

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

H. Matsubara¹ and A. Tamii²

¹*Nishina Center, RIKEN*

²*RCNP, Osaka University*

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1. Tensor Correlation in Nuclear Ground States

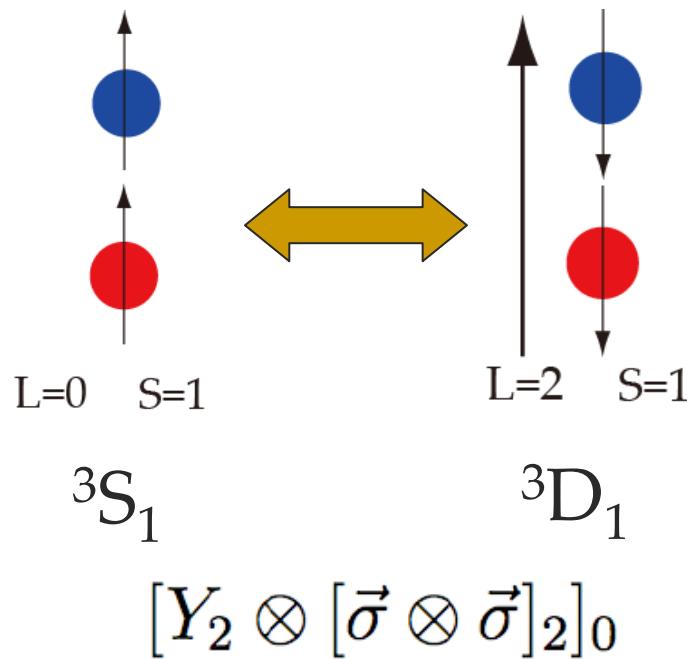
- Spin- $M1$ Excitation and Sum-Rule
(H. Matsubara *et al.*,)

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

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

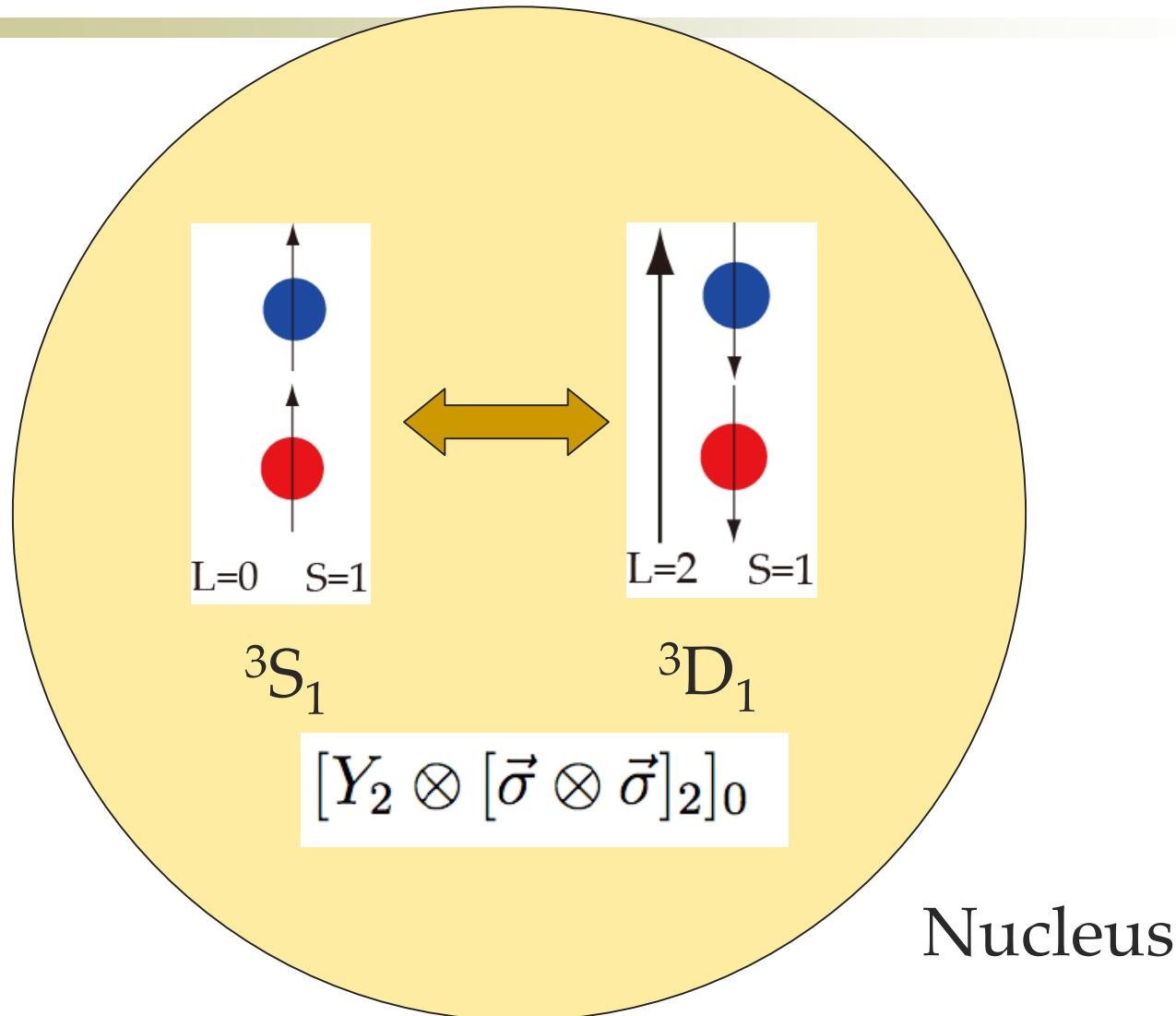
Spin- $M1$ Excitation and Sum-Rule

Deuteron



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

Tensor Correlation in Nuclear Ground States

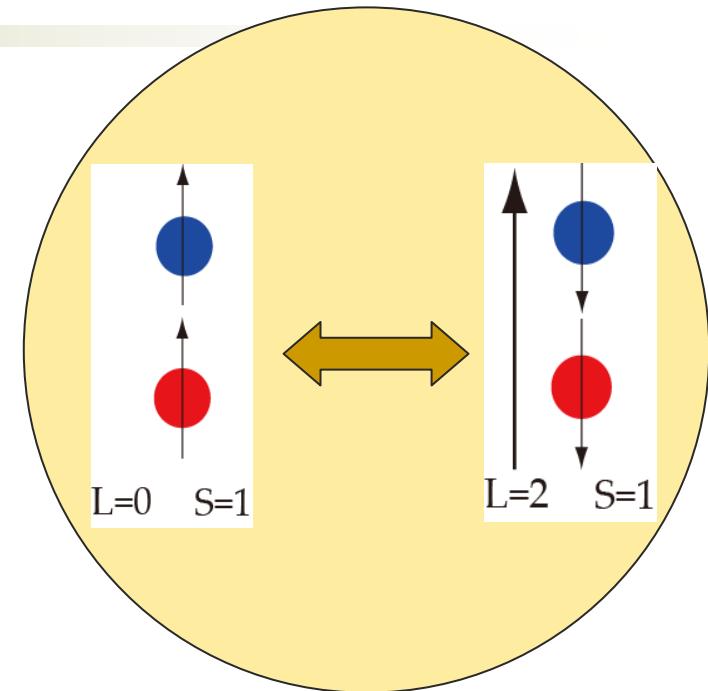


The same mixing should exist in nuclear ground states.
“Tensor Correlation”

Proton and Neutron Spin Operators

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

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



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.

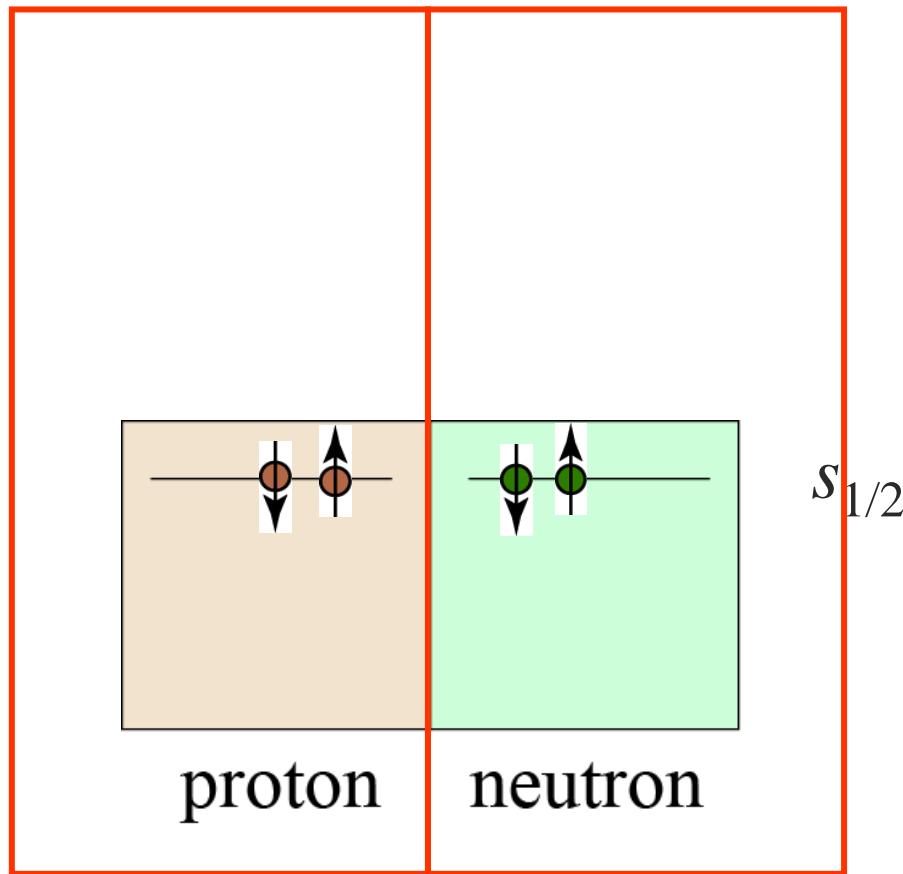
$$\vec{S}_p + \vec{S}_n \equiv \sum_{i=1}^A \frac{1}{2} \vec{\sigma}_i = \frac{1}{2} \vec{\sigma}$$

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

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

Tensor Correlation in Particle-Hole Configurations

Simplest case: ${}^4\text{He}$



Consideration with
single particle orbits

uncorrelated
ground state

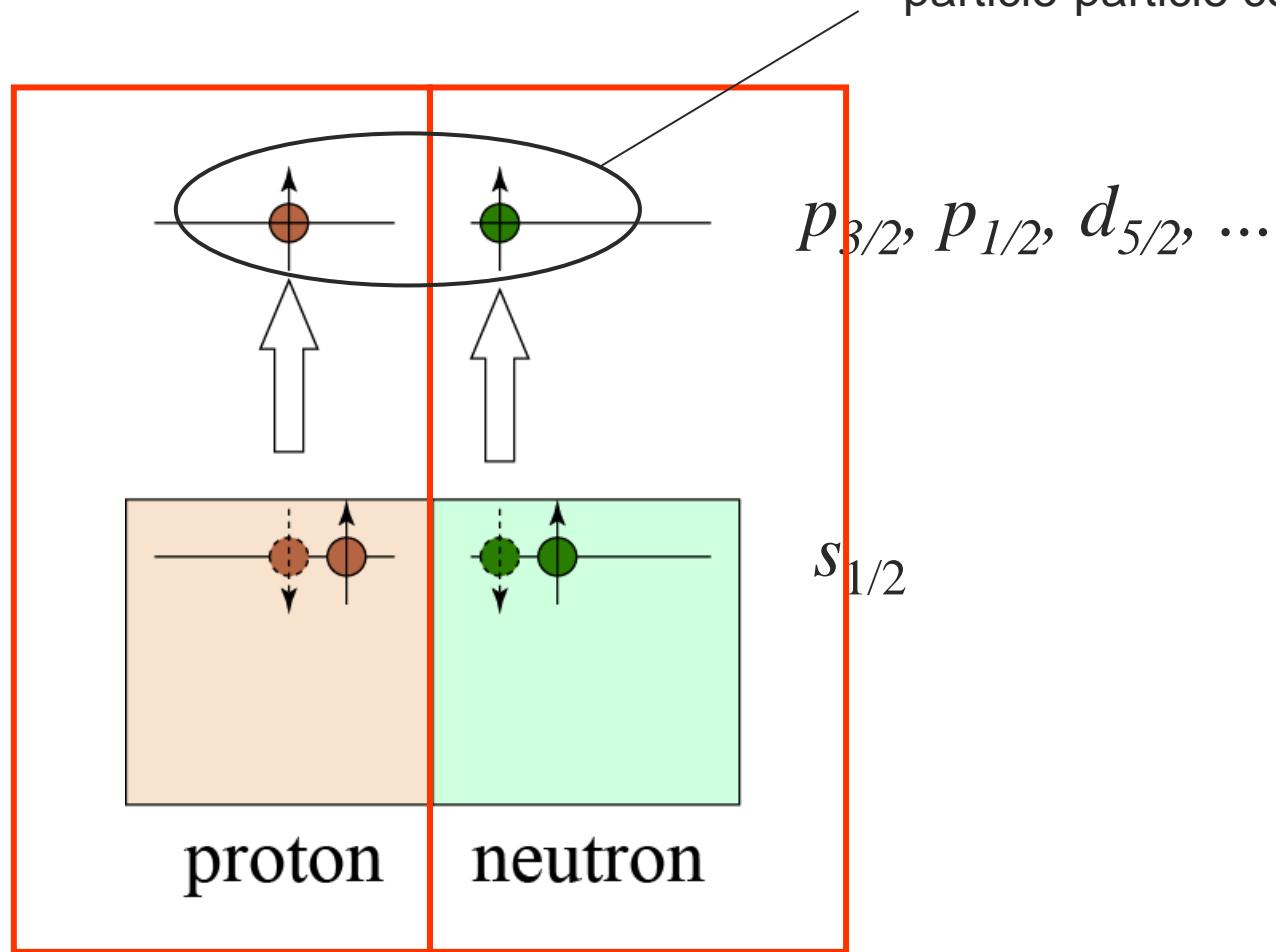
$$\langle \vec{S}_p \rangle = 0 \quad \langle \vec{S}_n \rangle = 0$$

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

Tensor Correlation in Particle-Hole Configurations

Simplest case: ${}^4\text{He}$

particle-particle coupling



$$\langle \vec{S}_p \rangle \neq 0 \quad \langle \vec{S}_n \rangle \neq 0$$

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

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

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

- large amplitude
- Important channel for pionic correlation

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

Positive $\langle \vec{S}_p \cdot \vec{S}_n \rangle$ is a signature of the tensor correlation

Precise calculation of ^4He with realistic NN interactions

by W. Horiuchi

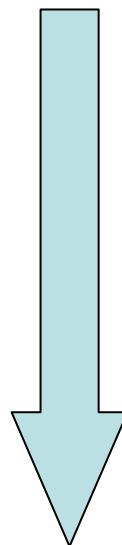
Spin matrix elements of the ^4He ground state

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

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

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

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

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

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

closure approximation

IV spin-M1 transition matrix elements

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

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: $0^+; T=0$

						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 0.102s	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 93.2581	
						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 9.3365	
						Cl 29 0.0316s	Cl 30 0.0474s	Cl 31 0.15s	Cl 32 0.298s	Cl 33 0.32s	Cl 34 22m	Cl 35 75.78	
						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 0.498s	P 30 100	P 31 14.26s	
						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 0.059s	Al 23 0.47s	Al 24 2.053s	Al 25 7.183s	Al 26 4e+05v	Al 27 100	
						Mg 19 0.0135s	Mg 20 0.0988s	Mg 21 0.122s	Mg 22 3.875s	Mg 23 11.32s	Mg 24 78.99	Mg 25 100	
						Na 18 0.039s	Na 19 0.416s	Na 20 0.4479s	Na 21 0.4479s	Na 22 2.682v	Na 23 100	Na 24 14.96s	
						Ne 16 0.1092s	Ne 17 1.672s	Ne 18 17.22s	Ne 19 90.48s	Ne 20 0.27	Ne 21 0.27	Ne 22 9.25	
						F 15 1e-19s	F 16 0.75m	F 17 1.39s	F 18 99.757	F 19 100	F 20 11.16s	F 21 4.158s	
C 8	C 9 0.1265s	C 10 19.25s	C 11 0.00058s	C 12 99.93	O 13 1.177m	O 14 2.037m	O 15 99.757	O 16 0.036	O 17 0.205	O 18 26.91s	O 19 13.51s	O 20 0.193s	
	N 11 0.011s	N 12 99.655m	N 13 99.632	N 14 0.368	N 15 7.13s	N 16 4.173s	N 17 0.624s	N 18 0.304s	N 19 0.142s	N 20 0.095s	N 21 0.21s	N 22 0.024s	
	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 0.00509s	B 17 0.00292s	B 18 0.00292s	B 19 0.00292s	C 20 0.0141s
	Be 7 5.12d	Be 8 6.7e-17s	Be 9 100	Be 10 1.51e+06	Be 11 13.81s	Be 12 0.0215s	Be 13 0.0215s	Be 14 0.00848s	Li 6 7.59	Li 7 92.41	Li 8 0.838s	Li 9 0.1783s	Li 11 0.0085s
	He 3 0.000137	He 4 99.9999			He 6 0.81s		He 8 0.119s						
H 1 99.9885	H 2 0.0115	H 3 12.33v											
	n 10.23m												

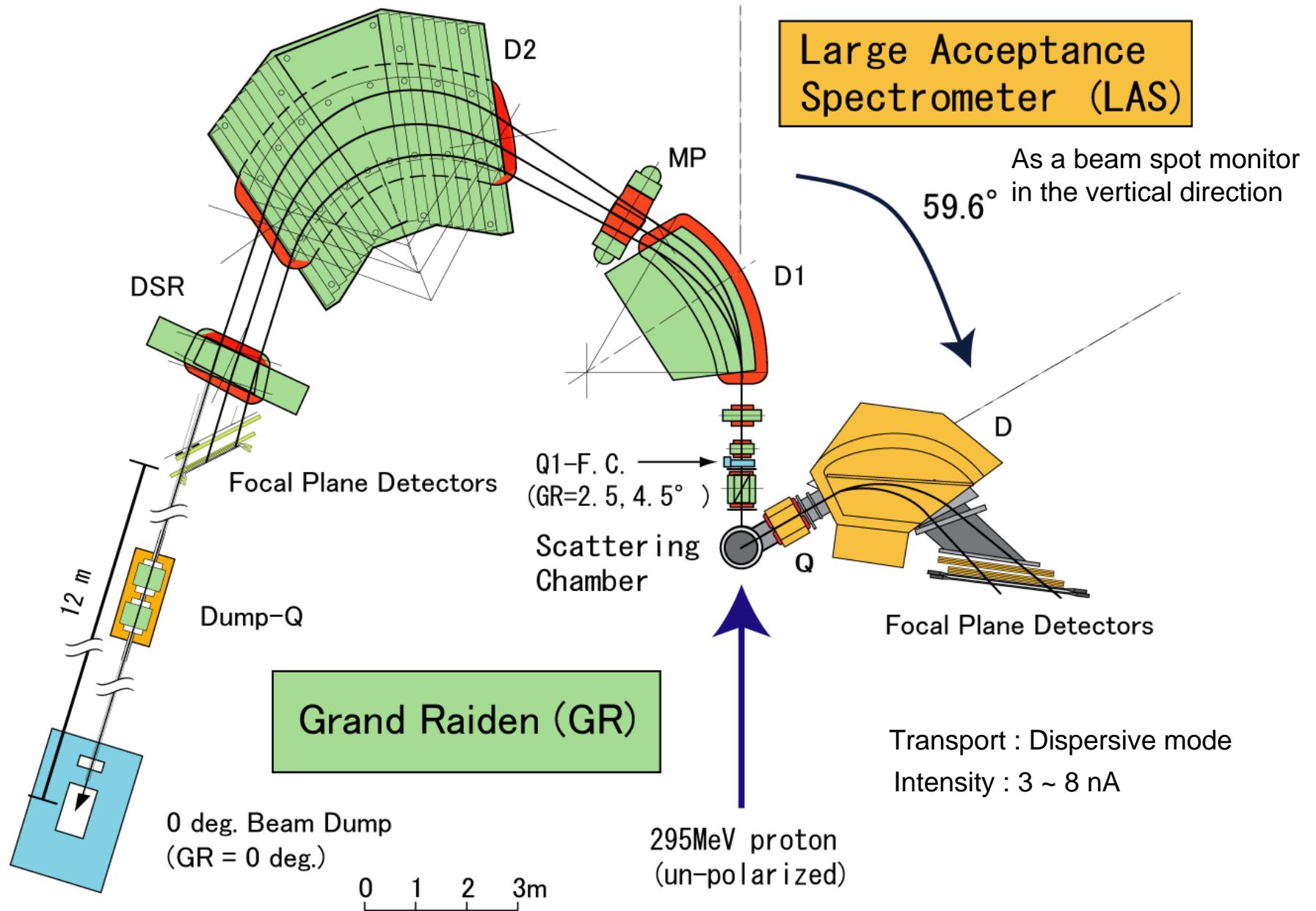
We focus on these nuclei.

Stable self-conjugate even-even nuclei:

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

We measured (p,p') for all the above nuclei except ${}^4\text{He}$.

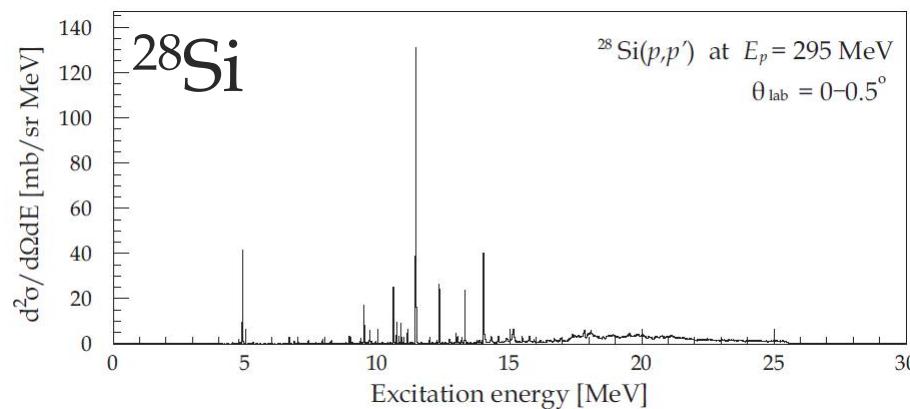
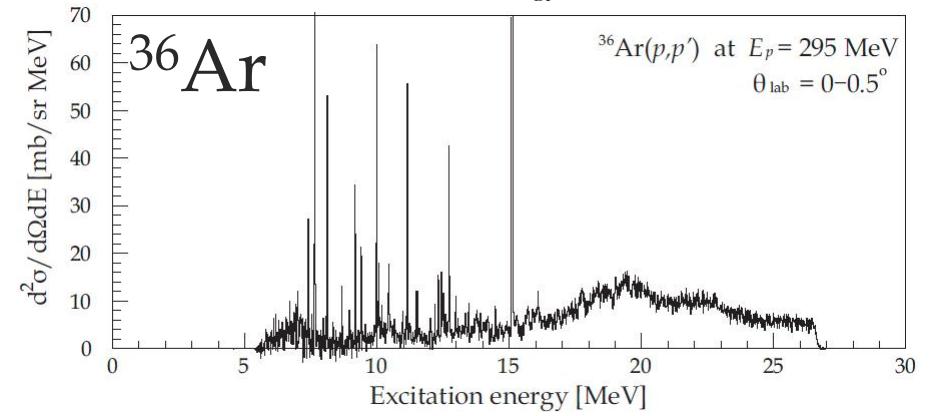
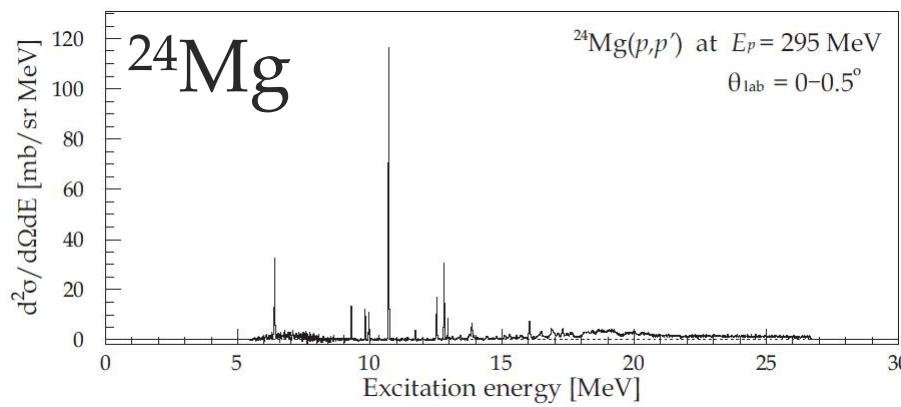
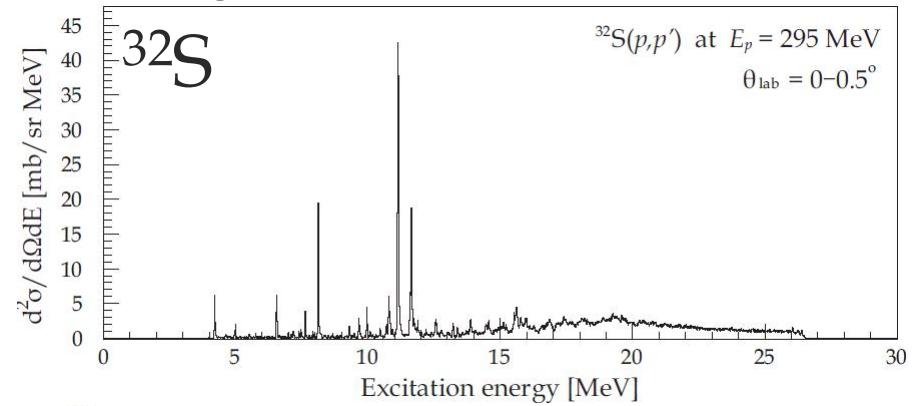
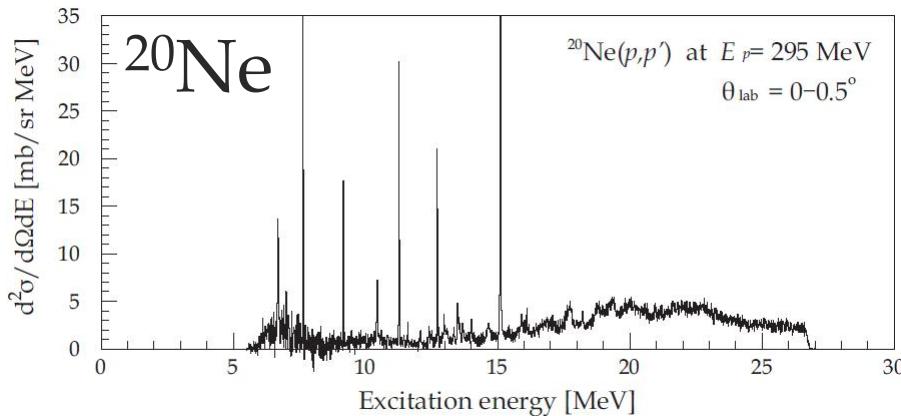
Spectrometer Setup for 0-deg (p, p') at RCNP



(p,p') Spectra at $E_p = 295$ MeV

measured at 0-15 deg.

RCNP-E299

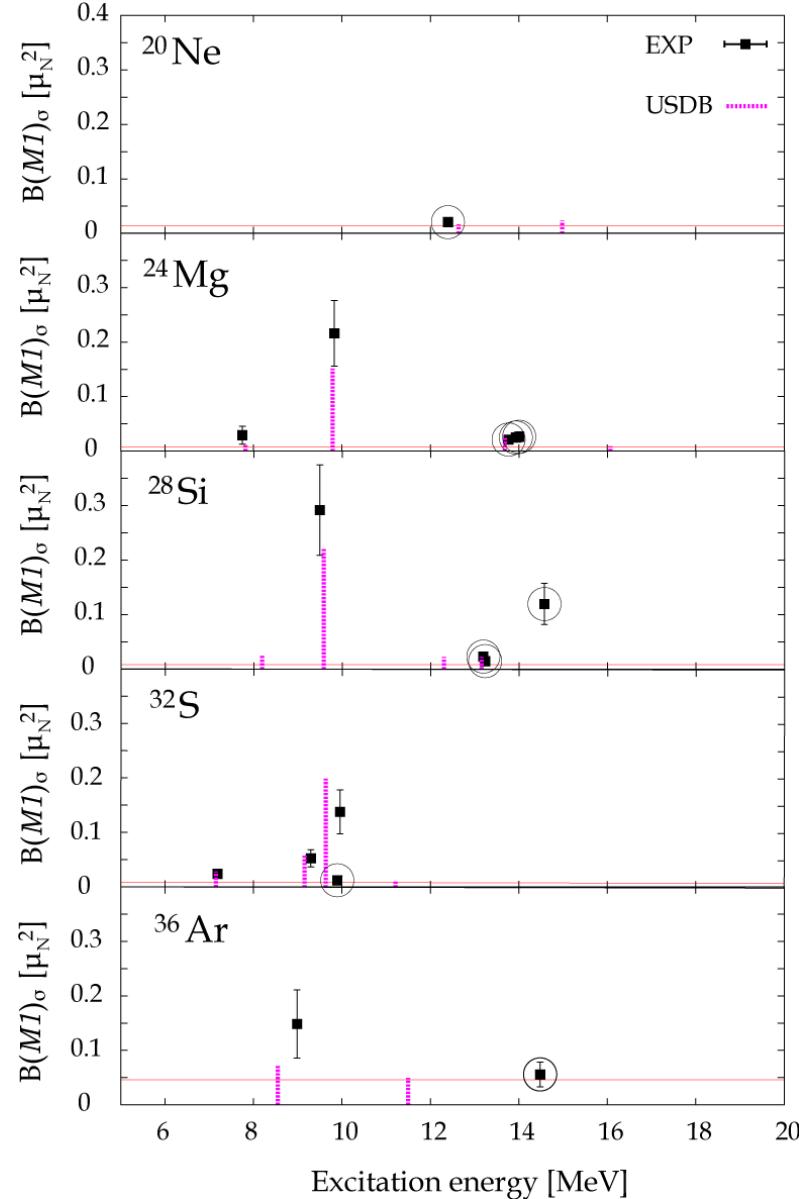


IS/IV 1^+ states were identified from angular distribution for each of IS and IV transitions.
 The cross sections at the most forward angles have been converted to the spin-M1 strengths.

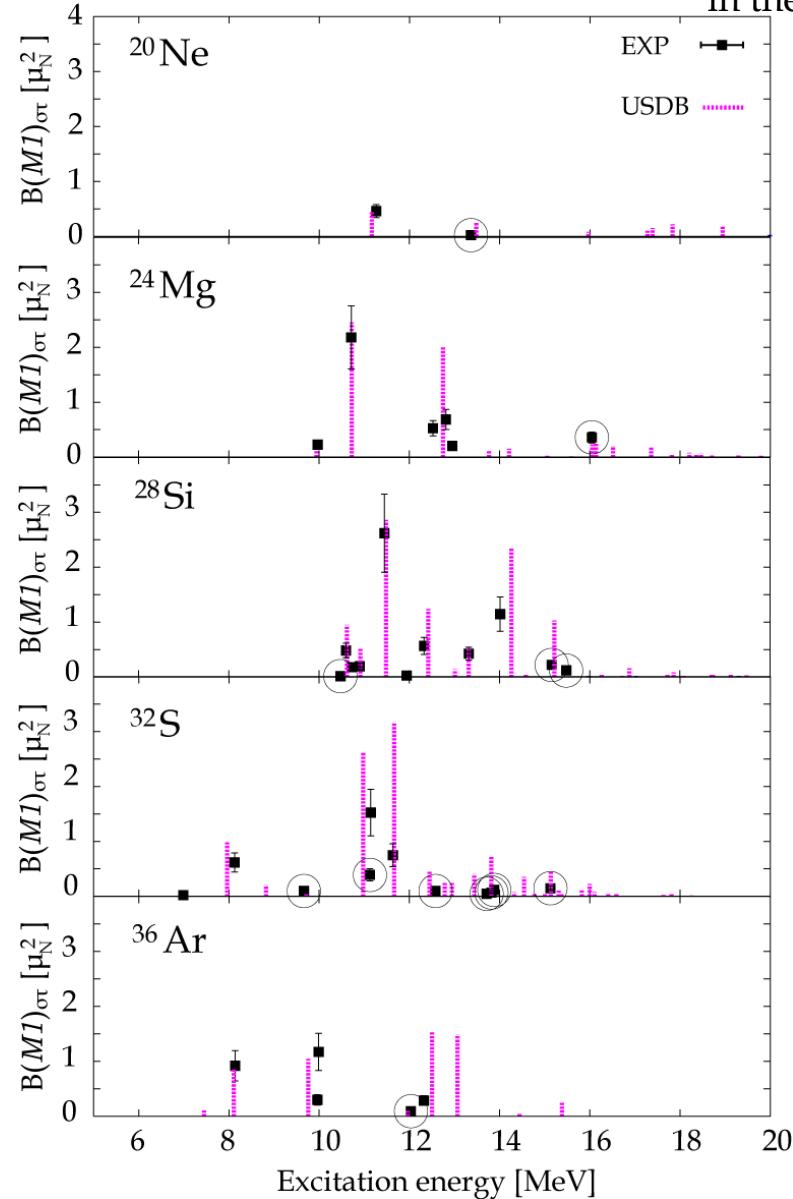
Spin-M1 Strength Distribution

○ shows tentative
1⁺ assignment

IS



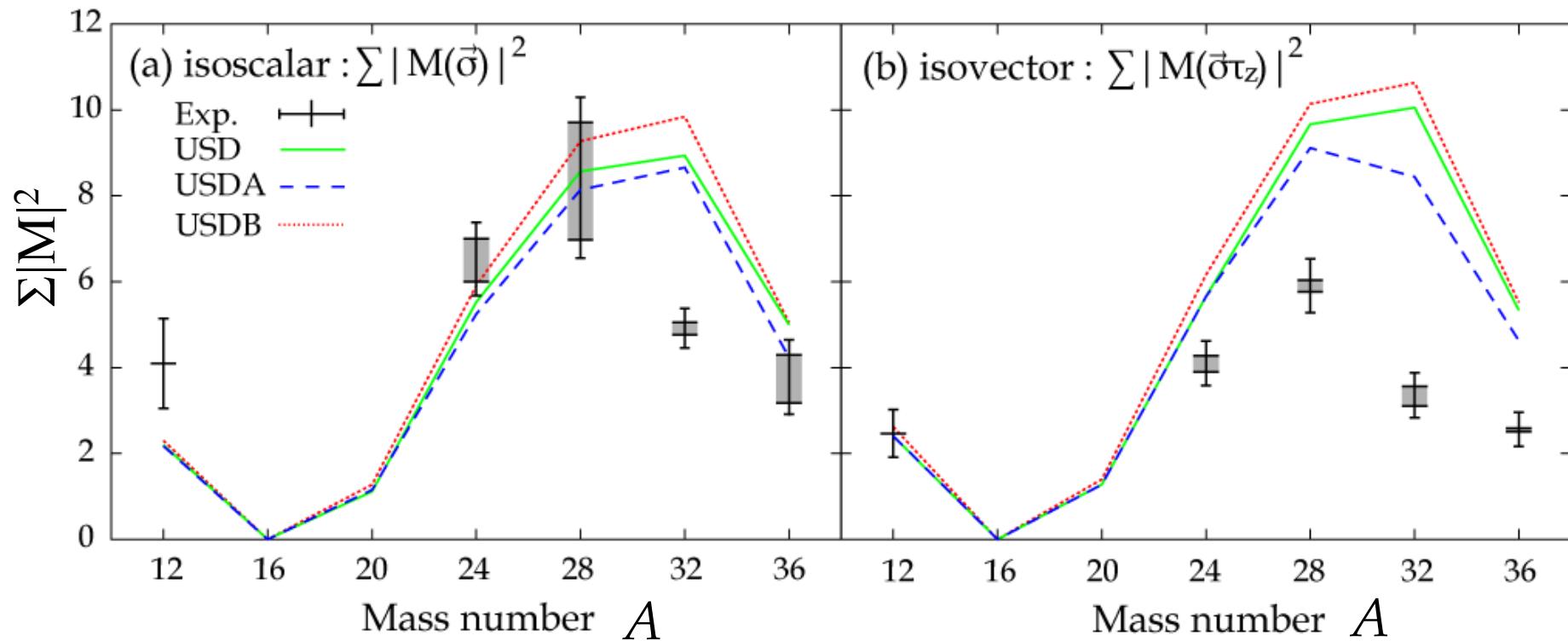
IV



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

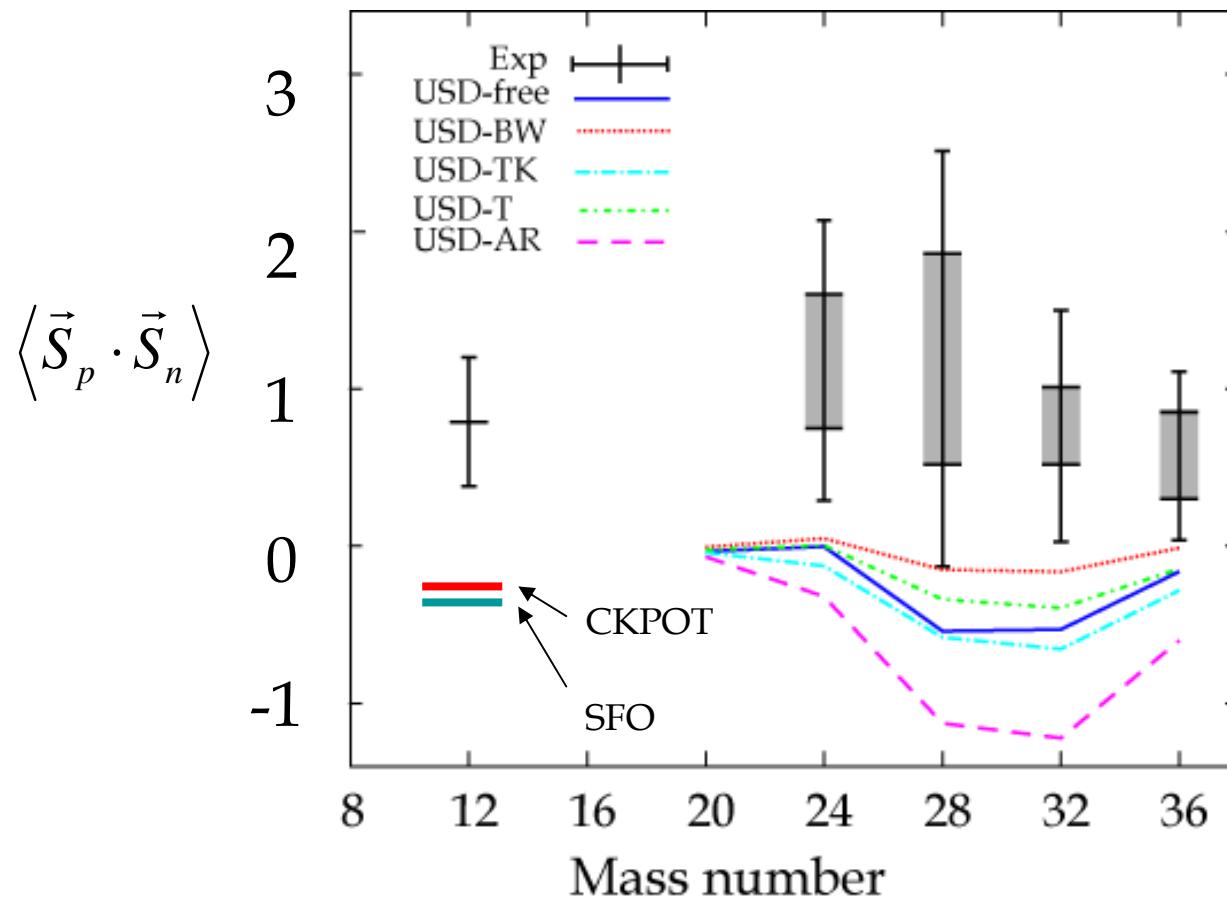
IS/IV Spin-M1 Matrix Elements

- 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 ${}^4\text{He}$ ground state

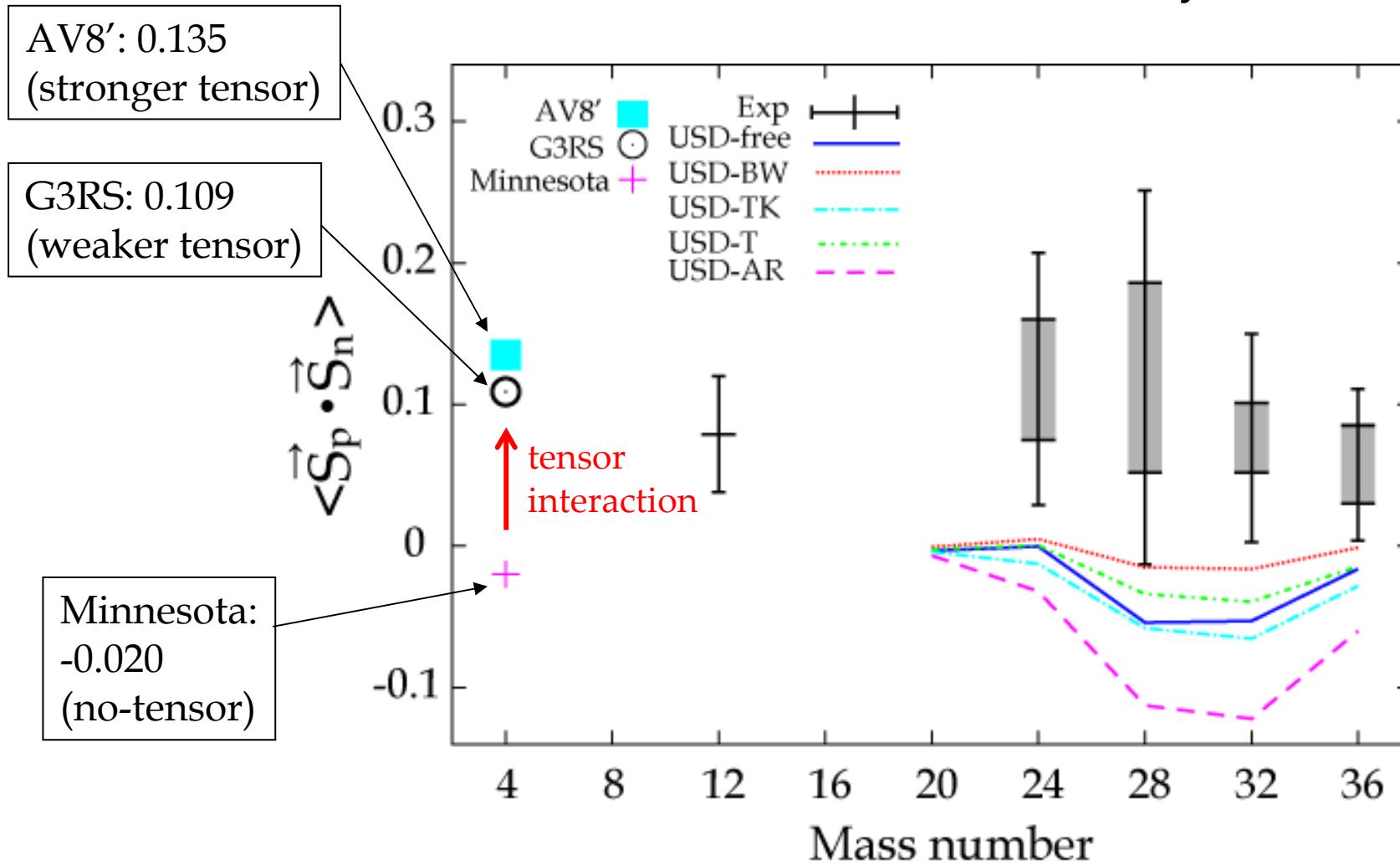
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$$\vec{S} = \vec{S}_p + \vec{S}_n$$

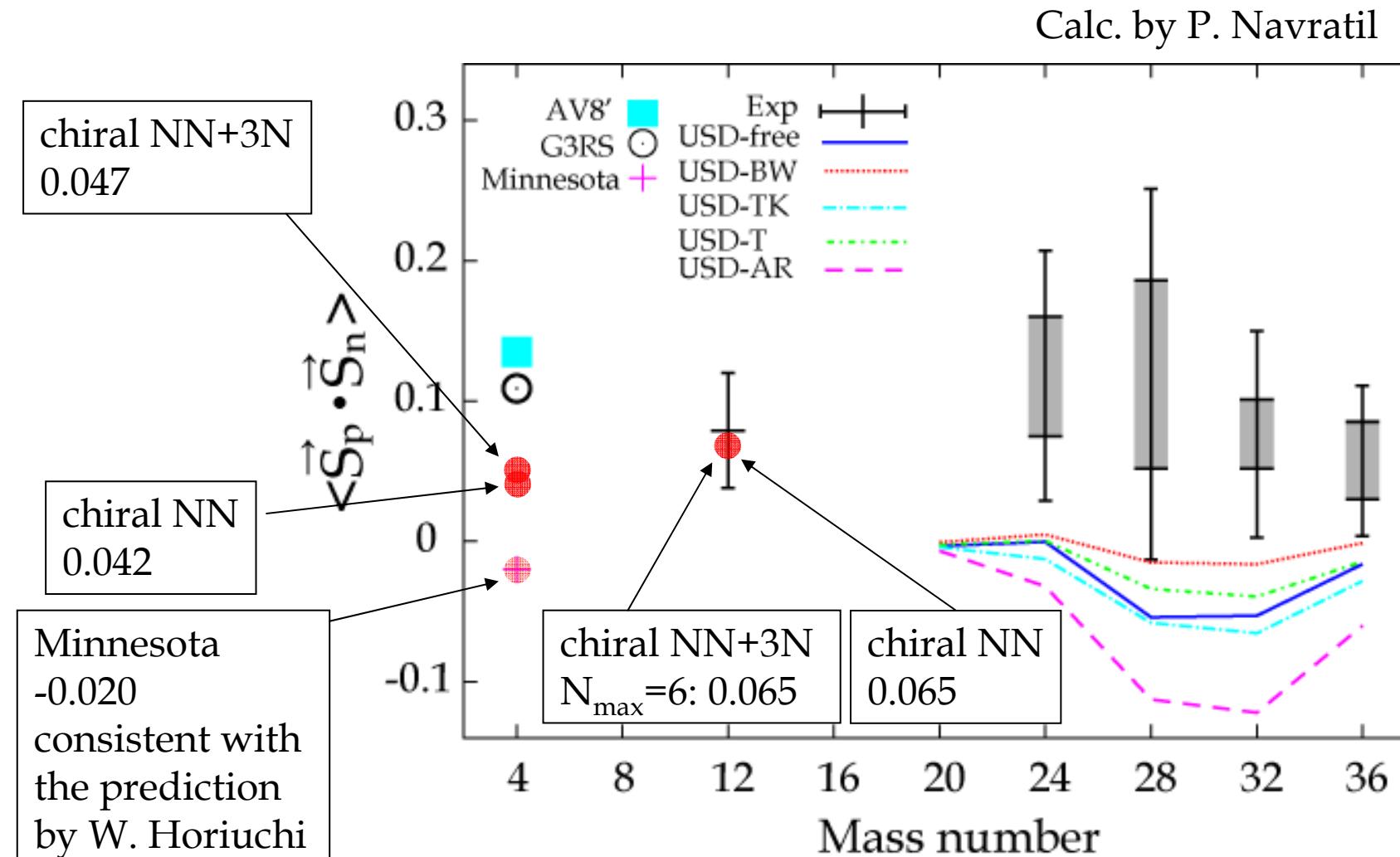
Y. Suzuki, W. Horiuchi et al., FBS42, 33(2007)
H. Feldmeier, W. Horiuchi et al., PRC84, 054003(2011)

Calculation with Modern Realistic Interactions for ^4He

^4He calc. by W. Horiuchi



Predictions by Non-Core Shell Model



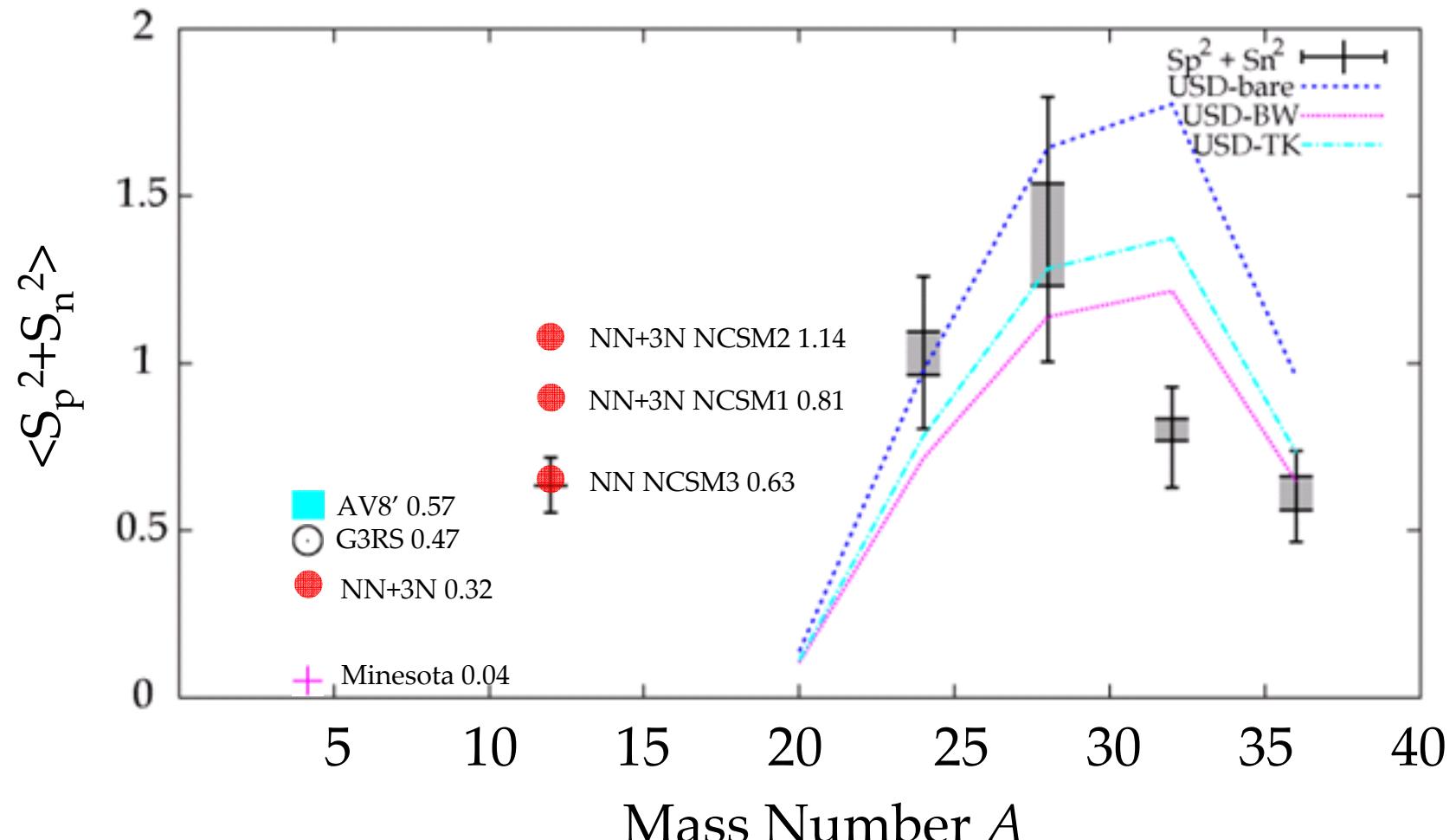
^4He : Entem-Machleidt N3LO 500 NN, N2LO 500 3N

^{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)

$$\langle S^2 \rangle = \langle S_p^2 + S_n^2 \rangle$$



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 ${}^4\text{He}$

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

Tensor operator has a characteristic dependence on spin.

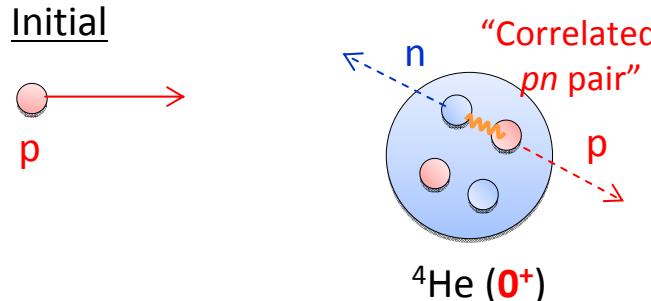
$$V_T = V_T(r) \left\{ 3 \frac{(\vec{\sigma}_p \cdot \vec{r})(\vec{\sigma}_n \cdot \vec{r})}{r^2} - \vec{\sigma}_p \cdot \vec{\sigma}_n \right\}$$

Acts only on S=1.

Study of **channel spin S** of **correlated NN pair** must be essential.
“ We started from the study of ${}^4\text{He}$ because of its simplicity.”

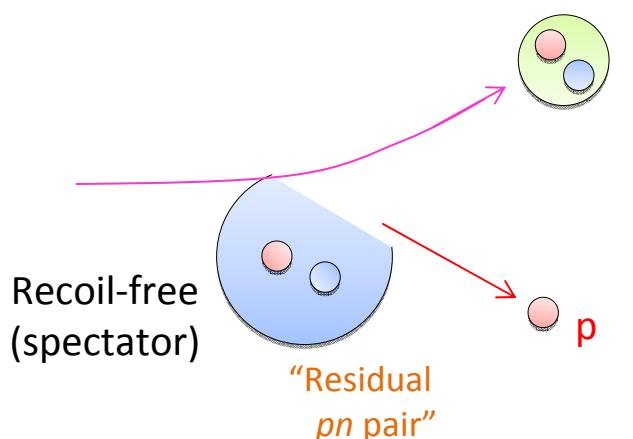
- Method : **(p,dp)** measurement

Initial



Final

Selective for high-momentum component



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

Residual
pn pair

$E_R^{\text{rel}} = 2.2 \text{ MeV}$

Deuteron State
S=1 ($J = 1^+$)

$0 \leq E_R^{\text{rel}} \leq 1 \text{ MeV}$

Continuum State
S=0 ($J = 0^+$)

Correlated
pn pair

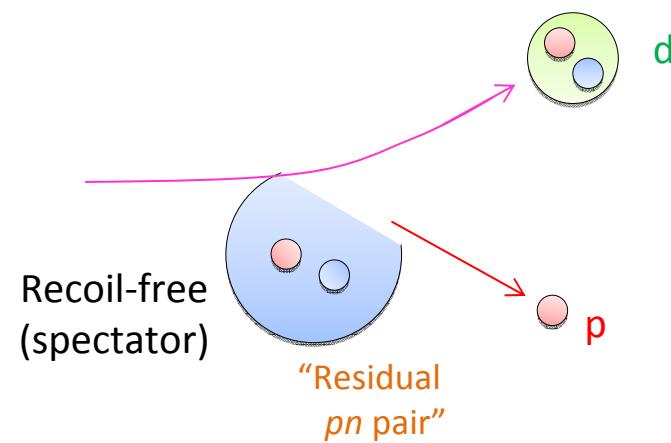
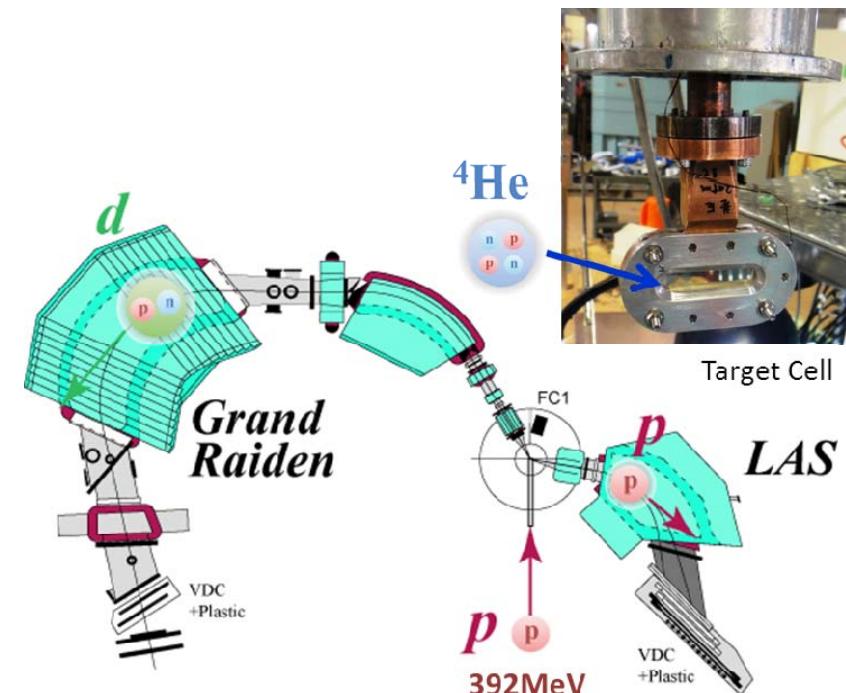
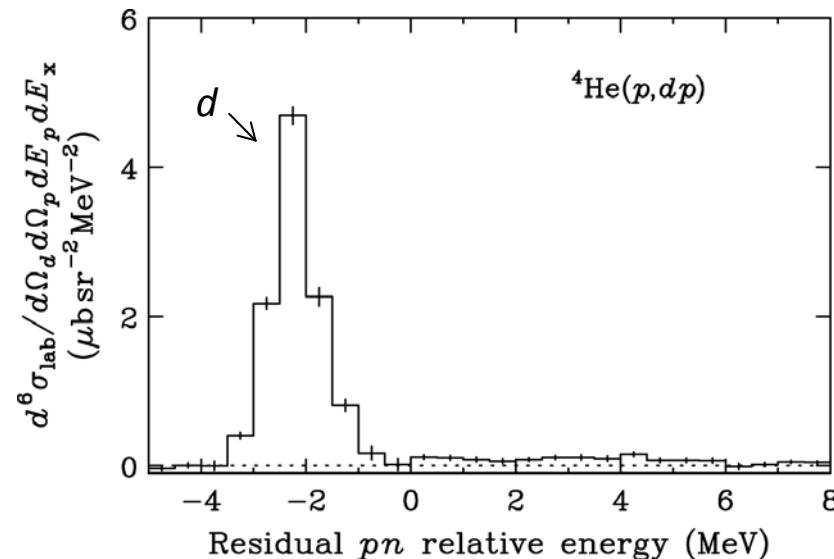
S=1

S=0

“ We can identify the spin of correlated pn pair ! ”

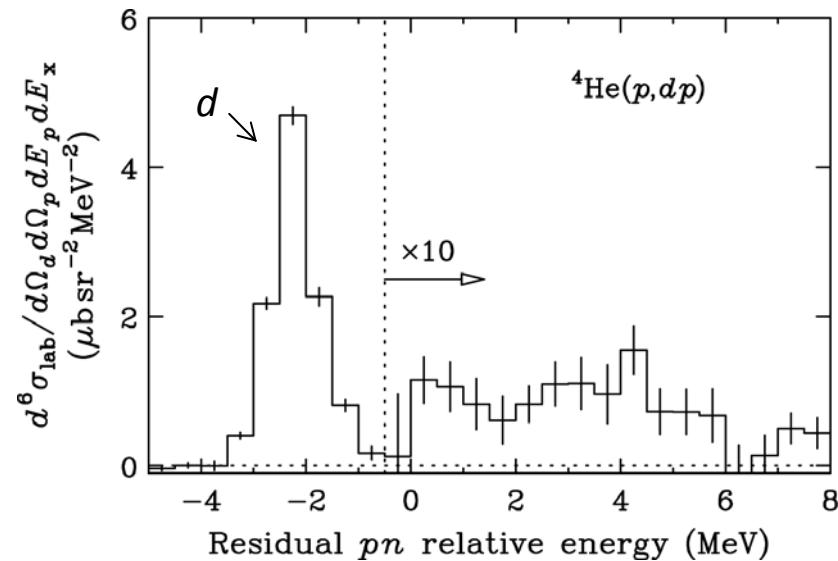
Preliminary spectrum

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



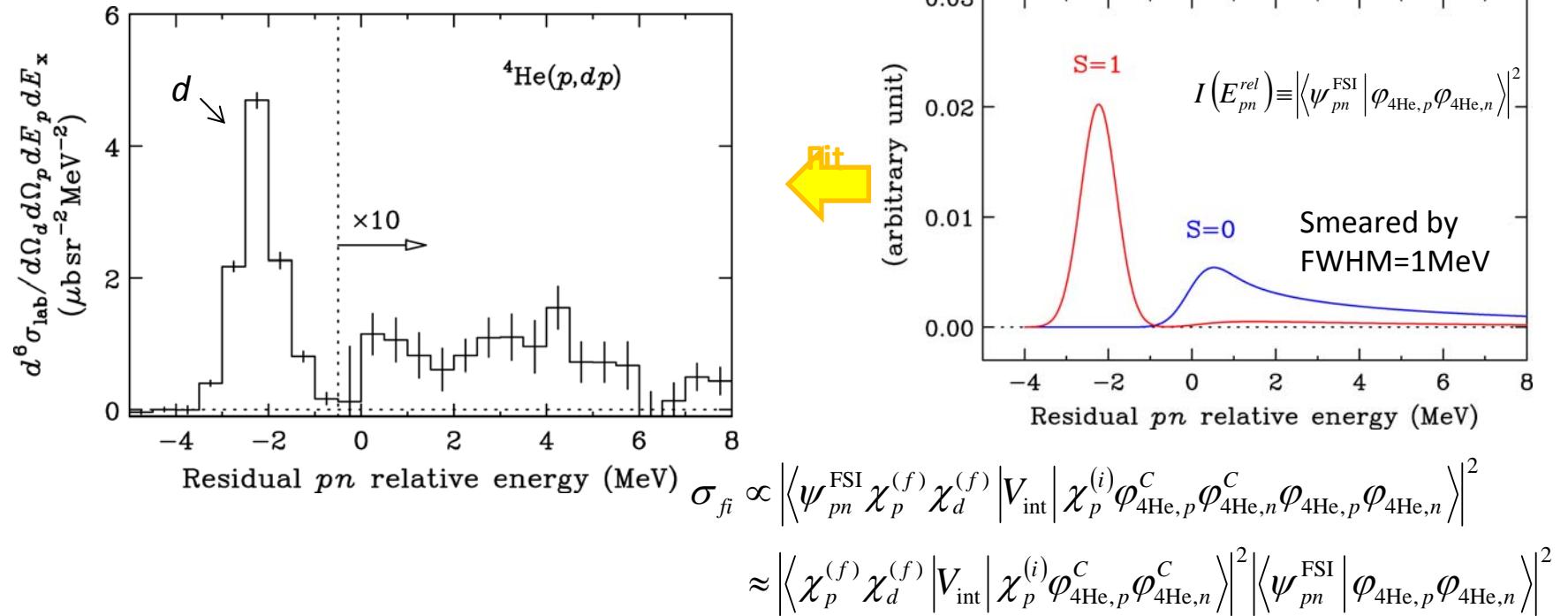
Preliminary spectrum

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



Ratio between the S=1 and S=0 contributions

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



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

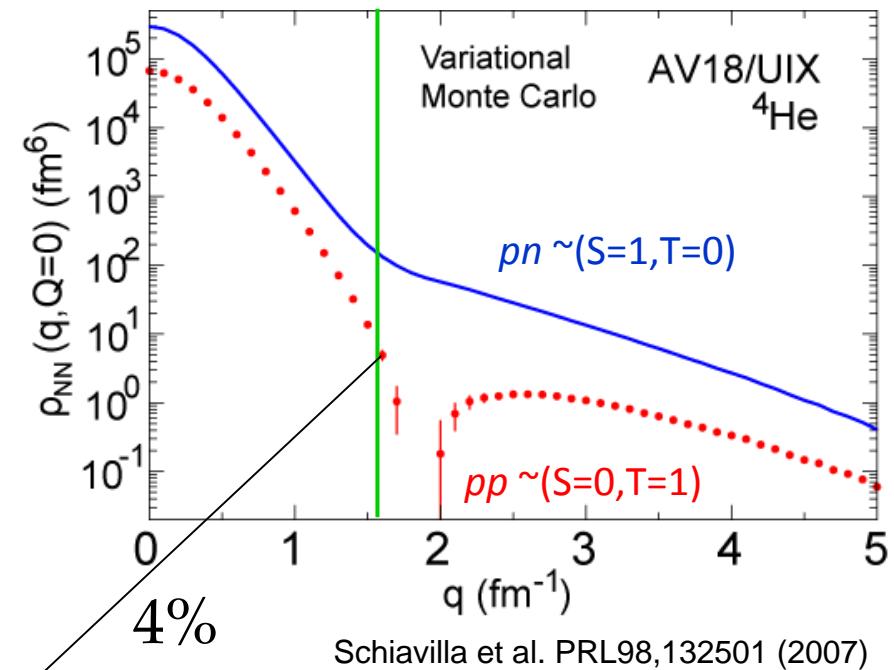
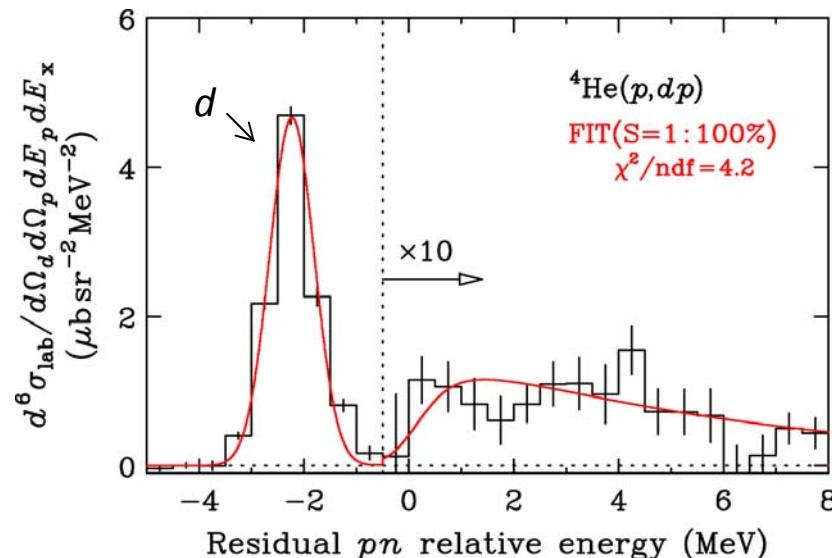
$|\psi_{pn}^{\text{FSI}}\rangle$: pn wave function calculated by using NN potential (AV18)
[Continuum-discretization for $E_{\text{rel}}>0$]

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

Ratio between the S=1 and S=0 contributions

315MeV/c

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



RESULT

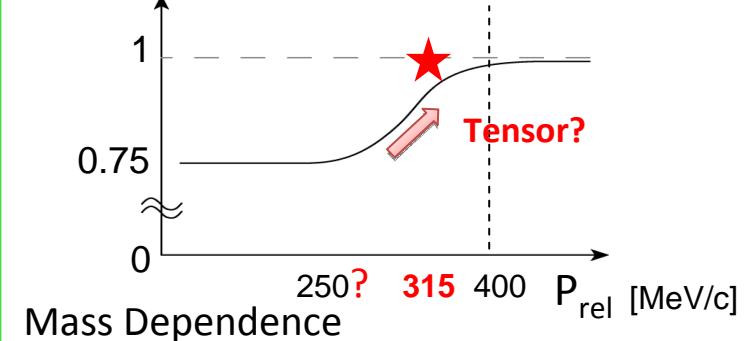
- $S=1 : 100 (+0/-2) \%$
- $S=0 : 0 (+2/-0) \%$
- $\chi^2/\text{ndf} = 4.2$ [prelim.]

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

NEXT STEP

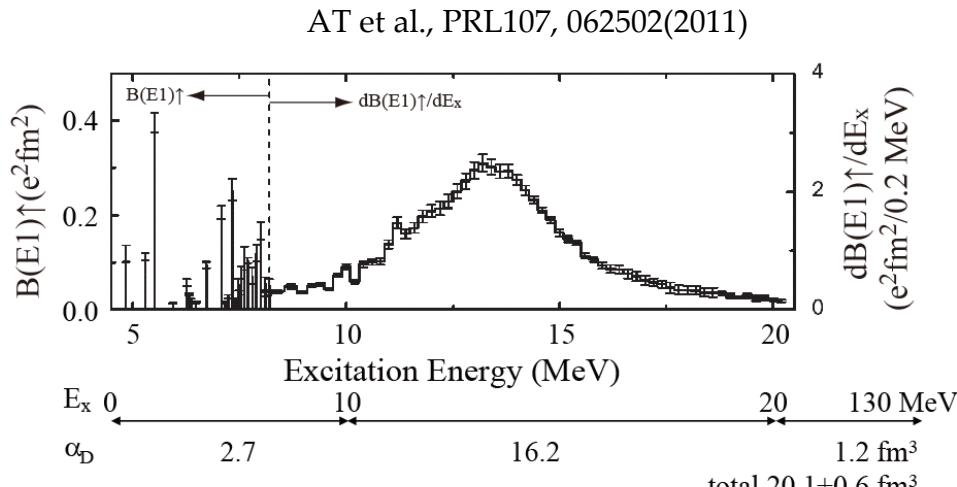
momentum dependence

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



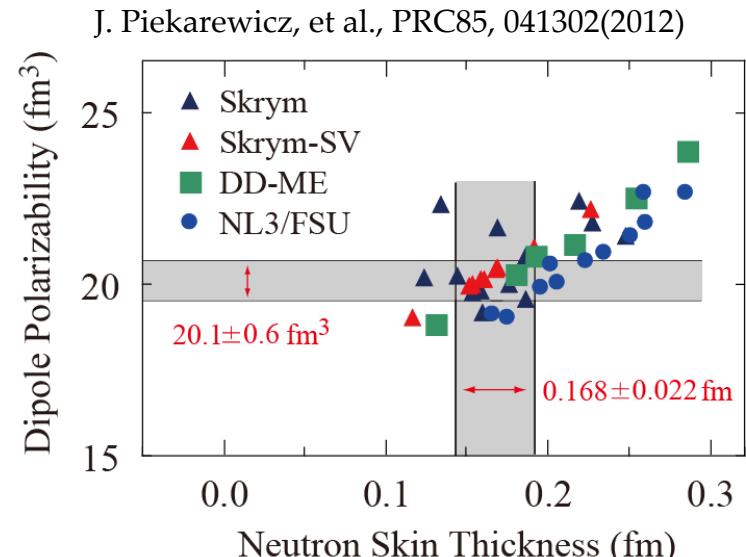
E1 Response of ^{208}Pb
and
Symmetry Energy of the Nuclear EOS

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

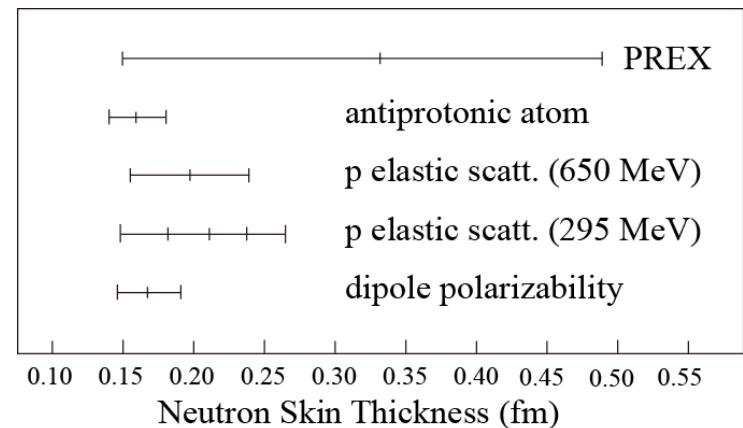


Dipole Polarizability

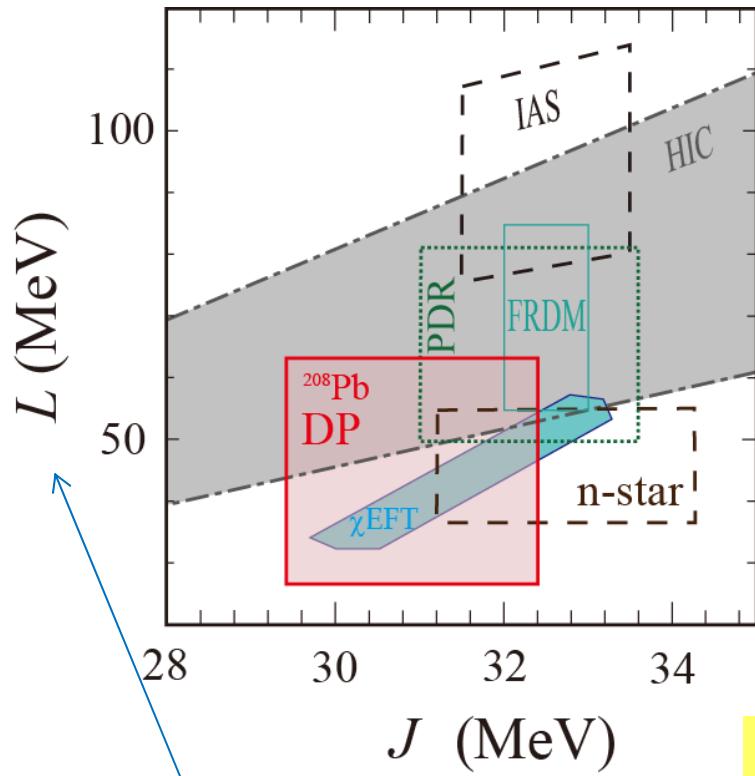
$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega} = 20.1 \pm 0.6 \text{ fm}^3$$



Neutron Skin Thickness of $^{208}\text{Pb} = 0.168 \pm 0.022 \text{ fm}$
including model dependence



Determination of Symmetry Energy



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

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

M.B. Tsang *et al.*, PRC86, 015803 (2012).

I. Tews *et al.*, arXiv:1206.0025v1

and this work (DP) $L=45\pm18$ MeV

$J=30.9\pm1.5$ 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

χ EFT: Chiral Effective Field Theory

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

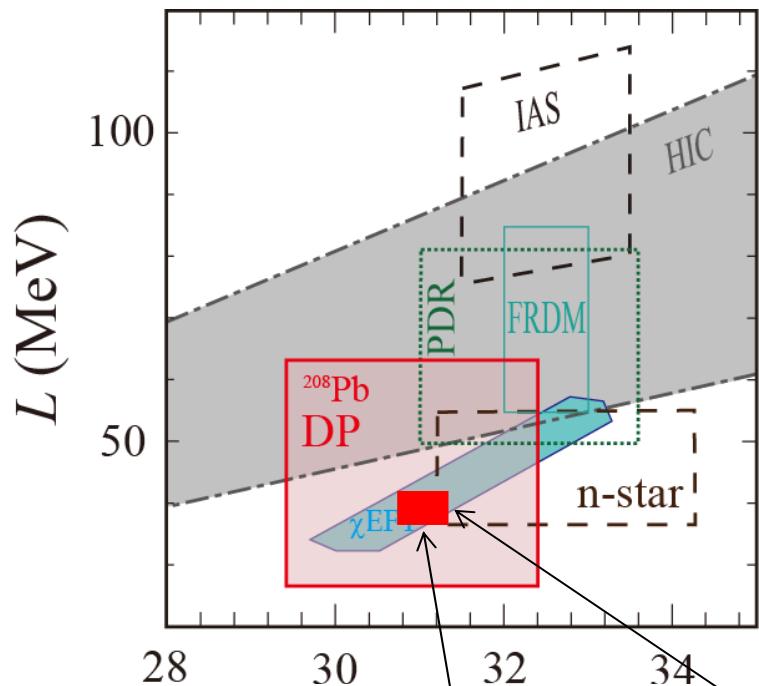
barionic
pressure

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

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

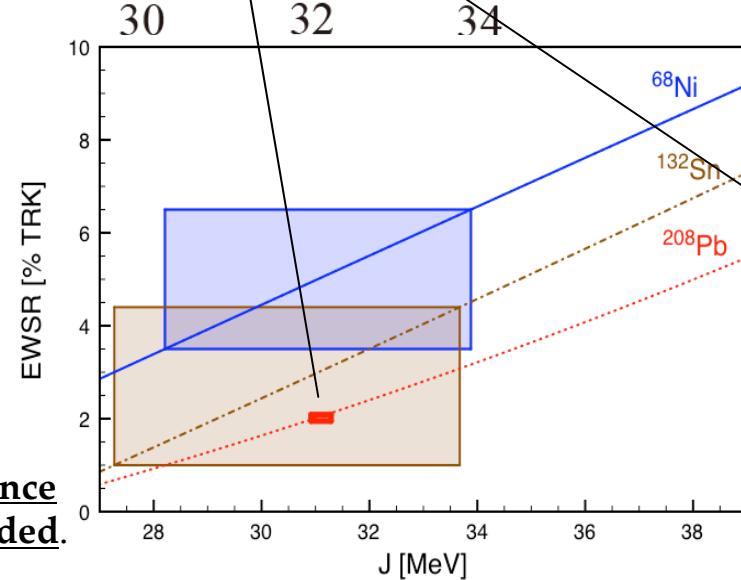
Saturation Density
 $\sim 0.16 \text{ fm}^{-3}$

Determination of Symmetry Energy



PDR EWSR
RQRPA
by N. Paar
@COMEX4

Model dependence
should be included.



M.B. Tsang *et al.*, PRC86, 015803 (2012).

I. Tews *et al.*, arXiv:1206.0025v1

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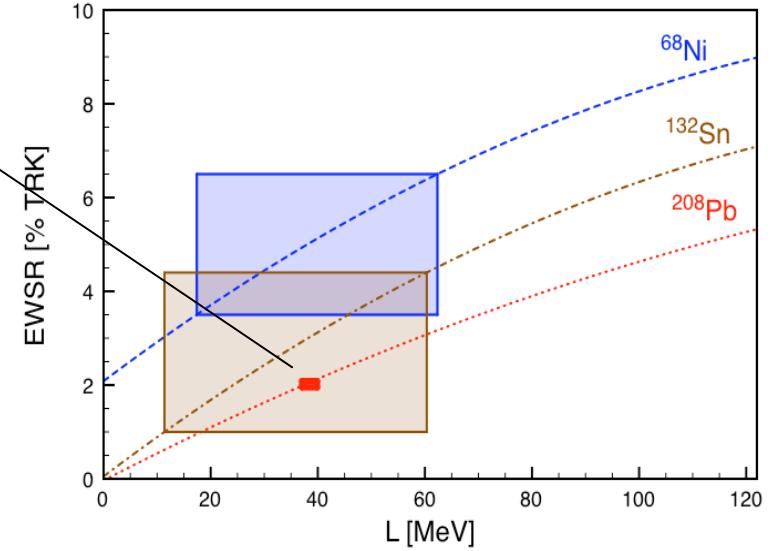
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Contents

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 ${}^4\text{He}$

(K. Miki *et al.*,)

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

*Thank you
for your attention!*

