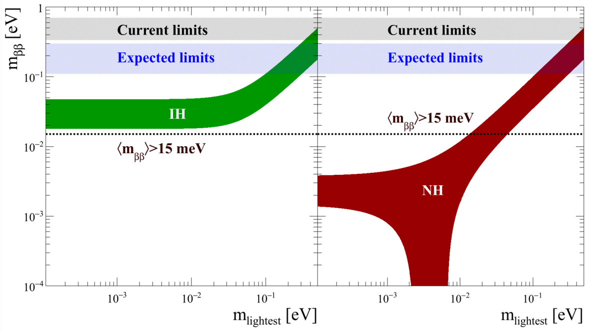
Experimentally determined nuclear-structure properties of $0\nu2\beta$ decay candidates

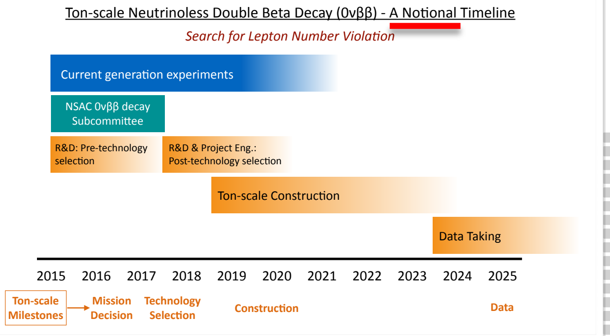
Ben Kay, Physics Division, Argonne National Laboratory

Nuclear ab initio theories and neutrino physics
INT-18-1a Week 5, 29 March 2018

Overview

- *Basic premises (ground-state nucleon occupancies, pairing)*
- *Experiments (now a 10-year project, 4 candidates 'done')*
- *Analysis techniques*
- *Normalizations*
- *Quenching*
- *An overview of results, compared with theory*
- *Comments on pairing*





Ton-scale Neutrinoless Double Beta Decay (0νββ) - A Notional Timeline

Search for Lepton Number Violation

Current generation experiments

NSAC 0νββ decay Subcommittee

R&D: Pre-technology selection

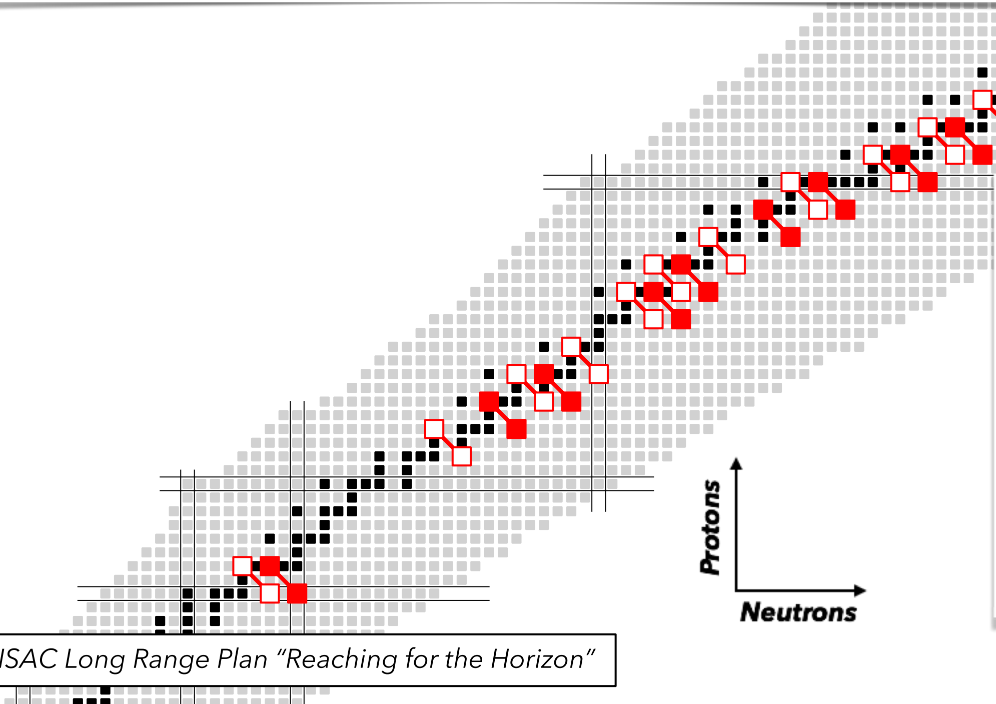
R&D & Project Eng.: Post-technology selection

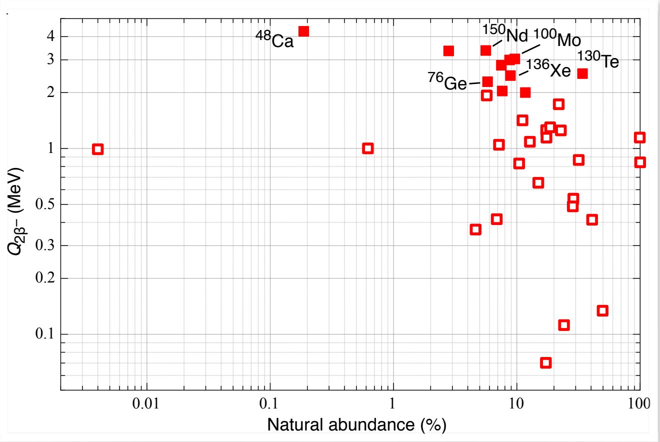
Ton-scale Construction

Data Taking

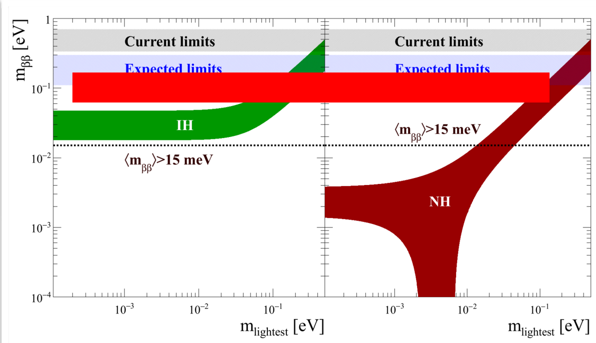
2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

Ton-scale Milestones → Mission Decision · Technology Selection · Construction · Data



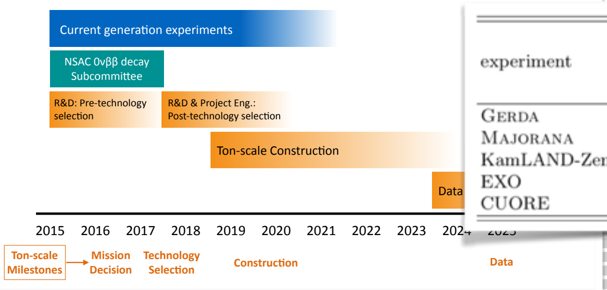


2015 NSAC Long Range Plan “Reaching for the Horizon”



Ton-scale Neutrinoless Double Beta Decay (0νββ) - A Notional Timeline

Search for Lepton Number Violation


Current generation experiments

NSAC 0νββ decay Subcommittee

R&D: Pre-technology selection

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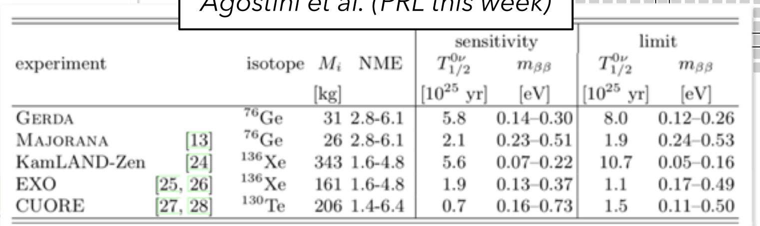
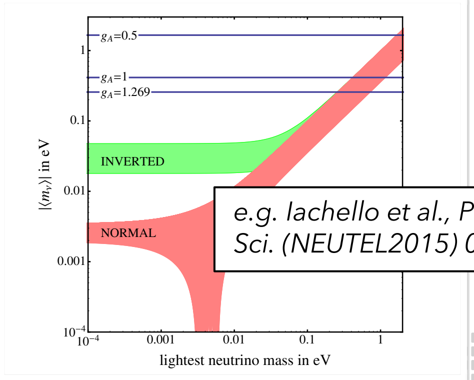
Ton-scale Construction

Data

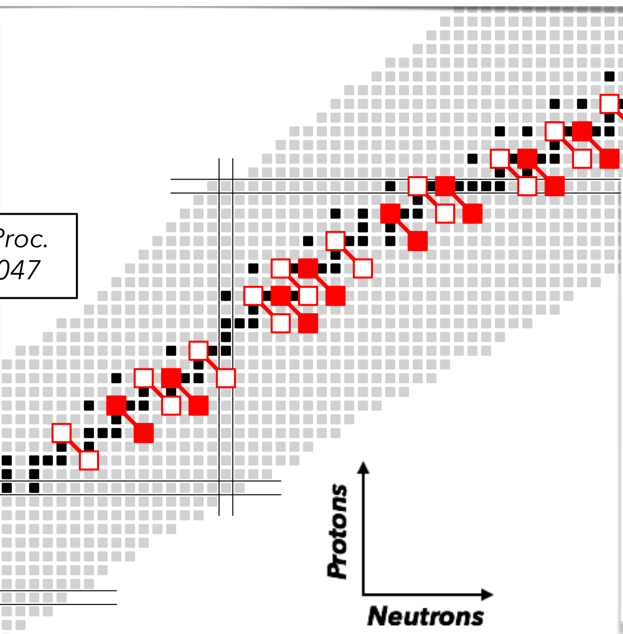
Agostini et al. (PRL this week)

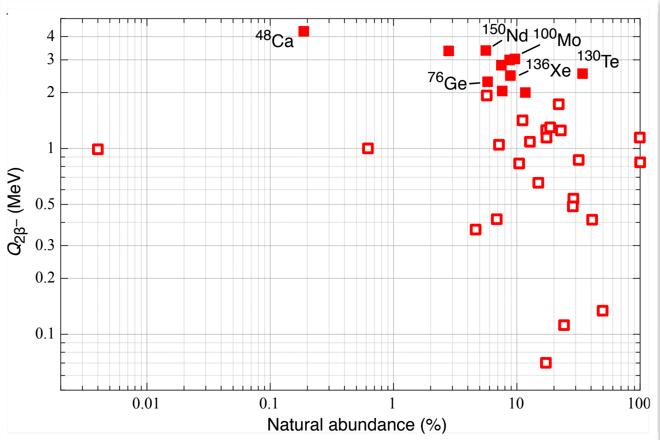


experiment		isotope	M_i [kg]	NME	sensitivity $T^{0\nu}_{1/2}$ [10^{25} yr]	sensitivity $m_{\beta\beta}$ [eV]	limit $T^{0\nu}_{1/2}$ [10^{25} yr]	limit $m_{\beta\beta}$ [eV]
GERDA		^{76}Ge	31	2.8–6.1	5.8	0.14–0.30	8.0	0.12–0.26
MAJORANA	[13]	^{76}Ge	26	2.8–6.1	2.1	0.23–0.51	1.9	0.24–0.53
KamLAND-Zen	[24]	^{136}Xe	343	1.6–4.8	5.6	0.07–0.22	10.7	0.05–0.16
EXO	[25, 26]	^{136}Xe	161	1.6–4.8	1.9	0.13–0.37	1.1	0.17–0.49
CUORE	[27, 28]	^{130}Te	206	1.4–6.4	0.7	0.16–0.73	1.5	0.11–0.50



e.g. Iachello et al., Proc. Sci. (NEUTEL2015) 047

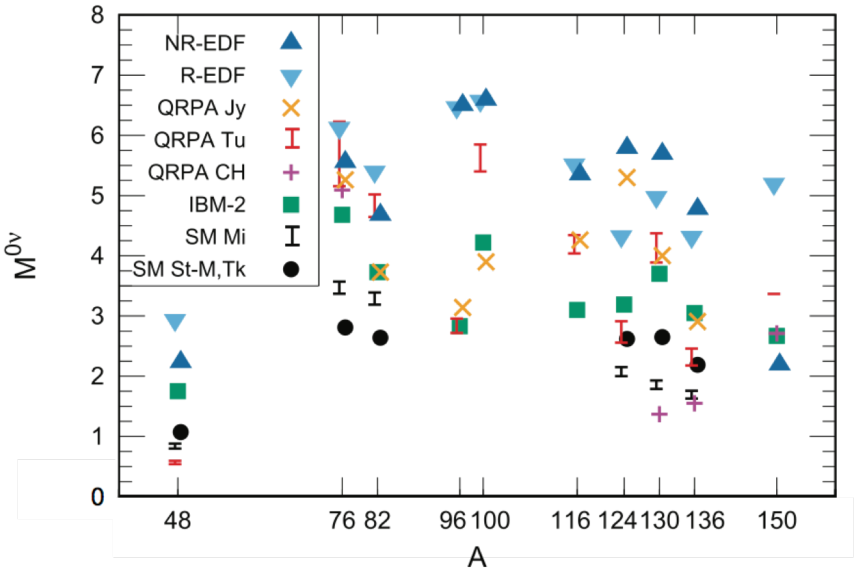


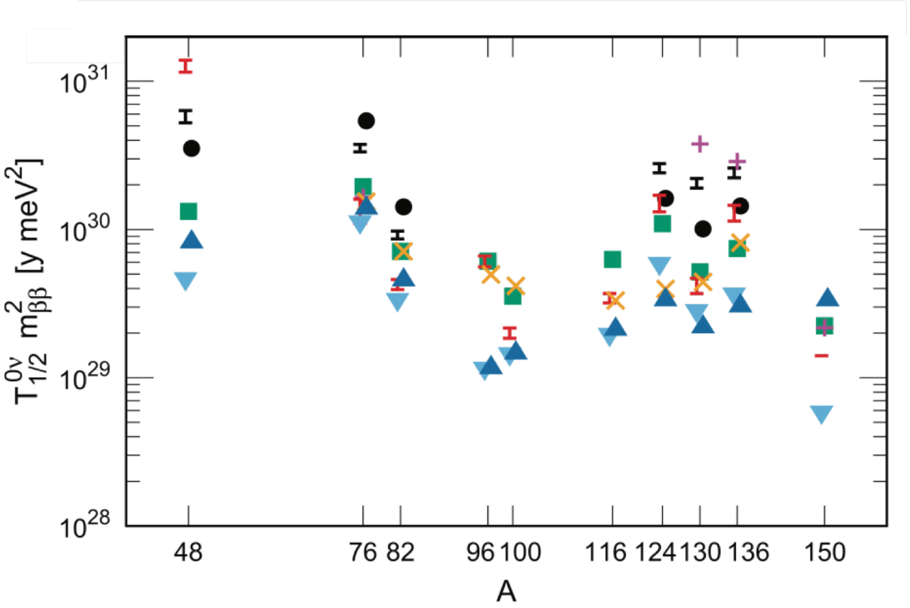


2015 NSAC Long Range Plan "Reaching for the Horizon"

Connecting half-life and mass

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



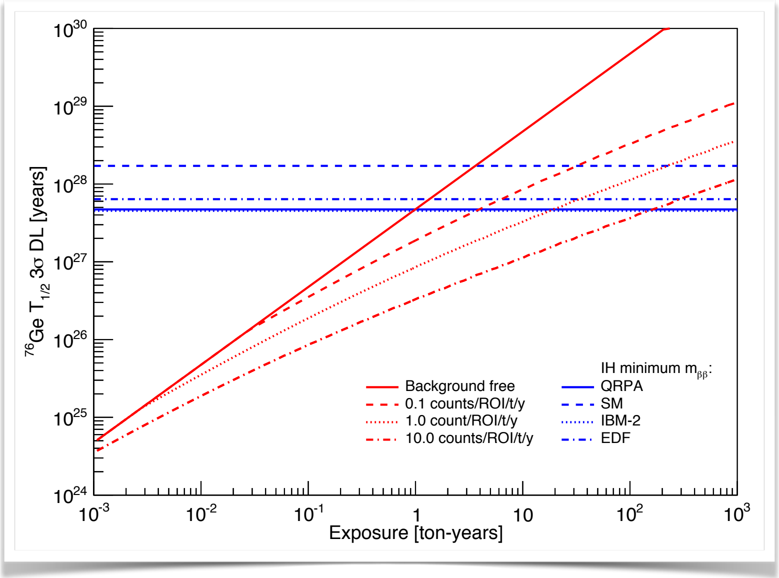


Engel and Menéndez, Rep. Prog. Phys. ***80***, *046301 (2017)*

Nuclear matrix elements

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

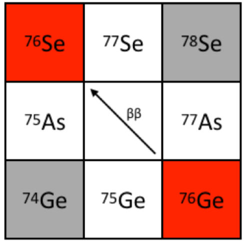
$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \propto 1/|\text{NME}|^2$$



Experimental searches are often discussed in terms of their sensitivity to a given half life, accounting for enrichment, efficiency, backgrounds, resolution, and mass, though NP has a significant role …

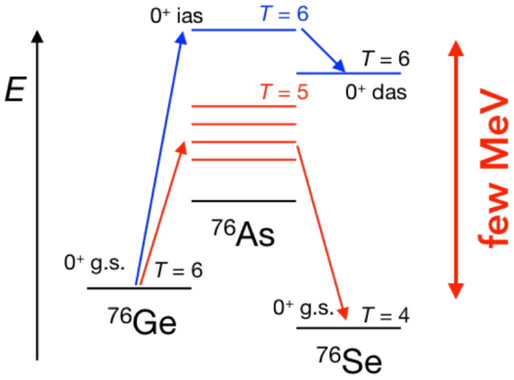
Figure taken from one of Jason Detwiler's talks found online

Mechanism, rationale



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

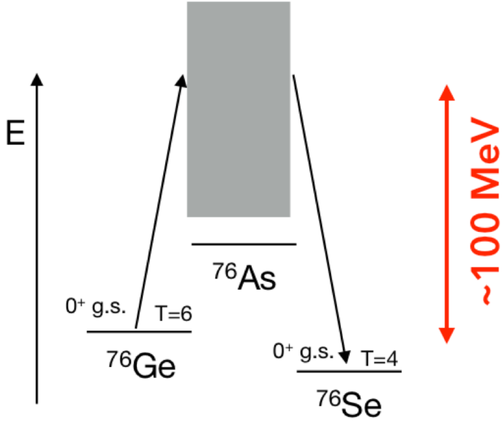
2ν2β
Dominated by Gamow-Teller transitions via 1^+ states in the intermediate nucleus, confined to low excitation energy



Can probe/do probe:

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

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



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)

Bernadette Rebeiro talked about this earlier in the week

- 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}Ge→^{76}Se, ^{100}Mo→^{100}Ru, ^{130}Te→^{130}Xe, and ^{136}Xe→^{136}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*

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D. K. Sharp et al., upcoming works on A = 116, 124, and 150 neutron occupancies

Collaborators

Initiative led by Argonne and Manchester groups

Experiments at MLL (Munich), WNSL (Yale), RCNP (Osaka), and IPN (Orsay)

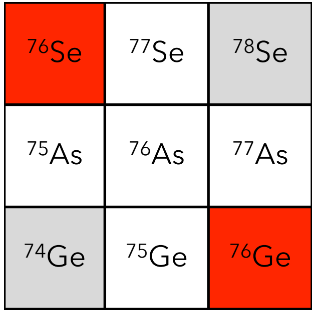
[Tandem facilities (except of RCNP), with beams around 10 MeV/u, high-resolution magnetic spectrographs. They are among the few facilities left in the world where these measurements are possible.]

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, 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, ++

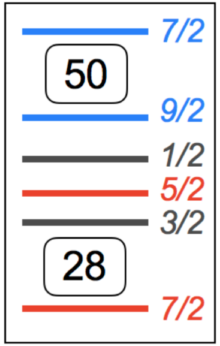
Now more 70 collaborators as participants in the various experiments

Focus of this talk

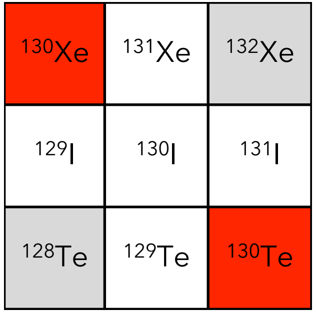
$\pi = \nu$



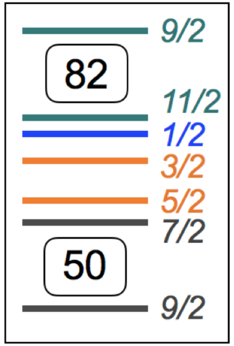
^{76}Se	^{77}Se	^{78}Se
^{75}As	^{76}As	^{77}As
^{74}Ge	^{75}Ge	^{76}Ge



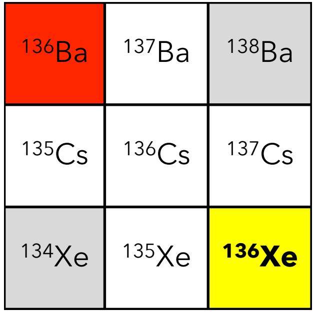
$\pi = \nu$



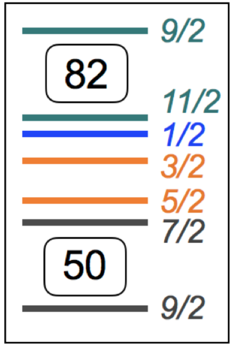
^{130}Xe	^{131}Xe	^{132}Xe
^{129}I	^{130}I	^{131}I
^{128}Te	^{129}Te	^{130}Te



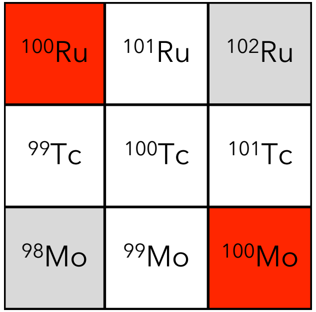
$\pi = \nu$



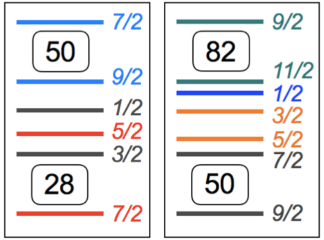
^{136}Ba	^{137}Ba	^{138}Ba
^{135}Cs	^{136}Cs	^{137}Cs
^{134}Xe	^{135}Xe	**^{136}Xe**



$\pi \neq \nu$



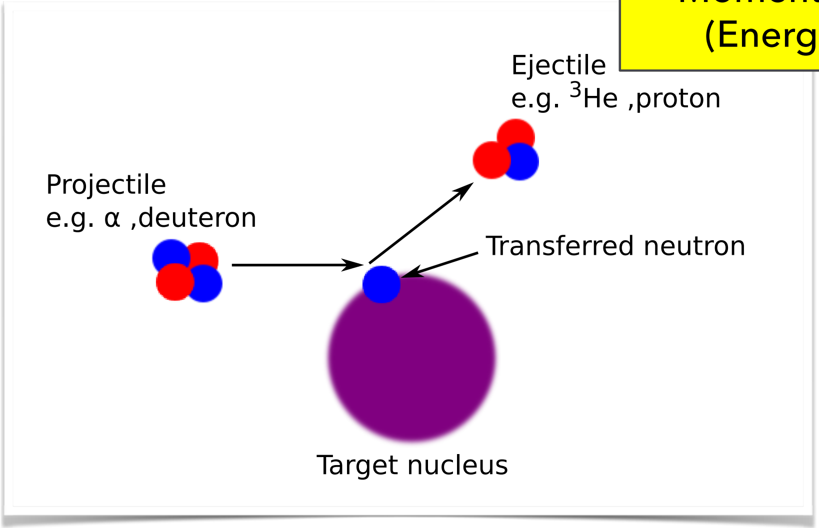
^{100}Ru	^{101}Ru	^{102}Ru
^{99}Tc	^{100}Tc	^{101}Tc
^{98}Mo	^{99}Mo	^{100}Mo

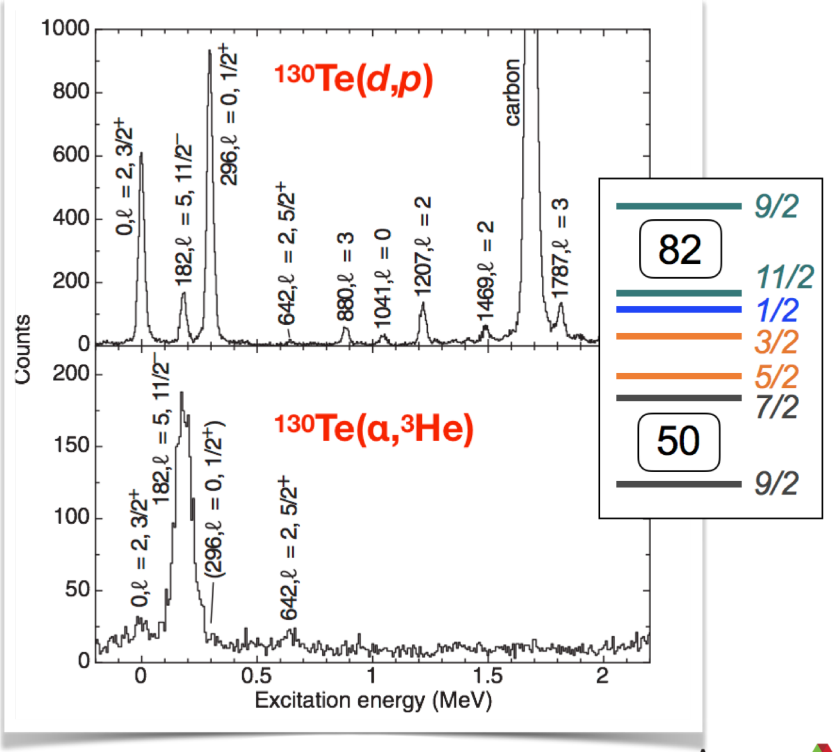


Transfer reactions (what is measured)

Around 10 MeV/u (direct reactions)
Variety of reactions (momentum matching)

Yield
(Cross section)
Momentum
(Energy)

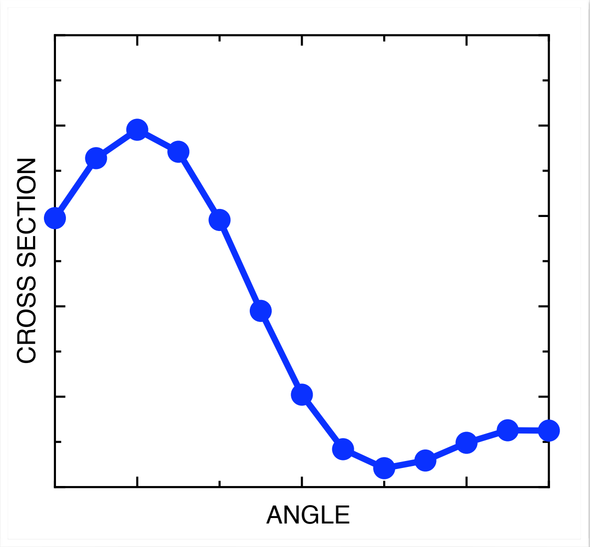




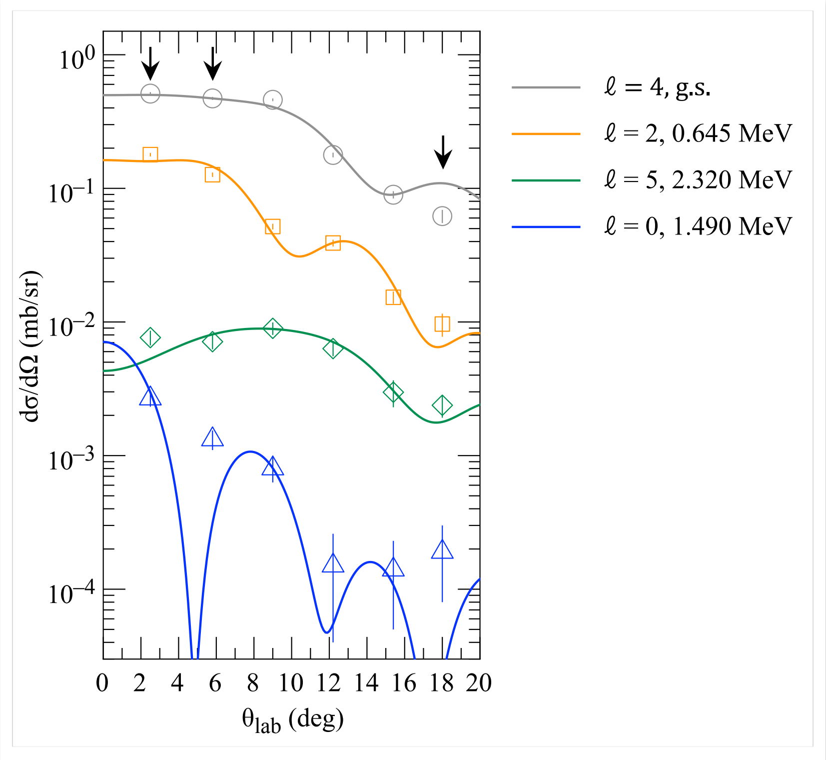
*Spectra from BPK et al., Phys. Rev. C **87**, 011302(R) (2013)*

Transfer reactions (what is inferred)

Measure at several angles, shapes characteristic of ℓ



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



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

Nuclear structure (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

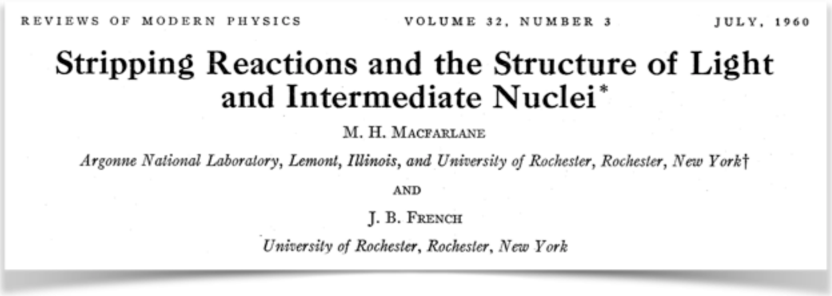
$$\frac{d\sigma}{d\Omega}\Big|_{\text{measured}} = g S'_j \frac{d\sigma}{d\Omega}\Big|_{\text{calculated}}$$

Spectroscopic factor: *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 experimental consideration****.* ***ISPM cross sections****.*

Does it work? / model dependency? etc.

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



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

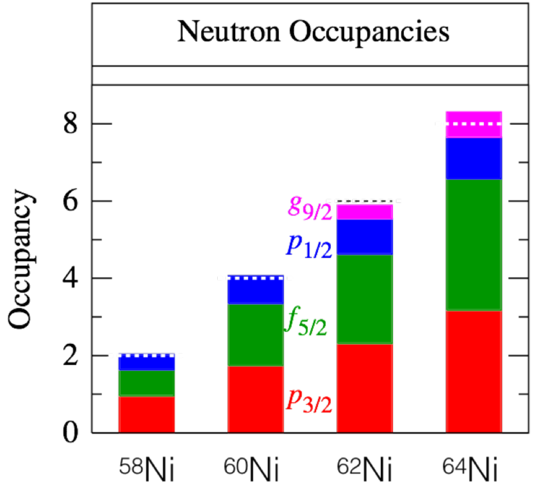
J. B. FRENCH

University of Rochester, Rochester, New York

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

$$N_j \equiv S'/S$$

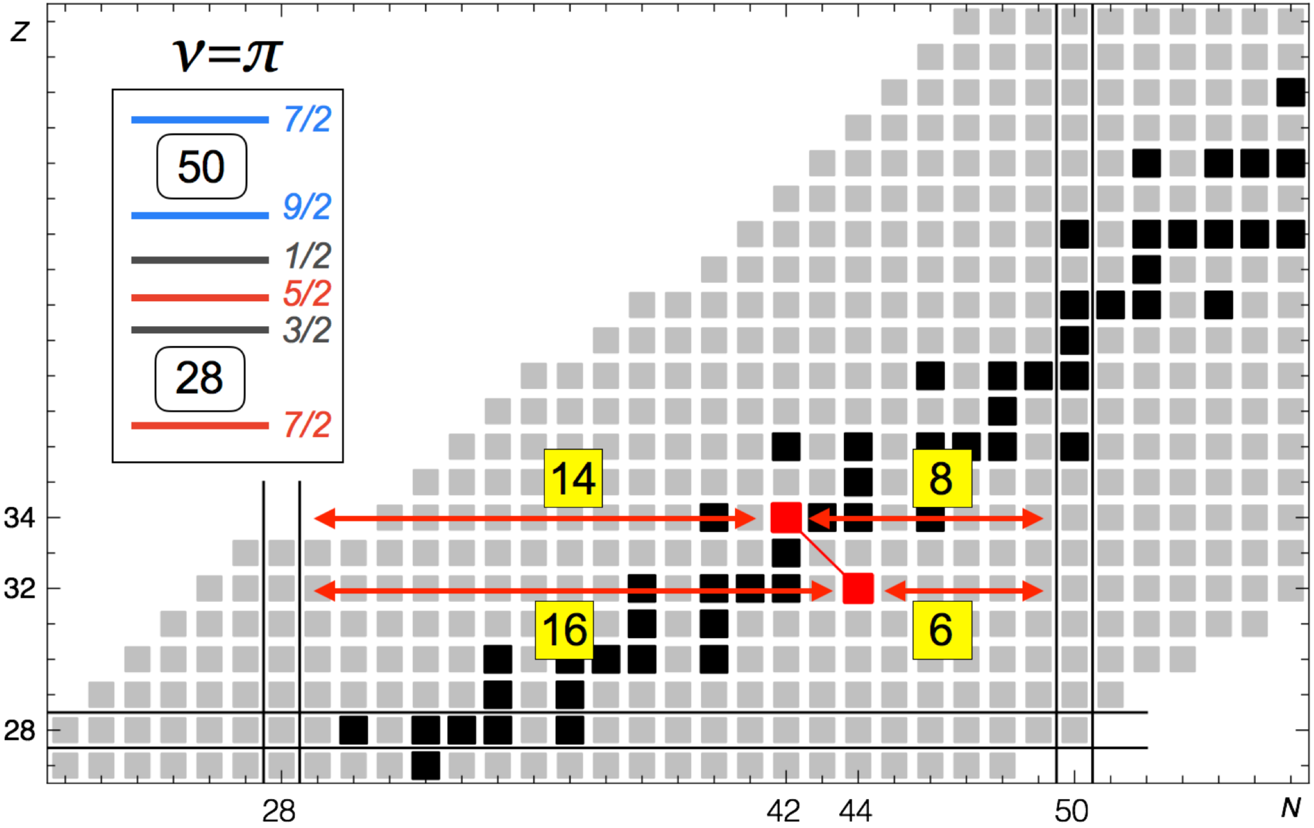
$$N_j \equiv (\Sigma G_+ S'_{\mathrm{adding}} + \Sigma G_- S'_{\mathrm{removing}})/(2j+1)$$

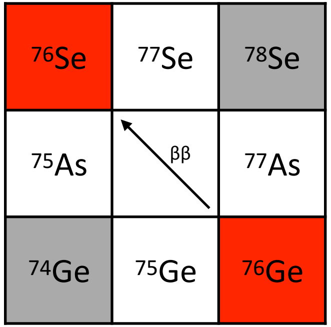


- But is the normalization just arbitrary?

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

Analysis, e.g., ^{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	

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

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

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		

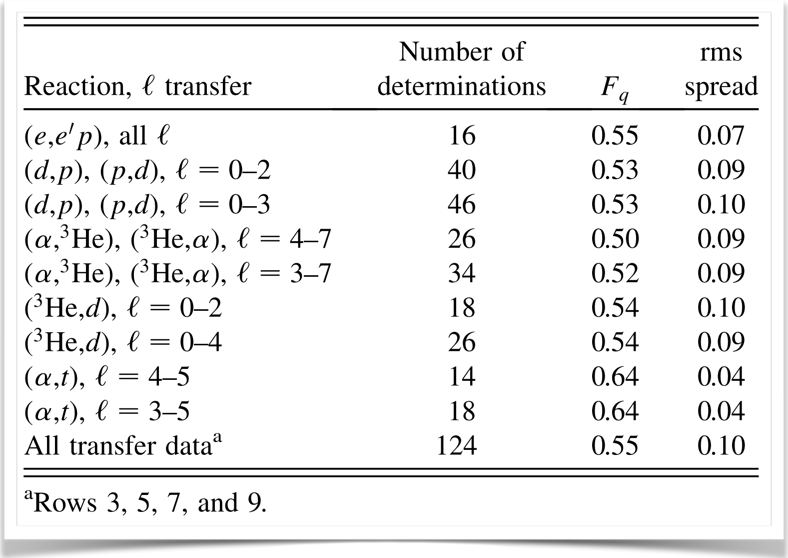
E	ℓ	$(2j+1)S'$	$(2j+1)S$
160	1	0.44	0.82
225	4		
421	2		
505	2		
629	1	0.15	0.28
884	2		
1021	1	0.12	0.22
1048	1	0.04	0.07
1250	0		
1385	2		

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

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

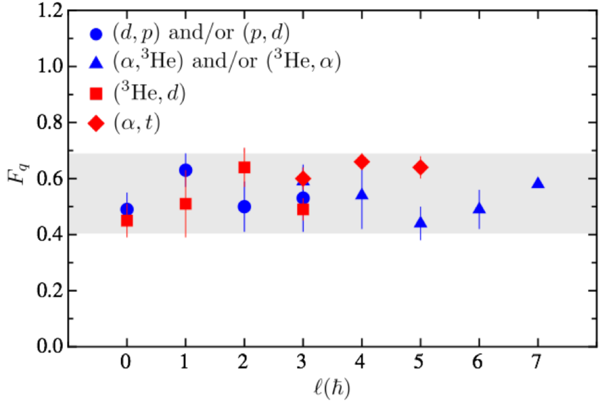
What's the significance of the normalization

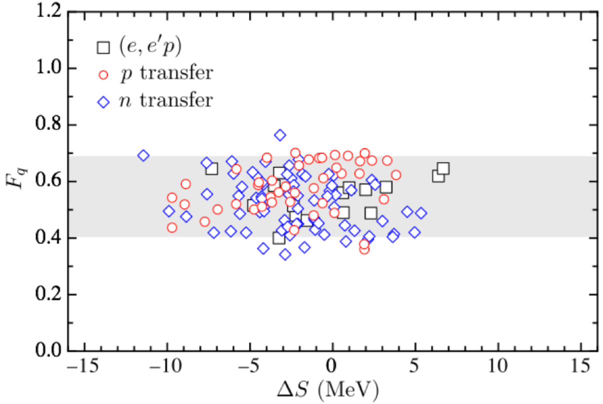
The normalization appears meaningful, a ***ubiquitous feature*** of low-lying single-particle strength, independent of *A*, *l*, nucleon type, reaction, *N-Z*.



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
$(\alpha,^3\text{He})$, $(^3\text{He},\alpha)$, $\ell = 4$–7	26	0.50	0.09
$(\alpha,^3\text{He})$, $(^3\text{He},\alpha)$, $\ell = 3$–7	34	0.52	0.09
$(^3\text{He},d)$, $\ell = 0$–2	18	0.54	0.10
$(^3\text{He},d)$, $\ell = 0$–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.





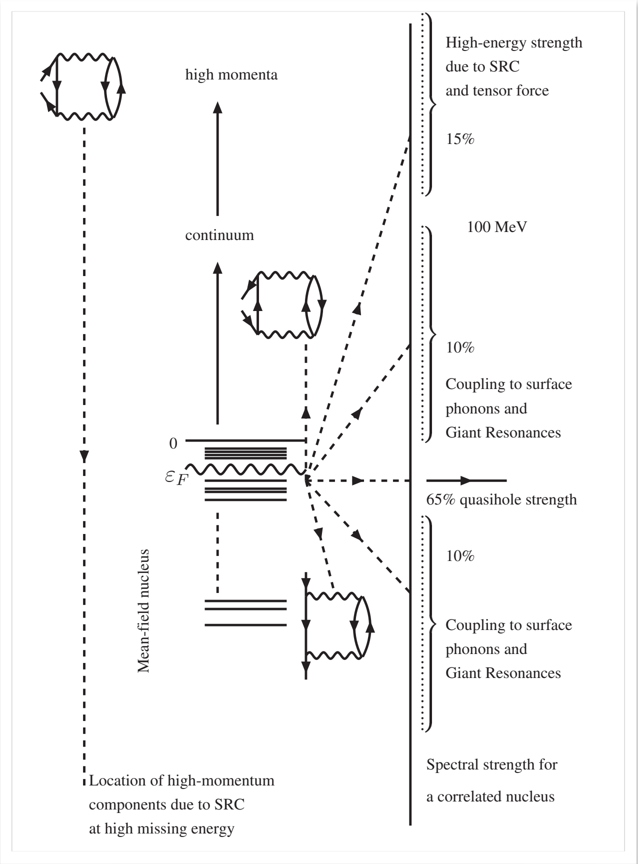
BPK et al., Phys. Rev. Lett. ***111****, 042502 (2013)*

Quenching of s. p. cross sections

*“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:

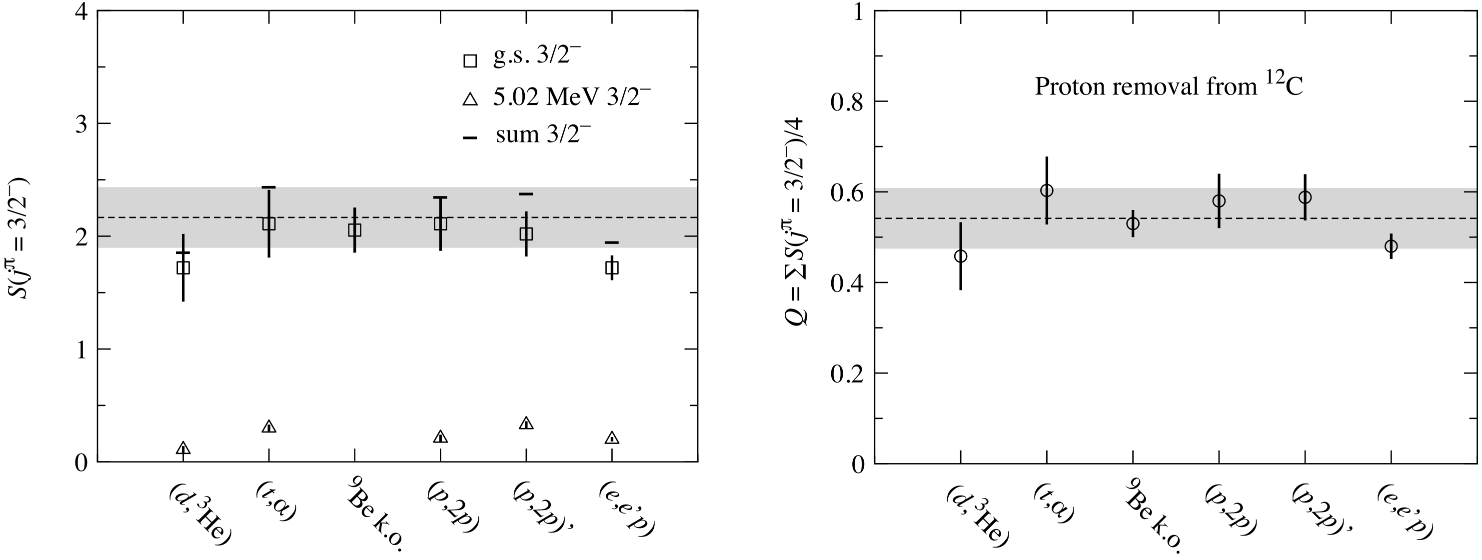
- *Academic in terms of change in occupancies*
- Arguably essential in terms of trusting the data
- How does theory handle it?



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

Quenching factor (a bit more)

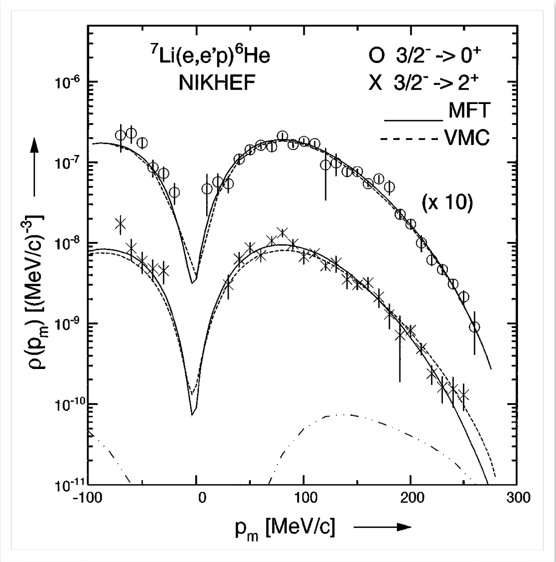
There are a handful of isotopes where reliable experimentally determined cross sections exist from numerous 'equivalent' probes, e.g., proton removal from ^{12}C. A consistent picture emerges.

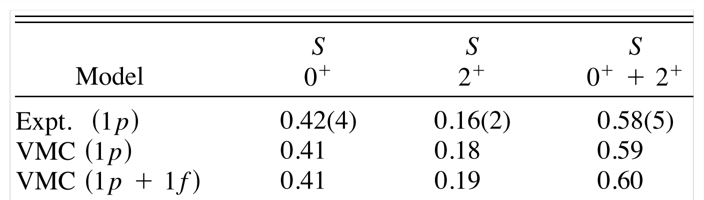


Evaluated Nuclear Structure Data File (www.nndc.bnl.gov)

Quenching factor, theory

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

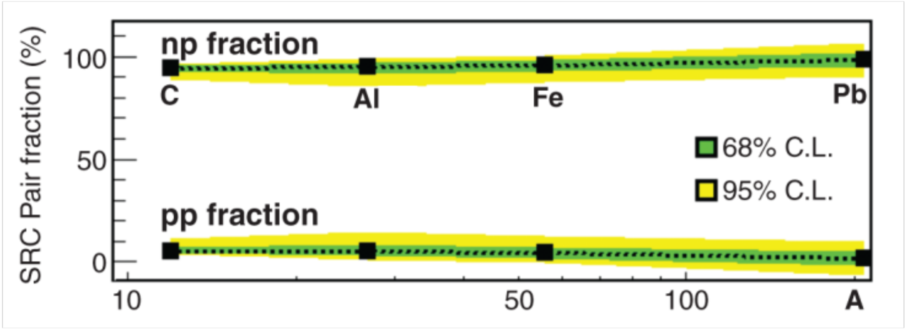
Lapikas, Wessling, and Wiringa, Phys. Rev. Lett. ***82****, 4404 (1999)*

Quenching factor (…)

- No obvious change with neutron excess (*np dominates*) or binding energy (at least near stability) [though new results about high mtm fractions … and N/Z ratio]

- 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? In the sense that there is missing physics / model space, and correlations, in the the calculations*

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

Aside: the g_A problem

(Shown earlier in the week)

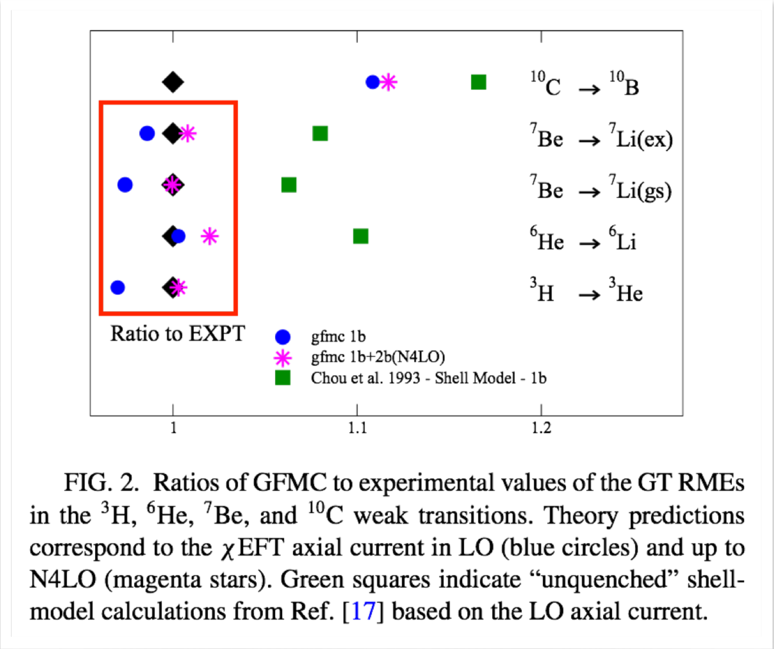
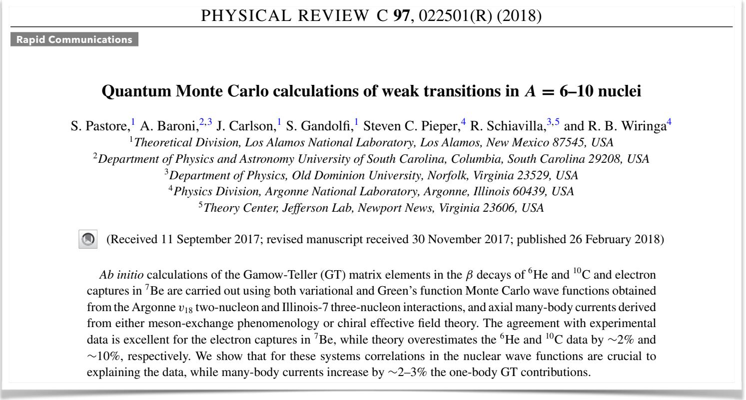


FIG. 2. Ratios of GFMC to experimental values of the GT RMEs in the ^{3}H, ^{6}He, ^{7}Be, and ^{10}C weak transitions. Theory predictions correspond to the χEFT axial current in LO (blue circles) and up to N4LO (magenta stars). Green squares indicate "unquenched" shell-model calculations from Ref. [17] based on the LO axial current.



PHYSICAL REVIEW C **97**, 022501(R) (2018)

Rapid Communications

Quantum Monte Carlo calculations of weak transitions in $A = 6$–10 nuclei

S. Pastore,[1] A. Baroni,[2,3] J. Carlson,[1] S. Gandolfi,[1] Steven C. Pieper,[4] R. Schiavilla,[3,5] and R. B. Wiringa[4]
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[2]*Department of Physics and Astronomy University of South Carolina, Columbia, South Carolina 29208, USA*
[3]*Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA*
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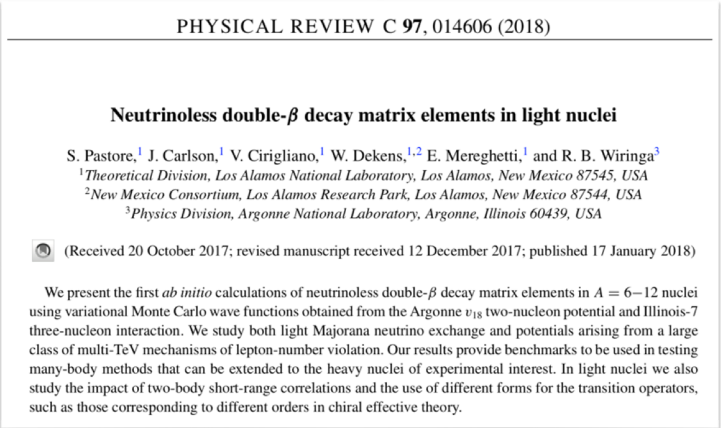
(Received 11 September 2017; revised manuscript received 30 November 2017; published 26 February 2018)

Ab initio calculations of the Gamow-Teller (GT) matrix elements in the β decays of ^{6}He and ^{10}C and electron captures in ^{7}Be are carried out using both variational and Green's function Monte Carlo wave functions obtained from the Argonne v_{18} two-nucleon and Illinois-7 three-nucleon interactions, and axial many-body currents derived from either meson-exchange phenomenology or chiral effective field theory. The agreement with experimental data is excellent for the electron captures in ^{7}Be, while theory overestimates the ^{6}He and ^{10}C data by $\sim$2% and $\sim$10%, respectively. We show that for these systems correlations in the nuclear wave functions are crucial to explaining the data, while many-body currents increase by $\sim$2–3% the one-body GT contributions.



PHYSICAL REVIEW C **97**, 014606 (2018)

Neutrinoless double-β decay matrix elements in light nuclei

S. Pastore,[1] J. Carlson,[1] V. Cirigliano,[1] W. Dekens,[1,2] E. Mereghetti,[1] and R. B. Wiringa[3]
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(Received 20 October 2017; revised manuscript received 12 December 2017; published 17 January 2018)

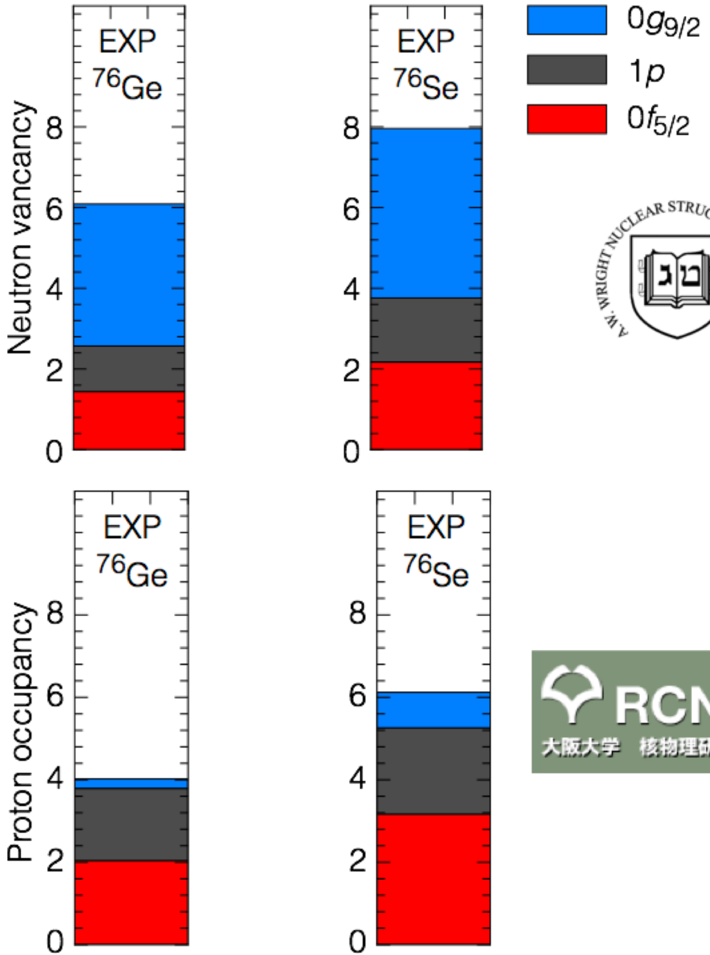
We present the first *ab initio* calculations of neutrinoless double-β decay matrix elements in $A = 6$–12 nuclei using variational Monte Carlo wave functions obtained from the Argonne v_{18} two-nucleon potential and Illinois-7 three-nucleon interaction. We study both light Majorana neutrino exchange and potentials arising from a large class of multi-TeV mechanisms of lepton-number violation. Our results provide benchmarks to be used in testing many-body methods that can be extended to the heavy nuclei of experimental interest. In light nuclei we also study the impact of two-body short-range correlations and the use of different forms for the transition operators, such as those corresponding to different orders in chiral effective theory.

… old results

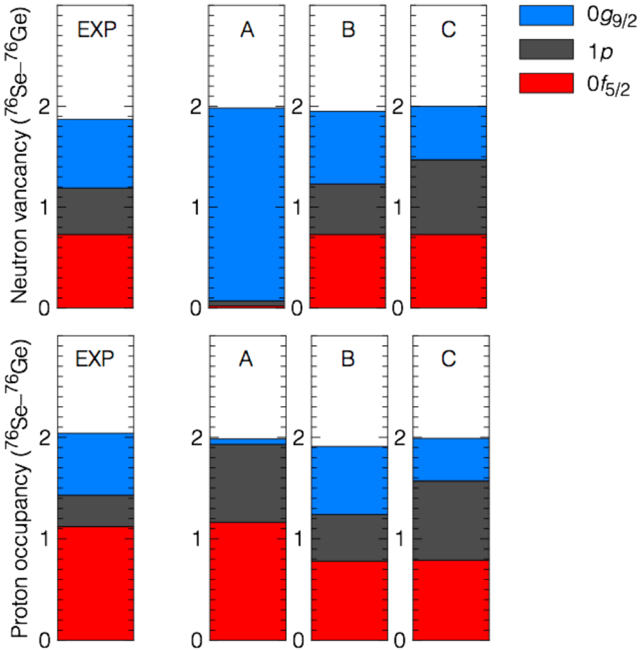
Isotope	$0f_{5/2}$	$1p_{1/2,3/2}$	$0g_{9/2}$	Sum	Expect
^{74}Ge	1.8	1.1	4.3	7.2	8
^{76}Ge	***1.4***	***1.1***	***3.5***	***6.0***	***6***
^{76}Se	***2.2***	***1.6***	***4.2***	***8.0***	***8***
^{78}Se	2.3	0.9	2.8	6.1	6

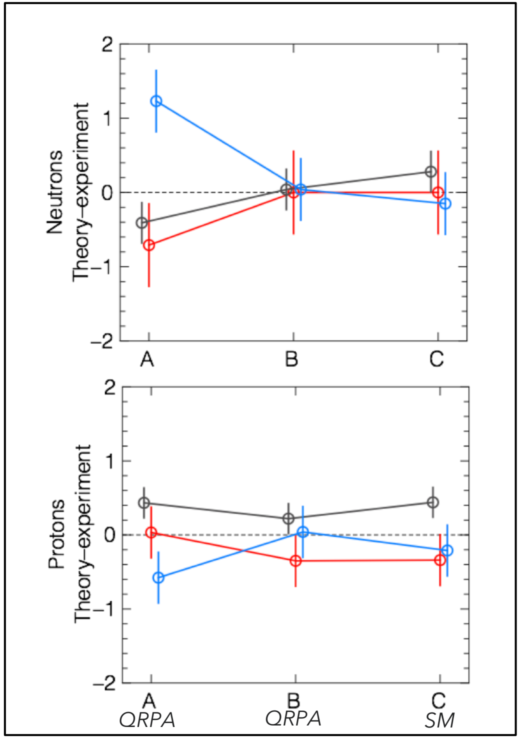
Isotope	$0f_{5/2}$	$1p_{1/2,3/2}$	$0g_{9/2}$	Sum	Expect
^{74}Ge	1.89	1.52	0.37	3.78	4
^{76}Ge	***1.75***	***2.04***	***0.23***	***4.02***	***4***
^{76}Se	***2.09***	***3.17***	***0.86***	***6.12***	***6***
^{78}Se	2.35	1.82	2.05	6.22	6

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



Change in occupancy

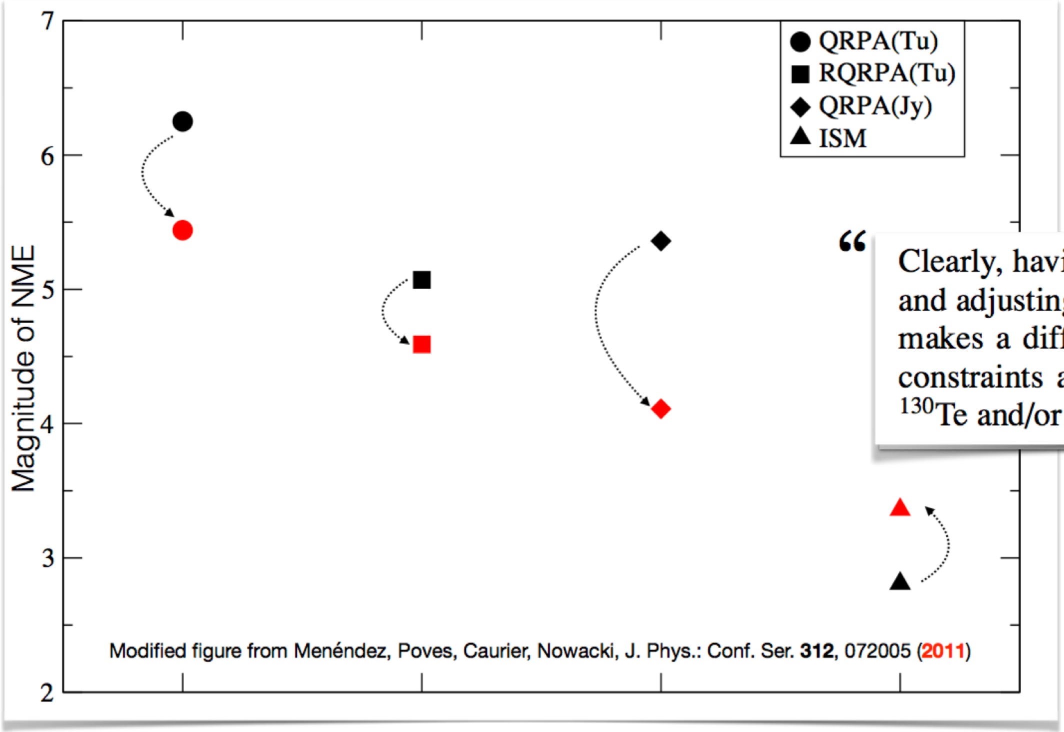




J. P. Schiffer et al., Phys. Rev. Lett. **100**, 112501 (2008) [neutrons]
BPK et al., Phys. Rev. C **79**, 021301(R) (2009) [protons]
Rodin et al., Nucl. Phys. A **766**, 107 (2006) [A]
Suhonen et al., Phys. Lett. B **668**, 277 (2006) [B]
Caurier et al., Phys. Rev. Lett. **100**, 052503 (2008) [C]

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

Impact?



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.”

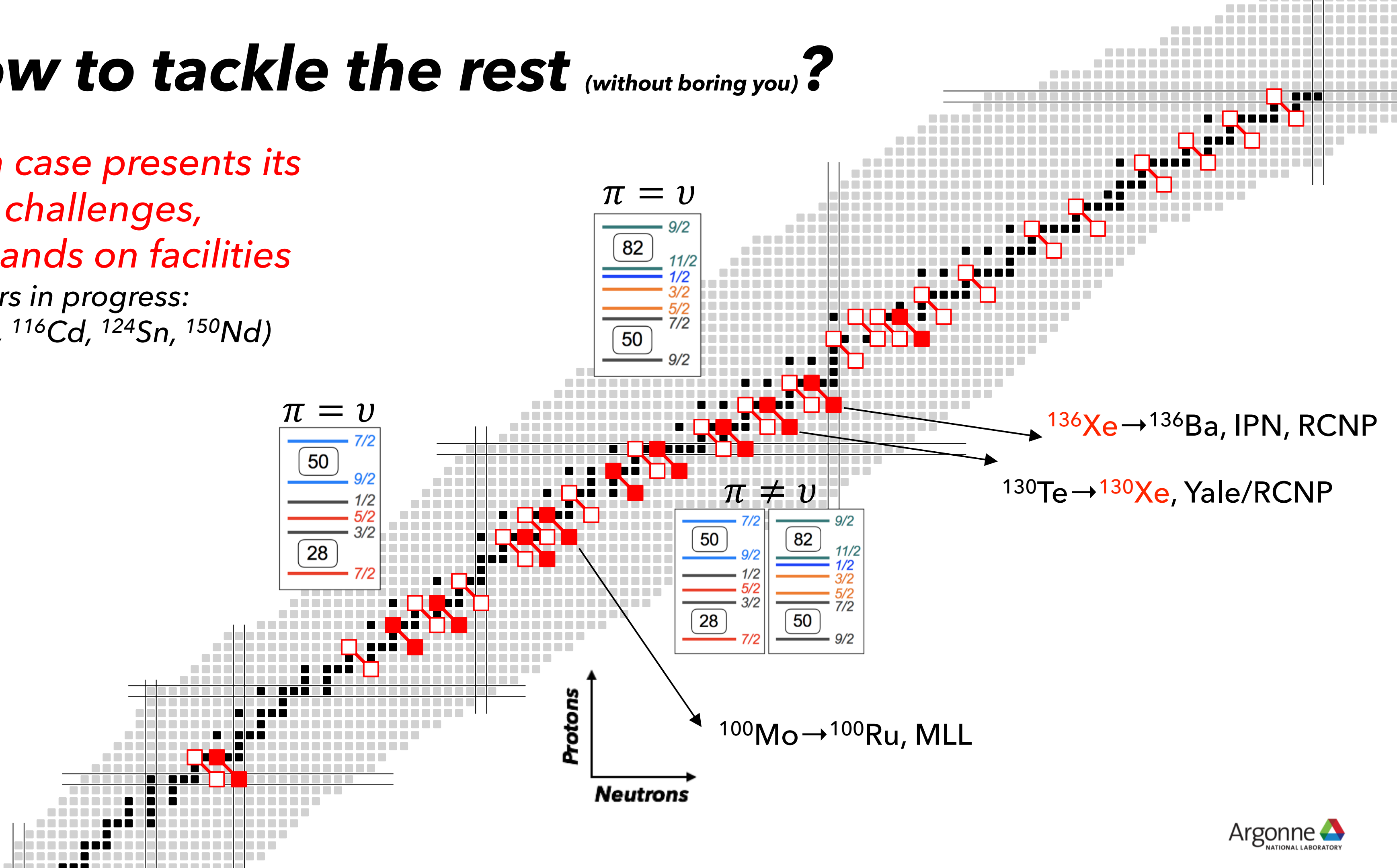
Yes, some. Much discussed. A *40-70% reduction* in the well-known gap between QRPA and the ISM, resulted. This predated recent IBM work and newer calculations.

*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

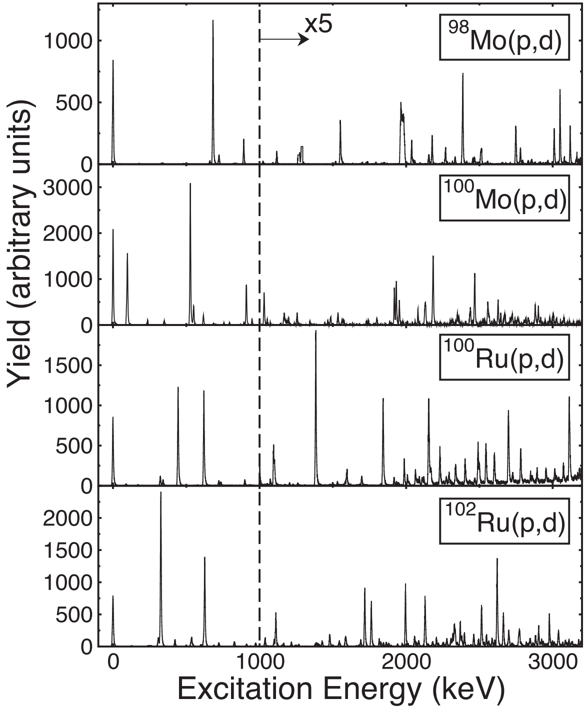
^{100}Mo→^{100}Ru, MLL

A = 100 occupancies

*J. Suhonen and O. Civitarese, Nucl. Phys. A **924**, 1 (2014) [WS, WS ADJ]*
*J. Kotila and J. Barea, Phys. Rev. C **94**, 034320 (2016) [IBM]*

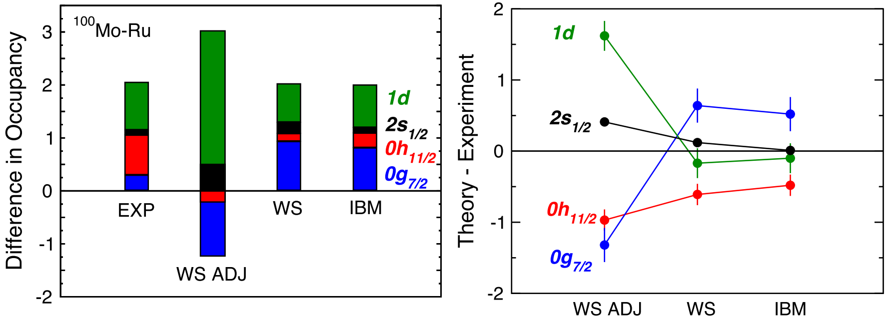
High level density, Munich Q3D (as good as 8-keV FWHM resolution

Technische Universität München

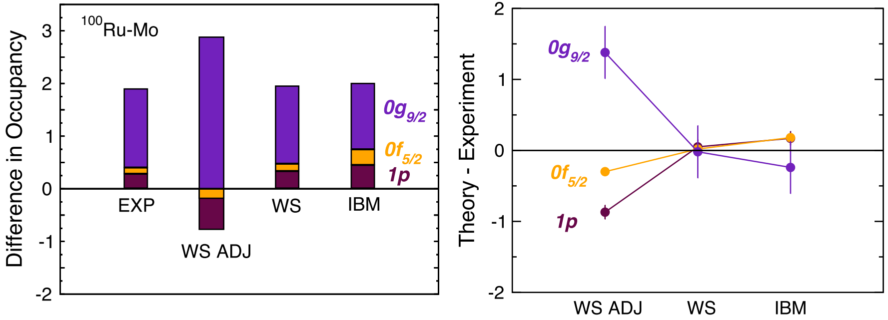


*Freeman et al., Phys. Rev. C **96**, 054325 (2017)*

NEUTRONS



PROTONS

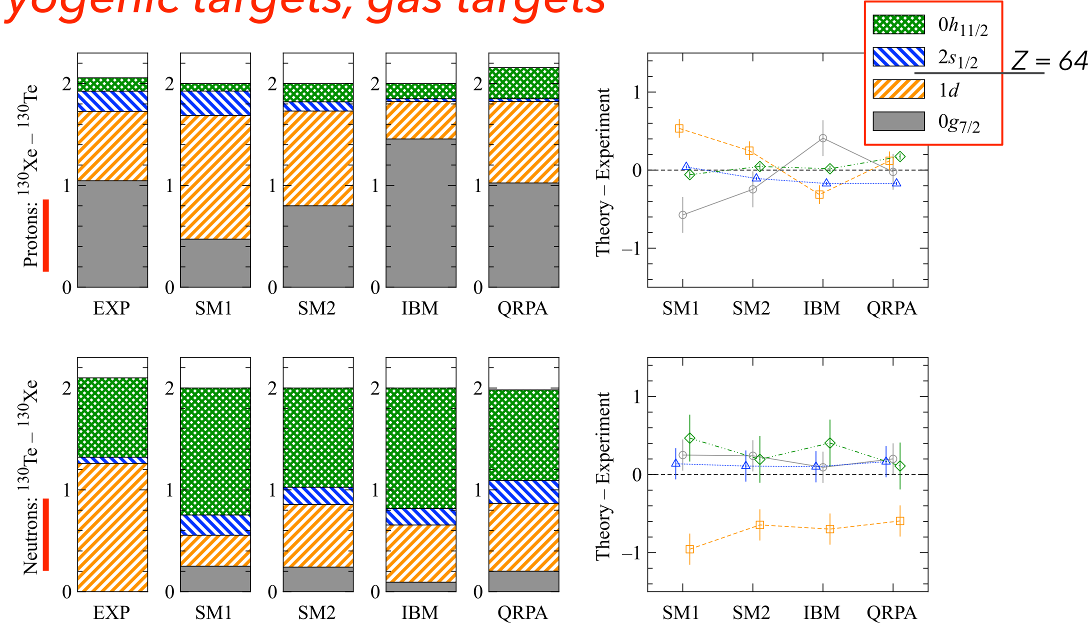


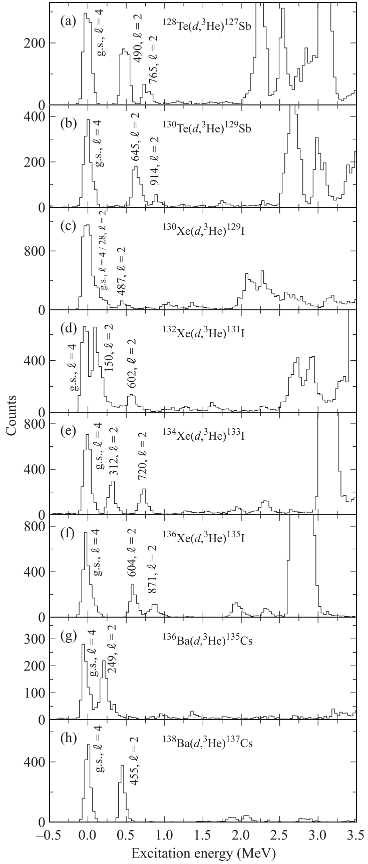
Argonne NATIONAL LABORATORY

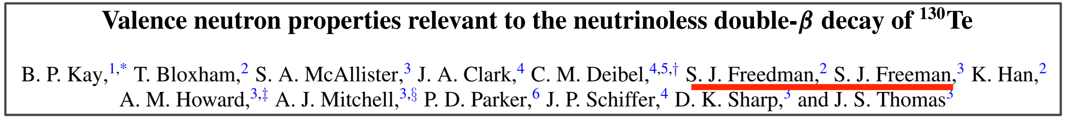
A = 130 occupancies

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]

Cryogenic targets, gas targets







Valence neutron properties relevant to the neutrinoless double-β decay of ^{130}Te

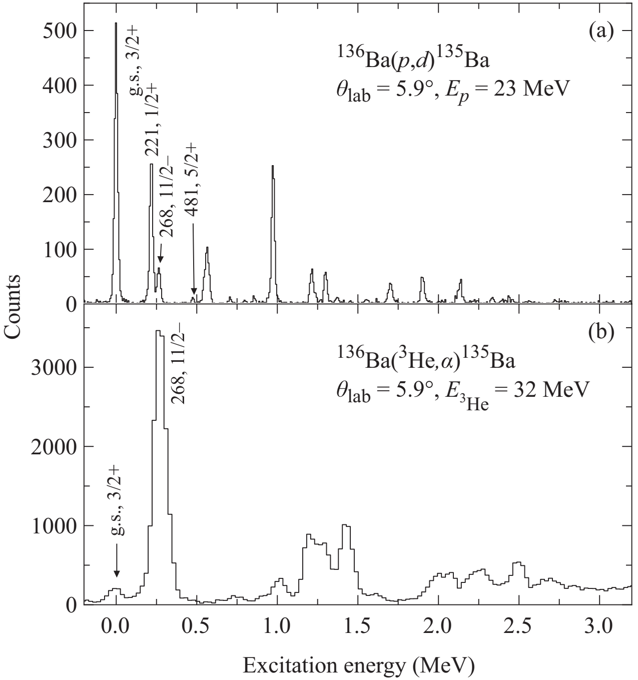
B. P. Kay,[1,*] T. Bloxham,[2] S. A. McAllister,[3] J. A. Clark,[4] C. M. Deibel,[4,5,†] S. J. Freedman,[2] S. J. Freeman,[3] K. Han,[2] A. M. Howard,[3,‡] A. J. Mitchell,[3,§] P. D. Parker,[6] J. P. Schiffer,[4] D. K. Sharp,[3] and J. S. Thomas[3]

BPK et al., *Phys. Rev. C* **87**, 011302(R) (2013)
J. P. Entwisle et al., *Phys. Rev. C* **93**, 064312 (2016)

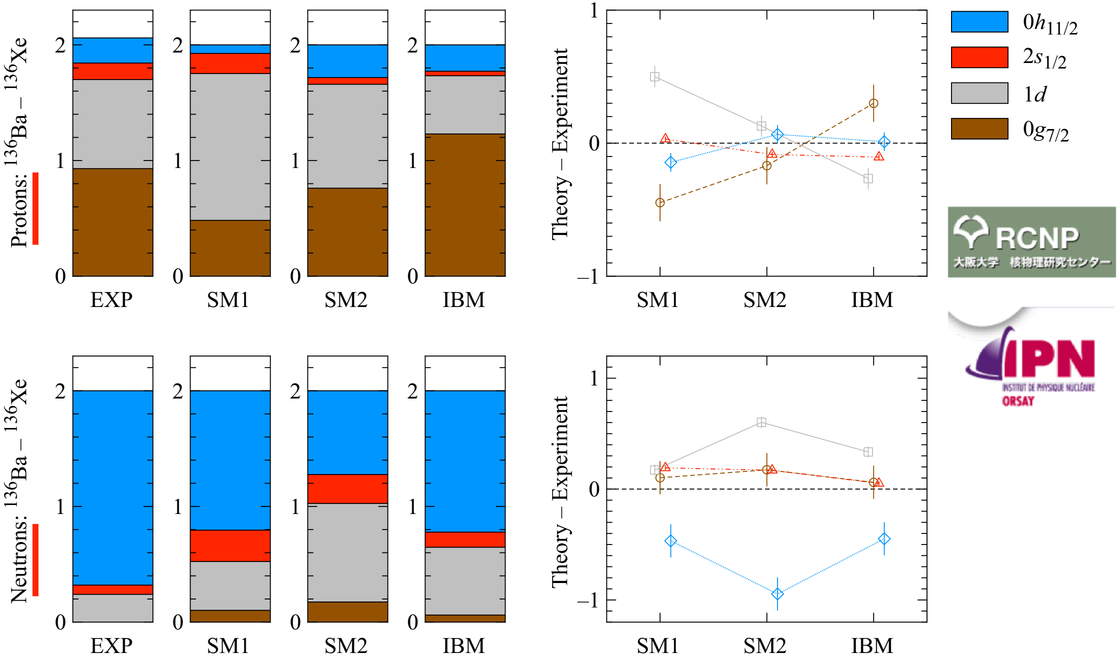
A = 136 occupancies

*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]*

Taking advantage of ^{136}Xe being a good closed shell for neutrons

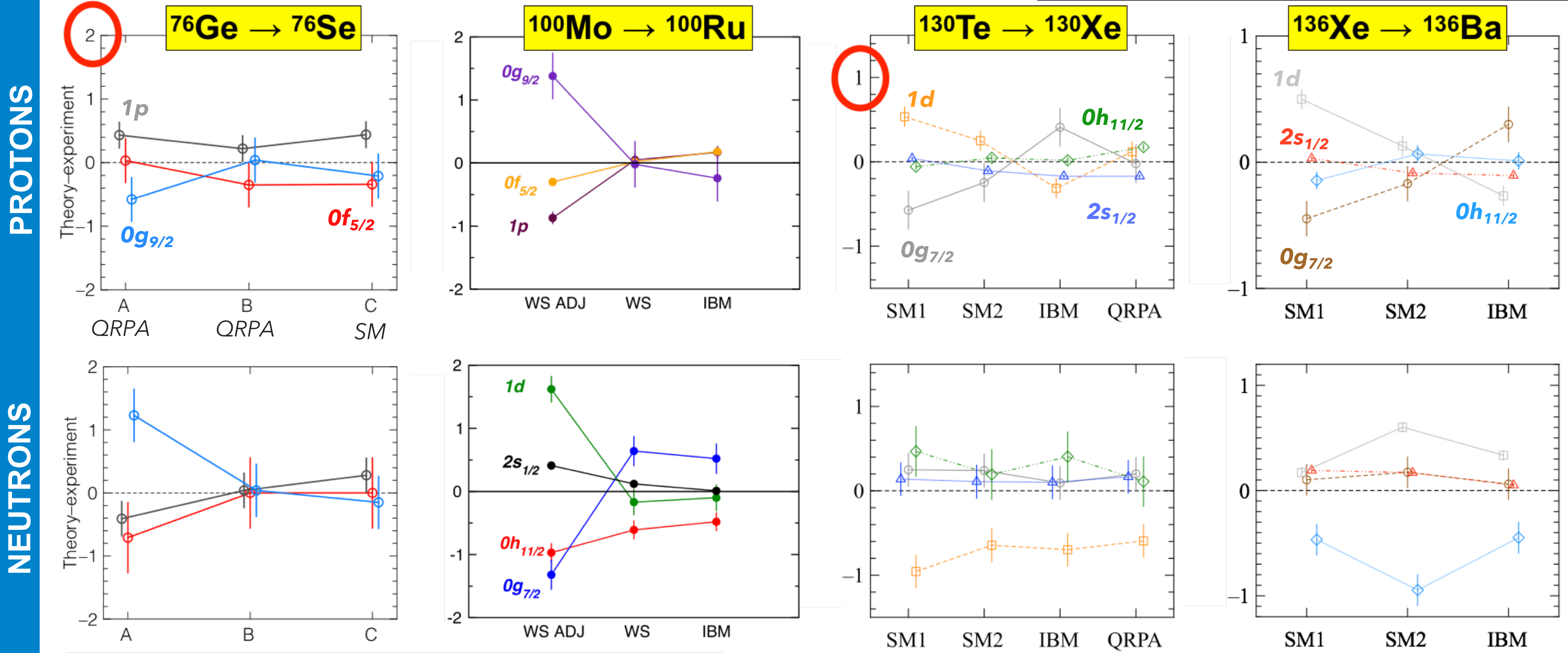


*J. P. Entwisle et al., Phys. Rev. C **93**, 064312 (2016)*
*S. V. Szwec et al., Phys. Rev. C **94**, 054314 (2016)*



Overview of all results

Schiffer et al., Phys. Rev. Lett. ***100****, 112501 (2008)*
BPK et al., Phys. Rev. C ***79****, 021301(R) (2009)*
BPK 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)*
Freeman et al., Phys. Rev. C ***96****, 054325 (2017)*



(References to theory work can be found in references above)

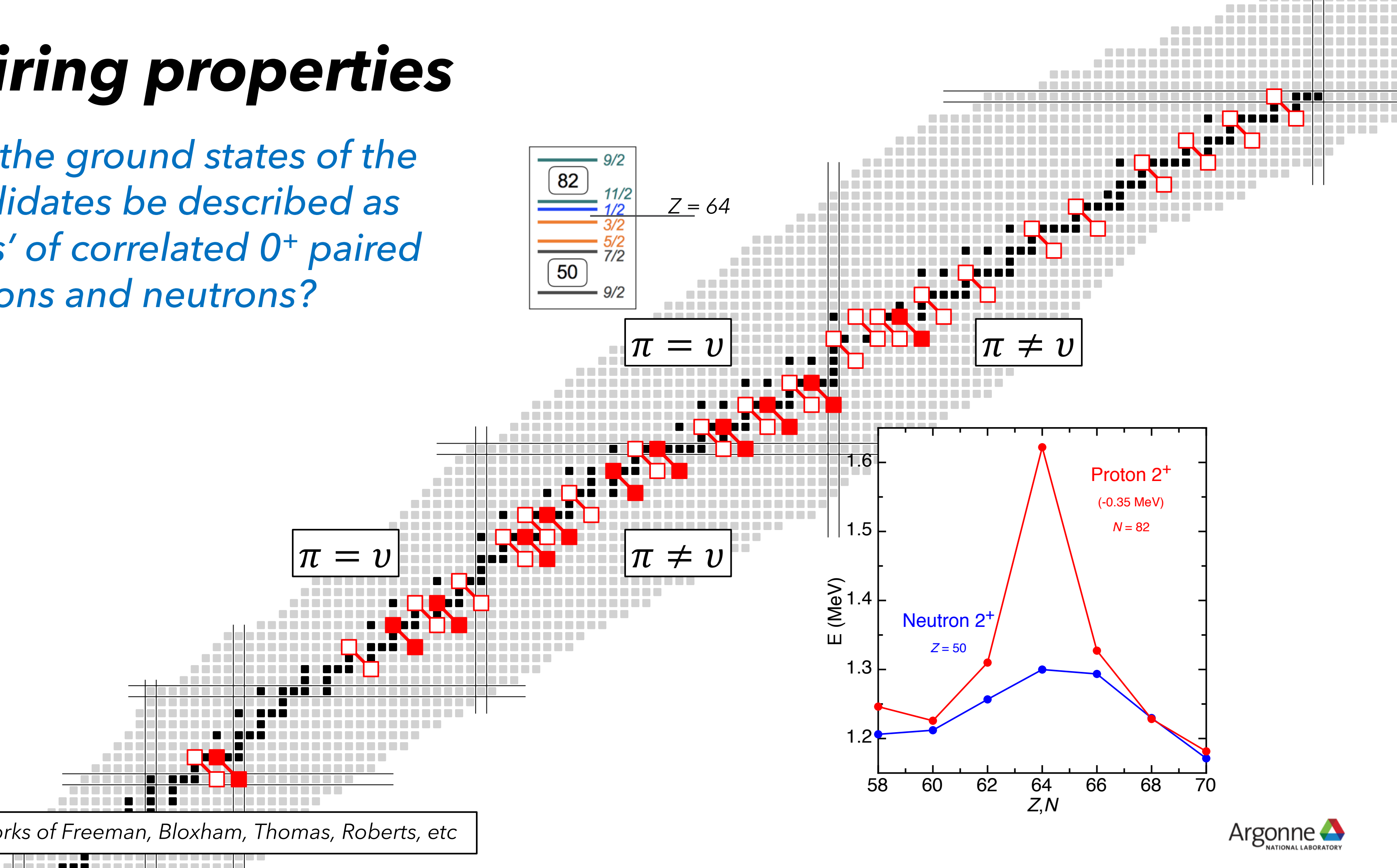
Comment on occupancies

- 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*

While likely challenging theoretically, it would be interesting to know what the consequence of 'shutting off' part of the model-space would be (*e.g. the $g_{7/2}$ neutrons above tin, or comparing e.g. JUN45 and GXPF1A – or even more simplistic approaches*)

Pairing properties

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



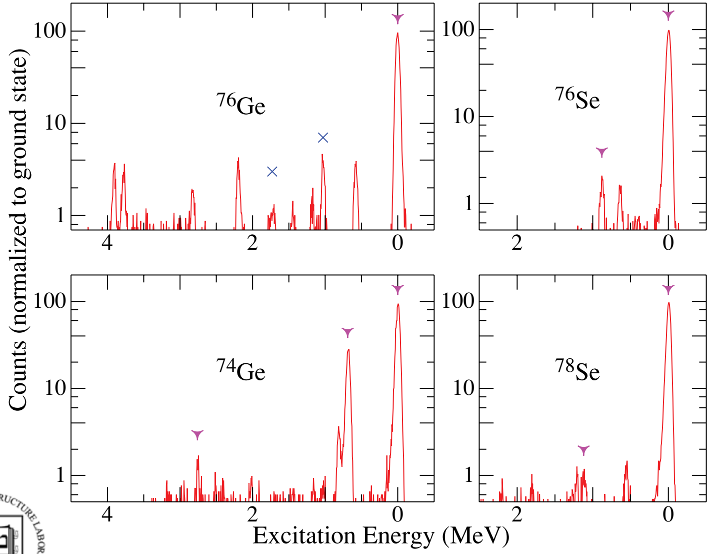
e.g. works of Freeman, Bloxham, Thomas, Roberts, etc

Pairing around A ~ 76

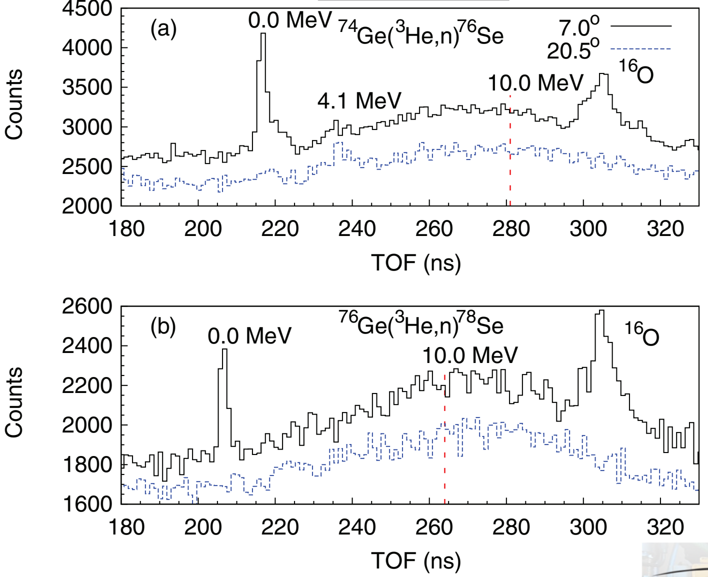
Pair-transfer reactions are a simple and effective probe of pairing correlations

No evidence of ‘pairing vibrations’ in the A = 76 region

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

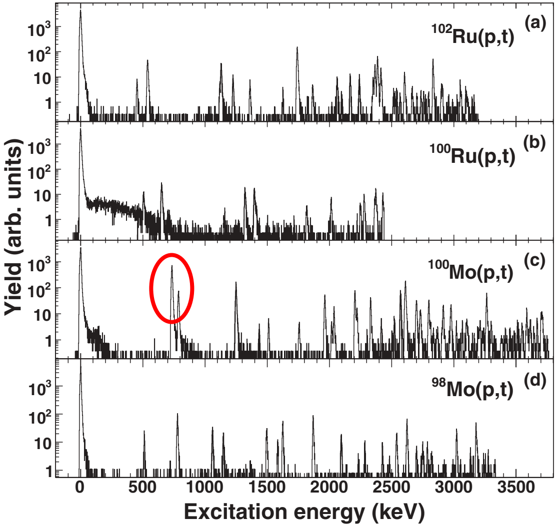


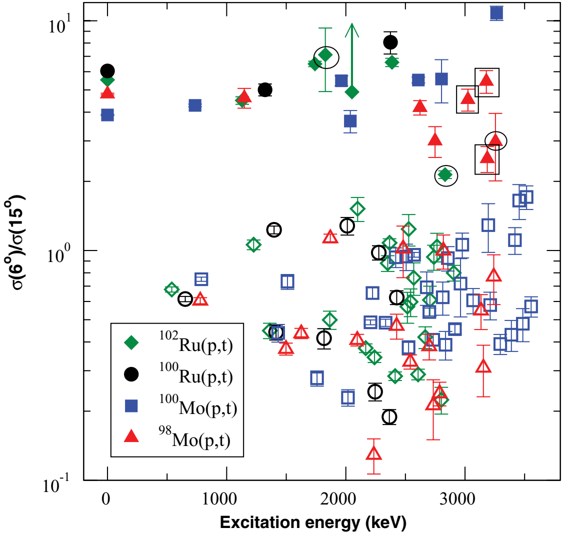
Ge(^{3}He,*n*)

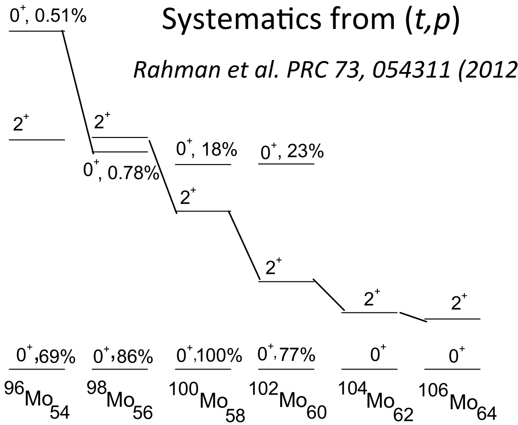


S. J. Freeman et al., Phys. Rev. C ***75****, 051301(R) (2007) [neutrons]*
A. Roberts et al., Phys. Rev. C ***87****, 051305(R) (2013) [protons]*

Pairing around A ~ 100







Systematics from (*t,p*)

Rahman et al. PRC 73, 054311 (2012)

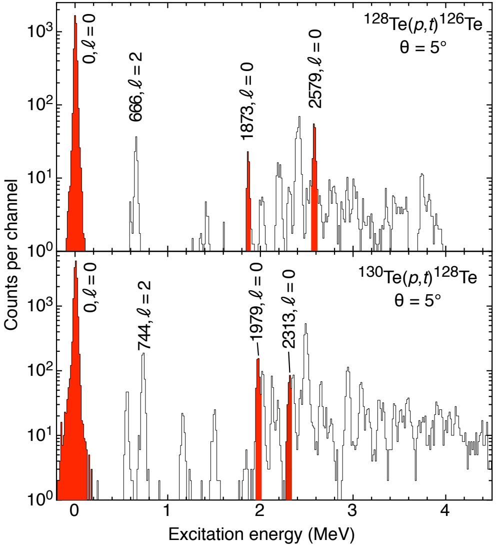
Transitions strengths normalised to ^{100}Mo gs.

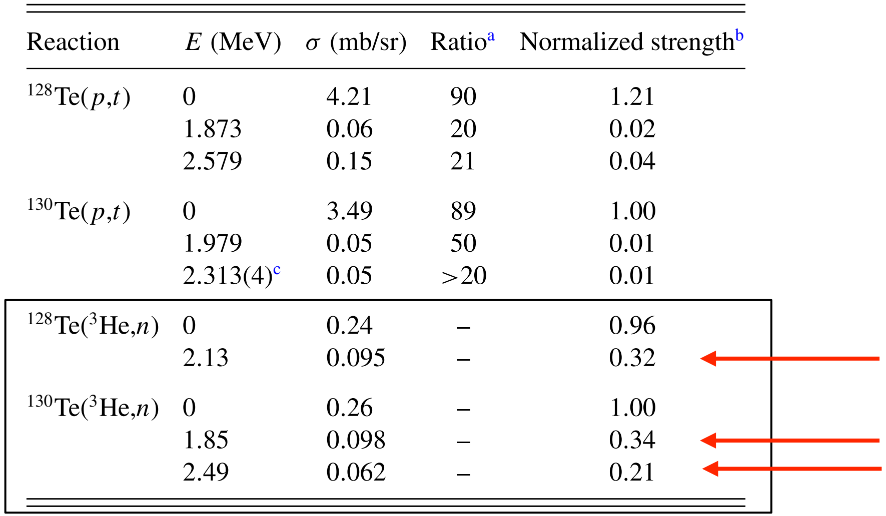
<u>A transitional region with deformation playing a role in the nuclear structure:</u>

- 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 (<u>proton work remains to be done</u>)*

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

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*)

$E0$ lifetimes, Ge and Se (approved exp. at TRIUMF)
Revisiting two-proton transfer [Xe(^{3}He,n) at ANL]
Other programs (e.g. ***RCNPs CE reactions***, Catania DCE)
And … many more (most covered this week)