Spectroscopic Factors in the Islands of Inversion: The Nilsson Strong Coupling Limit

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Outline

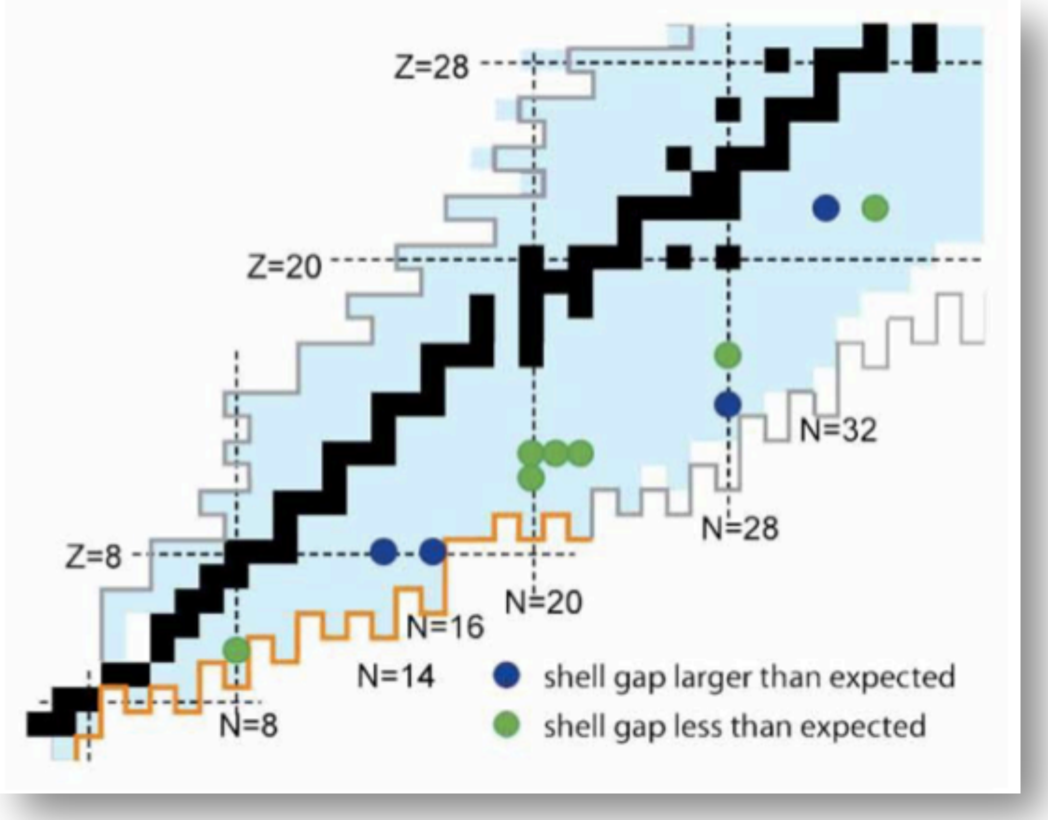
- **The 'Islands of Inversion' – what we know**
- **Spectroscopic Factors in the Nilsson Strong Coupling Limit**
    - ***N*=20 Island of Inversion**
    - ***N*= 8 ^{12}Be**
- **Structure of ^{29}F**
- **Summary**

Evolution of Shell Structure and Collectivity

"Classic" magic numbers are generally correct only for stable and near stable isotopes.

Experimental studies of new exotic isotopes revealed changes in shell structure and collectivity, and provided insight on the important role played by the tensor (and 3N) in these changes.

R.V.F Janssens, Nature **435** (2005).



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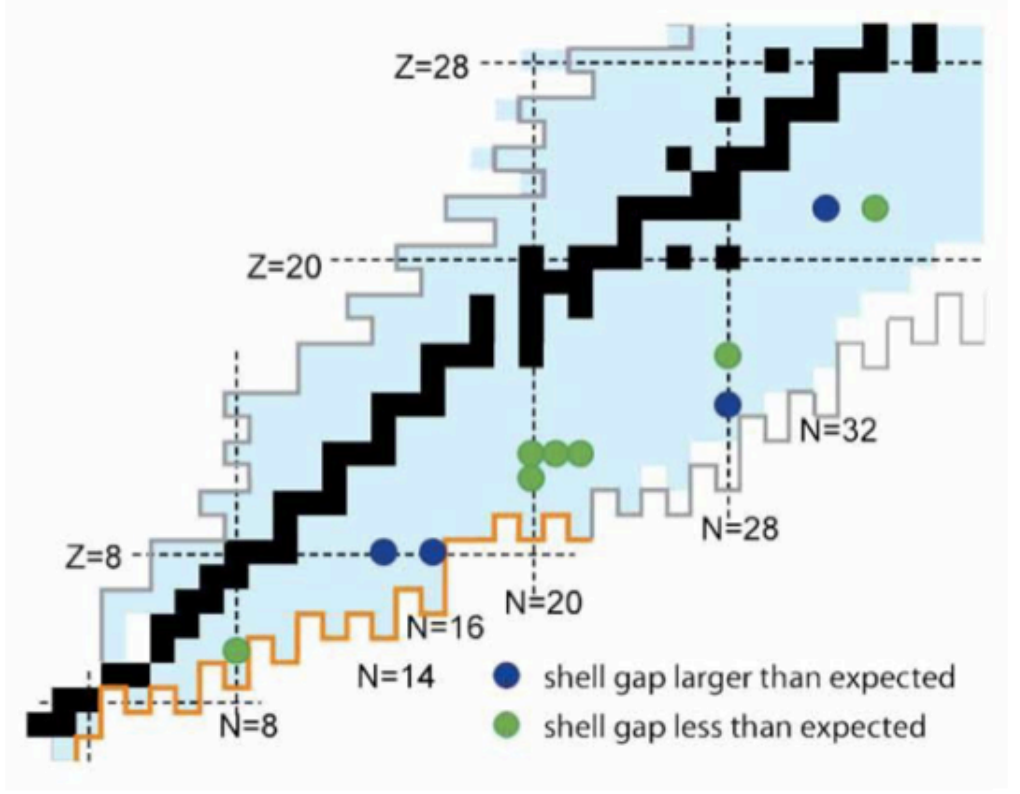
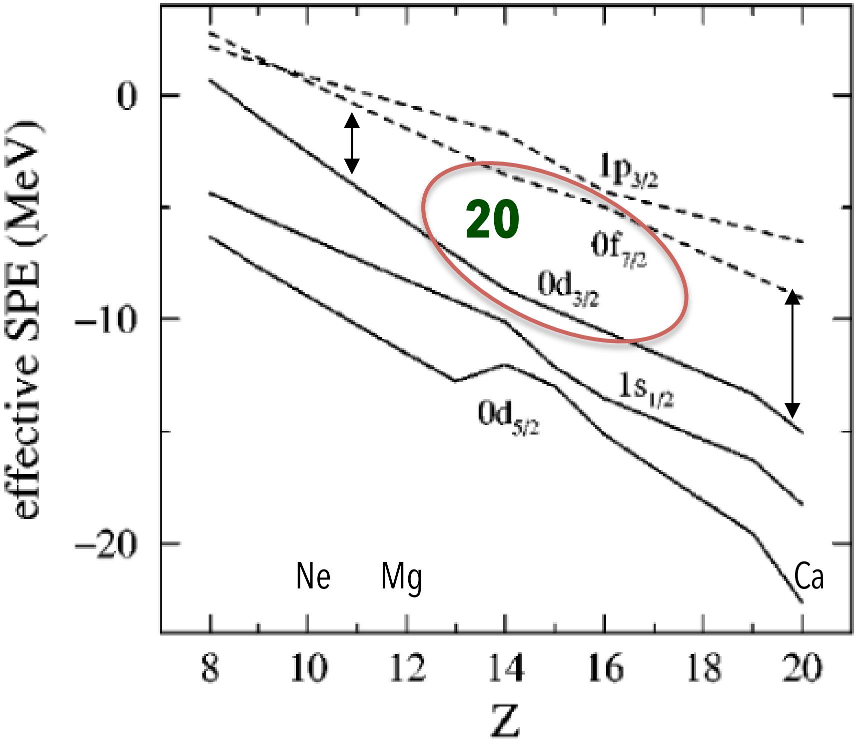


A delicate balance between the monopole field and correlations.

$$\boxed{H = E_{sp} + GP^{+}P + xQ\cdot Q}$$

N=20 Shell Gap

Y.Utsuno et al PRC **60,** 011301(R) (1999).

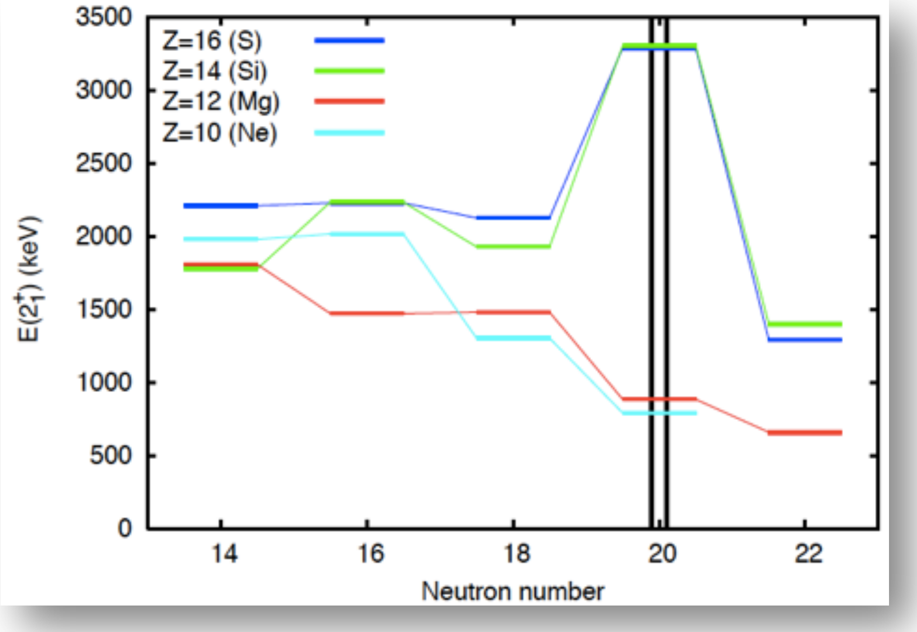


$\pi\ d_{5/2}$ ⇐|⇒ $\pi\ d_{3/2}$

Role of the $\pi d_{5/2}$- $\nu d_{3/2}$ interaction

Δl=Δj=2

➛Quadrupole Correlations



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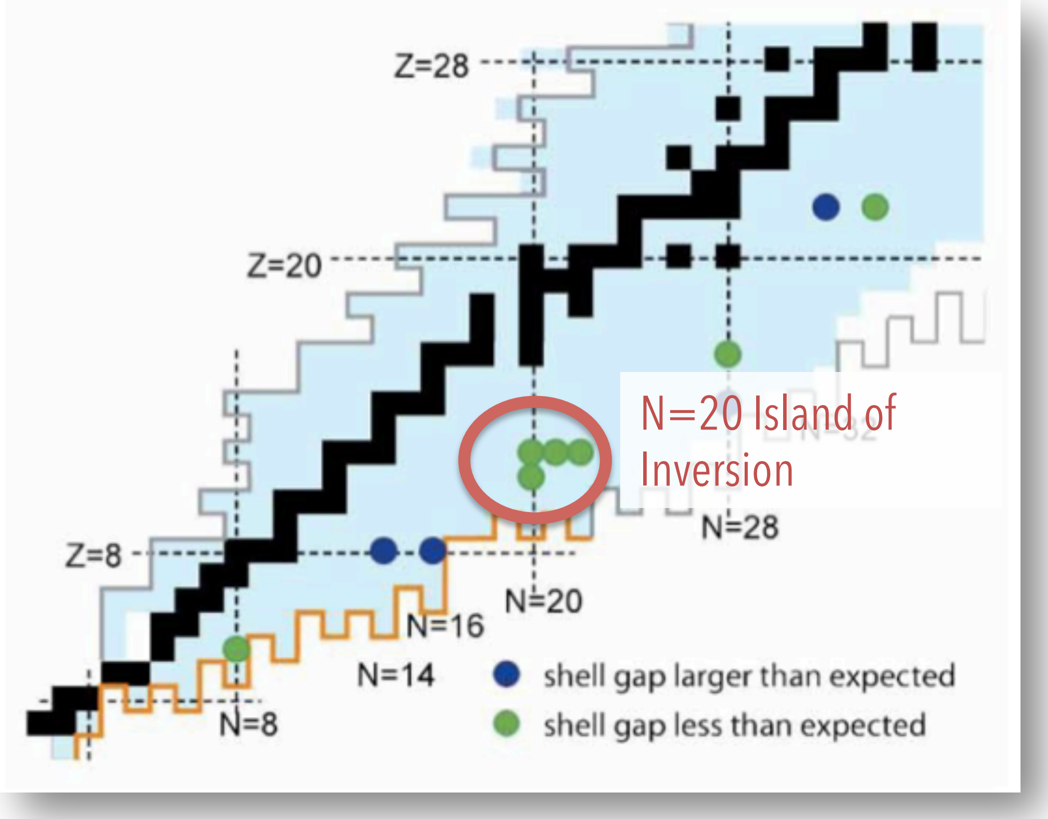

N=20 Island of Inversion

^{32}Mg, at the center of this region, has been a subject of intense work for many years, both experimental and theoretical.

⇒ Much evidence has been obtained for the existence of deformed ground states.

H.L.C. *et al.*, Phys. Rev. C **93**, 031303(R) (2016). A. L. Richard. *et al.*, Phys. Rev. C **96**, 011303(R) (2017).

^{33}Mg -1n KO

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Structure of ^{33}Mg sheds new light on the $N = 20$ island of inversion

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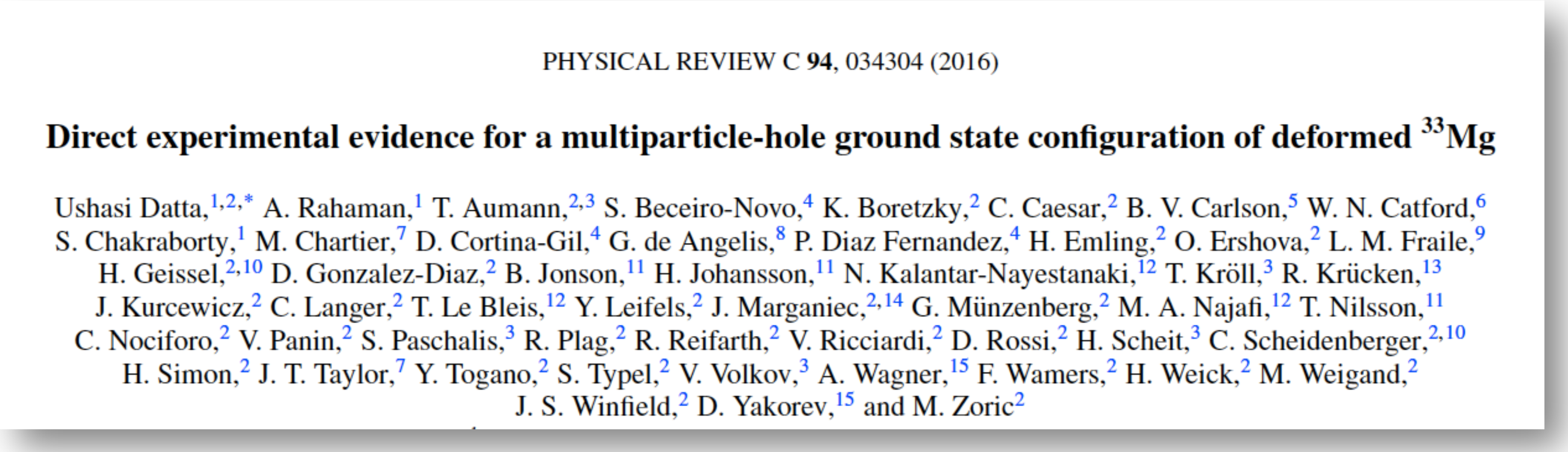
- Longitudinal momentum distribution from the one-neutron removal reaction on a C target at 898 MeV/A.
- Experiment performed at the FRS, GSI.

⇒ An increased contribution from the $2p_{3/2}$ orbital is required to explain the observation showing its lowering compared to existing model predictions.

^{33}Mg – Coulomb breakup



PHYSICAL REVIEW C **94**, 034304 (2016)

Direct experimental evidence for a multiparticle-hole ground state configuration of deformed ^{33}Mg

Ushasi Datta,[1,2,*] A. Rahaman,[1] T. Aumann,[2,3] S. Beceiro-Novo,[4] K. Boretzky,[2] C. Caesar,[2] B. V. Carlson,[5] W. N. Catford,[6]
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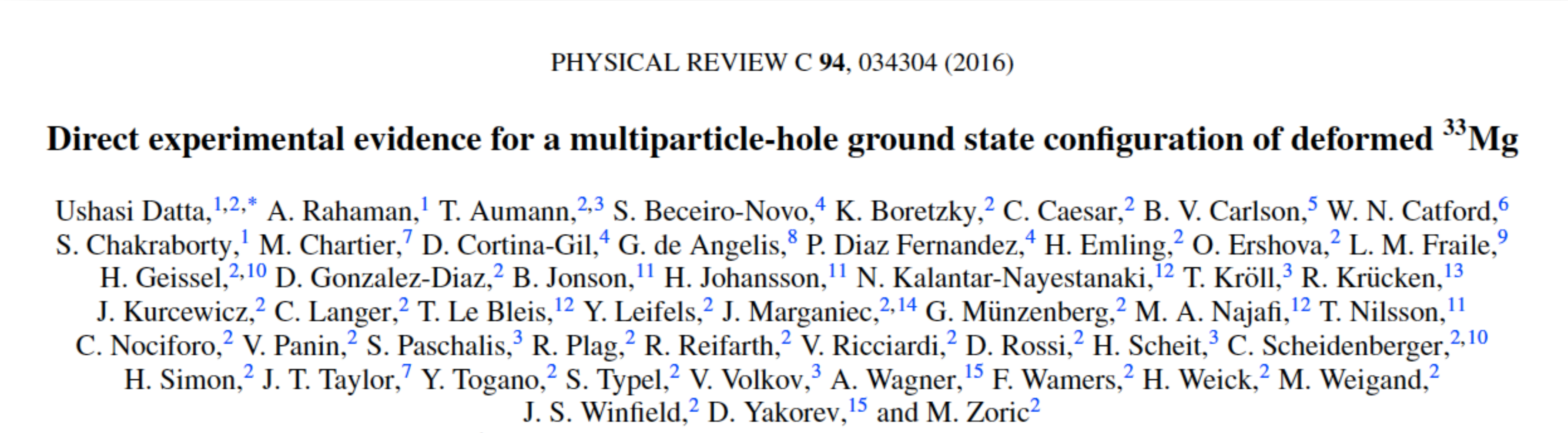
J. S. Winfield,[2] D. Yakorev,[15] and M. Zoric[2]

- Coulomb Dissociation at 400 MeV/A – experimental evidence of a multiparticle-hole ground state configuration in ^{33}Mg

^{33}Mg – Coulomb breakup



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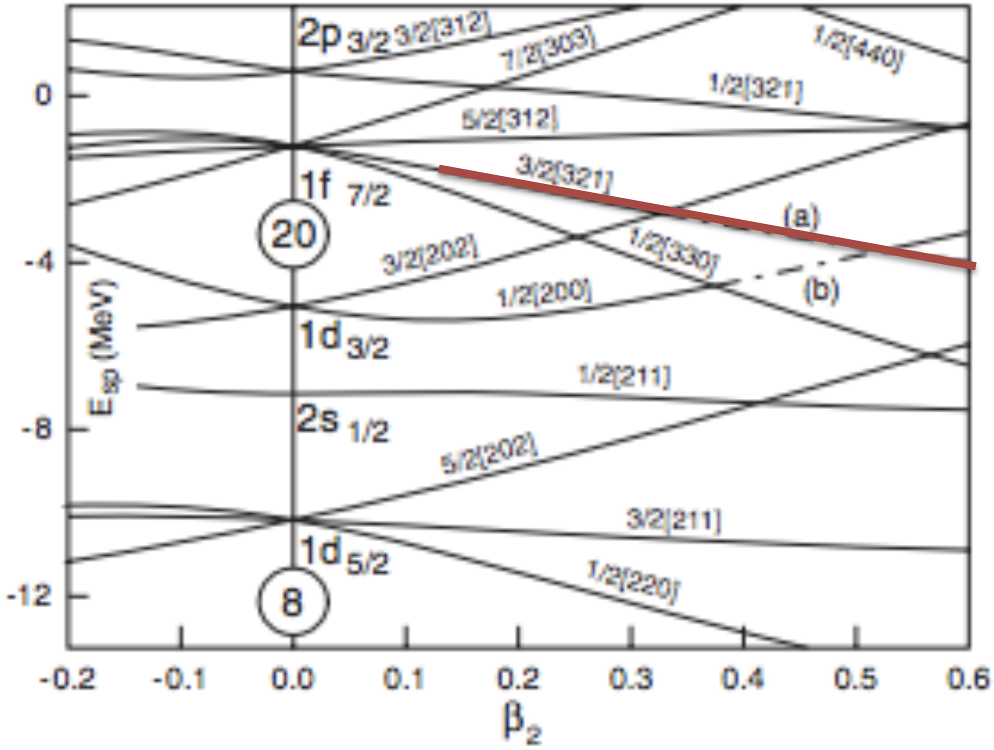
- Coulomb Dissociation at 400 MeV/A – experimental evidence of a multiparticle-hole ground state configuration in ^{33}Mg

⇒ Based on the fact that nuclei inside the islands are well deformed, we consider the description of these reactions in a rotational framework.

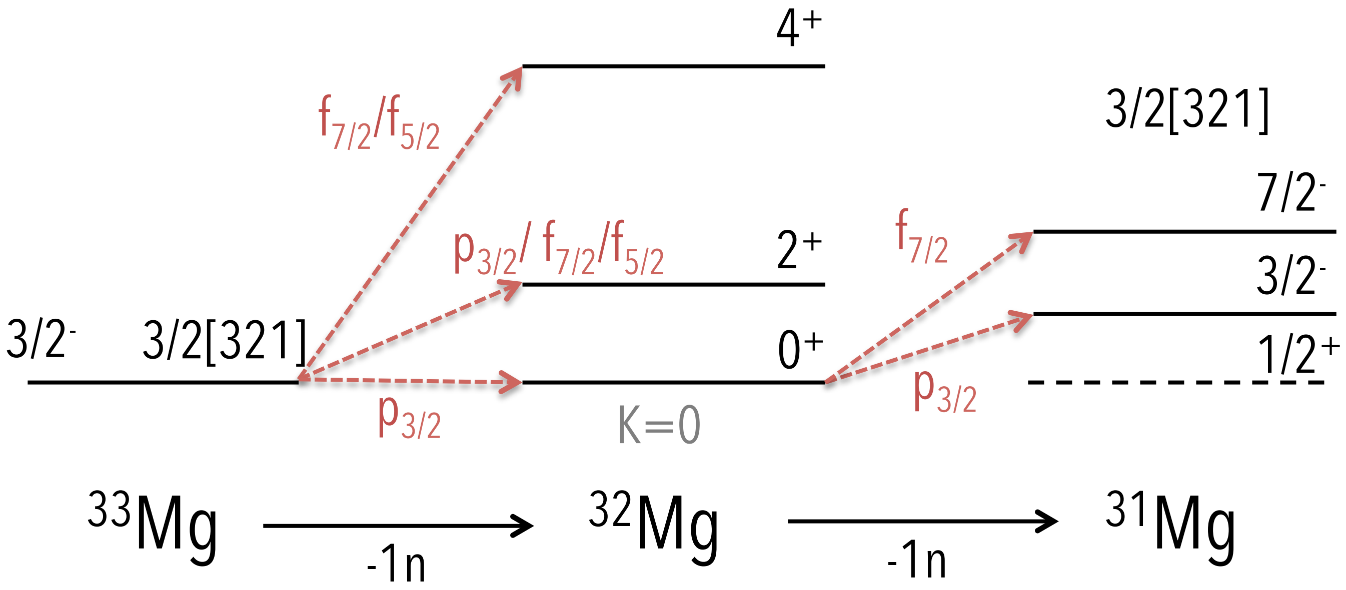
^{33}Mg -1n removal à la Nilsson

Assume ground state of ^{33}Mg is the 3/2[321] neutron Nilsson level



$$|\tfrac{3}{2}[321]\rangle = C_{3/2,1}|p_{3/2}\rangle + C_{5/2,3}|f_{5/2}\rangle + C_{7/2,3}|f_{7/2}\rangle$$

^{33}Mg -1n removal à la Nilsson

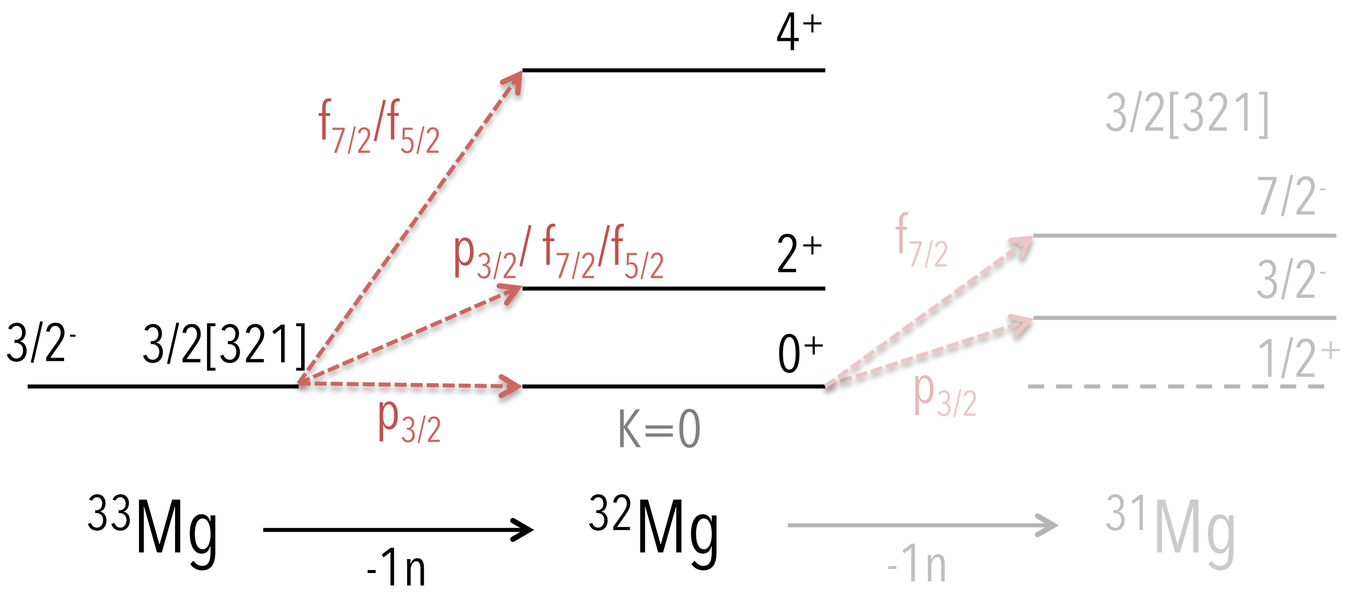


$$\frac{d\sigma}{d\Omega} = \sum_{j,\ell} g^2 \langle I_i j K_i \Delta K | I_f K_f \rangle^2 C^2_{j,\ell} \langle \phi_f | \phi_i \rangle^2 \sigma_\ell^{-1n}$$

$$= \sum_{j,\ell} S_{j,\ell} \times \sigma_\ell^{-1n}$$

B. Elbek and P. Tjom,
Advances in Nucl. Phys. **3**, 259 (1969)

^{33}Mg -1n removal à la Nilsson



4^+

$f_{7/2}/f_{5/2}$

3/2[321]

$7/2^-$

$p_{3/2}/\ f_{7/2}/f_{5/2}$

2^+

$f_{7/2}$

$3/2^-$

$3/2^-$ 3/2[321]

0^+

$1/2^+$

$p_{3/2}$

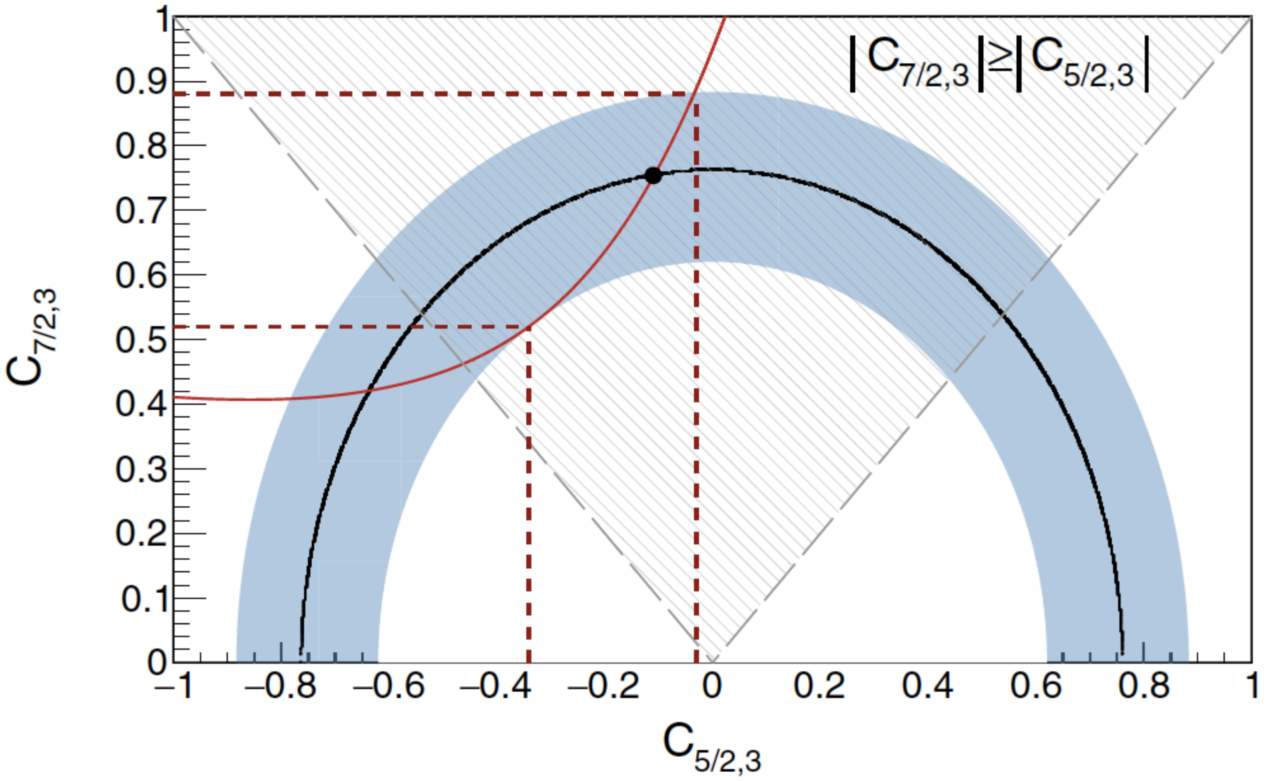
K=0

$p_{3/2}$

^{33}Mg $\xrightarrow[-1n]{}$ ^{32}Mg $\xrightarrow[-1n]{}$ ^{31}Mg

$$\boxed{S_{j,\ell}(-1n) = 2\langle \tfrac{3}{2}\ j\ \tfrac{3}{2}\ -\tfrac{3}{2}|I\ 0\rangle^2 C_{j,\ell}^2}$$

^{33}Mg Magnetic Moment

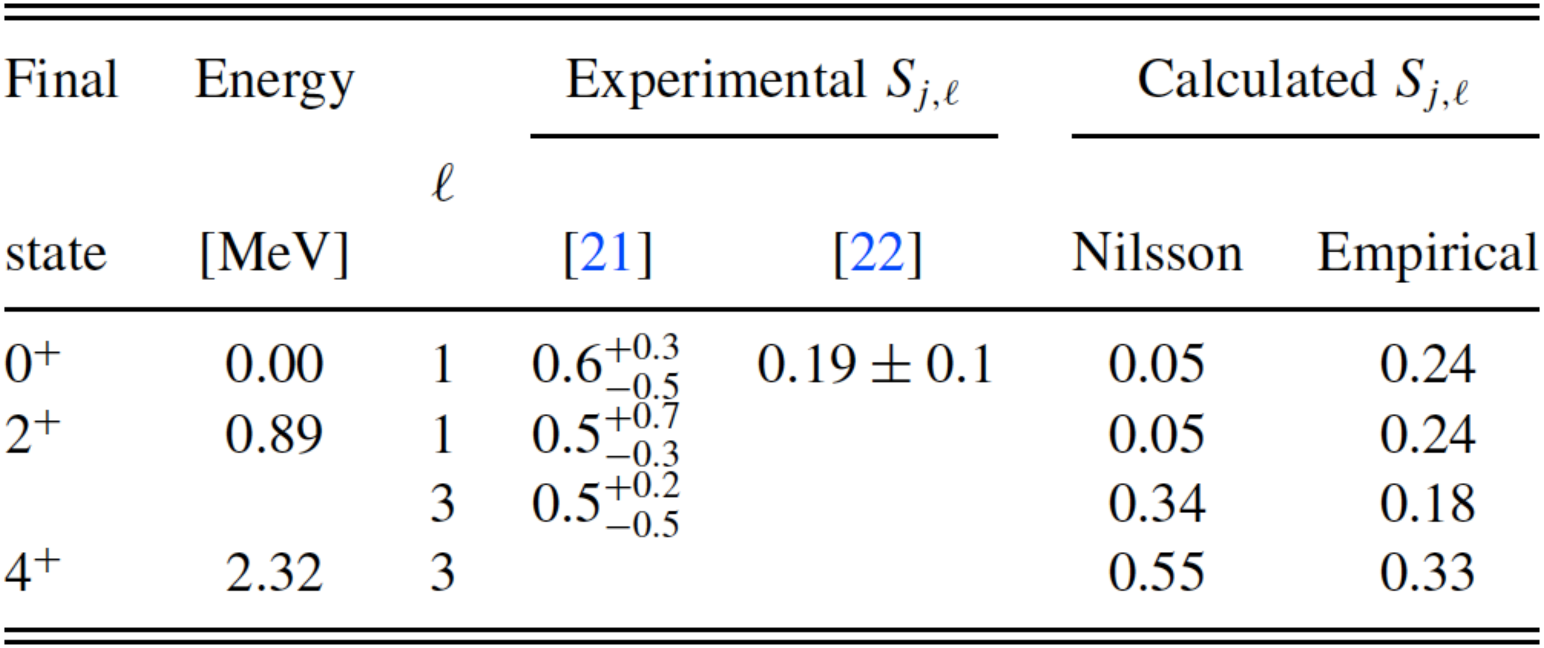


$$\mu = \frac{3}{5}\left(g_s\langle s_3\rangle + g_R\right)$$

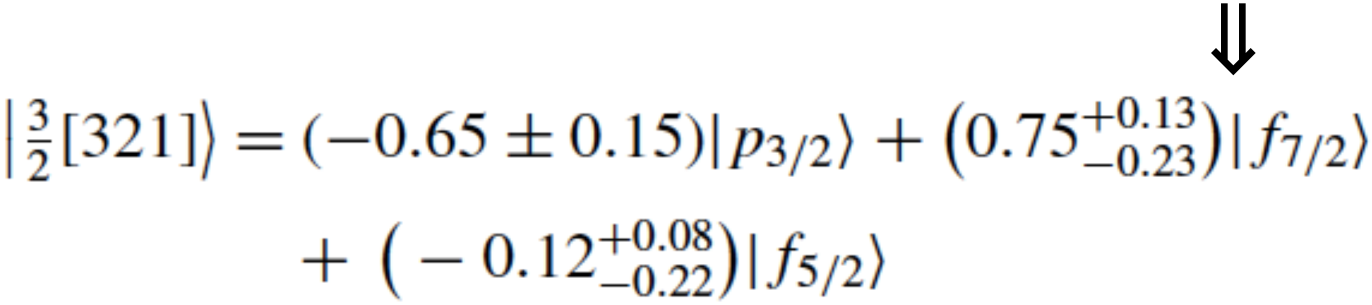
$$\langle s_3\rangle = \frac{1}{2}\Big(C^2_{3/2,1} + \frac{3}{7}\left(C^2_{7/2,3} - C^2_{5/2,3}\right) - \frac{4\sqrt{10}}{7}C_{7/2,3}C_{5/2,3}\Big)$$

⇒ Fully constrain amplitudes based on measured spectroscopic factors, magnetic moment and wavefunction normalization condition

^{33}Mg -1n removal à la Nilsson



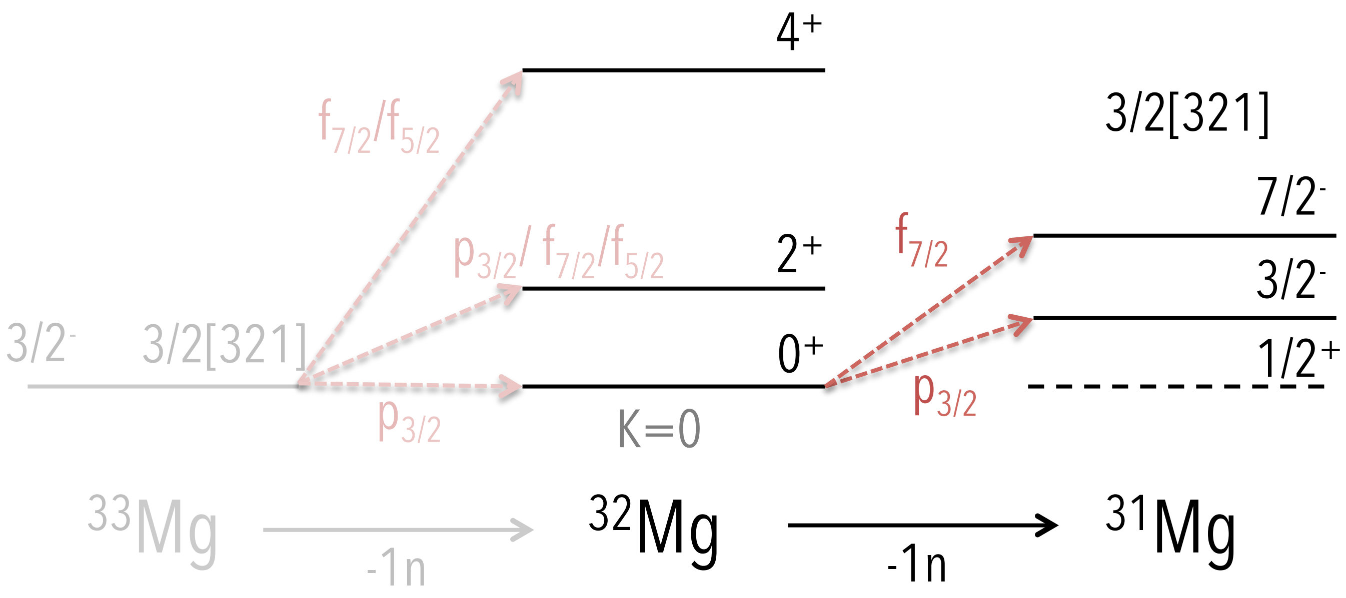
Final state	Energy [MeV]	ℓ	Experimental $S_{j,\ell}$ [21]	Experimental $S_{j,\ell}$ [22]	Calculated $S_{j,\ell}$ Nilsson	Calculated $S_{j,\ell}$ Empirical
0^+	0.00	1	$0.6^{+0.3}_{-0.5}$	0.19 ± 0.1	0.05	0.24
2^+	0.89	1	$0.5^{+0.7}_{-0.3}$		0.05	0.24
		3	$0.5^{+0.2}_{-0.5}$		0.34	0.18
4^+	2.32	3			0.55	0.33



$$\Downarrow$$

$$\left|\tfrac{3}{2}[321]\right\rangle = (-0.65 \pm 0.15)|p_{3/2}\rangle + \left(0.75^{+0.13}_{-0.23}\right)|f_{7/2}\rangle + \left(-0.12^{+0.08}_{-0.22}\right)|f_{5/2}\rangle$$

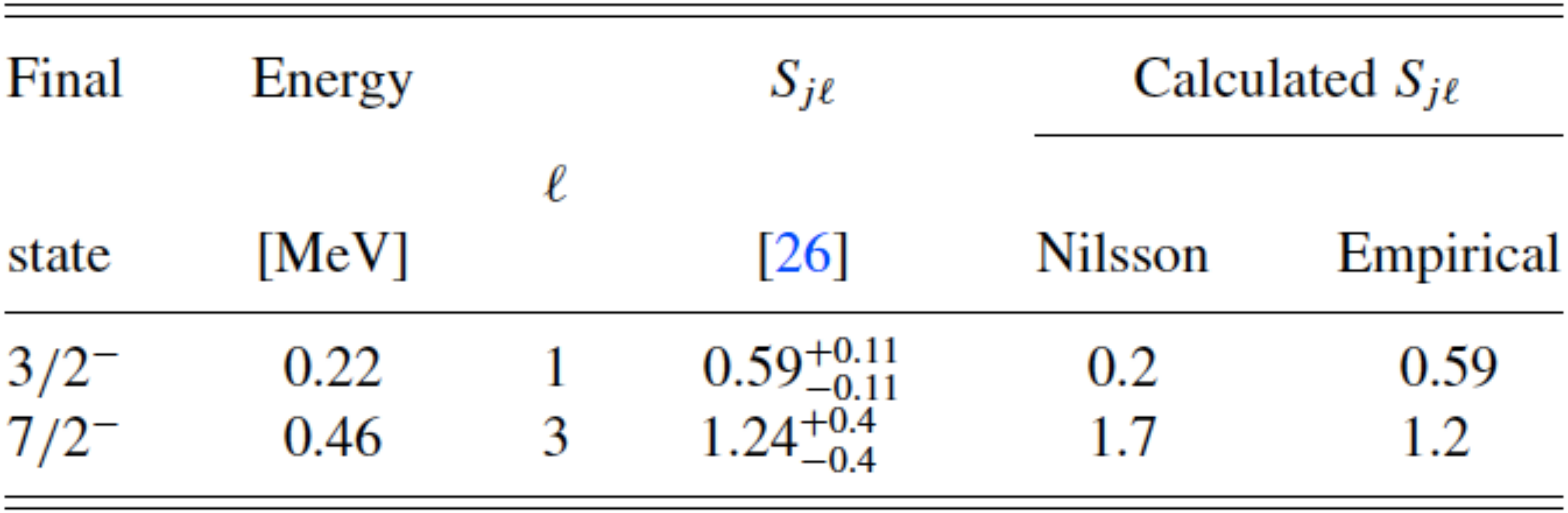
^{32}Mg -1n removal à la Nilsson



$$\boxed{S_{3/2,1}(-1n) = 2C^2_{3/2,1}}$$

$$\boxed{S_{7/2,3}(-1n) = 2C^2_{7/2,3}}$$

^{32}Mg -1n removal à la Nilsson



Final state	Energy [MeV]	ℓ	$S_{j\ell}$ [26]	Calculated $S_{j\ell}$ Nilsson	Calculated $S_{j\ell}$ Empirical
$3/2^-$	0.22	1	$0.59^{+0.11}_{-0.11}$	0.2	0.59
$7/2^-$	0.46	3	$1.24^{+0.4}_{-0.4}$	1.7	1.2

$\Downarrow$

$$\left|\tfrac{3}{2}[321]\right\rangle \approx (-0.54 \pm 0.05)|p_{3/2}\rangle + (0.79 \pm 0.13)|f_{7/2}\rangle + (-0.29 \pm 0.36)|f_{5/2}\rangle.$$

J. R. Terry *et al.*, Phys. Rev. C **77**, 014316 (2008).

A.O. Macchiavelli, HLC *et al.*, Phys. Rev. C **96**, 054302 (2017).

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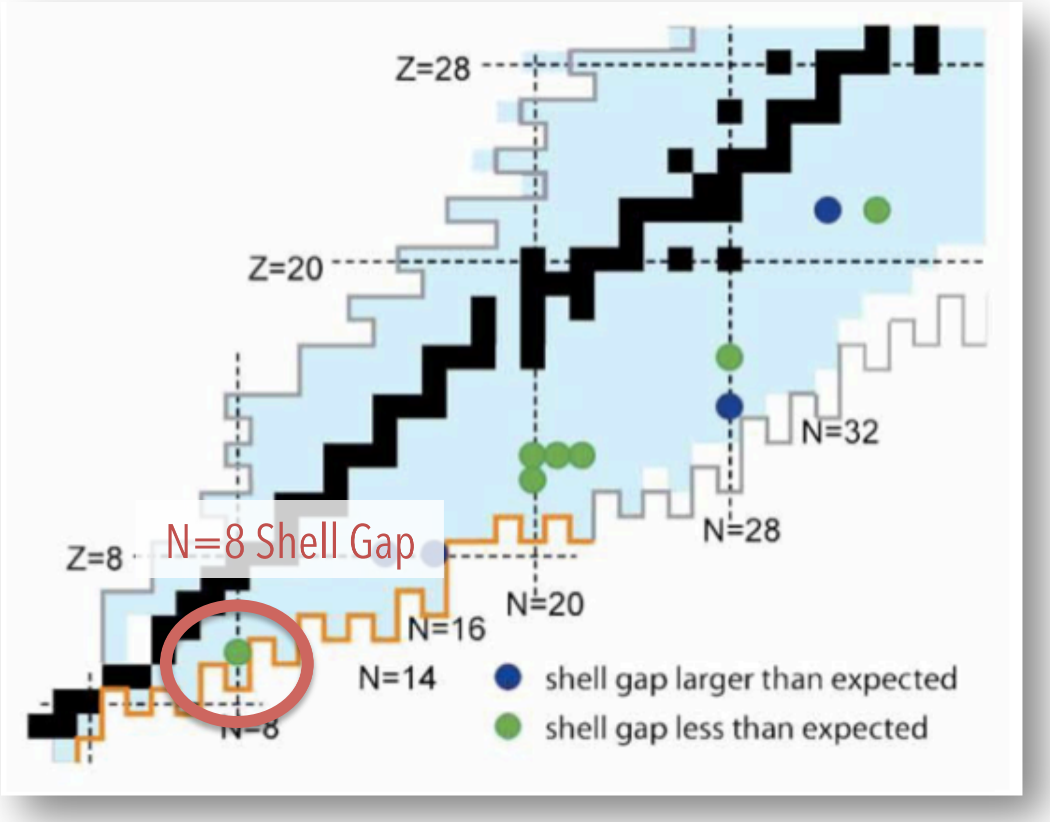
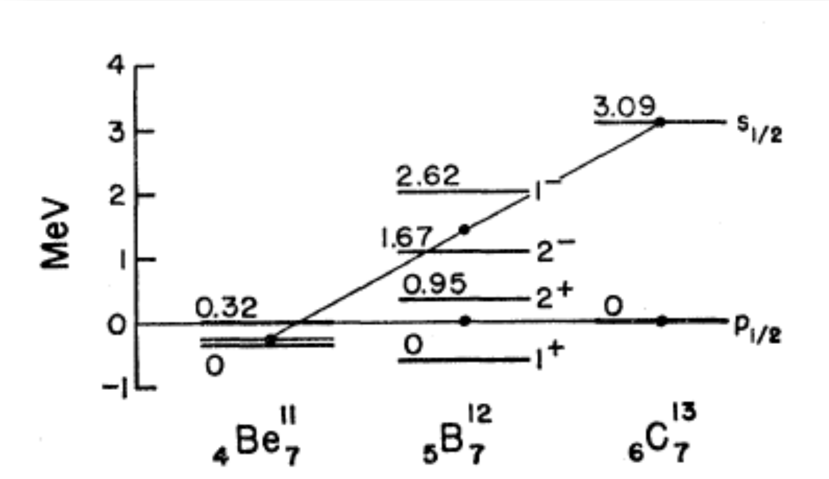
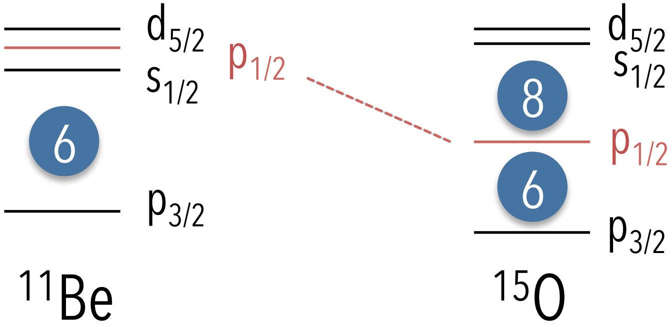


N=8 Shell Gap

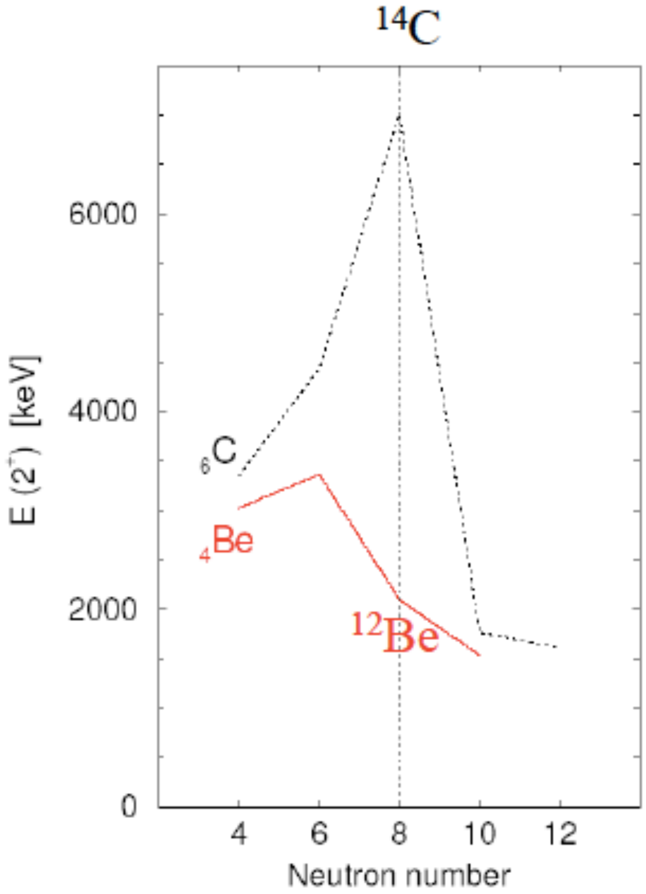
The "First" Island of Inversion: *N*=8





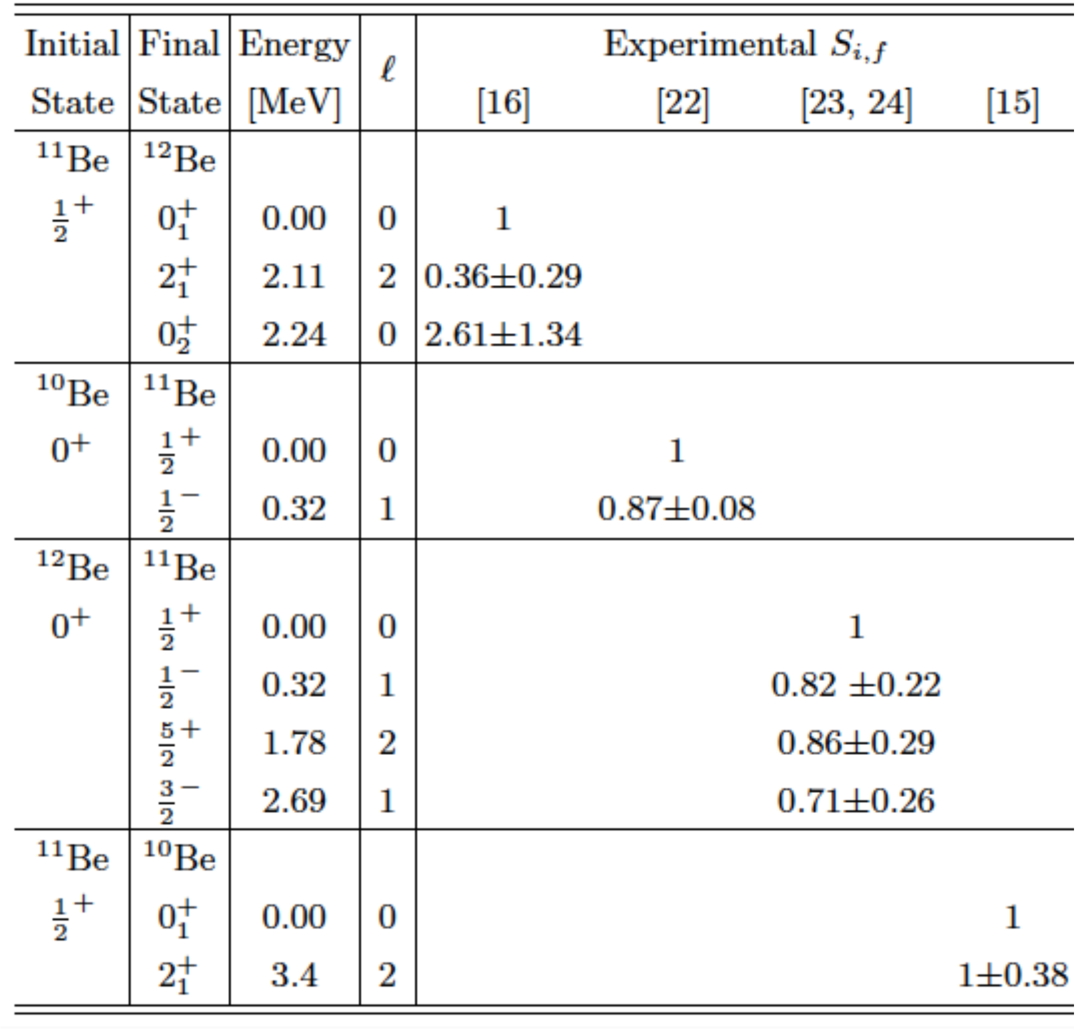
Role of $\pi p_{3/2}$-$\nu p_{1/2}$ Interaction

N=8 Shell Closure



I. Talmi and I. Unna, Phys. Rev. Lett. 4 469 (1960)

Direct Reactions Studies



Initial State	Final State	Energy [MeV]	ℓ	Experimental $S_{i,f}$			
				[16]	[22]	[23, 24]	[15]
^{11}Be	^{12}Be						
$\frac{1}{2}^+$	0_1^+	0.00	0	1			
	2_1^+	2.11	2	0.36±0.29			
	0_2^+	2.24	0	2.61±1.34			
^{10}Be	^{11}Be						
0^+	$\frac{1}{2}^+$	0.00	0		1		
	$\frac{1}{2}^-$	0.32	1		0.87±0.08		
^{12}Be	^{11}Be						
0^+	$\frac{1}{2}^+$	0.00	0			1	
	$\frac{1}{2}^-$	0.32	1			0.82 ±0.22	
	$\frac{5}{2}^+$	1.78	2			0.86±0.29	
	$\frac{3}{2}^-$	2.69	1			0.71±0.26	
^{11}Be	^{10}Be						
$\frac{1}{2}^+$	0_1^+	0.00	0				1
	2_1^+	3.4	2				1±0.38

R. Kanungo *et al.*, PLB **682**, 391 (2010).

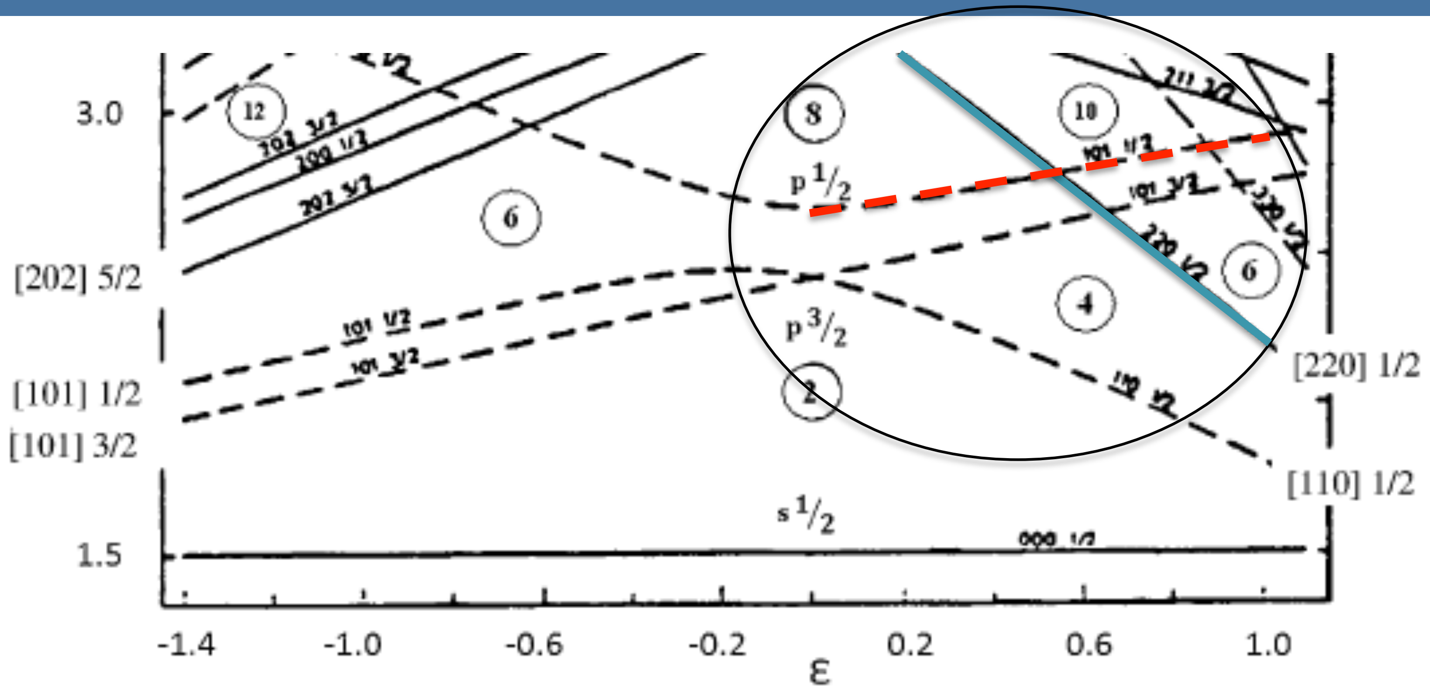
K. T. Schmitt *et al.*, PRL **108**, 192701 (2012).

A. Navin, et al., PRL **85**, 266 (2000).

S. Pain, et al. PRL **96**, 032502 (2006).

J.S. Winfield *et al.*,
Nucl. Phys. A **683**, 48 (2001)

The Nilsson Picture

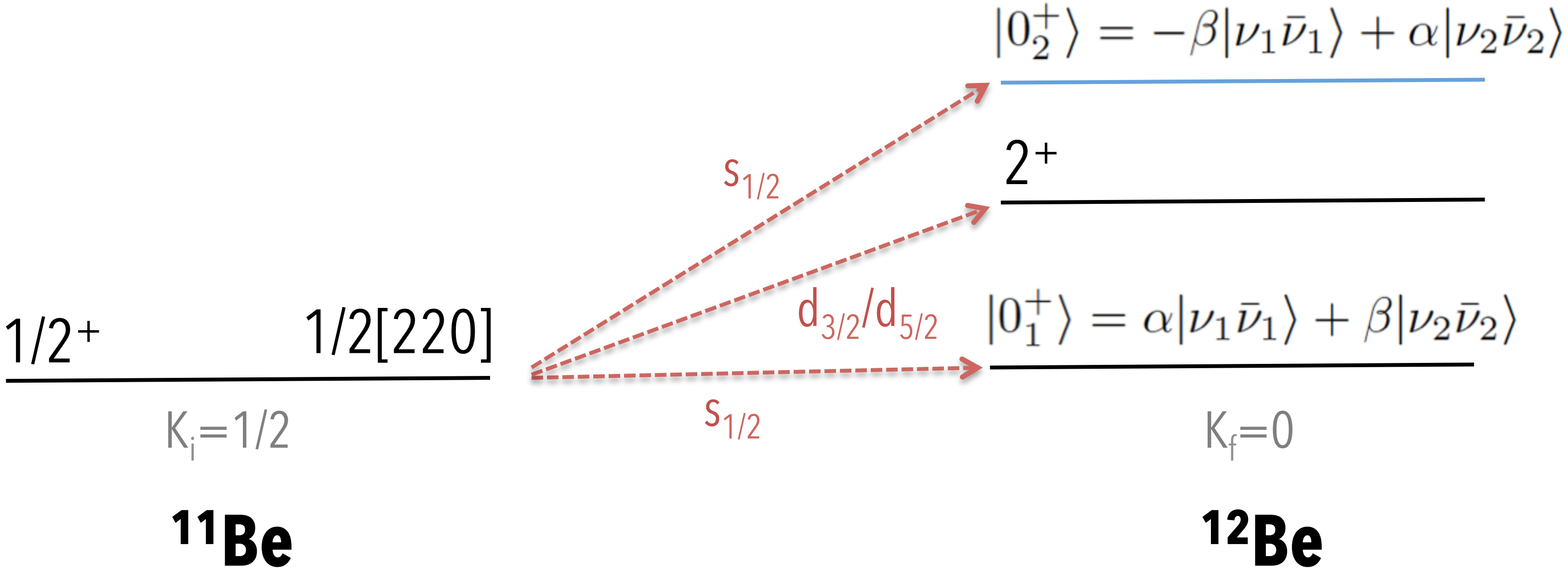


$$|\tfrac{1}{2}[220]\rangle = C_{1/2,0}|s_{1/2}\rangle + C_{3/2,2}|d_{3/2}\rangle + C_{5/2,2}|d_{5/2}\rangle$$

$$|\tfrac{1}{2}[101]\rangle = C_{1/2,1}|p_{1/2}\rangle + C_{3/2,1}|p_{3/2}\rangle$$

A. Bohr and B. R. Mottelson, Nuclear Structure Volume II
W. Von Oertzen, M. Freer, and Y. Kanada-En'yo Physics Reports **432,** 43 (2006).
I. Hamamoto and S. Shimoura J. Phys. G: Nucl. Part. Phys. **34**, 2715 (2007).

^{11}Be(d,p)^{12}Be à la Nilsson



$|0_2^+\rangle = -\beta|\nu_1\bar{\nu}_1\rangle + \alpha|\nu_2\bar{\nu}_2\rangle$

2^+

$|0_1^+\rangle = \alpha|\nu_1\bar{\nu}_1\rangle + \beta|\nu_2\bar{\nu}_2\rangle$

$1/2^+$ 1/2[220]

$K_i=1/2$

$s_{1/2}$

$d_{3/2}/d_{5/2}$

$s_{1/2}$

$K_f=0$

^{11}Be

^{12}Be

$$S_{i,f} = \frac{(2I_i+1)}{(2I_f+1)} g^2 \langle I_i j K_i \Delta K | I_f K_f \rangle^2 C_{j,\ell}^2 \langle \phi_f | \phi_i \rangle^2$$

Analysis

- Total of 15 relations (11 direct reaction spectroscopic factors + magnetic moment of ^{11}Be + 3 wavefunction normalizations) connect the experimental data to 7 unknown amplitudes
- Determine amplitudes from a χ^2-minimization procedure.

⇒ Weighted fit of the relative spectroscopic factor values with respect to the ground state transition for each of the data sets, and of the absolute value of the ^{11}Be ground-state magnetic moment.

Analysis and Results

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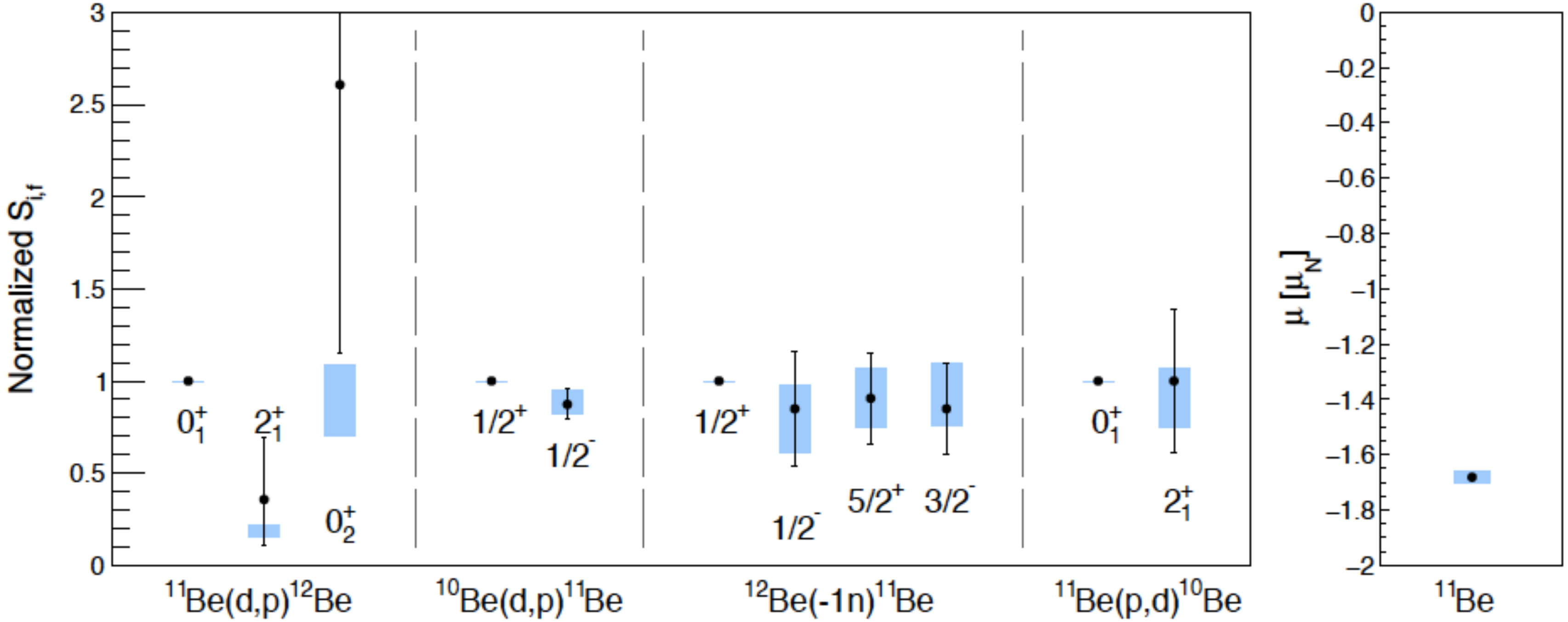


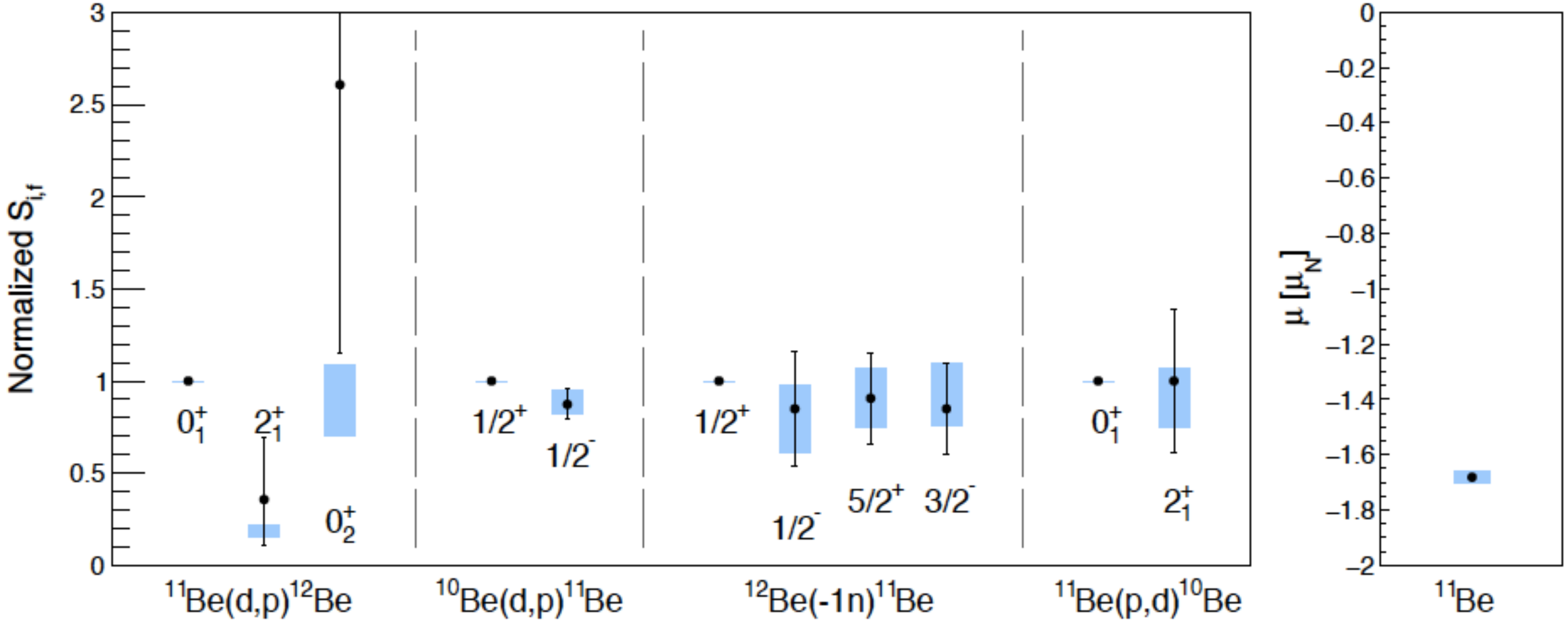
Analysis and Results

$$|\tfrac{1}{2}[220]\rangle \approx -0.72(4)|s_{1/2}\rangle - 0.09(2)|d_{3/2}\rangle + 0.69(4)|d_{5/2}\rangle$$

$$|\tfrac{1}{2}[101]\rangle \approx 0.68(4)|p_{1/2}\rangle + 0.73(3)|p_{3/2}\rangle$$

$$\alpha = 0.73(4) \text{ and } \beta = 0.69(4)$$

A.O. Macchiavelli, HLC *et al.*, submitted.



Summary I

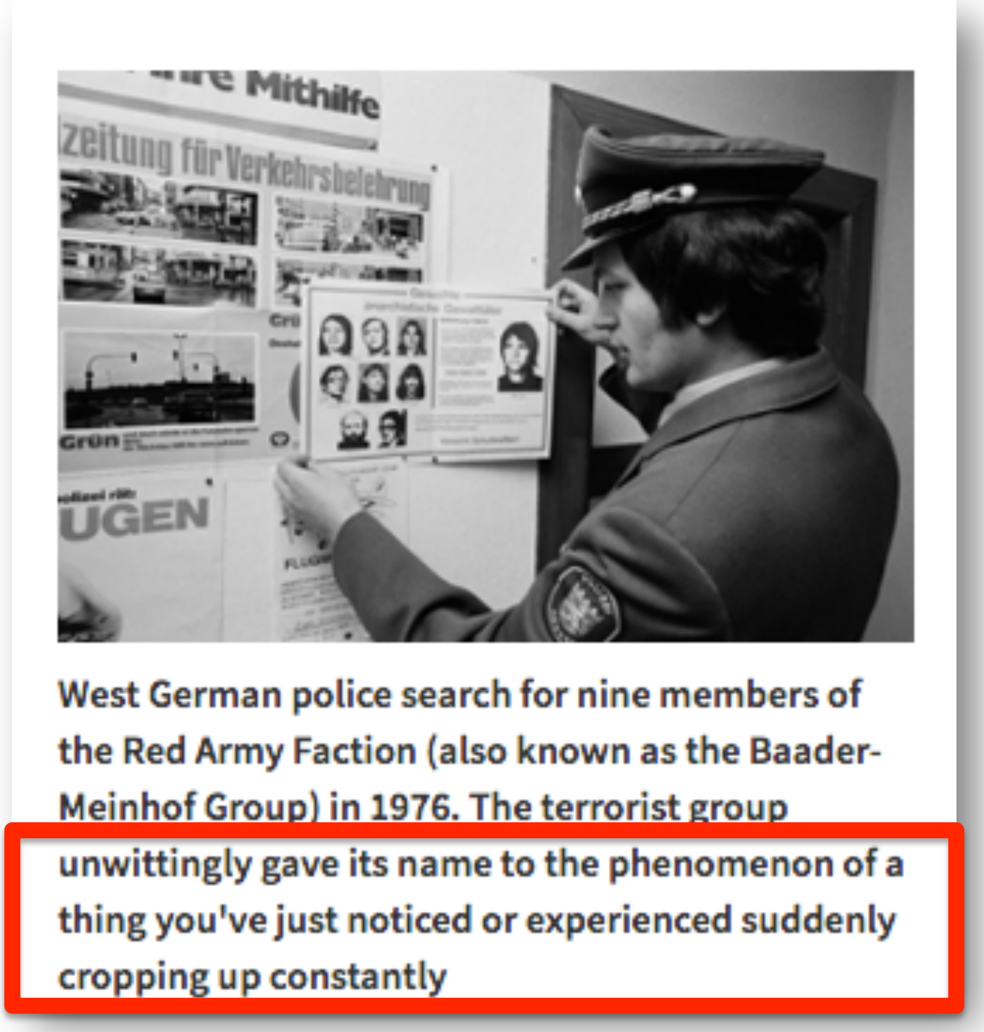
- Description of nucleon knockout and transfer reactions in the deformed 'Islands of Inversion' at $N=8$ and $N=20$ allows a straightforward analysis of results

- Nilsson wavefunction amplitudes are directly related to the spectroscopic factors

- $N=20$ – adjusted wavefunction for 3/2[321] level is consistent with reduced $1f_{7/2}$-$2p_{3/2}$ gap, consistent with other approaches

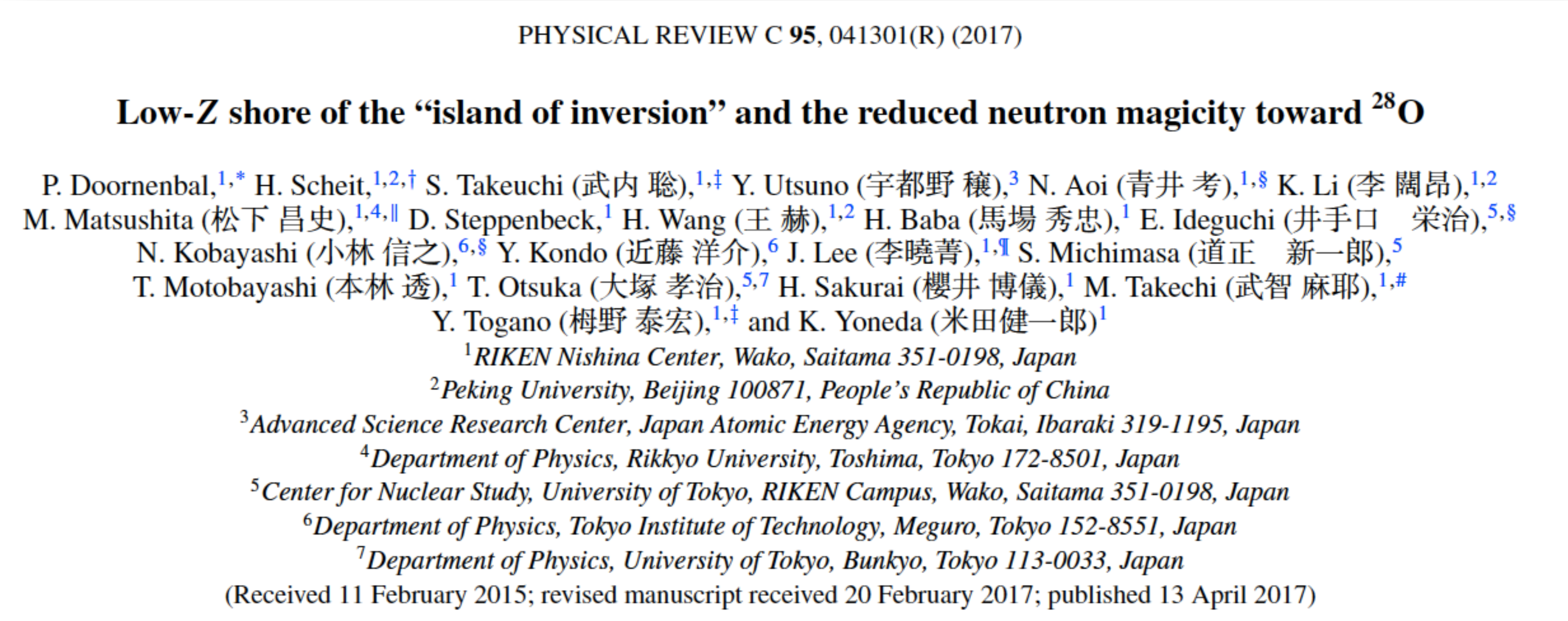
- $N=8$ – minimization of wavefunctions to all available data provides excellent agreement; predictions for other reactions are possible

Manifestation of the Baader-Meinhof Phenomenon in AOM



West German police search for nine members of the Red Army Faction (also known as the Baader-Meinhof Group) in 1976. The terrorist group unwittingly gave its name to the phenomenon of a thing you've just noticed or experienced suddenly cropping up constantly

Structure of ^{29}F



PHYSICAL REVIEW C **95**, 041301(R) (2017)

Low-*Z* shore of the "island of inversion" and the reduced neutron magicity toward ^{28}O

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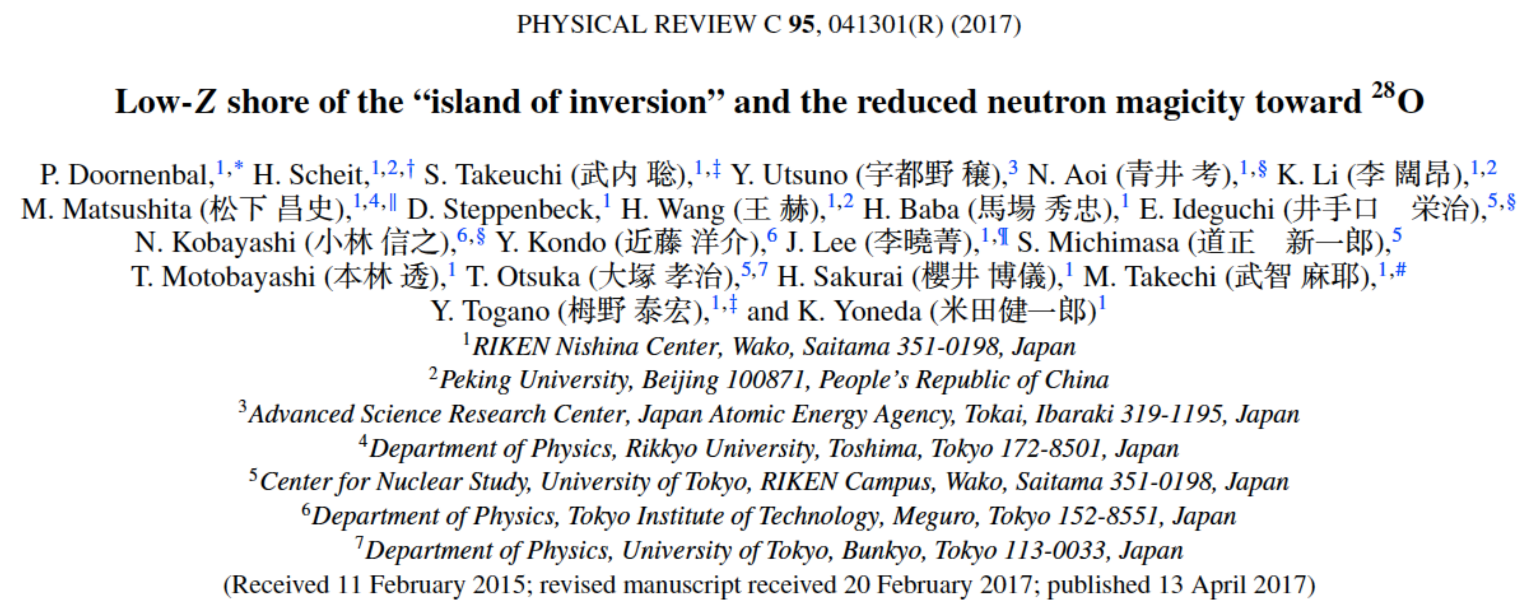
- $1/2^+$ in ^{29}F identified; shell model calculations using effective interactions indicate that the *N*=20 gap is quenched in ^{29}F, and the "Island of Inversion" extends to proton number *Z*=9.
- Strong correlation of $1/2^+$ energy to the *N*=20 gap, observed energy suggests persistent reduced neutron gap for ^{28}O.

Structure of ^{29}F



PHYSICAL REVIEW C **95**, 041301(R) (2017)

Low-Z shore of the "island of inversion" and the reduced neutron magicity toward ^{28}O

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- $1/2^+$ in ^{29}F identified; shell model calculations using effective interactions indicate that the $N=20$ gap is quenched in ^{29}F, and the "Island of Inversion" extends to proton number $Z=9$.
- Strong correlation of $1/2^+$ energy to the $N=20$ gap, observed energy suggests persistent reduced neutron gap for ^{28}O.

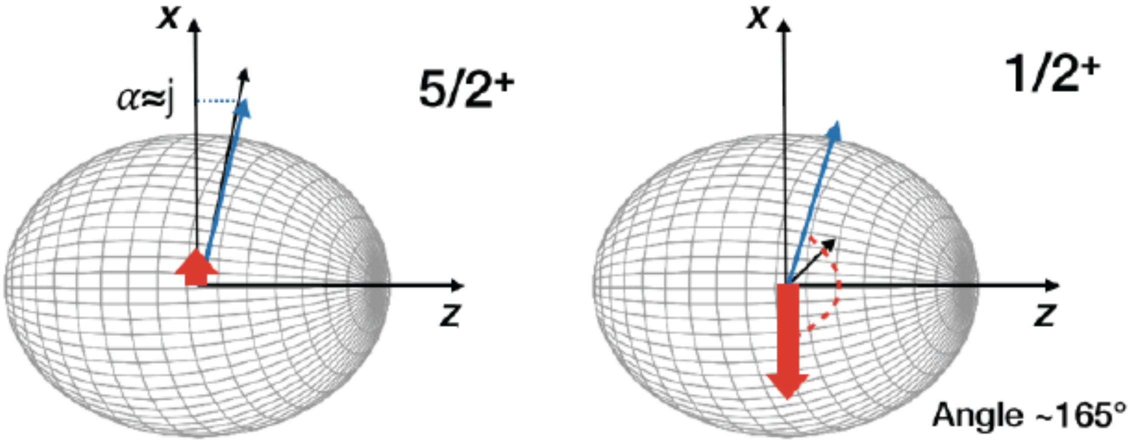
⇒ PRM description – neutron + ^{28}O

Structure of ^{29}F

PRM
Hamiltonian

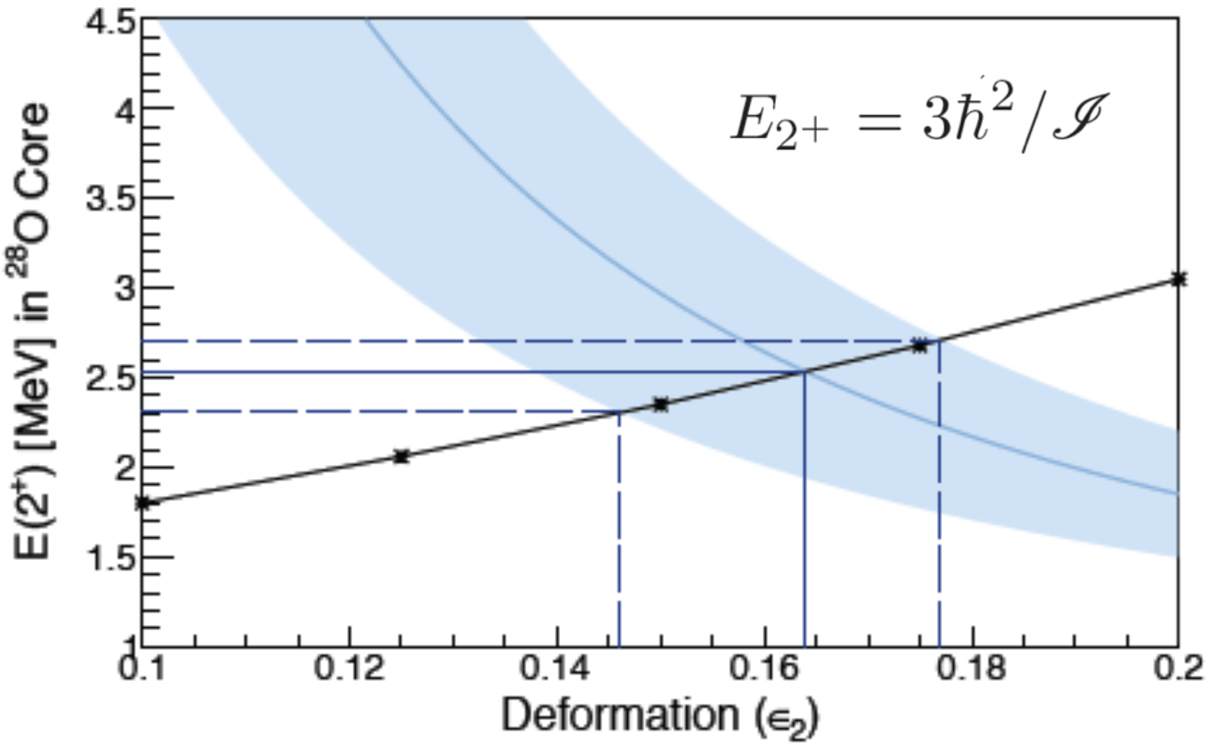
$$H = E_\Omega + \frac{\hbar^2}{2\mathcal{J}} I(I+1) + H_C$$

$$H_C = -\frac{\hbar^2}{2\mathcal{J}}(I_+ j_- + I_- j_+)$$



At small/moderate deformation, Coriolis matrix elements dominate over intrinsic level spacings, and rotation-aligned coupling limit is reached.

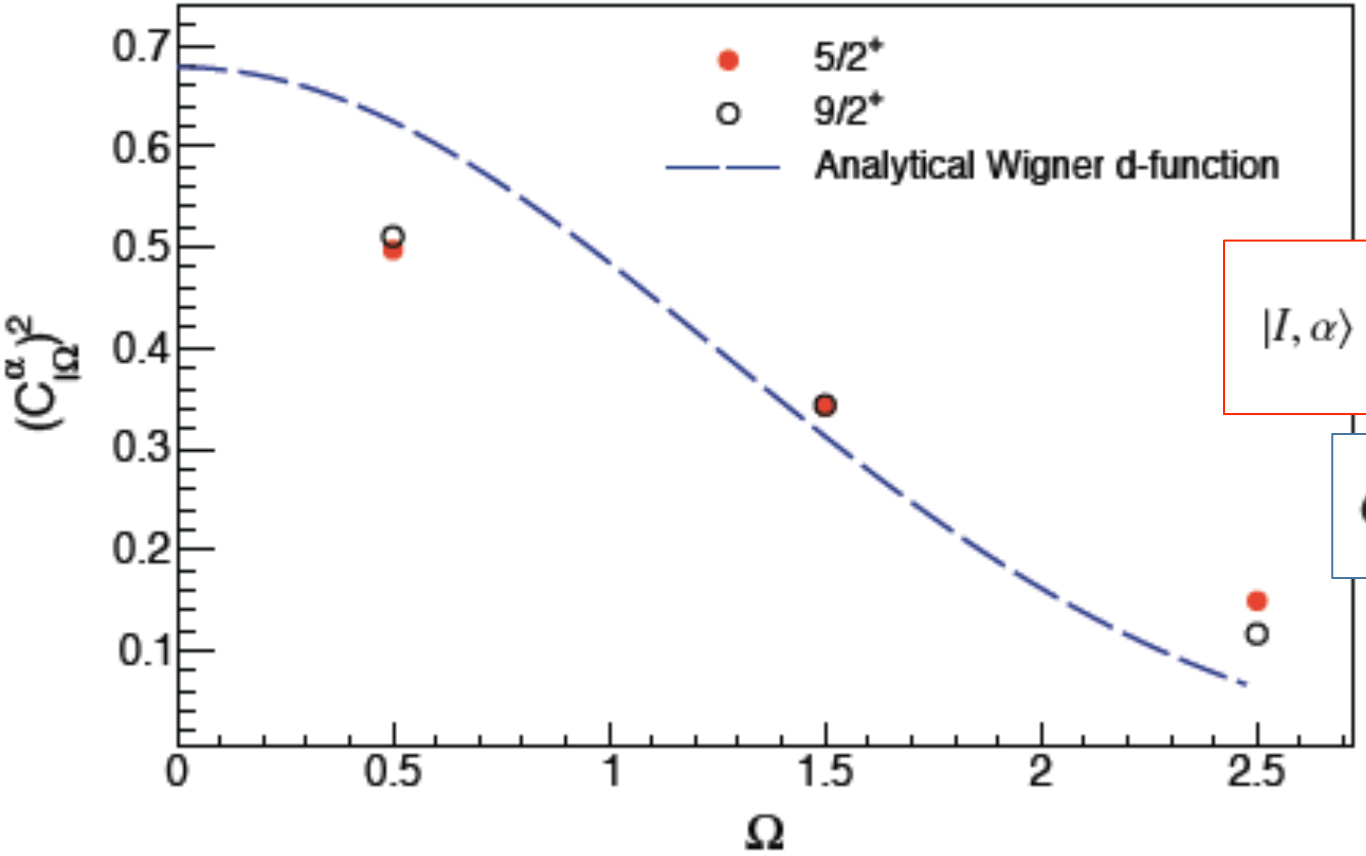
Structure of ^{29}F: PRM Solution



PRM

$$\mathscr{I} = \frac{\mathscr{I}_{rigid}}{(1+(\frac{2\Delta}{\hbar\omega_0\epsilon_2})^2)^{3/2}}$$

Structure of ^{29}F: Decoupled Band



$$|I,\alpha\rangle = \sum_{\Omega_p=1/2}^{5/2} C^{\alpha}_{I\Omega_p}|I,\Omega_p\rangle$$

$$C^{\alpha}_{I\Omega} \approx d^{j}_{\alpha,\Omega}(\pi/2)$$

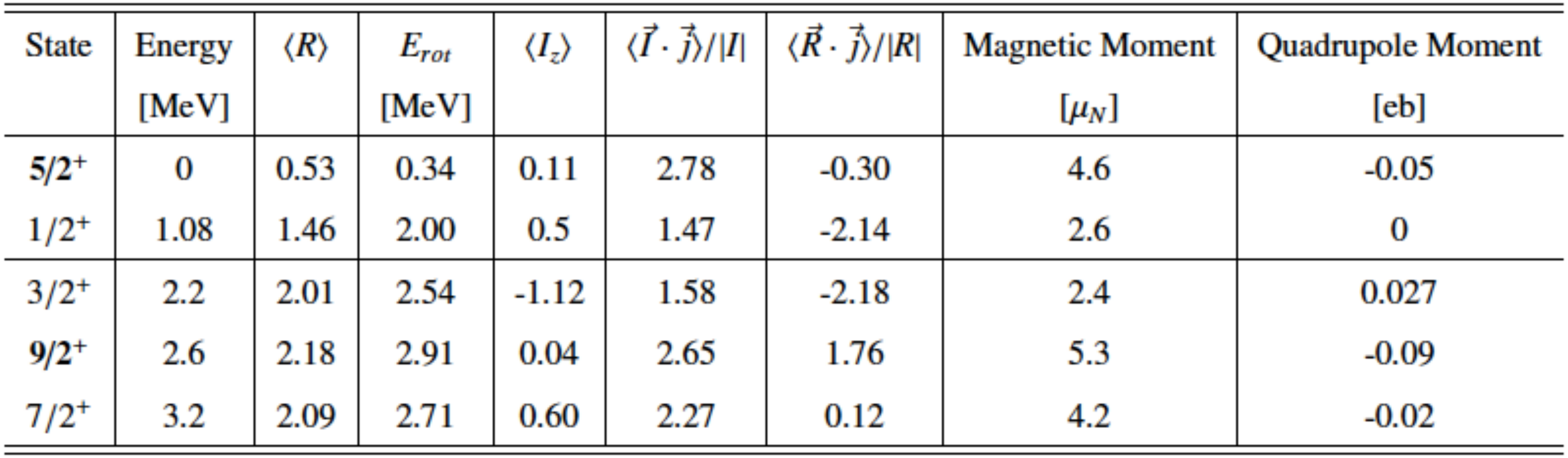
Structure of ^{29}F: PRM Solution

State	Energy [MeV]	$\langle R \rangle$	E_{rot} [MeV]	$\langle I_z \rangle$	$\langle \vec{I} \cdot \vec{j} \rangle / \lvert I \rvert$	$\langle \vec{R} \cdot \vec{j} \rangle / \lvert R \rvert$	Magnetic Moment [μ_N]	Quadrupole Moment [eb]
$5/2^+$	0	0.53	0.34	0.11	2.78	-0.30	4.6	-0.05
$1/2^+$	1.08	1.46	2.00	0.5	1.47	-2.14	2.6	0
$3/2^+$	2.2	2.01	2.54	-1.12	1.58	-2.18	2.4	0.027
$9/2^+$	2.6	2.18	2.91	0.04	2.65	1.76	5.3	-0.09
$7/2^+$	3.2	2.09	2.71	0.60	2.27	0.12	4.2	-0.02

Population in -1p Knockout

$$\frac{\sigma^{\ell=0}_{1/2^+}}{\sigma^{\ell=2}_{5/2^+}} \approx \frac{\sum_{i=1}^{3} C_{1/2,1/2_i} \cdot c_{s_{1/2},1/2_i} \cdot u_{1/2_i}}{\sum_{\Omega_p=1/2}^{5/2} C_{5/2,\Omega_p} \cdot c_{d_{5/2},\Omega_p} \cdot u_{\Omega_p}} \approx 13\%$$

Structure of ^{29}F: PRM Solution



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⇒ Measured 11(3)% !!

A.O. Macchiavelli, HLC *et al.*, Phys. Lett. B (2017) – in press.

Summary II

- The low-lying structure of ^{29}F ($1/2^+$ state at 1.08 MeV) can be understood in terms of the rotation-aligned coupling limit of the PRM
- Coriolis coupling on the $d_{5/2}$ proton Nilsson multiplet gives rise to a decoupled band with $5/2^+$ bandhead and $1/2^+$ with energy depending on core (^{28}O) 2^+ energy
- Consistent solution with moderate deformation ($\varepsilon \sim 0.16$) and E(2^+) in ^{28}O = 2.5(2) MeV, in line with large scale shell model
- Predictions for double-decoupled band in ^{30}F – 6^- ground state?

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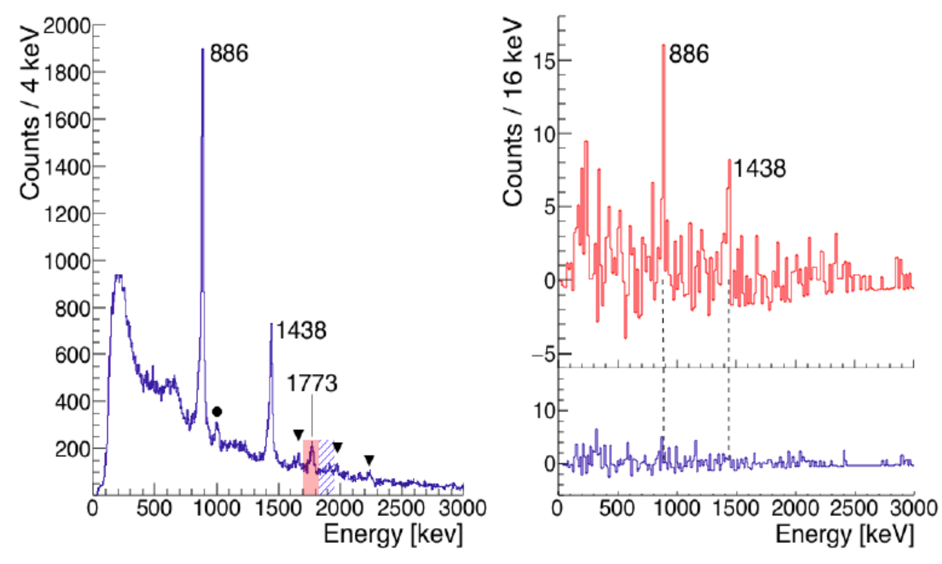
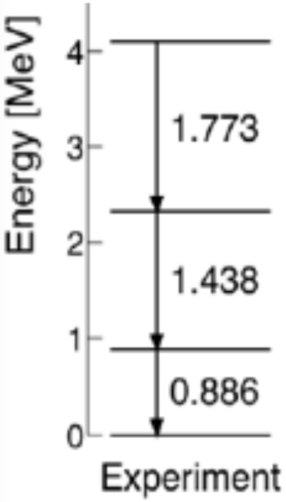
Thank you!

Backup

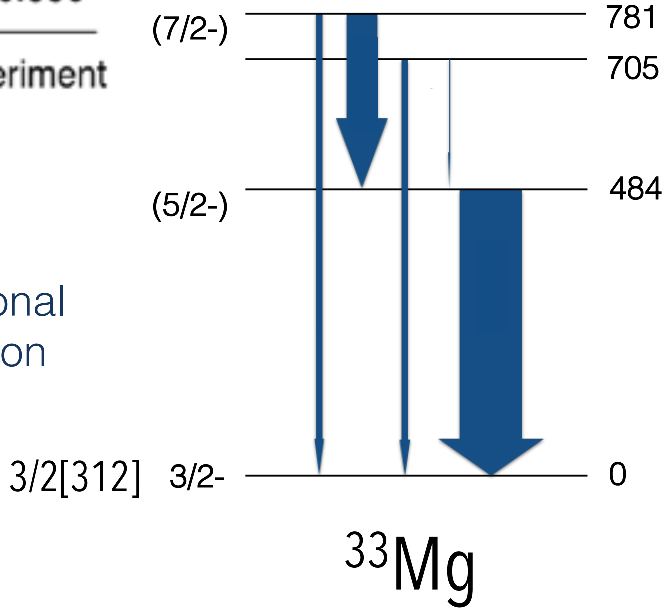
Rotational Band Structure in ^{32,33}Mg

H.L.C. *et al.*, Phys. Rev. C **93**, 031303(R) (2016).





- ^{33}Mg populated in the same experiment shows a rotational band that can be described in leading order as a neutron (Nilsson 3/2[312]) coupled to the ^{32}Mg core



A. L. Richard. *et al.*, Phys. Rev. C **96**, 011303(R) (2017).