An Overview of
Nucleon-Transfer Studies on ^{76}Ge, ^{130}Te, ^{136}Xe

Ben Kay, Physics Division, Argonne National Laboratory

MEDEX 2017

Overview

- Brief introduction of $0\nu2\beta$ decay and the **NME challenge**
- Overview of **experimental approach** to determining occupancies
- Analysis details—how **model dependent** are the results**?**
- What does **quenching** mean (the other quenching)**?**
- **Results** of nucleon transfer reactions
- Some **comments**

Collaborators

Single-nucleon transfer reactions on $^{76}Ge \rightarrow {}^{76}Se$, $^{130}Te \rightarrow {}^{130}Xe$, $^{136}Xe \rightarrow {}^{136}Ba$
Initiative led by the **Argonne** and **Manchester** groups
Experiments at WNSL (Yale), RCNP (Osaka), IPN (Orsay)

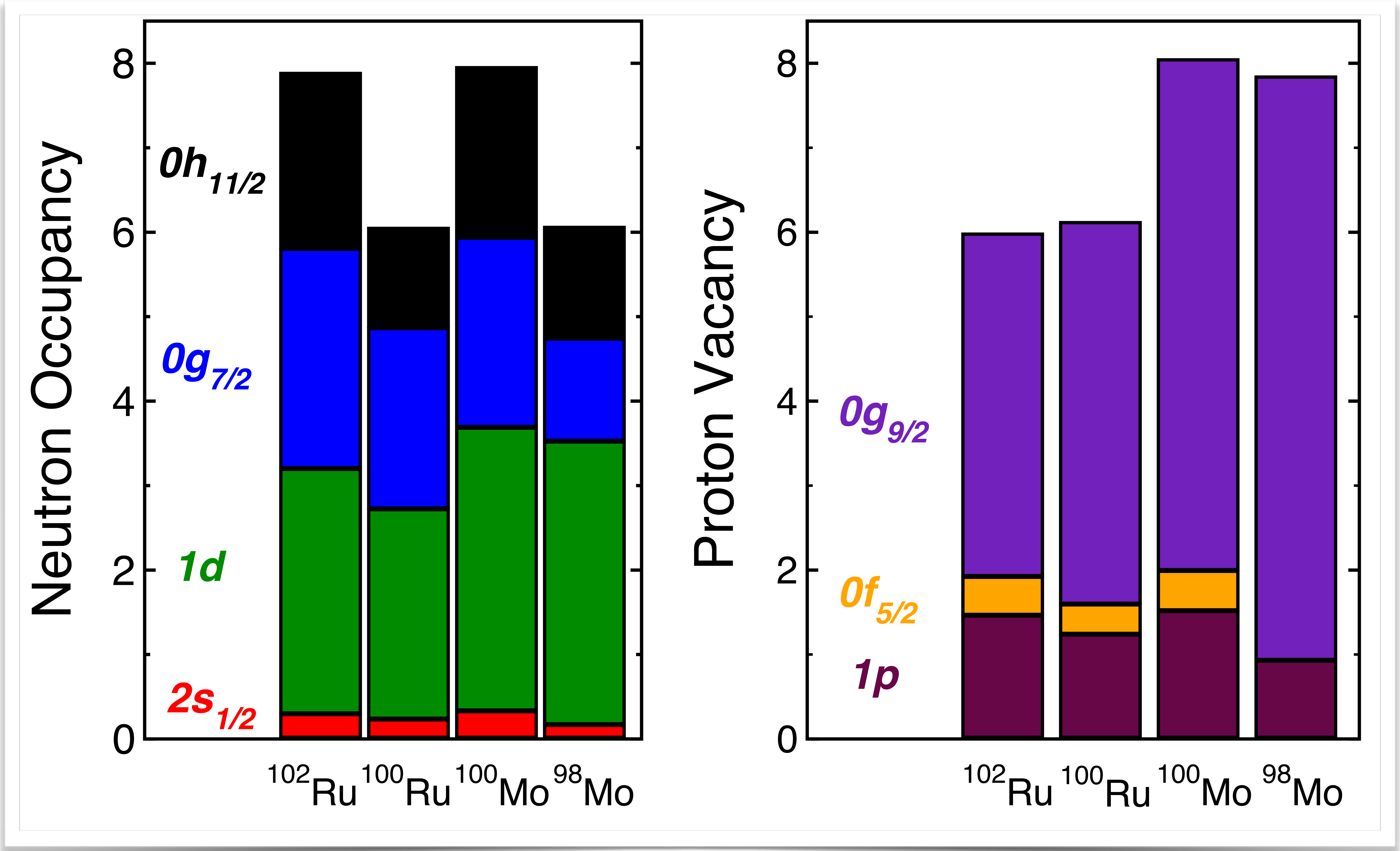
J. P. Schiffer, S. J. Freeman, J. A. Clark, C. Deibel, C. R. Fitzpatrick, S. Gros, A. Heinz, D. Hirata, C. L. Jiang, B. P. Kay, A. Parikh, P. D. Parker, K. E. Rehm, A. C. C. Villari, V. Werner, and C. Wrede, T. Adachi, H. Fujita, Y. Fujita, P. Grabmayr, K. Hatanaka, D. Ishikawa, H. Matsubara, Y. Meada, H. Okamura, Y. Sakemi, Y. Shimizu, H. Shimoda, K. Suda, Y. Tameshige, A. Tamii, T. Bloxham, S. A. McAllister, S. J. Freedman, K. Han, A. M. Howard, A. J. Mitchell, D. K. Sharp, J. S. Thomas, J. P. Entwisle, A. Tamii, S. Adachi, N. Aoi, T. Furuno, T. Hashimoto, C. R. Hoffman, E. Ideguchi, T. Ito, C. Iwamoto, T. Kawabata, B. Liu, M. Miura, H. J. Ong, G. Süsoy, T. Suzuki, S. V. Szwec, M. Takaki, M. Tsumura, T. Yamamoto T. E. Cocolios, L. P. Gaffney, V. Guimarães, F. Hammache, P. P. McKee, E. Parr, C. Portail, N. de Séréville, J. F. Smith, I. Stefan.

Schiffer et al., Phys. Rev. Lett. ***100**, 112501 (2008)*
Kay et al., Phys. Rev. C ***79**, 021301(R) (2009)*
Kay et al., Phys. Rev. C ***87**, 011302(R) (2013)*
Entwisle et al., Phys. Rev. C ***93**, 064312 (2016)*
Szwec et al., Phys. Rev. C ***94**, 054314 (2016)*

MEDEX 13
MEDEX 17

Related work

Sean Freeman talked on the nucleon occupancies for the A = 100 and 150 systems and their connection to theoretical calculations.



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0ν2β decay

REACHING FOR THE HORIZON

(US perspective)
The last NSAC Long Range Planning exercise placed an emphasis on 0ν2β-decay

https://science.energy.gov/np/nsac/

0ν2β decay

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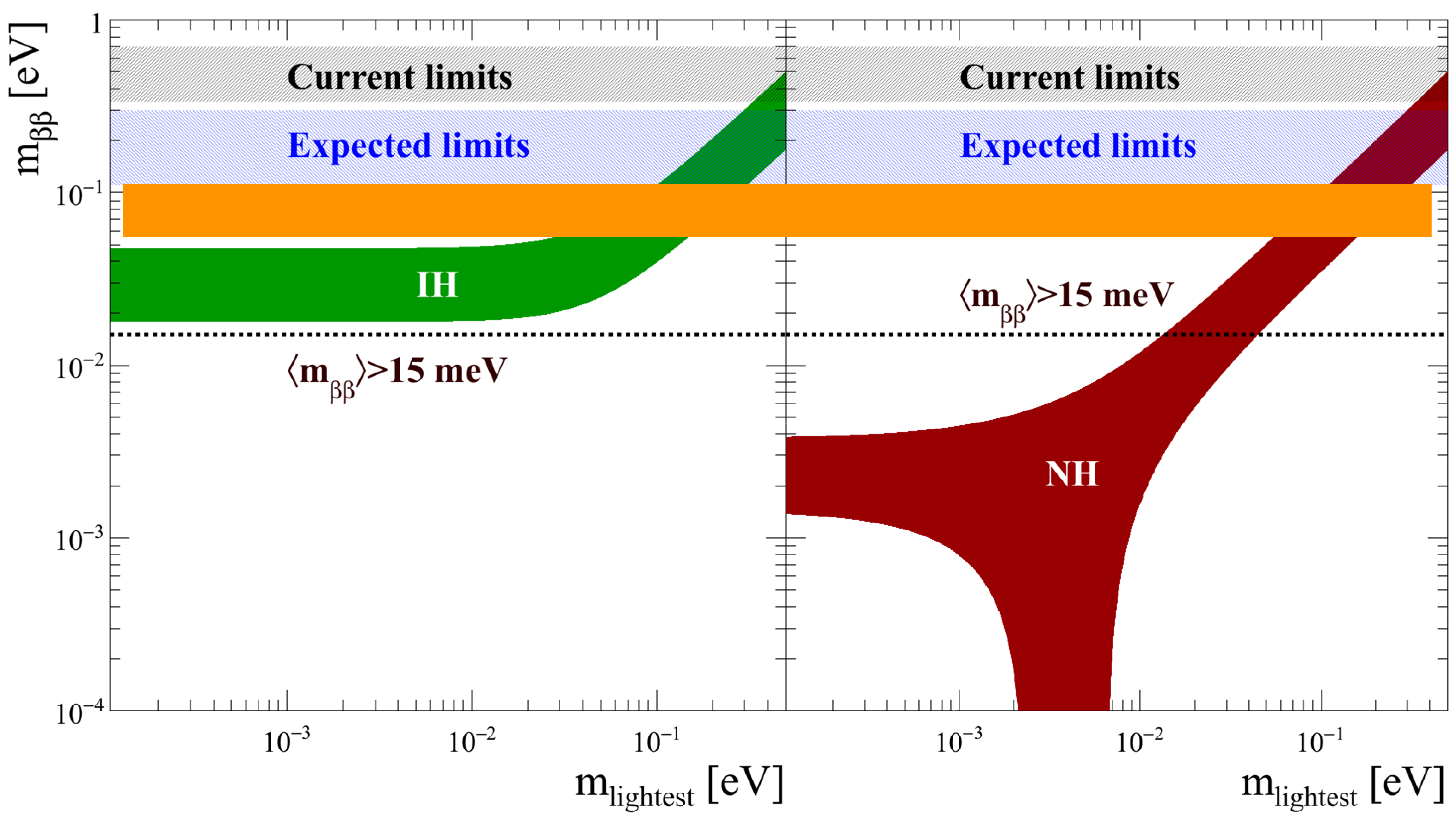
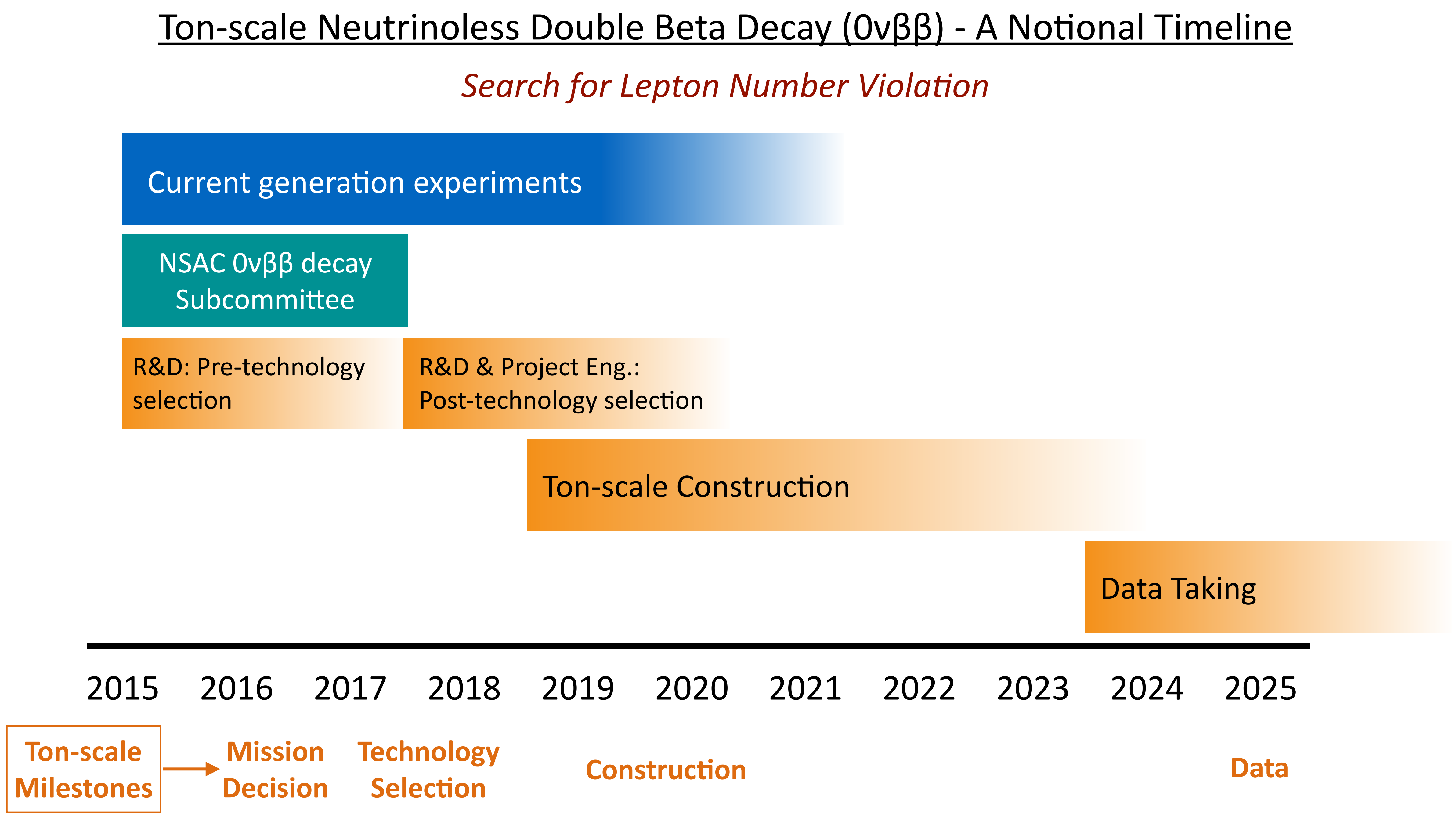




$0\nu2\beta$ decay

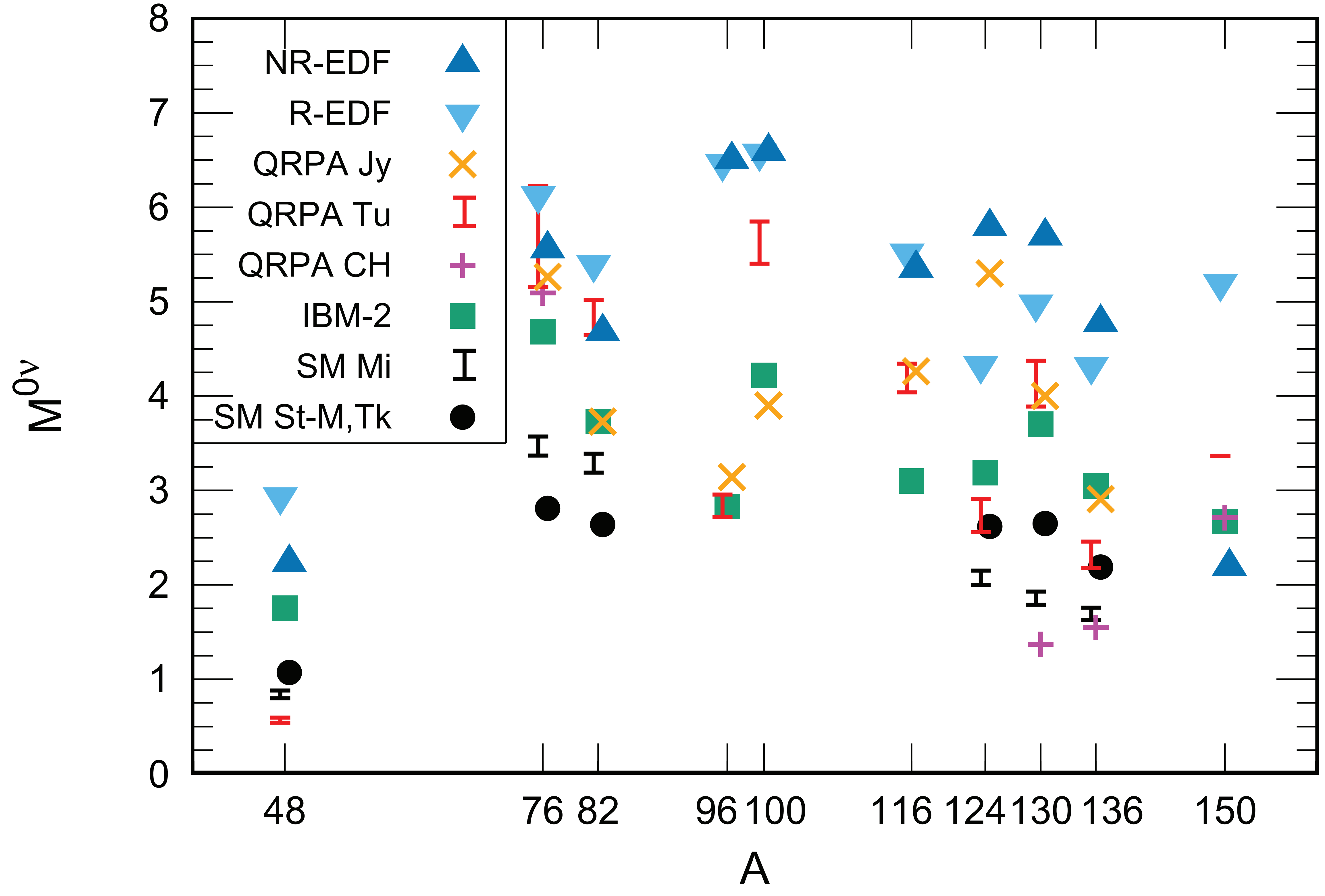
REACHING FOR THE HORIZON

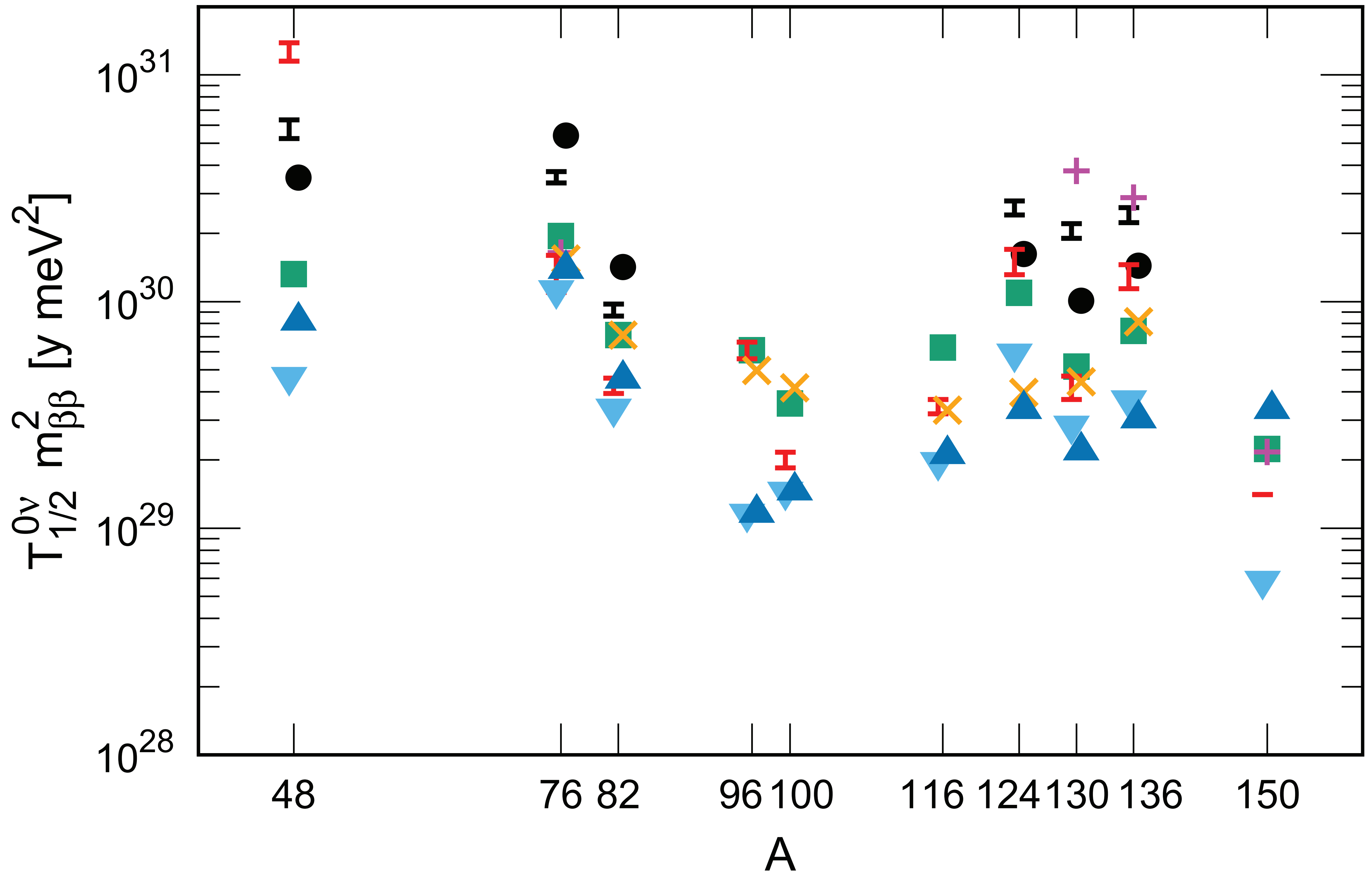
(US perspective)
The last NSAC Long Range Planning exercise placed an emphasis on $0\nu2\beta$-decay

> *"Since neutrinoless double beta decay measurements use the atomic nucleus as a laboratory, nuclear theory is critical in connecting experimental results to the underlying lepton-number violating interactions and parameters through nuclear matrix elements, which account for the strong interactions of neutrons and protons. Currently, there exists about a factor of two uncertainty in the relevant matrix elements, but by the time a ton-scale experiment is ready to take data, **we expect reduced uncertainties** as a result of the application to this problem of improved methods to solve the nuclear many-body physics."*

0ν2β decay and NMEs

$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta} \rangle|^2$$





Engel and Menéndez, Rep. Prog. Phys. ***80****, 046301 (2017)*

0ν2β decay and NMEs and searches

$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta}\rangle|^2$$

$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \propto 1/|\text{NME}|^2$$

Experimental searches are often discussed in terms of their sensitivity to a given half life, accounting for ***enrichment****,* ***efficiency****,* ***backgrounds****,* ***resolution****, and* ***mass****.*

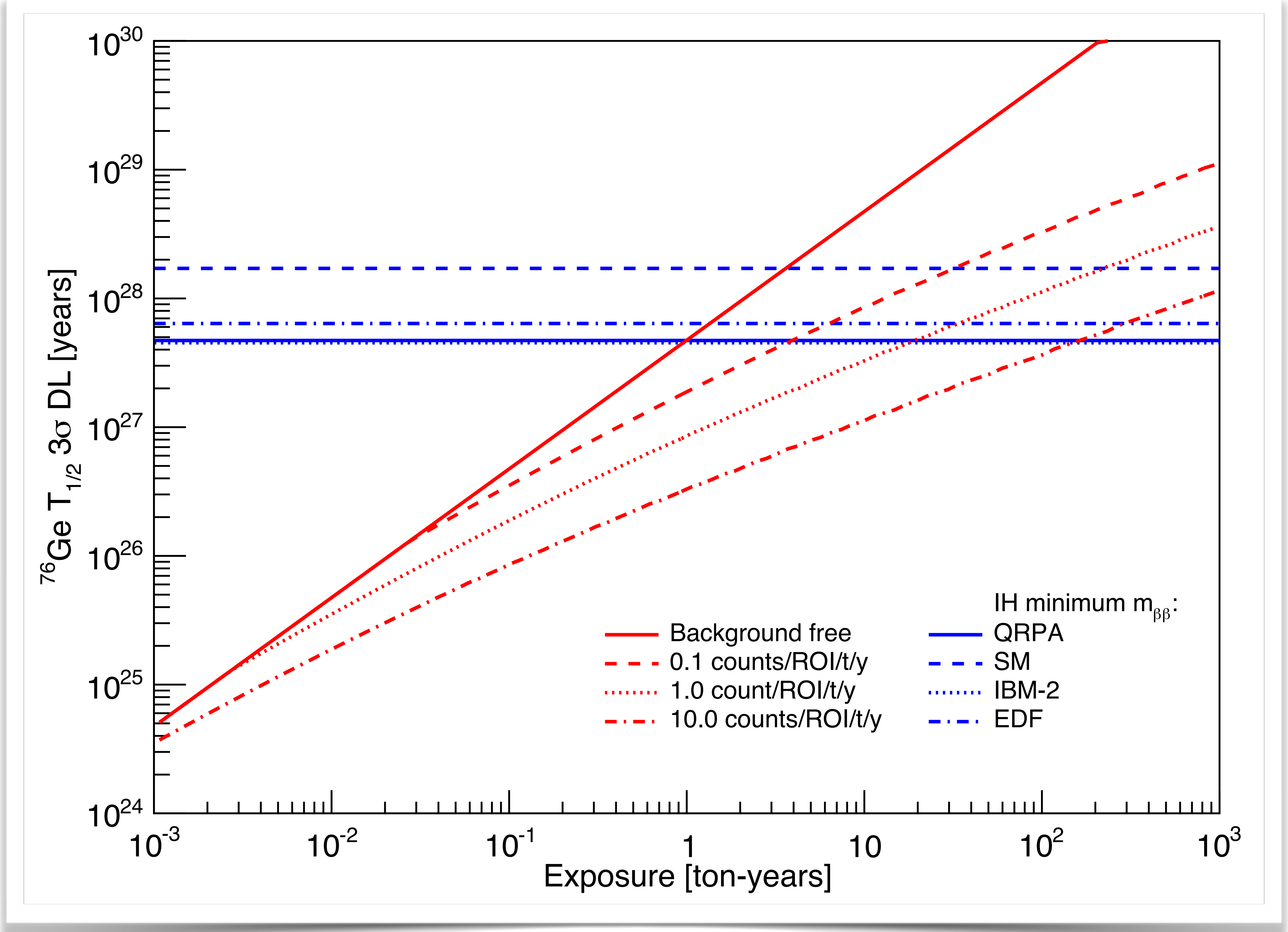


Figure taken from one of Jason Detwiler's talks found online

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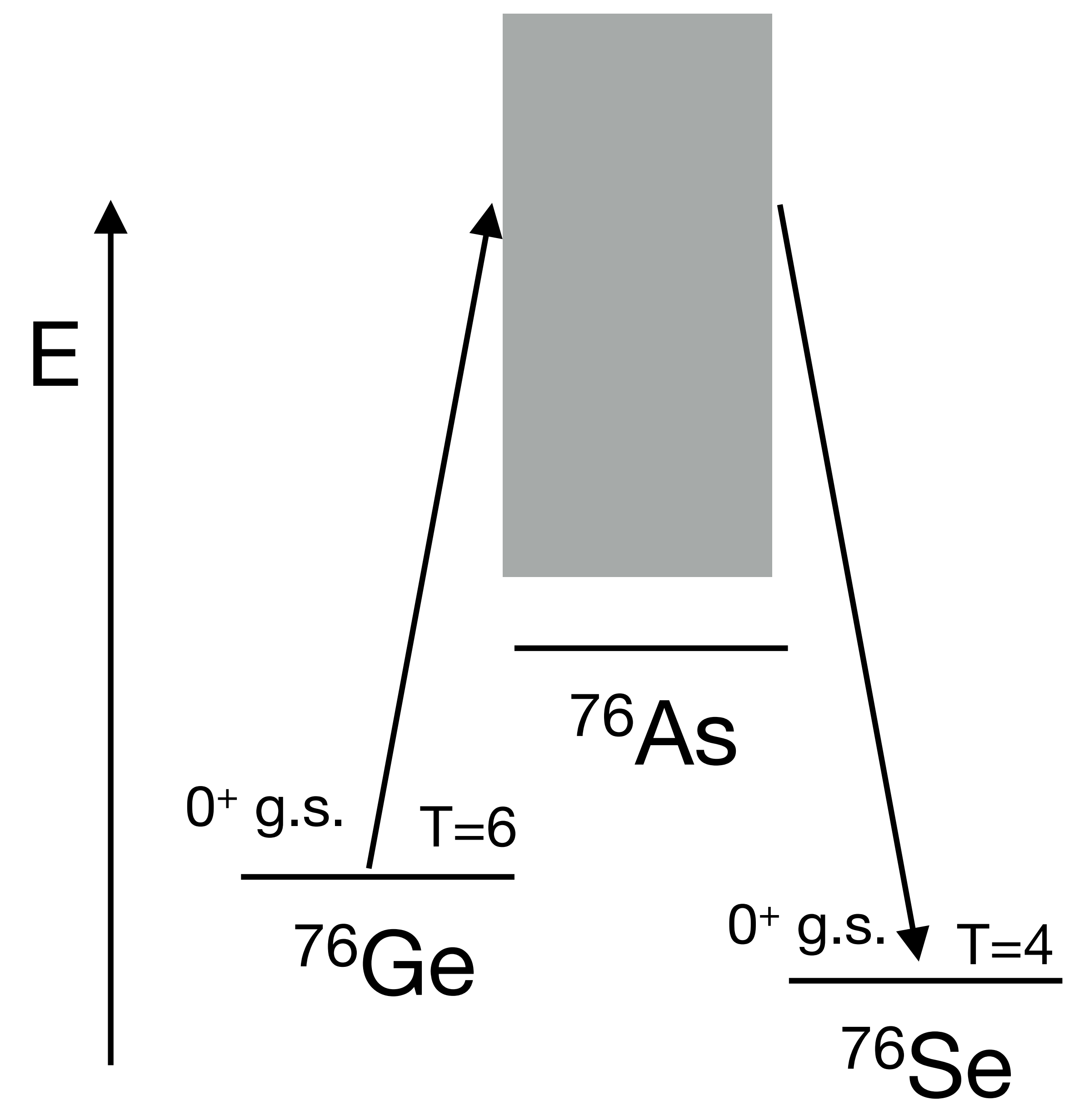
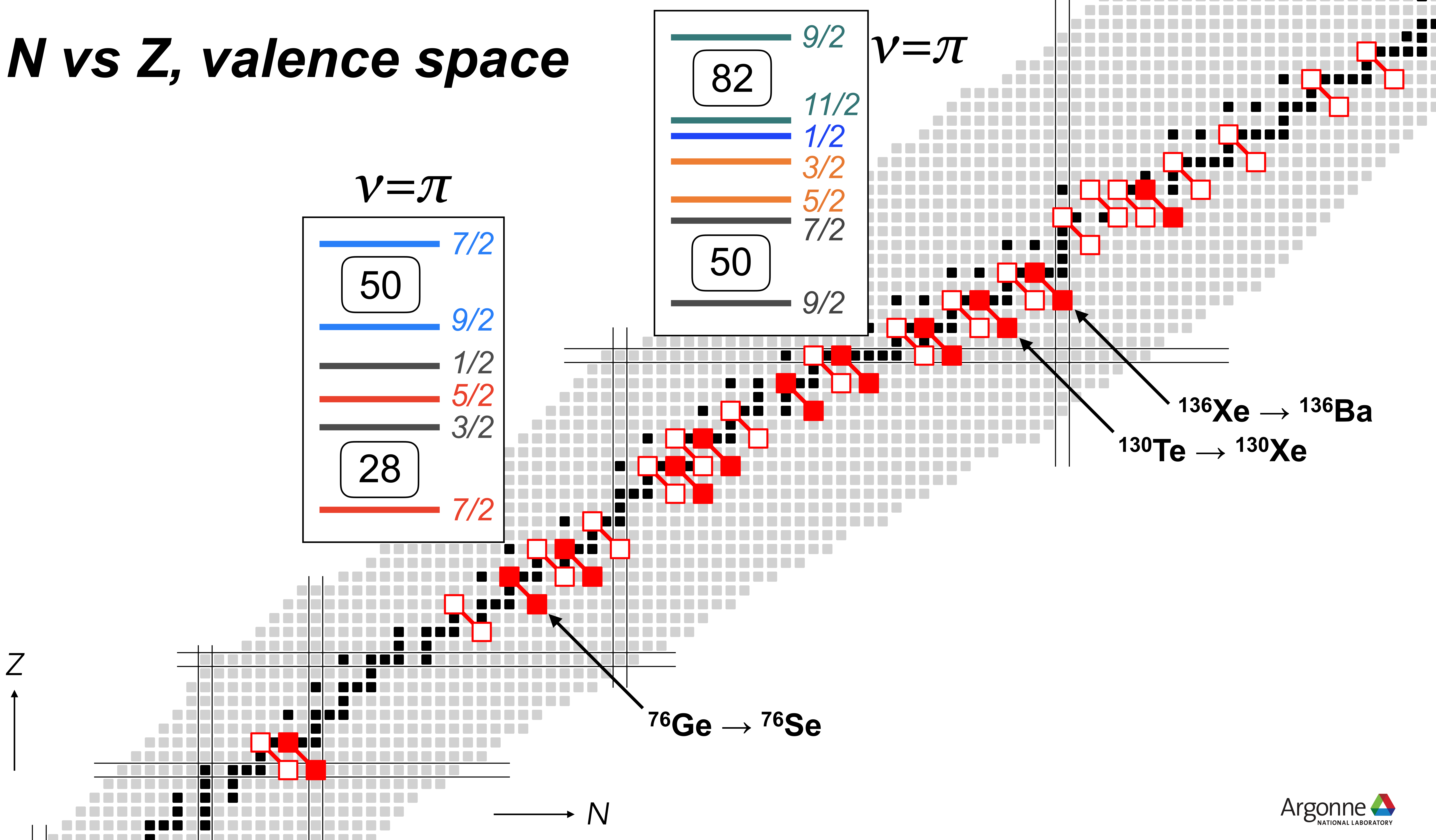
0ν2β decay and nuclear structure

- Focus on the **initial and final ground states**—determine the arrangement of protons and neutron about the Fermi surface
- (Same argument put forward by Sean Freeman in earlier talk)
- Other approaches may include, e.g., ^{76}Ge(^{18}Ne,^{18}O)^{76}Se (see previous talk)

0ν2β
Probes all intermediate states up to 10s of MeV, any spin, up to 5 to 6ħ

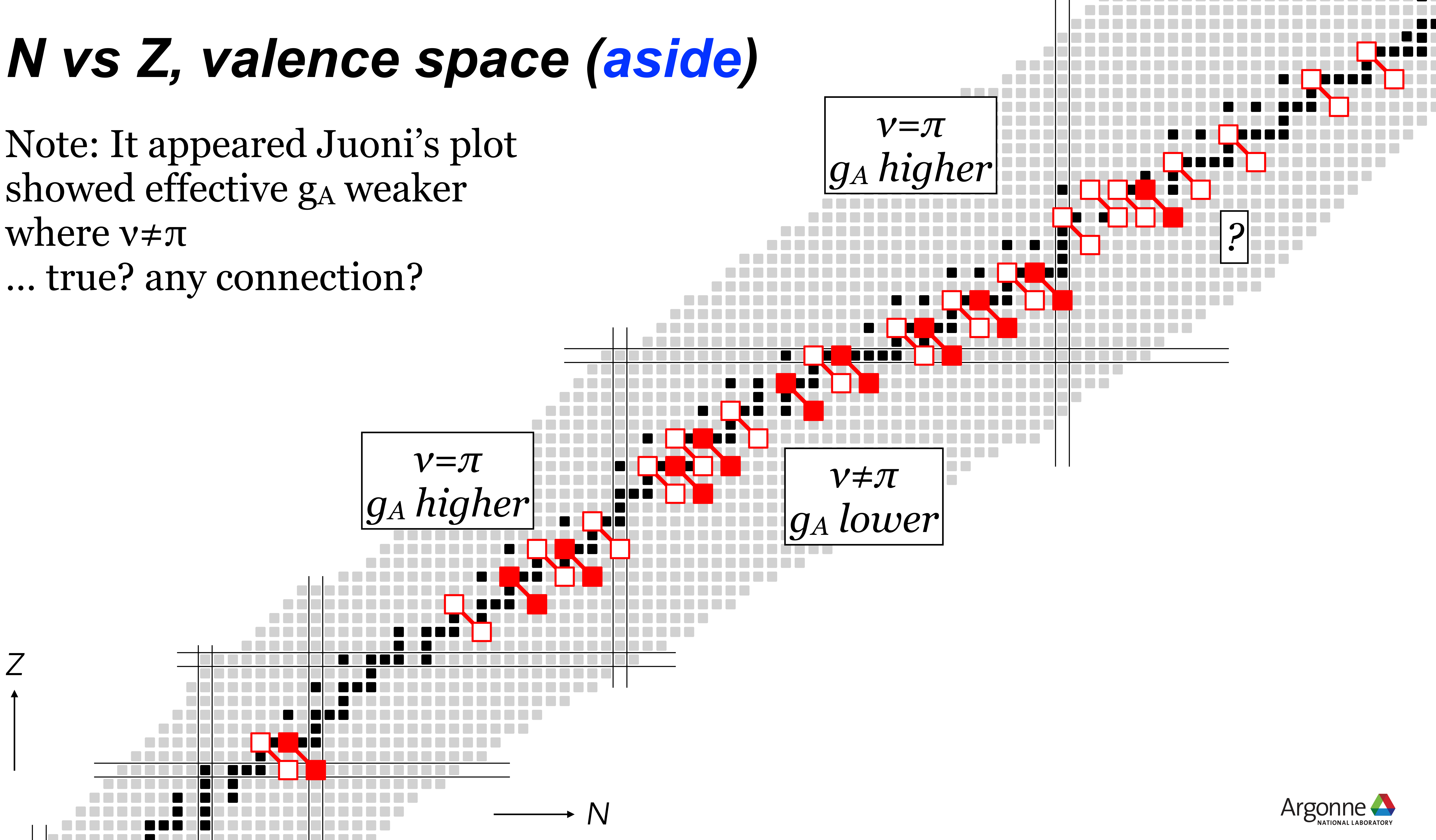


N vs Z, valence space



N vs Z, valence space (aside)

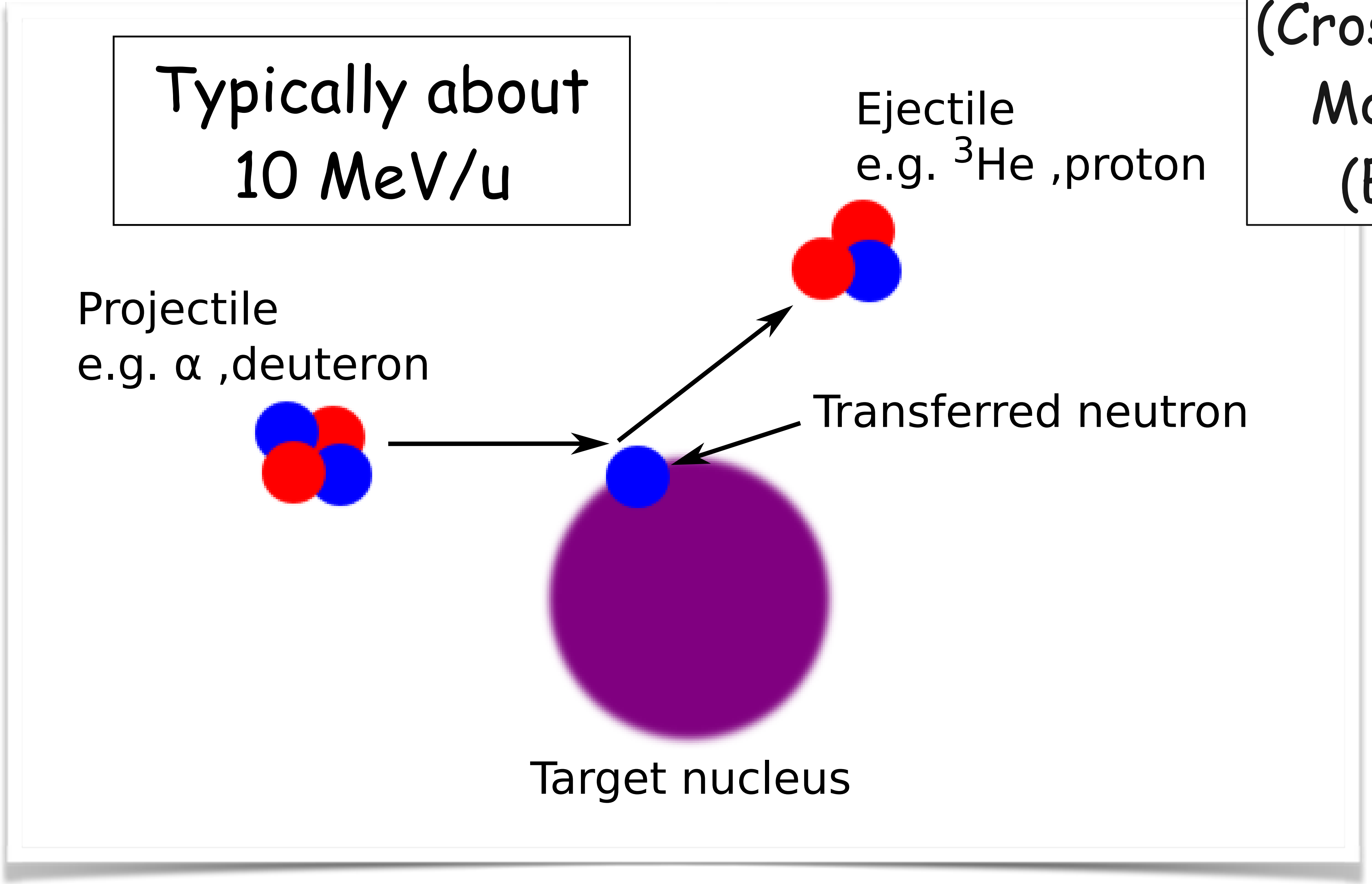
Note: It appeared Juoni's plot showed effective g_A weaker where $\nu \neq \pi$
... true? any connection?

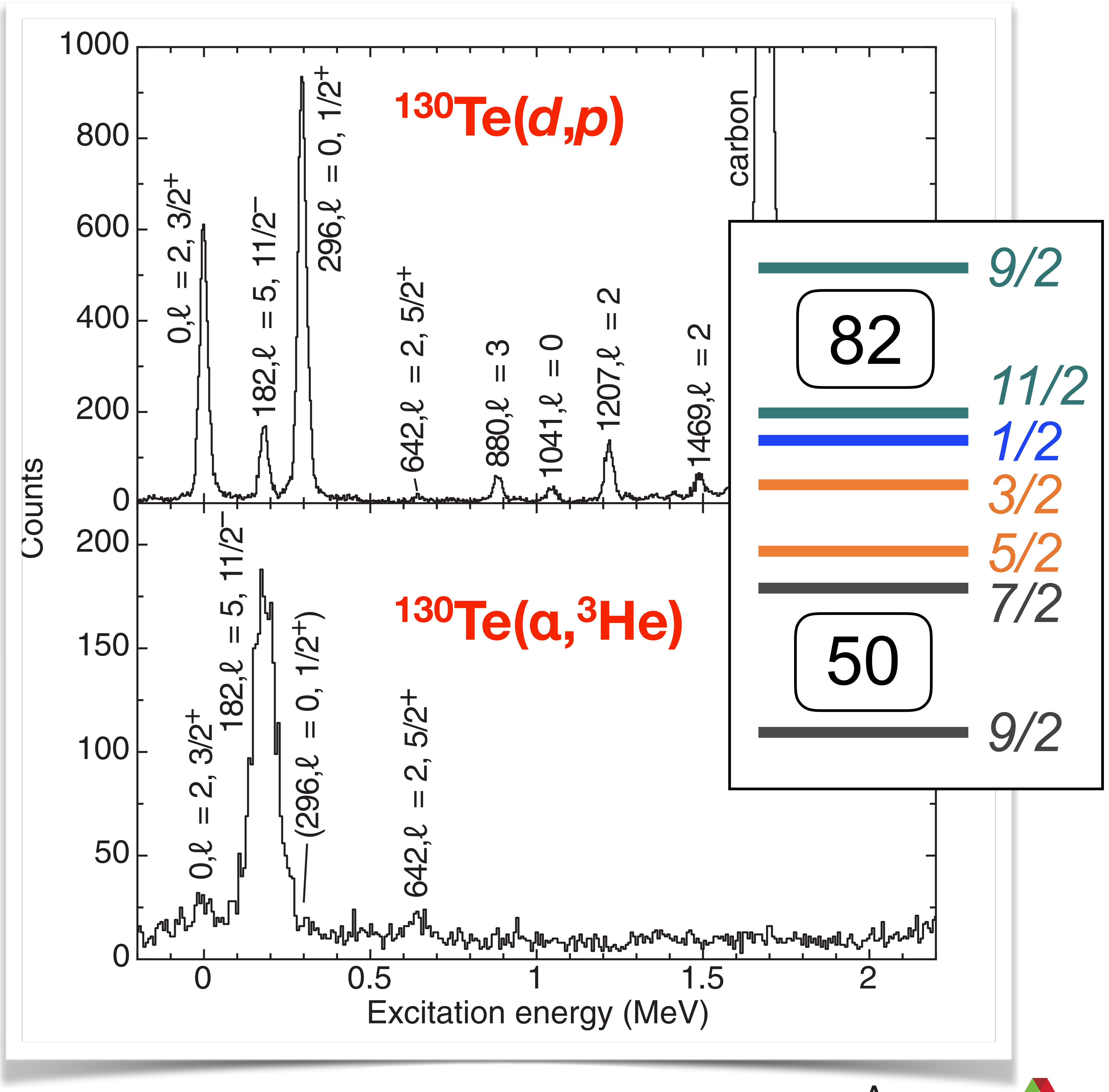


Single-nucleon transfer (observables)

Transfer reactions a few MeV/u above the Coulomb barrier
Direct reactions

Yield
(Cross section)
Momentum
(Energy)



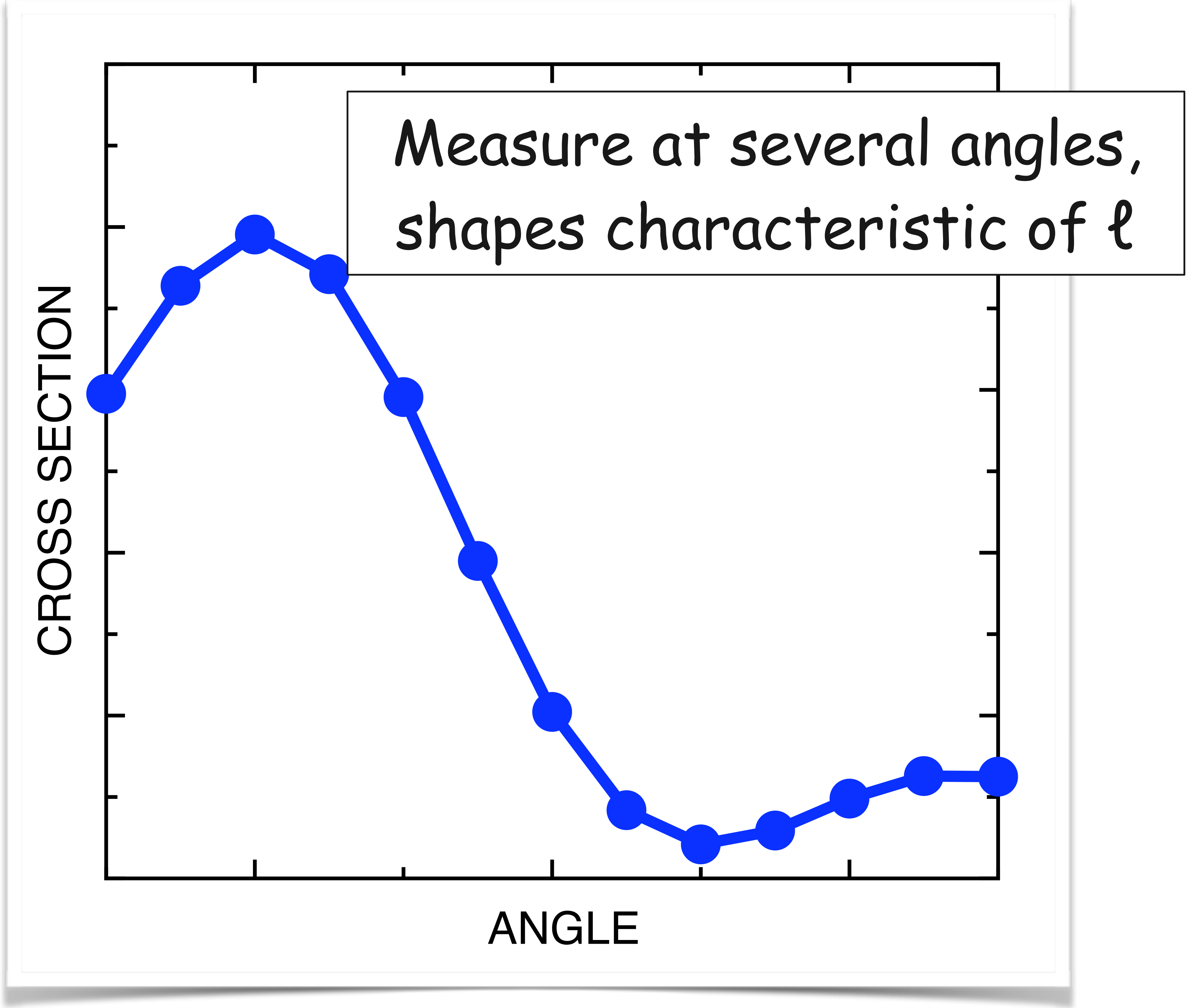


*Kay et al., Phys. Rev. C **79**, 021301(R) (2009)*

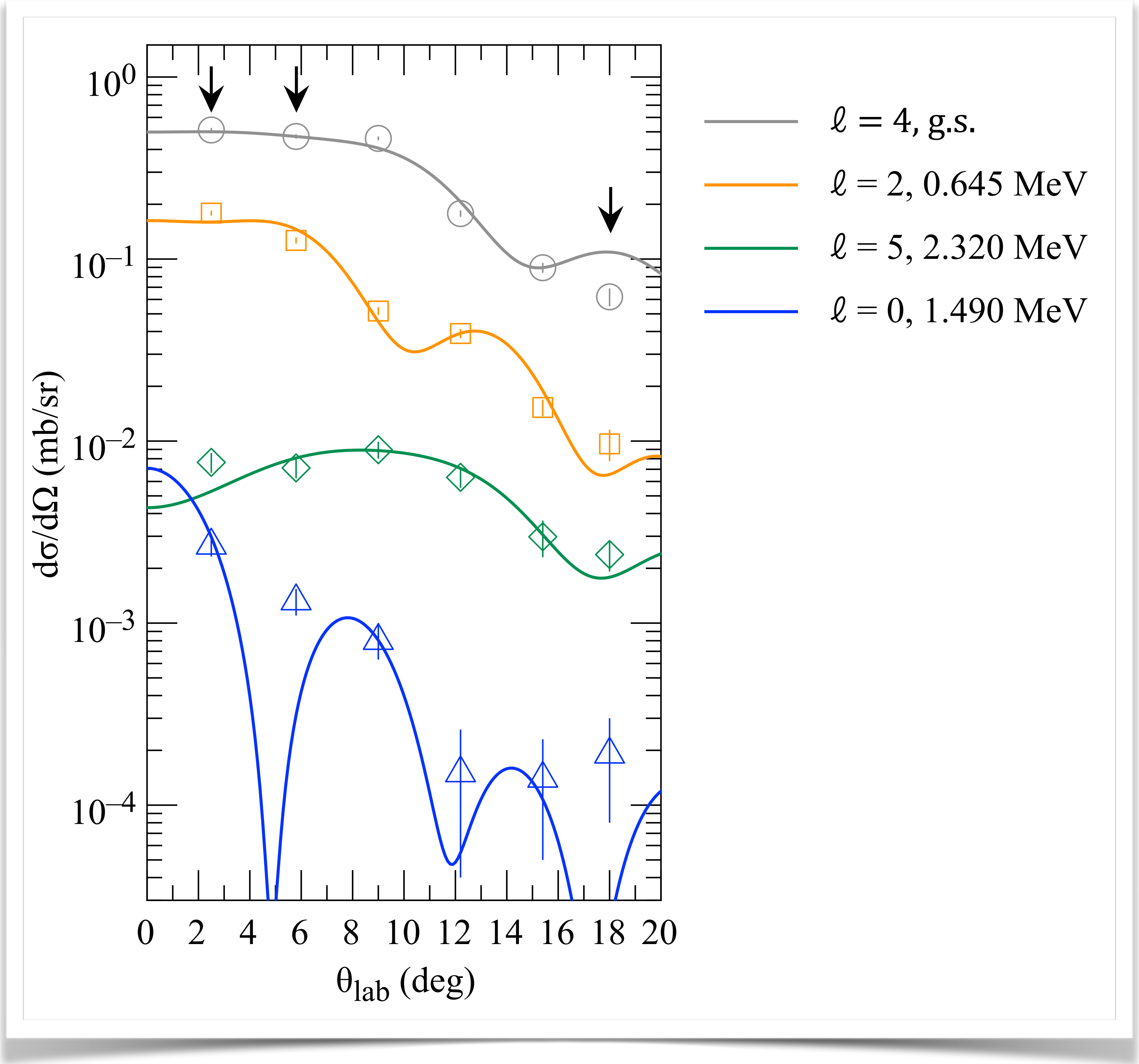
Single-nucleon transfer (derived quantities)

Transfer reactions a few MeV/u above the Coulomb barrier

Direct reactions



$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{measured}} = gS'_j \left.\frac{d\sigma}{d\Omega}\right|_{\text{calculated}}$$



Entwisle et al., Phys. Rev. C **93**, 064312 (2016)

A parameterized model

- >50 years experience / refinement
- Parameterized (Wood-Saxon potentials, derivatives)
- Lots of logical check points (e.g., parameters are consistent with those derived from electron scattering … radii, etc.), a wealth of nucleon scattering data
- The spectroscopic factor is a ‘reduced cross section’ — modest corrections to account for kinematics and spins

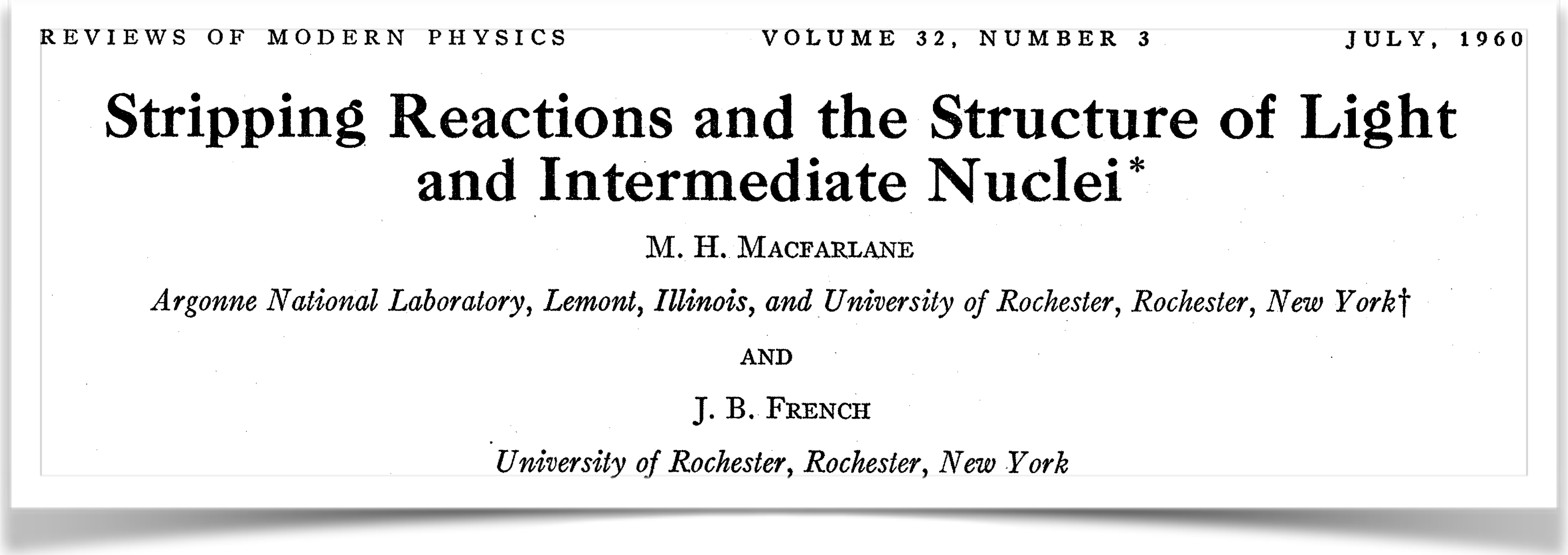
$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{measured}} = gS'_j \left.\frac{d\sigma}{d\Omega}\right|_{\text{calculated}}$$

Spectroscopic factor: simply a measure of the overlap between the final state and the initial state plus/minus one nucleon

Distorted-wave Born Approximation, requires several ingredients and a little bit of respect!

Does it work? How to relate to occupancies?

- Need a **normalization**
- Typical **uncertainty is between +/-0.1-0.2 nucleons**
- Demonstrated in many systems (groups of isotopes/isotones) across the chart of isotopes


REVIEWS OF MODERN PHYSICS VOLUME 32, NUMBER 3 JULY, 1960

Stripping Reactions and the Structure of Light and Intermediate Nuclei*

M. H. MACFARLANE

Argonne National Laboratory, Lemont, Illinois, and University of Rochester, Rochester, New York†

AND

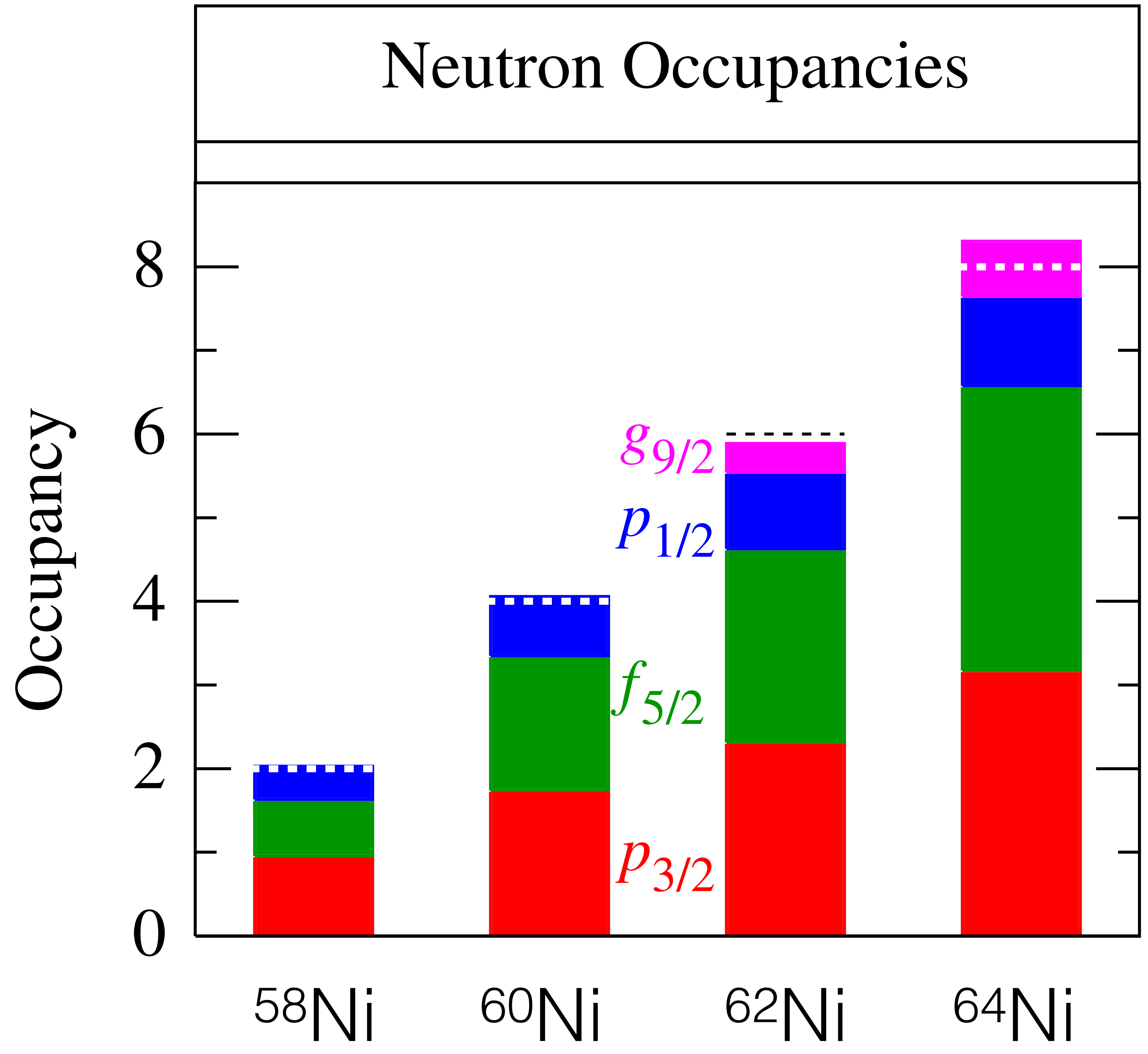
J. B. FRENCH

University of Rochester, Rochester, New York

$$S' \equiv \sigma_{\rm exp}/\sigma_{\rm DWBA}$$

$$N_j \equiv S'/S$$

$$N_j \equiv (\Sigma G_+ S'_{\rm adding} + \Sigma G_- S'_{\rm removing})/(2j+1).$$



- But is the normalization just arbitrary?

J. P. Schiffer et al., Phys. Rev. Lett. ***108****, 022501 (2012) [work prompted largely because of the 0ν2β-decay program]*

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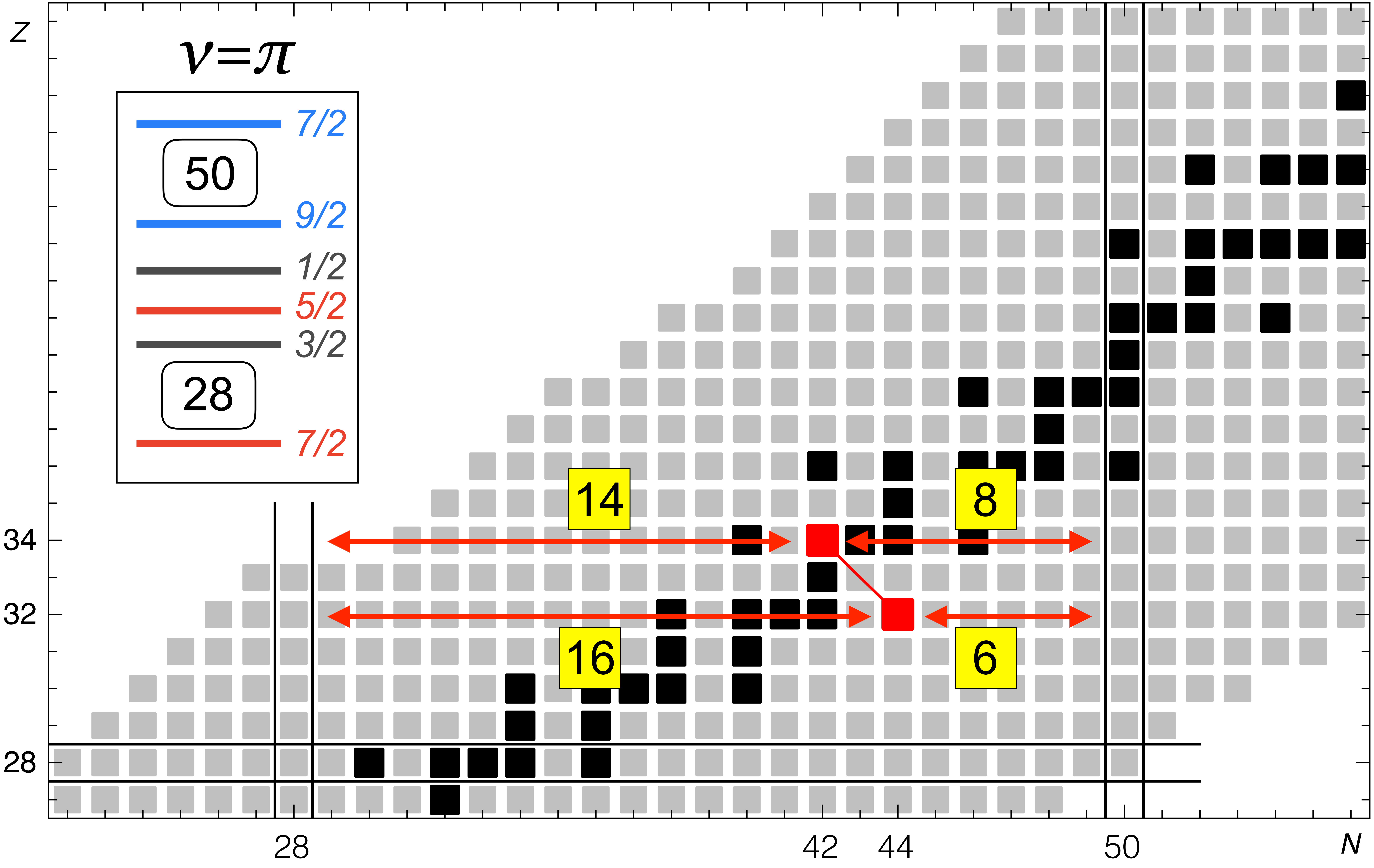
$^{76}Ge \rightarrow {}^{76}Se$ valence space



Analysis—sum rules and normalization

...in which cross sections becomes occupancies

^{76}Ge(p,d)

E	ℓ	S'
0	1	0.45
191	4	
248	1	0.12
317	3	
457	3	
575	1	1.29
651	3	
885	1	0.10
1137	1	0.11
1250	3	
1410	0	
1451	1	0.37
1580	3	

^{76}Ge(d,p)

E	ℓ	$(2j+1)S'$
160	1	0.44
225	4	
421	2	
505	2	
629	1	0.15
884	2	
1021	1	0.12
1048	1	0.04
1250	0	
1385	2	

$$N_j \equiv [\sum S'_{\text{removing}} + \sum (2j+1)S'_{\text{adding}}]/(2j+1)$$

$$N_j \equiv [(0.45 + 0.12 + 1.29 + 0.10 + 0.11 + 0.37) + (0.44 + 0.15 + 0.12 + 0.04)]/(2+4) = 0.53$$

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Analysis—sum rules and normalization

…in which cross sections becomes occupancies

^{76}Ge(*p*,*d*)

E	*ℓ*	*S'*	*S*
0	1	0.45	0.85
191	4		
248	1	0.12	0.23
317	3		
457	3		
575	1	1.29	2.43
651	3		
885	1	0.10	0.19
1137	1	0.11	0.21
1250	3		
1410	0		
1451	1	0.37	0.70
1580	3		

^{76}Ge(*d*,*p*)

E	*ℓ*	(2*j*+1)*S'*	(2*j*+1)*S*
160	1	0.44	0.82
225	4		
421	2		
505	2		
629	1	0.15	0.28
884	2		
1021	1	0.12	0.22
1048	1	0.04	0.07
1250	0		
1385	2		

$$\boxed{N_j \equiv [\sum S'_{\text{removing}} + \sum (2j+1)S'_{\text{adding}}]/(2j+1)}$$

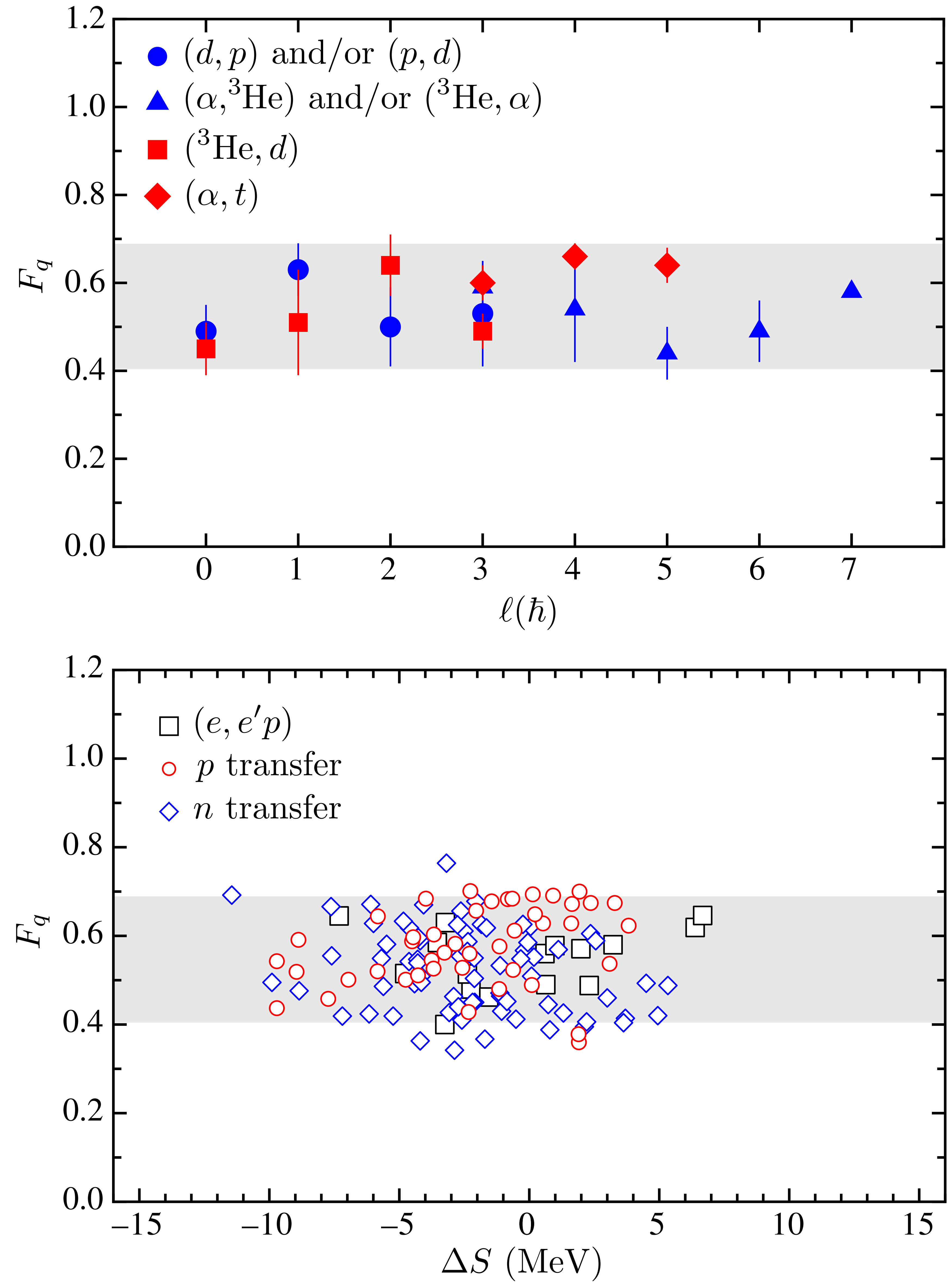
$$N_j \equiv [(0.45+0.12+1.29+0.10+0.11+0.37) + (0.44+0.15+0.12+0.04)]/(2+4) = 0.53$$

Quenching Factor

The normalization appears meaningful, a ubiquitous feature of low-lying single-particle strength, independent of A, *l*, nucleon type, reaction

Reaction, ℓ transfer	Number of determinations	F_q	rms spread
$(e,e'p)$, all ℓ	16	0.55	0.07
(d,p), (p,d), $\ell = 0$–2	40	0.53	0.09
(d,p), (p,d), $\ell = 0$–3	46	0.53	0.10
$(\alpha,{}^3\mathrm{He})$, $({}^3\mathrm{He},\alpha)$, $\ell = 4$–7	26	0.50	0.09
$(\alpha,{}^3\mathrm{He})$, $({}^3\mathrm{He},\alpha)$, $\ell = 3$–7	34	0.52	0.09
$({}^3\mathrm{He},d)$, $\ell = 0$–2	18	0.54	0.10
$({}^3\mathrm{He},d)$, $\ell = 0$–4	26	0.54	0.09
(α,t), $\ell = 4$–5	14	0.64	0.04
(α,t), $\ell = 3$–5	18	0.64	0.04
All transfer data[a]	124	0.55	0.10

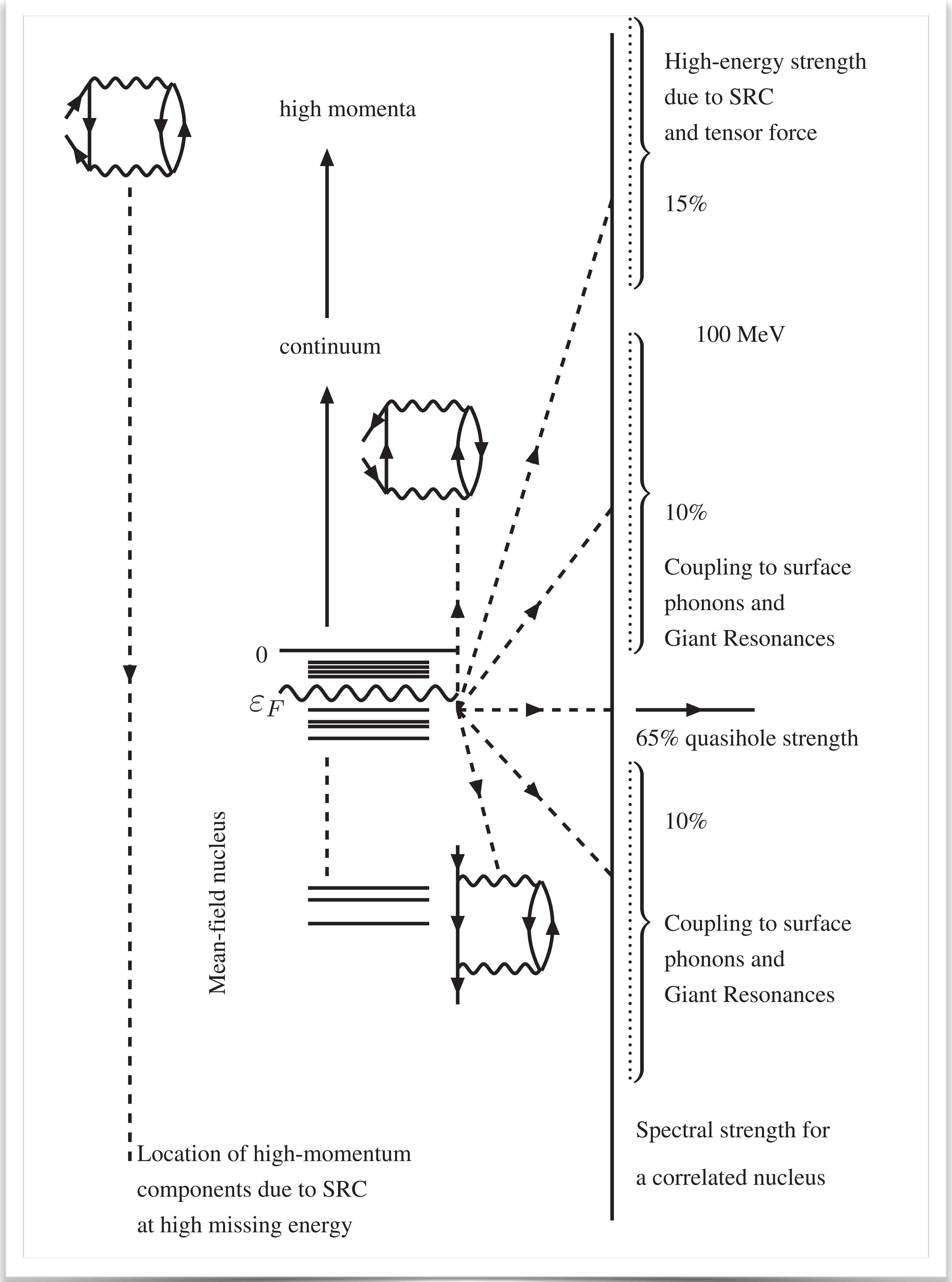
[a]Rows 3, 5, 7, and 9.



Kay et al., Phys. Rev. Lett. ***111****, 042502 (2013)*

Quenching Factor

“Thus at any time only 2/3 of the nucleons in the nucleus act as independent particles moving in the nuclear mean field. The remaining third of the nucleons are correlated.”*



__Key points:__

- ***Academic* in terms of *change* in occupancies**
- Arguably ***essential*** in terms of trusting the data
- How does theory handle it?

*V. R. Pandharipande, I. Sick, P. K. A. deWitt Huberts, Rev. Mod. Phys. **69**, 981 (1997)
W. H. Dickhoff J. Phys. G: Nucl. Part. Phys. **37**, 064007 (2010)

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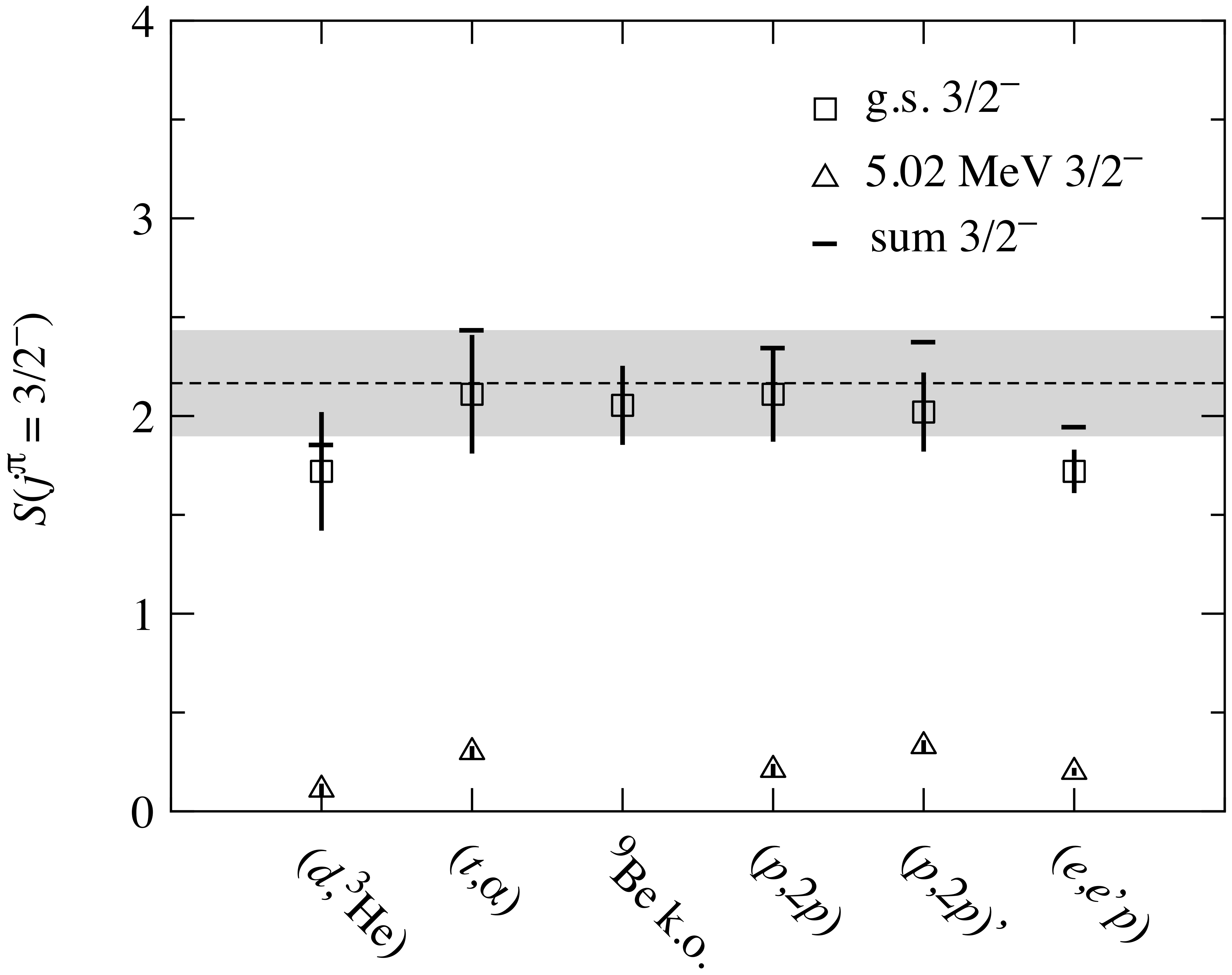
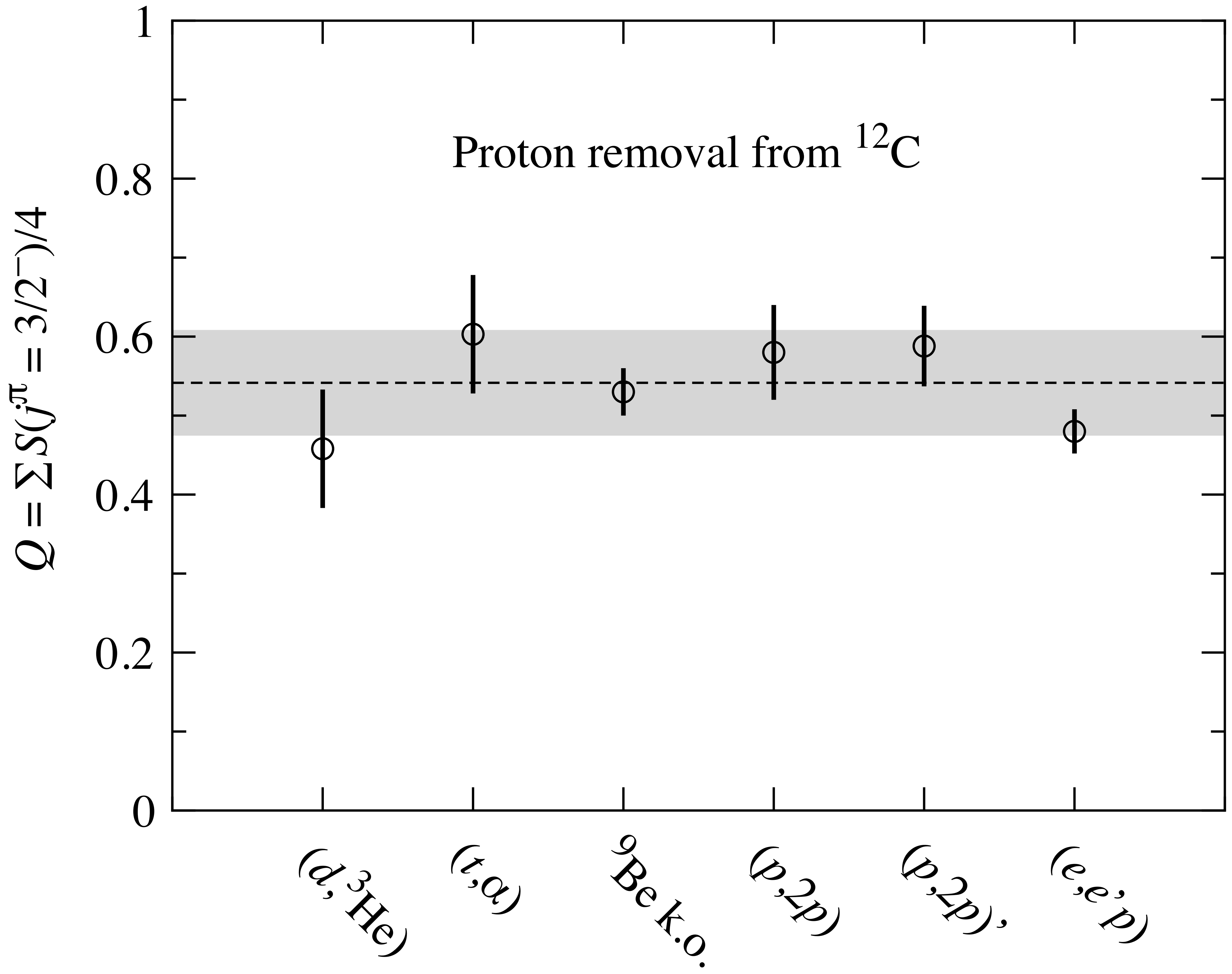
Quenching Factor

There are a handful of isotopes where reliable experimentally determined cross sections exist from numerous ‘equivalent’ probes, e.g., proton removal from ^{12}C.

Same physics results

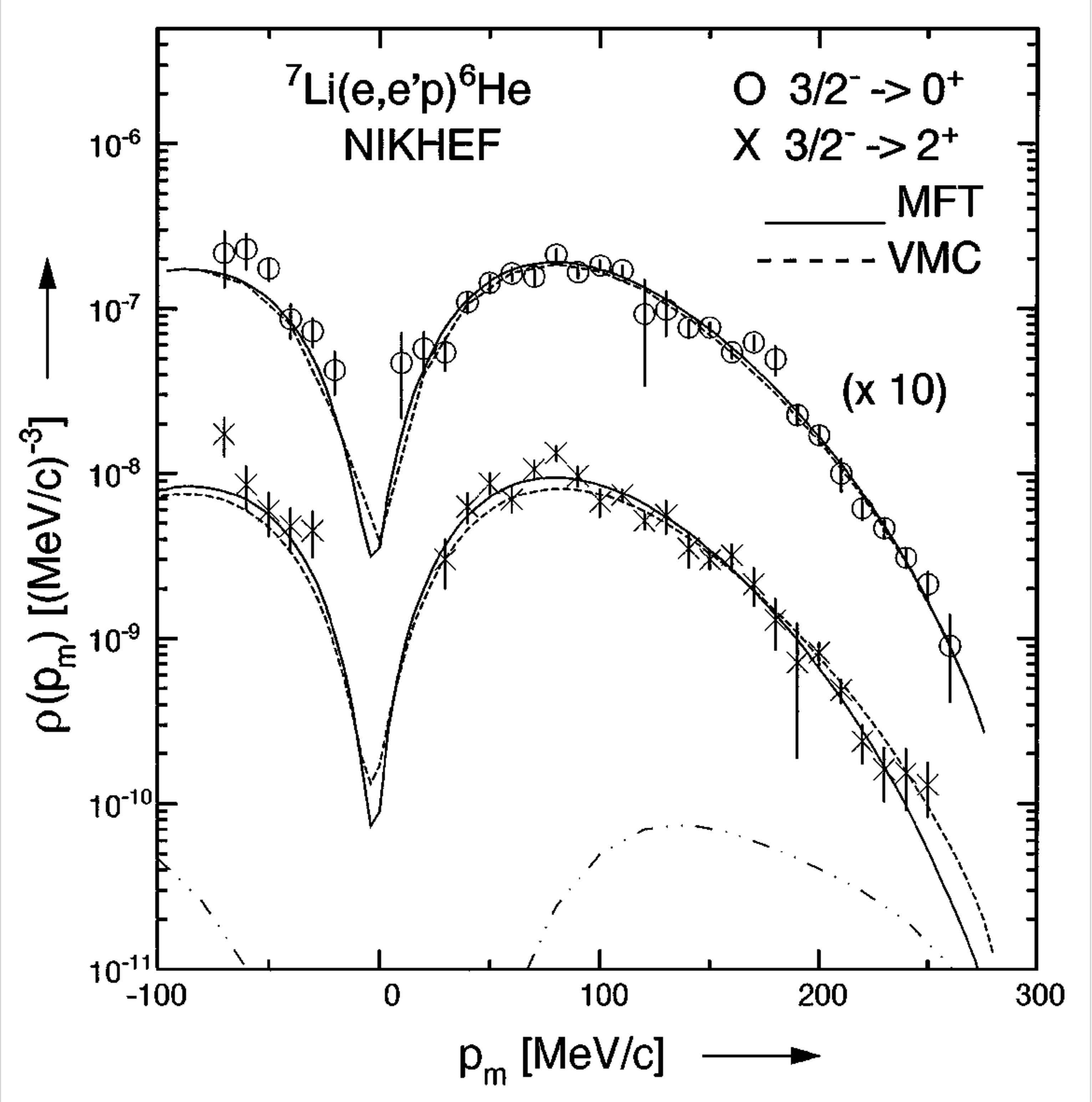




Evaluated Nuclear Structure Data File (www.nndc.bnl.gov)

Quenching Factor

- Tempting to conclude it is well understood
- Not captured in, e.g., shell model (SM does not know of SRC)
- *Ab initio* calculations do capture it beautifully (in light nuclei)



Model	S 0^+	S 2^+	S $0^+ + 2^+$
Expt. $(1p)$	0.42(4)	0.16(2)	0.58(5)
VMC $(1p)$	0.41	0.18	0.59
VMC $(1p + 1f)$	0.41	0.19	0.60

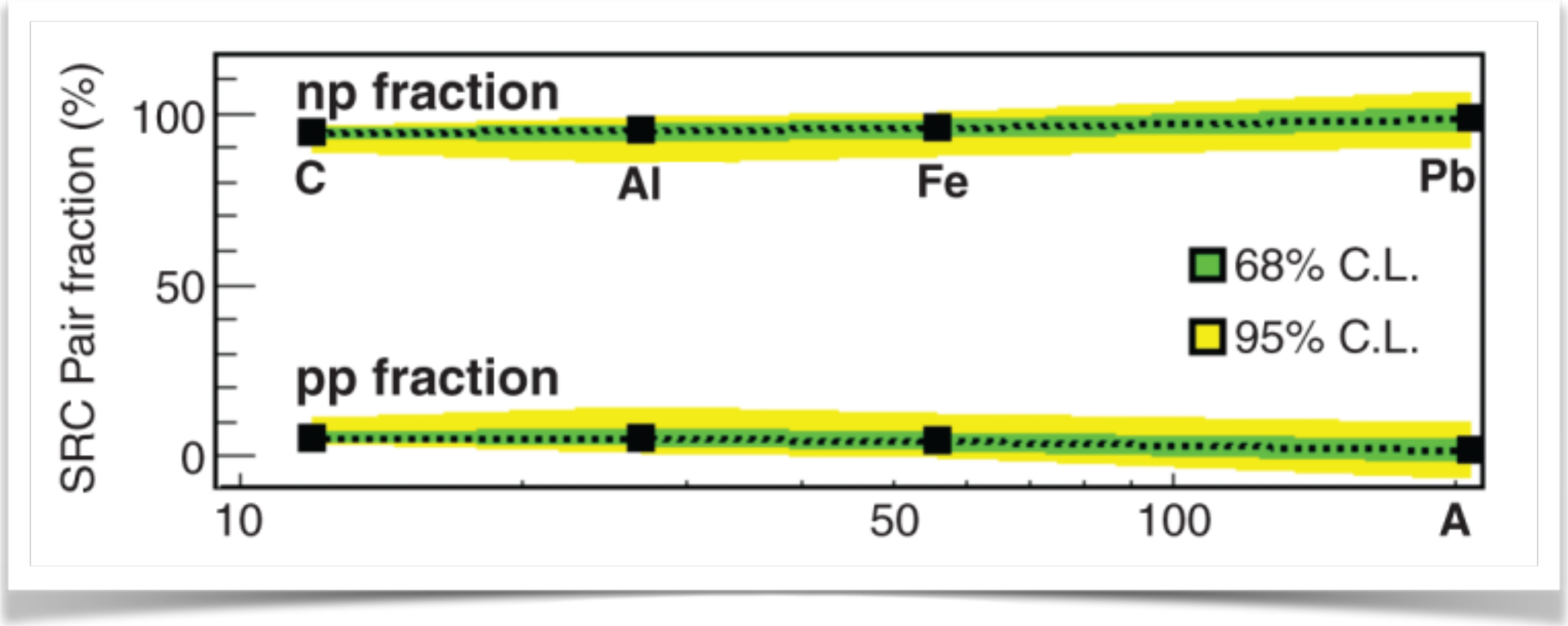
*Lapikás, Wesseling, and Wiringa, Phys. Rev. Lett. **82**, 4404 (1999)*

Quenching Factor (a few other comments)

- No obvious change with neutron excess (*np* dominates) or binding energy (at least near stability)

- Note, there are very good (*e,e'p*) and (*e,e'n*) data on ^{48}Ca

- Arguably not necessary to explore (*e,e'p*) [no obvious facilities] … results agree with nucleon transfer



- Does it relate to quenching of g_A? Not obvious, but likely in the sense that there is missing physics / model space in calculations

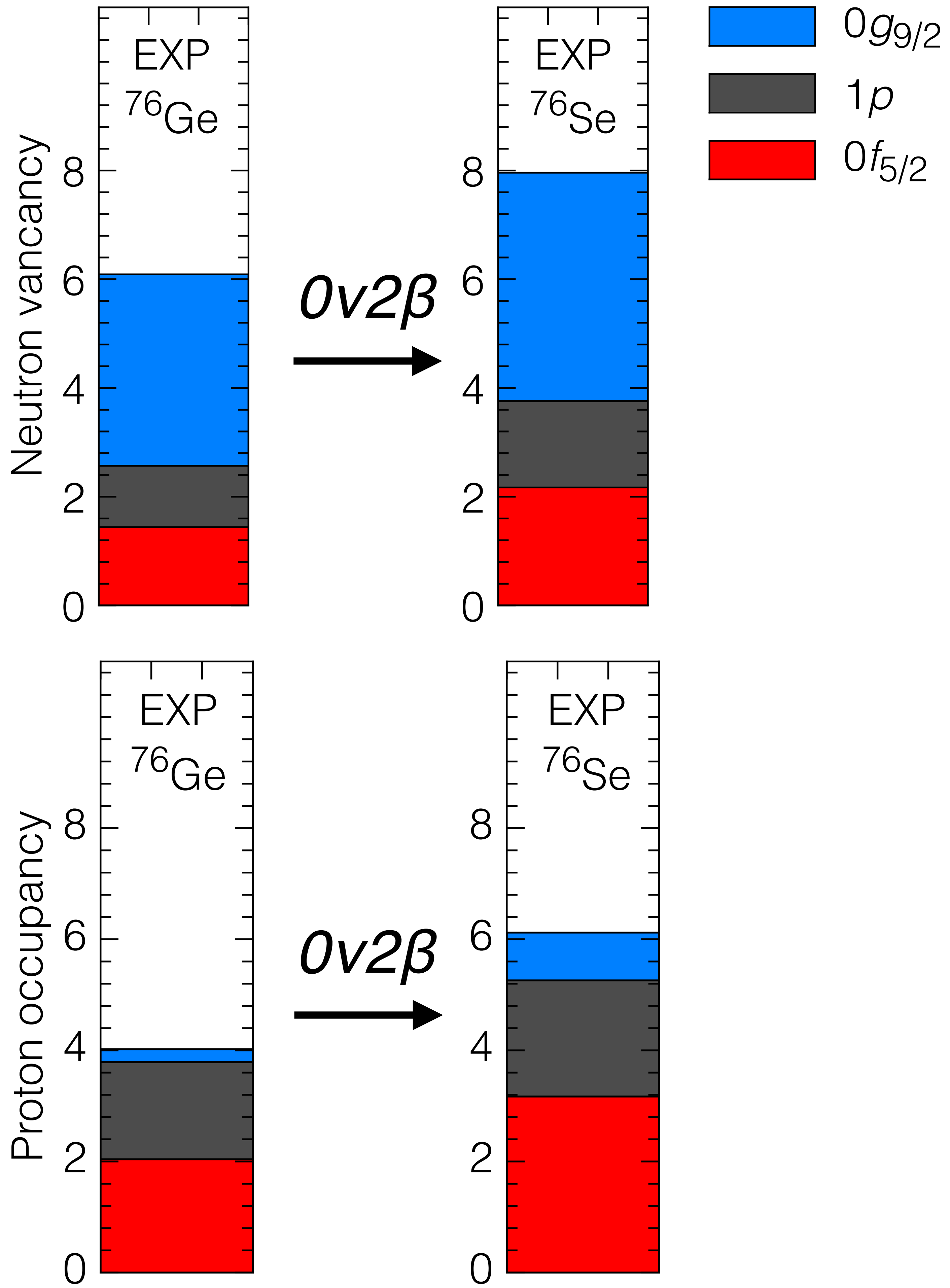
O. Hen et al. Science ***346****, 614 (2014)*

Occupancies for ^{76}Ge, ^{76}Se

Already well known by MEDEX13 ...

Isotope	$0f_{5/2}$	$1p_{1/2,3/2}$	$0g_{9/2}$	Sum	Expect
^{74}Ge	1.8	1.1	4.3	7.2	8
^{76}Ge	***1.4***	***1.1***	***3.5***	***6.0***	***6***
^{76}Se	***2.2***	***1.6***	***4.2***	***8.0***	***8***
^{78}Se	2.3	0.9	2.8	6.1	6

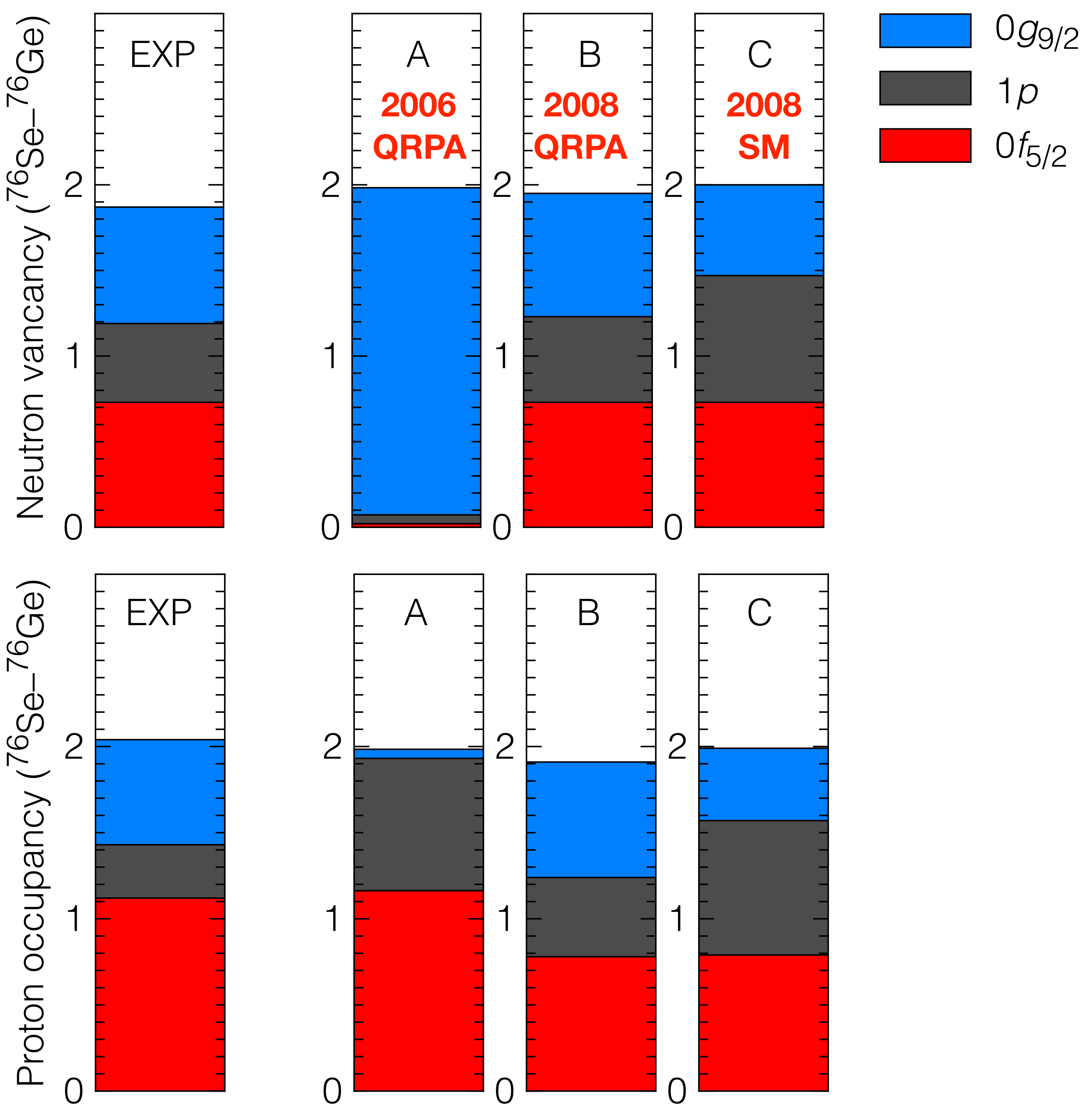
Isotope	$0f_{5/2}$	$1p_{1/2,3/2}$	$0g_{9/2}$	Sum	Expect
^{74}Ge	1.89	1.52	0.37	3.78	4
^{76}Ge	***1.75***	***2.04***	***0.23***	***4.02***	***4***
^{76}Se	***2.09***	***3.17***	***0.86***	***6.12***	***6***
^{78}Se	2.35	1.82	2.05	6.22	6

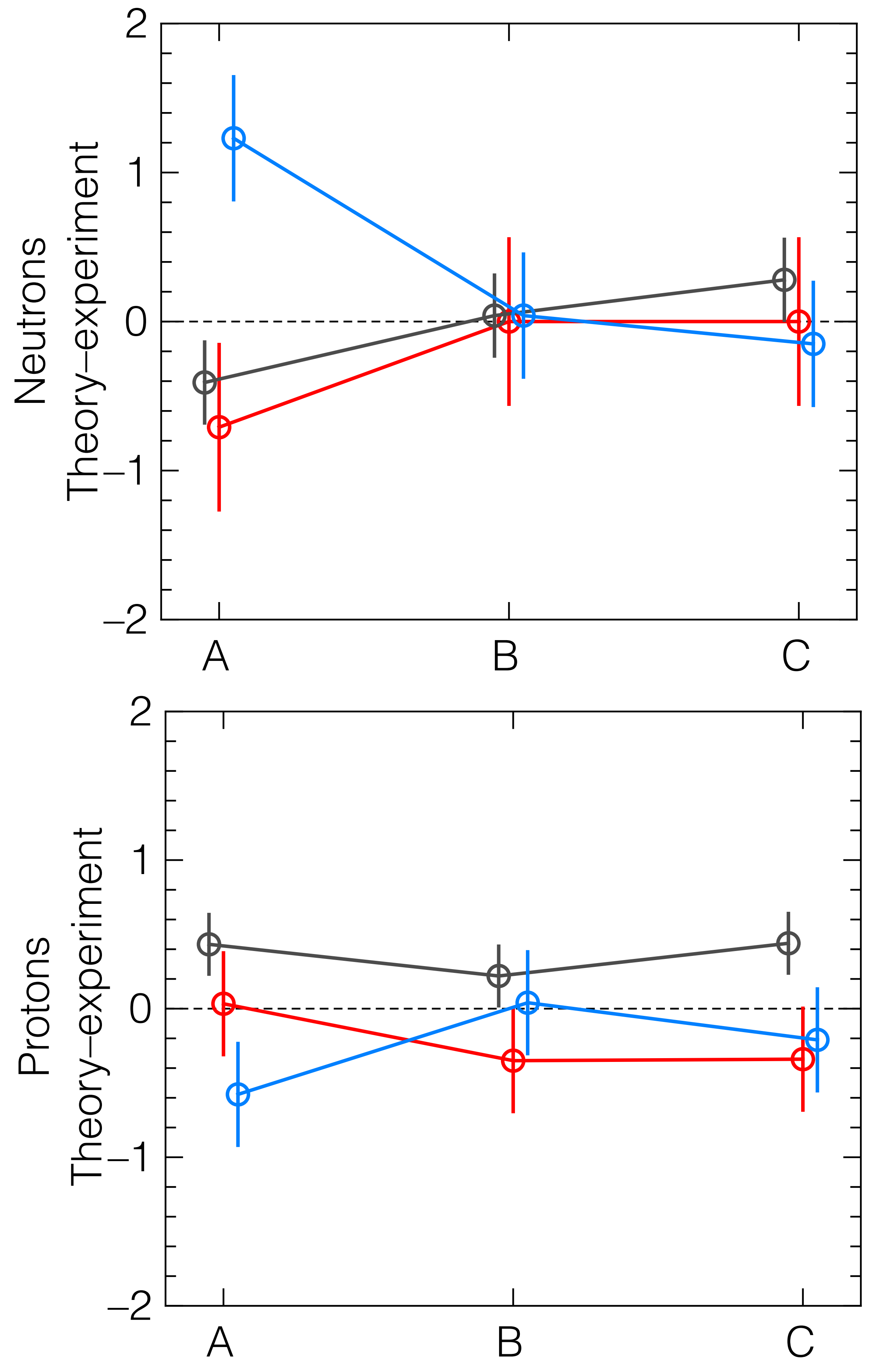


*J. P. Schiffer et al., Phys. Rev. Lett. **100**, 112501 (2008) [neutrons]*
*B. P. Kay et al., Phys. Rev. C **79**, 021301(R) (2009) [protons]*

Change in Occupancies for ^{76}Ge, ^{76}Se

Already well known by MEDEX13 … new IBM calculations not shown



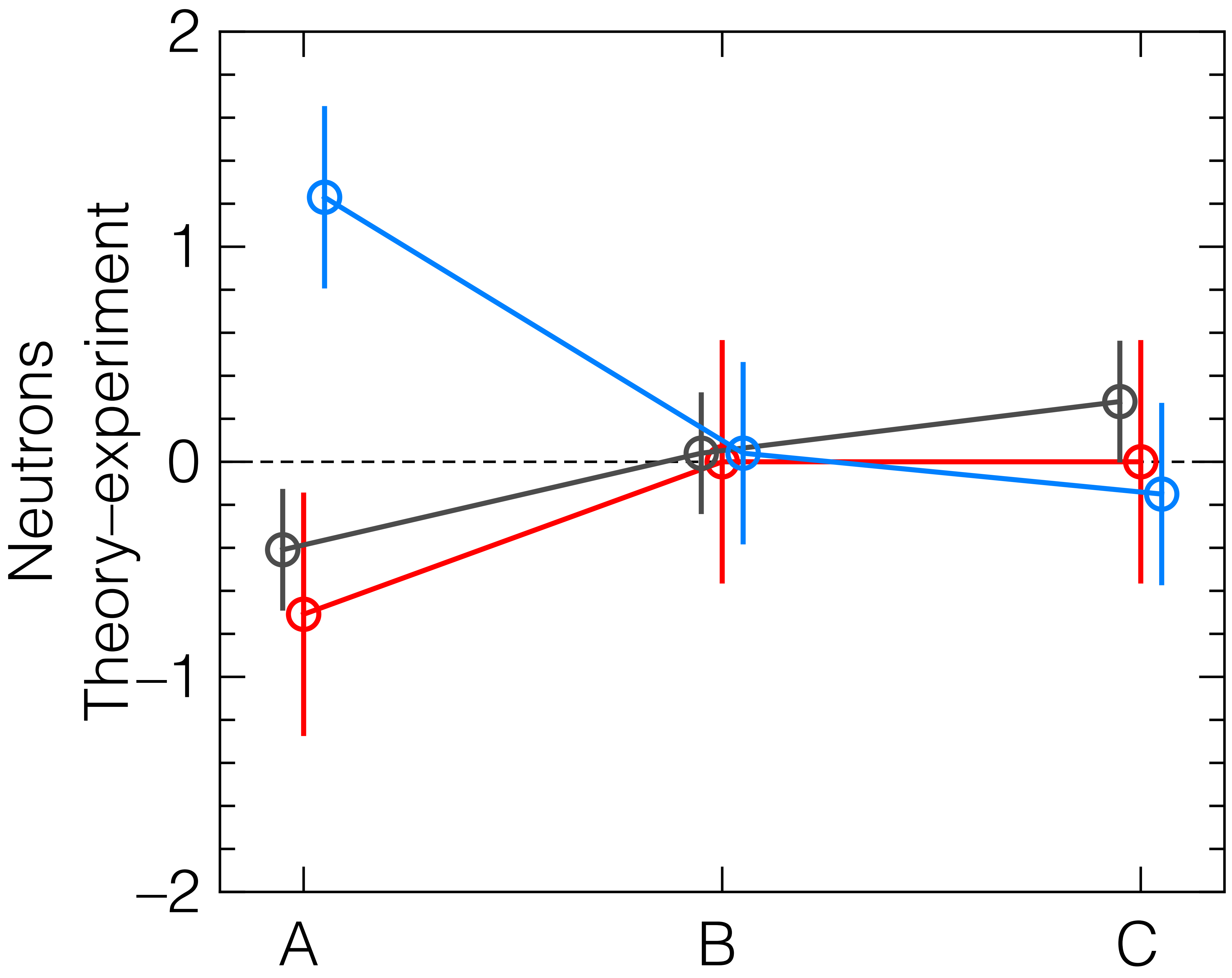


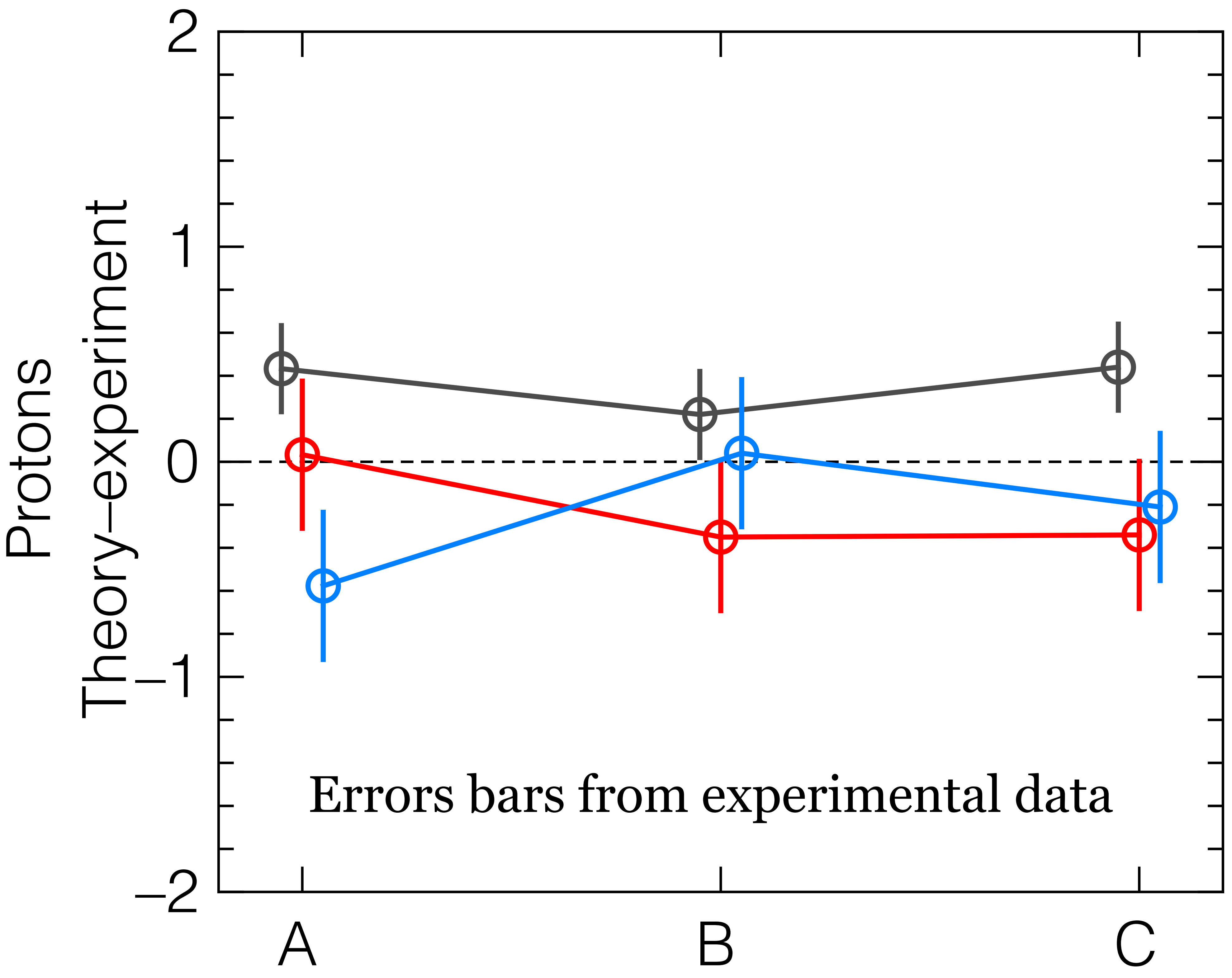
Errors bars from experimental data

J. P. Schiffer et al., Phys. Rev. Lett. ***100****, 112501 (2008) [neutrons]*
B. P. Kay et al., Phys. Rev. C ***79****, 021301(R) (2009) [protons]*
Rodin et al., Nucl. Phys. A ***766****, 107 (2006) [A]*
Suhonen et al., Phys. Lett. B ***668****, 277 (2006) [B]*
*Caurier et al., Phys. Rev. Lett.****100****, 052503 (2008) [C]*

Change in Occupancies for ^{76}Ge, ^{76}Se

Already well known by MEDEX13 … new IBM calculations not shown





J. P. Schiffer et al., Phys. Rev. Lett. ***100****, 112501 (2008) [neutrons]*
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Rodin et al., Nucl. Phys. A ***766****, 107 (2006) [A]*
Suhonen et al., Phys. Lett. B ***668****, 277 (2006) [B]*
*Caurier et al., Phys. Rev. Lett.****100****, 052503 (2008) [C]*

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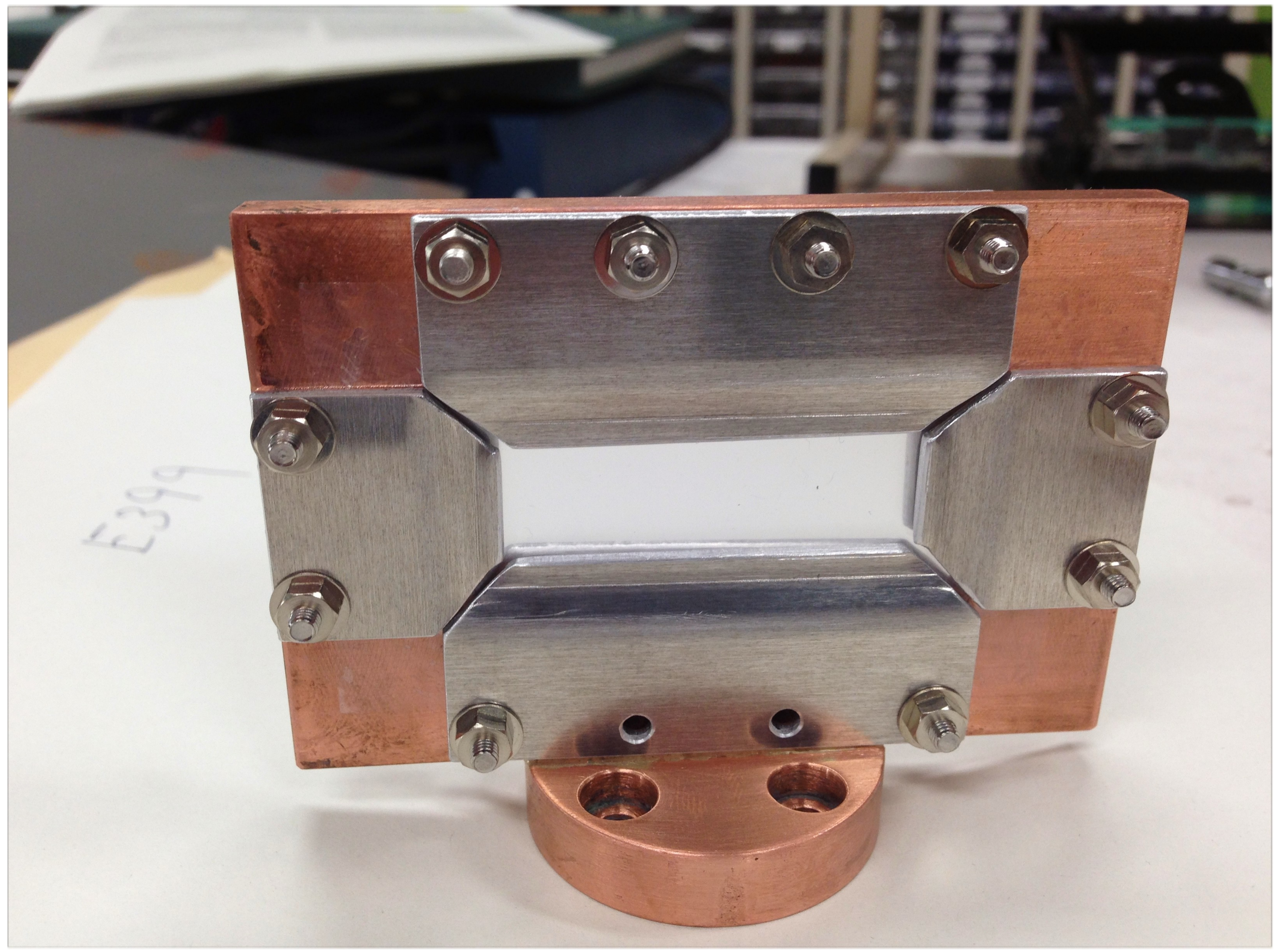
Te-130 → Xe-130

Have to overcome the obstacles of having a gaseous target:

- Neutron transfer using a 'frozen' Xe target ☞ Yale's WSNL
- Proton transfer using a Xe gas target ☞ RCNP Osaka



Proton Occupancies above Z = 50

Recent results

Isotope	$0g_{7/2}$	$1d$	$2s_{1/2}$	$0h_{11/2}$	Total	Expected
^{128}Te	1.13(9)	0.33(3)	0.012(10)	0.41(4)	1.87(10)	2
^{130}Te	1.32(10)	0.32(3)	0.011(10)	0.24(3)	1.89(11)	2
^{130}Xe	2.37(20)	1.00(11)	0.21(2)	0.37(3)	3.95(24)	4
^{132}Xe	2.60(10)	0.94(5)	0.13(2)	0.41(4)	4.07(12)	4
^{134}Xe	3.14(10)	0.71(4)	0.022(10)	0.37(4)	4.24(12)	4
^{136}Xe	2.93(10)	0.52(3)	0.057(6)	0.40(4)	3.91(11)	4
^{136}Ba	3.86(10)	1.29(8)	0.20(2)	0.62(6)	5.97(14)	6
^{138}Ba	4.38(10)	1.15(8)	0.050(16)	0.59(7)	6.17(15)	6
^{130}Xe – ^{130}Te	1.05(23)	0.68(12)	0.20(2)	0.13(4)	2.06(26)	2
^{136}Ba – ^{136}Xe	0.93(14)	0.77(9)	0.14(2)	0.22(7)	2.06(18)	2

Extracted occupancies by demanding the **sums of the $0g_{7/2}$, $1d$, $2s_{1/2}$, and $0h_{11/2}$** strength equal **2, 4, and 6 for Te, Xe, and Ba**, respectively. Numbers here represented a common normalization [**=0.60(3)**] applied to all.

seem familiar?

J. P. Entwisle et al., Phys. Rev. C ***93****, 064312 (2016)*

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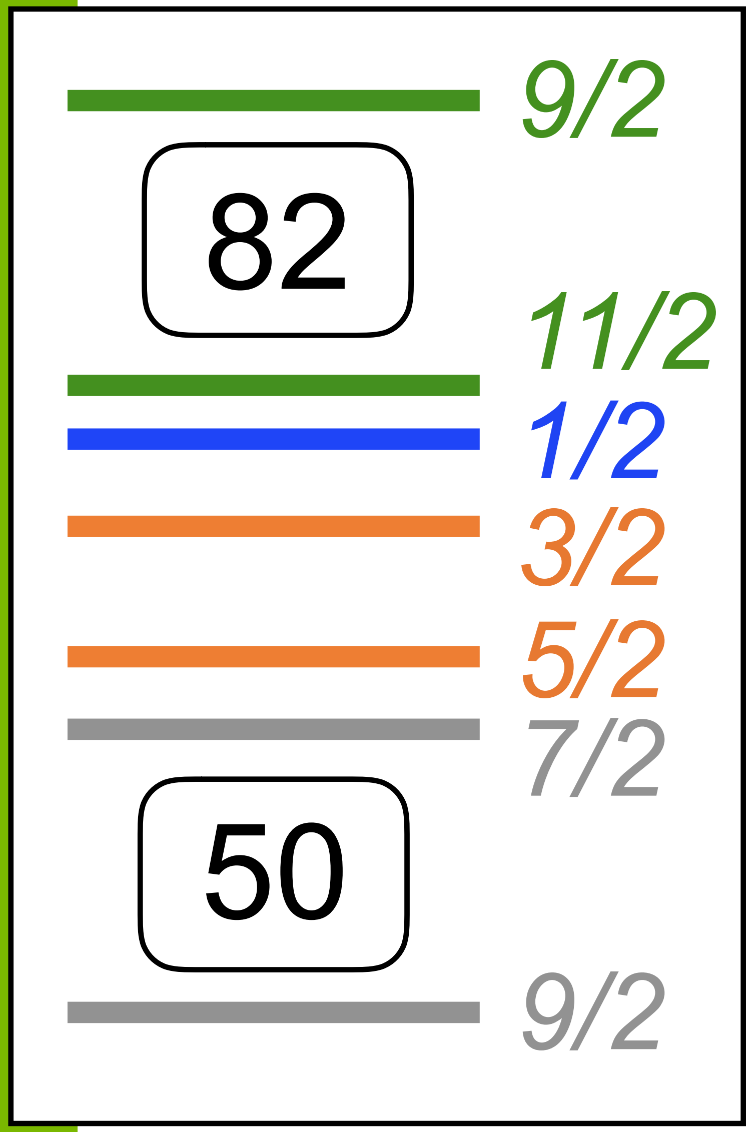
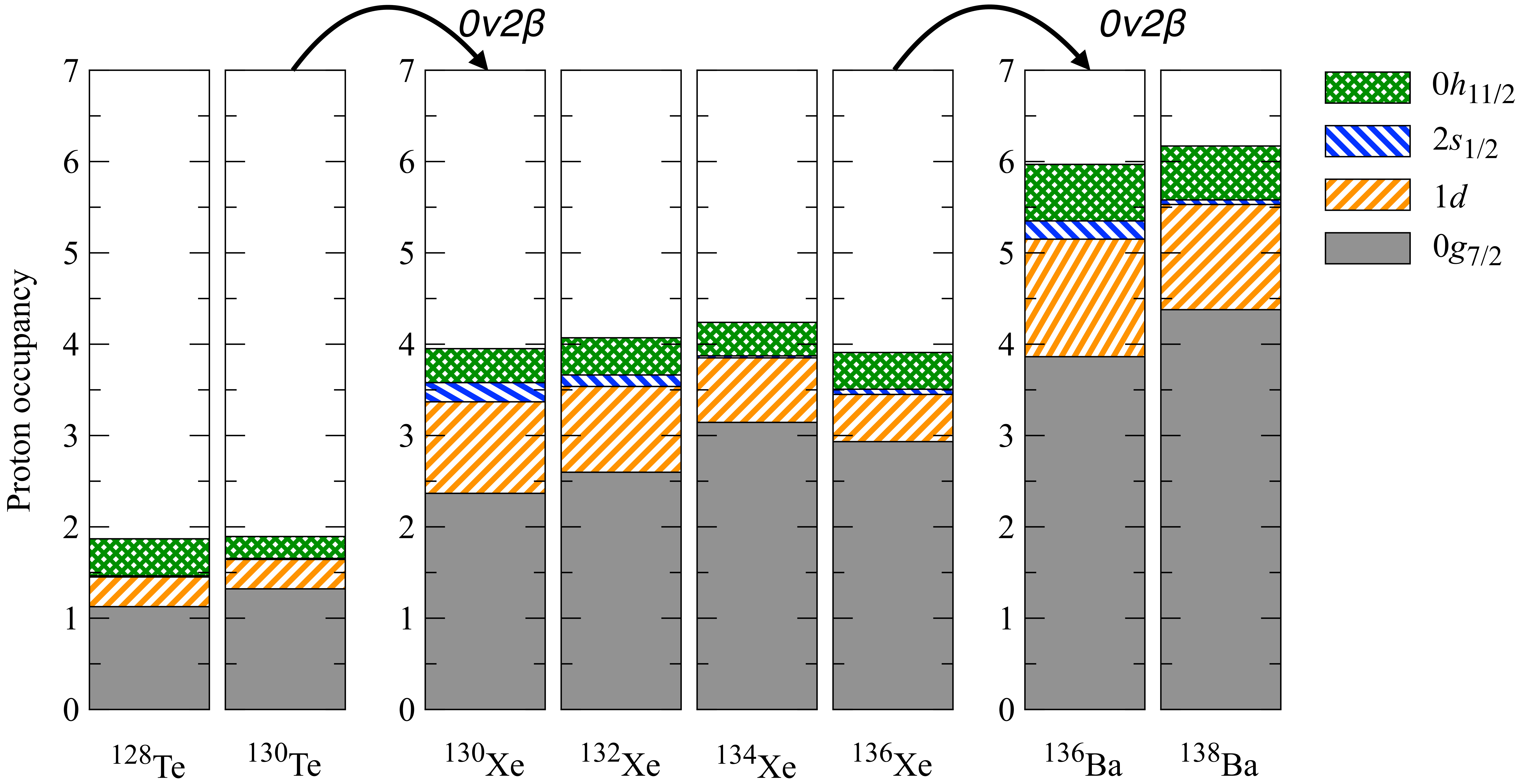
Proton Occupancies above Z = 50





J. P. Entwisle et al., Phys. Rev. C **93**, 064312 (2016)

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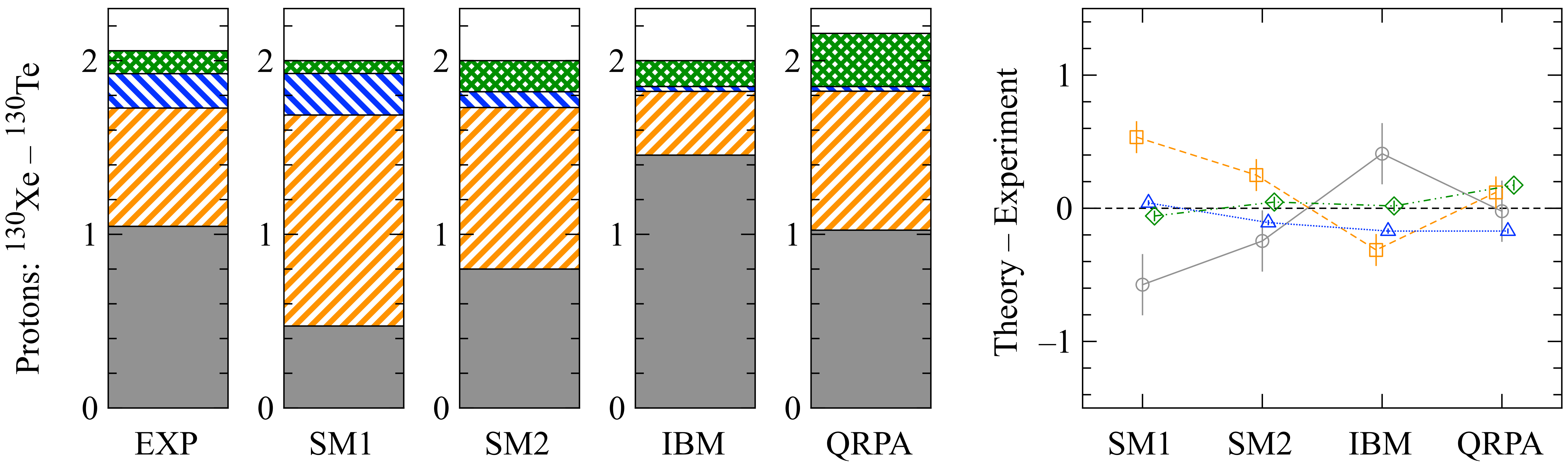
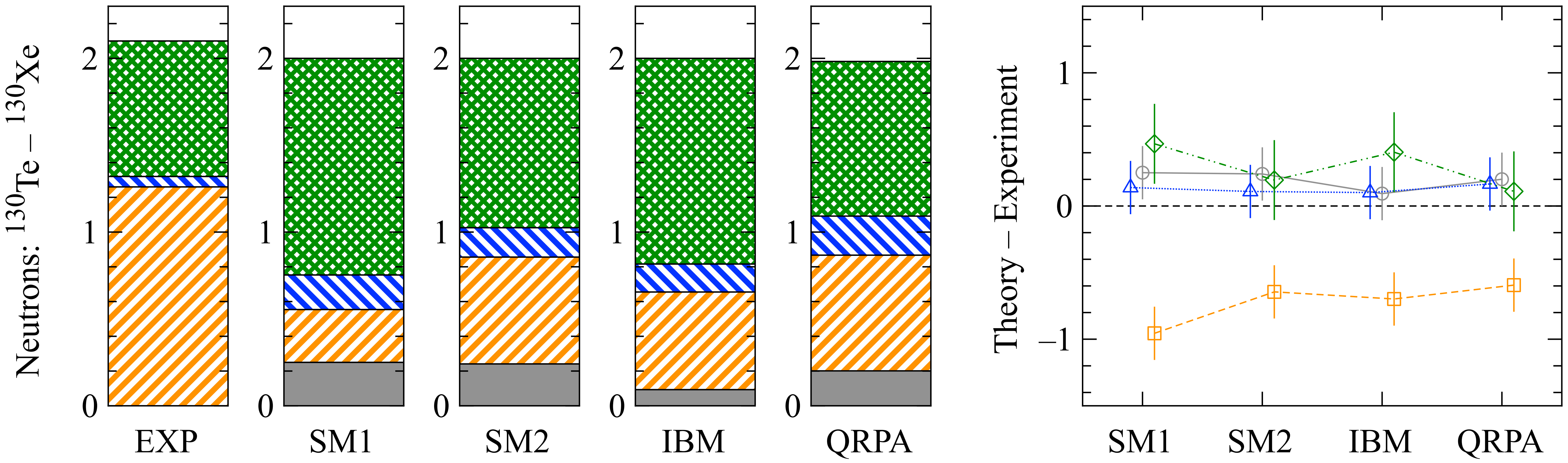
Change in Occupancies for ^{130}Te, ^{130}Xe

RCNP data



Yale data

(from previous exp.)

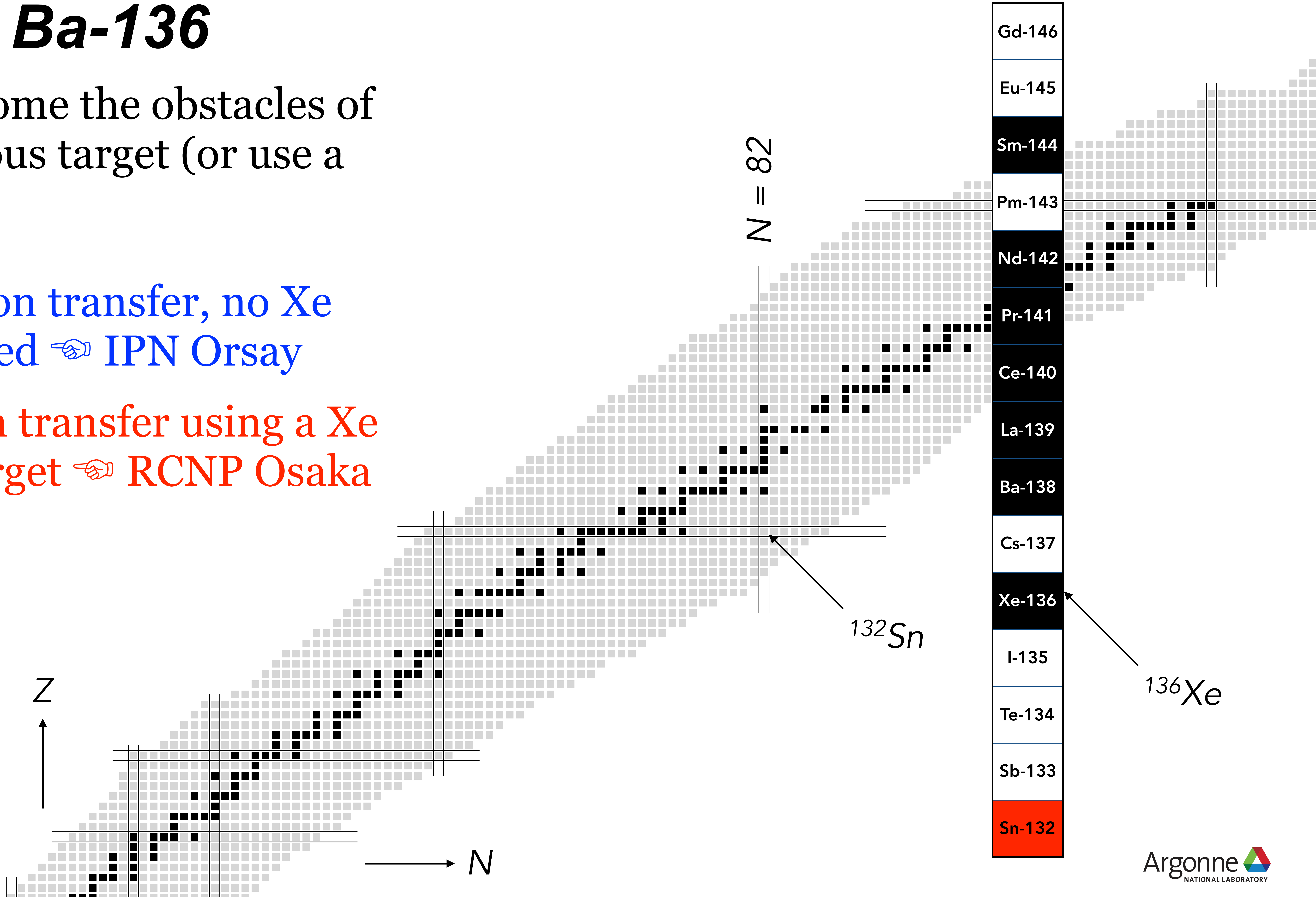


*J. P. Entwisle et al., Phys. Rev. C **93**, 064312 (2016) [protons]*
*B. P. Kay et al., Phys. Rev. C **87**, 011302(R) (2013) [neutrons]*
*A. Neacsu and M. Horoi, Phys. Rev. C **91**, 024309 (2015) [SM1]*
*J. Menéndez et al., Nucl. Phys. A **818**, 139 (2009) [SM2]*
*J. Kotila and J. Barea, Phys. Rev. C **94**, 034320 (2016) [IBM]*
*J. Suhonen and O. Civitarese, Nucl. Phys. A **847**, 207 (2010) [QRPA]*

Xe-136 → Ba-136

Have to overcome the obstacles of having a gaseous target (or use a trick):

- Neutron transfer, no Xe involved ☜ IPN Orsay
- Proton transfer using a Xe gas target ☜ RCNP Osaka



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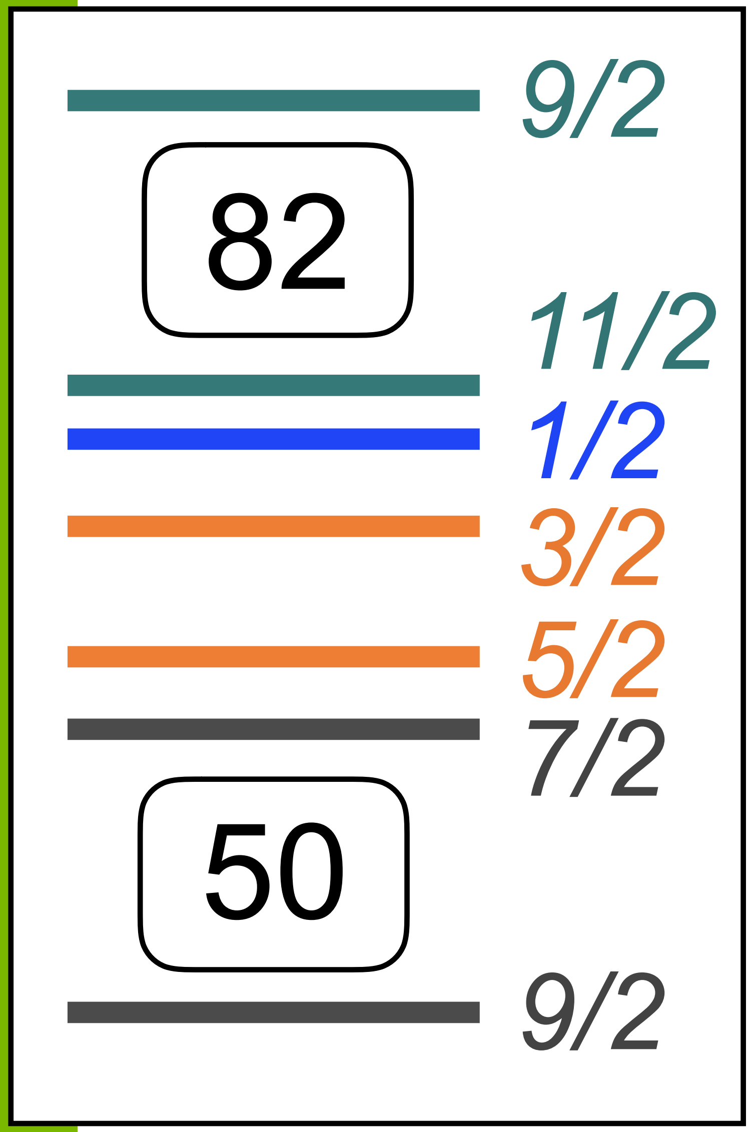
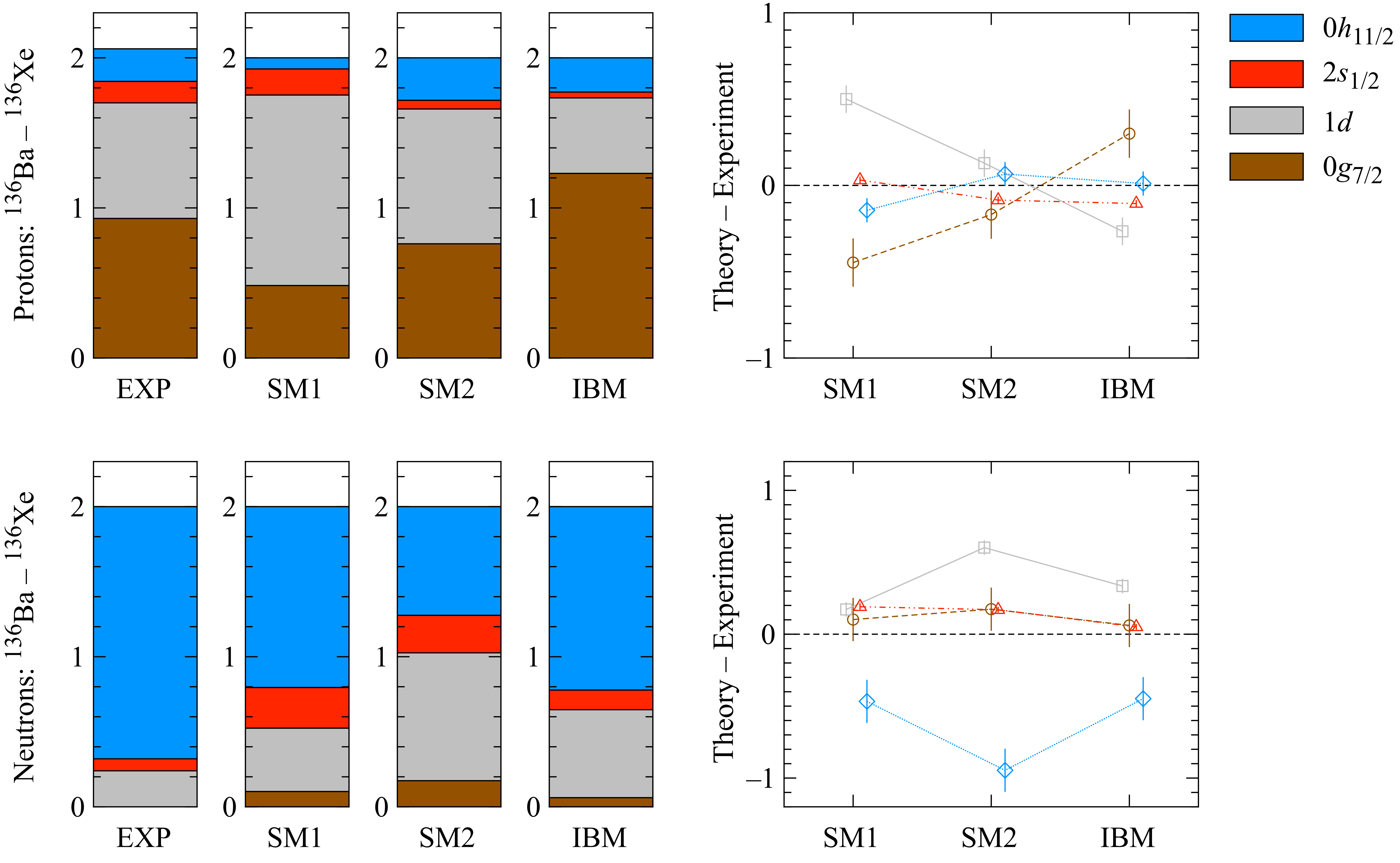
Change in Occupancies for ^{136}Xe, ^{136}Ba



RCNP data

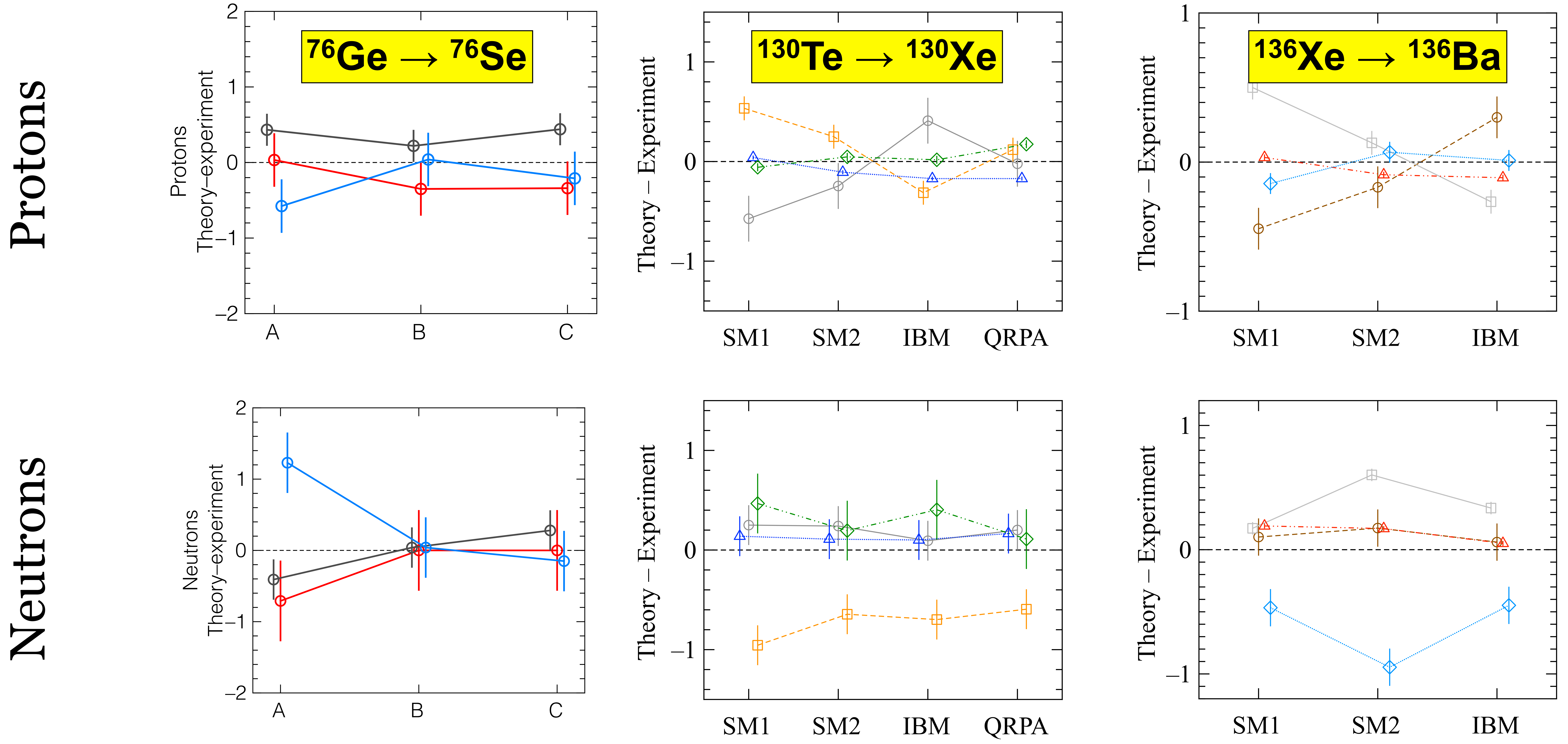
Orsay data



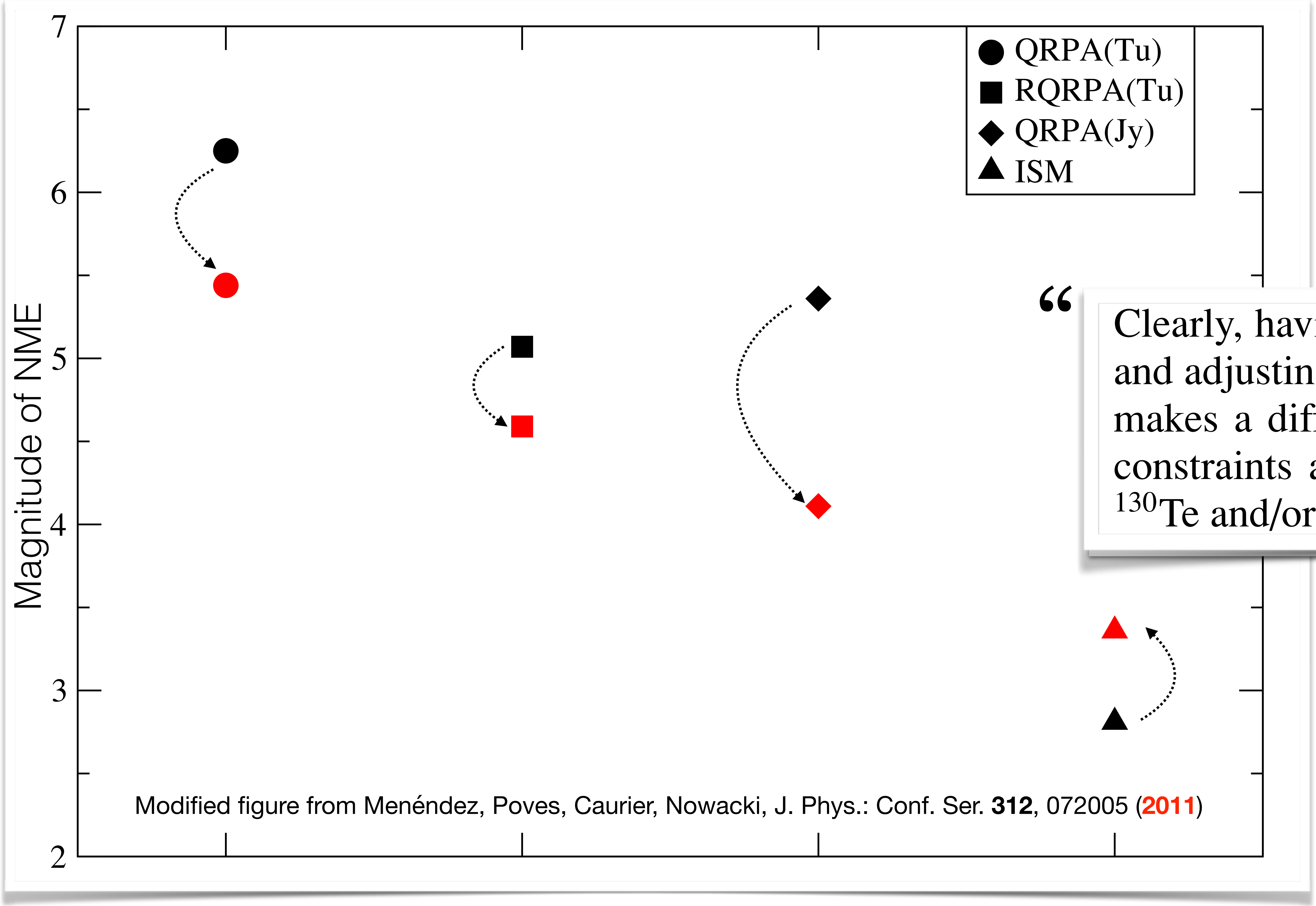
*J. P. Entwisle et al., Phys. Rev. C **93**, 064312 (2016) [protons]*
*S. V. Szwec et al., Phys. Rev. C **94**, 054314 (2016) [neutrons]*
*A. Neacsu and M. Horoi, Phys. Rev. C **91**, 024309 (2015) [SM1]*
*J. Menéndez et al., Nucl. Phys. A **818**, 139 (2009) [SM2]*
*J. Kotila and J. Barea, Phys. Rev. C **94**, 034320 (2016) [IBM]*

Experiment and theory (in conclusion)

There are numerous substantial disagreements, some concerns (while the NME might be relatively insensitive to the the occupancies, should be correct?)



Impact on NMEs



"Clearly, having the experimental orbit occupancies available, and adjusting the input to fulfill the corresponding constraint, makes a difference. It would be very useful to have similar constraints available also in other systems, in particular for ^{130}Te and/or ^{136}Xe."

Yes, some. Though much discussed, a ***40-70% reduction*** in the well-known gap between QRPA and the ISM, resulted. This predated recent IBM work and newer calculations.

*Šimkovic et al., Phys. Rev. C **79**, 055501 (2009) [last sentence of that paper]*

Summary

- Single-nucleon spectroscopic factors offer a robust description of nuclear structure in terms of occupancies
- 'Close' to the observable (cross section → reduced cross section)
- The model dependencies are small compared to many other problems
- Other probes key (pairing, etc., not covered here)
- Promising things on the horizon (*ab initio* with e.g., ^{8}He worked on) ^{48}Ca within reach? and so on (is ^{48}Ca the best 'playground'?)

Schiffer et al., Phys. Rev. Lett. ***100****, 112501 (2008)*
Kay et al., Phys. Rev. C ***79****, 021301(R) (2009)*
Kay et al., Phys. Rev. C ***87****, 011302(R) (2013)*
Entwisle et al., Phys. Rev. C ***93****, 064312 (2016)*
Szwec et al., Phys. Rev. C ***94****, 054314 (2016)*

E0 lifetimes, Ge and Se (approved exp. at TRIUMF)
Revisiting two-proton transfer [Xe(3He,n) at ANL]
Other programs (e.g. RCNPs CE reactions, Catania)