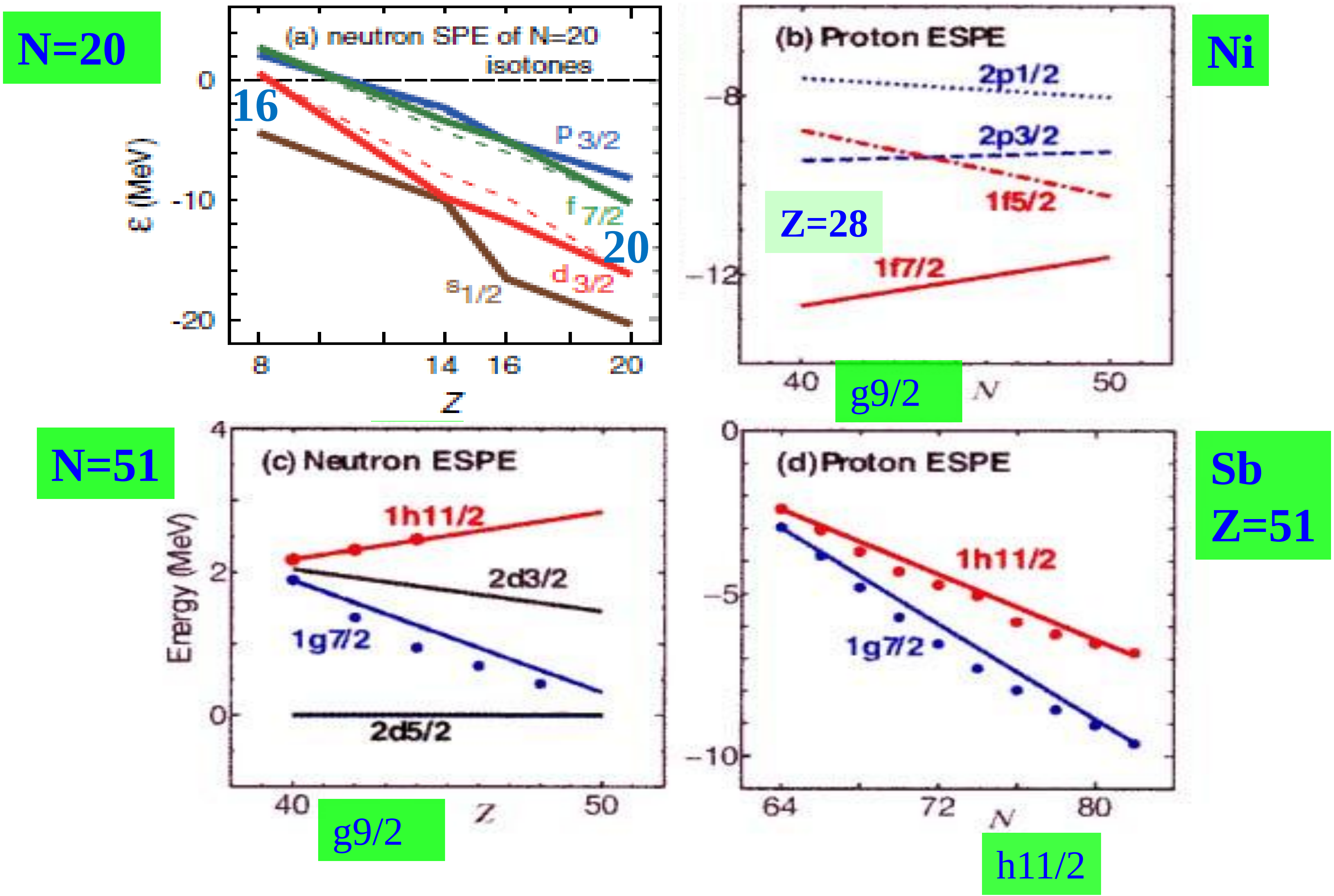
Negret et al., PRL 97 (2006)

$^{14}C \rightarrow {}^{14}N$

Transition $J_i^\pi T_i, J_f^\pi T_f$	Experiment	PSDMK2		OFU*	Present SFO		PSDWBP	PSDWBT
Space		$0\hbar\omega$	$2\hbar\omega$	$0\hbar\omega$	$0\hbar\omega$	$2\hbar\omega$	$0\hbar\omega$	$0\hbar\omega$
$^{14}C \rightarrow {}^{14}N$								
$0^+1, 1^+0$	$0.346(3)\times10^{-6}$	0.02259	0.00831	0.00922	0.00329	0.533×10^{-4}	0.00651	0.0175

Effective SPE

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



- **Modification of SFO**

Full inclusion of tensor force

·p-sd: tensor->π+ρ

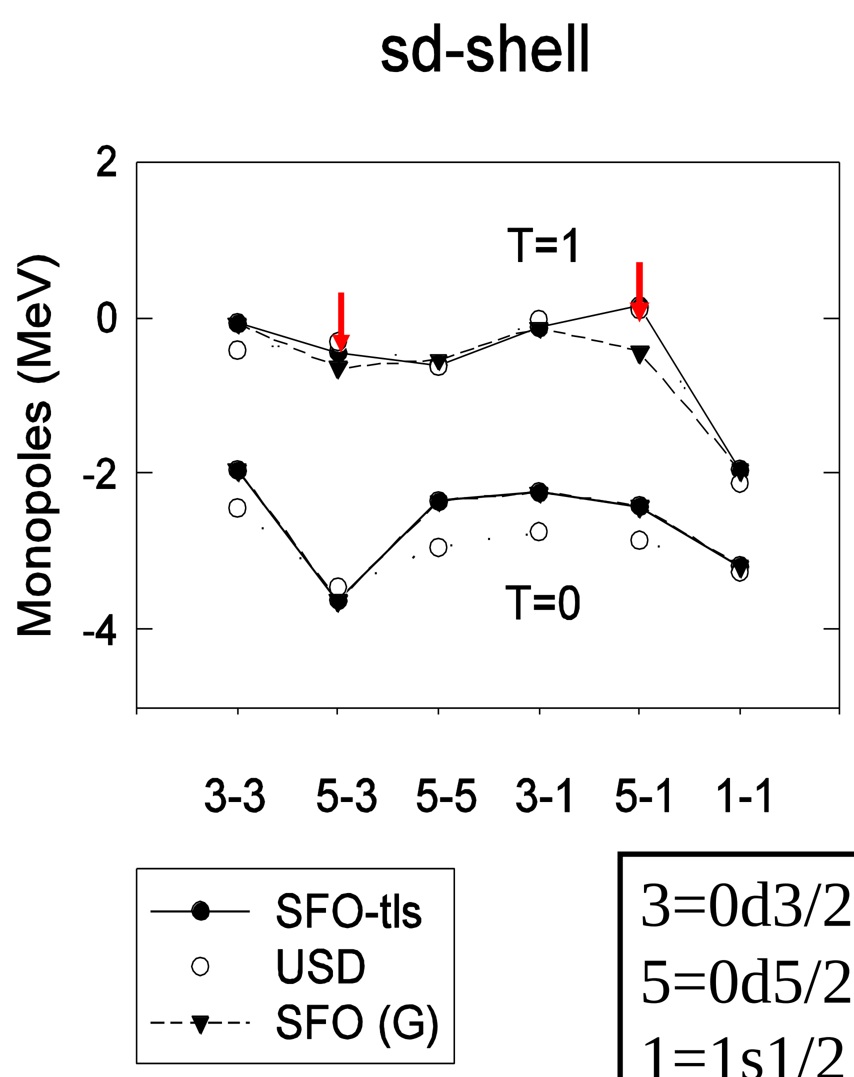
LS -> σ+ρ+ω

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

·sd: Kuo G-matrix

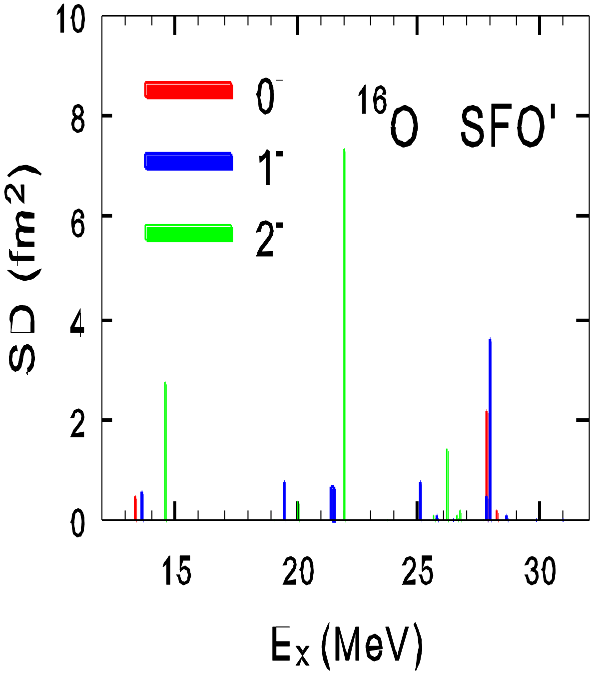
T=1 monopole terms more repulsive

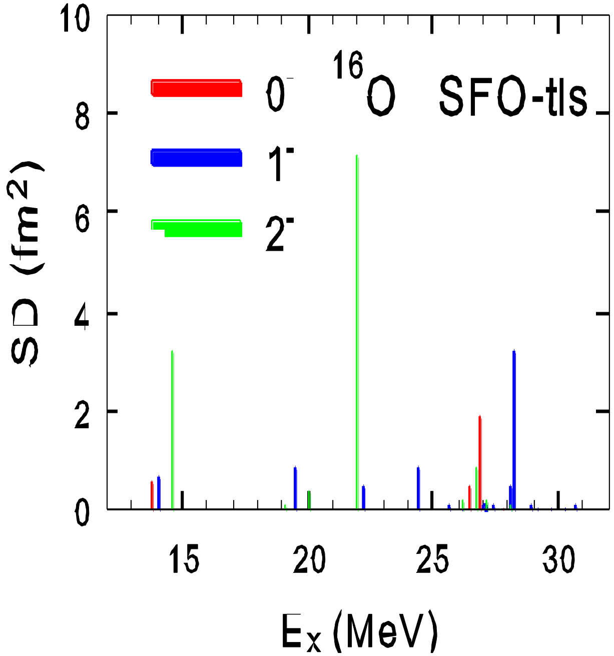
→ SFO-tls

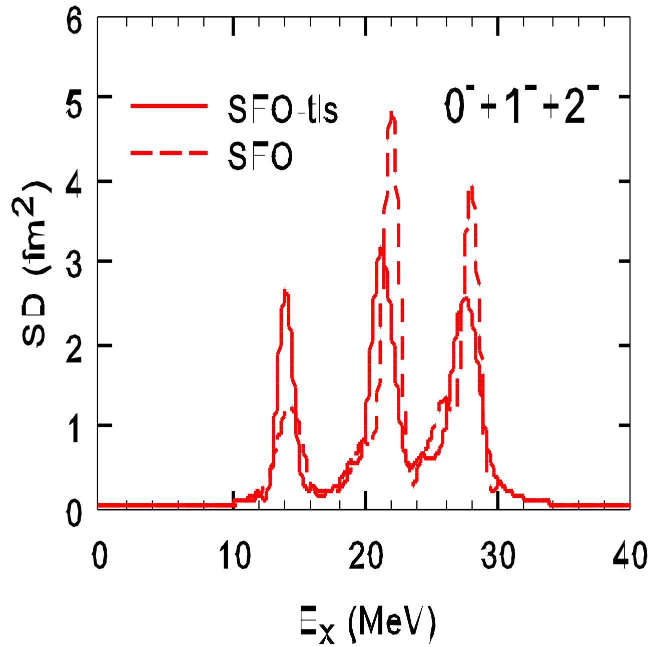


3=0d3/2
5=0d5/2
1=1s1/2

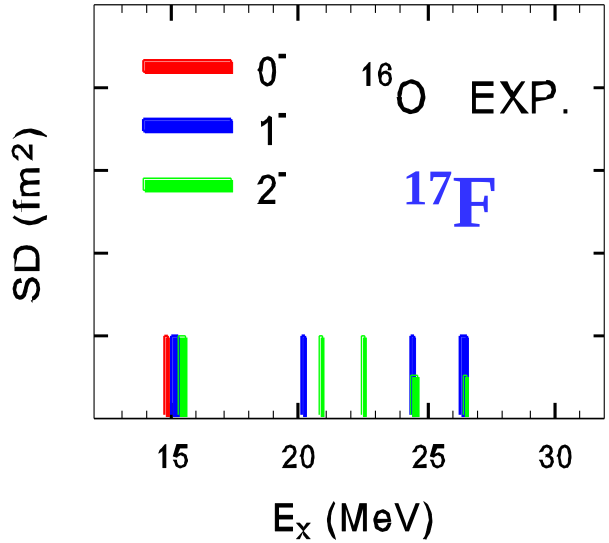
Spin-dipole strengths in ^{16}O

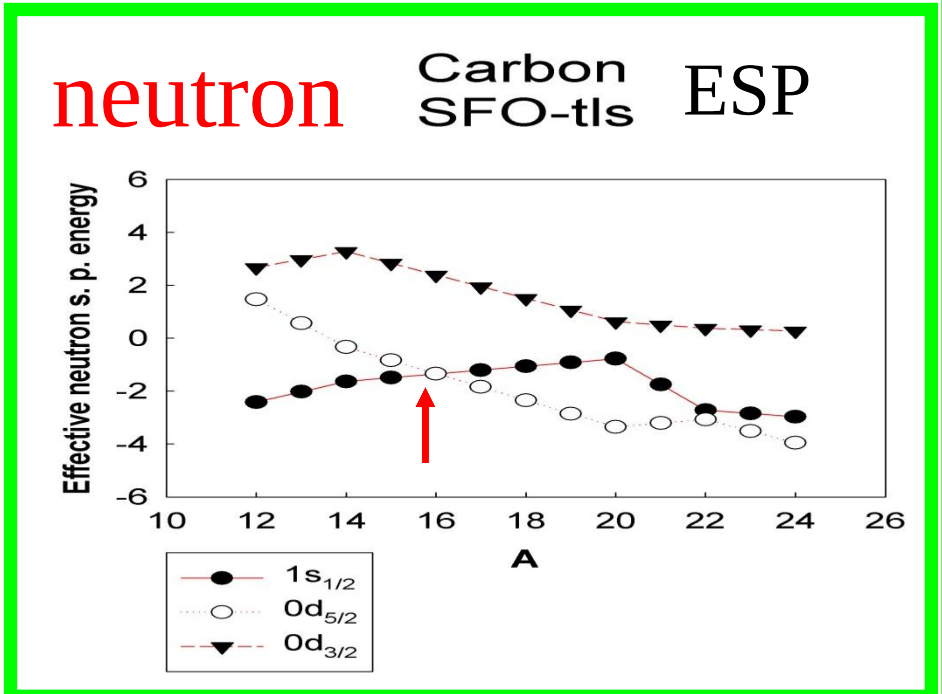


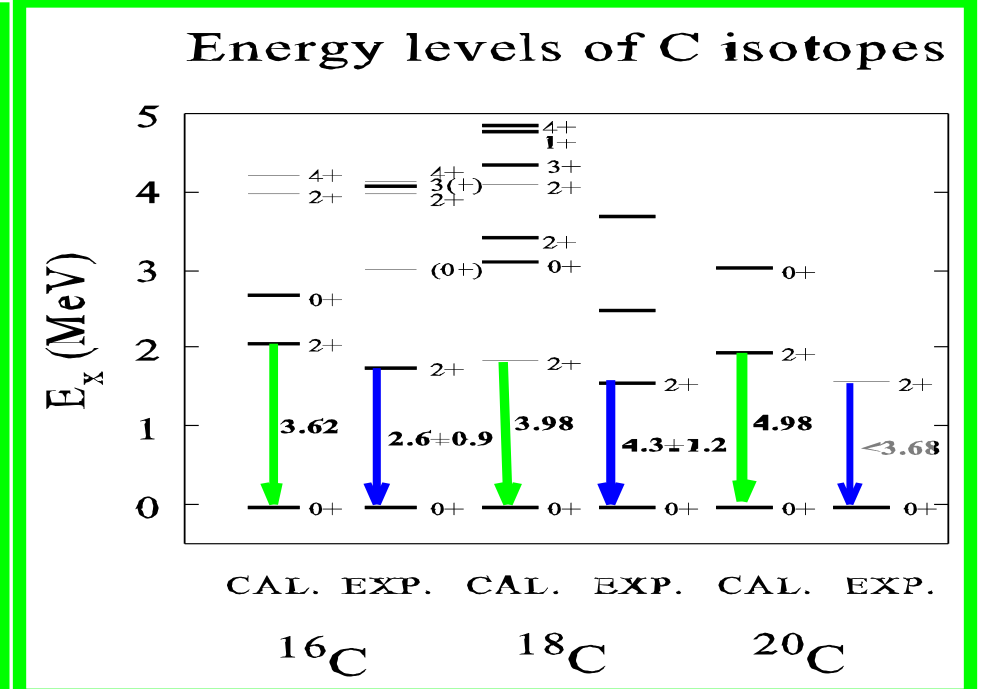


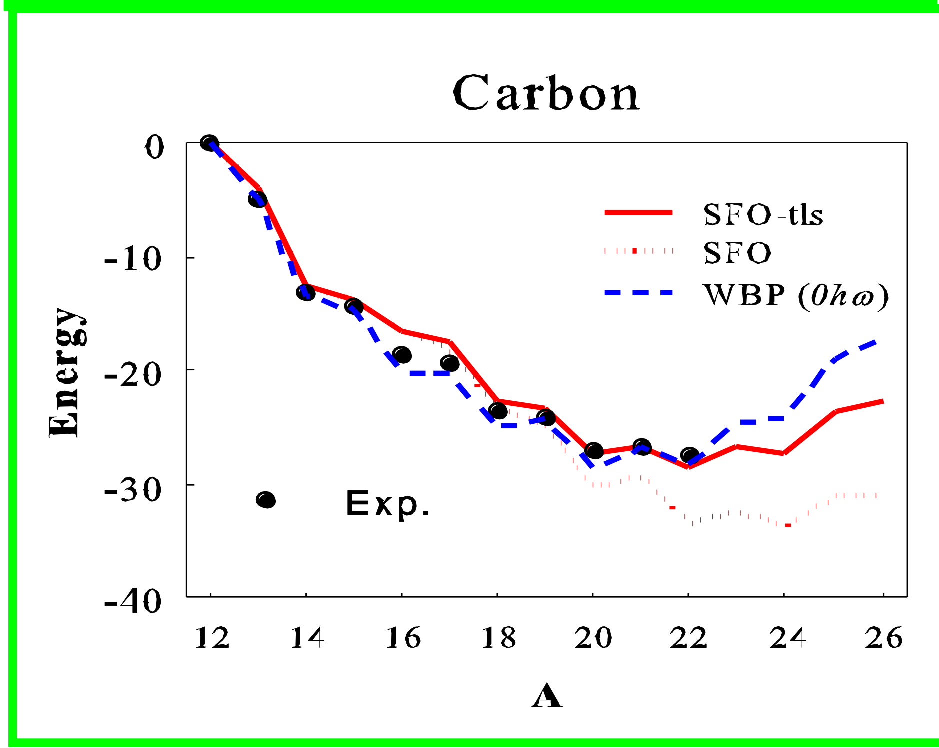


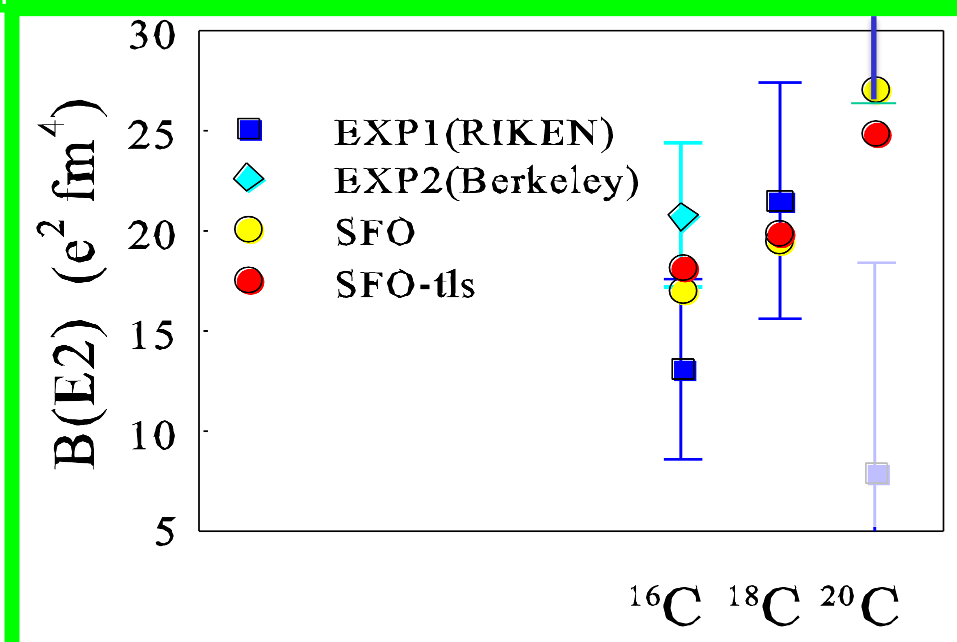
$$O(\lambda) = r[Y^1 \times \sigma]^\lambda t_-$$











N dependent e_n 0.33 0.27 0.22

VMU= Monopole based Universal Interaction

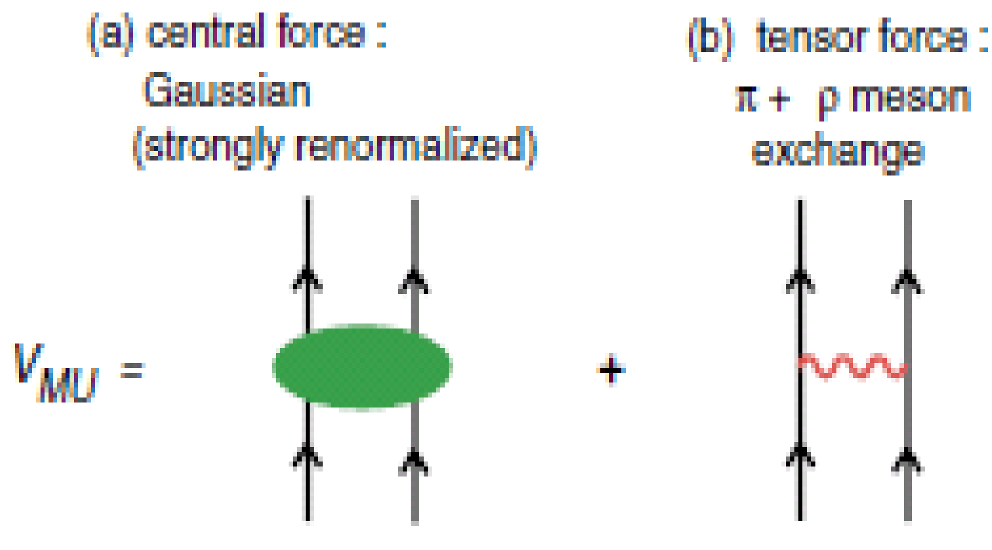
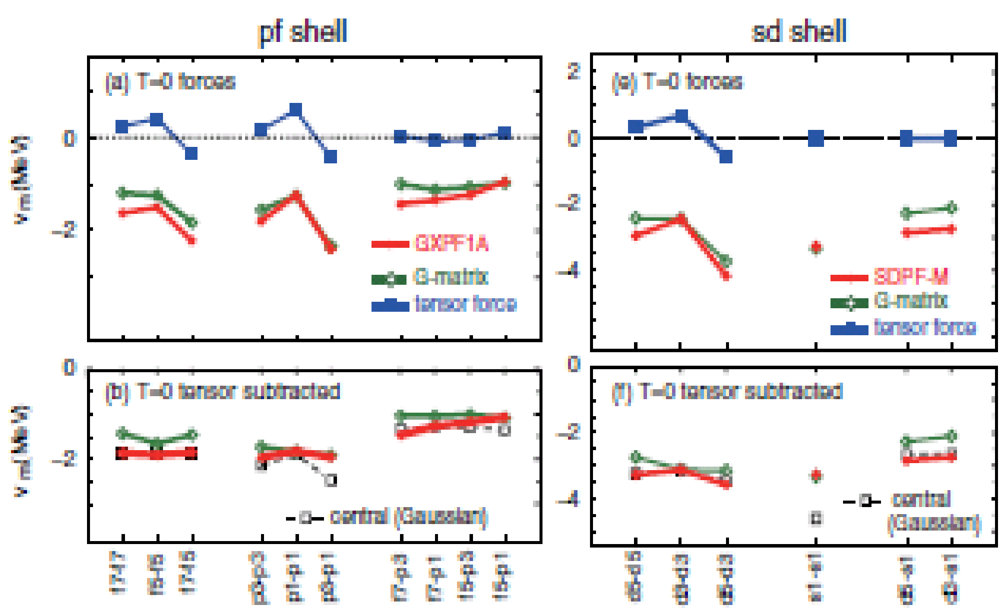
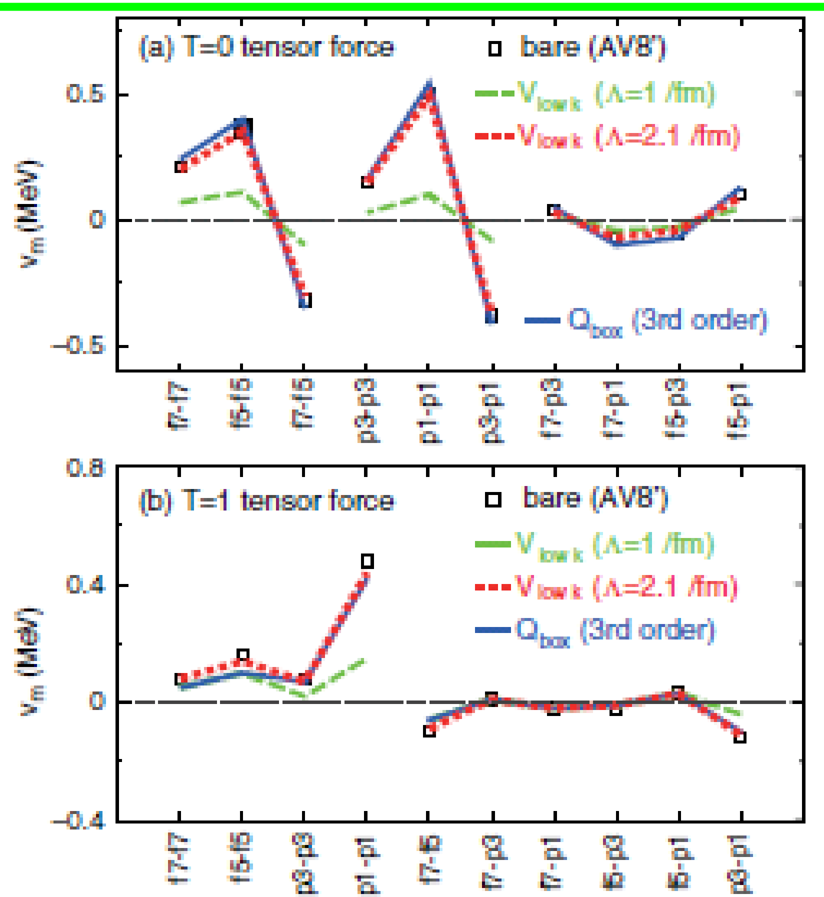


FIG. 2 (color online). Diagrams for the V_{MU} interaction.





Tensor:
bare≈renormalized

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

^{40}Ar (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

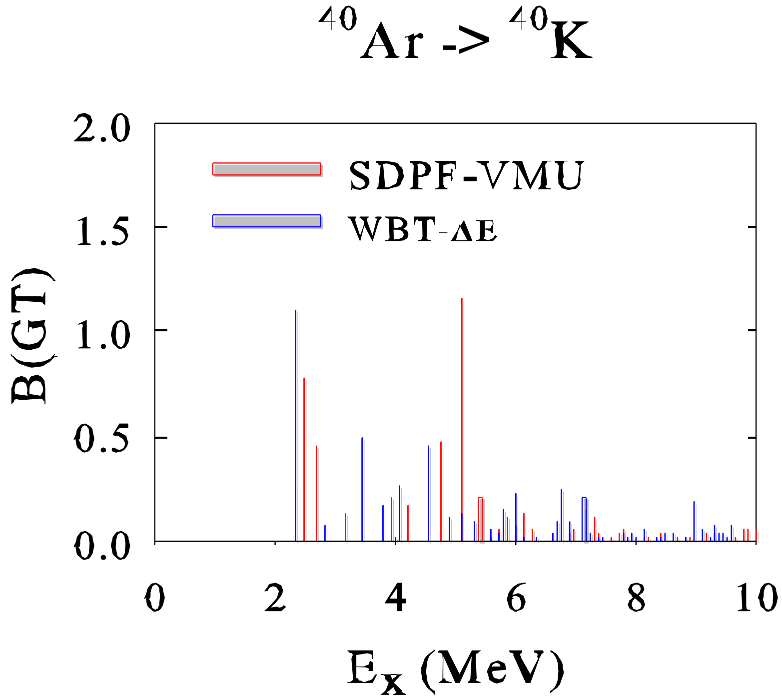
Solar ν cross sections folded over ^{8}B ν spectrum

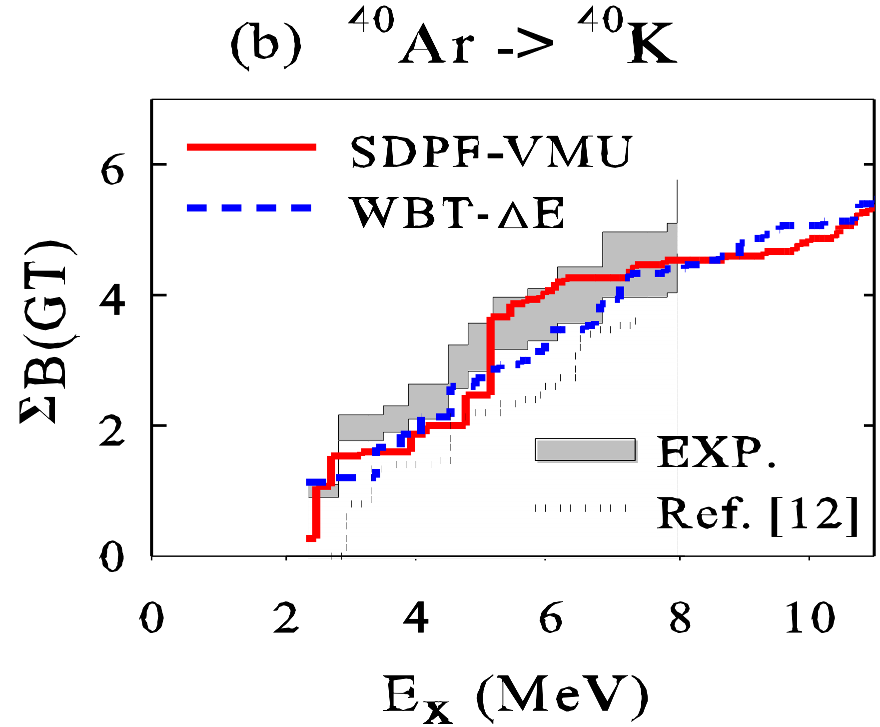
$B(GT) = \Sigma|\langle f||f_q \sigma t_-||i\rangle|^2$ f_q =0.775 (Ormand et al.)

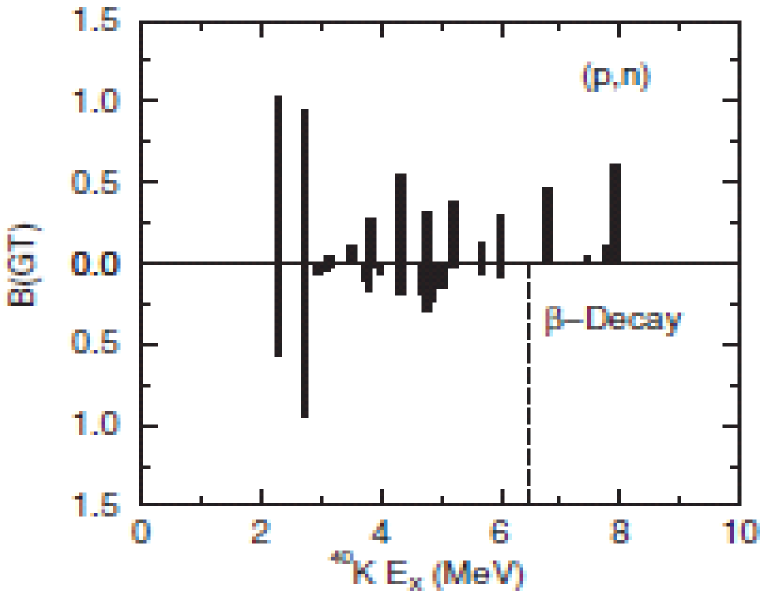
- p-sd

p: SFO sd: SDPF-M p-sd: VMU

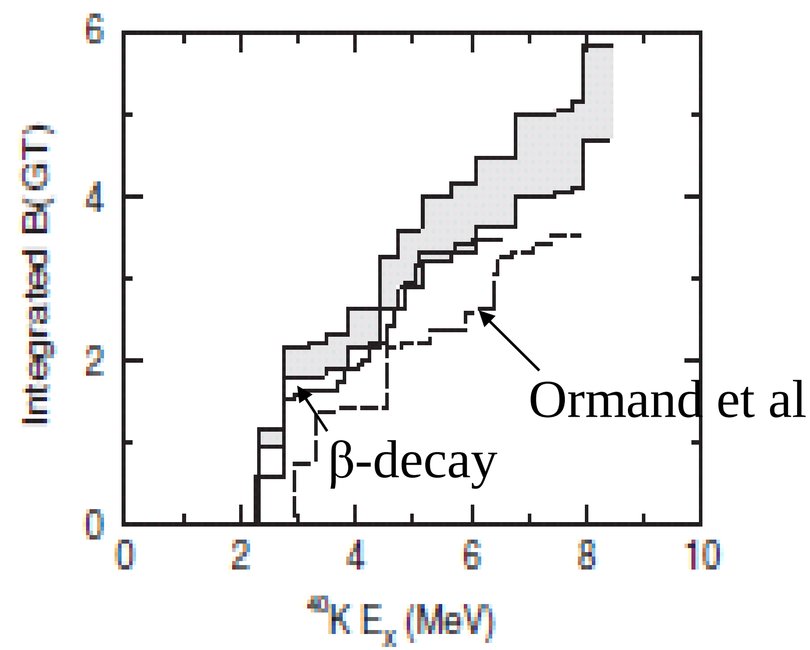
Cenxi et al.



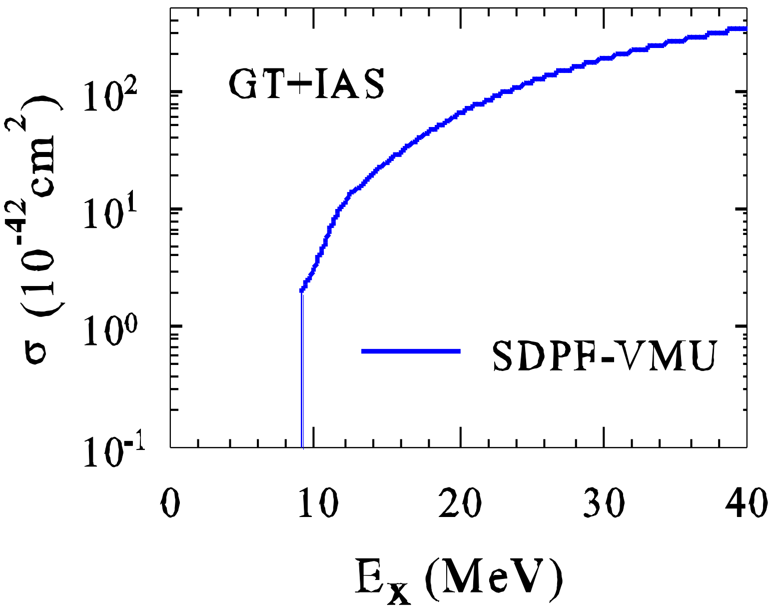


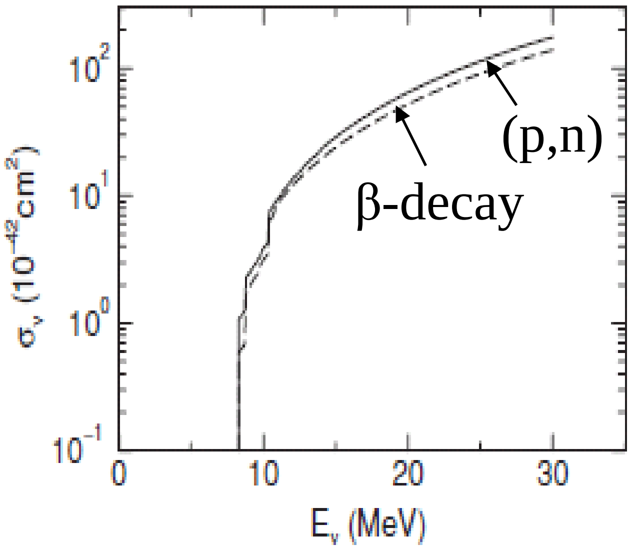


(p,n) Bhattacharya et al., PR C80 (2009)



$^{40}Ar \rightarrow {}^{40}K$





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

GT+IAS
E_e > 5 MeV : ICARUS

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

	GT	IAS	GT+IAS
SDPF-VMU:	10.99	2.10*	13.1 × $10^{-43}cm^2$
WBT-ΔE :	10.78	2.10	12.9
(WBT:	2.81	2.10	4.9)
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

Three-body Forces and Structure of O and Ca isotopes

Shell model

G-matrix vs. G-matrix + three-body force

G = BonnC, CD-Bonn for Ca; 3^{rd}-order Q-box

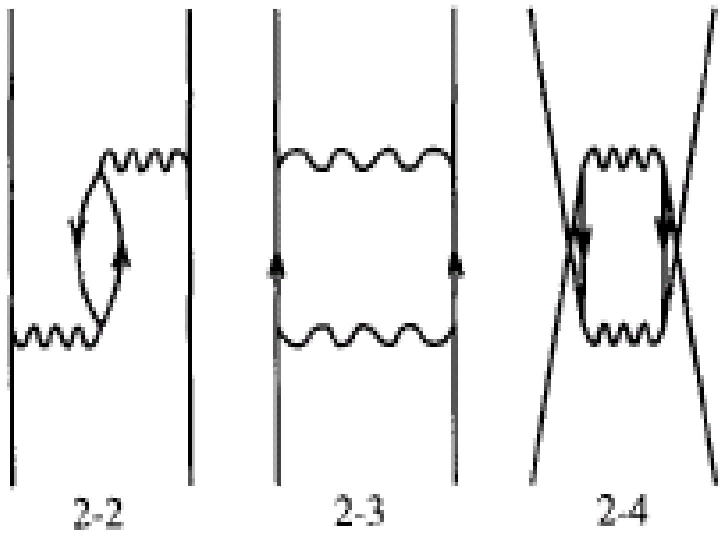
G = Kuo, BonnC, CD-Bonn for O

Hjorth-Jensen, Kuo, Osnes Phys. Rep. 261 (1995) 125.

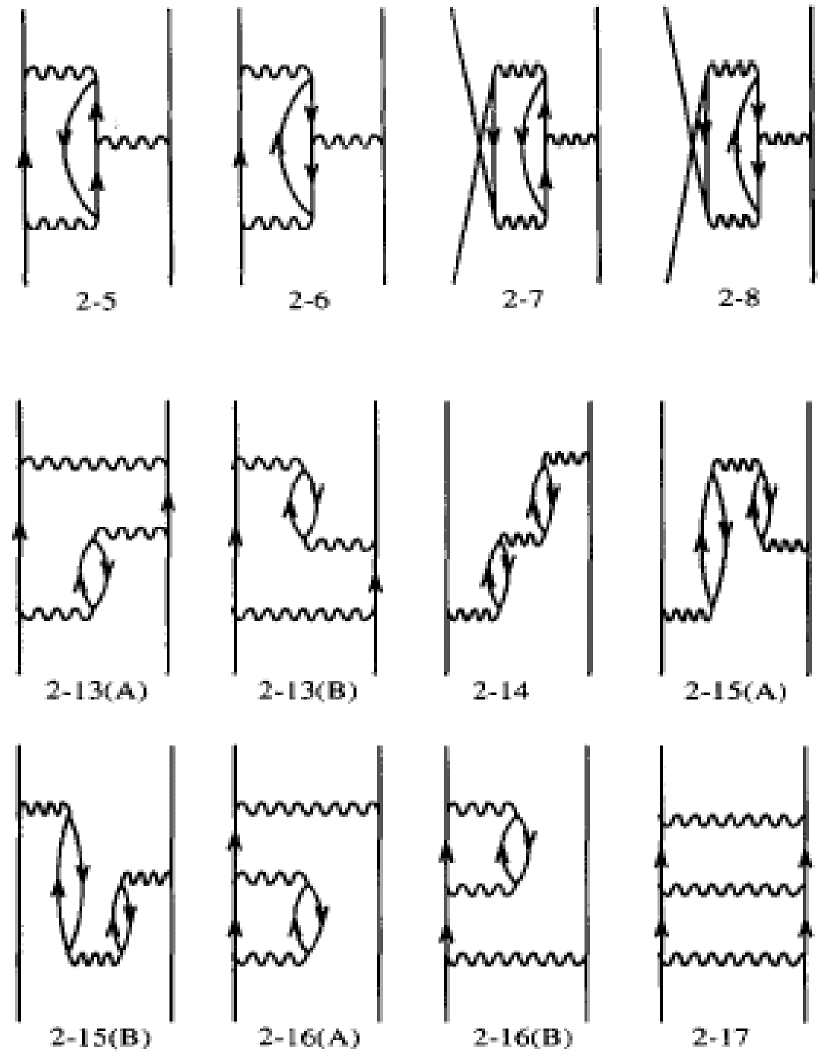
FM (Fujita-Miyazawa) three-body force

Δ-excitation by two-pion exchange

- Effective neutron single-particle energies
- Ground state energies
- E_x (2^+)
- M1 transition in ^{48}Ca



+3rd-order



core-polarization effects

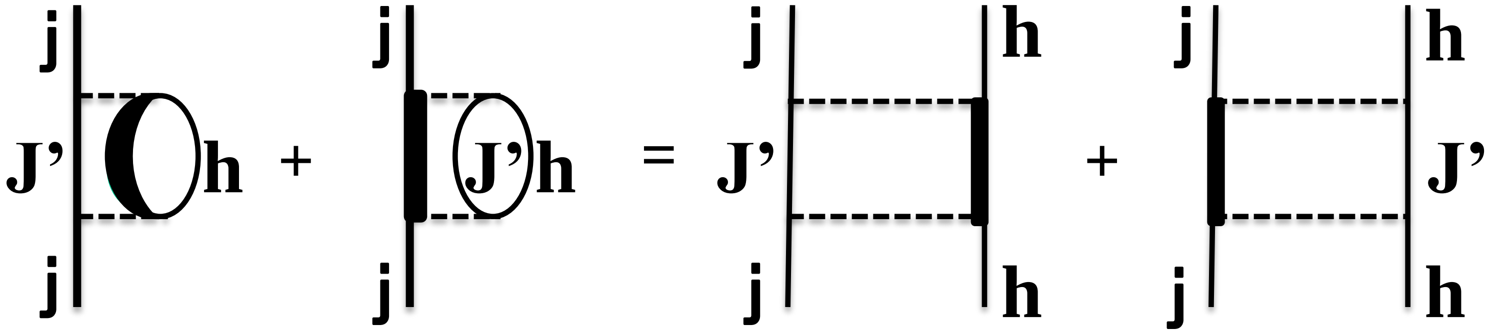
Kuo (HJ): 2nd-order, up to 2hw
BonnC: 3rd-order, up to 2-4 hw
CD-Bonn: 3rd-order, up to 24hw
box: 13hw

Hjorth-Jensen et al., Phys. Rep. 261, 125 (1995)
T. T. S. Kuo, Nucl. Phys. A103, 71 (1967)

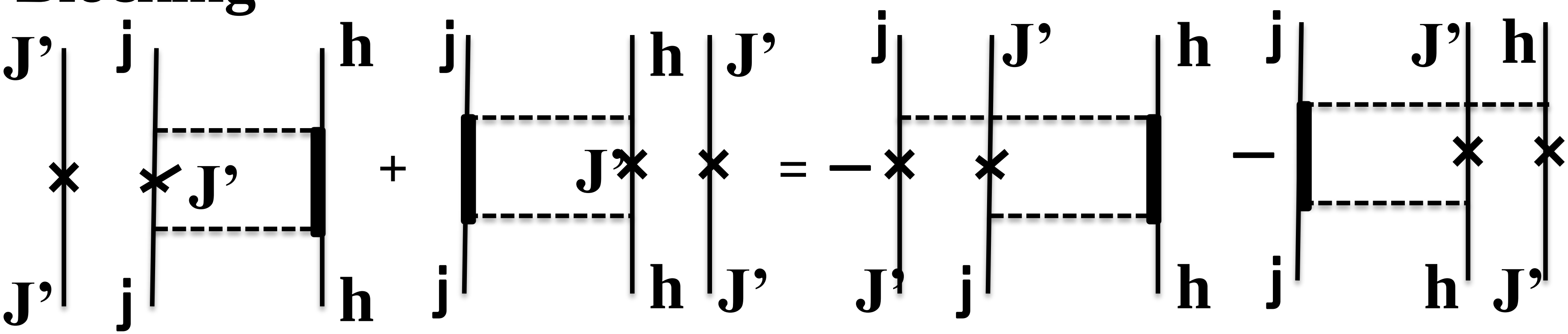
etc.

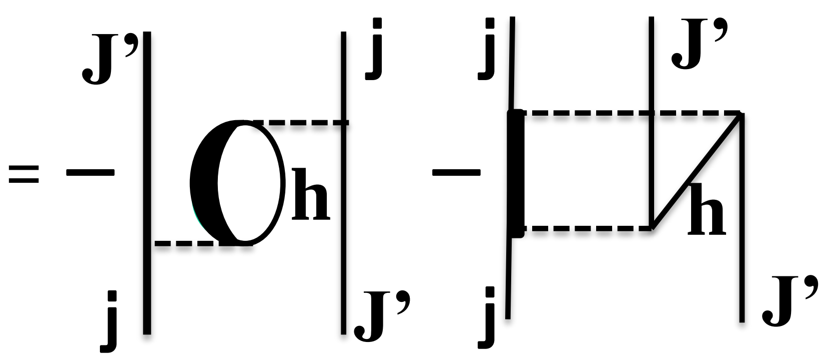
● Three-body force = FM (Fujita-Miyazawa)

Δ-excitation by two-pion exchange → repulsion between valence neutrons (T=1)



Blocking

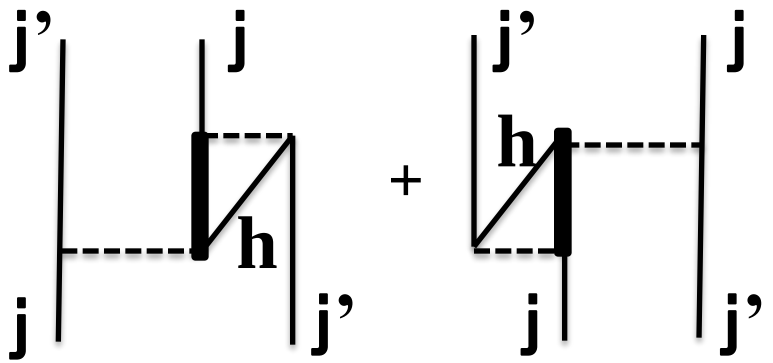




$$\frac{1}{\Delta E}[<\Delta j'|V|hj>^2+<\Delta j'|V|jh>^2]$$

repulsion

h $\longleftrightarrow$ **j**

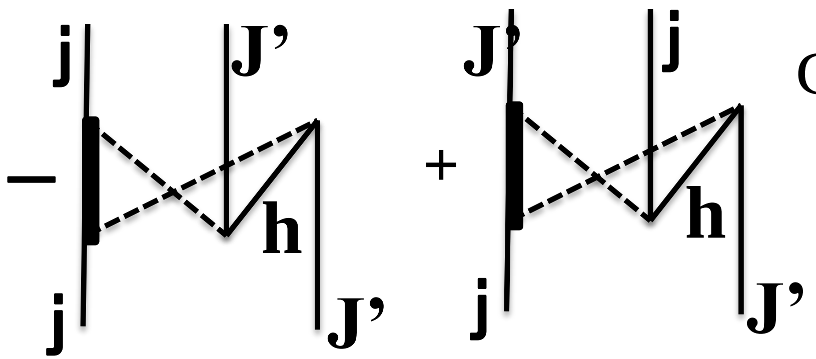


$$-\frac{1}{\Delta E}[<\Delta j'|V|jh><\Delta j'|V|hj>+<\Delta j'|V|hj><\Delta j'|V|jh>]$$

$$S_1=\frac{1}{\Delta E}<\Delta j'|V|hj-jh>^2$$

$$S=S_1+S_1(j\leftrightarrow j')=\frac{1}{\Delta E}[<\Delta j'|V|hj-jh>^2+<\Delta j|V|hj'-j'h>^2]$$

Crossing-term



$$C_1 = \frac{1}{\Delta E} < \Delta h \,|\, V \,|\, jj' - j'j > < \Delta h \,|\, V \,|\, jj' > \Big/ \sqrt{1+\delta_{jj'}}$$

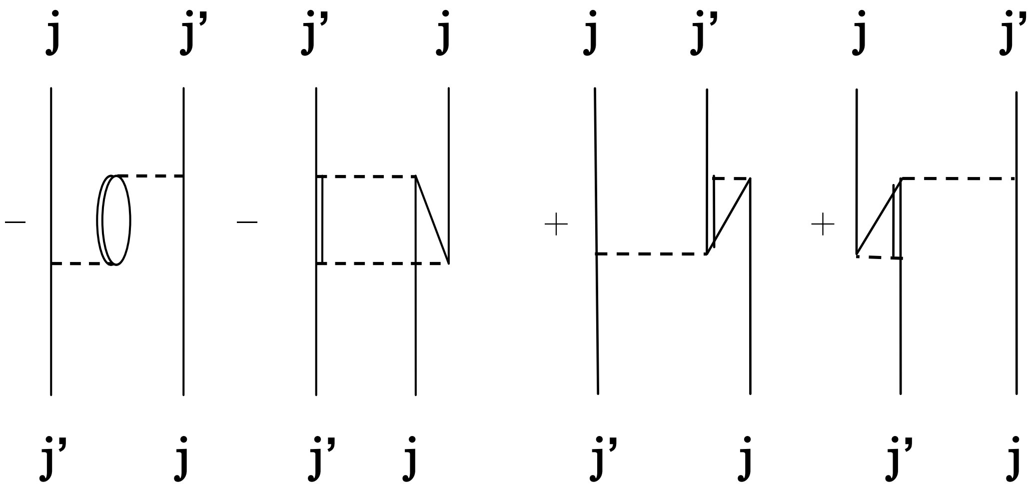
$$\mathbf{C = C_1 + C_1(j \longleftrightarrow j') =} \; \frac{1}{\Delta E} < \Delta h \,|\, V \,|\, jj' - j'j >^2 \; /(1+\delta_{jj'})$$

$$\mathbf{S + C =} \; \frac{1}{\Delta E}\left[< \Delta j' \,|\, V \,|\, hj - jh >^2 + < \Delta j \,|\, V \,|\, hj' - j'h >^2 \right]$$

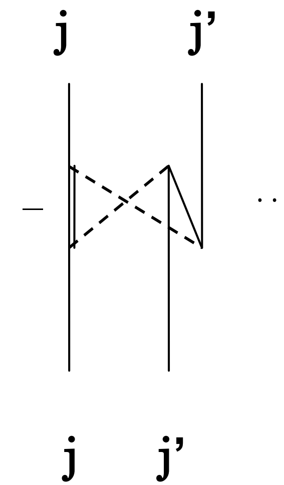
$$+ \frac{1}{\Delta E} < \Delta h \,|\, V \,|\, jj' - j'j >^2 \; /(1+\delta_{jj'})$$

Monopole terms from 3-body force induced by Δ excitations

(A)

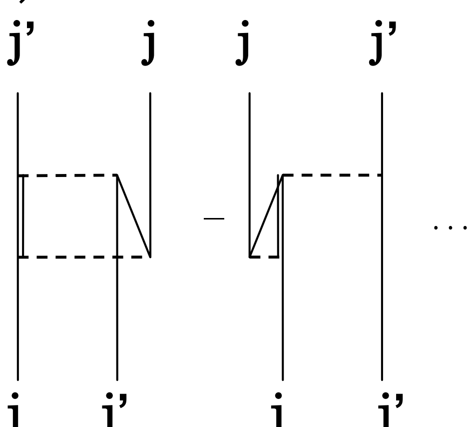


(B)



$$\frac{1}{\Delta E}\left|< pj\,|V|\,hj'-j'h>\right|^2 \qquad \frac{1}{\Delta E}\left|< ph\,|V|\,jj'-j'j>\right|^2$$

(C)



$$-\frac{1}{\Delta E}< pj\,|V|\,jh-hj>< pj'|V|\,j'h-hj'>

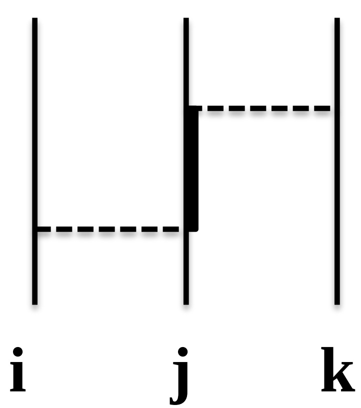
Matrix elements of three-body force

$$\frac{1}{6}<123\ |(1-P_{12}-P_{23}-P_{13}+P_{231}+P_{321})\sum_{i\neq j\neq k}V_{ijk}(1-P_{12}-P_{23}-P_{13}+P_{231}+P_{321})|123>$$

$$=<123\ |\sum_{i\neq j\neq k}V_{ijk}(1-P_{12}-P_{23}-P_{13}+P_{231}+P_{321})|123>$$

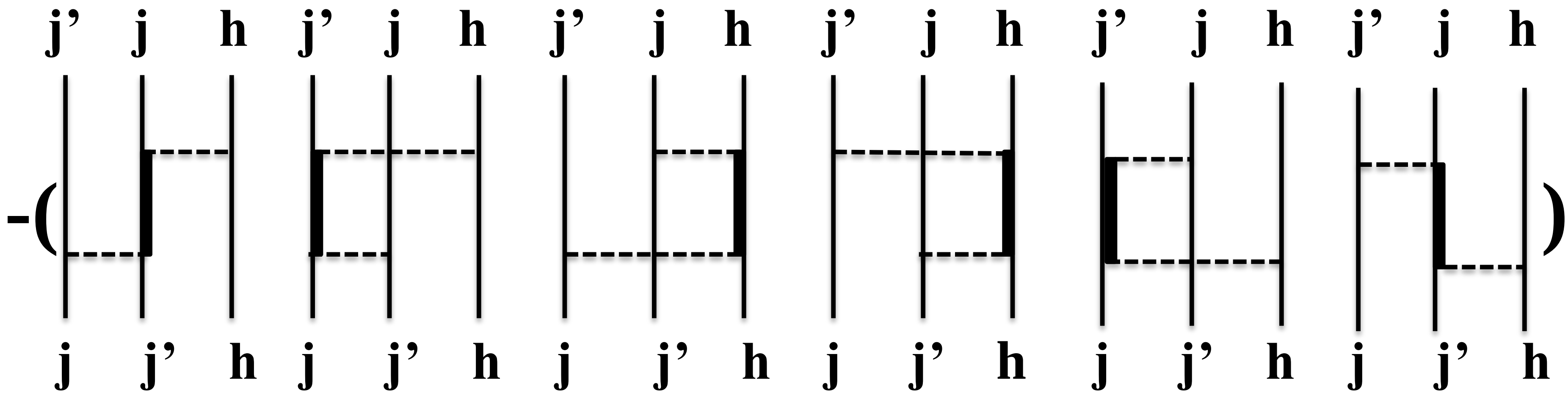
$$=<123\ |(1-P_{12}-P_{23}-P_{13}+P_{231}+P_{321})V_{123}(1-P_{12}-P_{23}-P_{13}+P_{231}+P_{321})|123>$$

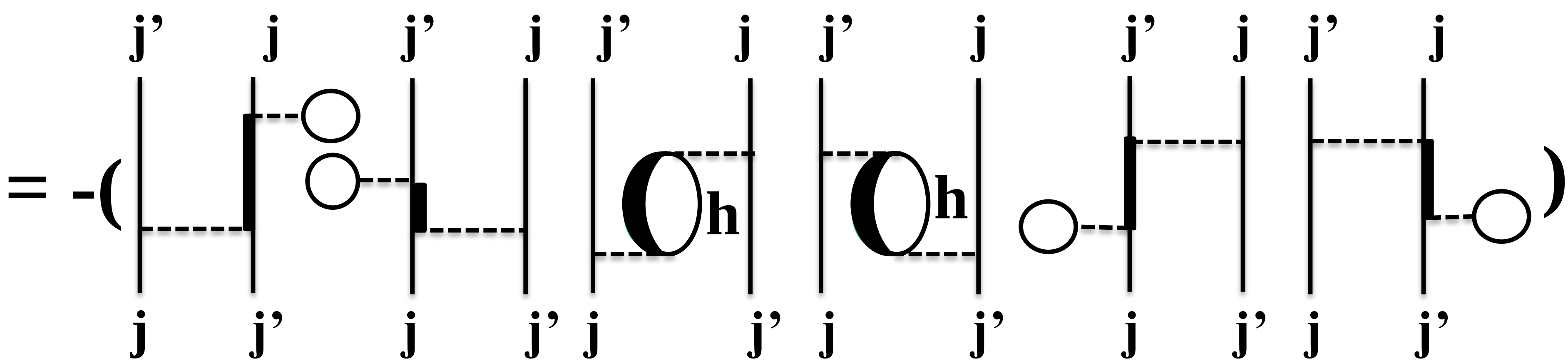
$$V_{ijk}=-\frac{1}{M_\Delta-M_N}\left(\frac{ff^*}{\mu^2}\right)^2\vec{\tau}_k\cdot\vec{T}_j^{\,+}\frac{\vec{\sigma}_k\cdot\vec{q}_k\vec{S}_j^{\,+}\cdot\vec{q}_k}{q_k^{\,2}+\mu^2}\vec{T}_j\,\vec{\tau}_i\,\frac{\vec{S}_j\cdot\vec{q}_i\vec{\sigma}_i\cdot\vec{q}_i}{q_i^{\,2}+\mu^2}$$



$$\vec{S}_j^{\,+}\cdot\vec{q}_k\vec{S}_j^{\,+}\cdot\vec{q}_i=\frac{2}{3}\vec{q}_k\cdot\vec{q}_i-\frac{i}{3}(\vec{q}_k\times\vec{q}_i)\sigma_{jz}$$

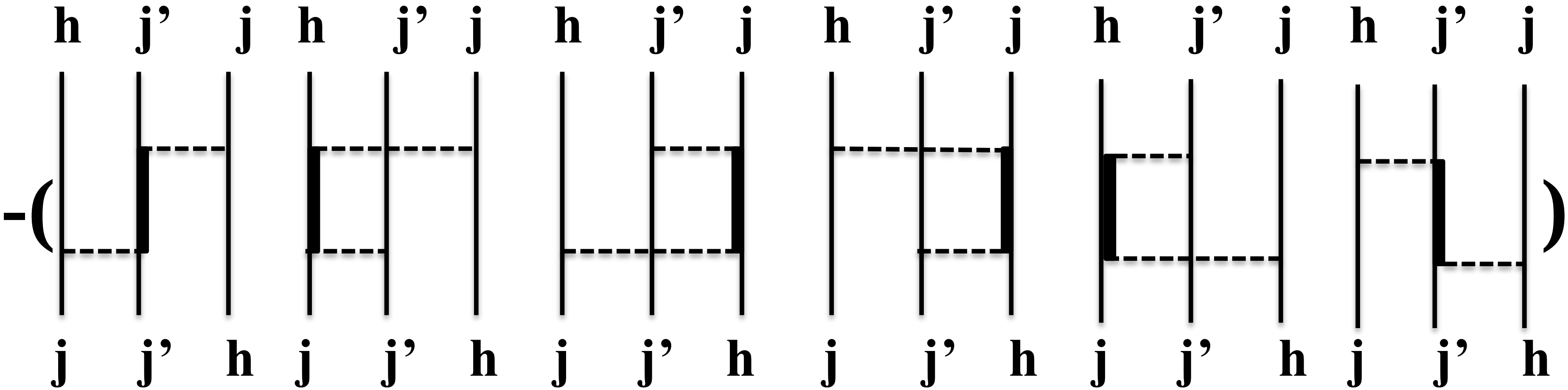
e.g $\quad <123|\sum_{i\neq j\neq k} V_{ijk}\,|-P_{12}\,|123>$

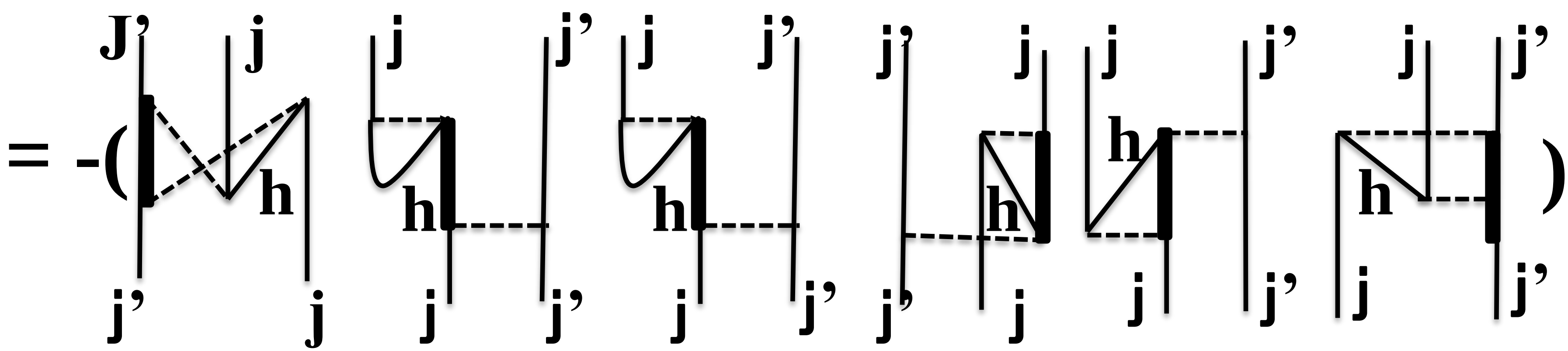




$$=\frac{1}{\Delta E}[<\Delta j'|\,V\,|hj>^2+<\Delta j\,|\,V\,|hj'>^2]$$

e.g $\quad <123|\sum_{i\neq j\neq k} V_{ijk}\,|-P_{13}|123>$





$$=\frac{1}{\Delta E}<\Delta h\,|\,V\,|\,j'\,j>^2+\frac{1}{\Delta E}[<\Delta j\,|\,V\,|\,jh><\Delta j'|\,V\,|\,hj'>$$

$$+<\Delta j'|\,V\,|\,hj'><\Delta j\,|\,V\,|\,jh>]+\frac{1}{\Delta E}<\Delta j\,|\,V\,|\,j'\,h>^2$$

$$\mathbf{S+C+D=}\ \frac{1}{\Delta E}\{[<\Delta j'|V|hj-jh>^2+<\Delta j|V|hj'-j'h>^2]$$

$$-[<\Delta j|V|hj-jh><\Delta j'|V|hj'-j'h>$$

$$+<\Delta j'|V|hj'-j'h><\Delta j|V|hj-jh>]\}/(1+\delta_{jj'})$$

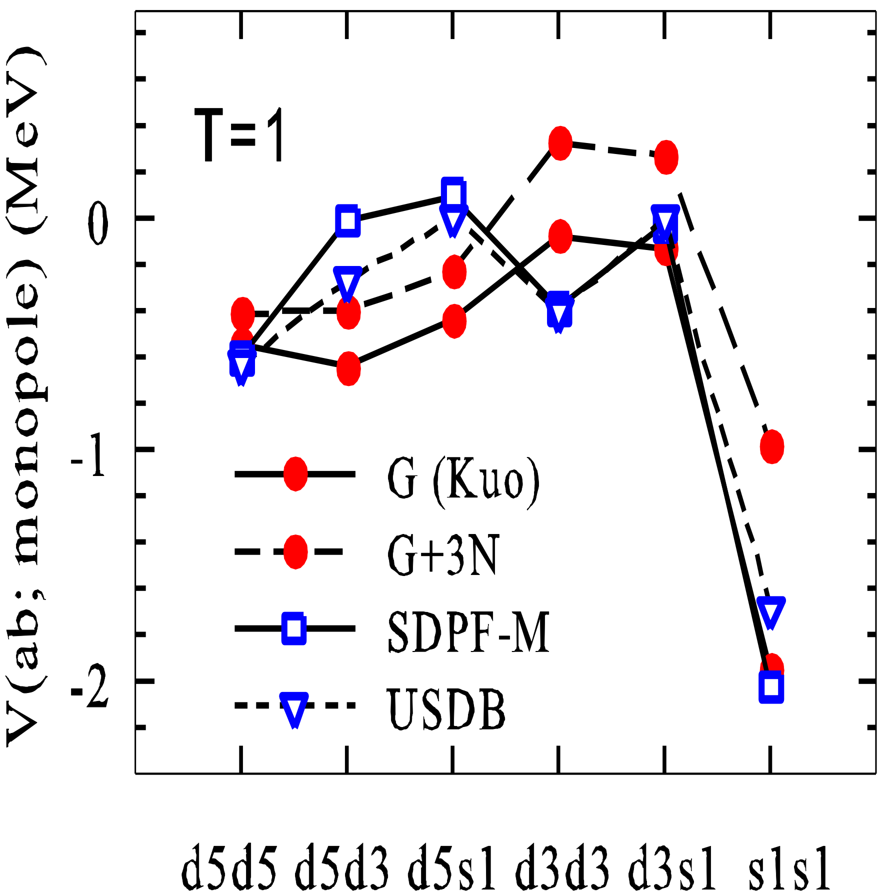
$$+\frac{1}{\Delta E}<\Delta h|V|jj'-j'j>^2/(1+\delta_{jj'})$$

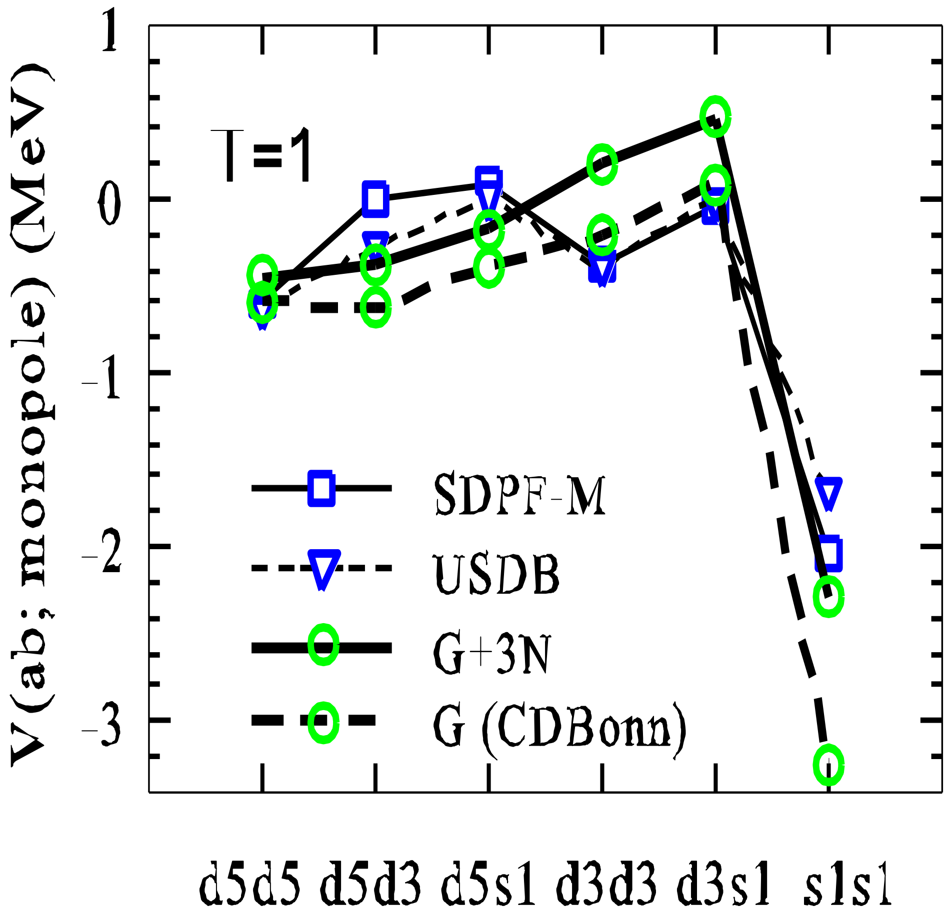
$$|j>=|jm>$$

$$|j'>=|j'm'>$$

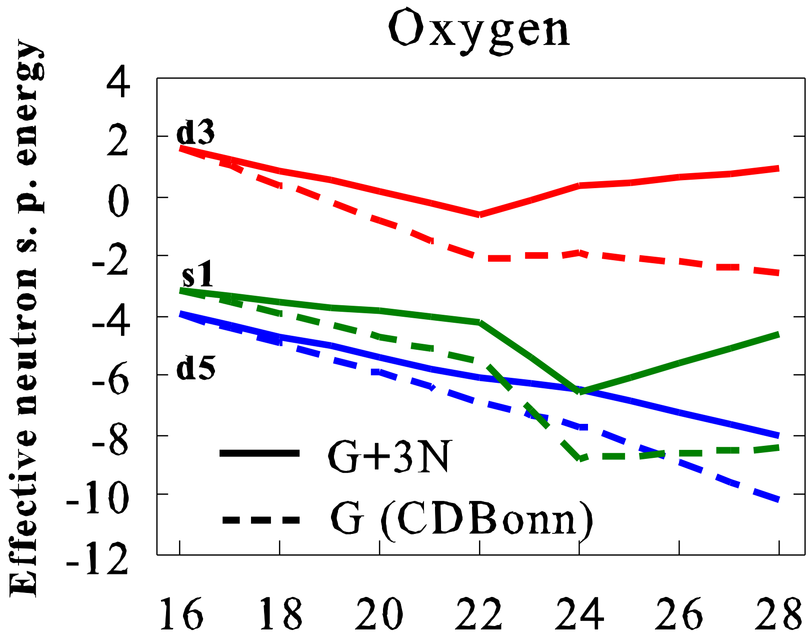
● Oxygen isotopes

Monopoles for sd-shell: T=1

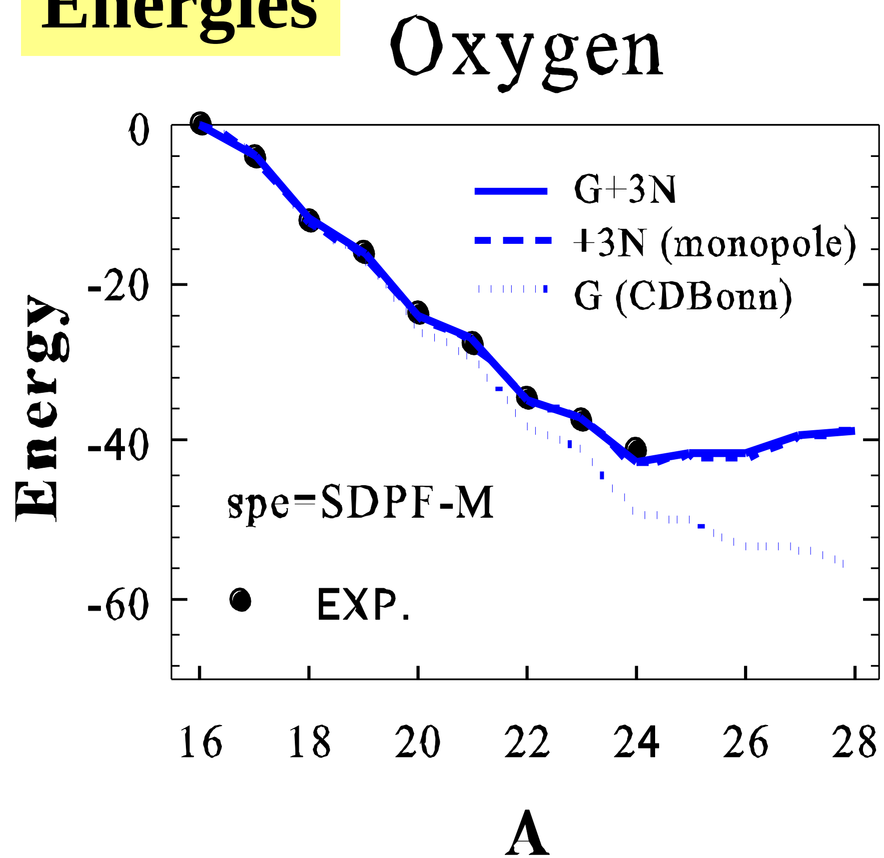




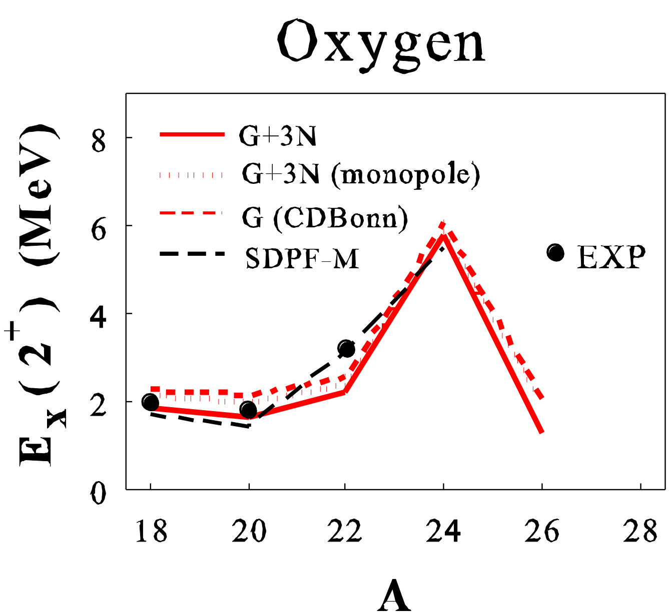
ESPE



Energies



$E(2^+)$

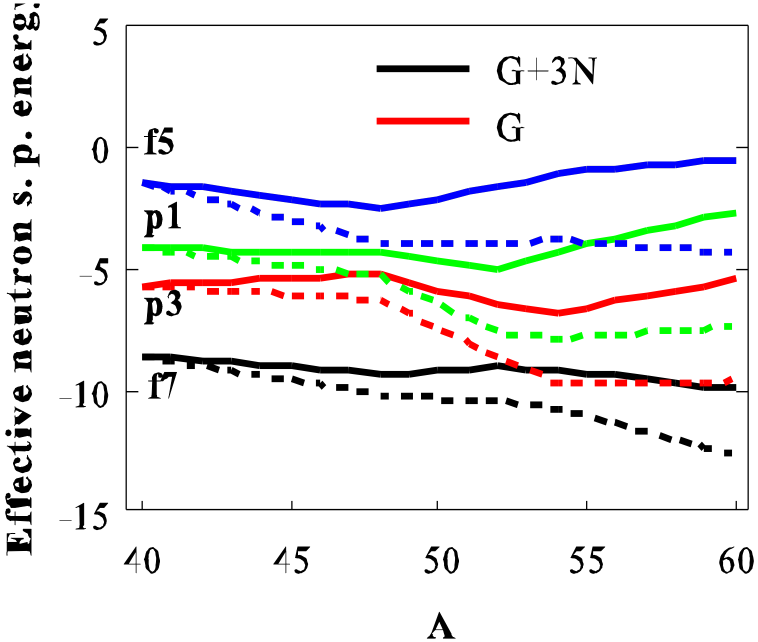


3N →repulsion

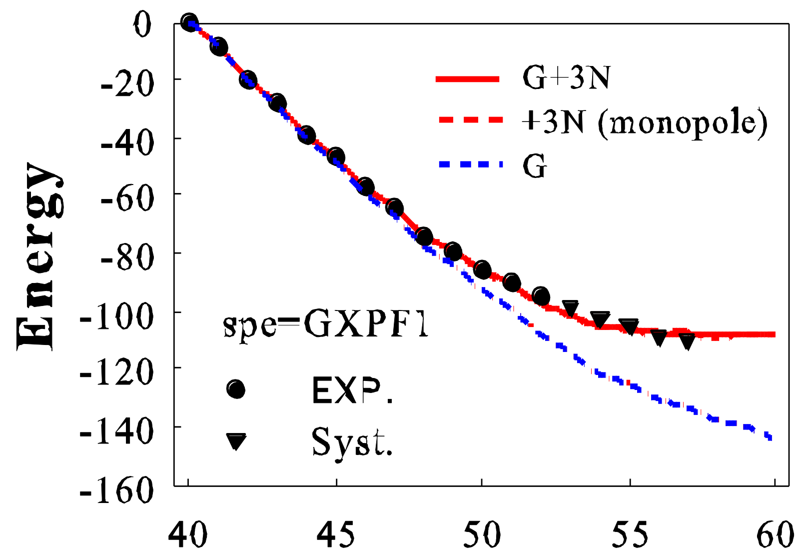
→ drip line at ^{24}O

Otsuka, Suzuki, Holt, Schwenk, Akaishi, PRL 105 032501 (2010)

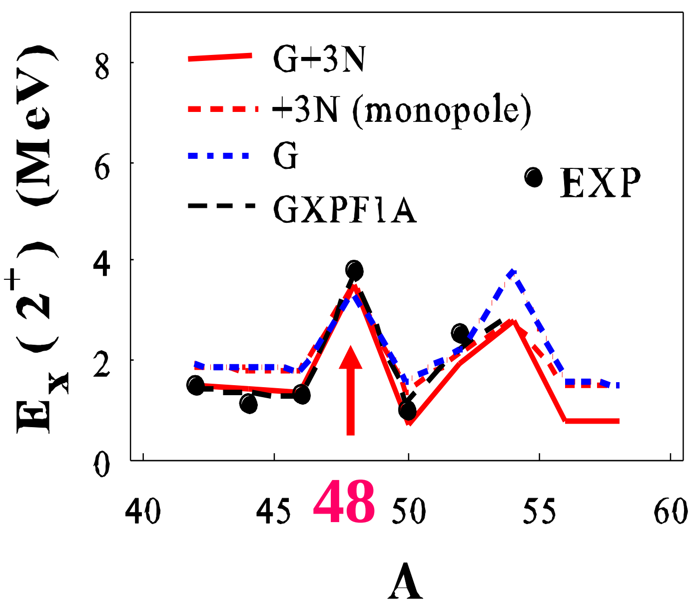
ESPE



Energies of Ca isotopes



3-body force →repulsion

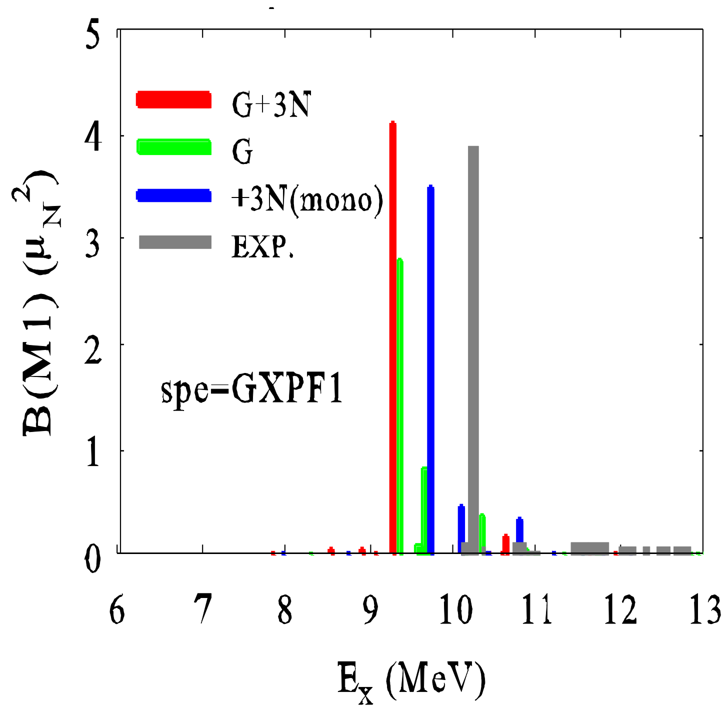


^{48}Ca B(M1)

+3N →

Concentration

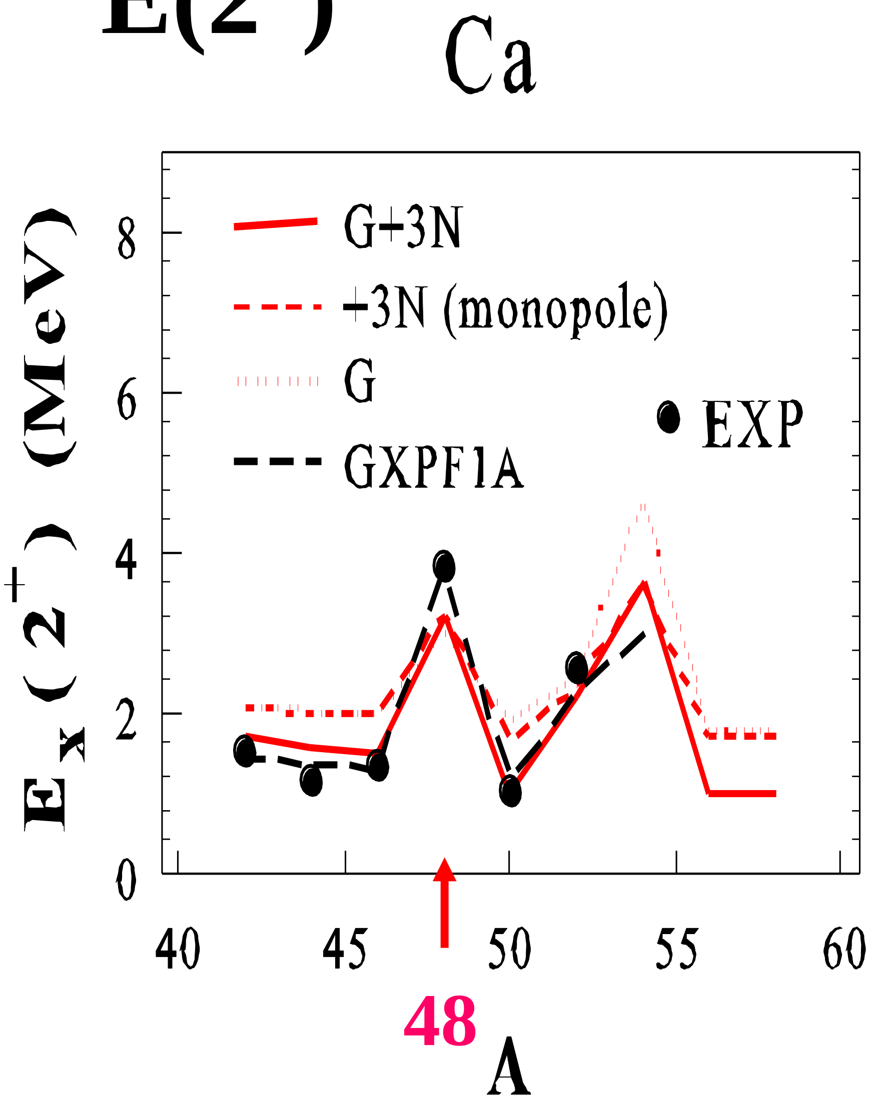
Of the strength

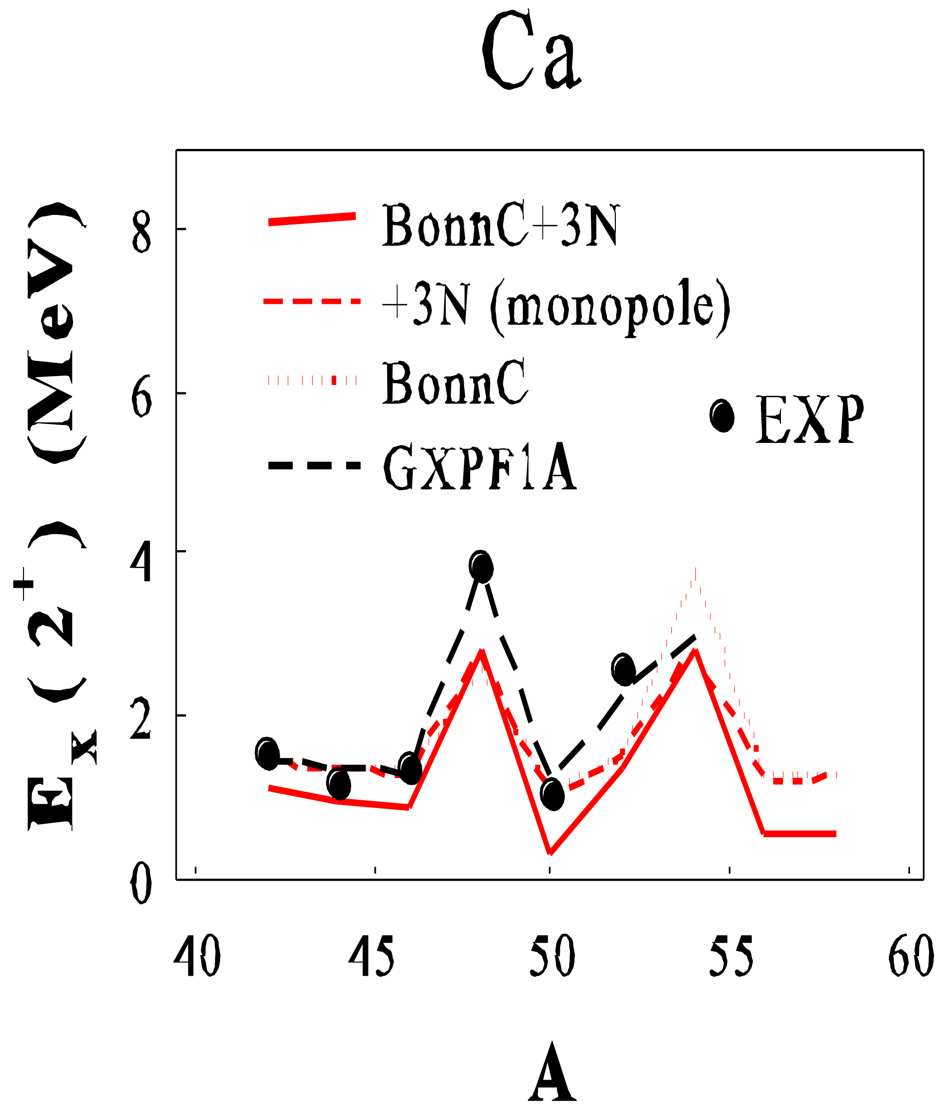


EXP.: Steffen et al.

NP A404, 413 (1983)

$E(2^+)$

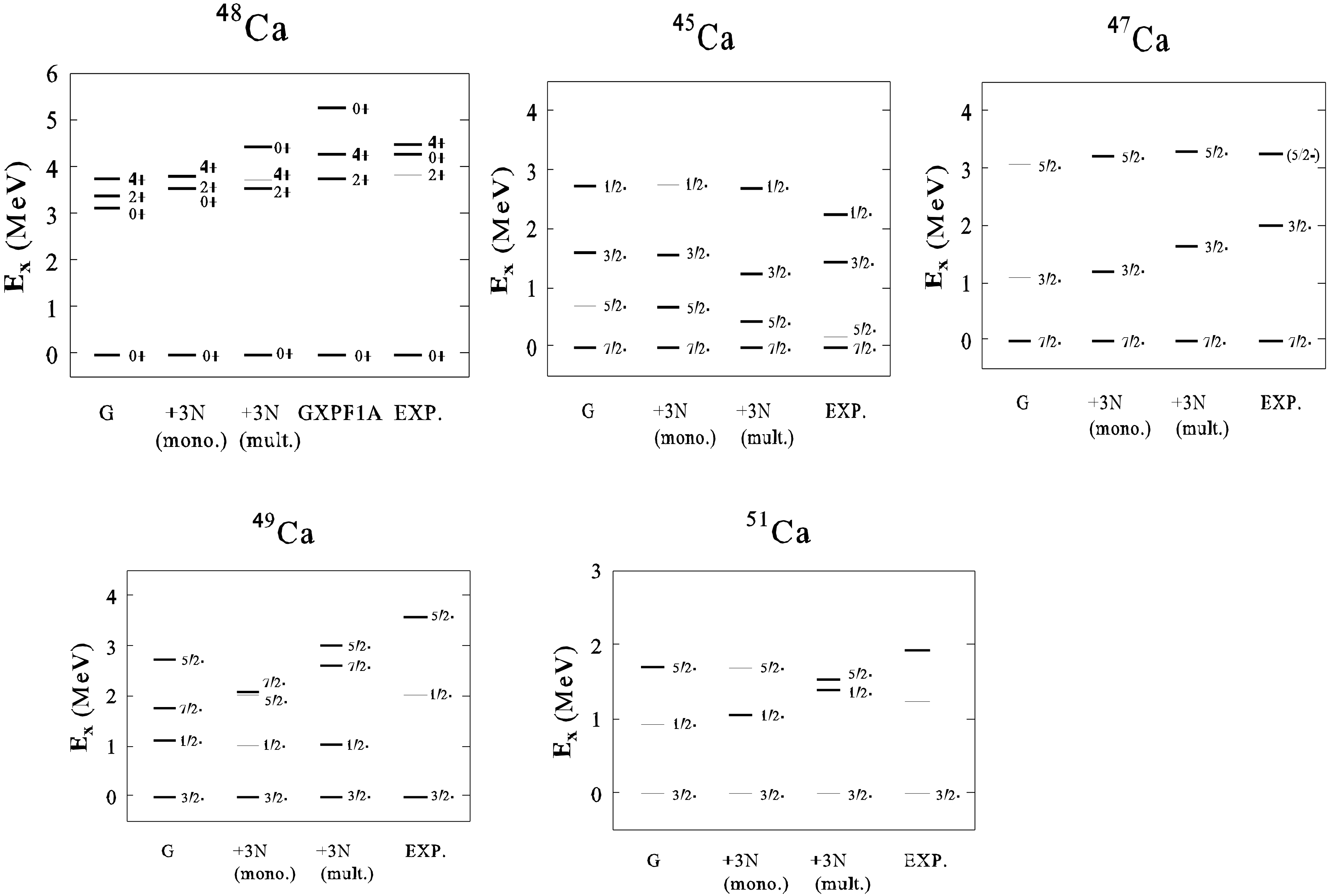




Box 10 hw; up to 16hw exc.

up to 2hw exc.

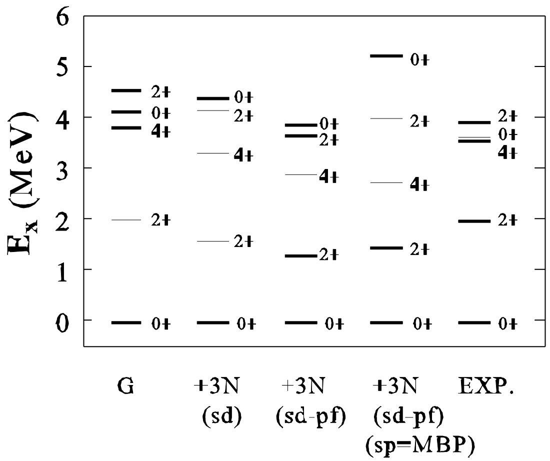
3N → Shell closure at ^{48}Ca



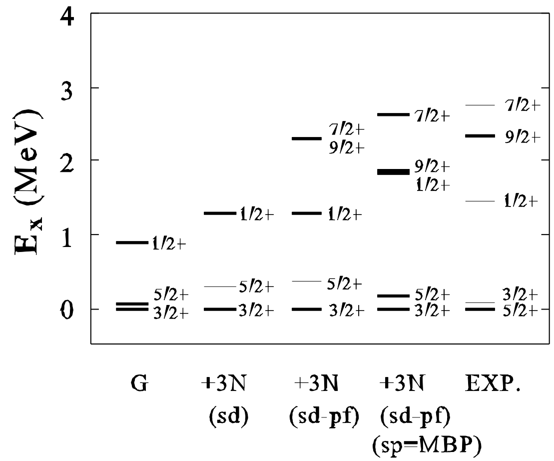
^{48}Ca
^{45}Ca
^{47}Ca
^{49}Ca
^{51}Ca
E_x (MeV)
G
+3N (mono.)
+3N (mult.)
GXPF1A
EXP.
0+
2+
4+
1/2-
3/2-
5/2-
7/2-
(5/2-)

sd-$p_{3/2}f_{7/2}$ G-matrix + 3N (FM)

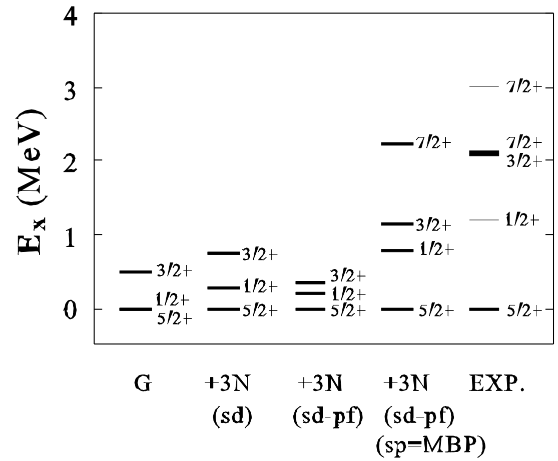
^{18}O



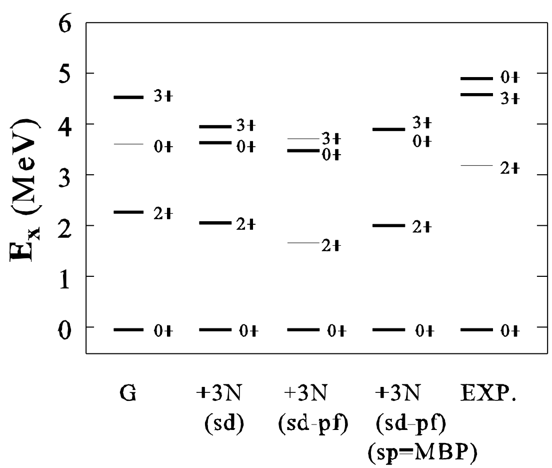
^{19}O



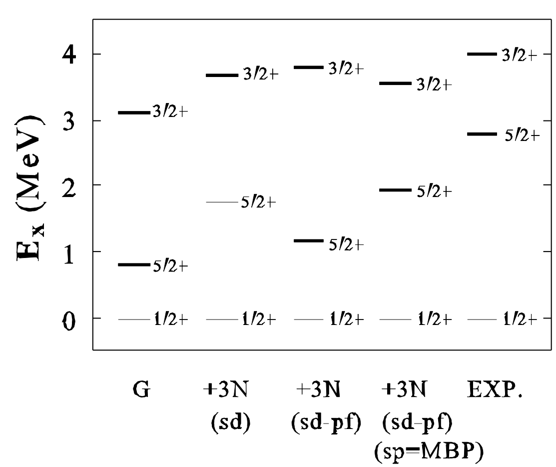
^{21}O



^{22}O

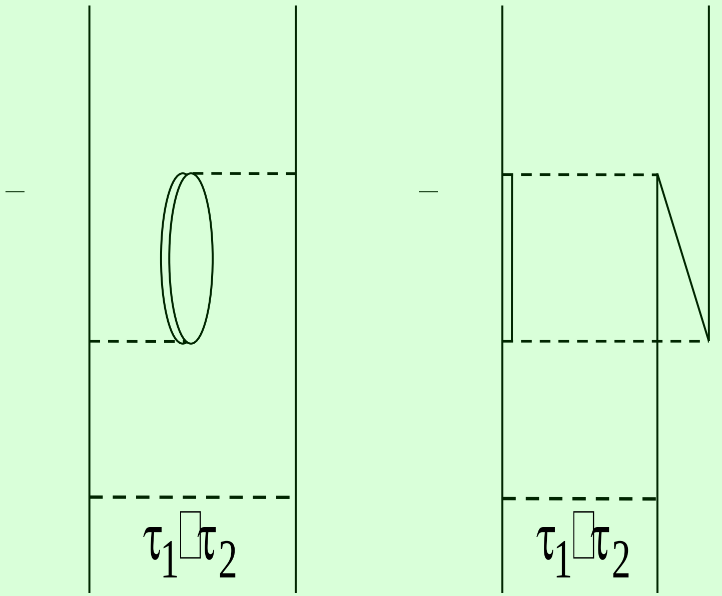


^{23}O



Monopoles in T=0

Higher order terms

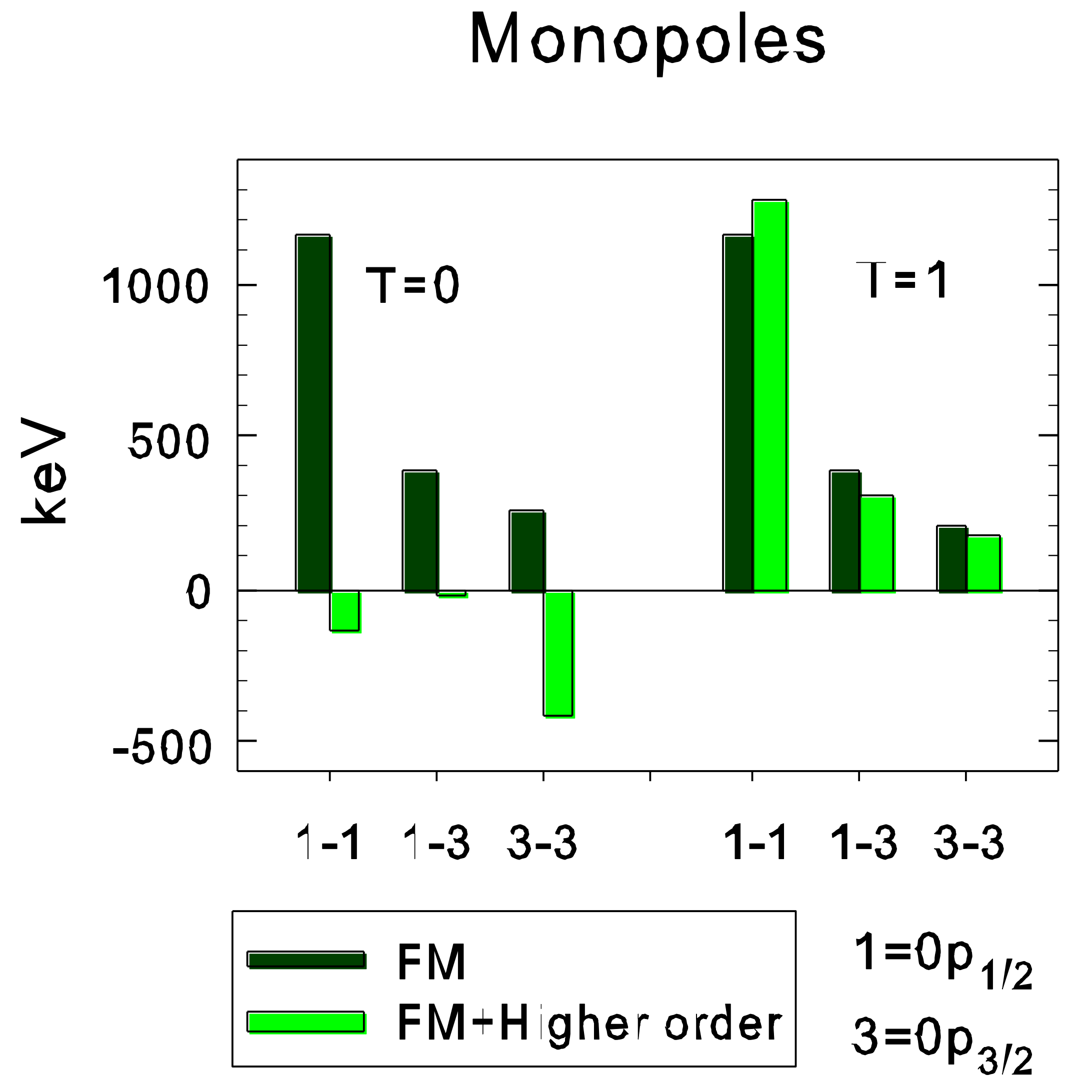


T=1 T=0

1 : 3x(-3)=-9

Monopoles for π & AV8'

Core=^{4}He



Summary

Tensor force → proper shell evolutions and better description of spin modes in nuclei

- **GT strengths in ^{12}C and ^{14}C**
- **Spin-dipole strength in ^{16}O**
- **Shell evolution in C isotopes**
- **GT strength in ^{40}Ar and ^{40}Ar (ν, e^-) ^{40}K induced by solar ν**

Three-body force → repulsion in T=1 monopoles

- **Proper shell evolutions in neutron-rich nuclei**
- **Drip-line of O**
- **M1 strengths in ^{48}Ca**

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