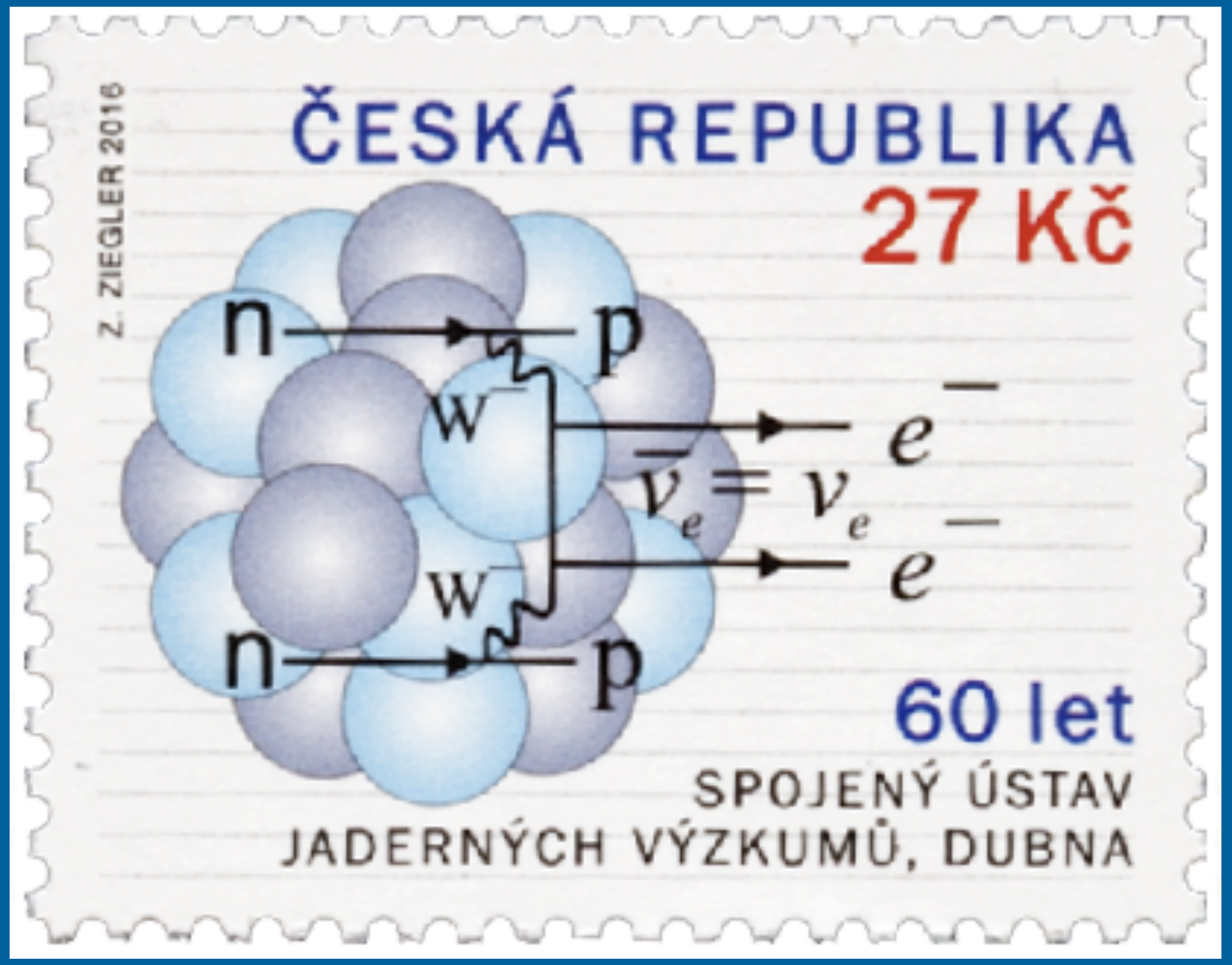
Nuclear Matrix Elements for 0νββ decay - Experiment



*This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Contract Number DE-AC02-06CH11357.

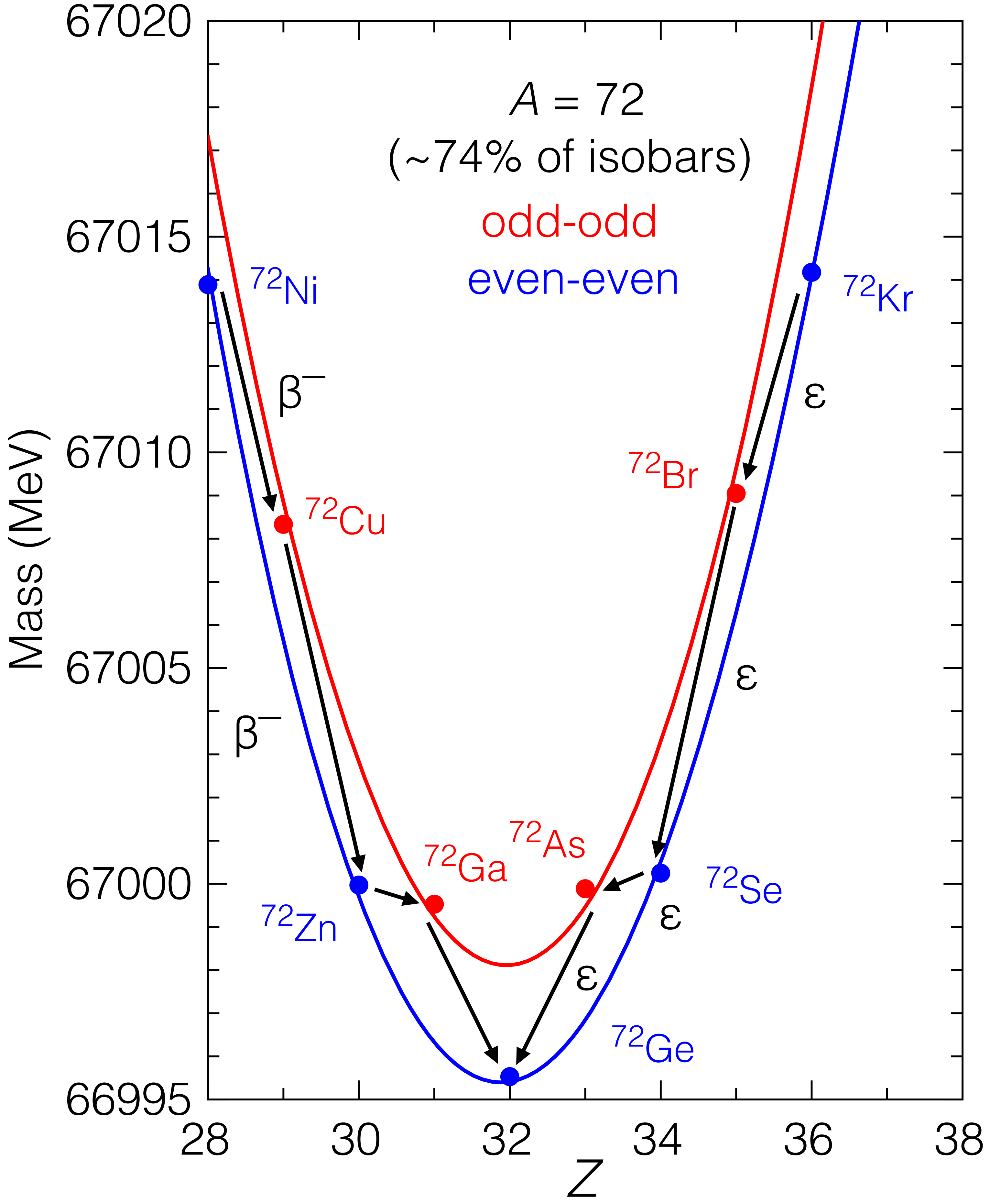
Overview

Over the past two decades, a wealth of experimental has been collected to explore single-particle aspects of 0vββ-decay candidates in a direct challenge to nuclear theory. Other groups (theory and experiment) have explored other properties such as the ground state shapes.

- *Basic premises (ground-state nucleon occupancies, pairing)*
- *Experiments (now a 10-year+ project)*
- *Analysis techniques*
- *Normalizations, quenching*
- *An overview of results, compared with theory*
- *Comments on pairing, quenching*
- *Shapes (breifly)*

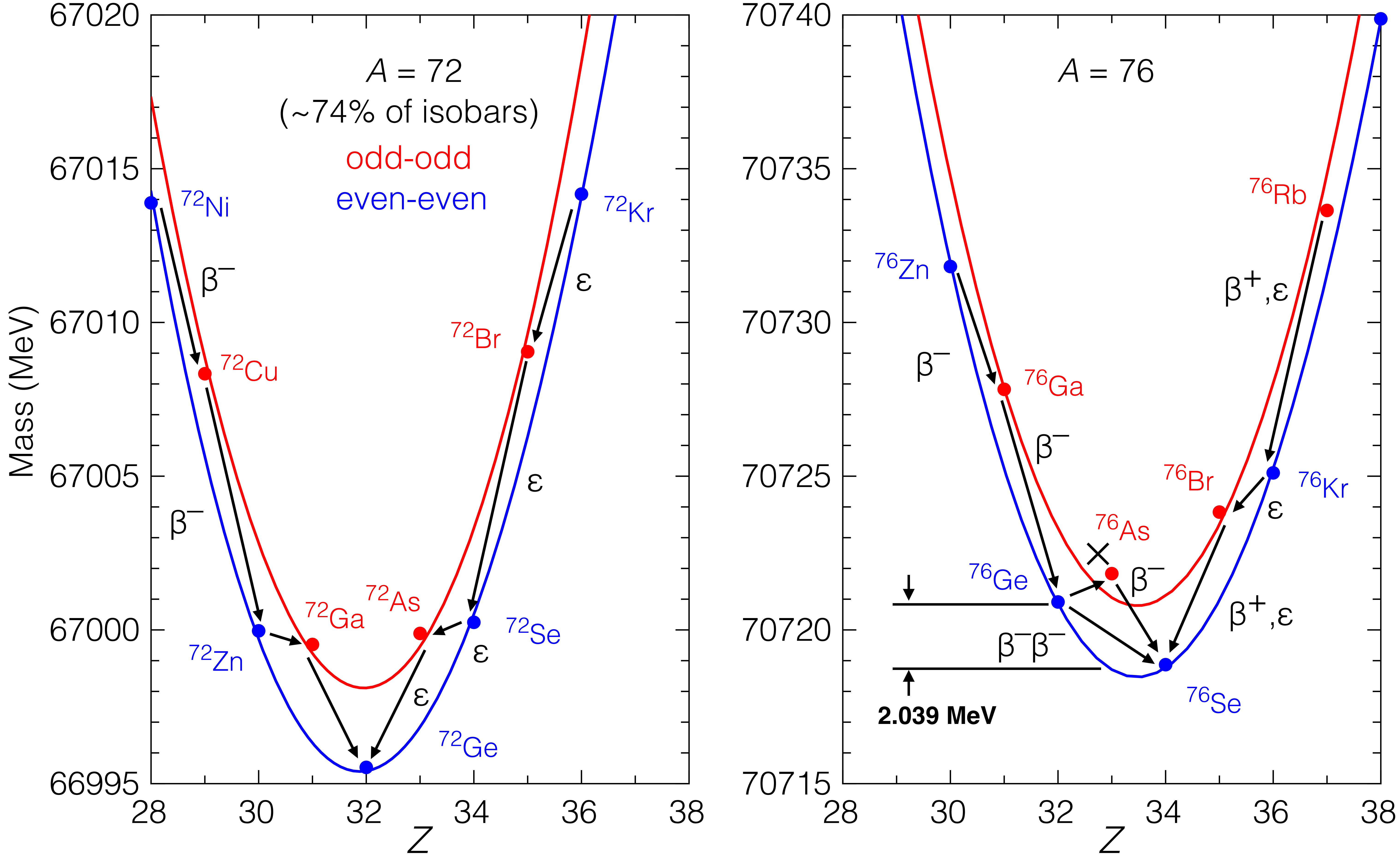
For a great overview on many aspects of 0vββ decay, see: M. Agostini et al. Rev. Mod. Phys. ***95****, 025002 (****2023****)*

Beta decay, double beta decay ...



Pairing in nuclei results in a displacement of even-even and odd-odd mass parabolas for given isobars. Data from AME 2012.

Beta decay, double beta decay …



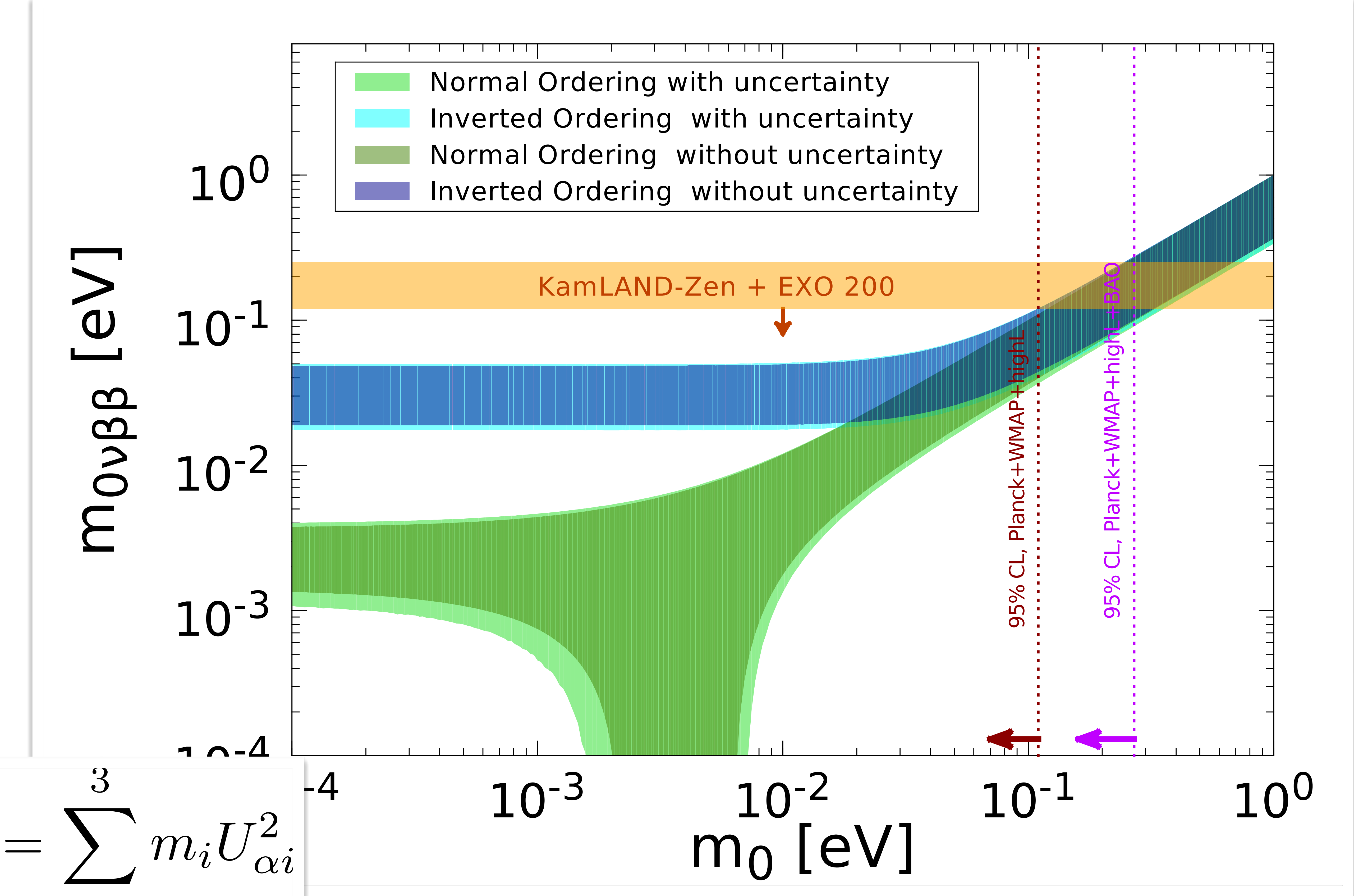
Pairing in nuclei results in a displacement of even-even and odd-odd mass parabolas for given isobars. Data from AME 2012.

Precise masses ⇒ precise Q value.

Beta decay, double beta decay …

Elucidating the nature of neutrinos is one of the major challenges to contemporary science —

- Majorana or Dirac?
- Lepton number conservation?
- Absolute mass scale?
- Mass mechanisms?
- Matter-antimatter asymmetry?
- …



$$m_{\beta\beta} = \sum_{n=1}^{3} m_i U_{\alpha i}^2$$

Param	Best fit	Range
Δm_{12}^2 $/10^{-5}$ ev^2	7.50	7.00-8.09
Δm_{13}^2 $/10^{-3}$ ev^2	2.473	2.2276-2.695
θ_{12}°	33.36	31.09-35.89
θ_{13}°	8.66	7.19-9.96
θ_{23}°	40.0, 50.4	35.54.8

$$U_{\alpha i} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\beta_1} & 0 & 0 \\ 0 & e^{i\beta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

PMNS matrix

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, $0 \le \theta_{ij} \le \pi/2$

*E.g., from article, NPB **893**, 89 (**2015**)*

Beta decay, double beta decay ...

Elucidating the nature of neutrinos is one of the major challenges to contemporary

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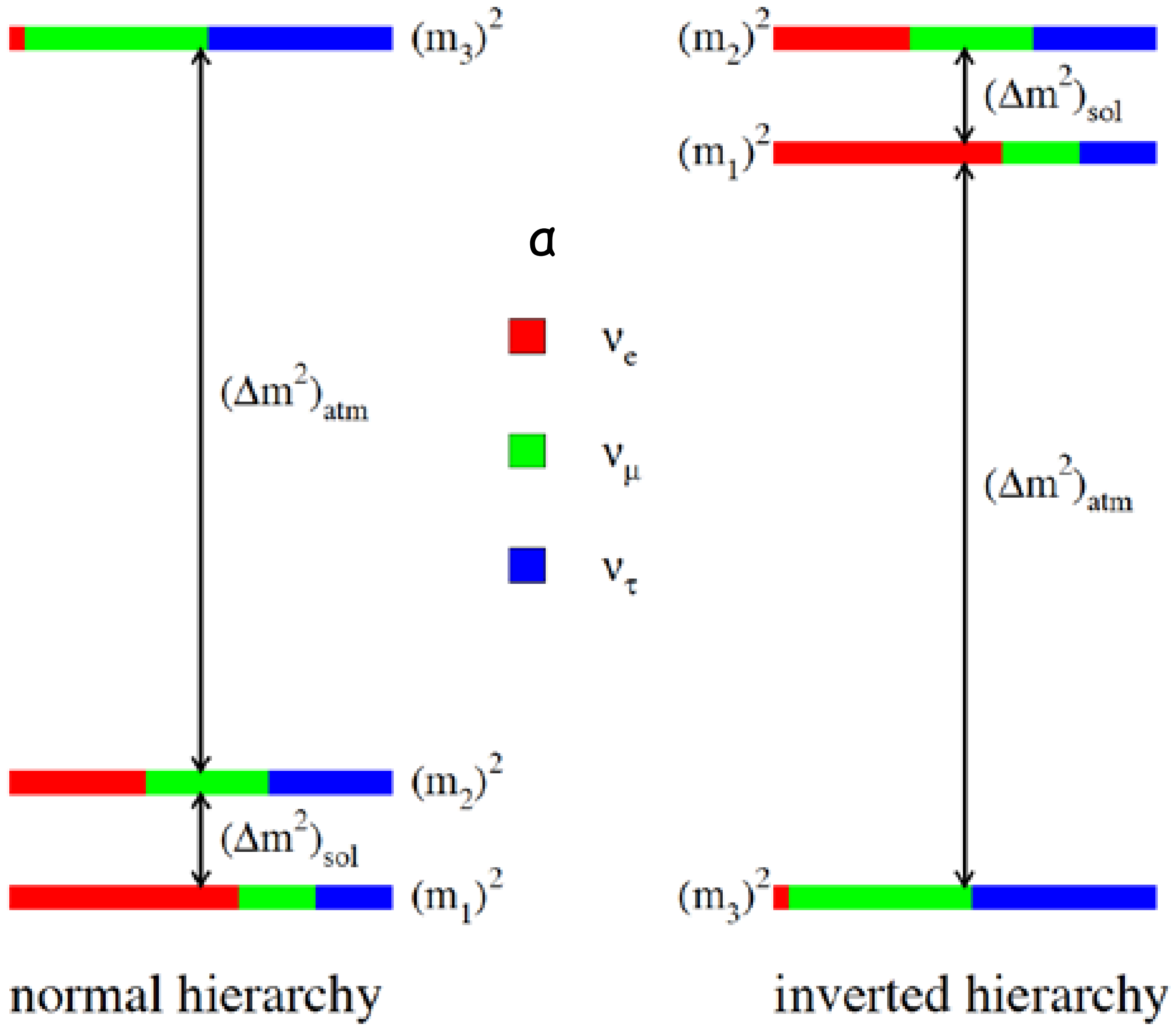
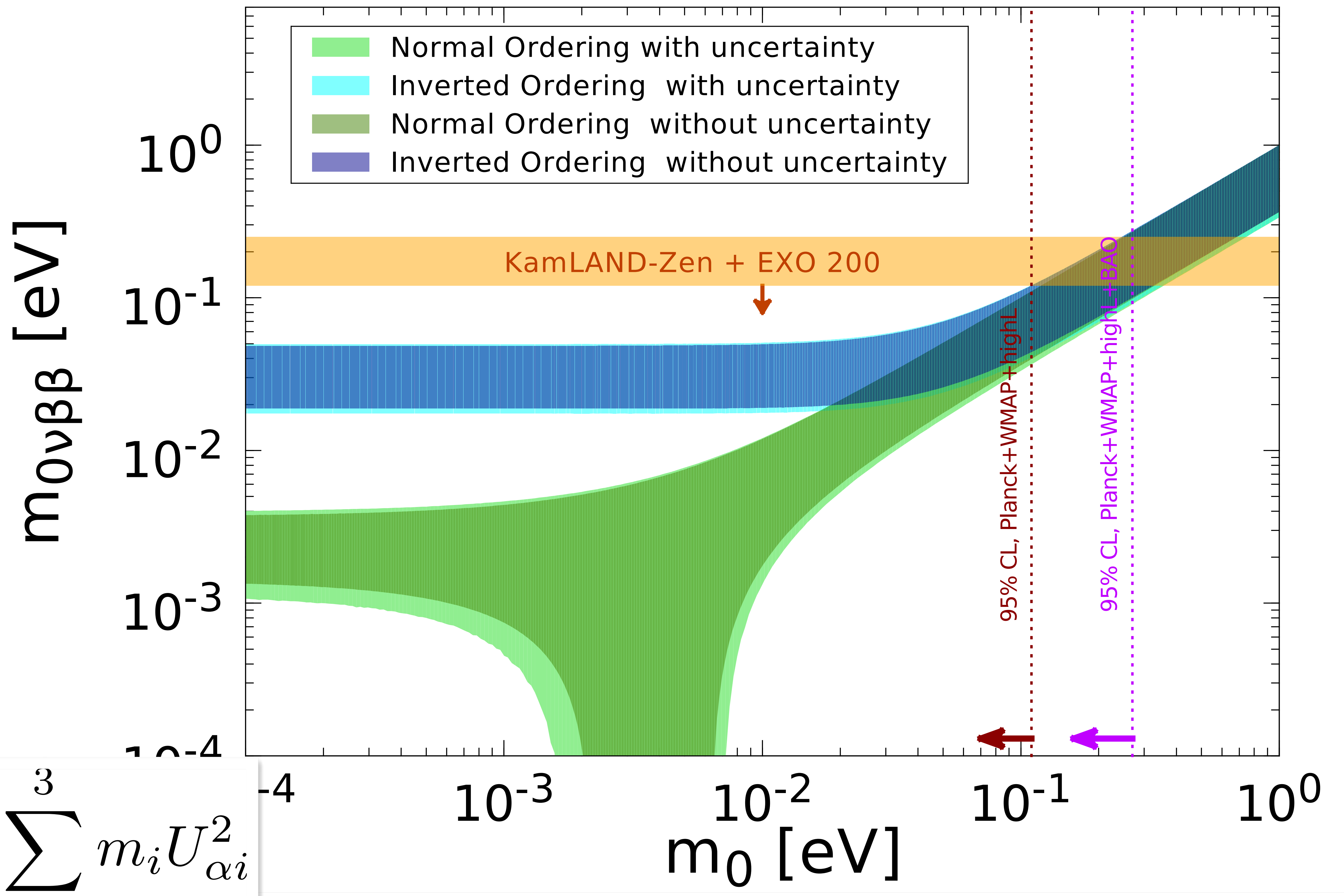


$$m_{\beta\beta} = \sum_{n=1}^{3} m_i U_{\alpha i}^2$$

θ13°	8.66	7.19-9.96
θ23°	40.0, 50.4	35.54.8



$$m_{\beta\beta} = \sum_{n=1}^{3} m_i U_{\alpha i}^2$$

$$U_{\alpha i} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\beta_1} & 0 & 0 \\ 0 & e^{i\beta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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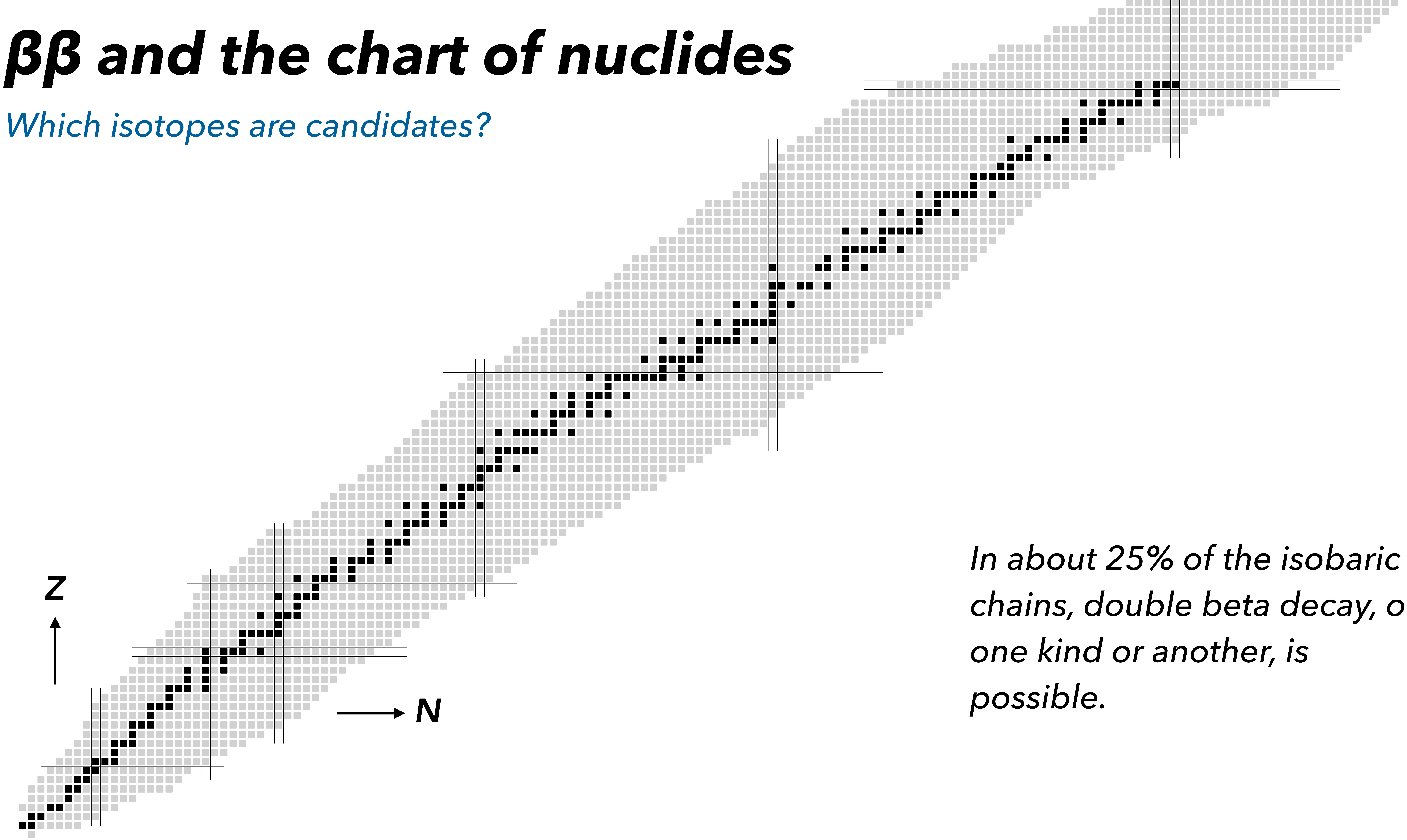
ββ and the chart of nuclides

Which isotopes are candidates?

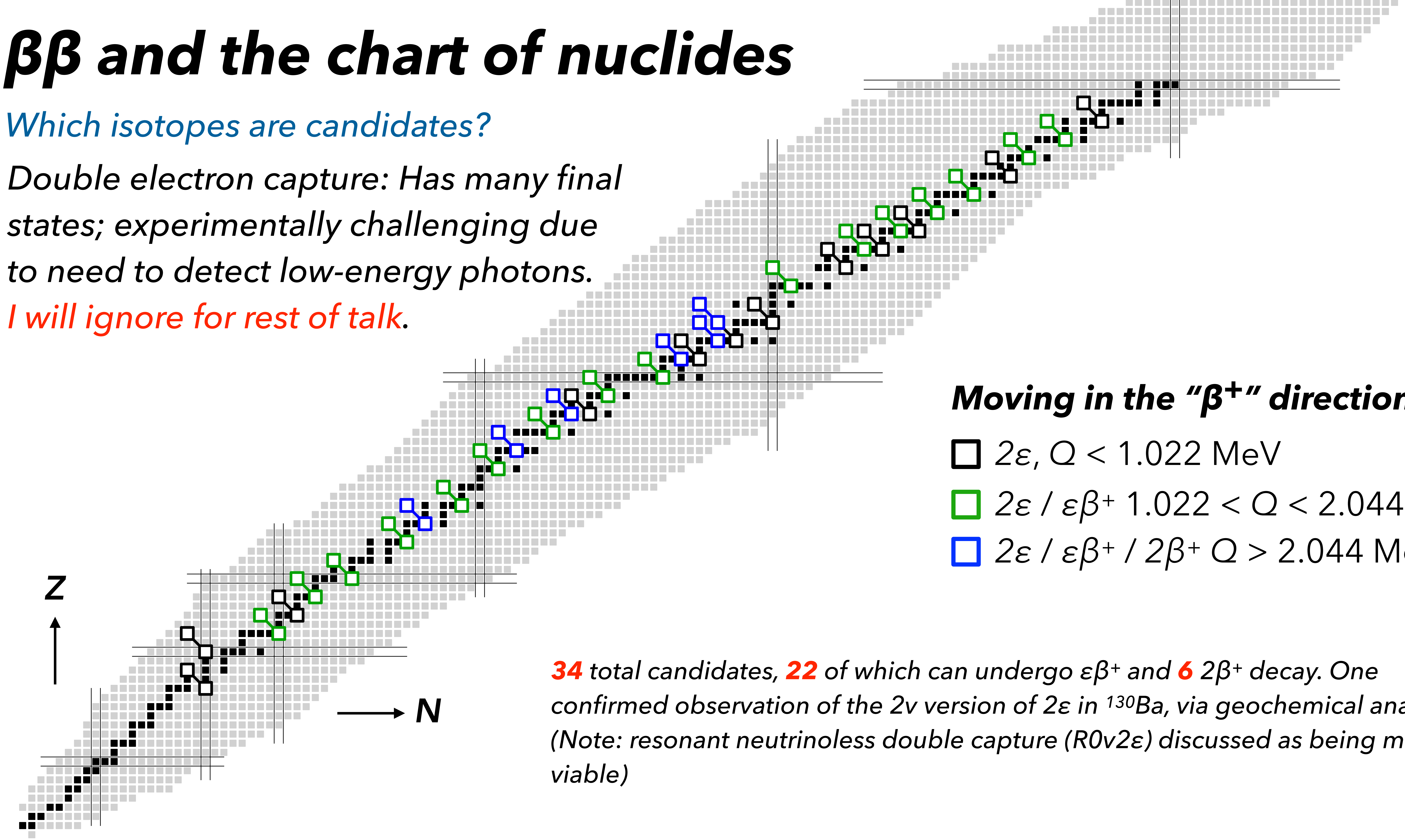


In about 25% of the isobaric chains, double beta decay, of one kind or another, is possible.

ββ and the chart of nuclides

Which isotopes are candidates?

Double electron capture: Has many final states; experimentally challenging due to need to detect low-energy photons. *I will ignore for rest of talk.*



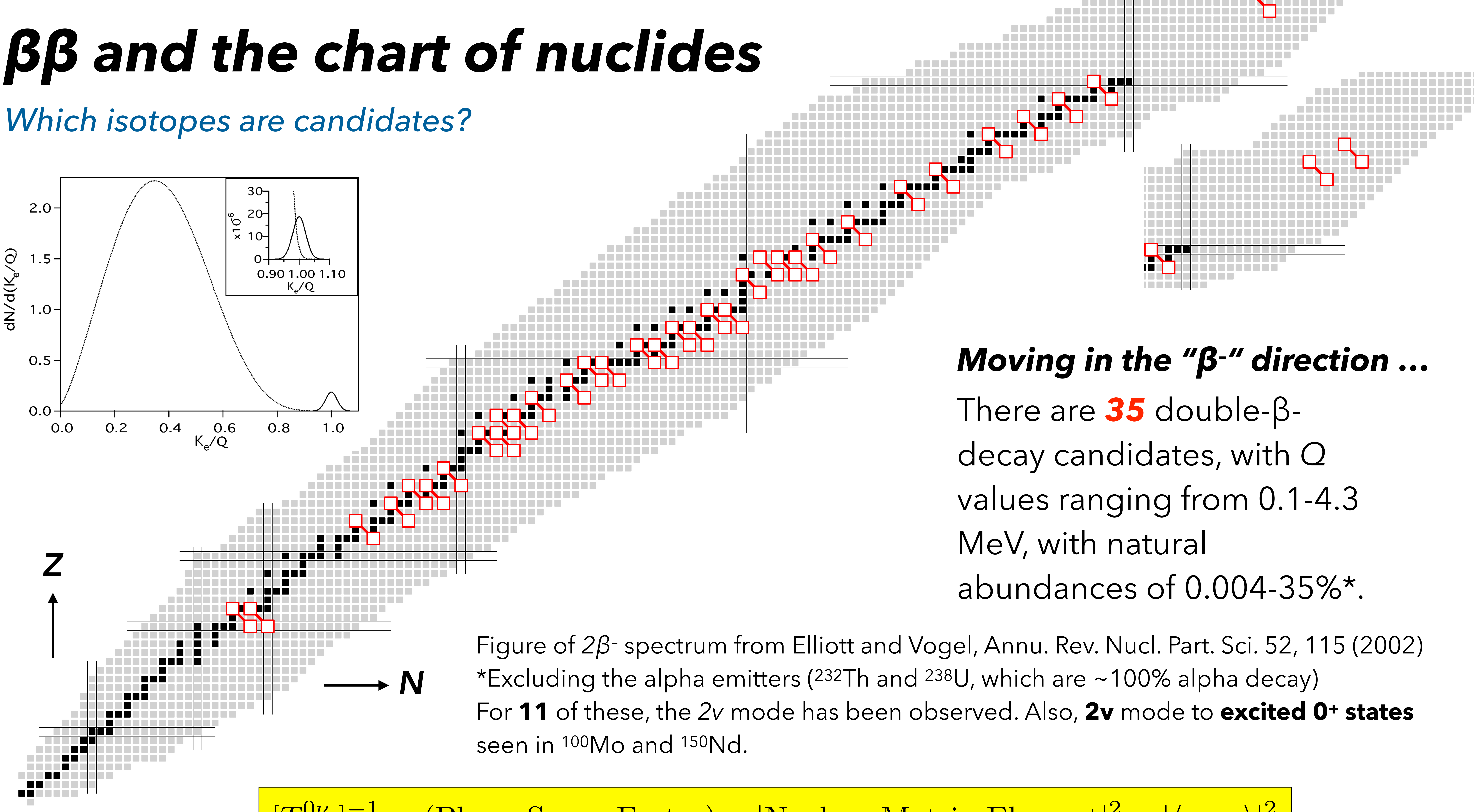
Moving in the "β^+" direction ...

- ☐ 2ε, $Q < 1.022$ MeV
- 🟩 2ε / $\varepsilon\beta^+$ $1.022 < Q < 2.044$ MeV
- 🟦 2ε / $\varepsilon\beta^+$ / $2\beta^+$ $Q > 2.044$ MeV

34 *total candidates,* ***22*** *of which can undergo $\varepsilon\beta^+$ and* ***6*** *$2\beta^+$ decay. One confirmed observation of the 2v version of 2ε in ^{130}Ba, via geochemical analysis. (Note: resonant neutrinoless double capture (R0v2ε) discussed as being more viable)*

ββ and the chart of nuclides

Which isotopes are candidates?



Moving in the "β⁻" direction …

There are **35** double-β-decay candidates, with *Q* values ranging from 0.1-4.3 MeV, with natural abundances of 0.004-35%*.

Figure of 2*β*⁻ spectrum from Elliott and Vogel, Annu. Rev. Nucl. Part. Sci. 52, 115 (2002)

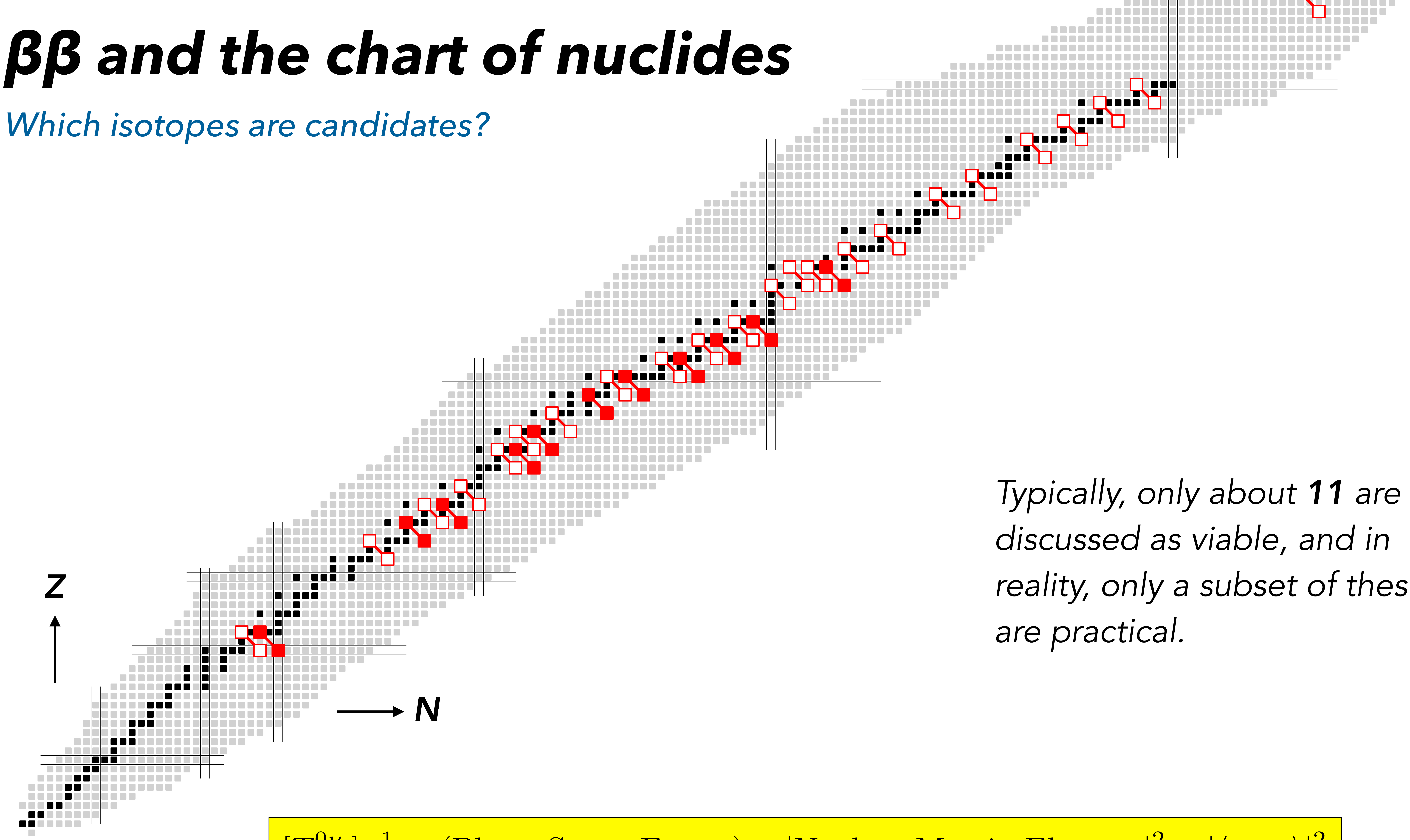
*Excluding the alpha emitters (^{232}Th and ^{238}U, which are ~100% alpha decay)

For **11** of these, the *2v* mode has been observed. Also, **2v** mode to **excited 0⁺ states** seen in ^{100}Mo and ^{150}Nd.

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

ββ and the chart of nuclides

Which isotopes are candidates?



*Typically, only about **11** are discussed as viable, and in reality, only a subset of these are practical.*

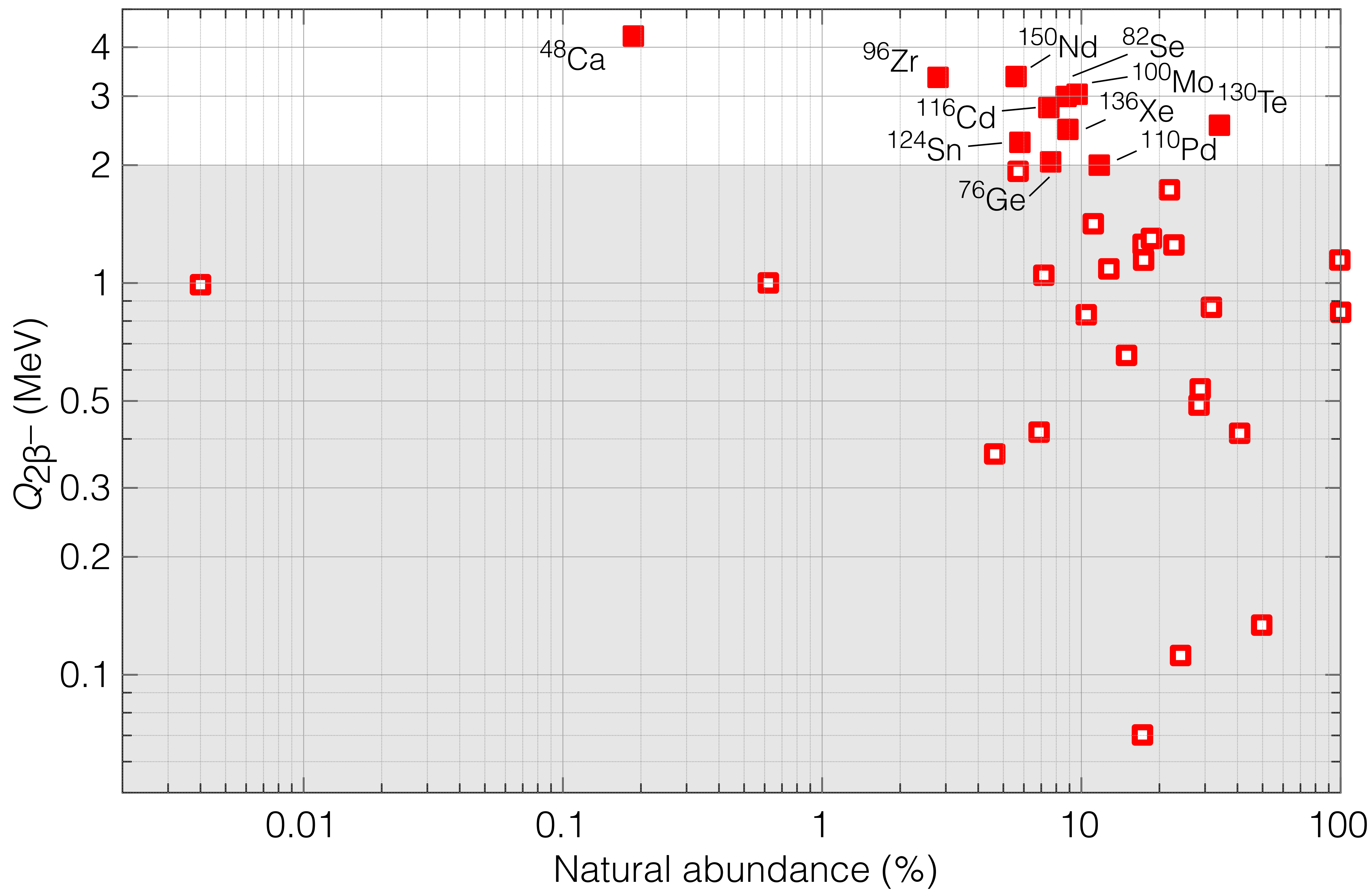
$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta} \rangle|^2$$

0νββ candidates

Best candidates?

Large Q value is desired … backgrounds. Additionally, the ***decay probability scales with ~Q^5 and Z***.

The rest is a compromise between natural abundance, detector technology, economics, ***and nuclear structure***.



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0νββ candidates

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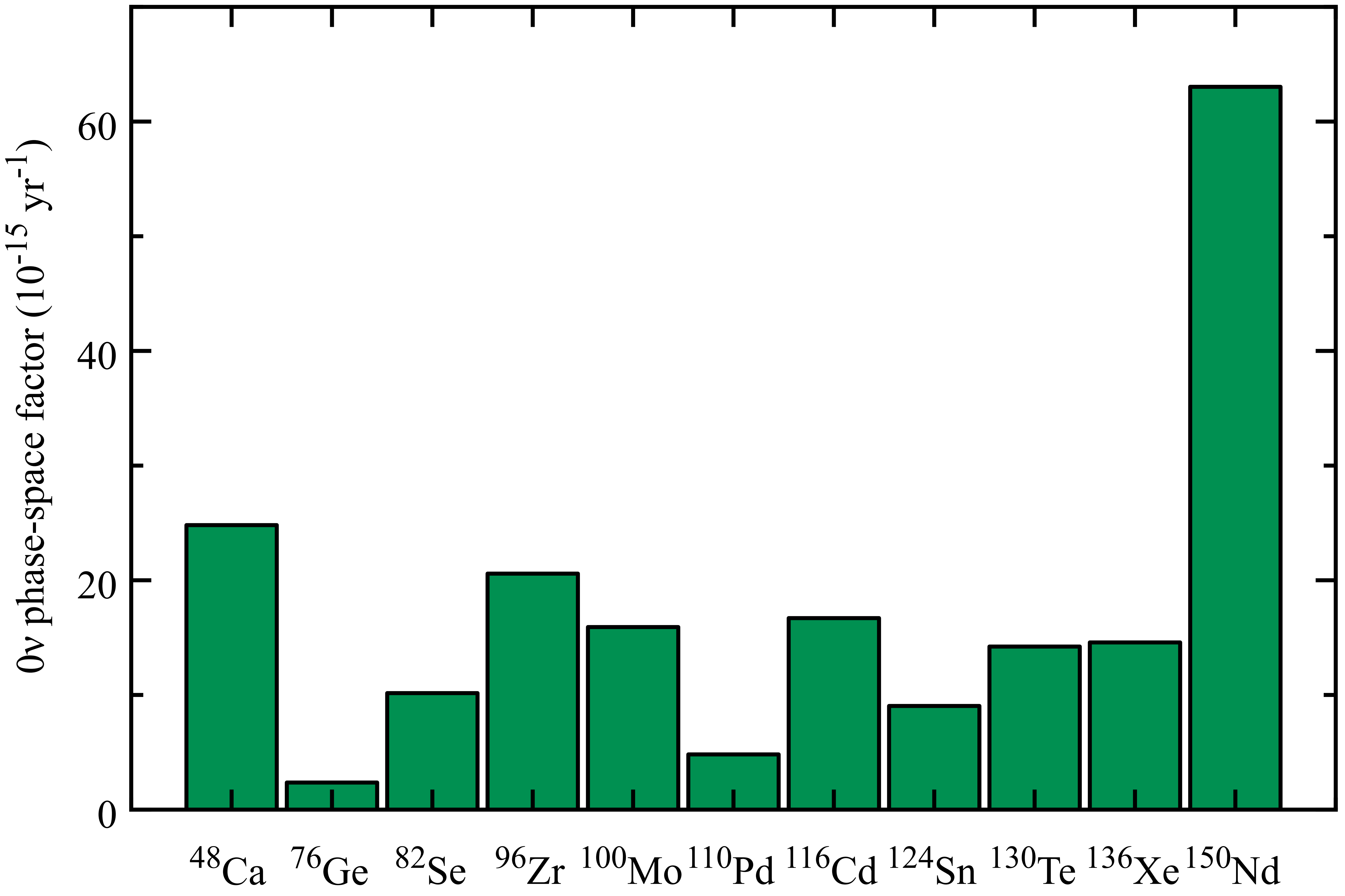


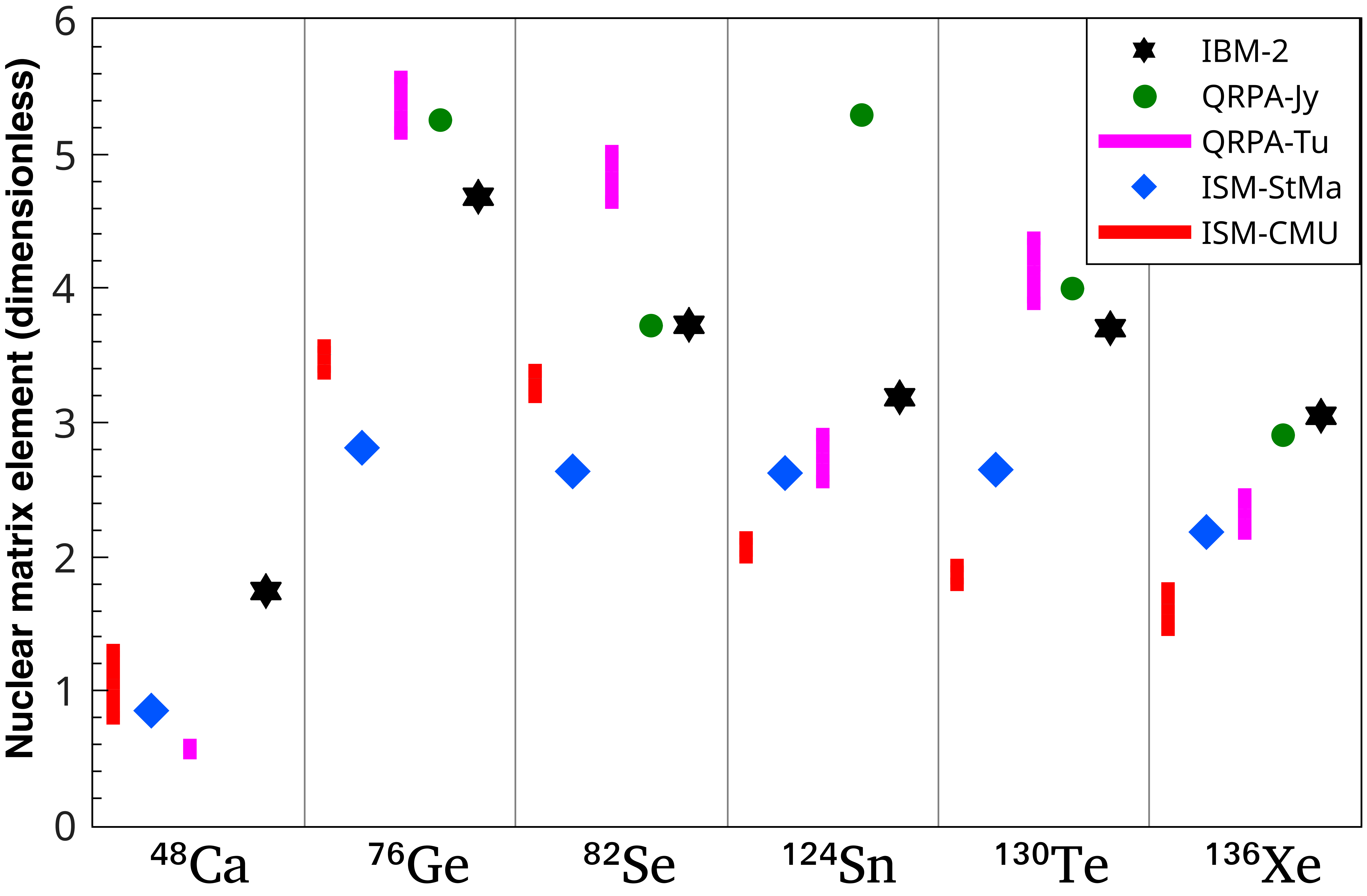
Data: Kotila and Iachello, Phys. Rev. C 85, 034316 (2012).

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

NMEs -- "the principal problem"

Many groups, using different models and assumptions, carry out these calculations. The spread is considerable.

*Horoi and Neacsu, Phys. Rev. C **93**, 024308 (2016)*



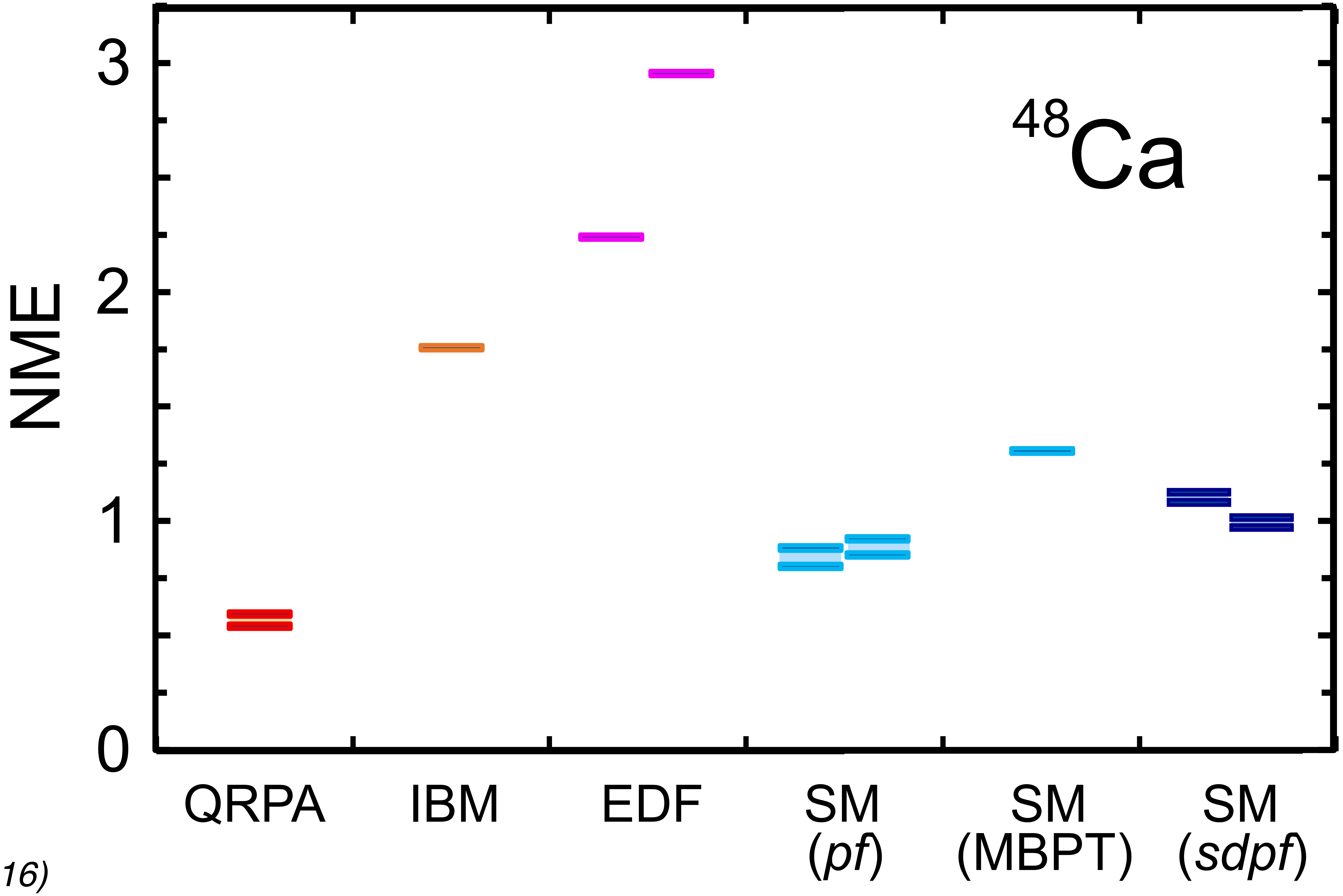
$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta}\rangle|^2$$

NMEs -- "the principal problem"

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

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

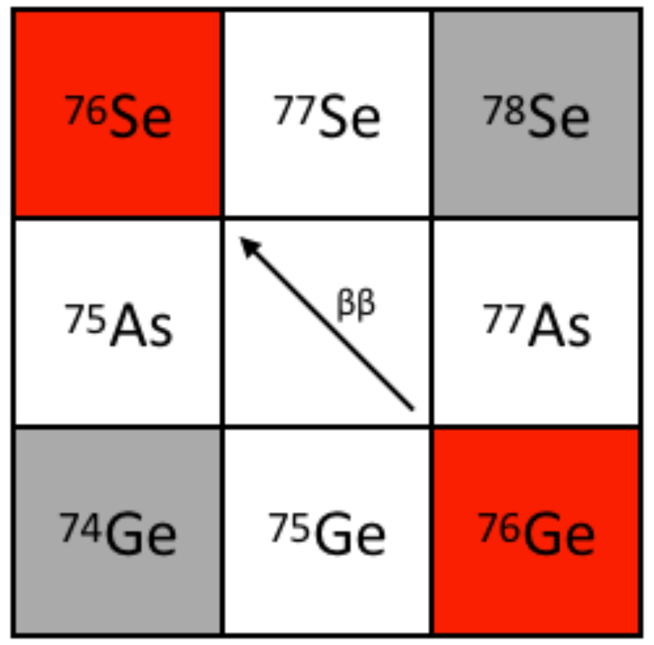
$\propto |\mathrm{NME}|^2$



Iwata et al., Phys. Rev. Lett. **116**, 112502 (2016)

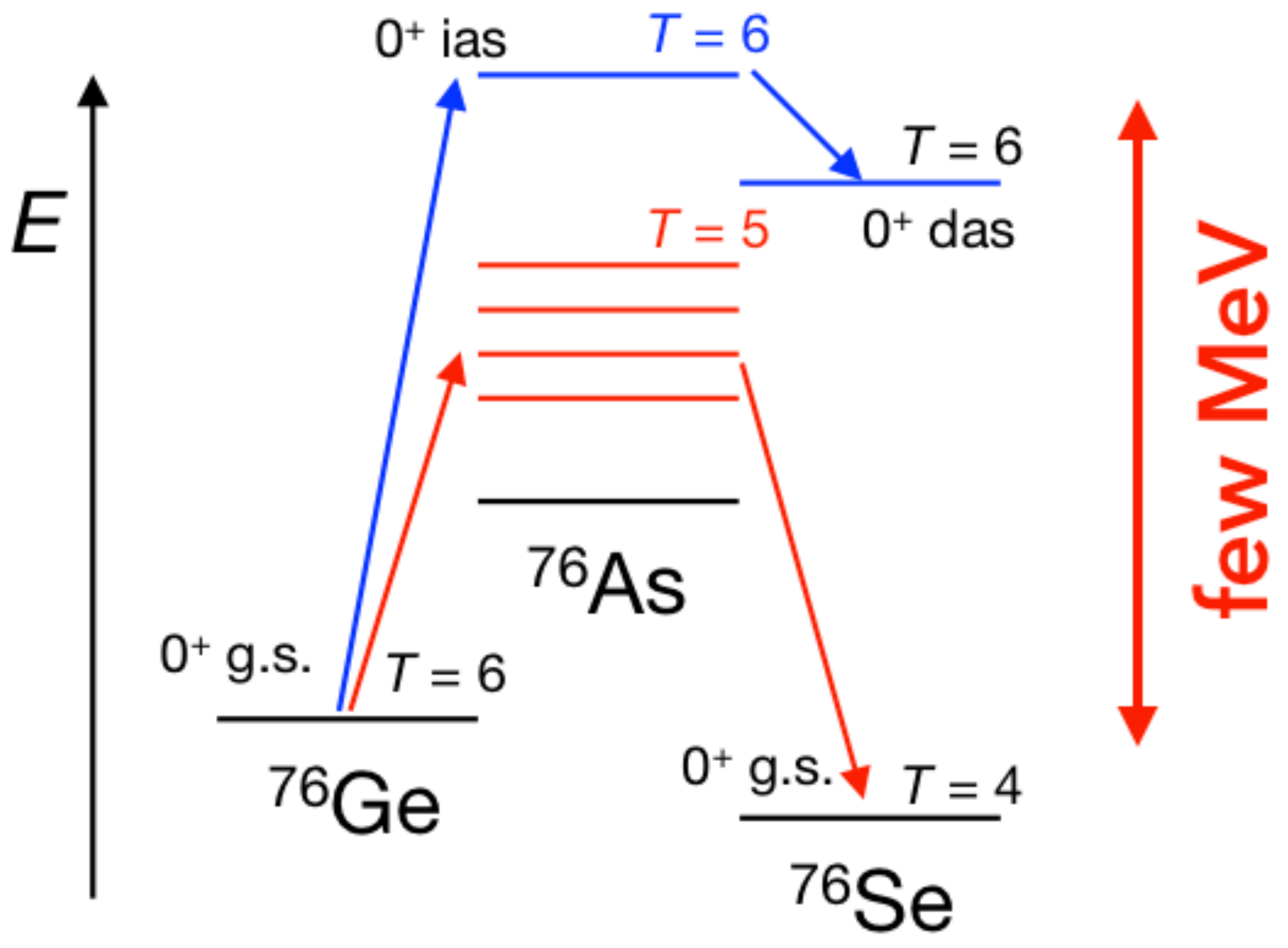
$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta}\rangle|^2$$

Mechanism, rationale for our work



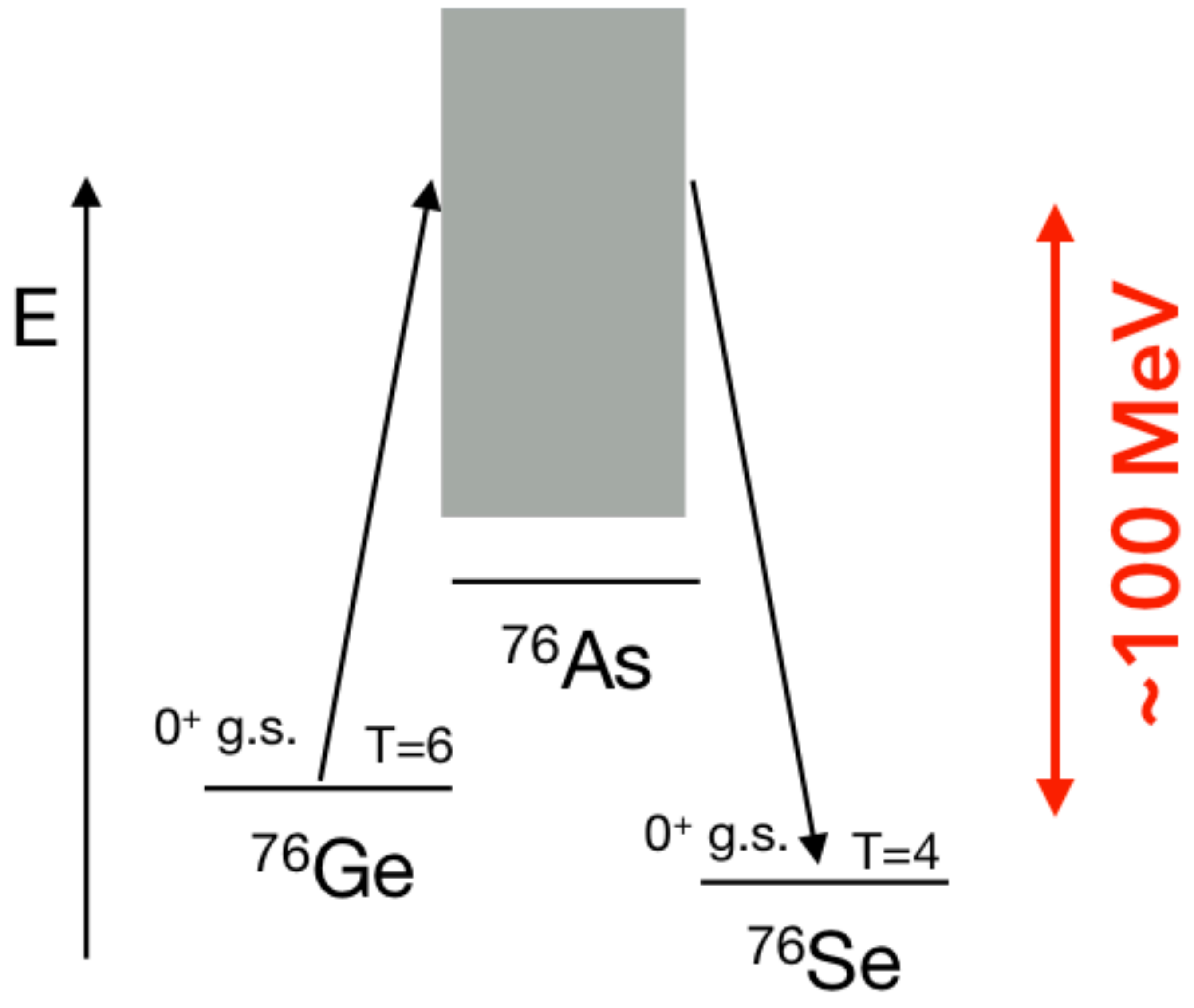
2v2β

Dominated by Gamow-Teller transitions via 1^+ states in the intermediate nucleus, confined to low excitation energy



0v2β

Probes all intermediate states up to 10s of MeV, any spin, up to 5 to 6h



Can probe/do probe:

e.g., ^{76}Ge(p,n)^{76}As, ^{76}Se(n,p)^{76}As

No obvious probe*:

e.g., ^{76}Ge(^{18}Ne,^{18}O)^{76}Se

Ground states …

- *Single- and two-particle properties should be important:*
  - *How do the protons and neutrons rearrange themselves going from the initial to final state? (we can probe that)*
  - *Are the ground states 'simple' BCS like states? (we can probe that too)*
- *Can knowledge of the above inform or constrain theoretical calculations?*
- *How well are the uncertainties (in the analysis of the experimental data) understood?*
- *(Are all these things not already known (after all, these are [essentially] stable isotopes?)*

Series of experiments …

Single-nucleon and two-nucleon transfer on nuclei involved in the $^{76}\text{Ge}\rightarrow{}^{76}\text{Se}$, $^{100}\text{Mo}\rightarrow{}^{100}\text{Ru}$, $^{130}\text{Te}\rightarrow{}^{130}\text{Xe}$, *and* $^{136}\text{Xe}\rightarrow{}^{136}\text{Ba}$ *decays*

Original works, including cross sections and analyzed data:

S. J. Freeman et al., Phys. Rev. C ***75****, 051301(R) (****2007****): A = 76 neutron pairing*

J. P. Schiffer et al., Phys. Rev. Lett. ***100****, 112501 (****2008****): A = 76neutron occupancies*

B. P. Kay et al., Phys. Rev. C ***79****, 021301(R) (****2009****): A = 76 proton occupancies*

T. Bloxham et al., Phys. Rev. C ***82****, 027308 (****2010****): A = 130 neutron (and proton) pairing*

J. S. Thomas et al., Phys. Rev. C ***86****, 047304 (****2012****): A = 100 neutron pairing*

B. P. Kay et al., Phys. Rev. C ***87****, 011302(R) (****2013****): A = 130 neutron occupancies*

A. Roberts et al., Phys. Rev. C ***87****, 051305(R) (****2013****): A = 76 proton pairing*

J. P. Entwisle et al., Phys. Rev. C ***93****, 064312 (****2016****): A = 130 and A = 136 proton occupancies*

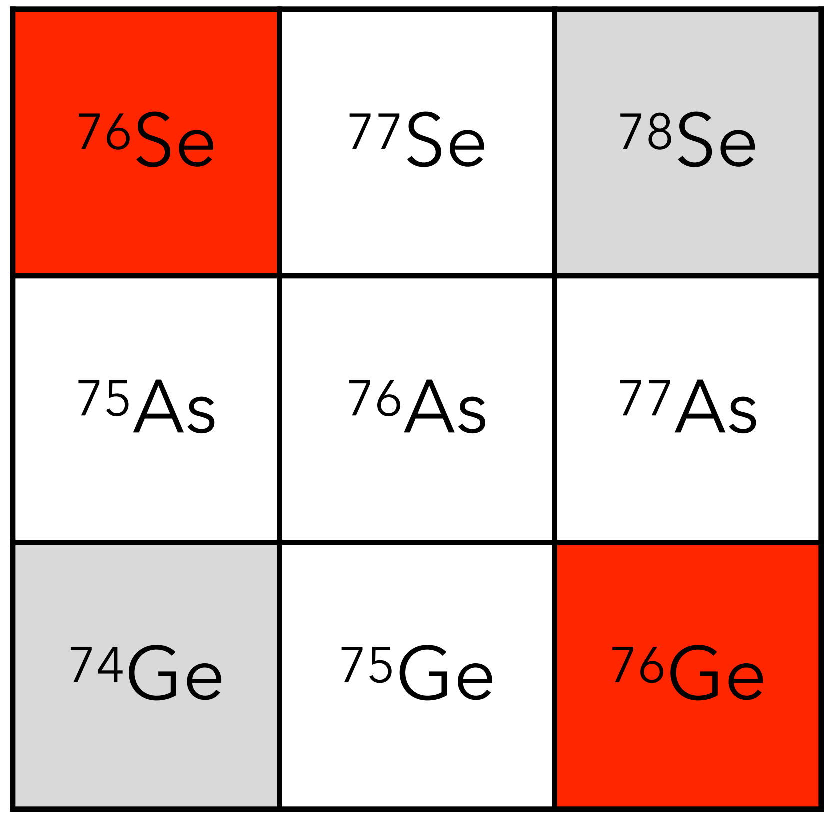
S. V. Szwec et al., Phys. Rev. C ***94****, 054314 (****2016****): A = 136 neutron occupancies*

S. J. Freeman et al., Phys. Rev. C ***96****, 054325 (****2017****): A = 100 proton and neutron occupancies*

Focus of brief experimental highlights

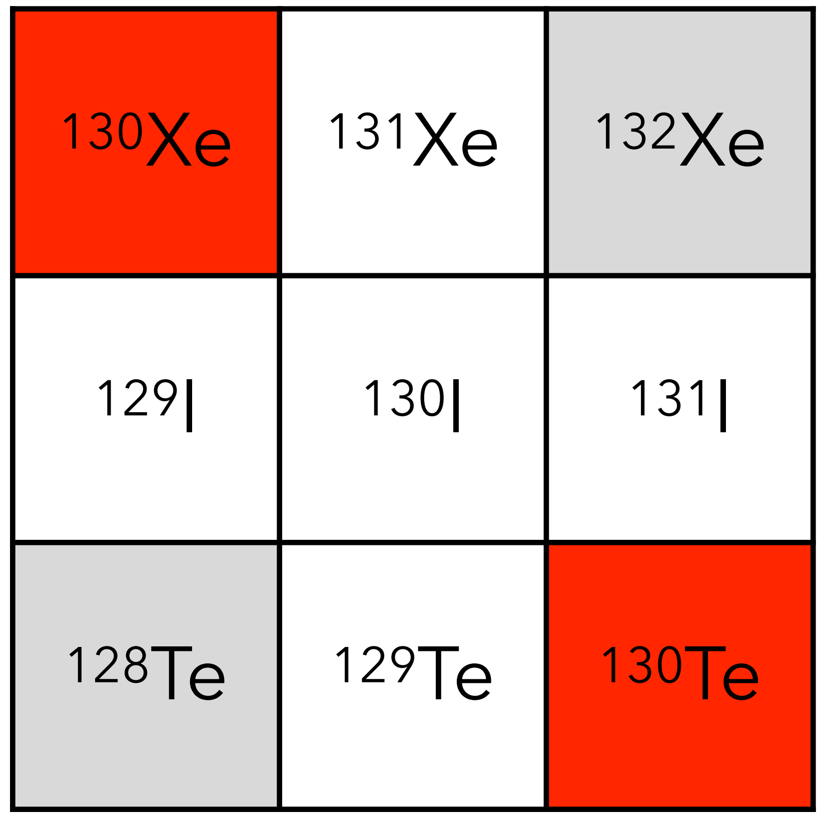
Single-nucleon and two-nucleon transfer on nuclei involved in the ^{76}Ge→^{76}Se, ^{100}Mo→^{100}Ru, ^{130}Te→^{130}Xe, and ^{136}Xe→^{136}Ba decays

$\pi = \upsilon$



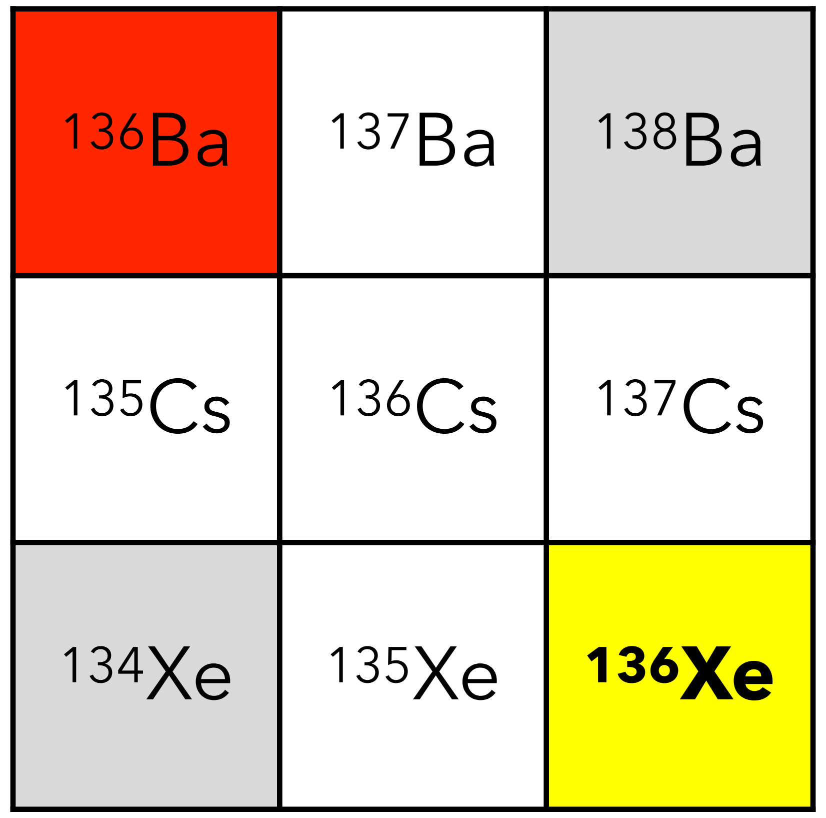
^{76}Se	^{77}Se	^{78}Se
^{75}As	^{76}As	^{77}As
^{74}Ge	^{75}Ge	^{76}Ge

$\pi = \upsilon$



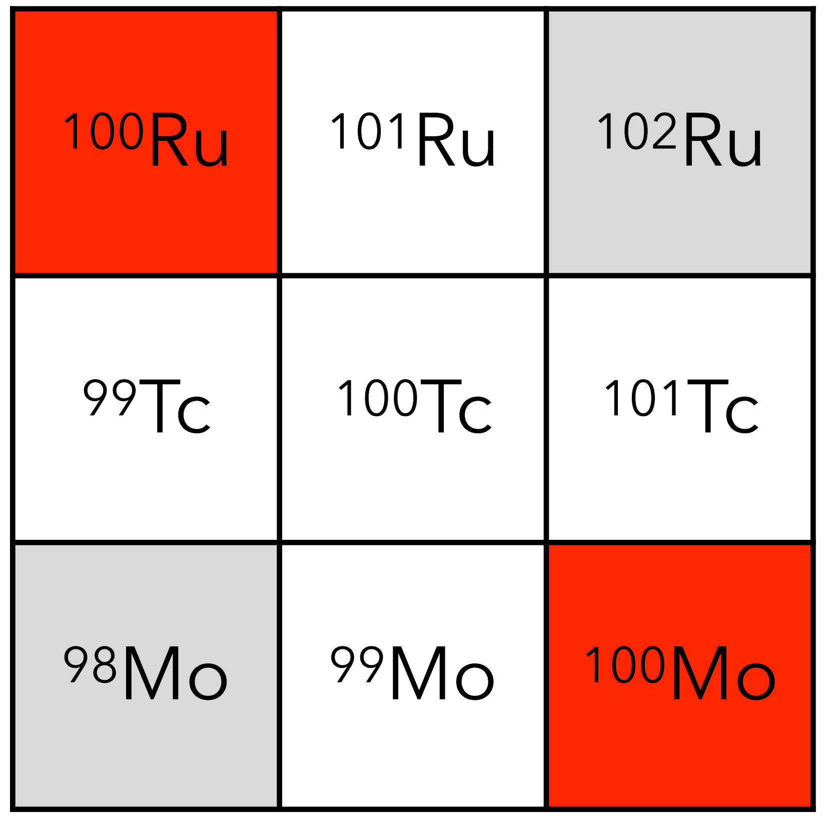
^{130}Xe	^{131}Xe	^{132}Xe
^{129}I	^{130}I	^{131}I
^{128}Te	^{129}Te	^{130}Te

$\pi = \upsilon$

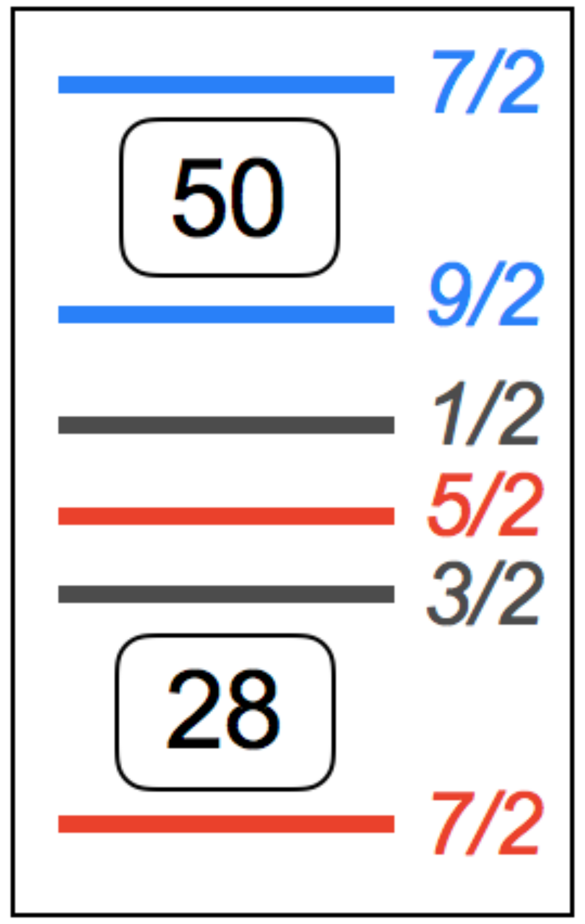


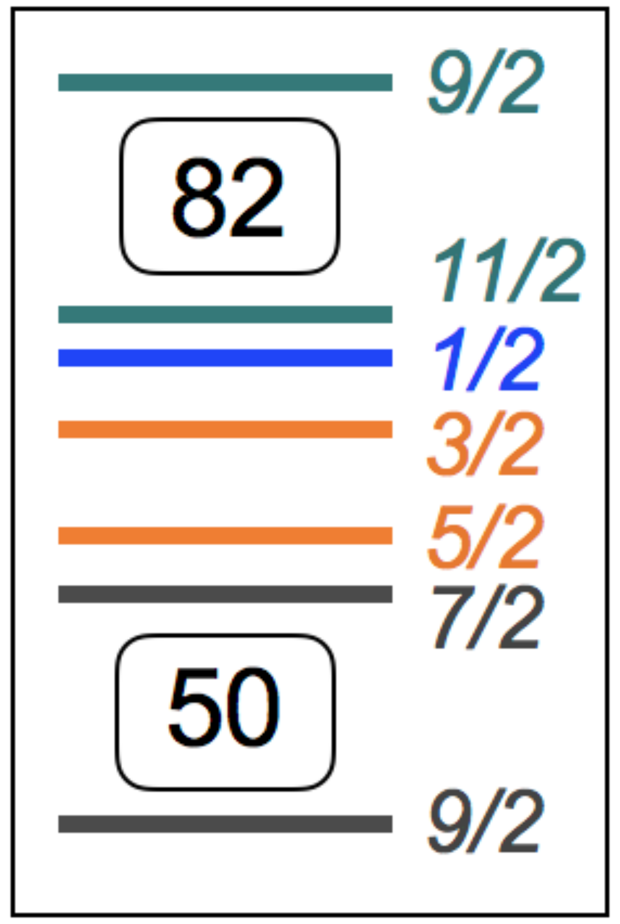
^{136}Ba	^{137}Ba	^{138}Ba
^{135}Cs	^{136}Cs	^{137}Cs
^{134}Xe	^{135}Xe	**^{136}Xe**

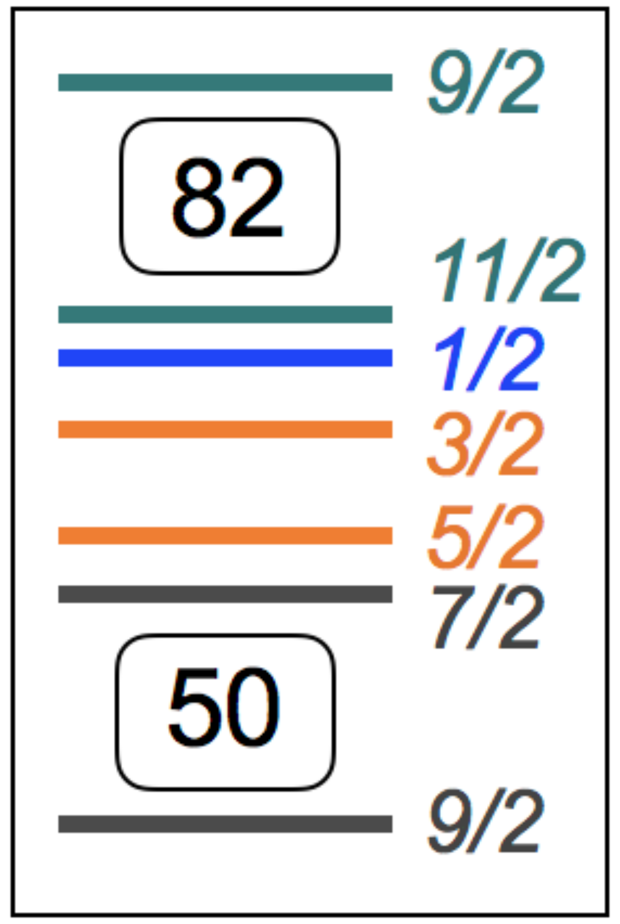
$\pi \neq \upsilon$

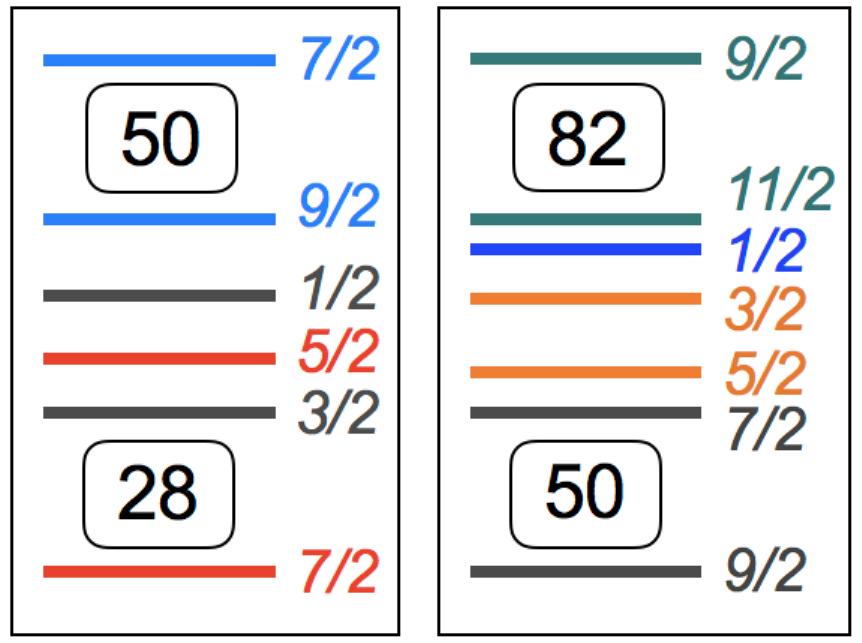


^{100}Ru	^{101}Ru	^{102}Ru
^{99}Tc	^{100}Tc	^{101}Tc
^{98}Mo	^{99}Mo	^{100}Mo







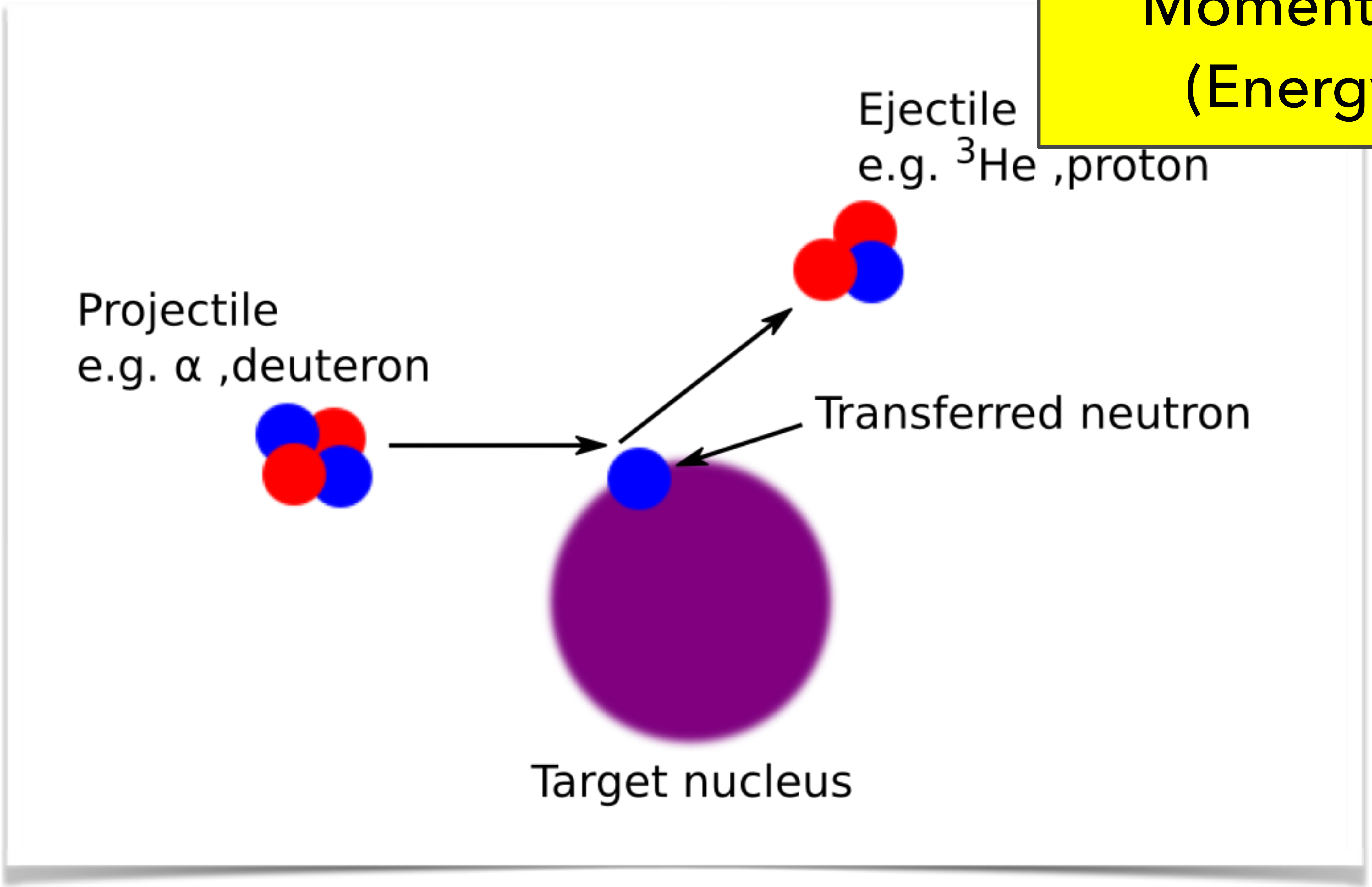


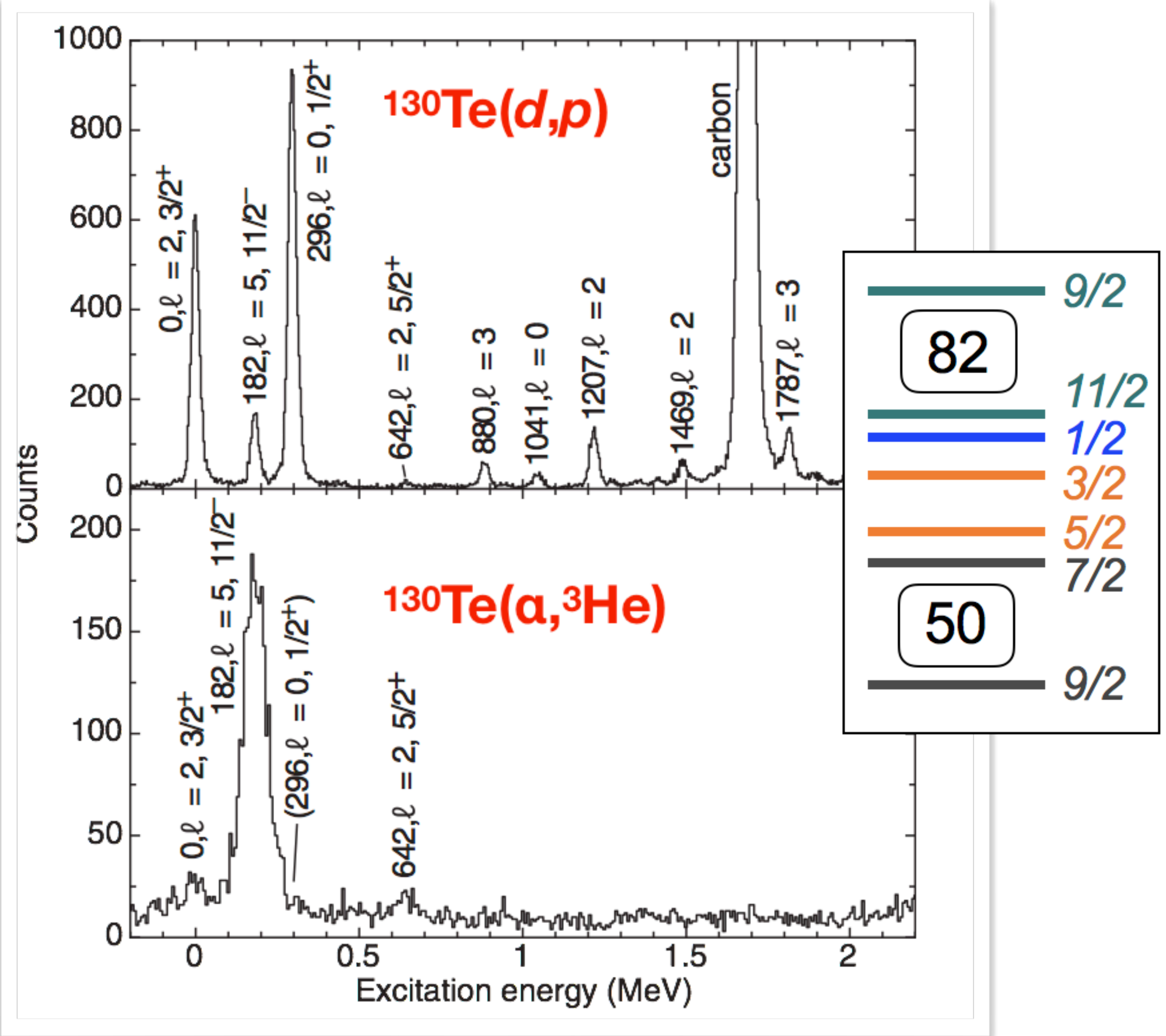
Reminder (again), transfer reactions

Around 10 MeV/u (direct reactions)

Variety of reactions (momentum matching)

Yield
(Cross section)
Momentum
(Energy)





*Spectra from BPK et al., Phys. Rev. C **87**, 011302(R) (**2013**)*

Does it work? A question not asked yet

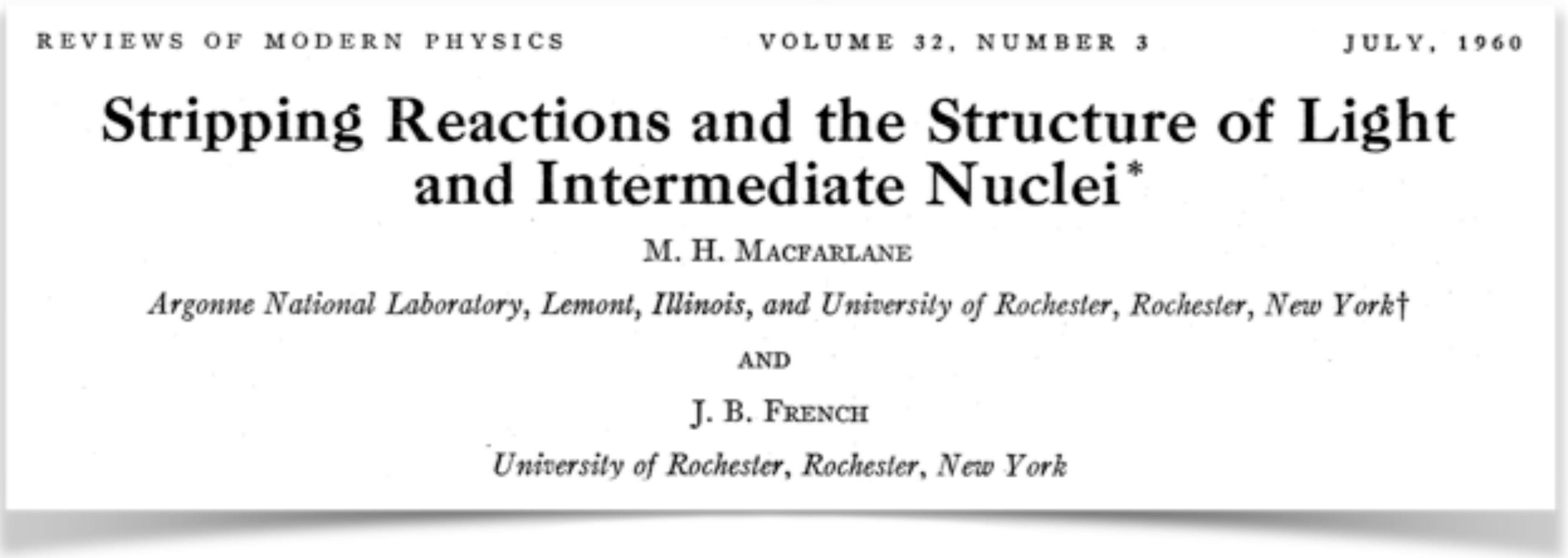
- Need a normalization
- Typical uncertainty is between +/-0.1-0.2 nucleons
- Demonstrated in many systems (groups of isotopes/isotones) across the chart of nuclides

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

$$N_j \equiv S'/S$$

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

- But is the normalization just arbitrary?



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

Stripping Reactions and the Structure of Light and Intermediate Nuclei*

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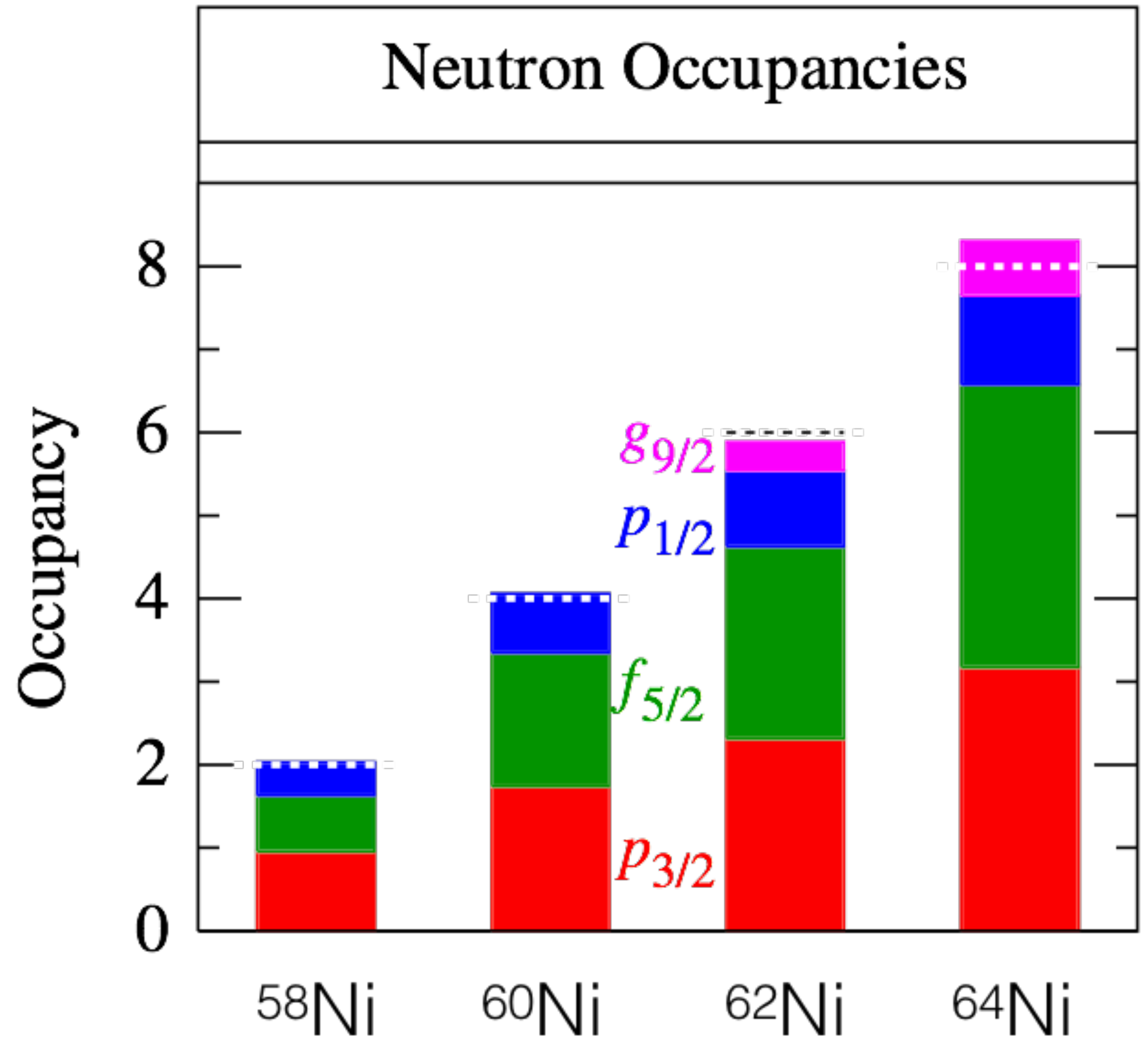
AND

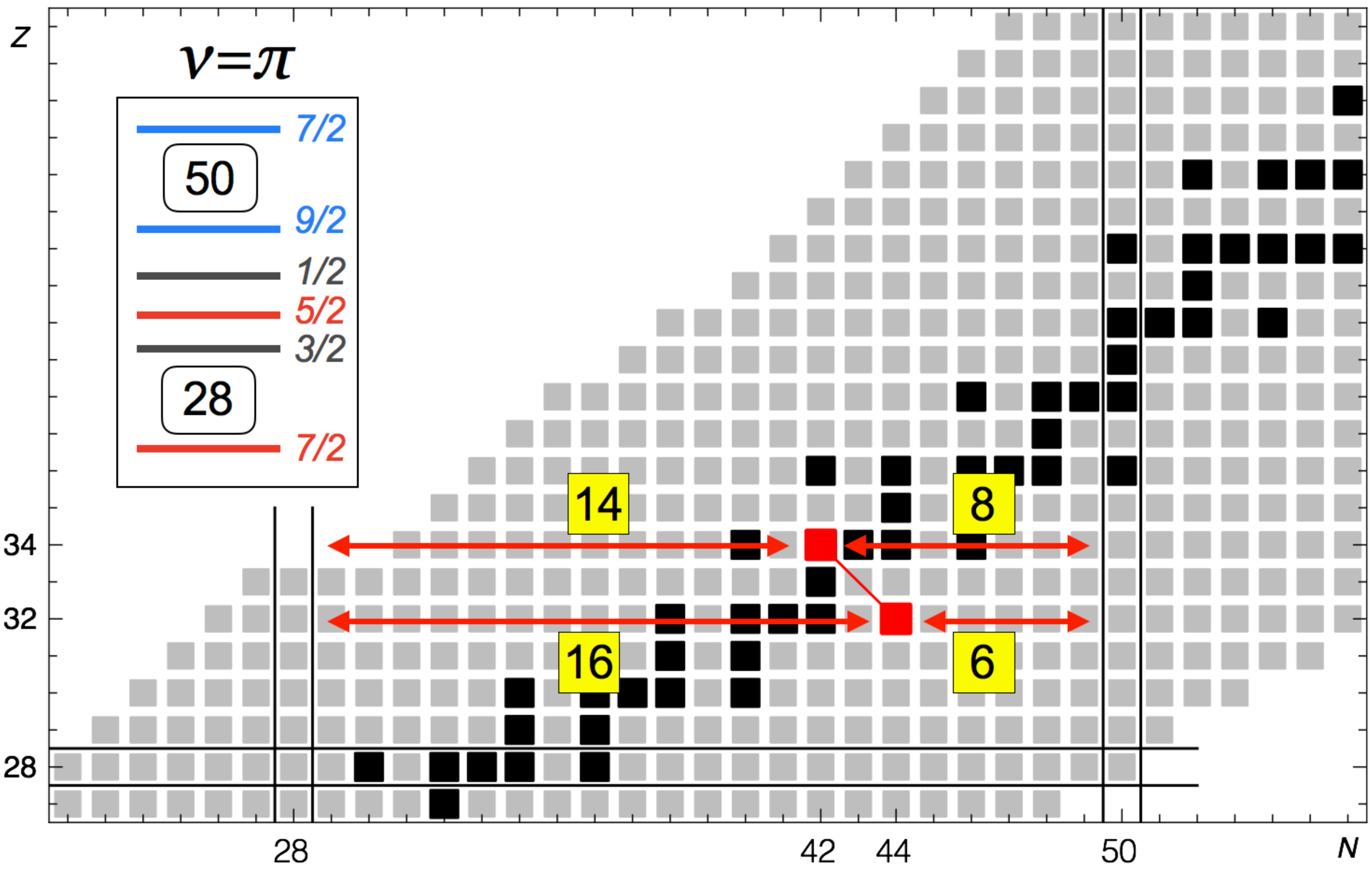
J. B. FRENCH

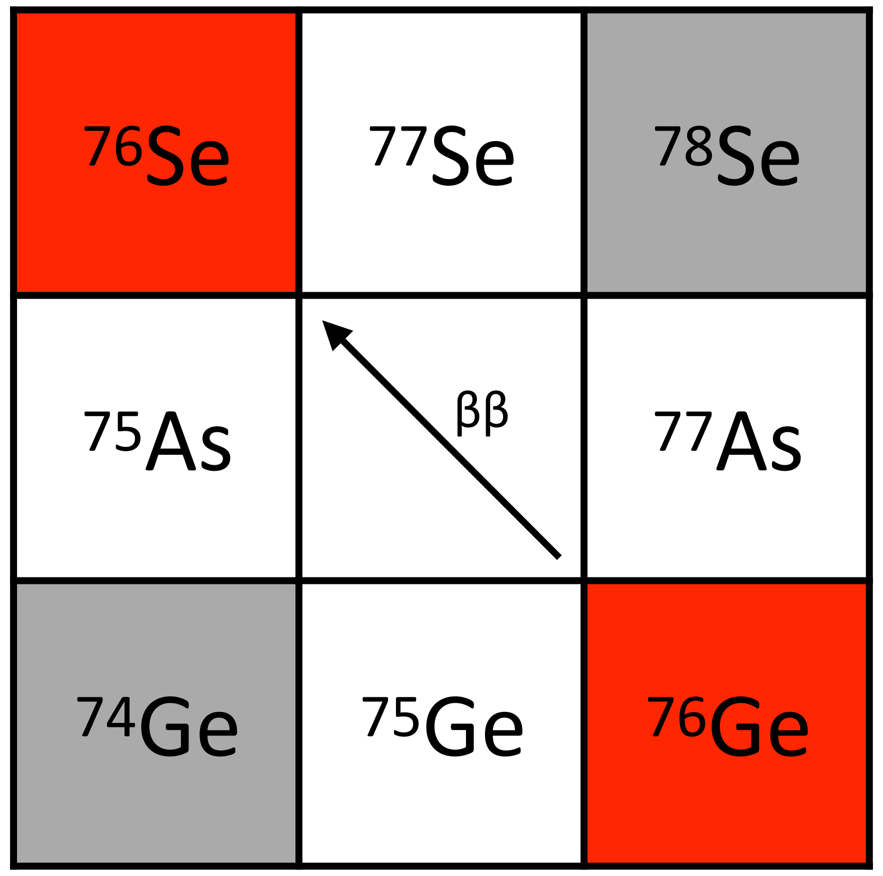
University of Rochester, Rochester, New York



Ni occupancies from J. P. Schiffer et al., Phys. Rev. Lett. **108**, 022501 (**2012**)

Analysis, e.g., of ^{76}Ge,Se





^{76}Se	^{77}Se	^{78}Se
^{75}As	ββ	^{77}As
^{74}Ge	^{75}Ge	^{76}Ge

Analysis - sum rules and normalization

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	

E	*ℓ*	(2*j*+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	

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

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

Analysis - sum rules and normalization

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		

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		

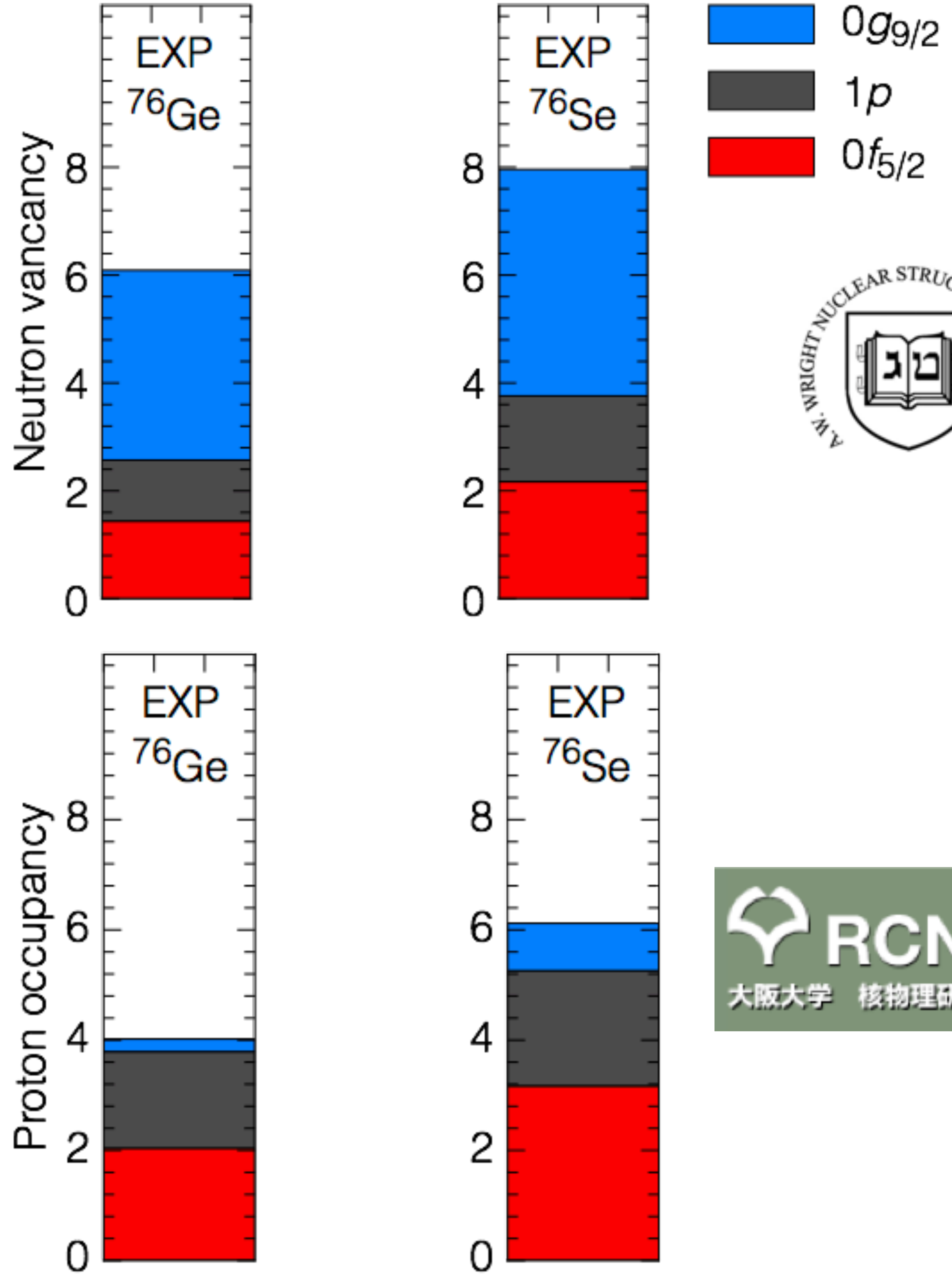
$$N_j \equiv [\sum S'_{\text{removing}} + \sum (2j+1) S'_{\text{adding}}]/(2j+1)$$

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

… old results

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

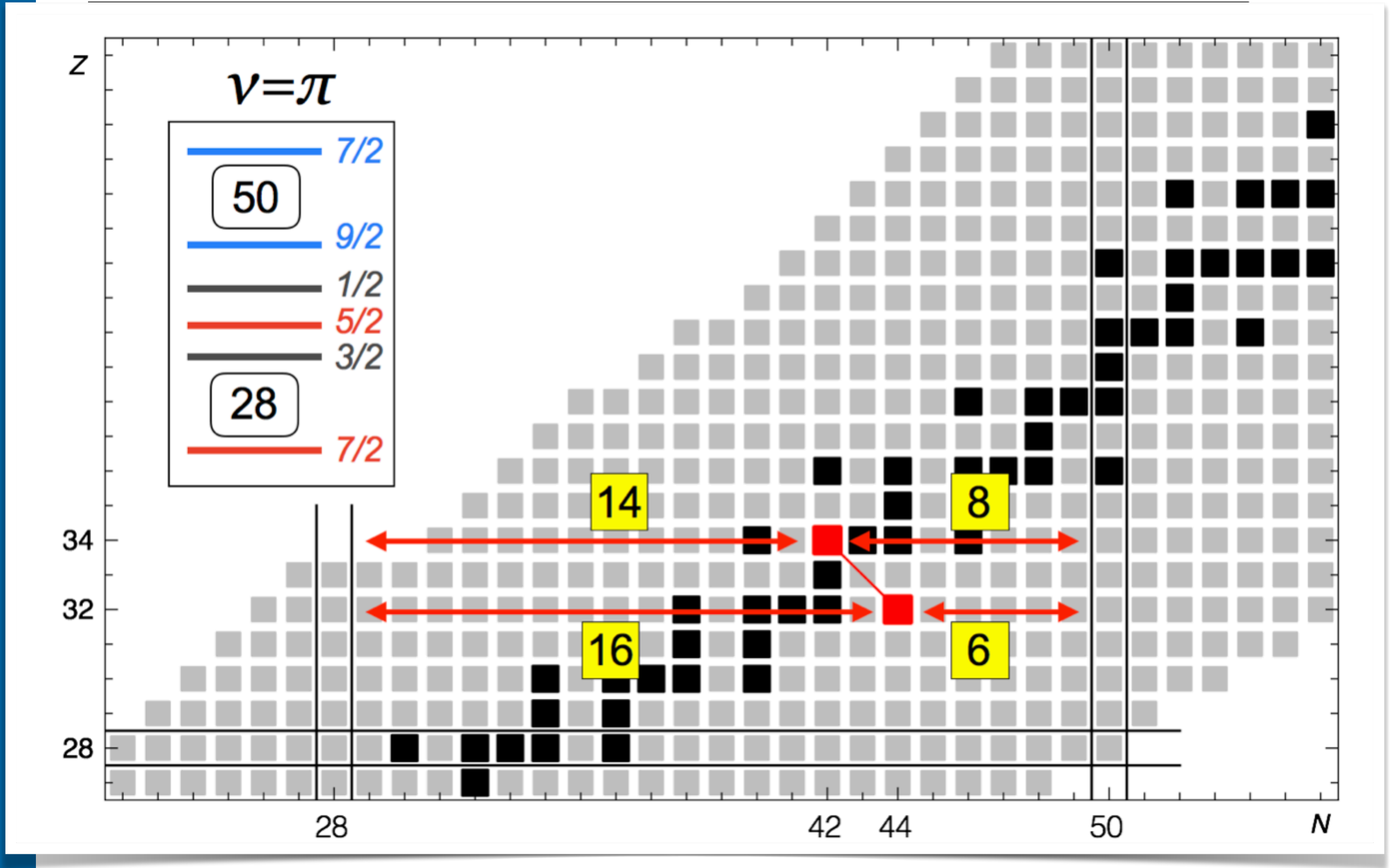


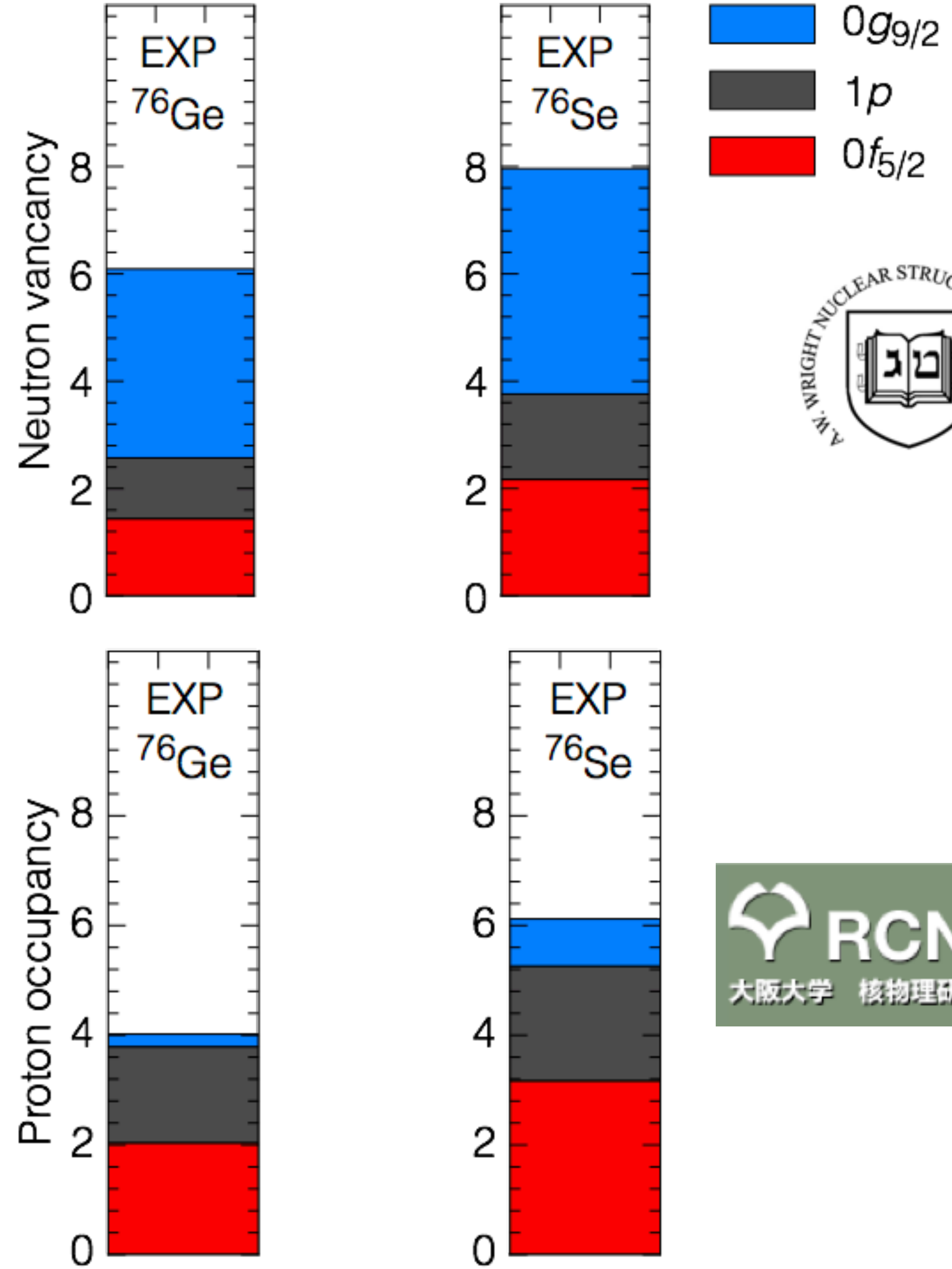
J. P. Schiffer et al., Phys. Rev. Lett. ***100****, 112501 (****2008****) [neutrons]*

BPK et al., Phys. Rev. C ***79****, 021301(R) (****2009****) [protons]*

... old results

Isotope	$0f_{5/2}$	$1p_{1/2,3/2}$	$0g_{9/2}$	Sum	Expect
^{78}Se	2.35	1.82	2.05	6.22	6

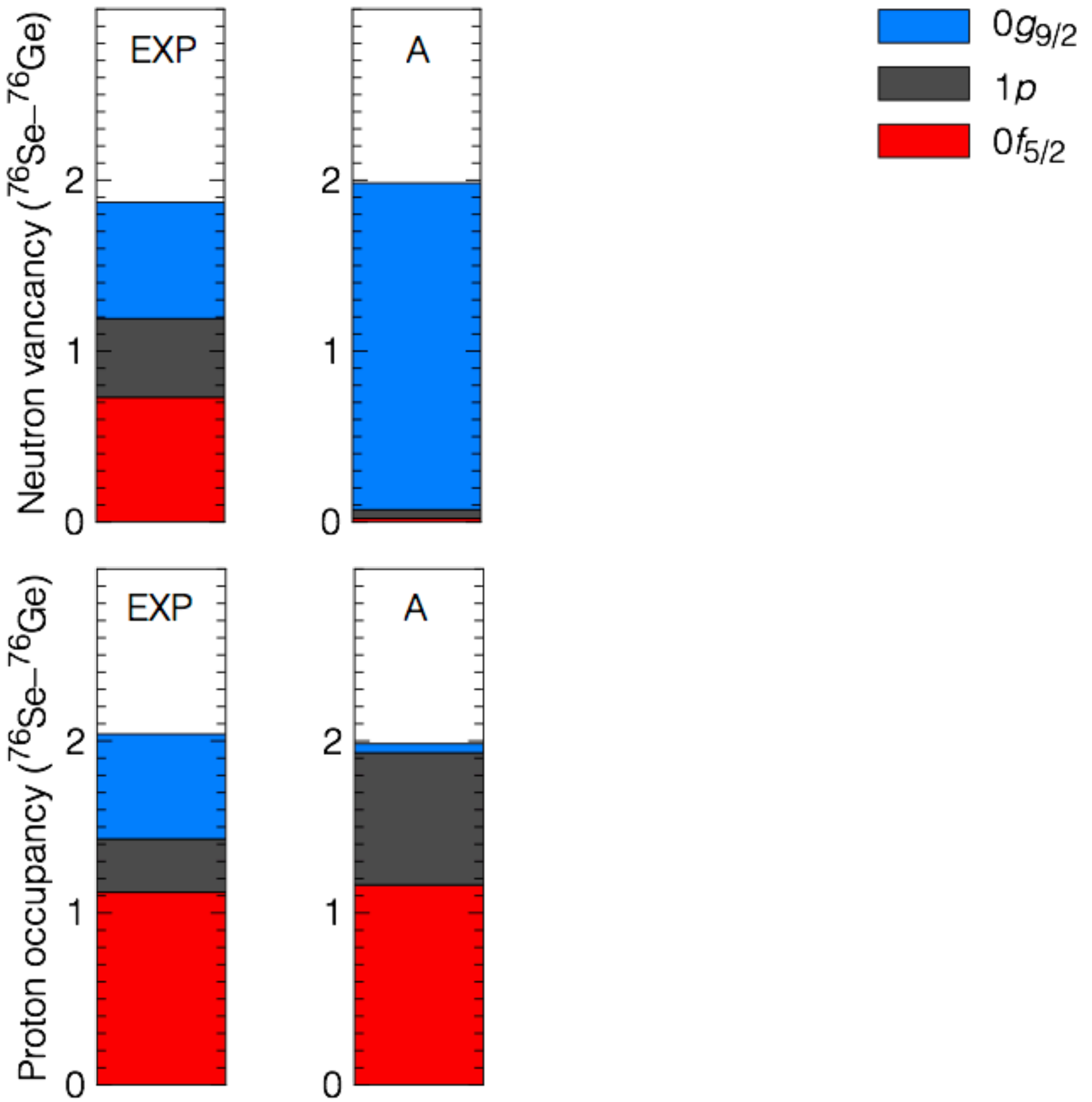


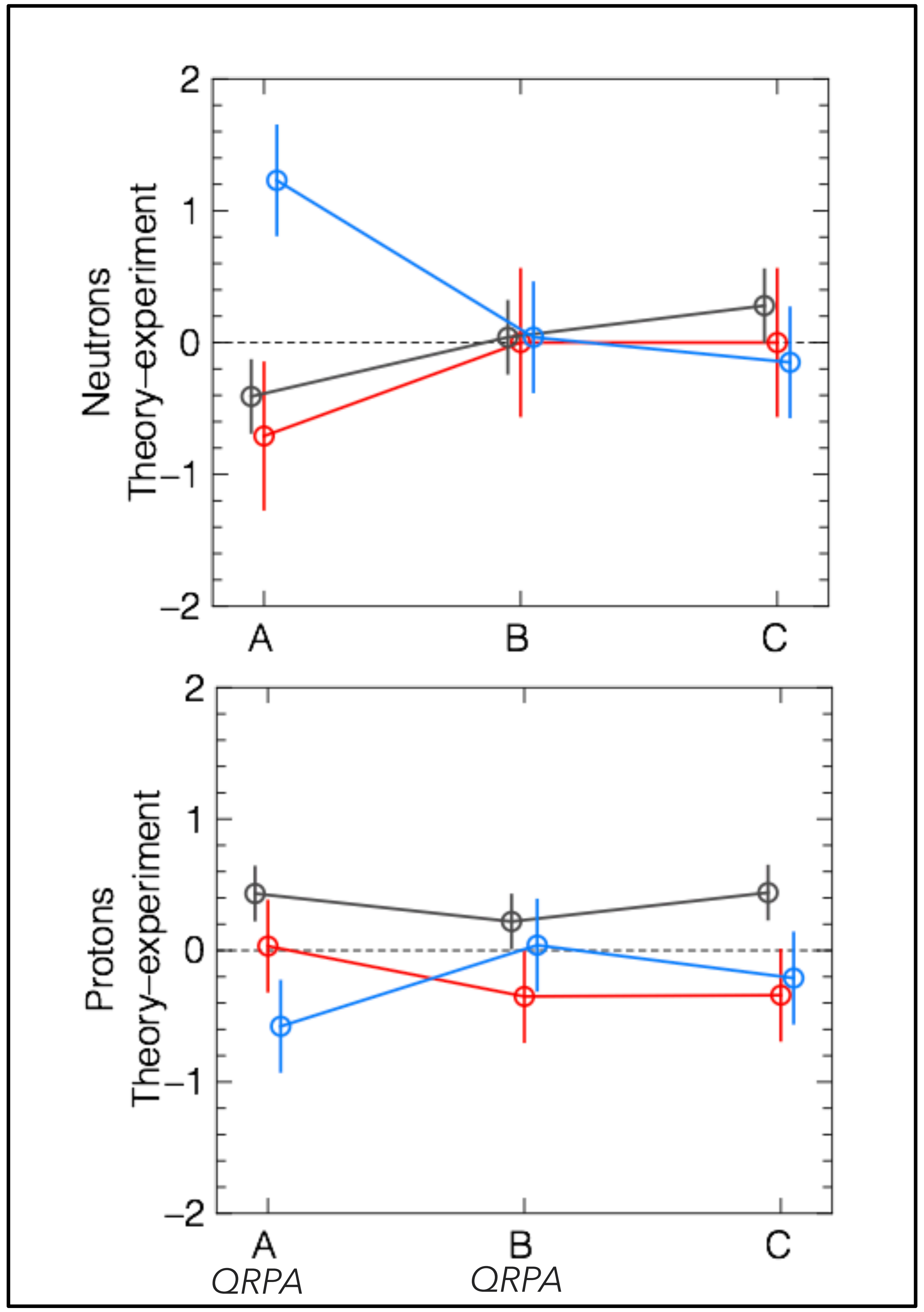


J. P. Schiffer et al., Phys. Rev. Lett. **100**, 112501 (**2008**) [neutrons]

BPK et al., Phys. Rev. C **79**, 021301(R) (**2009**) [protons]

Change in occupancy

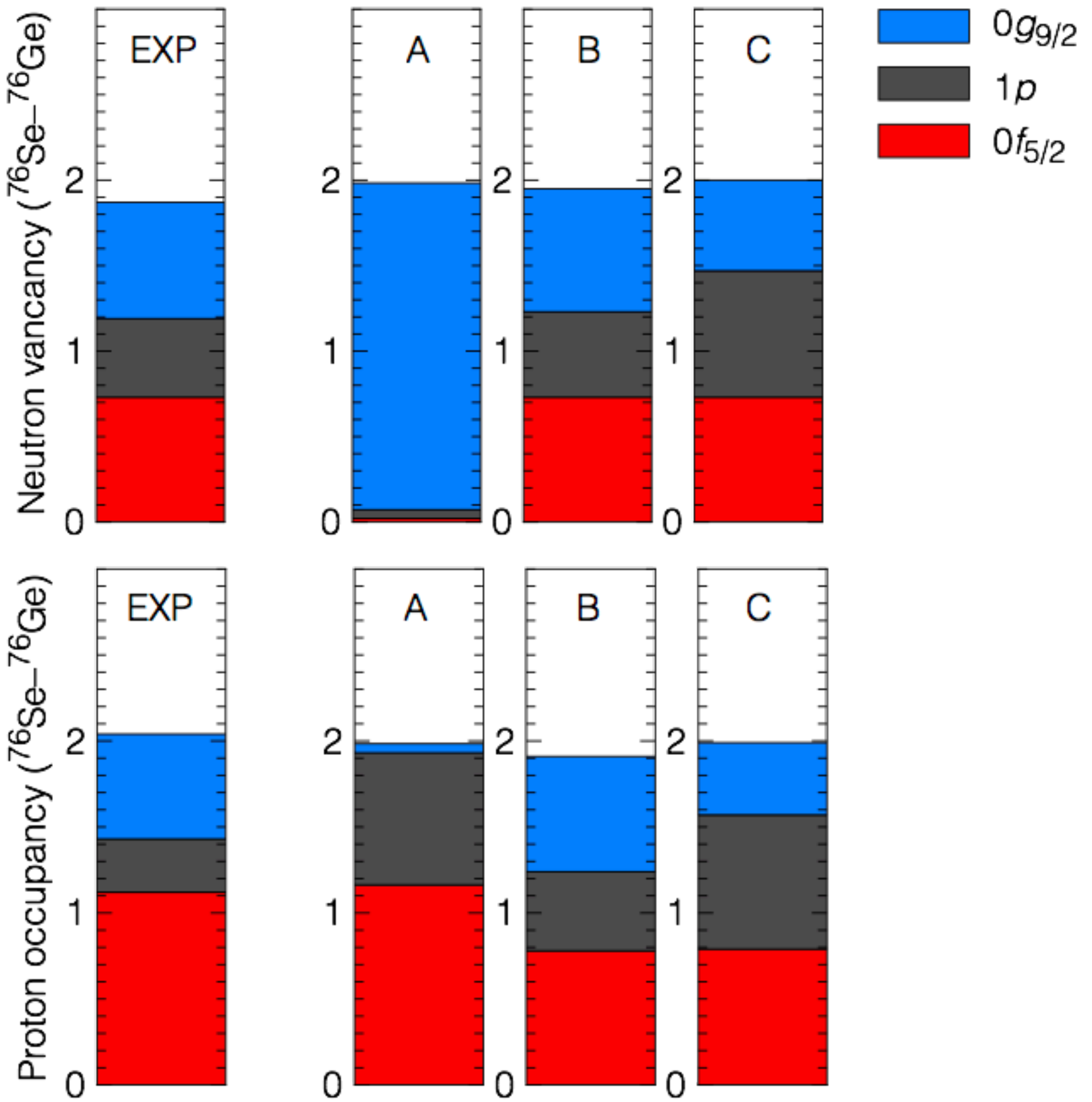


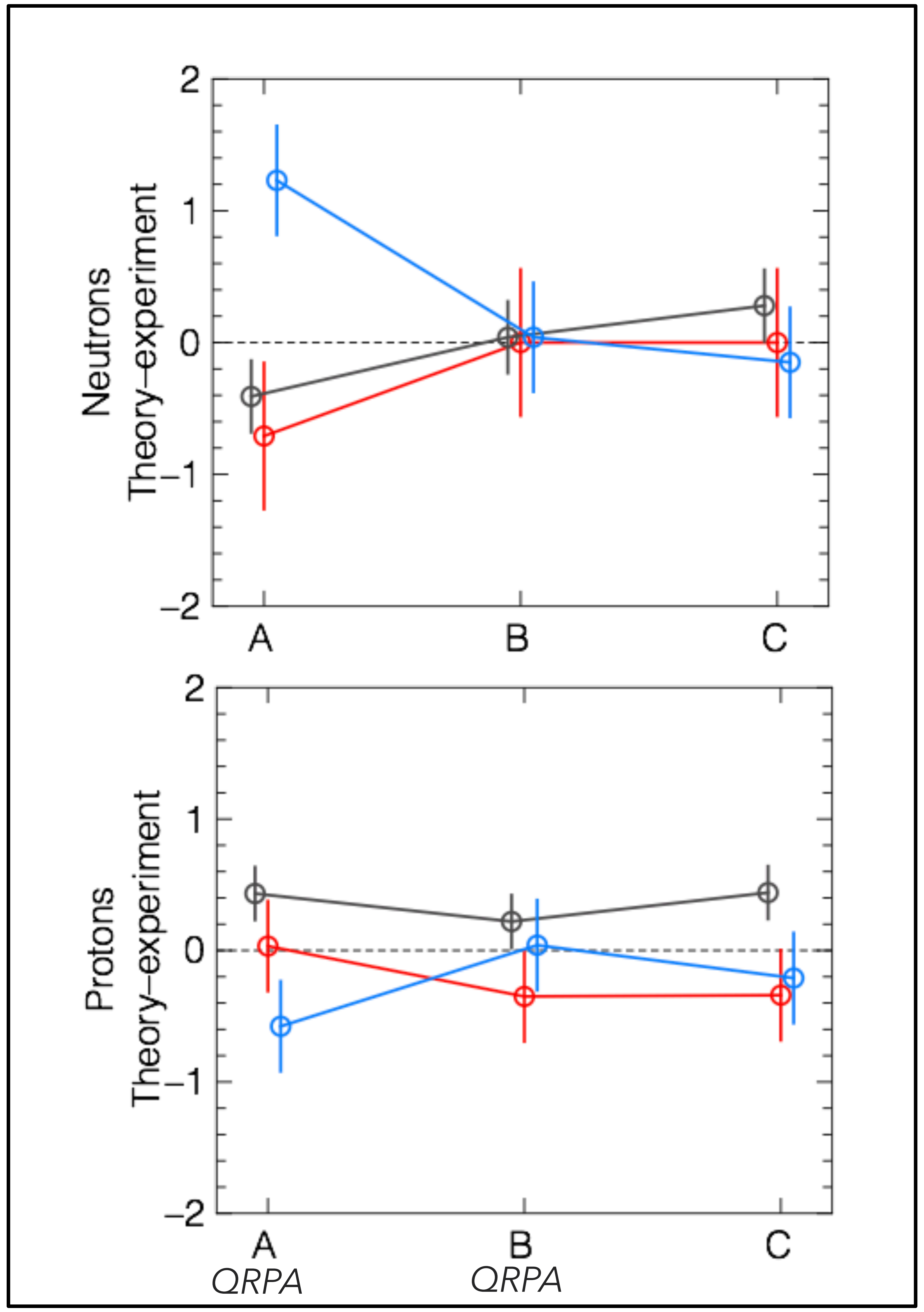


J. P. Schiffer et al., Phys. Rev. Lett. ***100****, 112501 (2008) [neutrons]*
BPK et al., Phys. Rev. C ***79****, 021301(R) (2009) [protons]*
Rodin et al., Nucl. Phys. A ***766****, 107 (2006) [A]*
Suhonen et al., Phys. Lett. B ***668****, 277 (2006) [B]*
*Caurier et al., Phys. Rev. Lett.****100****,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

Error bars are dominated by the systematic uncertainties relating to the analysis
(Does not include more recent IBM results)

Change in occupancy





J. P. Schiffer et al., Phys. Rev. Lett. ***100****, 112501 (2008) [neutrons]*
BPK et al., Phys. Rev. C ***79****, 021301(R) (2009) [protons]*
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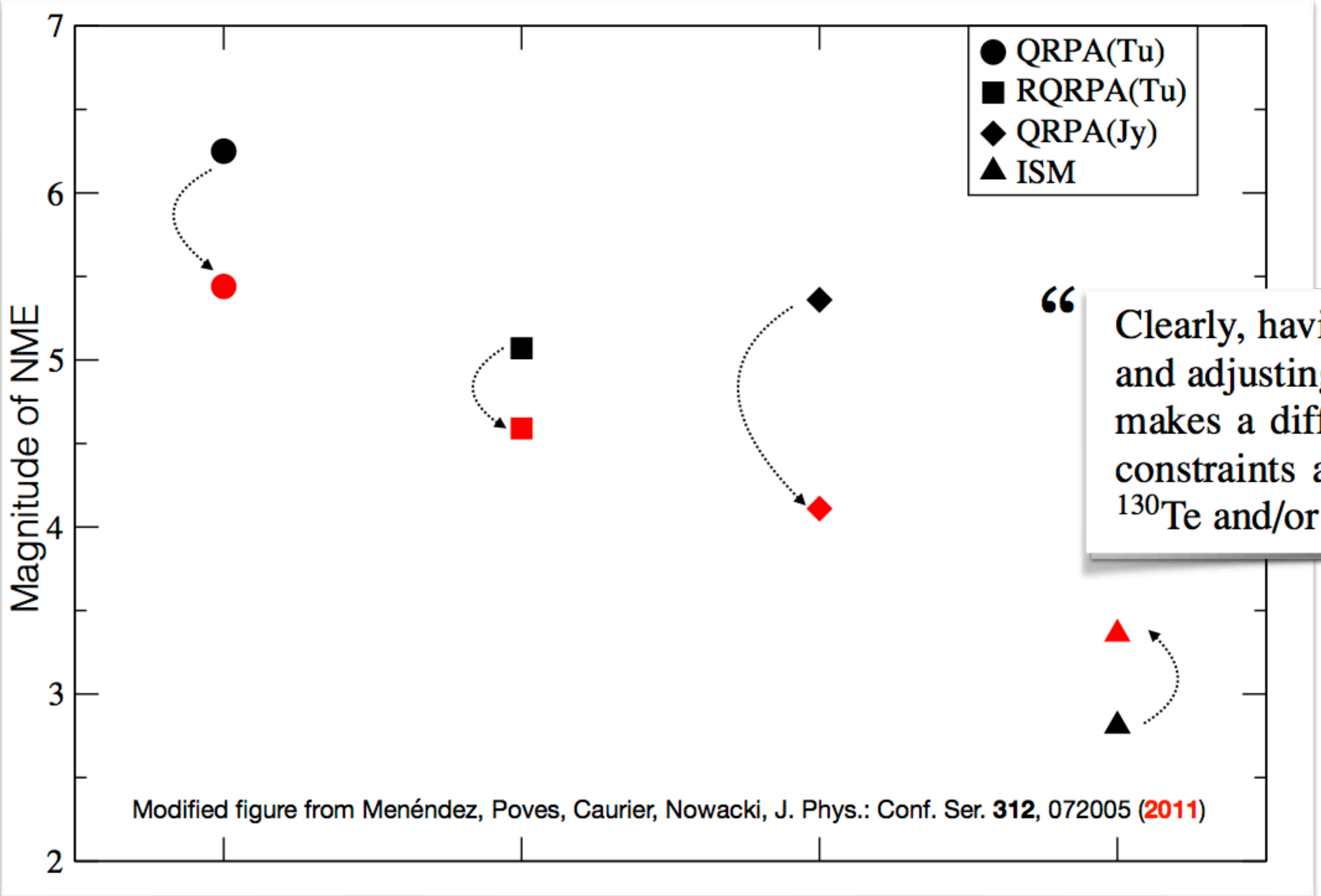
*Caurier et al., Phys. Rev. Lett.****100****, 052503 (2008) [C]*

Error bars are dominated by the systematic uncertainties relating to the analysis (Does not include more recent IBM results)

Impact? Any? Maybe ...



Modified figure from Menéndez, Poves, Caurier, Nowacki, J. Phys.: Conf. Ser. **312**, 072005 (**2011**)

> “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.”

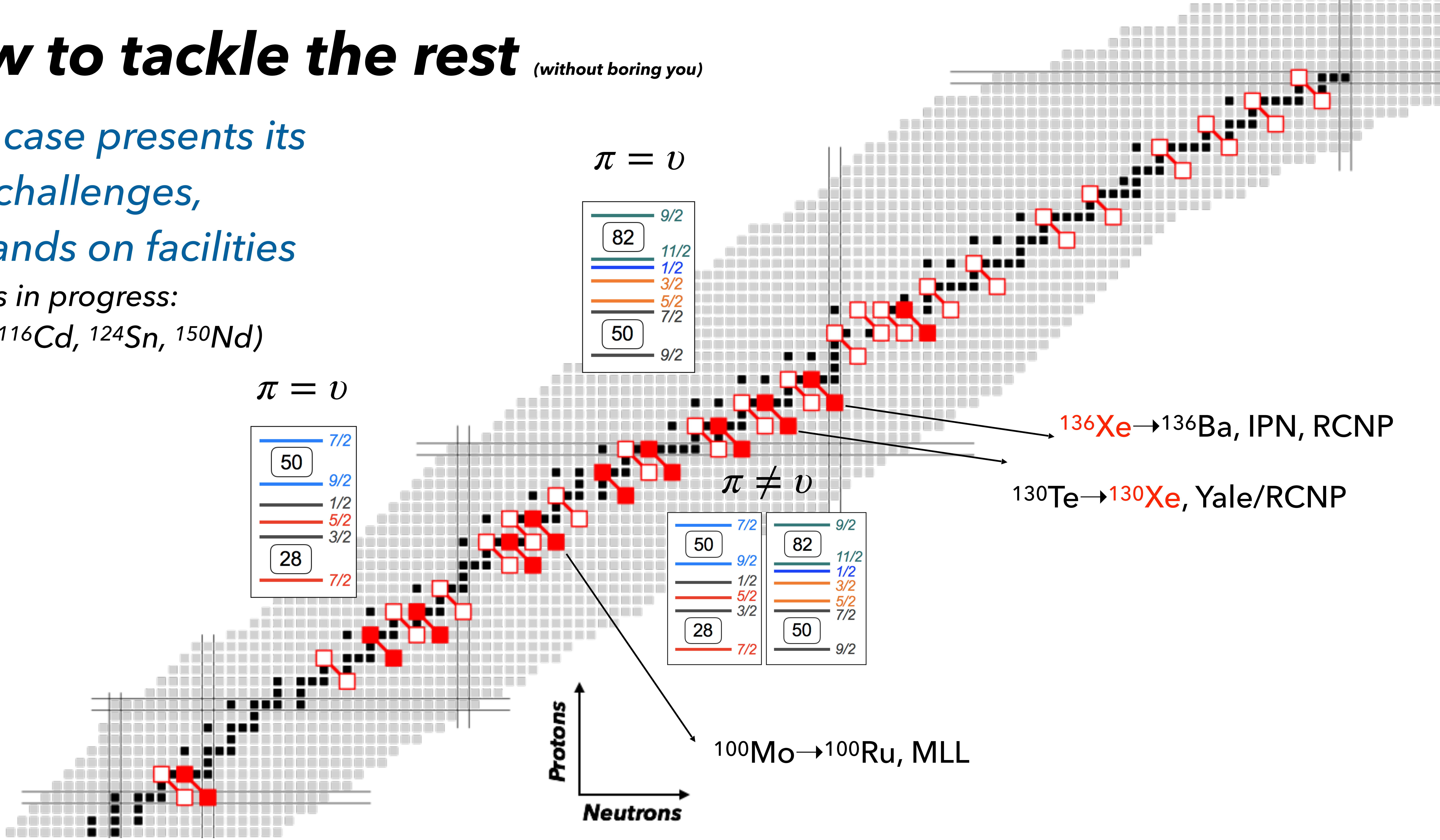
Yes, some. Much discussed. A *40-70% reduction* in the well-known gap between QRPA and the ISM, resulted. This predated recent IBM work and newer calculations.

Šimkovic et al., Phys. Rev. C ***79****, 055501 (****2009****) [quote]*

How to tackle the rest *(without boring you)*

Each case presents its own challenges, demands on facilities

(Others in progress: [^{82}Se], ^{116}Cd, ^{124}Sn, ^{150}Nd)



^{136}Xe→^{136}Ba, IPN, RCNP

^{130}Te→^{130}Xe, Yale/RCNP

^{100}Mo→^{100}Ru, MLL

How to tackle the rest *(without boring you)*

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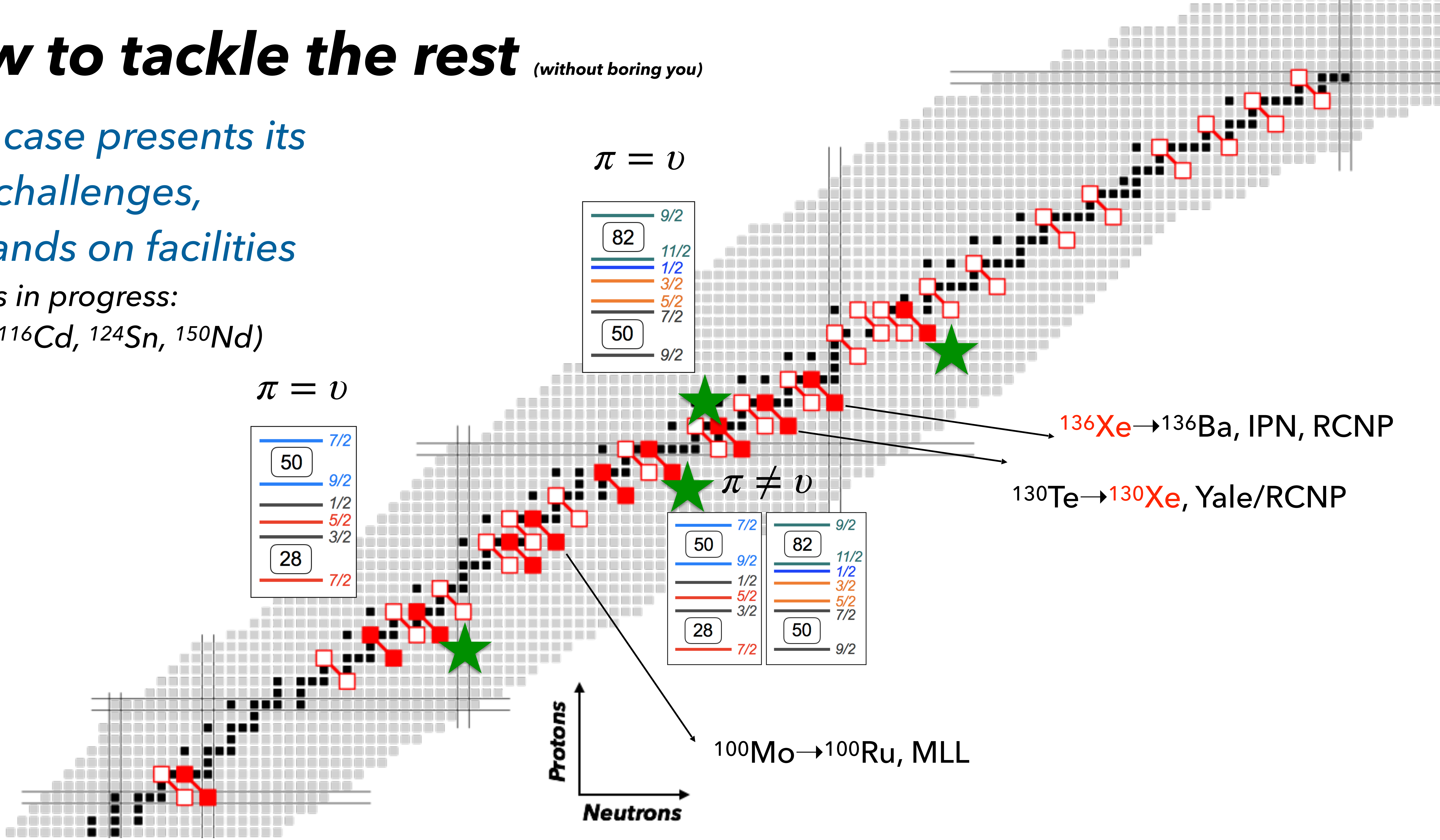


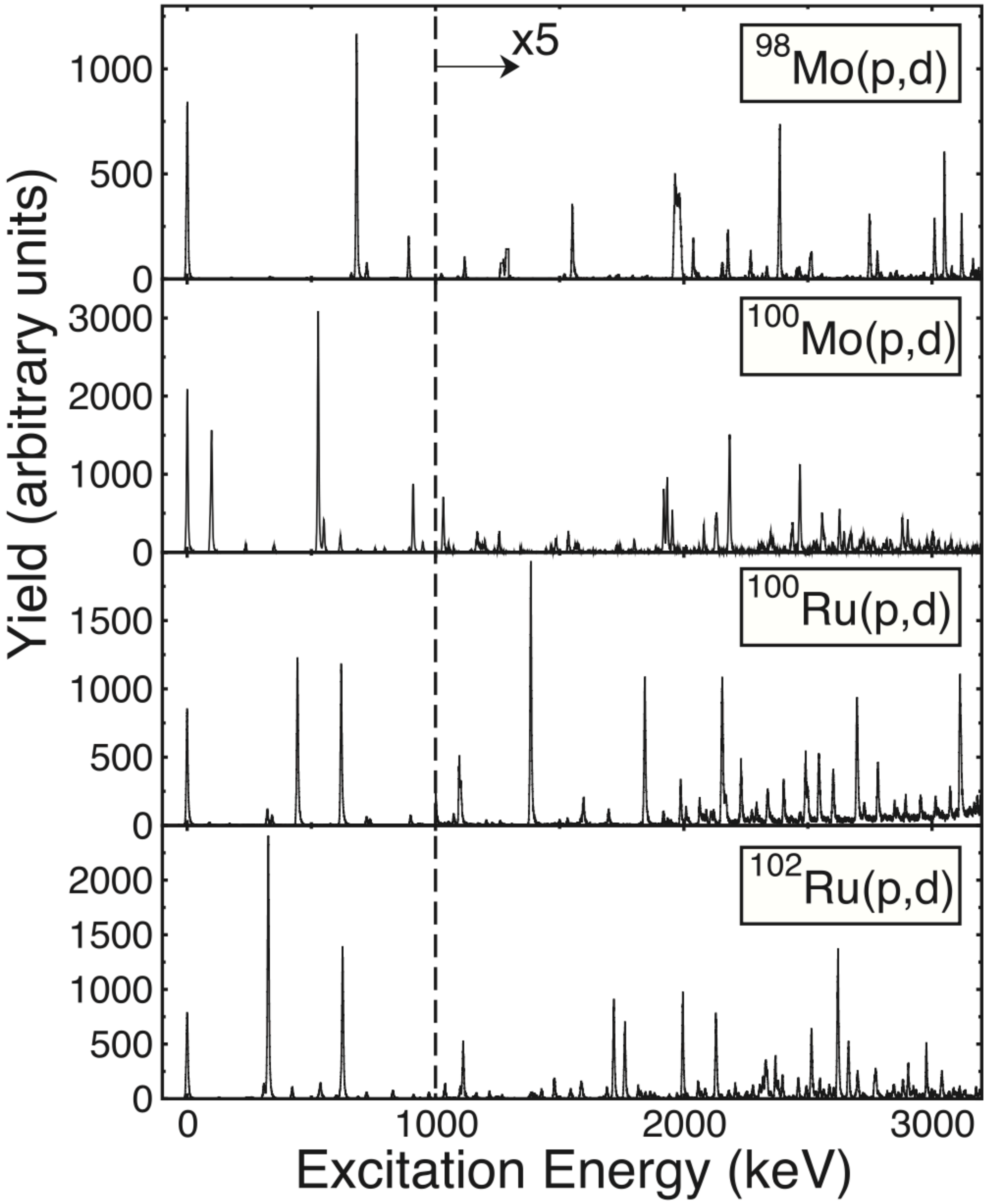
^{136}Xe→^{136}Ba, IPN, RCNP

^{130}Te→^{130}Xe, Yale/RCNP

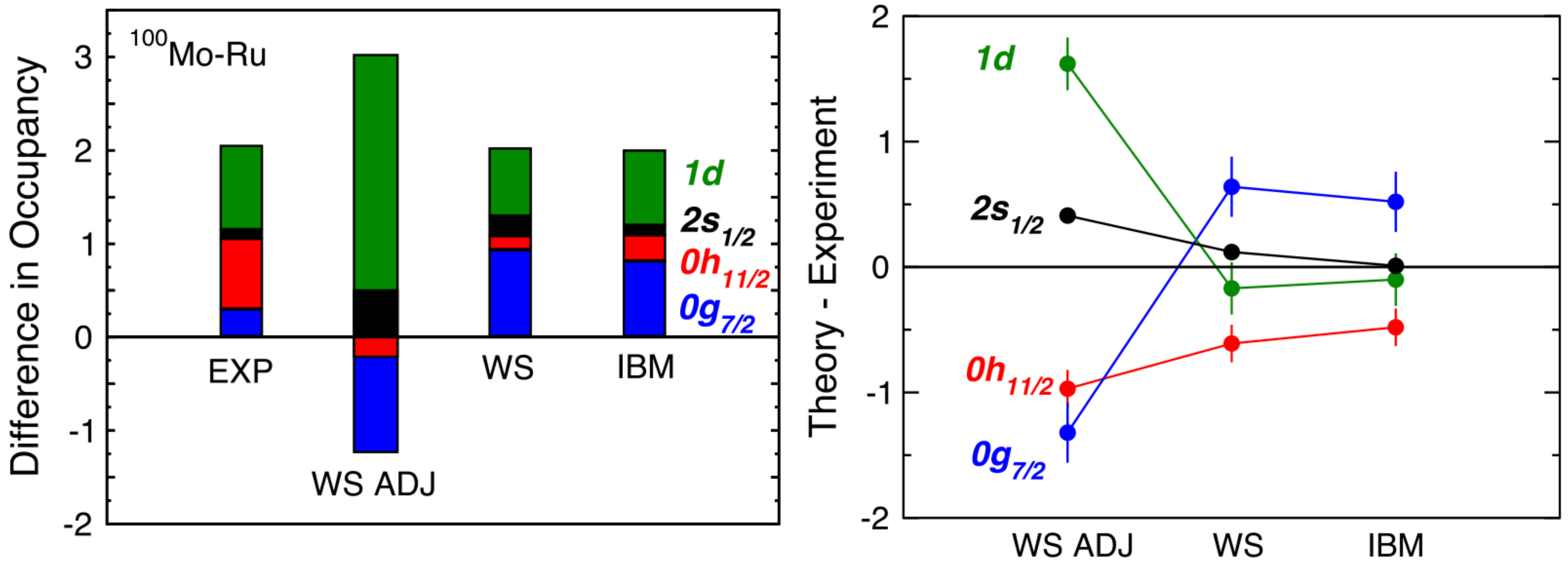
^{100}Mo→^{100}Ru, MLL

A = 100 occupancies

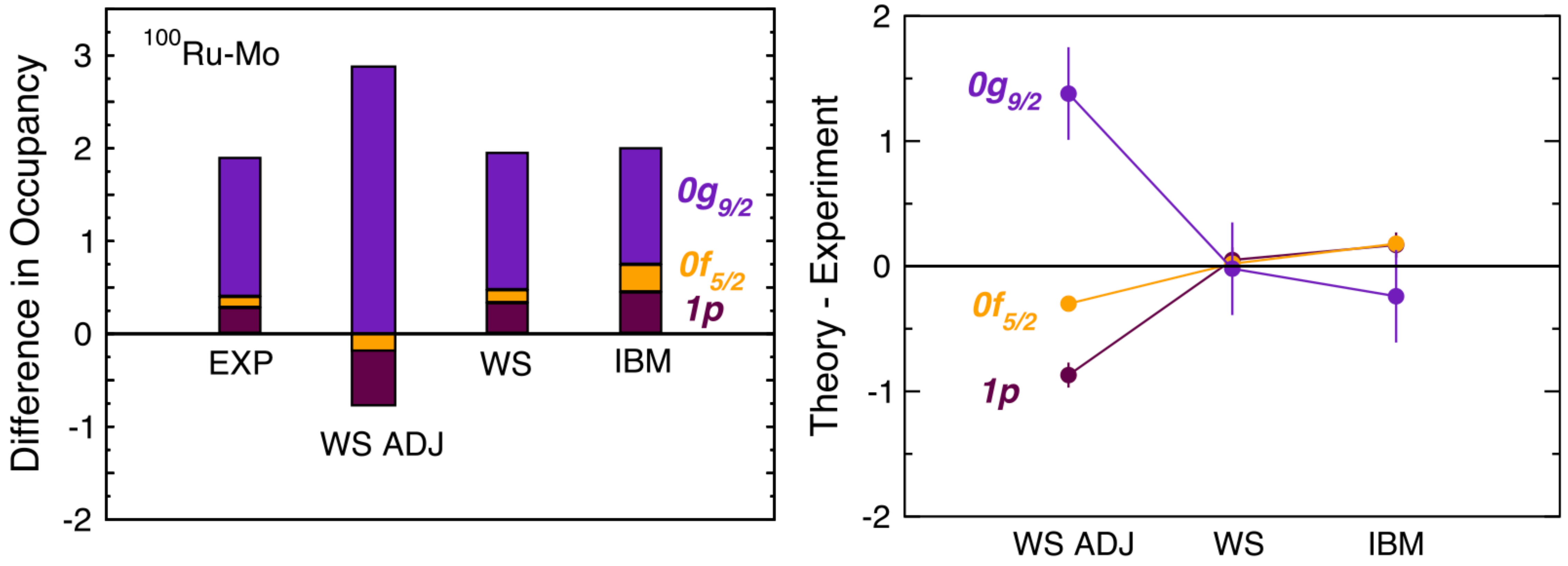
High level density, Munich Q3D (as good as 8-keV FWHM resolution



NEUTRONS



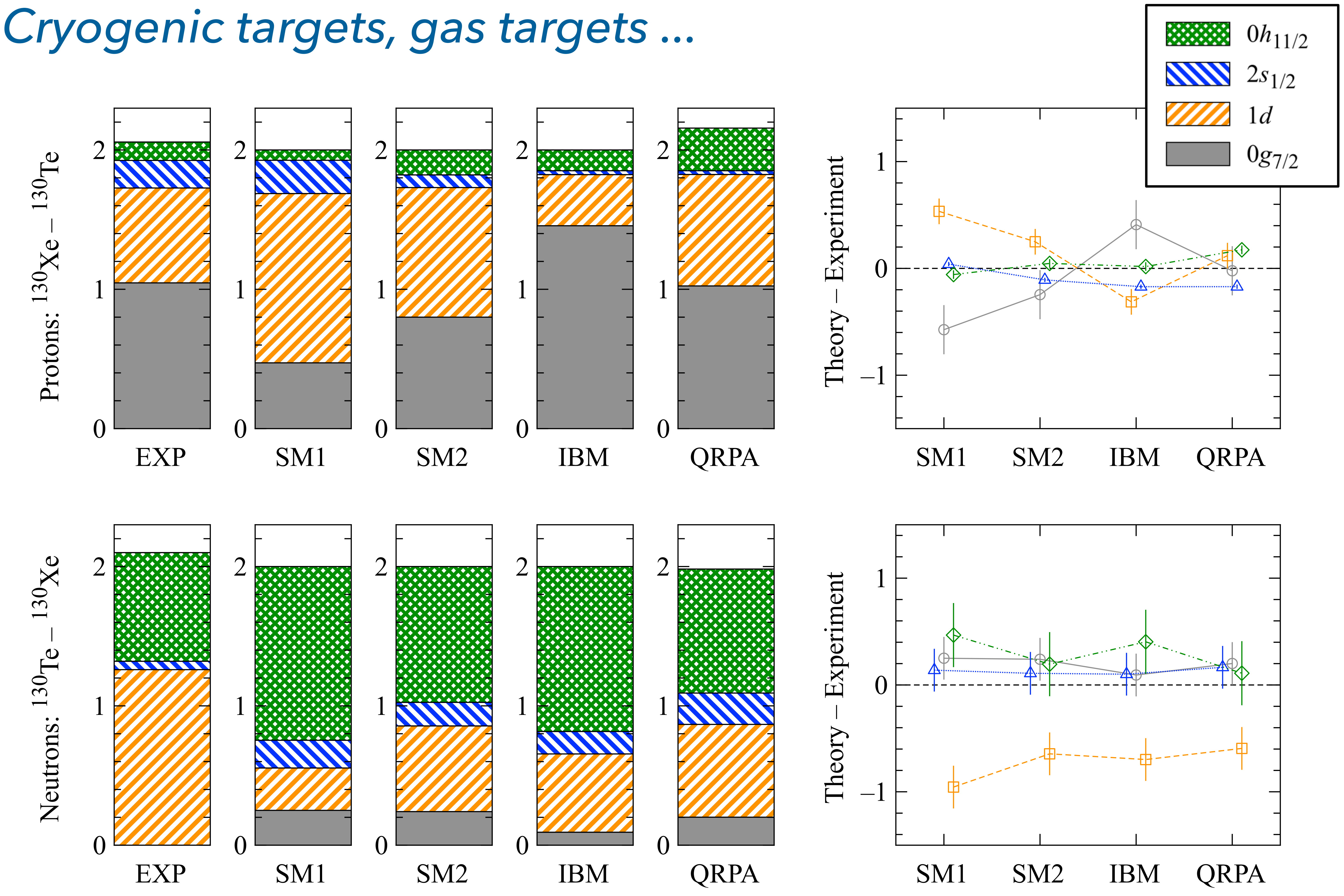
PROTONS

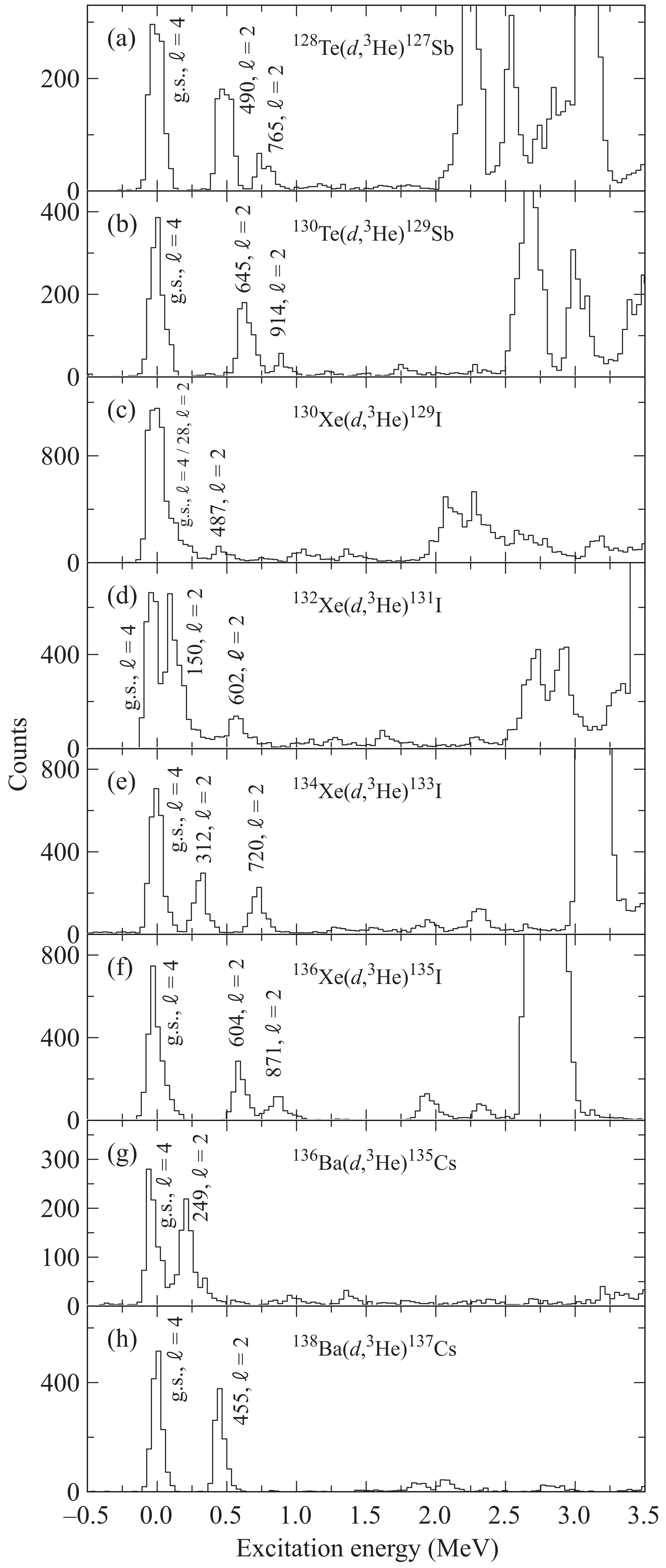


Freeman et al., Phys. Rev. C ***96****, 054325 (****2017****)*

A = 130 occupancies

Cryogenic targets, gas targets …



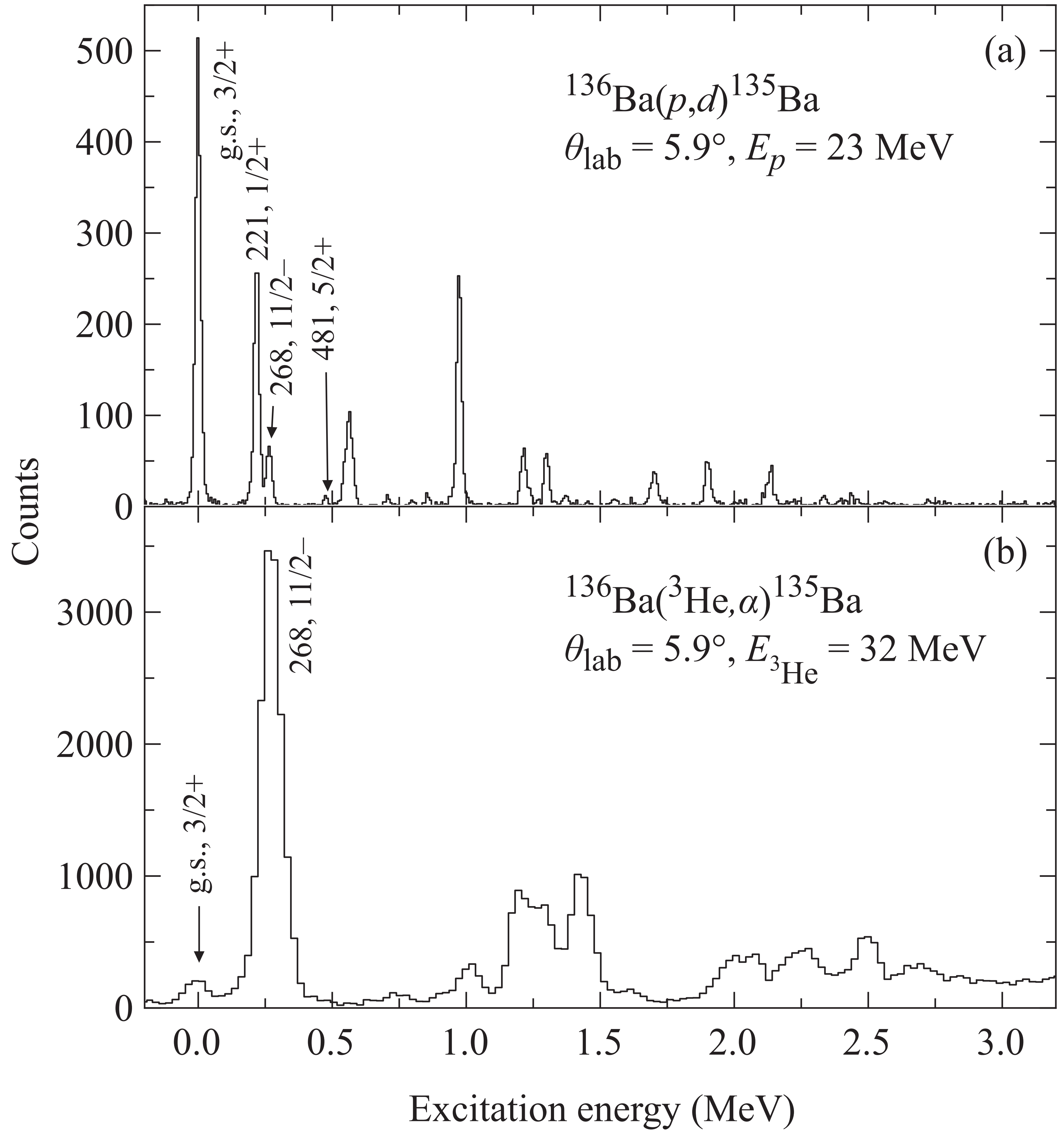


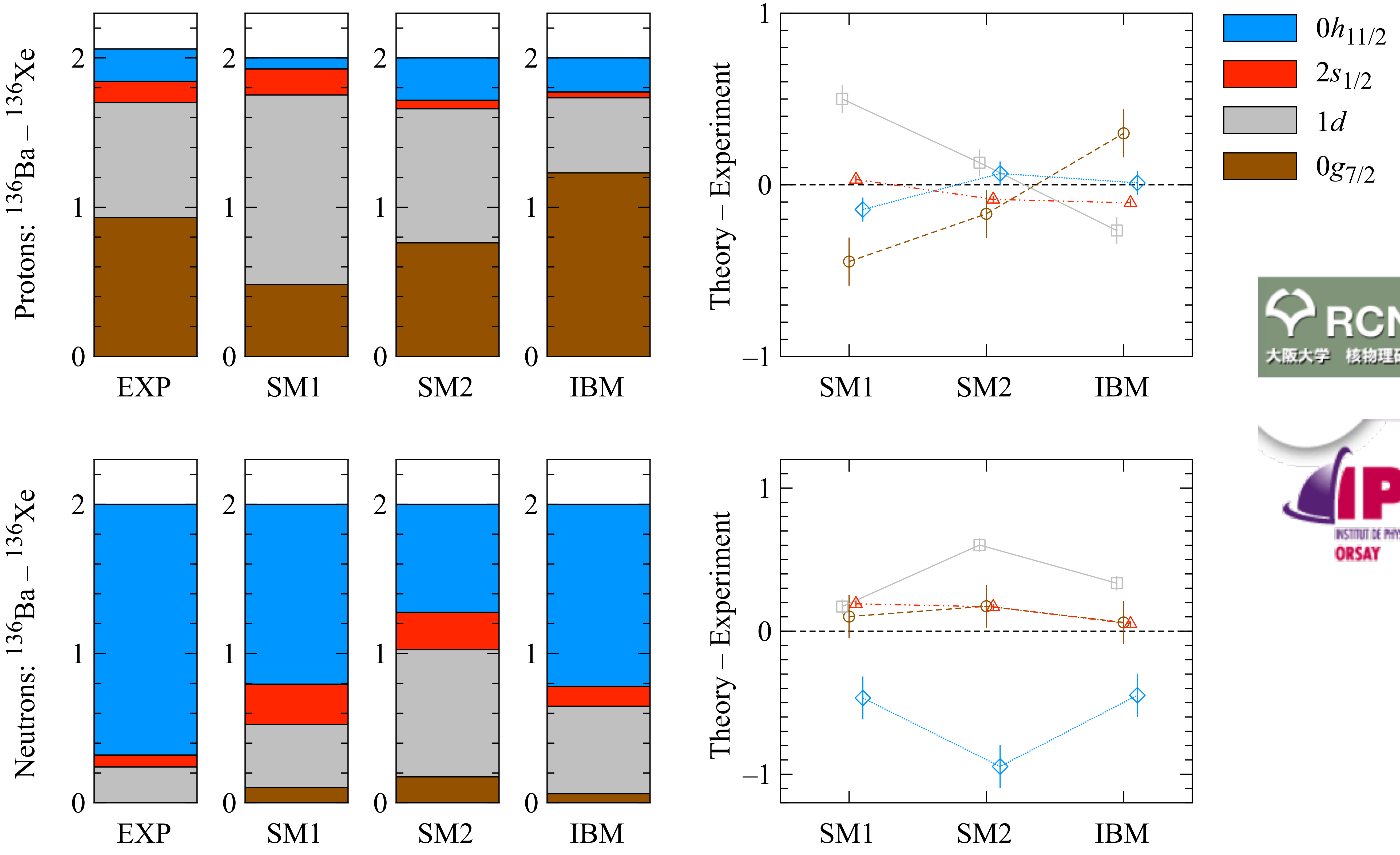
BPK et al., Phys. Rev. C ***87****, 011302(R) (****2013****)*

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

A = 130 occupancies

Take advantage of N = 82 being a good closed shell for neutrons





S. V. Szwec et al., Phys. Rev. C **94**, 054314 (**2016**)

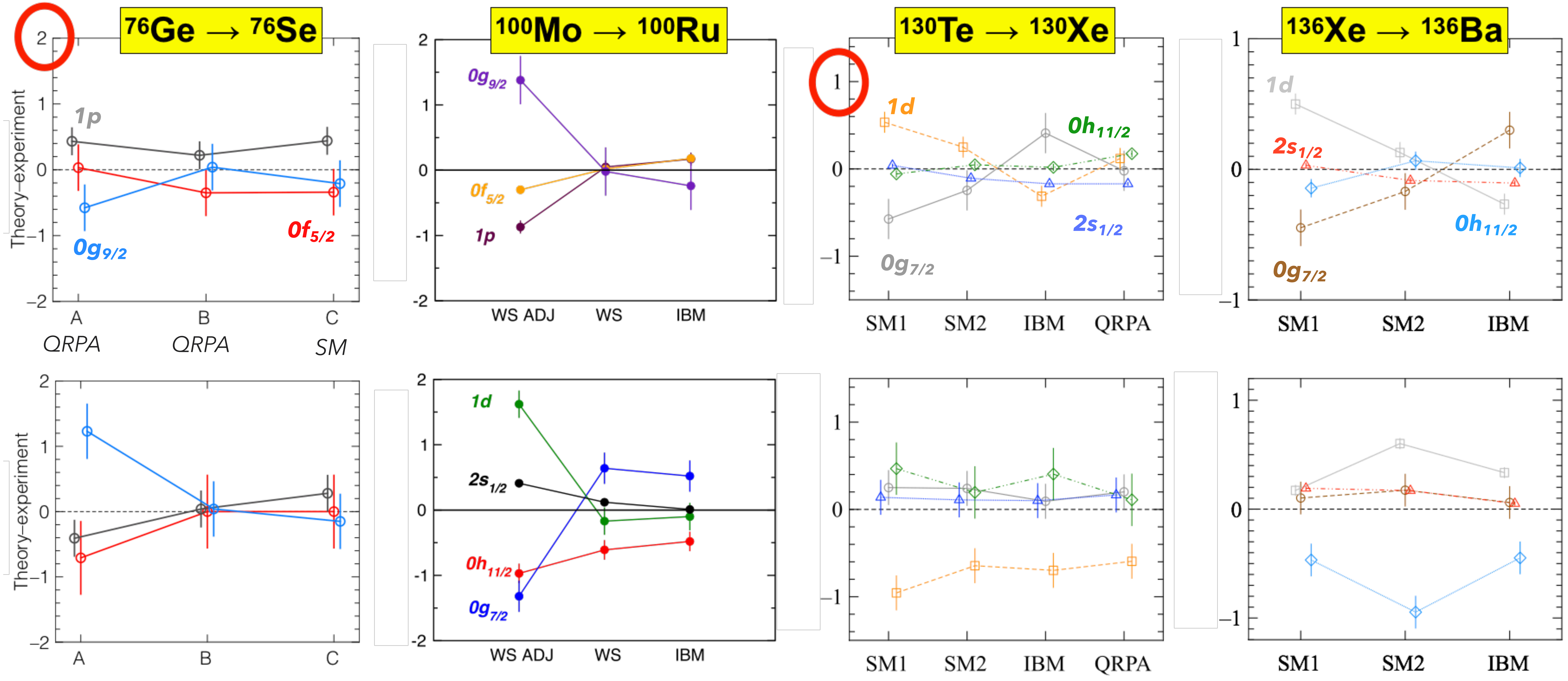
J. P. Entwisle et al., Phys. Rev. C **93**, 064312 (**2016**)

Overview of all results

A decade of work …

PROTONS

NEUTRONS



Comment on occupancies

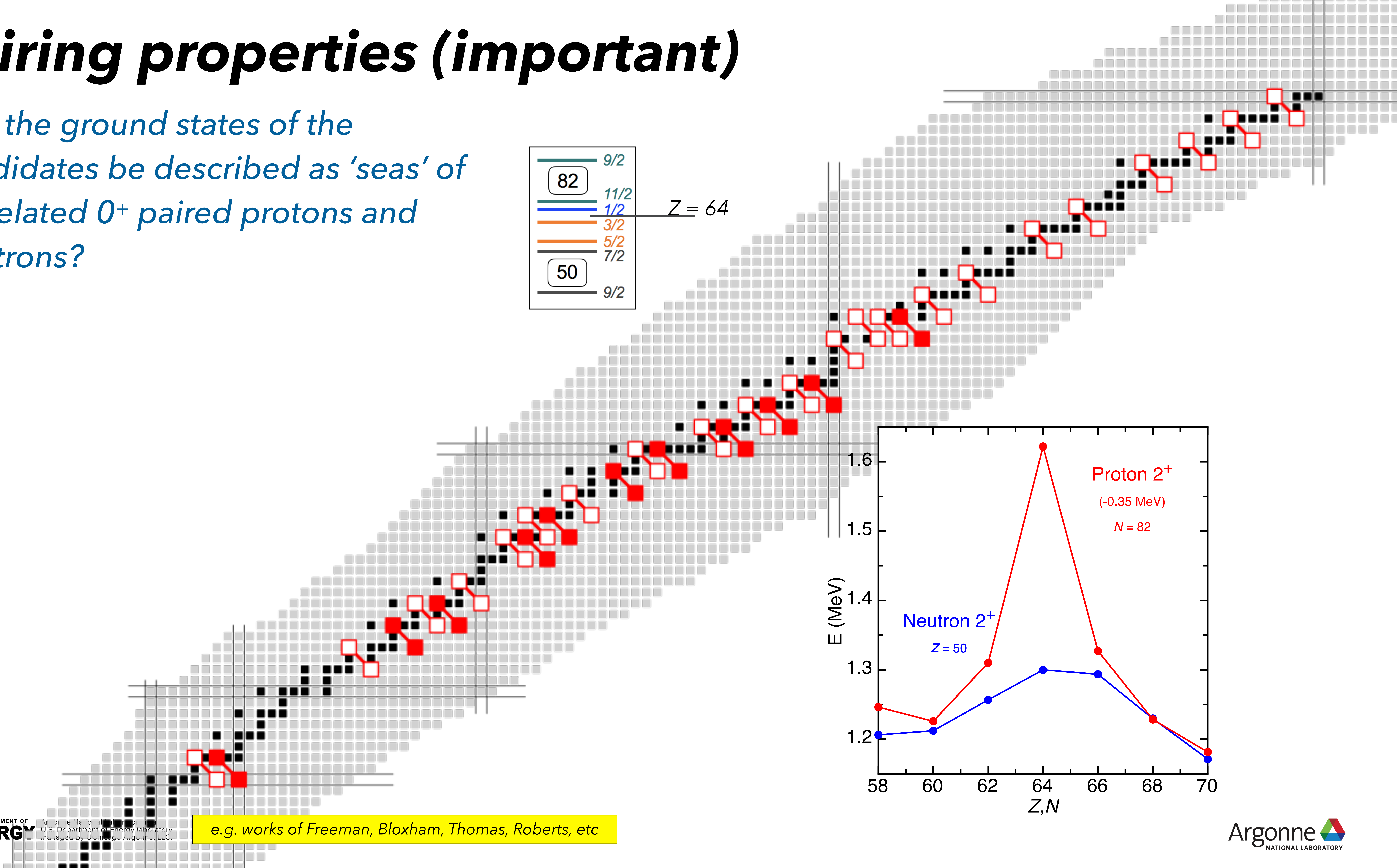
A decade of work …

- The agreement is perhaps qualitatively okay, in some instances within the uncertainties *(but not for both protons and neutrons)*, *but quite poor on the whole*

  ➢ *We can ask whether it matters? … it does, regardless of how (in)sensitive the NME is to the change in occupancies*

Pairing properties (important)

Can the ground states of the candidates be described as 'seas' of correlated 0^+ paired protons and neutrons?



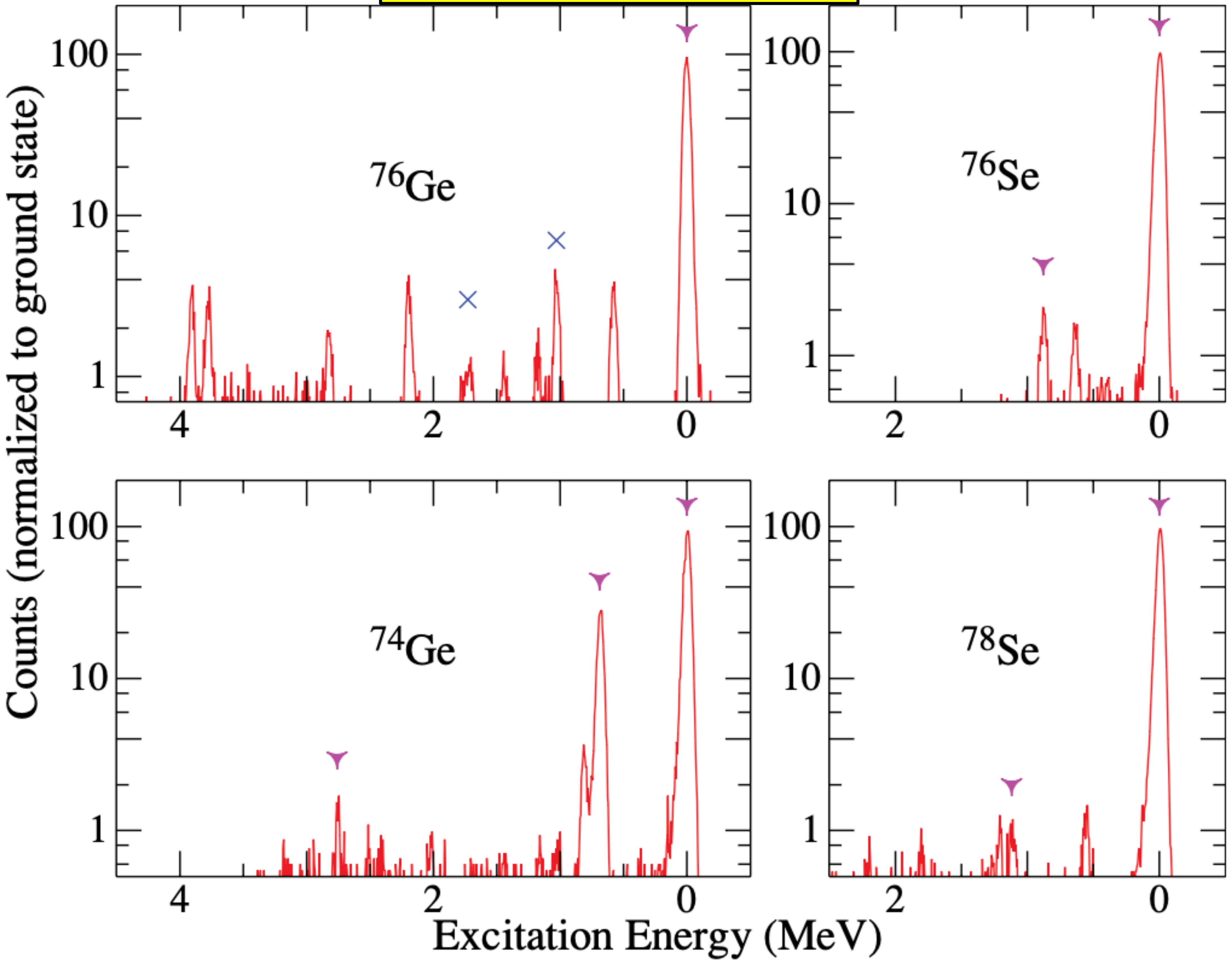
e.g. works of Freeman, Bloxham, Thomas, Roberts, etc

Pairing around A ~ 76

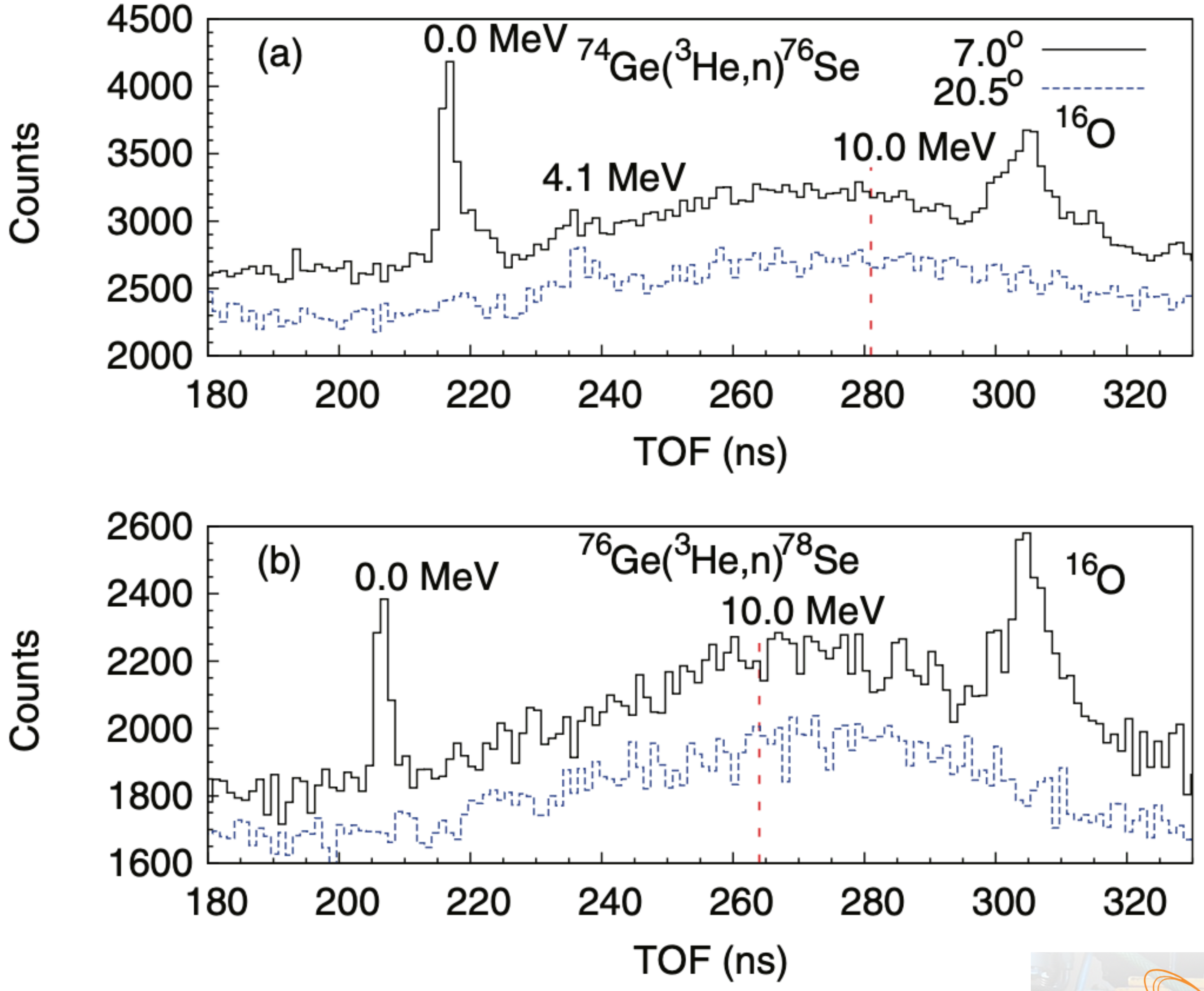
Pair-transfer reactions are a simple and effective probe of pairing correlations

No evidence of 'pairing vibrations' in the A = 76 region

Ge(*p*,*t*) and Se(*p*,*t*)



Ge(^{3}He,*n*)

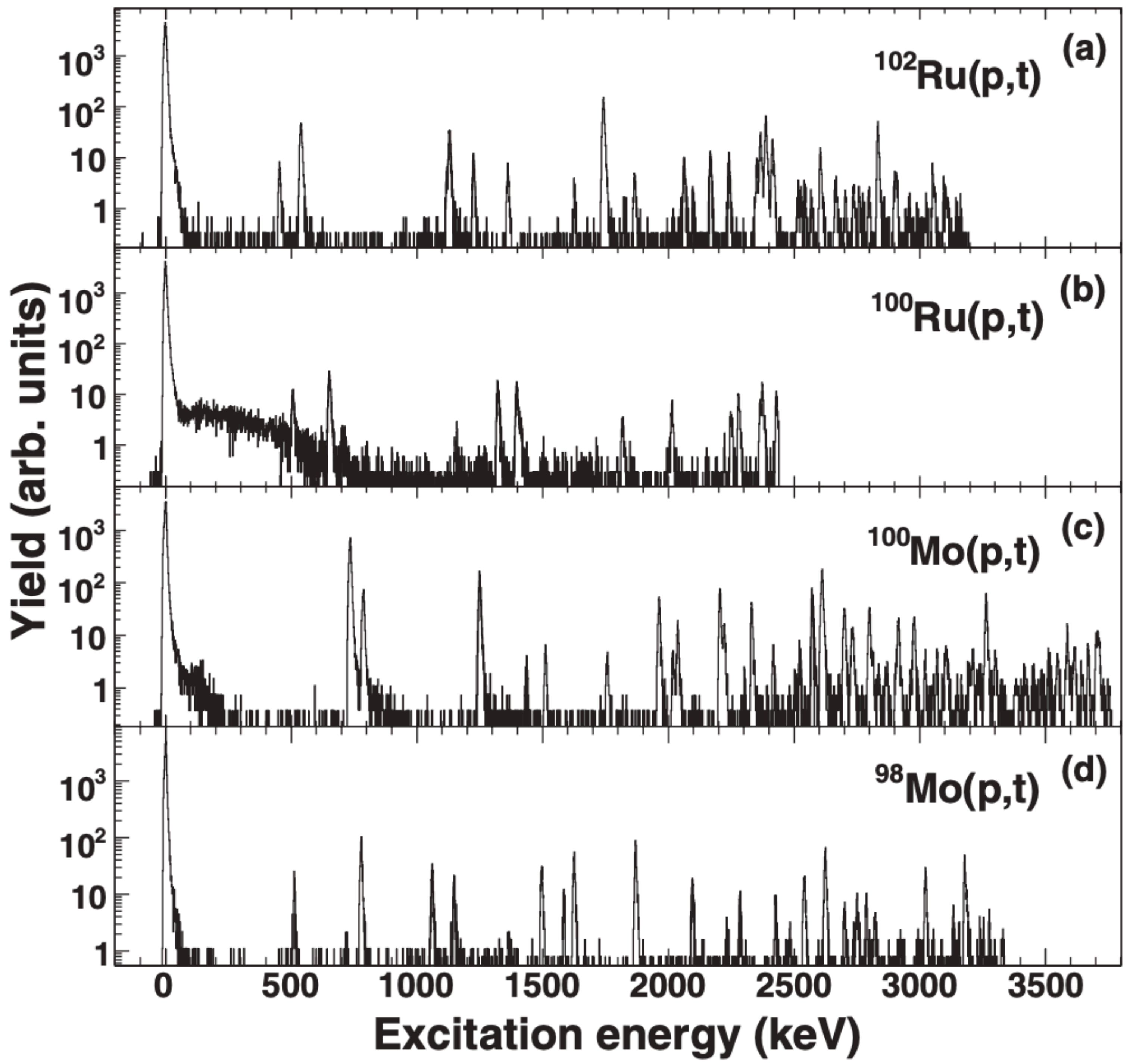


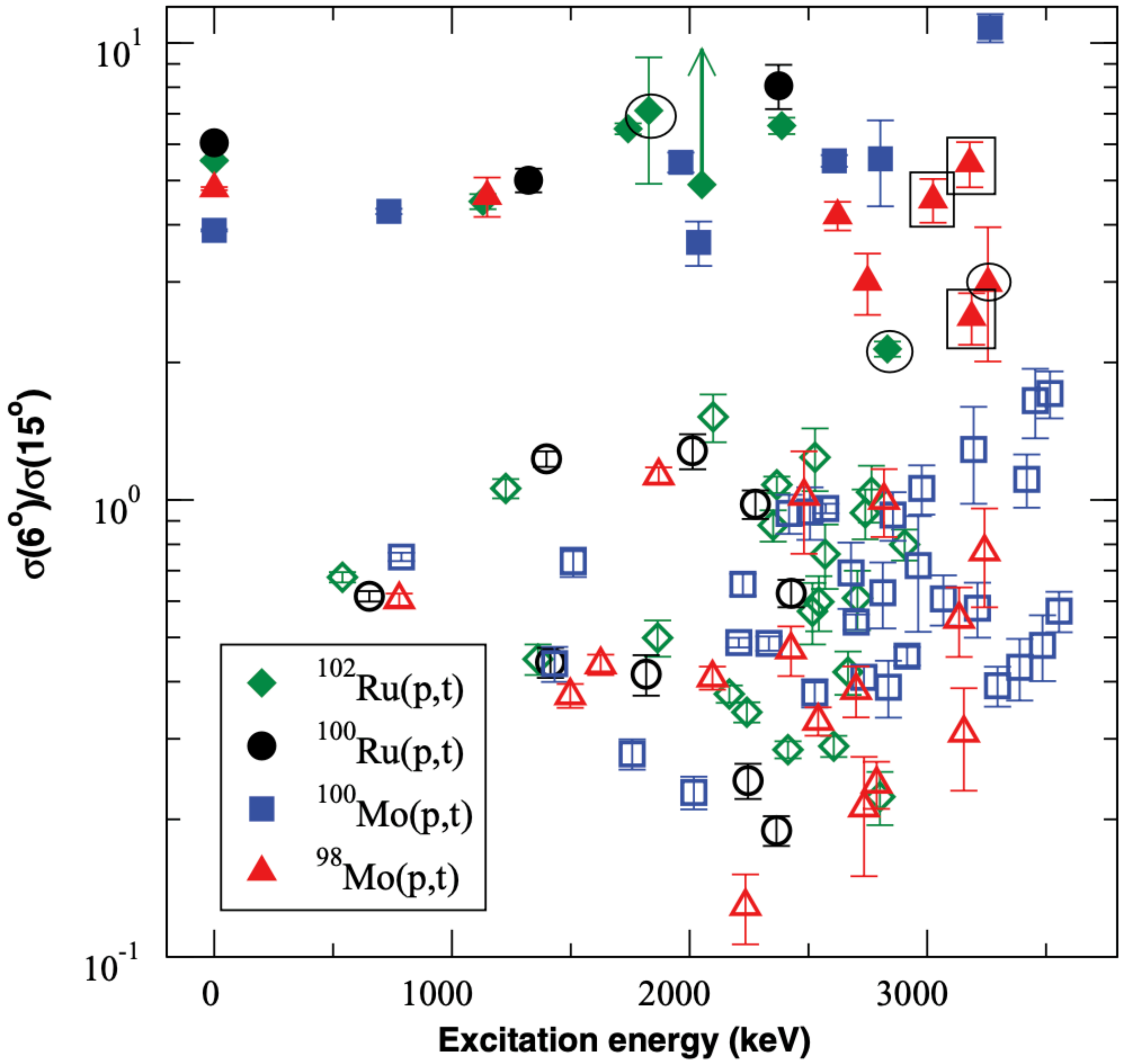
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

S. J. Freeman et al., Phys. Rev. C ***75****, 051301(R) (****2007****) [neutrons]*

A. Roberts et al., Phys. Rev. C ***87****, 051305(R) (****2013****) [protons]*

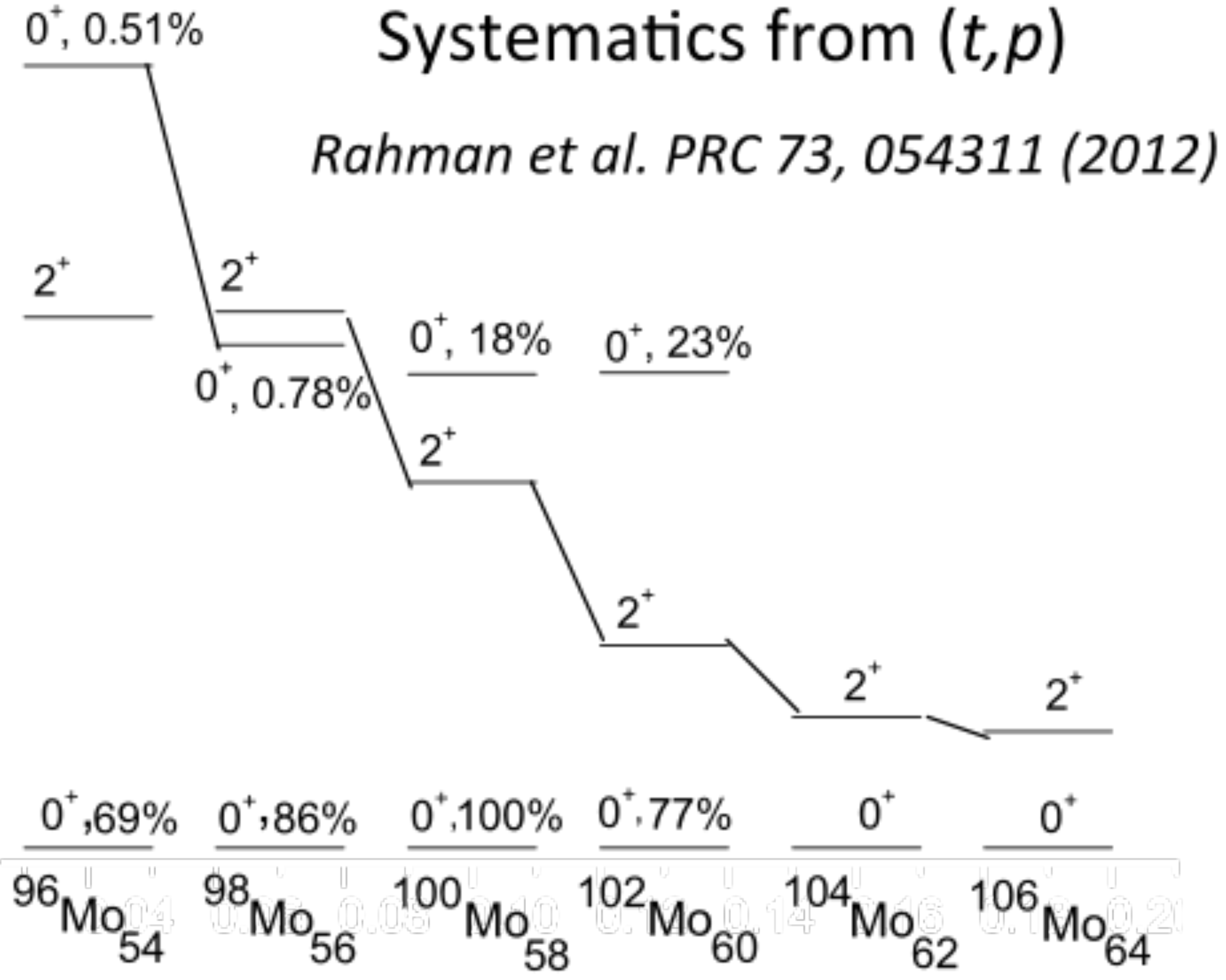
Pairing around A ~ 100





Systematics from *(t,p)*

Rahman et al. PRC 73, 054311 (2012)



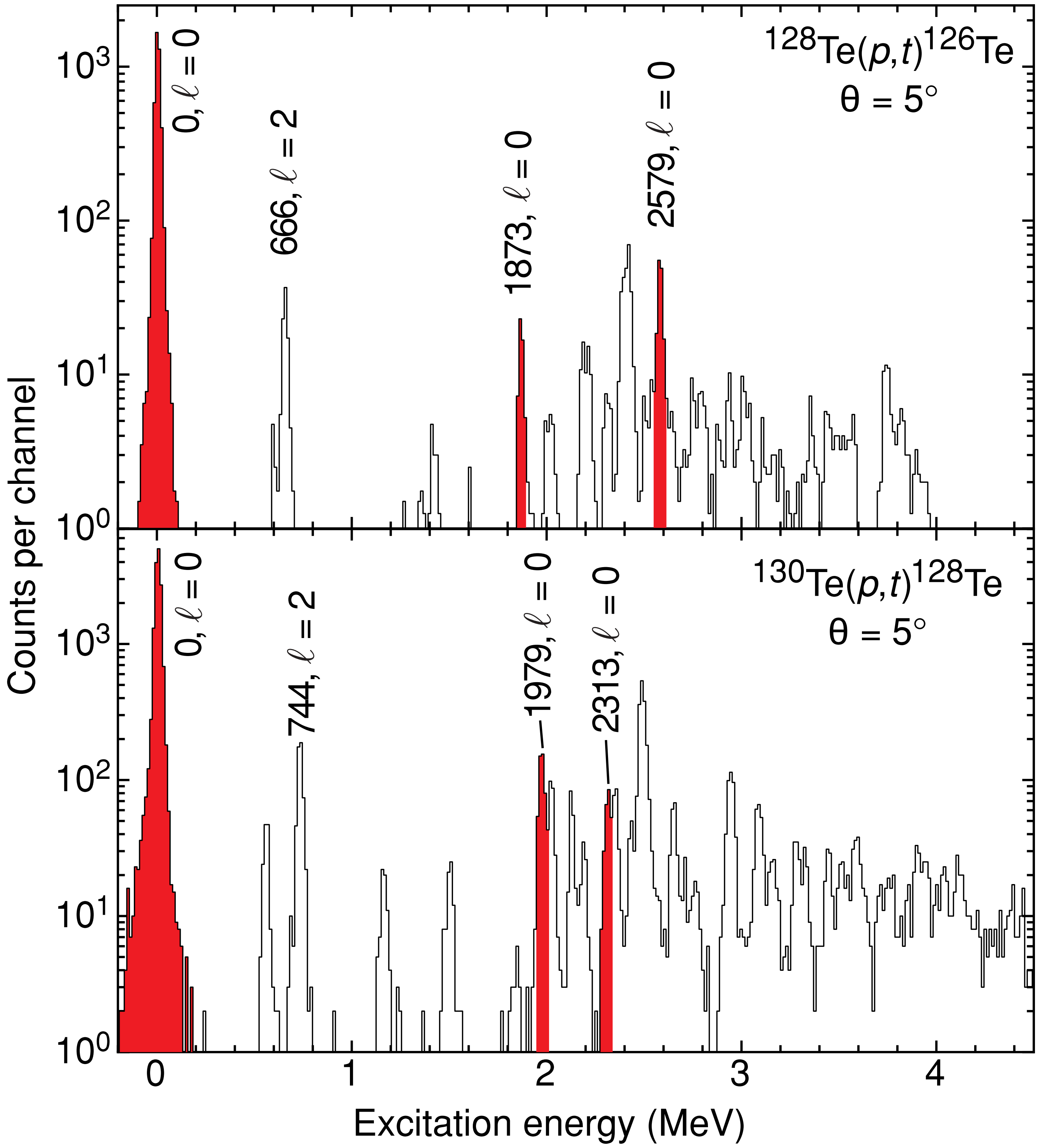
Transitions strengths normalised to ^{100}Mo gs.

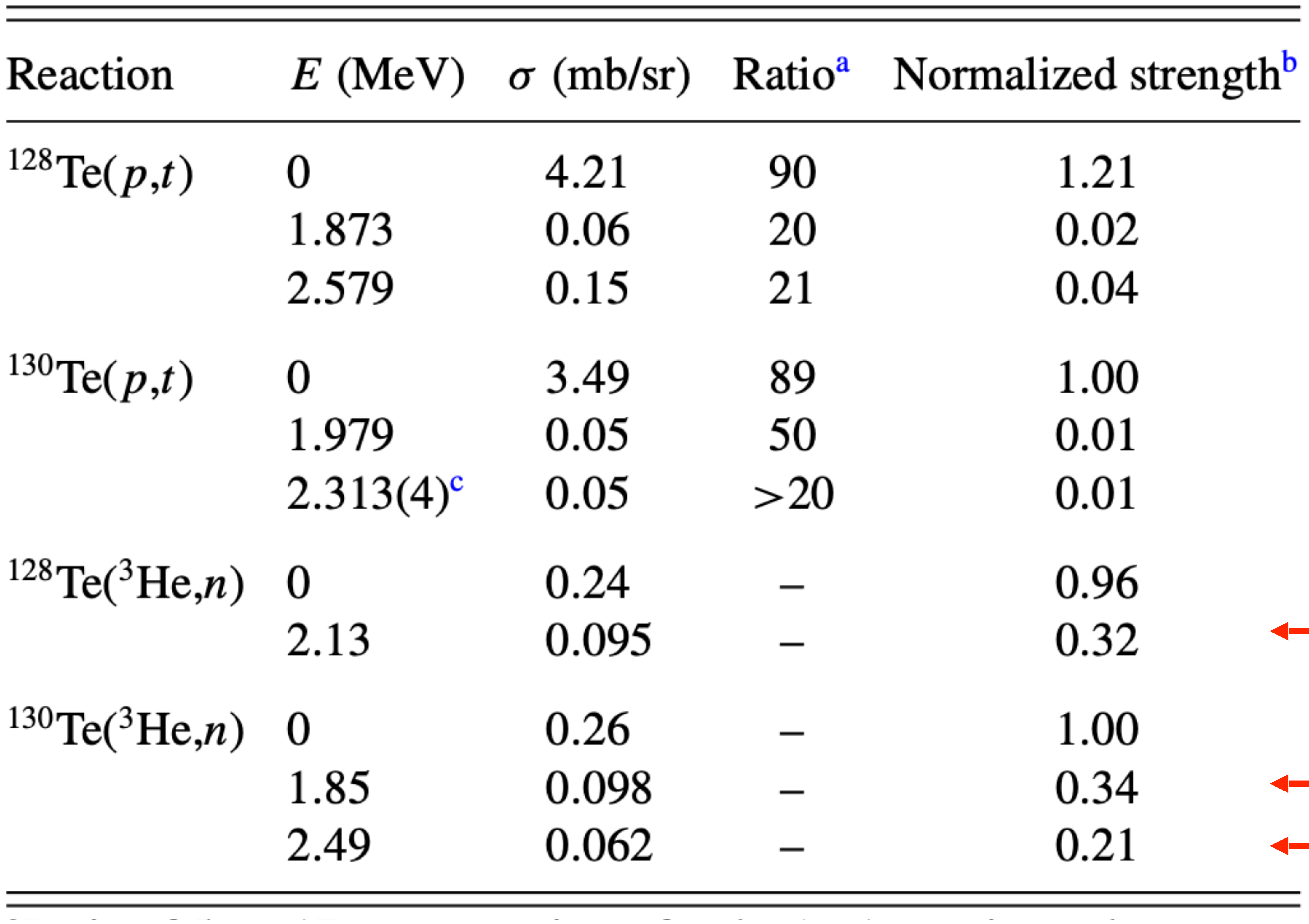
A transitional region with deformation playing a role in the nuclear structure:

- Reactions leading to and from ^{100}Ru show ~95% of the L=0(p,t) strength is in the g.s. (on the spherical side of the transitional region)
- For *^{100}Mo about 20% of the L=0(p,t)* strength is an excited 0+, a shape-transitional nucleus
- *No evidence for pairing vibrations, but structure is complicated*

*J. S. Thomas et al., Phys. Rev. C **86**, 047304 (**2012**)*

Pairing around A ~ 130,136





Reaction	E (MeV)	σ (mb/sr)	Ratio[a]	Normalized strength[b]
^{128}Te(p,t)	0	4.21	90	1.21
	1.873	0.06	20	0.02
	2.579	0.15	21	0.04
^{130}Te(p,t)	0	3.49	89	1.00
	1.979	0.05	50	0.01
	2.313(4)[c]	0.05	>20	0.01
^{128}Te(^{3}He,n)	0	0.24	–	0.96
	2.13	0.095	–	0.32
^{130}Te(^{3}He,n)	0	0.26	–	1.00
	1.85	0.098	–	0.34
	2.49	0.062	–	0.21

From the proton-pair adding Te(^{3}He,n) reactions by Alford et al., significant strength is seen in ℓ= 0 transitions to excited states …

A classic case of pair vibration and likely a consequence of a sub-shell gap at Z = 64

Consequences for QRPA? (Does the shell-model include this feature also?)

*T. Bloxham et al., Phys. Rev. C **82**, 027308 (**2010**) [neutrons]*

*W. P. Alford et al., Nucl. Phys. A **323**, 339 (**1979**) [protons]*

Summary on the 0v2β occupancies

Experimental nuclear-structure data is an essential part of the story of the NME challenge

The candidates are not 'generically similar' systems (pairing, e.g. Z = 64, closed shells, deformation, etc., all different in each case)

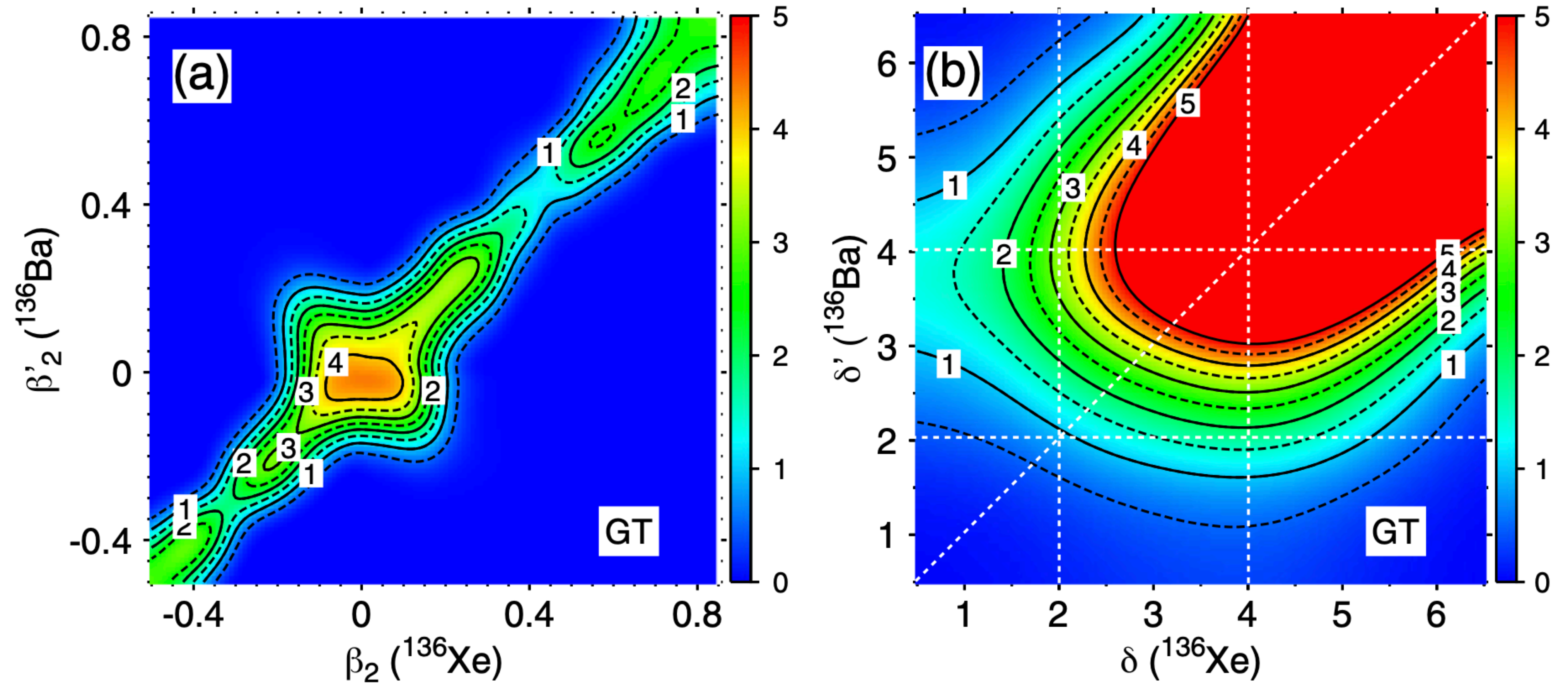
'Traditional' calculations do not reliably reproduce information extracted from experiments (what level of agreement should we expect?)

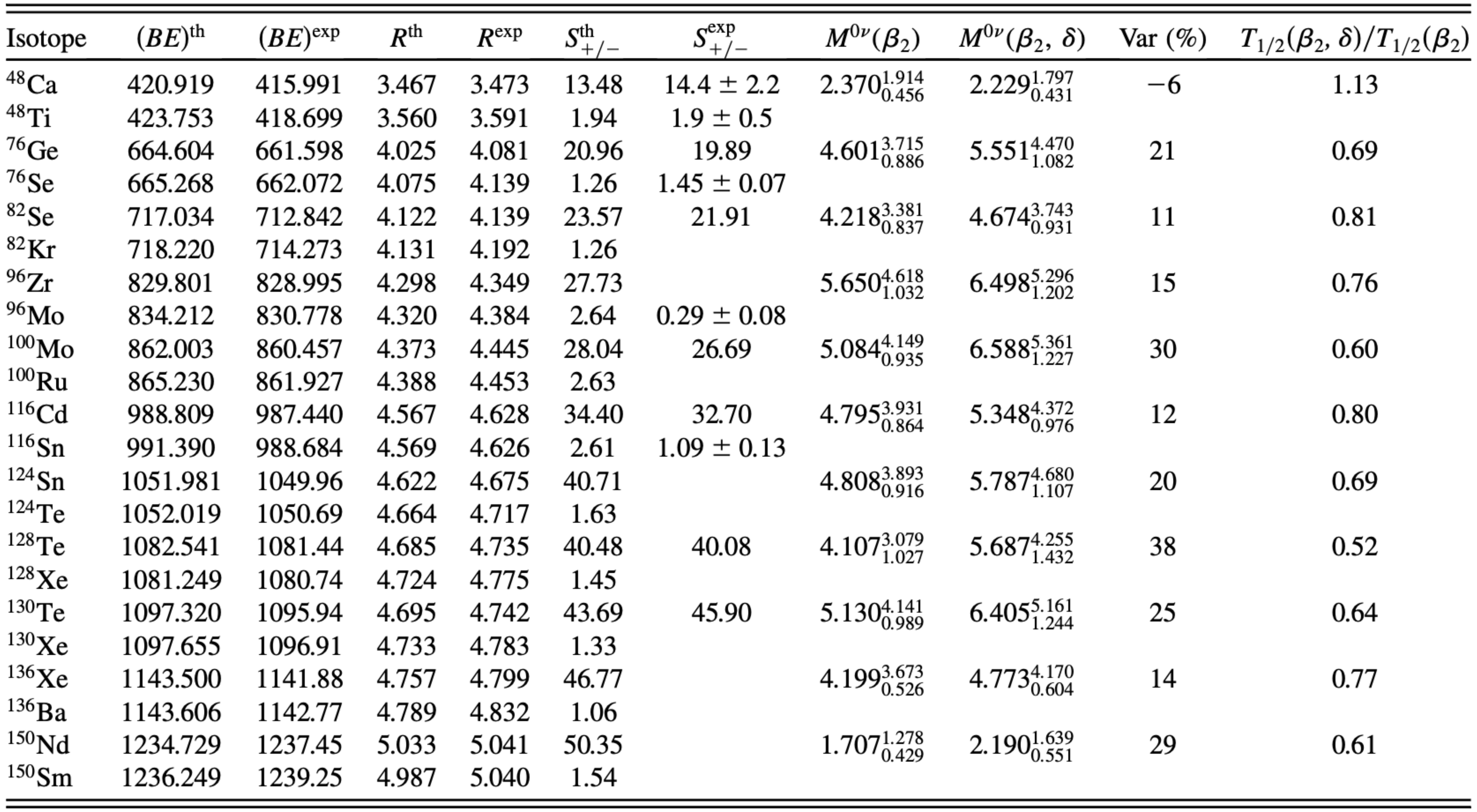
New ab initio calculations likely essential (model space, interactions, Hamiltonians, correlations, weak currents, all still being worked on)

Quenching (not of g_A, but of occupancy) likely has some consequence also

Shapes …

Here, the naive expectation is that parent-daughter systems with similar shapes are likely to be favored over those that are different.*



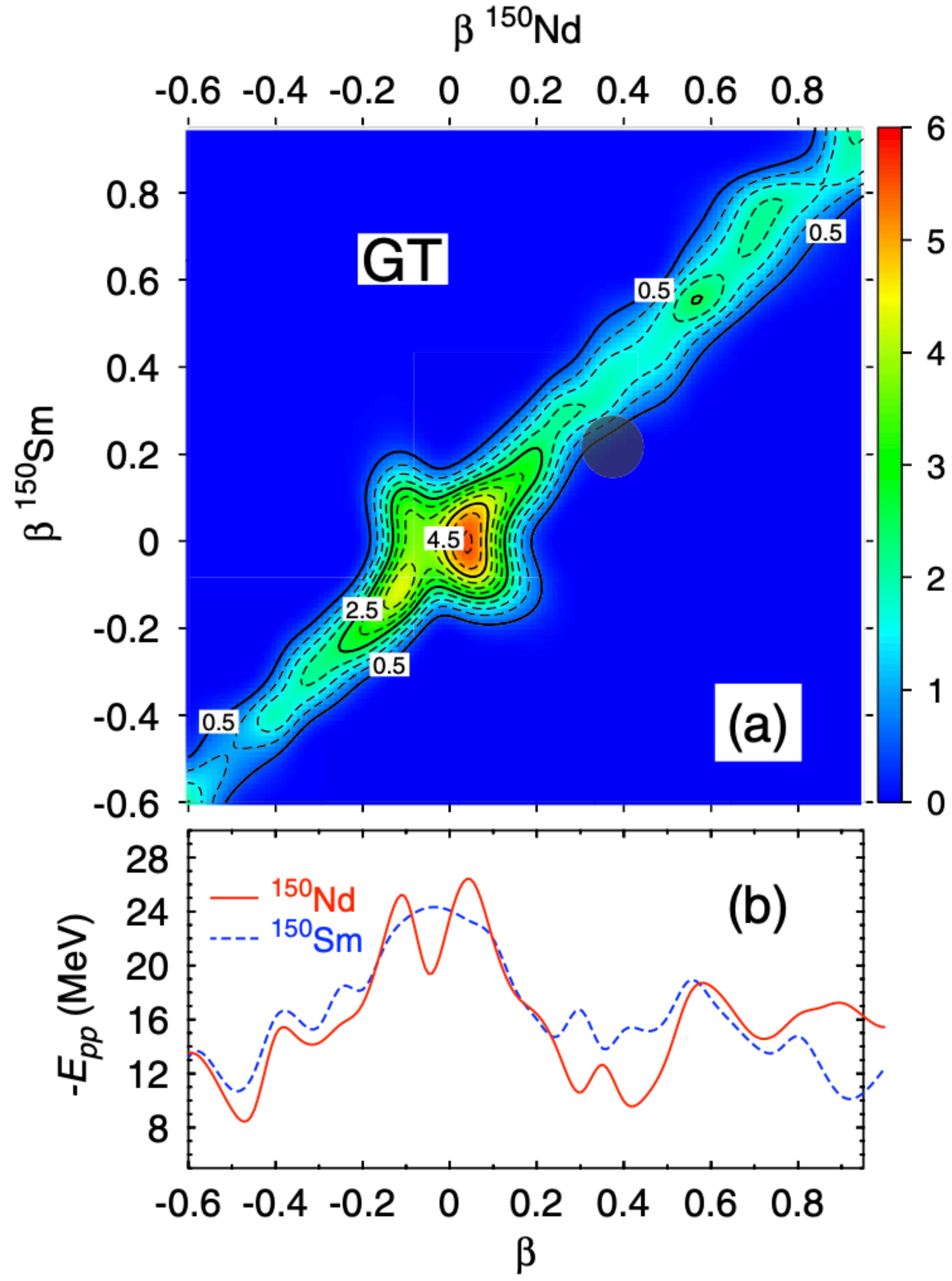


Isotope	$(BE)^{\mathrm{th}}$	$(BE)^{\mathrm{exp}}$	R^{th}	R^{exp}	$S^{\mathrm{th}}_{+/-}$	$S^{\mathrm{exp}}_{+/-}$	$M^{0\nu}(\beta_2)$	$M^{0\nu}(\beta_2, \delta)$	Var (%)	$T_{1/2}(\beta_2, \delta)/T_{1/2}(\beta_2)$
^{48}Ca	420.919	415.991	3.467	3.473	13.48	14.4 ± 2.2	$2.370^{1.914}_{0.456}$	$2.229^{1.797}_{0.431}$	−6	1.13
^{48}Ti	423.753	418.699	3.560	3.591	1.94	1.9 ± 0.5				
^{76}Ge	664.604	661.598	4.025	4.081	20.96	19.89	$4.601^{3.715}_{0.886}$	$5.551^{4.470}_{1.082}$	21	0.69
^{76}Se	665.268	662.072	4.075	4.139	1.26	1.45 ± 0.07				
^{82}Se	717.034	712.842	4.122	4.139	23.57	21.91	$4.218^{3.381}_{0.837}$	$4.674^{3.743}_{0.931}$	11	0.81
^{82}Kr	718.220	714.273	4.131	4.192	1.26					
^{96}Zr	829.801	828.995	4.298	4.349	27.73		$5.650^{4.618}_{1.032}$	$6.498^{5.296}_{1.202}$	15	0.76
^{96}Mo	834.212	830.778	4.320	4.384	2.64	0.29 ± 0.08				
^{100}Mo	862.003	860.457	4.373	4.445	28.04	26.69	$5.084^{4.149}_{0.935}$	$6.588^{5.361}_{1.227}$	30	0.60
^{100}Ru	865.230	861.927	4.388	4.453	2.63					
^{116}Cd	988.809	987.440	4.567	4.628	34.40	32.70	$4.795^{3.931}_{0.864}$	$5.348^{4.372}_{0.976}$	12	0.80
^{116}Sn	991.390	988.684	4.569	4.626	2.61	1.09 ± 0.13				
^{124}Sn	1051.981	1049.96	4.622	4.675	40.71		$4.808^{3.893}_{0.916}$	$5.787^{4.680}_{1.107}$	20	0.69
^{124}Te	1052.019	1050.69	4.664	4.717	1.63					
^{128}Te	1082.541	1081.44	4.685	4.735	40.48	40.08	$4.107^{3.079}_{1.027}$	$5.687^{4.255}_{1.432}$	38	0.52
^{128}Xe	1081.249	1080.74	4.724	4.775	1.45					
^{130}Te	1097.320	1095.94	4.695	4.742	43.69	45.90	$5.130^{4.141}_{0.989}$	$6.405^{5.161}_{1.244}$	25	0.64
^{130}Xe	1097.655	1096.91	4.733	4.783	1.33					
^{136}Xe	1143.500	1141.88	4.757	4.799	46.77		$4.199^{3.673}_{0.526}$	$4.773^{4.170}_{0.604}$	14	0.77
^{136}Ba	1143.606	1142.77	4.789	4.832	1.06					
^{150}Nd	1234.729	1237.45	5.033	5.041	50.35		$1.707^{1.278}_{0.429}$	$2.190^{1.639}_{0.551}$	29	0.61
^{150}Sm	1236.249	1239.25	4.987	5.040	1.54					

Demostrated in EDF calculations for quadrupole deformation: N. L. Vaquero et al., Phys Rev. Lett. ***111****, 142501 (****2013****)*

Shapes ...

Here, the naive expectation is that parent-daughter systems with similar shapes are likely to be favored over those that are different.*

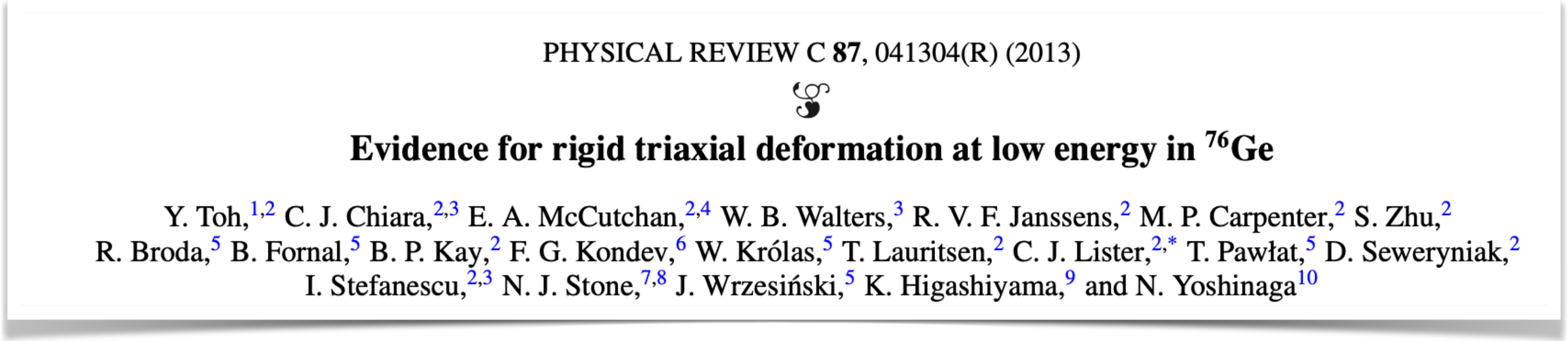


In summary, we have presented the first calculations of $0\nu\beta\beta$ decay within the energy density functional framework including beyond-mean-field effects. We have analyzed the role of the intrinsic quadrupole deformation and pairing content of the nuclei involved in this process. Decays between spherical initial and final shapes are found to be favored while large differences in deformation significantly hinder the transition probability. Our calculations constitute the first consistent evaluation of the $0\nu\beta\beta$ decay of ^{150}Nd.

Demostrated in EDF calculations for quadrupole deformation: N. L. Vaquero et al., Phys Rev. Lett. ***111****, 142501 (****2013****)*

Shapes … ^{76}Ge and triaxiality

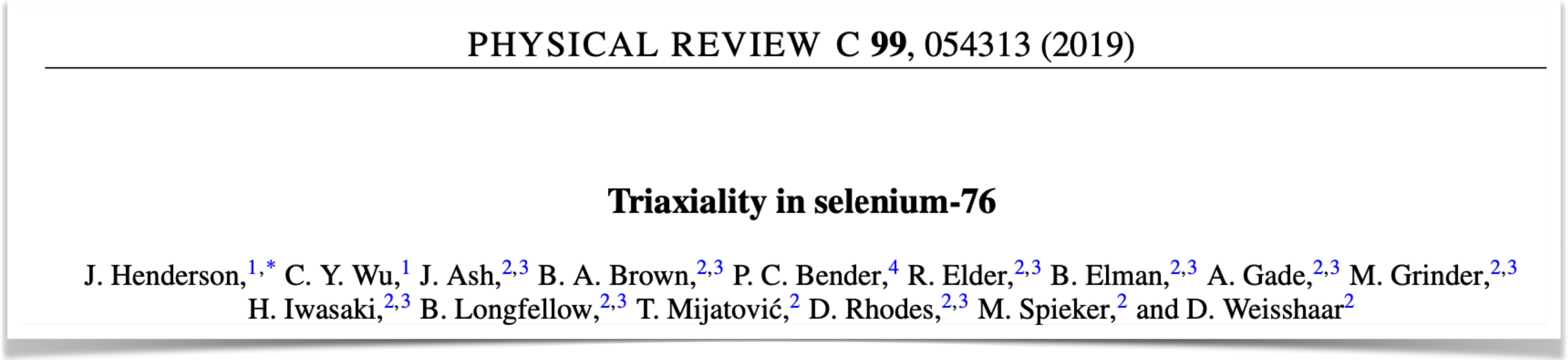
Here, the naive expectation is that parent-daughter systems with similar shapes are likely to be favored over those that are different.*



PHYSICAL REVIEW C **87**, 041304(R) (2013)

Evidence for rigid triaxial deformation at low energy in ^{76}Ge

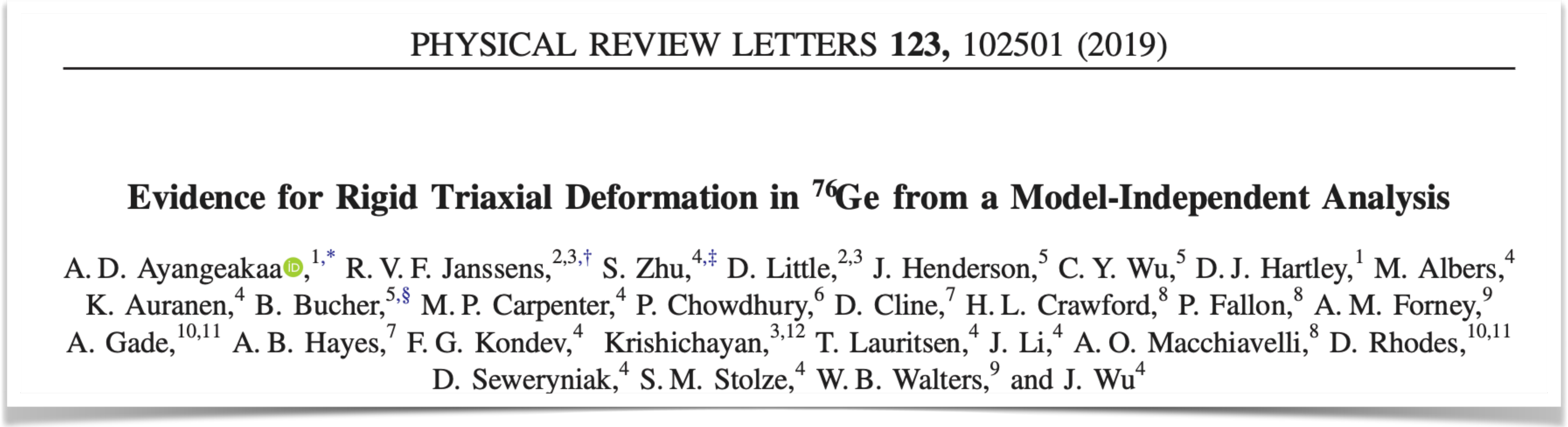
Y. Toh,[1,2] C. J. Chiara,[2,3] E. A. McCutchan,[2,4] W. B. Walters,[3] R. V. F. Janssens,[2] M. P. Carpenter,[2] S. Zhu,[2] R. Broda,[5] B. Fornal,[5] B. P. Kay,[2] F. G. Kondev,[6] W. Królas,[5] T. Lauritsen,[2] C. J. Lister,[2,*] T. Pawłat,[5] D. Seweryniak,[2] I. Stefanescu,[2,3] N. J. Stone,[7,8] J. Wrzesiński,[5] K. Higashiyama,[9] and N. Yoshinaga[10]



PHYSICAL REVIEW C **99**, 054313 (2019)

Triaxiality in selenium-76

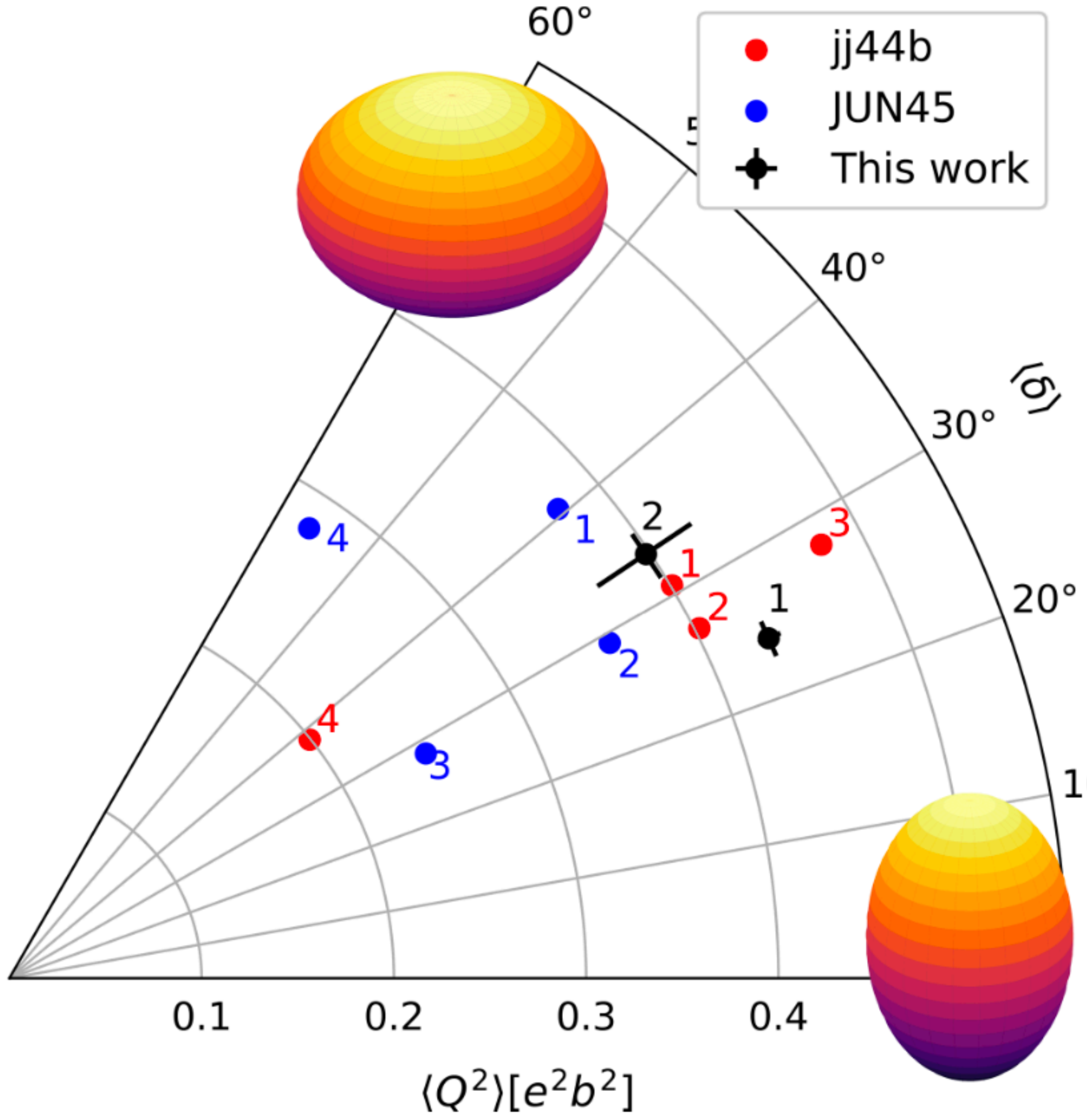
J. Henderson,[1,*] C. Y. Wu,[1] J. Ash,[2,3] B. A. Brown,[2,3] P. C. Bender,[4] R. Elder,[2,3] B. Elman,[2,3] A. Gade,[2,3] M. Grinder,[2,3] H. Iwasaki,[2,3] B. Longfellow,[2,3] T. Mijatović,[2] D. Rhodes,[2,3] M. Spieker,[2] and D. Weisshaar[2]



PHYSICAL REVIEW LETTERS **123**, 102501 (2019)

Evidence for Rigid Triaxial Deformation in ^{76}Ge from a Model-Independent Analysis

A. D. Ayangeakaa,[1,*] R. V. F. Janssens,[2,3,†] S. Zhu,[4,‡] D. Little,[2,3] J. Henderson,[5] C. Y. Wu,[5] D. J. Hartley,[1] M. Albers,[4] K. Auranen,[4] B. Bucher,[5,§] M. P. Carpenter,[4] P. Chowdhury,[6] D. Cline,[7] H. L. Crawford,[8] P. Fallon,[8] A. M. Forney,[9] A. Gade,[10,11] A. B. Hayes,[7] F. G. Kondev,[4] Krishichayan,[3,12] T. Lauritsen,[4] J. Li,[4] A. O. Macchiavelli,[8] D. Rhodes,[10,11] D. Seweryniak,[4] S. M. Stolze,[4] W. B. Walters,[9] and J. Wu[4]



Conclusions

Experimental nuclear-structure data is an essential part of the story of the NME challenge

The occupancy story is likely not resolved

Pairing properties could be explored further

A great deal of detailed spectroscopy has been carried out (not shown in this talk) via e.g. (n,nγ) measurement

Shapes and shape differences (of 0vββ-decay candidates) can be explored further … there are many probes of nuclear shape, Coulomb excitation, inelastic scattering, spectroscopy, …, each with their own limitations, …