Recent Progress of Spin-Isospin Excitations in Nuclei
---- 21st Int. Symp. On Spin Physics (Spin2014) ------
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Two topics
- Gamow-Teller Collective states in $^{8}He(p,n)^{8}Li$ and $^{12}Be(p,n)^{12}B$
- spin-isospin SU(4) symmetry in N=Z+2 nuclei in pf shell nuclei

Spin-isospin physics: Gamow-Teller responses

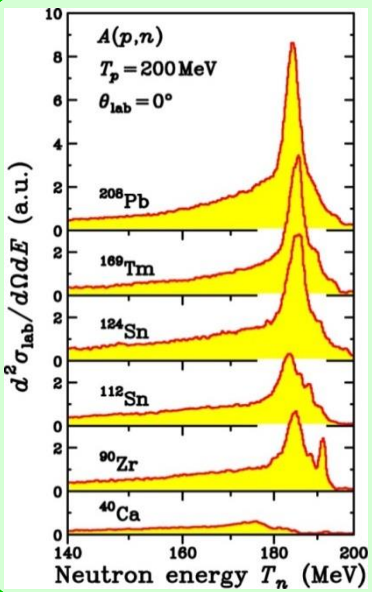
Progress in Last century

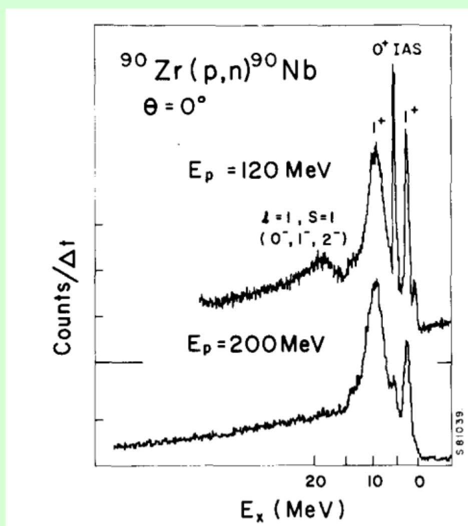
Courtesy of H. Sakai

- 1963 GT giant resonance predicted, GT(Ikeda) sum rule 3(N-Z) collectivity?
- ~1980 GT giant resonances established
- Strength quenched/missing: 50-60% of 3(N-Z) due to Δ-h or 2p-2h ?
- 1997 ~90% of 3(N-Z) found (2p-2h dominance)

- Charge-exchange reactions on stable target nuclei
- CHEX reactions: (p,n)/(n,p) and (^{3}He,t)/(t,^{3}He) reactions at intermediate energy

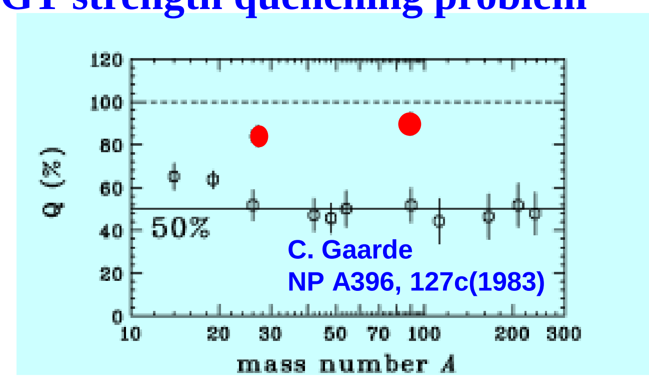
- C. Garrde, NPA396(1982)127c.





- Wakasa et al., PR C55, 2909 (1997)

GT strength quenching problem



- **Wakasa et al.,** PR C **55**, 2909 (1997)

Spin-isospin physics: Gamow-Teller responses

This century

- Unstable beams → extend the horizon of spin-isospin responses
- Charge-exchange reactions in inverse kinematics

Gamow-Teller giant resonance under extreme condition

1. Spin-isospin correlations in N>>Z nuclei
2. Quenching of Spin-orbit interaction (tensor correlations)
3. Coupling to the continuun
4. Isoscalar spin-triplet pairing in N~Z nuclei

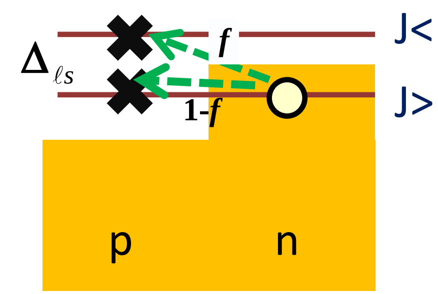
Recent observations at (N-Z)/A extreme at RIKEN/CNS

Gamow-Teller Giant Resonances in very light neutron rich nuclei, ^{8}He & ^{12}Be

Spin-isospin correlations in schematic model

- **GTGR (IAS) induced by *ph* residual interaction:**

$$V_{12} = \kappa_{\sigma\tau}\vec{\sigma}_1\vec{\sigma}_2\vec{\tau}_1\vec{\tau}_2 \quad (\kappa_\tau \vec{\tau}_1\vec{\tau}_2)$$

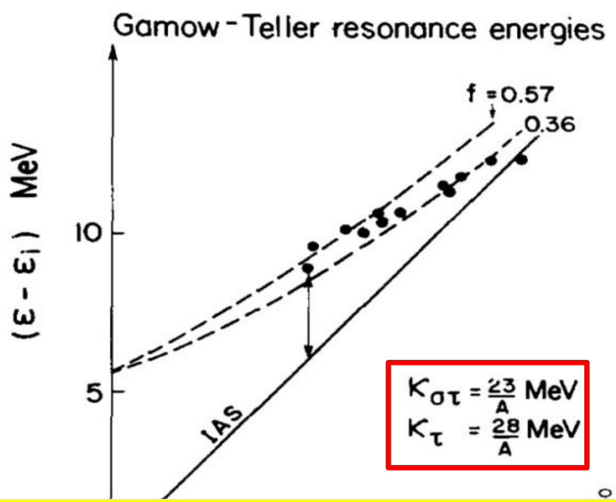


- **Dispersion relation for the collective state(GTGR)**

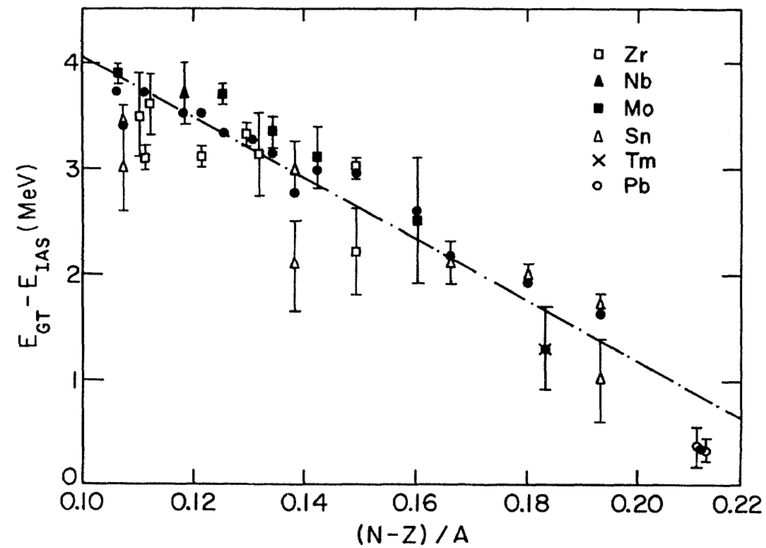
$$\frac{2(N-Z)(1-f)}{\epsilon_i - \epsilon} + \frac{2(N-Z)f}{\epsilon_i + \Delta_{\ell s} - \epsilon} = \frac{1}{\kappa_{\sigma\tau}}$$

two p-h configurations for GT

- **C. Garrde, NPA396(1982)127c.**



- **Nakayama et al.,PLB114(1982)217**



$$E_{\mathrm{GT}} - E_{\mathrm{IAS}} = \Delta_{\ell s} + 2\frac{(\kappa_{\mathrm{GT}} - \kappa_{\mathrm{F}})}{A}(N-Z)$$

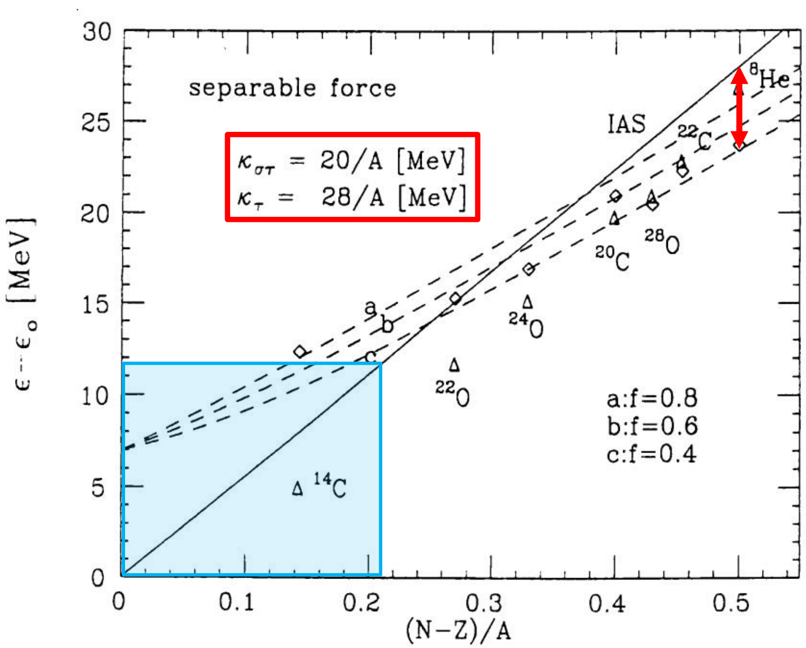
$$(\kappa_{\mathrm{F}} - \kappa_{\mathrm{GT}})A = 9.25\ \mathrm{MeV}$$

one-p-h configuration for GT

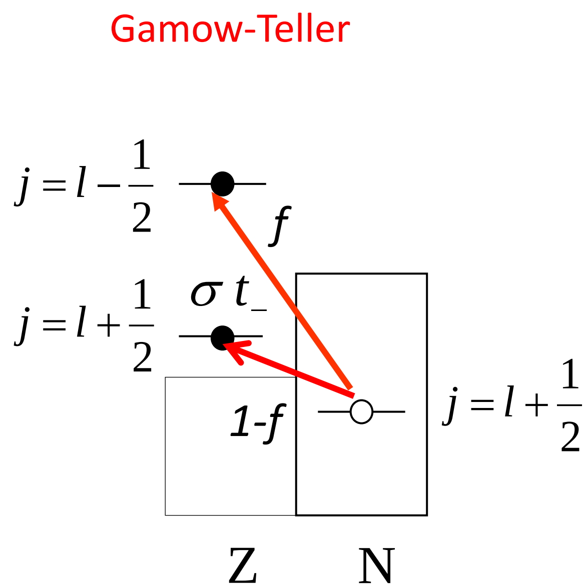
Data:
(N-Z)/A < 0.21 was missing in 20th century
$E_{\mathrm{GT}} - E_{\mathrm{IAS}} > 0$

- **Predicted in 1993 by Sagawa-Hamamoto-Ishihara, PLB303,215**

Hartree-Fock + RPA (TDA) calculation with（BKN+spin-orbit (^{16}O))



- Relatively large $E_{GT} - E_{IAS} < 0$
- 8He : $E_{GT} - E_{IAS} = -4.5$ MeV (f=0.44)



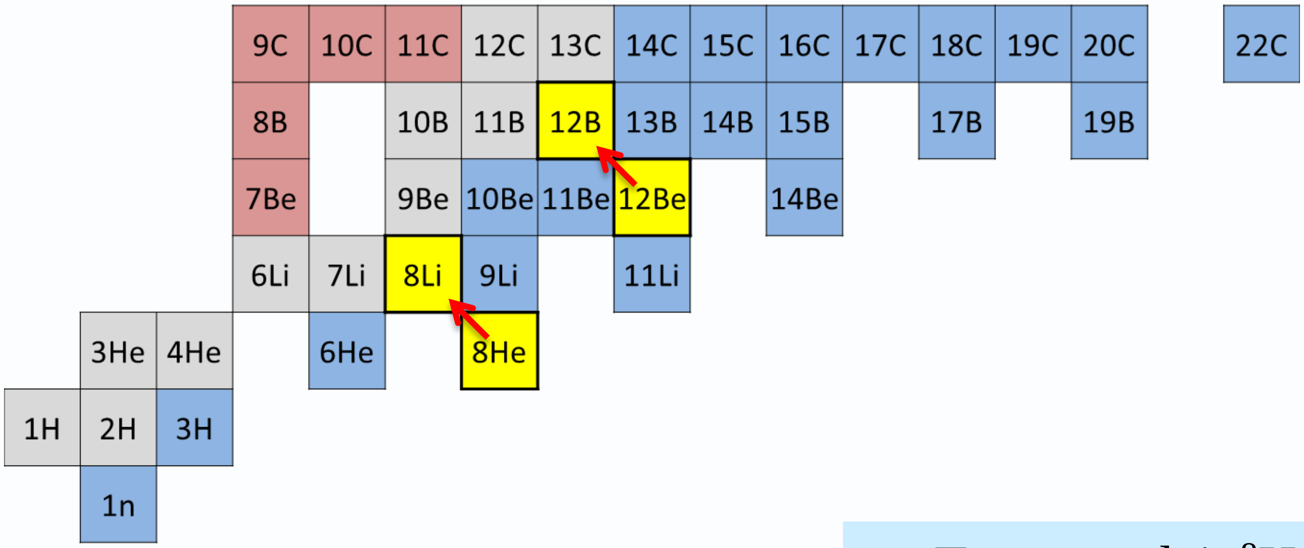
$$f = \frac{B(\mathrm{GT} j_> \to j_<)}{B(\mathrm{GT} j_> \to j_<) + B(\mathrm{GT} j_> \to j_>)} = 4/9 = 0.44 \qquad l = 1$$

$$= 8/15 = 0.53 \qquad l = 2$$

$$= 12/21 = 0.57 \qquad l = 3$$

$$= 16/27 = 0.59 \qquad l = 4$$

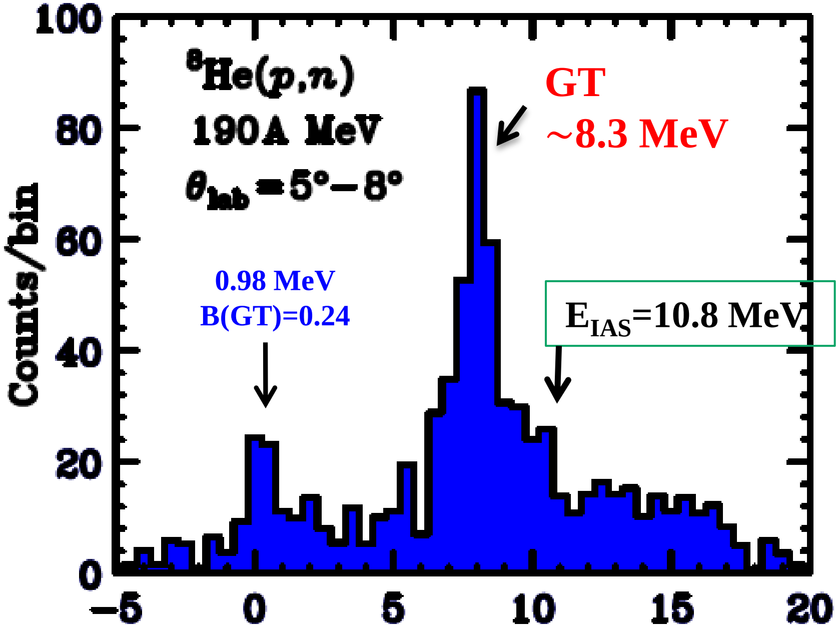
GT responses in very neutron rich light nuclei

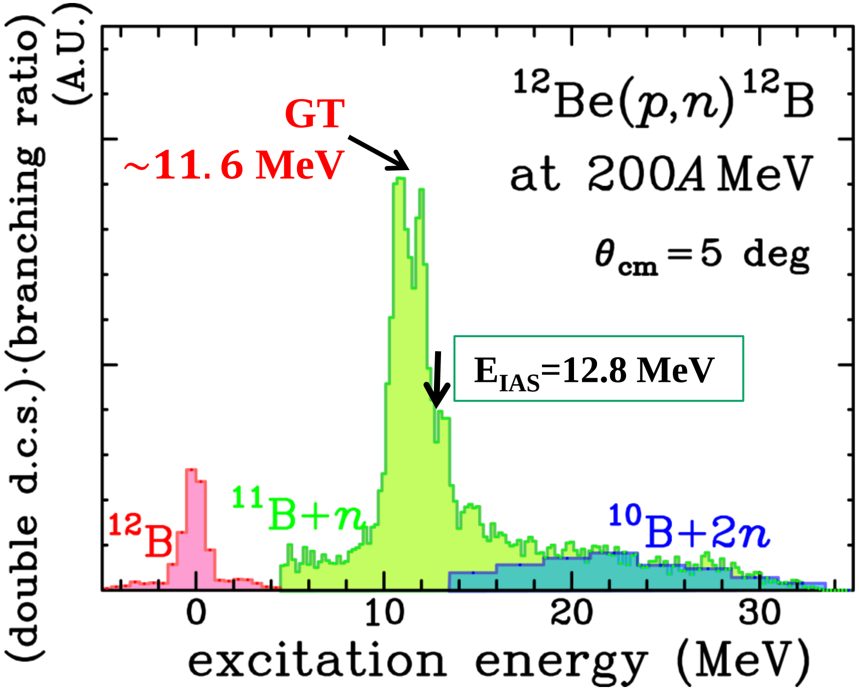


- Target nuclei: ^{8}He and ^{12}Be
  (N-Z)=4
- Large neutron to proton ratio
  - $(N\text{-}Z)/A$ = 0.33(^{12}Be), 0.5(^{8}He)
- (p,n) reaction in inverse kinematics
- ^{8}He(p,n) by Kobayashi *et al.*,
- ^{12}Be(p,n) by Yako *et al.*,

Experimental Results

- $^{8}He(p,n)$ at 200 MeV/u (Kobayashi)
- $^{12}Be(p,n)$ at 200 MeV/u (Yako)





$E_{GT} - E_{IAS} = -2.5 \pm 0.5$ MeV

$E_{GT} - E_{IAS} = -1.2 \pm 0.4$ MeV

Shell structure characterics

- p-shell dominance for ^{8}He
- Deformation or 2p-2h state mixing in the ground state in ^{12}Be

mixing of 2s1d configurations in ^{12}Be

SFO' interaction (2s1/2 s.p.e. is lowered to obtain B(GT:12Be->12B(g.s.)):

large 2hw excitation components in the ground state

$|^{12}Be\rangle = 0.55|p^8\rangle + 0.82|p^6(sd)^2\rangle$

Occupation probabilities of neutrons (# of particles)

p-orbits	4.61
s-orbit	0.68
d-orbit	0.71

TABLE I: Calculated $E_{\rm GT} - E_{\rm IAS}$ values for $\kappa_{\sigma\tau} = \frac{21}{A}$, $\frac{22}{A}$ and $\frac{23}{A}$ MeV with several assumed neutron-orbit configurations for ^{8}He and ^{12}Be together with experimental values. For comparison purpose, the results for ^{208}Pb is also given. In all calculations, $\kappa_{\tau} = \frac{28}{A}$ MeV is assumed.

	$\Delta E = E_{\rm GT} - E_{\rm IAS}$ (MeV)			
$\kappa_{\sigma\tau}$ (MeV)	$\frac{21}{A}$	$\frac{22}{A}$	$\frac{23}{A}$	adopted ν configuration
^{8}He	-3.01	-2.03	-1.16	$(1p_{3/2})^4$
	Exp. -2.5 ± 0.5 [10]			
^{12}Be	-2.20	-1.58	-0.95	$(1p_{3/2})^4(1p_{1/2})^2$
	$+0.96$	$+1.75$	$+2.55$	$(1p_{3/2})^4(2s_{1/2})^2$
RPA model	$+0.09$	$+0.73$	$+1.37$	$(1p_{3/2})^4(2d_{5/2})^2$
spin-orbit splitting	-1.55	-0.91	-0.26	SFO configuration [20]
$\Delta\varepsilon_{ls} = -20 l\cdot s A^{-2/3}$	$-1.73.$	-1.10	-0.46	WBP' configuration [22]
	Exp. -1.2 ± 0.4 [11]			
^{208}Pb	-0.29	$+0.10$	$+0.50$	
	Exp. $+0.4\pm0.2$ [7]			

Shell model + Nakayama (b)+ SHI

TABLE II: Calculated results of excitation energies of GT and IAS and B(GT) values in ^{8}Li ^{12}B . The $E_{\rm IAS}$ values for ^{8}Li and ^{12}B are taken from [15] and [16], respectively.

	^{8}Li	$E_{\rm GT}$ (MeV)	$E_{\rm IAS}$ (MeV)	ΔE (MeV)	B(GT)
$0\hbar\omega$	(8-16)POT	7.5	11.7	−4.2	10.7
	(6-16)2BME	8.3	11.1	−2.8	9.7
$(0+2)\hbar\omega$	SFO	7.8	12.1	−4.3	8.8
	WBT'	5.9	10.8	−4.9	5.6
	SFO(6-16)	8.2	11.1	−2.9	8.3
	Eq.(5)[9]	—	—	−7.5	—
	SHI[2]	9.0	13.7	−4.7	9.4
	^{8}He(β^-)[23]	∼9	10.8	−1.8	∼3.1
	(p,n) exp.[10, 12]	8.3±0.5	10.8	−2.5±0.5	(8 ± 4)

$$S_{\beta-} - S_{\beta+} = \langle i|\, 2T_z \cdot 3\, |i\rangle = 3(N-Z)$$

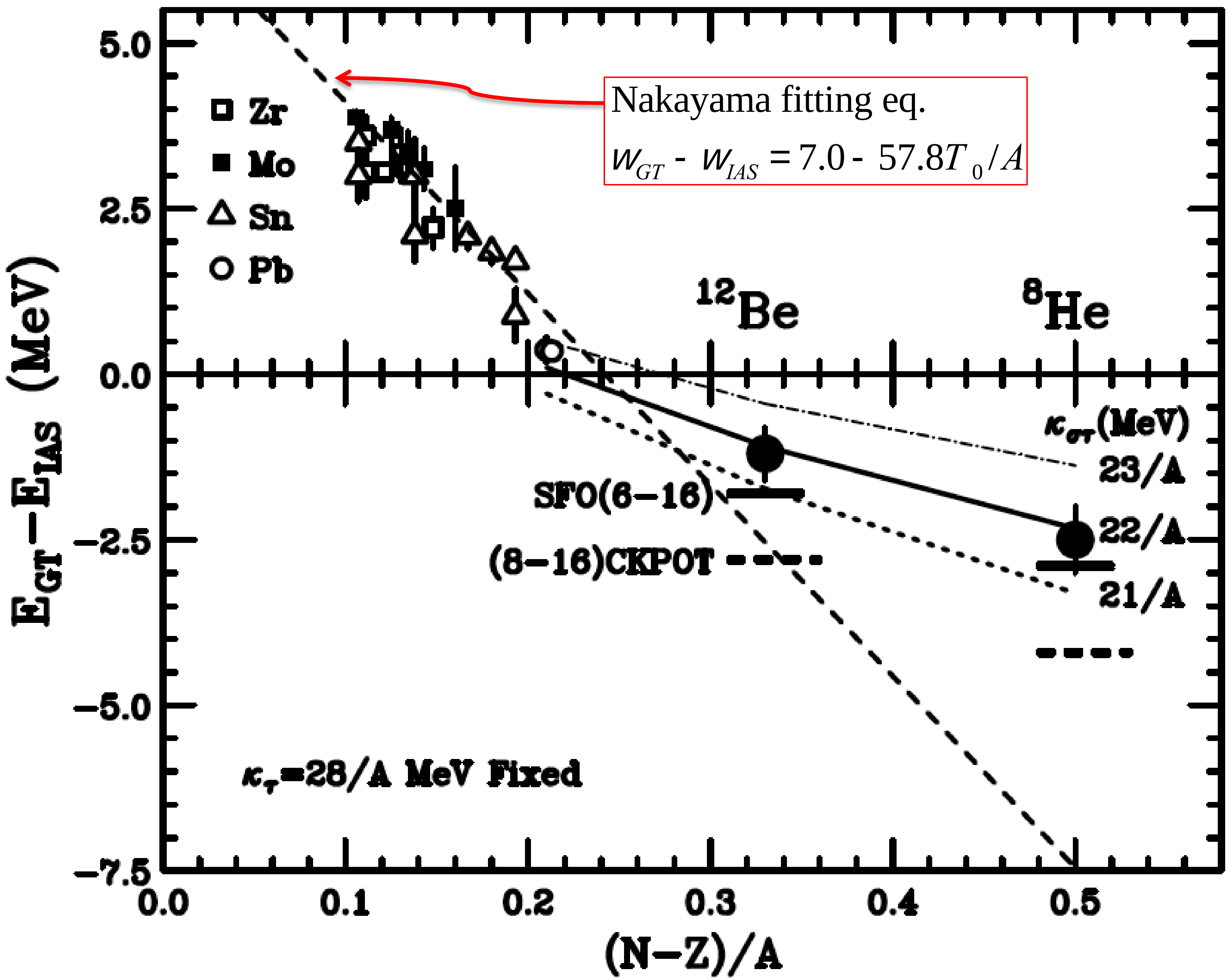
=12 for ^{8}He

Shell model + Nakayama (b)

	^{12}B	$E_{\rm GT}$ (MeV)	$E_{\rm IAS}$ (MeV)	ΔE(MeV)	B(GT)
$0\hbar\omega$	(8-16)POT	11.0	13.8	-2.8	9.3
	(6-16)2BME	12.3	14.4	-2.1	7.4
$(0+2)\hbar\omega$	SFO	11.6	13.8	-2.2	8.9
	WBT'	9.5	13.2	-3.7	6.4
	SFO(6-16)	12.5	14.3	-1.8	8.5
	Eq.(5)[9]	—	—	-2.5	—
	(p,n) exp.[11]	11.5±0.4	12.7	-1.2±0.4	(10 ± 2)

$$S_{\beta-} - S_{\beta+} = \langle i|\, 2T_z \cdot 3\, |i\rangle = 3(N-Z)$$

=12 for ^{12}Be



Nakayama fitting eq.
$w_{GT} - w_{IAS} = 7.0 - 57.8 T_0 / A$
Zr
Mo
Sn
Pb
^{12}Be
^{8}He
$\kappa_{\sigma\tau}$(MeV)
23/A
22/A
21/A
SFO(6−16)
(8−16)CKPOT
κ_{τ}=28/A MeV Fixed
$E_{GT} - E_{IAS}$ (MeV)
(N−Z)/A
5.0
2.5
0.0
−2.5
−5.0
−7.5
0.0
0.1
0.2
0.3
0.4
0.5

Pairing interactions and Spin-Isospin response

T=1 pairing (n-n, p-p pairing correlations) → T=1 superfluidity

- mass (odd-even staggering)
- energy spectra (gap between the first excited state and the ground state in even-even nuclei)
- moment of inertia
- n-n or p-p Pair transfer reactions
- fission barrier (large amplitude collective motion)

T=1 S=0 pairing and T=0 S=1 pairing interactions

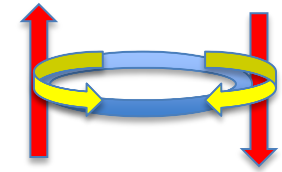
T=1 pairing (n-n, p-p pairing correlations) ➔ T=1 superfluidity

- mass (odd-even staggering)
- energy spectra (gap between the first excited state and the ground state in even-even nuclei
- moment of inertia
- n-n or p-p Pair transfer reactions
- fission barrier (large amplitude collective motion)

T=0 pairing (p-n pairing with S=1) ➔ S=1 superfluidity

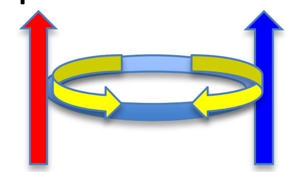
- N=Z Wigner energy (still controversial)
- Energy spectra in nuclei with N=Z (T=0 and $J=J_{max}$)
- n-p pair transfer reaction
- Super-allowed Gamow-Teller transition between SU(4) supermultiples (C.L. Bai et al.)

Two particle systems



T=1, S=0 pair

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



T=0, S=1 pair

$$\left|(L=0,S=1)J=1,T=0\right\rangle \text{Þ}$$

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

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

How we can disentangle in quantum many-body systems.

➔ two kinds of superfluidity?

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)

Low-Energy Collective Gamow-Teller States and Isoscalar Pairing Interaction

C.L. Bai[1)], H. Sagawa[2,3)], G. Colò[4)], Y. Fujita[5,6)], H.Q. Zhang[7,8)], X.Z. Zhang[7)], and F.R. Xu[8)]

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

$$\hat{O}(GT) = st_{\pm}$$

s, t and st are generators of SU(4)

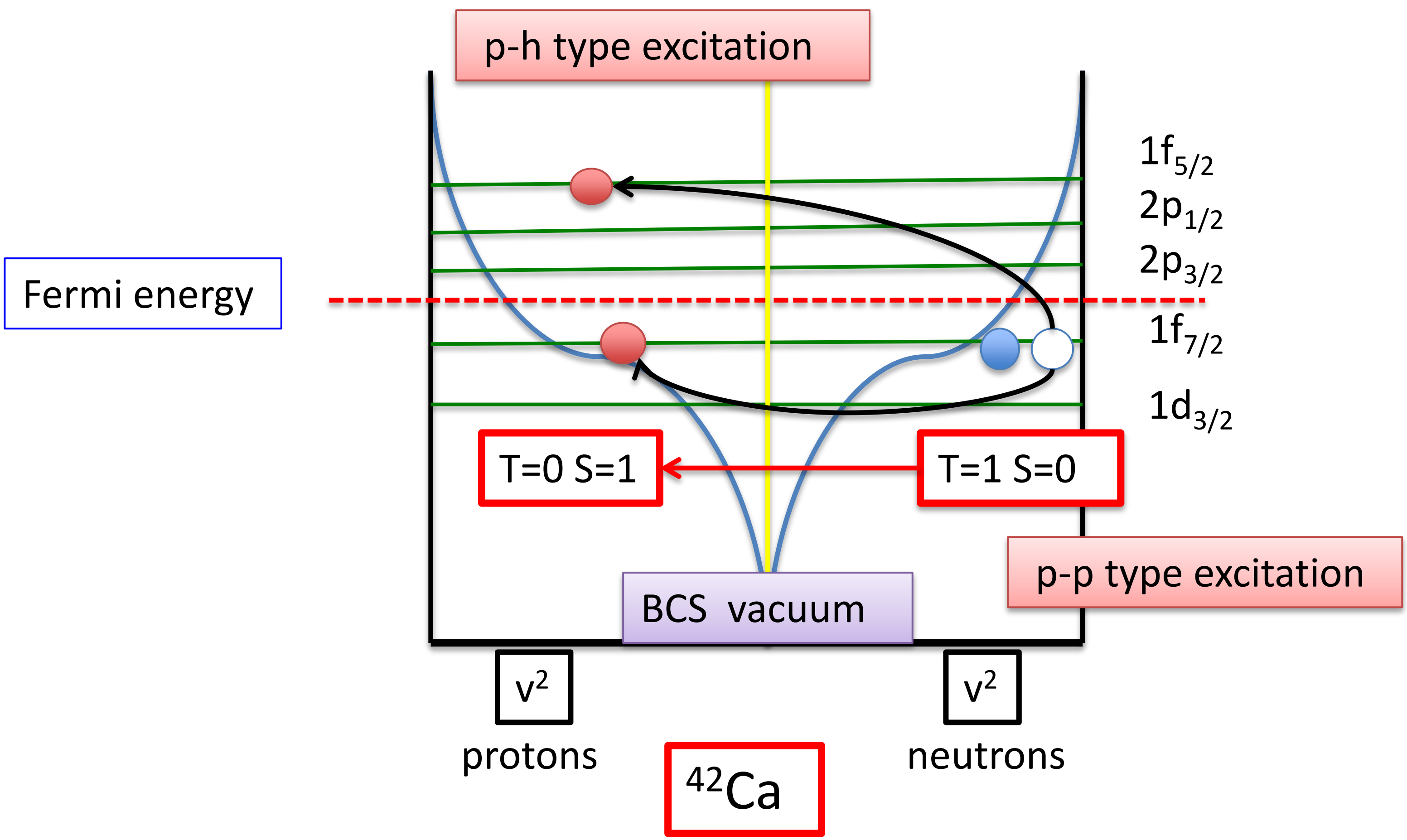
Does Supermultiplet Wigner SU(4) symmetry revive in *pf* shell?
(E. Wigner 1937, F. Hund 1937)
(T=1, S=0) →(T=0, S=1) GT transition is allowed and enhanced .

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

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

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

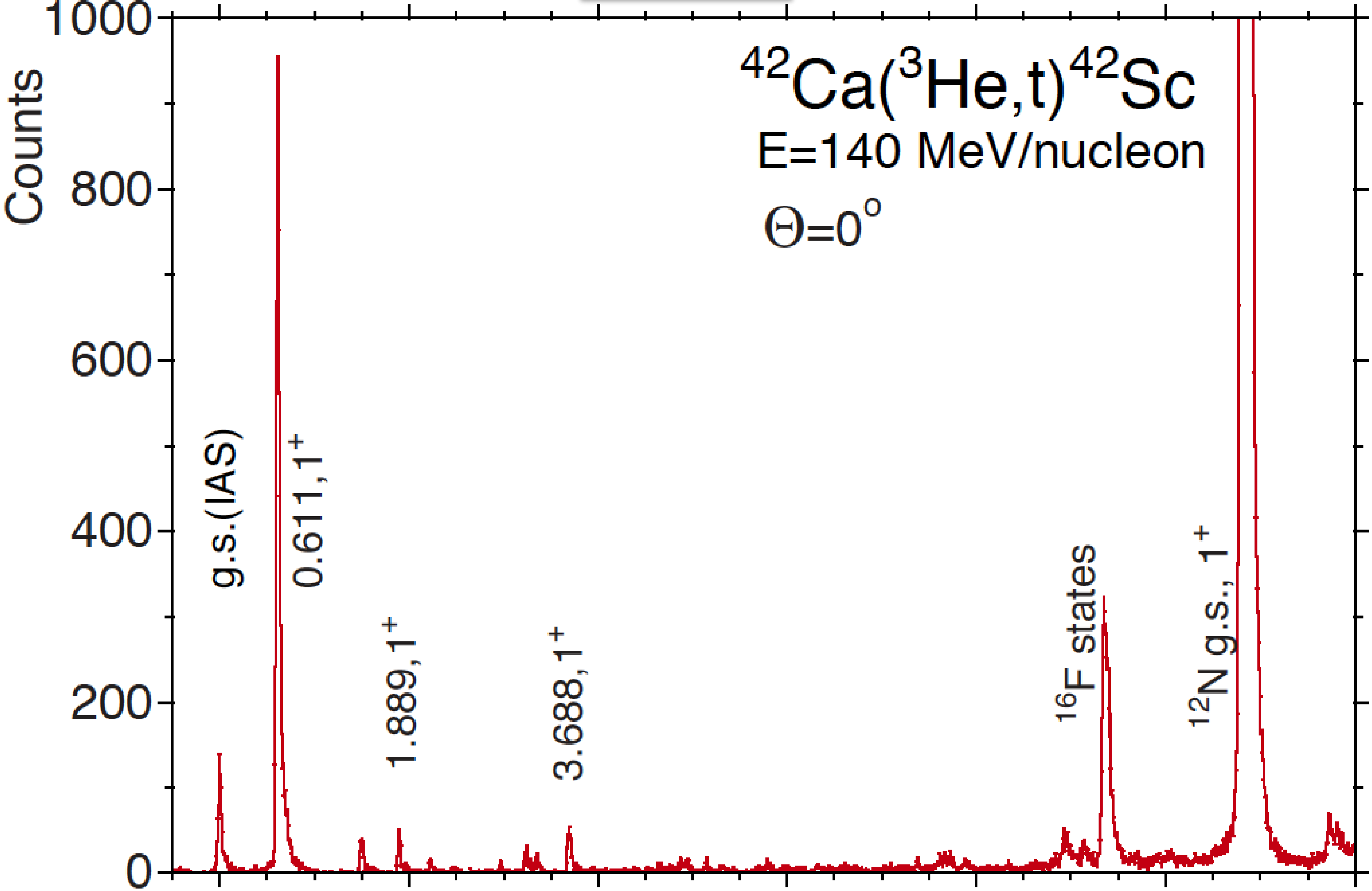
$$\hat{O}(GT) = st_{\pm}$$



Supermultiplet : Wigner SU(4) symmetry

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

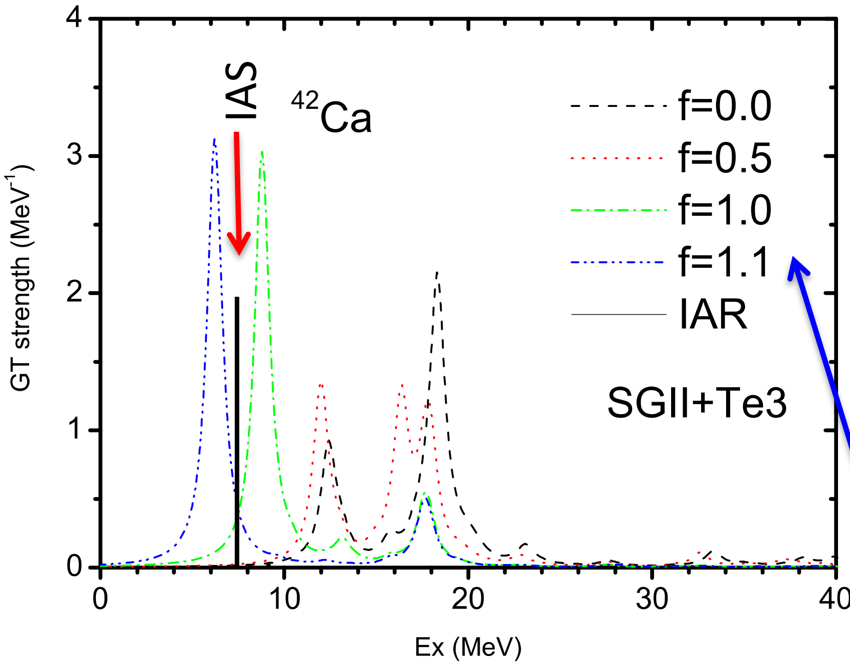
N=Z+2

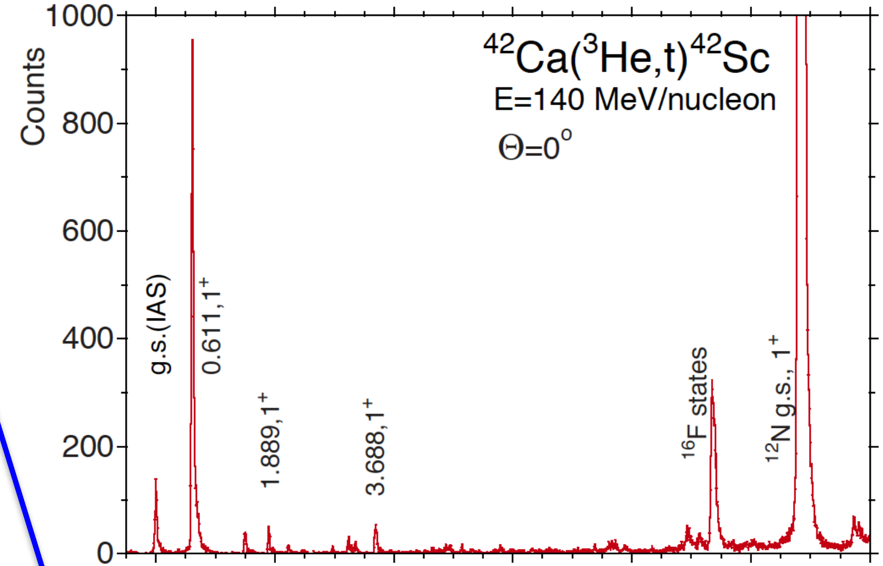


Y. Fujita et al., PRL112, 112502 (2014)

Spin-triplet T=0 pairing is attractive and shift down GT strength near IAS

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

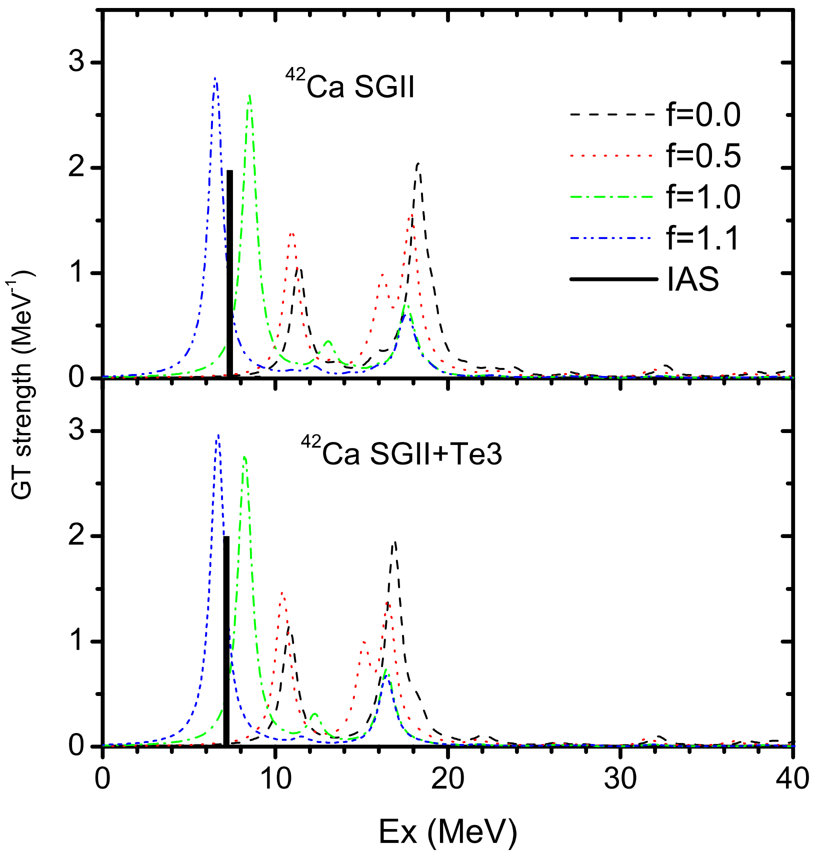




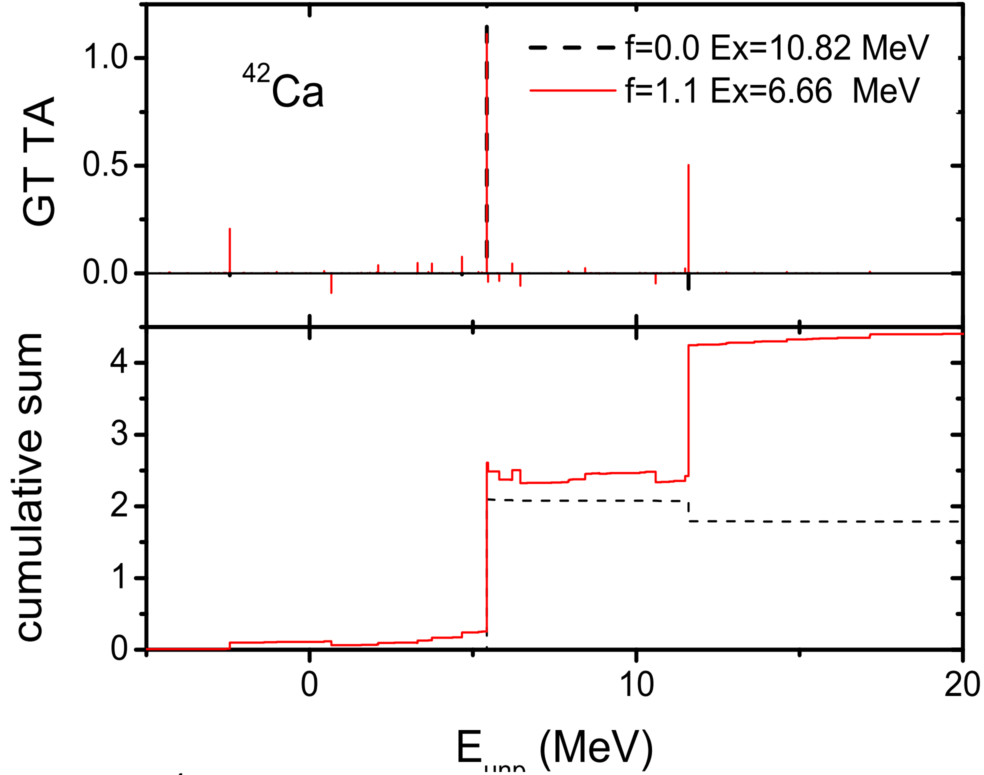
f =IS/IV pairing

C.L. Bai, G. Colo and HS, PRC (2014) in press.

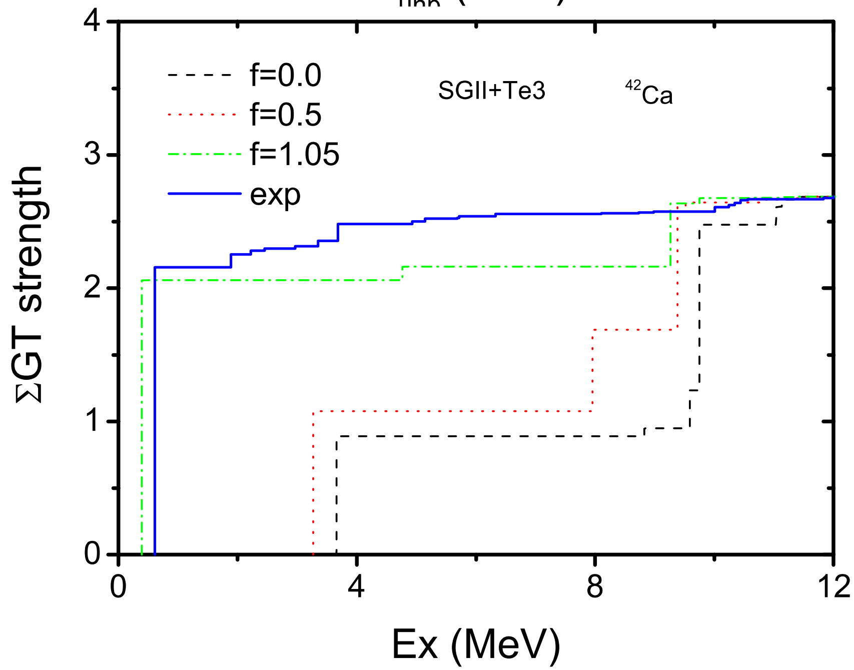
HFB+QRPA with T=1 and T=0 pairing
T=1 pairing in HFB
T=0 pairing in QRPA



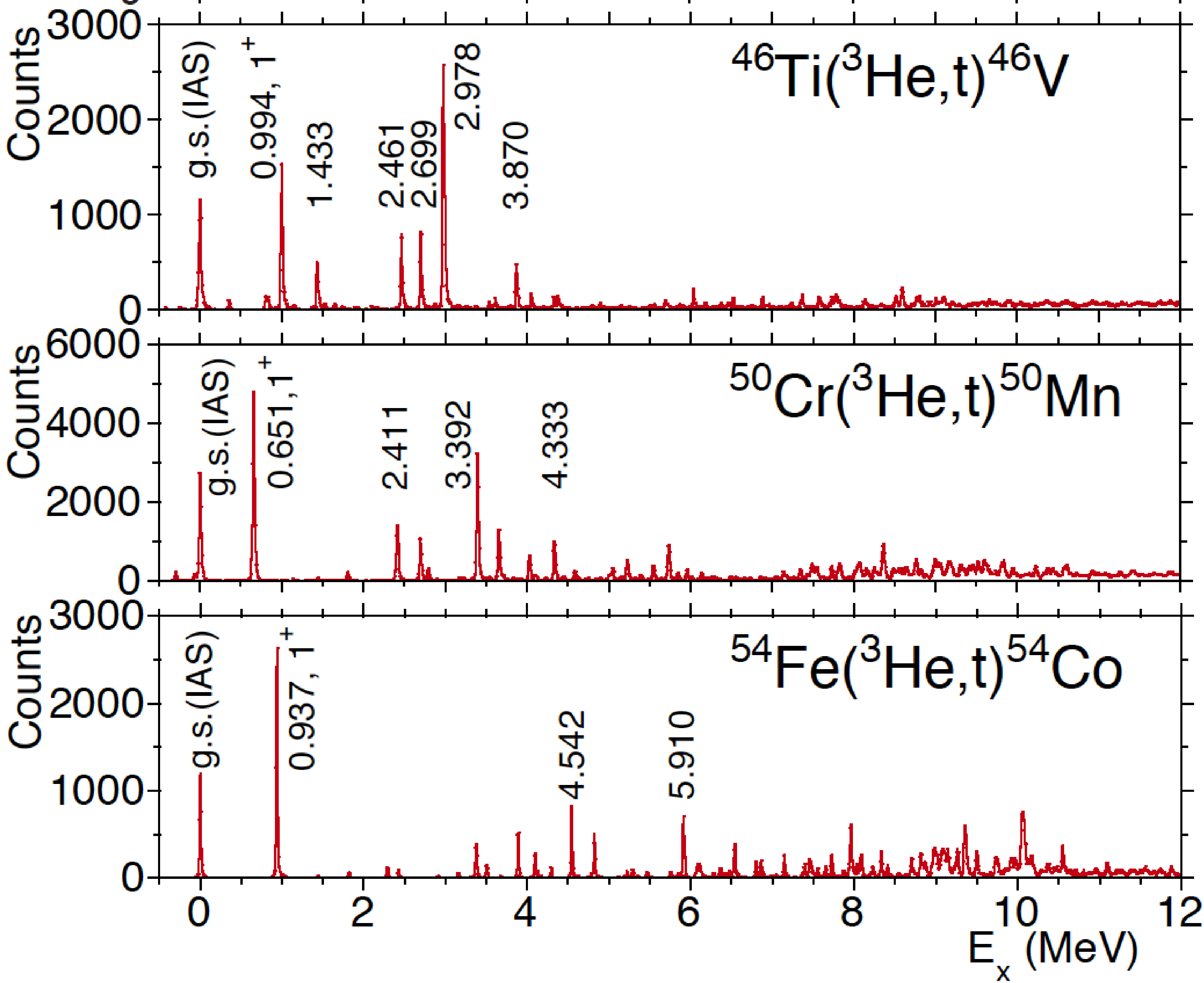
GT strength (MeV⁻¹)
42Ca SGII
f=0.0
f=0.5
f=1.0
f=1.1
IAS
42Ca SGII+Te3
Ex (MeV)



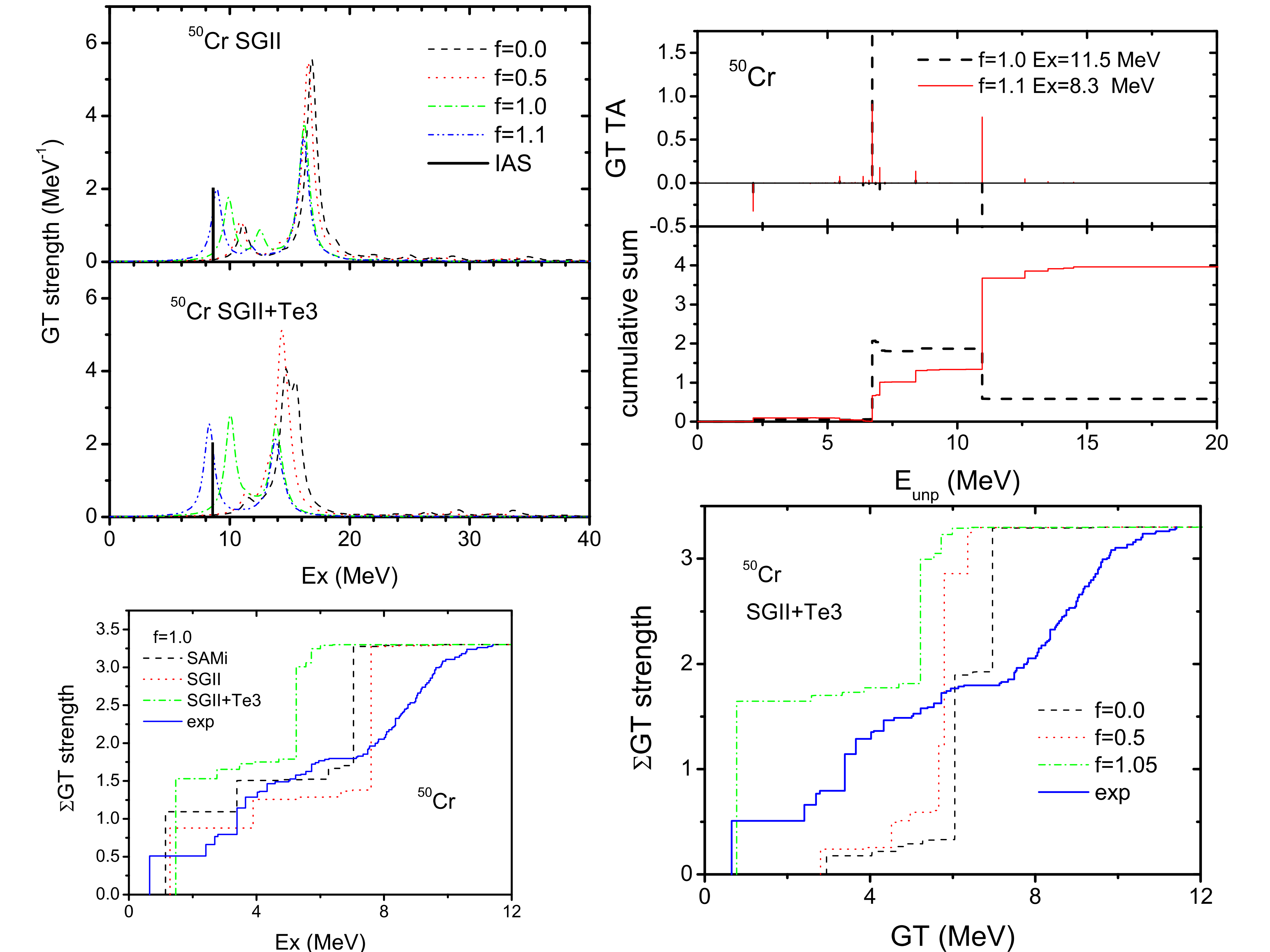
GT TA
42Ca
f=0.0 Ex=10.82 MeV
f=1.1 Ex=6.66 MeV
cumulative sum
Eunp (MeV)



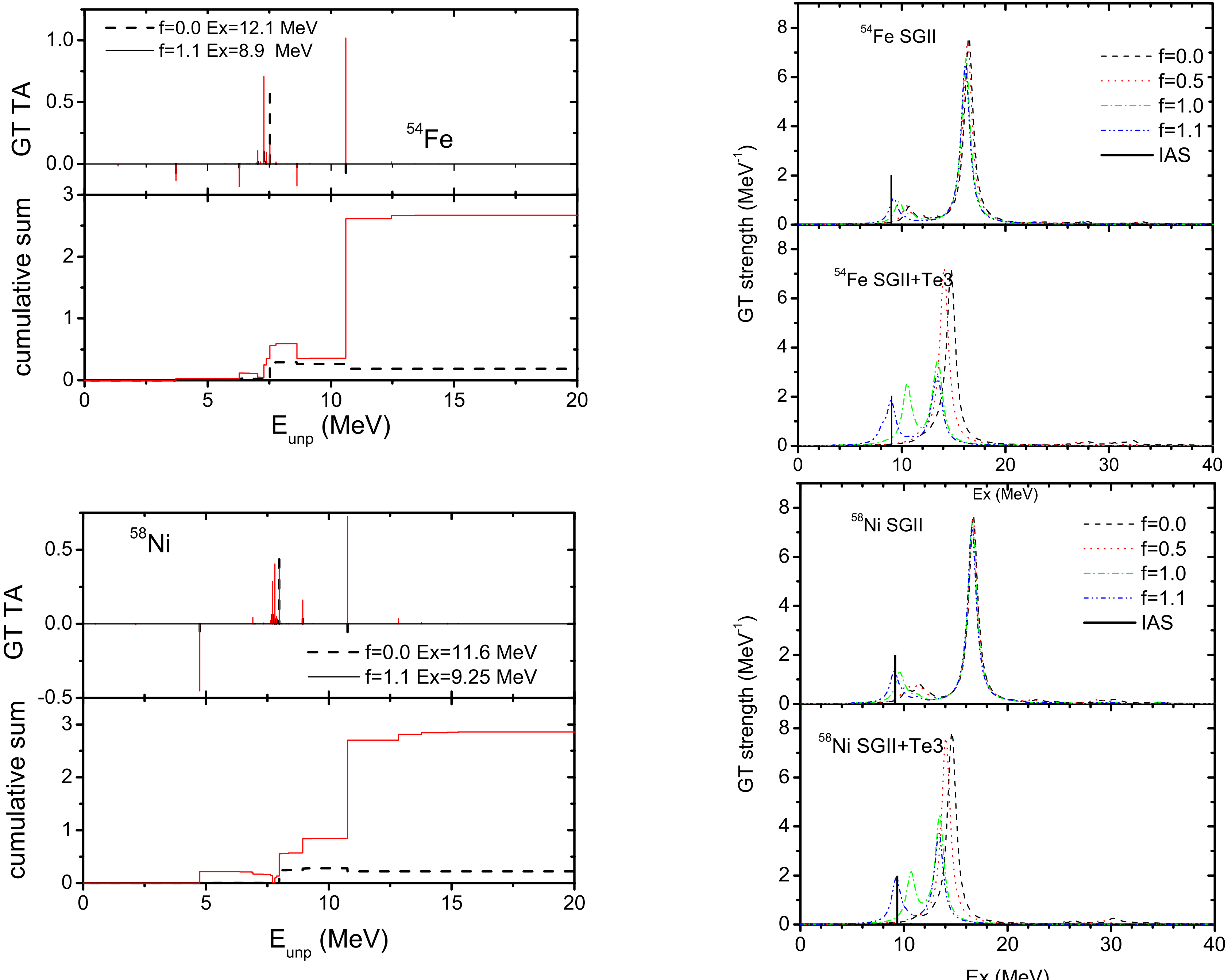
ΣGT strength
f=0.0
f=0.5
f=1.05
exp
SGII+Te3
42Ca
Ex (MeV)



^{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
Counts
E_x (MeV)



50Cr SGII
f=0.0
f=0.5
f=1.0
f=1.1
IAS
50Cr SGII+Te3
GT strength (MeV-1)
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
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
GT strength (MeV-1)
54Fe SGII+Te3
Ex (MeV)
58Ni SGII
58Ni SGII+Te3

Summary

1. Collectivity enhancement in N>>Z nuclei.
2. Role of T=0 pairing is studied in Gamow-Teller transitions of N=Z+2 nuclei .
3. It is pointed out the enhancement of GT strength in the low energy peak just above IAS state is due to the strong T=0 pairing correlations in the final states.

➔ Revive of Supermultiplets of (T=1,S=0) and (T=0 ,S=1) pairs in *pf* shell nuclei

4. A cooperative effect of T=0 pairing and tensor interactions are found in nuclei at the middle of pf shell.
5. 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.
6. Energy spectra and M1 transitions in odd-odd N=Z nuclei show a manifestation of strong T=0 pairing correlations.

Future Perspectives for next few years

Experiment

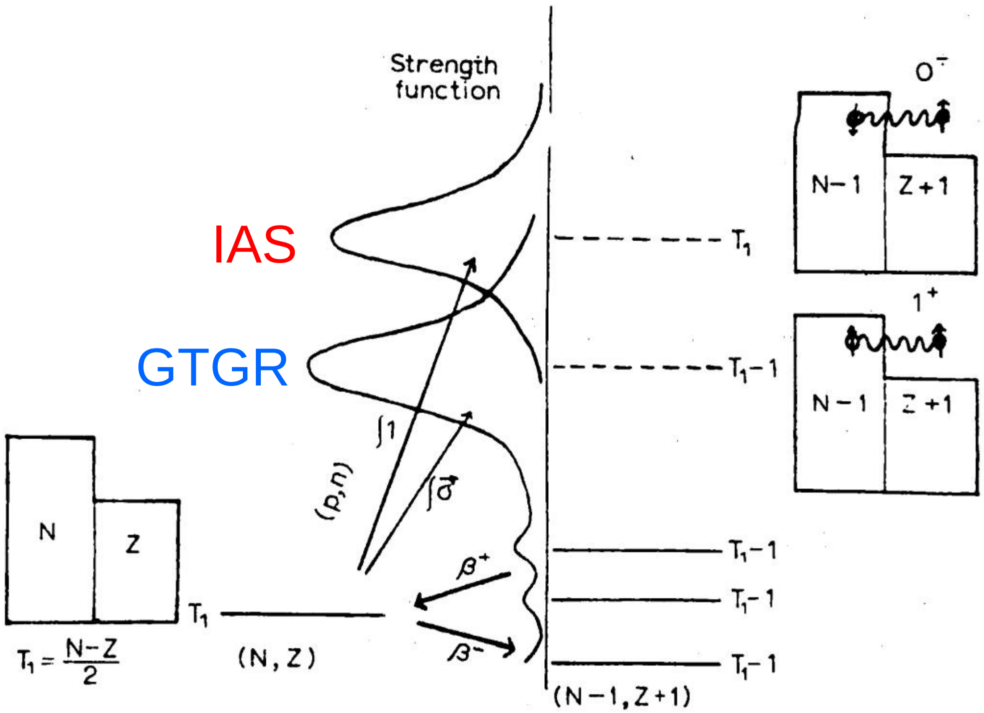
To establish firmly the collectivity in very neutron rich light nuclei, the measurements of GTGR as well as IAS in the neutron drip line nuclei such as ^{14}Be ($(N-Z)/A$=0.429) , ^{20,22}C ($(N-Z)/A$=0.400, 0.455) and ^{24}O ($(N-Z)/A$=0.333) are of highly desired.

Theory

1. What happens on spin-orbit splitting due to the existence of more neutrons ?
2. Coupling to the continuum?
3. Deformation vs. 2hw and 4hw mixings?
4. RPA or shell model (IAS: self consistency is important)

K. Ikeda, S. Fujii and J. I. Fujita: Phys. Lett. 2 (1962) 169, 3 (1963) 271

Existence of Gamow-Teller giant resonance



Anderson and Wong, 1961

$$[H, \boldsymbol{\sigma\tau}] \neq 0$$

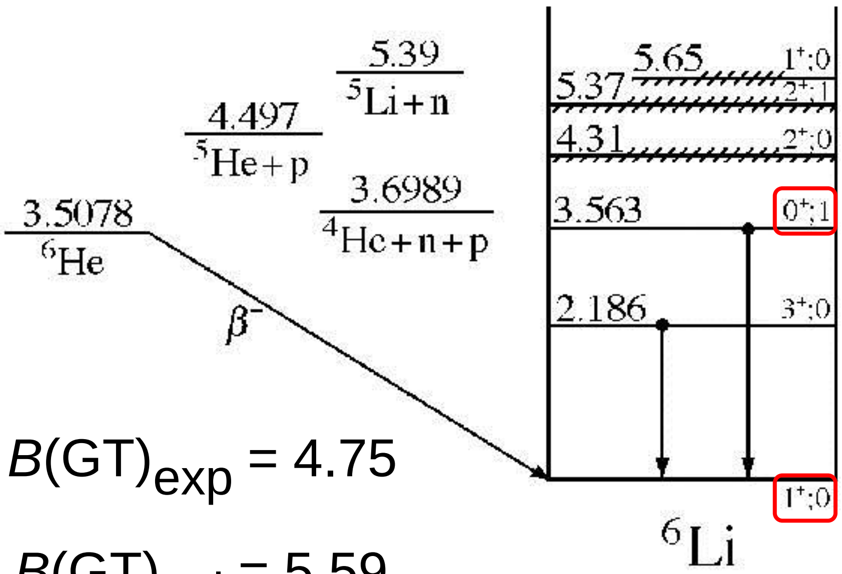
$$[H, T_z] \approx 0$$

IAS is predicted higher than GTGR in energy! Isospin consideration.

Super-allowed transitions

Transitions between states which are well approximated by **Wigner super-multiplet** scheme, and the spatial symmetry is conserved. Both **Fermi** and **Gamow-Teller** transitions

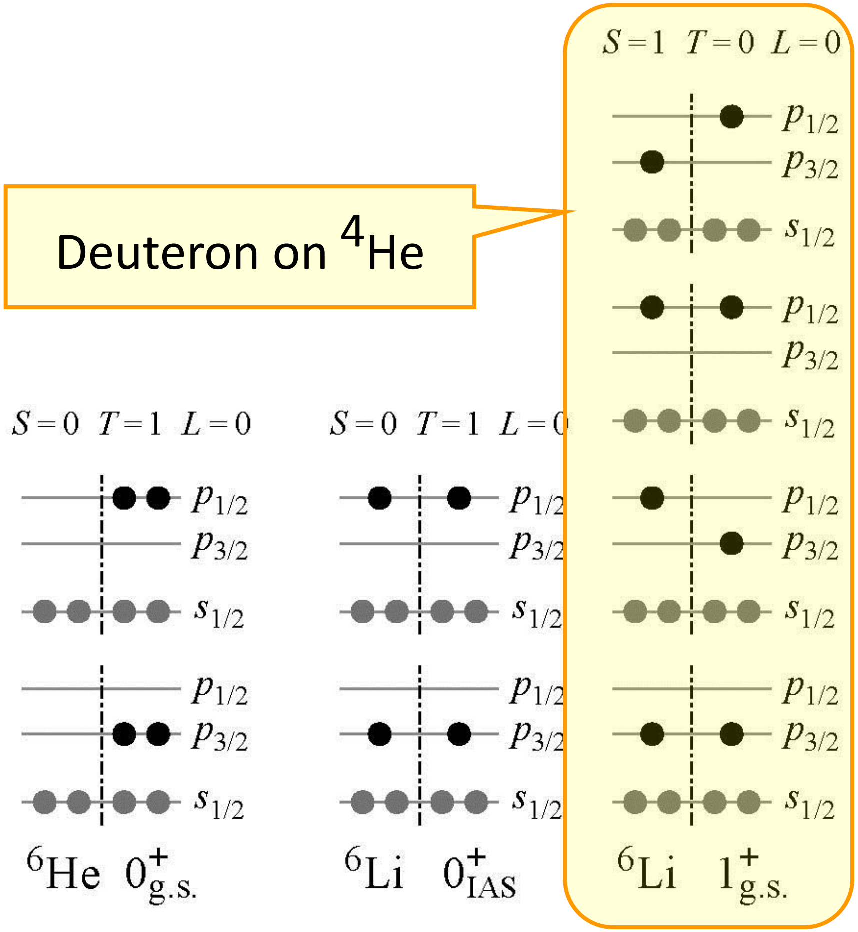
Example : ${}^{6}\mathrm{He} \to {}^{6}\mathrm{Li}$



$B(\mathrm{GT})_{exp} = 4.75$

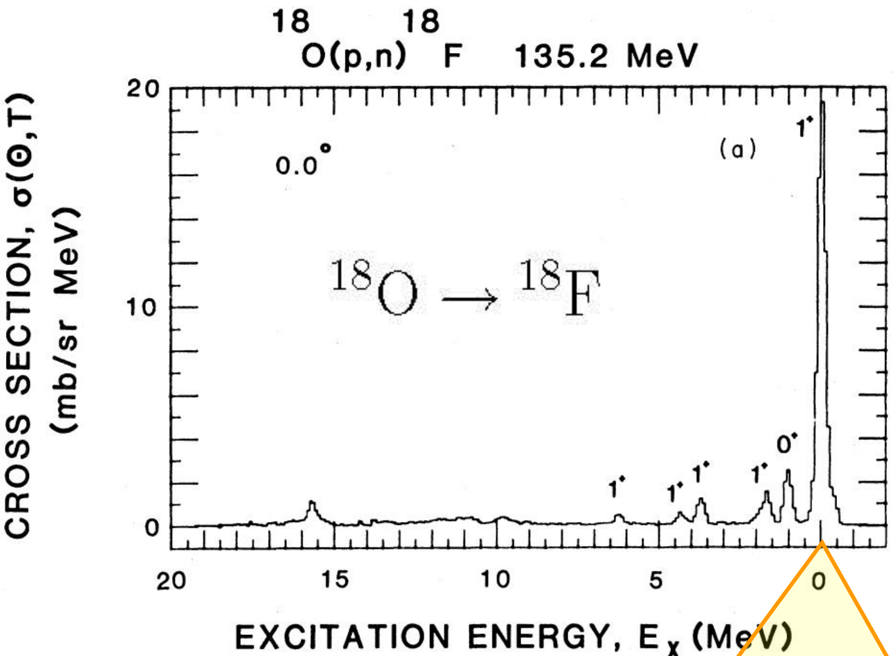
$B(\mathrm{GT})_{cal} = 5.59$

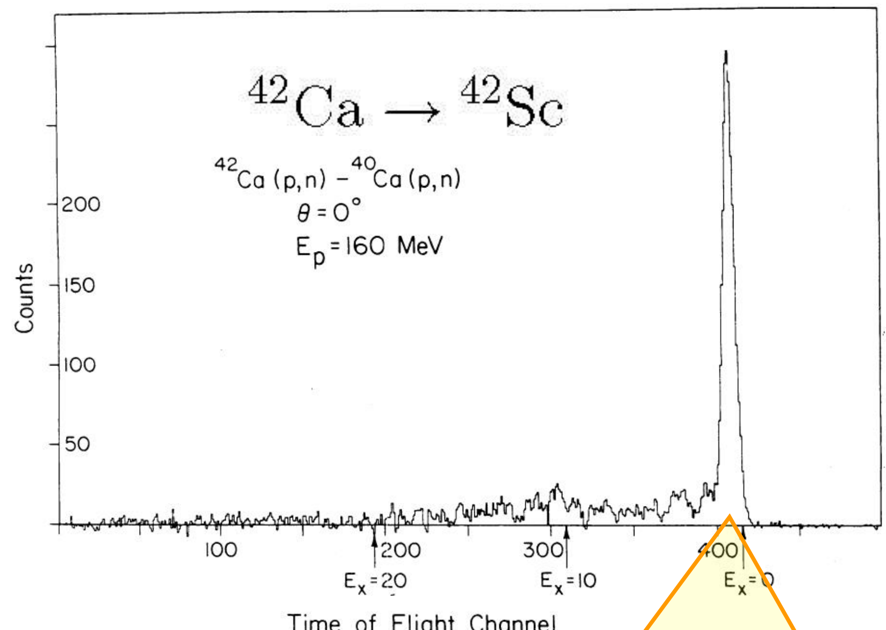
Sum-rule value = 6.00



Other candidates

Target : two neutrons on an *LS*-closed core, sum-rule = 6.00





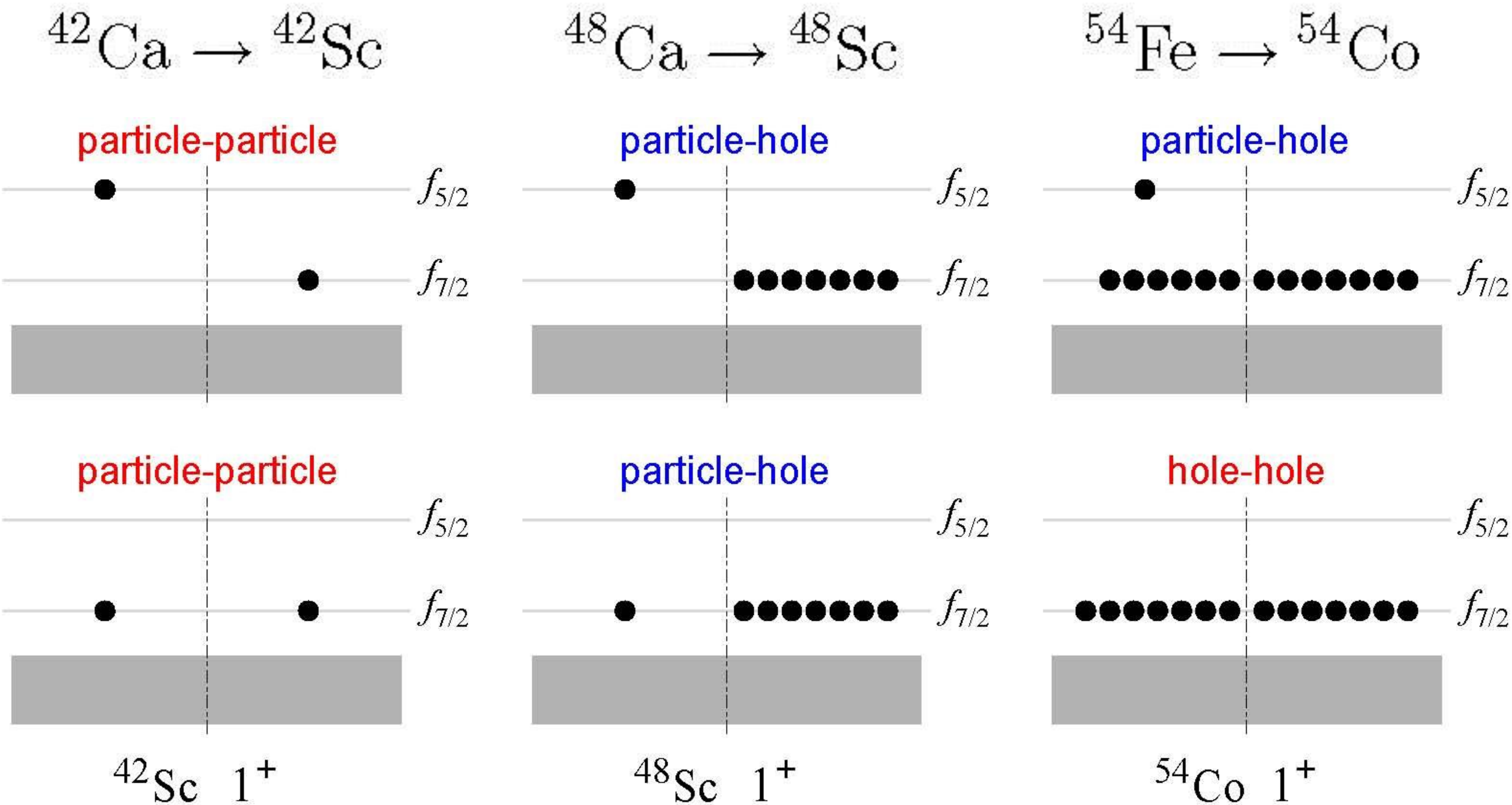
From ^{18}O (*p,n*) ^{18}F
B(GT) = 3.23

From ^{42}Ti (β^+) ^{42}Sc
B(GT) = 2.67

The lowest 1^+ state exhausts about 90% of the observed GT strength.

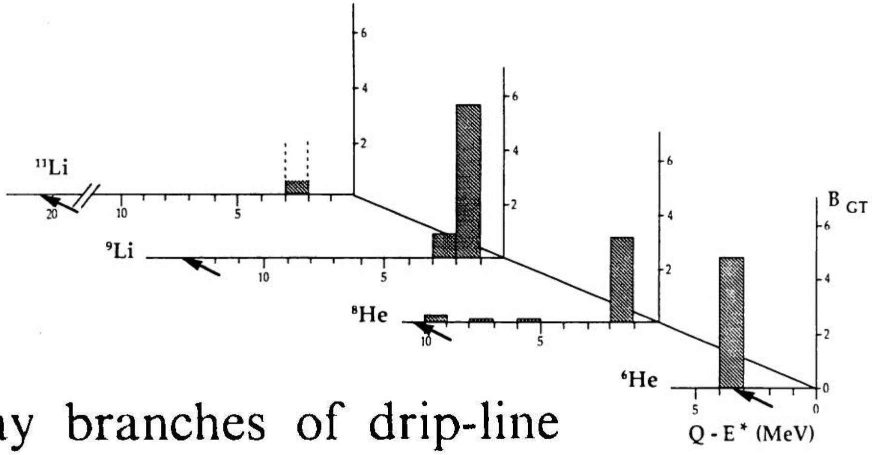
Particle-particle vs particle-hole

Particle-particle (hole-hole) is attractive. Particle-hole is repulsive.



A super-allowed GT transition to a high-lying state?

M.J.G. Borge *et al*. (ISOLDE Collaboration)
Z. Phys. A340 (1991) 255



The Wigner super-multiplet scheme could be good in *p*-shell nuclei.

Table 2. Strong Gamow-Teller beta-decay branches of drip-line nuclei

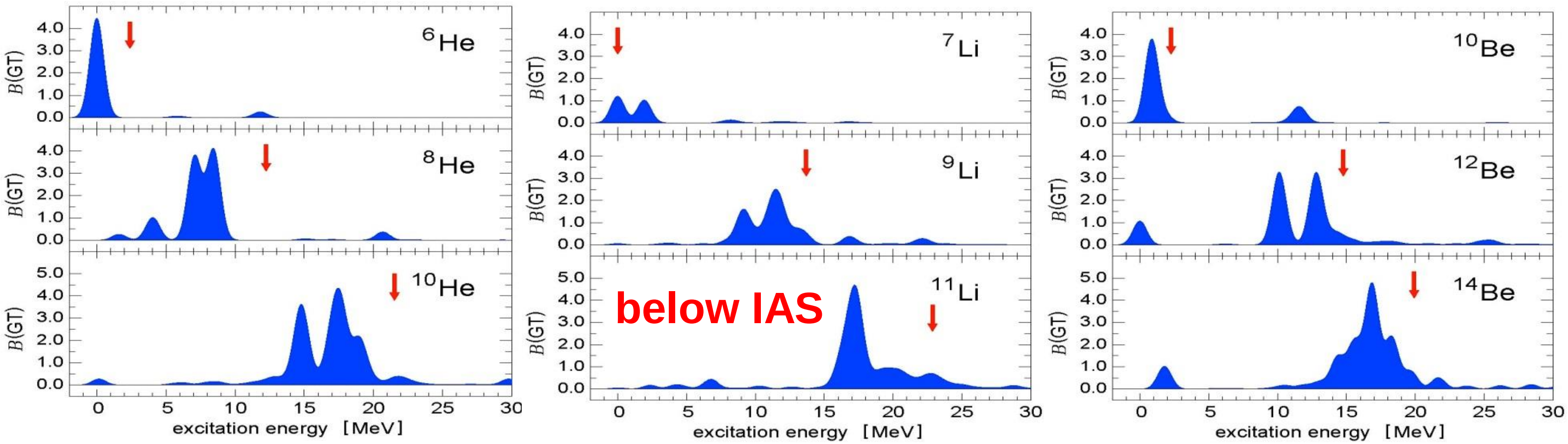
Decay	Level energy (MeV)	Level width (MeV)	Emitted particle	B_{GT}	log ft
$^{6}He \rightarrow {}^{6}Li$	0.0	Stable	–	4.75	2.91
$^{8}He \rightarrow {}^{8}Li$	~ 9	~1	n, t	3.14	3.09
$^{9}Li \rightarrow {}^{9}Be$	11.81	0.40	n, α	5.6	2.84
$^{11}Li \rightarrow {}^{11}Be$[a]	~18.5	~0.5	xn, t	> 0.5	< 4

[a] Only the triton branch is included in the calculation of B_{GT}

SUMMARY

The SU(4) super-multiplet scheme is best realized in *p*-shell nuclei.

Super-allowed GT transitions are expected not only to the lowest state in $N \sim Z$ nuclei but also to high-lying states in neutron-rich nuclei.



Decay	Level energy (MeV)	Level width (MeV)	Emitted particle	B_{GT}	$\log ft$
$^{6}He \rightarrow {}^{6}Li$	0.0	Stable	–	4.75	2.91
$^{8}He \rightarrow {}^{8}Li$	∼ 9	∼1	*n*, *t*	3.14	3.09
$^{9}Li \rightarrow {}^{9}Be$	11.81	0.40	*n*, *α*	5.6	2.84
$^{11}Li \rightarrow {}^{11}Be^{a}$	∼18.5	∼0.5	*xn*, *t*	> 0.5	< 4

Isoscalar Spin-Triplet Pairing correlations and Spin-Isospin Response

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Low-Energy Collective Gamow-Teller States and Isoscalar Pairing Interaction

C.L. Bai[1)], H. Sagawa[2,3)], G. Colò[4)], Y. Fujita[5,6)], H.Q. Zhang[7,8)], X.Z. Zhang[7)], and F.R. Xu[8)]

PRC(2014) in press.

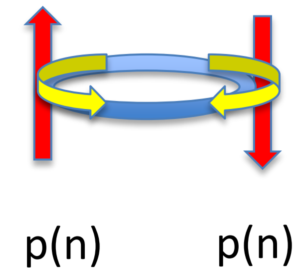
THE UNIVERSITY OF AIZU · to Advance Knowledge for Humanity · 1993

RIKEN NiSHiNA CENTER

T=1 S=0 pairing and T=0 S=1 pairing interactions

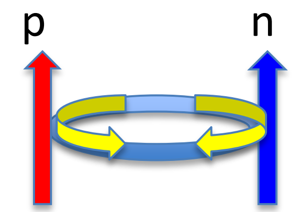
T=1, S=0 pair

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



T=0, S=1 pair

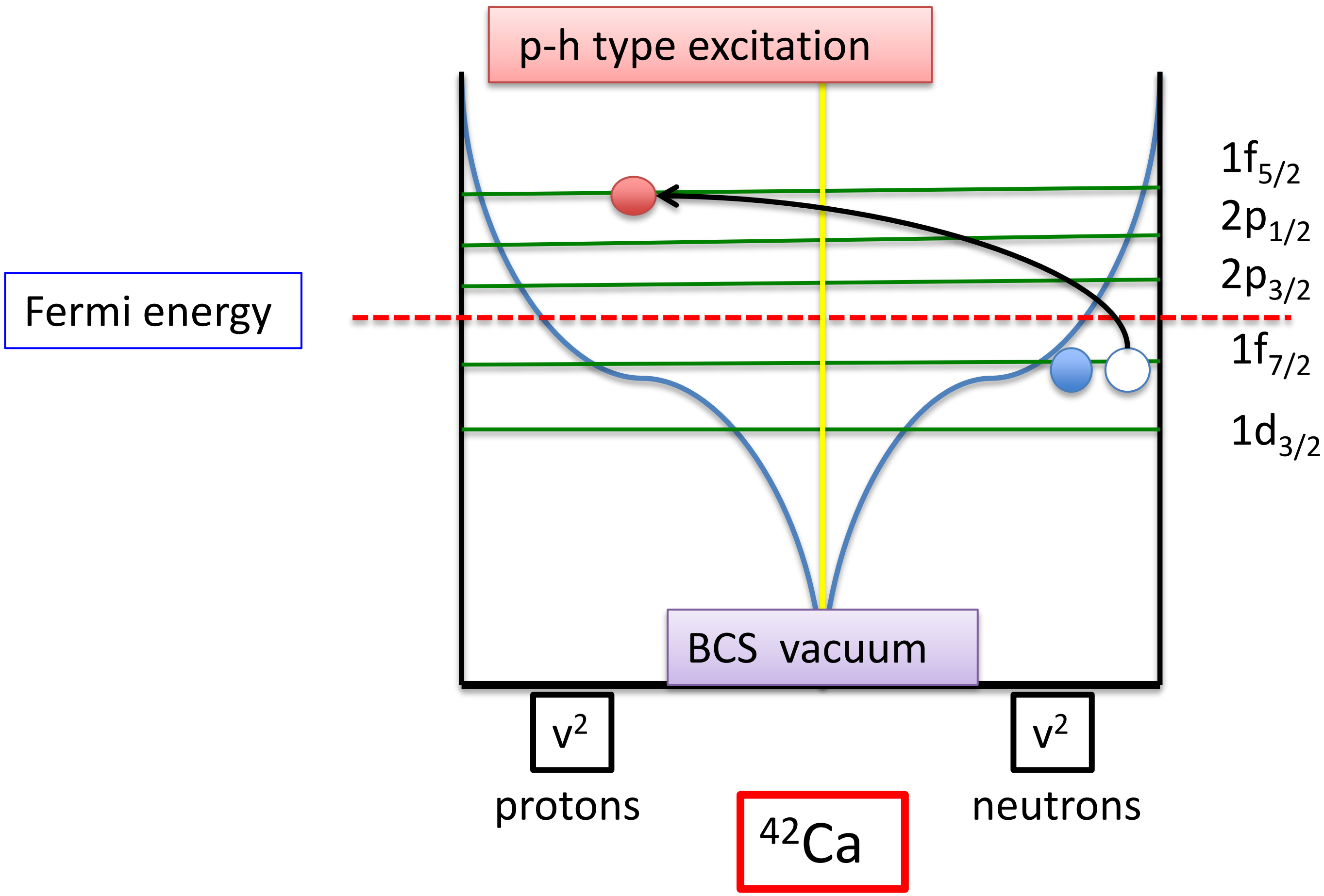
$$\left|(L=0,S=1)J=1,T=0\right\rangle$$ Þ



How we can disentangle in quantum many-body systems.
➔ two kinds of superfluidity?

Gamow-Teller transitions in N=Z+2 nuclei

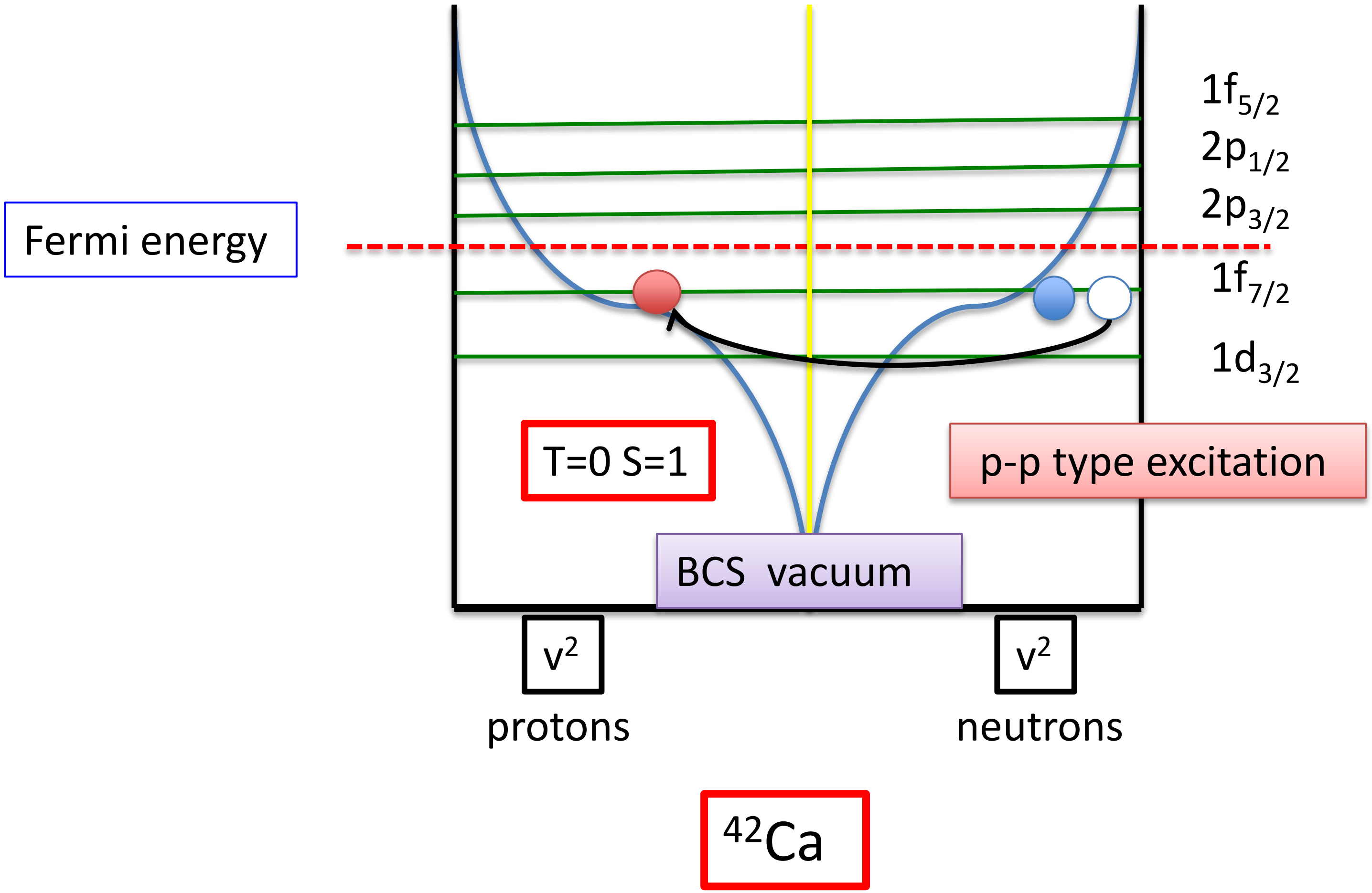
$$\hat{O}(GT) = st_{\pm}$$



Supermultiplet : Wigner SU(4) symmetry

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

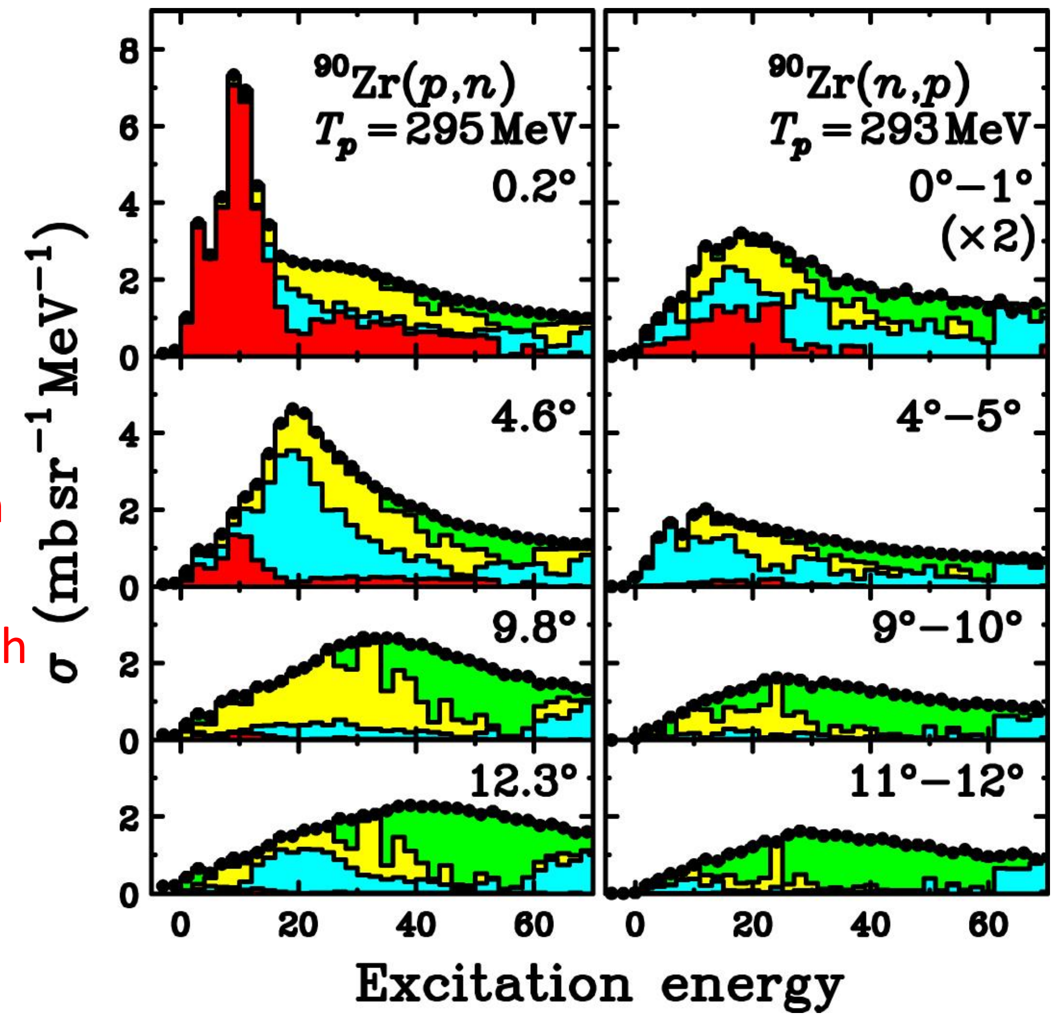
Gamow-Teller transitions in N=Z+2 nuclei



Results of MDA for ^{90}Zr(p,n) & (n,p) at 300 MeV

T. Wakasa et al.,PRC **55**, 2909 (1997) *K.Yako et al.,PLB 615, 193 (2005)*

- Multipole Decomposition (MD) Analyses
  - (p,n)/(n,p) data have been analyzed with the same MD technique
  - (p,n) data have been re-analyzed up to 70 MeV
- Results
  - (p,n)
    - Almost L=0 for GTGR region (No Background)
    - Fairly large L=0 (GT) strength up to 50 MeV excitation
  - (n,p)
    - L=0 strength up to 30MeV



Model-independent sum rule : GT(Ikeda) sum rule

$$S_{\beta-} - S_{\beta+} = \frac{1}{2J_i+1}\sum_f |\langle f\| \sum_{i=1}^{A} t_-(i)\boldsymbol{\sigma}_i \|i\rangle|^2 - \frac{1}{2J_i+1}\sum_f |\langle f\| \sum_{i=1}^{A} t_+(i)\boldsymbol{\sigma}_i \|i\rangle|^2$$

$$= \langle i| \sum_{i,j=1}^{A} (t_+(j)t_-(i) - t_-(i)t_+(j))\, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j |i\rangle$$

$$[t_+(j), t_-(i)] = \delta_{ij}\, 2t_z(i), \qquad \sum_{i=1}^{A} 2t_z(i) = 2T_z \qquad \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_i = 3$$

$$S_{\beta-} - S_{\beta+} = \langle i|\, 2T_z \cdot 3\, |i\rangle = 3(N-Z)$$

=12 for ^{8}He and ^{12}Be

cf: Fermi transition

$$S_{F-} - S_{F+} = \langle i|\, 2T_z\, |i\rangle = N - Z$$