p-n Spin Correlation in the Ground State Studied by Measuring Spin-M1 Excitations in the *sd*-Shell Region

H. Matsubara[1] and A. Tamii[2]

[1]*Nishina Center, RIKEN*
[2]*RCNP, Osaka University*

Contents

1. Tensor Correlation in Nuclear Ground States

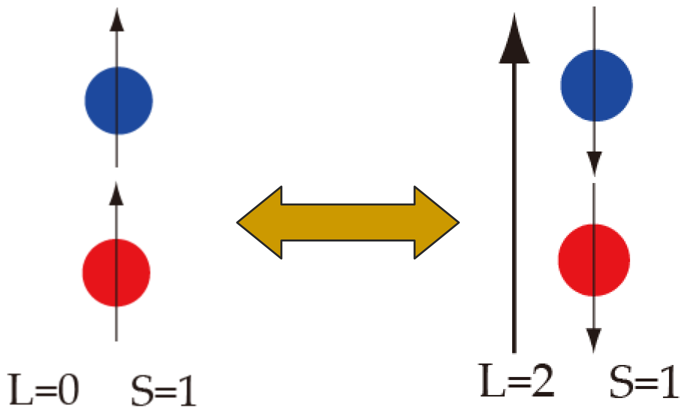
● Spin-*M1* Excitation and Sum-Rule
(H. Matsubara *et al*.,)

●Channel-Spin *S* of Correlated *p*-*n* Pairs in ^{4}He
(K. Miki *et al*.,)

2. E1 Response of ^{208}Pb and Symmetry Energy
of the Nuclear EOS

Spin-*M1* Excitation and Sum-Rule

Deuteron

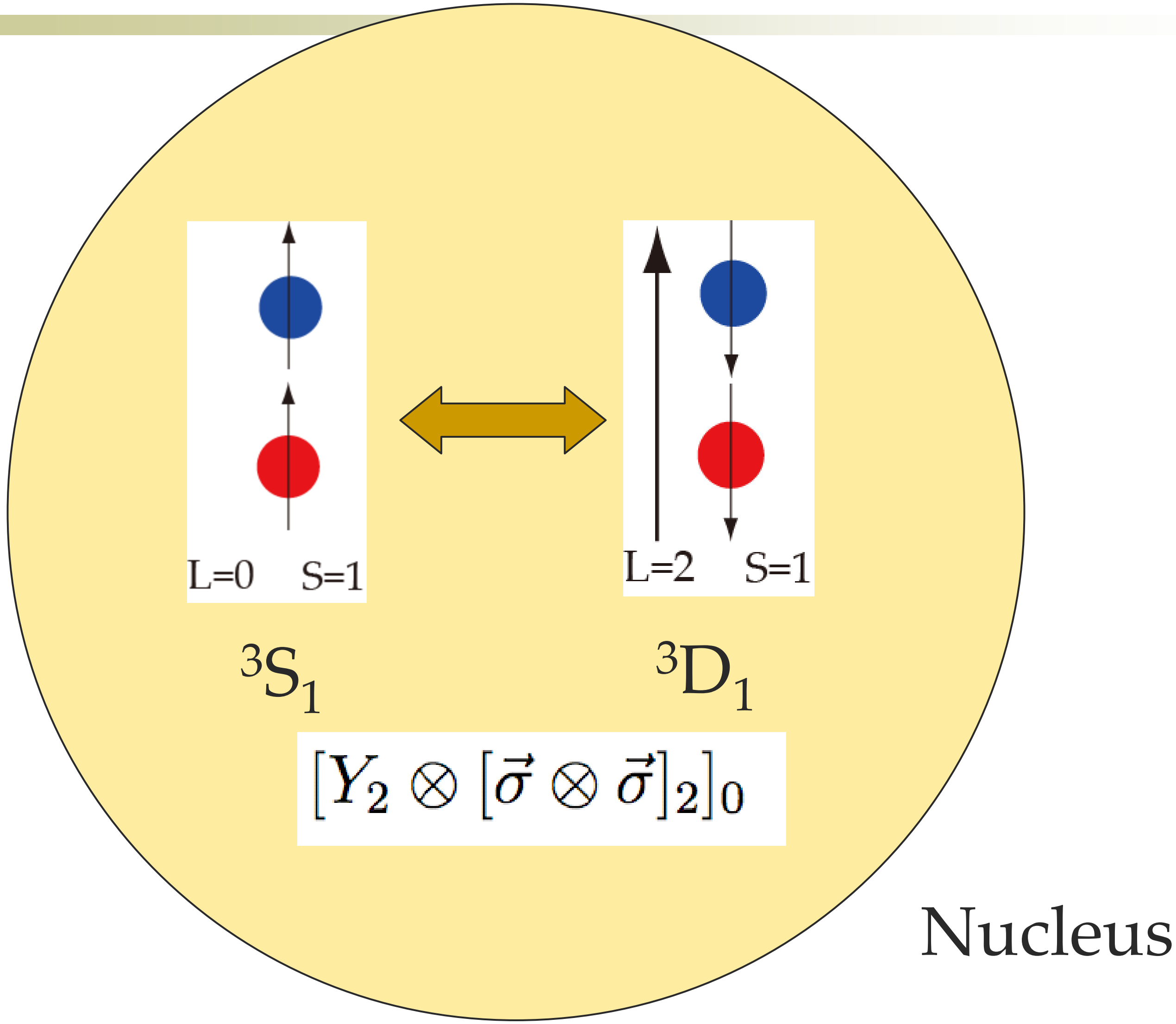


$^3S_1$ $^3D_1$

$$[Y_2 \otimes [\vec{\sigma} \otimes \vec{\sigma}]_2]_0$$

Mixing between $^3S_1$ and $^3D_1$ by tensor interaction is important to bind a deuteron

Tensor Correlation in Nuclear Ground States



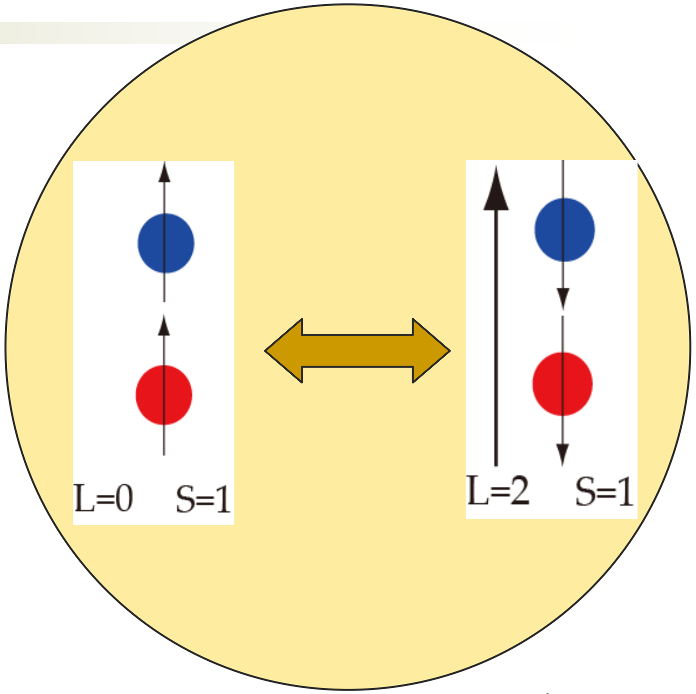
The same mixing should exist in nuclear ground states.

"Tensor Correlation"

Proton and Neutron Spin Operators

$$\vec{S}_p \equiv \sum_{i=1}^{Z} \vec{s}_i = \sum_{i=1}^{Z} \frac{\vec{\sigma}_i}{2}$$ for protons

$$\vec{S}_n \equiv \sum_{i=1}^{N} \vec{s}_i = \sum_{i=1}^{N} \frac{\vec{\sigma}_i}{2}$$ for neutrons



Nucleus

$$\left\langle \vec{S}_p \cdot \vec{S}_n \right\rangle$$ ***p-n* spin-correlation function**:

g.s. expectation value of $\vec{S}_p \cdot \vec{S}_n$
could be a signature of the tensor correlation.

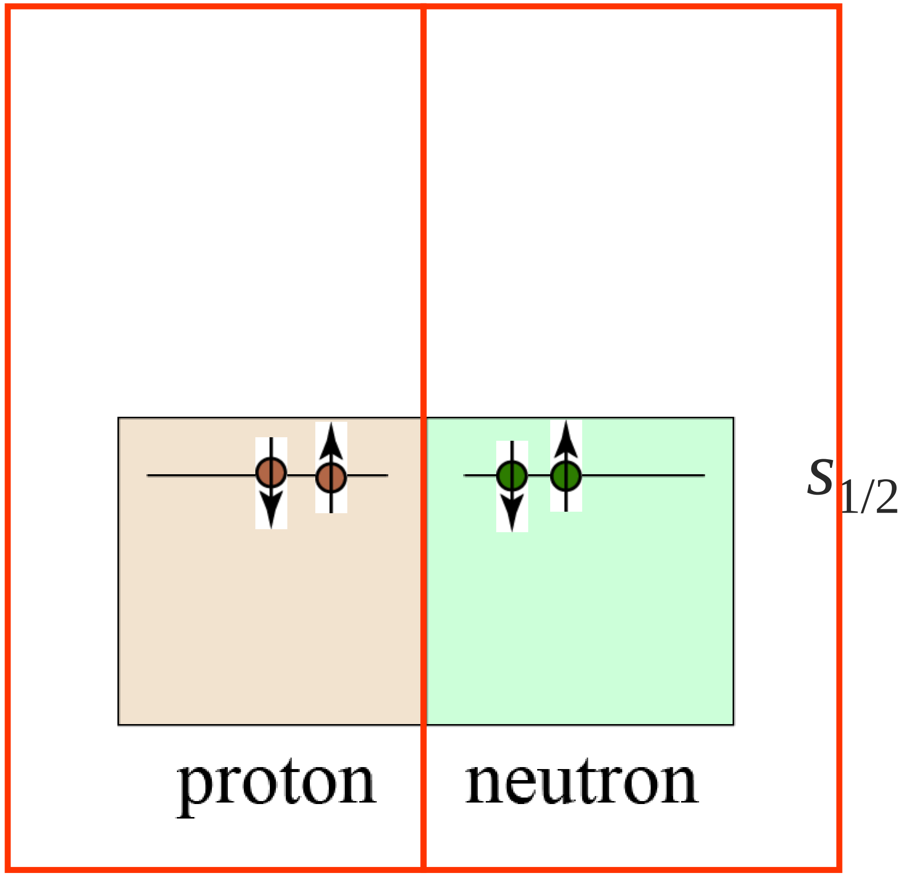
$$\vec{S}_p + \vec{S}_n \equiv \sum_{i=1}^{A} \frac{1}{2} \vec{\sigma}_i = \frac{1}{2} \vec{\sigma}$$

$$\vec{S}_n - \vec{S}_p \equiv \sum_{i=1}^{A} \frac{1}{2} \vec{\sigma}_i \tau_{z,i} = \frac{1}{2} \vec{\sigma} \tau_z$$

$$\left\langle \vec{S}_p \cdot \vec{S}_n \right\rangle = +0.25$$ for a deuteron

Tensor Correlation in Particle-Hole Configurations

Simplest case: ^{4}He



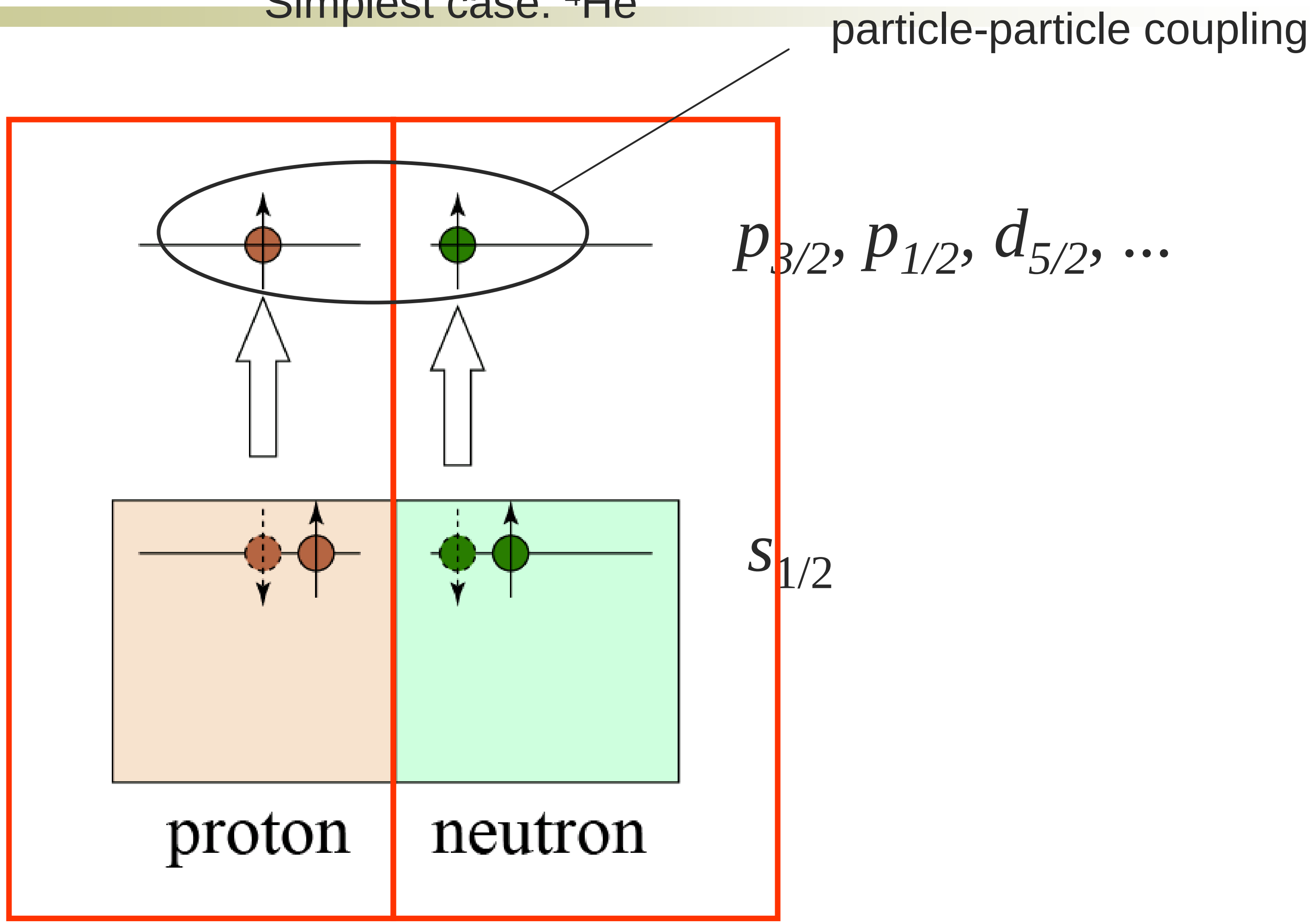
Consideration with single particle orbits

uncorrelated ground state

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

Tensor Correlation in Particle-Hole Configurations

Simplest case: ^{4}He



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

$\langle S_p \cdot S_n \rangle$ geometrical values

by Y. Ogawa

2p2h channels in 4He, in p-p coupling

$[[kl]JT[s_{1/2}s_{1/2}]JT]$	$\langle 2p2h\|\vec{S}_p \cdot \vec{S}_n\|2p2h\rangle$
● $[p_{1/2}\ p_{1/2}]10$	1.11
● $[d_{3/2}\ d_{3/2}]10$	0.56
● $[f_{5/2}\ f_{5/2}]10$	0.37
$[g_{7/2}\ g_{7/2}]10$	0.27
$[h_{9/2}\ h_{9/2}]10$	0.22
$[i_{11/2}\ i_{11/2}]10$	0.18
$[j_{13/2}\ j_{13/2}]10$	0.15

j = l -1/2

$[[kl]JT[s_{1/2}s_{1/2}]JT]$	$\langle 2p2h\|\vec{S}_p \cdot \vec{S}_n\|2p2h\rangle$
$[p_{3/2}\ p_{3/2}]10$	-0.22
$[d_{5/2}\ d_{5/2}]10$	-0.24
$[f_{7/2}\ f_{7/2}]10$	-0.20
$[g_{9/2}\ g_{9/2}]10$	-0.17
$[h_{11/2}\ h_{11/2}]10$	-0.15
$[i_{13/2}\ i_{13/2}]10$	-0.13
$[j_{15/2}\ j_{15/2}]10$	-0.12

j = l +1/2

$[[kl]JT[s_{1/2}s_{1/2}]JT]$	$\langle 2p2h\|\vec{S}_p \cdot \vec{S}_n\|2p2h\rangle$
● $[s_{1/2}\ d_{3/2}]10$	2.00
● $[p_{3/2}\ f_{5/2}]10$	2.00
● $[d_{5/2}\ g_{7/2}]10$	2.00
● $[f_{7/2}\ h_{9/2}]10$	2.00
$[g_{9/2}\ i_{11/2}]10$	2.00
$[h_{11/2}\ j_{13/2}]10$	2.00

$$[Y_2 \otimes [\vec{\sigma} \otimes \vec{\sigma}]_2]_0$$

large amplitude

● Important channel for pionic correlation

$$|C_\alpha|^2 \langle 2p2h : \alpha|\vec{S}_p \cdot \vec{S}_n|2p2h : \alpha\rangle$$

Positive $\langle S_p \cdot S_n \rangle$ is a signature of the tensor correlation

Precise calculation of ^{4}He with realistic NN interactions

by W. Horiuchi

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

	$\langle \vec{S}_p^2 + \vec{S}_n^2 \rangle$	$\langle \vec{S}_p \cdot \vec{S}_n \rangle$	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)

$\langle \vec{S}_p \cdot \vec{S}_n \rangle$ is **sensitive** to the tensor correlation in the ground state, and may give **quantitative evaluation** of the correlation.

How to measure it?

We have measured IS/IV s**pin-M1 transition strengths** and used **sum-rules** to extract the **ground state property**.

How to Measure $\langle \vec{S}_p \cdot \vec{S}_n \rangle$ - Sum-Rule

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

$$\vec{S}_n - \vec{S}_p \equiv \sum_{i=1}^{A} \frac{1}{2} \vec{\sigma}_i \tau_{z,i} = \frac{1}{2} \vec{\sigma} \tau_z$$

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

$$= \frac{1}{16} \left\{ \sum \left| M(\vec{\sigma}) \right|^2 - \sum \left| M(\vec{\sigma}\tau_z) \right|^2 \right\}$$

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

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

closure approximation

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

$$= \frac{1}{4} \sum \left| M(\vec{\sigma}\tau_z) \right|^2$$ IV spin-M1 transition matrix elements

$$\left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 \right\rangle = \frac{1}{4} \sum \left| M(\vec{\sigma}) \right|^2$$ IS spin-M1 transition matrix elements

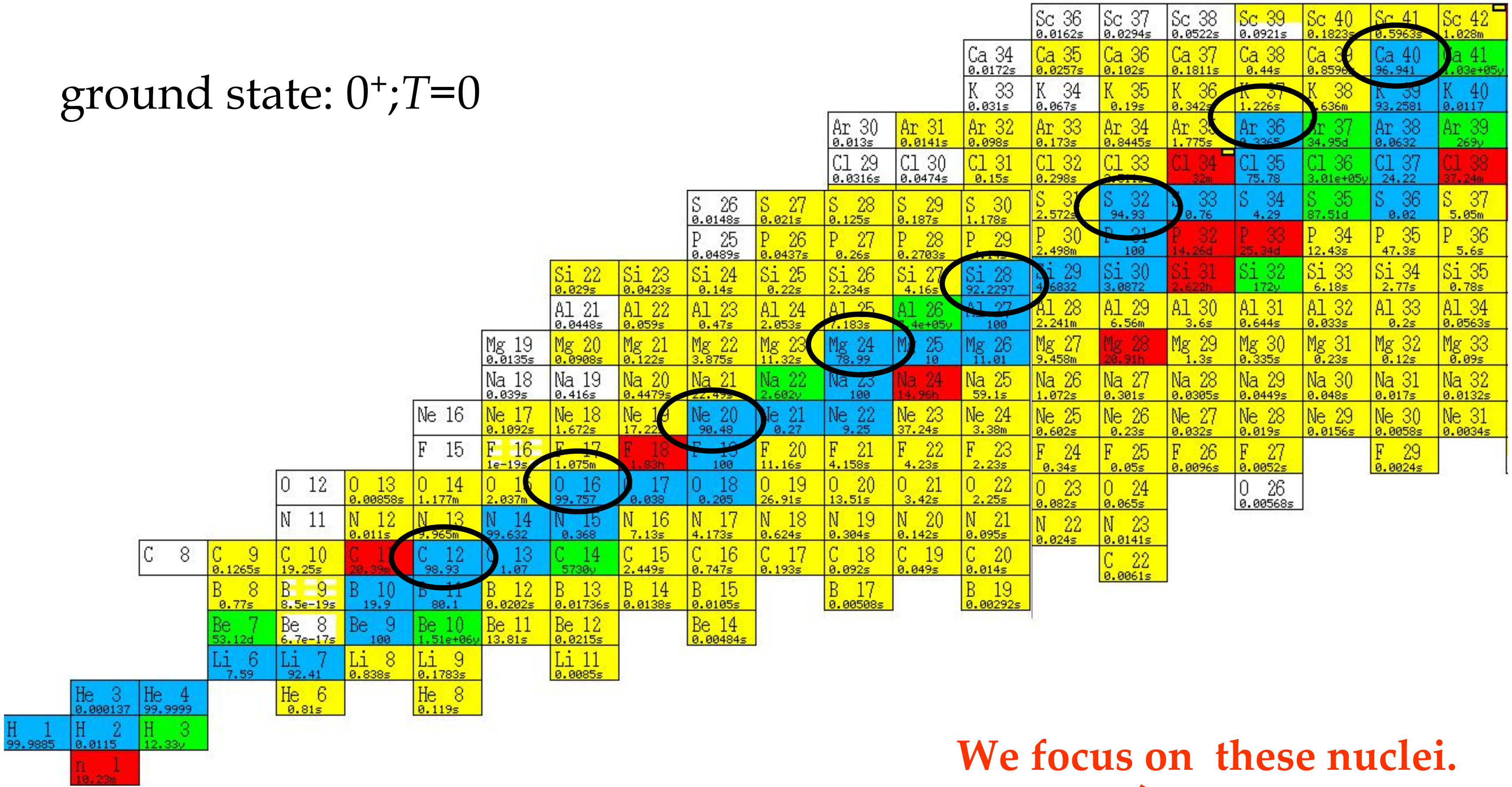
$$\langle \vec{S}_n^2 + \vec{S}_p^2 \rangle = \frac{1}{4} \left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 + \left(\vec{S}_n - \vec{S}_p\right)^2 \right\rangle$$

$$= \frac{1}{16} \left\{ \sum \left| M(\vec{\sigma}) \right|^2 + \sum \left| M(\vec{\sigma}\tau_z) \right|^2 \right\}$$

The ground state expectation value can be extracted from the sum-rules of the IS/IV spin-M1 transition matrix elements.

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

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



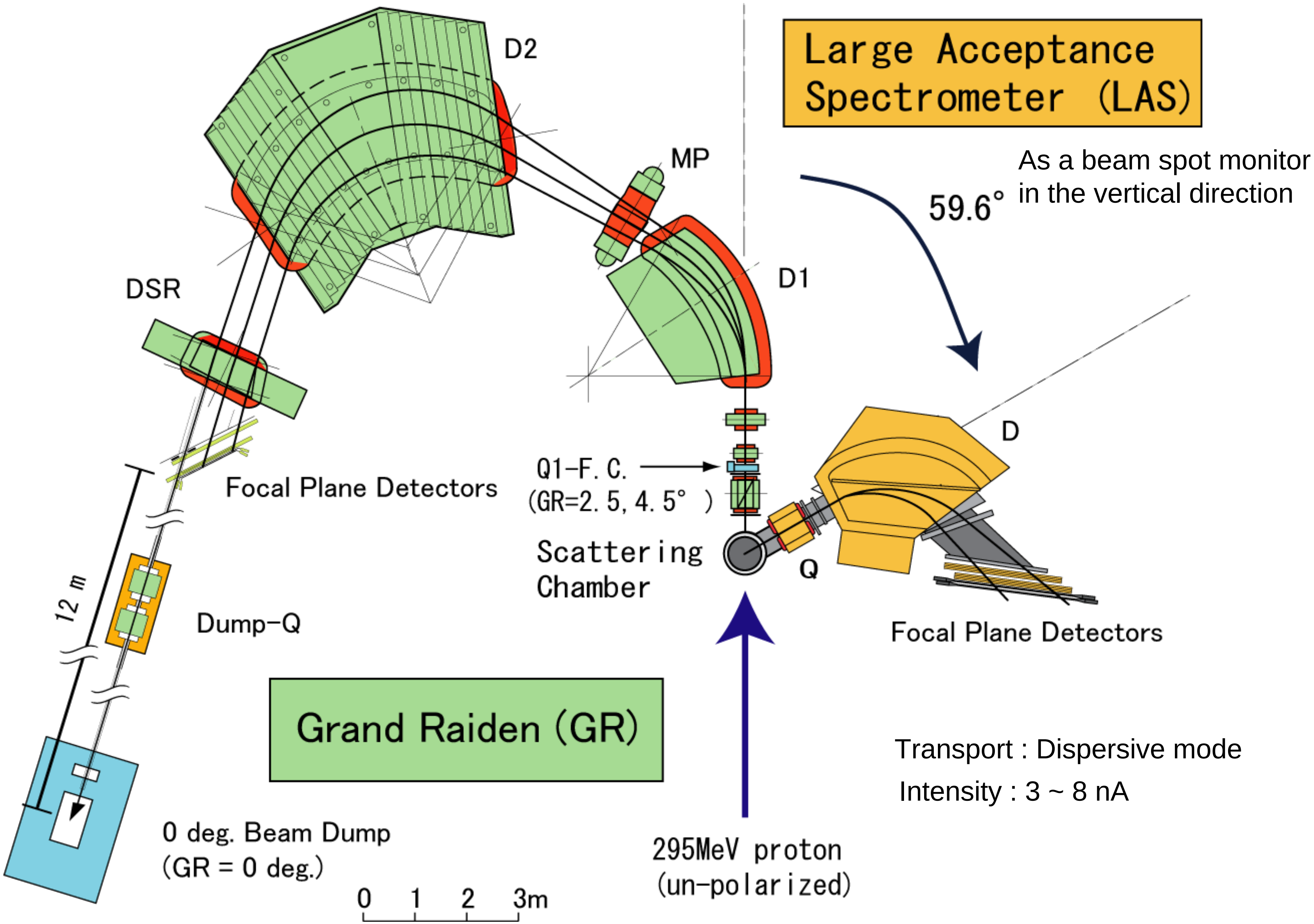
We focus on these nuclei.

Stable self-conjugate even-even nuclei:

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

We measured (p,p′) for all the above nuclei except ^{4}He.

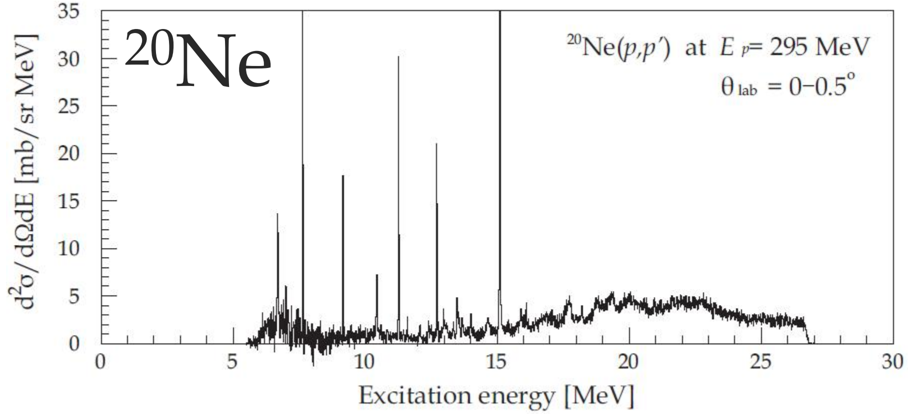
Spectrometer Setup for 0-deg (p,p′) at RCNP

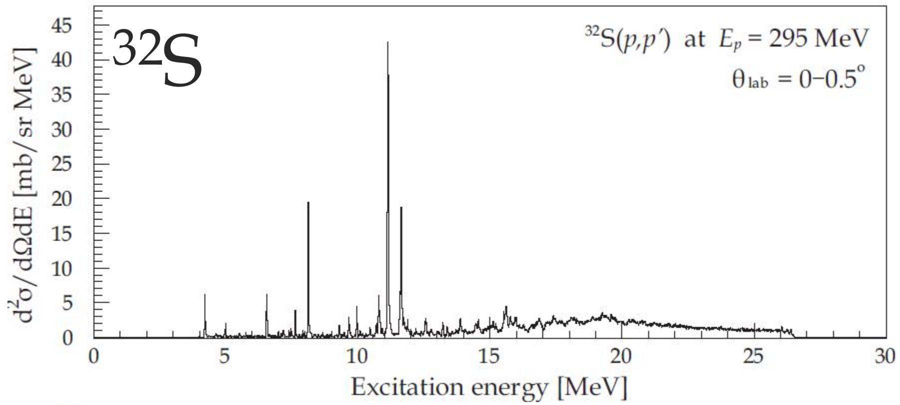


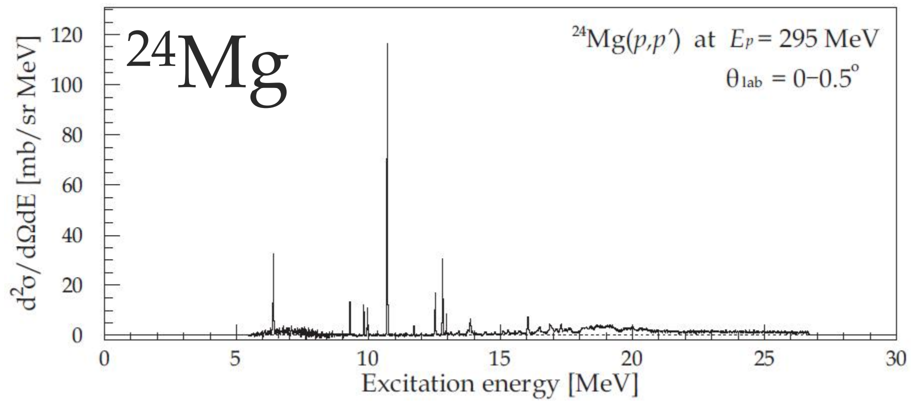
(p,p′) Spectra at E_p=295 MeV

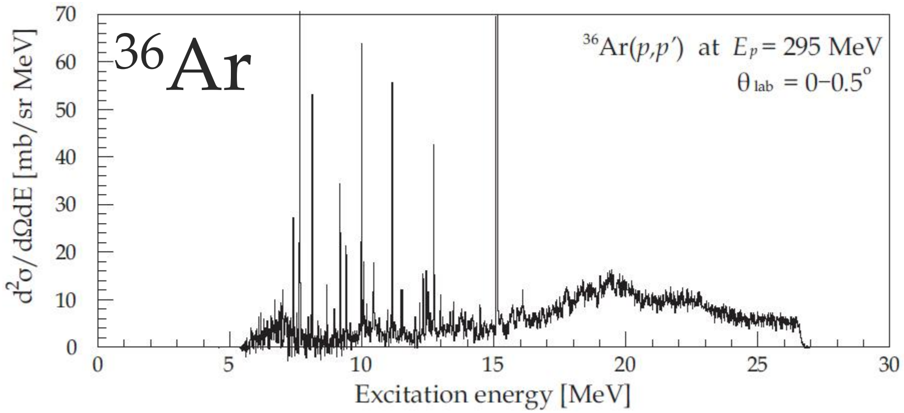
RCNP-E299

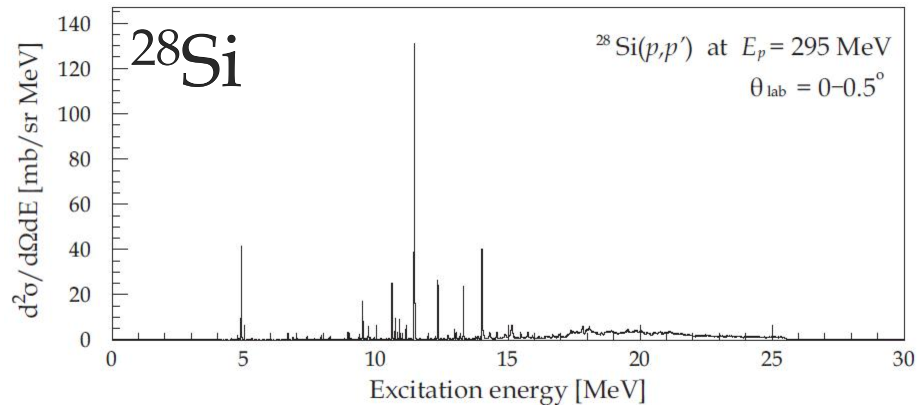
measured at 0-15 deg.











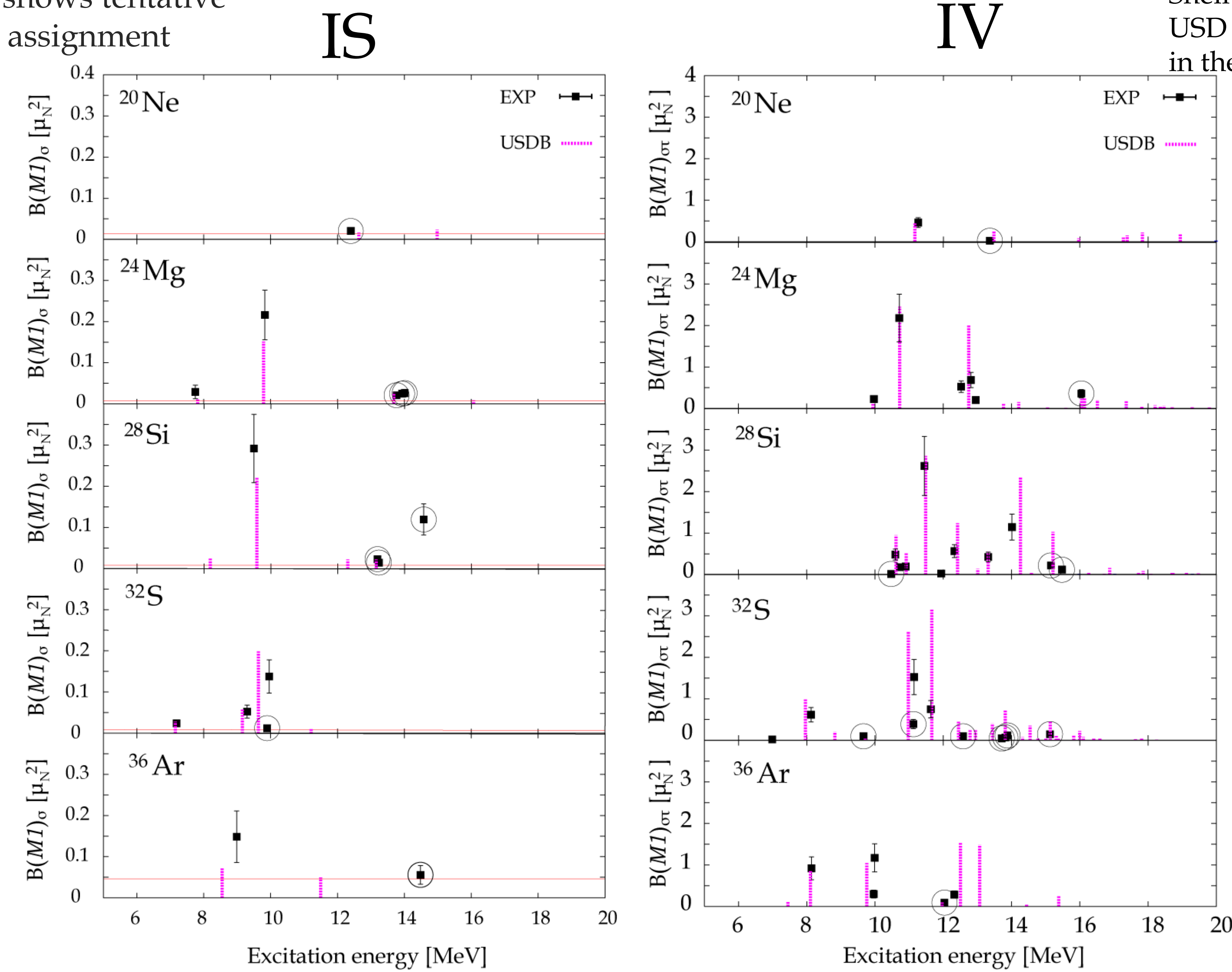
IS/IV 1^+ states were identified from angular distribution for each of IS and IV transitions.

The cross sections at the most forward angles have were converted to the spin-M1 strengths.

Spin-M1 Strength Distribution

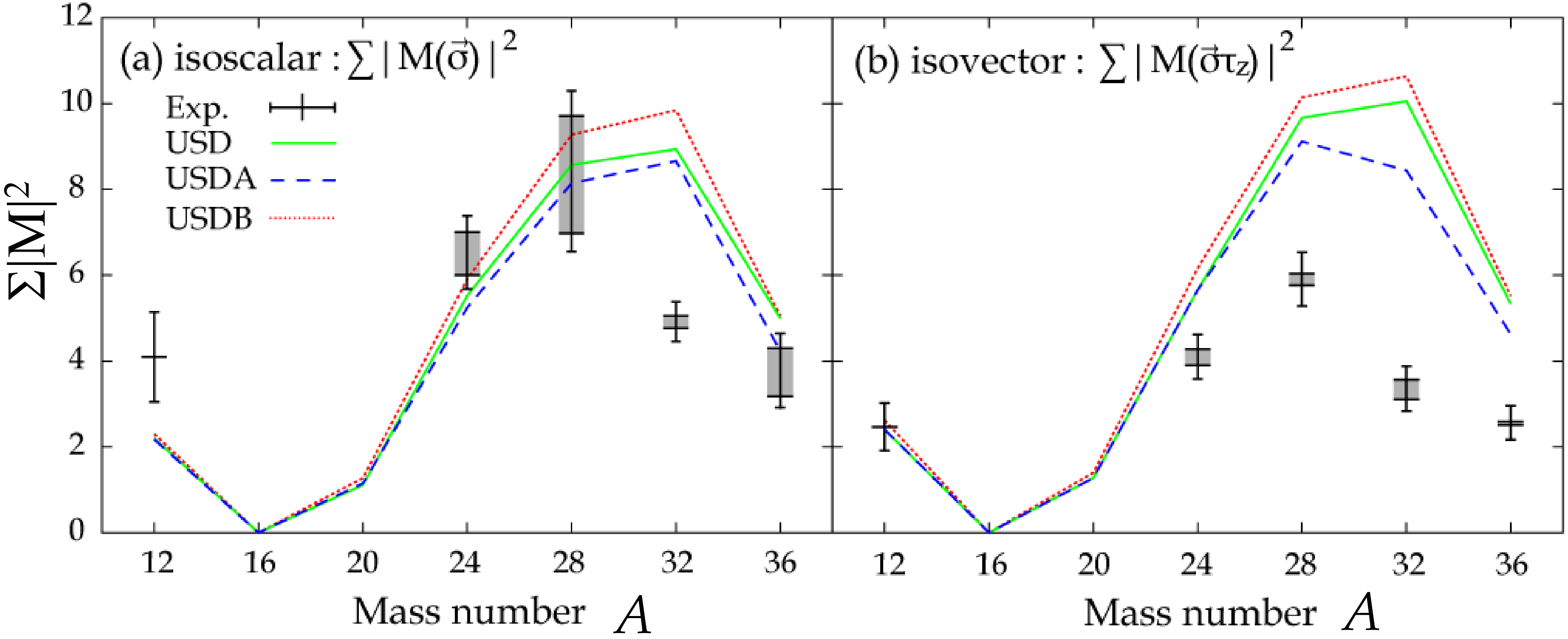
○ shows tentative 1⁺ assignment

Shell-Model
USD free *g*-factor
in the *sd*-shell



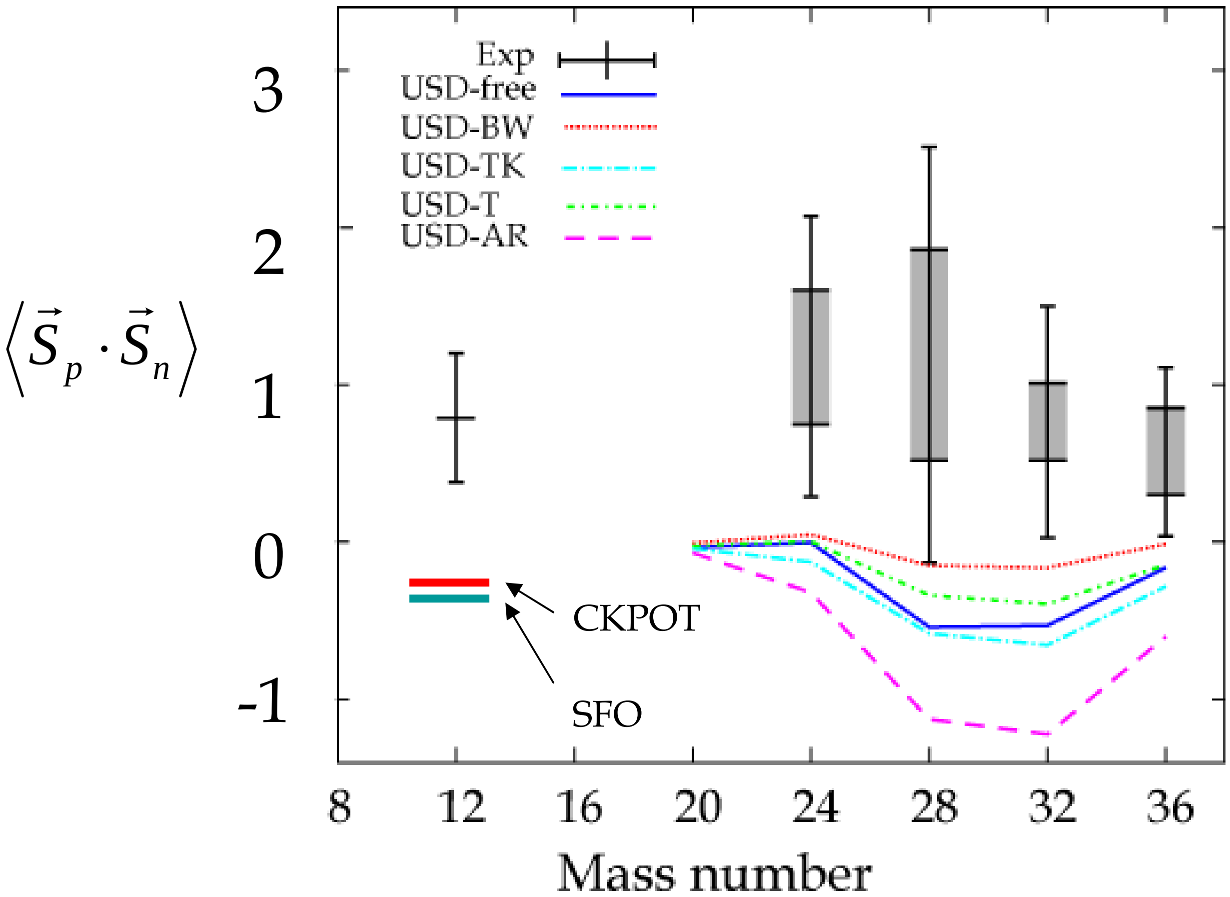
IS/IV Spin-M1 Matrix Elements

- summed strengths up to 16 MeV
- comparison with a shell-model calculation with USD int.



p-n Spin Correlation Function

- summed strengths up to 16 MeV
- comparison with a shell-model calculation with USD int.



Precise calculation of for a nucleon system with realistic NN interaction

by W. Horiuchi

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

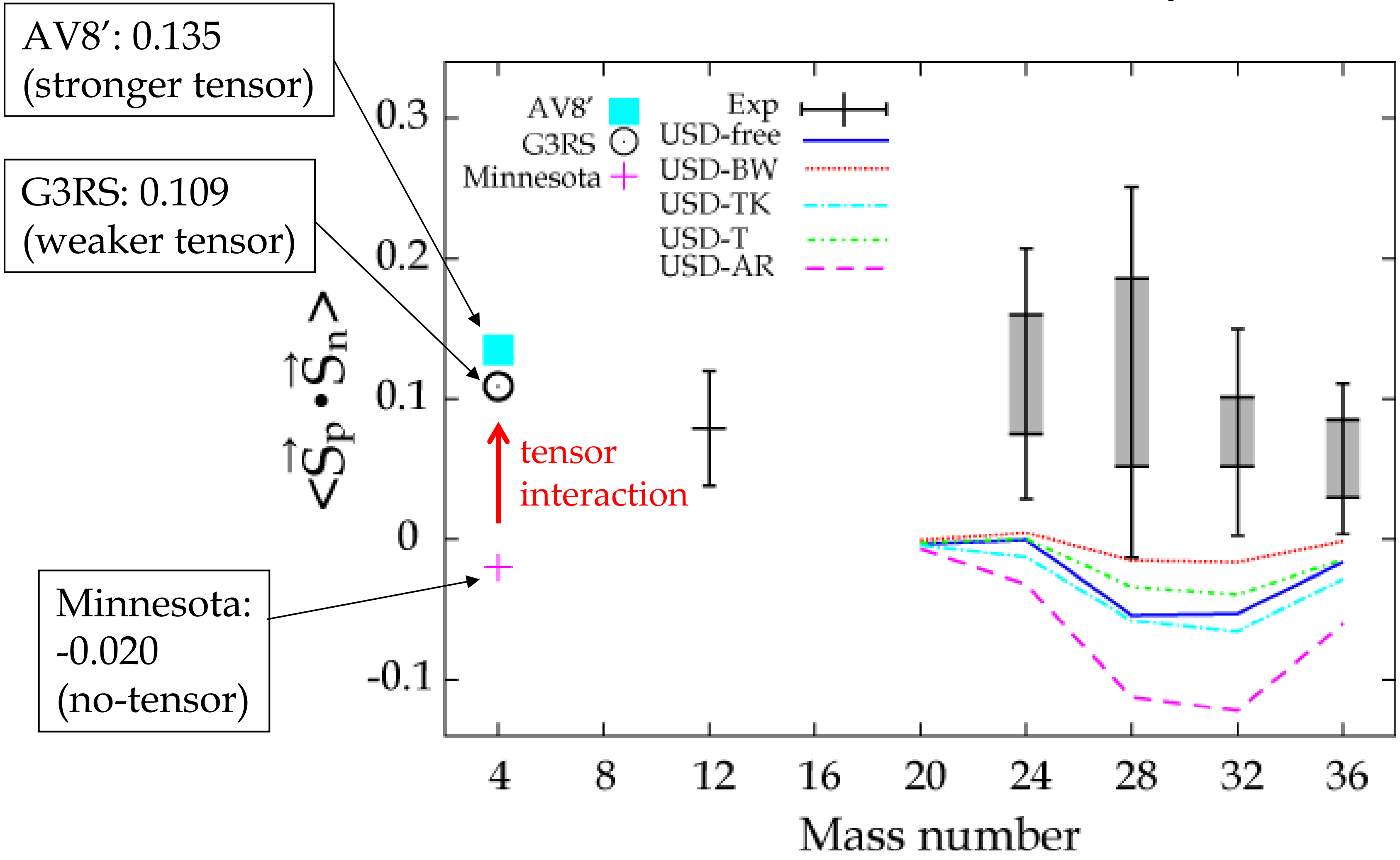
	$\langle \vec{S}_p^2 + \vec{S}_n^2 \rangle$	$\langle \vec{S}_p \cdot \vec{S}_n \rangle$	S=0	S=1	S=2
AV8' Stronger tensor int.	0.572	0.135	85.8%	0.4%	13.9%
G3RS Weaker tensor int.	0.465	0.109	88.5%	0.3%	11.3%
Minnesota No tensor int.	0.039	-0.020	100%	0%	0%

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

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

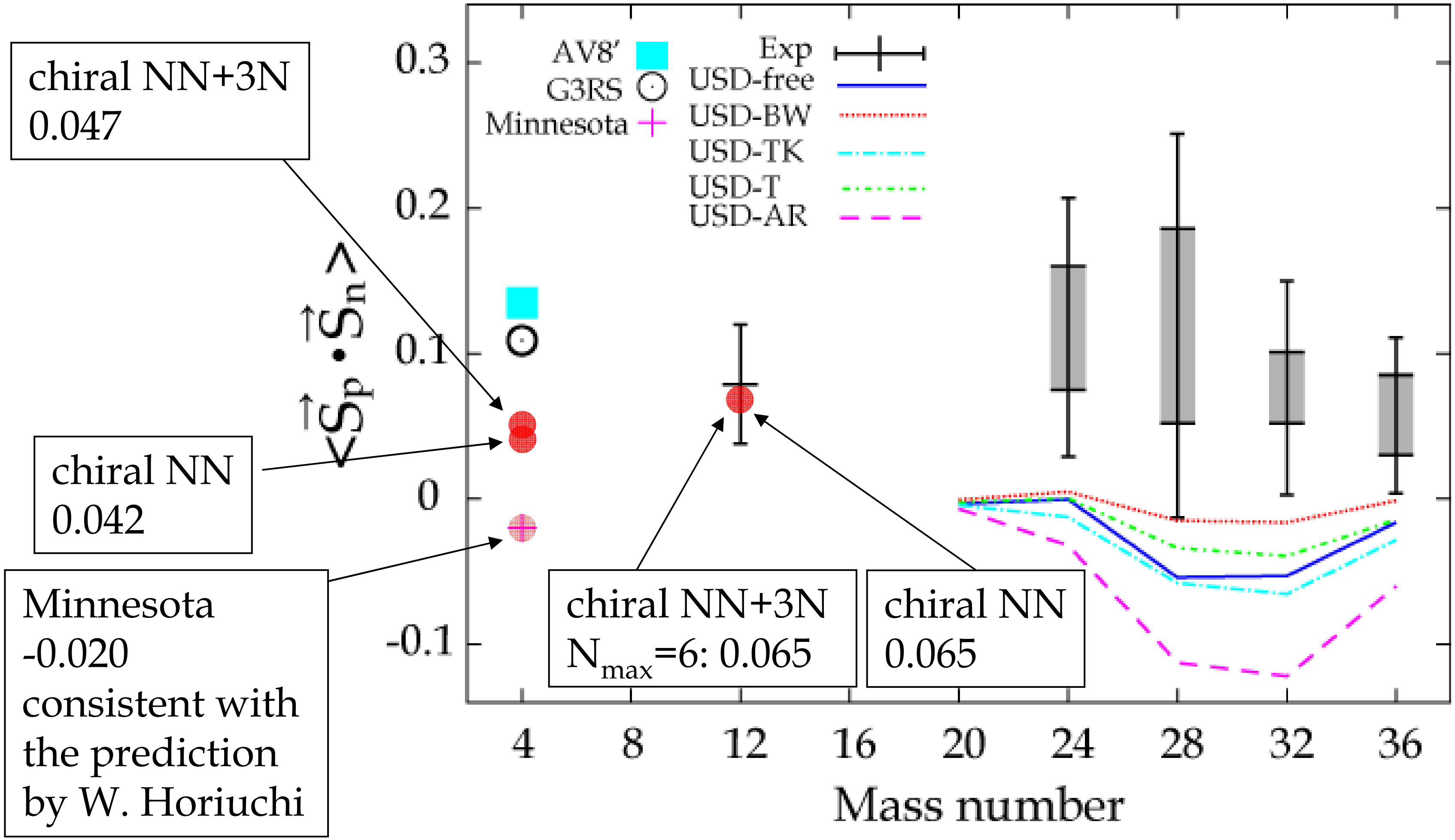
Calculation with Modern Realistic Interactions for ^{4}He

^{4}He calc. by W. Horiuchi



Predictions by Non-Core Shell Model

Calc. by P. Navratil



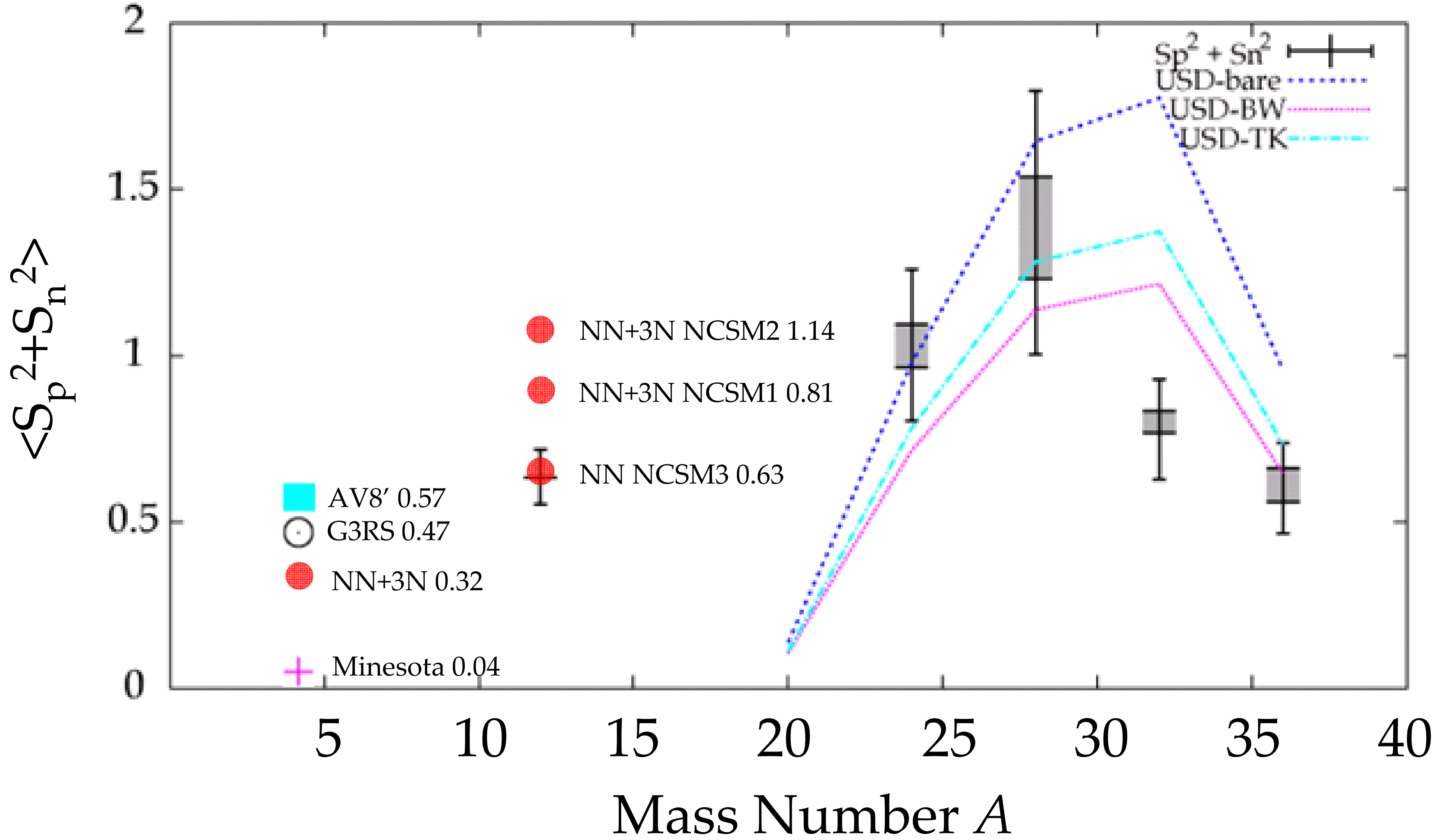
[4]He: Entem-Machleidt N3LO 500 NN, N2LO 500 3N

[12]C NN: Entem-Machleidt N3LO 500 NN, NCSM2

[12]C NN+3N: Entem-Machleidt N3LO 500 NN, N2LO 500 3N, NCSM3

E.C. Simpson et al., PRC86, 054609 (2012)

$$<S^2> = <S_p{}^2 + S_n{}^2>$$



W. Horiuchi

P. Navratil

Theoretical predictions are hoped for higher masses and on mass dependence with realistic tensor interaction.

Ab initio calculations up to A~12.

Channel-Spin S of Correlated p-n pairs in ^{4}He

Study of tensor correlations in ^{4}He via the ^{4}He(p,dp) reaction

Tensor operator has
a characteristic dependence on spin.

$$V_T = V_T(r)\left\{3\frac{(\vec{\sigma}_p\cdot\vec{r})(\vec{\sigma}_n\cdot\vec{r})}{r^2} - \vec{\sigma}_p\cdot\vec{\sigma}_n\right\}$$

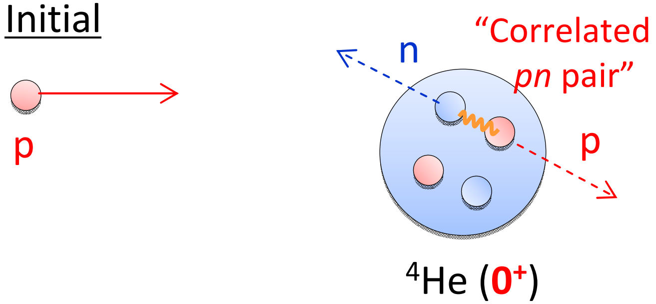
Acts only on <u>S=1</u>.

⇨ Study of **channel spin *S*** of **correlated *NN* pair** must be essential.

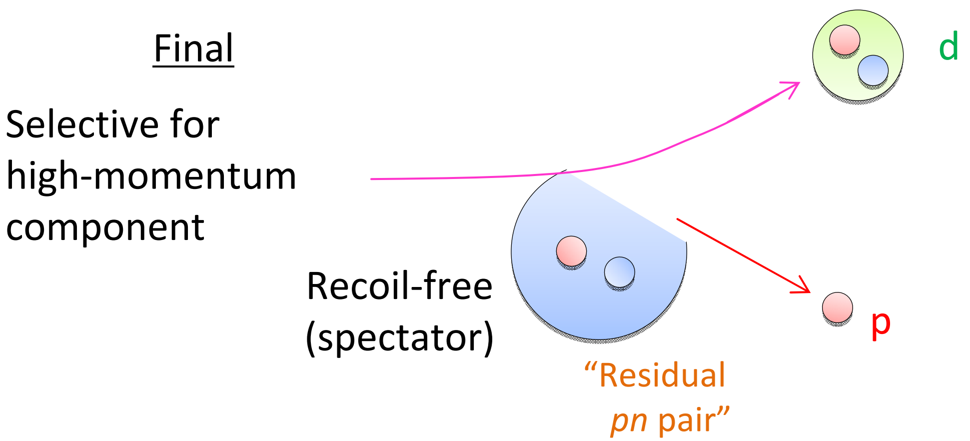
" We started from the study of ^{4}He because of its simplicity. "

- <u>Method</u> : **(p,dp)** measurement

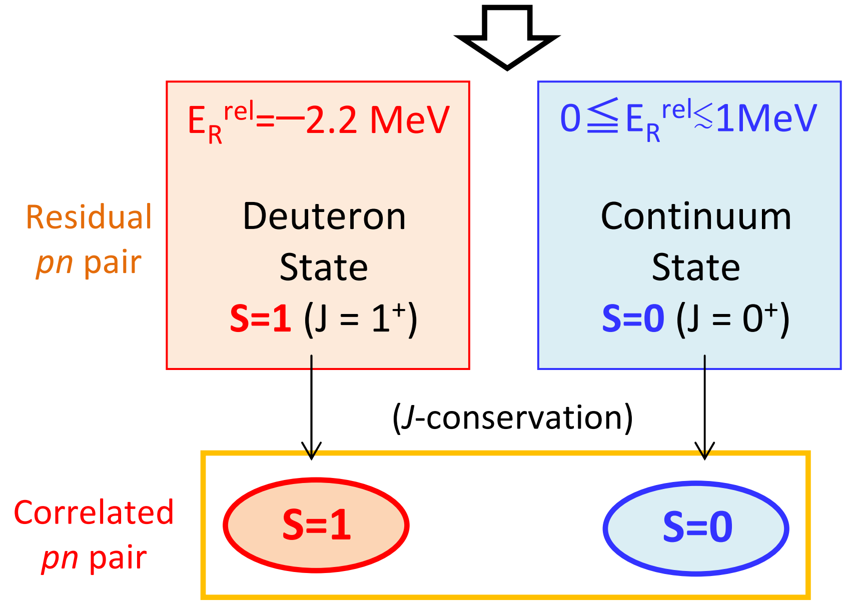
<u>Initial</u>



<u>Final</u>



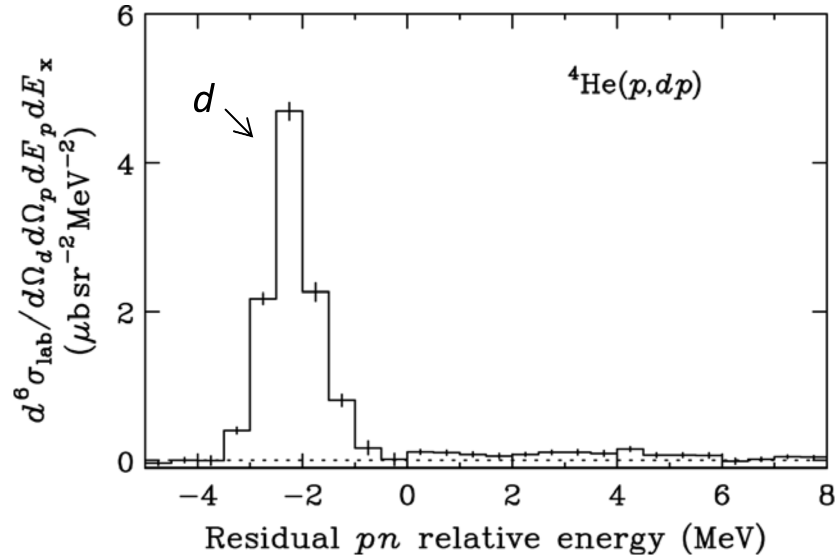
The excitation energy of residual nuclei (E_R^{rel}) can be determined by missing mass method.

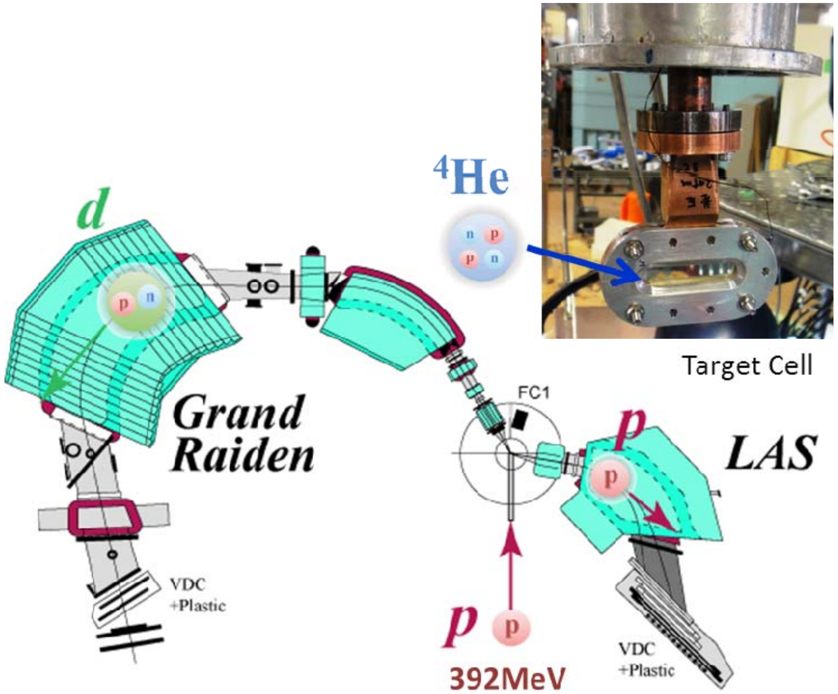


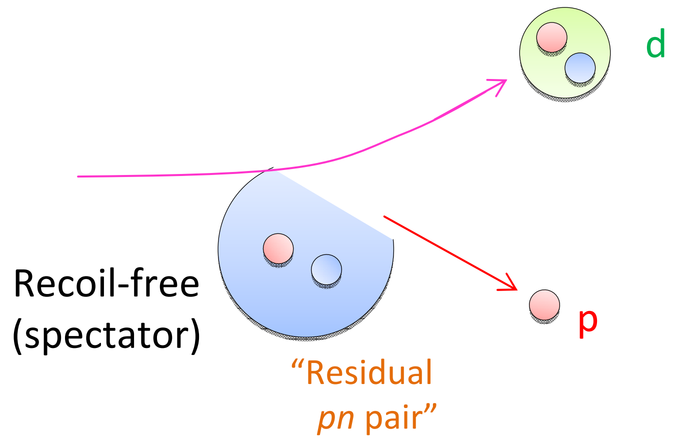
" We can identify
the spin of correlated *pn* pair ! "

Preliminary spectrum

- Only one spectrum at P_{rel}=315MeV/c

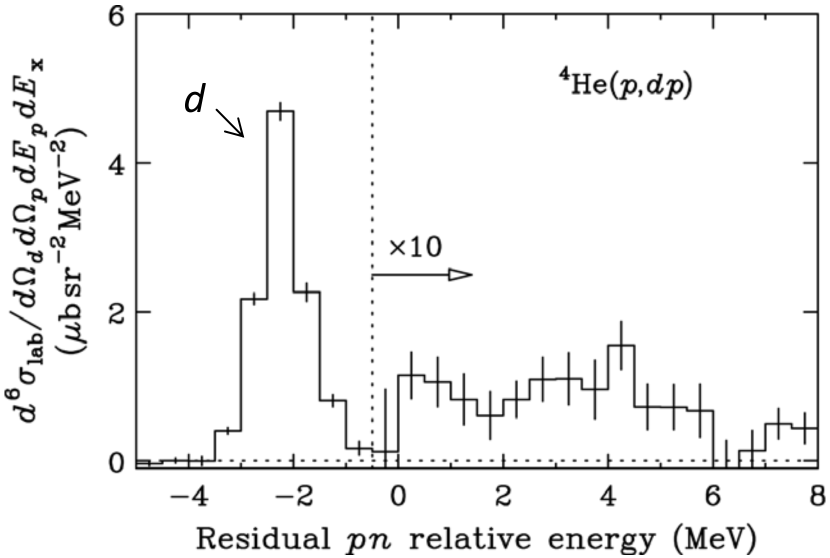






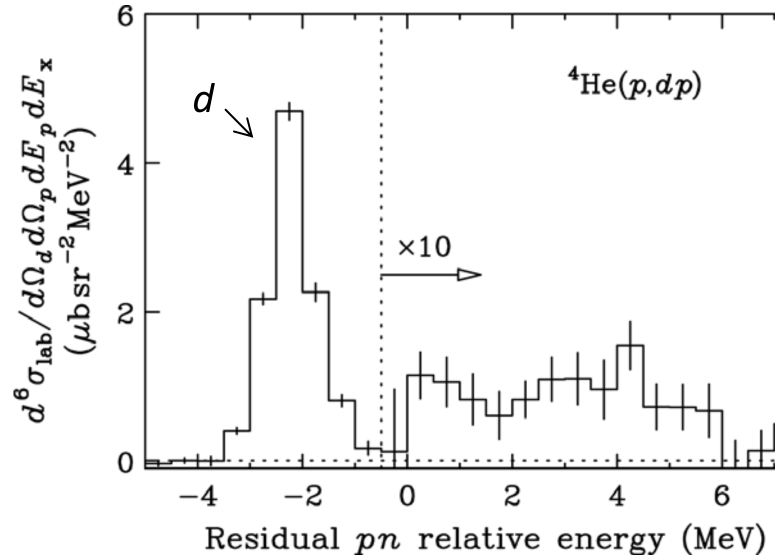
Preliminary spectrum

- Only one spectrum at P_{rel}=315MeV/c

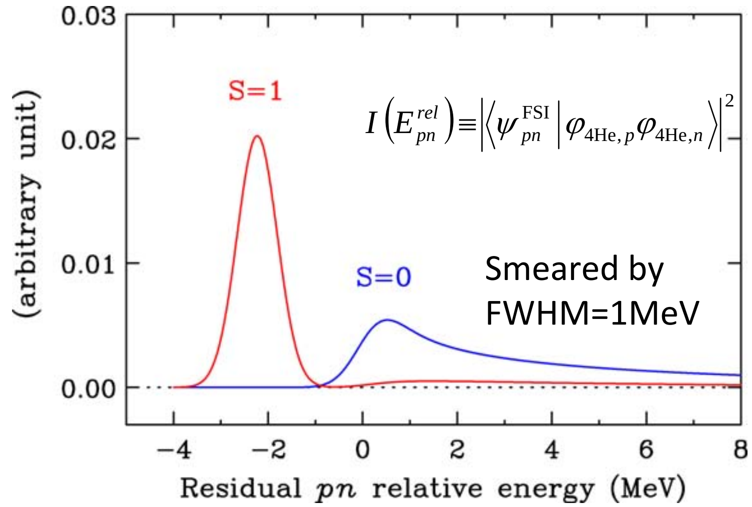


Ratio between the S=1 and S=0 contributions

- Only one spectrum at P_{rel}=315MeV/c



Fit



$$\sigma_{fi} \propto \left|\left\langle \psi_{pn}^{\rm FSI}\chi_p^{(f)}\chi_d^{(f)} \middle| V_{\rm int} \middle| \chi_p^{(i)}\varphi_{4{\rm He},p}^C\varphi_{4{\rm He},n}^C\varphi_{4{\rm He},p}\varphi_{4{\rm He},n} \right\rangle\right|^2$$

$$\approx \left|\left\langle \chi_p^{(f)}\chi_d^{(f)} \middle| V_{\rm int} \middle| \chi_p^{(i)}\varphi_{4{\rm He},p}^C\varphi_{4{\rm He},n}^C \right\rangle\right|^2 \left|\left\langle \psi_{pn}^{\rm FSI} \middle| \varphi_{4{\rm He},p}\varphi_{4{\rm He},n} \right\rangle\right|^2$$

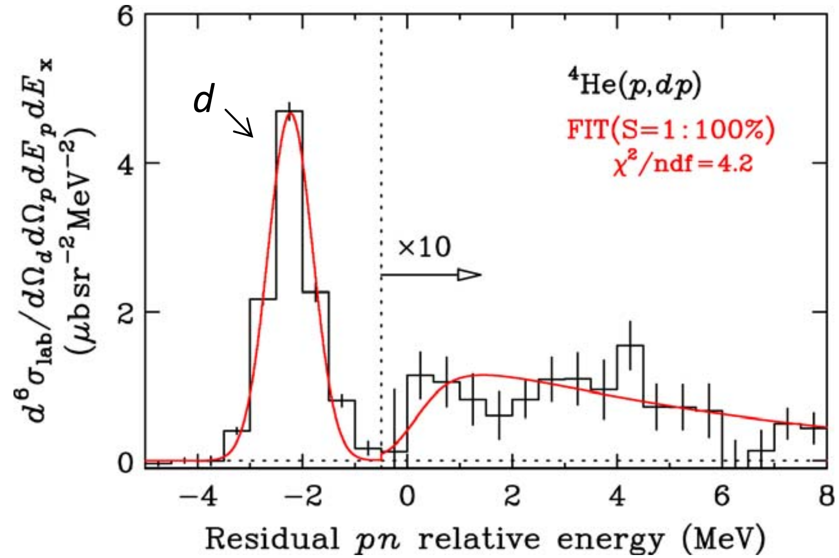
Calculation $\left|\left\langle \psi_{pn}^{\rm FSI} \middle| \varphi_{4{\rm He},p}\varphi_{4{\rm He},n} \right\rangle\right|^2$

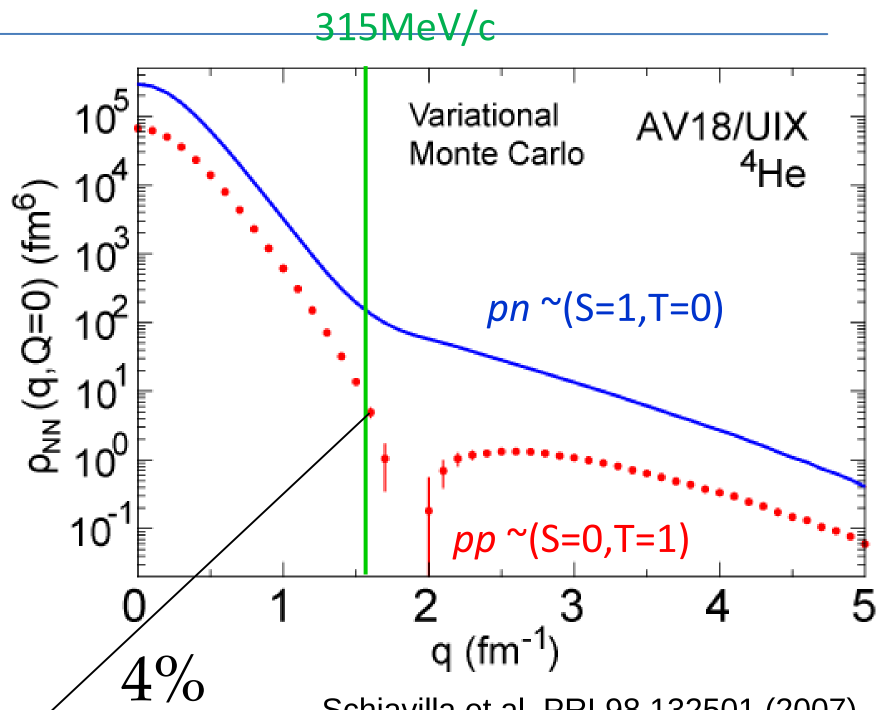
$\left|\psi_{pn}^{\rm FSI}\right\rangle$: pn wave function calculated by using NN potential (AV18)
[Continuum-discretization for Erel>0]

$\left|\varphi_{4{\rm He},p}\right\rangle$, $\left|\varphi_{4{\rm He},n}\right\rangle$: Gaussian with the same r.m.s. as $\sqrt{\rho_c(r)}$

Ratio between the S=1 and S=0 contributions

- Only one spectrum at P_{rel}=315MeV/c





Schiavilla et al. PRL98,132501 (2007)

RESULT

- S=1 : **100** (+0/−2) %
- S=0 : **0** (+2/−0) %

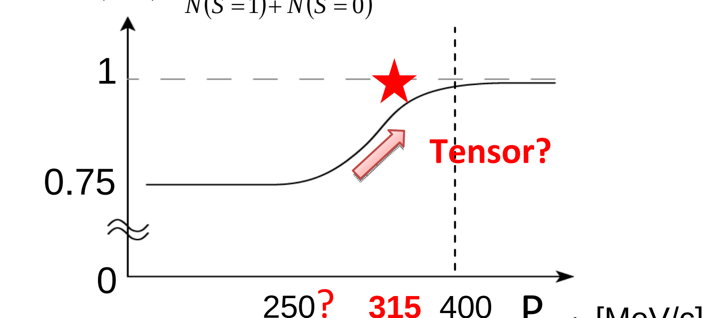
χ^2/ndf=4.2 [prelim.]

" Dominance of S=1 suggests strong tensor correlation at P_{rel}=315MeV/c. "

NEXT STEP

momentum dependence

$$R(S=1)=\frac{N(S=1)}{N(S=1)+N(S=0)}$$

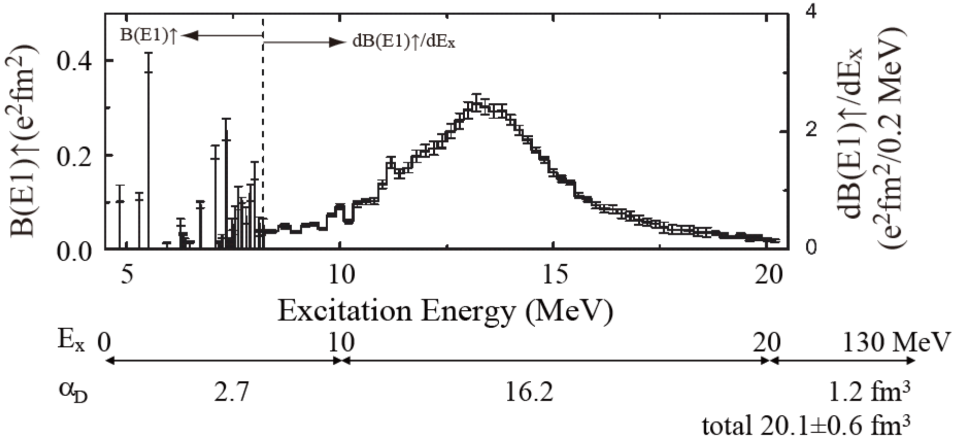


Mass Dependence

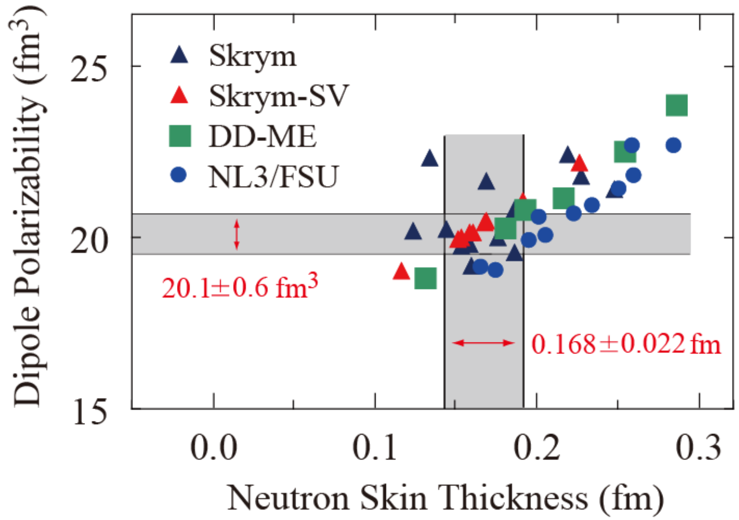
E1 Response of ^{208}Pb
and
Symmetry Energy of the Nuclear EOS

Complete B(E1) Distribution of ^{208}Pb
Determined by Coulomb Excitation by (p,p') at Forward Angles

AT et al., PRL107, 062502(2011)



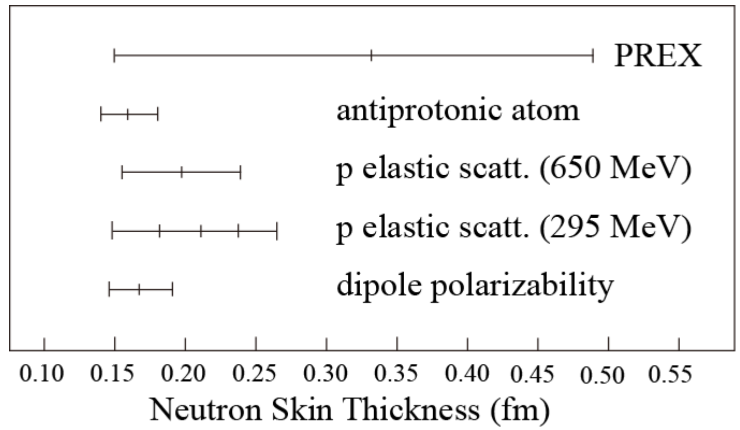
J. Piekarewicz, et al., PRC85, 041302(2012)



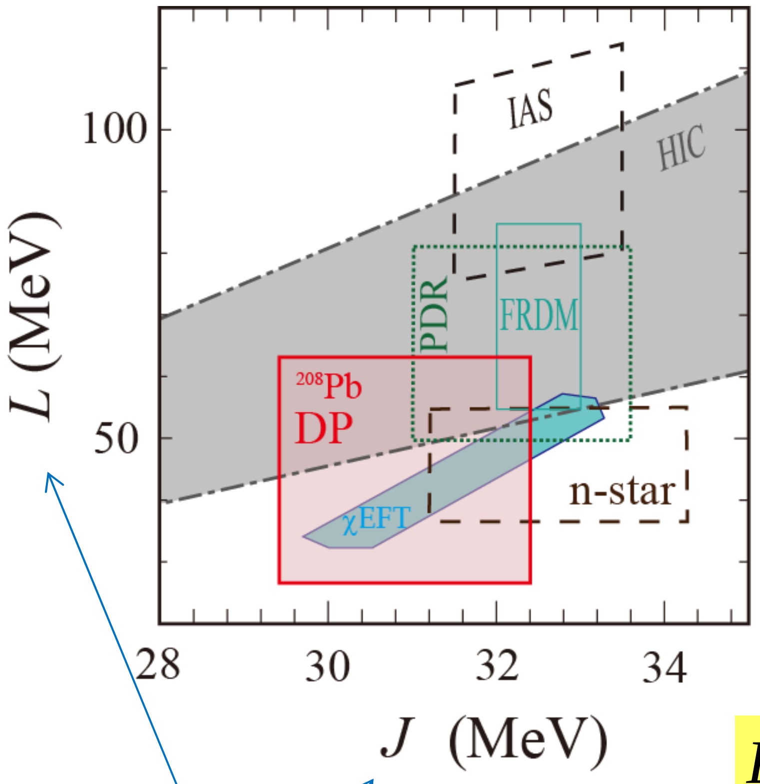
Dipole Polarizability

$$\alpha_D = \frac{\hbar c}{2\pi^2}\int \frac{\sigma_{abs}}{\omega^2}\, d\varpi = \frac{8\pi}{9}\int \frac{dB(E1)}{\omega}$$ **=20.1±0.6 fm³**

Neutron Skin Thickness of ^{208}Pb = **0.168±0.022 fm**
including model dependence



Determination of Symmetry Energy



M.B. Tsang *et al.*, PRC**86**, 015803 (2012).

I. Tews et al., arXiv:1206.0025v1

and this work (DP) L=45±18 MeV
J=30.9±1.5 MeV

Preliminary

DP: Dipole Polarizability
HIC: Heavy Ion Collision
PDR: Pygmy Dipole Resonance of ^{68}Ni and ^{132}Sn
IAS: Isobaric Analogue State
FRDM: Finite Range Droplet Model
(nuclear mass analysis)
n-star: Neutron Star Observation
χEFT: Chiral Effective Field Theory

$$L \propto P \propto R_{n-star}^4$$

barionic pressure

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,0) + S(\rho)\delta^2 + \ldots$$

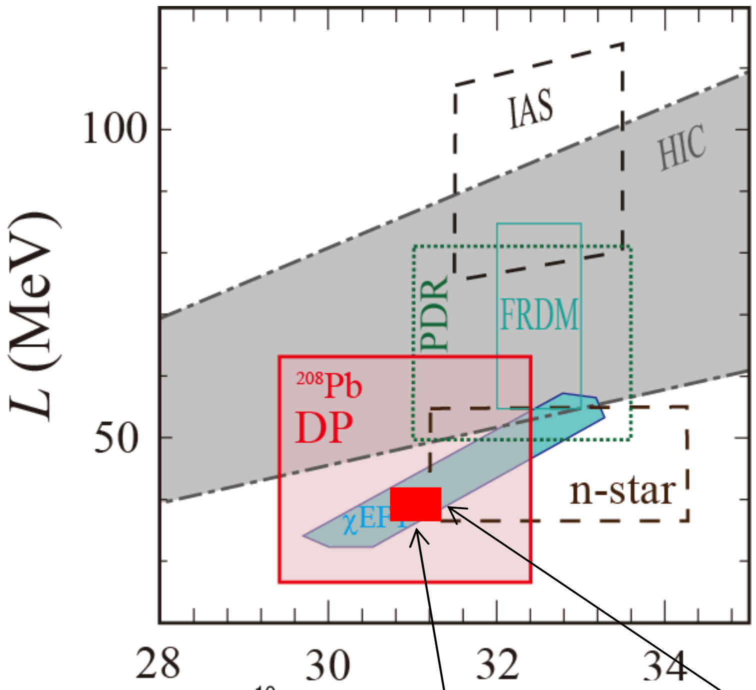
$$S(\rho) = J + \frac{L}{3\rho_0}(\rho-\rho_0) + \frac{K_{sym}}{18\rho_0^2}(\rho-\rho_0)^2 + \ldots$$

$$\rho(r) = \rho_n(r) + \rho_p(r)$$

$$\delta(r) = \frac{\rho_n(r) - \rho_p(r)}{\rho_n(r) + \rho_p(r)}$$

Saturation Density
~0.16 fm^{-3}

Determination of Symmetry Energy



M.B. Tsang *et al.*, PRC**86**, 015803 (2012).

I. Tews et al., arXiv:1206.0025v1

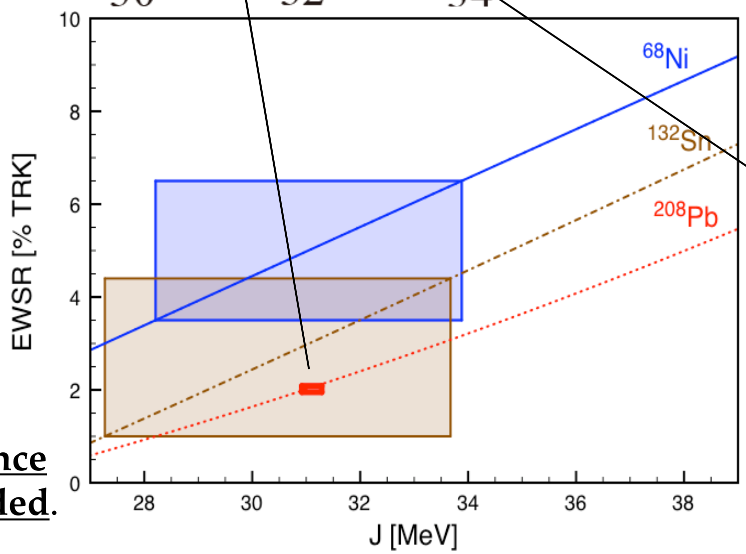
and this work (DP) L=45±18 MeV
J=30.9±1.5 MeV

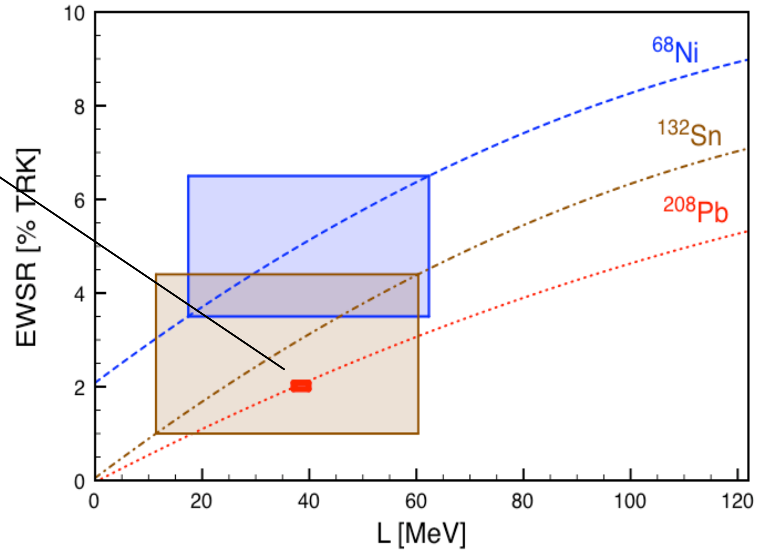
Preliminary

DP: Dipole Polarizability
HIC: Heavy Ion Collision
PDR: Pygmy Dipole Resonance of ^{68}Ni and ^{132}Sn
IAS: Isobaric Analogue State
FRDM: Finite Range Droplet Model
(nuclear mass analysis)
n-star: Neutron Star Observation
χEFT: Chiral Effective Field Theory

PDR EWSR
RQRPA
by N. Paar
@COMEX4

Model dependence should be included.





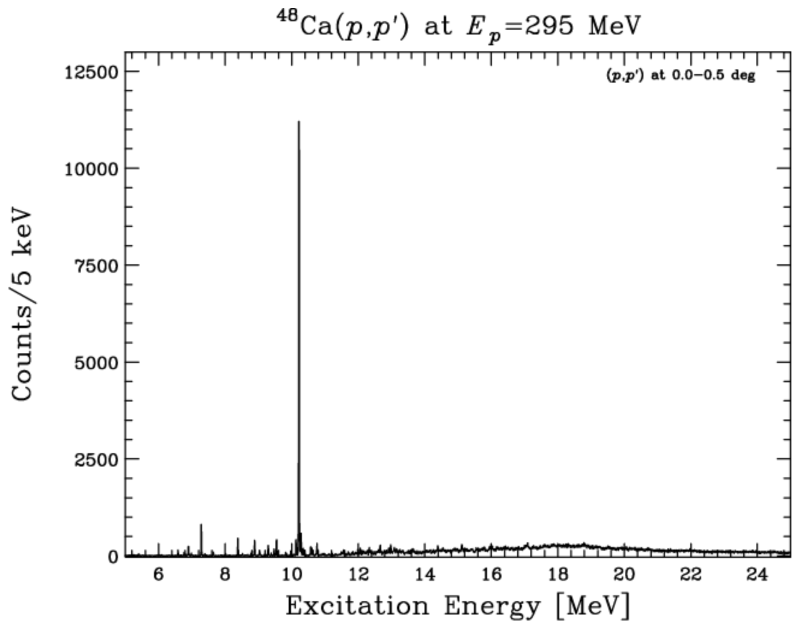
Contents

1. Tensor Correlation in Nuclear Ground States

● Spin-*M1* Excitation and Sum-Rule
(H. Matsubara *et al*.,)

●Channel-Spin *S* of Correlated *p*-*n* Pairs in ^{4}He
(K. Miki *et al*.,)

2. E1 Response of ^{208}Pb and Symmetry Energy
of the Nuclear EOS



Thank you for your attention!