Recent progress in quests of Spin and Spin-isospin excitations

COMEX6, October 29, Cape Town , South Africa

Hiroyuki Sagawa RIKEN/University of Aizu

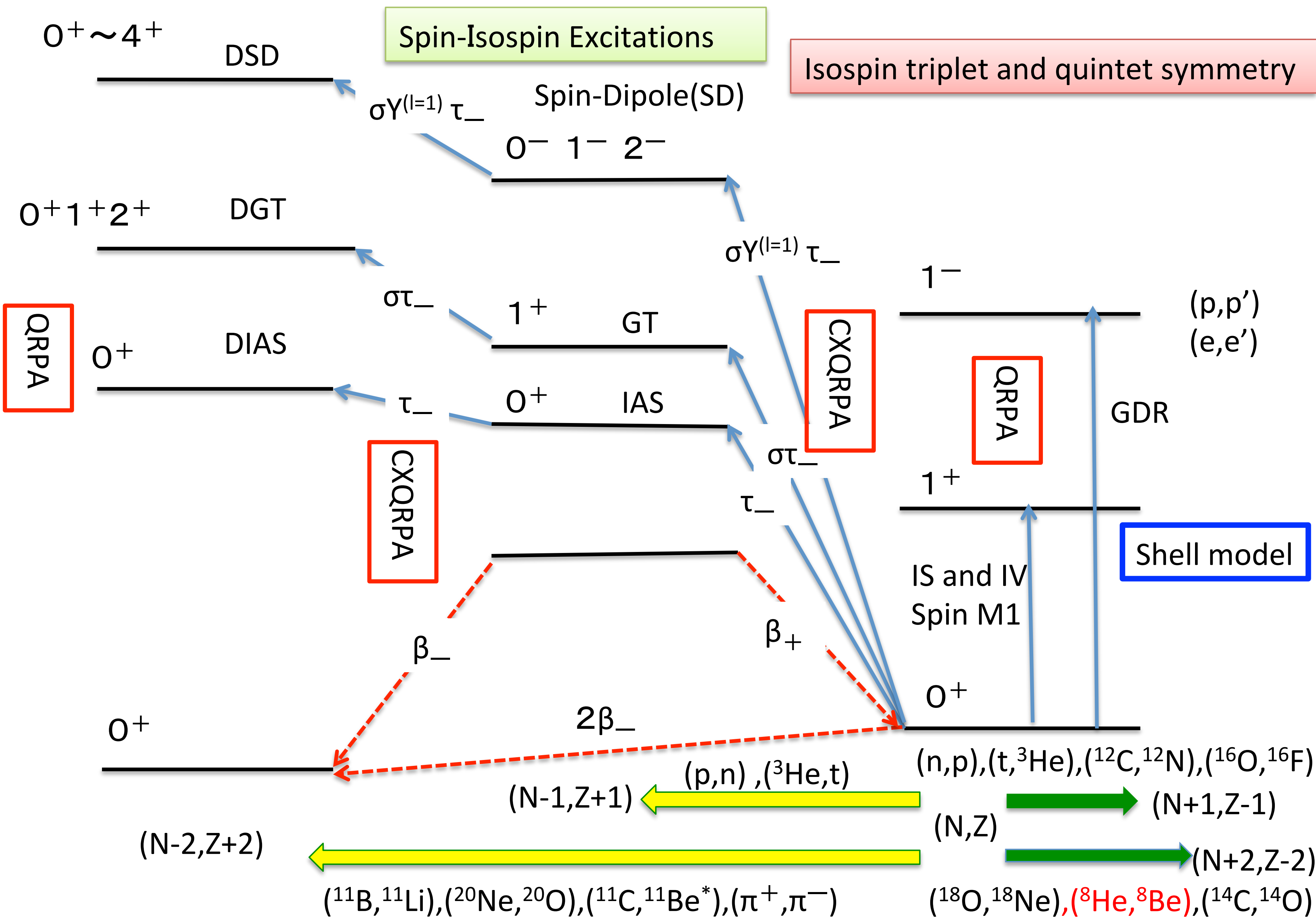
1. Introduction
2. Competitions between IS and IV pairing correlations in N=Z nuclei
   Superfluidity phase: IS spin-triplet pairing interaction
3. Spin and Gamow-Teller transitions from High Spin Isomers
4. Summary and future perspectives

Three dimensions in research of Spin-Isospin modes

- T-> high isospin (radioactive beams),
  isospin Fermisphere
- J-> high spin (isomer beams), spin Fermisphere
- dilute-density (halo, skin)
  -> n-p pair, alpha condensation
- pair transfer reactions (nn, pp, pn)

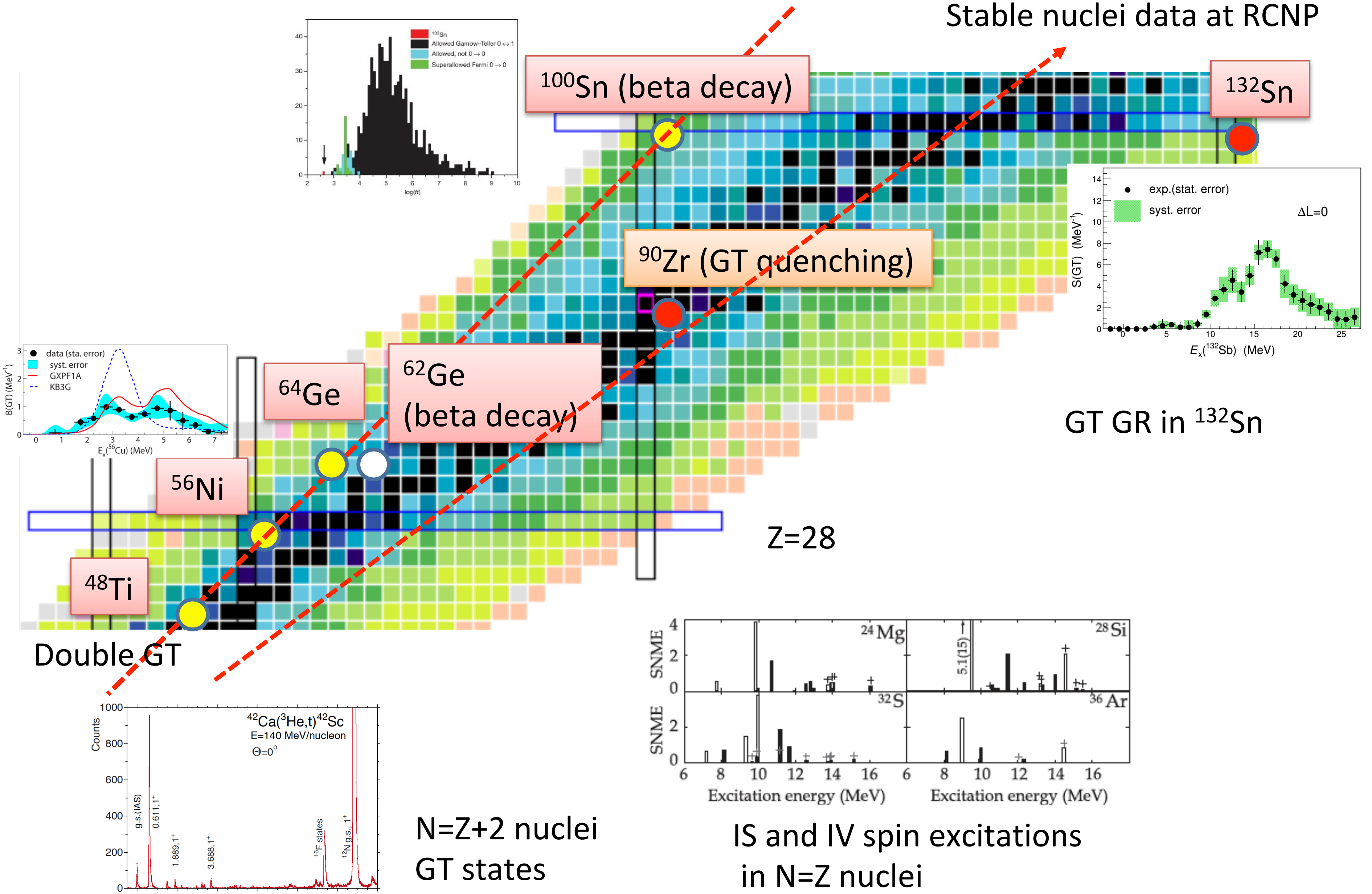
- Charge-exchange reactions (Single and double)
  → spin-isospin responses (GT, SD, DGT, DSD...)

Light ions: (p,n), (n,p),(^{3}He,t),(t,^{3}He)
Heavy ions:(^{11}B,^{11}Li),(^{20}Ne,^{20}O),(^{11}C,^{11}Be*), (^{18}O,^{18}Ne),(^{8}He,^{8}Be),(^{14}C,^{14}O)



Spin-Isospin Excitations
Isospin triplet and quintet symmetry
0+∼4+
DSD
σY(l=1) τ−
Spin-Dipole(SD)
0− 1− 2−
0+1+2+
DGT
σY(l=1) τ−
στ−
1+
GT
1−
(p,p')
(e,e')
QRPA
0+
DIAS
τ−
0+
IAS
CXQRPA
QRPA
GDR
CXQRPA
στ−
τ−
1+
Shell model
IS and IV
Spin M1
β−
β+
0+
2β−
0+
(n,p),(t,3He),(12C,12N),(16O,16F)
(p,n) ,(3He,t)
(N-1,Z+1)
(N+1,Z-1)
(N,Z)
(N-2,Z+2)
(N+2,Z-2)
(11B,11Li),(20Ne,20O),(11C,11Be*),(π+,π−)
(18O,18Ne),(8He,8Be),(14C,14O)

Recent Progresses in spin-isospin excitations

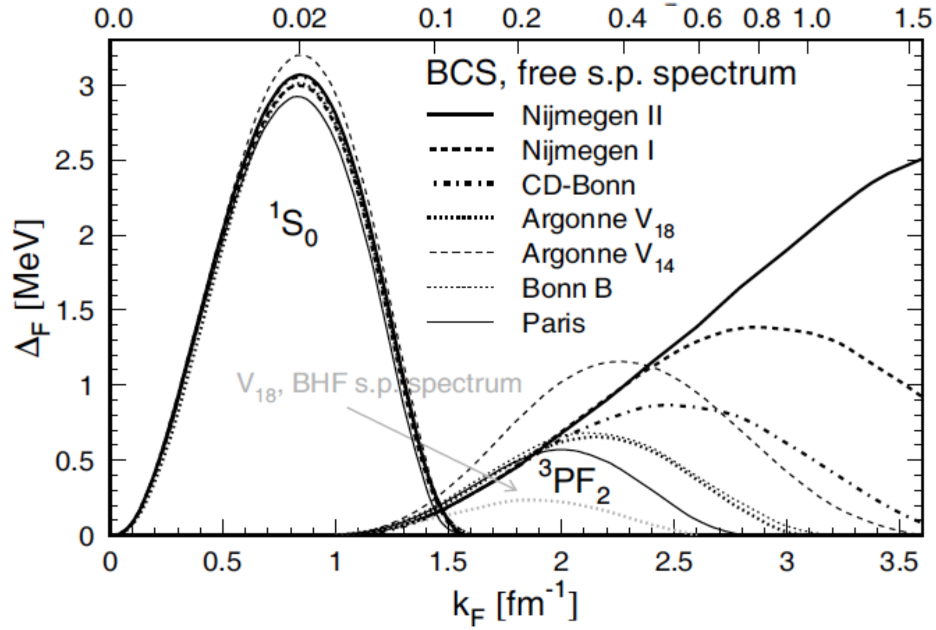


Competition between IS spin-triplet and IV spin-single pairing correlations

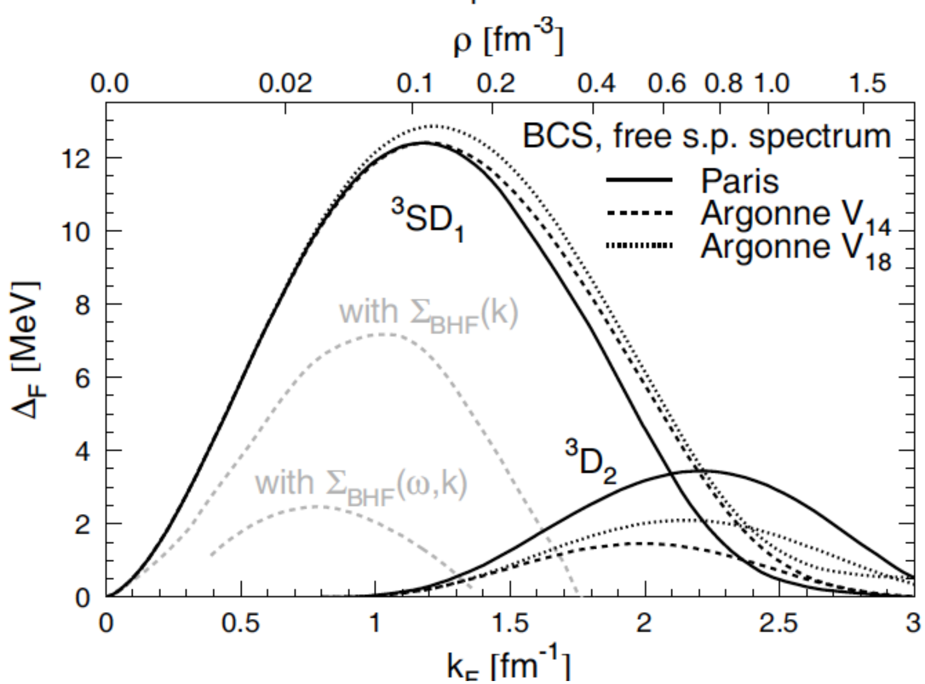
Gamow-Teller transitions in N=Z+2 nuclei

n-p pair condensation in nuclei with N~Z

Isospin $T = 1$ $^1S_0$ and $^3PF_2$ gaps in neutron matter evaluated in BCS approximation



Int. Journ. of Mod. Phys.
E14, 513 (2005)
U. Lombardo et al..



Isospin $T = 0$ $^3SD_1$ and $^3D_2$ gaps in symmetric nuclear matter

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)

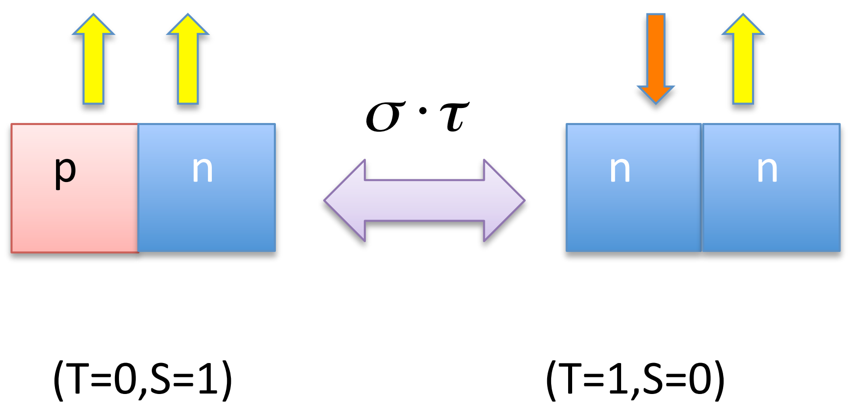
Supermultiplet : Wigner SU(4) symmetry
(E. Wigner 1937, F. Hund 1937)
(T=1, S=0) → (T=0, S=1) GT transition is allowed and enhanced .

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

$$V_{T=0}(\mathbf{r}_1, \mathbf{r}_2) = f V_0 \frac{1 + P_\sigma}{2} \left(1 - \frac{\rho(\mathbf{r})}{\rho_o}\right) \delta(\mathbf{r}_1 - \mathbf{r}_2), \quad (2)$$

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

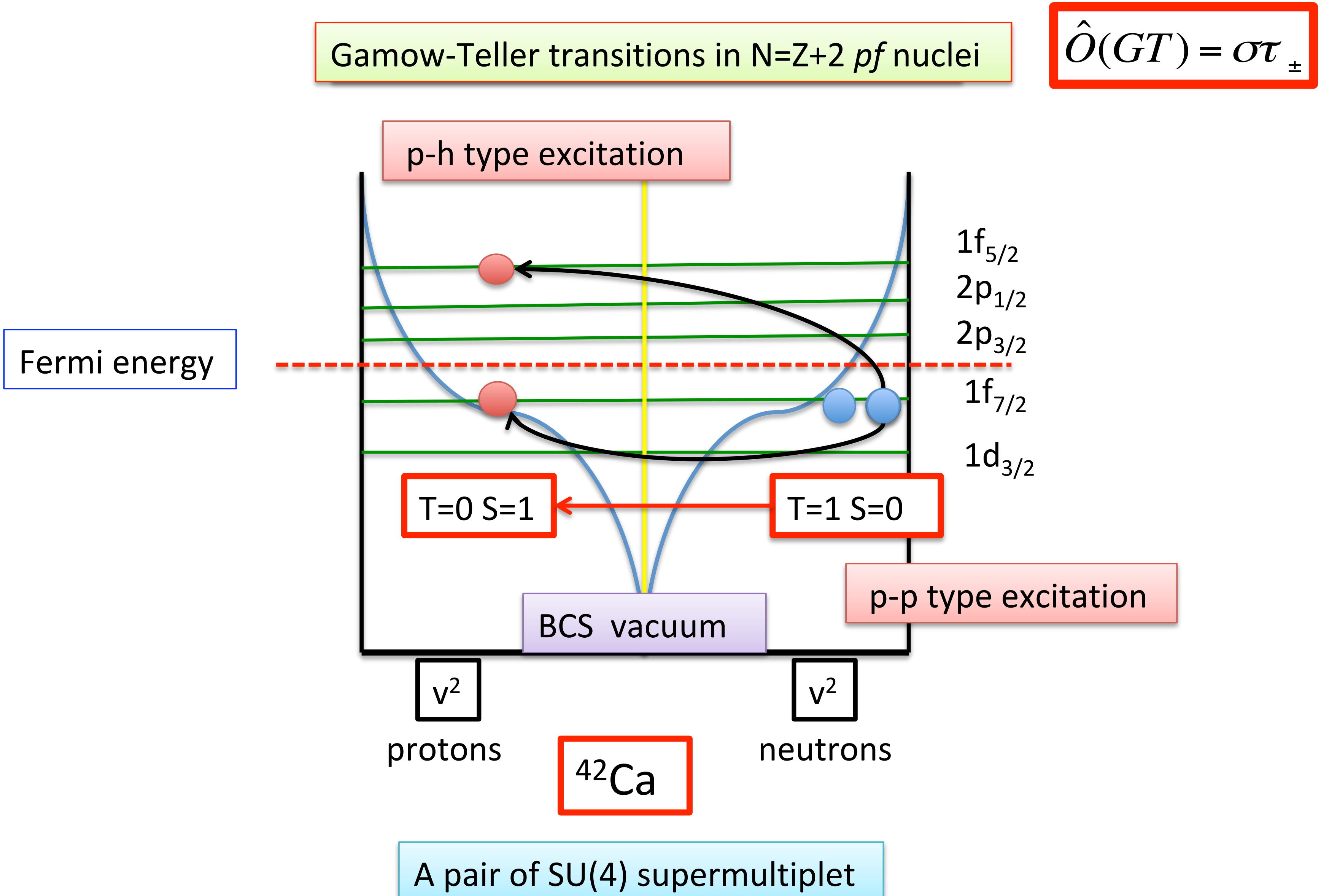
Spacial symmetry is the same between the initial and final states



B(GT)=6

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

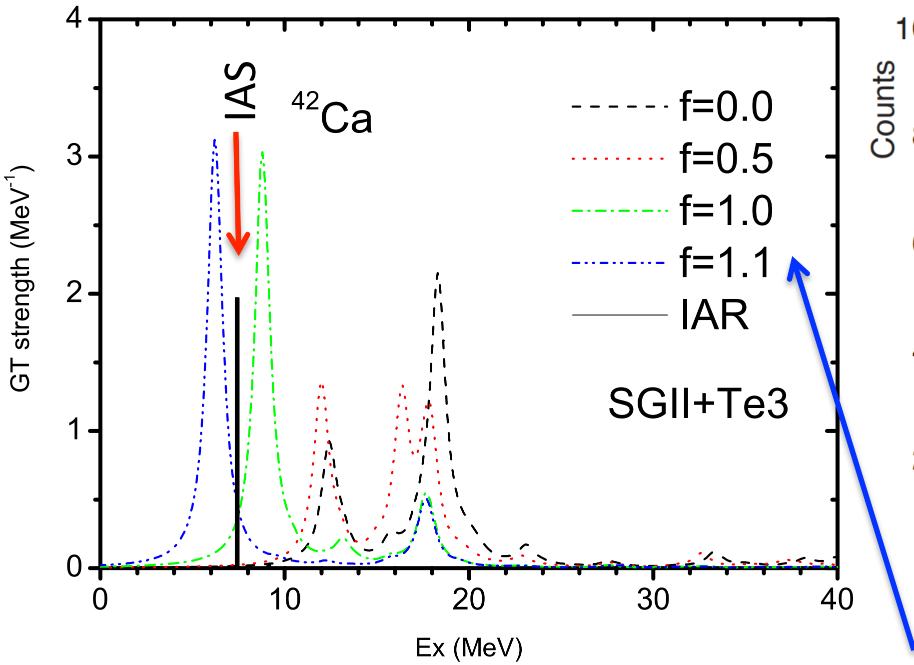
What happens in pf shell nuclei with strong spin-orbit and
spin-triplet pairing interactions?

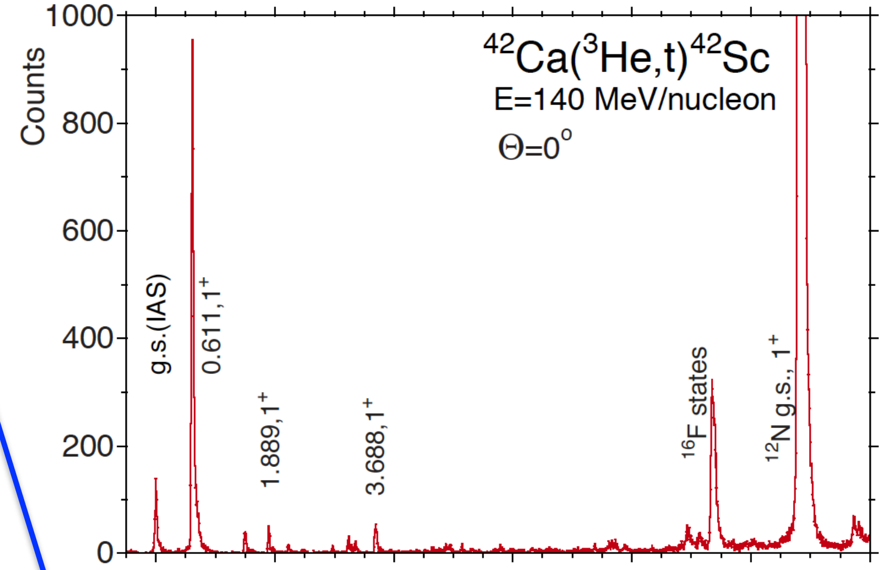


Gamow-Teller transitions in N=Z+2 pf nuclei
$\hat{O}(GT) = \sigma\tau_{\pm}$
p-h type excitation
Fermi energy
$1f_{5/2}$
$2p_{1/2}$
$2p_{3/2}$
$1f_{7/2}$
$1d_{3/2}$
T=0 S=1
T=1 S=0
p-p type excitation
BCS vacuum
v^2
v^2
protons
neutrons
^{42}Ca
A pair of SU(4) supermultiplet

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

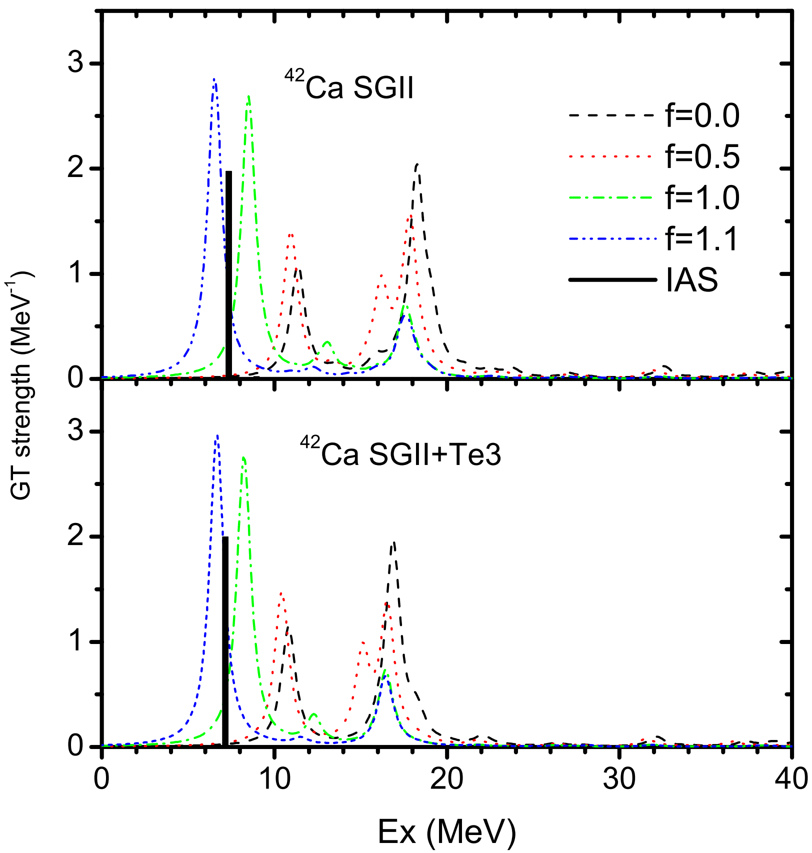


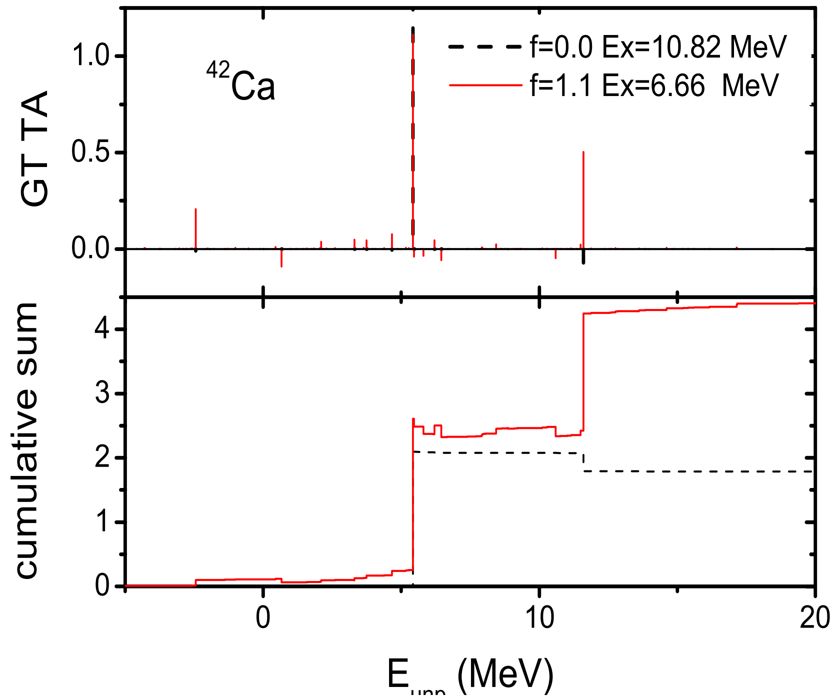


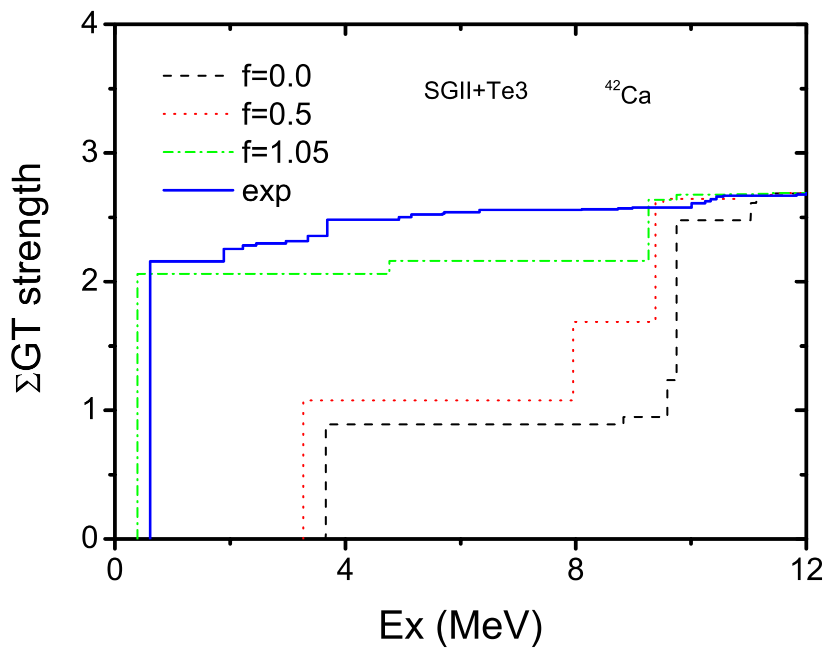
f =IS/IV pairing

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

T=0 pairing strength in QRPA is changed as a parameter f.



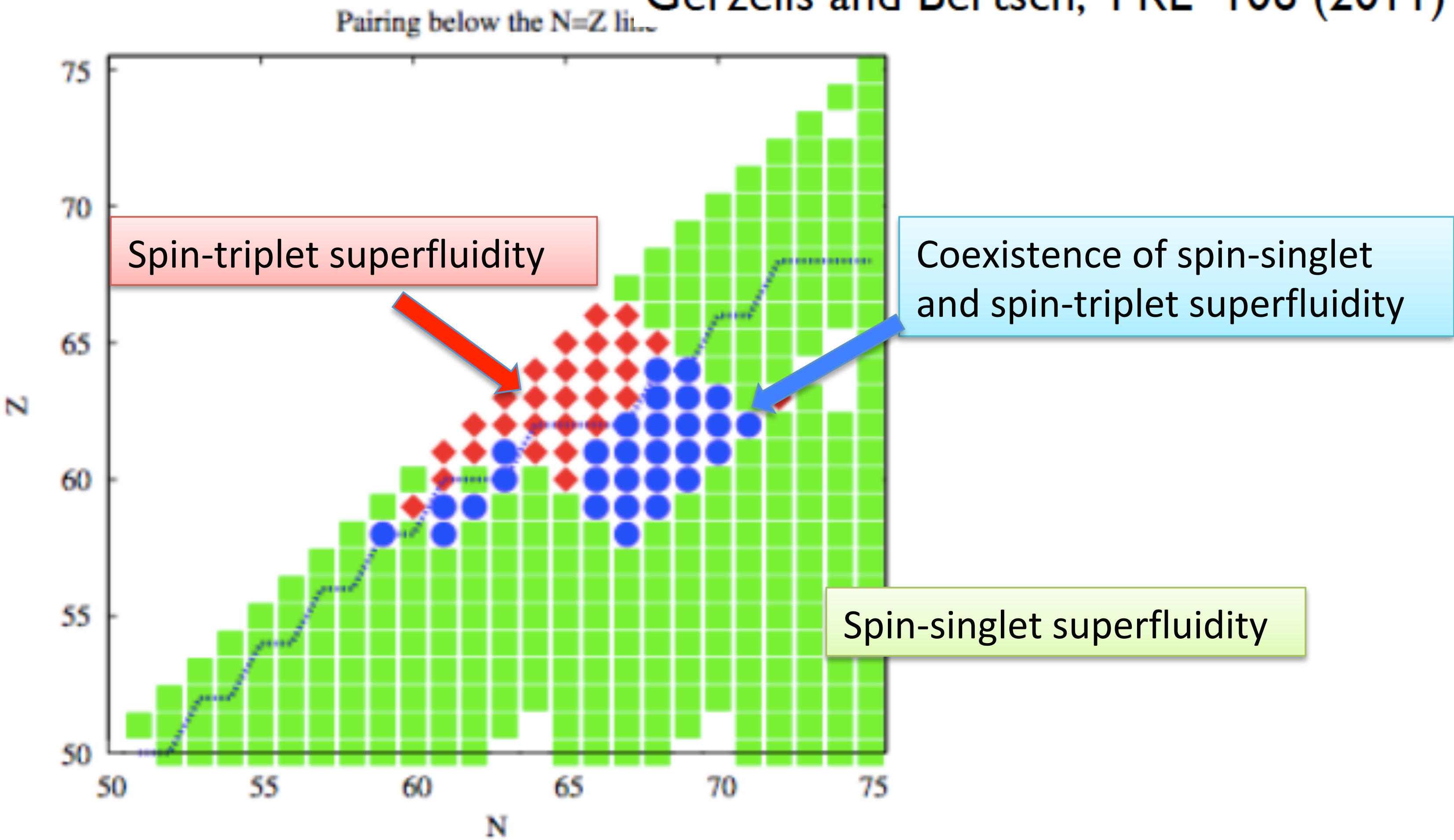




Effect of tensor correlations is small in ^{42}Ca.

Neutron-proton pair condensates

Gerzelis and Bertsch, PRL 106 (2011)



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)

Deformed HFB calculations with a realistic interaction in N=Z nuclei: a competition between T=0 and T=1 pairing interactions

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Eunja Ha, Myung-Ki Cheoun, H. Sagawa, Phys. Rev. C, **97** 024320 (2018).

Eunja Ha, Myung-Ki Cheoun, H. Sagawa, Phys. Rev. C, **97** 064322 (2018).

+preprint (2018)

Deformed HFB with a realistic interaction (CD Bonn)

T=1 channel nn,pp,np
T=0 channel   np

Nuclear Hamiltonian

$$H = H_0 + H_{\rm int} \ ,$$

$$H_0 = \sum_{\rho_\alpha \alpha\alpha'} \epsilon_{\rho_\alpha\alpha\alpha'} c^\dagger_{\rho_\alpha\alpha\alpha'} c_{\rho_\alpha\alpha\alpha'} \quad ,$$

$$H_{\rm int} = \sum_{\rho_\alpha\rho_\beta\rho_\gamma\rho_\delta,\alpha\beta\gamma\delta.\ \alpha'\beta'\gamma'\delta'} V_{\rho_\alpha\alpha\alpha'\rho_\beta\beta\beta'\rho_\gamma\gamma\gamma'\rho_\delta\delta\delta'} c^\dagger_{\rho_\alpha\alpha\alpha'} c^\dagger_{\rho_\beta\beta\beta'} c_{\rho_\delta\delta\delta'} c_{\rho_\gamma\gamma\gamma'} ,$$

HFB transformation

$$a^\dagger_{\rho_\alpha\alpha\alpha''} = \sum_{\rho_\beta\beta\beta'} (u_{\alpha\alpha''\beta\beta'} c^\dagger_{\rho_\beta\beta\beta'} + v_{\alpha\alpha''\beta\beta'} c_{\rho_\beta\bar\beta\beta'}),$$

$$a_{\rho_\alpha\bar\alpha\alpha''} = \sum_{\rho_\beta\beta\beta'} (u_{\bar\alpha\alpha''\bar\beta\beta'} c_{\rho_\beta\bar\beta\beta'} - v_{\bar\alpha\alpha''\bar\beta\beta'} c^\dagger_{\rho_\beta\beta\beta'}). \qquad (6)$$

$\alpha,\beta,\gamma,\delta$: real (bare) s.p. states with Ω

α',β': isospin quantum number (bare) particle (p and n)

α'',β'': isospin of quasi-particle (1 and 2)

ρ_α: sign of Ω, $\pm\Omega$ (angular momentum projection on the symmetry axis)

Deformed BCS transformation

$$a^\dagger_{\rho_\alpha \alpha\alpha''} = \sum_{\rho_\beta \beta\beta'} (u_{\alpha\alpha''\beta\beta'} c^\dagger_{\rho_\beta\beta\beta'} + v_{\alpha\alpha''\beta\beta'} c_{\rho_\beta\bar{\beta}\beta'}),$$

$$a_{\rho_\alpha \bar{\alpha}\alpha''} = \sum_{\rho_\beta \beta\beta'} (u_{\bar{\alpha}\alpha''\bar{\beta}\beta'} c_{\rho_\beta\bar{\beta}\beta'} - v_{\bar{\alpha}\alpha''\bar{\beta}\beta'} c^\dagger_{\rho_\beta\beta\beta'}). \qquad (6)$$

$$\begin{pmatrix} a_1^\dagger \\ a_2^\dagger \\ a_{\bar{1}} \\ a_{\bar{2}} \end{pmatrix}_\alpha = \begin{pmatrix} u_{1p} & u_{1n} & v_{1p} & v_{1n} \\ u_{2p} & u_{2n} & v_{2p} & v_{2n} \\ -v_{1p} & -v_{1n} & u_{1p} & u_{1n} \\ -v_{2p} & -v_{2n} & u_{2p} & u_{2n} \end{pmatrix}_\alpha \begin{pmatrix} c_p^\dagger \\ c_n^\dagger \\ c_{\bar{p}} \\ c_{\bar{n}} \end{pmatrix}_\alpha ,$$

where the u and v coefficients are calculated by the following DBCS equation

$$\begin{pmatrix} \epsilon_p - \lambda_p & 0 & \Delta_{p\bar{p}} & \Delta_{p\bar{n}} \\ 0 & \epsilon_n - \lambda_n & \Delta_{n\bar{p}} & \Delta_{n\bar{n}} \\ \Delta_{p\bar{p}} & \Delta_{p\bar{n}} & -\epsilon_p + \lambda_p & 0 \\ \Delta_{n\bar{p}} & \Delta_{n\bar{n}} & 0 & -\epsilon_n + \lambda_n \end{pmatrix}_\alpha \begin{pmatrix} u_{\alpha''p} \\ u_{\alpha''n} \\ v_{\alpha''p} \\ v_{\alpha''n} \end{pmatrix}_\alpha = E_{\alpha\alpha''} \begin{pmatrix} u_{\alpha''p} \\ u_{\alpha''n} \\ v_{\alpha''p} \\ v_{\alpha''n} \end{pmatrix}_\alpha .$$

Pairing Gaps

$$\Delta_{nn}, \Delta_{pp} : \text{ real}$$

$$\Delta_{np} : \text{ complex}$$

$$\Delta_{p\bar{p}_\alpha} = \Delta_{\alpha p \bar{\alpha} p} = -\sum_{J,c,d} g_{\rm pp} F^{J0}_{\alpha a \bar{\alpha} a} F^{J0}_{\gamma c \bar{\delta} c} G(aacd, J, T=1)(u^*_{1p_c} v_{1p_d} + u^*_{2p_c} v_{2p_d}) \ ,$$

$$\Delta_{p\bar{n}_\alpha} = \Delta_{\alpha p \bar{\alpha} n} = -\sum_{J,c,d} g_{\rm np} F^{J0}_{\alpha a \bar{\alpha} a} F^{J0}_{\gamma c \bar{\delta} c} [G(aacd, J, T=1) Re(u^*_{1n_c} v_{1p_d} + u^*_{2n_c} v_{2p_d}) + iG(aacd, J, T=0) Im(u^*_{1n_c} v_{1p_d} + u^*_{2n_c} v_{2p_d})] \ ,$$

We do not include

Δ_{np} and $\Delta_{\overline{np}}$ explicitly, but include implicitly multiplying a factor 2 on the T=0 pairing matrix

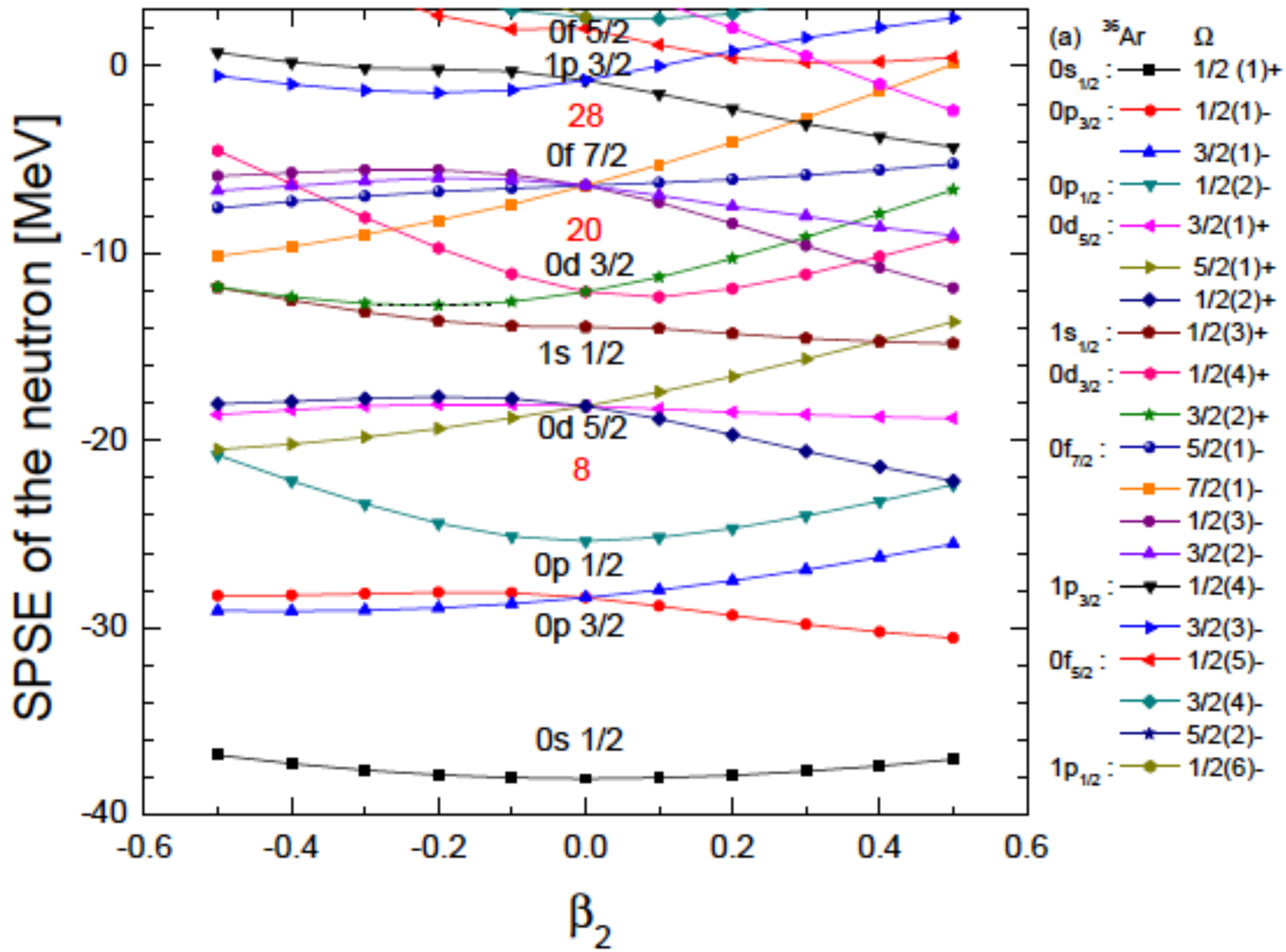
4 point formulas for empirical gaps

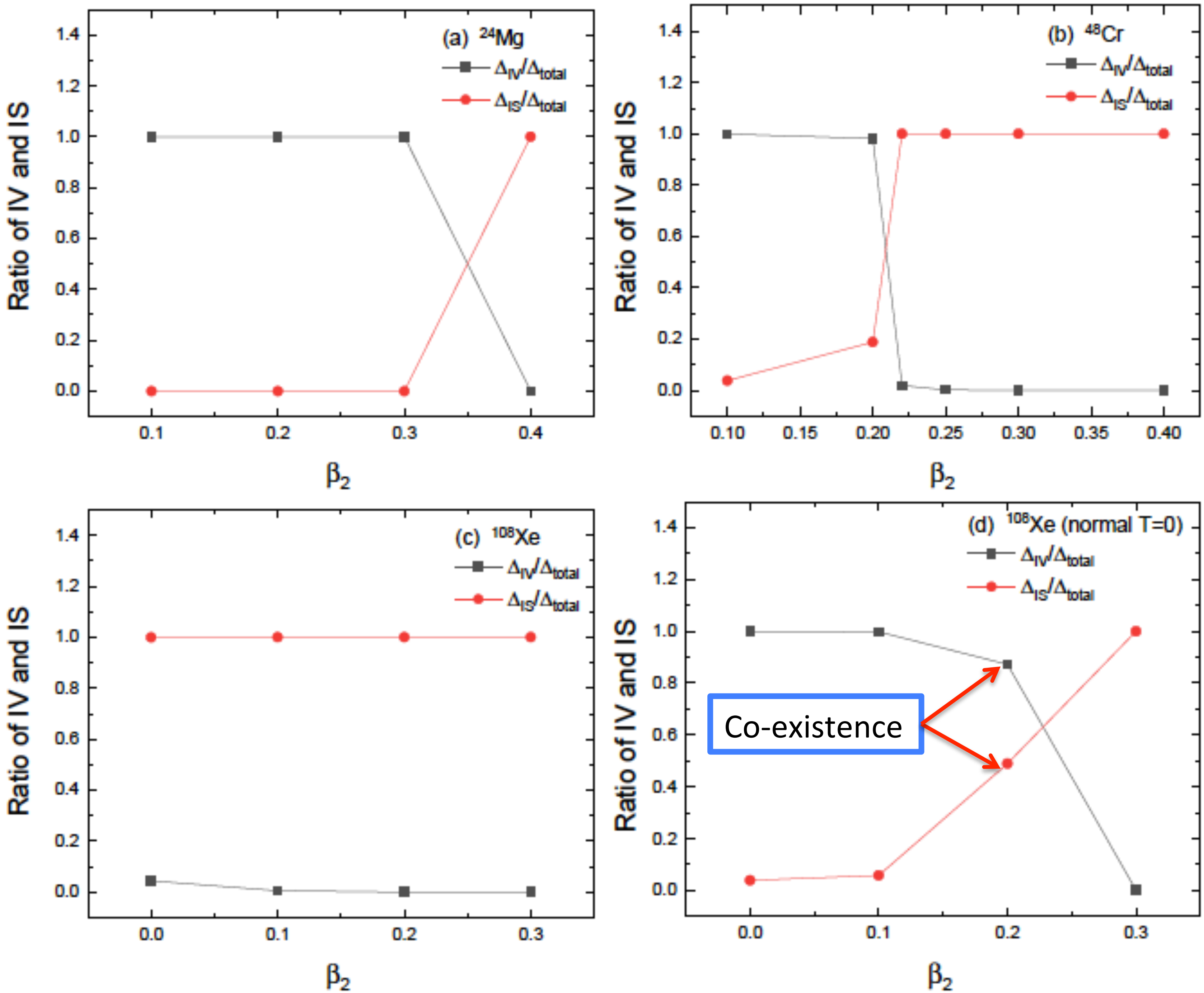
$$\Delta_p^{\rm emp} = \tfrac{1}{8}[M(Z+2,N) - 4M(Z+1,N) + 6M(Z,N) - 4M(Z-1,N) + M(Z-2,N)], \quad (14)$$

$$\Delta_n^{\rm emp} = \tfrac{1}{8}[M(Z,N+2) - 4M(Z,N+1) + 6M(Z,N) - 4M(Z,N-1) + M(Z,N-2)]. \quad (15)$$

Nucleus	$\|\beta_2^{E2}\|$ [29]	β_2^{RMF} [30]	β_2^{FRDM} [31]	β_2^{Ours}	Δ_p^{emp}	Δ_n^{emp}	$\delta_{np}^{\mathrm{emp}}$
^{24}Mg	0.605	0.416	0.	0.300	3.123	3.193	1.844
^{36}Ar	0.256	-0.207	-0.255	-0.200	2.265	2.311	1.373
^{48}Cr	0.337	0.225	0.226	0.200	2.128	2.138	1.442
^{64}Ge	–	0.217	0.207	0.100	1.807	2.141	1.435
^{108}Xe	–	–	0.162	0.100	1.467	1.496	0.605
^{128}Gd	–	0.350	0.341	0.100	1.415	1.393	0.592

Deformed Woods-Saxon potential for s.p. energies in ^{36}Ar





(a) 24Mg
ΔIV/Δtotal
ΔIS/Δtotal
Ratio of IV and IS
β2
(b) 48Cr
ΔIV/Δtotal
ΔIS/Δtotal
Ratio of IV and IS
β2
(c) 108Xe
ΔIV/Δtotal
ΔIS/Δtotal
Ratio of IV and IS
β2
(d) 108Xe (normal T=0)
ΔIV/Δtotal
ΔIS/Δtotal
Ratio of IV and IS
β2
Co-existence

Gamow-Teller transitions from high-spin isomers in $N = Z$ nuclei

H. Z. Liang(梁豪兆),[1,2] H. Sagawa,[1,3] M. Sasano,[1] T. Suzuki(鈴木俊夫),[4,5] and M. Honma[3]

Phys. Rev. C 98, 014311 (2018) - Published 9 July 2018

Ikeda Gamow-Teller sum rule
=> proton and neutron Fermi sphere

$$S_- - S_+ \equiv \sum_{f,\nu} |\langle f|\hat{O}_\nu^-|i\rangle|^2 - \sum_{f,\nu} |\langle f|\hat{O}_\nu^+|i\rangle|^2 = 3(N-Z)$$

New sum rule for GT transitions from High Spin Isomers
=> spin-up and spin-down Fermi sphere

the intrinsic frame of deformed nuclei,

$$\hat{O}_\nu^\pm = \sum_\alpha \sigma_\nu(\alpha) t_\pm(\alpha) \,,$$

HSI: I=12^+ in ^{52}Fe is most likely to be oblate deformation.
Ex=6.96MeV $t_{1/2}$=45.9s
I=21^+ in ^{94}Au Ex=6.67MeV $t_{1/2}$=0.4s

Combinations of spin-up and spin-down opeartors

$$\Delta S(t_-) \equiv S(\sigma_{-1}t_-) - S(\sigma_{+1}t_-) = 2\sum_\alpha \langle i|\sigma_0(\alpha)t_+(\alpha)t_-(\alpha)|i\rangle \,,$$

$$\Delta S(t_+) \equiv S(\sigma_{-1}t_+) - S(\sigma_{+1}t_+) = 2\sum_\alpha \langle i|\sigma_0(\alpha)t_-(\alpha)t_+(\alpha)|i\rangle \,.$$

$$\Delta S(t_-) - \Delta S(t_+) = 4\sum_\alpha \langle i|\sigma_0(\alpha)t_z(\alpha)|i\rangle = 2(\langle S_n\rangle - \langle S_p\rangle) \,,$$

$$\Delta S(t_-) + \Delta S(t_+) = 2\sum_\alpha \langle i|\sigma_0(\alpha)|i\rangle = 2(\langle S_n\rangle + \langle S_p\rangle) \,,$$

Sum rule values depend on the spin expectation of protons ad neutrons. Notice |i> is High spin isomers.

HSI I=12$^+$ in ^{52}Fe Oblate deformation

$$[Nn_3\Lambda\Omega] = [303\tfrac{7}{2}]_{\pi(\nu)} \text{ and } [312\tfrac{5}{2}]_{\pi(\nu)}$$

Angular momentum projection in Laboratory frame

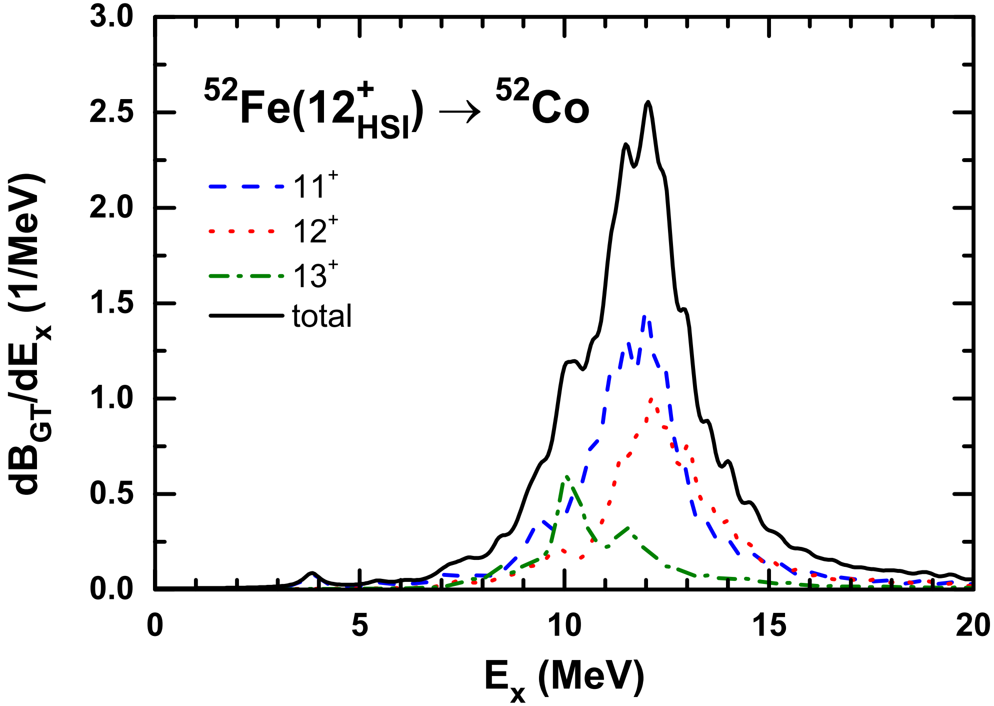
$$\Phi_{KIM} = \left(\frac{2I+1}{16\pi^2}\right)^{1/2} \times \left(\Psi_K(q)D^I_{MK}(\omega) + (-)^{I+K}\Psi_{\bar{K}}(q)D^I_{M-K}(\omega)\right)$$

$$\hat{O}_{\rm GT}(1\mu) = \sum_\nu \hat{O}_\nu D^1_{\mu\nu}(\omega)\,.$$

$$\langle K'I'||\hat{O}_{\rm GT}||KI\rangle = (2I+1)^{1/2}\langle IK1\Delta K|I'K'\rangle\langle K'||\hat{O}||K\rangle$$

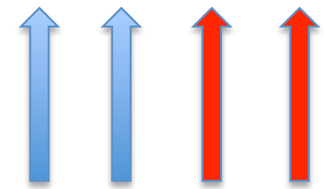
TABLE II. $B_{\rm GT}$ strengths for the transitions $I \to I'$ with the 4-qp configuration of protons and neurons $[Nn_3\Lambda\Omega] = [N0N(\Lambda+1/2)]_{\nu(\pi)}$ and $[N1(N-1)(\Lambda+1/2)]_{\nu(\pi)}$. Sum values in the last line are evaluated with $I=12$ and $j=7/2$.

	$I'=I-1$	$I'=I$	$I'=I+1$
$\Delta K=-1$	$\frac{2(4j-1)(2I-1)}{j(2I+1)}$	$\frac{2(4j-1)}{j(I+1)}$	$\frac{2(4j-1)}{j(2I+1)(I+1)}$
$\Delta K=0$	—	$\frac{4I}{I+1}$	$\frac{4}{I+1}$
$\Delta K=+1$	—	—	$\frac{2}{j}$
sum	6.83	4.26	0.90



^{52}Fe Ex=6.958MeV
life time 45.9s

Seniority four states

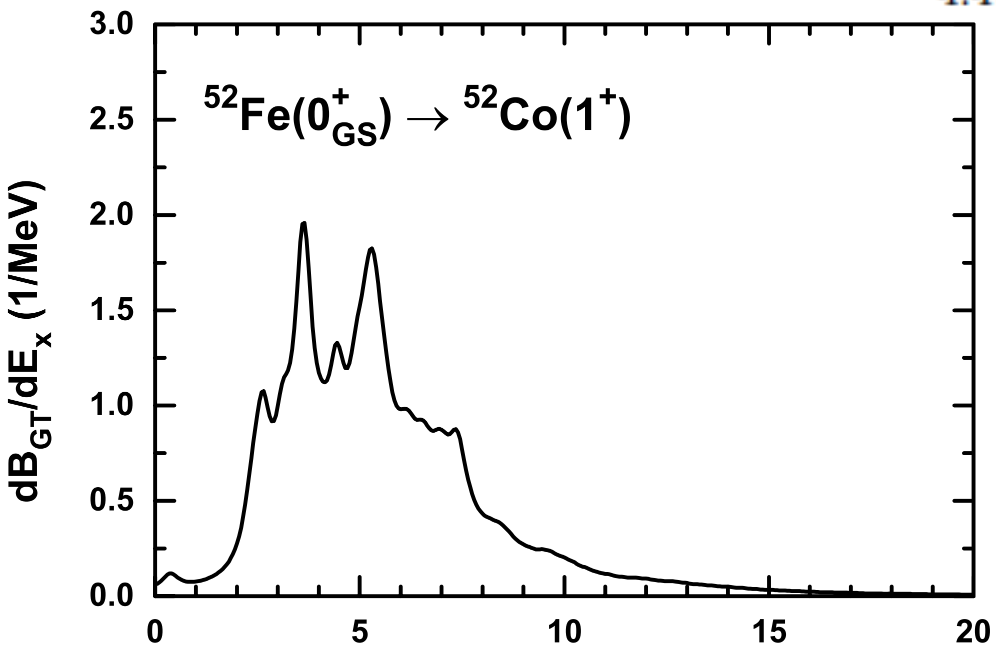


$$I_i = 12^+$$

$$I_n^\pi = 6^+ \quad I_p^\pi = 6^+$$

$$B(GT)_{sum}:$$

4.47, 3.11, and 1.44 for the $I' = 11$, 12, and 13



Brink-Axel hypothesis
on GR top of excited states

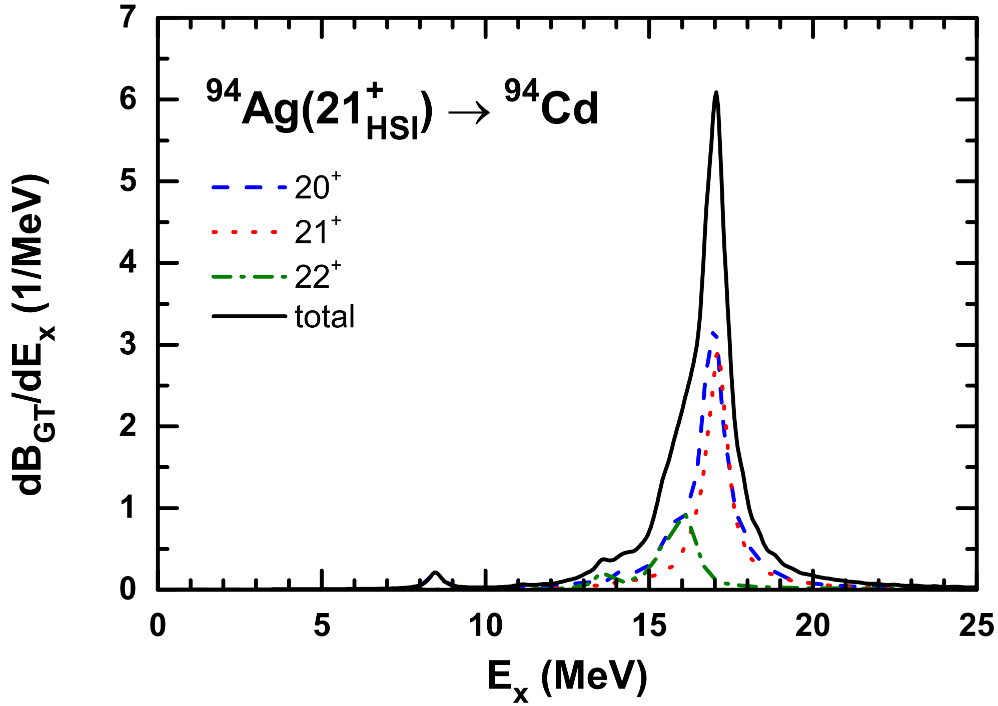
^{94}Ag

$$[Nn_3\Lambda\Omega] = [404\tfrac{9}{2}]_{\pi(\nu)},\ [413\tfrac{7}{2}]_{\pi(\nu)},\ \text{and}\ [422\tfrac{5}{2}]_{\pi(\nu)}$$

$$I_n^\pi = \frac{21}{2}^+ \qquad I_p^\pi = \frac{21}{2}^+ \qquad I_i = 21^+$$

TABLE III. $B_{\rm GT}$ strengths for the transition $I \to I'$ with the 6-qp configuration of protons and neurons $[Nn_3\Lambda\Omega] = [N0N(\Lambda+1/2)]_{\nu(\pi)}$, $[N1(N-1)(\Lambda+1/2)]_{\nu(\pi)}$, and $[N2(N-2)(\Lambda+1/2)]_{\nu(\pi)}$. The sum values in the last line are evaluated with $I = 21$ and $j = 9/2$.

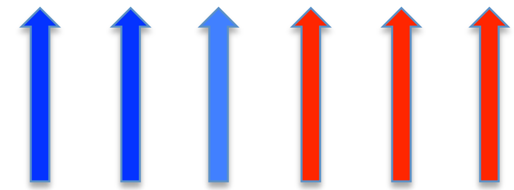
	$I' = I-1$	$I' = I$	$I' = I+1$
$\Delta K = -1$	$\frac{2(2I-1)}{2I+1}\frac{6j-3}{j}$	$\frac{2}{I+1}\frac{6j-3}{j}$	$\frac{2}{(2I+1)(I+1)}\frac{6j-3}{j}$
$\Delta K = 0$	—	$\frac{6I}{I+1}$	$\frac{6}{I+1}$
$\Delta K = +1$	—	—	$\frac{6}{j}$
sum	10.17	6.21	1.61



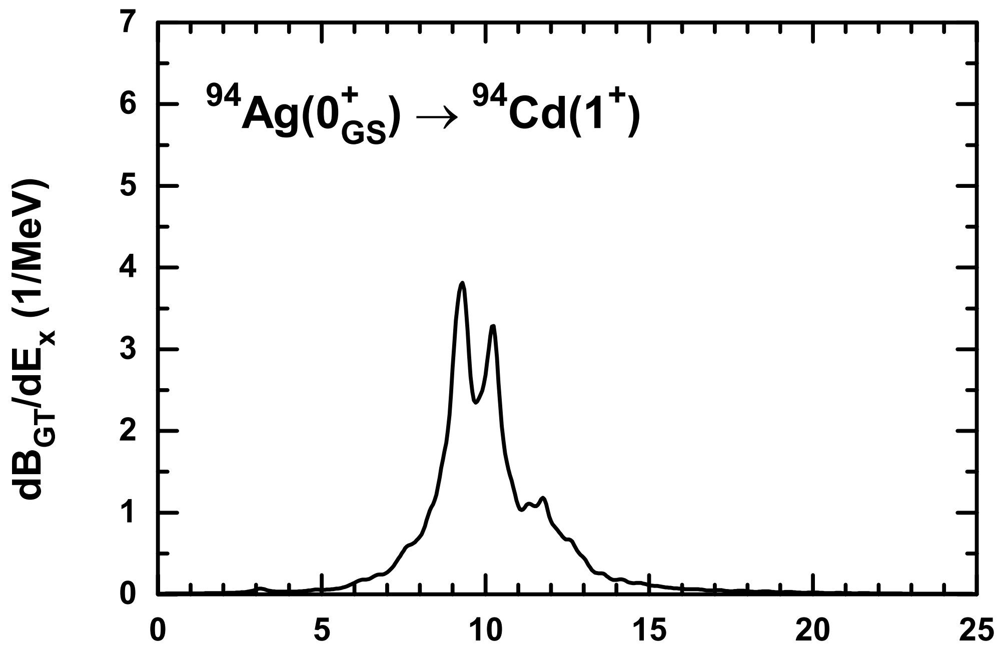
Seniority six states

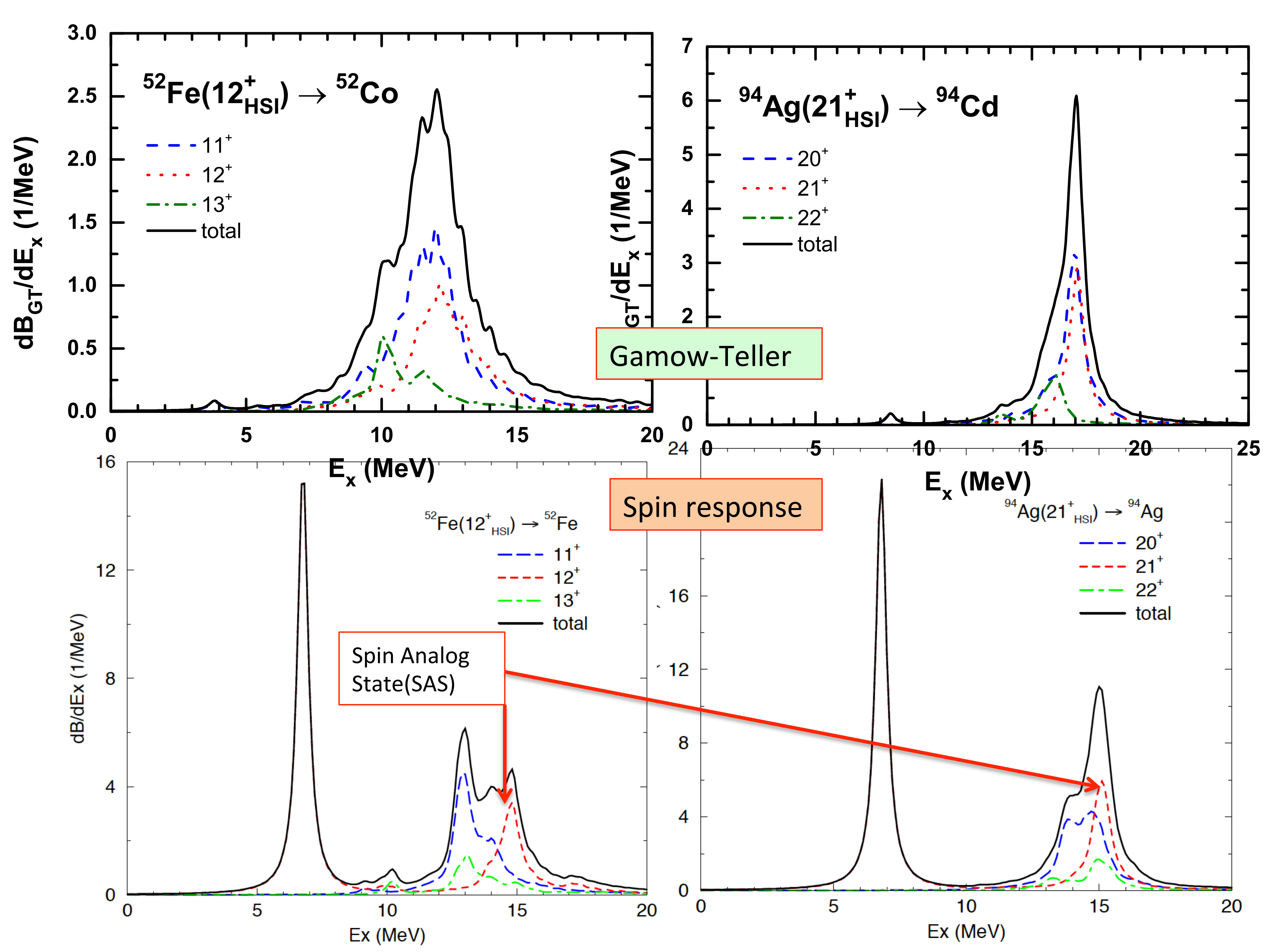
$I_i = 21^+$

$$(1g_{9/2})_n^{21/2}(1g_{9/2})_p^{21/2}$$



^{94}Ag Ex=6.67MeV
Life Time 0.4s





52Fe(12+HSI) → 52Co
11+
12+
13+
total
dBGT/dEx (1/MeV)
Ex (MeV)
94Ag(21+HSI) → 94Cd
20+
21+
22+
total
Gamow-Teller
Spin response
52Fe(12+HSI) → 52Fe
Spin Analog State(SAS)
dB/dEx (1/MeV)
Ex (MeV)
94Ag(21+HSI) → 94Ag

Summary: spin-isospin states in N=Z nucleus

1. Cooperative role of T=0 and T=1 pairings induce
   (SU(4) symmetry restoration in spin-isospin space)
   =>large Gamow-Teller transitions of N=Z+2 nuclei at lower energy

2. HFB results: T=0 superfluidity may coexist with T=1 superfluidity.
   The deformation plays an important role to realize spin-triplet superfluid phase in the ground state: surface =>spin-singlet
   center => spin-triplet
   more theoretical study : Isospin projection and angular momentum projection

3. HIS-GT: new sum rule in the spin-up and spin-down Fermi sphere.
   (Ikeda GT sum rule: isospin-up and -down Fermi sphere.
   provide effective spin-spin residual and spin-isospin residual interactions in extreme spin polarized space.

4. Fine fittings of energy density functions of spin and spin-isospin channels
   (which was done already for Shell model interactions: GPFX1J
   BY Toshio Suzuki, Michio Honma)

Recent progress(M1 transitions)

1. For N=Z odd-odd nuclei, a strong competition between S=0 and S=1 pairing correlations is observed near the ground states.
2. How Spin-triplet superfluidity can be seen in nuclear many-body system: abrupt or smooth (crossover) transitions?
3. Large quenching in the IV spin response was observed which is consistent with magnetic moments and Gamow-Teller beta-decay matrix.
4. IS spin sum rule strength shows much smaller quenching than IV spin ones.
5. Strong spin-triplet pairing gives positive contribution to the spin-spin neutron-proton correlations in N=Z nuclei.