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

Lecture VI

Spin Magnetic Response of Nuclei
n-*p* Correlation

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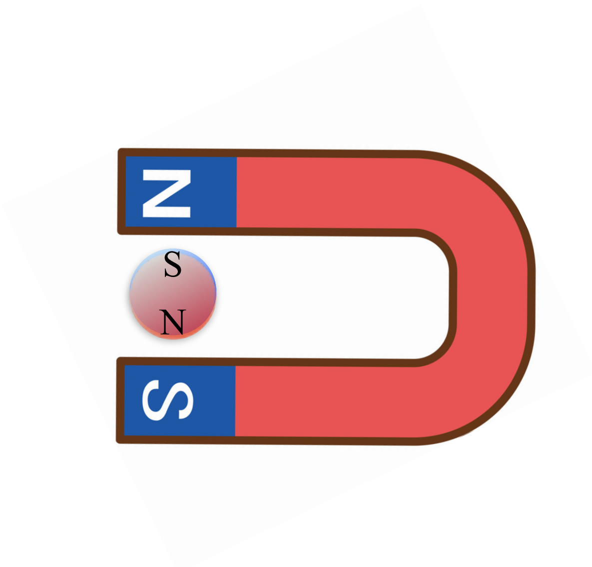
https://www.menti.com/alwqsv7cirbx

Spin Magnetic Response of Nuclei and n-p Correlation



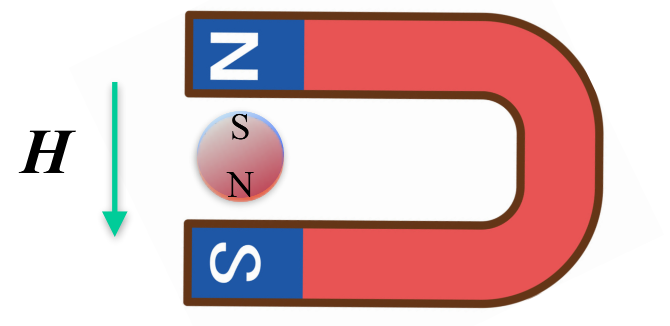
Spin-Magnetic Susceptibility

Magnetic dipole (*M1*) operator

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

IS(1) and IV(τ) terms

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

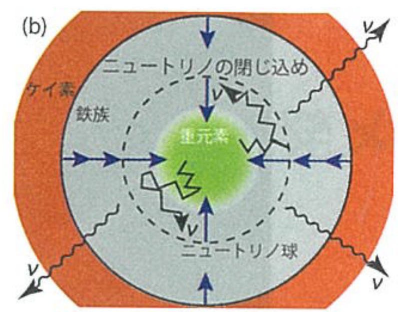


$$\mathbf{M} = \chi_\sigma \mathbf{H}$$

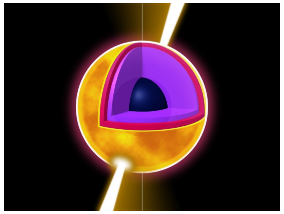
χ_σ: magnetic susceptibility 磁化率

- Spin part of magnetization of nuclear matter
- Magnetic response of nuclear matter (in e.g. magneter)
- Neutrino trap in the core of supernova

  Neutrino transparency
- Ferromagnetic state in a neutron star

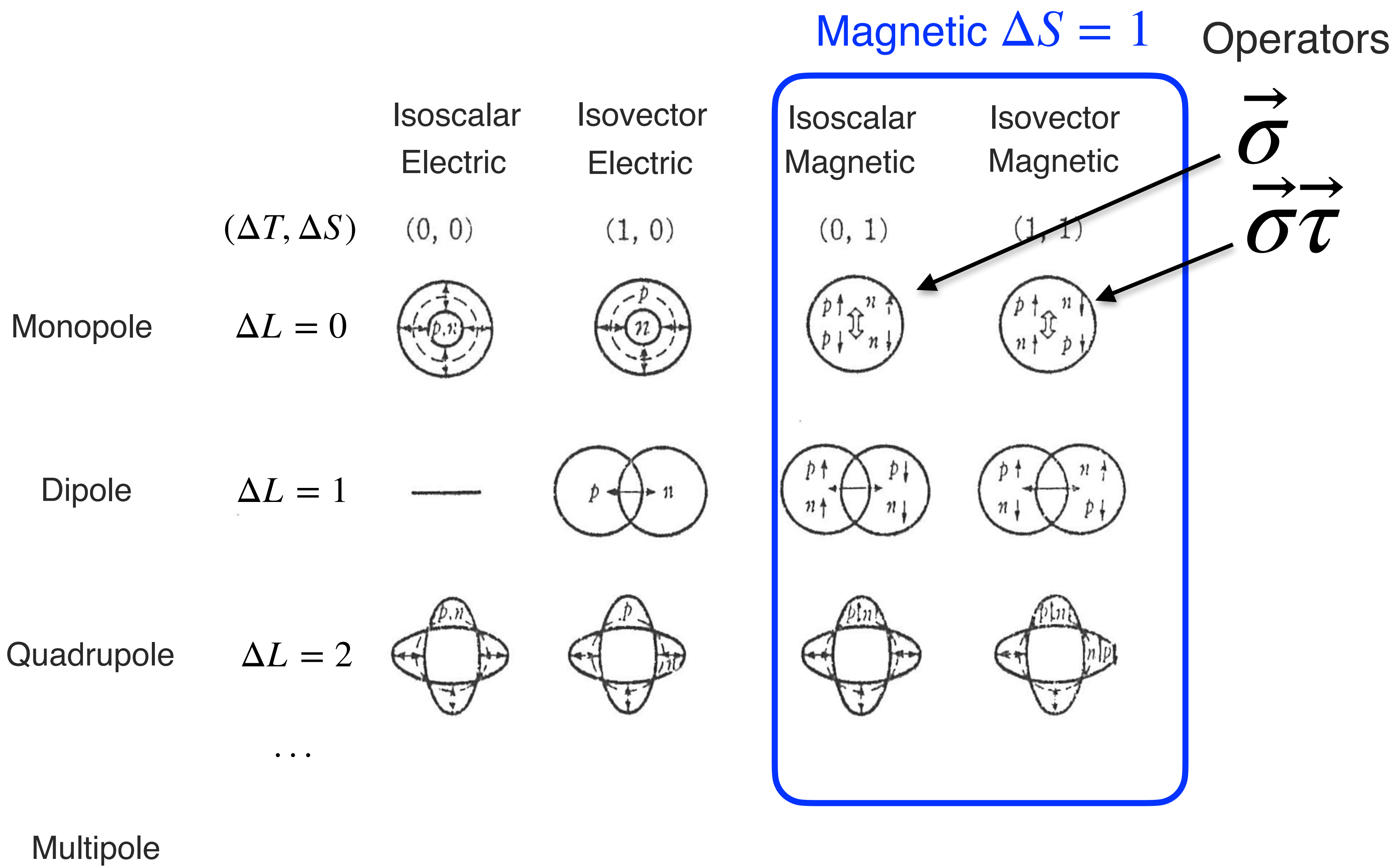


Neutrino Sphere



Magneter $10^{14\text{-}16}$ Gauss

Collective Vibrational Excitations



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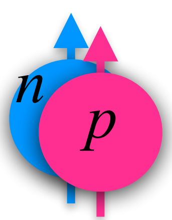
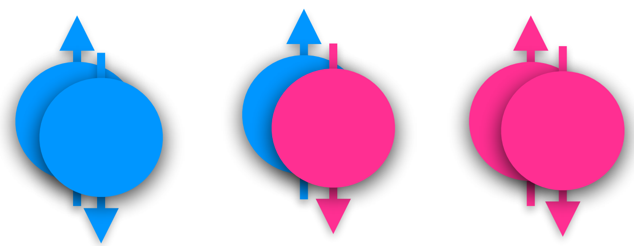
IS and IV pairings



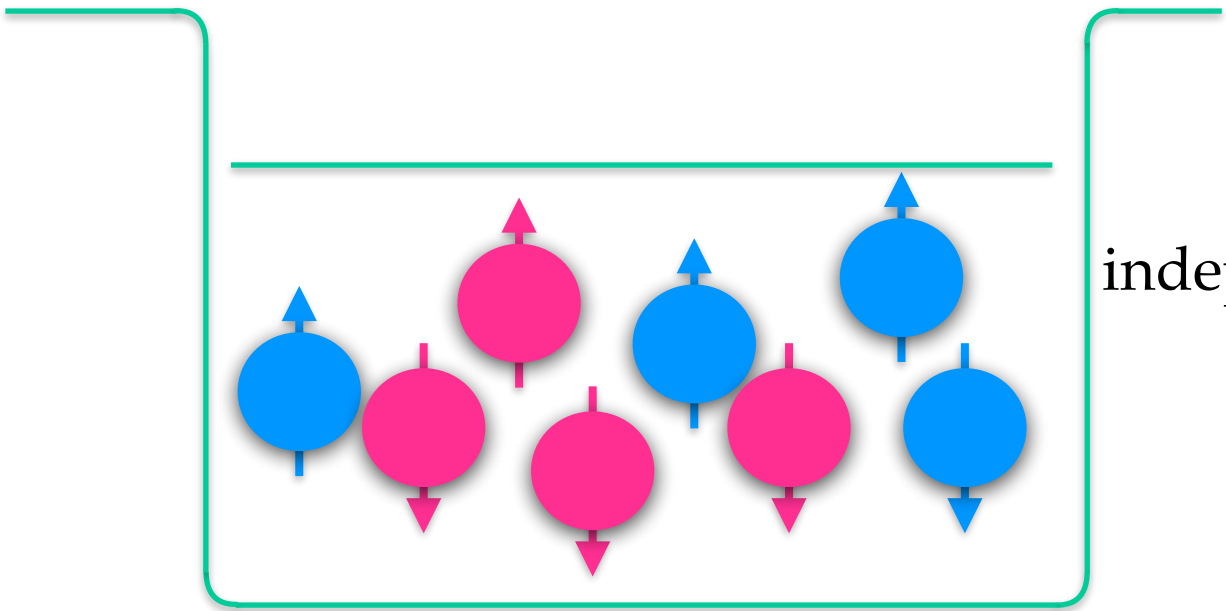


IS (T=0, S=1)

Isoscalar *np*-paring

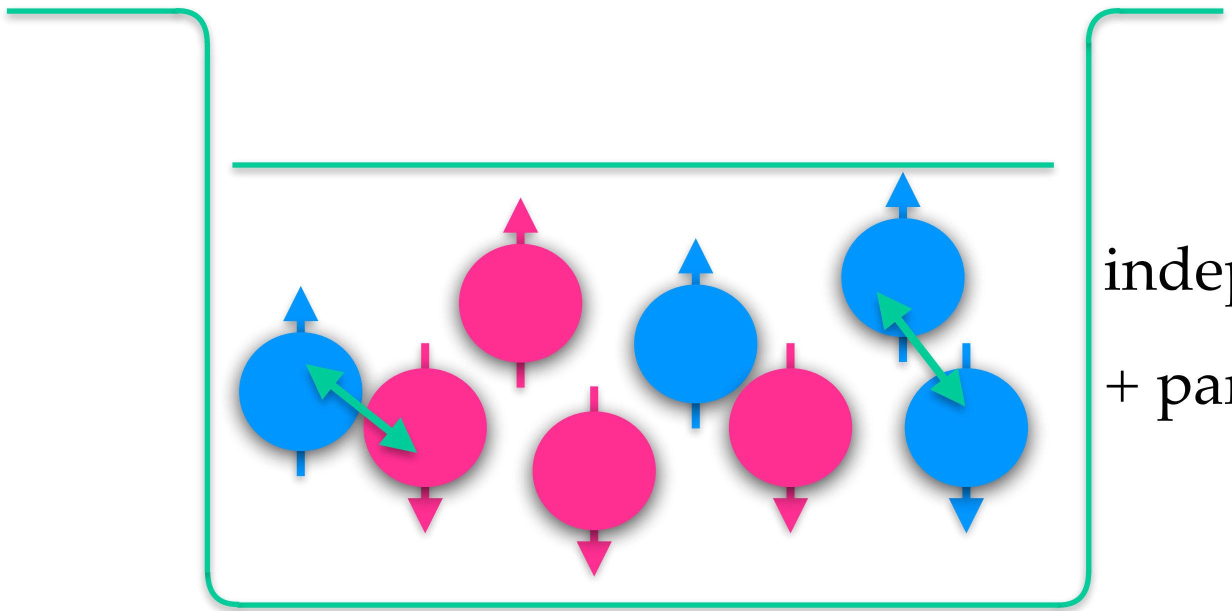
IV (T=1, S=0)

pairing in the ground state W.F.



unperturbed ground state

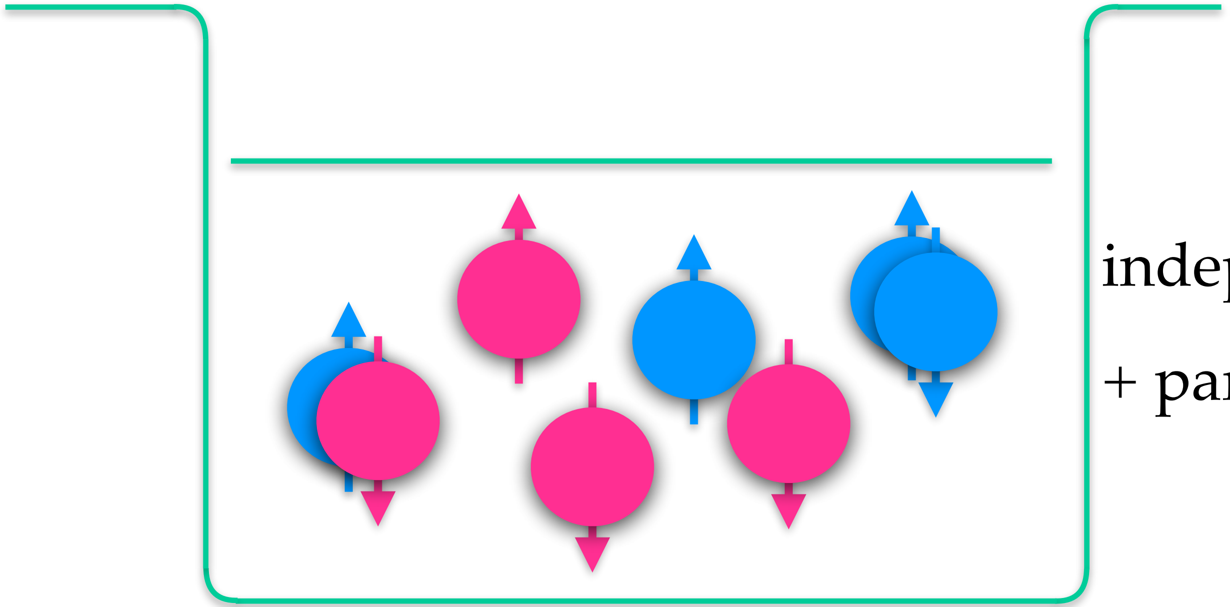
pairing in the ground state W.F.



independent particles

+ paring interactions

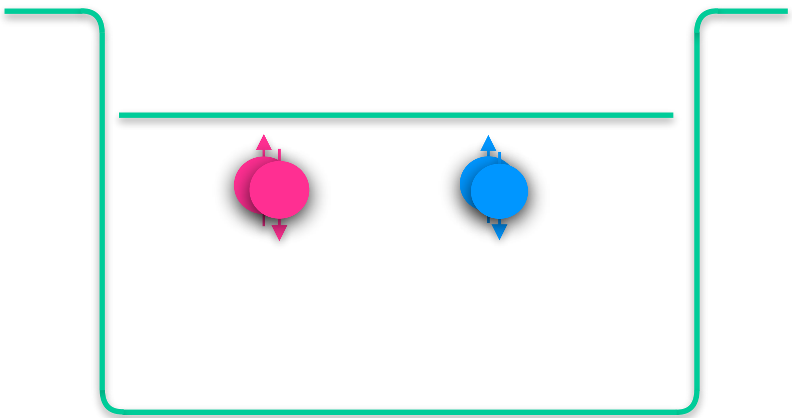
pairing in the ground state W.F.

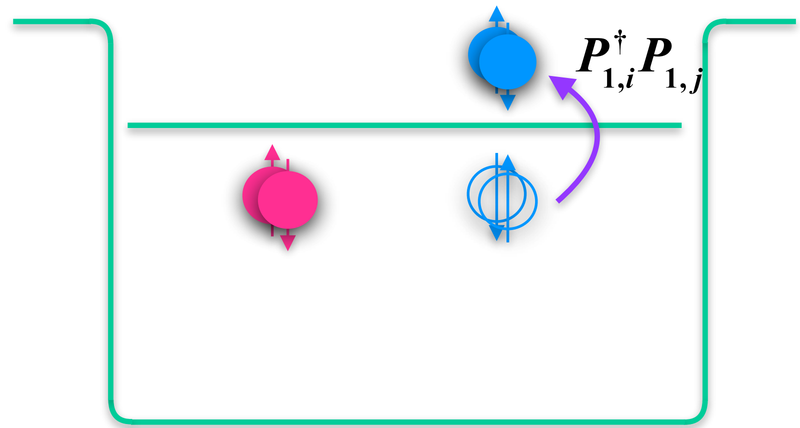


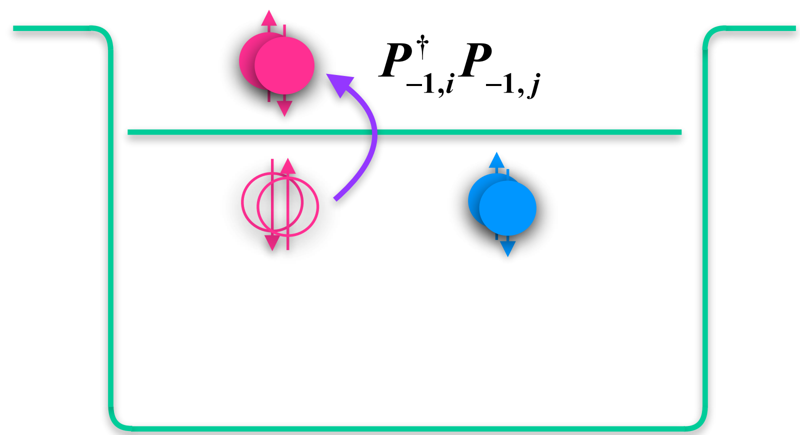
independent particles

+ paring interactions

pairing in the ground state W.F.





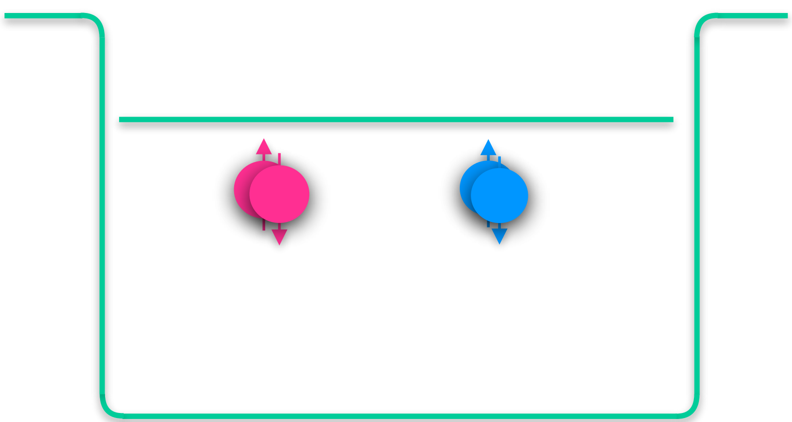


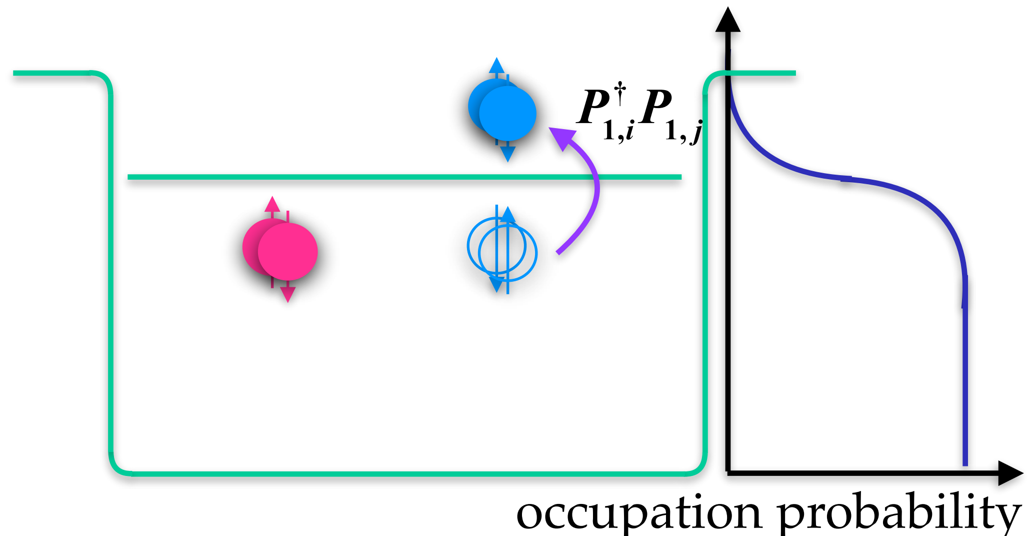
$$P^\dagger_{1,i} = \nu^\dagger_i \nu^\dagger_{\bar{i}}$$

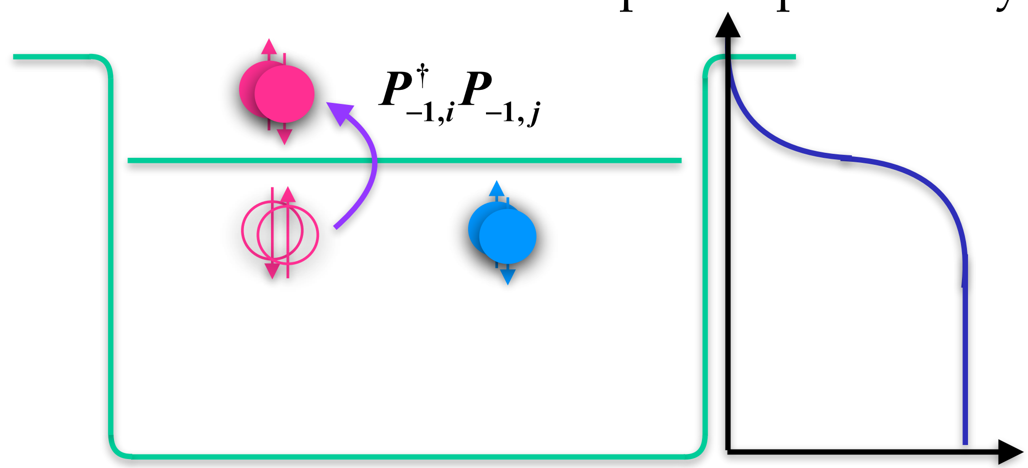
$$P^\dagger_{-1,i} = \pi^\dagger_i \pi^\dagger_{\bar{i}}$$

isovector "pairing" correlation
= BCS type correlation

pairing in the ground state W.F.





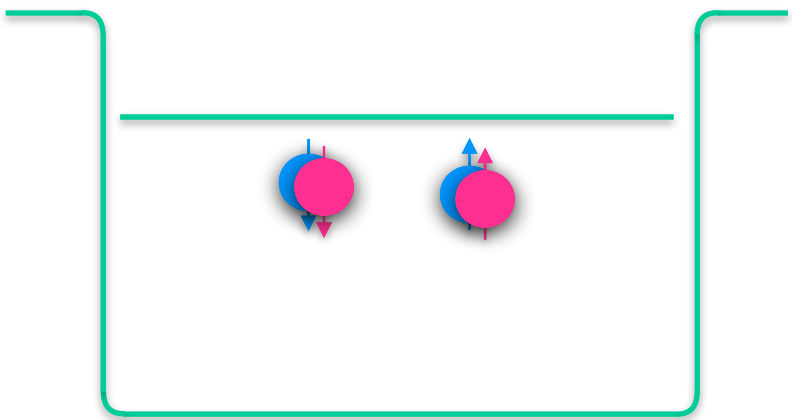


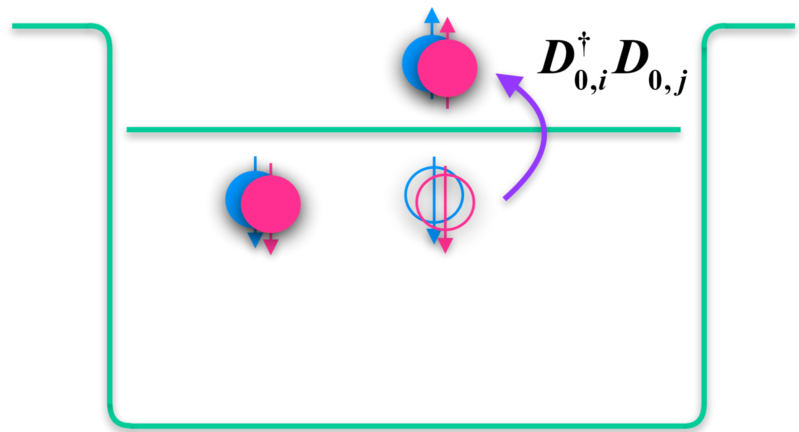
$$P^{\dagger}_{1,i} = \nu^{\dagger}_{i}\nu^{\dagger}_{\bar{i}}$$

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

isovector “pairing” correlation
= BCS type correlation

np pairing in the ground state W.F.

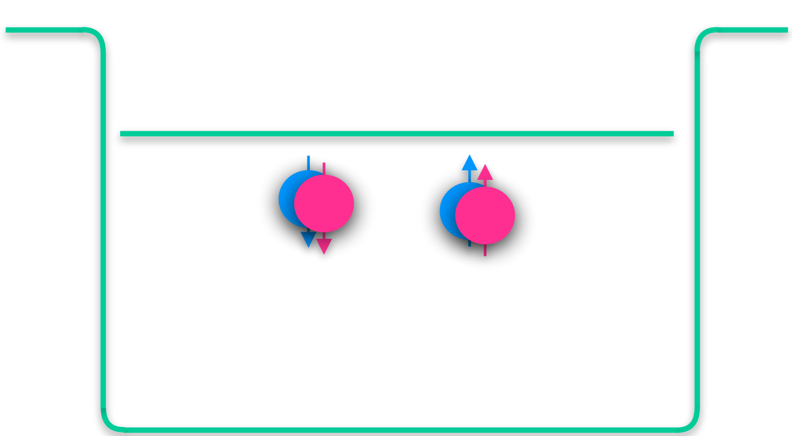


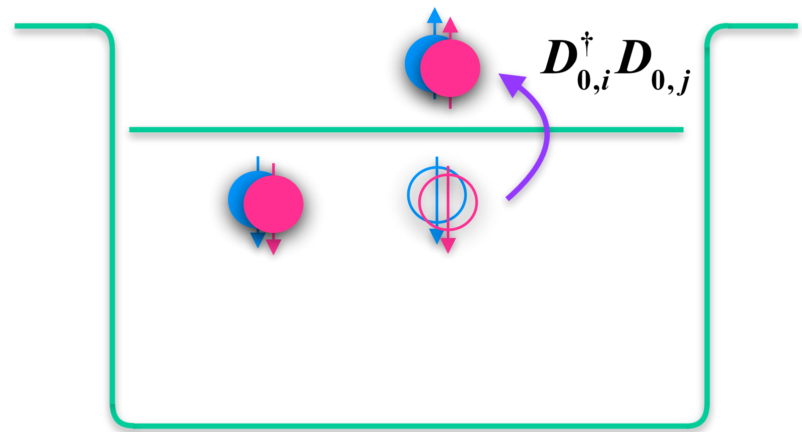


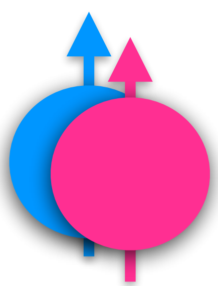
$$D^\dagger_{0,i} = \frac{1}{\sqrt{2}}\left(\nu^\dagger_i \pi^\dagger_{\bar{i}} - \pi^\dagger_i \nu^\dagger_{\bar{i}}\right)$$

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

np pairing in the ground state W.F.





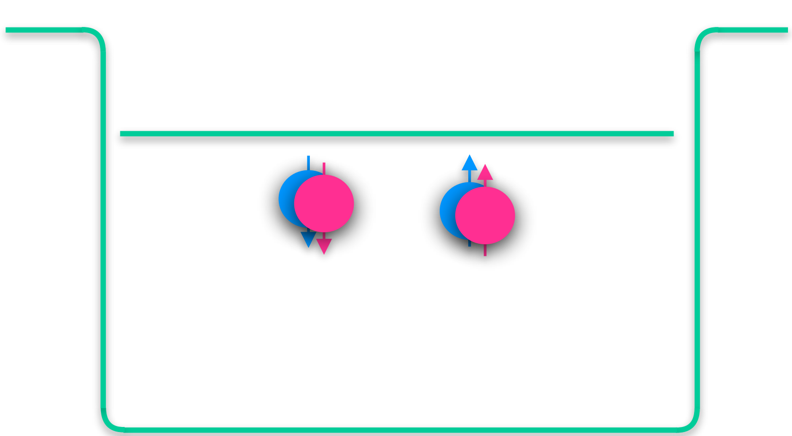


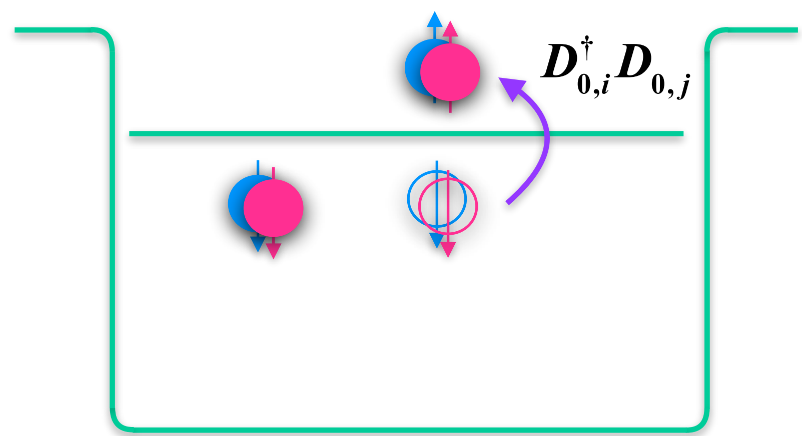
n-spin and *p*-spin: aligned

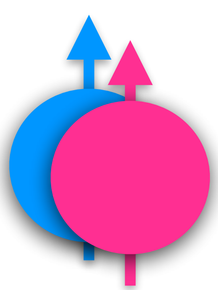
$$\langle \vec{s}_n \cdot \vec{s}_p \rangle > 0$$

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

np pairing in the ground state W.F.





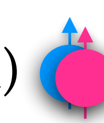


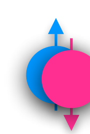
n-spin and *p*-spin: aligned

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

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

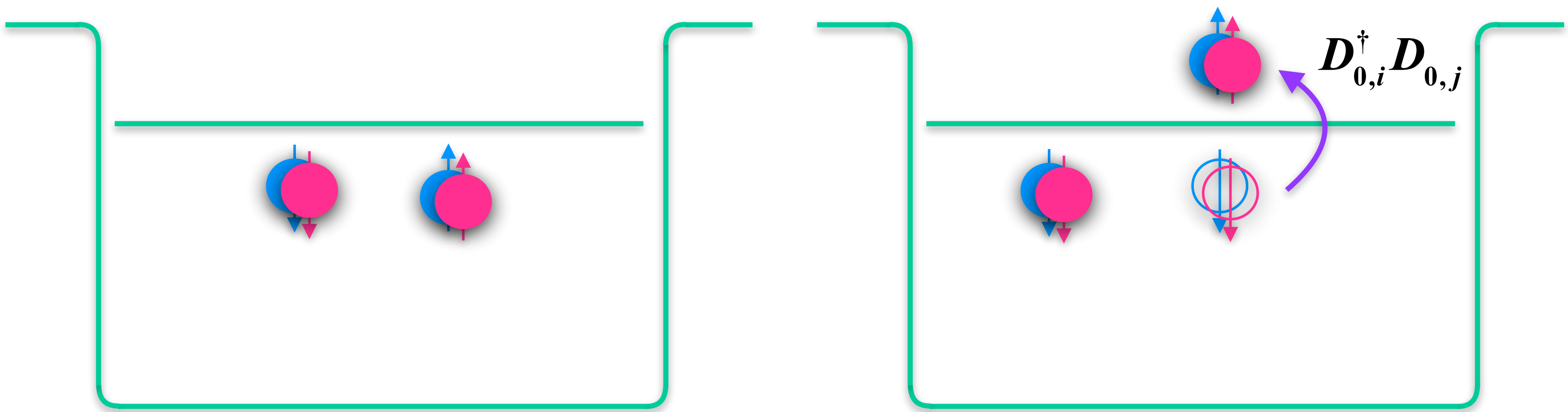
$$\left\langle \vec{s}_n \cdot \vec{s}_p \right\rangle = \begin{cases} +\dfrac{1}{4} & \text{for IS } np \text{ pair (deuteron)} \\ -\dfrac{3}{4} & \text{for IV } np \text{ pair} \end{cases}$$

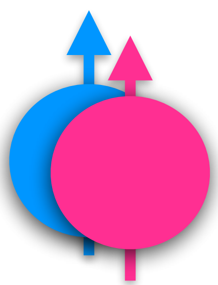




$$\vec{S}^2 = \left(\vec{s}_n + \vec{s}_p\right)^2 = \vec{s}_n^{\ 2} + \vec{s}_p^{\ 2} + 2\vec{s}_n \cdot \vec{s}_p$$

np pairing in the ground state W.F.



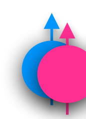


n-spin and *p*-spin: aligned

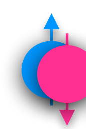
$$\langle \vec{s}_n \cdot \vec{s}_p \rangle > 0$$

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

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

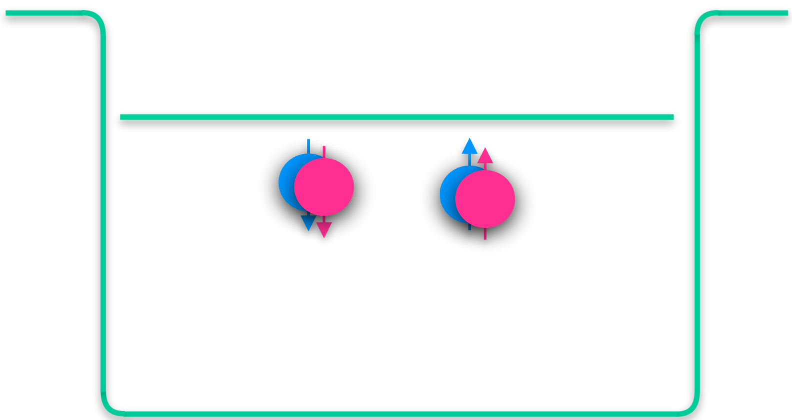
for IS *np* pair (deuteron) 

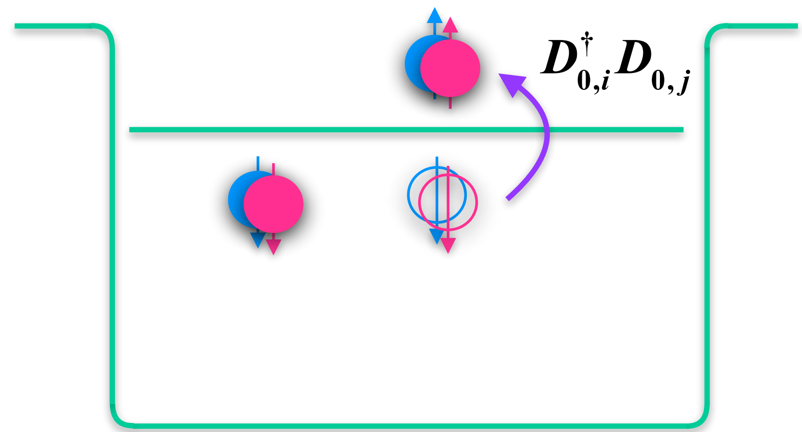
statistical weight = 3

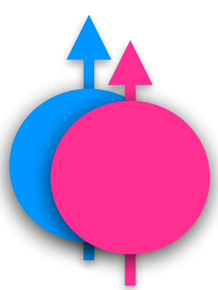
for IV *np* pair 

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

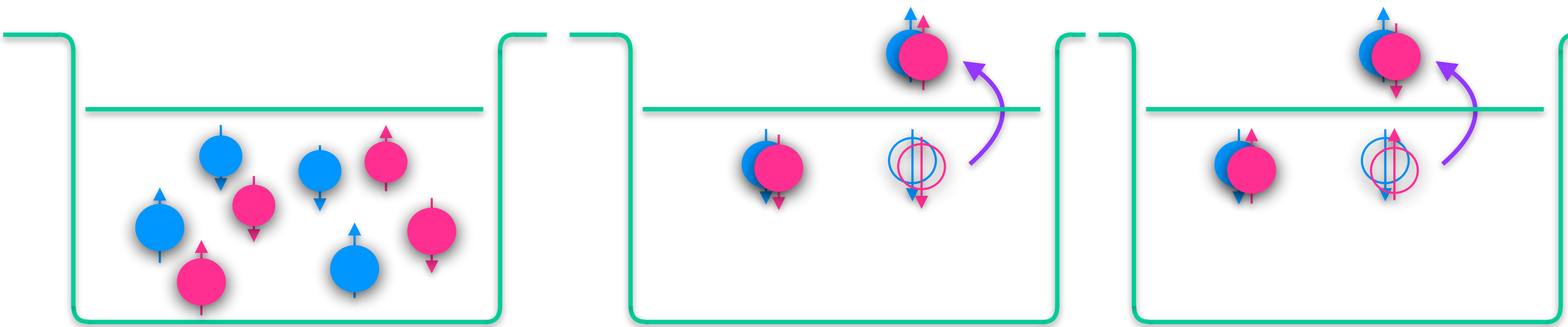
np spin correlation function

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

$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle$: *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	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

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

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

$$M(\sigma) = \left\langle f \| \vec{\sigma} \| i \right\rangle$$

IS Reduced Matrix Element

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

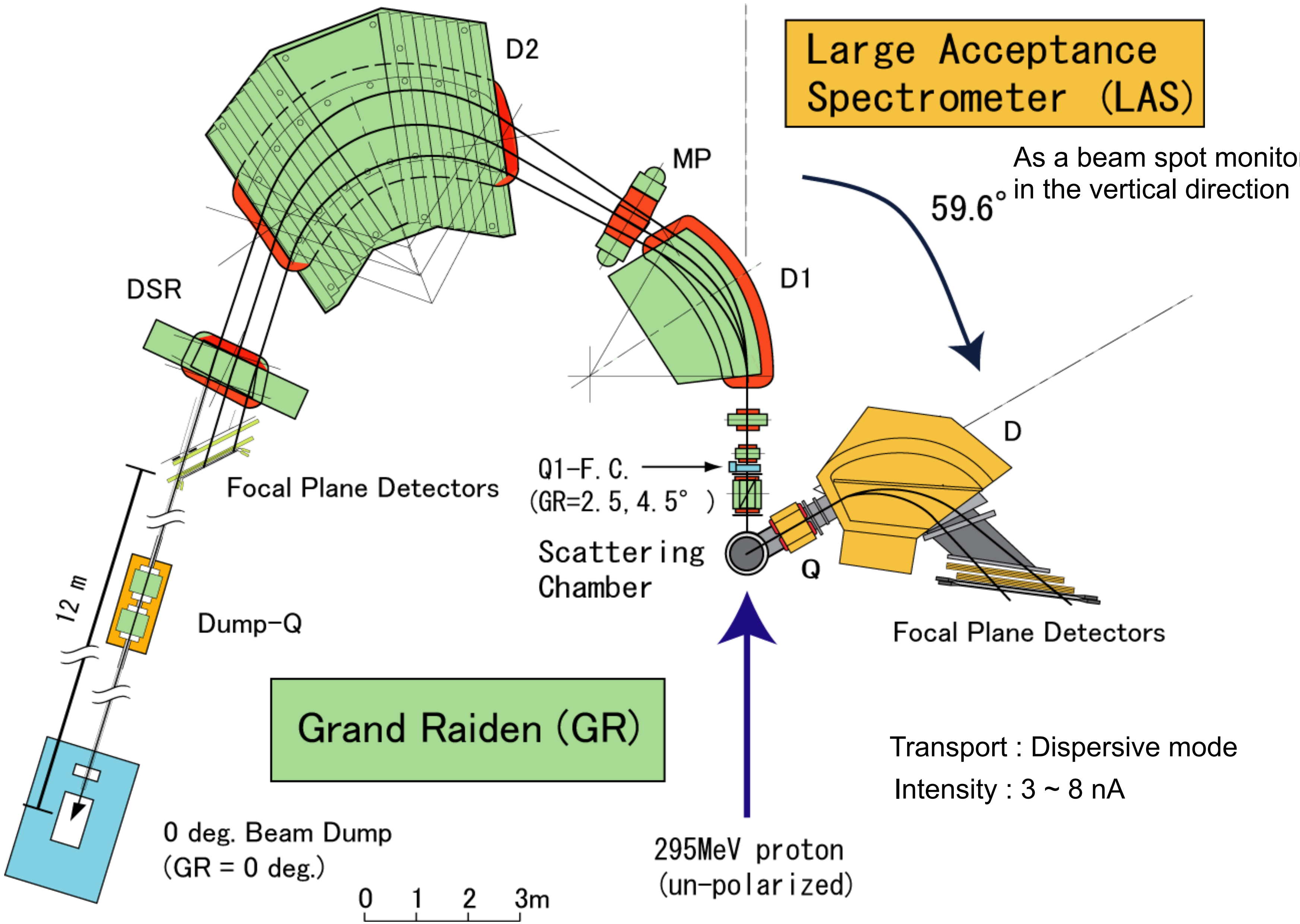
$$B(M1)_{\sigma\tau} = \frac{3}{4\pi} \frac{1}{2J_i + 1} \left(\frac{g_s^{IV}}{2} \right)^2 \left| \left\langle f \| \vec{\sigma} \tau_z \| i \right\rangle \right|^2 \mu_N^2$$

$$M(\sigma\tau) = \left\langle f \| \vec{\sigma} \tau_z \| i \right\rangle$$

IV Reduced Matrix Element

Experimental Methods

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

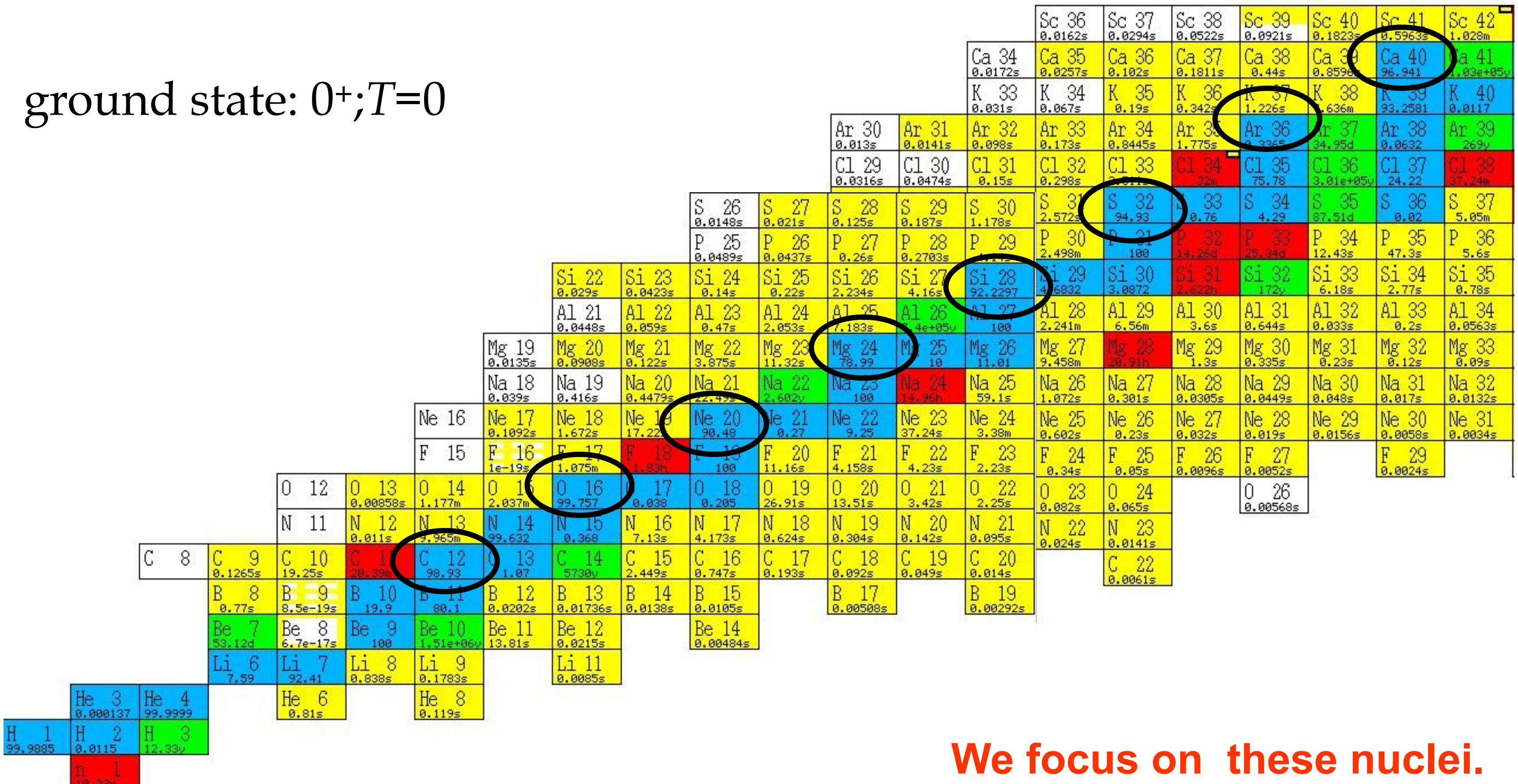


Transport : Dispersive mode

Intensity : 3 ~ 8 nA

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

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



We focus on these nuclei.

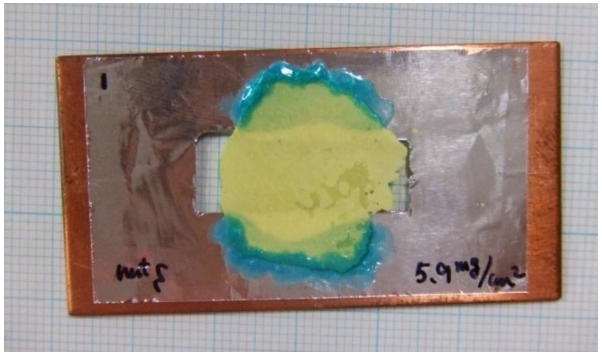
Stable self-conjugate even-even nuclei:

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

Targets

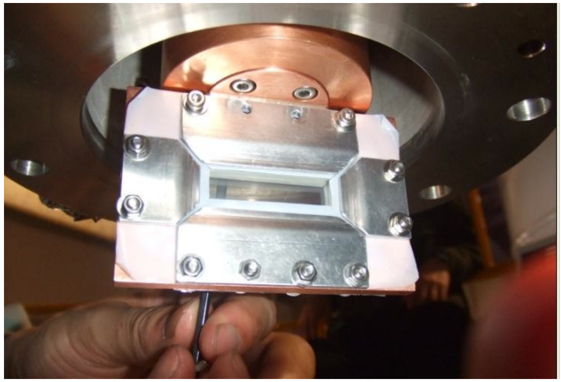
^{12}C, ^{24}Mg, ^{28}Si: self-supporting target

Cooled ^{32}S self-supporting target



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

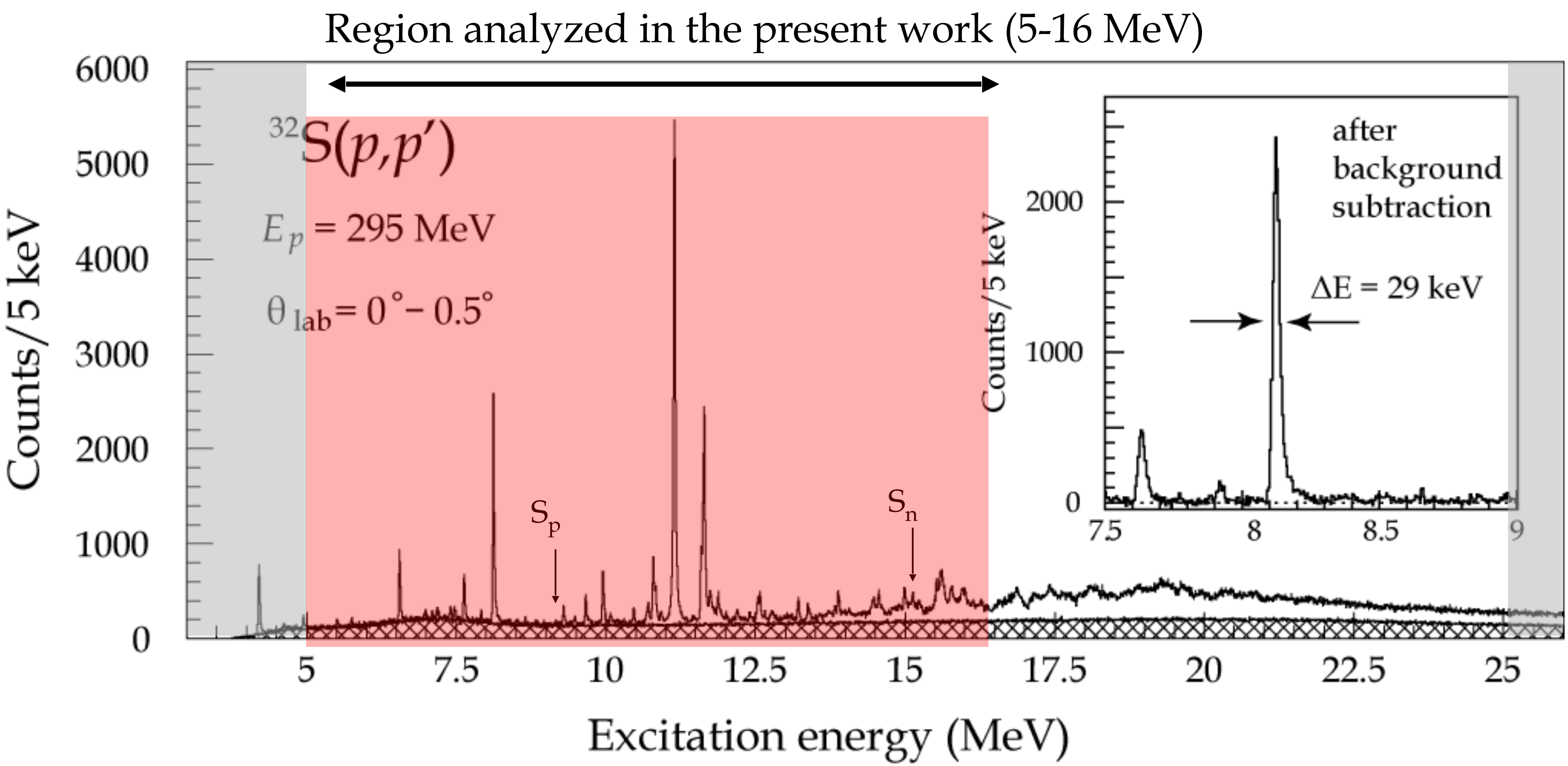
Gas Cell Target (^{36}Ar)



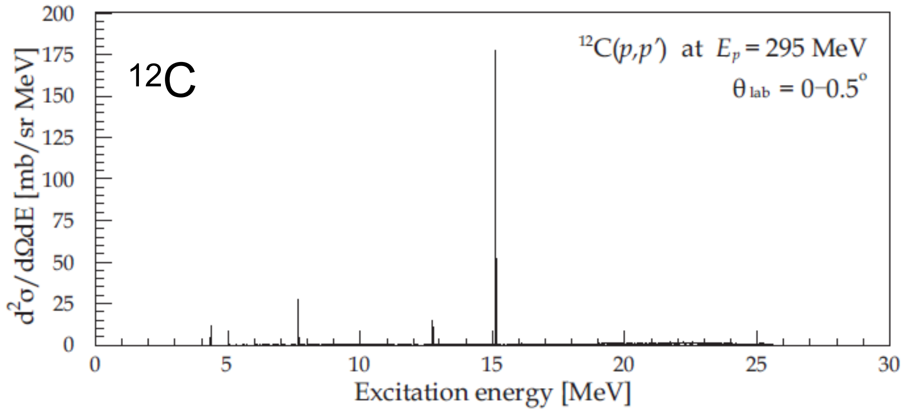
H. Matsubara *et al.*, NIMA 678, 122 (2012)

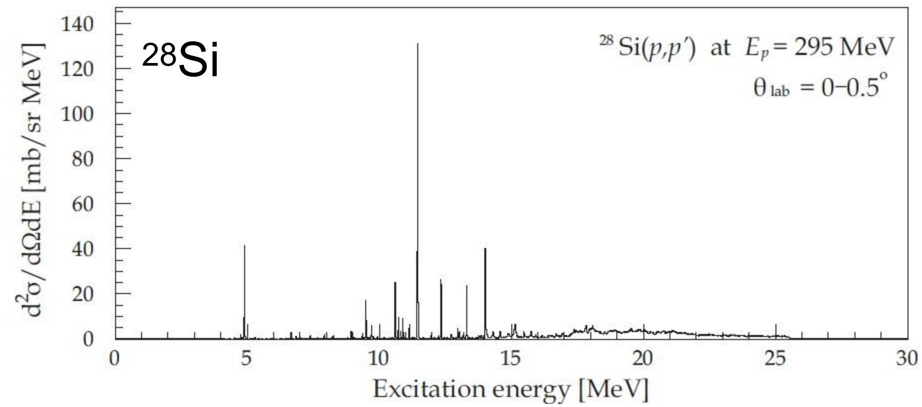
Aramide window of 6 μm^t

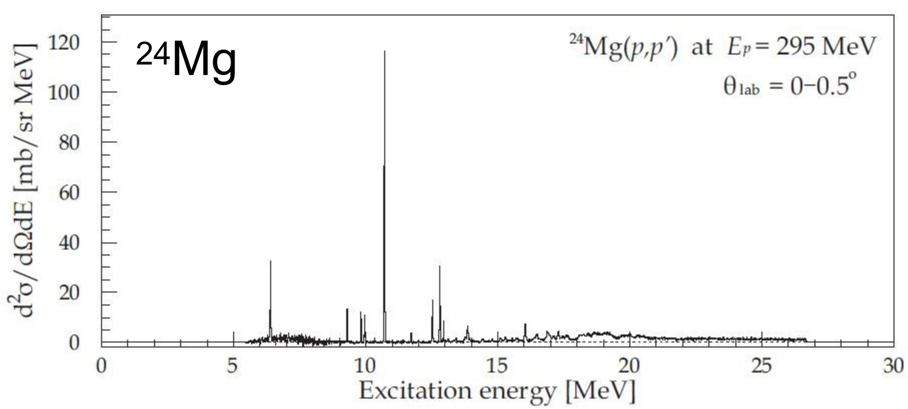
High energy-resolution spectrum

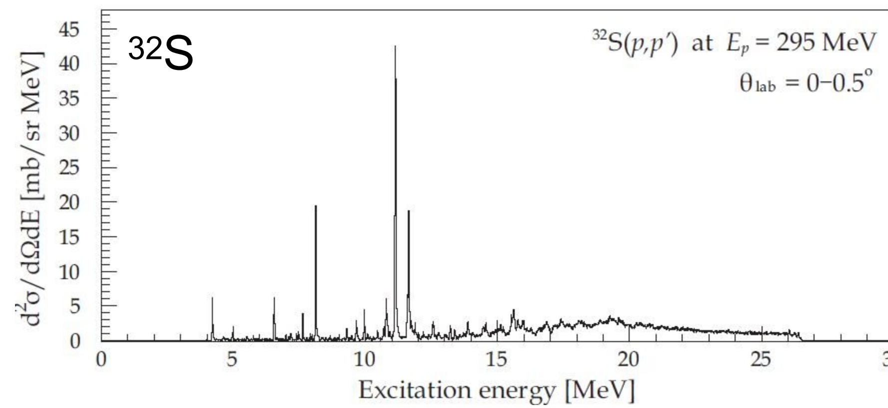


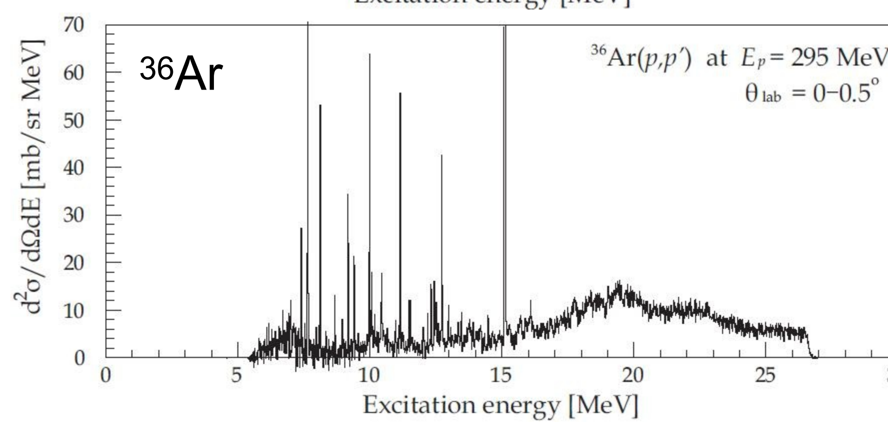
Energy spectra at 0-degrees







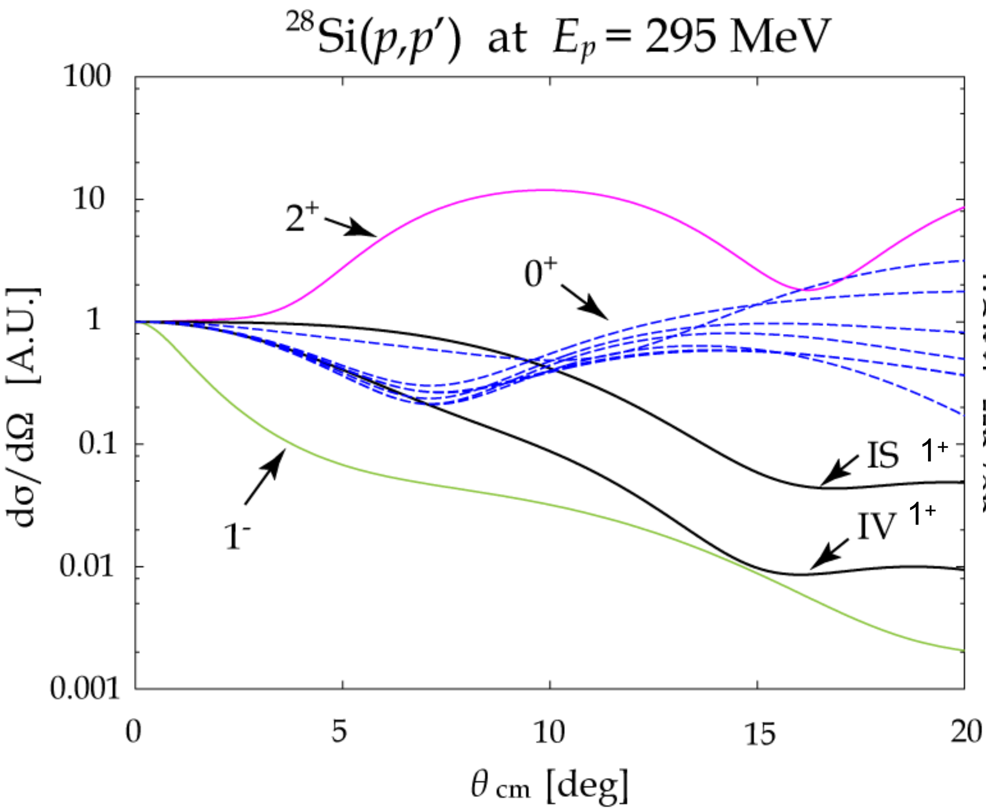


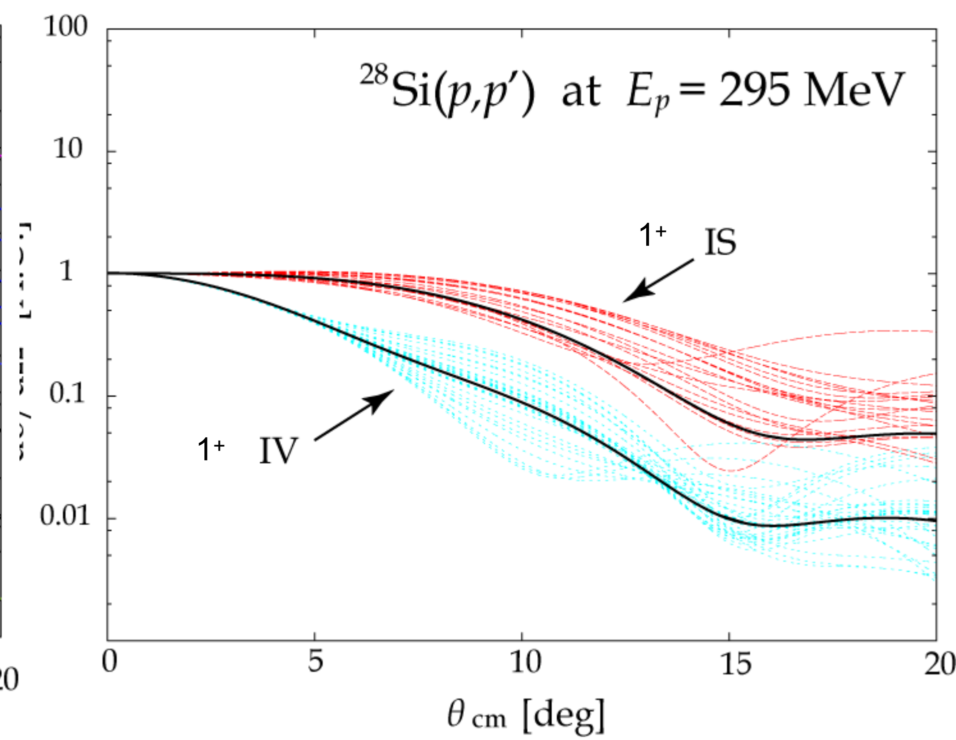


Angular distribution for J^{π} assignment

- 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)

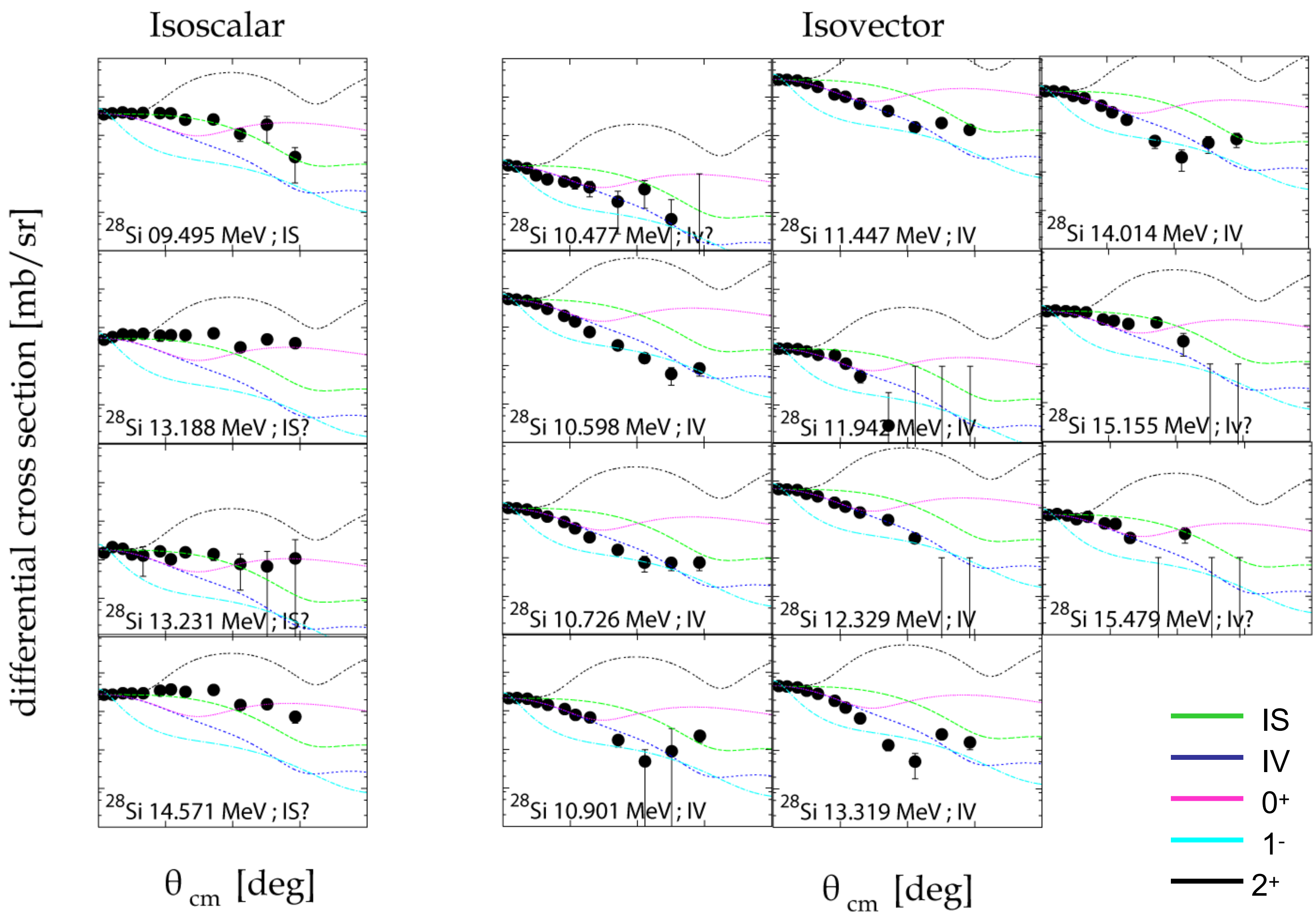




- Forward peaking for L=0 transition.
- *M1* has the maximum at 0 degree.
- 0^+, IS-1^+, IV-1^+ and others

- 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 andγ-decay measurements

(on the assumption of the isospin symmetry).

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

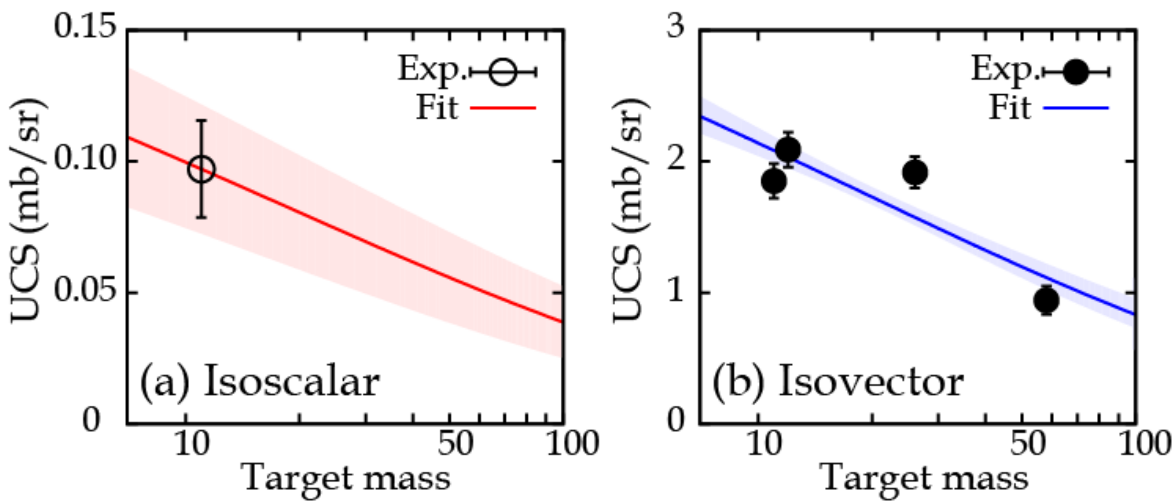
(*T*= IS or IV)

UCS Kinematical factor SNME

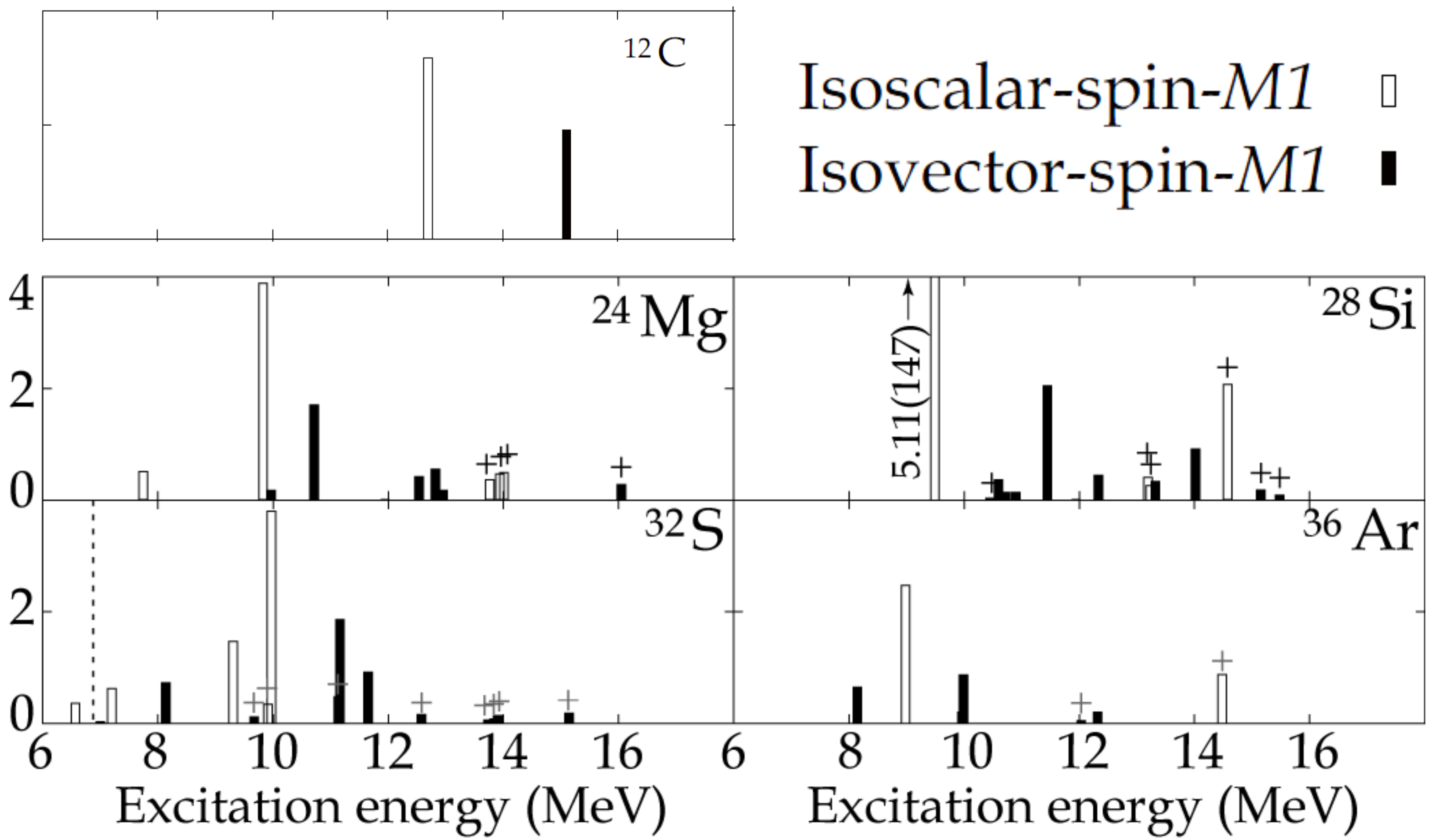
$$\hat{\sigma}_T(A) = N \exp\left(-xA^{1/3}\right)$$

T.N. Taddeucci, NPA469 (1987).

- Function taken from the mass dependence of GT UCS

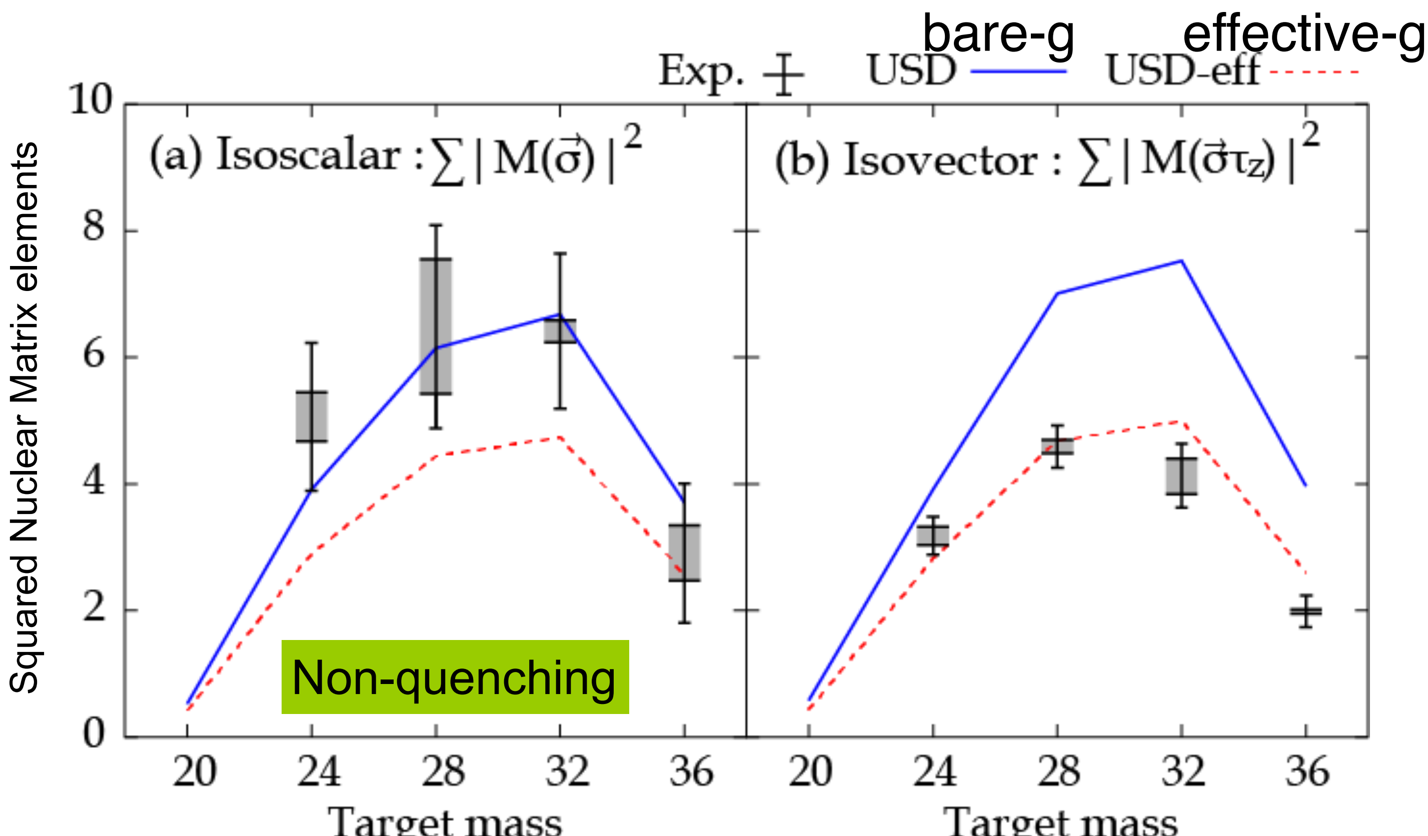


IS / IV-spin-M1 distribution



Spin-M1 SNME

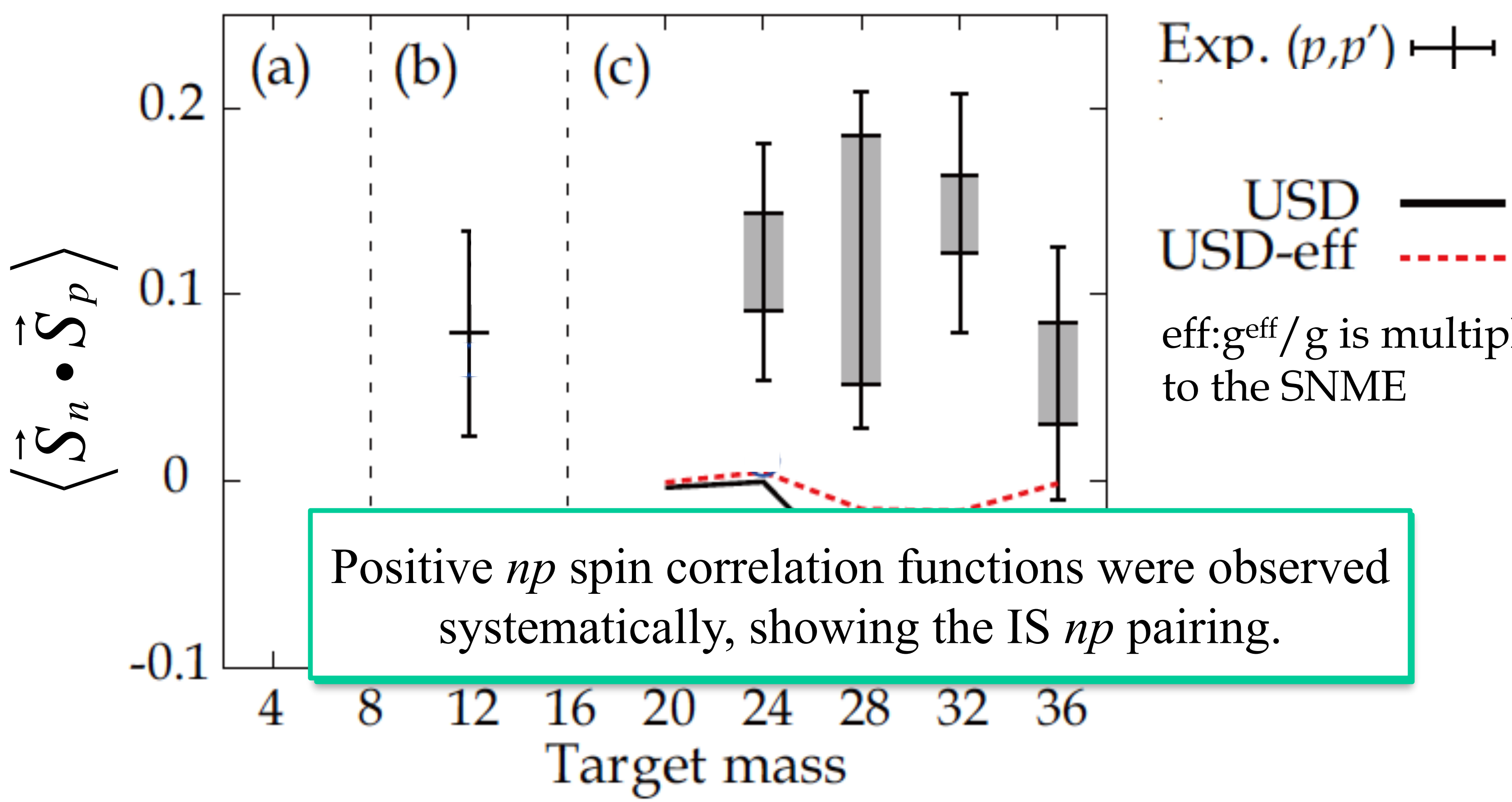
- Summed <u>up to **16 MeV**</u>.
- Compared with shell-model predictions using the USD interaction



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

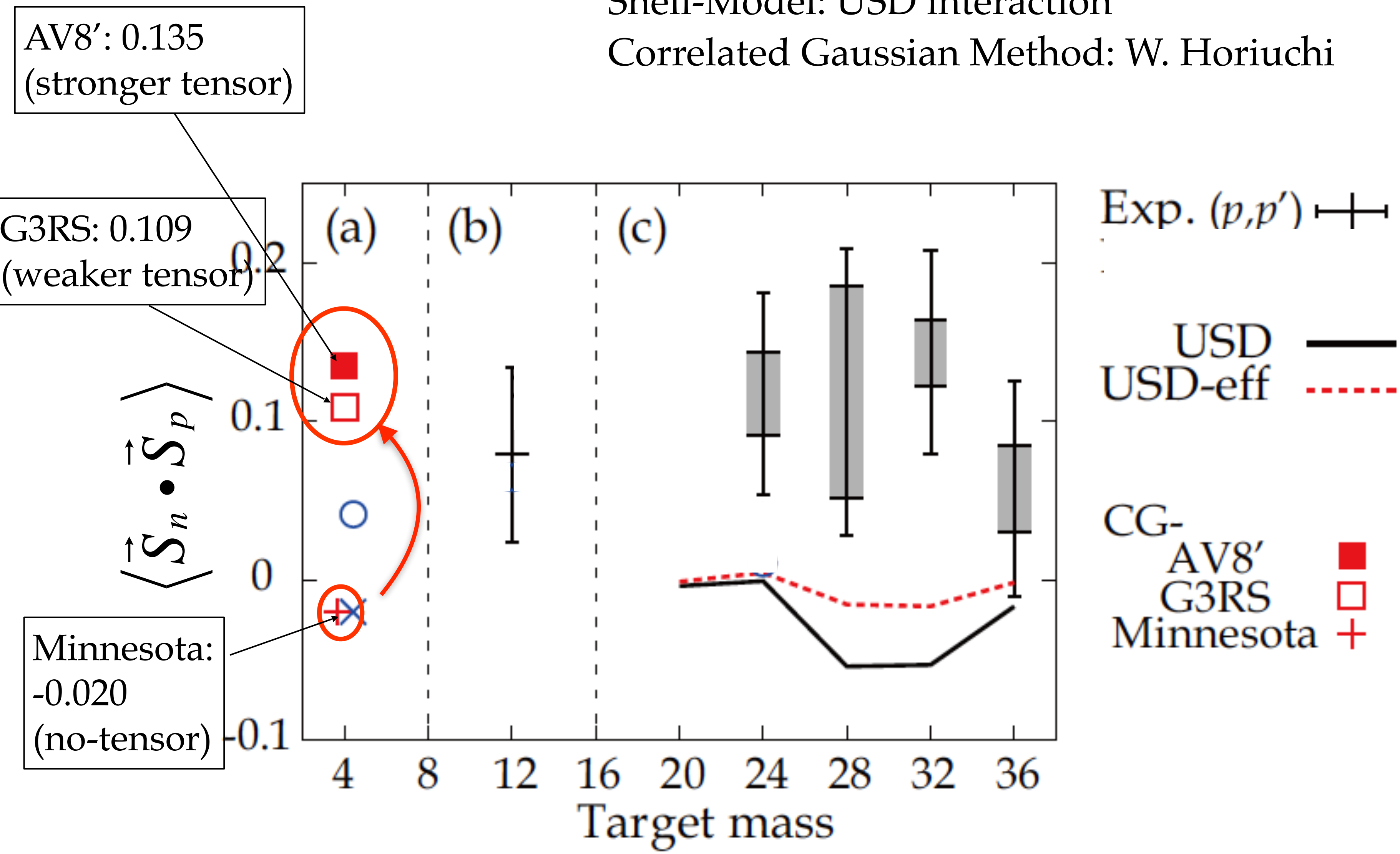
	$\langle \vec{S}_n^2 + \vec{S}_p^2 \rangle$	$\langle \vec{S}_n \cdot \vec{S}_p \rangle$	S=0	S=1	S=2
AV8' Stronger tensor int.	0.572	0.135	85.8%	0.4%	13.9%
G3RS Weaker tensor int.	0.465	0.109	88.5%	0.3%	11.3%
Minnesota No tensor int.	0.039	-0.020	100%	0%	0%

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

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

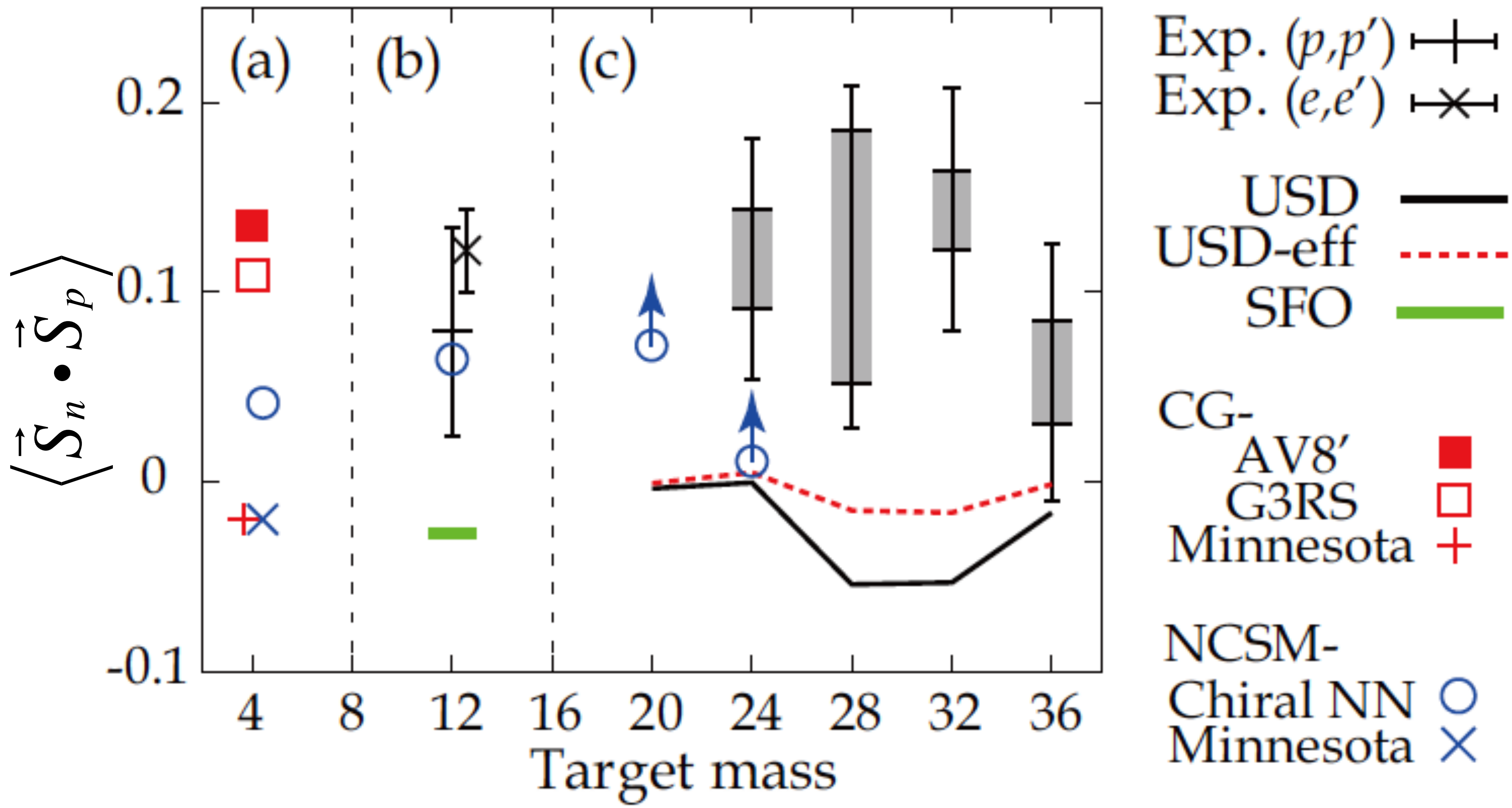
np Spin Correlation Function

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



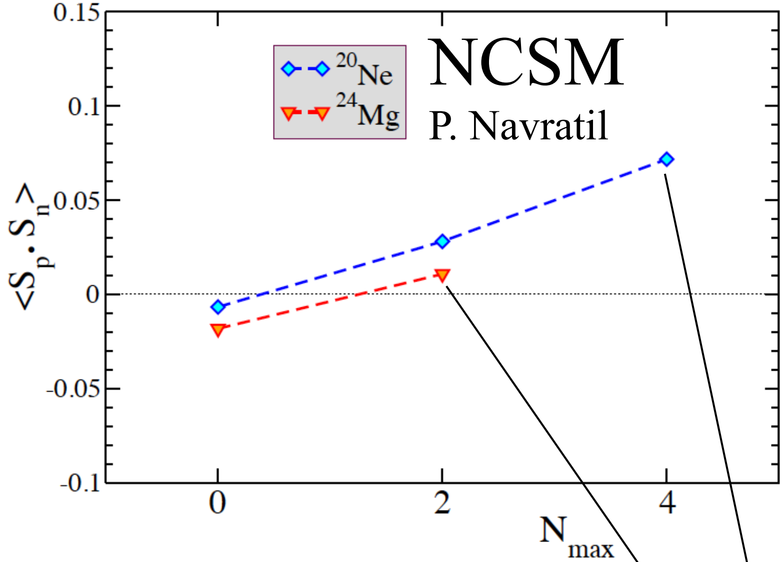
np Spin Correlation Function

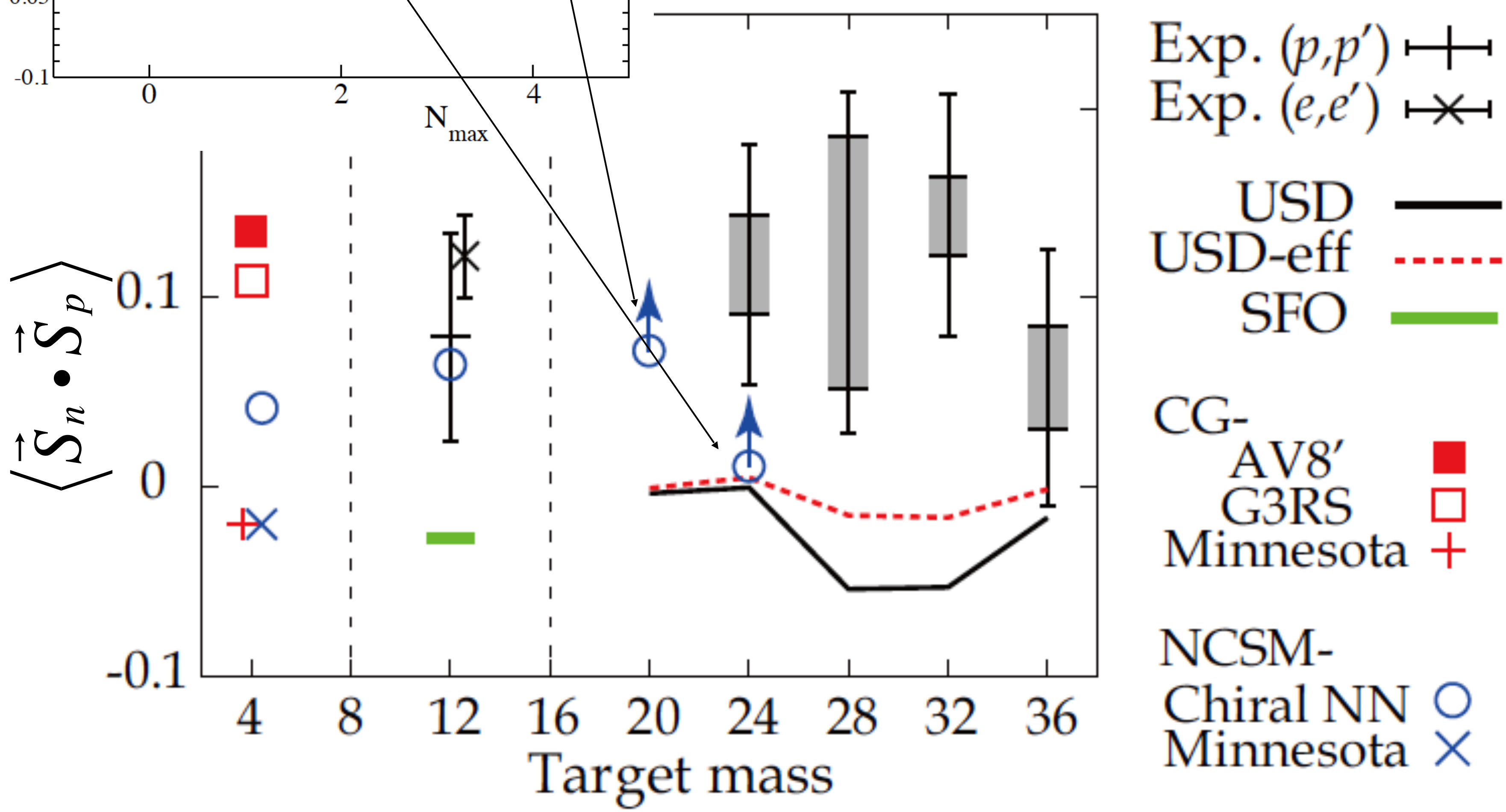
Shell-Model: USD interaction
Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil



rrelation Function

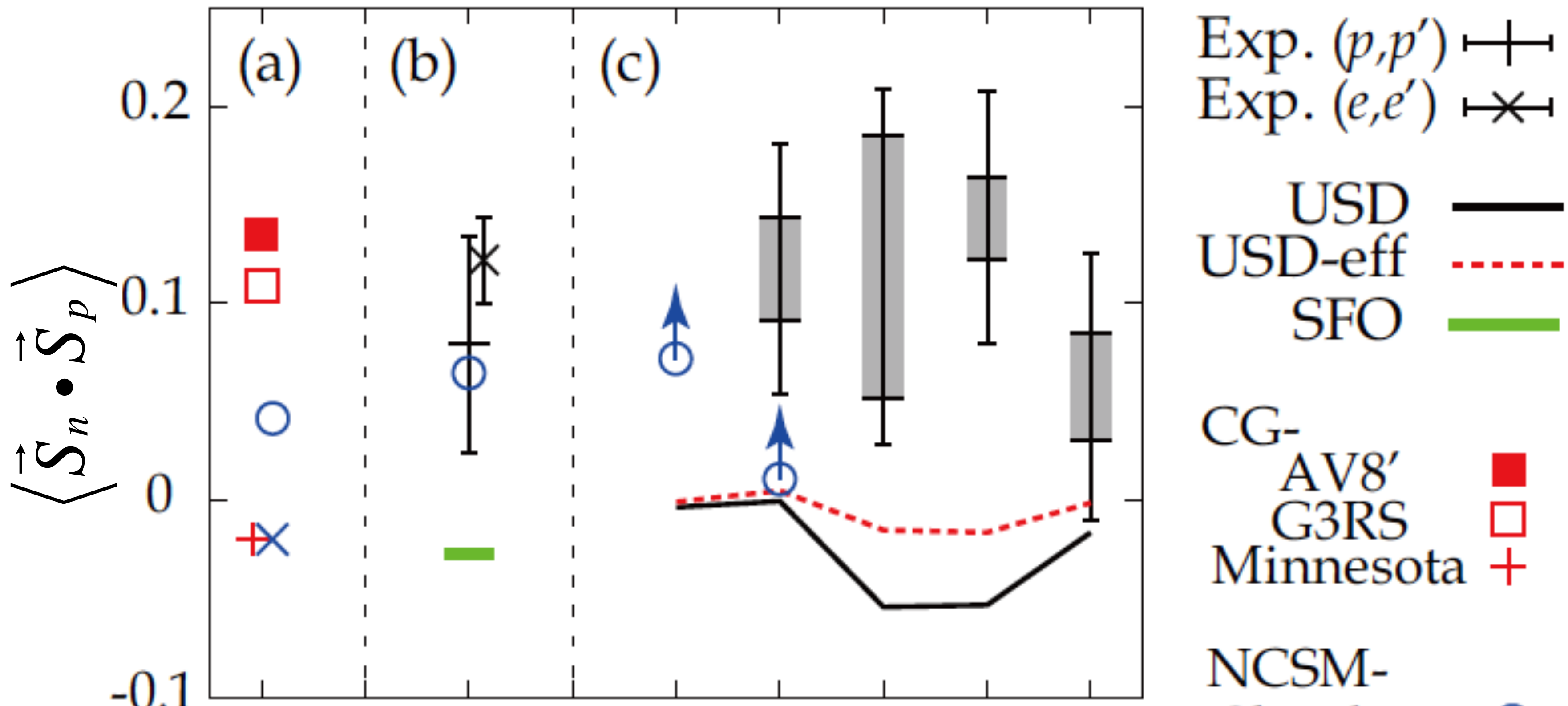
orrelated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil
hell-Model: USD interaction





np Spin Correlation Function

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

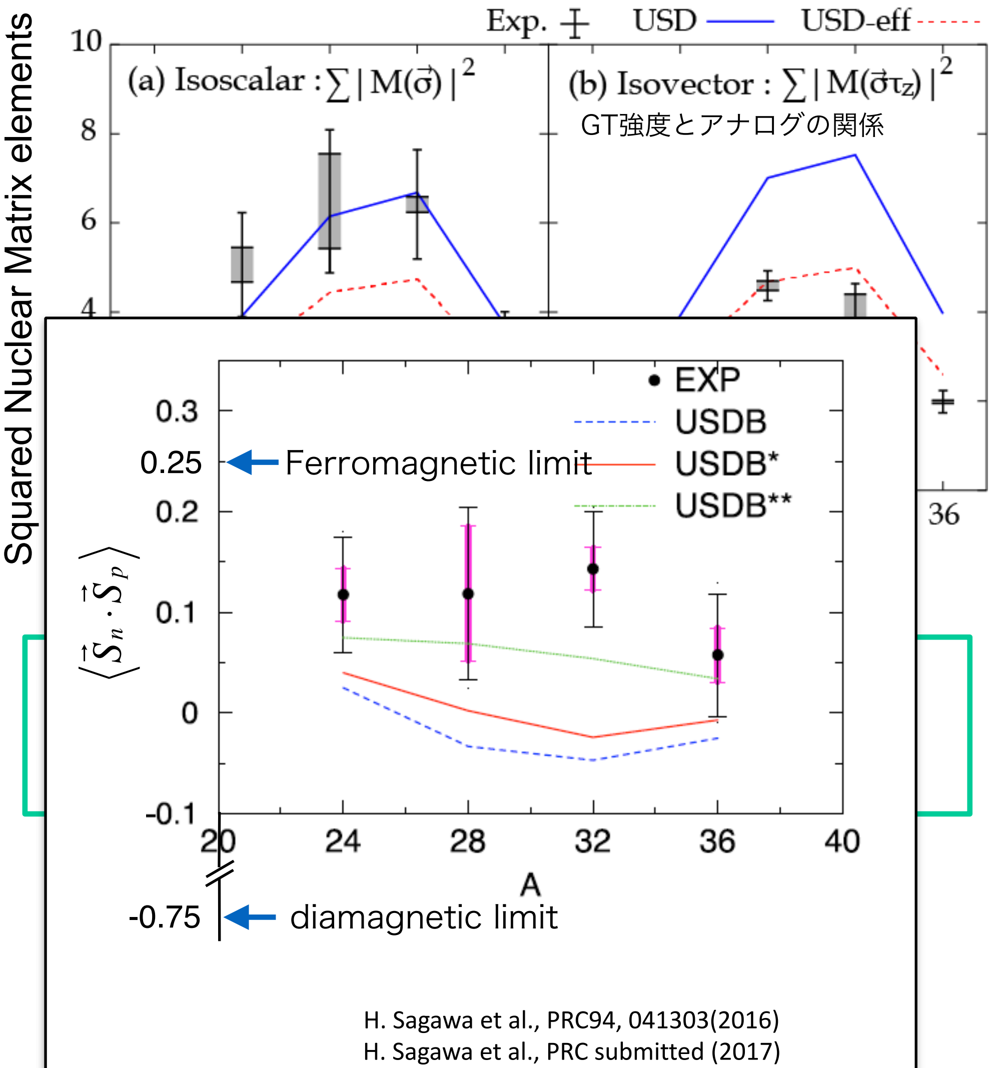


Further theoretical studies on the *sd*-shell nuclei by ab-initio type calculations with realistic interactions are very interesting.

np Spin Correlation Function

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

eff: correction with $\frac{g^{eff}}{g^{bare}}$

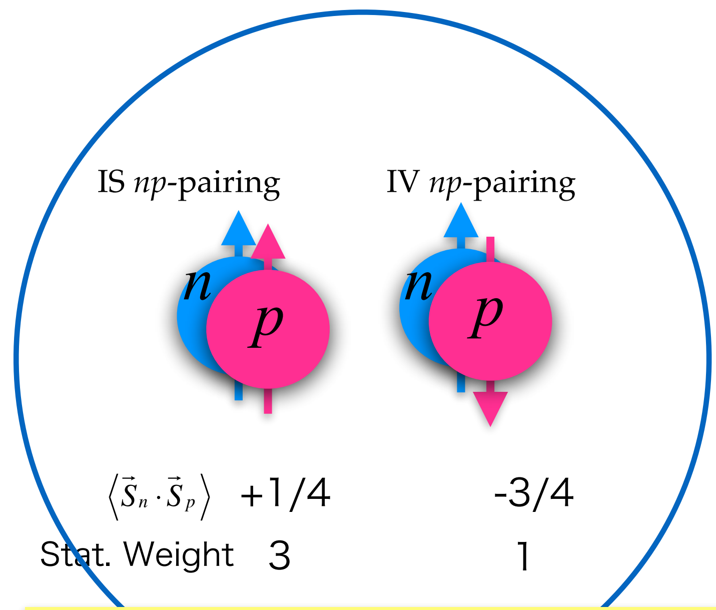


np spin correlation function of a nuclear ground state

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

IS - IV

> 0



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

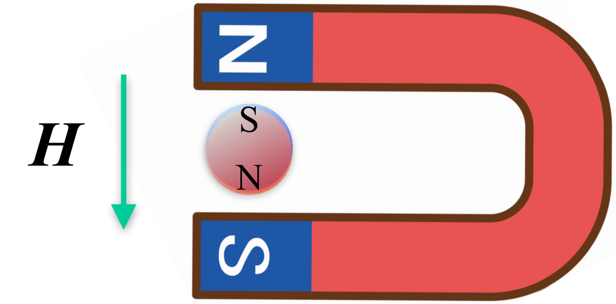
Spin-Magnetic Susceptibility

Magnetic dipole (*M1*) operator

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

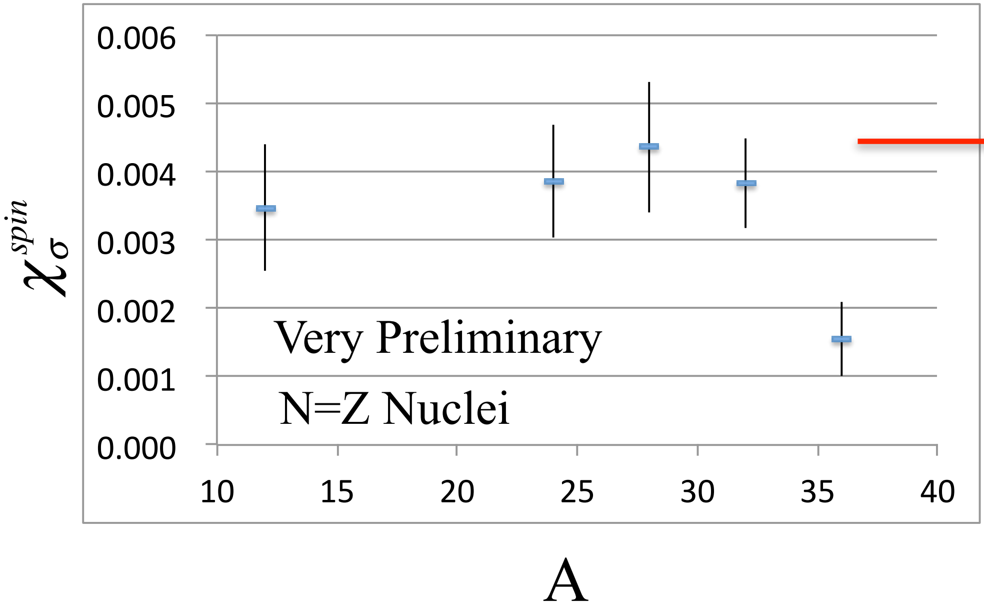
IS(1) and IV(τ) terms

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



$\mathbf{M} = \chi_\sigma \mathbf{H}$

χ_σ: magnetic susceptibility 磁化率



0.0044(7) MeV^{-1} at ρ=0.16 fm^{-3}

Neutron Matter AFDMC model

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

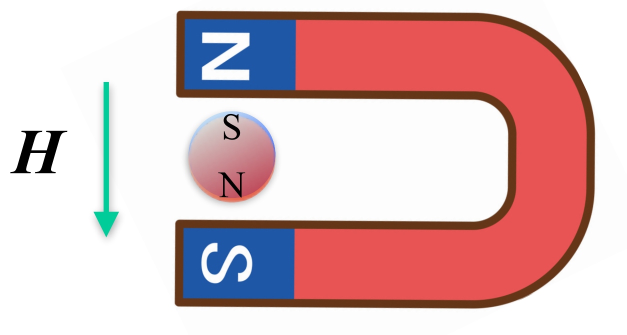
Spin-Magnetic Susceptibility

Magnetic dipole (*M1*) operator

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

IS(1) and IV(τ) terms

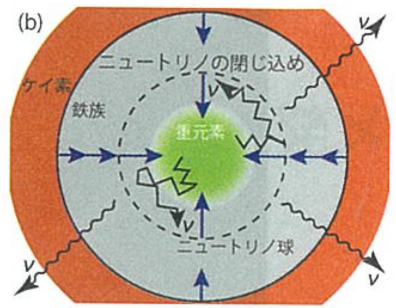
$$\chi_\sigma^{spin} = \frac{8}{3N}\sum_f \frac{1}{\omega}\left|\langle f|\sum_i \boldsymbol{\sigma}_i|0\rangle\right|^2$$



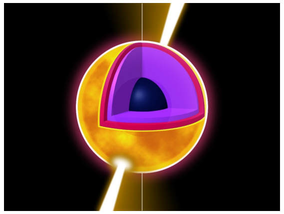
$$\mathbf{M} = \chi_\sigma \mathbf{H}$$

χ_σ: magnetic susceptibility 磁化率

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



Neutrino Sphere



Magneter $10^{14\text{-}16}$ Gauss