np Spin-Correlation in the Ground State Studied by Spin-*M1* Transitions

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Osaka University, Japan

for RCNP-E299 Collaborations

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Neutron-Proton Correlations

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Submitted to PRL

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Outline

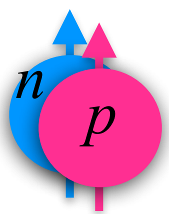
1. *np* Pairing Correlations
2. *np* Spin-Correlation Function and Spin-M1 Sum-rule
3. Experimental Methods
4. Results
5. Discussions
6. Summary

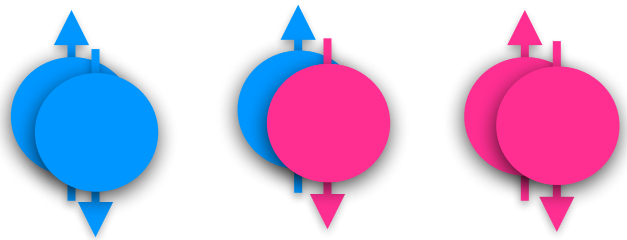
np Pairing Correlations

- spin-aligned *np*-pairs — B. Cederwall et al., Nature **469**, 68 (2011)
- *np* pairing, mass analysis — Frauendorf and Macciavelli, PPNP**78**, 24 (2014)
- high-momentum correlated nucleon pairs — R. Subedi et al., Science 320, 1476 (2008); I. Korover et al., PRL 113, 022501 (2014)
- *pn* contact — R. Weiss et al., PRL114, 012501 (2015); S. Tan Ann. Phys. 323, 2952(2008)
- pairing vibrations — F. Cappuzzello et al., Nature Comm. 6, 6743 (2015).
- low-E super GT state — Y. Fujita et al., PRL (2014).
- transfer reactions/knock out reactions
- …

We'd like to add one more alternative approach.

IS and IV pairings



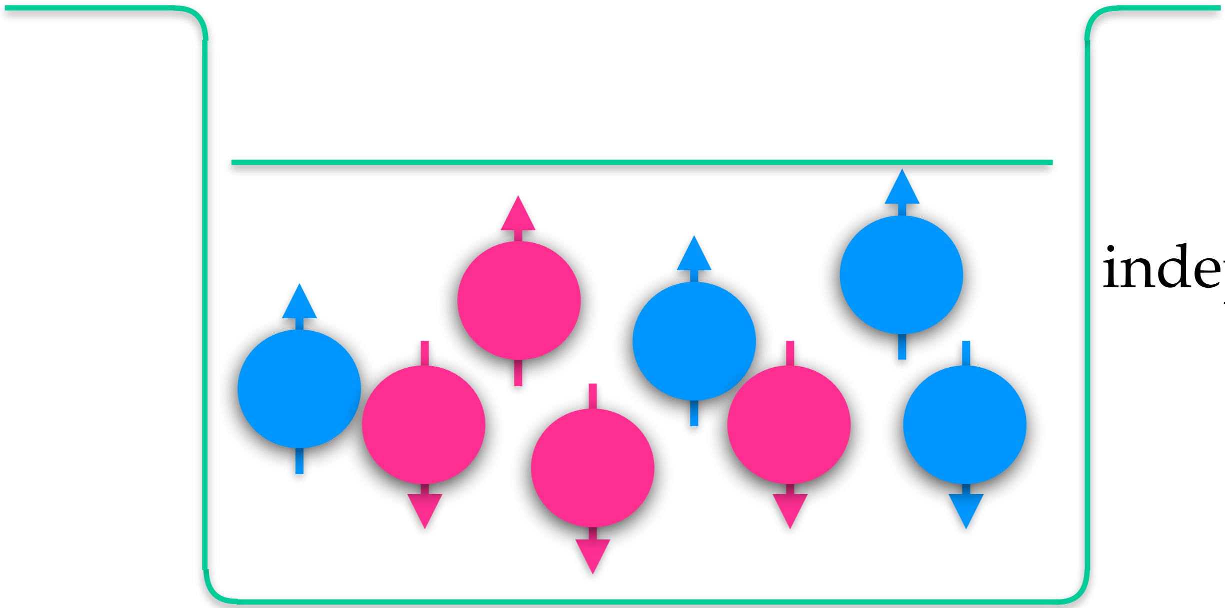


IS (T=0, S=1)

Isoscalar *np*-paring

IV (T=1, S=0)

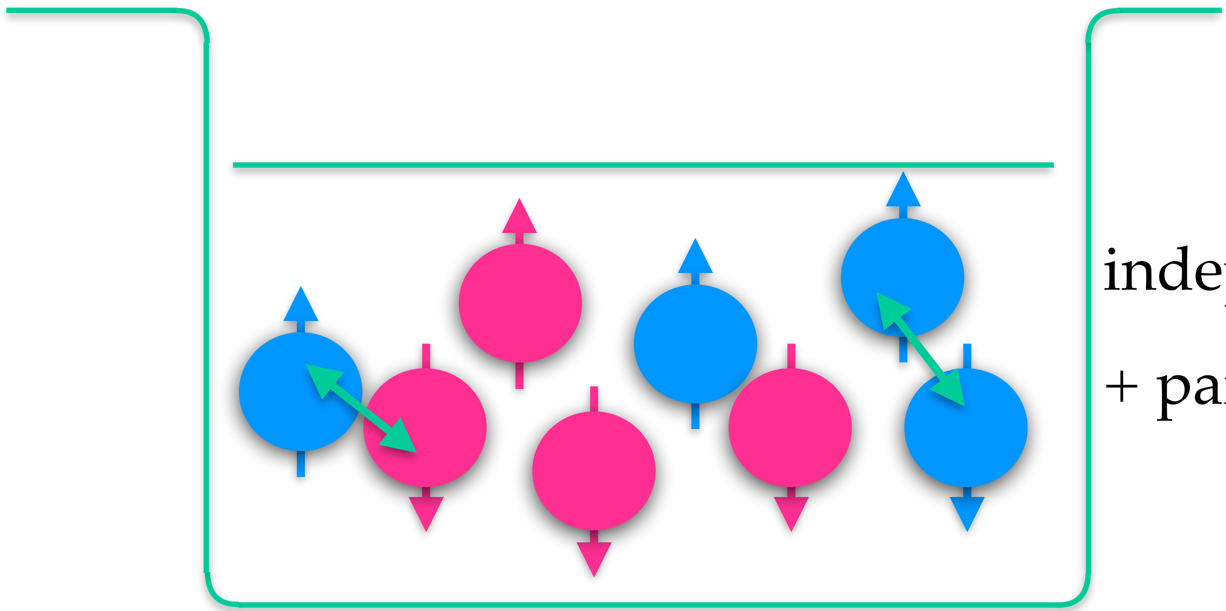
pairing in the ground state W.F.



independent particles

unperturbed ground state

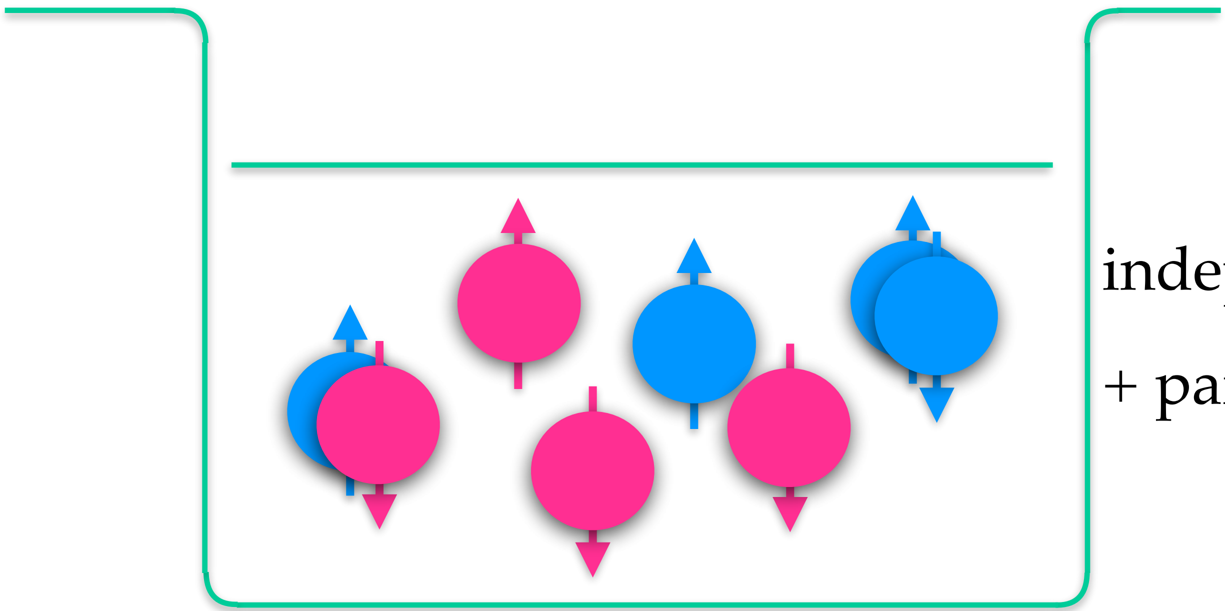
pairing in the ground state W.F.



independent particles

+ paring interactions

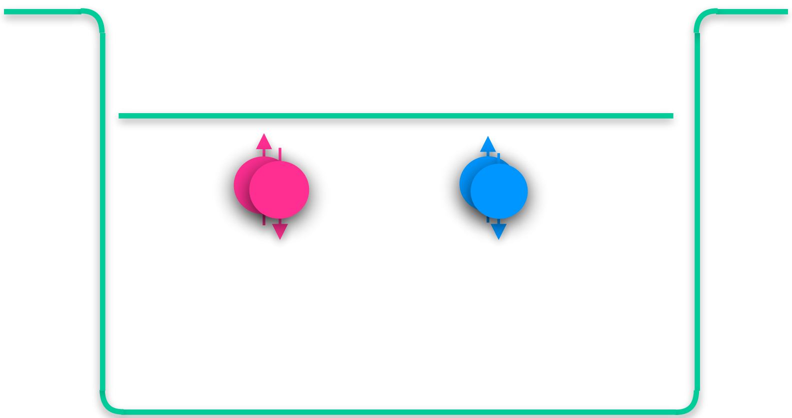
pairing in the ground state W.F.

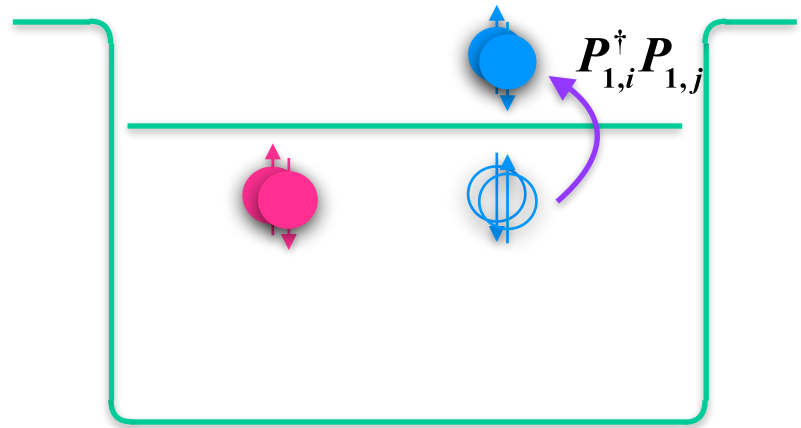


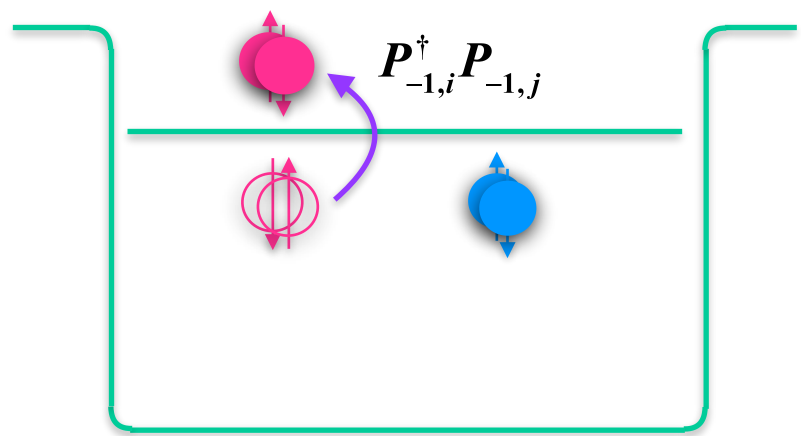
independent particles

+ paring interactions

pairing in the ground state W.F.





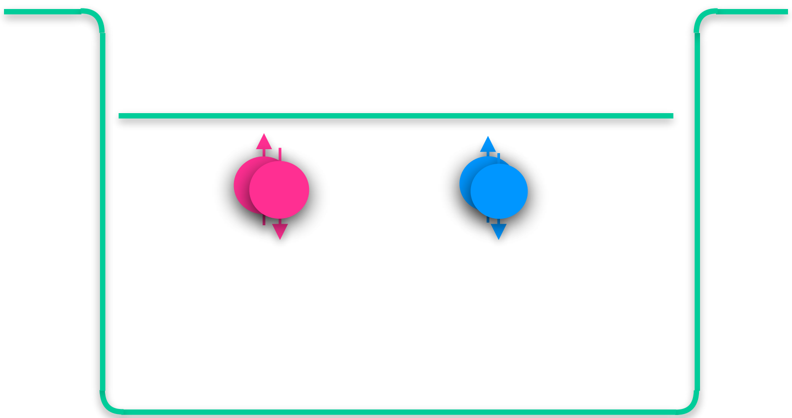


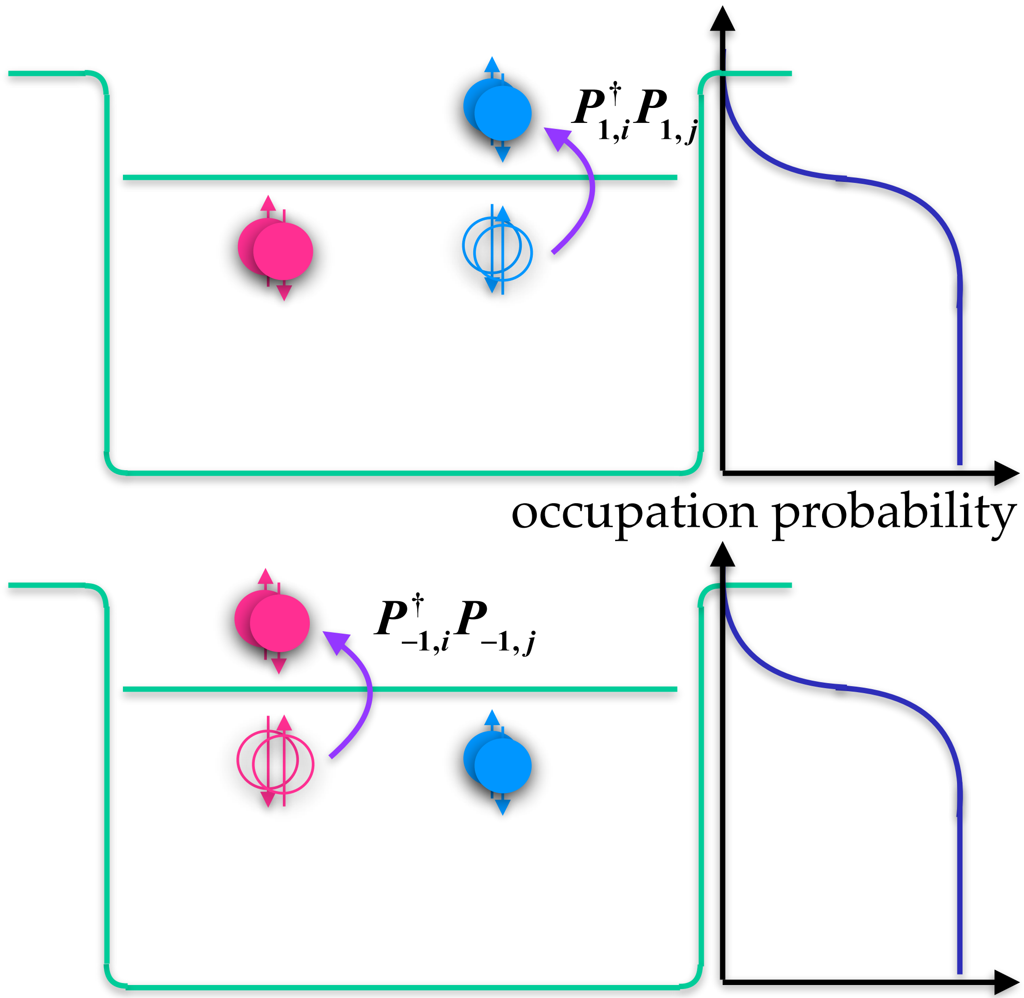
$$P^\dagger_{1,i} = \nu^\dagger_i \nu^\dagger_{\bar{i}}$$

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

isovector “pairing” correlation
= BCS type correlation

pairing in the ground state W.F.



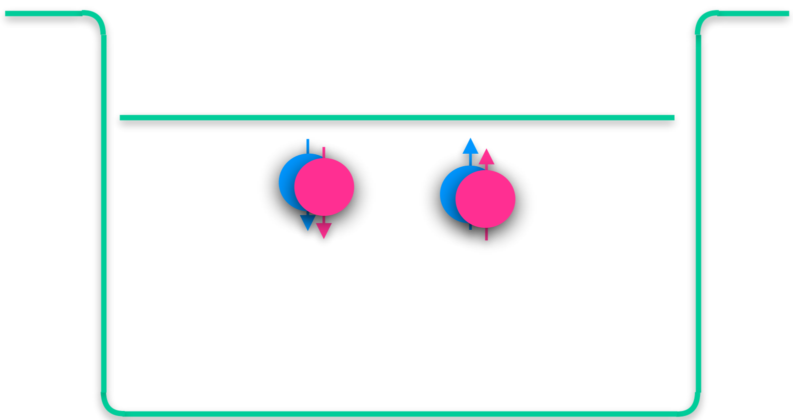


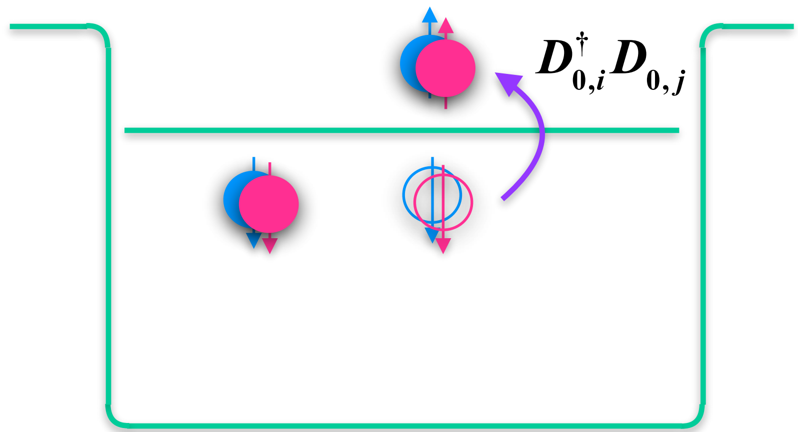
$$P^\dagger_{1,i} = \nu^\dagger_i \nu^\dagger_{\bar{i}}$$

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

isovector “pairing” correlation
= BCS type correlation

np pairing in the ground state W.F.

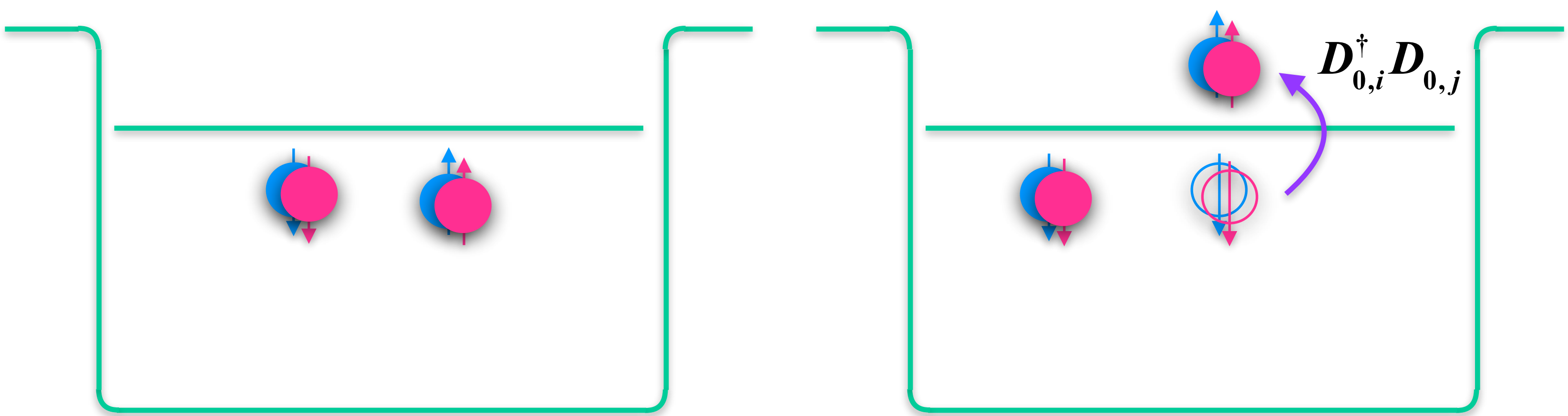


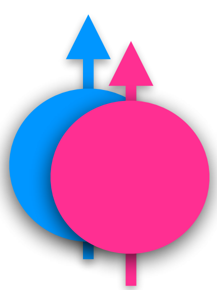


$$D^\dagger_{0,i} = \frac{1}{\sqrt{2}}\left(\nu_i^\dagger \pi_{\bar{i}}^\dagger - \pi_i^\dagger \nu_{\bar{i}}^\dagger\right)$$

isoscalar “pairing” correlation
by *e.g.* tensor correlation

np pairing in the ground state W.F.



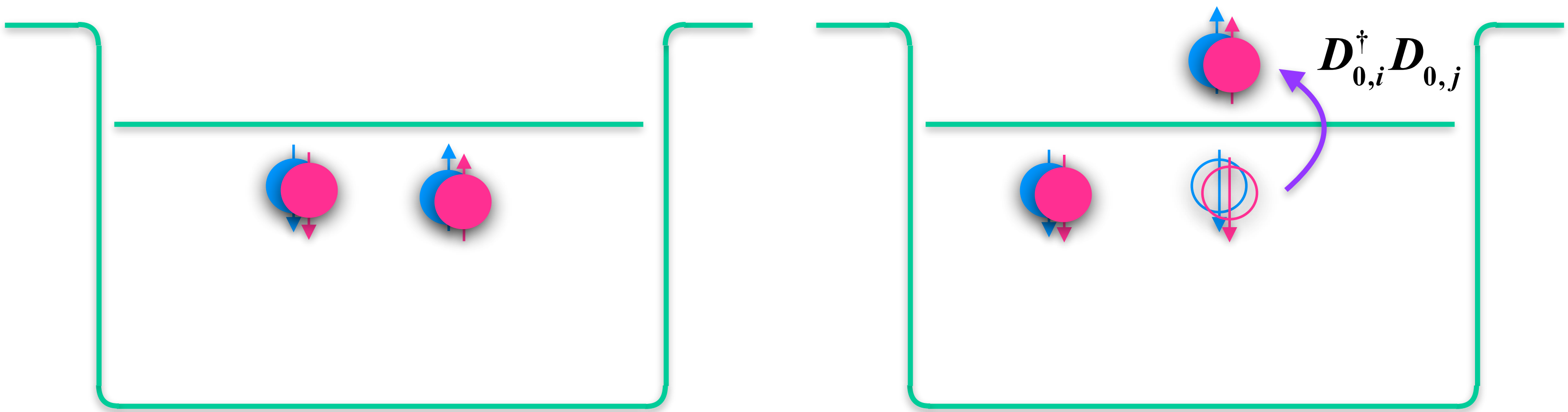


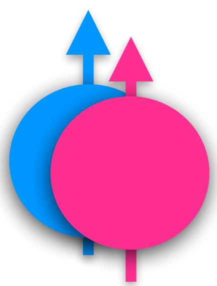
n-spin and *p*-spin:
aligned

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

isoscalar “pairing” correlation
by *e.g.* tensor correlation

np pairing in the ground state W.F.





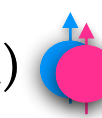
n-spin and *p*-spin:
aligned

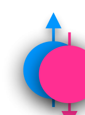
$$\left\langle \vec{s}_n \cdot \vec{s}_p \right\rangle > 0$$

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

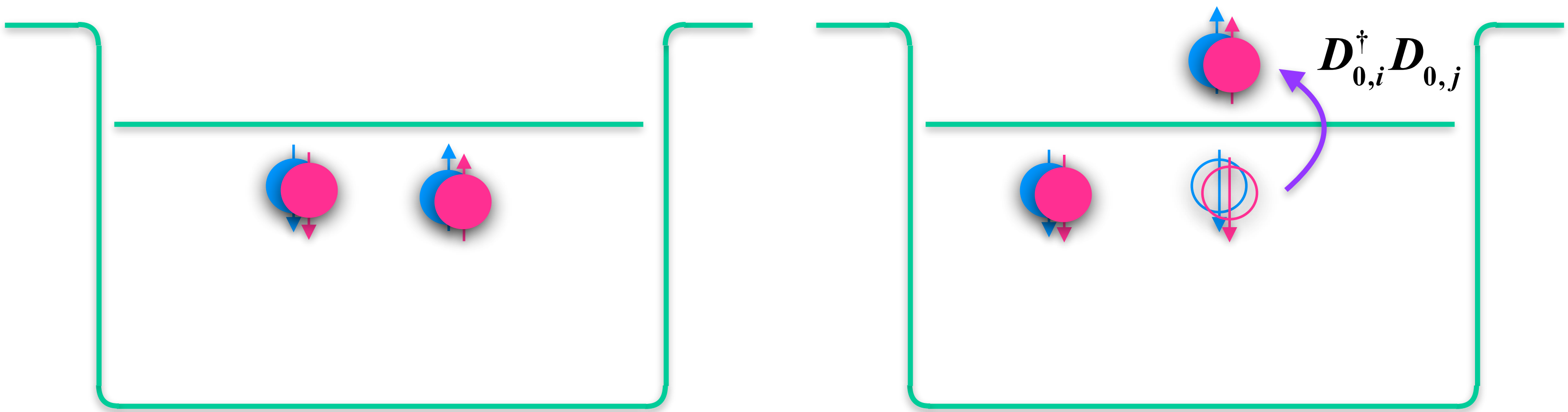
isoscalar "pairing" correlation
by *e.g.* tensor correlation

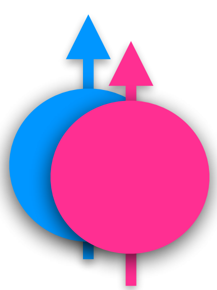
$$\left\langle \vec{s}_n \cdot \vec{s}_p \right\rangle = \begin{cases} +\dfrac{1}{4} & \text{for IS } np \text{ pair (deuteron)} \\ -\dfrac{3}{4} & \text{for IV } np \text{ pair} \end{cases}$$





np pairing in the ground state W.F.



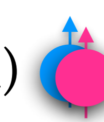


n-spin and *p*-spin: aligned

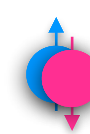
$$\langle \vec{s}_n \cdot \vec{s}_p \rangle > 0$$

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

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

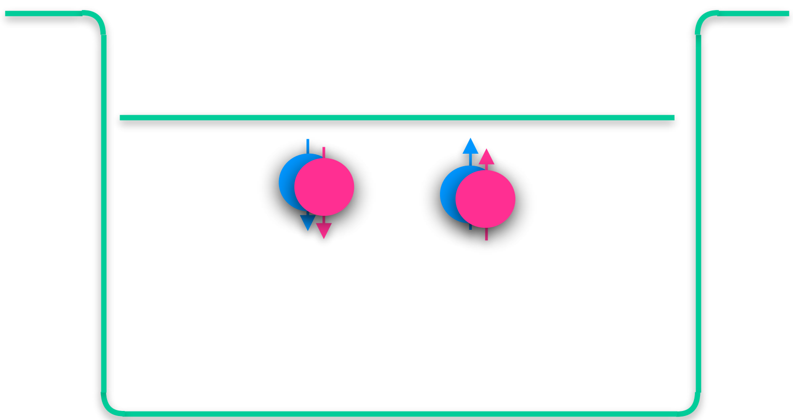
for IS *np* pair (deuteron) 

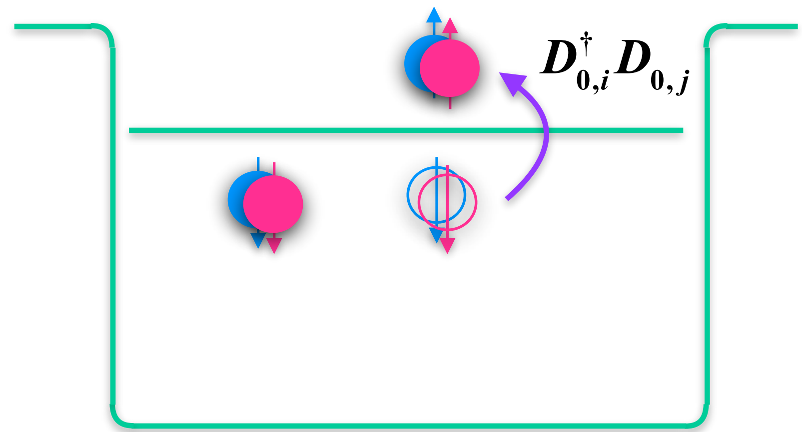
statistical weight = 3

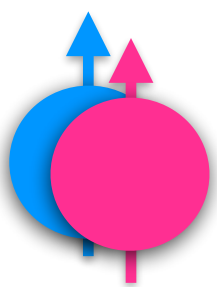
for IV *np* pair 

statistical weight = 1

np pairing in the ground state W.F.







n-spin and *p*-spin: aligned

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

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

⇩

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

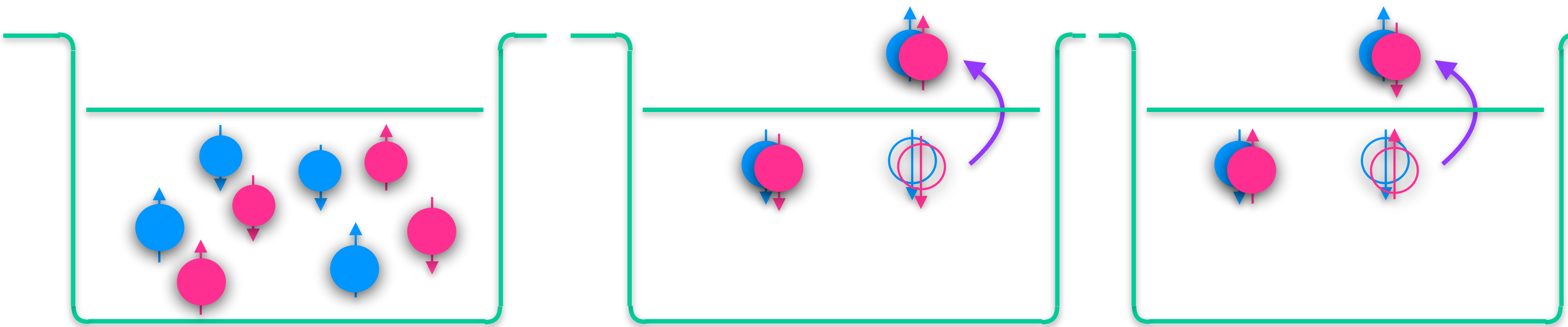
np spin correlation function

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

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



unperturbed ground state

$$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle = 0$$

also for IV pp/nn parings

IS *np* pairing

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

IV *np* pairing

$$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle < 0$$

How to Study the *np* Spin Correlation Function?

→ IS/IV spin-M1 excitations and Sum-Rule

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

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

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

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

closure

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

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

IV spin-M1 squared nuclear matrix elements (SNME)

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

IS spin-M1 SNME

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

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

Spin-*M1* Reduced Transition Strength

M1 Operator

$$\hat{O}(M1) = \left[\sum_{k=1}^{Z} \left(g_l^p \vec{l}_k + g_s^p \vec{s}_k \right) + \sum_{k=Z+1}^{A} \left(g_l^n \vec{l}_k + g_s^n \vec{s}_k \right) \right] \mu_N$$

M1 Reduced Transition Strength

$$B(M1) = \frac{3}{4\pi} \frac{1}{2J_i + 1} \left| \left\langle f \left\| g_l^{IS} \vec{l} + \frac{g_s^{IS}}{2} \vec{\sigma} - \left(g_l^{IV} \vec{l} + \frac{g_s^{IV}}{2} \vec{\sigma} \right) \tau_z \right\| i \right\rangle \right|^2$$

T=0 Isoscalar (IS) Spin-M1 Reduced Transition Strength

$$B(M1)_\sigma = \frac{3}{4\pi} \frac{1}{2J_i + 1} \left(\frac{g_s^{IS}}{2} \right)^2 \left| \left\langle f \| \vec{\sigma} \| i \right\rangle \right|^2 \mu_N^2 \qquad M(\sigma) = \left\langle f \| \vec{\sigma} \| i \right\rangle$$

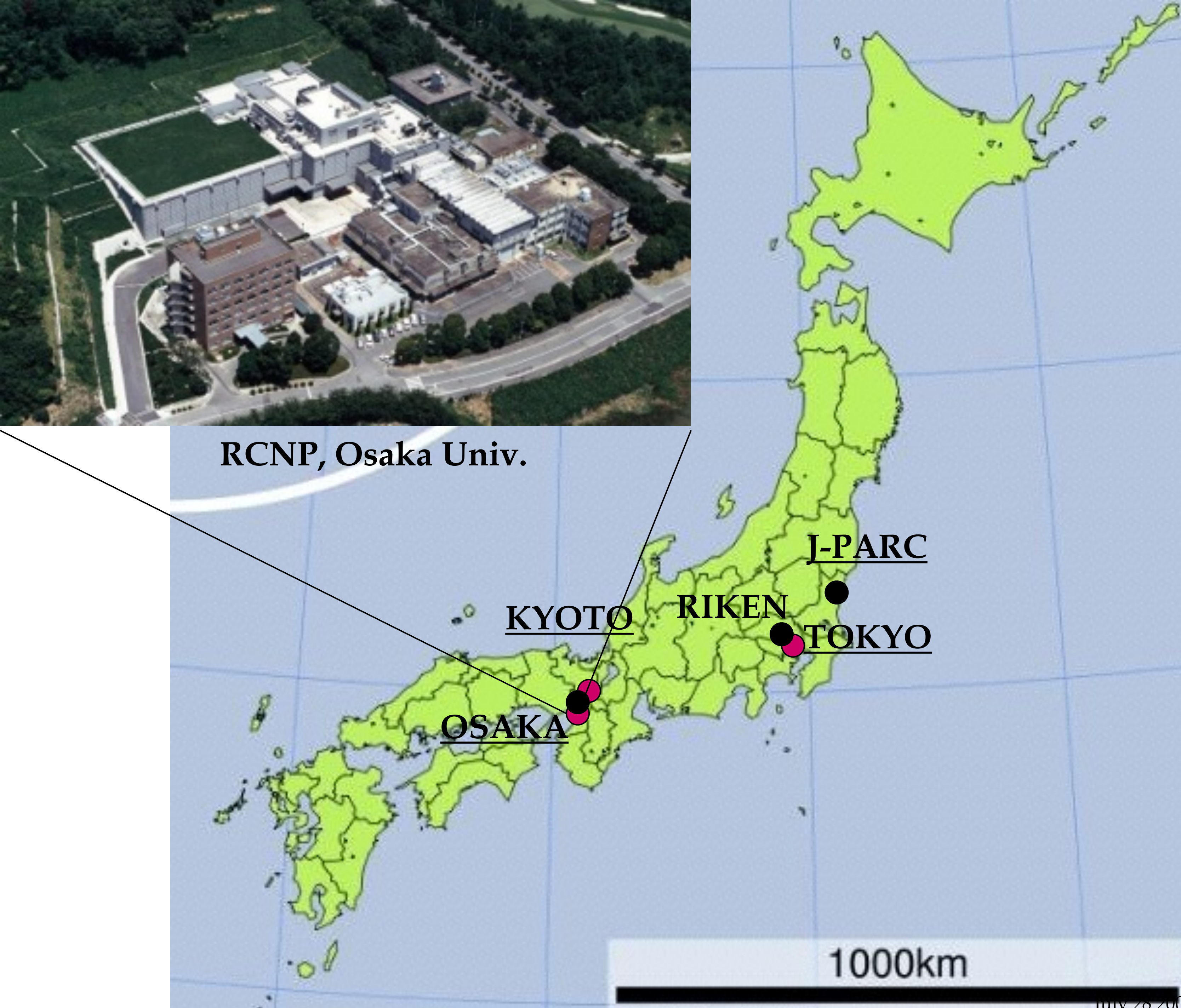
IS Reduced Matrix Element

T=1 Isovector (IV) Spin-M1 Reduced Transition Strength

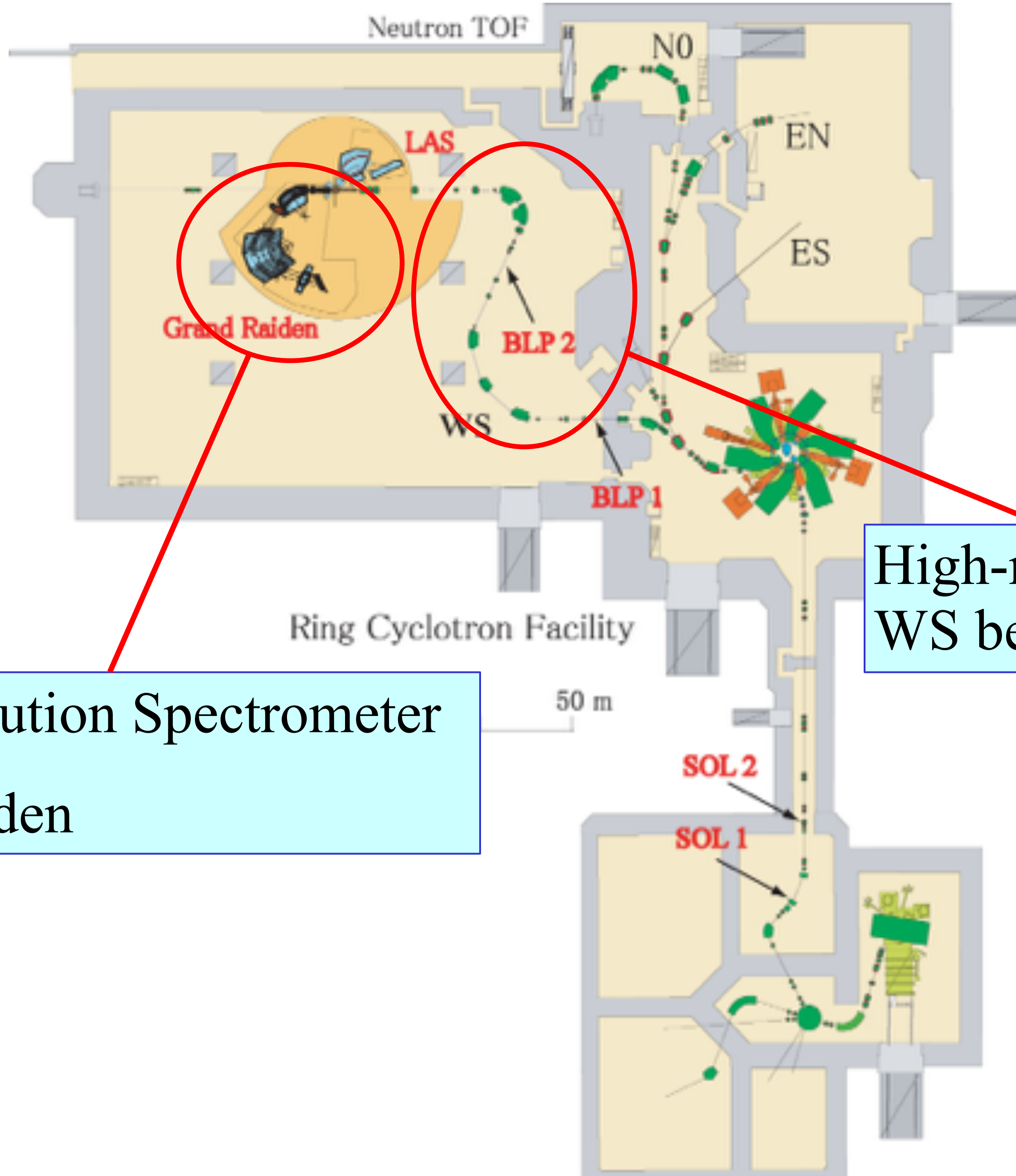
$$B(M1)_{\sigma\tau} = \frac{3}{4\pi} \frac{1}{2J_i + 1} \left(\frac{g_s^{IV}}{2} \right)^2 \left| \left\langle f \| \vec{\sigma} \tau_z \| i \right\rangle \right|^2 \mu_N^2 \qquad M(\sigma\tau) = \left\langle f \| \vec{\sigma} \tau_z \| i \right\rangle$$

IV Reduced Matrix Element

Experimental Methods


RCNP, Osaka Univ.
J-PARC
KYOTO
RIKEN
TOKYO
OSAKA
1000km

Research Center for Nuclear Physics, Osaka Univ.

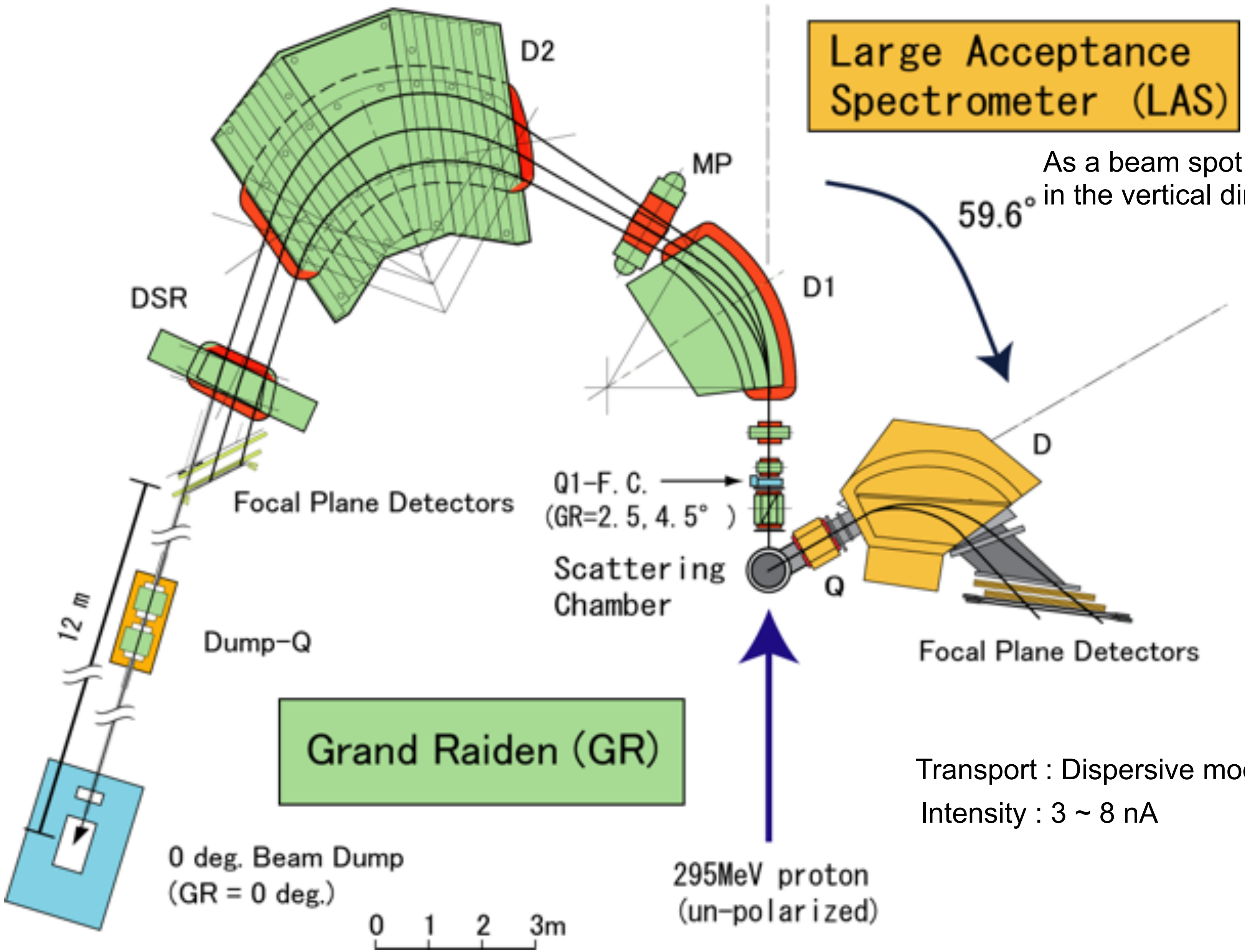


High-resolution
WS beam-line

High-resolution Spectrometer

Grand Raiden

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



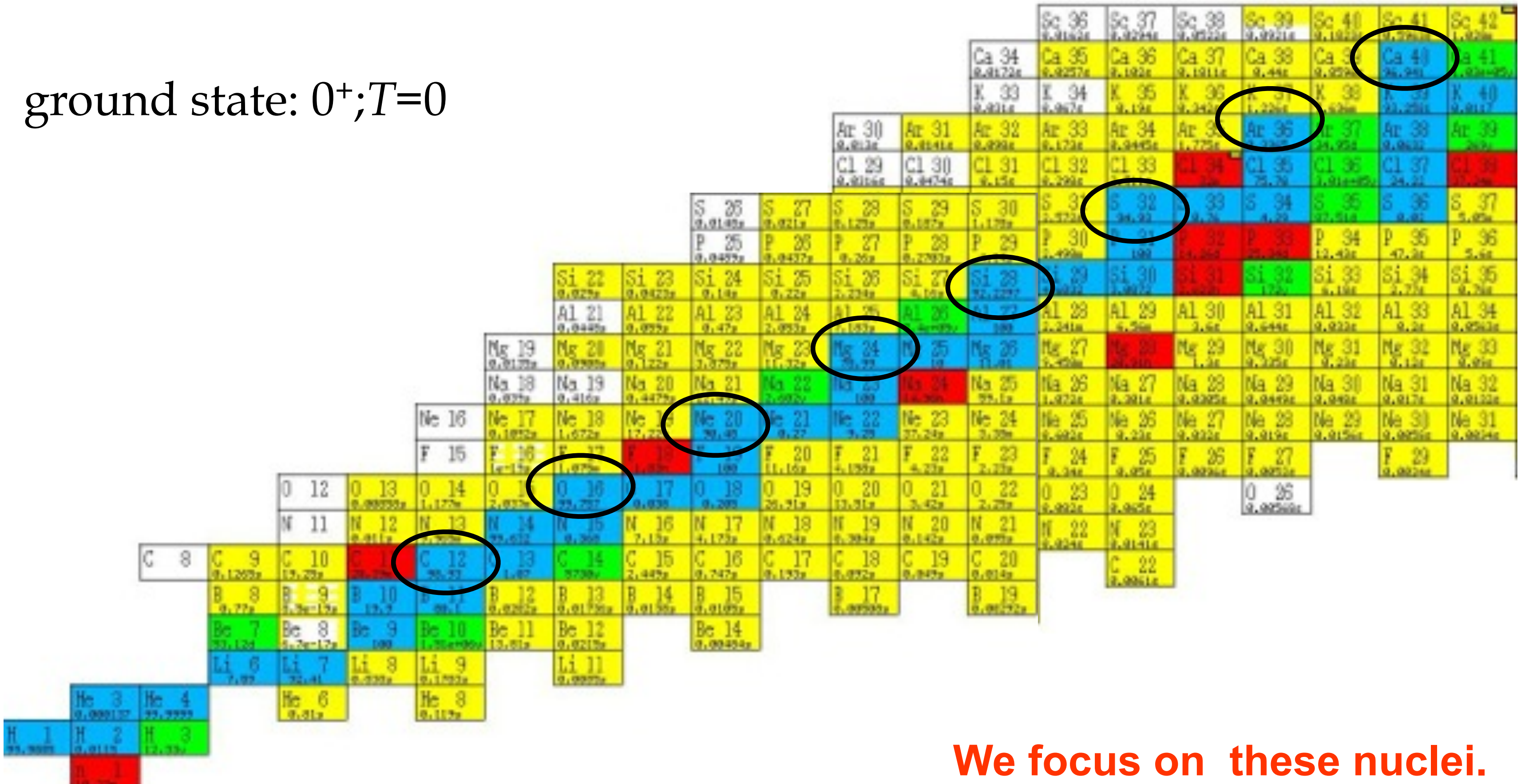
As a beam spot monitor in the vertical direction

Transport : Dispersive mode

Intensity : 3 ~ 8 nA

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

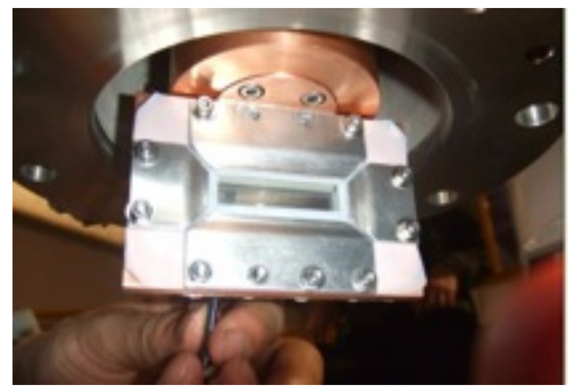
Targets

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

Cooled ^{32}S self-supporting target

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

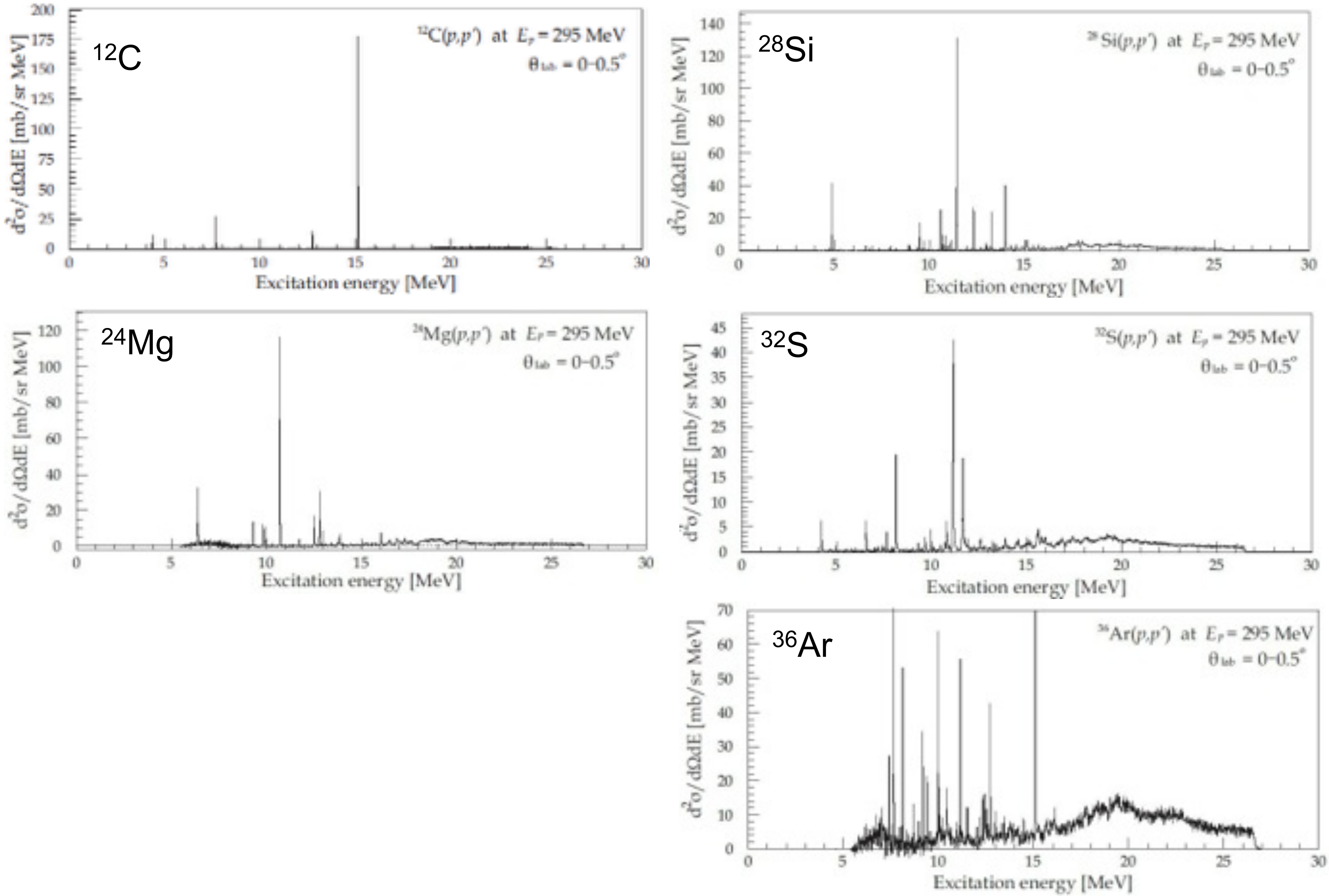
Gas Cell Target (^{36}Ar)



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

Aramide window of 6 μm^t

Energy spectra at 0-degrees

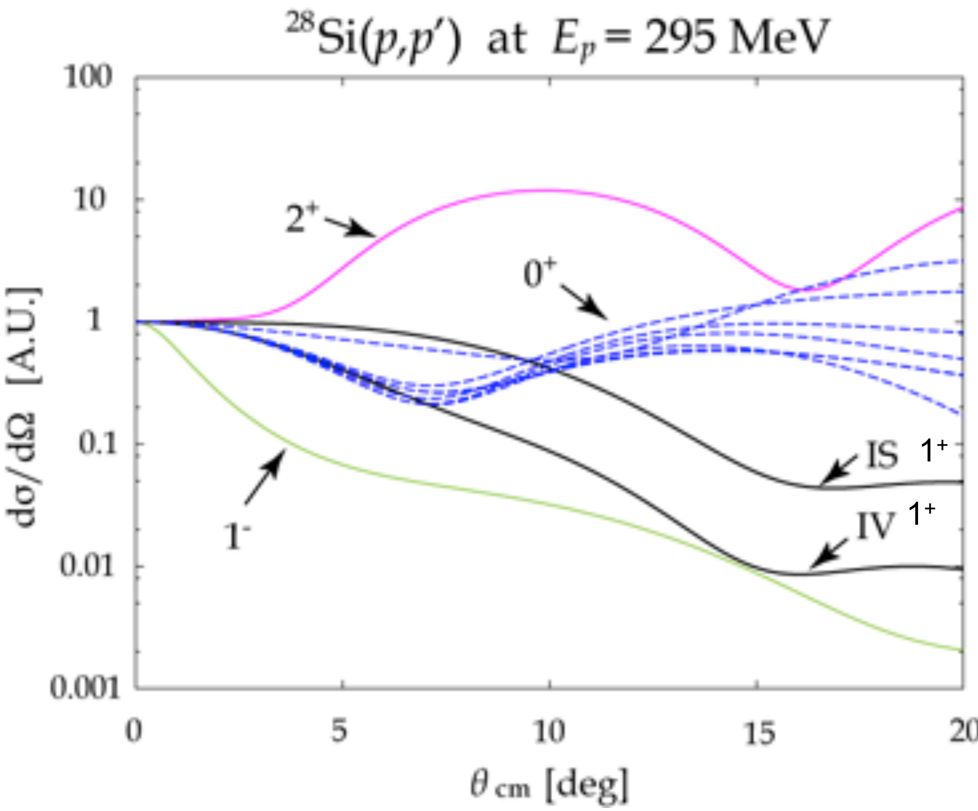


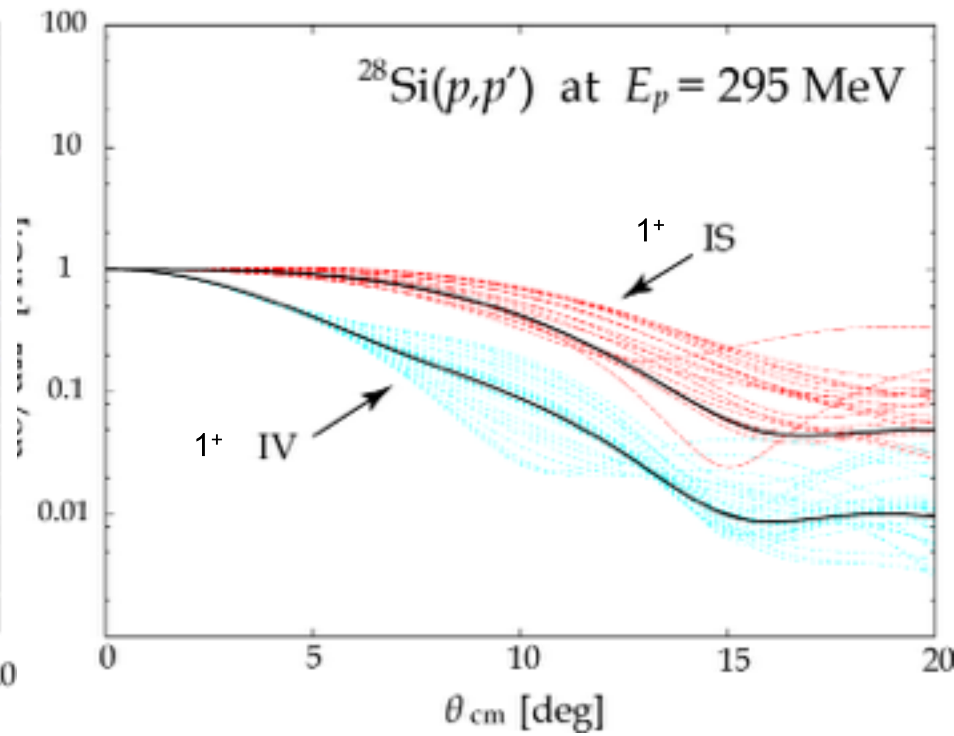
Angular distribution for J^{π} assignment

- 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)

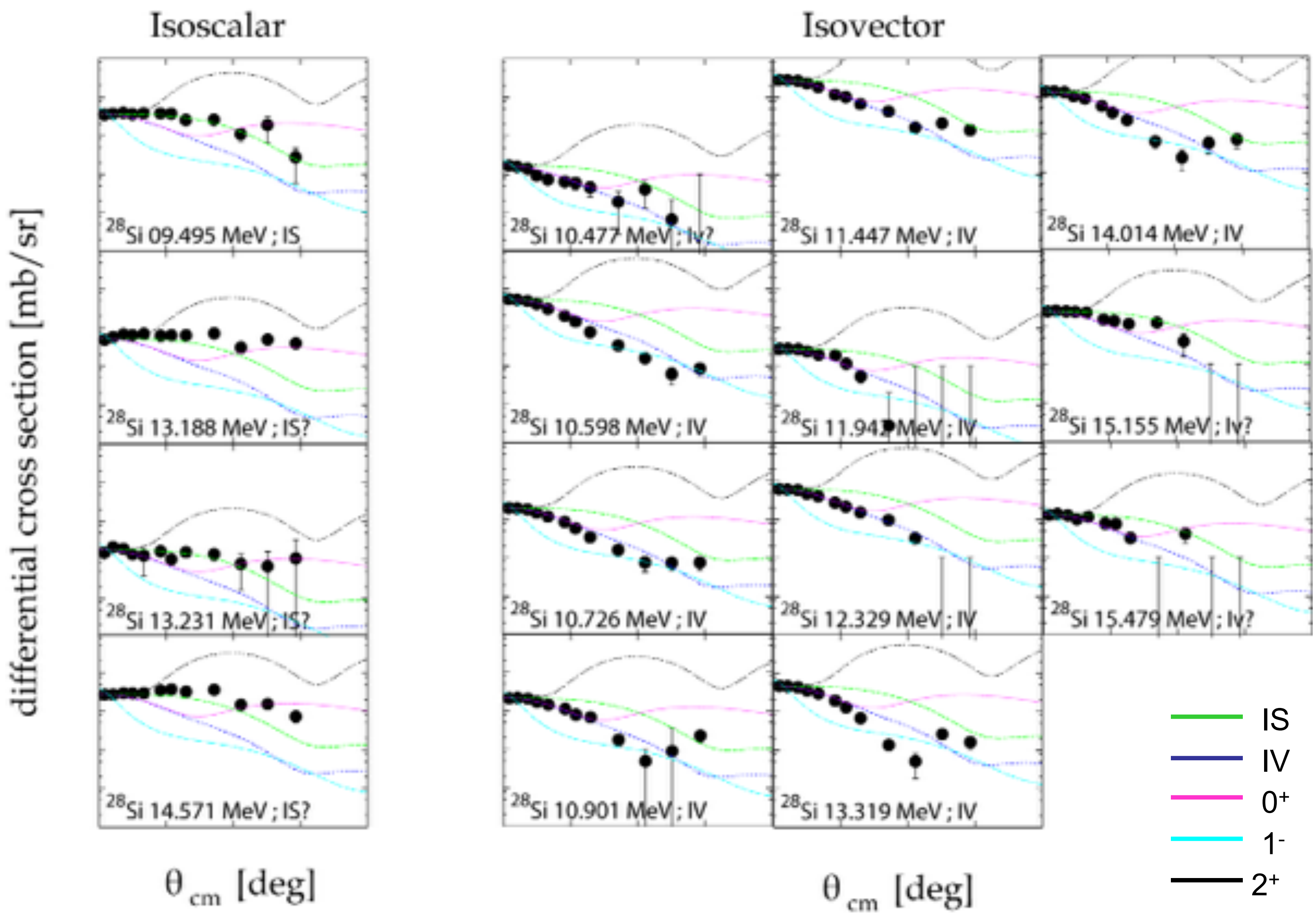




- Forward peaking for L=0 transition.
- *M1* has the maximum at 0 degree.
- 0^+, IS-1^+, IV-1^+ and others

- 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
(on the assumption of the isospin symmetry).

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

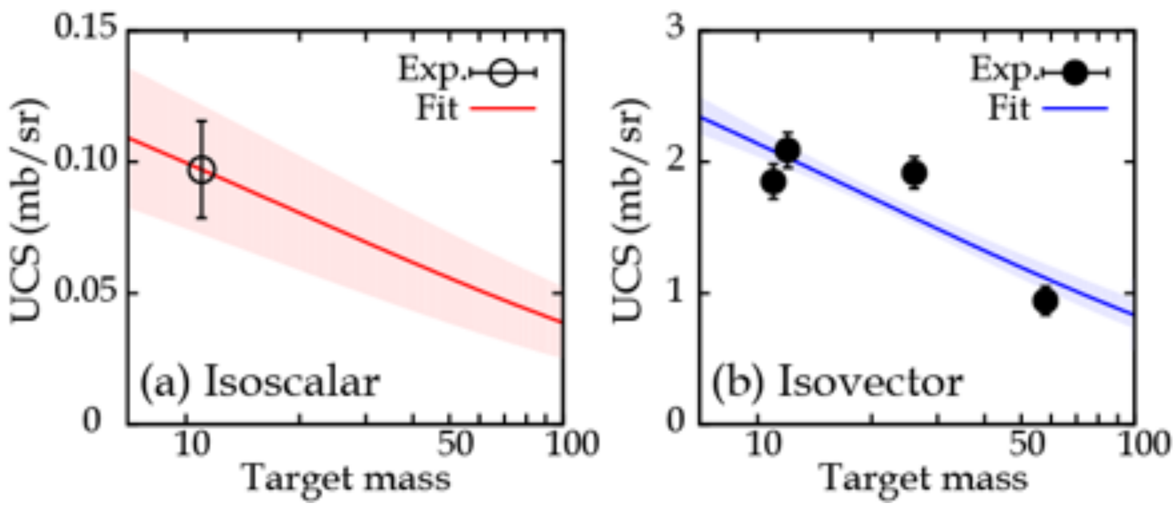
(T= IS or IV)

UCS — Kinematical factor — SNME

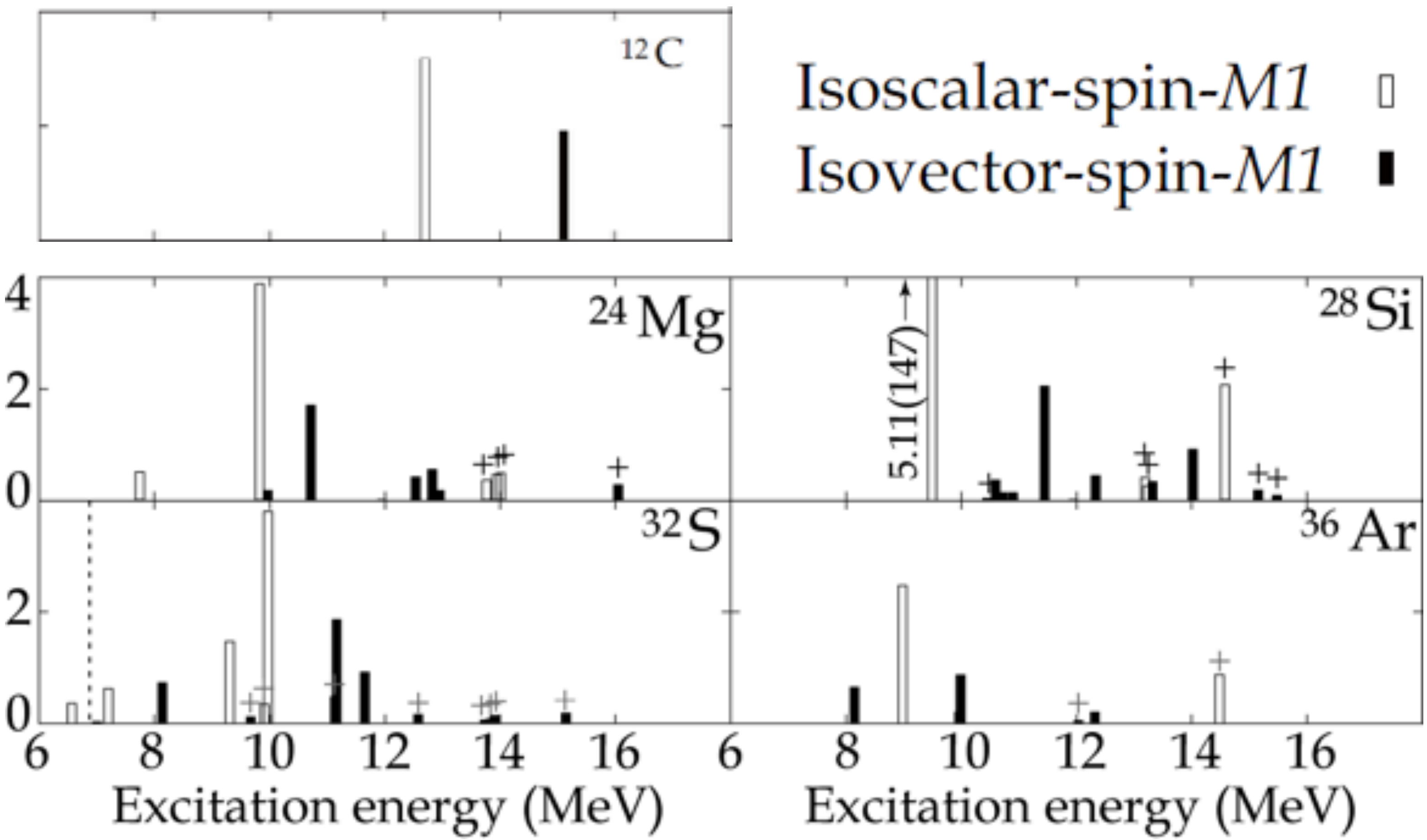
$$\hat{\sigma}_T(A) = N \exp\left(-xA^{1/3}\right)$$

T.N. Taddeucci, NPA469 (1987).

- Function taken from the mass dependence of GT UCS

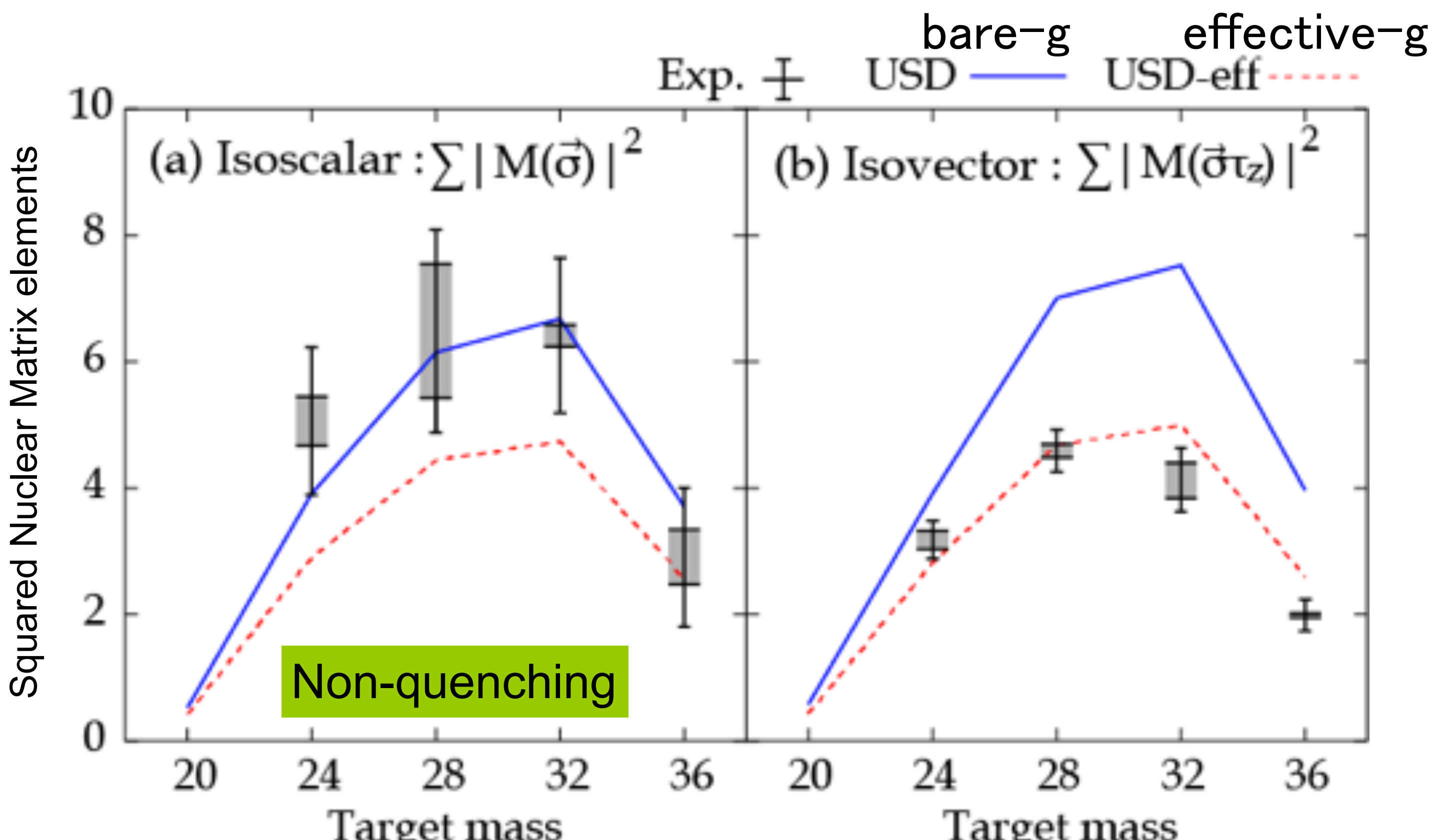


IS/IV-spin-M1 distribution



Spin-M1 SNME

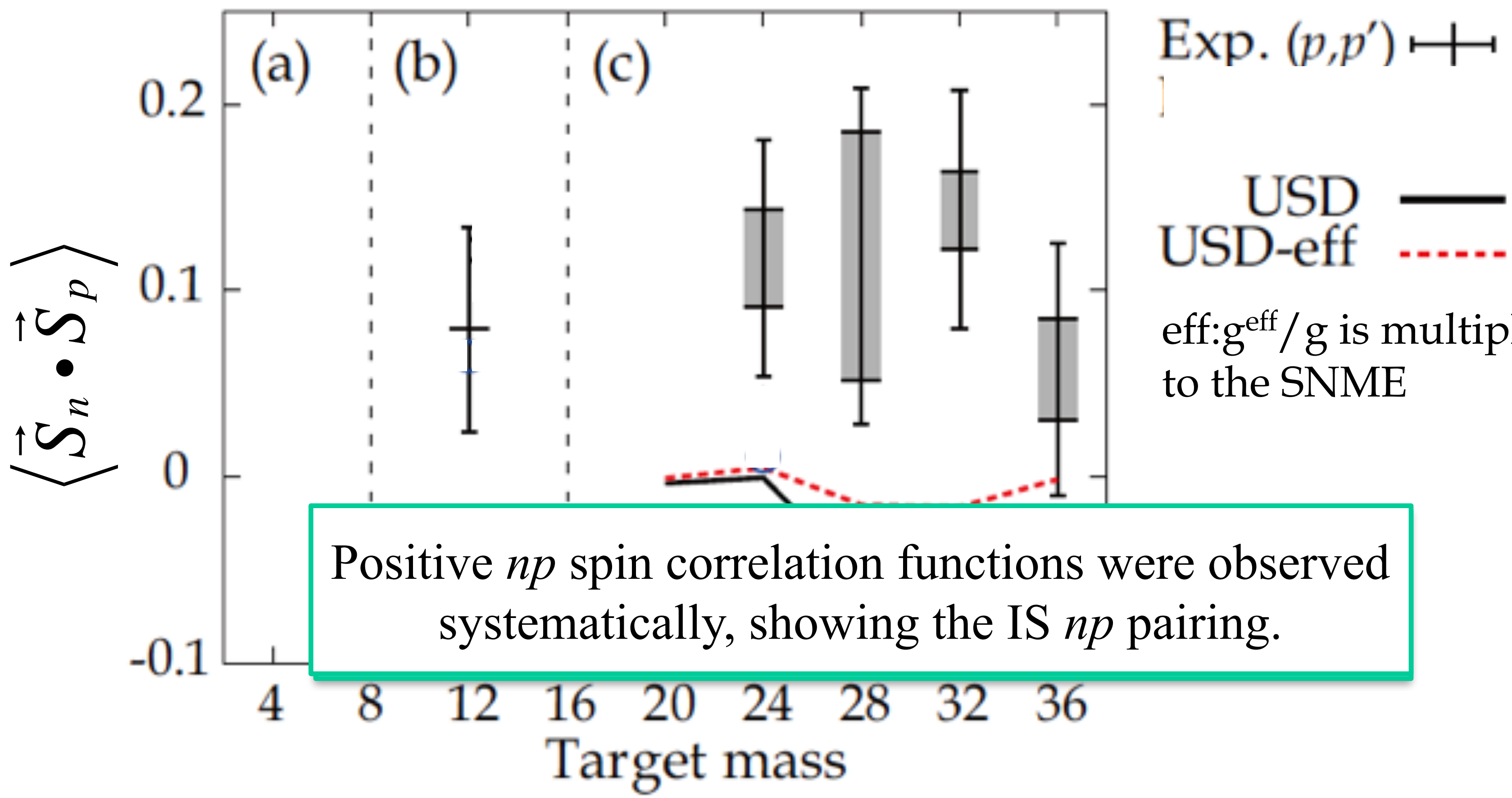
- Summed up to **16 MeV**.
- Compared with shell-model predictions using the USD interaction



Isoscalar spin-M1 SNME is not quenching.

np Spin Correlation Function

Shell-Model: USD interaction



eff: g^{eff}/g is multiplied to the SNME

Positive *np* spin correlation functions were observed systematically, showing the IS *np* pairing.

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

by W. Horiuchi

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

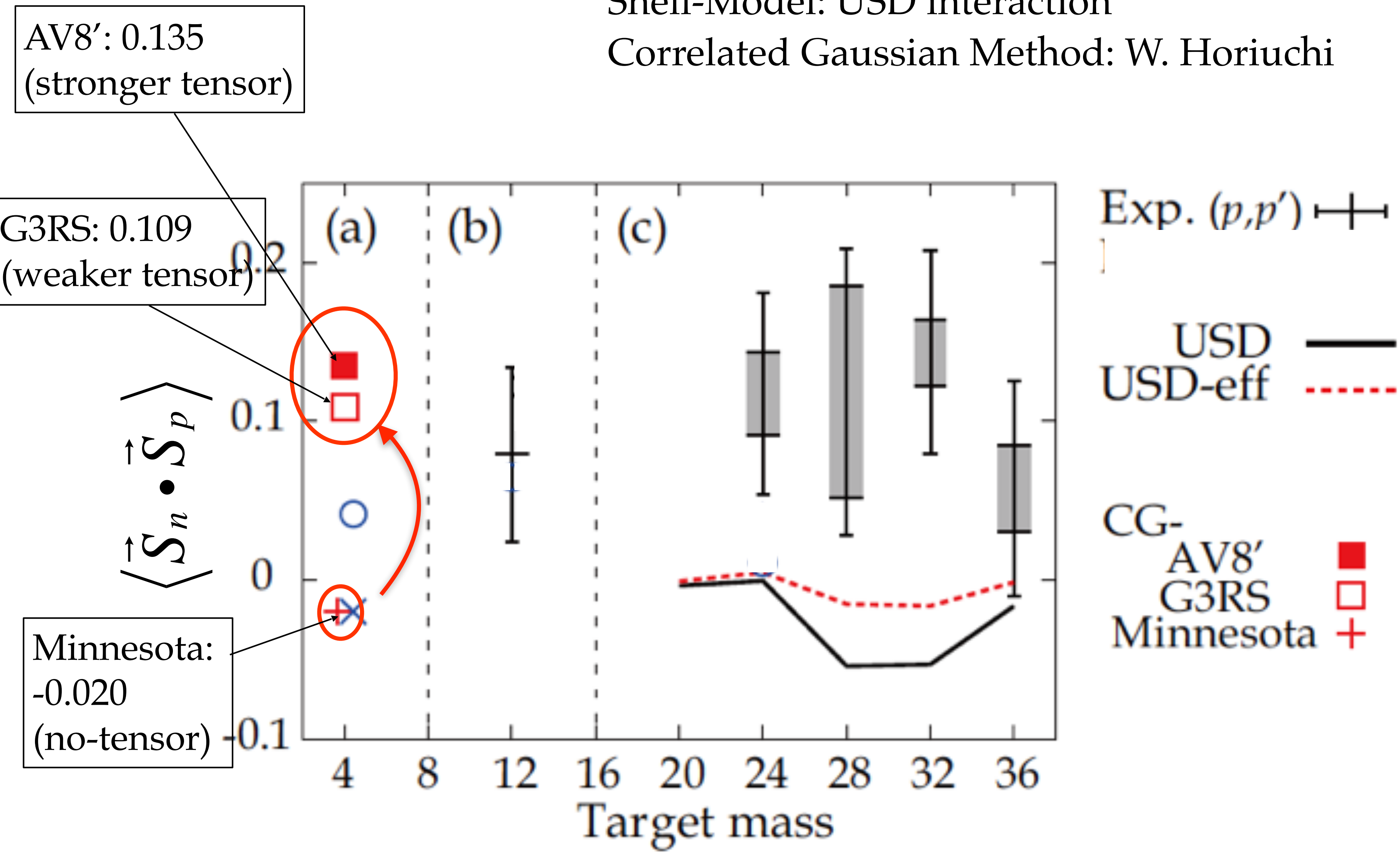
	$\langle \vec{S}_n^2 + \vec{S}_p^2 \rangle$	$\langle \vec{S}_n \cdot \vec{S}_p \rangle$	S=0	S=1	S=2
AV8' Stronger tensor int.	0.572	0.135	85.8%	0.4%	13.9%
G3RS Weaker tensor int.	0.465	0.109	88.5%	0.3%	11.3%
Minnesota No tensor int.	0.039	-0.020	100%	0%	0%

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

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

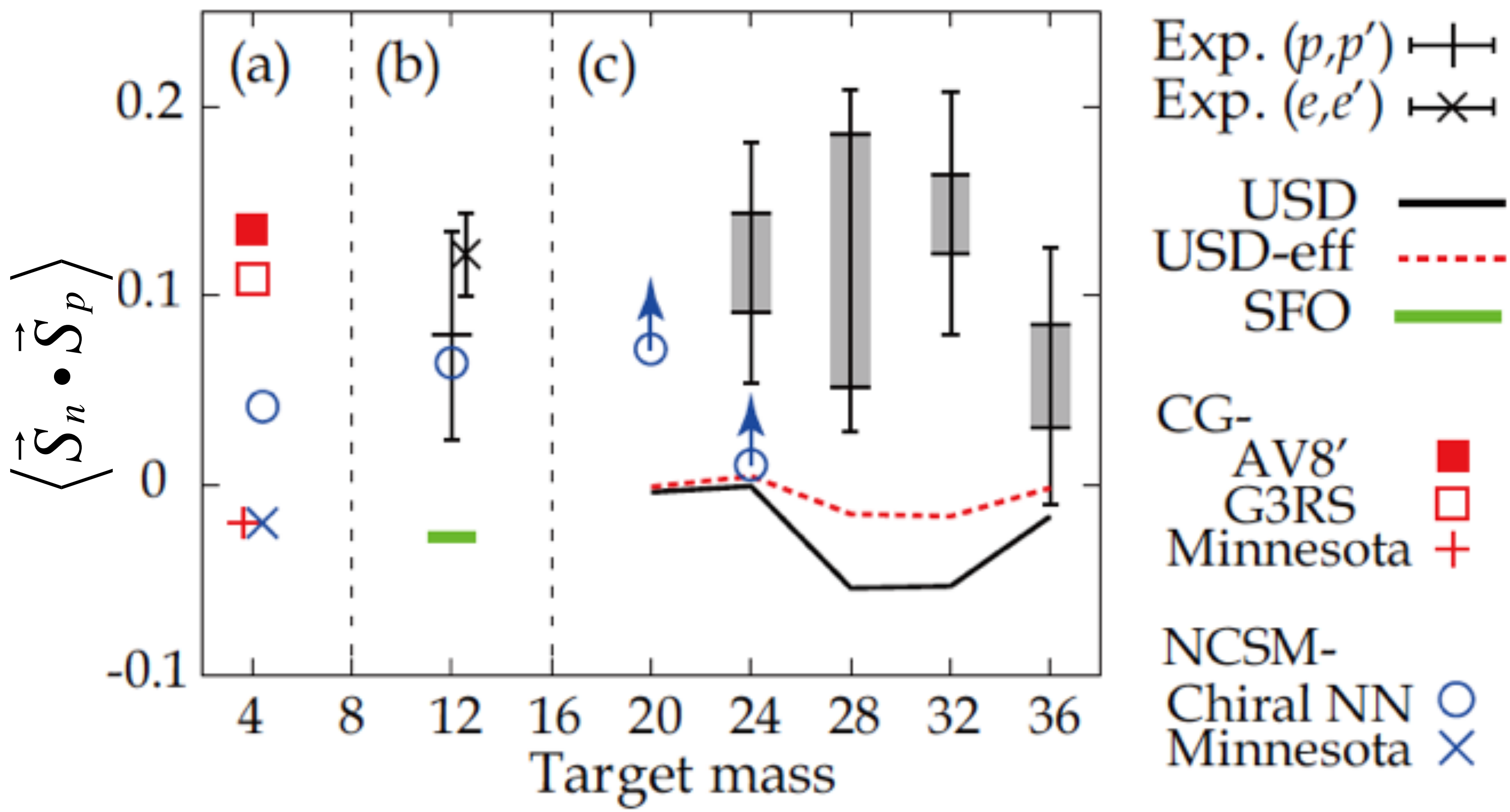
np Spin Correlation Function

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



np Spin Correlation Function

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

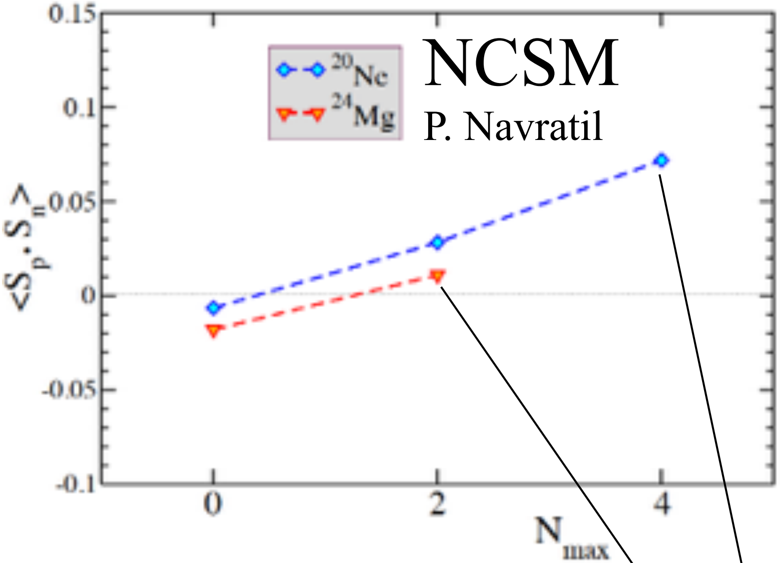


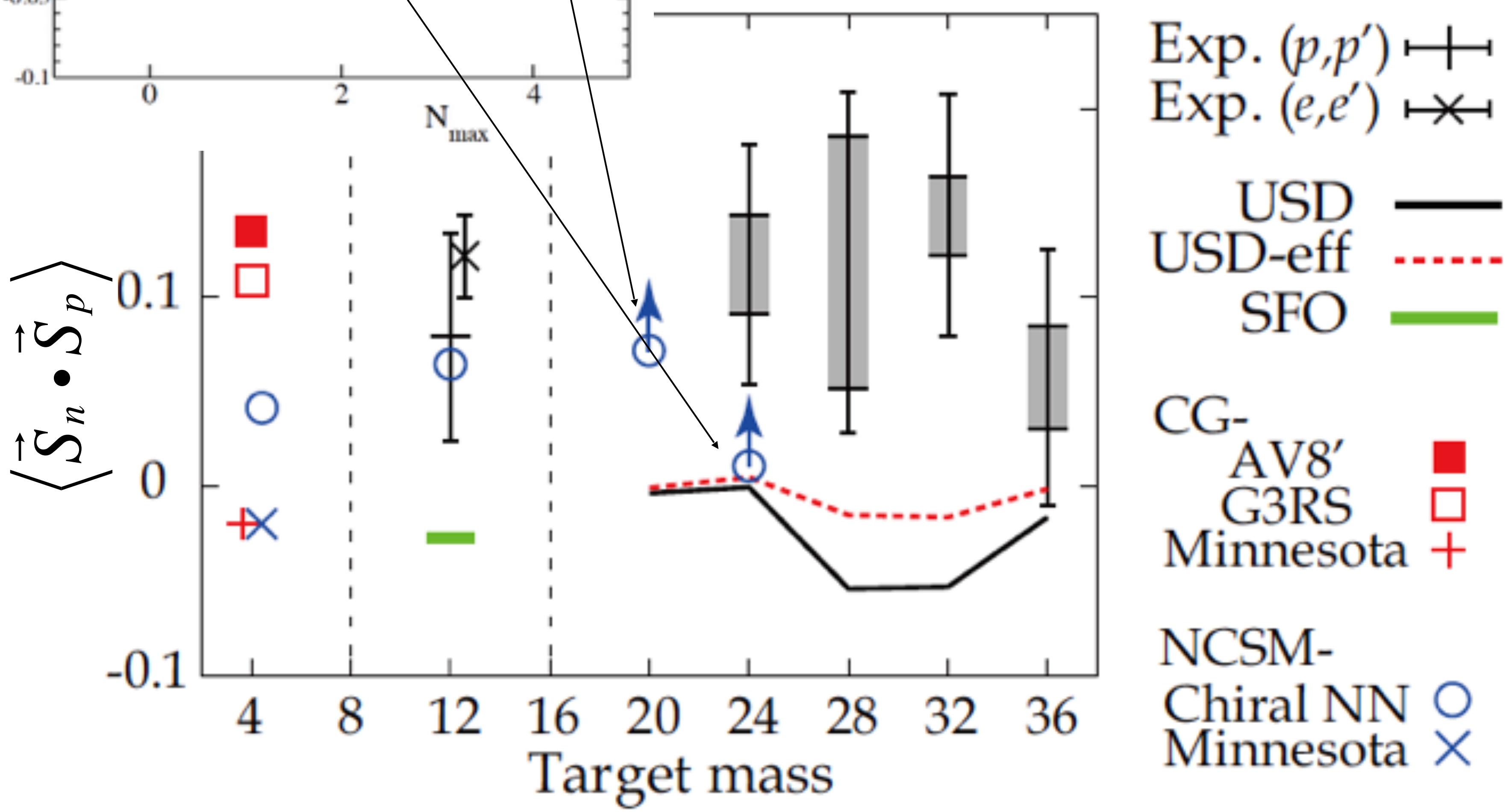
orrelation Function

orrelated Gaussian Method: W. Horiuchi

on-Core Shell Model: P. Navratil

hell-Model: USD interaction





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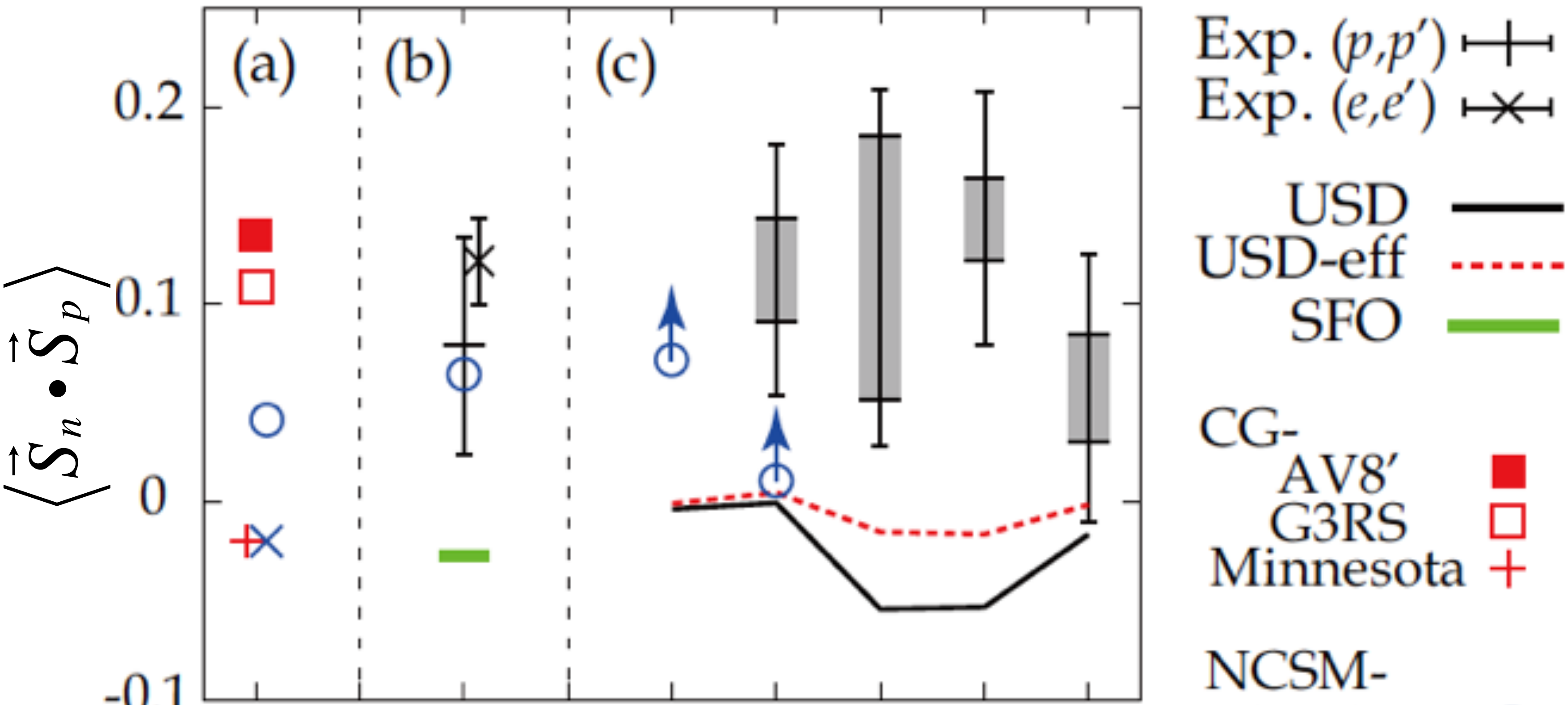


Further theoretical studies on the *sd*-shell nuclei by ab-initio type calculations with realistic interactions are very interesting.

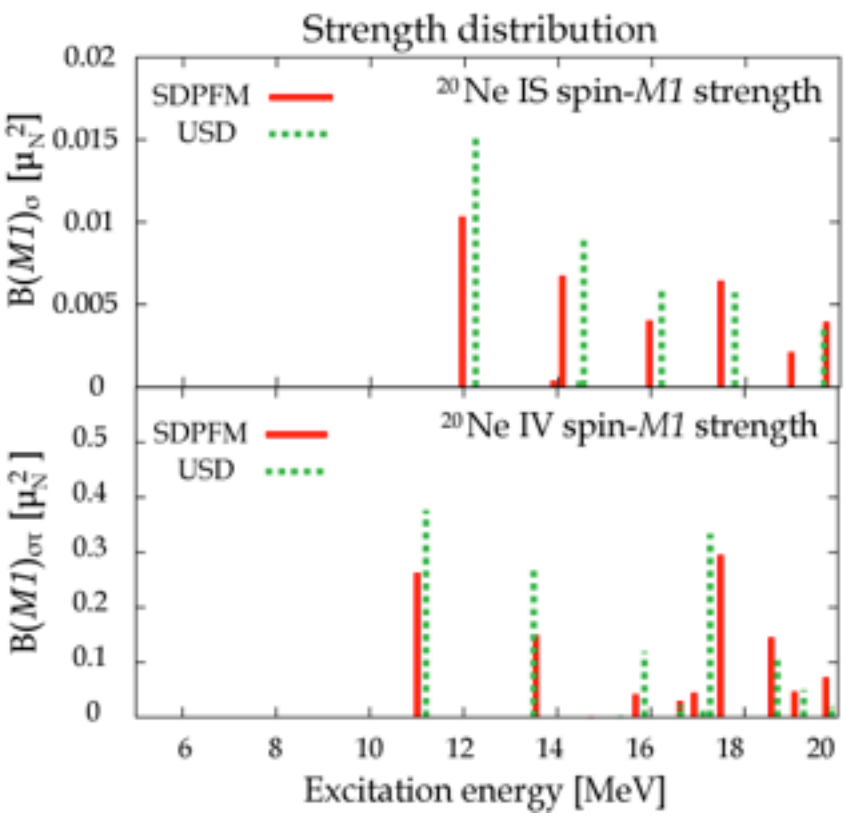
Discussion/Criticism

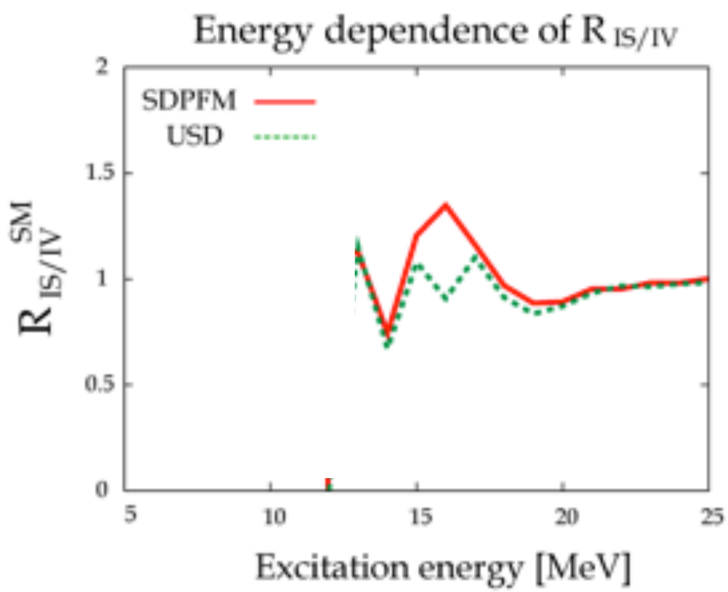
Model Space Dependence

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





Free g_s-factor

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 (A = 24)

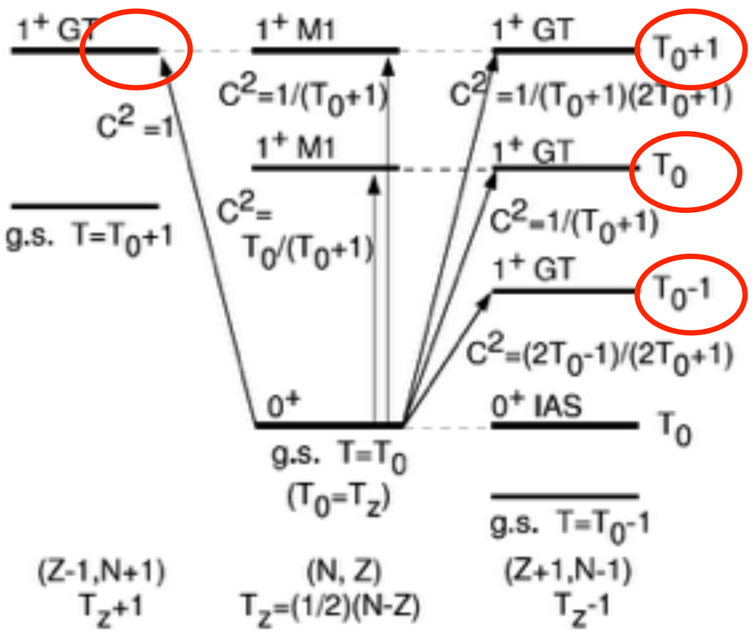
>90% in Ex<16 MeV (A = 28, 32, 36)

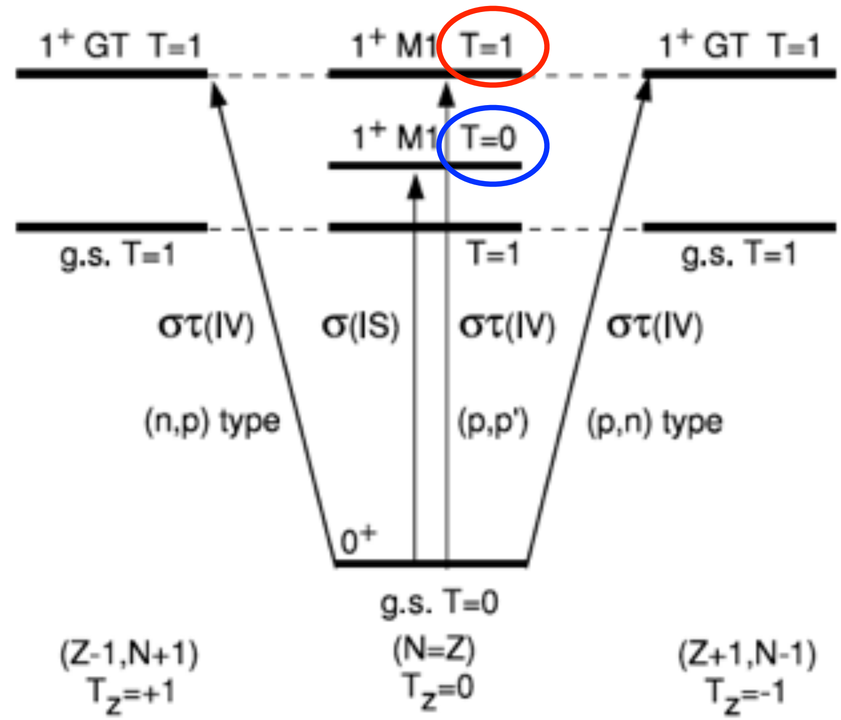
Measurement was done only below E_x=16 MeV.

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

Relation to Fujii-Fujita-Ikeda Sum-Rule for GT transitions and its quenching

No clear relation





Fujii-Fujita-Ikeda Sum-Rule

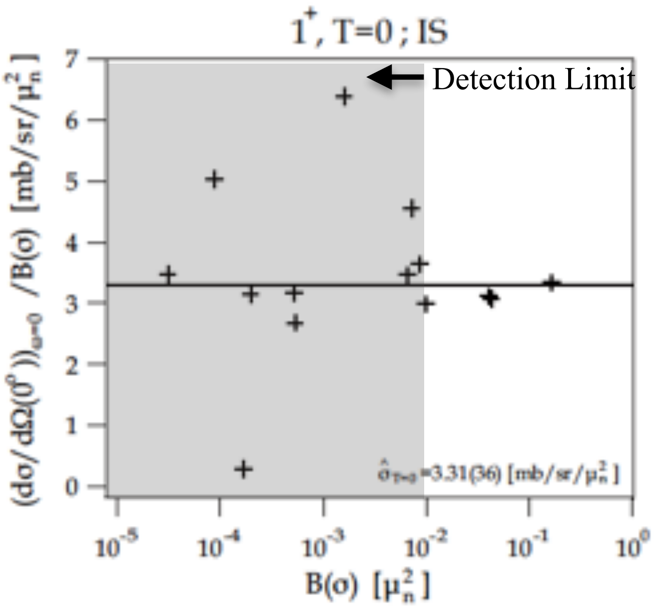
$$S_{-}^{(GT)} - S_{+}^{GT} = 3(N - Z)$$

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

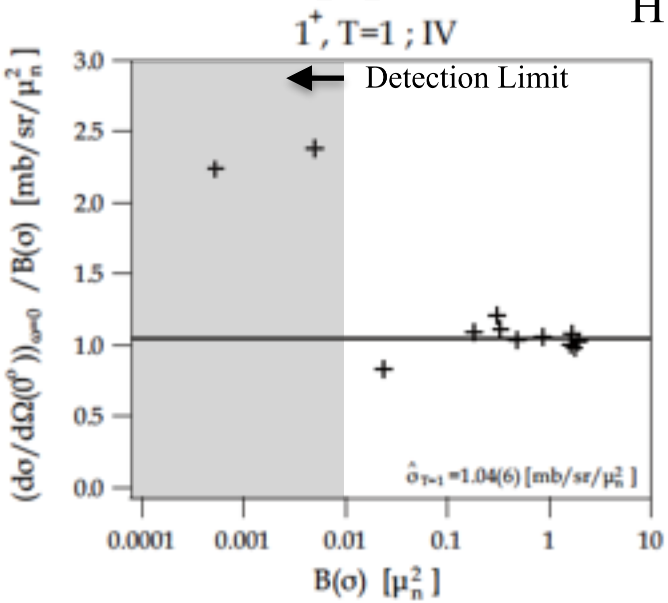
In the present work, IV spin-M1 corresponds to T_0+1.

Unit Cross Section and Proportionality
(theoretical study)

^{28}Si(p,p') IS

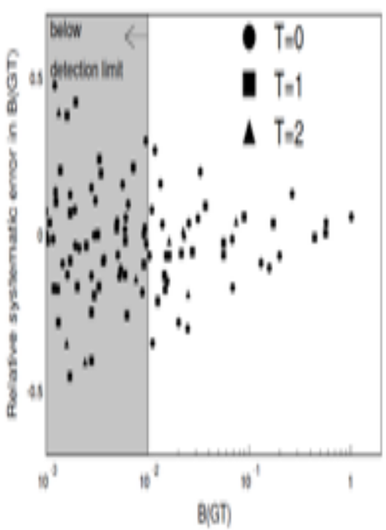


^{28}Si(p,p') IV



H. Matsubara, thesis

~ ^{28}Si(p,n)



^{26}Mg(^{3}He,t)

R.G.T. Zegers et al., PRC74, 24309(2004).

Relation to the IS Magnetic Moment and the effective g-factor

consistent with the present result

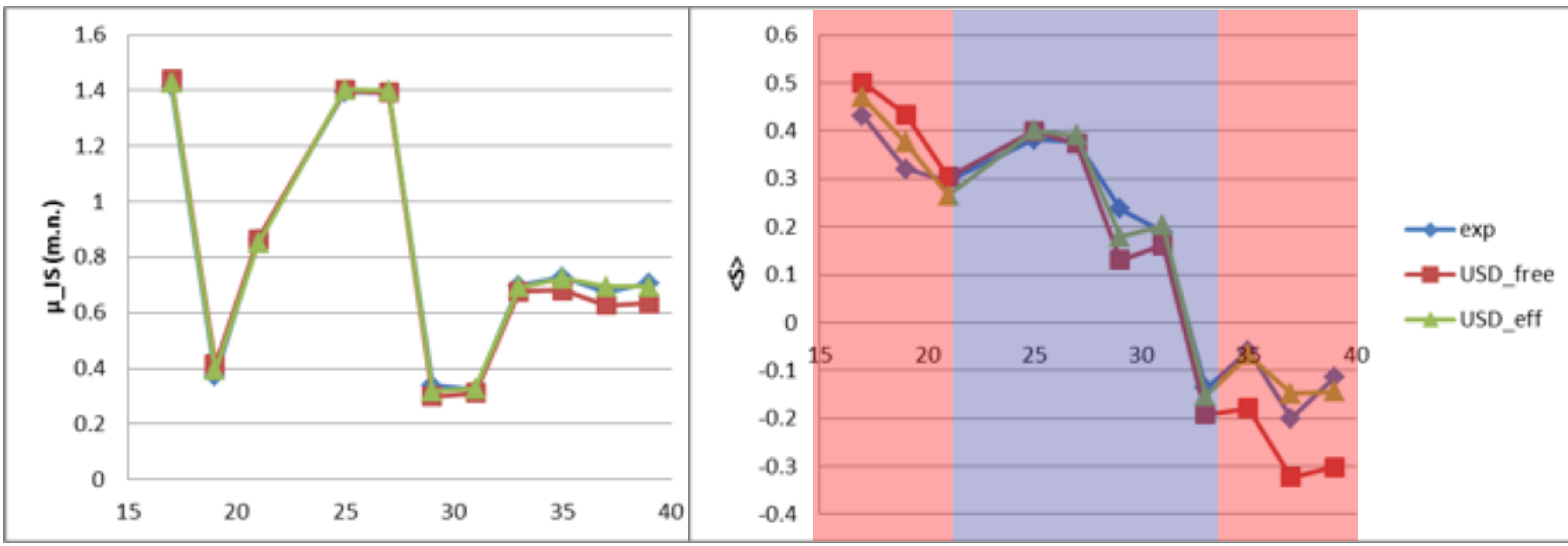
Empirical values were obtained to reproduce <S>.

$$\mu_{IS} = 0.38\langle s \rangle + 0.5J$$

Spin-matrix

The factors come from the g-factors in free space.

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



Quenching is large at the shell-edge.

Quenching is suppressed in the mid-shell.

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}C+γ
  - (^{12}C,^{12}C(1^{+},T=0;12.71 MeV)) in inverse kinematics for IV spin-M1
    $\rightarrow \alpha$+^{8}Be$\rightarrow \alpha+\alpha+\alpha$

Future Experimental Possibilites

- In general, the difference of IS and IV SNMEs in any spin-isospin mode can be a probe of *np* correlation for the relevant operator.

  e.g IS SDR and IV SDR for L=1 component of the IS *np*-pairing

IS/IV spin-*M1* response

ν-opacity and ν-transportation in SNe and PNS

SNe dynamics, nucleosynthesis, cooling of a proton neutron star

- GT, IS/IV-spinM1 response of nuclear matter
- IS-spinM1 response of pure neutron matter

Spin (magnetic) susceptibility and response to a strong magnetic field

$$\frac{\chi_\sigma}{2n} = \frac{4}{3N}\sum_f \frac{1}{\omega}\left|\langle f|\sum_i \boldsymbol{\sigma}_i|0\rangle\right|^2$$

Inversely energy weighted sum-rule of spin-M1 transition strengths.

G. Shen et al., PRC**87**, 025802 (2013)

Magnetic response of nuclear matter in a magnetar

Summary

- IS/IV-spin-M1 SNMEs have been studied by a high-resolution (*p*,*p*′) measurement at E_p=295 MeV

- No-quenching is observed in the IS-spin-M1 SNME while quenching is observed in the IV-spin-M1 SNME as is expected from the analogous GT transitions.

- The *np* spin correlation function extracted from the experimental data show systematically positive numbers, implying the IS *np* correlation in the ground states.

- A shell model calculation using the USD interaction does not reproduce the positives. However, predictions of the correlated Gaussian method on ^{4}He, and the non-core shell model look more consistent with the data.