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1-3, November, 2011 at Beihang Univ.

Proton-neutron spin correlation in ground states studied by measuring isoscalar and isovector spin-*M1* excitations in *N*=*Z* nuclei

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and RCNP-E299 collaboration

Study of the **Ground State** Property by Measuring **Excited States**

Dynamic

Excited State

Excitation energy,
transition strength

Sum-Rule

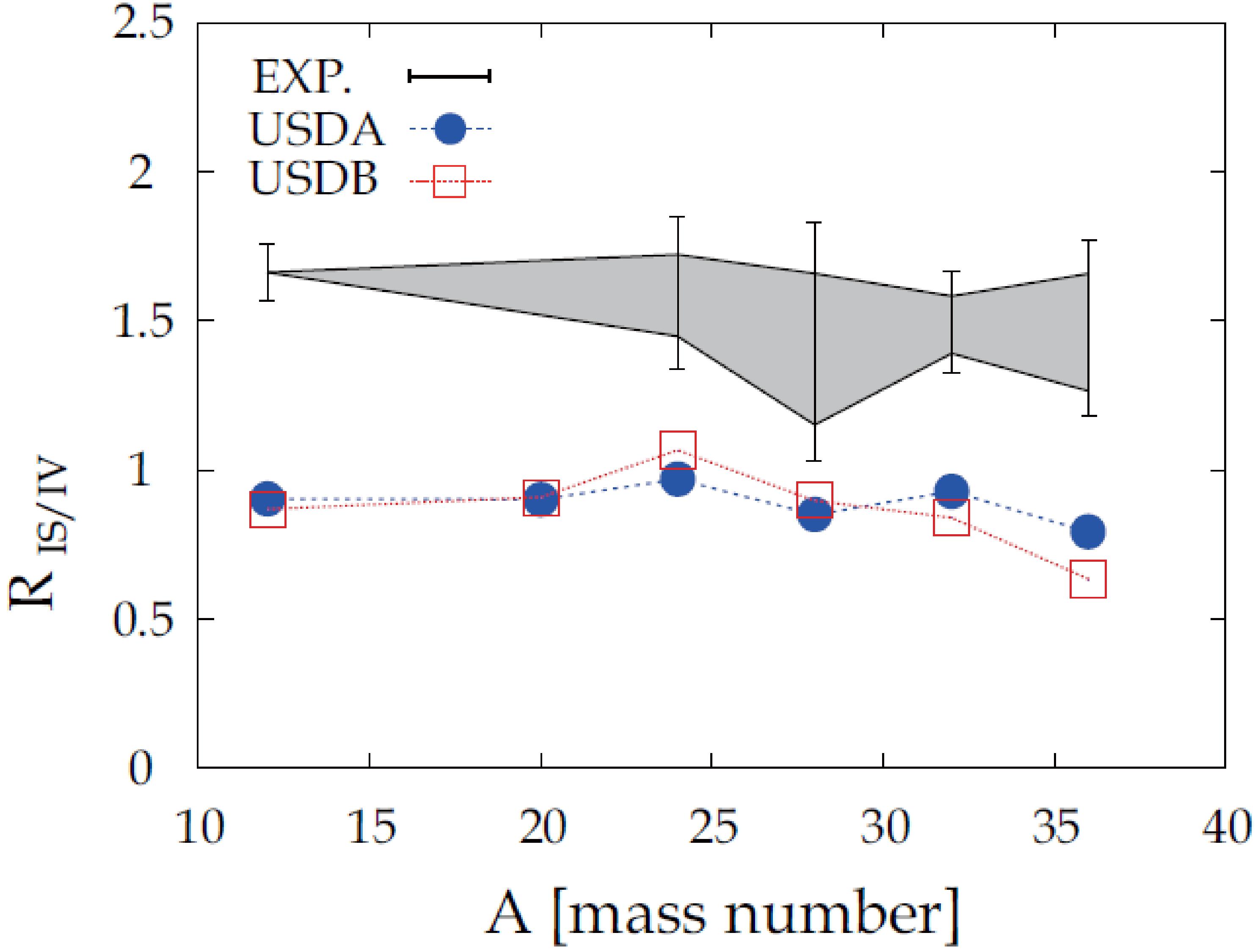
Excitation

Static
(+Dynamic)

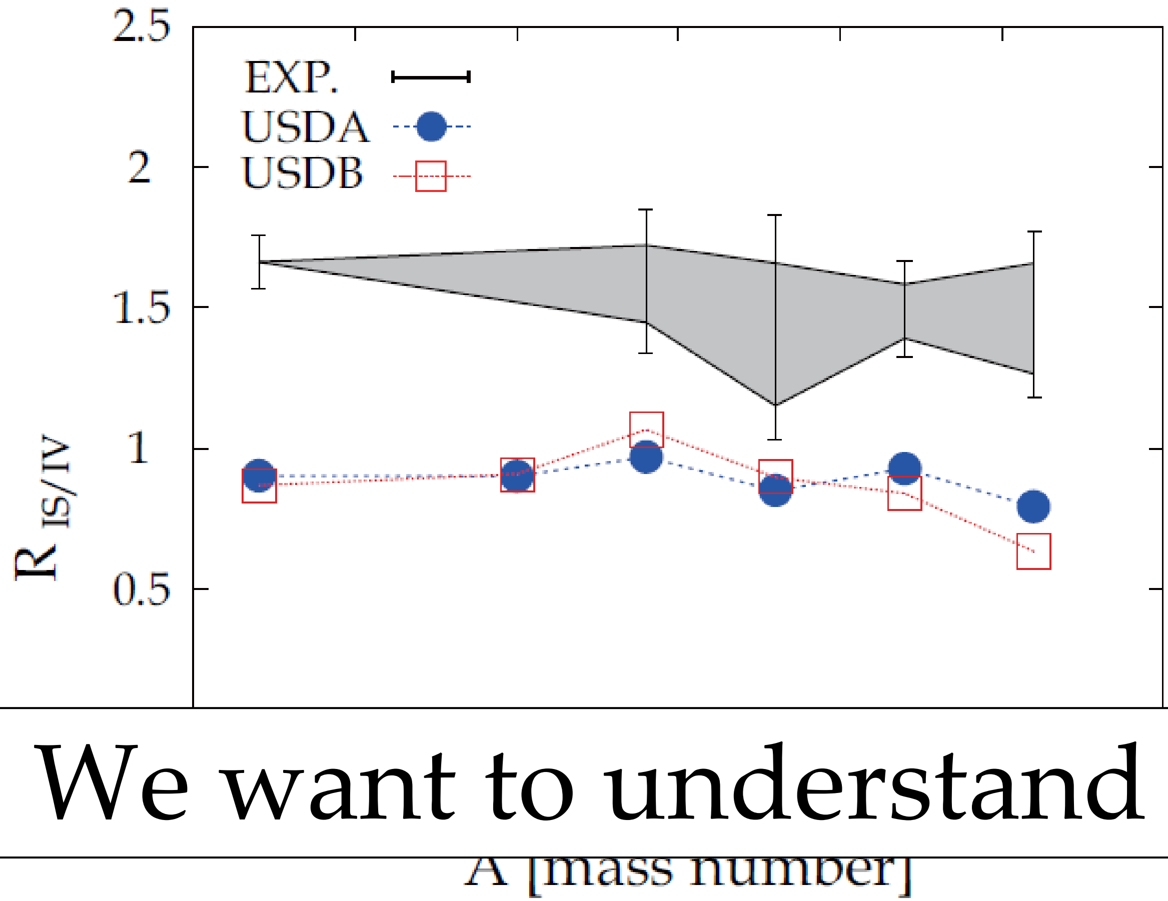
Ground State

Mass, spin, parity, magnetic moment,
deformation parameters, ….

Our Problem



$0^+ \rightarrow 1^+$ Excitation in N=Z Even-Even Nuclei



~ $1.5_{\pm 0.2 \pm 0.1}$ Exp.

~ 1.0 Theo.

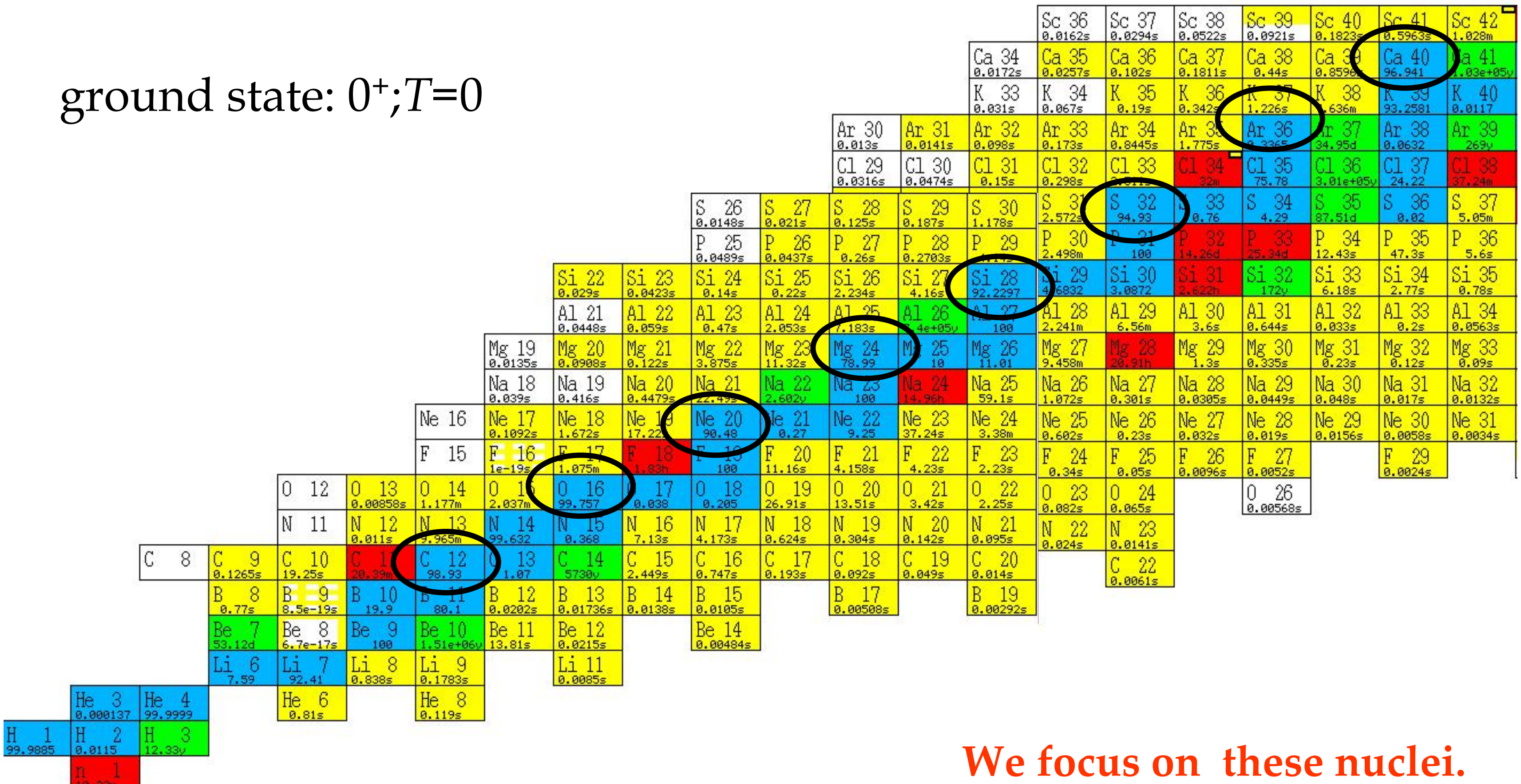
We want to understand it !

$$R_{IS/IV} \equiv \frac{\sum |M(\sigma)|^2}{\sum |M(\sigma\tau)|^2} = \frac{\sum_i \left| \langle 1_i^+ | \sigma | 0_{g.s.}^+ \rangle \right|^2}{\sum_i \left| \langle 1_i^+ | \sigma\tau | 0_{g.s.}^+ \rangle \right|^2}$$

Calc: shell model with the USDA/B effective interaction

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

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

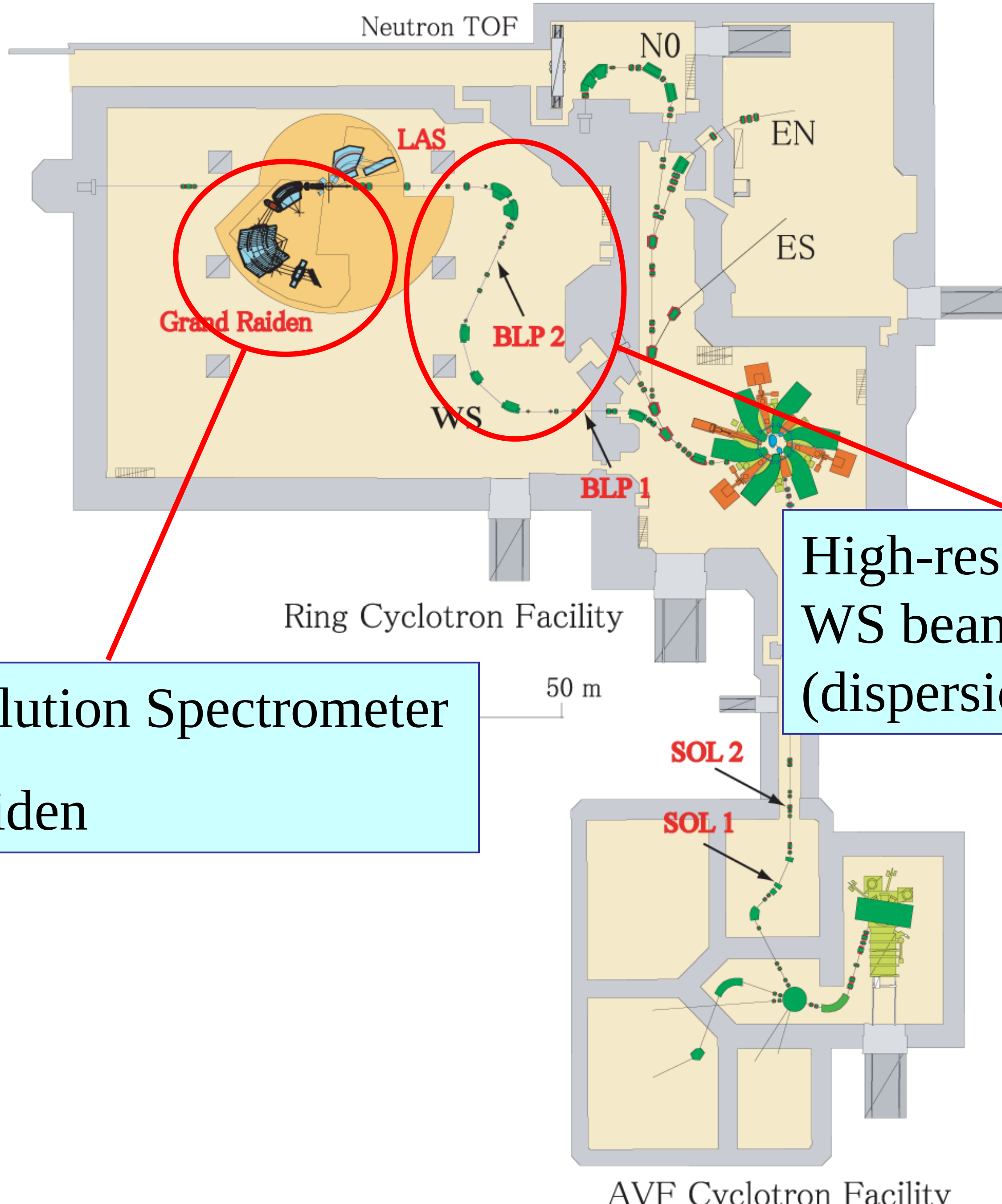


We focus on these nuclei.

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 expect ^{4}He.

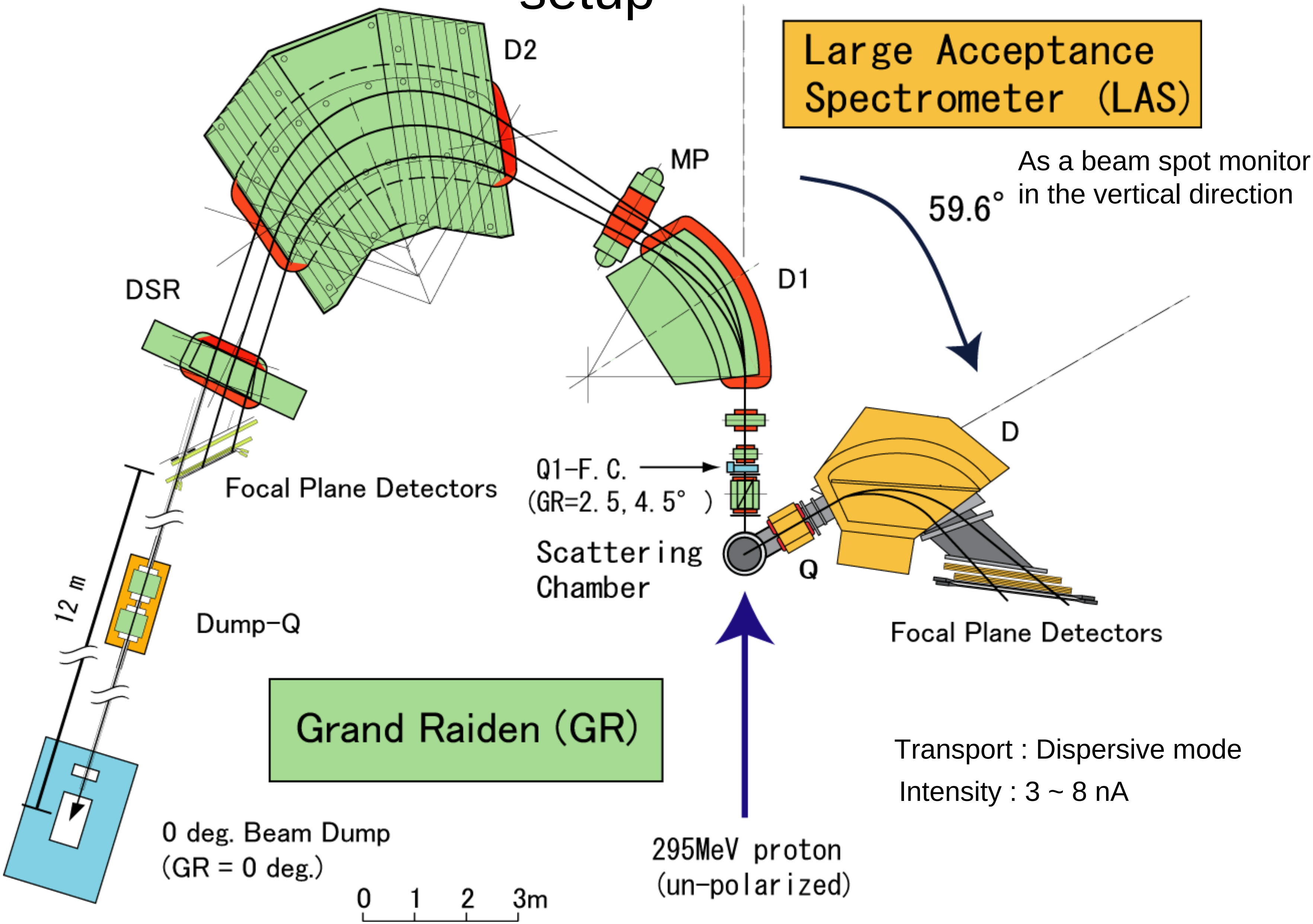


High-resolution Spectrometer

Grand Raiden

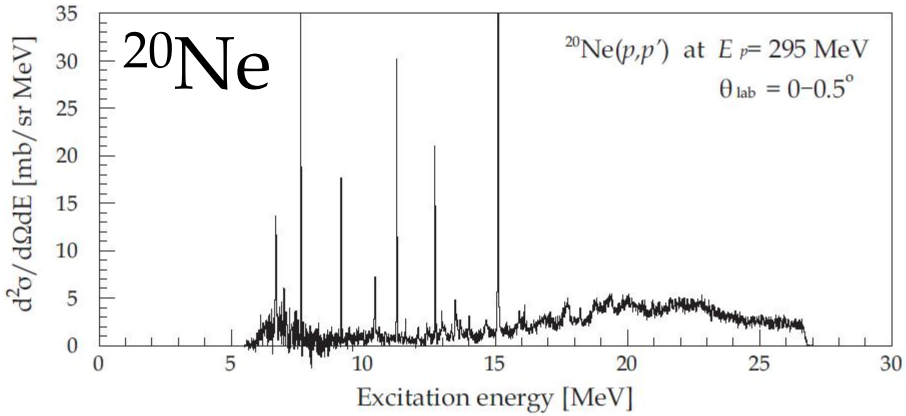
High-resolution
WS beam-line
(dispersion matching)

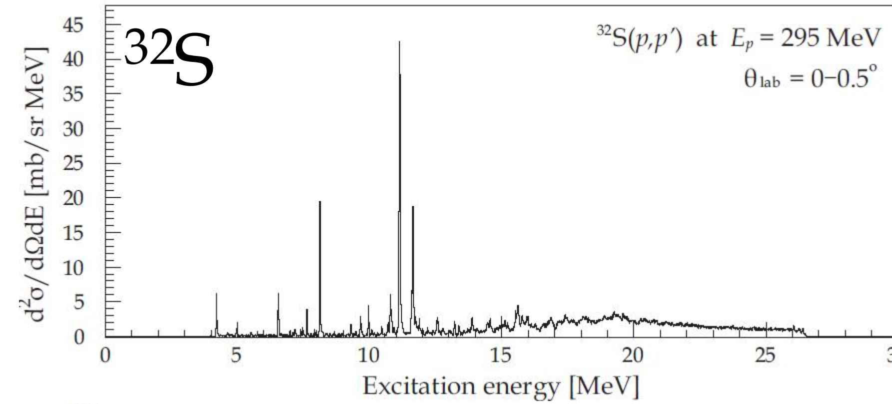
Spectrometers in the 0-deg. experiment setup

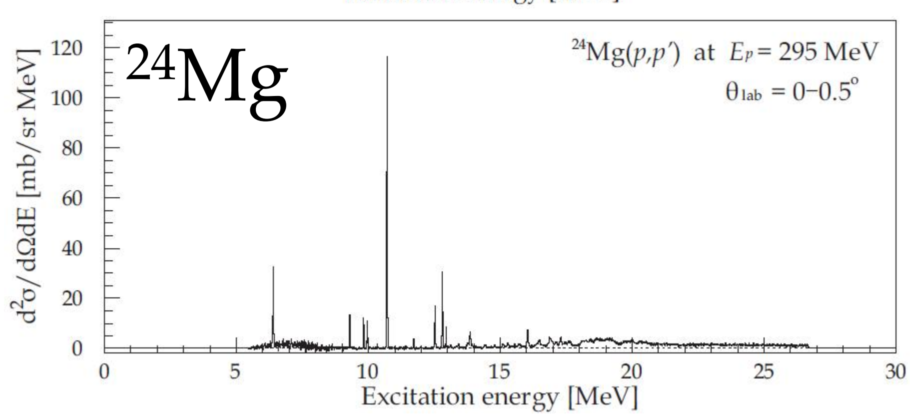


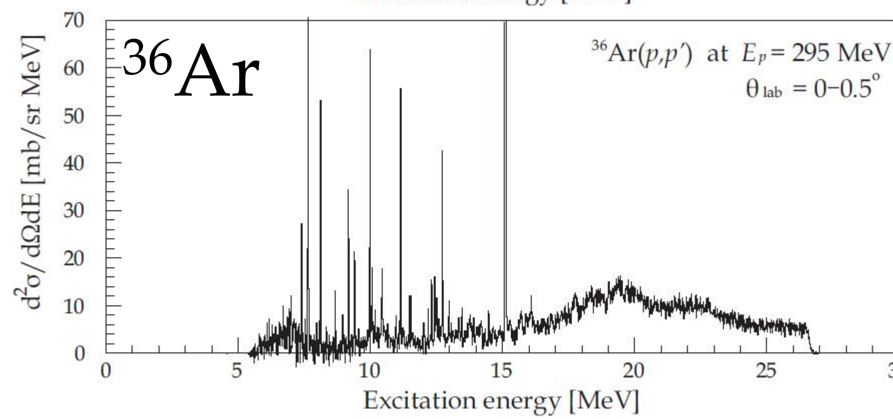
(p,p') Spectra at E_p=295 MeV

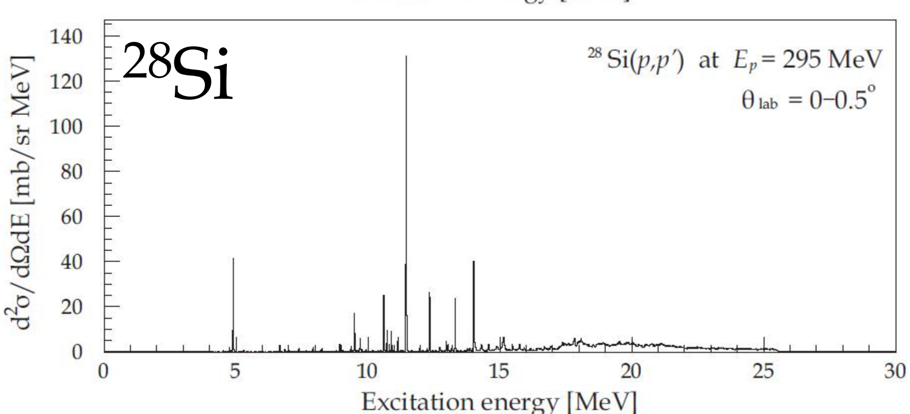
measured at 0-15 deg.







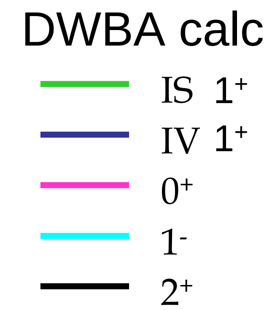


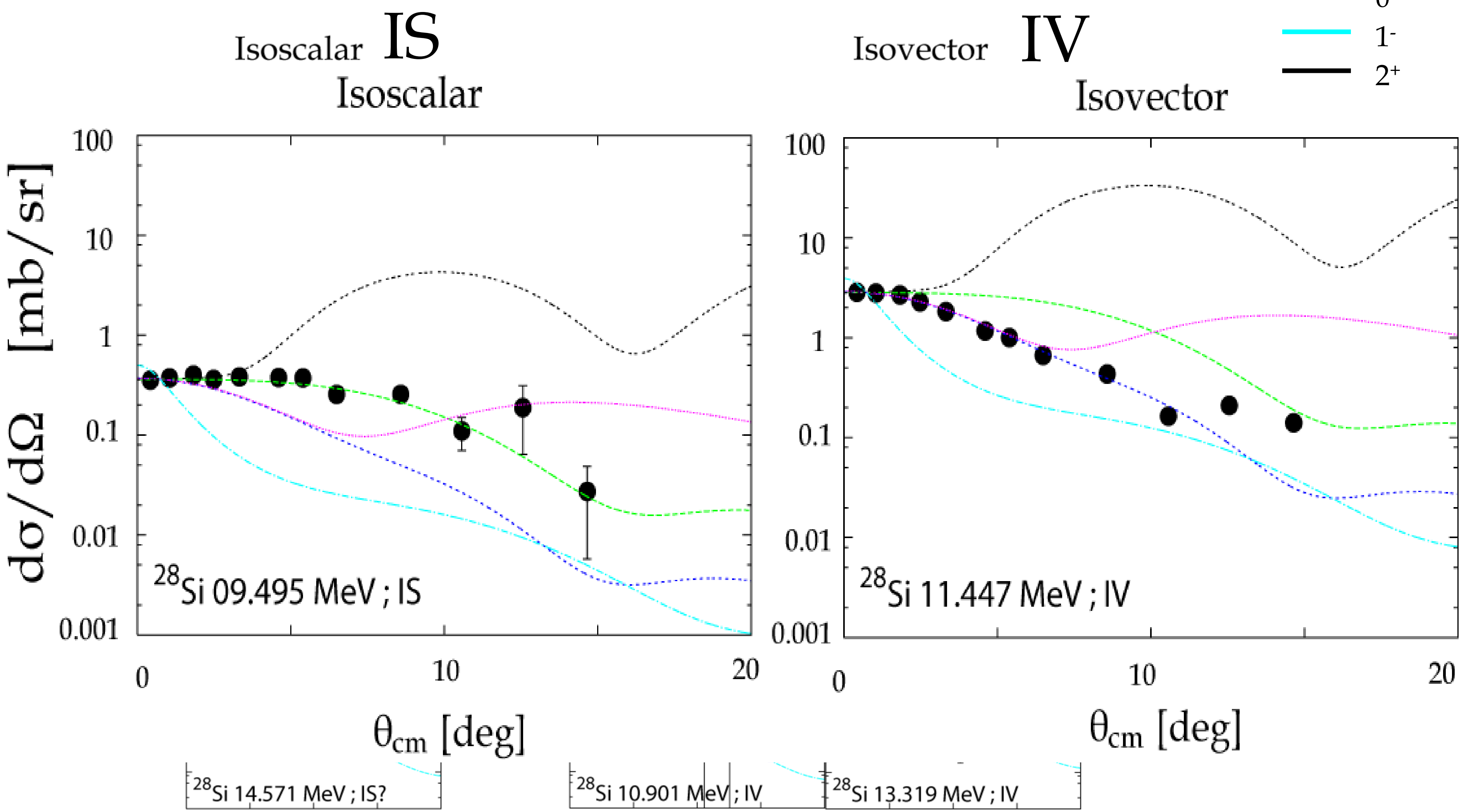


1^+ states were identified from angular distribution for each of IS and IV transitions.

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

Angular Distribution of Cross Section of IS/IV spin-*M1* excitations

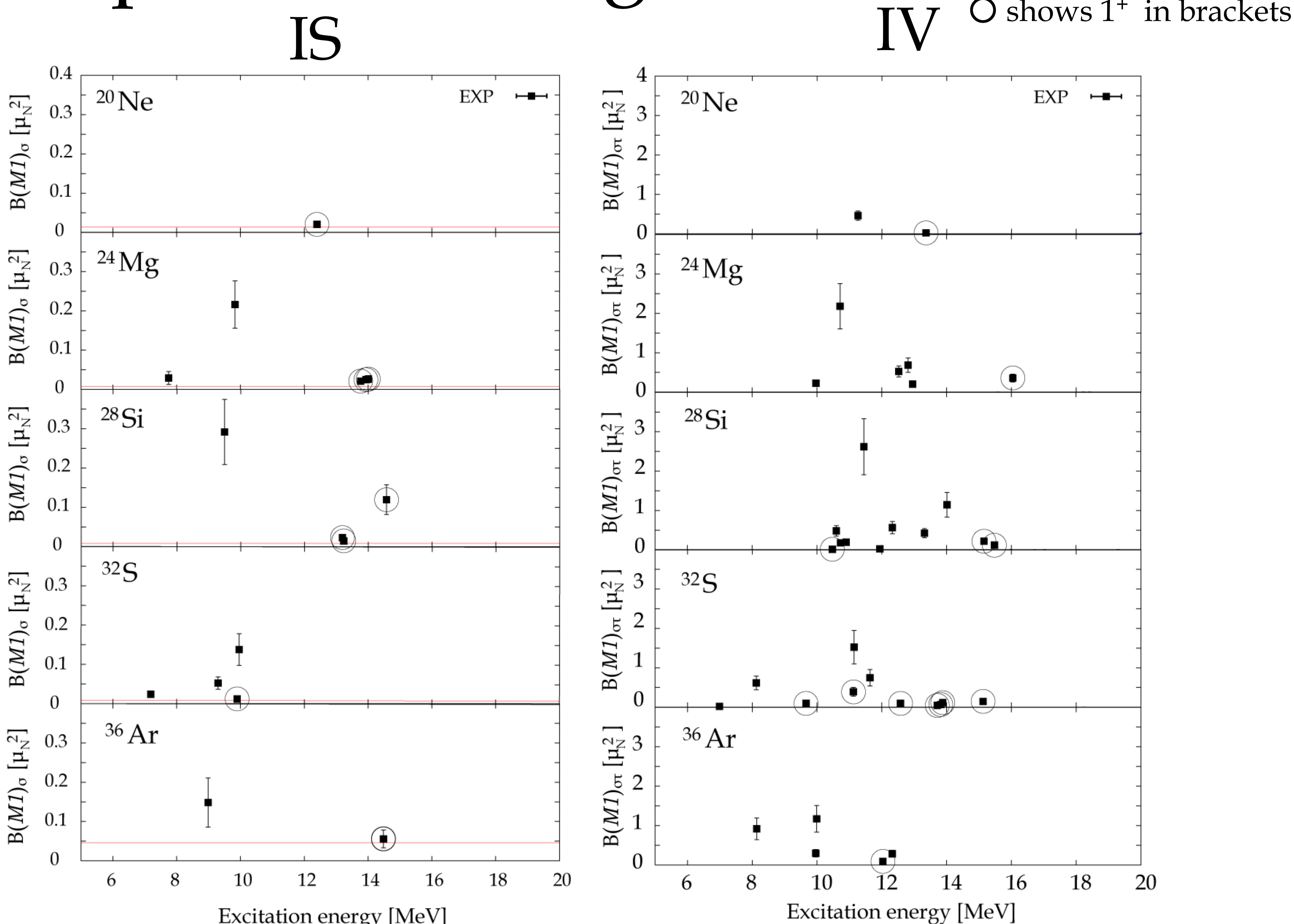




θ cm [deg

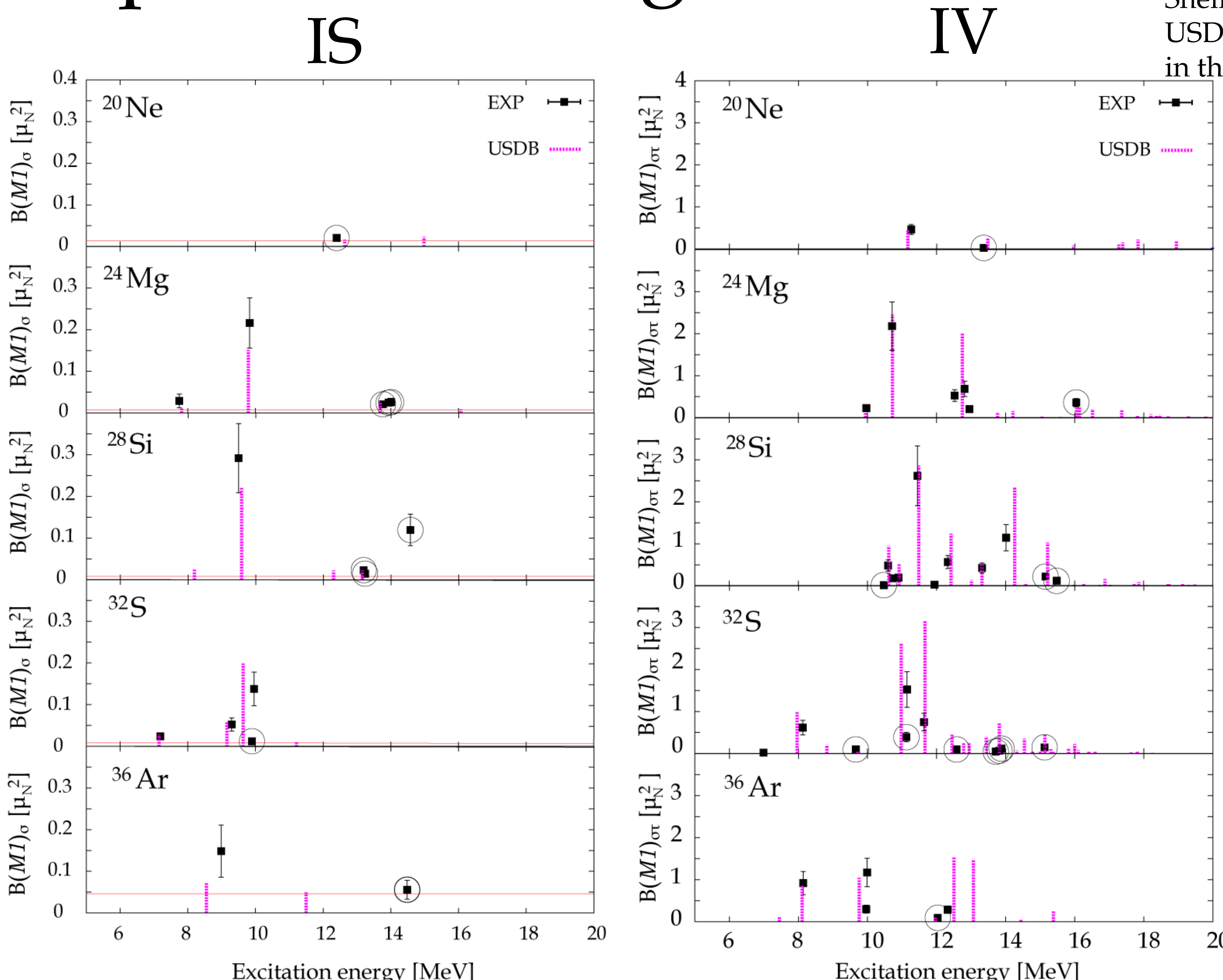
ΔT(IS or IV) has also been identified from angular distribution.

Spin-M1 Strength Distribution



Spin-M1 Strength Distribution

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

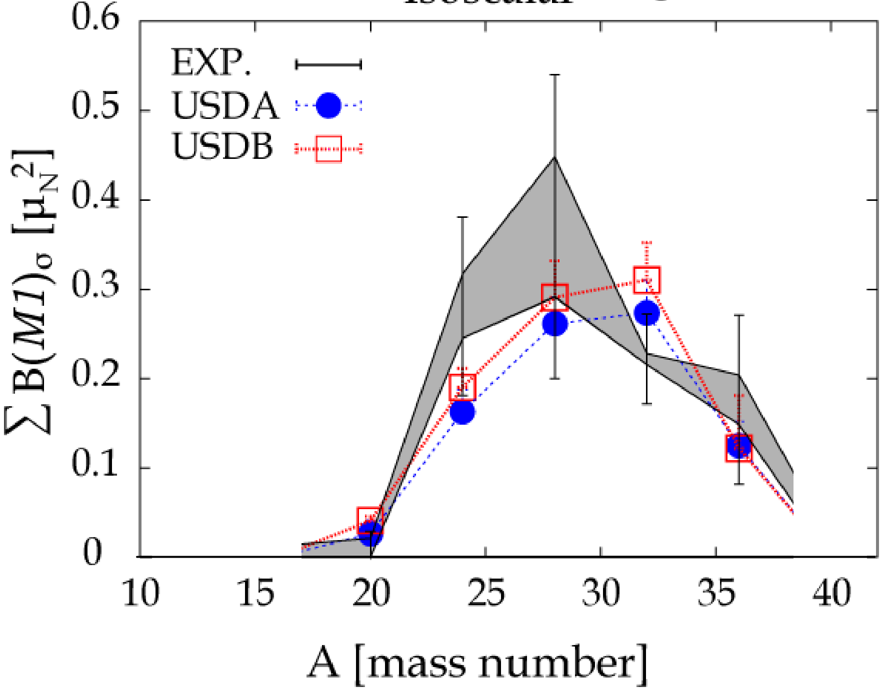


Summed Spin-M1 Strengths

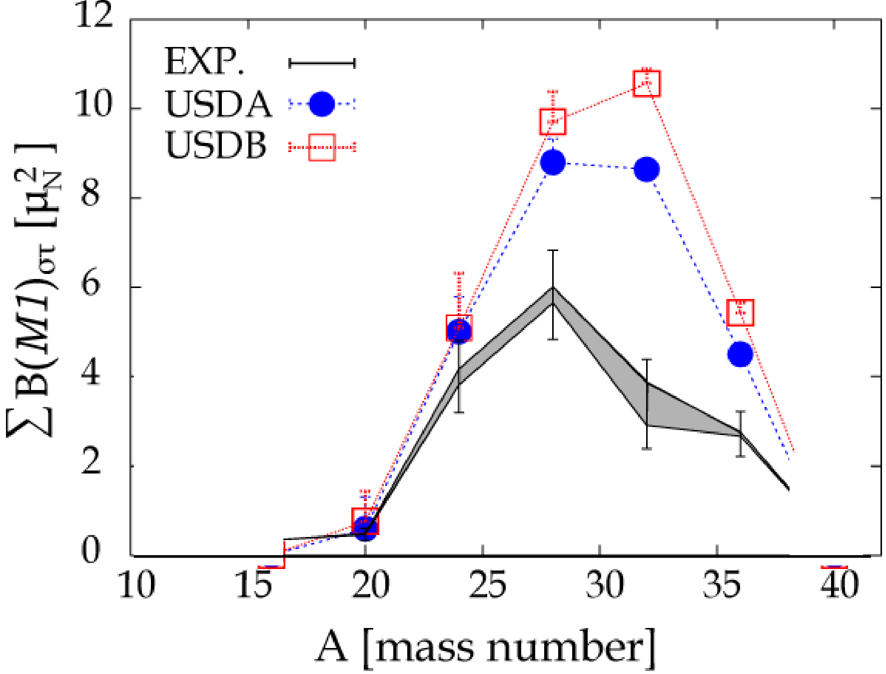
Ex<16 MeV, comparison with shell model
using **bare g_s-factor, USD** in the ***sd*-shell**.

OXBASH

Isoscalar IS



Isovector IV



The SM roughly reproduces the data.

The SM overestimates the data.
= quenching

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

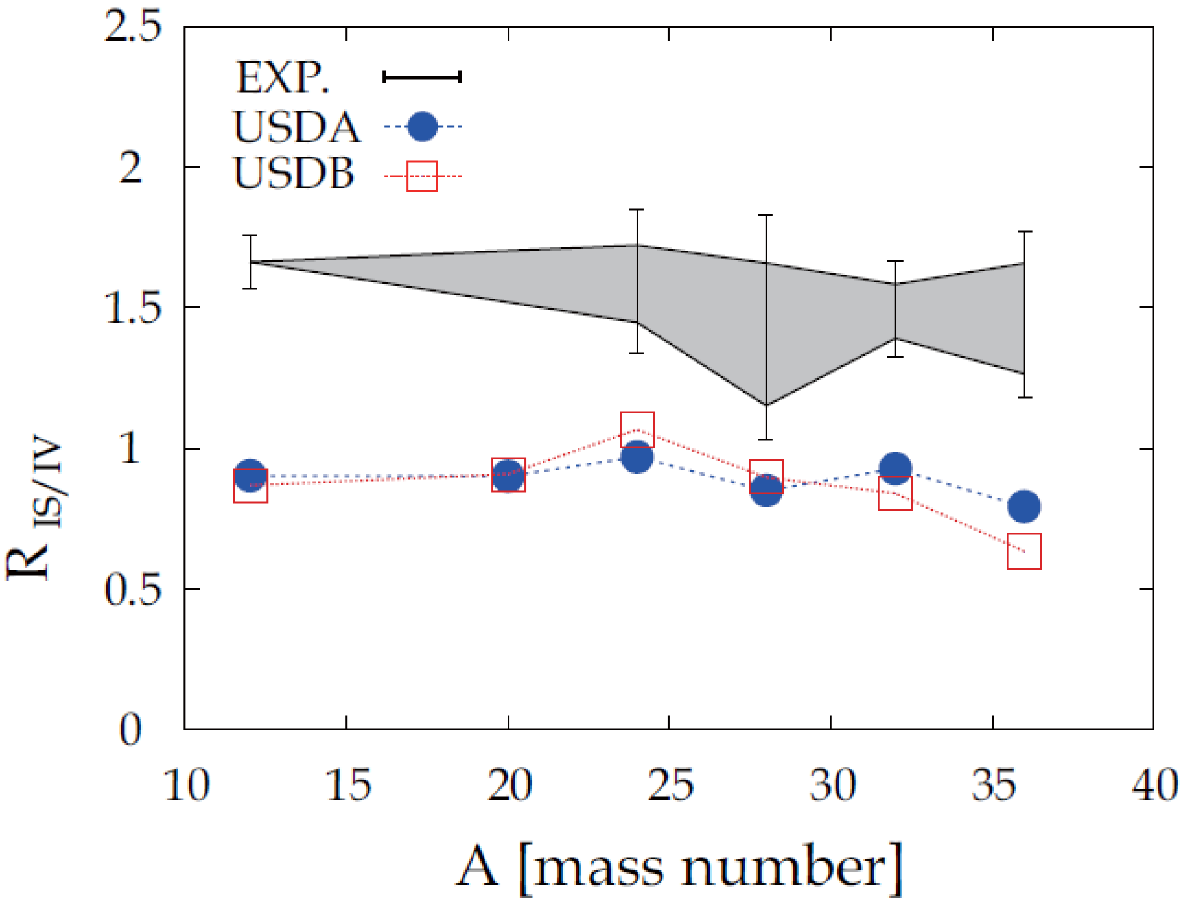
T=1 Isovector (IV) Spin-M1 Reduced Transition Strength

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

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

IV Reduced Matrix Element

$0^+ \rightarrow 1^+$ Excitation in N=Z Even-Even Nuclei



~ $1.5_{\pm 0.2 \pm 0.1}$
Exp.

~ 1.0 Theo.

$$R_{IS/IV} \equiv \frac{\sum |M(\sigma)|^2}{\sum |M(\sigma\tau)|^2} = \frac{\sum_i \left| \langle 1_i^+ | \sigma | 0_{g.s.}^+ \rangle \right|^2}{\sum_i \left| \langle 1_i^+ | \sigma\tau | 0_{g.s.}^+ \rangle \right|^2}$$

Calc: shell model with the USDA/B effective interaction

$$\vec{S}_p \equiv \sum_{i=1}^{Z} \vec{s}_i \quad \text{for protons} \qquad \vec{S}_n \equiv \sum_{i=Z+1}^{A} \vec{s}_i \quad \text{for neutrons}$$

$$\text{IS} \quad 4\sum \left| M(\sigma) \right|^2 = \sum_{f(1^+)} \left| \left\langle 1_f^+ \left\| \vec{S}_p + \vec{S}_n \right\| 0_{g.s.}^+ \right\rangle \right|^2$$

$$= \sum_{f(1^+)} \left\langle 0_{g.s.}^+ \left\| \vec{S}_p + \vec{S}_n \right\| 1_f^+ \right\rangle \left\langle 1_f^+ \left\| \vec{S}_p + \vec{S}_n \right\| 0_{g.s.}^+ \right\rangle$$

$$= \sum_{f} \left\langle 0_{g.s.}^+ \left\| \vec{S}_p + \vec{S}_n \right\| f \right\rangle \left\langle f \left\| \vec{S}_p + \vec{S}_n \right\| 0_{g.s.}^+ \right\rangle$$

$$= \left\langle 0_{g.s.}^+ \left\| \left(\vec{S}_p + \vec{S}_n \right)^2 \right\| 0_{g.s.}^+ \right\rangle$$

closure approximation

$$\text{IV} \quad 4\sum \left| M(\sigma\tau) \right|^2 = \left\langle 0_{g.s.}^+ \left\| \left(\vec{S}_p - \vec{S}_n \right)^2 \right\| 0_{g.s.}^+ \right\rangle$$

$$R_{IS/IV} \equiv \frac{\sum \left| M(\sigma) \right|^2}{\sum \left| M(\sigma\tau) \right|^2} = \frac{\left\langle 0_{g.s.}^+ \left\| \left(\vec{S}_p + \vec{S}_n \right)^2 \right\| 0_{g.s.}^+ \right\rangle}{\left\langle 0_{g.s.}^+ \left\| \left(\vec{S}_p - \vec{S}_n \right)^2 \right\| 0_{g.s.}^+ \right\rangle}$$

H. Matsubara,
H. Nakada *et al.*,

$$R_{IS/IV} \equiv \frac{\sum \left|M(\sigma)\right|^2}{\sum \left|M(\sigma\tau)\right|^2} = \frac{\left\langle 0^+_{g.s.} \left\| \left(\vec{S}_p + \vec{S}_n\right)^2 \right\| 0^+_{g.s.} \right\rangle}{\left\langle 0^+_{g.s.} \left\| \left(\vec{S}_p - \vec{S}_n\right)^2 \right\| 0^+_{g.s.} \right\rangle}$$

~ 1 shell-model (in sd-shell)

~ 1.5 exp.

$$C_S \equiv \frac{R_{IS/IV} - 1}{R_{IS/IV} + 1} = \frac{2\left\langle 0^+_{g.s.} \left\| \vec{S}_p \cdot \vec{S}_n \right\| 0^+_{g.s.} \right\rangle}{\left\langle 0^+_{g.s.} \left\| \vec{S}_p^{\,2} + \vec{S}_n^{\,2} \right\| 0^+_{g.s.} \right\rangle}$$

~ 0 shell-model (in sd-shell)

~ +0.2 >0 exp.

Note: C_s=+1/3 for the deuteron s-state.

$$2\left\langle 0^+_{g.s.} \left\| \vec{S}_p \cdot \vec{S}_n \right\| 0^+_{g.s.} \right\rangle = \left\langle 0^+_{g.s.} \left\| (\vec{S}_p + \vec{S}_n)^2 - \vec{S}_p^{\,2} - \vec{S}_n^{\,2} \right\| 0^+_{g.s.} \right\rangle$$

$$= 1(1+1) - 2(3/4) = 1/2$$

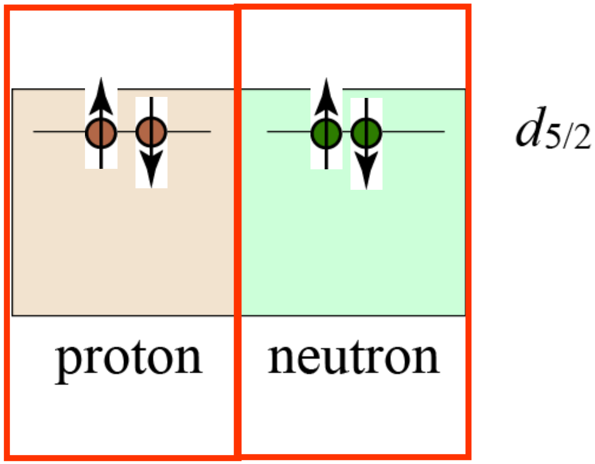
$$\left\langle 0^+_{g.s.} \left\| \vec{S}_p^{\,2} + \vec{S}_n^{\,2} \right\| 0^+_{g.s.} \right\rangle = 2(3/4) = 3/2$$

We want to understand it.

Tensor interaction must be playing an important role.

What kind of configurations can give a finite C_S value?

0p-0h state

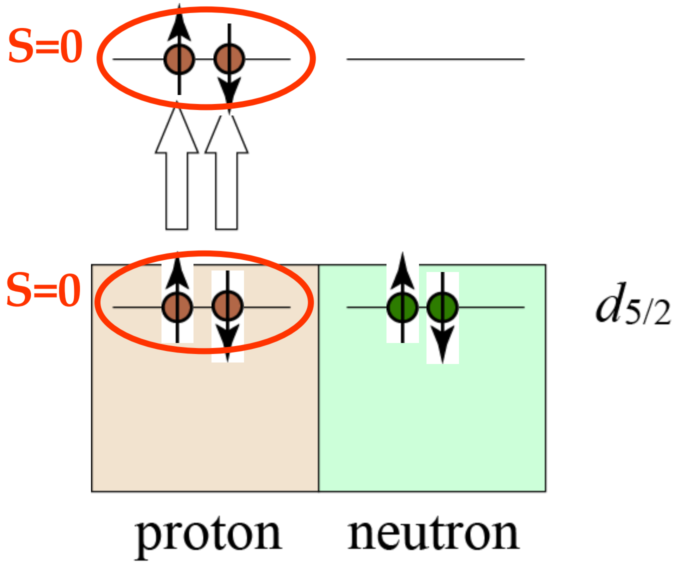


S_p=0 S_n=0

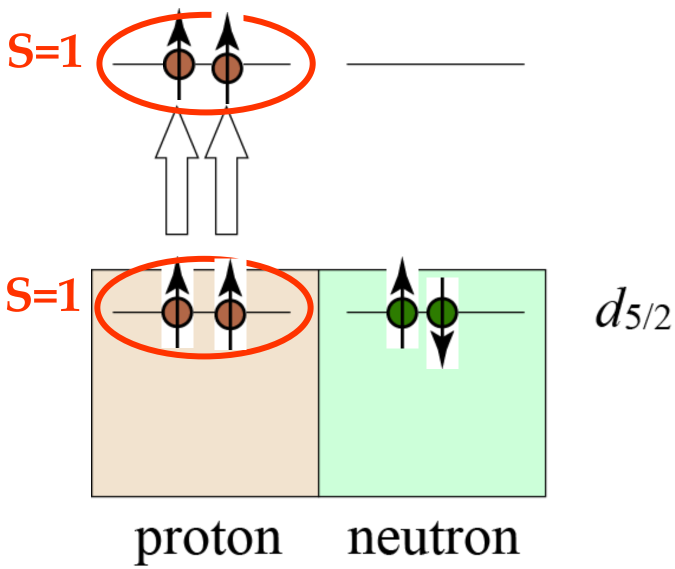
$$\frac{2\left\langle 0^+_{g.s.}\left\| \vec{S}_p \cdot \vec{S}_n \right\| 0^+_{g.s.}\right\rangle \quad = 0}{\left\langle 0^+_{g.s.}\left\| \vec{S}_p^{\,2} + \vec{S}_n^{\,2} \right\| 0^+_{g.s.}\right\rangle \quad = 0}$$

→

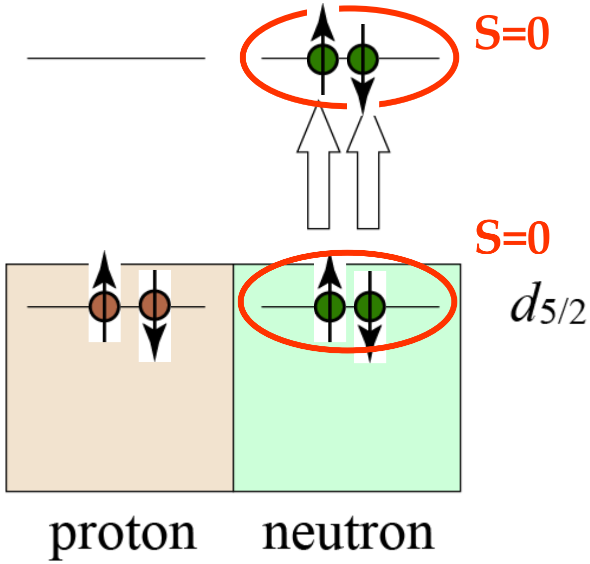
2p-2h configuration mixing in the ground state should be the origin of the finite C_S value.



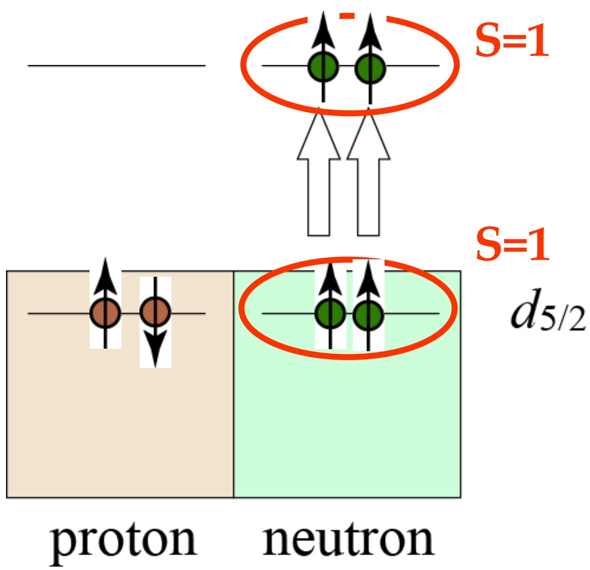
$$\frac{2\left\langle 0^+_{g.s.}\left\|\vec{S}_p\cdot\vec{S}_n\right\|0^+_{g.s.}\right\rangle \quad =0}{\left\langle 0^+_{g.s.}\left\|\vec{S}_p^{\,2}+\vec{S}_n^{\,2}\right\|0^+_{g.s.}\right\rangle \quad =0}$$



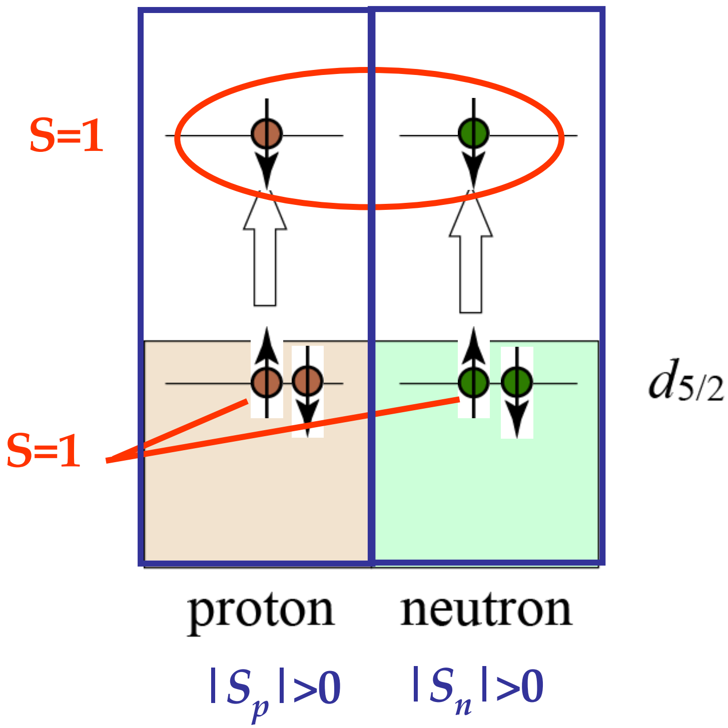
$$\frac{2\left\langle 0^+_{g.s.}\left\|\vec{S}_p\cdot\vec{S}_n\right\|0^+_{g.s.}\right\rangle \quad =0}{\left\langle 0^+_{g.s.}\left\|\vec{S}_p^{\,2}+\vec{S}_n^{\,2}\right\|0^+_{g.s.}\right\rangle \quad >0}$$



$$\frac{2\left\langle 0^+_{g.s.}\left\|\vec{S}_p\cdot\vec{S}_n\right\|0^+_{g.s.}\right\rangle \qquad =0}{\left\langle 0^+_{g.s.}\left\|\vec{S}_p^{\,2}+\vec{S}_n^{\,2}\right\|0^+_{g.s.}\right\rangle \qquad =0}$$



$$\frac{2\left\langle 0^+_{g.s.}\left\|\vec{S}_p\cdot\vec{S}_n\right\|0^+_{g.s.}\right\rangle \qquad =0}{\left\langle 0^+_{g.s.}\left\|\vec{S}_p^{\,2}+\vec{S}_n^{\,2}\right\|0^+_{g.s.}\right\rangle \qquad >0}$$



$$\frac{2\left\langle 0^+_{g.s.}\left\|\vec{S}_p\cdot\vec{S}_n\right\|0^+_{g.s.}\right\rangle \quad >0}{\left\langle 0^+_{g.s.}\left\|\vec{S}_p^{\,2}+\vec{S}_n^{\,2}\right\|0^+_{g.s.}\right\rangle \quad >0}$$

We are probing this kind of 2p-2h configuration mixing in the ground state.

→ *n*-*p* spin correlation, probably due to tensor interaction

We need the following three numbers for the ground state:

$$\left\langle 0^+_{g.s.} \left\| \vec{S}_p \cdot \vec{S}_n \right\| 0^+_{g.s.} \right\rangle$$

$$\left\langle 0^+_{g.s.} \left\| \vec{S}_p^{\,2} \right\| 0^+_{g.s.} \right\rangle$$

$$\left\langle 0^+_{g.s.} \left\| \vec{S}_n^{\,2} \right\| 0^+_{g.s.} \right\rangle$$

$$\vec{S}_p \equiv \sum_{i=1}^{Z} \vec{s}_i$$

$$\vec{S}_n \equiv \sum_{i=Z+1}^{A} \vec{s}_i$$

to compare theory with the experimental data

$$C_S \equiv \frac{R_{IS/IV} - 1}{R_{IS/IV} + 1} = \frac{2\left\langle 0^+_{g.s.} \left\| \vec{S}_p \cdot \vec{S}_n \right\| 0^+_{g.s.} \right\rangle}{\left\langle 0^+_{g.s.} \left\| \vec{S}_p^{\,2} + \vec{S}_n^{\,2} \right\| 0^+_{g.s.} \right\rangle}$$

~ 0 shell-model (in sd-shell)

~ +0.2 >0 exp.

Summary

We have measured isoscalar/isovector spin-M1 excitations in N=Z even-even nuclei in the *sd*-shell region.

The measured spin matrix elements (or reduced transition strengths) have been summed up to Ex=16 MeV.

The measured ratio between the isoscalar and isovector excitations could not reproduced by a conventional shell-model calculation.

We have observed tensor correlation in the ground state,

We appreciate your theoretical calculations and explanation.