Proton-neutron correlations from particle transfer reactions

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UNEDF

Short Overview

- Few more examples of proton-neutron correlations effects in nuclei
- Proton-neutron correlations effects observed in transfer reactions
- Which pieces of the shell model Hamiltonian seem to be responsible for these effects

Staggering of Ca Isotopes **Charge Radii**: A Shell Model Approach

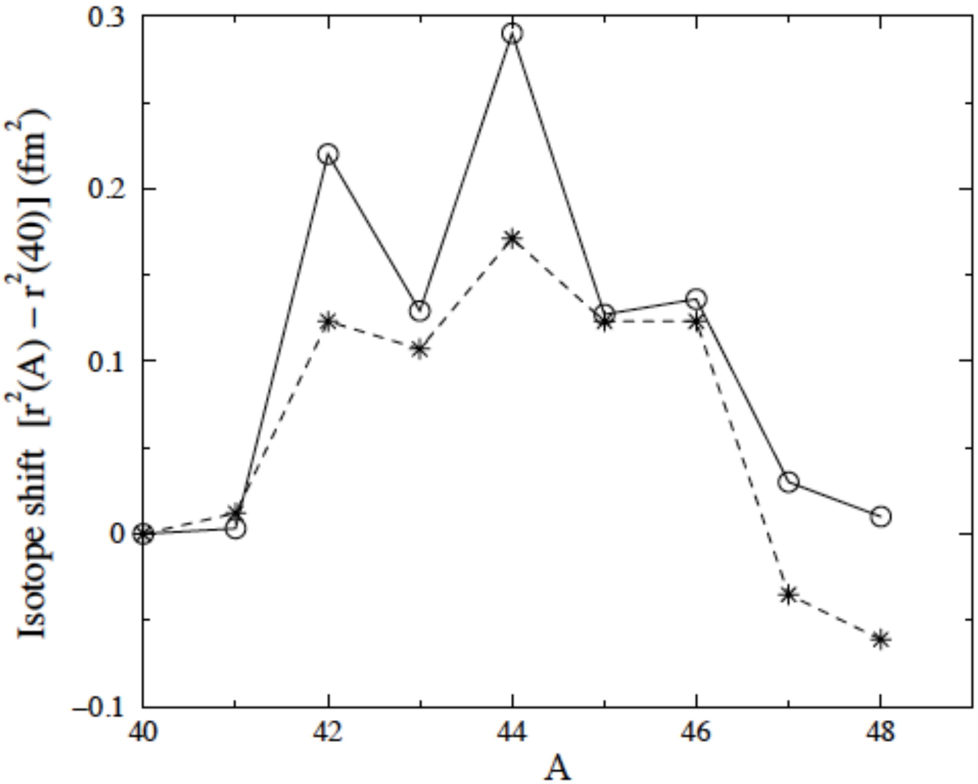


FIG. 2. Isotope shifts in calcium. The experimental data (circles connected by a solid line) and the shell model results, Eq.(1), (stars connected by a dashed line) are shown.

Valence space:

$d_{3/2}\,, s_{1/2}\,, f_{7/2}\,, p_{3/2}$

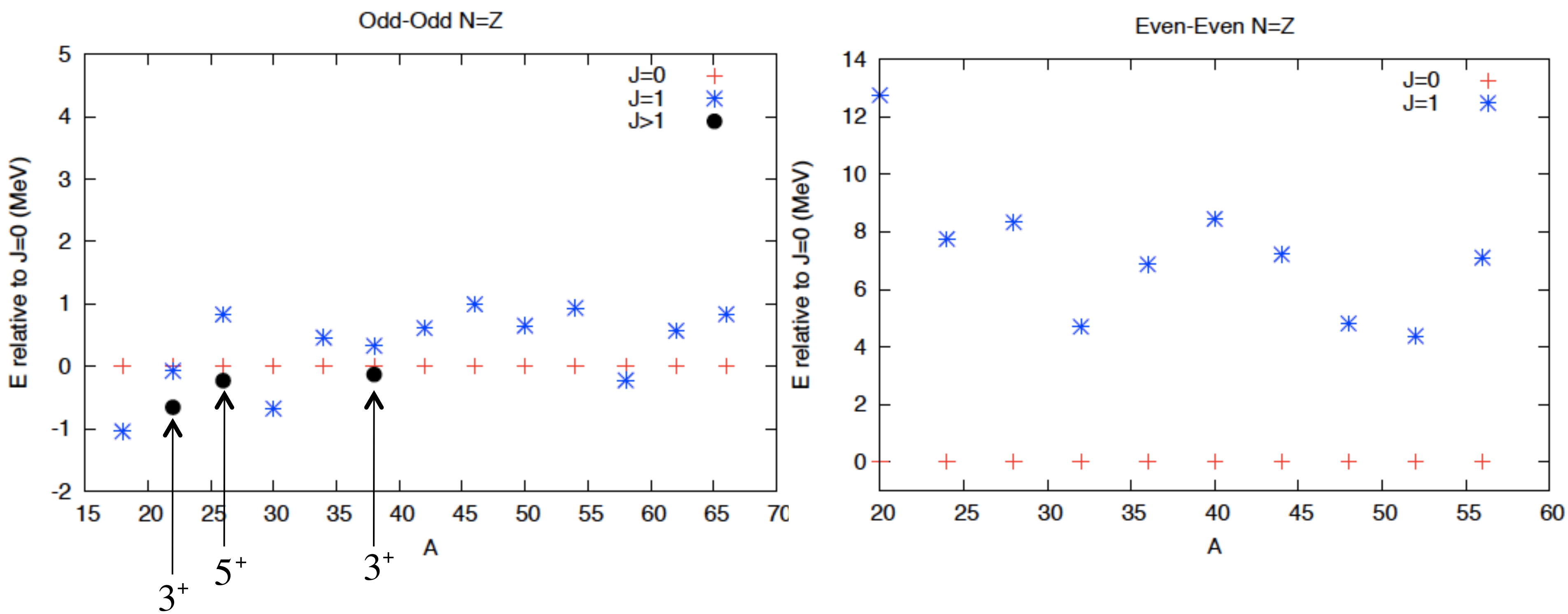
$$H_{valence} \equiv H_{2-body}$$

$$\langle r^2 \rangle_{ch} = \langle r^2 \rangle_{sd} n^p_{sd} + \langle r^2 \rangle_{pf} n^p_{pf}$$

E. Caurier et al, PLB **522**, 240 (2001)

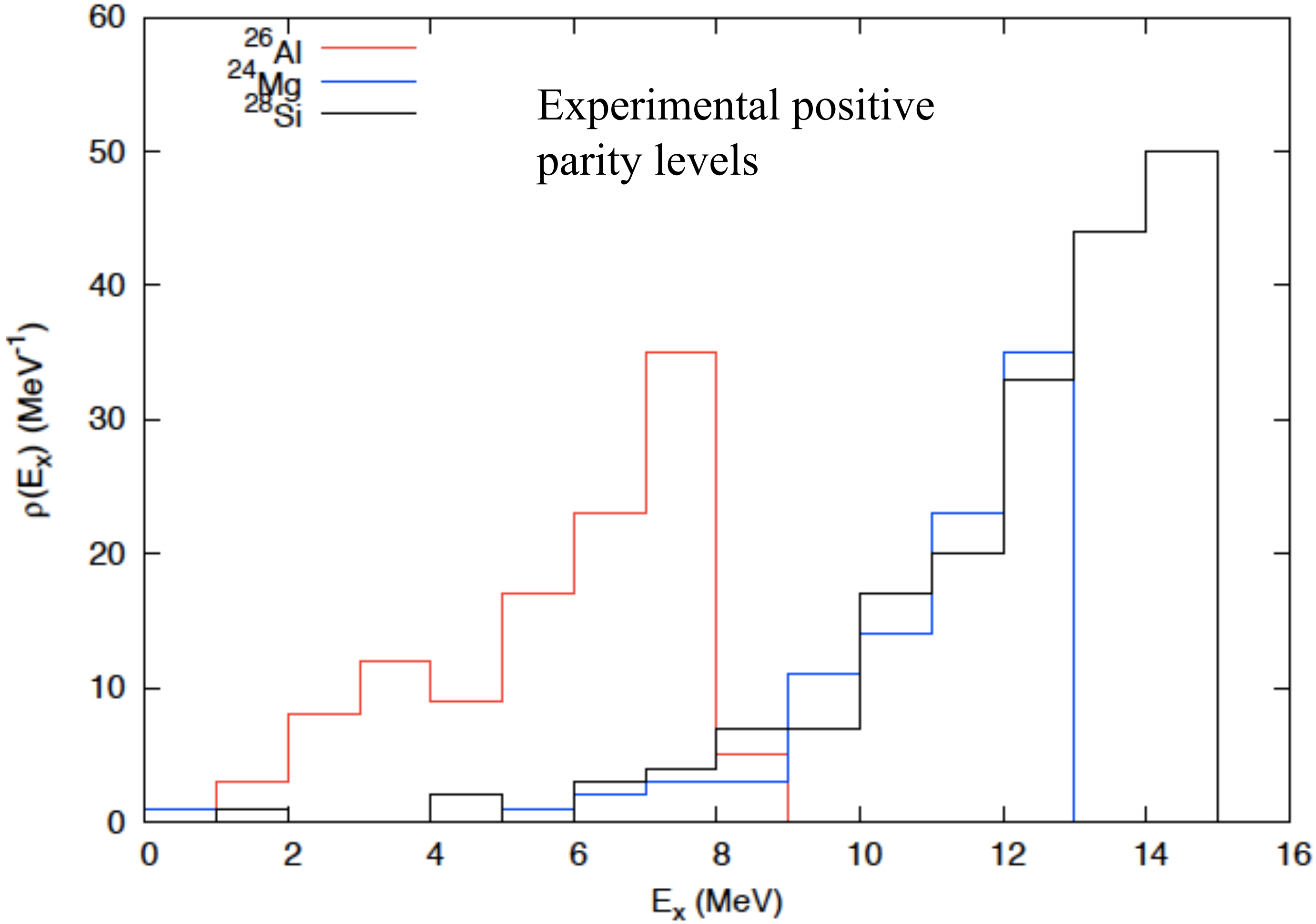
I. Talmi NPA **423**, 189 (1984)

Evolution of lowest 0^+ and 1^+ states in N=Z nuclei



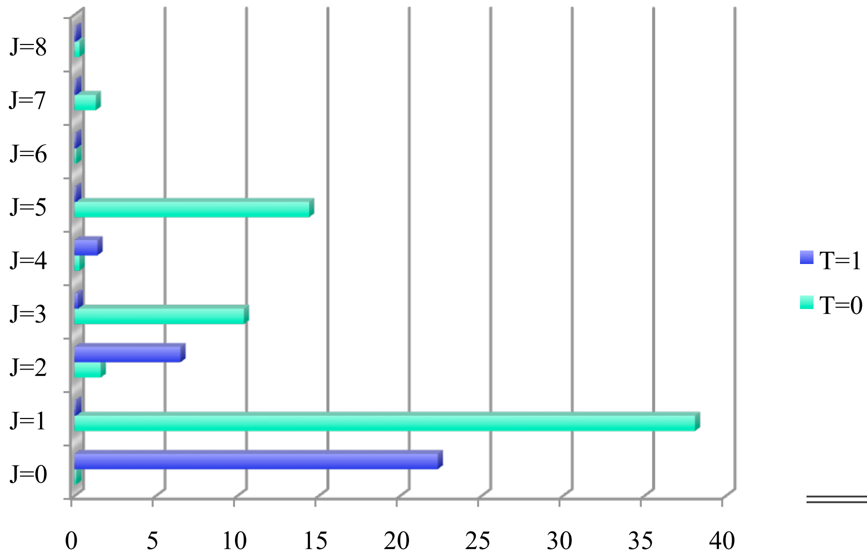
Notice the energy scales!

pn-pairing vs pp/nn pairing: Why the difference?



Enhanced realization probability of JT=01,10 g.s. for Odd-Odd nuclei

$$H = H_{TBRE}$$



$$Percentage\ {}^{30}_{15}P_{15}\ g.s.\ realizations$$

PHYSICAL REVIEW LETTERS

30 MARCH 1998

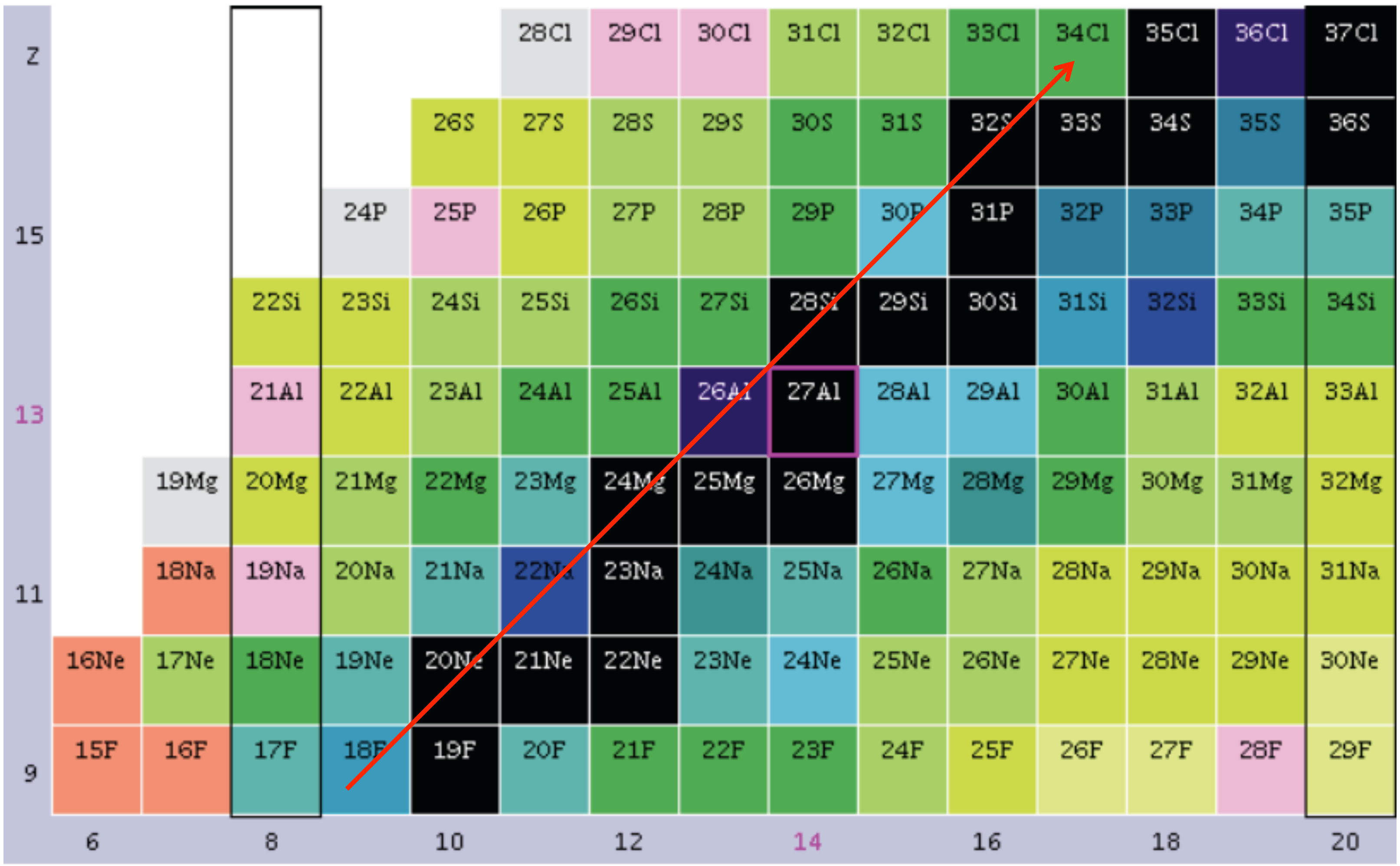
Orderly Spectra from Random Interactions

C. W. Johnson,[1] G. F. Bertsch,[2] and D. J. Dean[3]

N	Ω	Nucleus	$J=0, T=T_z$ g.s.	$J=0, T=T_z$ Total space
6	12	^{22}O	76%	9.8%
6	20	^{46}Ca	75%	3.5%
$N=4, Z=4$	12	^{24}Mg	66%	1.1%

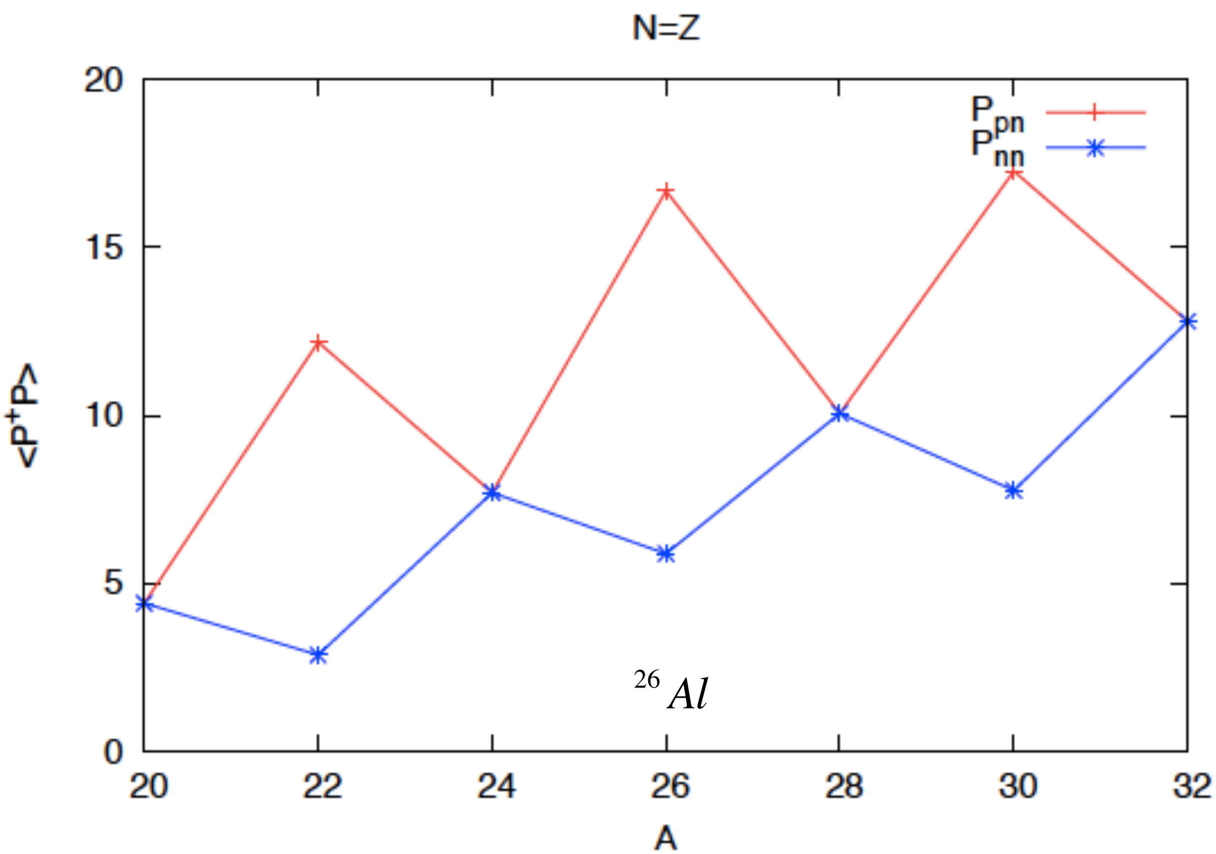
$$P_{JT=01} \equiv \frac{\#\,states(JT=01)}{\#\,states(M=0)} = 2.5\% \qquad P_{JT=10} \equiv \frac{\#\,states(JT=10)}{\#\,states(M=0)} = 1.6\%$$

N=Z *sd*-Nuclei



Z
28Cl 29Cl 30Cl 31Cl 32Cl 33Cl 34Cl 35Cl 36Cl 37Cl
26S 27S 28S 29S 30S 31S 32S 33S 34S 35S 36S
15
24P 25P 26P 27P 28P 29P 30P 31P 32P 33P 34P 35P
22Si 23Si 24Si 25Si 26Si 27Si 28Si 29Si 30Si 31Si 32Si 33Si 34Si
13
21Al 22Al 23Al 24Al 25Al 26Al 27Al 28Al 29Al 30Al 31Al 32Al 33Al
19Mg 20Mg 21Mg 22Mg 23Mg 24Mg 25Mg 26Mg 27Mg 28Mg 29Mg 30Mg 31Mg 32Mg
11
18Na 19Na 20Na 21Na 22Na 23Na 24Na 25Na 26Na 27Na 28Na 29Na 30Na 31Na
16Ne 17Ne 18Ne 19Ne 20Ne 21Ne 22Ne 23Ne 24Ne 25Ne 26Ne 27Ne 28Ne 29Ne 30Ne
9
15F 16F 17F 18F 19F 20F 21F 22F 23F 24F 25F 26F 27F 28F 29F
6 8 10 12 14 16 18 20

Decoupling the singlet pn-pairing



$H = H_{USDB}$

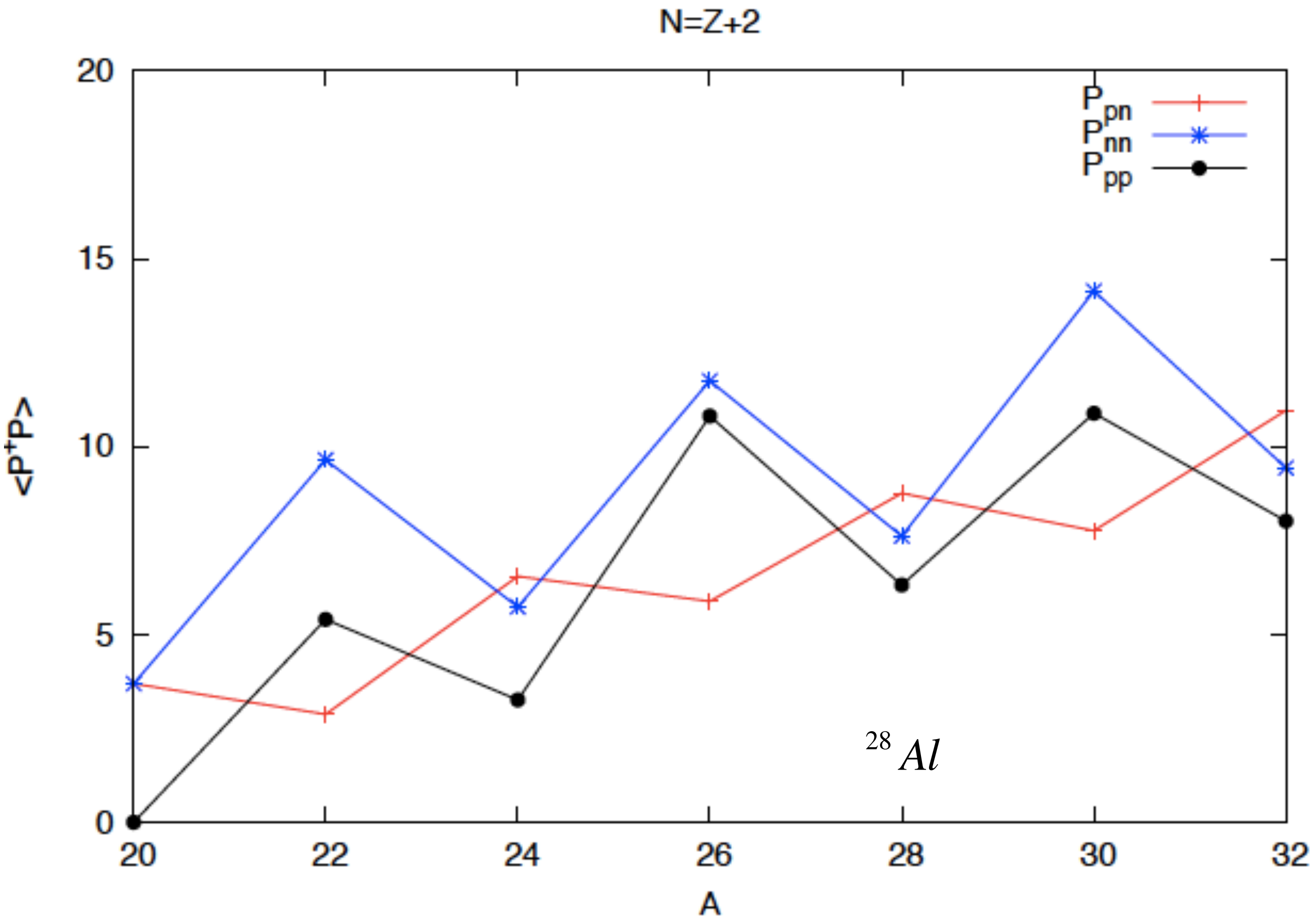
$$P_t = \frac{1}{\sqrt{2}} \sum_j [\tilde{a}_j \tilde{a}_j]_{L=0,T=1,T_3=t},$$

$$P_t^\dagger = \frac{1}{\sqrt{2}} \sum_j [a_j^\dagger a_j^\dagger]_{L=0,T=1,T_3=t}.$$

$$\langle (j_2^2)_{LT} | V_P | (j_1^2)_{LT} \rangle = [(2j_1+1)(2j_2+1)]^{1/2} \delta_{L0} \delta_{T1}$$

$$\mathcal{H}_P = \sum_{t=0,\pm 1} P_t^\dagger P_t$$

Decoupling the singlet pairing



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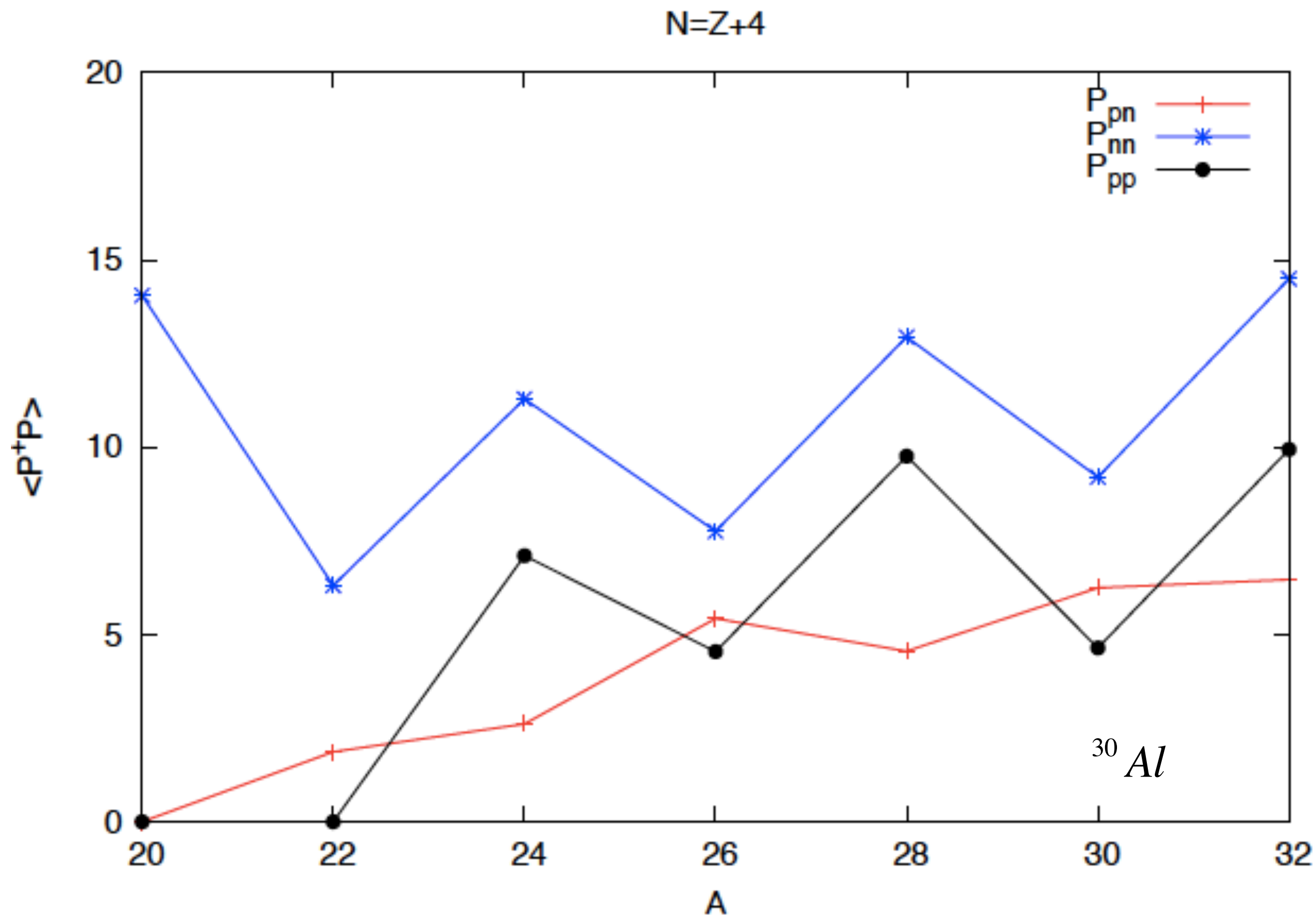
Decoupling the singlet pairing



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$$\mathcal{H}_P = \sum_{t=0,\pm 1} P_t^\dagger P_t$$

Spectroscopic Factors

$$S_{f,j,i} = \frac{|< \Psi_f^{A-1} J_f \| \tilde{a}_j \| \Psi_i^A \; J_i >|^2}{2J_i + 1}$$

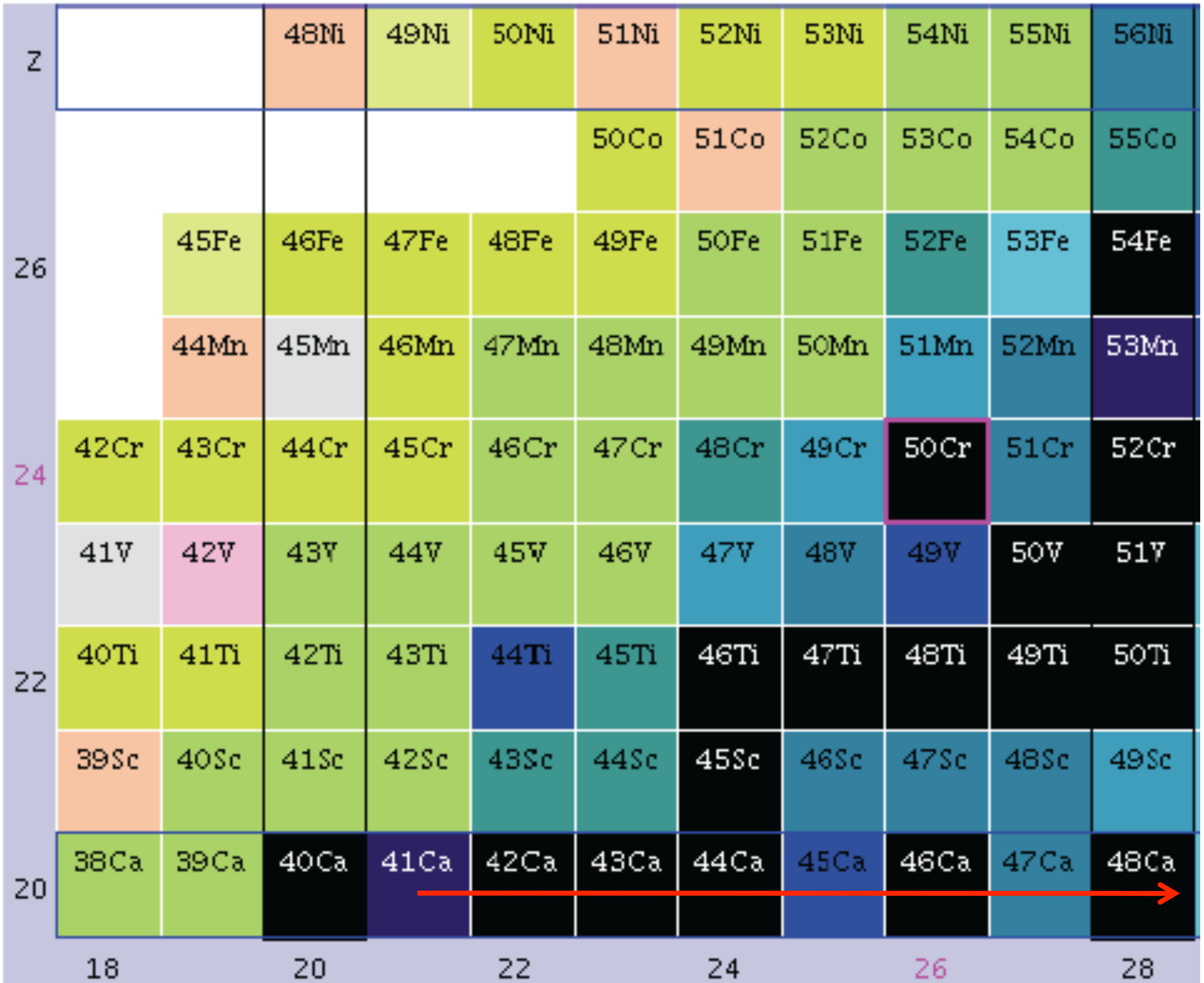
$$\sigma_j^- \approx S_j \left(\sigma_j\right)_{sp}$$ One particle removal cross section: e.g. (p,d)

$$\sigma_j^+ \approx \frac{2J_f + 1}{2J_i + 1} S_j \left(\sigma_j\right)_{sp}$$ e.g. (d,p)

Sum rule: s.p. occupation probability

$$\sum_{f-} S_{f,j,i} = < n_j >_i$$

pf-Nuclei



Z
48Ni 49Ni 50Ni 51Ni 52Ni 53Ni 54Ni 55Ni 56Ni
50Co 51Co 52Co 53Co 54Co 55Co
26
45Fe 46Fe 47Fe 48Fe 49Fe 50Fe 51Fe 52Fe 53Fe 54Fe
44Mn 45Mn 46Mn 47Mn 48Mn 49Mn 50Mn 51Mn 52Mn 53Mn
24
42Cr 43Cr 44Cr 45Cr 46Cr 47Cr 48Cr 49Cr 50Cr 51Cr 52Cr
41V 42V 43V 44V 45V 46V 47V 48V 49V 50V 51V
22
40Ti 41Ti 42Ti 43Ti 44Ti 45Ti 46Ti 47Ti 48Ti 49Ti 50Ti
39Sc 40Sc 41Sc 42Sc 43Sc 44Sc 45Sc 46Sc 47Sc 48Sc 49Sc
20
38Ca 39Ca 40Ca 41Ca 42Ca 43Ca 44Ca 45Ca 46Ca 47Ca 48Ca
18 20 22 24 26 28

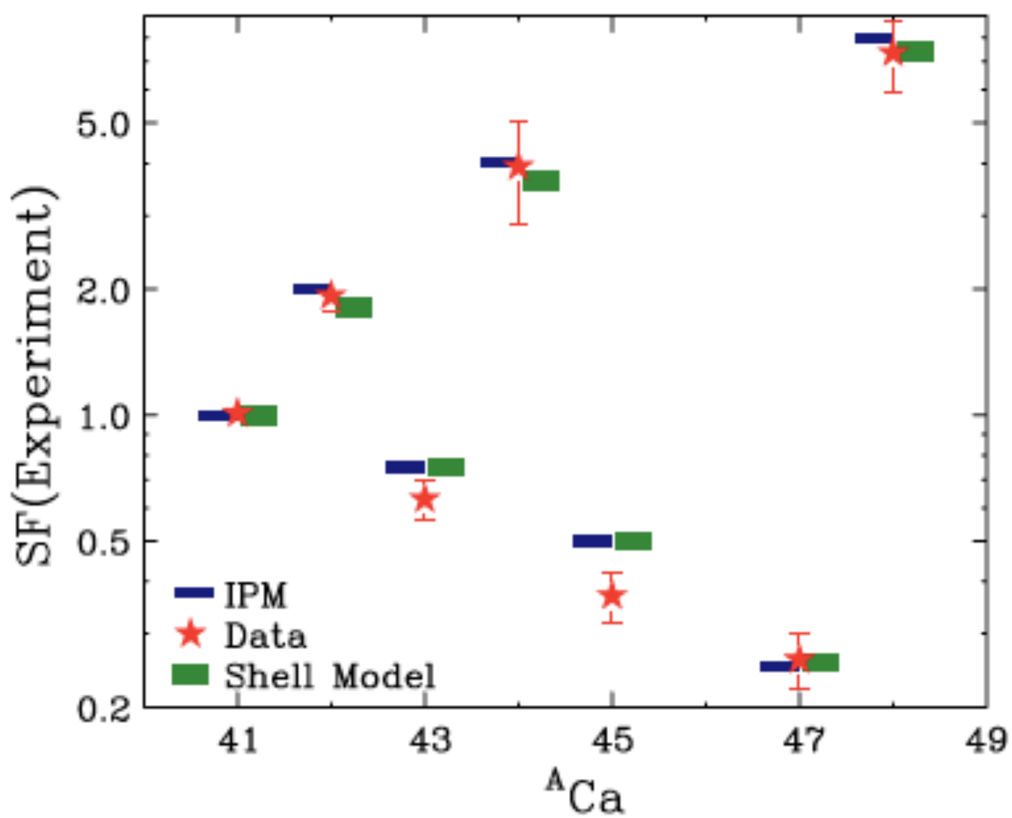
Spectroscopic Factors: Independent Particle Model (IPM)

IPM Model:

- n identical nucleons in
- One single j-shell: e.g. $f_{7/2}$
- Only pairing interaction

$$S_j = n \qquad n - even$$

$$S_j = \frac{(2j+1)-(n-1)}{(2j+1)} \qquad n - odd$$



B. Tsang, J. Lee, W. Lynch Phys. Rev. Lett. **95**, 222501 (2005)

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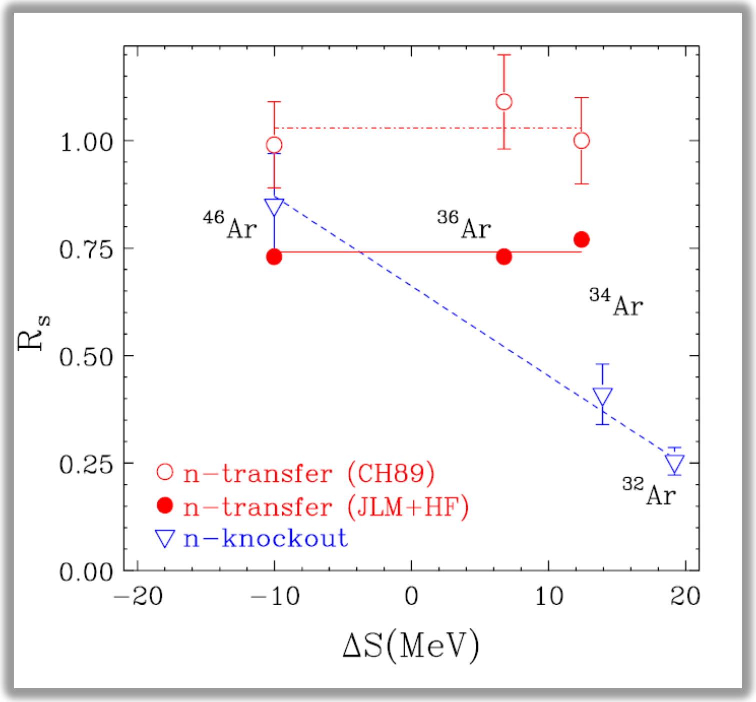
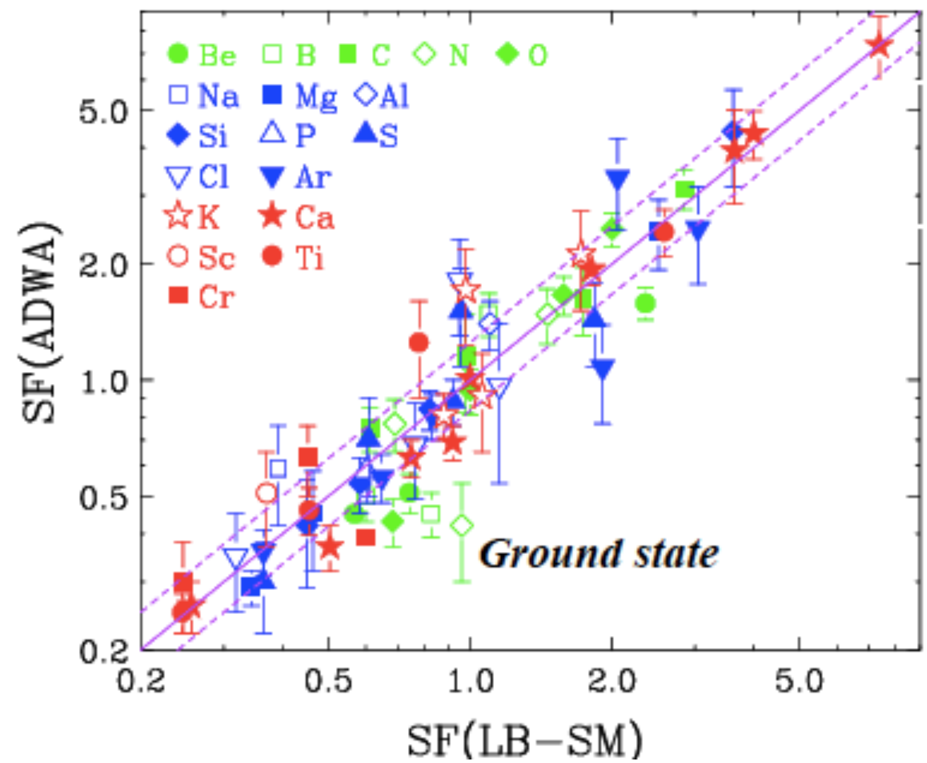
Are SFs (reliable) "observables"?

M.B. Tsang and J. Lee et al., PRL 95, 222501 (2005)



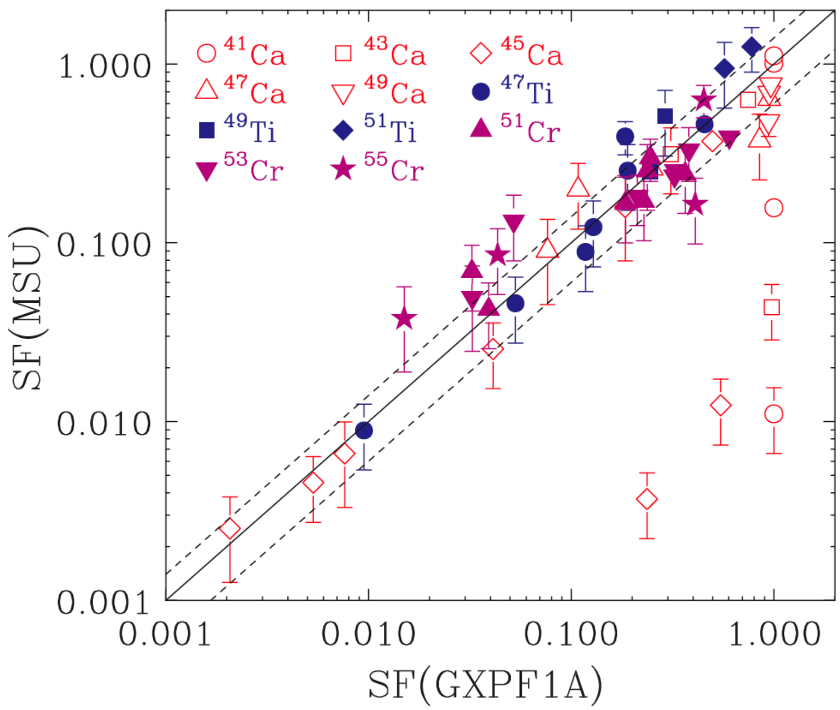
[Jenny Lee et al, PRL 2010]

[Gade et al, PRL 93, 042501]

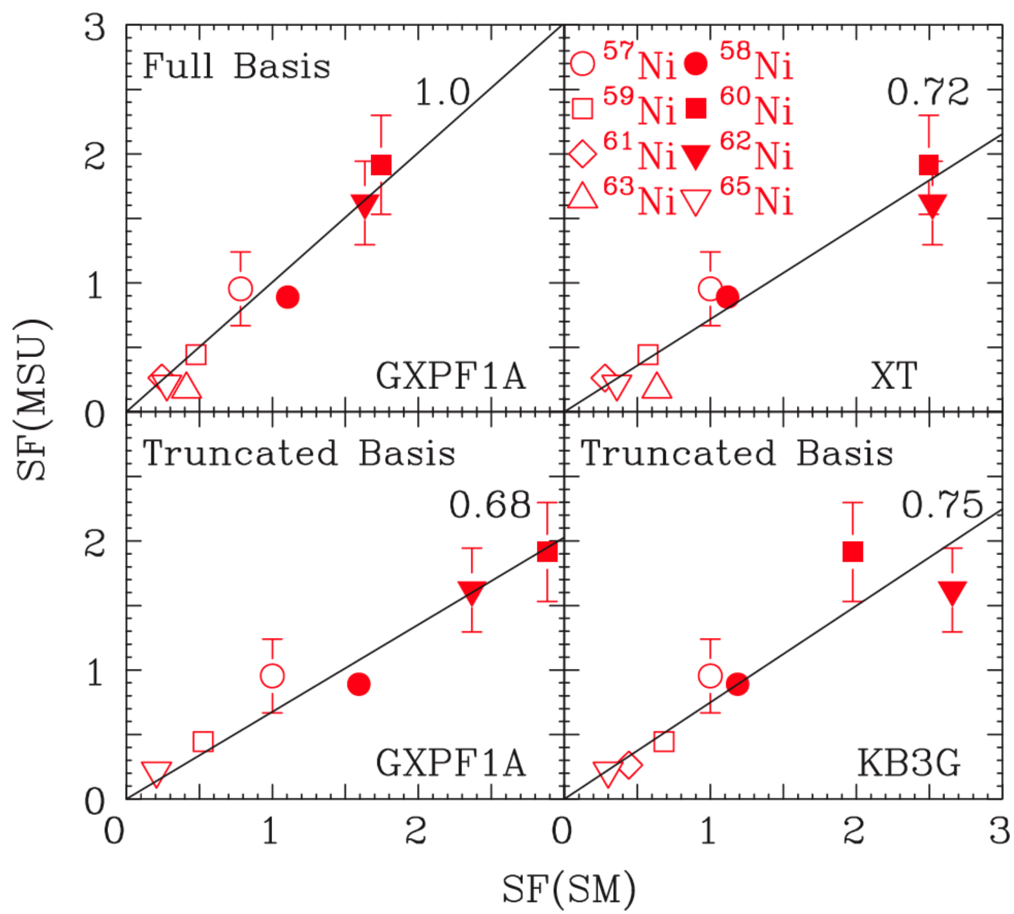


g.s. SFs seem to be more reliable

Spectroscopic factors in the pf-shell



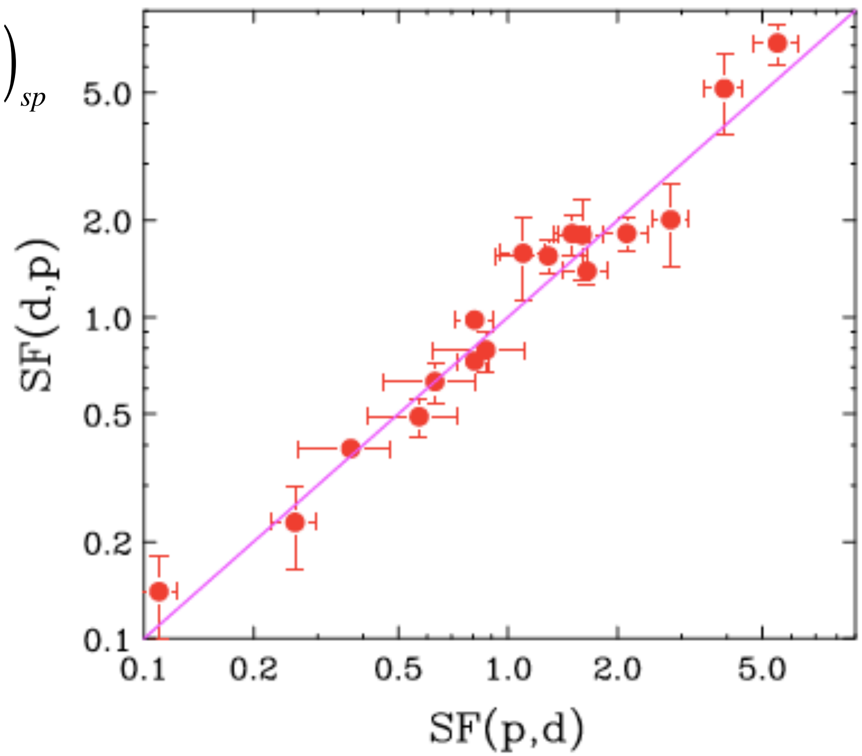
B. Tsang et al. Phys. Rev. Lett. **102**, 062501 (2009)



J. Lee et al. Phys. Rev. C **79**, 054601 (2009)

Spectroscopic Factors: (d,p) consistent with (p,d)

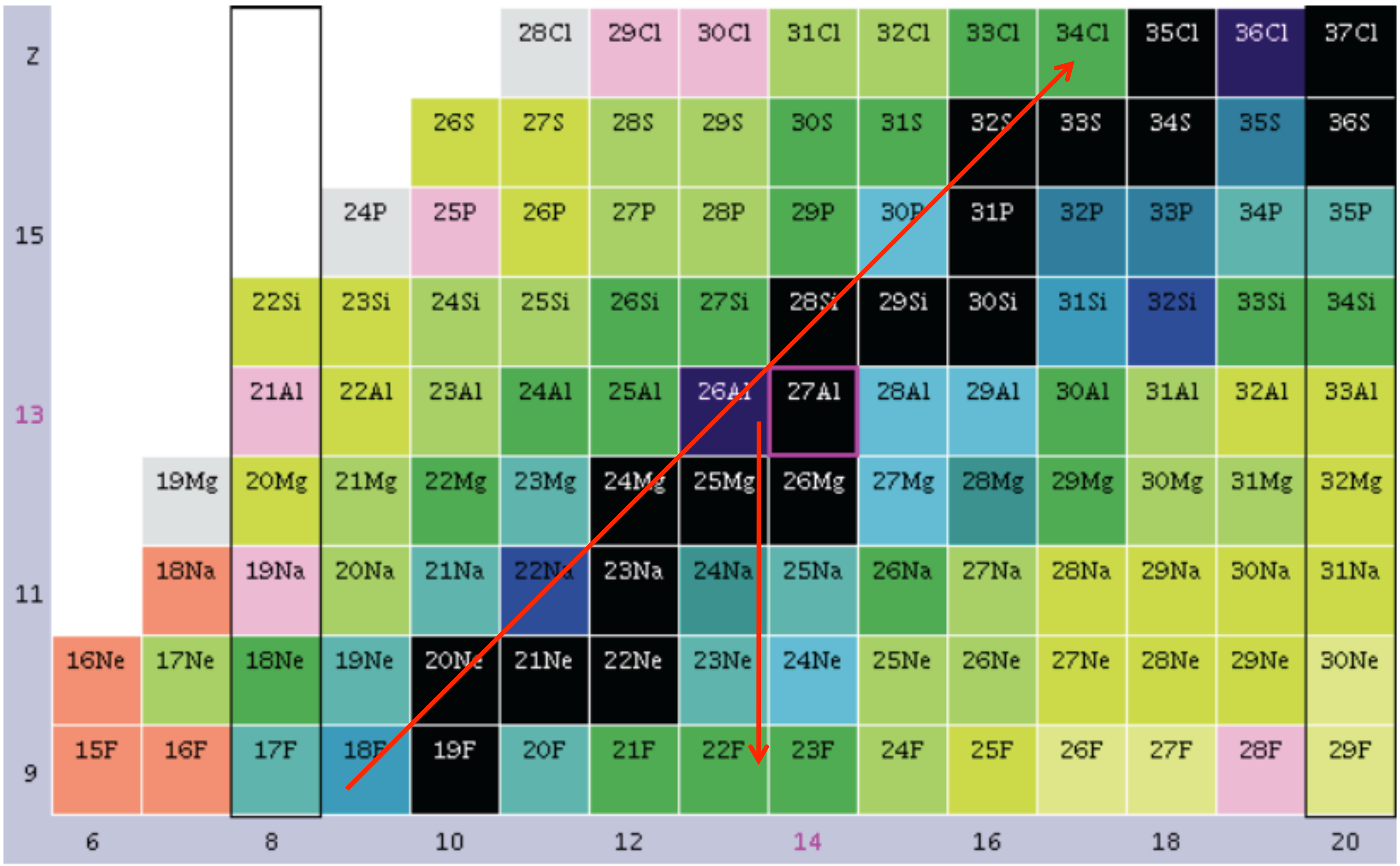
$$\sigma_j^+ \approx \frac{2J_f+1}{2J_i+1} S_j \left(\sigma_j\right)_{sp}$$



$$\sigma_j^- \approx S_j \left(\sigma_j\right)_{sp}$$

B. Tsang, J. Lee, W. Lynch Phys. Rev. Lett. **95**, 222501 (2005)

sd-Nuclei


Z
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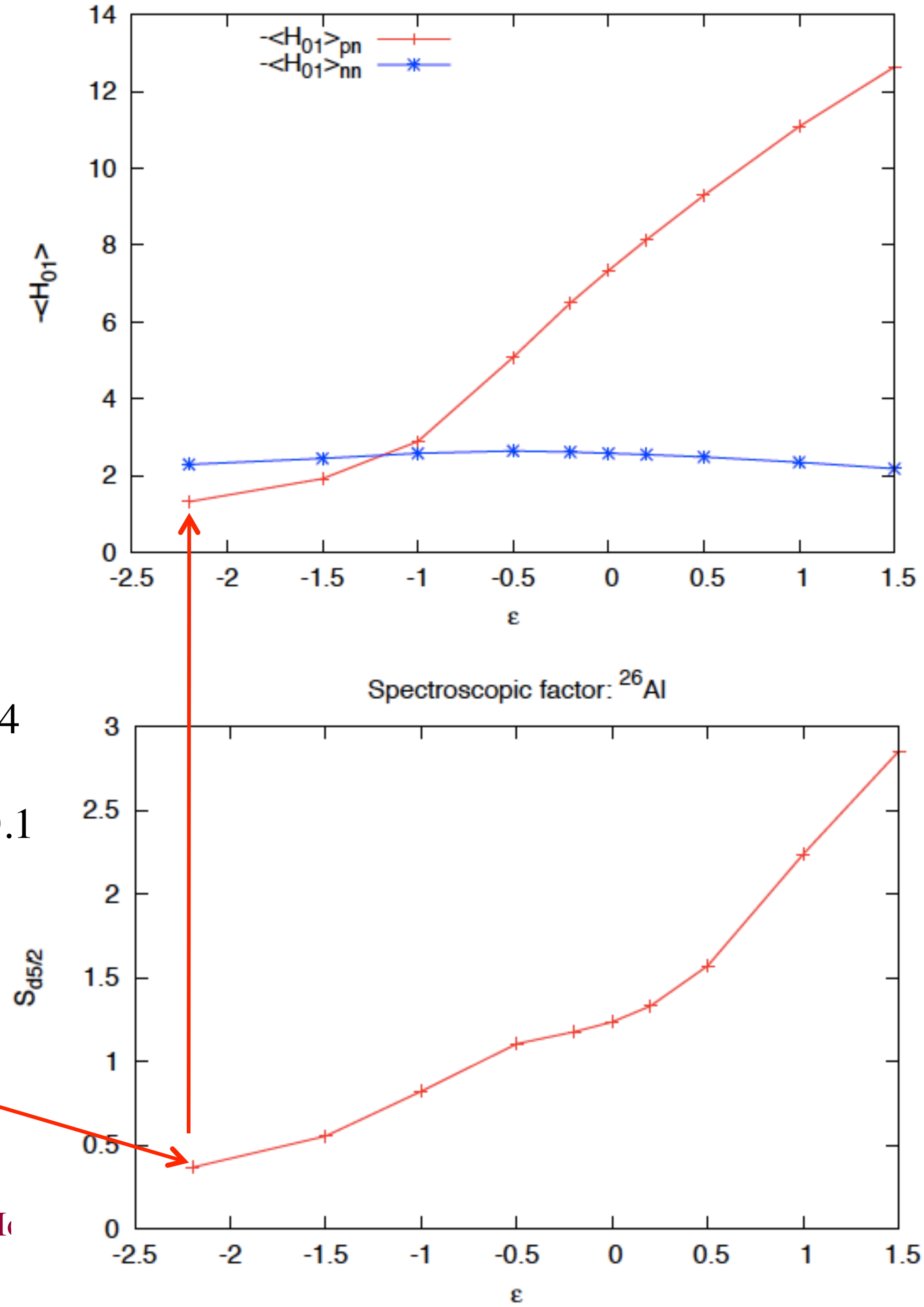
^{26}Al Spectroscopic Factors vs $(H_{01})_{pn}$

$$H = H(USDB) + \varepsilon\left[H_{01}(USDB)\right]_{t_3=0}$$

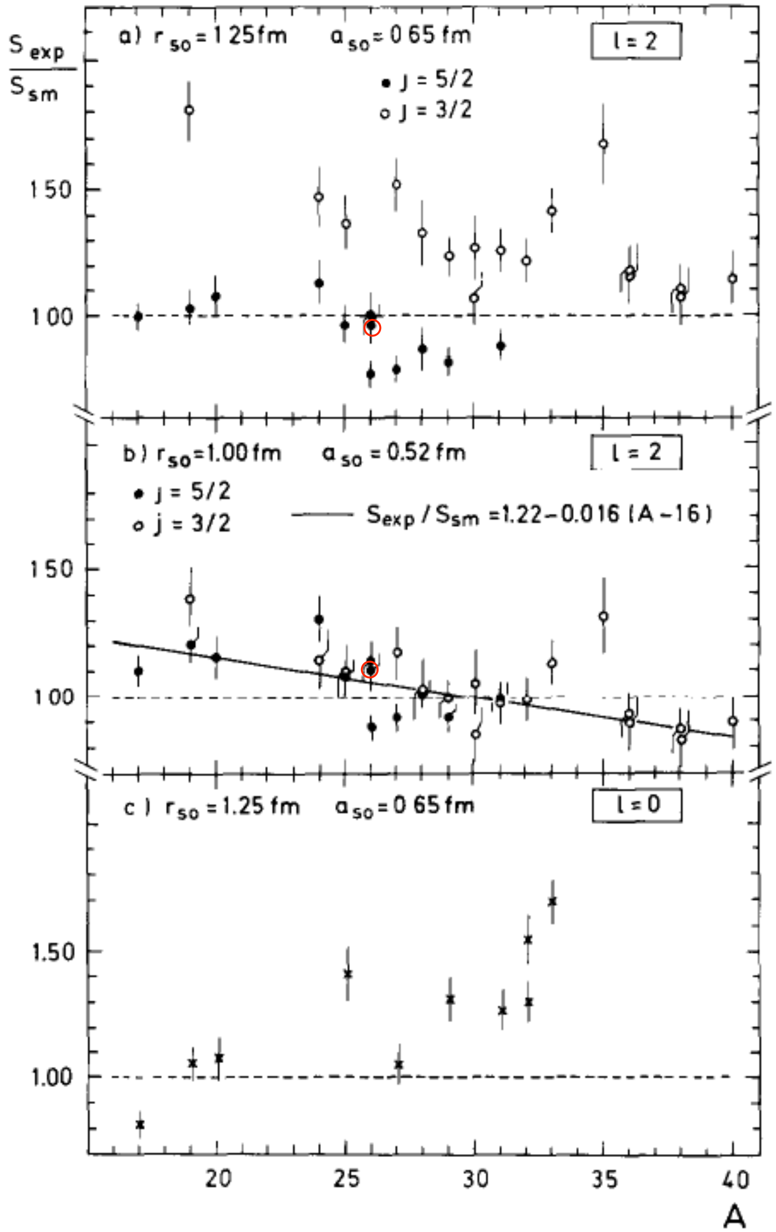
$${}^{26}_{13}Al_{13}(0^+)\rightarrow{}^{25}_{13}Al_{12}(5/2^+) + n:\ S_{5/2}(USDB) = 1.24$$

$${}^{24}_{11}Na_{13}(0^+)\rightarrow{}^{23}_{11}Na_{12}(5/2^+) + n:\ S_{5/2}(USDB) = 0.1$$

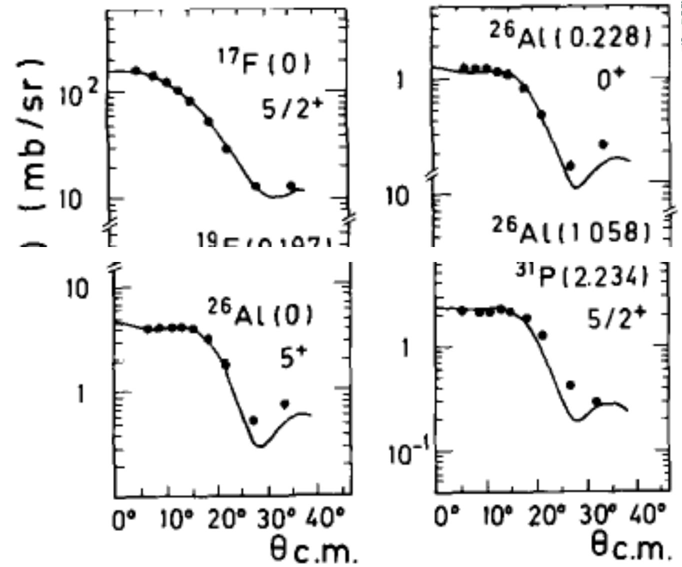
$${}^{26}Al:\ n = 5\ \Rightarrow S_{5/2}(IPM) = \frac{6-4}{6} = 0.33$$



^{26}Al Spectroscopic Factor Experimental Data



$(^3He, d)$ *reactions*



J. Vernotte et al. NPA 571, 1 (1994)

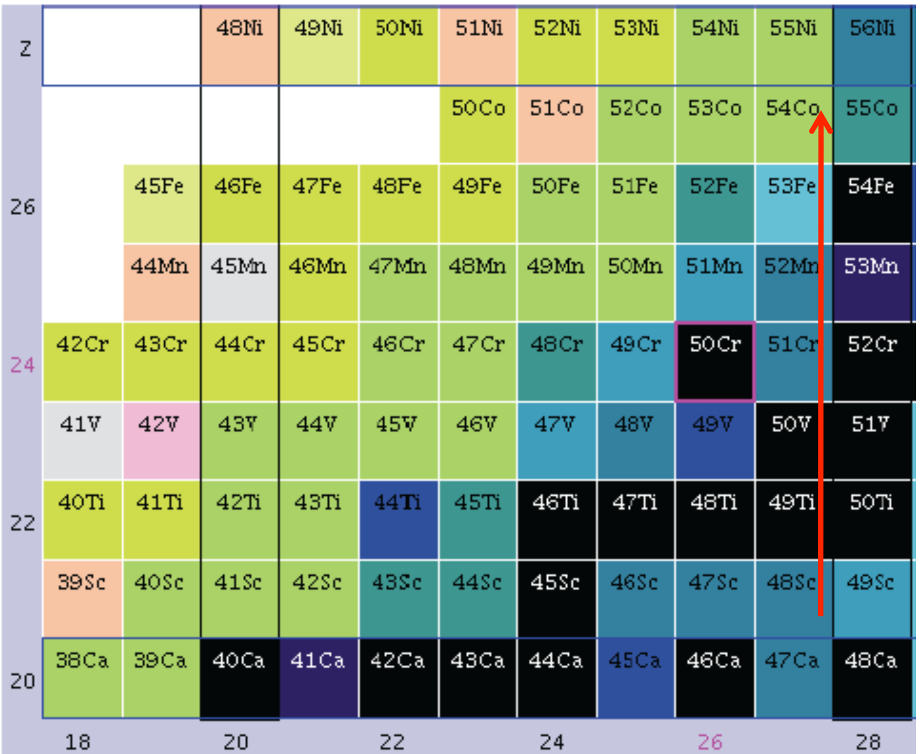
$$^{26}Al: S_{5/2}(USDB) = 1.24 \approx 4 \times S_{5/2}(IPM)$$

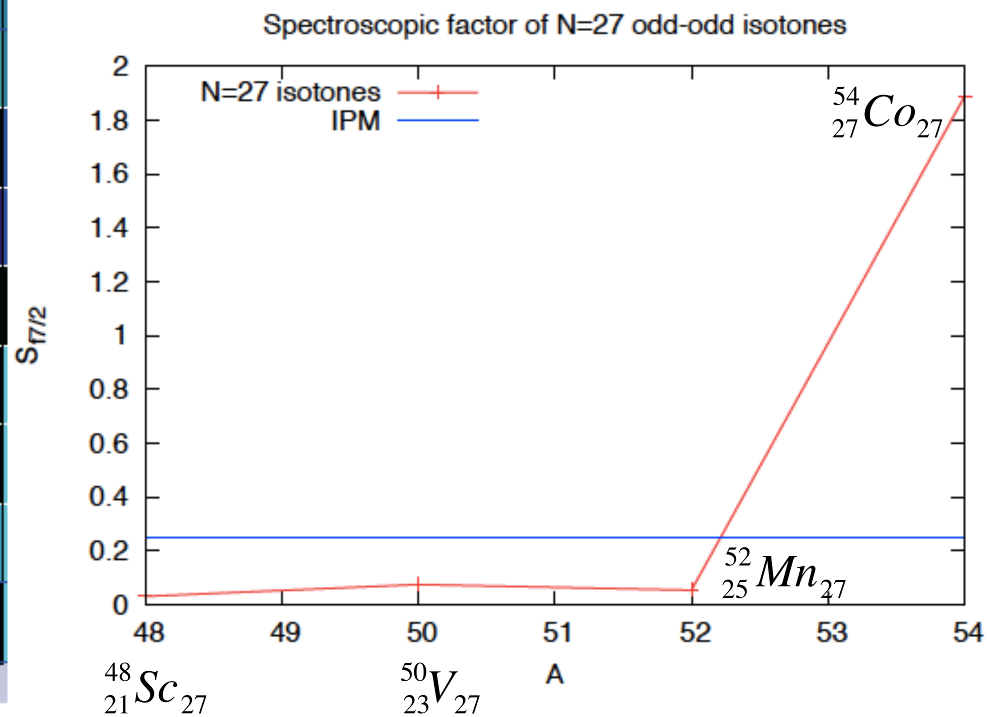
TABLE 5

C^2S-values from the present work and from the current literature

Final nucleus	E_x (MeV)	$J^\pi; T$	$n\ell j$	C^2S-values a	b	Other sources
^{26}Al	0	5+	$1d_{5/2}$	0.40	0.34 ± 0.06	0.52 [k]
	0.228	0+; 1	$1d_{5/2}$	1.22	0.90 ± 0.10	1.56 [k]
	1.058	1+	$1d_{5/2}$	0.71	0.55 ± 0.10	0.94 [k]

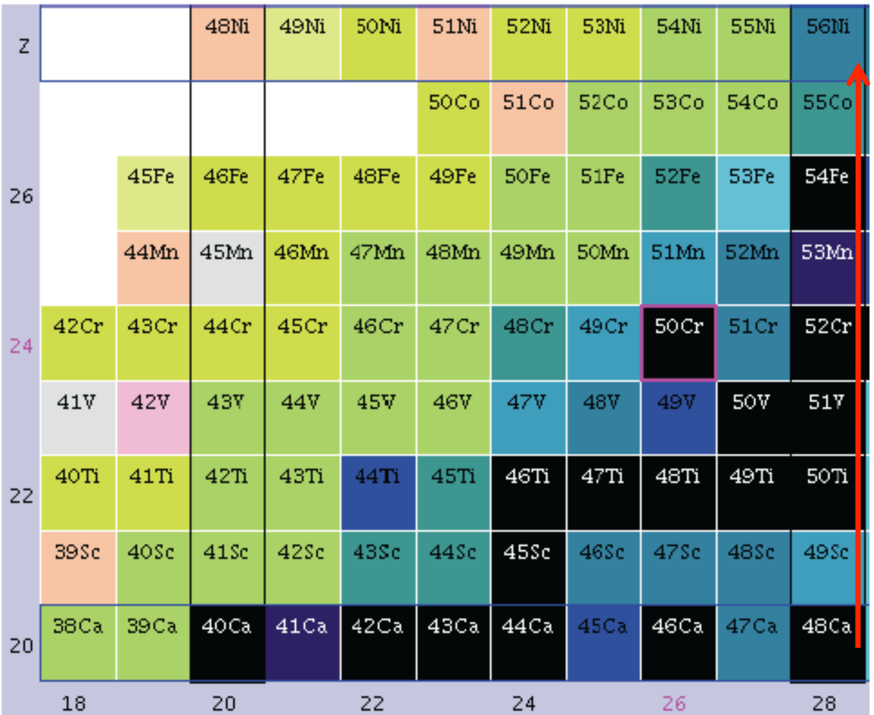
Can one measure $S_{7/2}$ for N=27 isotones?

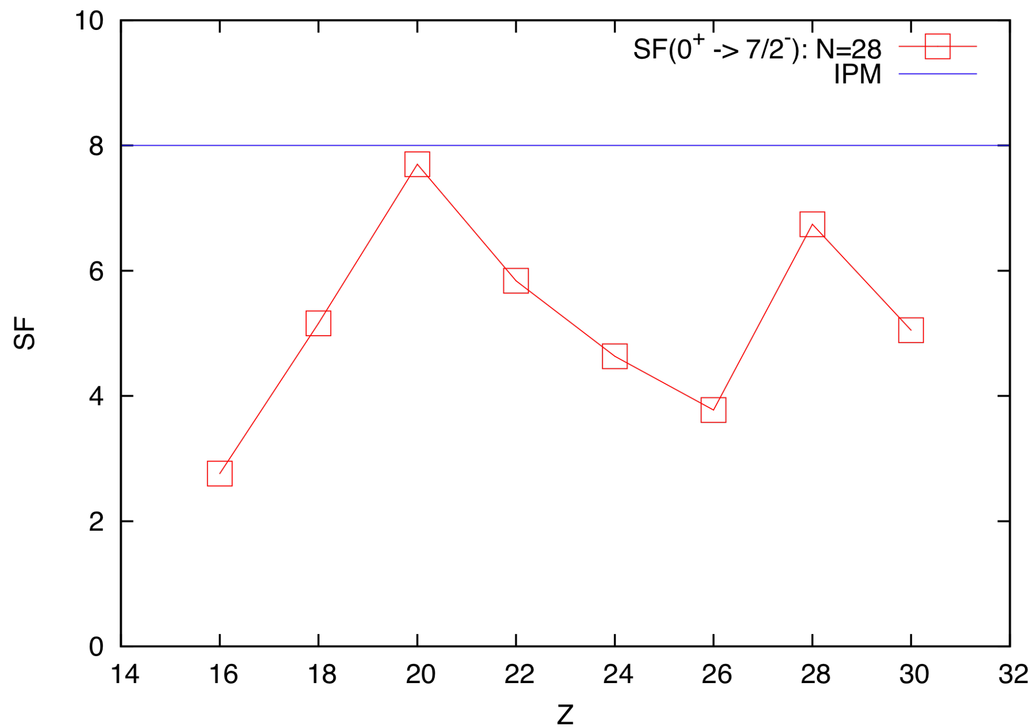




$$S_{7/2}\left(0^{+} \leftrightarrow \frac{7^{-}}{2}\right) = ?$$

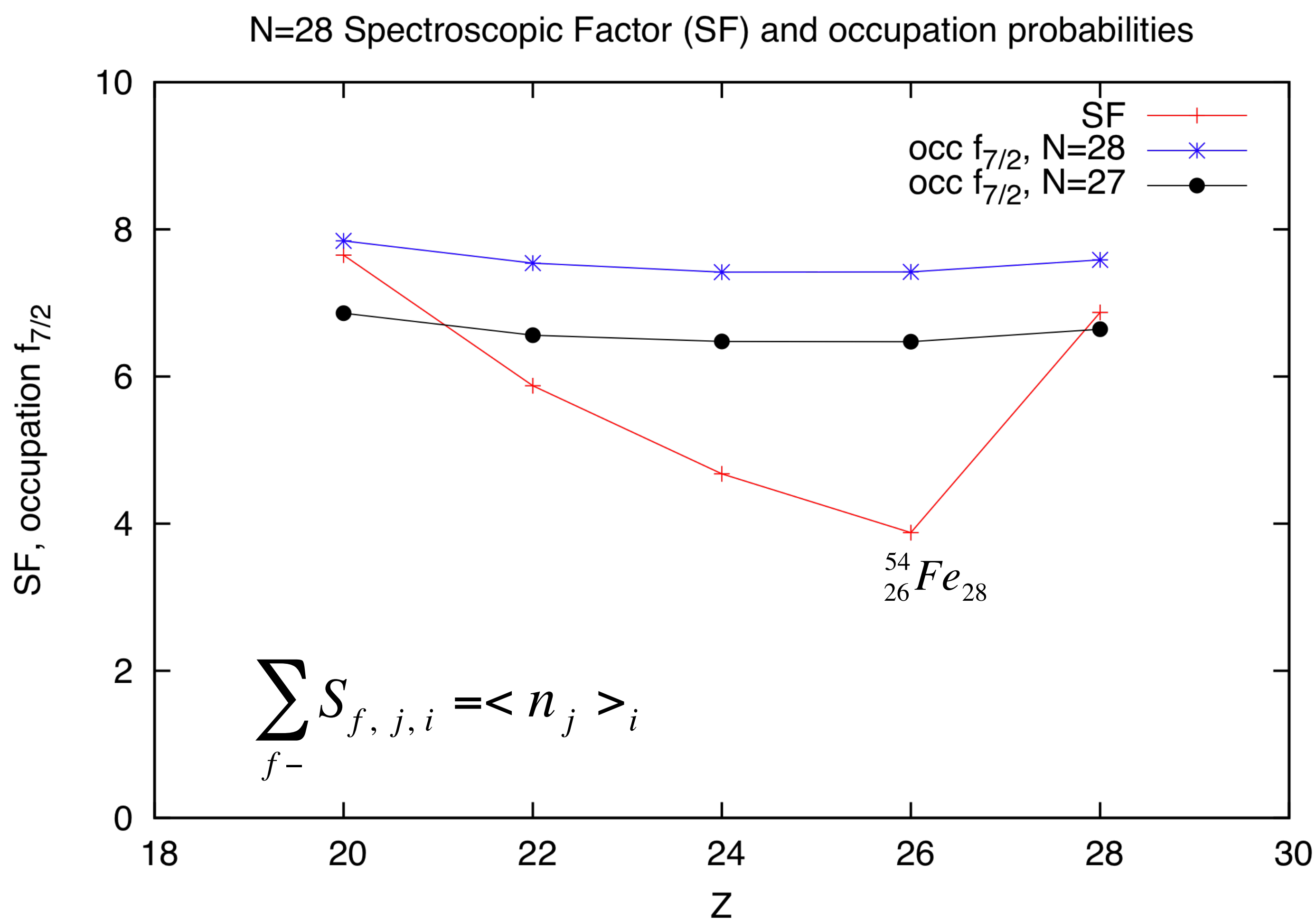
Can one measure **neutron** $S_{7/2}$ for N=28 isotones?





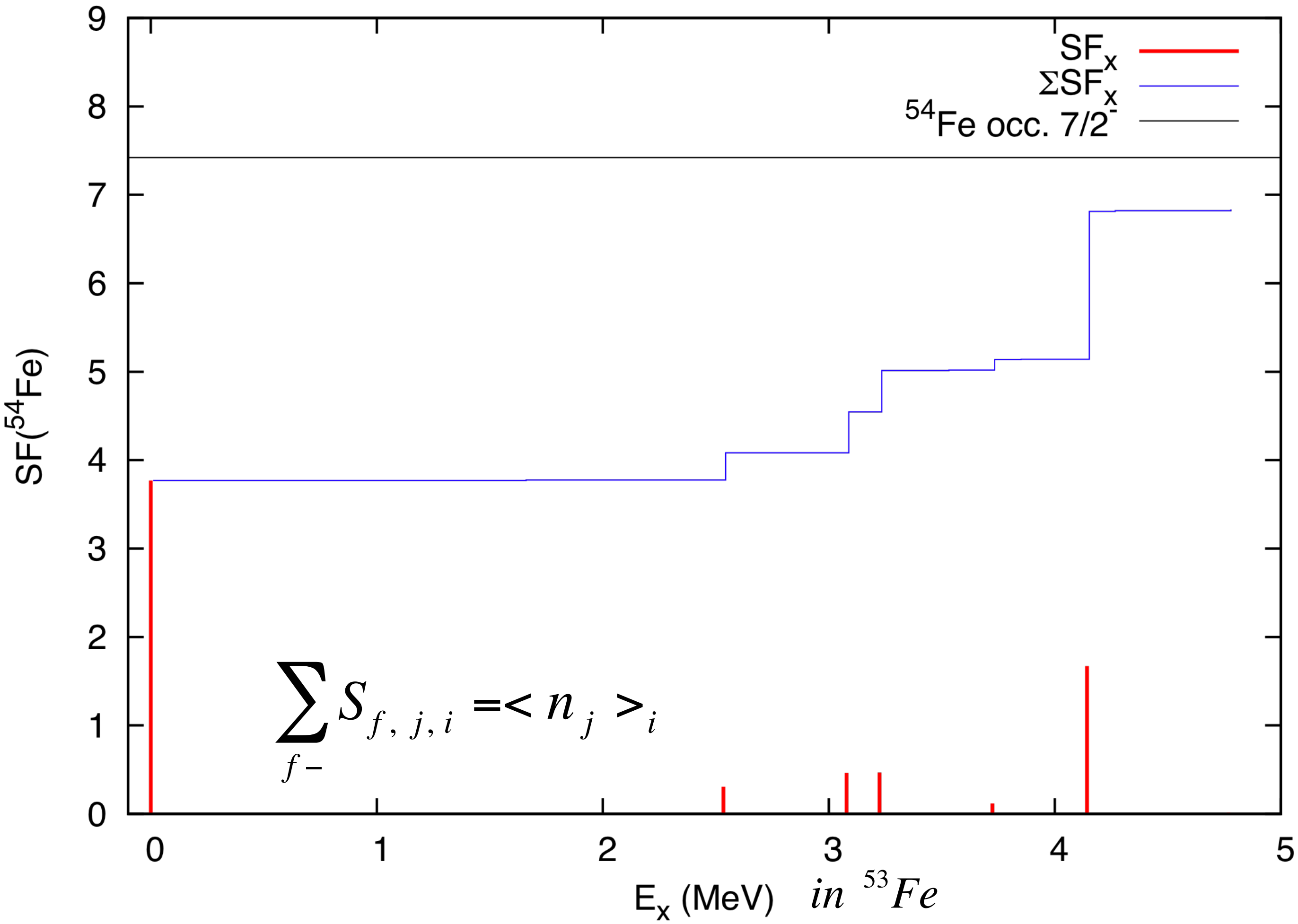
$$S_{7/2}\left(0^{+} \leftrightarrow \frac{7}{2}^{-}\right) = ?$$

$S_{7/2}$ for N=28 isotones and $f_{7/2}$ n-occupation



$$\sum_{f-} S_{f,j,i} = \langle n_j \rangle_i$$

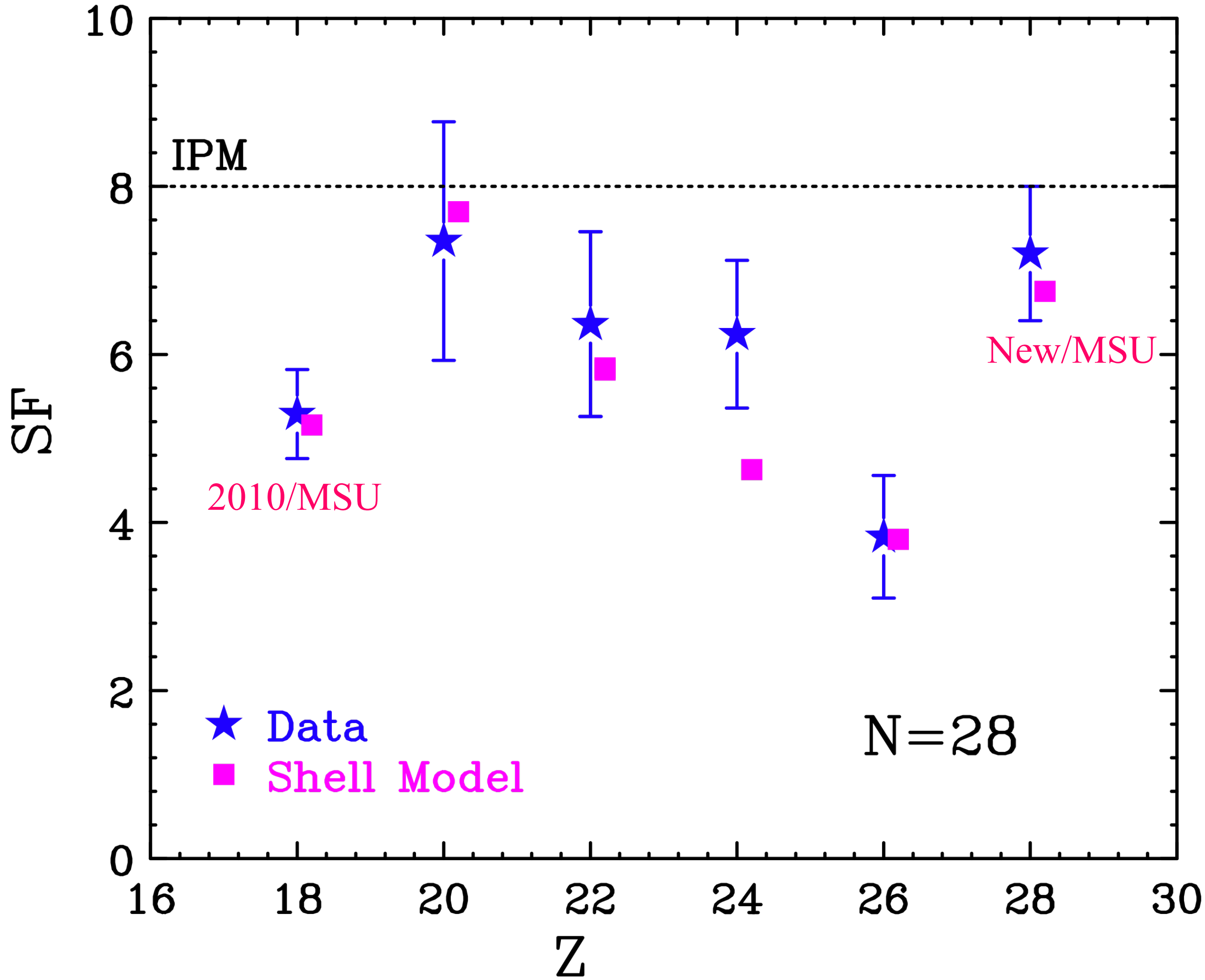
$S_{7/2}$ for N=28 isotones and $f_{7/2}$ n-occupation



$$\sum_{f-} S_{f,j,i} = \langle n_j \rangle_i$$

in ^{53}Fe

The Magic of Proton-Neutron Correlations

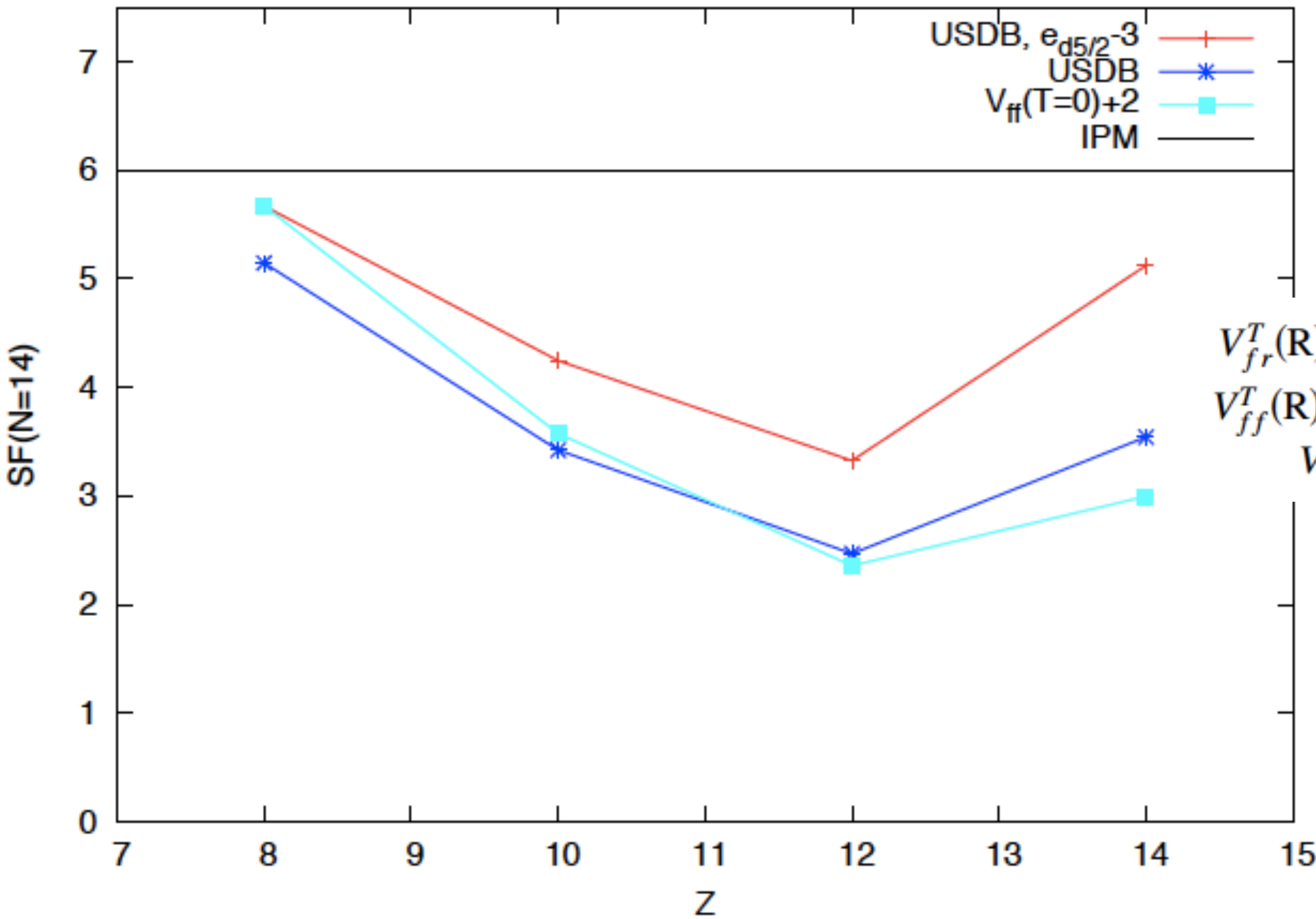


Data from Jenny and Betty

sd-Nuclei

Z	6		8		10		12		14		16		18		20
						28Cl	29Cl	30Cl	31Cl	32Cl	33Cl	34Cl	35Cl	36Cl	37Cl
					26S	27S	28S	29S	30S	31S	32S	33S	34S	35S	36S
15				24P	25P	26P	27P	28P	29P	30P	31P	32P	33P	34P	35P
			22Si	23Si	24Si	25Si	26Si	27Si	28Si	29Si	30Si	31Si	32Si	33Si	34Si
13			21Al	22Al	23Al	24Al	25Al	26Al	27Al	28Al	29Al	30Al	31Al	32Al	33Al
		19Mg	20Mg	21Mg	22Mg	23Mg	24Mg	25Mg	26Mg	27Mg	28Mg	29Mg	30Mg	31Mg	32Mg
11		18Na	19Na	20Na	21Na	22Na	23Na	24Na	25Na	26Na	27Na	28Na	29Na	30Na	31Na
	16Ne	17Ne	18Ne	19Ne	20Ne	21Ne	22Ne	23Ne	24Ne	25Ne	26Ne	27Ne	28Ne	29Ne	30Ne
9	15F	16F	17F	18F	19F	20F	21F	22F	23F	24F	25F	26F	27F	28F	29F

Which pieces of H_2 are responsible? The case of $S_{5/2}$ for N=14 isotones



$f \rightarrow 0d_{5/2}$

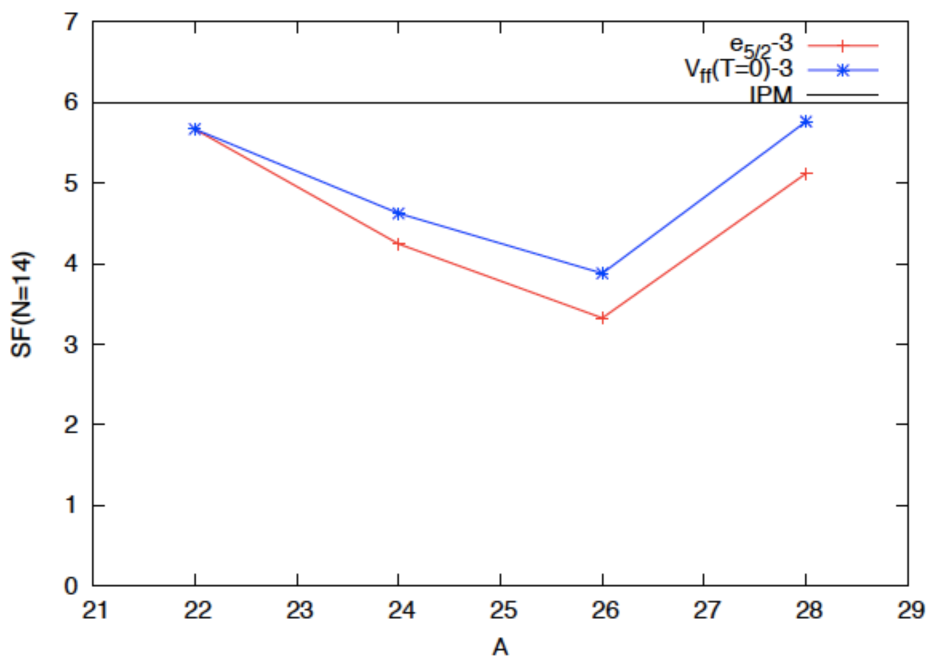
$r \rightarrow 0d_{1/2}, 1s_{1/2}$

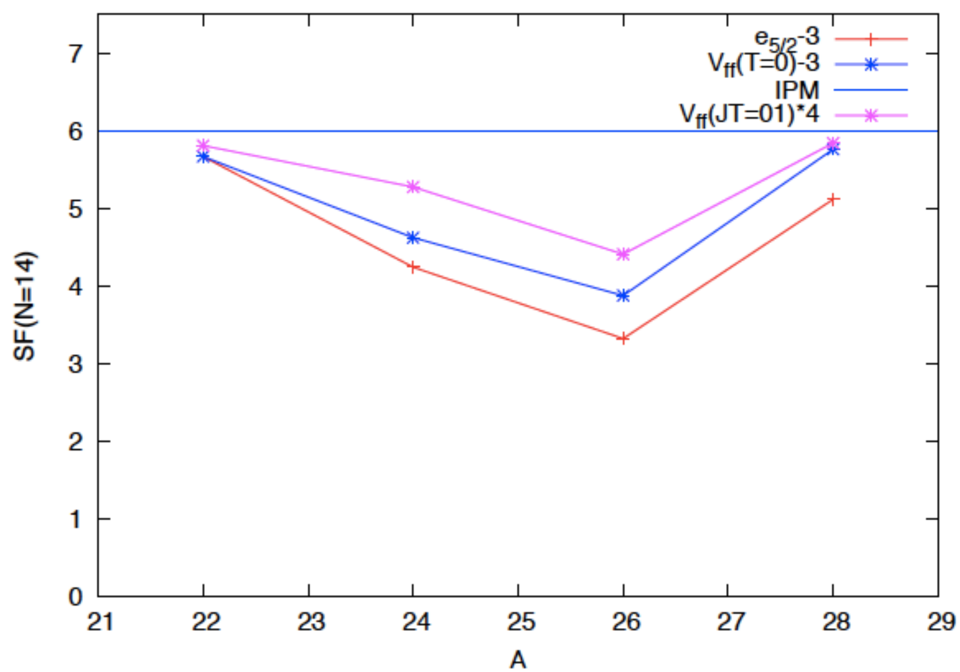
$$V^T_{fr}(\mathrm{R}) \longrightarrow V^T_{fr}(\mathrm{R}) - (-)^T \kappa + \chi'^T_{fr},$$
$$V^T_{ff}(\mathrm{R}) \longrightarrow V^T_{ff}\mathrm{R} - 1.5\,\kappa\,\delta_{T0} + \chi'^T_{ff},$$
$$V^T_{rr'}(\mathrm{R}) \longrightarrow V^T_{rr'}(\mathrm{R}) + \chi^T_{rr'}.$$

$\kappa = 1.1$

A. Zuker, PRL 90 (2003)

Which pieces of H_2 are responsible?
The case of $S_{5/2}$ for N=14 isotones





$$V^T_{fr}(\mathrm{R}) \longrightarrow V^T_{fr}(\mathrm{R}) - (-)^T \kappa + \chi'^T_{fr},$$
$$V^T_{ff}(\mathrm{R}) \longrightarrow V^T_{ff}\mathrm{R} - 1.5\,\kappa\,\delta_{T0} + \chi'^T_{ff},$$
$$V^T_{rr'}(\mathrm{R}) \longrightarrow V^T_{rr'}(\mathrm{R}) + \chi^T_{rr'}.$$

$$f \rightarrow 0d_{5/2}$$
$$r \rightarrow 0d_{1/2}, 1s_{1/2}$$

$$\langle (5/2,5/2)01 | V | (5/2,5/2)01 \rangle = -2.5 \rightarrow -8.5$$
$$\langle (5/2,5/2)01 | V | (3/2,3/2)01 \rangle = -1.1 \rightarrow -0.1$$
$$\langle (5/2,5/2)01 | V | (1/2,1/2)01 \rangle = -1.6 \rightarrow -0.6$$

No sensibilty to $JT = 10$ matrix elements

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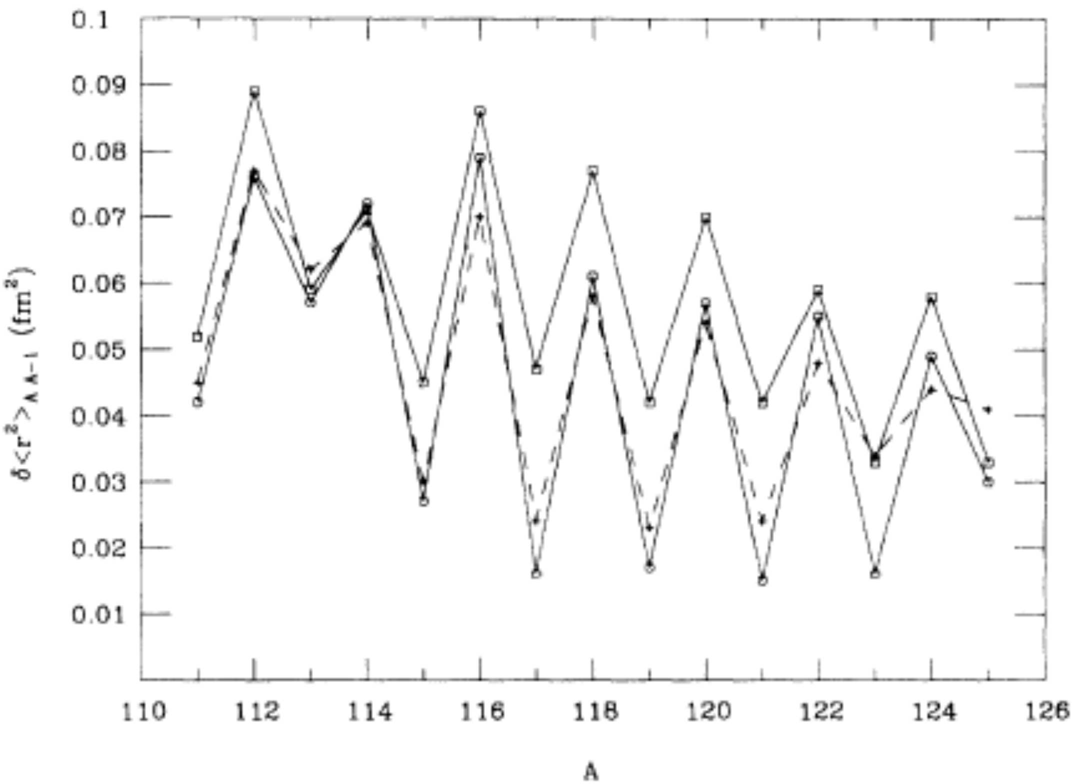
Proton-Neutron Pairing: A mean field approach ?



$$H = \sum_{i=p,n} (H_i^{\mathrm{MF}} + H_i^{\mathrm{pair}}) + H_4 \ ,$$

where

$$H_i^{\mathrm{MF}} = \sum_{s_i \sigma_i} E_{s_i} a^\dagger_{s_i \sigma_i} a_{s_i \sigma_i} \ , \quad i = p, n \ ,$$

$$H_i^{\mathrm{pair}} = -G_i P_i^\dagger P_i \ , \quad P_i = \sum_{s_i} a_{s_i -} a_{s_i +},$$

$$H_4 = -G_4 P_p^\dagger P_n^\dagger P_n P_p \ ,$$

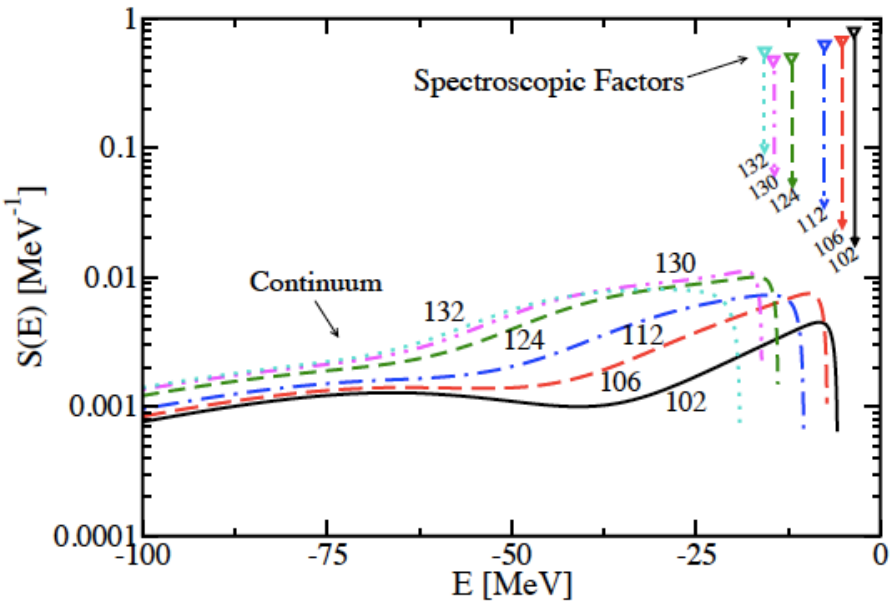
$$(G_p + G_4 \chi_n^2) \sum_{s_p} \frac{1}{\varepsilon_{s_p}} = 2,$$

$$(G_n + G_4 \chi_p^2) \sum_{s_n} \frac{1}{\varepsilon_{s_n}} = 2$$

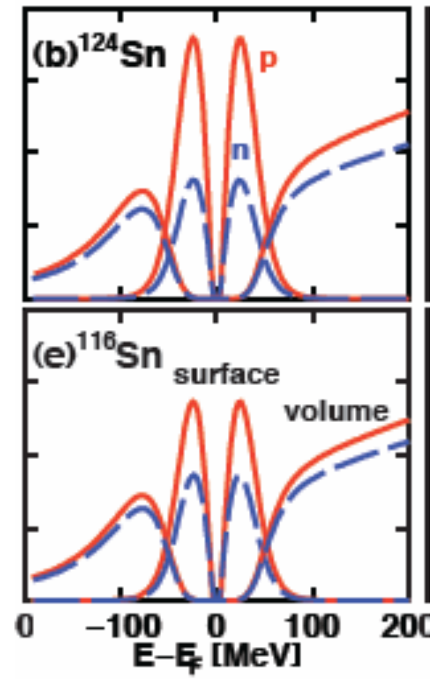
$$\varepsilon_{s_i} = [(E_{s_i} - \lambda_i)^{1/2} + \Delta_i^2]^{1/2}$$

Staggering of charge radii of Sn isotopes,
MH, PRC 50, 2834 (1995)

$H_3 \propto P_n^+ P_n \rho_p \quad \leftarrow$ *Zawischa, PRL* ***61***, 149 (1988)



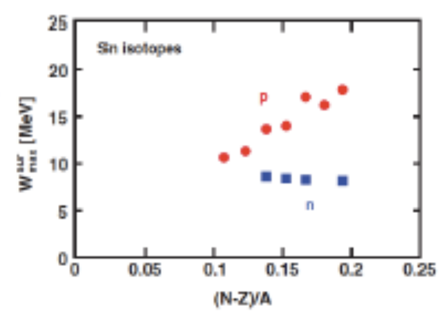
Sn	S	n
102	0.80	0.91
106	0.68	0.85
112	0.63	0.83
124	0.50	0.78
130	0.48	0.78
132	0.56	0.81



- Volume -> small asymmetry dependence determined in ^{208}Pb

$$W_{volume} = W^0_{volume} \pm \frac{N-Z}{A} W^1_{volume}$$

- Neutron surface -> no strong dependencies on A or (N-Z)/A
- Proton surface absorption -> increases with increasing neutron number



Summary and Outlook

- ✓ Spectroscopic factors could be a good tool to identify the enhanced proton-neutron correlations in N~Z nuclei.
- ✓ Large fluctuations of the neutron SF vs proton number are predicted by the shell model and observed in experiments: strong proton-neutron correlations **are essential** in nuclei!
- ✓ These correlations are challenging for mean field theories, but seems to be accommodated by the Green's function approach!
- ✓ Parts of the effective H responsible for these strong neutron-proton correlations were identified.
- ✓ This seems to be just the tip of the iceberg for proton-neutron correlation! More work necessary.