Quenching of IS and IV spin-M1 excitation strengths in N=Z nuclei
and
possible indication of *np* spin-spin correlation in the ground state

Hiroaki Matsubara

Department of Radiology, Kyoto Prefectural University of Medicine, Kyoto, Japan

Atsushi Tamii

Institute of Radiation Science/Research Center for Nuclear Physics/ Department of Physics, Osaka University, Japan

the RCNP-E299 Collaboration

NEWS Colloquium hosted by RCNP, July 14, 2021, Online

E299 Collaboration

RCNP, Osaka U.

H. Matsubara, A. Tamii, T. Adachi, K. Fujita, K. Hatanaka, D. Ishikawa, M. Kato, H. Okamura, Y. Tameshige, K. Suda, M. Yosoi

Univ. of Witwatersrand

J. Carter, H. Fujita

Kyusyu U. Dept. of Phys.

M. Dozono, S. Kuroita, Y. Yamada

IKP, Tech. U. of Darmstadt

P. Von Neumann-Cosel, B. Ozel, I. Poltoratska, A. Richter, A. Shevchenko

Osaka U. Dept. of Phys.

Y. Fujita

CNS, Univ. of Tokyo

T. Kawabata, K. Nakanishi, S. Sakaguchi, Y. Sasamoto, Y. Shimizu

Chiba U. Dept. of Phys.

H. Nakada

CYRIC, Tohoku U.

M. Itoh, Y. Sakemi

Miyazaki U. Dept. of App. Phys.

N. Fujita, A. Nonaka, H. Sakaguchi

IFIC-CSIC, Valencia

B. Rubio

*i*Themba LABs

F.D. Smit, R. Neveling

Niigata U.

Y. Shimbara

Kyoto U. Dept. of Phys.

J. Zenihiro

Hokkaido Univ.

W. Horiuchi,

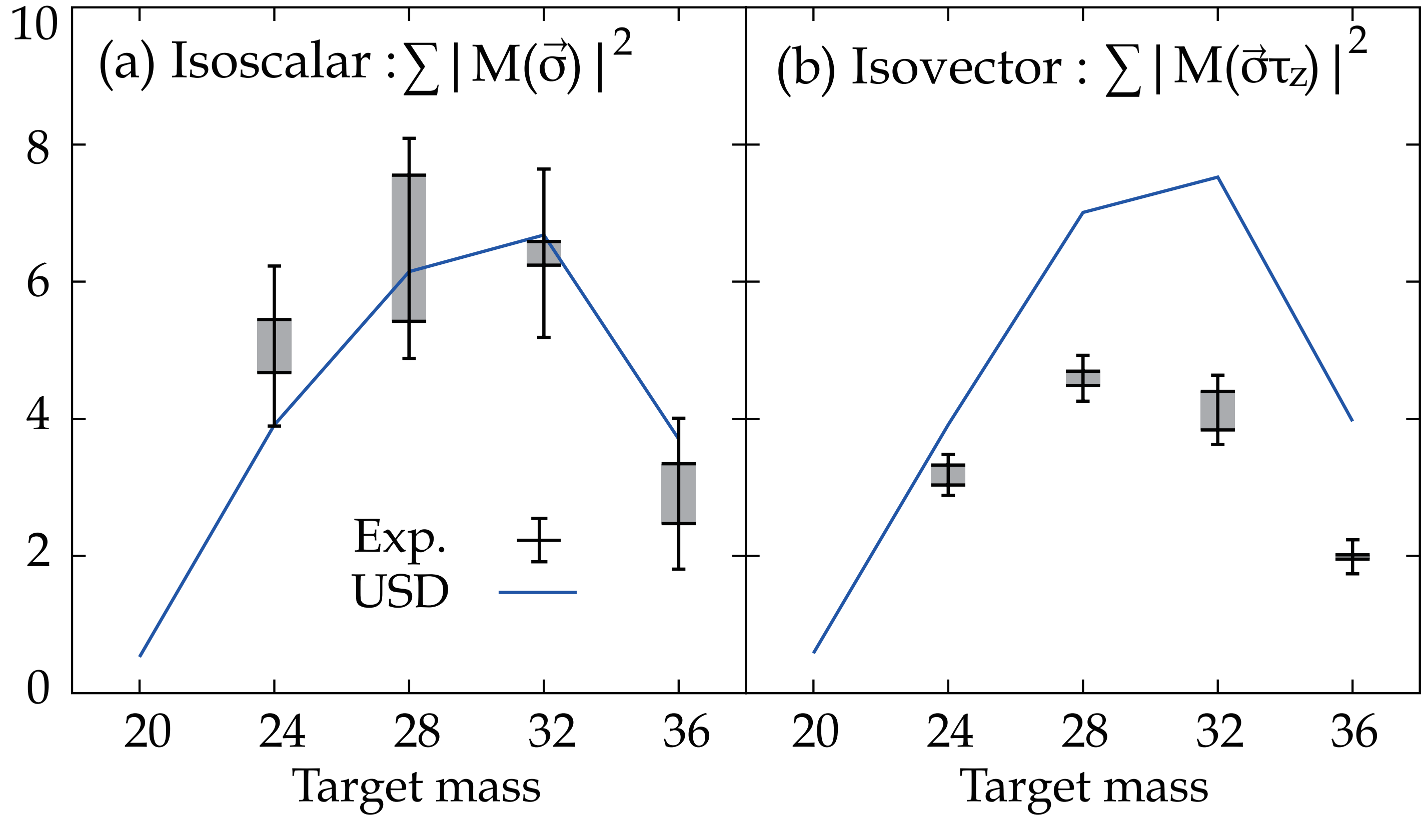
TRIUMF

P. Navratil

Outline

1. Quenching of the IS and IV spin-M1 SNMEs
2. *np* Pairing Correlations
3. *np* Spin-Spin Correlation Function
4. Experimental Methods
5. Results/Interpretation
6. Discussions/Criticism
7. Summary

Squared Nuclear Matrix Elements (SNMEs) of IS and IV spin-M1 excitations

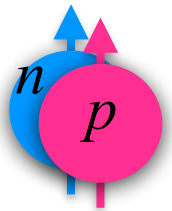


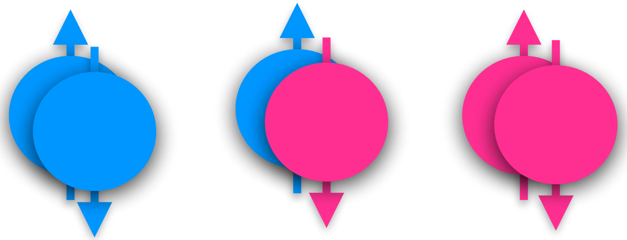
IV spin-M1 SNMEs are **quenching** from the shell model predication but **IS** spin-M1 SNMEs are **not**.

H. Matsubara, AT *et al.*, PRL2015

USD: Predications by Shell Model with the USD interaction.

IS and IV pairings



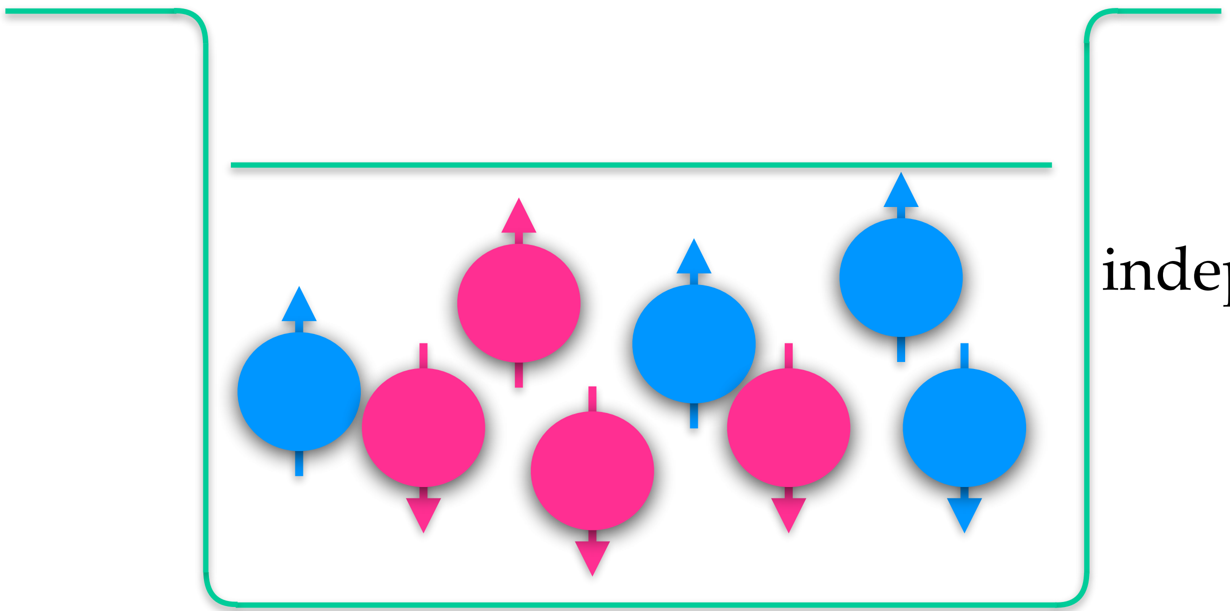


IS (T=0, S=1)

Isoscalar *np*-paring

IV (T=1, S=0)

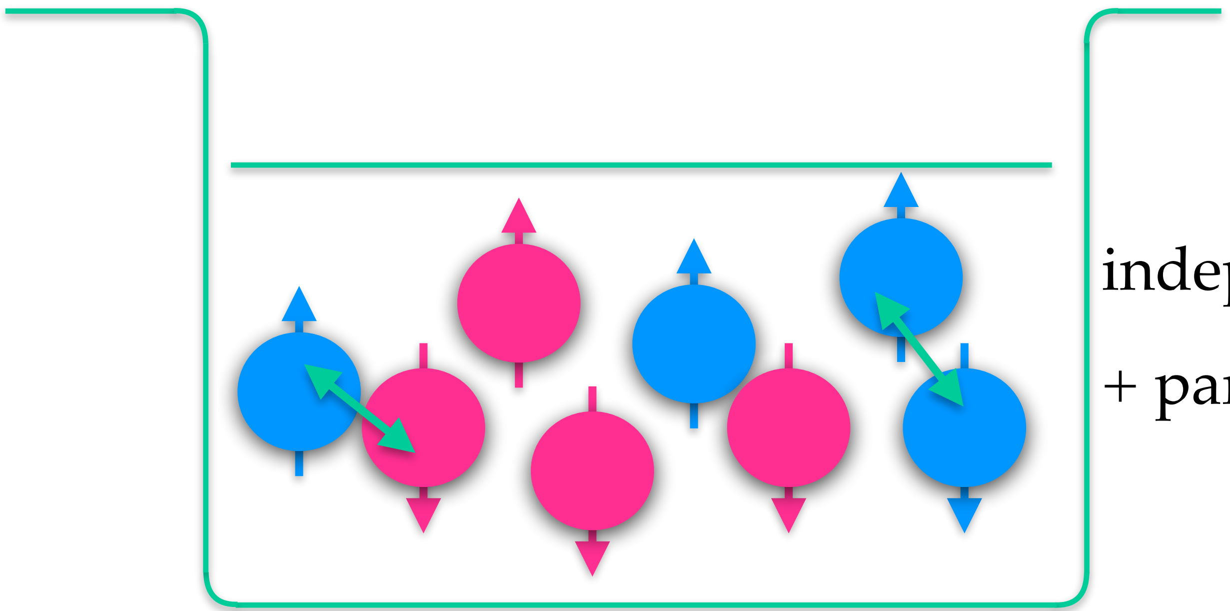
pairing in the ground state W.F.



independent particles

unperturbed ground state

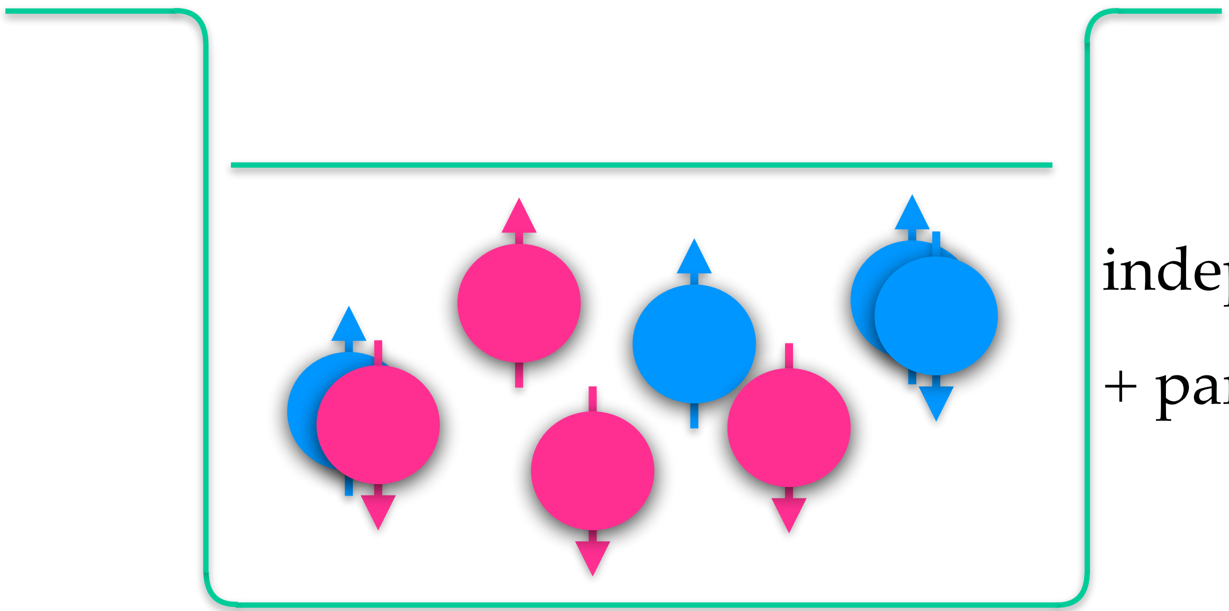
pairing in the ground state W.F.



independent particles

+ paring interactions

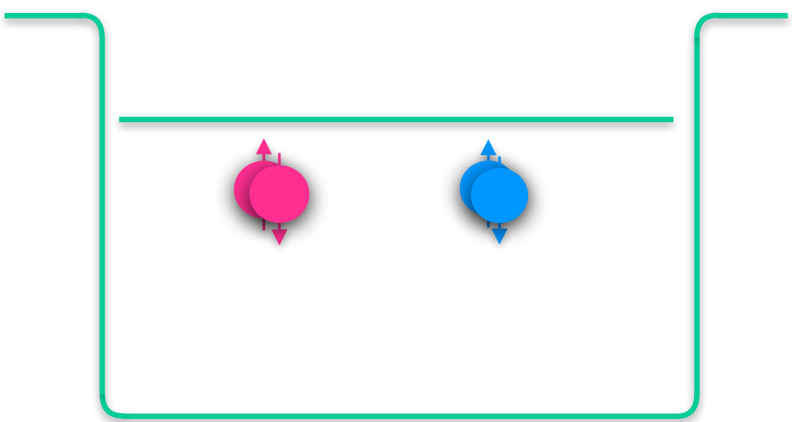
pairing in the ground state W.F.

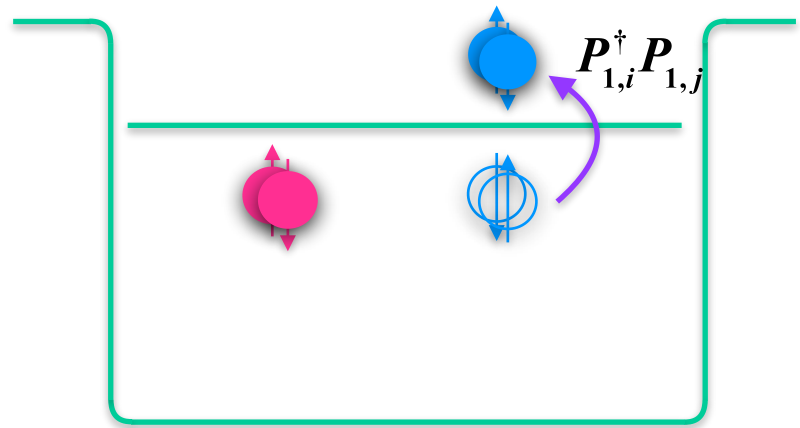


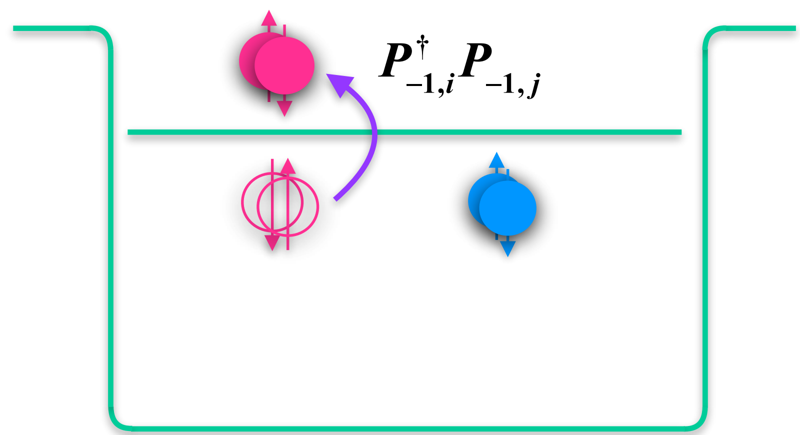
independent particles

+ paring interactions

pairing in the ground state W.F.





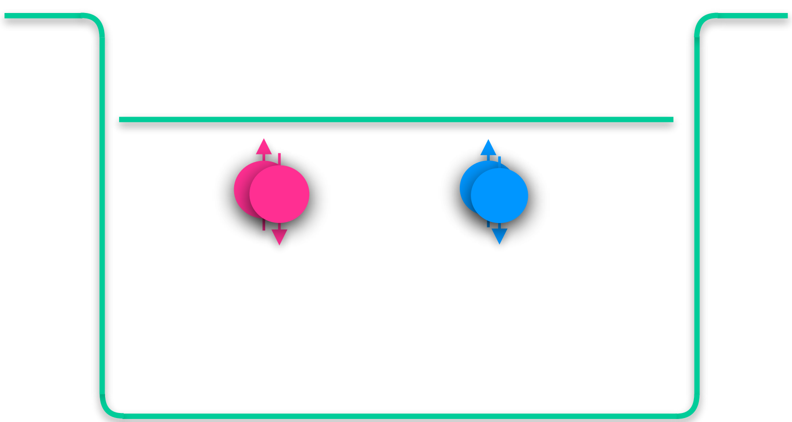


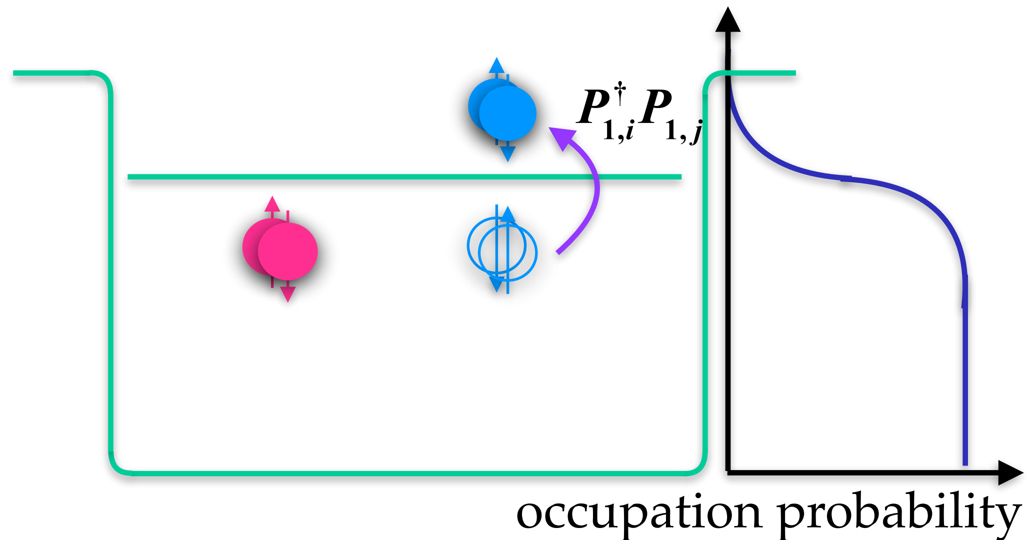
$$P^{\dagger}_{1,i} = \nu^{\dagger}_{i}\nu^{\dagger}_{\bar{i}}$$

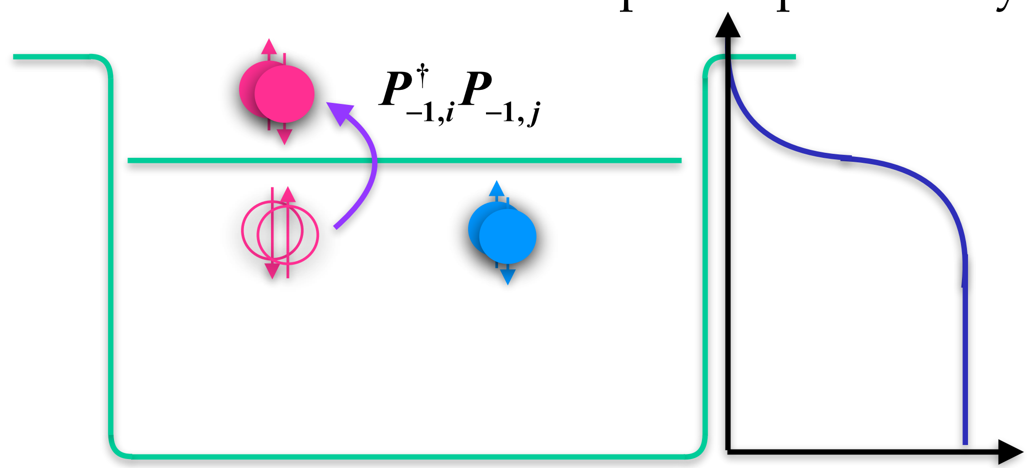
$$P^{\dagger}_{-1,i} = \pi^{\dagger}_{i}\pi^{\dagger}_{\bar{i}}$$

isovector "pairing" correlation
= BCS type correlation

pairing in the ground state W.F.





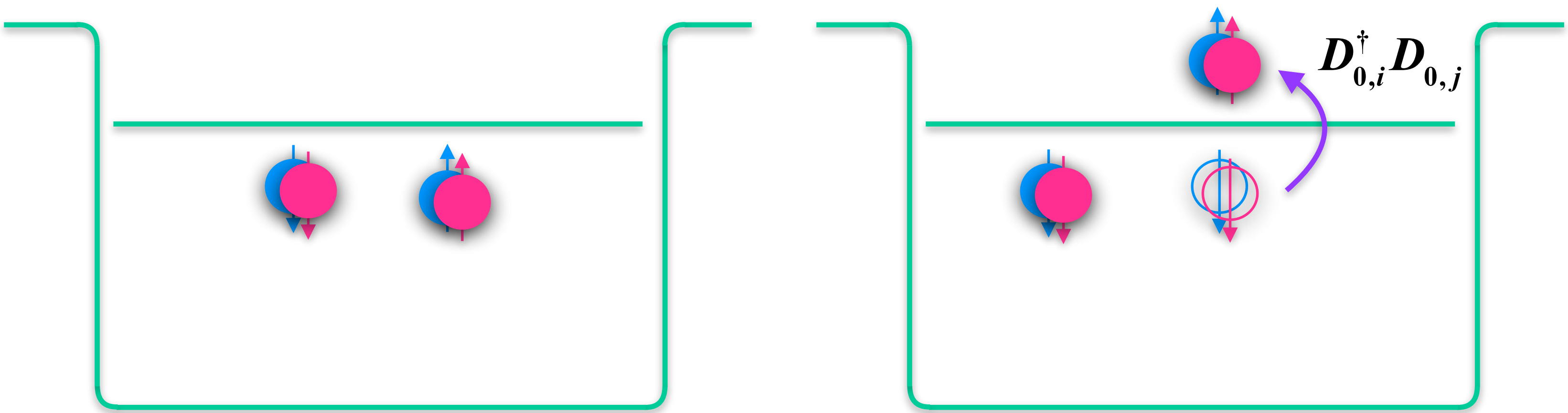


$$P^\dagger_{1,i} = \nu^\dagger_i \nu^\dagger_{\bar{i}}$$

$$P^\dagger_{-1,i} = \pi^\dagger_i \pi^\dagger_{\bar{i}}$$

isovector “pairing” correlation
= BCS type correlation

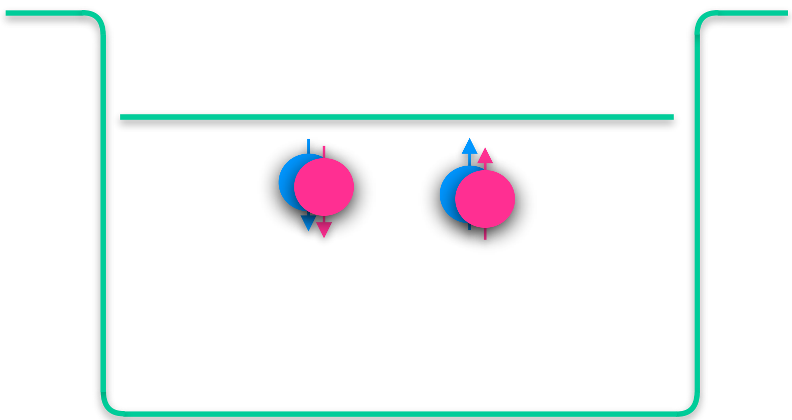
np pairing in the ground state W.F.

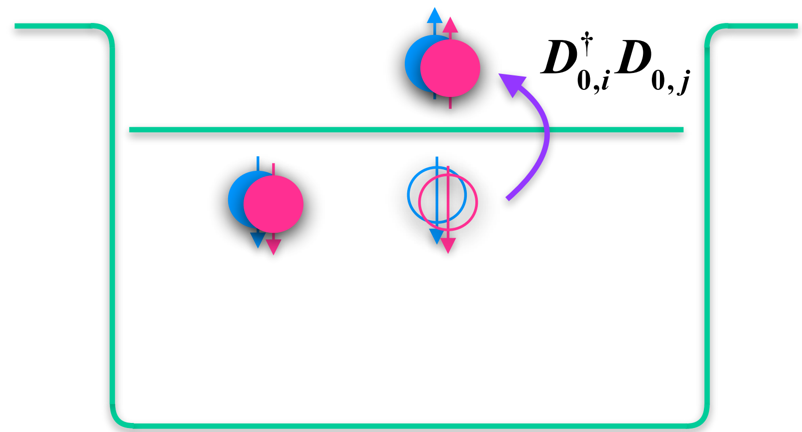


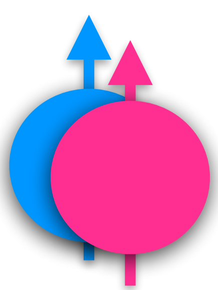
$$D^\dagger_{0,i} = \frac{1}{\sqrt{2}}\left(\nu^\dagger_i \pi^\dagger_{\bar{i}} - \pi^\dagger_i \nu^\dagger_{\bar{i}}\right)$$

isoscalar "pairing" correlation by *e.g.* tensor interaction

np pairing in the ground state W.F.





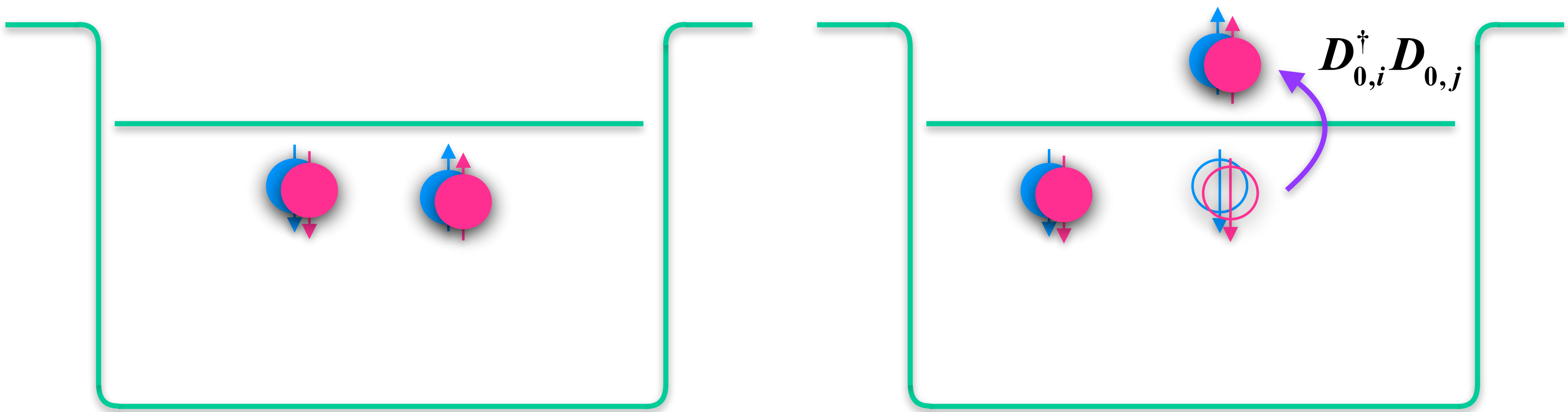


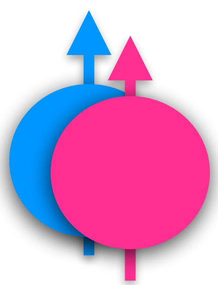
n-spin and *p*-spin: aligned

$$\langle \vec{s}_n \cdot \vec{s}_p \rangle > 0$$

isoscalar "pairing" correlation by *e.g.* tensor interaction

np pairing in the ground state W.F.



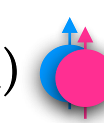


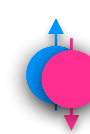
n-spin and *p*-spin: aligned

isoscalar "pairing" correlation by *e.g.* tensor correlation

$$\langle \vec{s}_n \cdot \vec{s}_p \rangle > 0$$

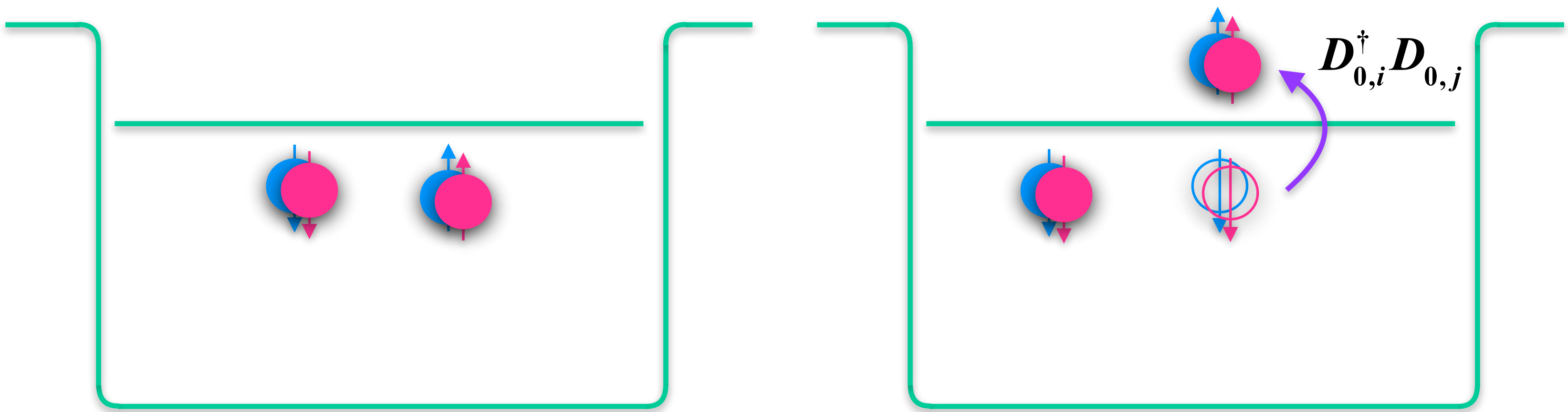
$$\langle \vec{s}_n \cdot \vec{s}_p \rangle = \begin{cases} +\dfrac{1}{4} & \text{for IS } np \text{ pair (deuteron)} \\ -\dfrac{3}{4} & \text{for IV } np \text{ pair} \end{cases}$$



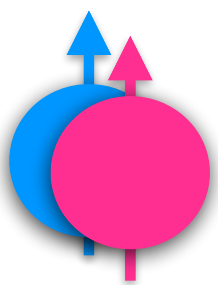


$$\vec{S}^2 = \left(\vec{s}_n + \vec{s}_p\right)^2 = \vec{s}_n^{\,2} + \vec{s}_p^{\,2} + 2\vec{s}_n \cdot \vec{s}_p$$

np pairing in the ground state W.F.



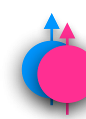
isoscalar "pairing" correlation
by *e.g*. tensor interaction

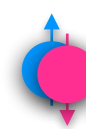


n-spin and *p*-spin:
aligned

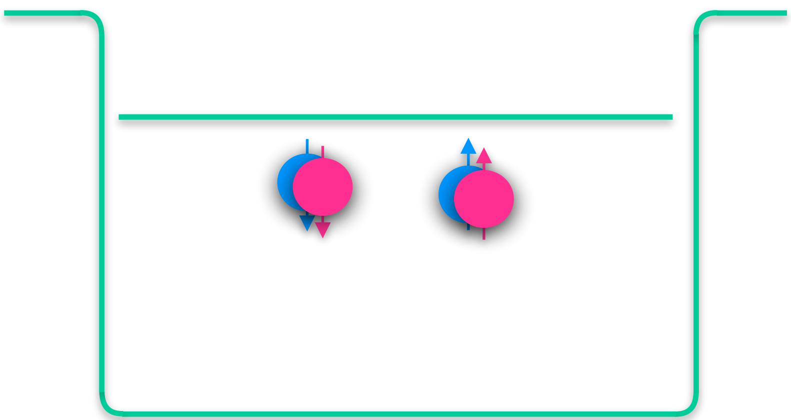
$$\left\langle \vec{s}_n \cdot \vec{s}_p \right\rangle > 0$$

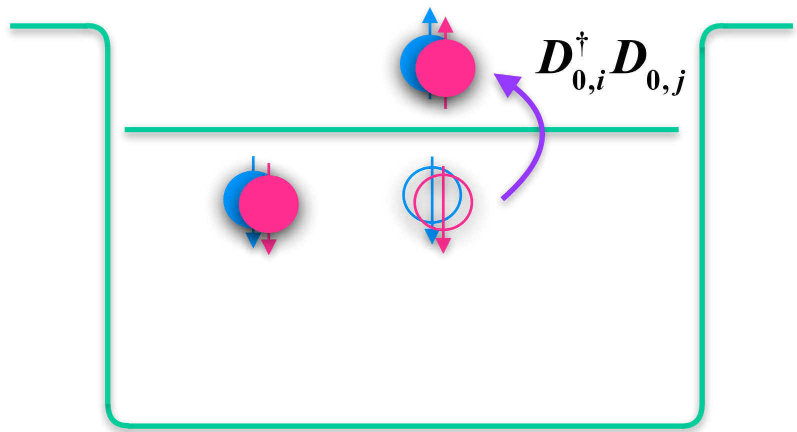
$$\left\langle \vec{s}_n \cdot \vec{s}_p \right\rangle = \begin{cases} +\dfrac{1}{4} & \text{for IS } np \text{ pair (deuteron)} \quad \text{statistical weight} = 3 \\ -\dfrac{3}{4} & \text{for IV } np \text{ pair} \quad \text{statistical weight} = 1 \end{cases}$$

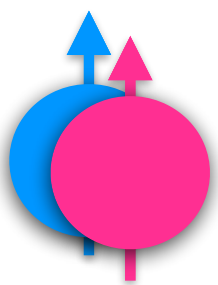




np pairing in the ground state W.F.







n-spin and *p*-spin: aligned

$$\langle \vec{s}_n \cdot \vec{s}_p \rangle > 0$$

isoscalar "pairing" correlation by *e.g.* tensor interaction

induces correlation between the directions of the *n*-spin and *p*-spin

***np* spin-spin correlation**

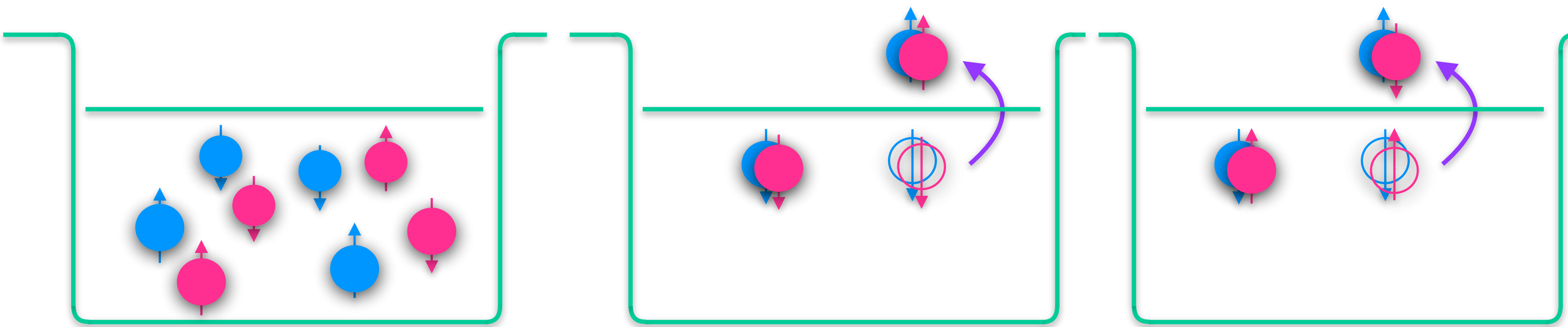
np spin-spin correlation function

$$\vec{S}_n \equiv \sum_i^N \vec{s}_{n,i} \qquad \vec{S}_p \equiv \sum_i^Z \vec{s}_{p,i}$$

$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle$: np spin-spin correlation function of the nuclear ground state

$$\vec{S}_n \equiv \sum_i^N \vec{s}_{n,i} \qquad \vec{S}_p \equiv \sum_i^Z \vec{s}_{p,i}$$

$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle$: *np* spin-spin correlation function of the nuclear ground state



unperturbed ground state	IS *np* pairing	IV *np* pairing
$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle = 0$	$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle > 0$	$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle < 0$

also for IV pp/nn parings

Relation of the *np* Spin-Spin Correlation Function to the Sum-Rule values of the IS/IV spin-M1 SNMEs

$$\vec{S}_n + \vec{S}_p = \sum_i^A \frac{1}{2}\vec{\sigma}_i$$

$$\vec{S}_n - \vec{S}_p = \sum_i^A \frac{1}{2}\vec{\sigma}_i \tau_z$$

$$\left\langle \left(\vec{S}_n - \vec{S}_p\right)^2 \right\rangle = \frac{1}{4}\left\langle \left(\vec{\sigma}\tau_z\right)^2 \right\rangle$$

$$= \frac{1}{4}\sum_f \langle 0|\vec{\sigma}\tau_z|f\rangle\langle f|\vec{\sigma}\tau_z|0\rangle$$

closure

$$= \frac{1}{4}\sum_f \left|\langle f|\vec{\sigma}\tau_z|0\rangle\right|^2$$

$$= \frac{1}{4}\boxed{\sum\left|M\left(\vec{\sigma}\tau_z\right)\right|^2}$$

IV spin-M1 squared nuclear matrix elements (SNME)

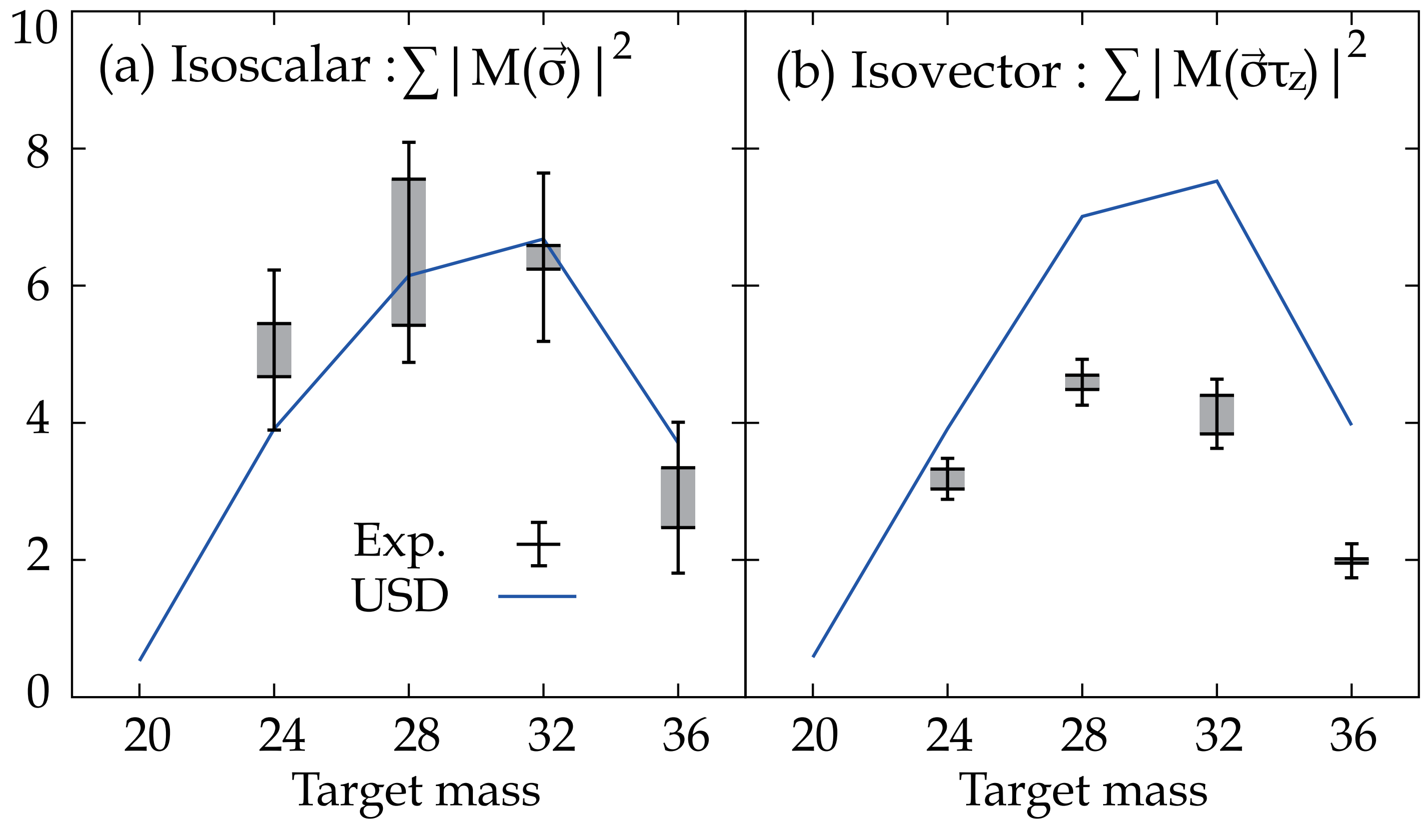
$$\left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 \right\rangle = \frac{1}{4}\boxed{\sum\left|M\left(\vec{\sigma}\right)\right|^2}$$

IS spin-M1 SNME

$$\boxed{\begin{aligned}\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle &= \frac{1}{4}\left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 - \left(\vec{S}_n - \vec{S}_p\right)^2 \right\rangle \\ &= \frac{1}{16}\left(\sum\left|M\left(\vec{\sigma}\right)\right|^2 - \sum\left|M\left(\vec{\sigma}\tau_z\right)\right|^2\right)\end{aligned}}$$

$$\boxed{\begin{aligned}\left\langle \vec{S}_n^2 + \vec{S}_p^2 \right\rangle &= \frac{1}{4}\left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 + \left(\vec{S}_n - \vec{S}_p\right)^2 \right\rangle \\ &= \frac{1}{16}\left(\sum\left|M\left(\vec{\sigma}\right)\right|^2 + \sum\left|M\left(\vec{\sigma}\tau_z\right)\right|^2\right)\end{aligned}}$$

Squared Nuclear Matrix Elements (SNMEs) of IS and IV spin-M1 excitations

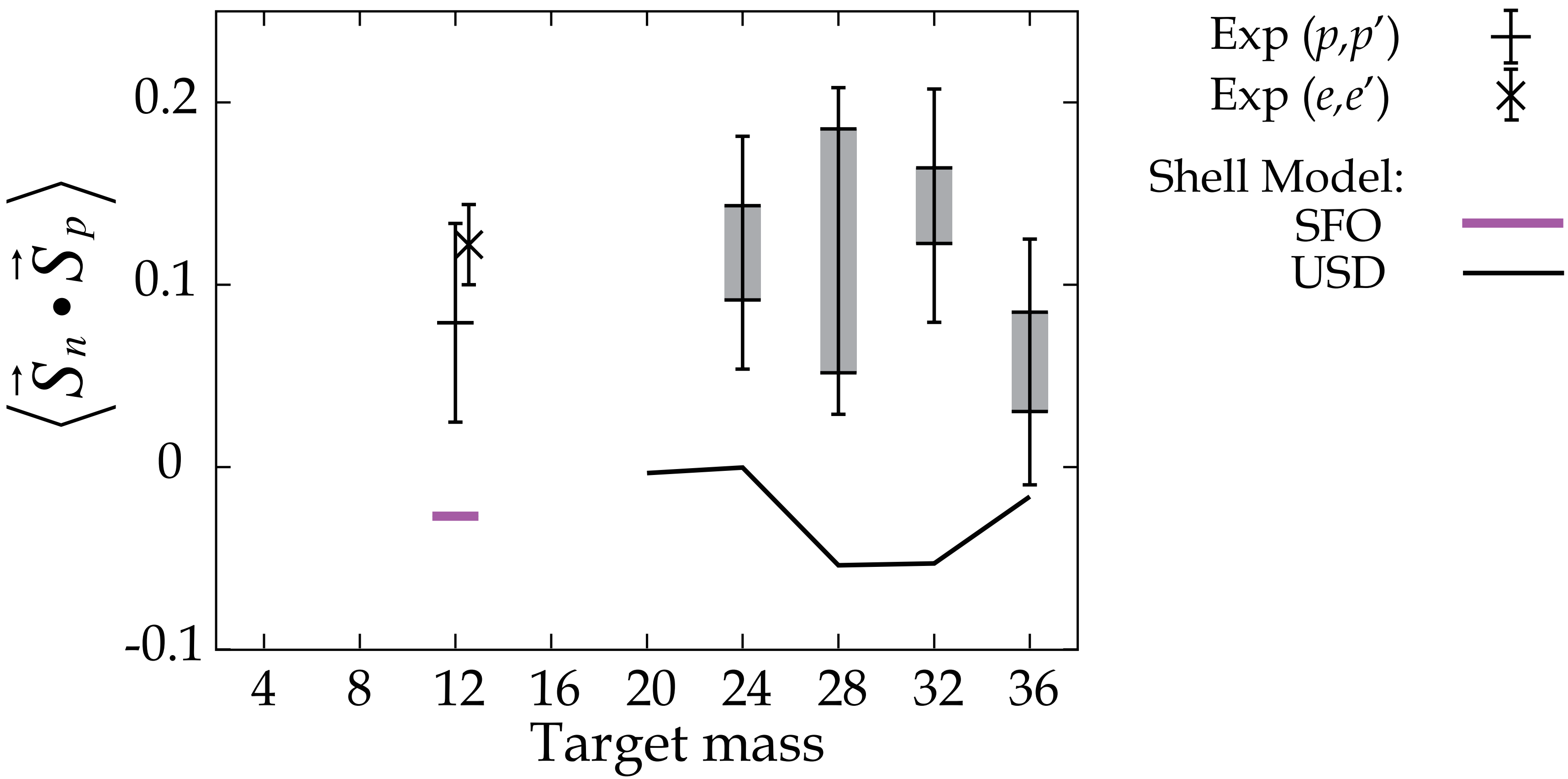


IV spin-M1 SNMEs are **quenching** from the shell model predication but **IS** spin-M1 SNMEs are **not**.

H. Matsubara, AT *et al.*, PRL2015

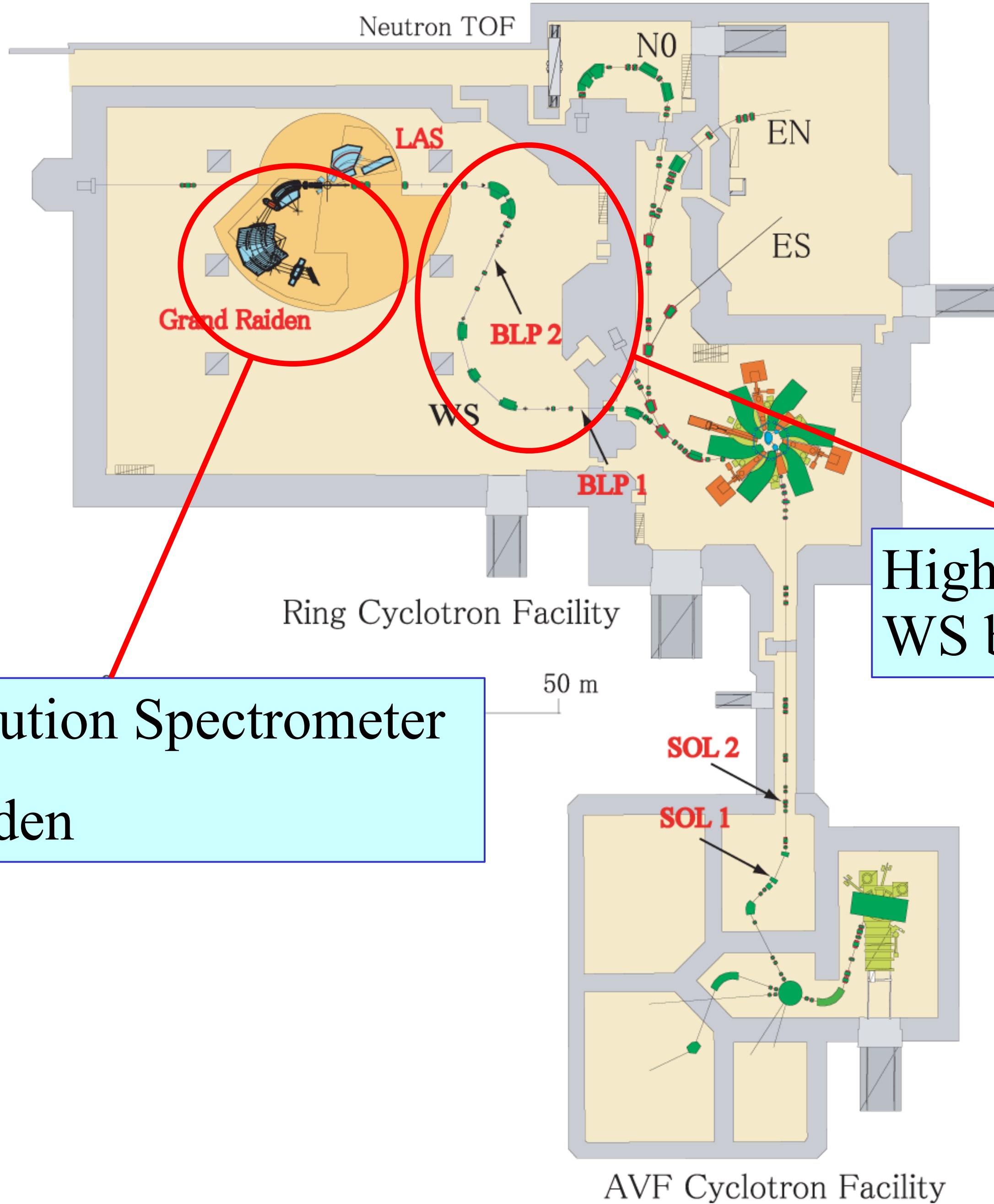
USD: Predications by Shell Model with the USD interaction.

np Spin-Spin Correlation Function



Experimental Methods

Research Center for Nuclear Physics, Osaka Univ.

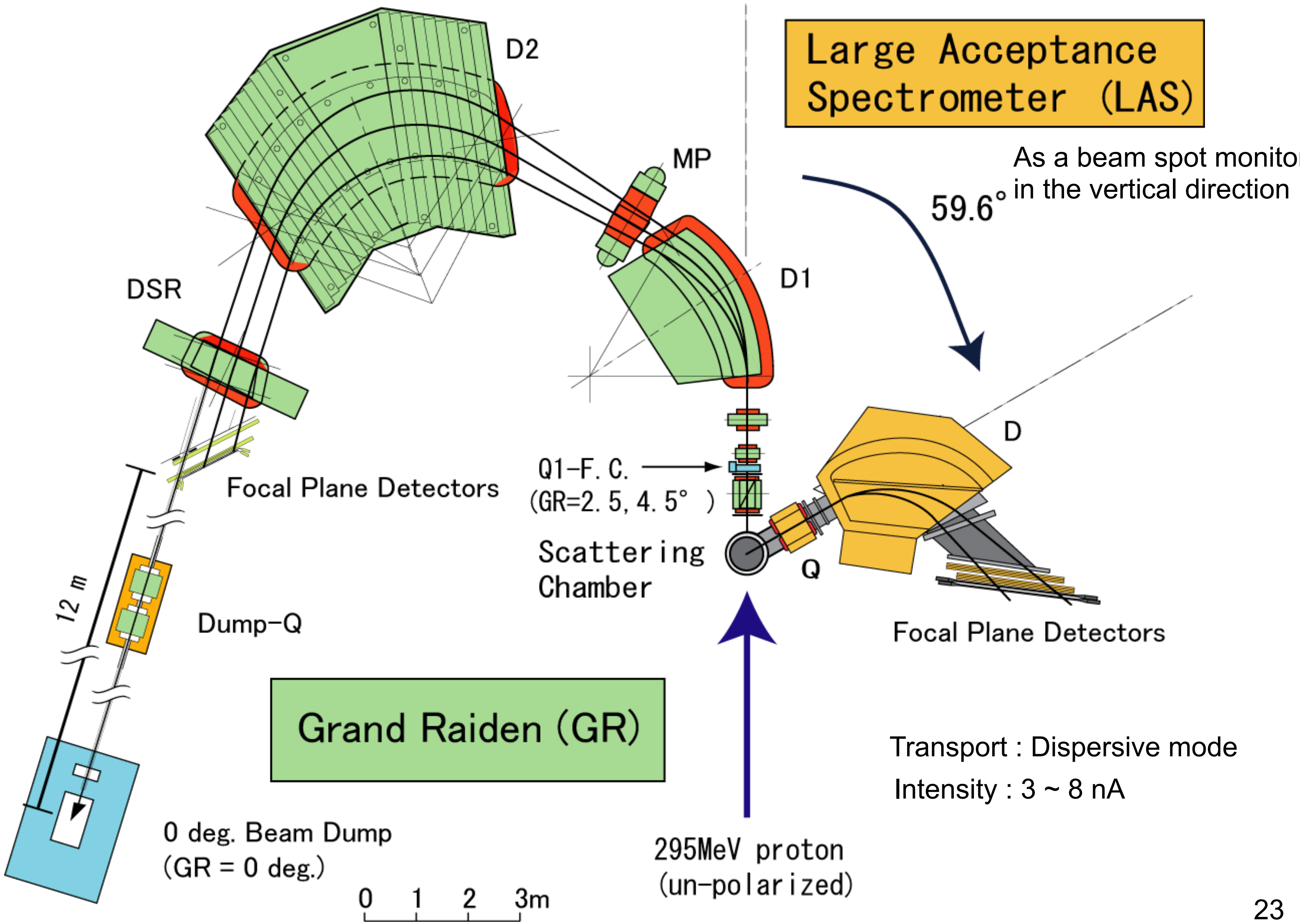


High-resolution WS beam-line

High-resolution Spectrometer

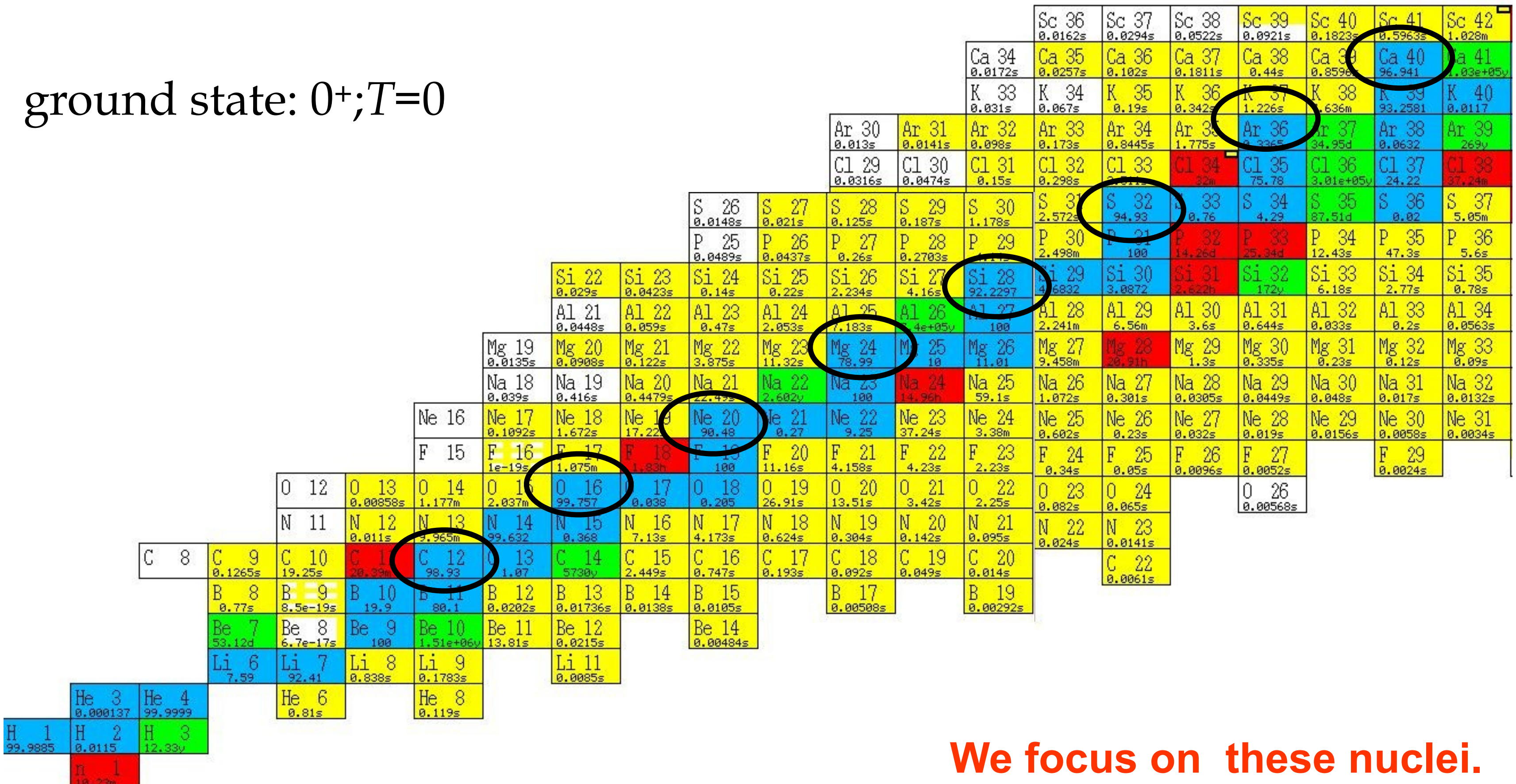
Grand Raiden

Spectrometer Setup for 0-deg (p,p') at RCNP



Self-Conjugate (N=Z) even-even Nuclei

ground state: $0^{+}; T=0$



We focus on these nuclei.

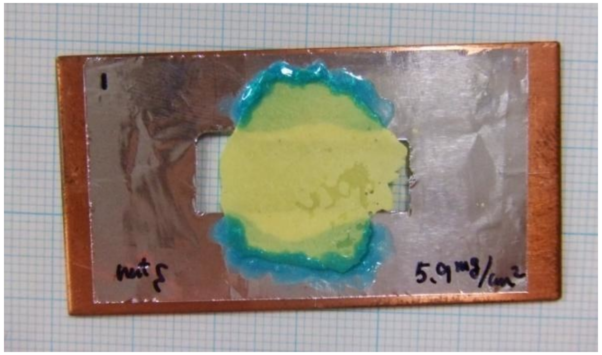
Stable self-conjugate even-even nuclei:

(^{4}He), ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca

Targets

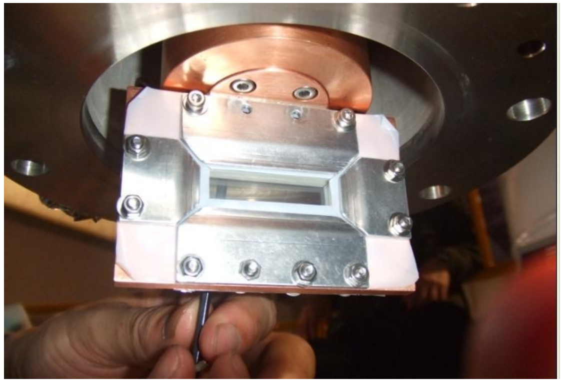
^{12}C, ^{24}Mg, ^{28}Si: self-supporting target

Cooled ^{32}S self-supporting target



H. Matsubara *et al.*, NIMB 267, 3682 (2009)

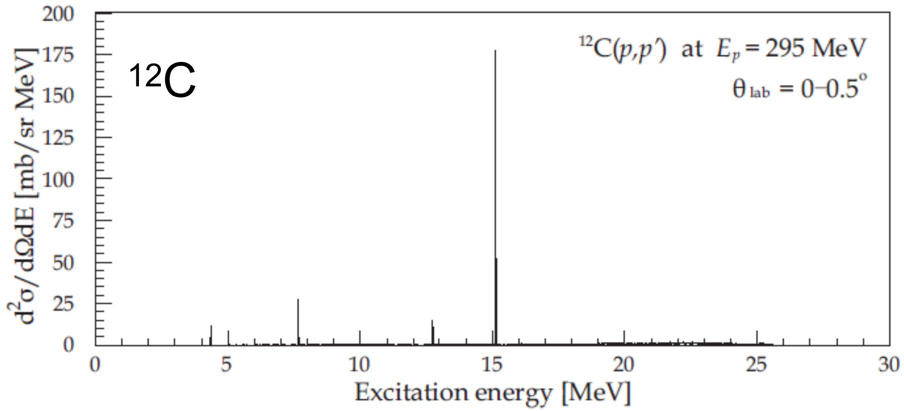
Gas Cell Target (^{36}Ar)

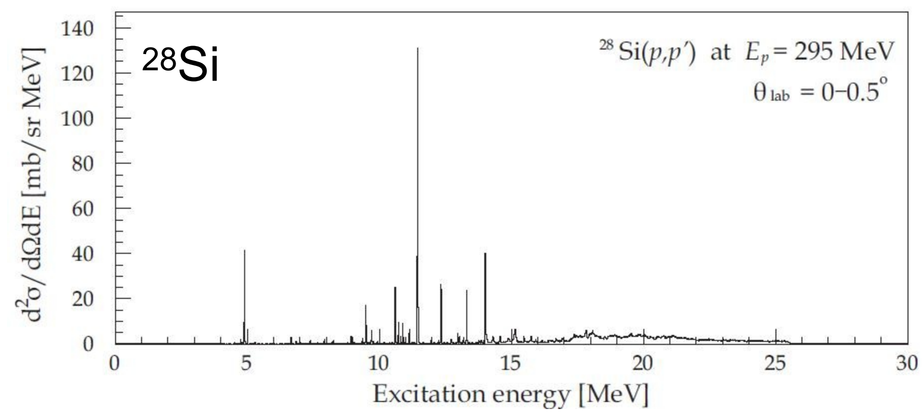


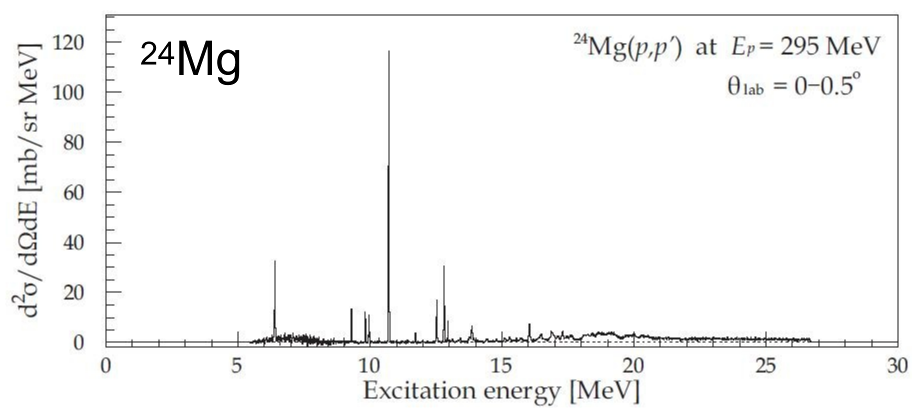
H. Matsubara *et al.*, NIMA 678, 122 (2012)

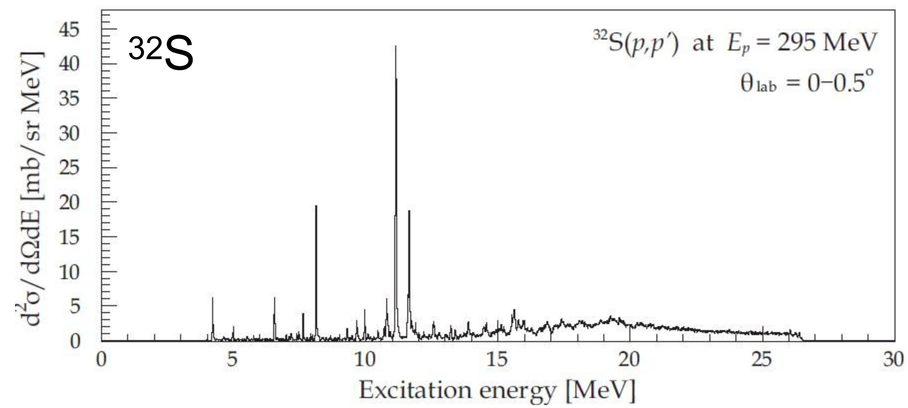
Aramide window of 6 μm^t

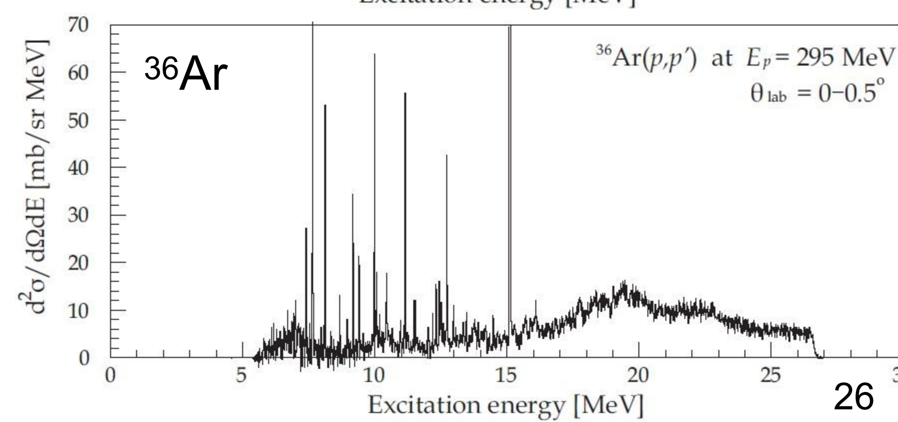
Energy spectra at 0-degrees







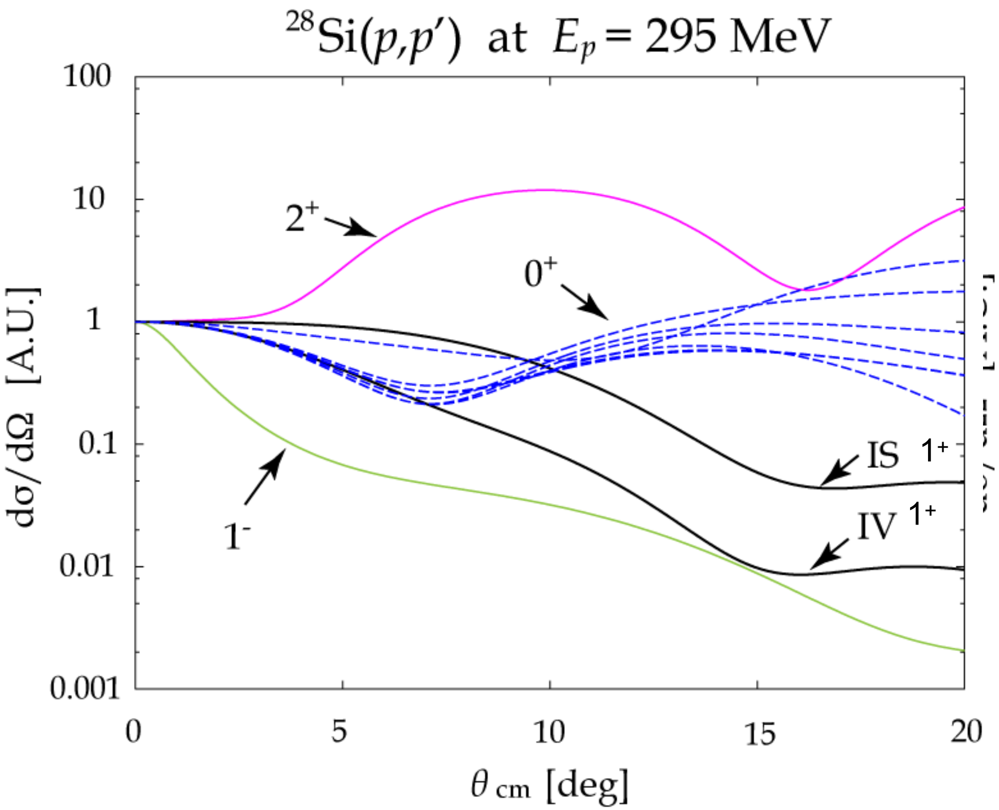


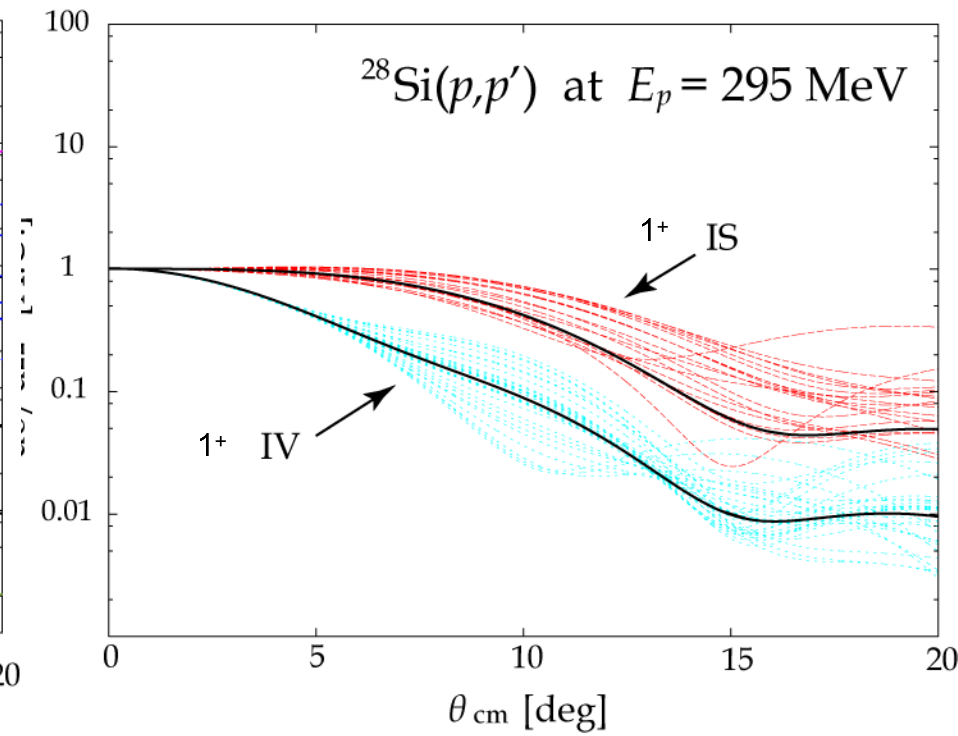


Angular distribution for J^{π} assignment

- Distorted wave Born approximation by DWBA07

Trans. density : USD, USDA, USDB (from shell model calculation)
NN interaction. : Franey and Love, PRC31(1985)488. (325 MeV data)

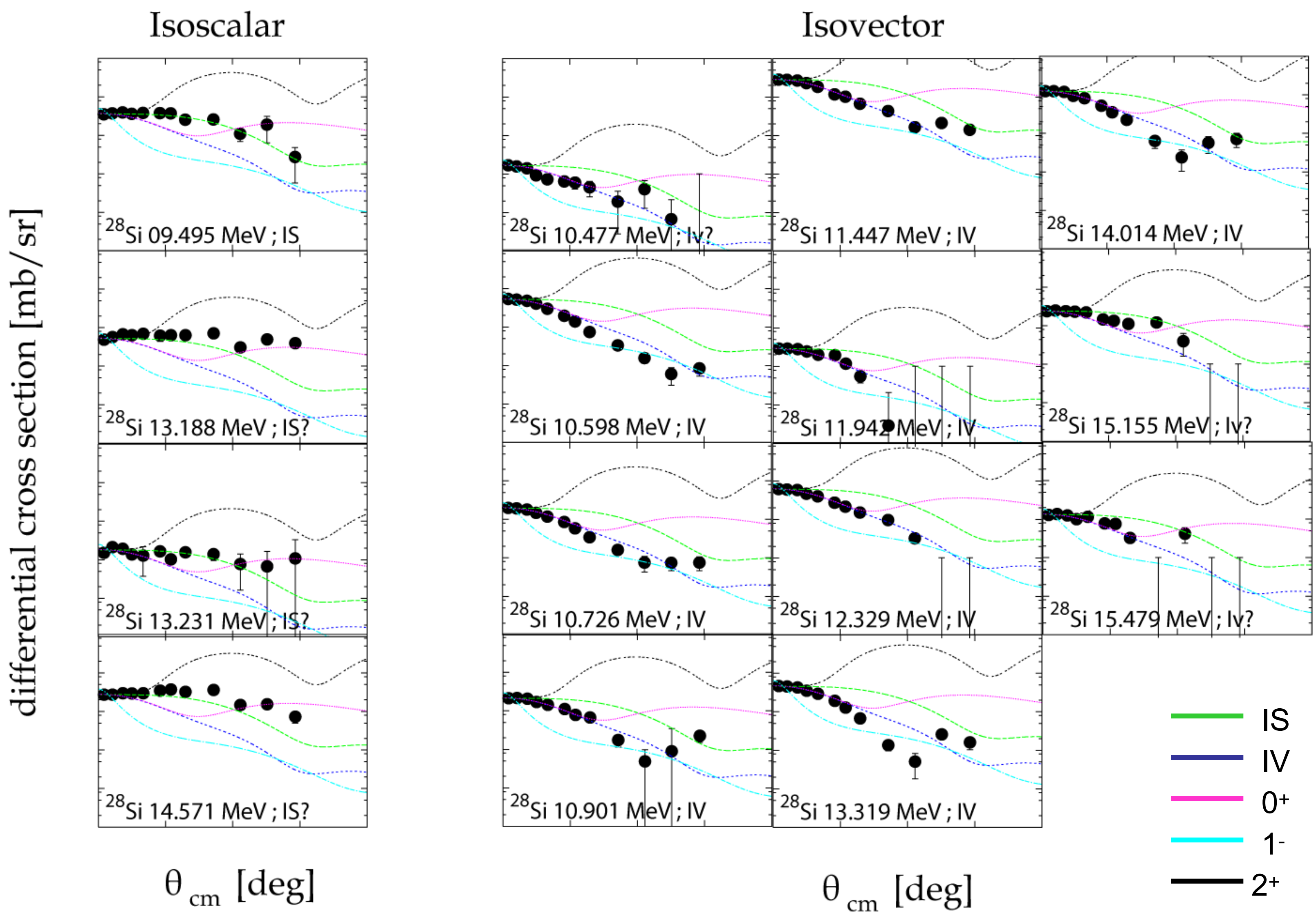




- Forward peaking for L=0 transition.
- *M1* has the maximum at 0 degree.
- 0^+, IS-1^+, IV-1^+ and others

- Distributions at 0-5 degree are similar.
- Difference between IS and IV is due to exchange tensor term.

IS, IV spin-*M1* angular dist. (^{28}Si)



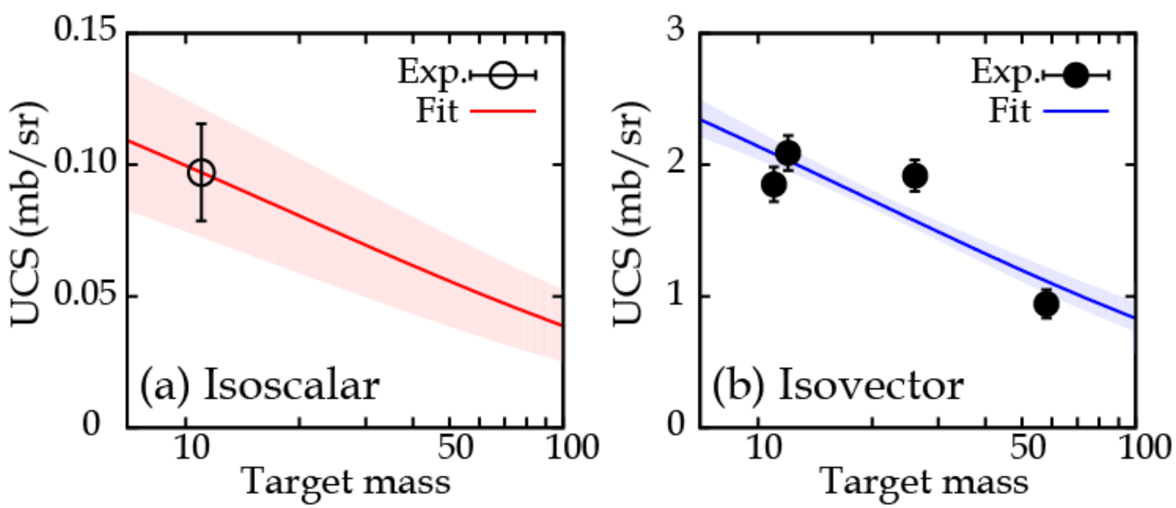
Unit cross section (UCS)

- Conversion factor from cross-section to Squared Nuclear Matrix Elements (SNME)
- Calibration from β andγ-decay measurements assuming the isospin symmetry

$$\frac{d\sigma}{d\Omega}(0^\circ) = \hat{\sigma}_T F_T(q, E_x) \left| M_f(\mathcal{O}_T) \right|^2$$

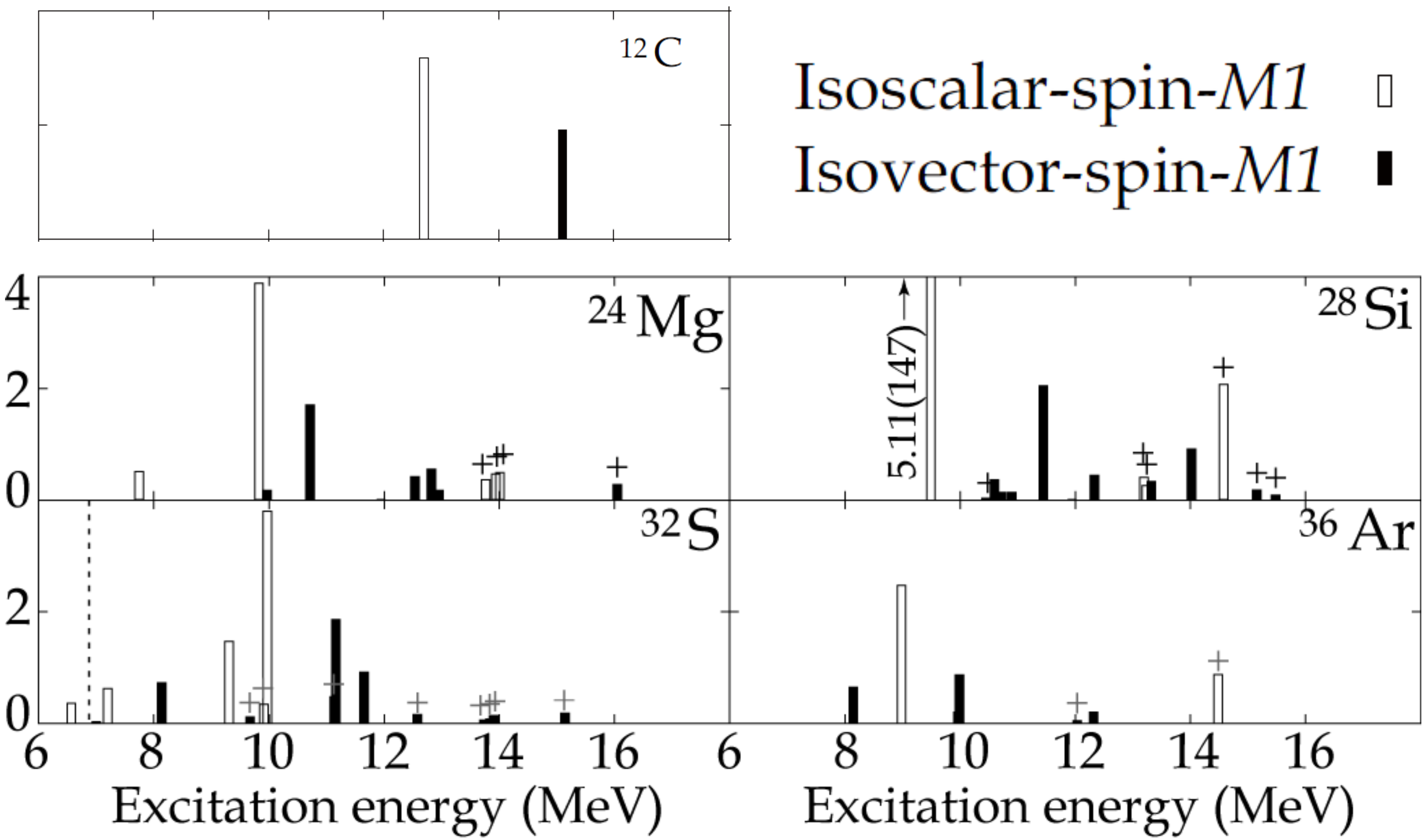
(T= IS or IV)

$$\hat{\sigma}_T(A) = N_T \exp\left(-x_T A^{1/3}\right)$$

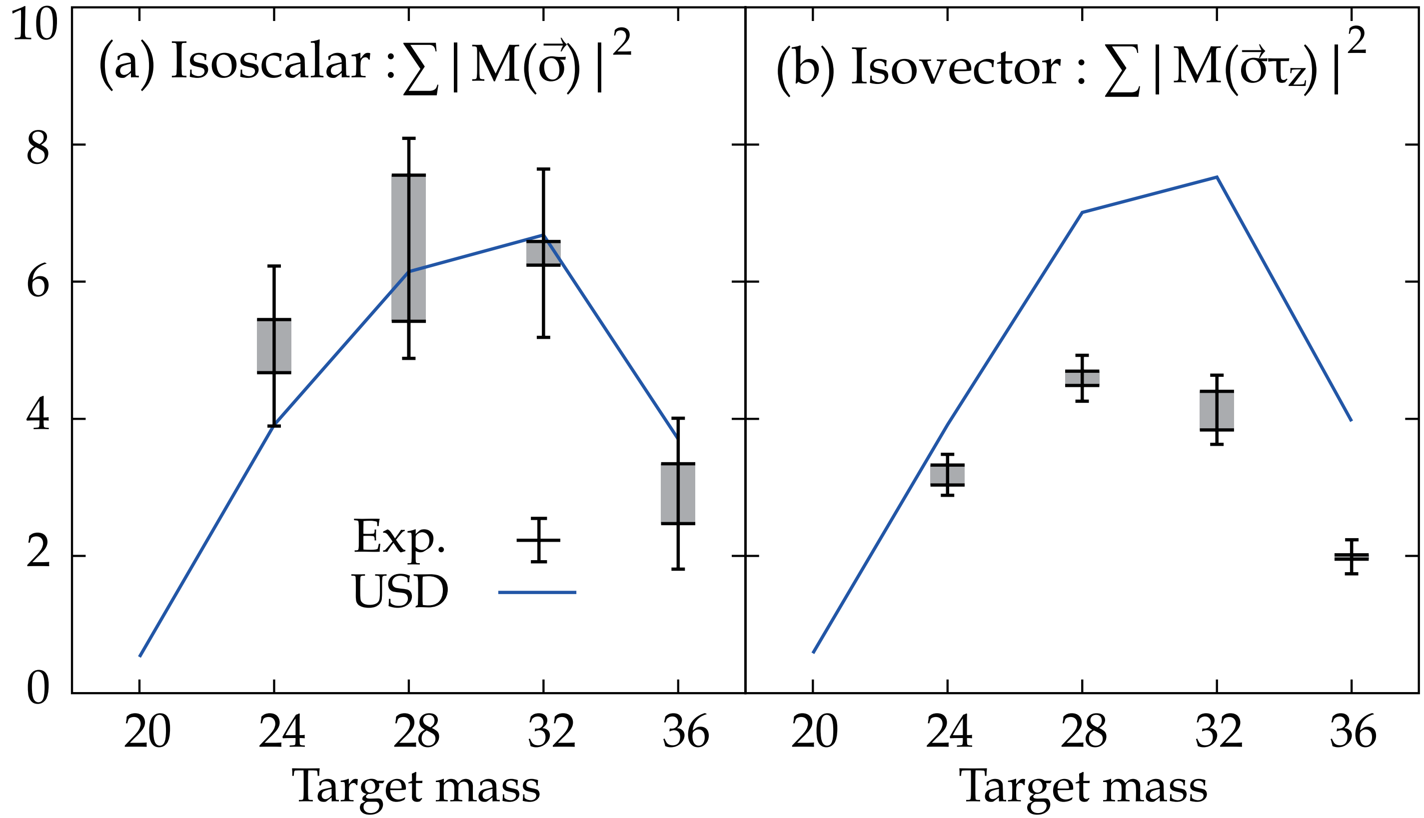


The same slope for IS is assumed as IV.

IS / IV-spin-M1 distribution



Squared Nuclear Matrix Elements (SNMEs) of IS and IV spin-M1 excitations

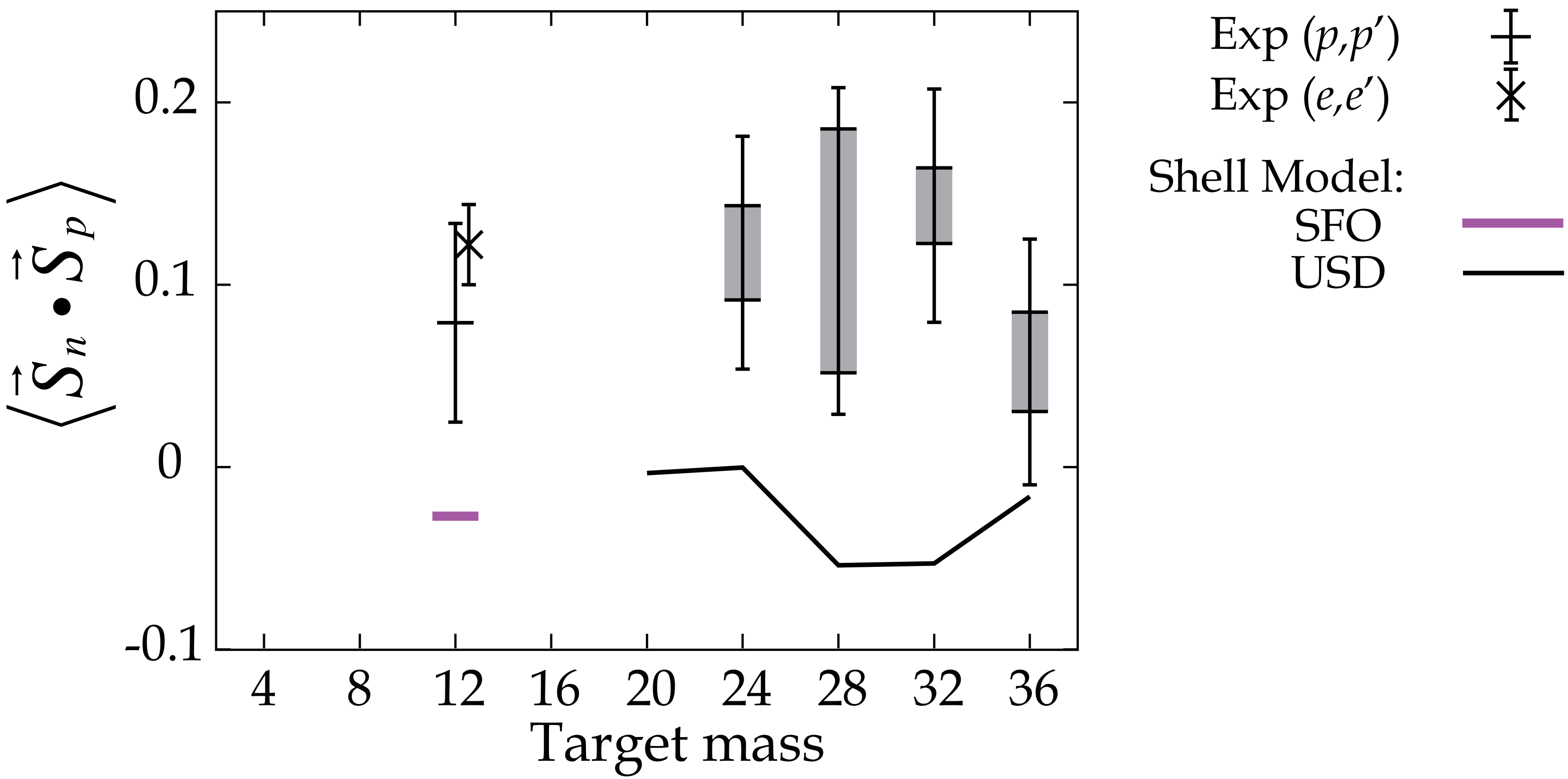


IV spin-M1 SNMEs are **quenching** from the shell model predication but **IS** spin-M1 SNMEs are **not**.

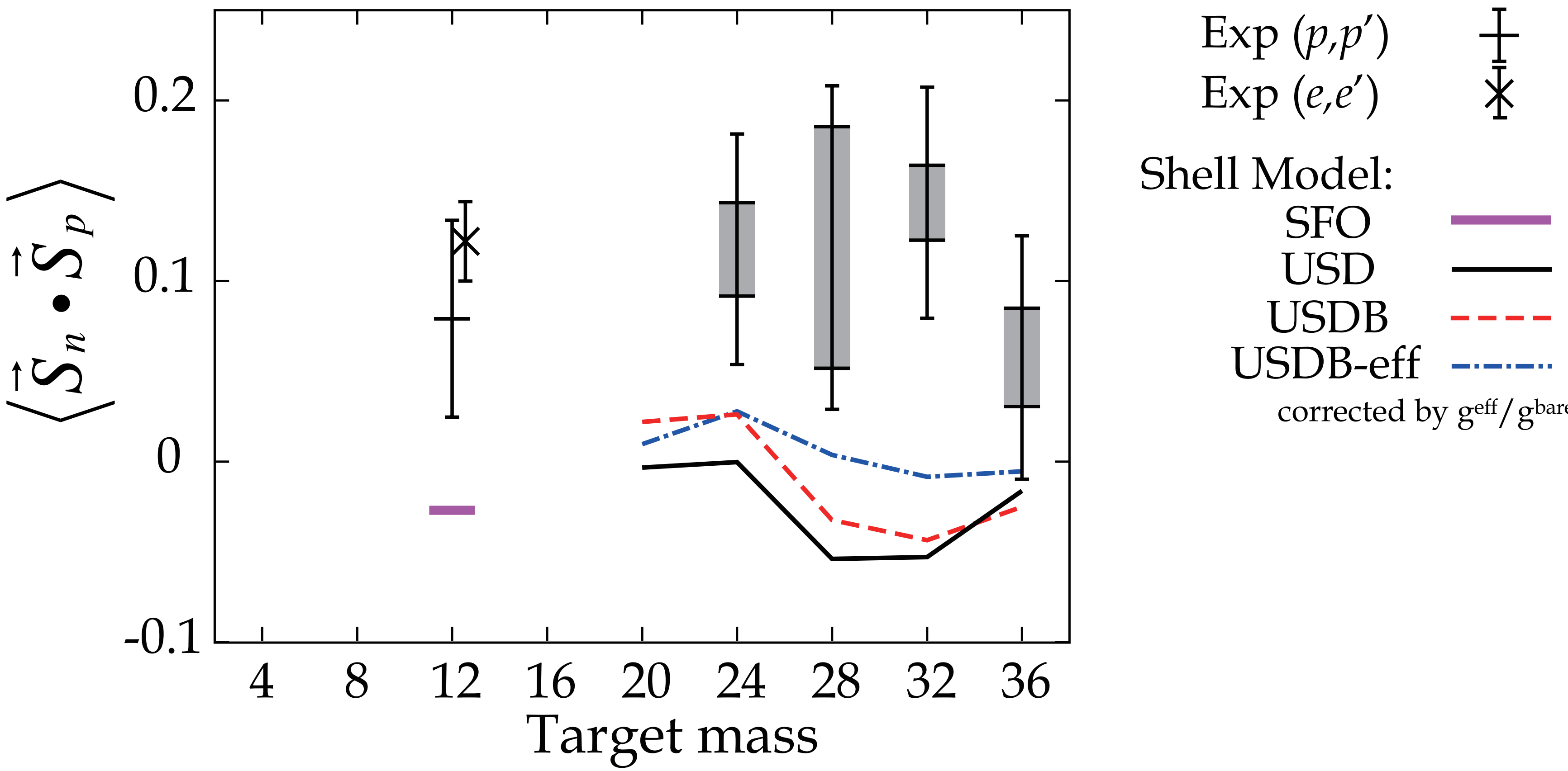
H. Matsubara, AT *et al.*, PRL2015

USD: Predications by Shell Model with the USD interaction.

np Spin-Spin Correlation Function



np Spin-Spin Correlation Function



Correlated Gaussian Calculation of the ^{4}He System with Realistic NN Interactions

by W. Horiuchi

Spin matrix elements of the ^{4}He ground state

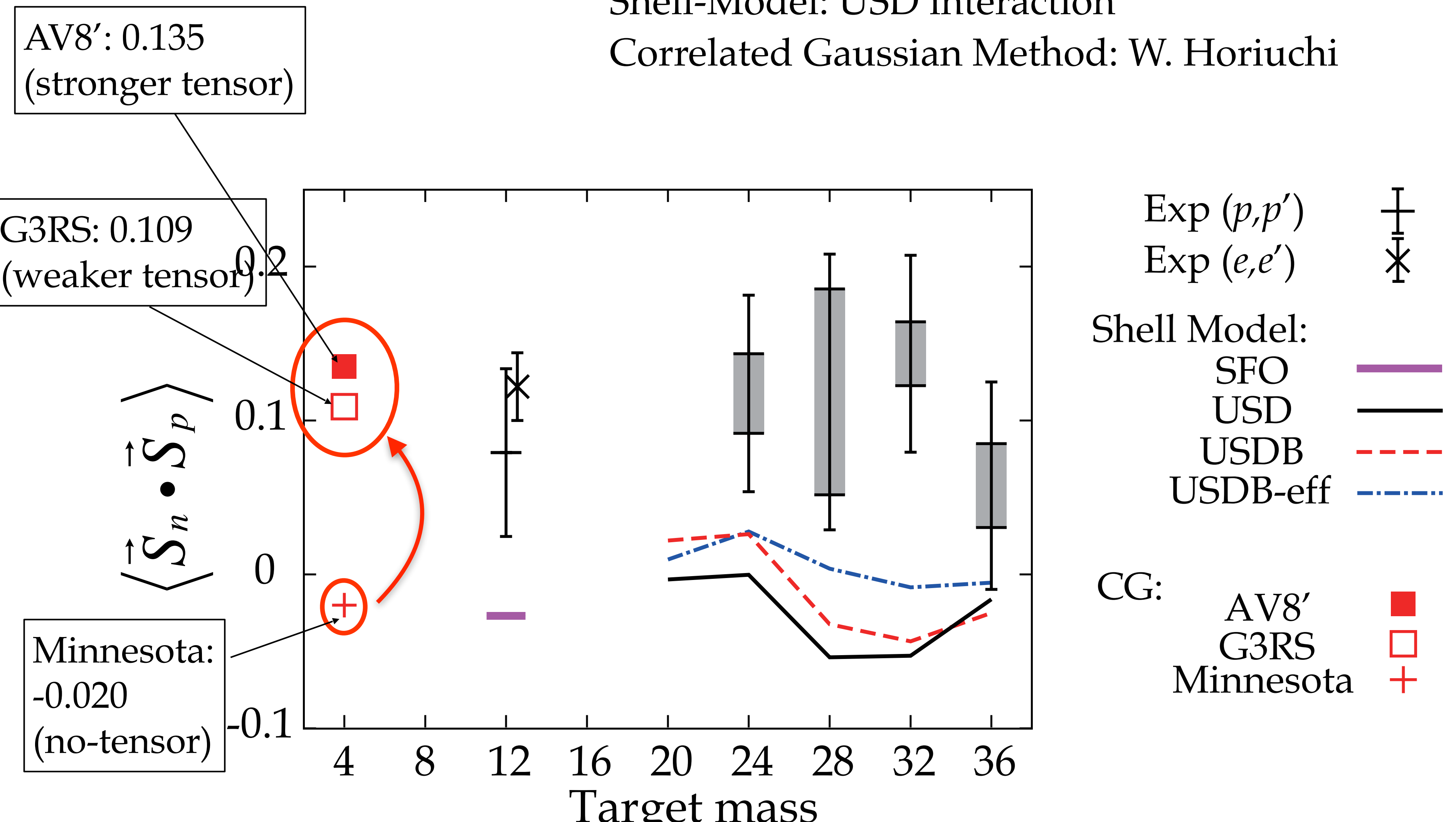
	$\langle \vec{S}_n^2 + \vec{S}_p^2 \rangle$	$\langle \vec{S}_n \cdot \vec{S}_p \rangle$	S=0	S=1	S=2
AV8' Stronger tensor int.	0.572	0.135	85.8%	0.4%	13.9%
G3RS Weaker tensor int.	0.465	0.109	88.5%	0.3%	11.3%
Minnesota No tensor int.	0.039	-0.020	100%	0%	0%

$$\vec{S} = \vec{S}_p + \vec{S}_n$$

Y. Suzuki, W. Horiuchi et al., FBS42, 33(2007)
H. Feldmeier, W. Horiuchi et al., PRC84, 054003(2011)

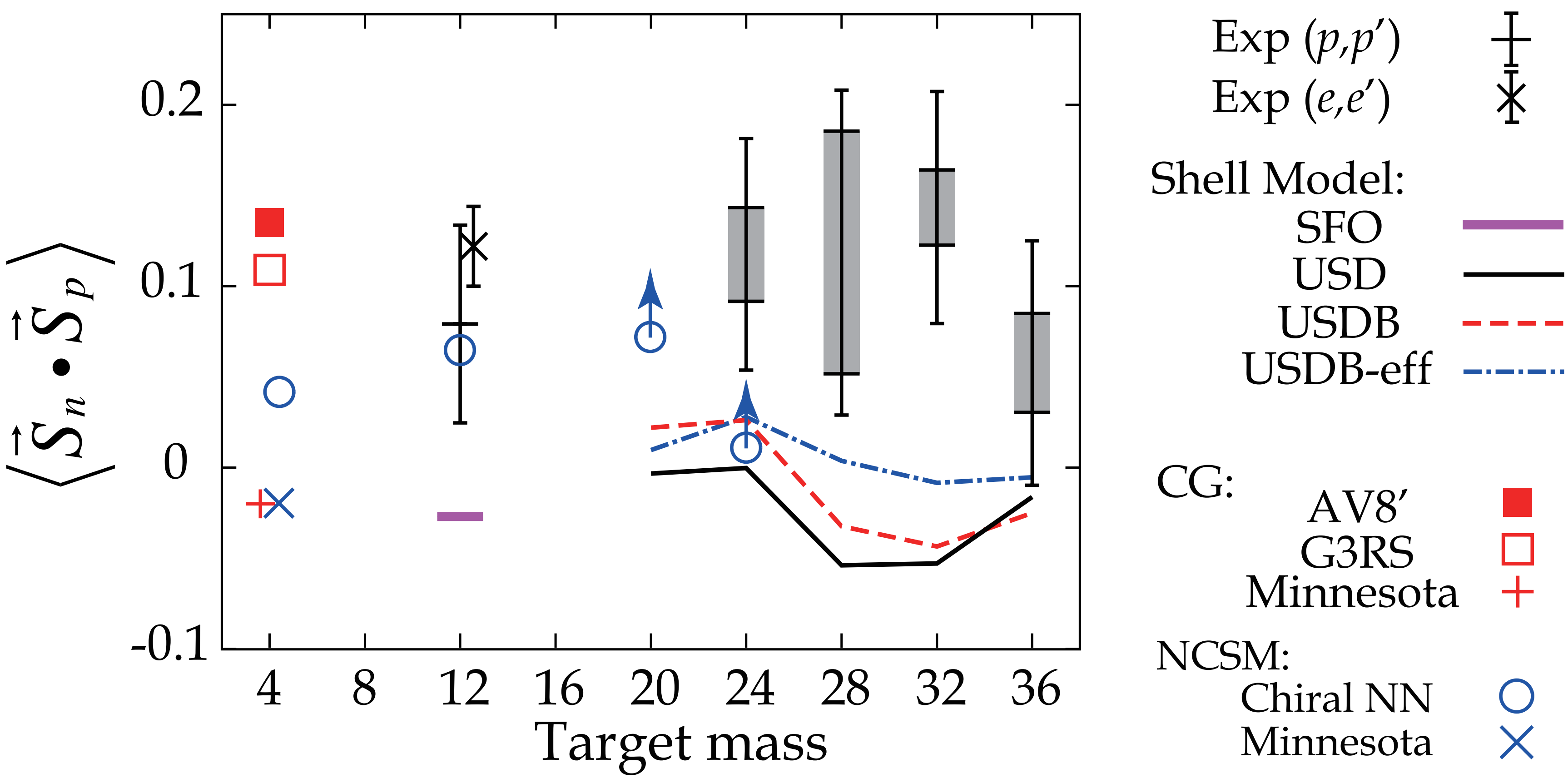
np Spin-Spin Correlation Function

Shell-Model: USD interaction
Correlated Gaussian Method: W. Horiuchi



np Spin-Spin Correlation Function

Shell-Model: USD interaction
Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil

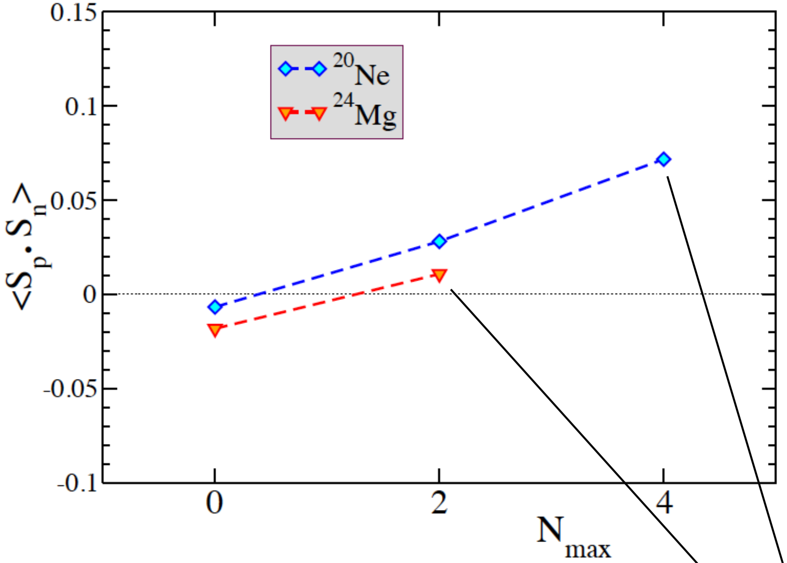


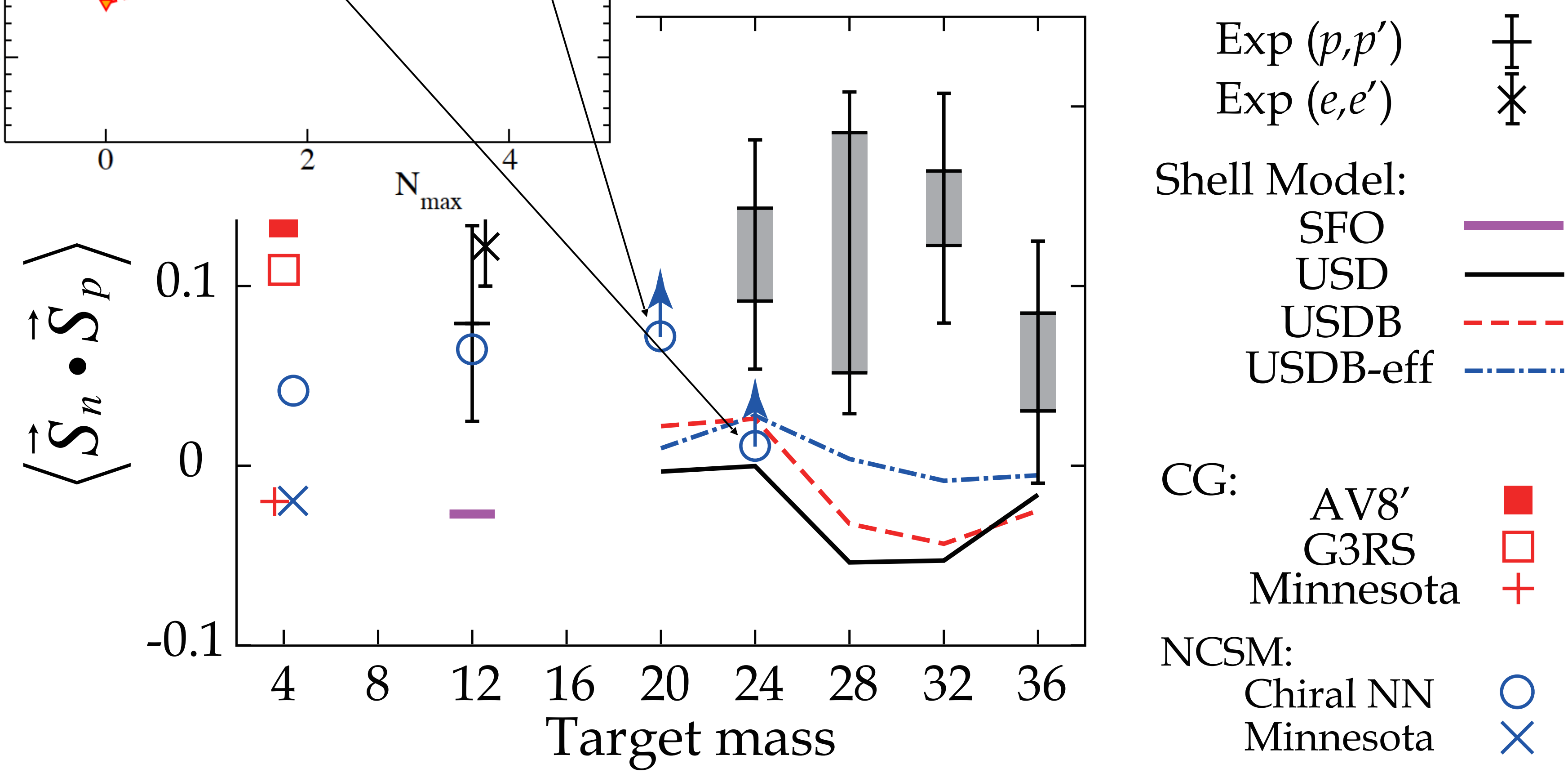
np Spin-Spin Correlation Function

ıell-Model: USD interaction

ɔrrelated Gaussian Method: W. Horiuchi

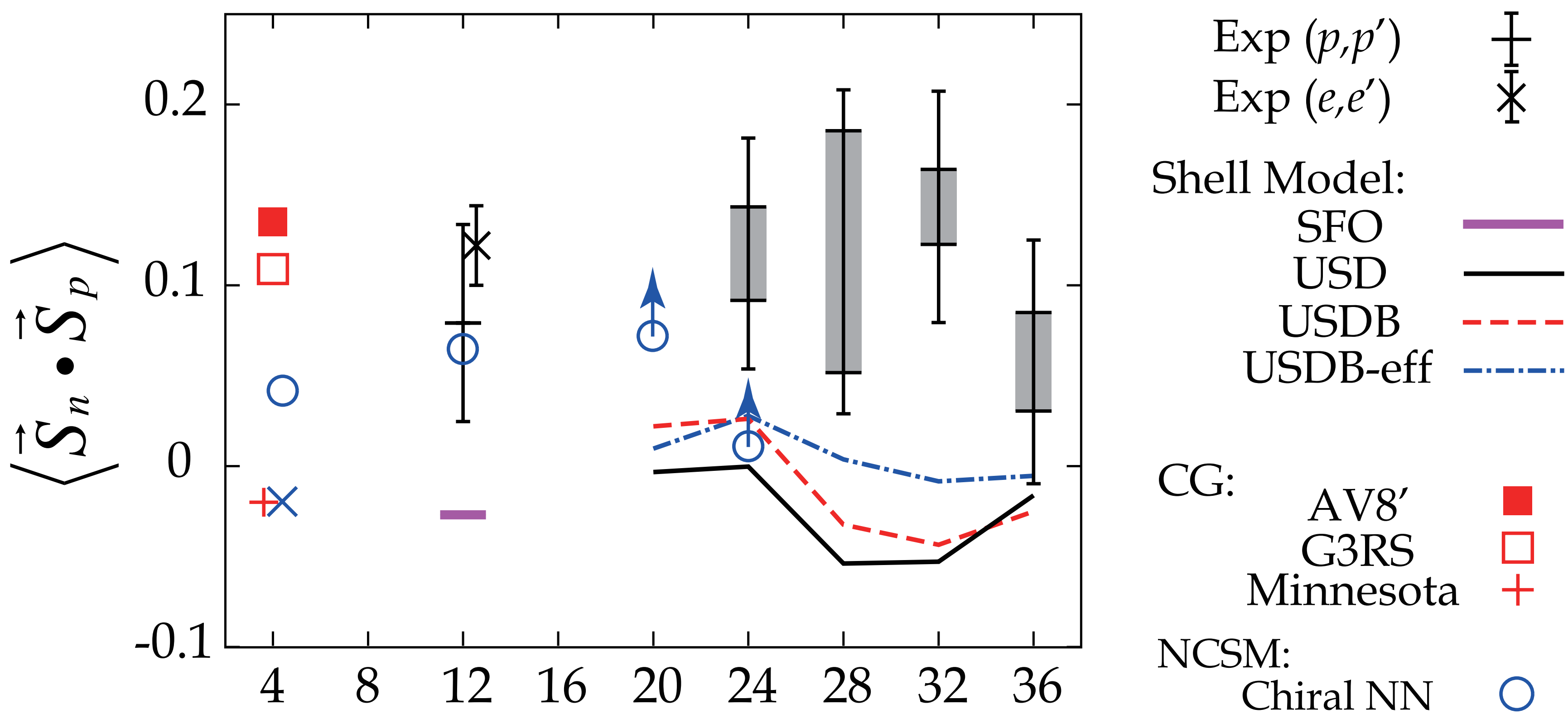
ɔn-Core Shell Model: P. Navratil





np Spin-Spin Correlation Function

Shell-Model: USD interaction
Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil



Further theoretical studies by ab-initio type calculations with realistic interactions are very interesting.

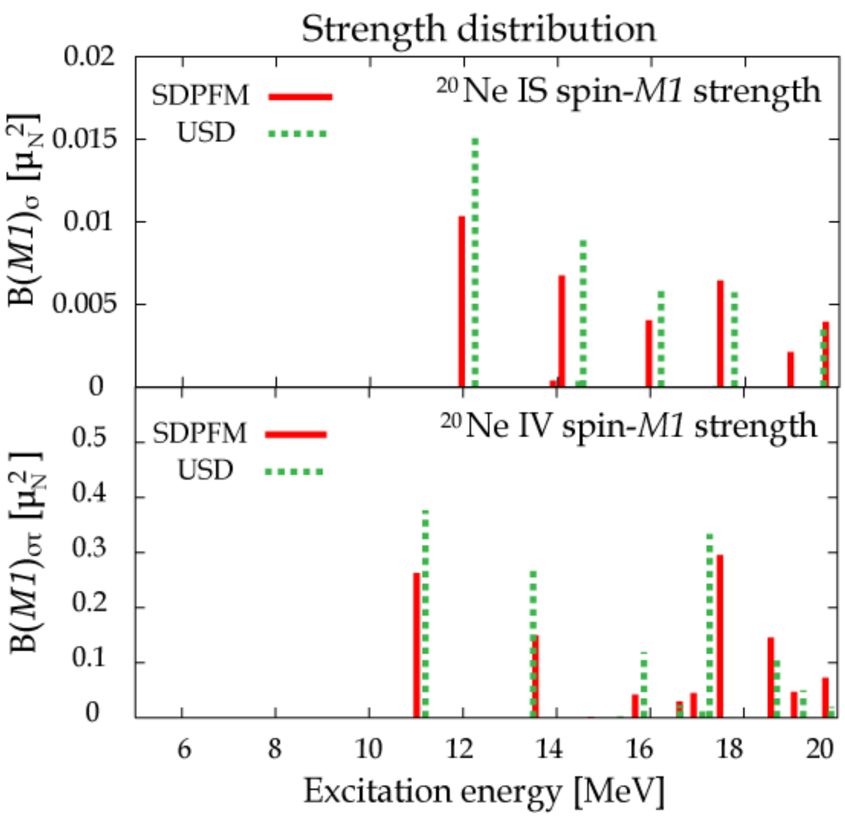
Discussion/Criticism

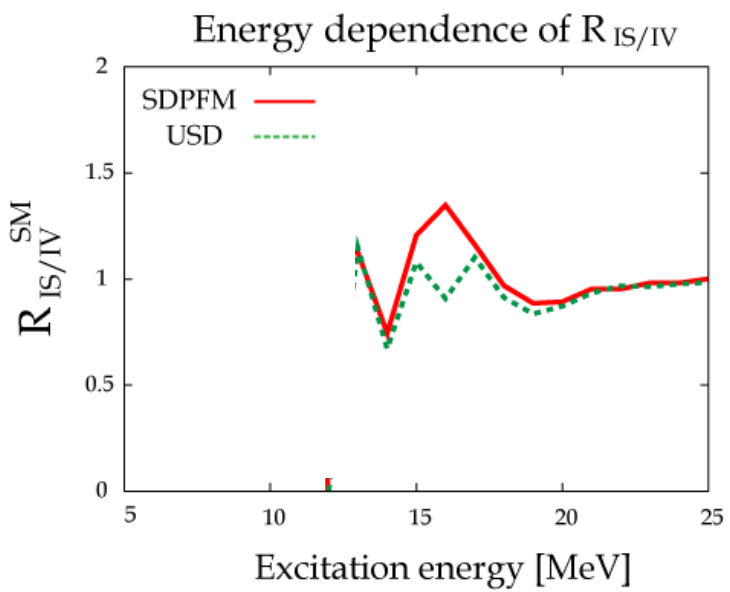
Model Space Dependence

No significant difference between *sd* and *sdpf* in the shell-model predictions for ^{20}Ne

The case of ^{20}Ne

USD = *sd*-shell
SDPFM = *sdpf*-shell





IS/IV Ratio to integrated up to the excitation energy of the horizontal axis.

Contribution from Strengths at Higher E_x.

No significant difference in the shell-model predictions.

Shell Model in sd-Shell, USD

	E_x<16.1MeV			E_x=all		
A	M(σ)	M(στ)	Diff	M(σ)	M(στ)	Diff
24	0.23	0.23	0.00	0.27	0.28	-0.01
28	0.37	0.42	-0.05	0.41	0.46	-0.05
32	0.40	0.45	-0.05	0.42	0.48	-0.06
36	0.22	0.24	-0.02	0.23	0.25	-0.02

~85% in Ex<16 MeV

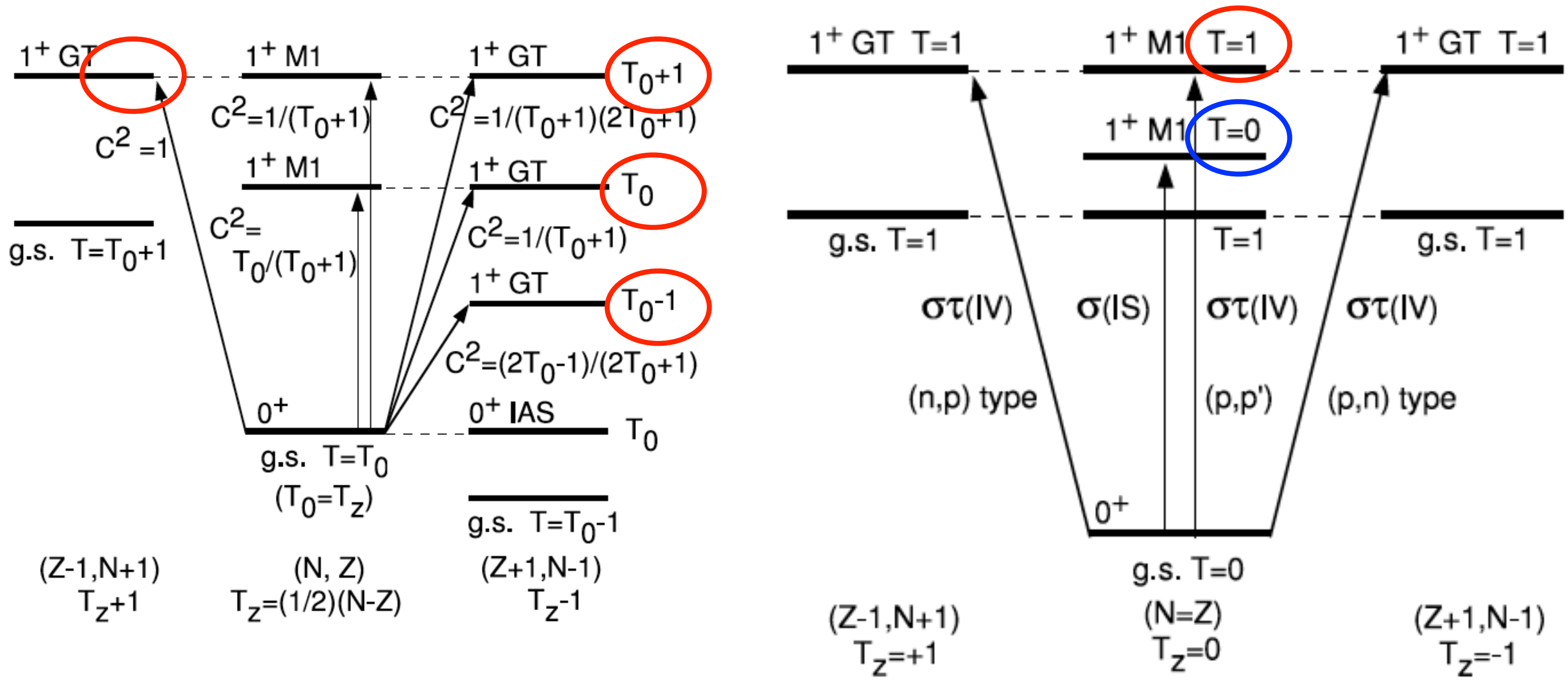
>90% in Ex<16 MeV

Measurement was done only below E_x=16 MeV.

Still a part of strength may be fragmented to upper excitation energies like B(GT).

Relation to the Ikeda Sum-Rule of GT transitions and their quenching

<u>No clear relation</u>



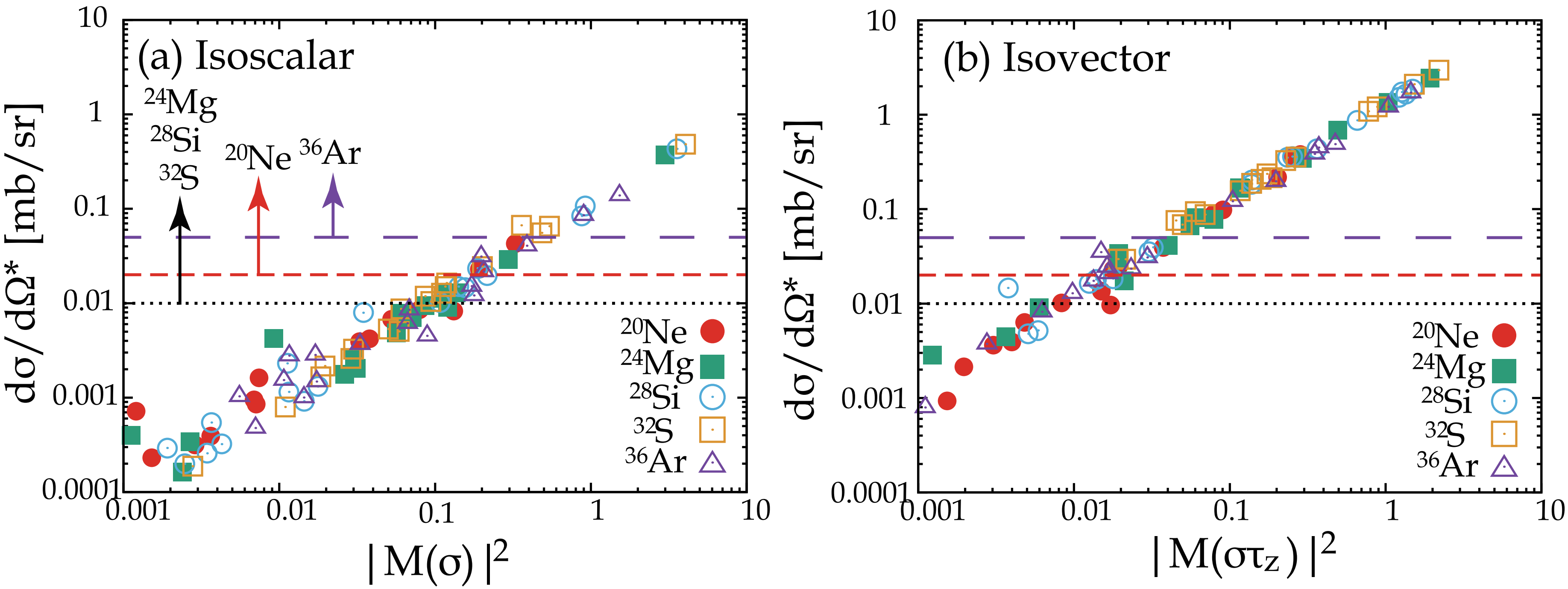
Fujii-Fujita-Ikeda Sum-Rule

$$S_{-}^{(GT)} - S_{+}^{GT} = 3(N - Z)$$

is the difference between S_- and S_+ and the main contribution is T_0-1

In the present work, IV spin-M1 corresponds to T_0+1.

Unit Cross Section and Proportionality
(theoretical study)



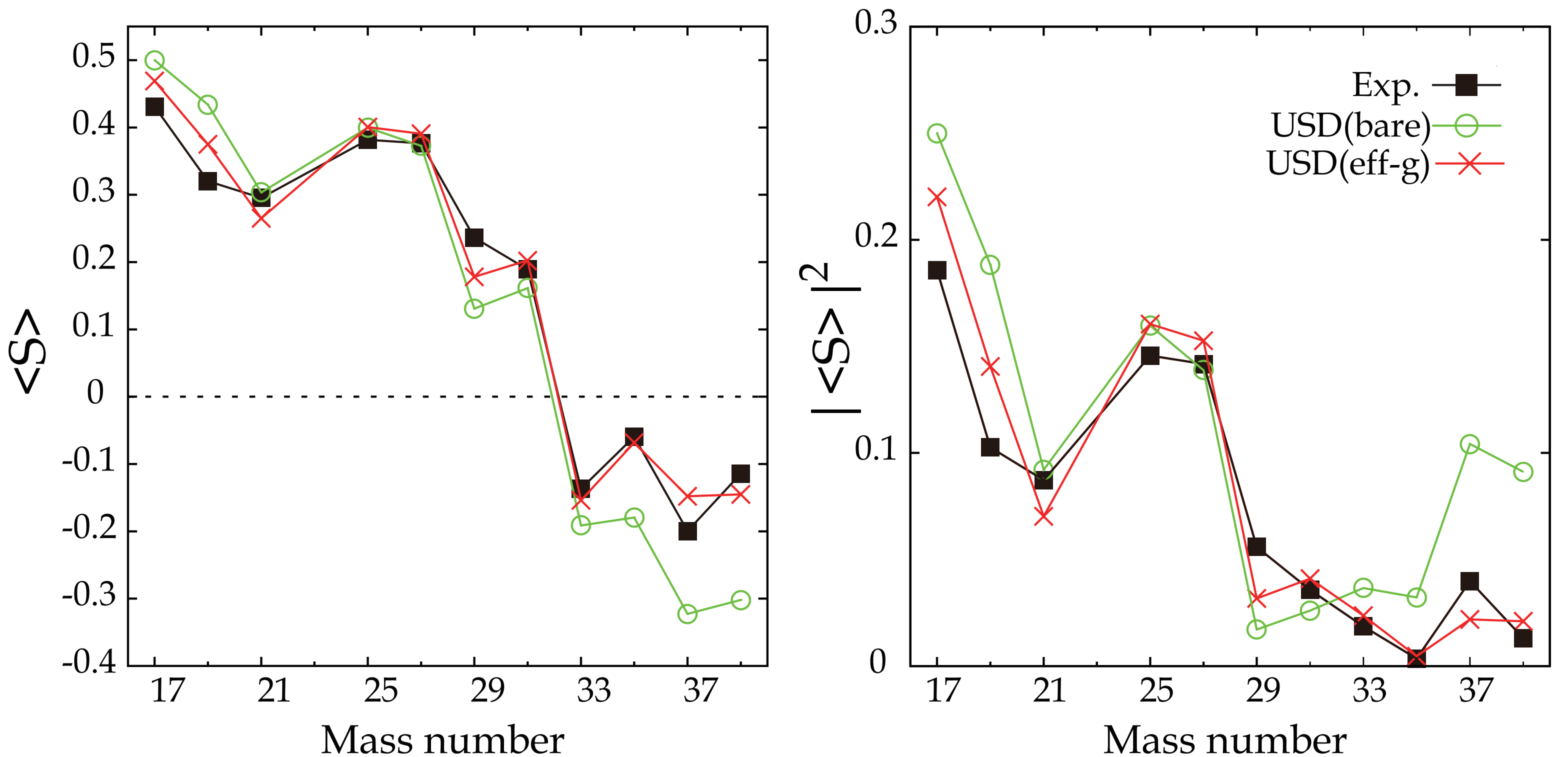
Well described by the proportionality at least for the states with detectable amount of cross sections.

Shell Model W.F. + DWBA Calc.

Relation to the IS Magnetic Moments and Their Quenching

consistent with the available data

Spin-matrix $\langle S \rangle \equiv \langle i | S_z | i \rangle_{M=J} = \dfrac{\mu_{\mathrm{IS}} - g_l^{\mathrm{IS}} \times J}{g_s^{\mathrm{IS}} - g_l^{\mathrm{IS}}},$

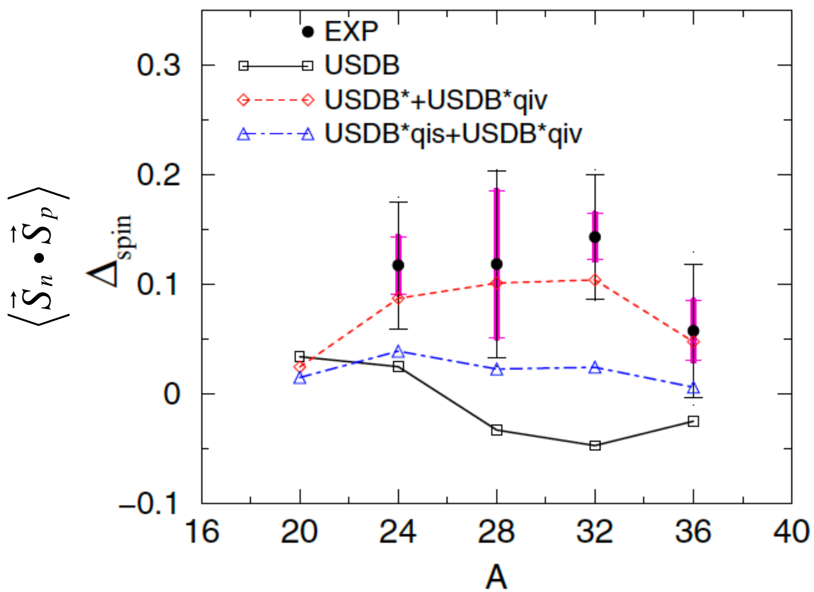


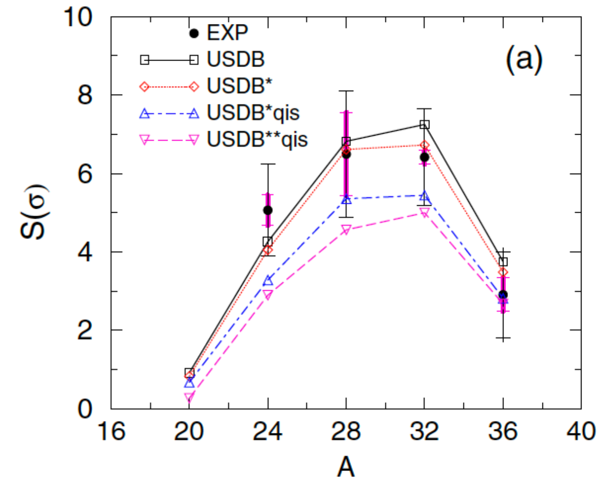
The **diagonal IS spin SNME** for the g.s., from IS magnetic moment, is **NOT quenched** in the mid-shell while quenched at around the edge.

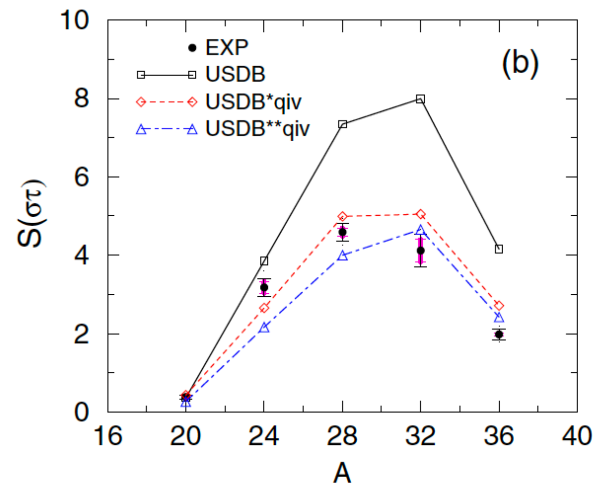
Adapted from B.A. Brown, NPA (1987)

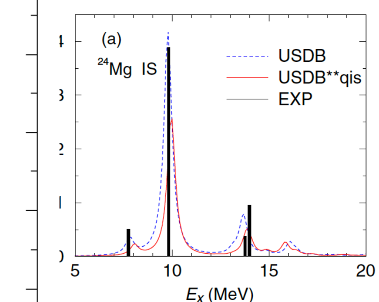
Recent shell-model study

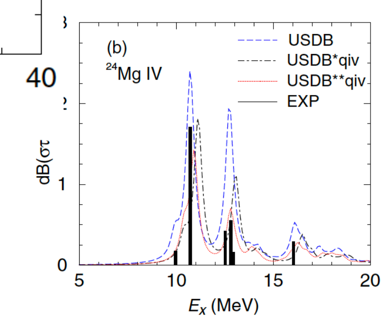
H. Sagawa and T. Suzuki, PRC97, 054333 (2018)











USDB*: IS spin-triplet pairing matrices are enhanced

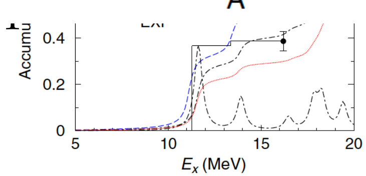


FIG. 2. Cumulative sums of the IS spin-$M1$ strength (top) and the

qiv: IV spin-operator is quenched (Towner et al.,)

qis: IS spin-operator is quenched by 10%

Recent shell-model study

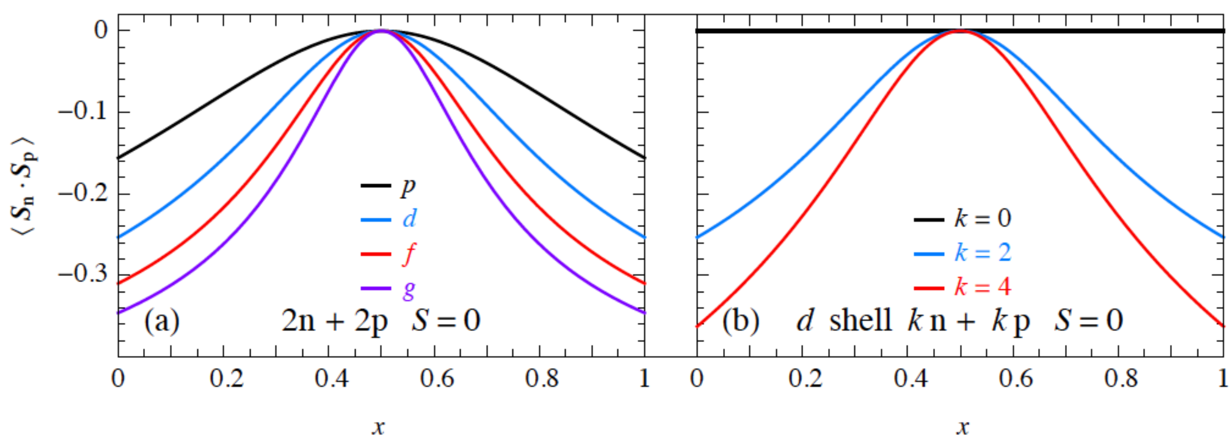
P. Van Isacker and A.O. Macchiavelli, arXiv:2105.07267, to be published in EJPA

Abstract. We present expressions for the matrix elements of the spin–spin operator $\vec{S}_n \cdot \vec{S}_p$ in a variety of coupling schemes. These results are then applied to calculate the expectation value $\langle \vec{S}_n \cdot \vec{S}_p \rangle$ in eigenstates of a schematic Hamiltonian describing neutrons and protons interacting in a single-l shell through a Surface Delta Interaction. The model allows us to trace $\langle \vec{S}_n \cdot \vec{S}_p \rangle$ as a function of the competition between the isovector and isoscalar interaction strengths and the spin–orbit splitting of the $j = l \pm 1/2$ shells. We find negative $\langle \vec{S}_n \cdot \vec{S}_p \rangle$ values in the ground state of all even–even $N = Z$ nuclei, contrary to what has been observed in hadronic inelastic scattering at medium energies. We discuss the possible origin of this discrepancy and indicate directions for future theoretical and experimental studies related to neutron–proton spin–spin correlations.

Schematic model for single l-shell corresponding $j = l \pm 1$ with surface delta interaction

$$H = \epsilon_- n_- + \epsilon_+ n_+ - 4\pi \sum_{T=0,1} a'_T \sum_{i<j} \delta(\vec{r}_i - \vec{r}_j)\delta(\vec{r}_i - R_0),$$

$$a\,x \equiv a_0 \text{ and } a(1-x) \equiv a_1$$



No solution for positive $<S_n \cdot S_p>$ in the parameter space

Future Experimental Possibilites

- Mass dependence of the *np* spin correlation function along the N=Z line
  Target nuclei are unstable above A=40.
  - (p,p′) and (d,d′) in inverse kinematics

- Isospin dependence of the *np* spin correlation function for N≠Z nuclei
  IS and IV transitions need to be selectively excited.
  For stable nuclei:
  - (^{6}Li,^{6}Li′γ) for IV spin-M1 excitations
  - (d,d) or (^{6}Li,^{6}Li′) for IS spin-M1 excitations

- Strength in the continuum and in unstable nuclei
  - (^{12}C,^{12}C(1^+,T=1;15.11 MeV)) in inverse kinematics for IS spin-M1
    $\rightarrow {}^{12}\mathrm{C}+\gamma$
  - (^{12}C,^{12}C(1^+,T=0;12.71 MeV)) in inverse kinematics for IV spin-M1
    $\rightarrow \alpha + {}^{8}\mathrm{Be} \rightarrow \alpha+\alpha+\alpha$

Summary

- Quenching of the IS and IV spin-M1 SNMEs was studied by a high-resolution (p,p') measurement at E_p=295 MeV
- No-quenching is observed in the IS-spin-M1 SNMEs while quenching is observed in the IV-spin-M1 SNME as is expected from the analogous GT transitions.
- The *np* spin-spin correlation function extracted from the experimental data show systematically positive numbers, implying the IS *np* correlation or deuteron like correlation in the ground states.
- A shell model calculation using the USD interaction does not reproduce the positives. However, predictions by the correlated Gaussian method on ^{4}He and the non-core shell model (not converged yet) look more consistent with the data.

H. Matsubara, AT *et al.*, PRL2015

H. Matsubara and AT, to be published in Frontiers in Astronomy and Space Sciences