Single and Double Charge exchange excitations of Spin-Isospin mode

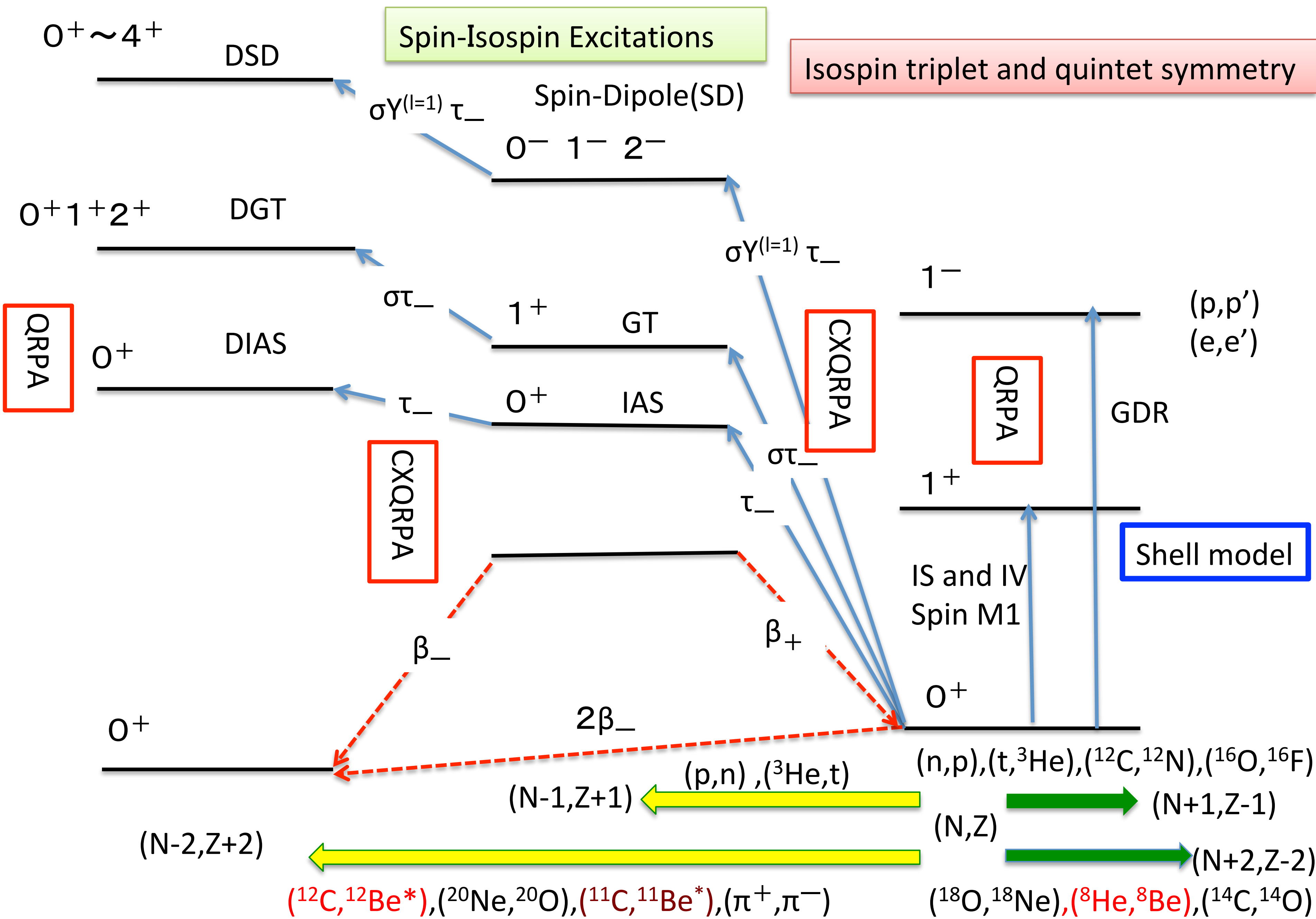
Nuclear Structure and Dynamics (NSD2019)
May 13-17, 2019
Venice, Italy

Hiroyuki Sagawa RIKEN/University of Aizu

1. Introduction
2. HF+BCS+QRPA for Double Gamow-Teller excitations
3. Quenching of GT, Spin-Dipole and spin M1 transitions
4. Summary

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

RIKEN NiSHiNA CENTER



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+
0+
2β_
(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)
(12C,12Be*),(20Ne,20O),(11C,11Be*),(π+,π−)
(18O,18Ne),(8He,8Be),(14C,14O)

Double beta decay(DBD) and double GTR

NISH

DBD

- 0ν mode $(A,Z) \rightarrow (A,Z+2) + 2e^-$
- 2ν mode $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu_e}$

0ν mode

- **Majorana vs. Dirac**
- **absolute mass : nuclear matrix element(NME) needed (depends on theory)**

- **Double GT(DGT) states : particular interest**

Connection to double beta decay

→Possible calibration standard of nuclear structure model for 2νββ decay

The (ββ-decay) matrix element, however, still remains very small and accounts for only a 10^{-4} to 10^{-3} of the total DGT sum rule. A precise calculation of such hindered transition is, of course, very difficult and is inherently a subject of large percent uncertainties. At present there is no direct way to "calibrate" such complicated nuclear structure calculations involving miniature fractions of the two-body DGT transitions. By studying the stronger DGT transitions and, in particular, the giant DGT states experimentally and as we do here, theoretically, one may be able to "calibrate" the calculations of ββ-decay nuclear elements.

by N. Auerbach, L. Zamick, and D. Zheng, Annals of Physics 192, 77 (1989).

Possible calibration of DGT with DIAS

Gamow-Teller (Ikeda) sum rule
$S_- - S_+ = 3(N-Z) = 24$

PHYSICAL REVIEW C **94**, 064325 (2016)

Sum rule study for double Gamow-Teller states

H. Sagawa[1,2] and T. Uesaka[1]

$$D^J_\pm = \frac{1}{2J_i+1}\sum_{J_f} |\langle J_f ||[\hat{O}_\pm \times \hat{O}_\pm]^J || J_i\rangle|^2, \qquad \hat{O}_\pm(\mathrm{GT}) = \sum_\alpha \sigma(\alpha) t_\pm(\alpha).$$

Initial state	$(J=0)$	$(J=2)$	DIAS	DIAS(DGT)	Σ_{sum}
^{6}He	12.0(12)	0.0 (0)	4	3.70(3.70)	0.211×10^{-3} (0.667)
^{8}He	39.7(40)	80.7 (80)	24	7.71(2.47)	0.052 (1.333)
^{14}C	8.98(12)	7.55 (0)	4	4.56 (0.15)	0.566 (1.333)
^{18}O	10.4(12)	3.96 (0)	4	7.72 (2.61)	0.297 (0.80)
^{20}O	35.5(40)	91.3 (80)	24	4.13 (1.74)	0.845 (1.60)
^{42}Ca	8.50(12)	8.75 (0)	4	3.80 (2.18)	0.66 (0.86)
^{44}Ca	32.6(40)	98.5(80)	24	2.31 (1.47)	1.38 (1.71)
^{46}Ca	72.3(84)	269.3(240)	60	1.89 (1.32)	2.20 (2.57)
^{48}Ca	135.5(144)	501.2(480)	112	3.70 (1.25)	1.59 (3.43)
^{90}Zr	196.3(220)	859.2(800)	180	(1.11)	(4.44)

$$D^{(J=0)}_- - D^{(J=0)}_+ = \langle i|[[\hat{O}_+ \times \hat{O}_+]^{(J=0)}, [\hat{O}_- \times \hat{O}_-]^{(J=0)}]|$$
$$= 2(N-Z)(N-Z+1) + \tfrac{4}{3}[(N-Z)S$$
$$- \langle i|[i\hat{\Sigma}\cdot(\hat{O}_- \times \hat{O}_+) + \hat{\Sigma}\cdot\hat{\Sigma}]|i\rangle], \quad ($$

$$D^{(J=2)}_- - D^{(J=2)}_+$$
$$= \langle i|\sum_\mu (-1)^\mu [[\hat{O}_+ \times \hat{O}_+]^{(J=2)}_\mu, [\hat{O}_- \times \hat{O}_-]^{(J=2)}_{-\mu}]|i\rangle$$
$$= 10(N-Z)(N-Z-2)$$
$$+ \frac{10}{3}[2(N-Z)S_+ + \langle i|[i\hat{\Sigma}\cdot(\hat{O}_- \times \hat{O}_+) + \hat{\Sigma}\cdot\hat{\Sigma}]|i\rangle].$$

$$\hat{\Sigma} = \sum_\alpha \sigma(\alpha)$$

$B(2\nu2\beta) \sim 0.02$
$\leq 10^{-5}\, S_{\mathrm{DGtT}}$

The QRPA state and QRPA phonon for standard (non-charge exchange) excitations are defined as

$$|k, I^\pi M\rangle \; = \; Q_k^\dagger(I^\pi M)|\hat{0}\rangle, \tag{3}$$

$$\begin{aligned} Q_k^\dagger(I^\pi M) \; &= \; \sum_{a \le a'} \frac{1}{\sqrt{1+\delta_{aa'}}}[Z_{aa'}^k(I^\pi)A_{aa'}^\dagger(I^\pi M) \\ &- \; W_{aa'}^k(I^\pi)\tilde{A}_{aa'}(I^\pi M)] \end{aligned} \tag{4}$$

The quasi-particle pair creation and annihilation operators read

$$\begin{aligned} A_{aa'}^\dagger(I^\pi M) \; &= \; [\alpha_a^\dagger \alpha_{a'}^\dagger]_{IM} \\ \tilde{A}_{aa'}(I^\pi M) \; &= \; (-1)^{I+M} A(I^\pi - M) = -[\tilde{\alpha_a}\tilde{\alpha_{a'}}]_{IM} \end{aligned} \tag{5}$$

the Bogoliubov-Valatin transformation,

$$\begin{pmatrix} \alpha_a^\dagger \\ \tilde{\alpha_a} \end{pmatrix} = \begin{pmatrix} u_a, v_a \\ u_a, -v_a \end{pmatrix} \begin{pmatrix} c_a^\dagger \\ \tilde{c_a} \end{pmatrix}$$

Fully self-consistent calculations
No closure approximation

The charge exchange QRPA phonon state is given by

$$|m, J^\pi M\rangle = \Gamma_m^\dagger(J^\pi M)|\hat{0}\rangle \quad (8)$$

where m labels the m−th excited state refereed to the QRPA vacuum and the phonon operator is defined by

$$\Gamma_m^\dagger(J^\pi M) = \sum_{pn}[X_{pn}^m(J^\pi)A_{pn}^\dagger(J^\pi M) - Y_{pn}^m(J^\pi)\tilde{A}_{pn}(J^\pi M)] \quad (9)$$

$$M^{DGTR}(0^+ \to 2^+) = \frac{1}{\sqrt{3}} \sum_{m,m'} \langle f, 2^+||\sigma\tau_-||m, 1^+\rangle \times \langle m, 1^+|m', 1^+\rangle\langle m', 1^+||\sigma\tau_-||GS, 0\rangle, \quad (10)$$

$$M^{DGTR}(0^+ \to 0^+) = \sum_{m,m'} \langle f, 0^+||\sigma\tau_-||m, 1^+\rangle \times \langle m, 1^+|m', 1^+\rangle\langle m', 1^+||\sigma\tau_-||GS, 0\rangle. \quad (11)$$

$$\left\langle I^\pi \middle\| \sigma\tau_- \middle\| 1^+ \right\rangle = \left\langle QRPA \middle\| [[\Gamma^+(1^+), \sigma\tau_-], Q(I^\pi)] \middle\| QRPA \right\rangle$$

Quenching of spin-isospin excitations

1. Gamow-teller and Spin-dipole: the same quenching factor? (renormalization of $0\nu\beta\beta$ and $2\nu\beta\beta$ matrix elements)
2. IS and IV spin modes: quenching or enhancement?
3. Delta-hole excitation and/or two-body meson exchange currents

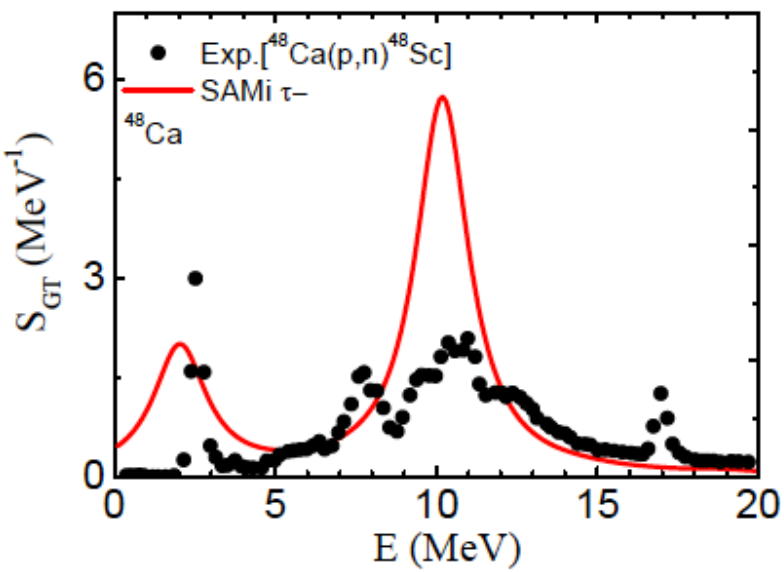


FIG. 1: (Color online) RPA response function for the GT transition operator $\hat{O}_-(\mathrm{GT}) = \sum_\alpha \sigma(\alpha)t_-(\alpha)$ to ^{48}Ca calculated by HF+RPA model with a Skyrme parameter set SAMi. Experimental data are taken from ref. [8]. Calculated results are averaged by a Lorenzian weighting function witht the width of 1MeV(

$0\nu\beta\beta$

$2\nu\beta\beta$

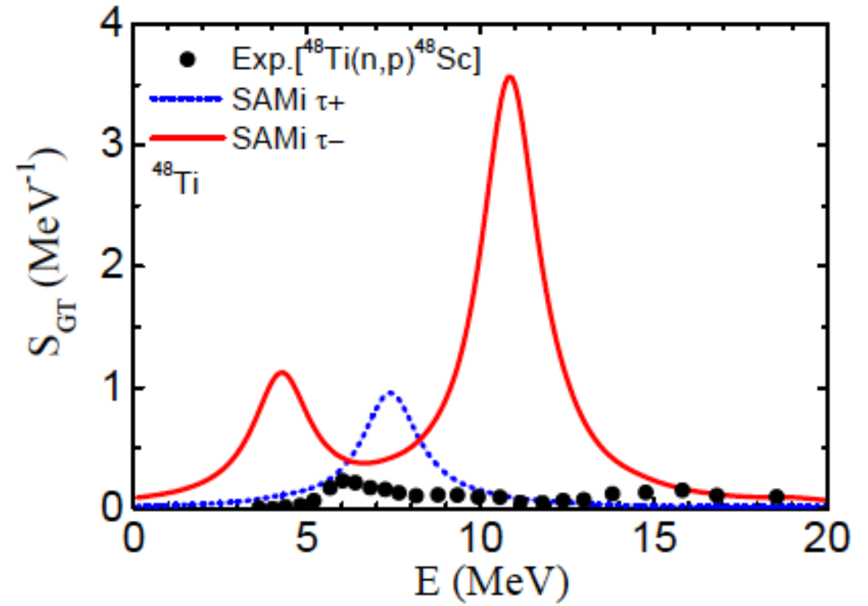
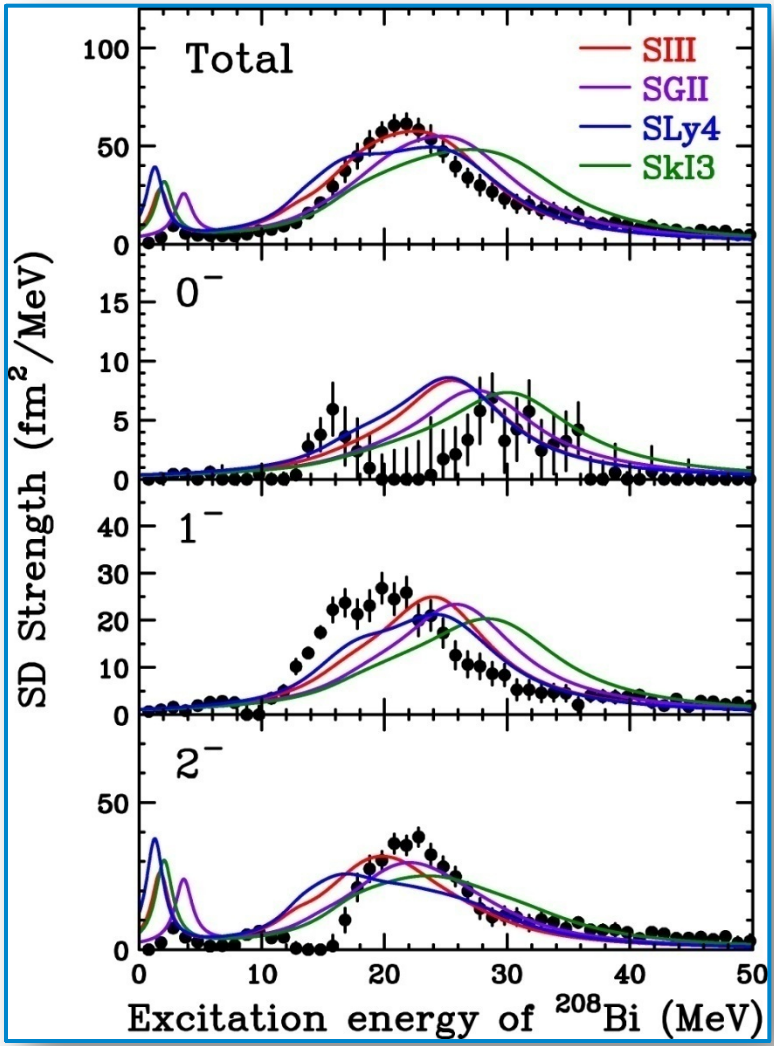


FIG. 3: (Color online) RPA response function for the G transition operator $\hat{O}_\pm(\mathrm{GT}) = \sum_\alpha \sigma(\alpha)t_\pm(\alpha)$ to ^{48}Ti cal lated by HF+RPA model with a Skyrme parameter set SA Experimental data are taken from ref. [8].

Data taken by K. Yako et al.

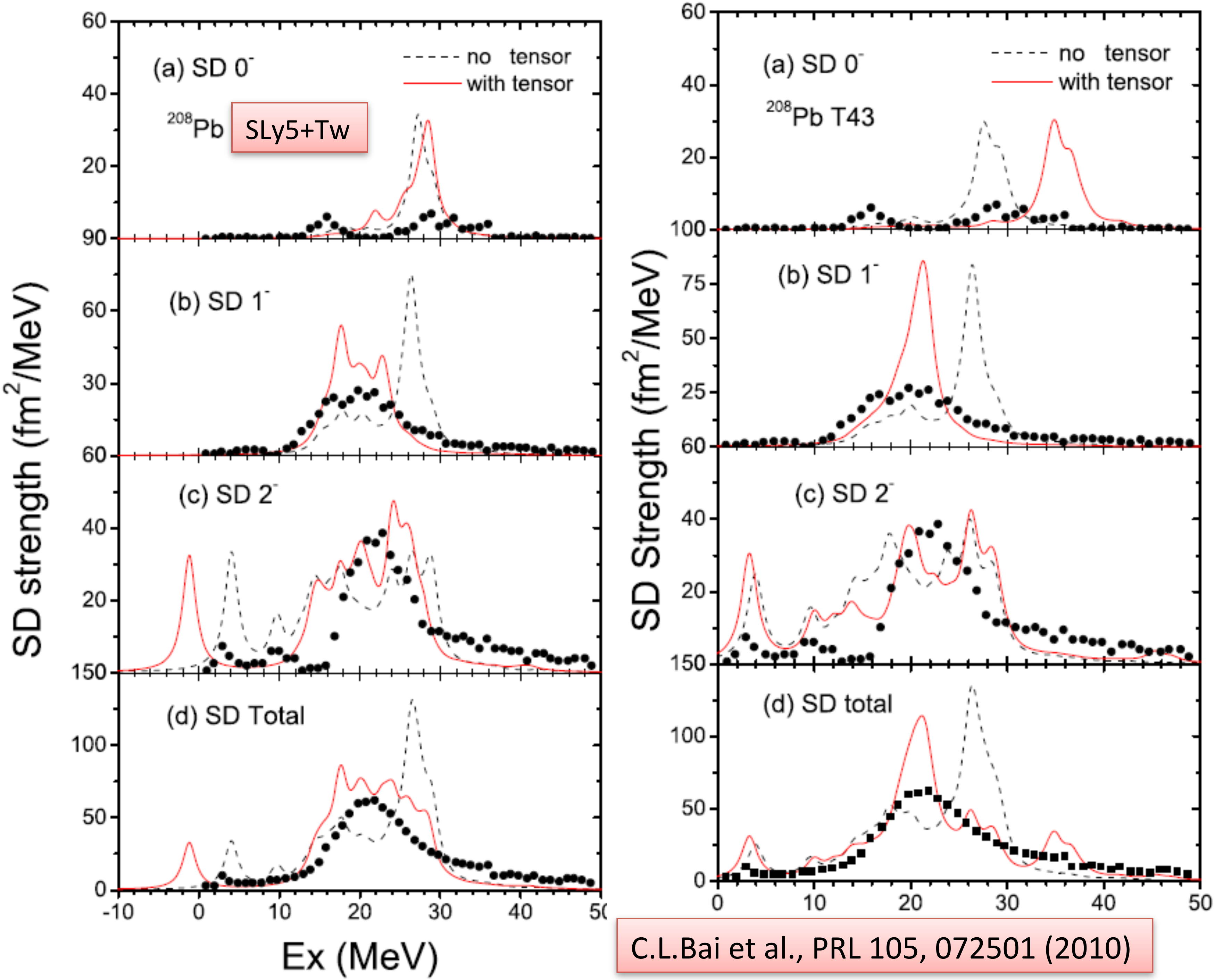
Puzzle in SD Strength Distributions（Wakasa, SIR2010,18-21 Feb.,2010)

H. Sagawa et al., PRC 76, 024301 (2007).



- Total strength
  - Asymmetric single bump
    - Extend up to ～50 MeV
    - Same as ^{90}Zr(p,n)results
  - SIII provides better description
- 0^- strength
  - Quenched
    - Seems to be fragmented
- 1^- strength
  - Softened compared with theory
    - Peak shift to lower E_x
- 2^- strength
  - Hardened compared with theory
    - Peak shift to higher E_x

- No Skyrme int. which reproduces both total and separated strengths
- ΔJ^{π}-dependent correlation ? → Require further investigations

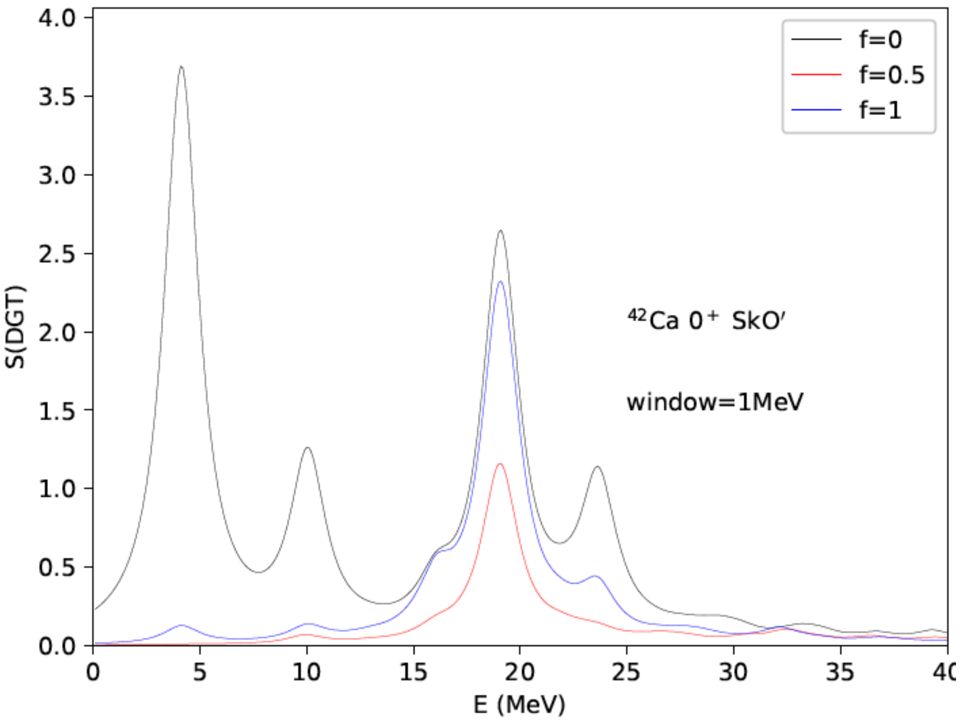


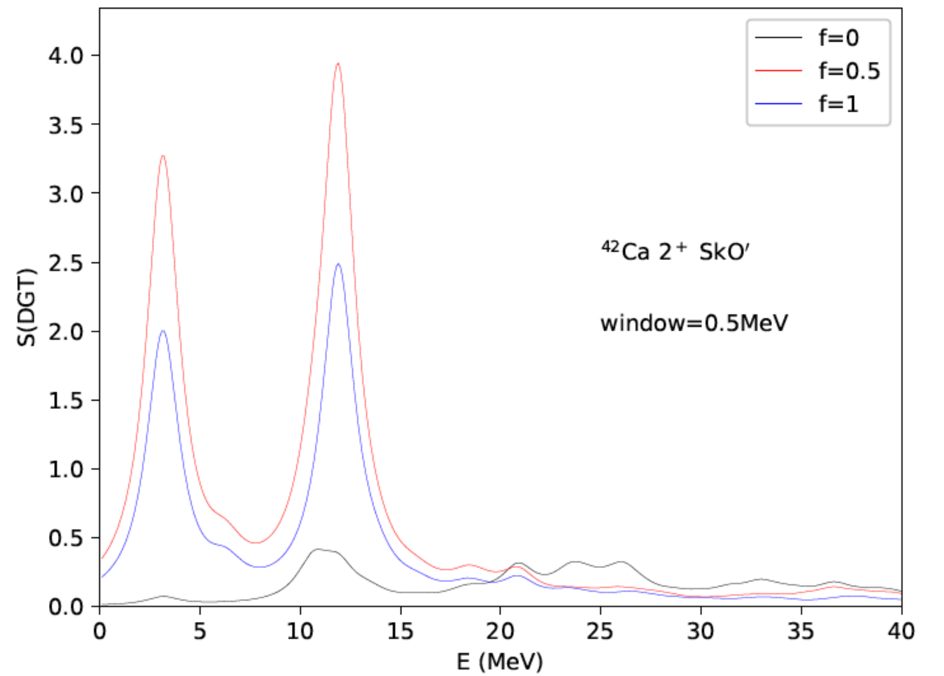
C.L.Bai et al., PRL 105, 072501 (2010)

Nuclear correlations study on DGT and DIAS

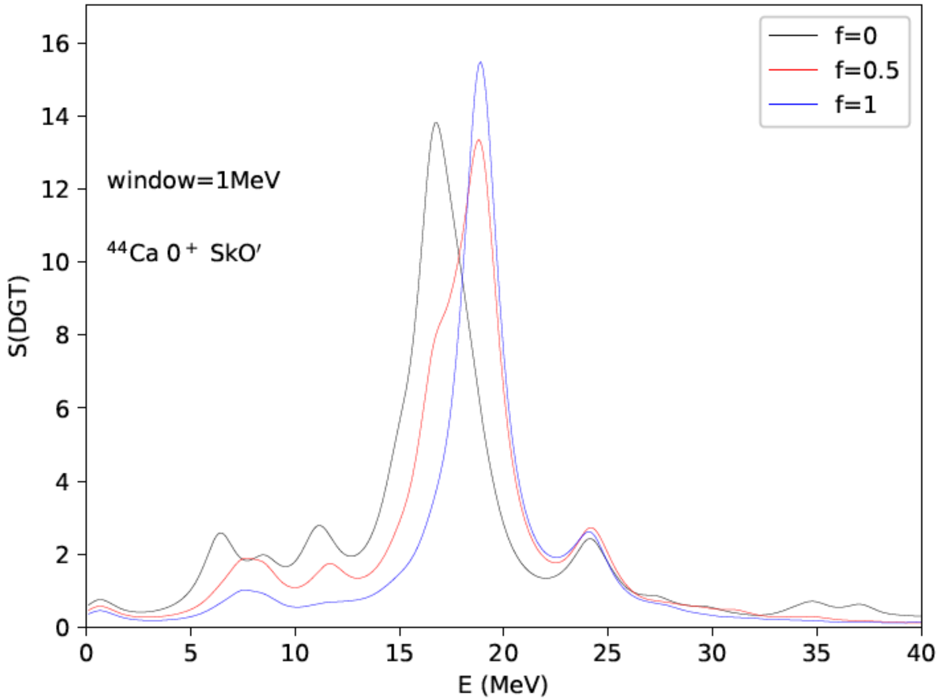
1. n-n and p-p pairing correlations
2. n-p pairing
3. Tensor correlations
4. CSB and CIB interactions

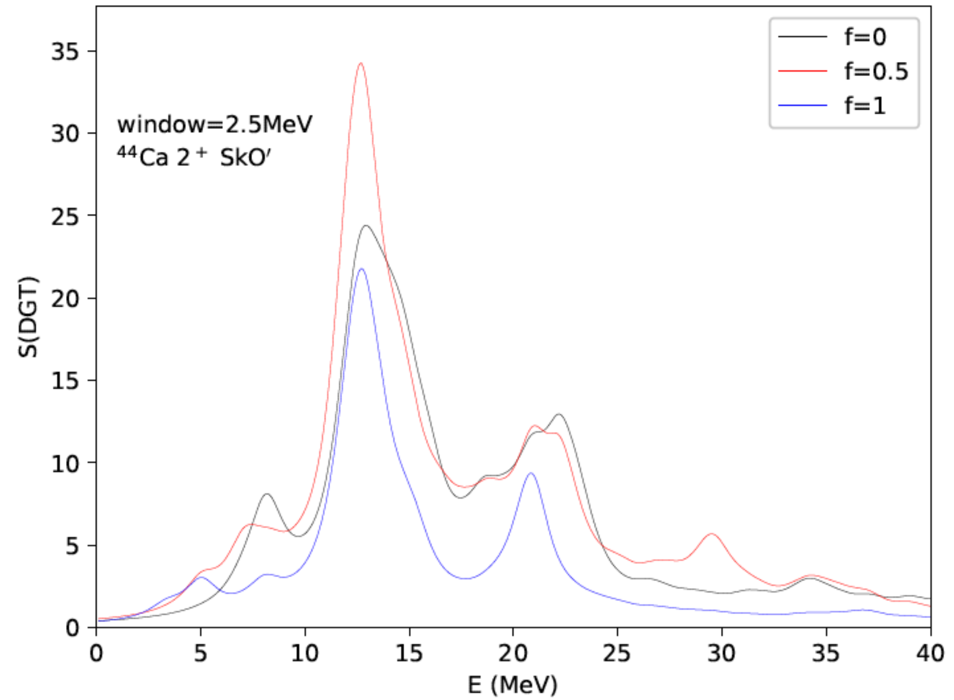
to be continued.





preliminary



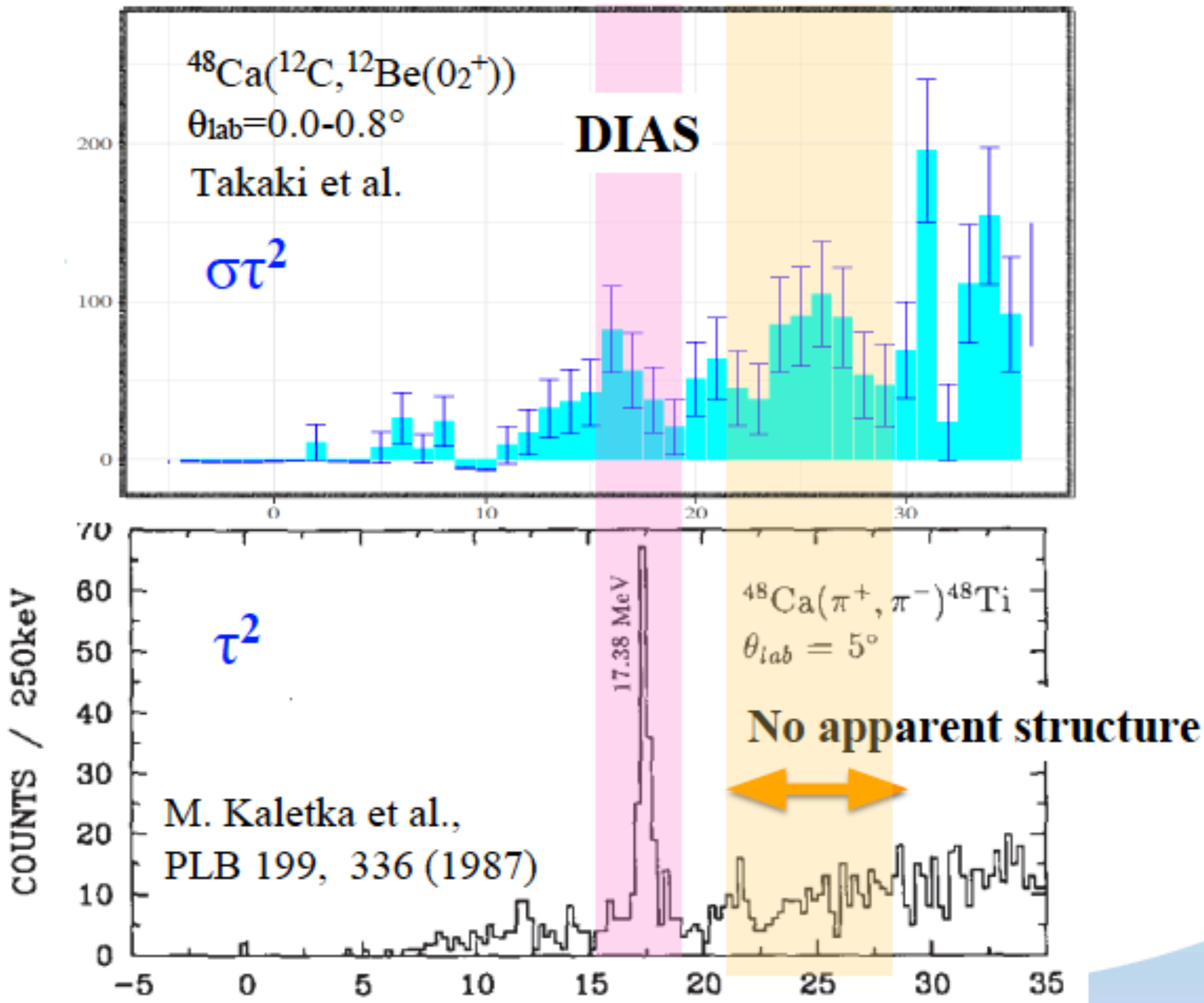


preliminary

(Ca isotopes, shell model calculations were performed by N. Shimizu et al. and N. Auerbach et al. (2018))

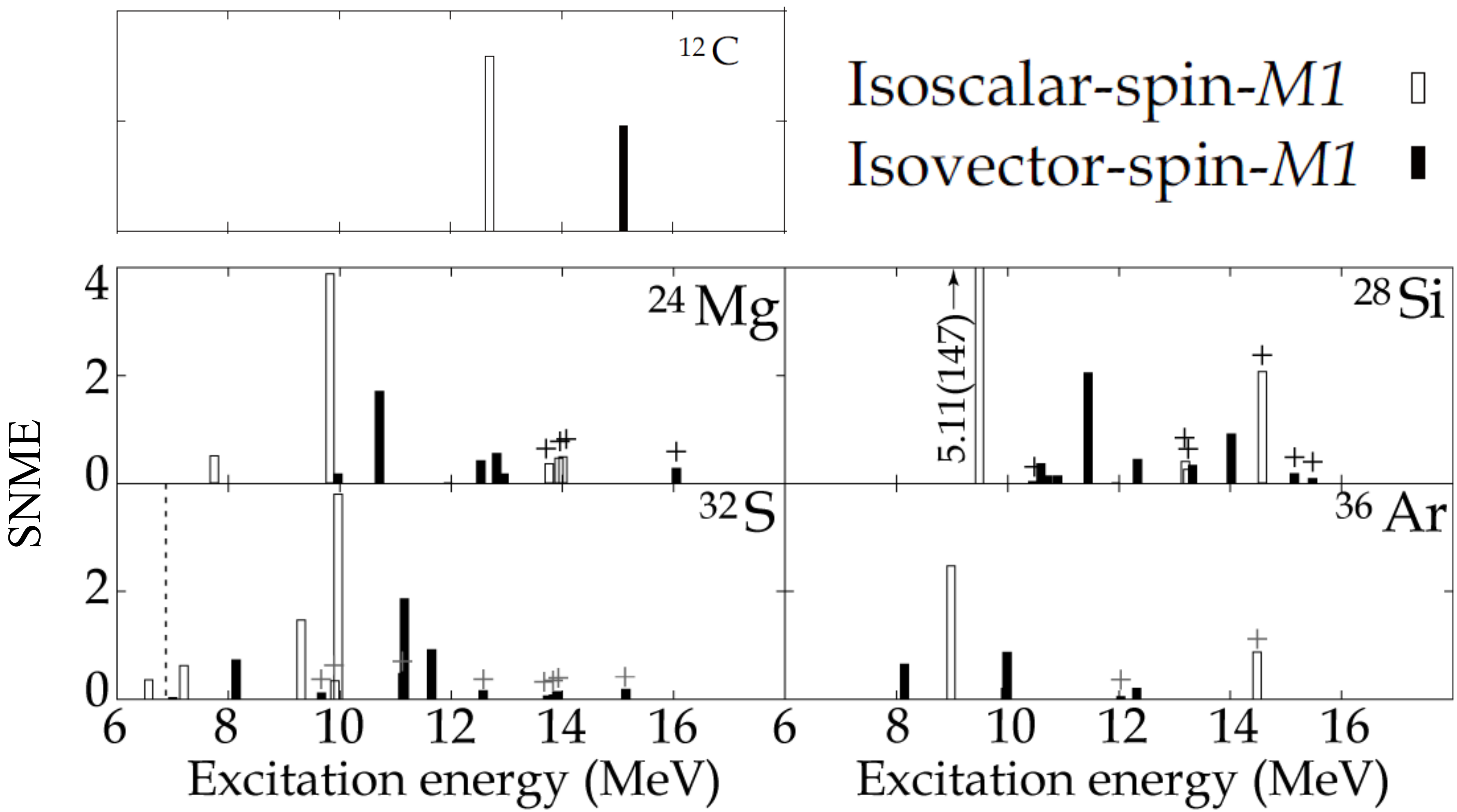
DCX Spectrum and comparison with (π^+,π^-)

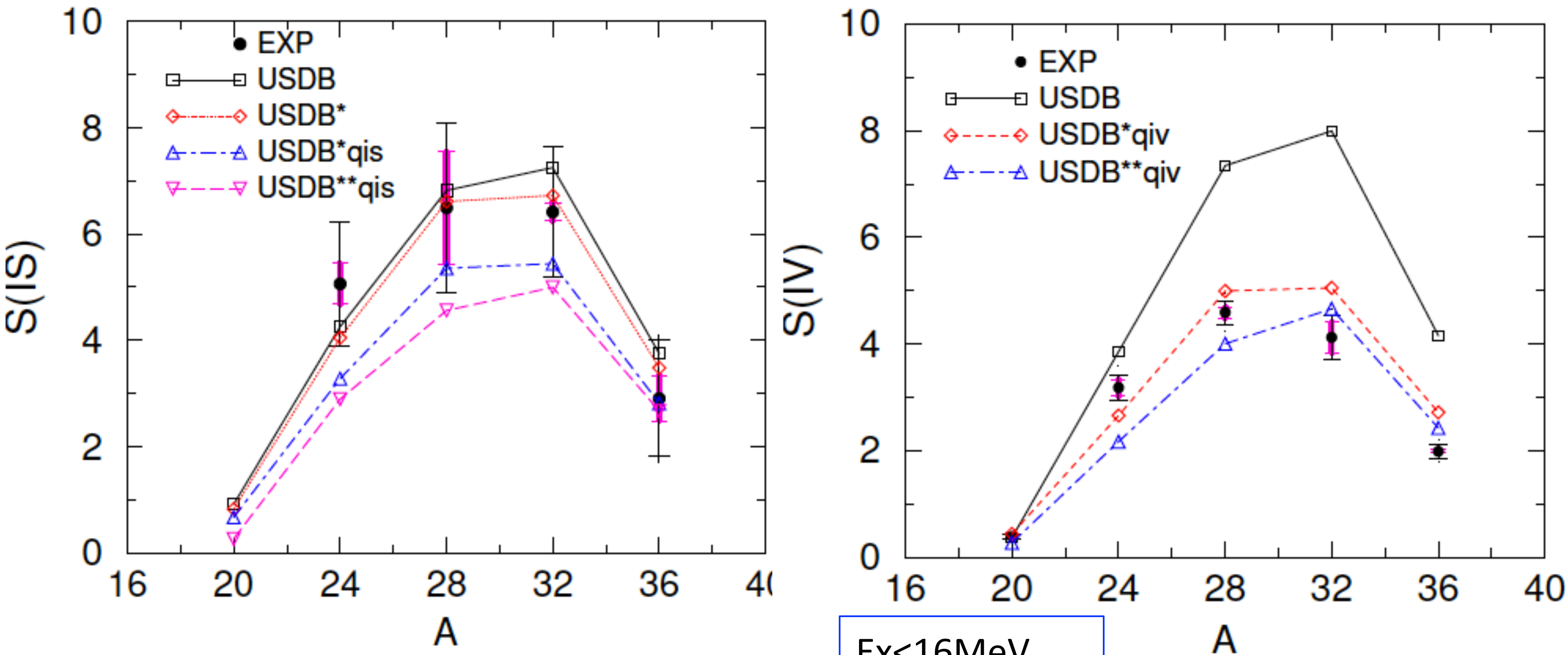
Courtesy of K. Yako (2019, RCNP experiment)



IS/IV-spin-M1 Squared Nuclear Matrix Elements (SNMEs)

Exp. Data, Matsubara, et al., PRL115, 102501(2015)
High energy resolution proton inelastic scattering with E_p=295MeV





Ex<16MeV

$$S(\vec{\sigma}) = \sum_f \frac{1}{2J_i + 1} |\langle J_f || \hat{O}_{IS} || J_i \rangle|^2,$$

$$S(\vec{\sigma}\tau_z) = \sum_f \frac{1}{2J_i + 1} |\langle J_f || \hat{O}_{IV} || J_i \rangle|^2.$$

Summary and future perspectives

1. GT states: 50% quenching of strength in ^{48}Ca:
   SD states in ^{208}Pb:20% quenching.
2. DGTR is a new Double phonon state and provide a key calibration unit for 2nu double beta decay cross section.
3. HF+HFB(BCS)+QRPA calculations are performed for Ca isotopes to Ti DGT transitions with n-n, p-p and n-p pairings.
4. IS spin M1 transitions are observed in N=Z sd-shell nuclei and give useful information to find out the IS and IV quenching of spin transitions.
5. No quenching of IS spin transitions => No delta-isobar coupling,
   IS spin-triplet pairing.

1. Extend calculations to medium-heavy and heavy nuclei
2. Double spin-dipole excitations