Isoscalar spin-triplet pairing and tensor correlations
on Spin-Isospin response

------------- Osaka,Japan, November 16-19, 2015 ----------------

Hiroyuki Sagawa RIKEN/University of Aizu

- Skyrme tensor interactions

Tensor interaction in mean field and density

Spin-triplet and spin-singlet pairing correlations
In Spin-Isospin excitations
Bohr-Mottelson Novel Prize 40th anniversary memorial issuse
Physics Scripta (2015)
H. Sagawa, C. L. Bai and G. Colo

THE UNIVERSITY OF AIZU · to Advance Knowledge for Humanity · 1993

RIKEN NiSHiNA CENTER

Skyrme-type tensor interactions

$$
\begin{aligned}
V^T = & \frac{T}{2}\{[(\sigma_1\cdot\mathbf{k}')(\sigma_2\cdot\mathbf{k}') - \frac{1}{3}(\sigma_1\cdot\sigma_2)\,\mathbf{k}'^2]\delta(\mathbf{r}_1-\mathbf{r}_2) \\
& +\delta(\mathbf{r}_1-\mathbf{r}_2)\left[(\sigma_1\cdot\mathbf{k})(\sigma_2\cdot\mathbf{k}) - \tfrac{1}{3}(\sigma_1\cdot\sigma_2)\,\mathbf{k}^2\right]\} \\
& +\frac{U}{2}\{(\sigma_1\cdot\mathbf{k}')\,\delta(\mathbf{r}_1-\mathbf{r}_2)\,(\sigma_2\cdot\mathbf{k}) + (\sigma_2\cdot\mathbf{k}')\,\delta(\mathbf{r}_1-\mathbf{r}_2)(\sigma_1\cdot\mathbf{k}) \\
& -\tfrac{2}{3}\left[(\sigma_1\cdot\sigma_2)\mathbf{k}'\cdot\delta(\mathbf{r}_1-\mathbf{r}_2)\mathbf{k}\right]\}
\end{aligned}
$$

:Triplet-even

:Triplet-odd

Two Advantages

1. A simple formula for spin-orbit splitting
2. Analytic formulas for multipole expansion for spin-dependent excitations

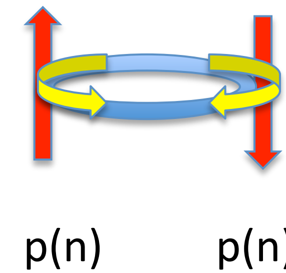
T.H.R. Skyrme, Nucl.Phys. 9,615(1959).
F.L. Stancu, D. M. Brink and H. Flocard, PLB68,108 (1977).

T.Lesinski, M. Bender, K. Bennaceur, T. Duguet, J. Meyer, Phys. Rev.C76, 014312(2007).
G.Colo, H. Sagawa, S. Fracasso, P.F. Bortignon, Phys. Lett. B 646 (2007) 227.
B.A.Brown, T. Duguet,T. Otsuka, D. Abe and T. Suzuki, Phys. Rev. C74(2006) 061303(R)

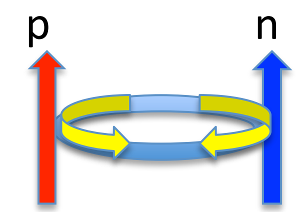
Two particle systems

T=1, S=0 pair

$$\left|(L=S=0)J=0,T=1\right\rangle \Rightarrow \left|(j=j^{'})J=0,T=1\right\rangle$$



T=0, S=1 pair



$$\left|(L=0,S=1)J=1,T=0\right\rangle \Rightarrow$$

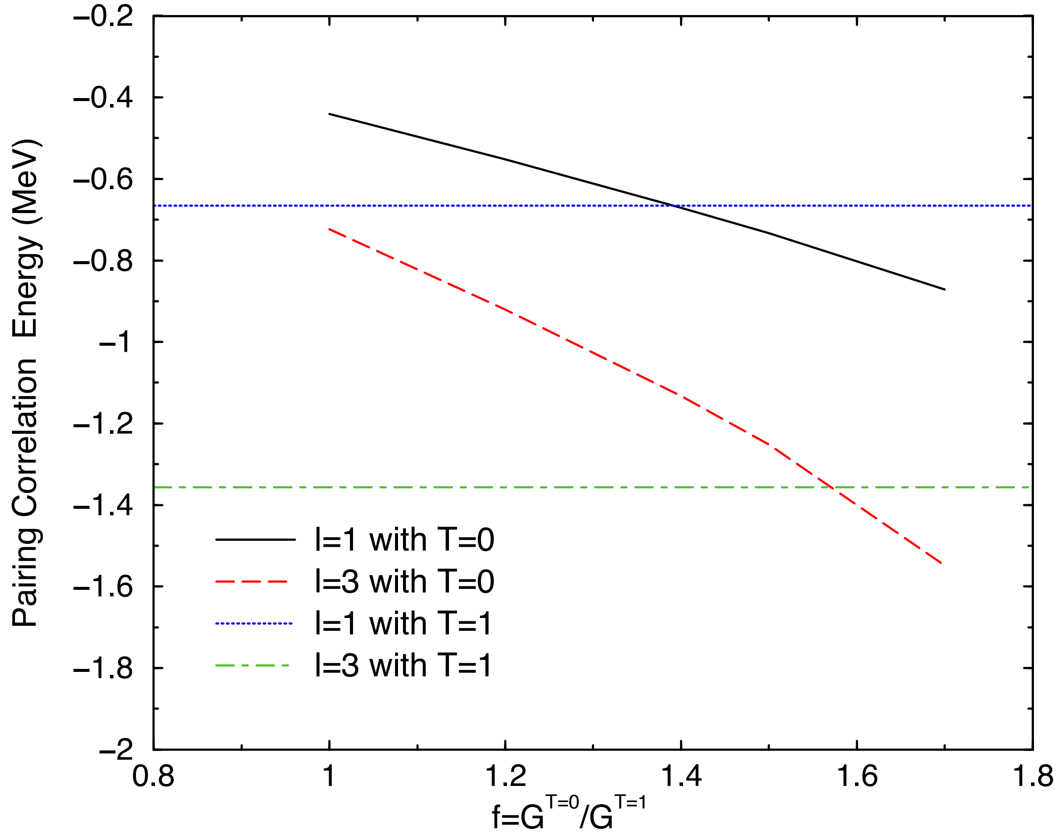
$$a\left|(l=l^{'} j=j^{'})J=1,T=0\right\rangle + b\left|((l=l^{'})j,j^{'}=j\pm 1)J=1,T=0\right\rangle$$

If there is strong spin-orbit splitting, it is difficult to make (T=0,S=1)pair.

But, T=0 $J=1^{+}$ state could be Gamow-Teller states in nuclei with N~Z
➔ strong GT states in N=Z+2 nuclei

SU(4) supermultiplet in spin-isospin space

Well-known in light p-shell nuclei (LS coupling dominance)



Pairing correlation energy of (J,T)=(0,1) and (1,0) states in *pf* shell

Even with large spin-orbit splitting for *f*-orbits, the spin-triplet correlations will be larger than the spin-singlet one for f>1.5

HS, Y. Tanimura and K. Hagino, PRC87, 034310 (2013)

TABLE I. Strengths of triplet and singlet interactions from shell-model fits an

Diagonalise the Hamiltonian

$V^{(T=1,S=0)}+V^{(T=0,S=1)}+V_{(spin\text{-}orbit)}$

Source	v_s (MeV fm^3)	v_t (MeV fm^3)	Ratio
sd shell [8]	280	465	1.65
fp shell [9]	291	475	1.63

G.F. Bertsch and Y. Luo, PRC81, 064320 (2010)

Cooperation of T=0 and T=1 pairing in Gamow-Teller states in N=Z nuclei

C. L. Bai, H.S., M.Sasano, T. Uesaka, K. Hagino, H.Q. Zhang, X.Z. Zhang,F.R.Xu

Phys. Lett. B719, pp. 116-121 (2013)

HFB+QRPA with T=1 and T=0 pairing

T=1 pairing in HFB

T=0 pairing in QRPA

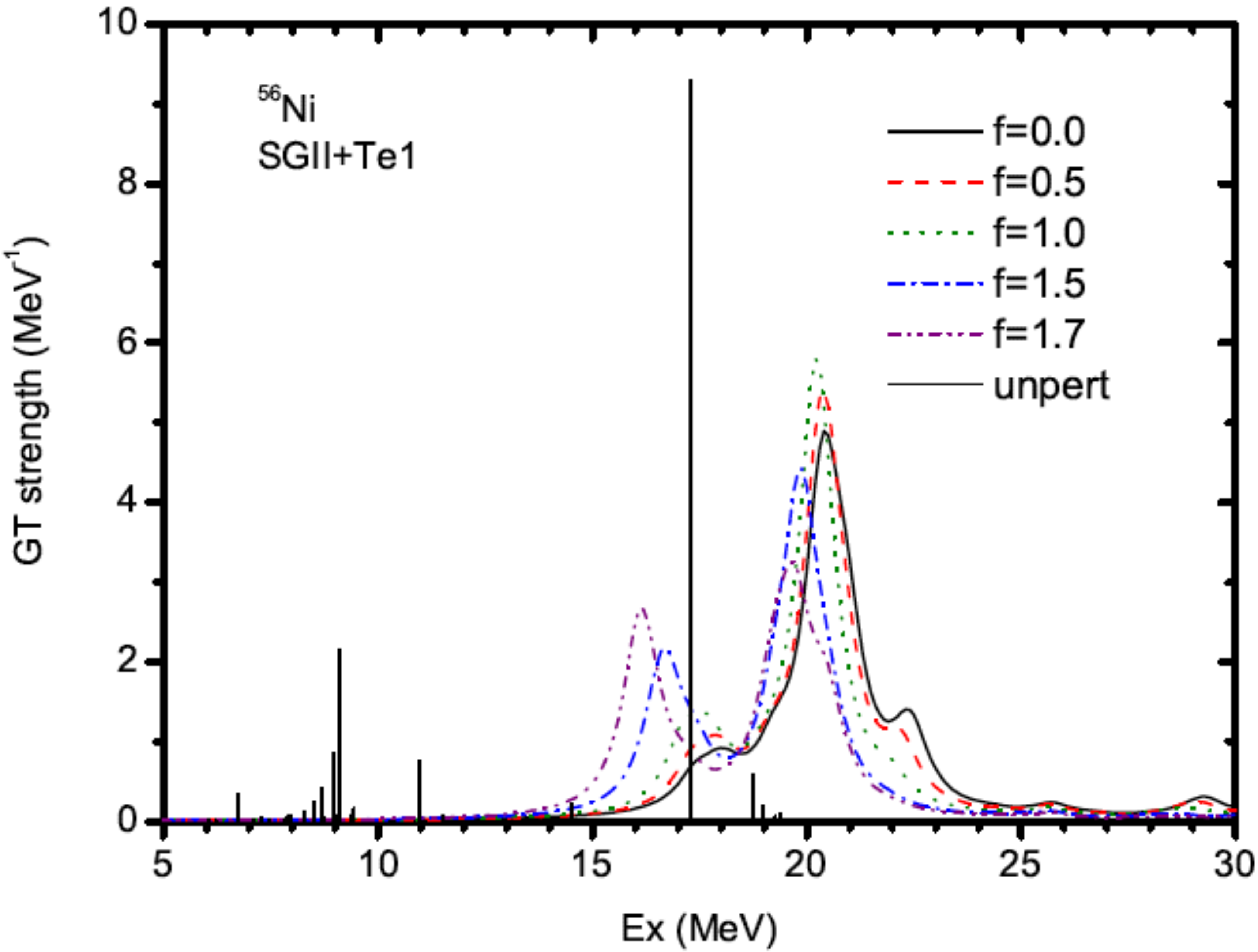
How large is the spin-triplet T=0 pairing corelation?

$$V_{T=1}(\mathbf{r}_1,\mathbf{r}_2) = V_0 \frac{1-P_\sigma}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_o}\right)\delta(\mathbf{r}_1-\mathbf{r}_2), \quad (1)$$

$$V_{T=0}(\mathbf{r}_1,\mathbf{r}_2) = fV_0 \frac{1+P_\sigma}{2}\left(1-\frac{\rho(\mathbf{r})}{\rho_o}\right)\delta(\mathbf{r}_1-\mathbf{r}_2), \quad (2)$$

As a possible manifestation of T=0 S=1 pairing correlations in nuclei N=Z.

$$\hat{O}(GT) = \sigma\tau_{\pm}$$



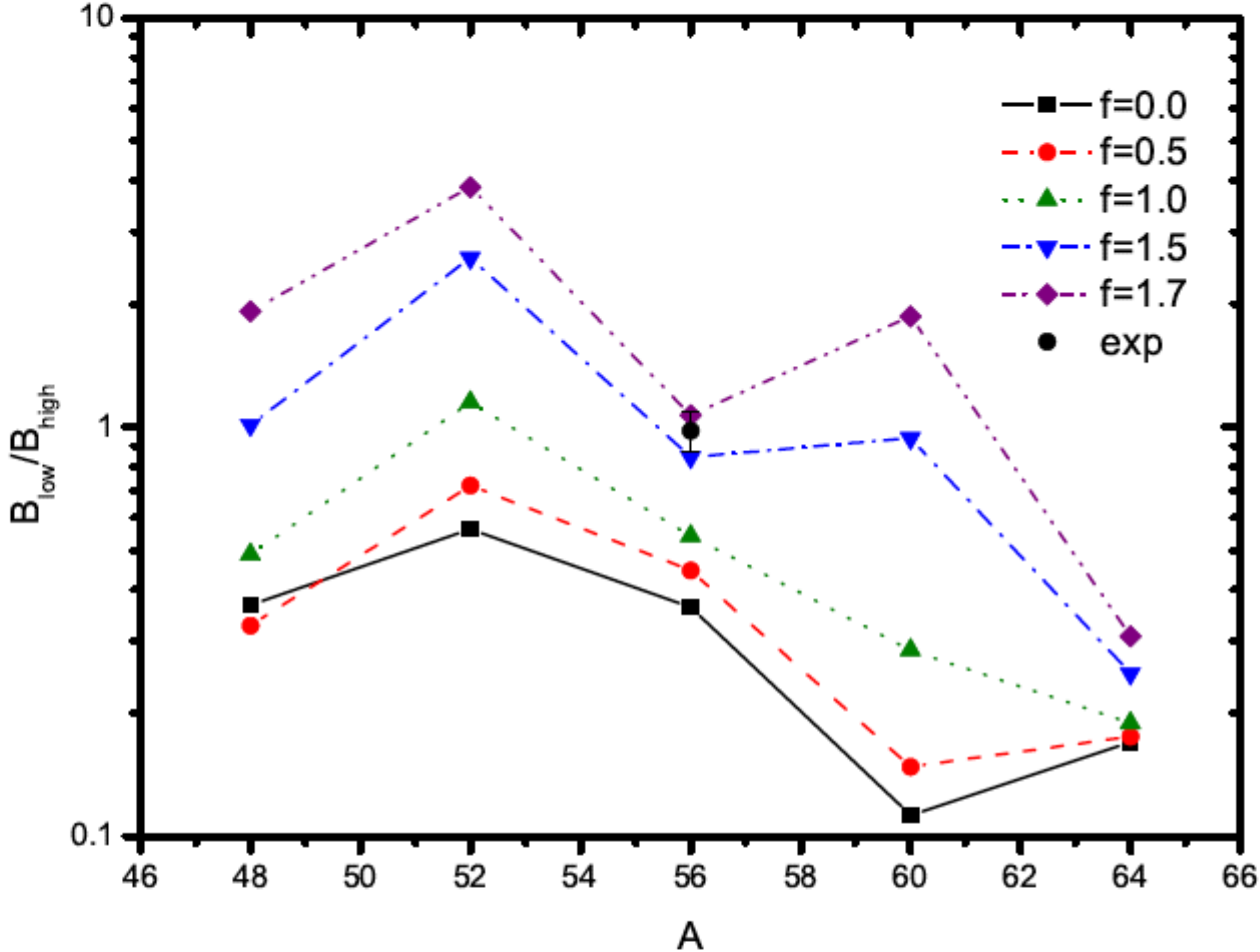
56Ni
SGII+Te1
f=0.0
f=0.5
f=1.0
f=1.5
f=1.7
unpert
GT strength (MeV-1)
Ex (MeV)
0
2
4
6
8
10
5
10
15
20
25
30

TABLE I: Amplitudes of main (np) particle-hole and particle-particle type configurations of GT states in ^{56}Ni. The QRPA calculations are performed without and with the T=0 pairing interaction in the cases of $f = 0$ and $f = 1.5$, respectively. The Skyrme interaction T21 is used for HF and p-h matrix calculations. The abbreviations B and C correspond to the GT reduced matrix element B=$(X u_\pi v_\nu - Y u_\nu v_\pi)\langle \pi || \hat{O}(\mathrm{GT}) || \nu \rangle$ and the normalization factor C=$X^2 - Y^2$, respectively, where X,Y are QRPA amplitudes and $\hat{O}$(GT) is GT transition operator in Eq. (3).

^{56}Ni		$f = 0$			
E_x (MeV)	B(GT)	$\nu(v_\nu^2)$	$\pi(v_\pi^2)$	B	C
17.5	1.41	$2p_{3/2}(0.20)$	$2p_{3/2}(0.21)$	0.358	0.127
		$1f_{7/2}(0.69)$	$1f_{5/2}(0.09)$	−0.229	0.006
		$1f_{7/2}(0.69)$	$1f_{7/2}(0.67)$	1.341	0.802
18.3	1.49	$2p_{1/2}(0.10)$	$2p_{3/2}(0.21)$	0.260	0.153
		$2p_{3/2}(0.20)$	$2p_{1/2}(0.11)$	0.846	0.740
21.3	7.88	$1f_{7/2}(0.69)$	$1f_{5/2}(0.09)$	2.48	0.742
S_-(GT)=18.28					
^{56}Ni		$f = 1.5$			
E_x (MeV)	B(GT)	$\nu(v_\nu^2)$	$\pi(v_\pi^2)$	B	C
16.6	4.82	$2p_{3/2}(0.20)$	$2p_{1/2}(0.11)$	−0.203	0.049
		$2p_{3/2}(0.20)$	$2p_{3/2}(0.21)$	−0.682	0.491
		$1f_{7/2}(0.69)$	$1f_{5/2}(0.09)$	−0.237	0.007
		$1f_{7/2}(0.69)$	$1f_{7/2}(0.67)$	−0.790	0.339
20.5	4.10	$1f_{7/2}(0.69)$	$1f_{5/2}(0.09)$	−1.900	0.437
S_-(GT)=14.75					

$$B = (X u_\pi v_\nu - Y u_\nu v_\pi)\left\langle \pi \left\| \hat{O}(GT) \right\| \nu \right\rangle$$

$$C = X^2 - Y^2$$



EXP: Sasano et al., PRL107 (2011)

Gamow-Teller Transitions in nuclei with N=Z+2

C.L. Bai, HS, G. Colo, Y. Fujita et al., PRC90, 054335 (2014)

HFB+QRPA with T=1 and T=0 pairing

T=1 pairing in HFB

T=0 pairing in QRPA

$$\hat{O}(GT) = \sigma\tau_{\pm}$$

σ, τ and $\sigma\tau$ are generators of SU(4)

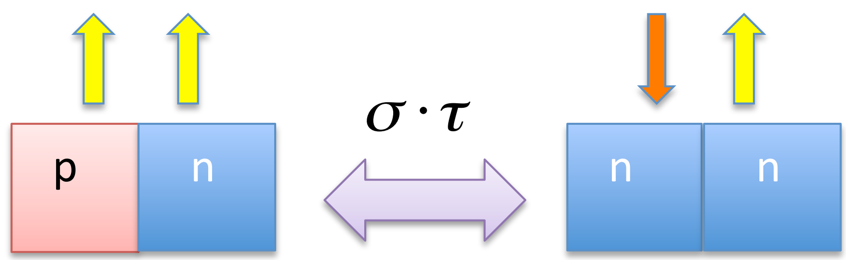
Supermultiplet : Wigner SU(4) symmetry

(E. Wigner 1937, F. Hund 1937)

(T=1, S=0) →(T=0, S=1) GT transition is allowed and enhanced .

Supermultiplet : Wigner SU(4) symmetry
(T=1, S=0) →(T=0, S=1) GT transition is allowed and enhanced .

Spacial symmetry is the same between the initial and final states



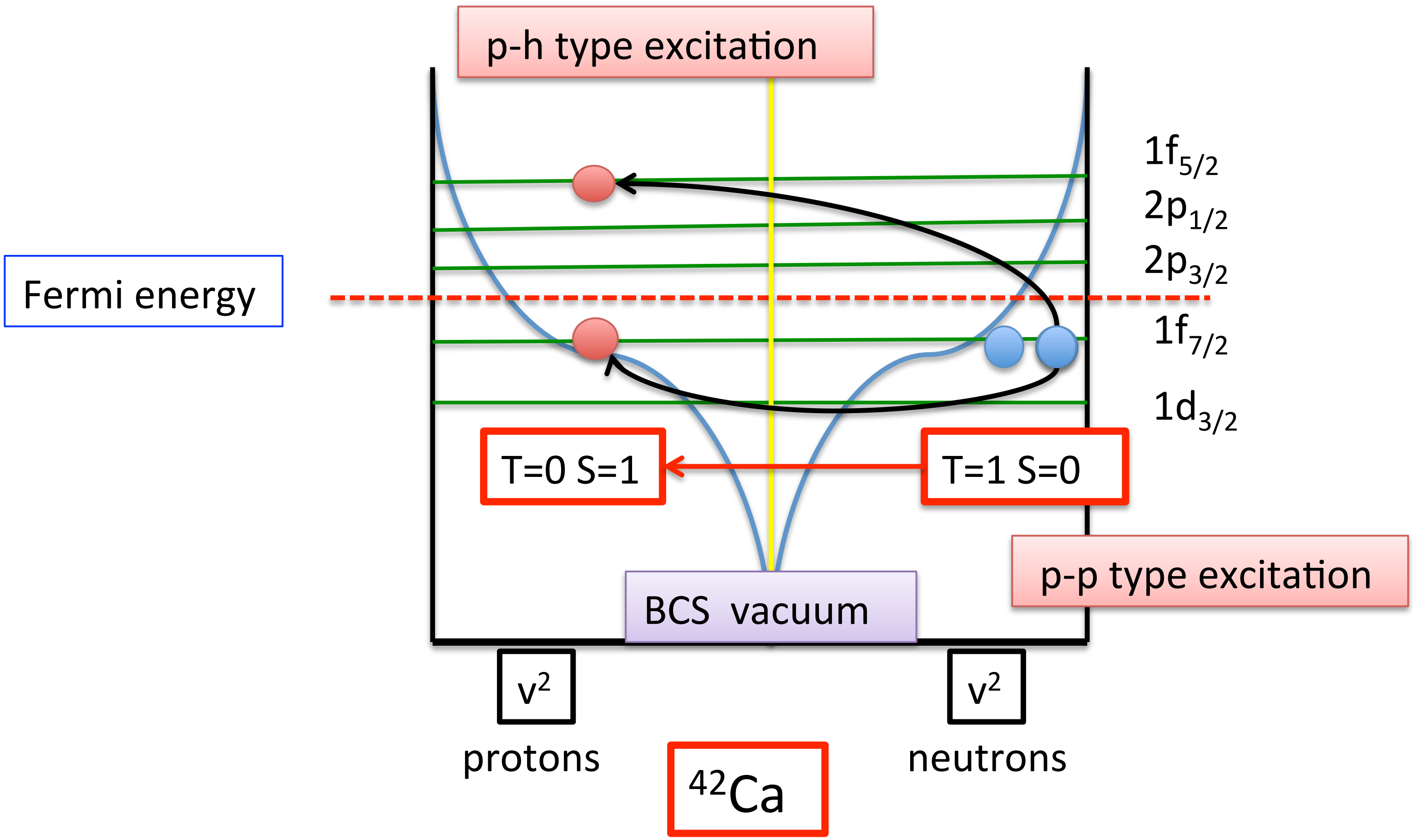
(T=0,S=1) (T=1,S=0)

B(GT)=6

What happens in pf shell nuclei with strong spin-triplet pairing interactions?

Gamow-Teller transitions in N=Z+2 *pf* nuclei

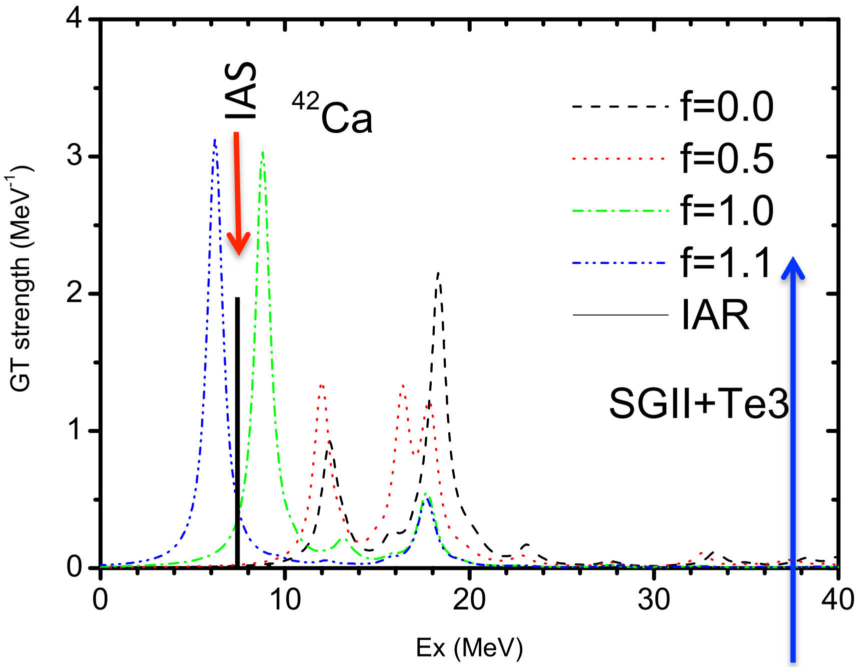
$$\hat{O}(GT) = \sigma\tau_{\pm}$$



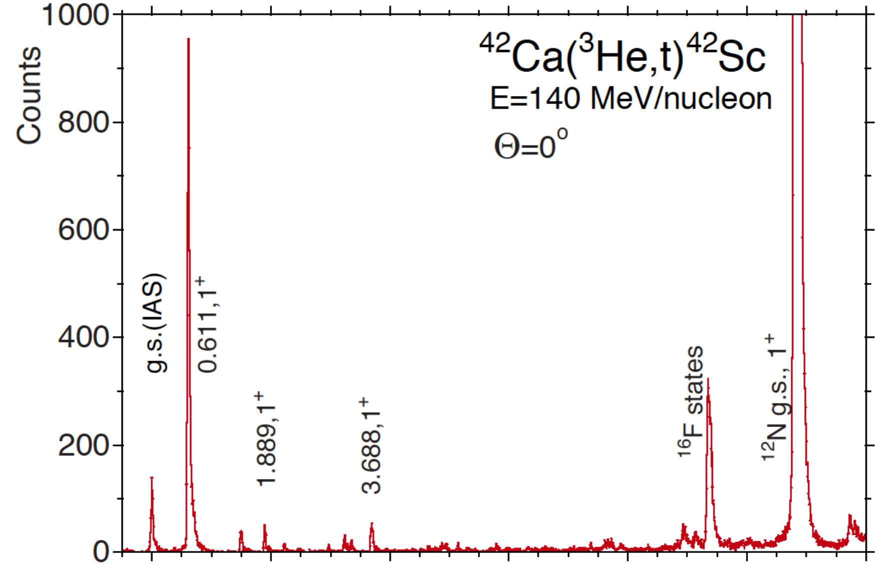
A pair of SU(4) supermultiplet

p-h spin-isospin interaction is strongly repulsive → higher energy collective Gamow-Teller states.

Spin-triplet T=0 pairing is attractive and shift down GT strength near IAS → SU(4) symmetry restoration



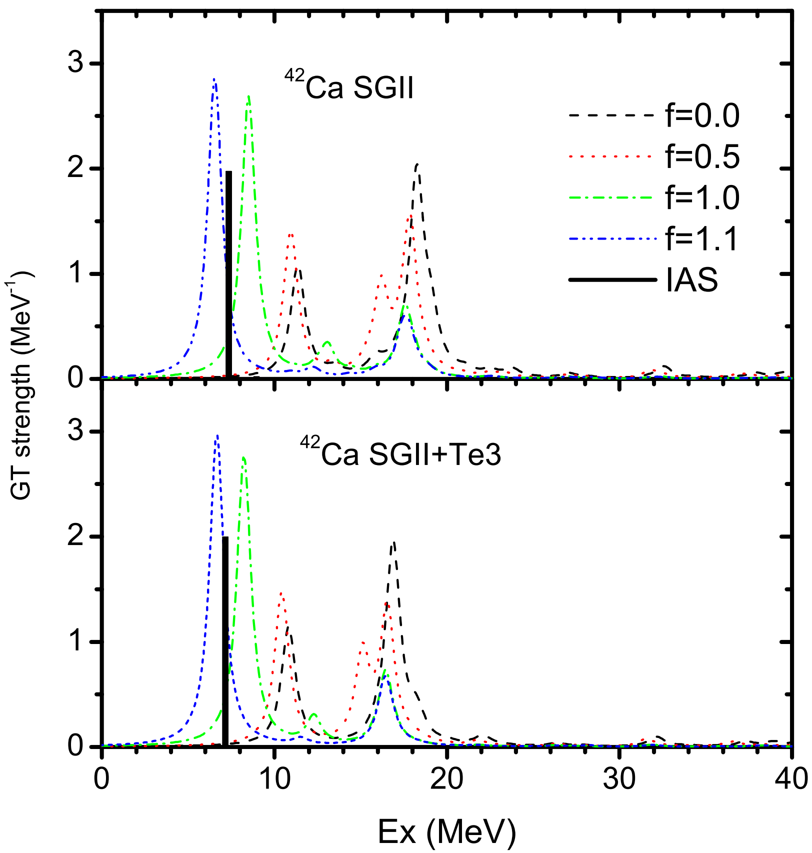
f =IS/IV pairing

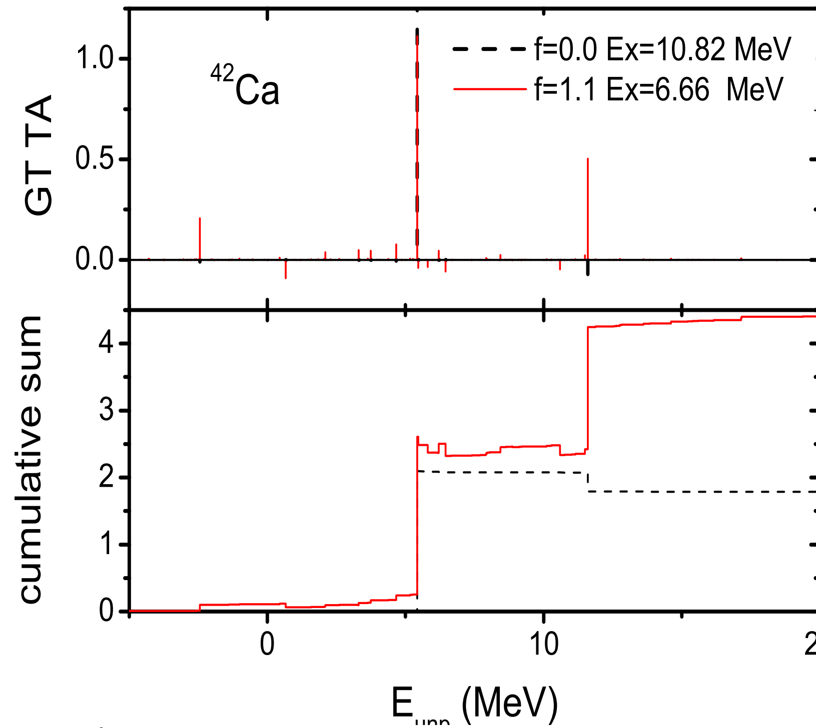


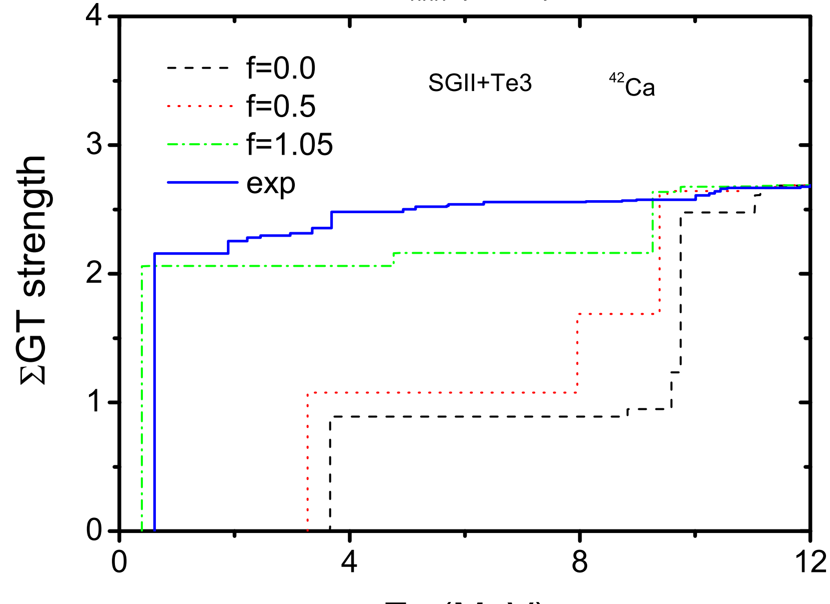
Y. Fujita et al., PRL112, 112502 (2014)

HFB+QRPA with T=1 and T=0 pairing

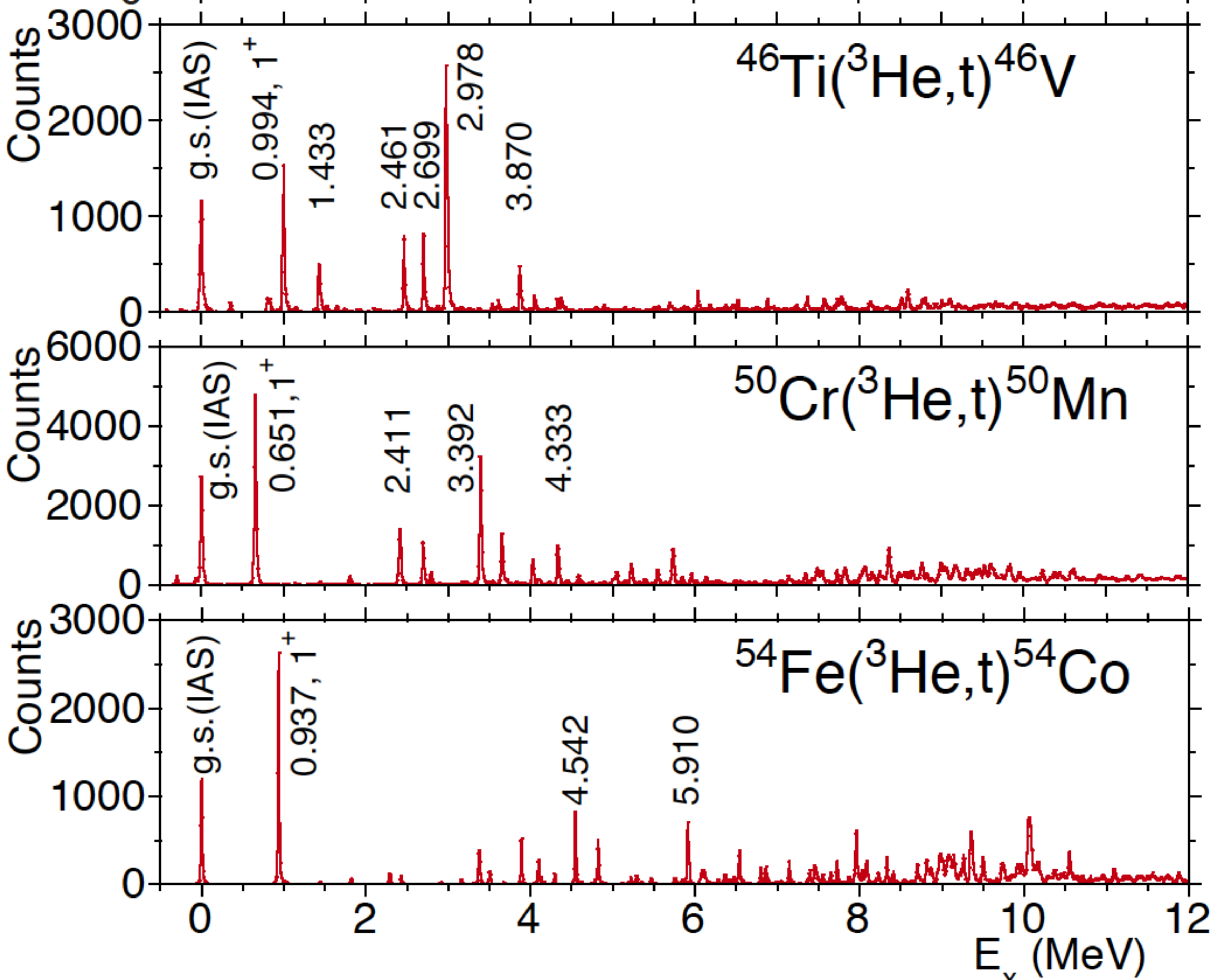
T=0 pairing strength in QRPA is changed by a factor f=spin-triplet/spin-singlet

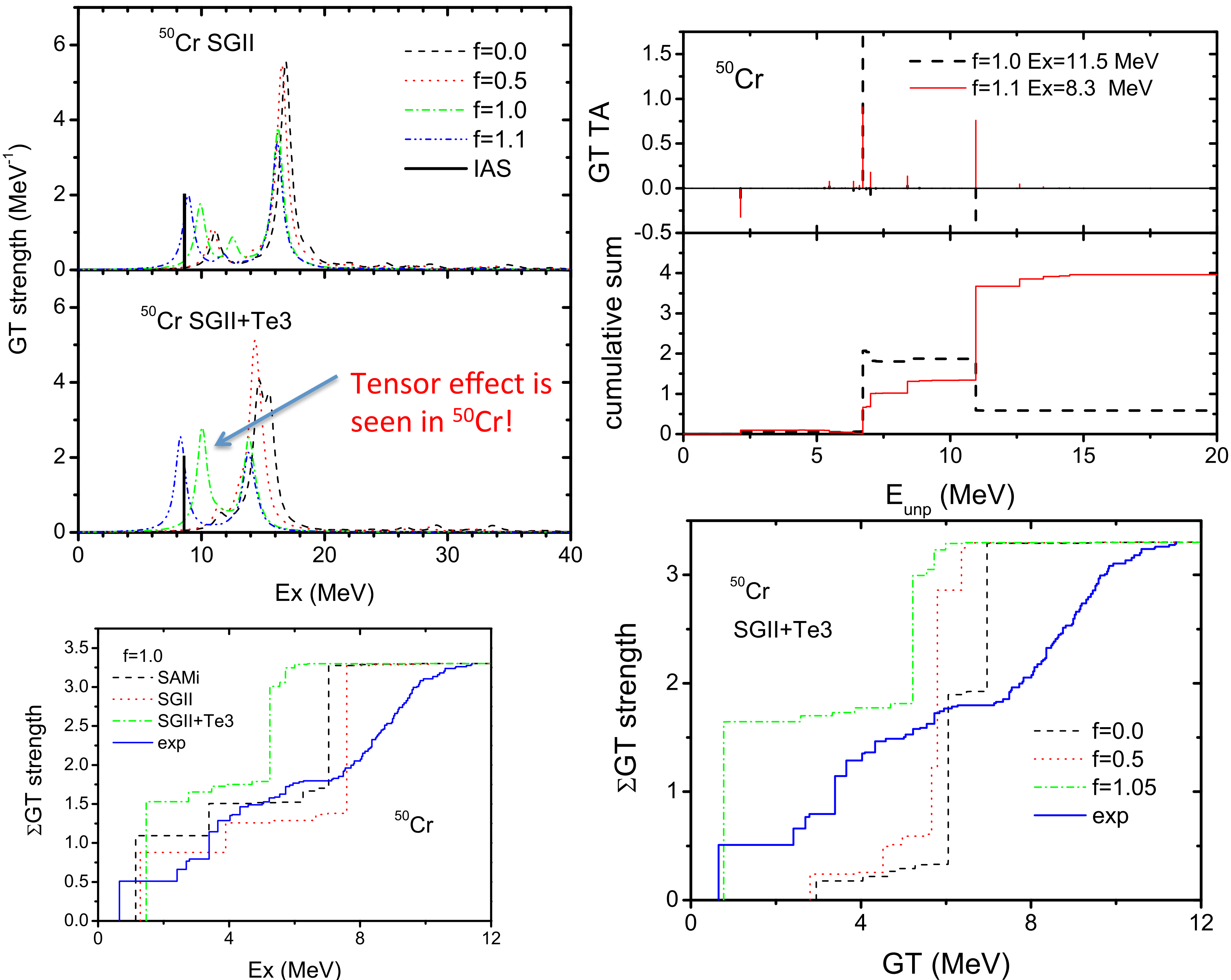




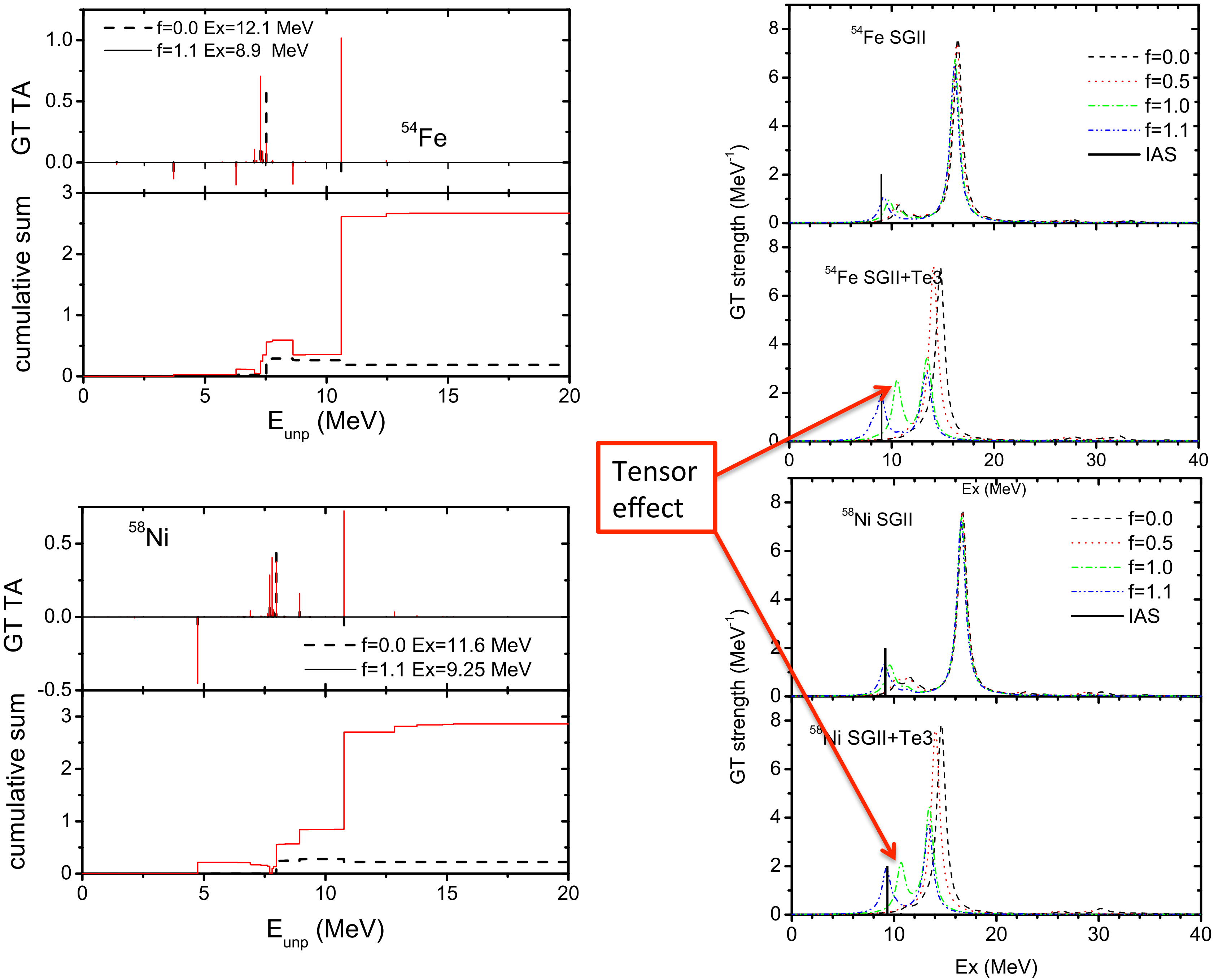


Effect of tensor correlations is small in ^{42}Ca.


Counts
^{46}Ti(^{3}He,t)^{46}V
g.s.(IAS)
0.994, 1^{+}
1.433
2.461
2.699
2.978
3.870
^{50}Cr(^{3}He,t)^{50}Mn
g.s.(IAS)
0.651,1^{+}
2.411
3.392
4.333
^{54}Fe(^{3}He,t)^{54}Co
g.s.(IAS)
0.937, 1^{+}
4.542
5.910
E_x (MeV)



50Cr SGII
f=0.0
f=0.5
f=1.0
f=1.1
IAS
GT strength (MeV-1)
50Cr SGII+Te3
Tensor effect is seen in 50Cr!
Ex (MeV)
50Cr
f=1.0 Ex=11.5 MeV
f=1.1 Ex=8.3 MeV
GT TA
cumulative sum
E unp (MeV)
f=1.0
SAMi
SGII
SGII+Te3
exp
ΣGT strength
50Cr
Ex (MeV)
50Cr
SGII+Te3
f=0.0
f=0.5
f=1.05
exp
ΣGT strength
GT (MeV)



f=0.0 Ex=12.1 MeV
f=1.1 Ex=8.9 MeV
GT TA
54Fe
cumulative sum
E_unp (MeV)
58Ni
f=0.0 Ex=11.6 MeV
f=1.1 Ex=9.25 MeV
54Fe SGII
f=0.0
f=0.5
f=1.0
f=1.1
IAS
54Fe SGII+Te3
GT strength (MeV-1)
Ex (MeV)
58Ni SGII
58Ni SGII+Te3
Tensor effect

Summary

1. Corperative effct of T=0 and T=1 pairing correlations enhance the low-energy GT strength in N=Z and N=Z+2 nuclei.

➔ Restoration of supermultiplet symmetry in (T=1,J=0) and (T=0 ,J=1) states in *pf* shell nuclei

2. A cooperative effect of T=0 pairing and tensor interactions are found in nuclei at the middle of *pf* shell.
3. The T=0 pairing strength is determined to be almost the same strength as the T=1 pairing from the observed relative energies of IAS and the low-energy GT states;
   f=strength(T=0)/(T=1)~1.0 irrespective of the adopted interactions.

Theory

a. Further study of Particle-vibration coupling:
   Yifei Niu, Gianluca Colo
b. Fine fittings of energy density functions for RPA and QRPA
   (which was done already for Shell model interactions:
   Toshio Suzuki, Michio Honma