

Nuclear Excited Studied by proton scattering
With a High-Resolution Magnetic Spectrometer

Lecture VI

Spin Magnetic Response of Nuclei

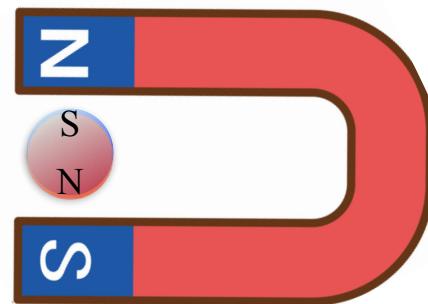
n-p Correlation

43 34 13 1 at <https://menti.com>

<https://www.menti.com/alwqsv7cirbx>



Spin Magnetic Response of Nuclei and n-p Correlation



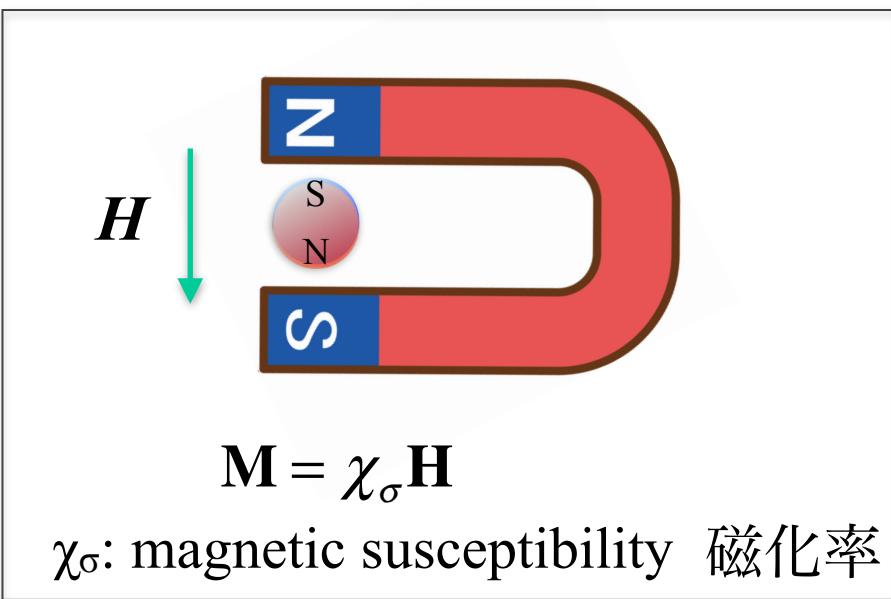
Spin-Magnetic Susceptibility

Magnetic dipole (*M1*) operator

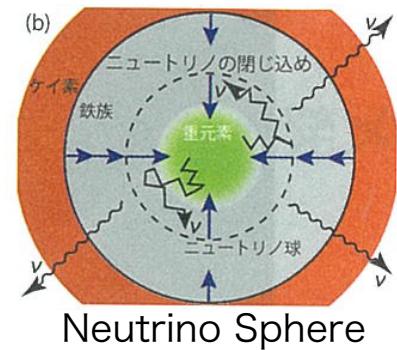
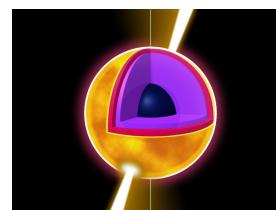
$$O(M1) = g_{\ell}^{\text{IS}} \ell + \underline{g_s^{\text{IS}} \sigma} + g_{\ell}^{\text{IV}} \ell \cdot \tau + \underline{g_s^{\text{IV}} \sigma \cdot \tau}$$

IS(1) and IV(τ) terms

$$\chi_{\sigma}^{\text{spin}} = \frac{8}{3N} \sum_f \frac{1}{\omega} \left| \langle f | \sum_i \sigma_i | 0 \rangle \right|^2$$

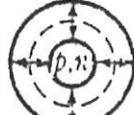
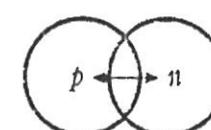
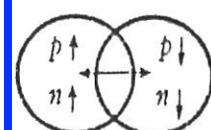
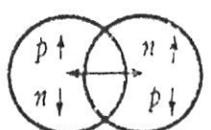
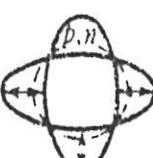
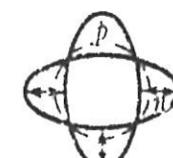
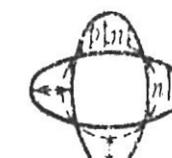


- Spin part of magnetization of nuclear matter
 - Magnetic response of nuclear matter (in e.g. magnetometer)
 - Neutrino trap in the core of supernova
- Neutrino transparency
- Ferromagnetic state in a neutron star



Magneter 10¹⁴⁻¹⁶ Gauss

Collective Vibrational Excitations

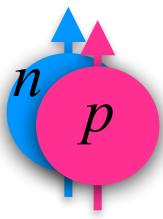
		Magnetic $\Delta S = 1$		Operators
		Isoscalar Electric	Isovector Electric	
	$(\Delta T, \Delta S)$	(0, 0)	(1, 0)	
Monopole	$\Delta L = 0$			 
Dipole	$\Delta L = 1$	—		 
Quadrupole	$\Delta L = 2$			 
Multipole	...			

Magnetic $\Delta S = 1$

Operators

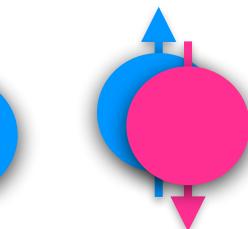
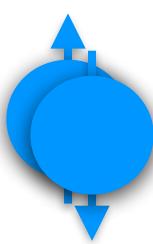
$$\vec{\sigma} \quad \vec{\sigma}\tau$$

IS and IV pairings



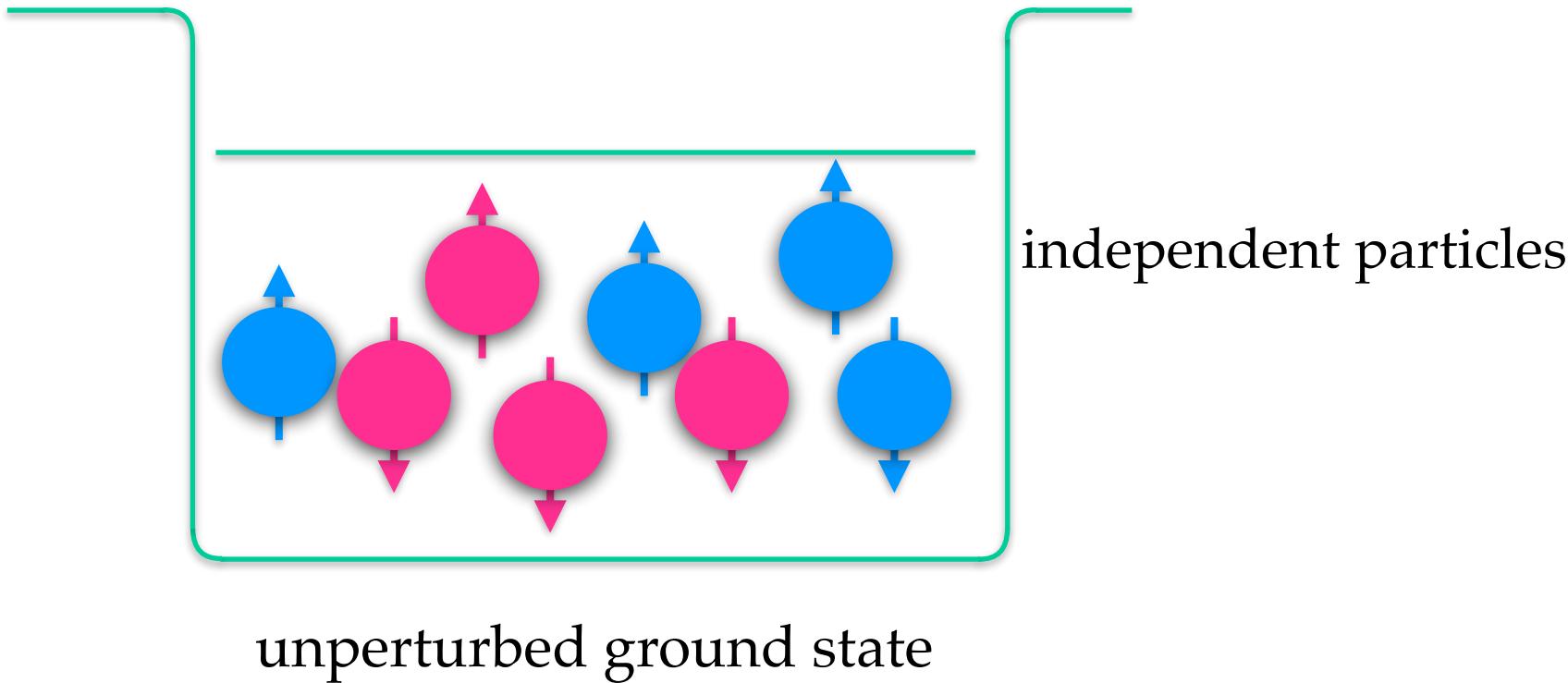
IS ($T=0, S=1$)

Isoscalar np -pairing

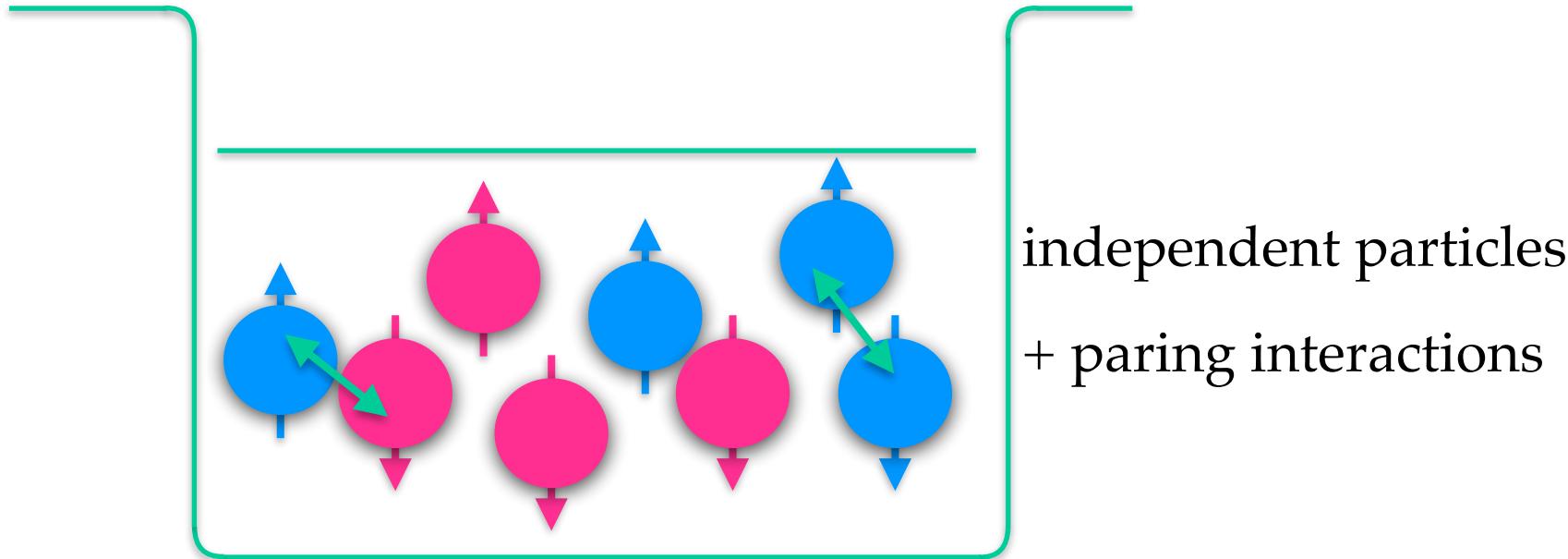


IV ($T=1, S=0$)

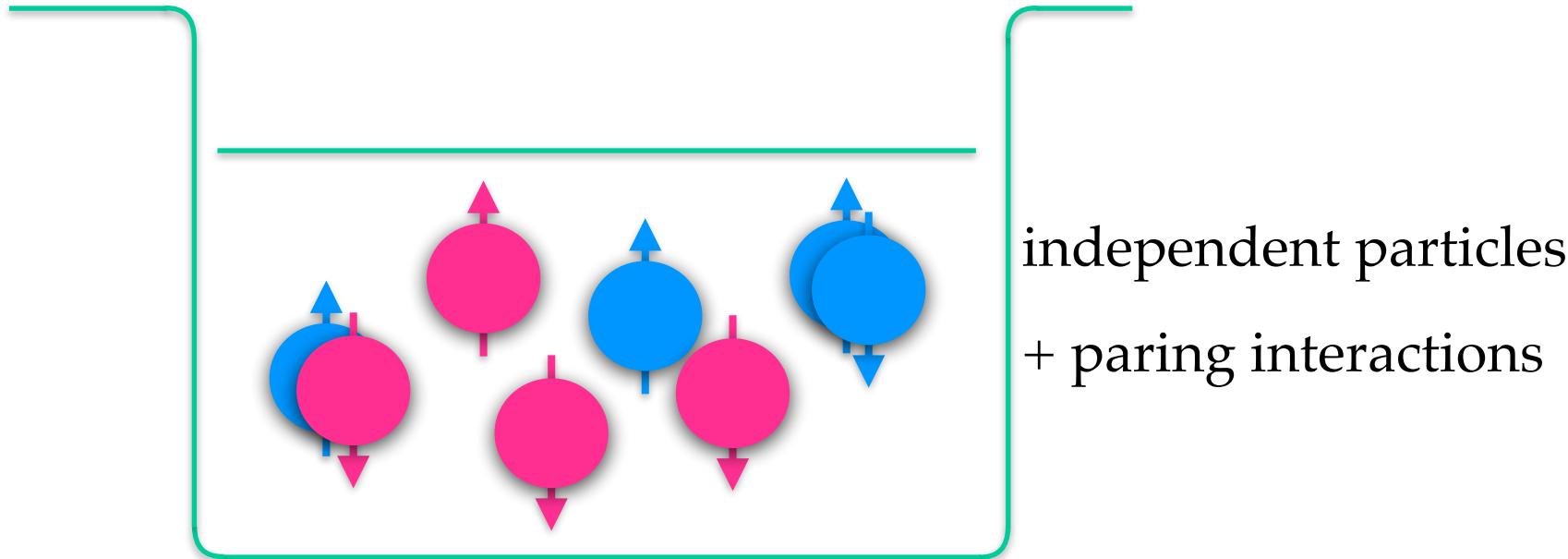
pairing in the ground state W.F.



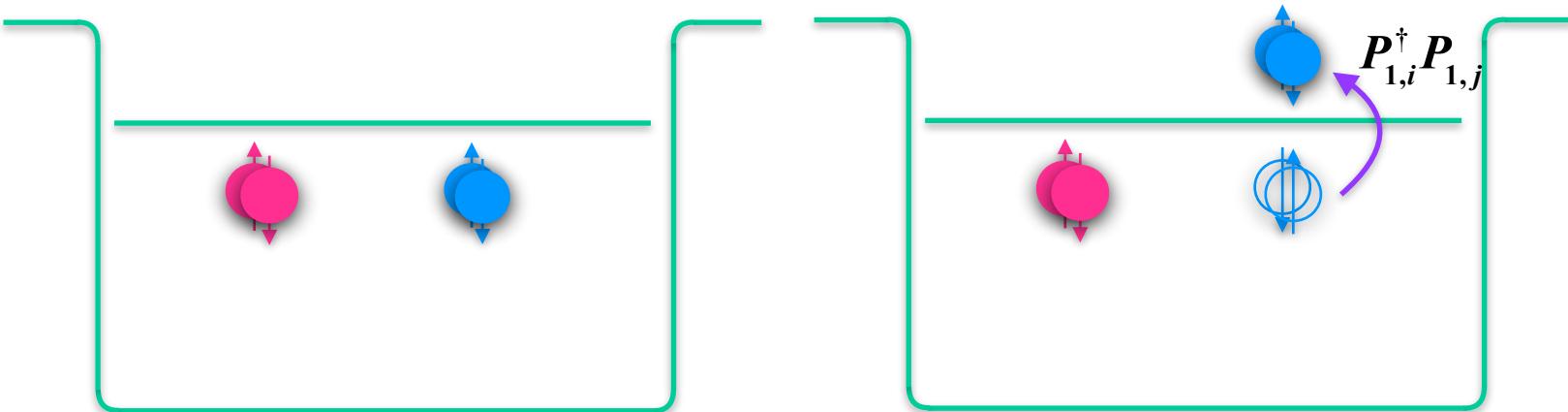
pairing in the ground state W.F.



pairing in the ground state W.F.

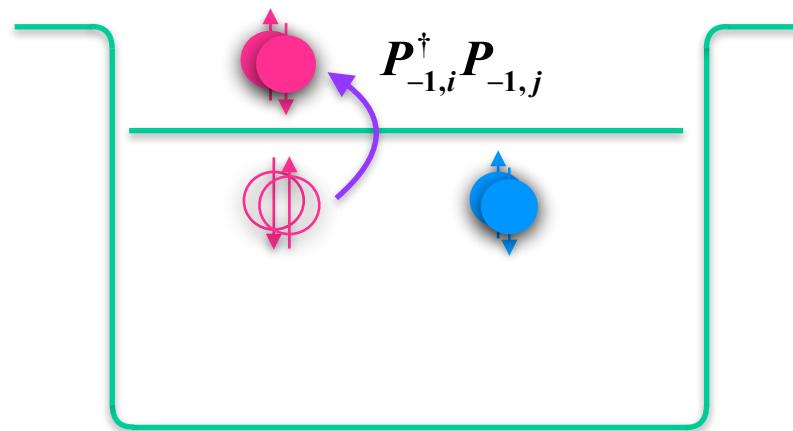


pairing in the ground state W.F.



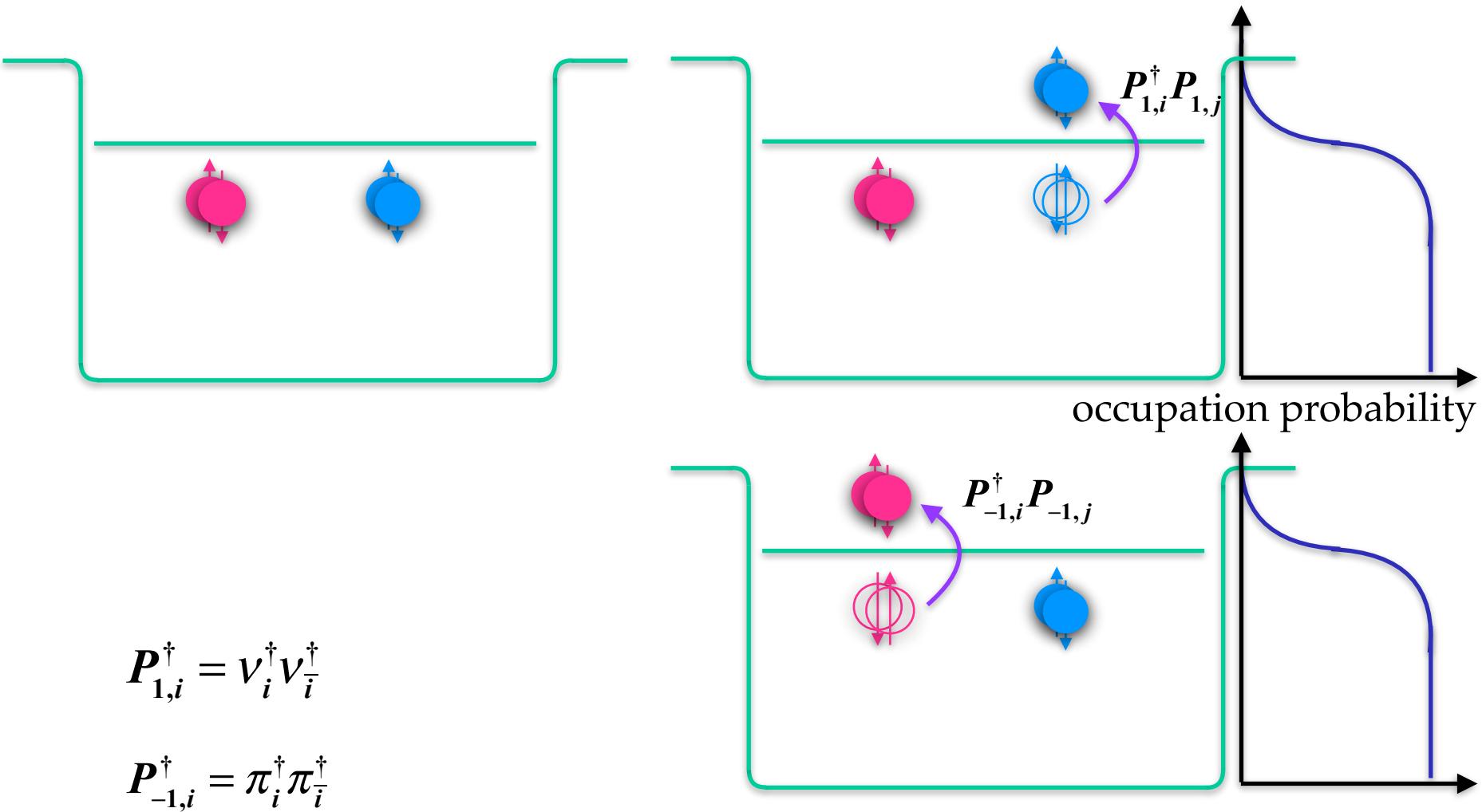
$$P_{1,i}^\dagger = V_i^\dagger V_i^\dagger$$

$$P_{-1,i}^\dagger = \pi_i^\dagger \pi_i^\dagger$$



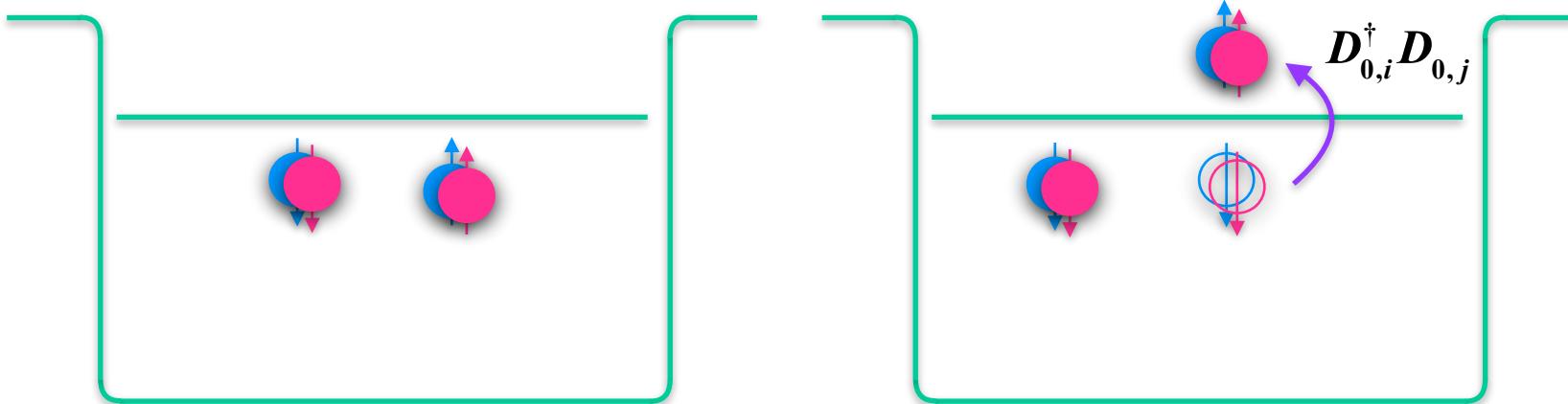
isovector “pairing” correlation
= BCS type correlation

pairing in the ground state W.F.



isovector “pairing” correlation
= BCS type correlation

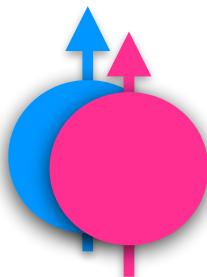
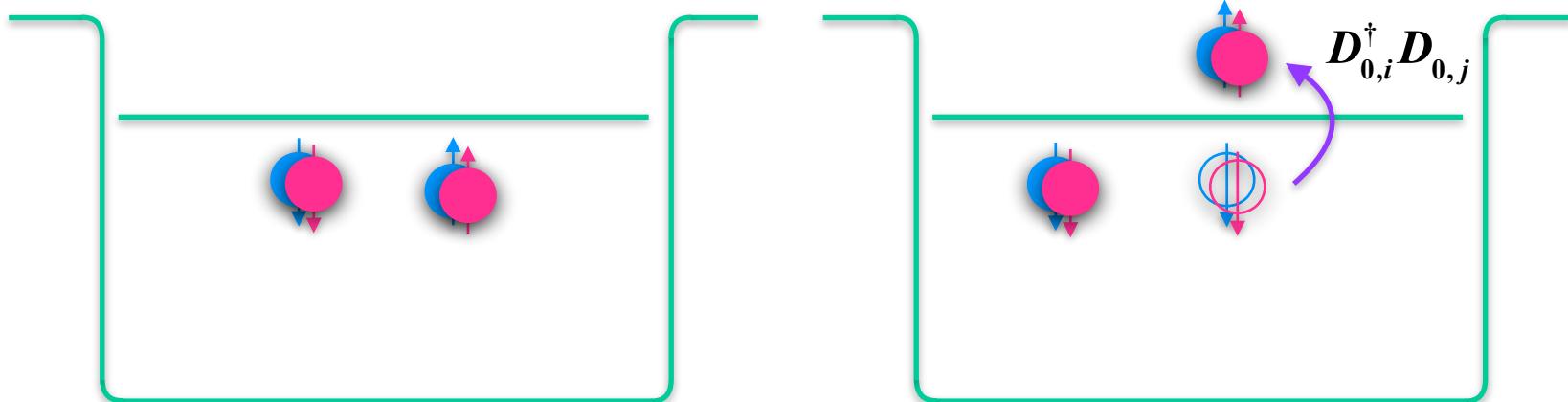
np pairing in the ground state W.F.



$$D_{0,i}^\dagger = \frac{1}{\sqrt{2}} \left(v_i^\dagger \pi_i^\dagger - \pi_i^\dagger v_i^\dagger \right)$$

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

np pairing in the ground state W.F.

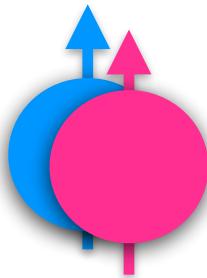
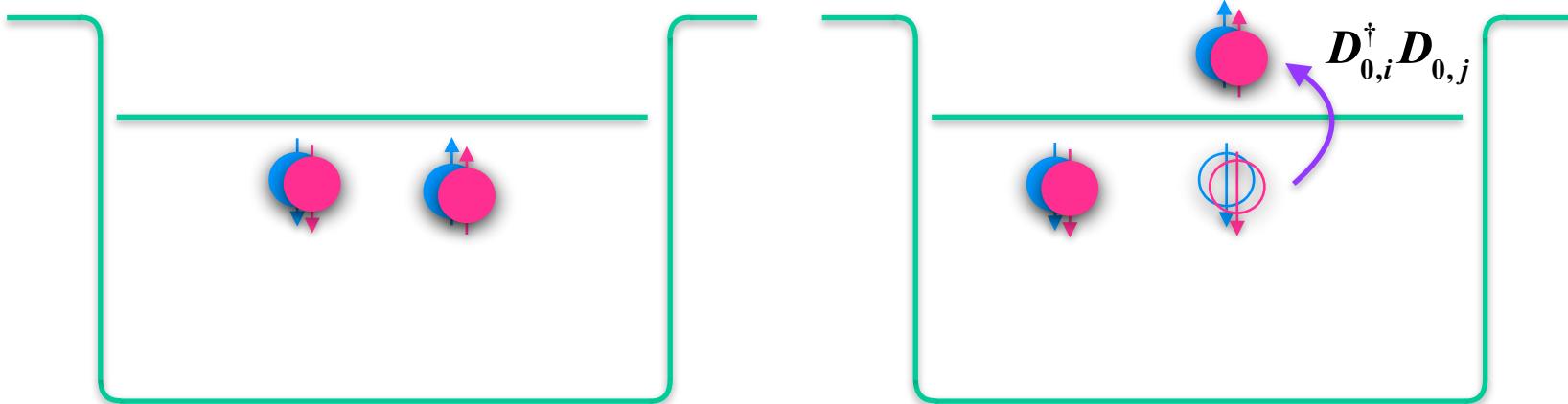


n -spin and p -spin:
aligned

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

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

np pairing in the ground state W.F.



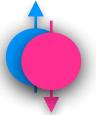
n -spin and p -spin:
aligned

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

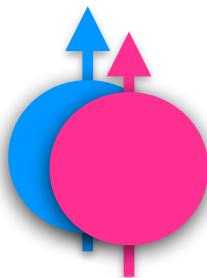
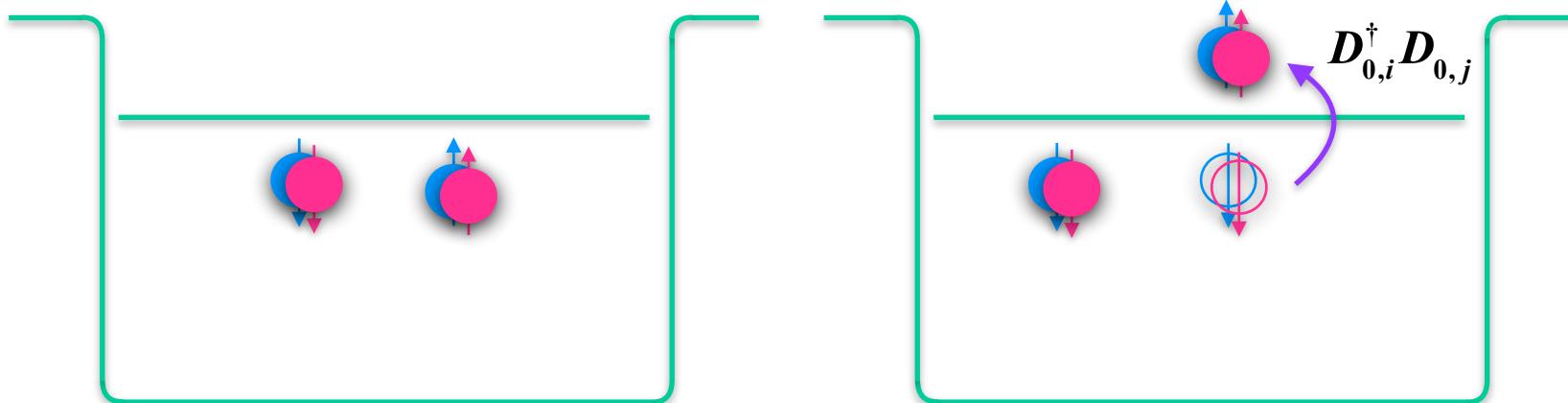
$$\vec{S}^2 = (\vec{s}_n + \vec{s}_p)^2 = \vec{s}_n^2 + \vec{s}_p^2 + 2\vec{s}_n \cdot \vec{s}_p$$

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

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



np pairing in the ground state W.F.

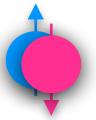
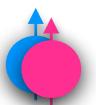


n -spin and p -spin:
aligned

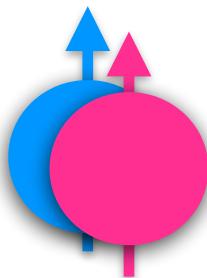
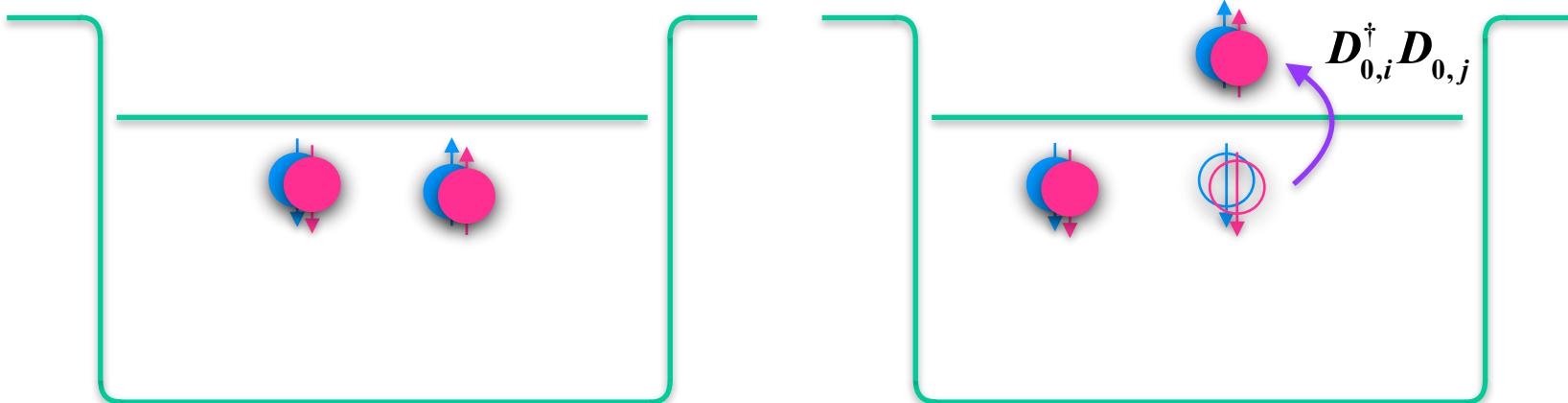
$$\langle \vec{s}_n \cdot \vec{s}_p \rangle > 0$$

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

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



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

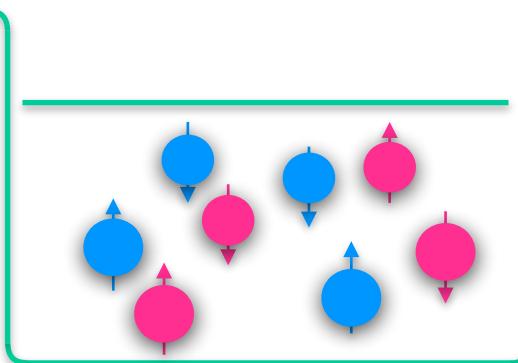
np spin correlation function

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

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

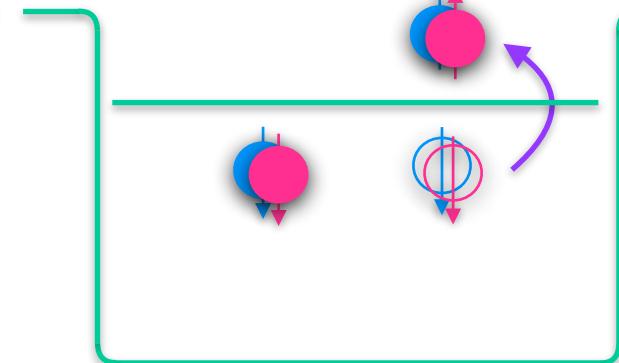
$$\vec{S}_n \equiv \sum_i^N \vec{s}_{n,i} \quad \vec{S}_p \equiv \sum_i^Z \vec{s}_{p,i}$$

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

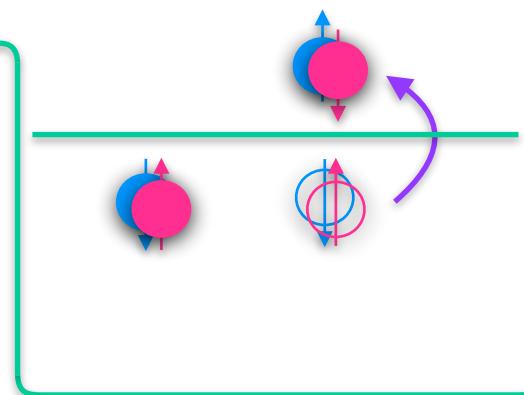


$$\langle \vec{S}_n \cdot \vec{S}_p \rangle = 0$$

also for IV pp/nn parings



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



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

How to Study the np Spin Correlation Function?

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

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

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

$$\begin{aligned} \langle (\vec{S}_n - \vec{S}_p)^2 \rangle &= \frac{1}{4} \langle (\vec{\sigma} \tau_z)^2 \rangle \\ &= \frac{1}{4} \sum_f \langle 0 | \vec{\sigma} \tau_z | f \rangle \langle f | \vec{\sigma} \tau_z | 0 \rangle \end{aligned}$$

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

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

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

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

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

closure

IV spin-M1 squared nuclear matrix elements (SNME)

IS spin-M1 SNME

Spin-M1 Reduced Transition Strength

M1 Operator

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

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

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

IS Reduced Matrix Element

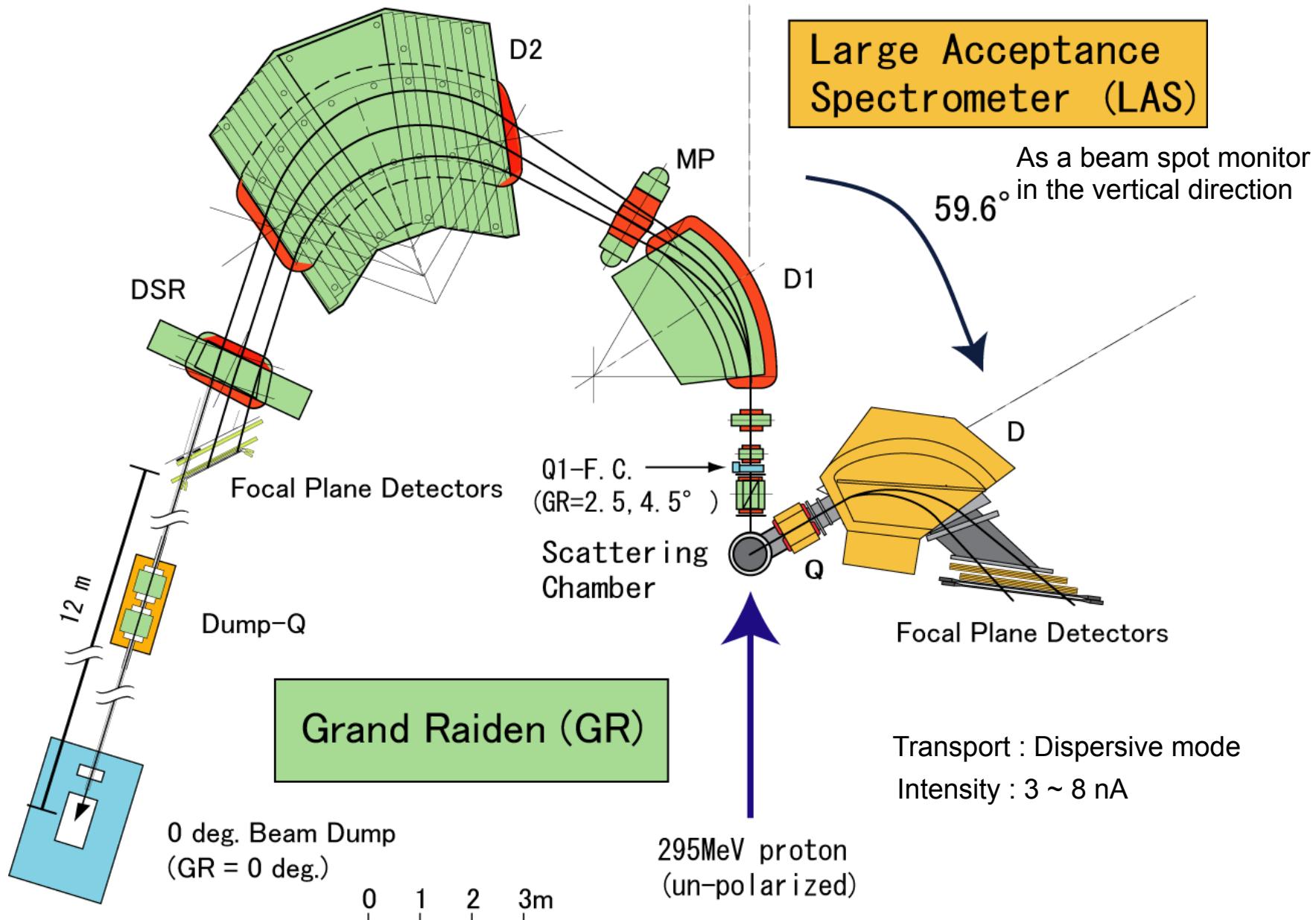
$T=1$ Isovector (IV) Spin-M1 Reduced Transition Strength

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

IV Reduced Matrix Element

Experimental Methods

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



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

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

				Sc 36 0.0162s	Sc 37 0.0294s	Sc 38 0.0522s	Sc 39 0.0921s	Sc 40 0.1823s	Sc 41 0.5963s	Sc 42 1.028m
				Ca 34 0.0172s	Ca 35 0.0257s	Ca 36 0.182s	Ca 37 0.1811s	Ca 38 0.44s	Ca 39 0.859s	Ca 40 96.941
				K 33 0.031s	K 34 0.067s	K 35 0.19s	K 36 0.342s	K 37 1.226s	K 38 6.36m	K 39 93.2981
				Ar 30 0.013s	Ar 31 0.0141s	Ar 32 0.098s	Ar 33 0.173s	Ar 34 0.8445s	Ar 35 1.775s	Ar 36 34.95d
				Cl 29 0.0316s	Cl 30 0.0474s	Cl 31 0.15s	Cl 32 0.298s	Cl 33 0.34s	Cl 34 75.7s	Cl 35 3.01e+05s
				S 26 0.0148s	S 27 0.021s	S 28 0.125s	S 29 0.187s	S 30 1.178s	S 31 2.572s	S 32 94.93
				P 25 0.0489s	P 26 0.0437s	P 27 0.26s	P 28 0.2703s	P 29 0.47s	P 30 2.495m	P 31 100
				Si 22 0.029s	Si 23 0.0423s	Si 24 0.14s	Si 25 0.22s	Si 26 2.234s	Si 27 4.16s	Si 28 92.2297
				Al 21 0.0448s	Al 22 0.859s	Al 23 0.47s	Al 24 2.853s	Al 25 7.183s	Al 26 4e+05s	Al 27 100
				Mg 19 0.0135s	Mg 20 0.0908s	Mg 21 0.122s	Mg 22 3.875s	Mg 23 11.32s	Mg 24 78.99	Mg 25 10
				Na 18 0.039s	Na 19 0.416s	Na 20 0.4479s	Na 21 2.449s	Na 22 2.682s	Na 23 100	Na 24 13.96s
				Ne 16 0.1092s	Ne 17 1.672s	Ne 18 17.22s	Ne 19 98.48	Ne 20 0.27	Ne 21 3.25	Ne 22 37.24s
				F 15 1e-19s	F 16 1.075m	F 17 1.837m	F 18 1.83s	F 19 100	F 20 11.16s	F 21 4.158s
O 12	0 13 0.00058s	0 14 1.177m	0 15 2.837m	0 16 2.837m	0 17 99.757	0 18 0.038	0 19 0.205	0 20 26.91s	0 21 13.51s	0 22 3.42s
N 11	N 12 0.011s	N 13 9.965m	N 14 99.632	N 15 0.368	N 16 7.13s	N 17 4.173s	N 18 0.624s	N 19 0.304s	N 20 0.142s	N 21 0.095s
C 8	C 9 0.1265s	C 10 19.25s	C 11 20.35m	C 12 98.93	C 13 1.07	C 14 2.449s	C 15 0.747s	C 16 0.193s	C 17 0.092s	C 18 0.049s
	B 8 0.77s	B 9 8.5e-19s	B 10 19.9	B 11 88.1	B 12 0.0202s	B 13 0.01736s	B 14 0.0138s	B 15 0.0105s	B 16 B 17 0.00508s	B 19 0.00292s
	Be 7 5.3.12d	Be 8 6.7e-17s	Be 9 100	Be 10 1.51e+06s	Be 11 13.81s	Be 12 0.0215s	Be 13 Be 14 0.00484s			
	Li 6 7.59	Li 7 92.41	Li 8 0.838s	Li 9 0.1783s	Li 10 0.0085s	Li 11 0.0085s				
He 3 0.000137	He 4 99.9999		He 6 0.81s		He 8 0.119s					
H 1 99.9985	H 2 0.0115	H 3 12.33u								
	B 1 10.43s									

We focus on these nuclei.

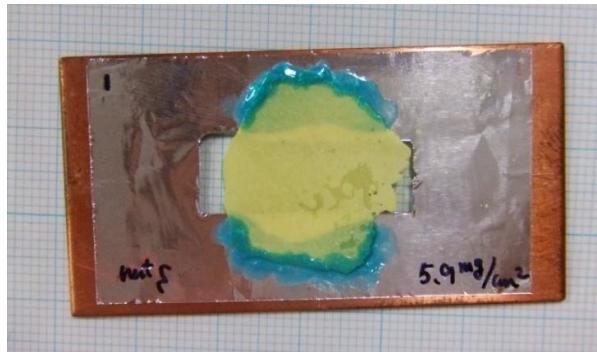
Stable self-conjugate even-even nuclei:

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

Targets

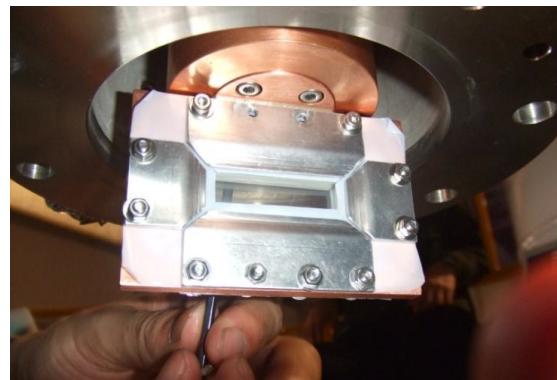
^{12}C , ^{24}Mg , ^{28}Si : self-supporting target

Cooled ^{32}S self-supporting target



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

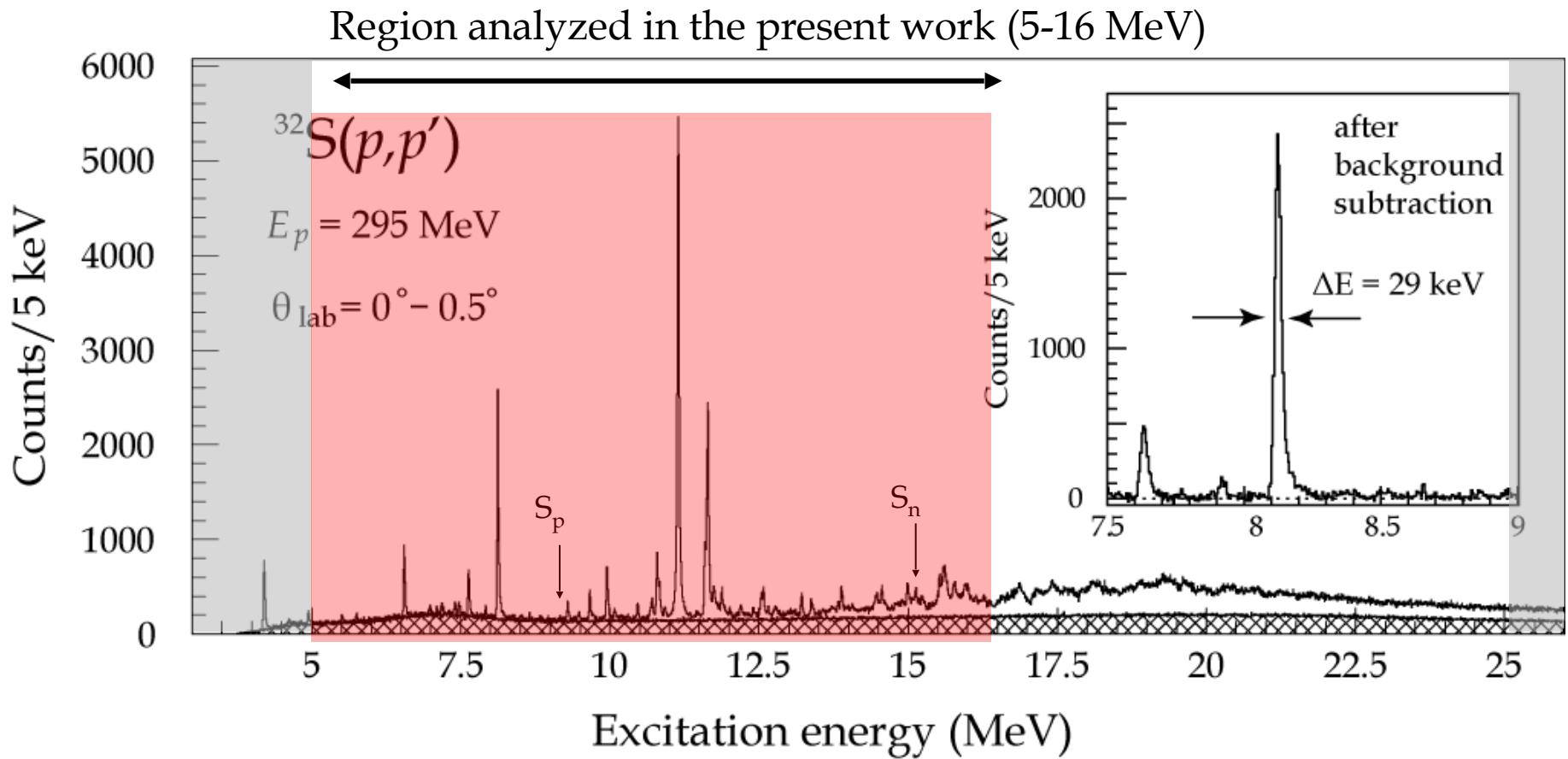
Gas Cell Target (^{36}Ar)



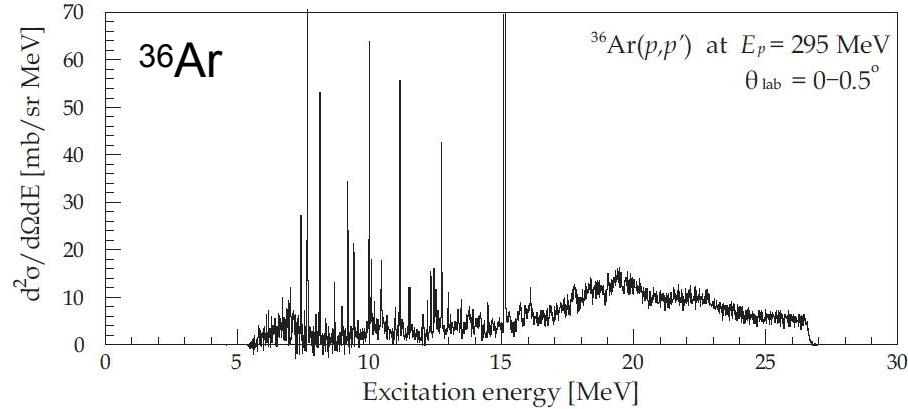
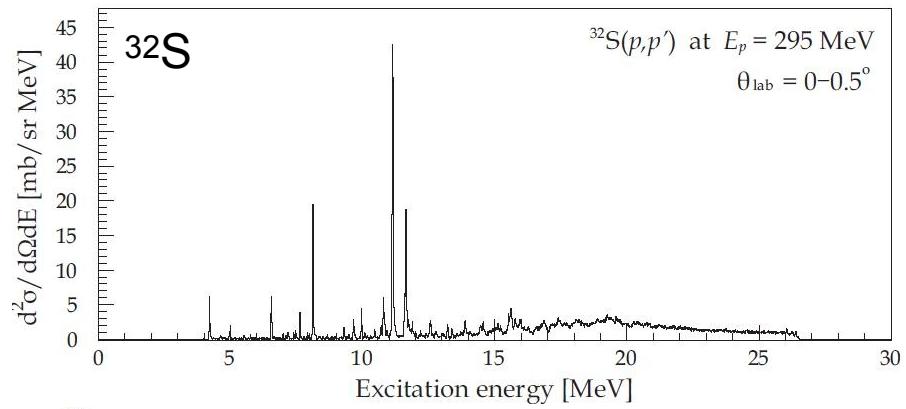
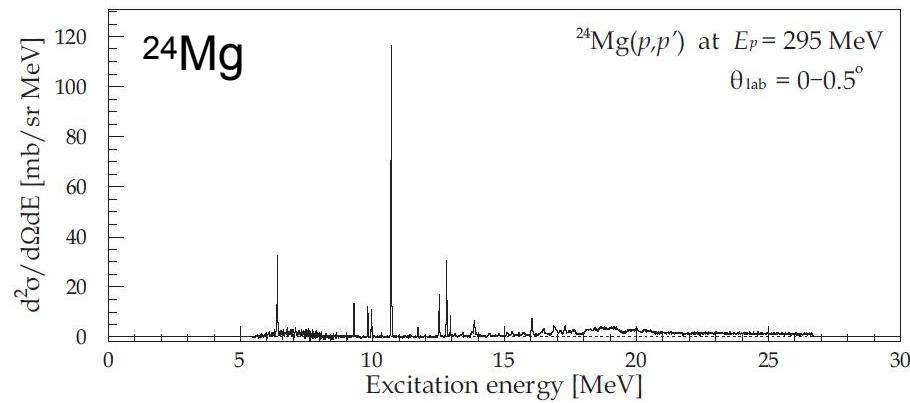
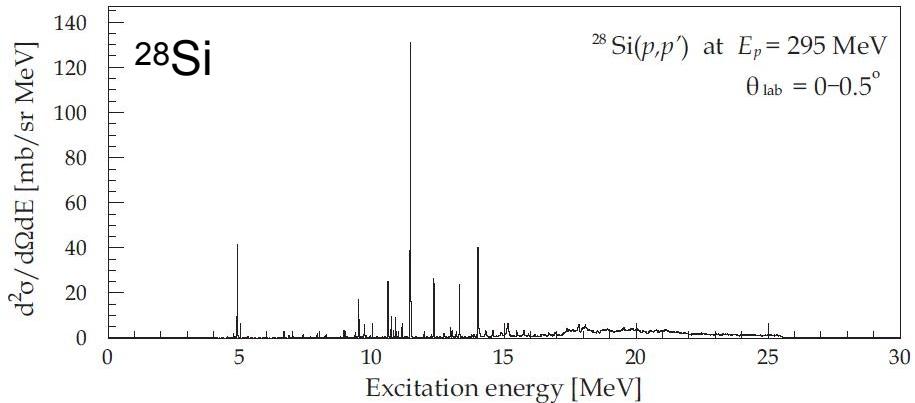
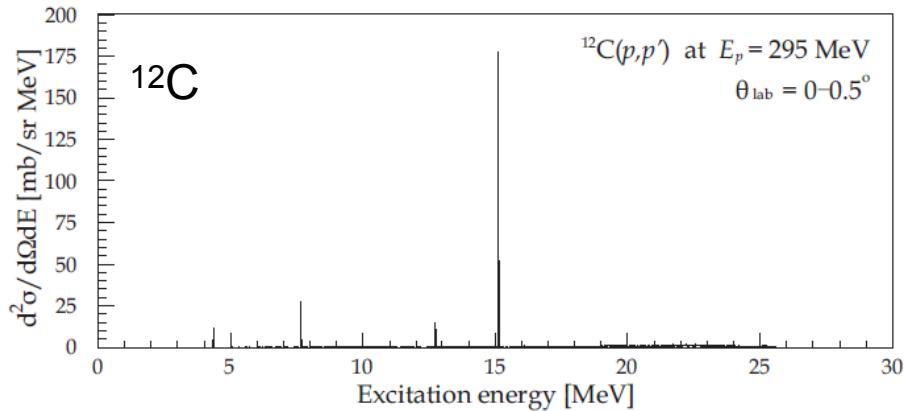
H. Matsubara *et al.*, NIMA 678, 122 (2012)

Aramidé window of $6 \mu\text{m}^t$

High energy-resolution spectrum



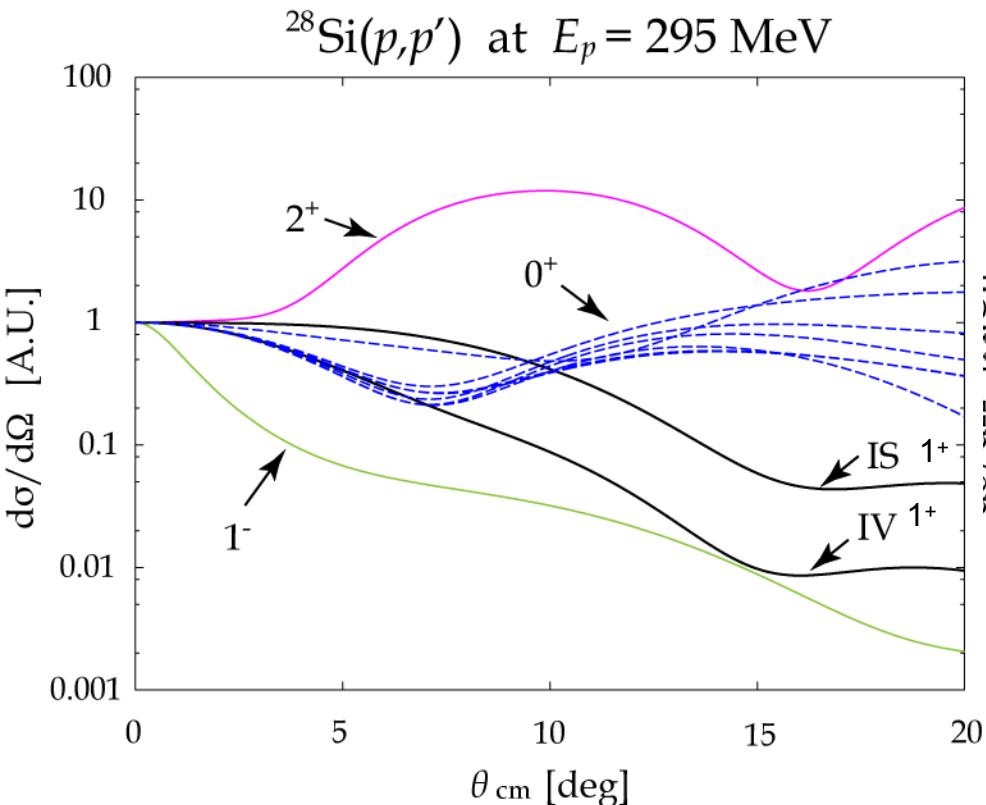
Energy spectra at 0-degrees



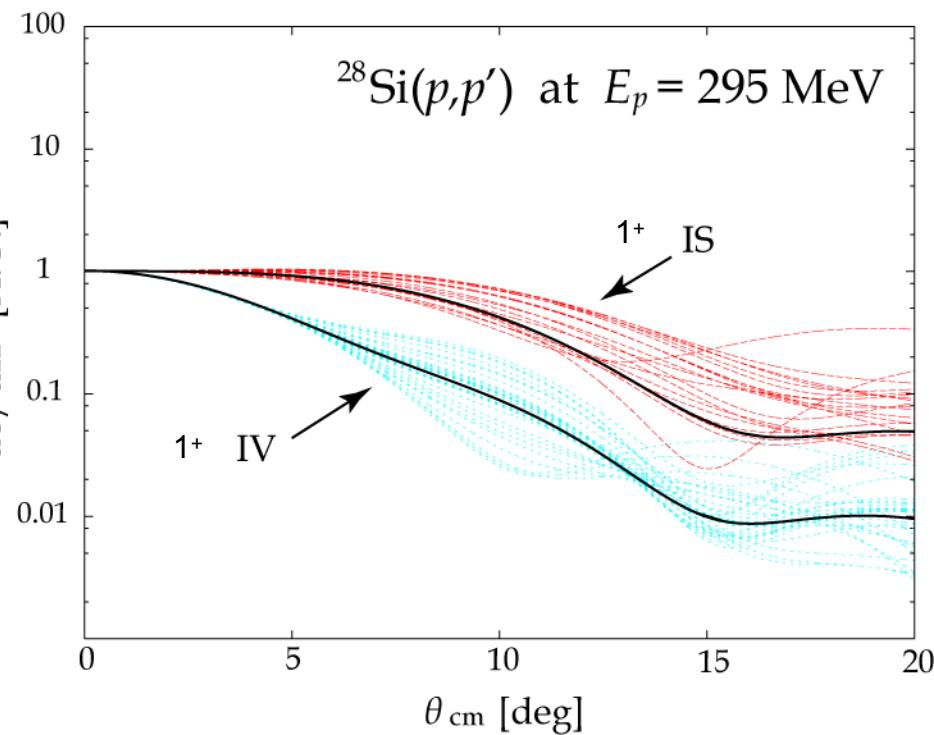
Angular distribution for J^π assignment

- 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)

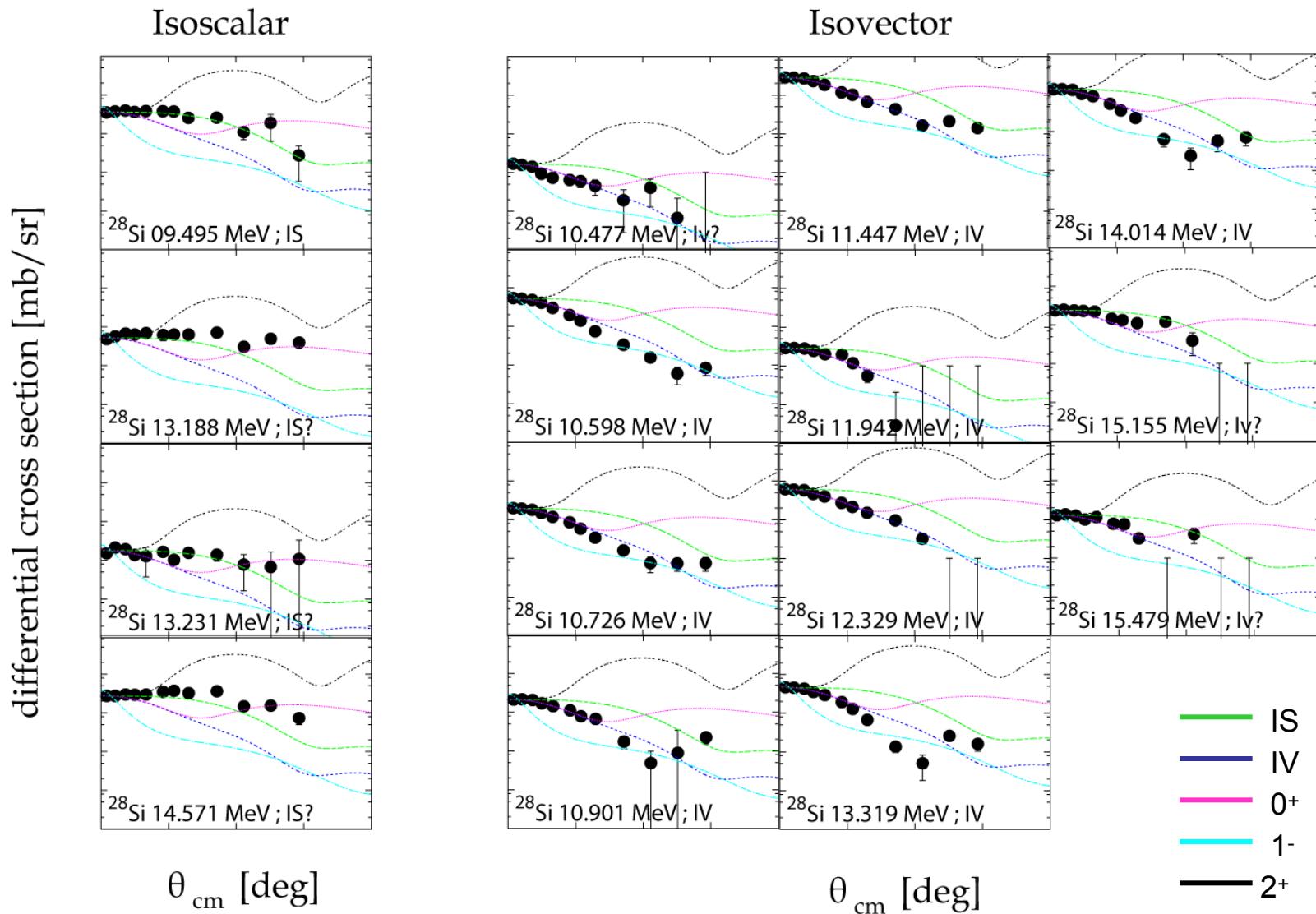


- Forward peaking for $L=0$ transition.
- $M1$ has the maximum at 0 degree.
- 0^+ , IS- 1^+ , IV- 1^+ and others



- 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 and γ -decay measurements
(on the assumption of the isospin symmetry).

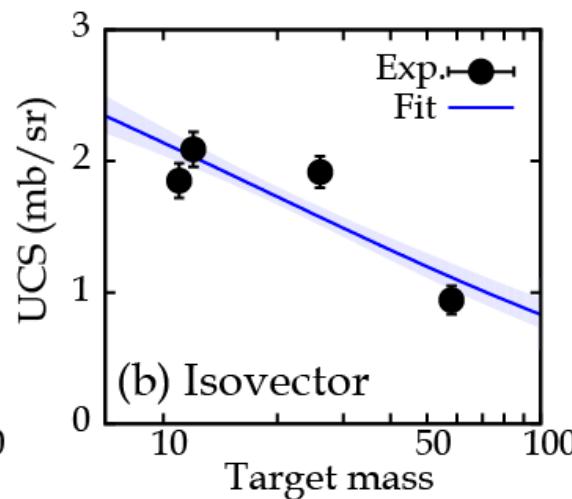
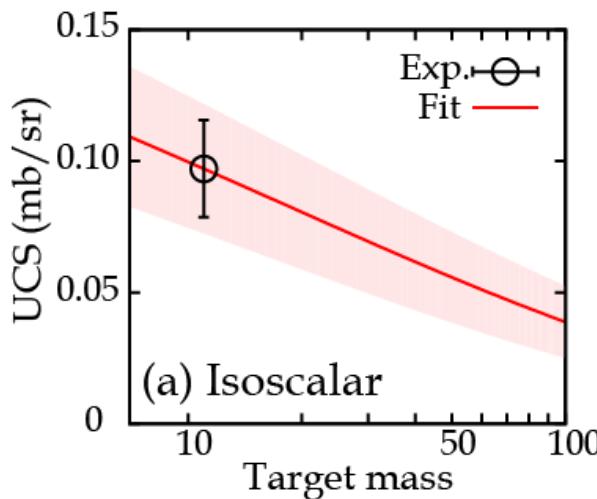
$$\frac{d\sigma}{d\Omega}(0^\circ) = \hat{\sigma}_T F(q, E_x) |M_f(O)|^2 \quad (T = \text{IS or IV})$$

UCS Kinematical factor SNME

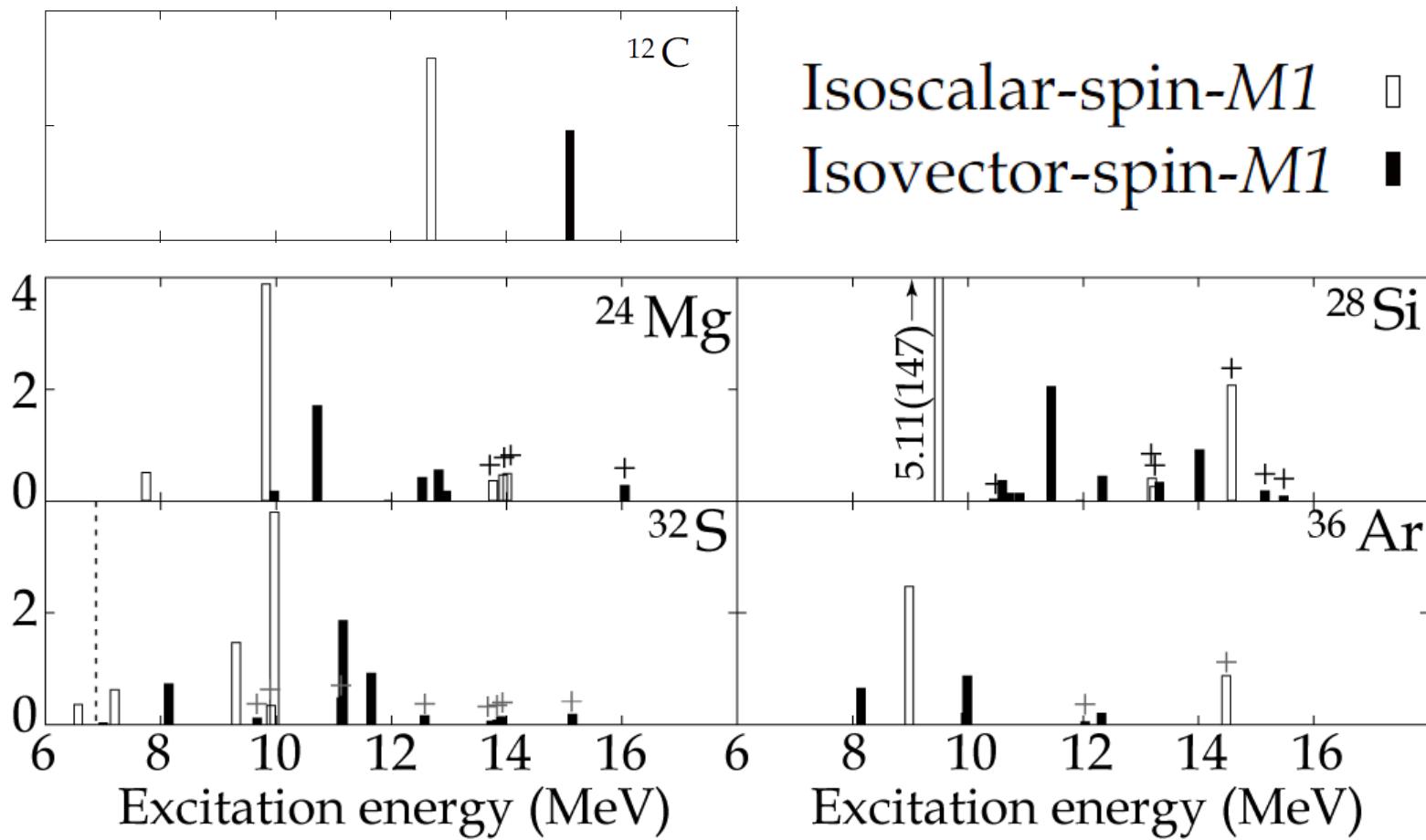
$$\hat{\sigma}_T(A) = N \exp(-xA^{1/3})$$

T.N. Taddeucci, NPA469 (1987).

- Function taken from the mass dependence of GT UCS

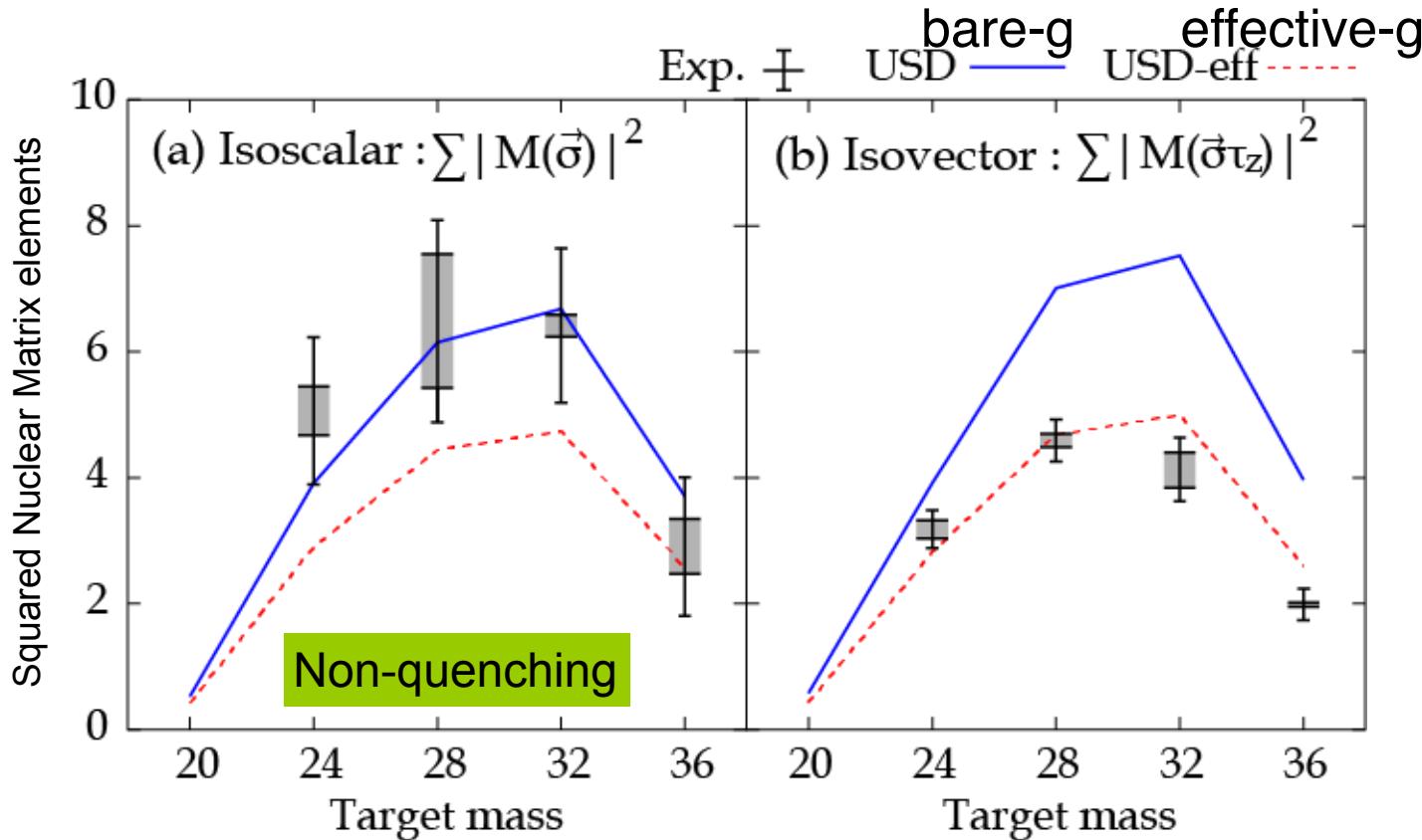


IS/IV-spin-M1 distribution



Spin-M1 SNME

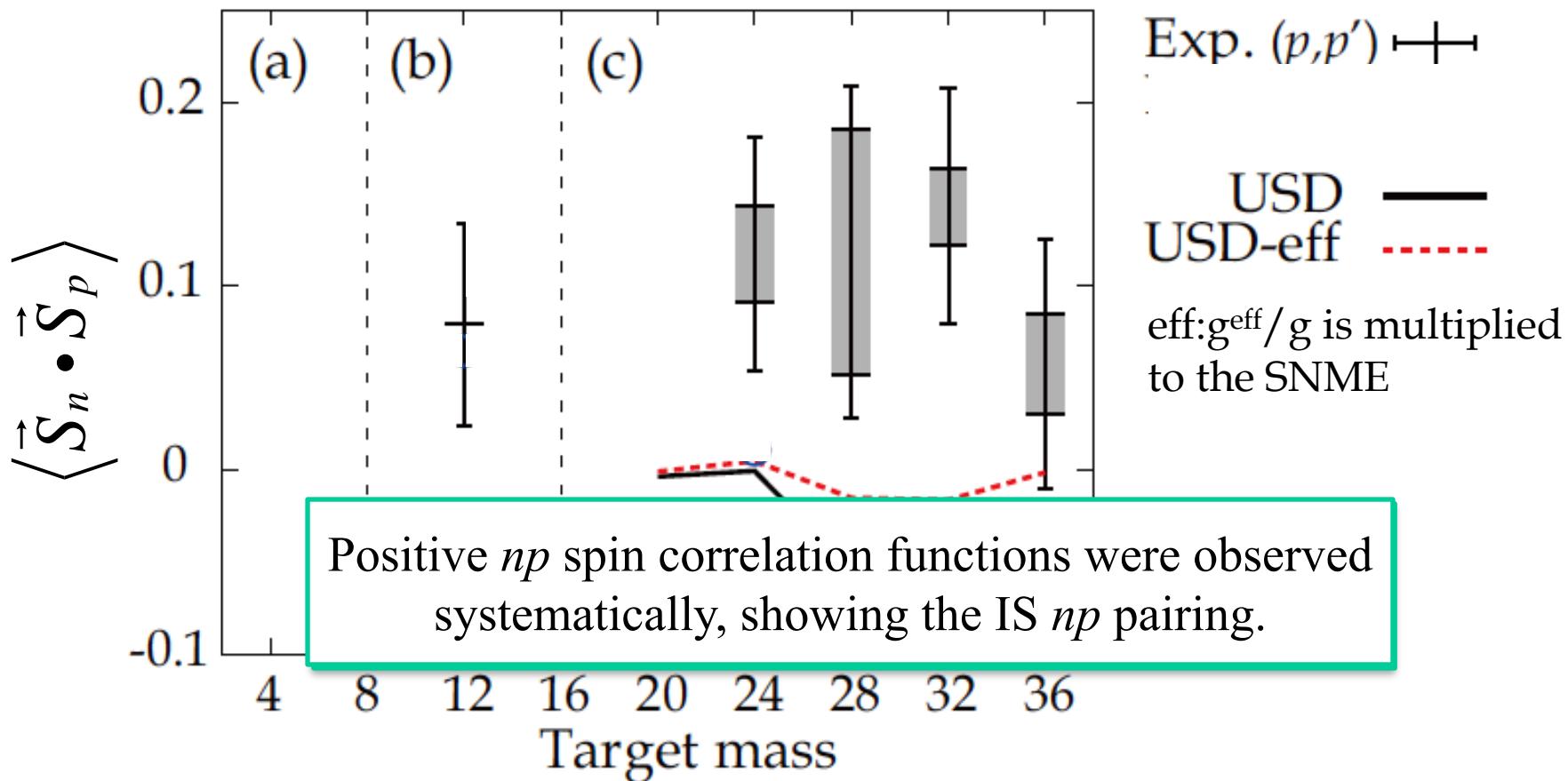
- Summed up to **16 MeV**.
- Compared with shell-model predictions using the USD interaction



Isoscalar spin-M1 SNME is not quenching.

np Spin Correlation Function

Shell-Model: USD interaction



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

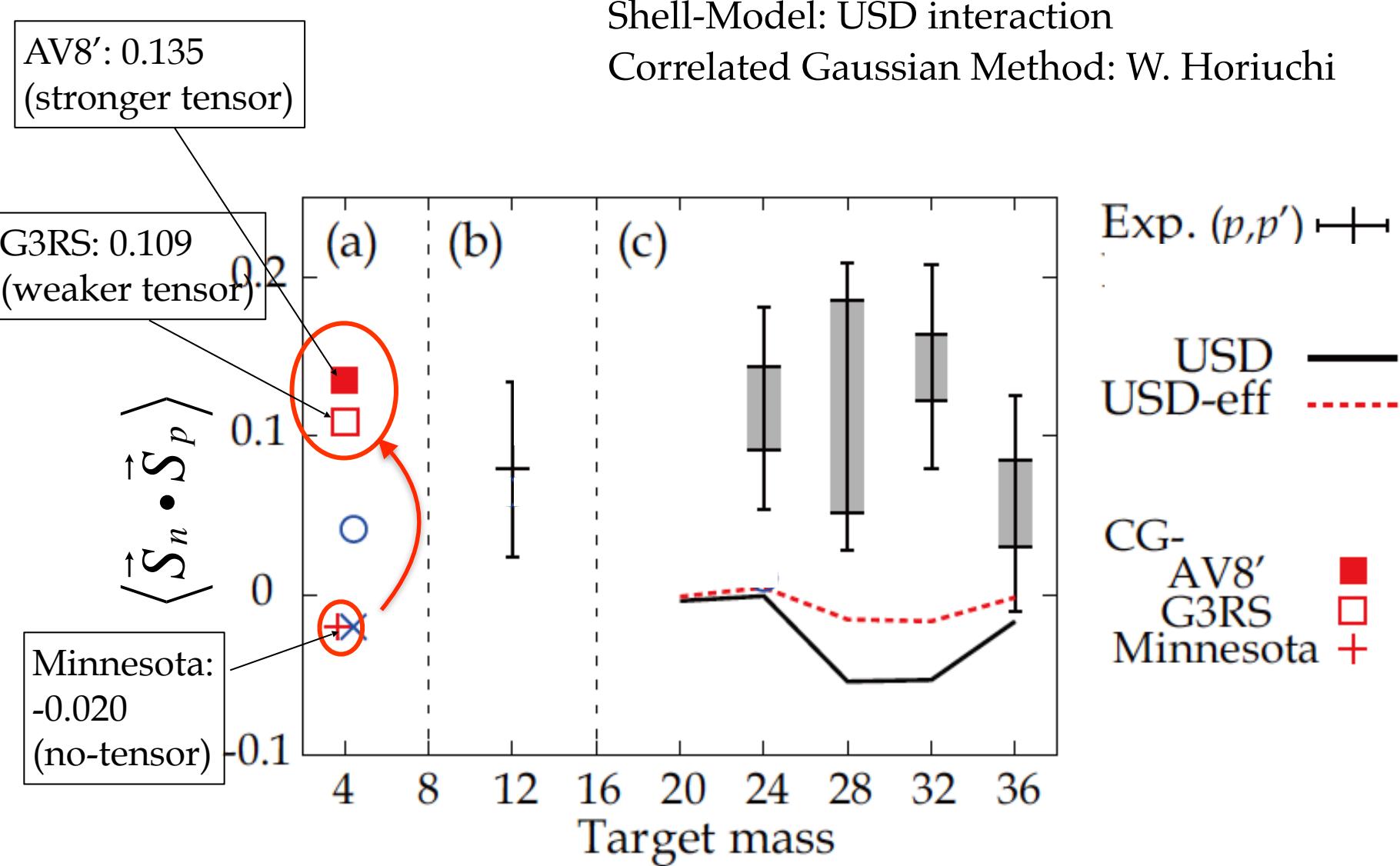
by W. Horiuchi

Spin matrix elements of the ${}^4\text{He}$ 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%

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

np Spin Correlation Function

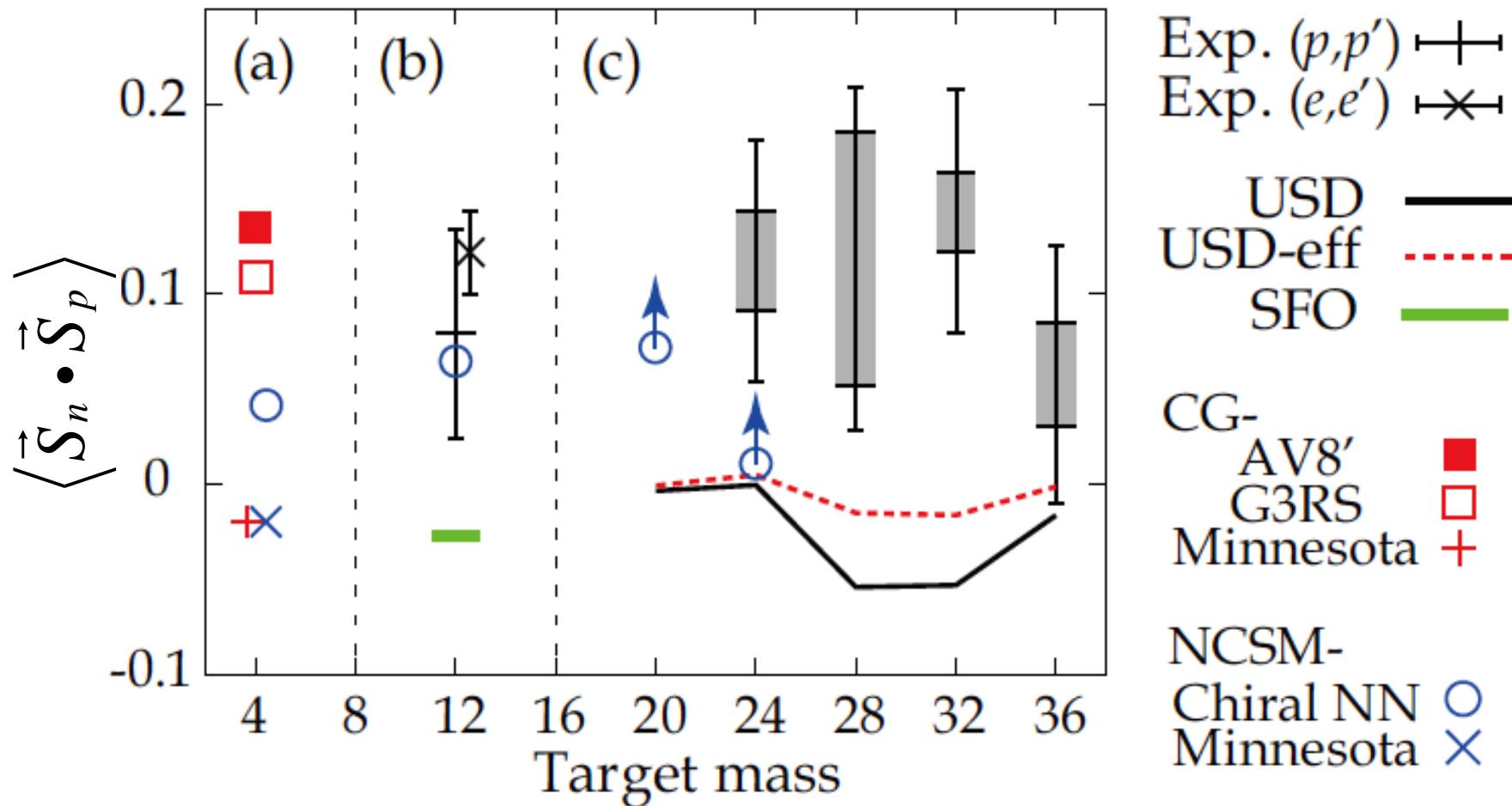


np Spin Correlation Function

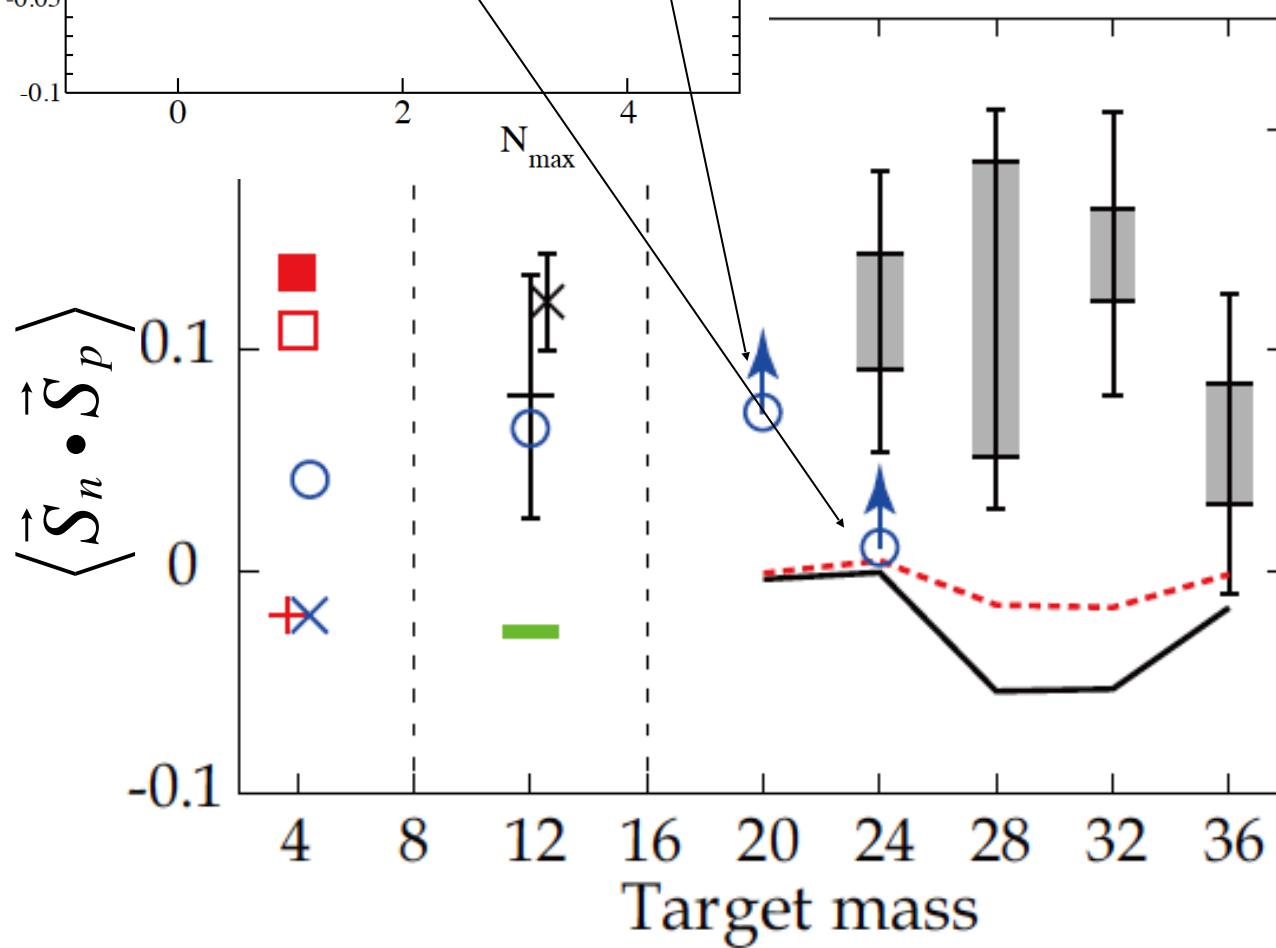
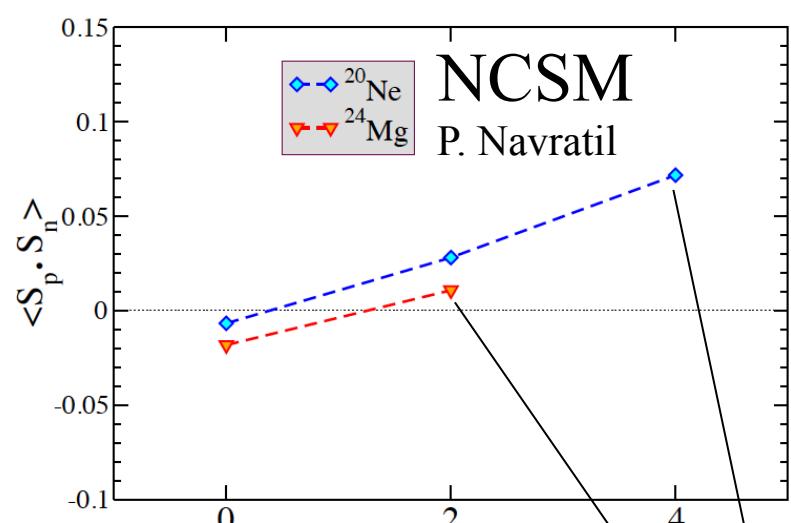
Shell-Model: USD interaction

Correlated Gaussian Method: W. Horiuchi

Non-Core Shell Model: P. Navratil



Correlation Function



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

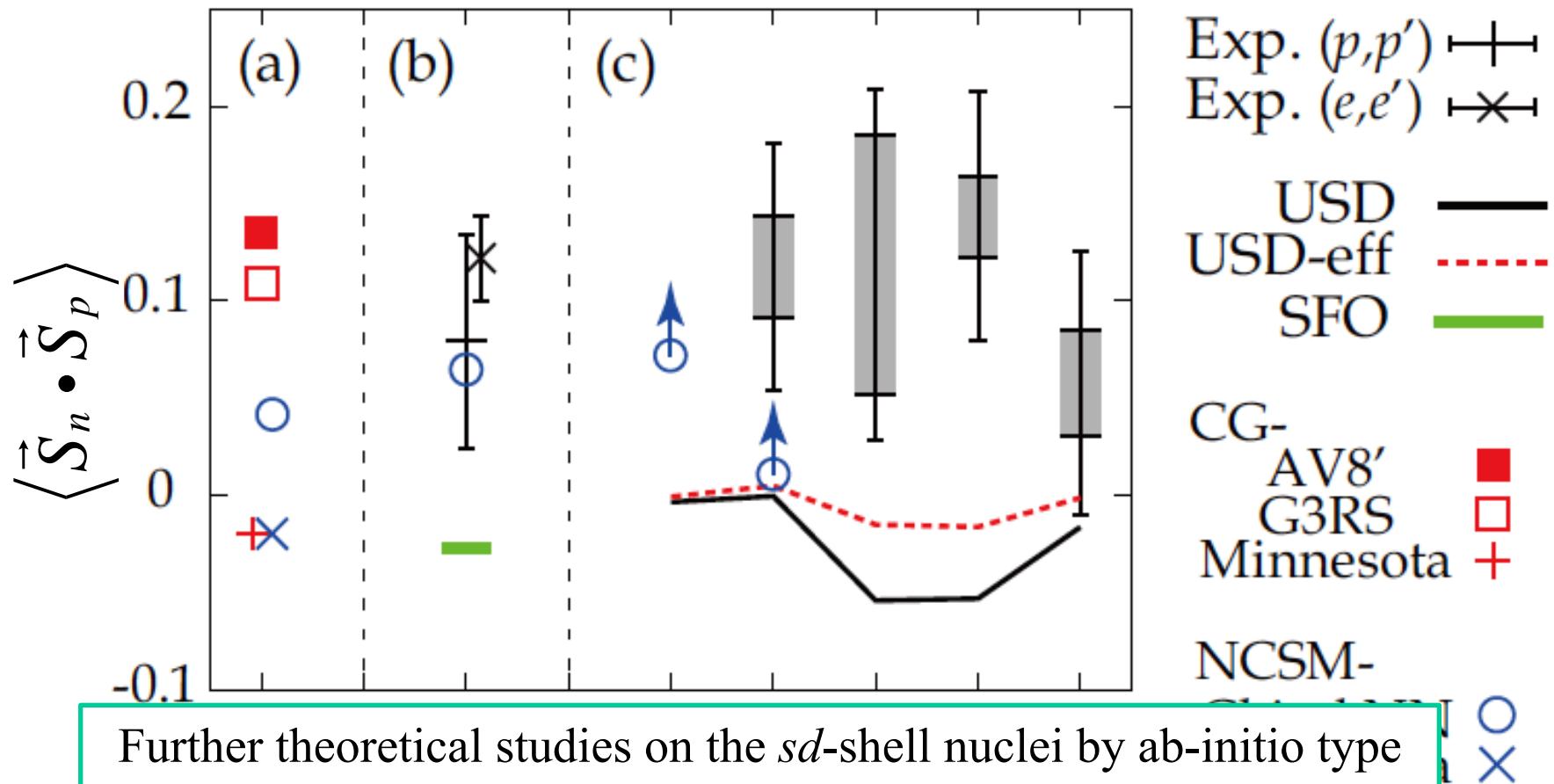
- Exp. (p,p')
- Exp. (e,e')
- USD
- USD-eff
- SFO
- CG-AV8'
- G3RS
- Minnesota
- NCSM-Chiral NN
- Minnesota

np Spin Correlation Function

Shell-Model: USD interaction

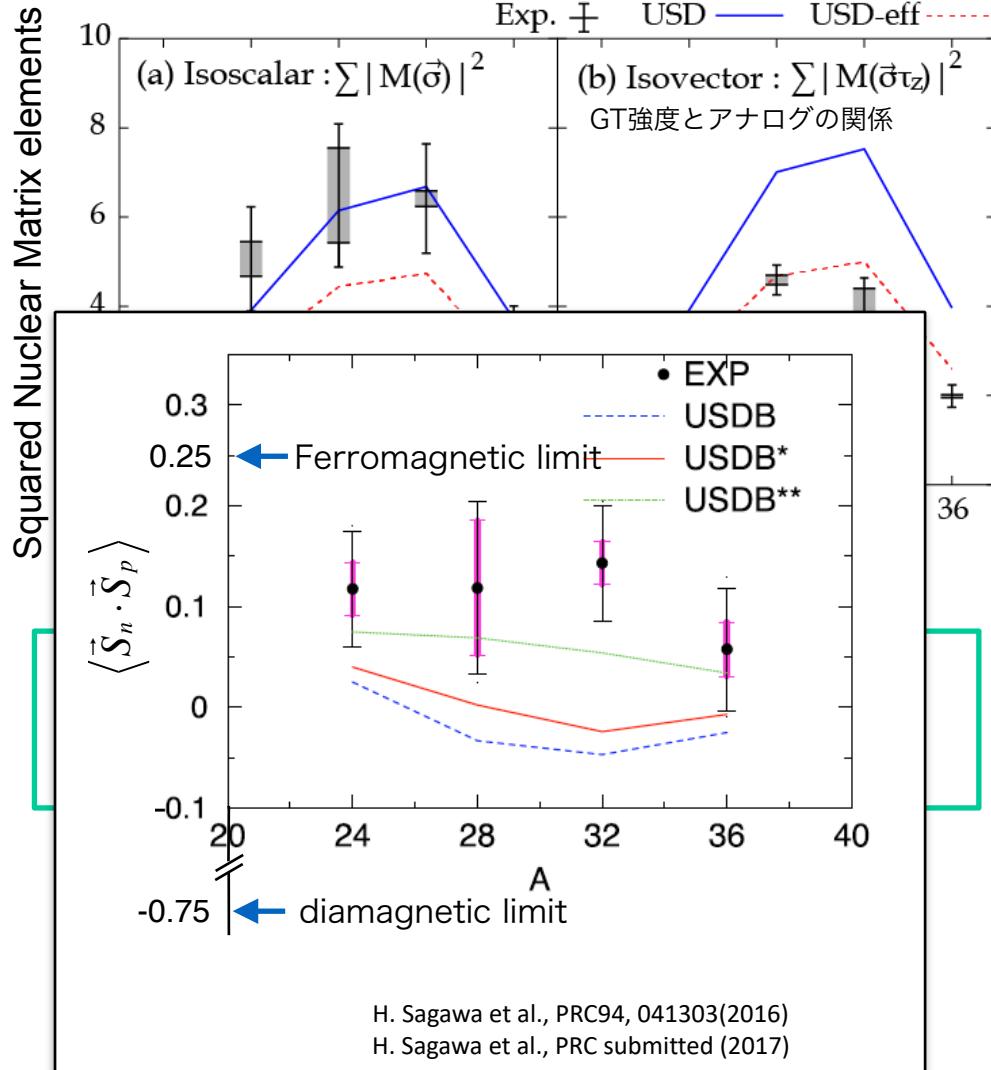
Correlated Gaussian Method: W. Horiuchi

Non-Core Shell Model: P. Navratil



np Spin Correlation Function

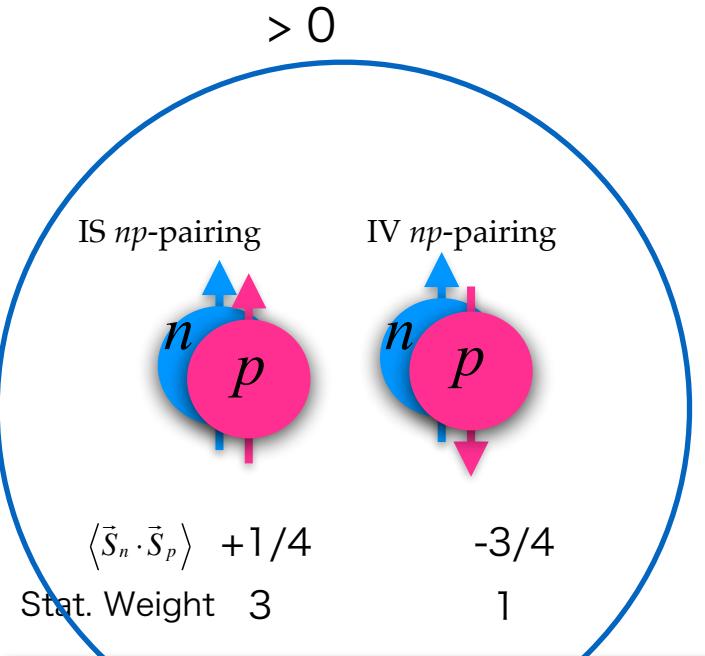
H. Matsubara et al., PRL115, 102501 (2015)



np spin correlation function of a nuclear ground state

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

IS - IV



IS *np* pairing is stronger than IV *np* pairing in N=Z nuclear ground states

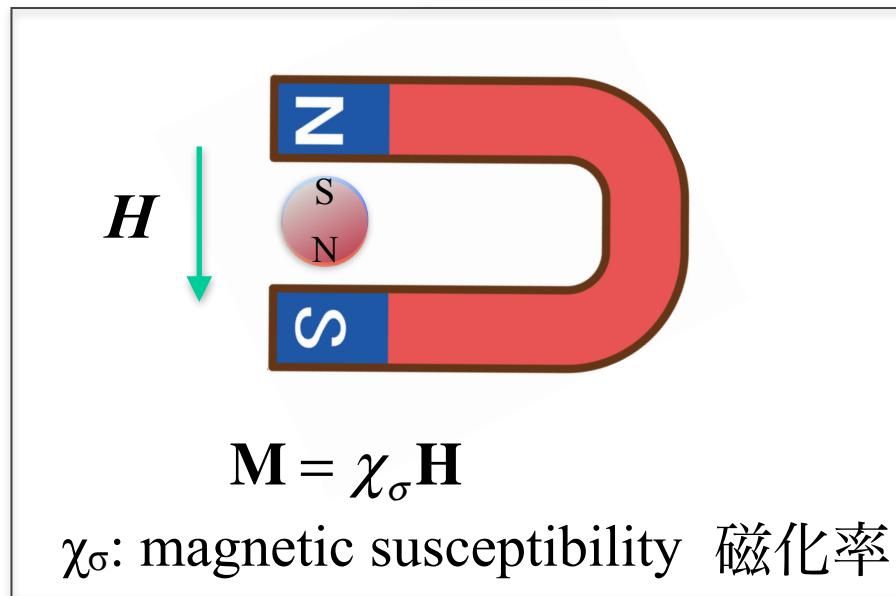
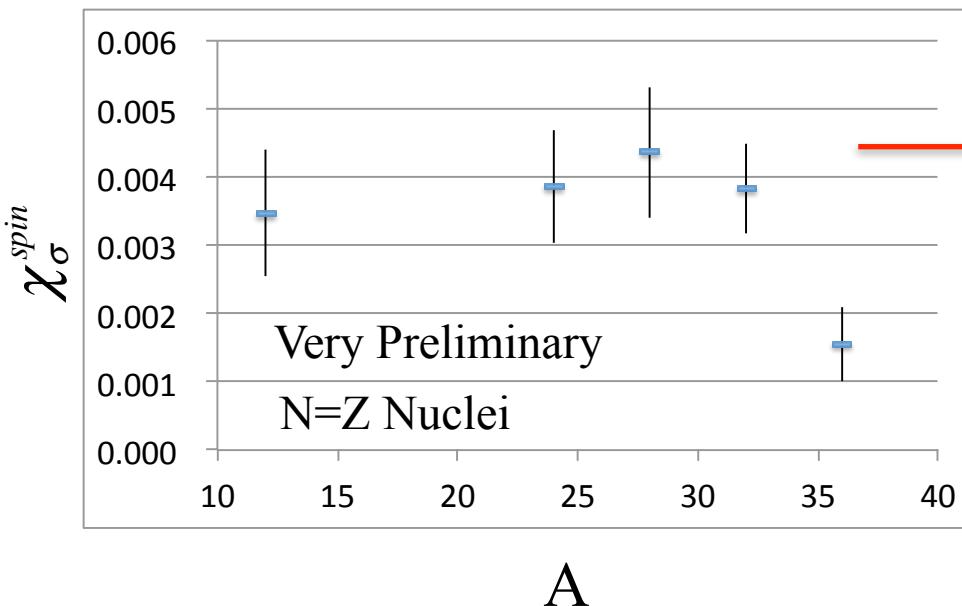
Spin-Magnetic Susceptibility

Magnetic dipole (*M1*) operator

$$O(M1) = g_\ell^{IS} \ell + \underline{g_s^{IS} \sigma} + g_\ell^{IV} \ell \cdot \tau + \underline{g_s^{IV} \sigma \cdot \tau}$$

IS(1) and IV(τ) terms

$$\chi_\sigma^{spin} = \frac{8}{3N} \sum_f \frac{1}{\omega} \left| \langle f | \sum_i \sigma_i | 0 \rangle \right|^2$$



0.0044(7) MeV⁻¹ at $\rho=0.16$ fm⁻³

Neutron Matter AFDMC model

G. Shen et al., PRC87, 025802 (2013)

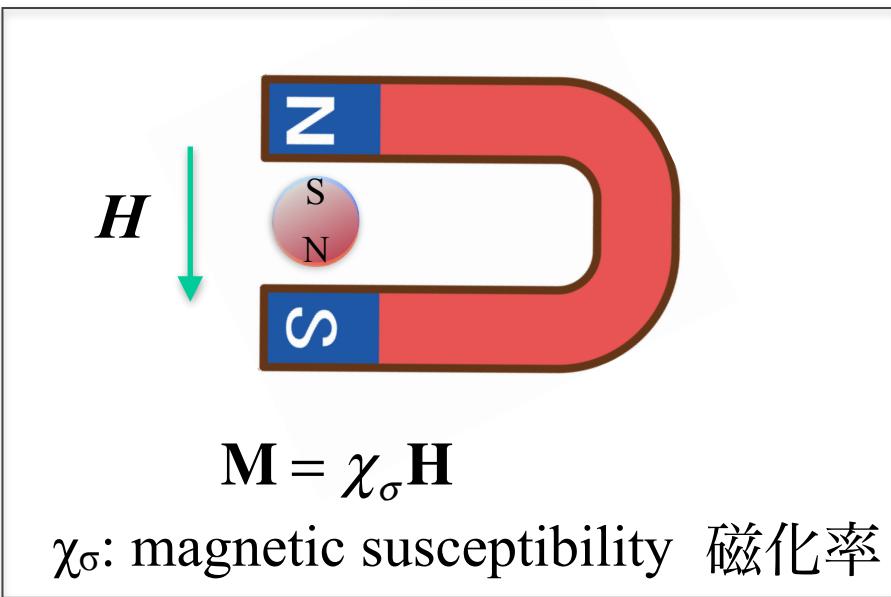
Spin-Magnetic Susceptibility

Magnetic dipole (*M1*) operator

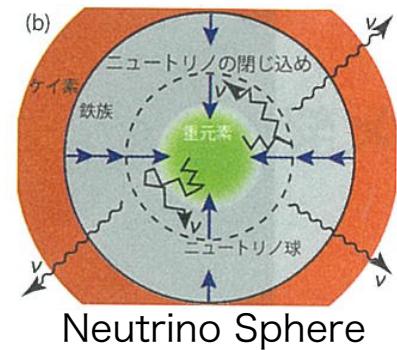
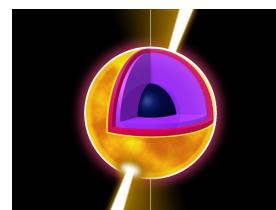
$$O(M1) = g_{\ell}^{\text{IS}} \ell + \underline{g_s^{\text{IS}} \sigma} + g_{\ell}^{\text{IV}} \ell \cdot \tau + \underline{g_s^{\text{IV}} \sigma \cdot \tau}$$

IS(1) and IV(τ) terms

$$\chi_{\sigma}^{\text{spin}} = \frac{8}{3N} \sum_f \frac{1}{\omega} \left| \langle f | \sum_i \sigma_i | 0 \rangle \right|^2$$



- Spin part of magnetization of nuclear matter
 - Magnetic response of nuclear matter (in e.g. magnetometer)
 - Neutrino trap in the core of supernova
- Neutrino transparency
- Ferromagnetic state in a neutron star



Magneter 10¹⁴⁻¹⁶ Gauss