Nuclear structure calculations for nuclei involved in neutrinoless double beta decay*

Or "nuclear structure properties relevant to the calculation of nuclear matrix elements for $0\nu2\beta$"

ANL HEP/PHY Joint Neutrino Meeting

13th April 2015

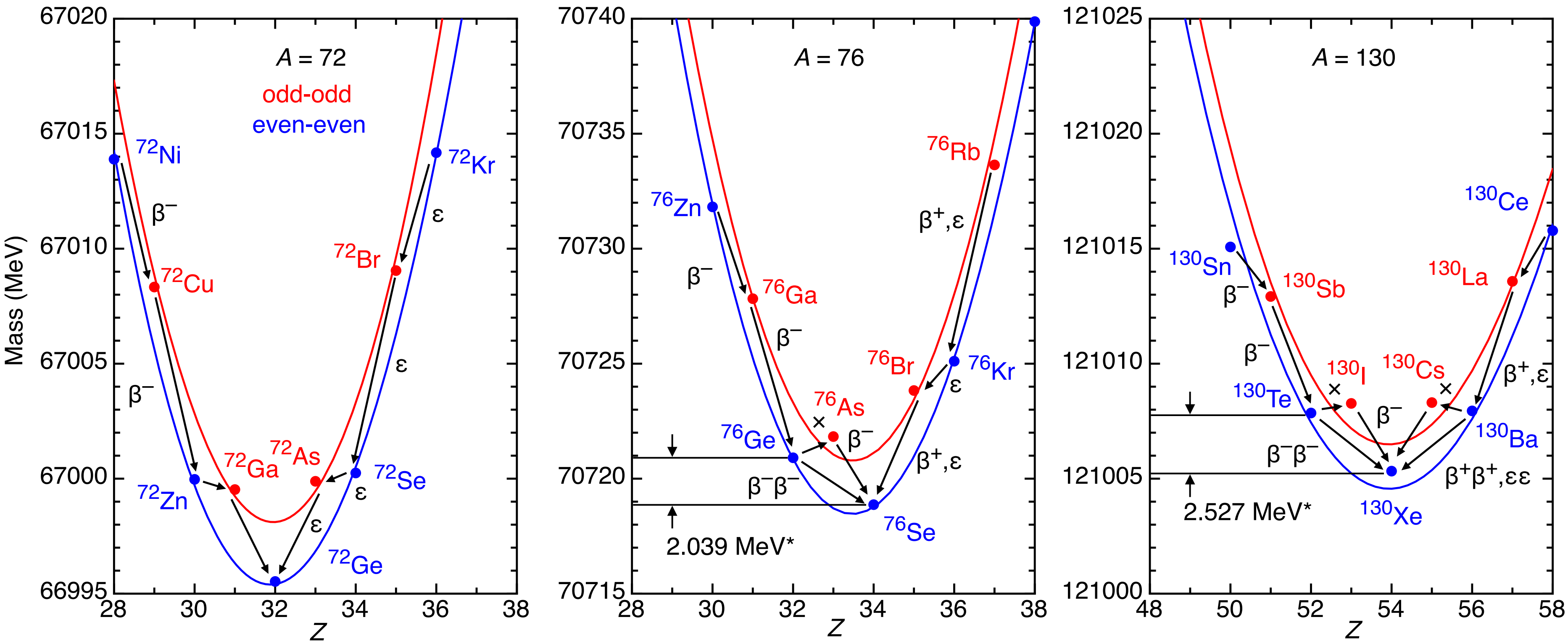
Ben Kay, PHY

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

Outline

- Neutrinoless double beta decay from a nuclear physicists perspective
- How can nuclear structure studies help?
  - theoretical calculations in serious disagreement with each other, can they be constrained by experimental data? single-particle structure … pairing properties
- Methods … experimental cross sections, DWBA, etc.
- An overview of our program … a snapshot
  - The $^{76}Ge \rightarrow ^{76}Se$, $^{130}Te \rightarrow ^{130}Xe$, and $^{136}Xe \rightarrow ^{136}Ba$ systems
- Outlook

Beta decay, double beta decay



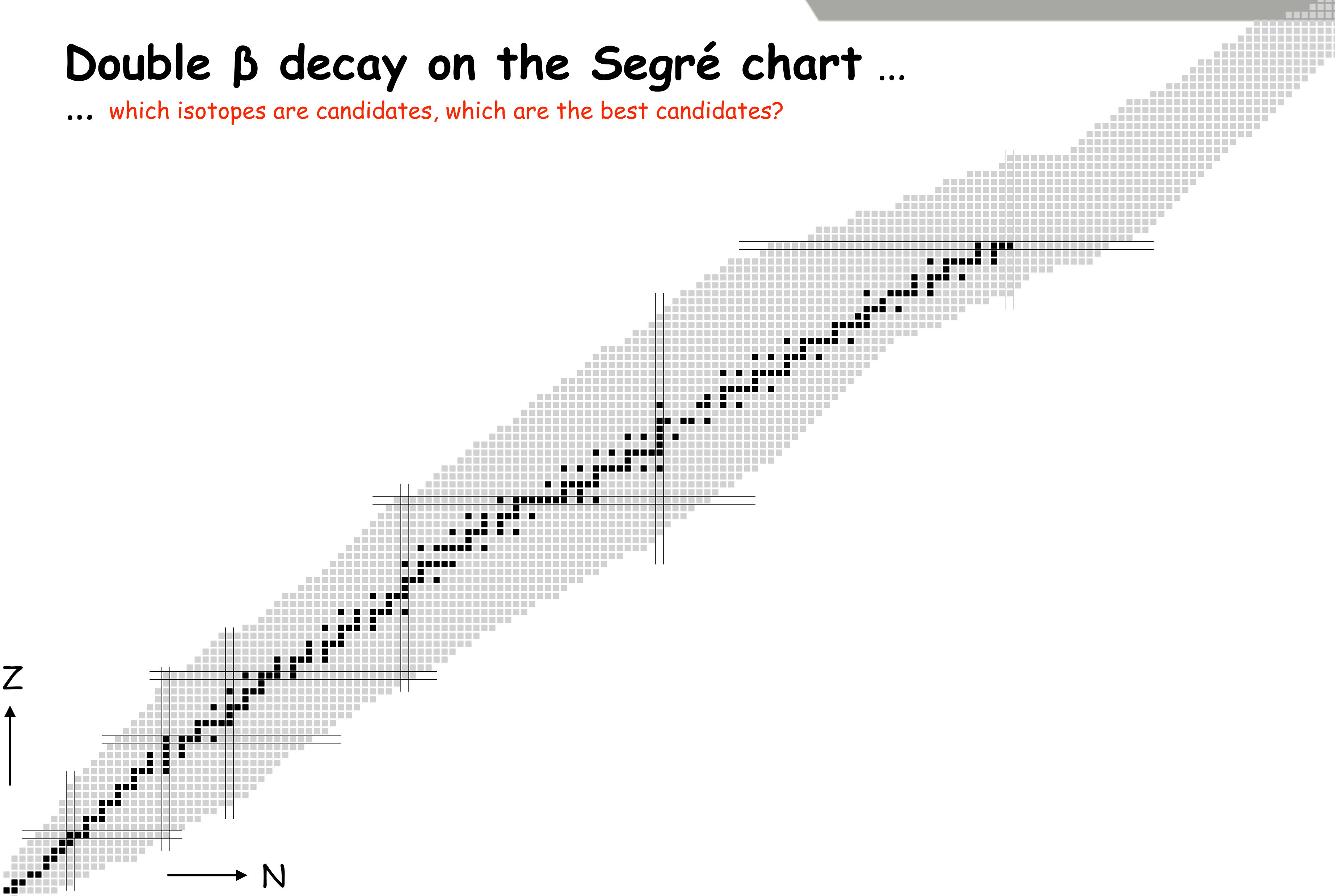
Pairing — displacement of even-even and odd-odd mass parabolas for given isobars with data from 2012 atomic mass evaluation.

*From, amongst many others, mass measurements at ANL [e.g., N. D. Scielzo et al., PRC **80**, 025501 (2009)]

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

Double β decay on the Segré chart …

… which isotopes are candidates, which are the best candidates?

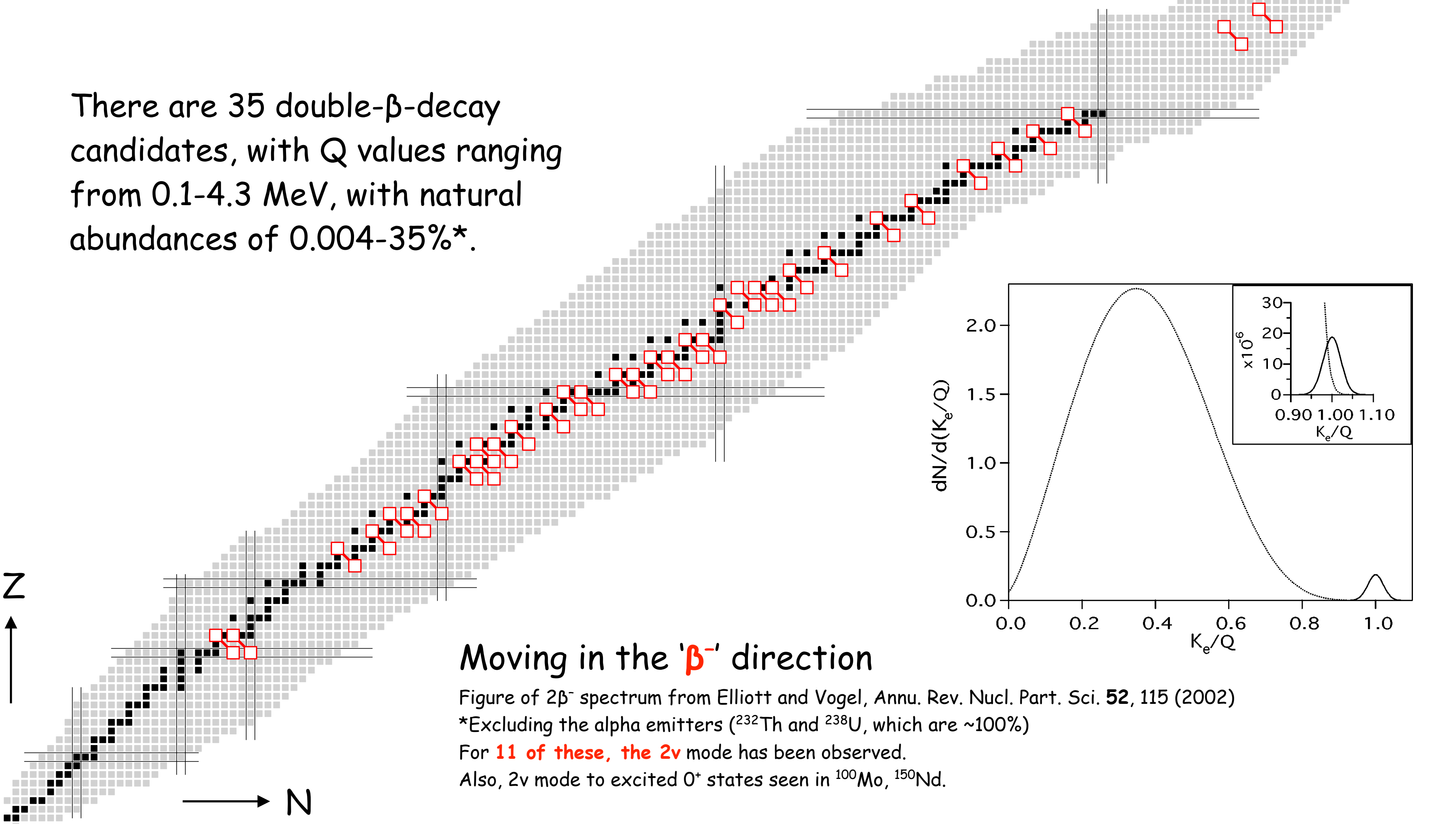


$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta}\rangle|^2$$

Double β decay on the Segré chart …

… which isotopes are candidates, which are the best candidates?

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



Moving in the 'β⁻' direction

Figure of 2β⁻ 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%)

For **11 of these, the 2ν** mode has been observed.

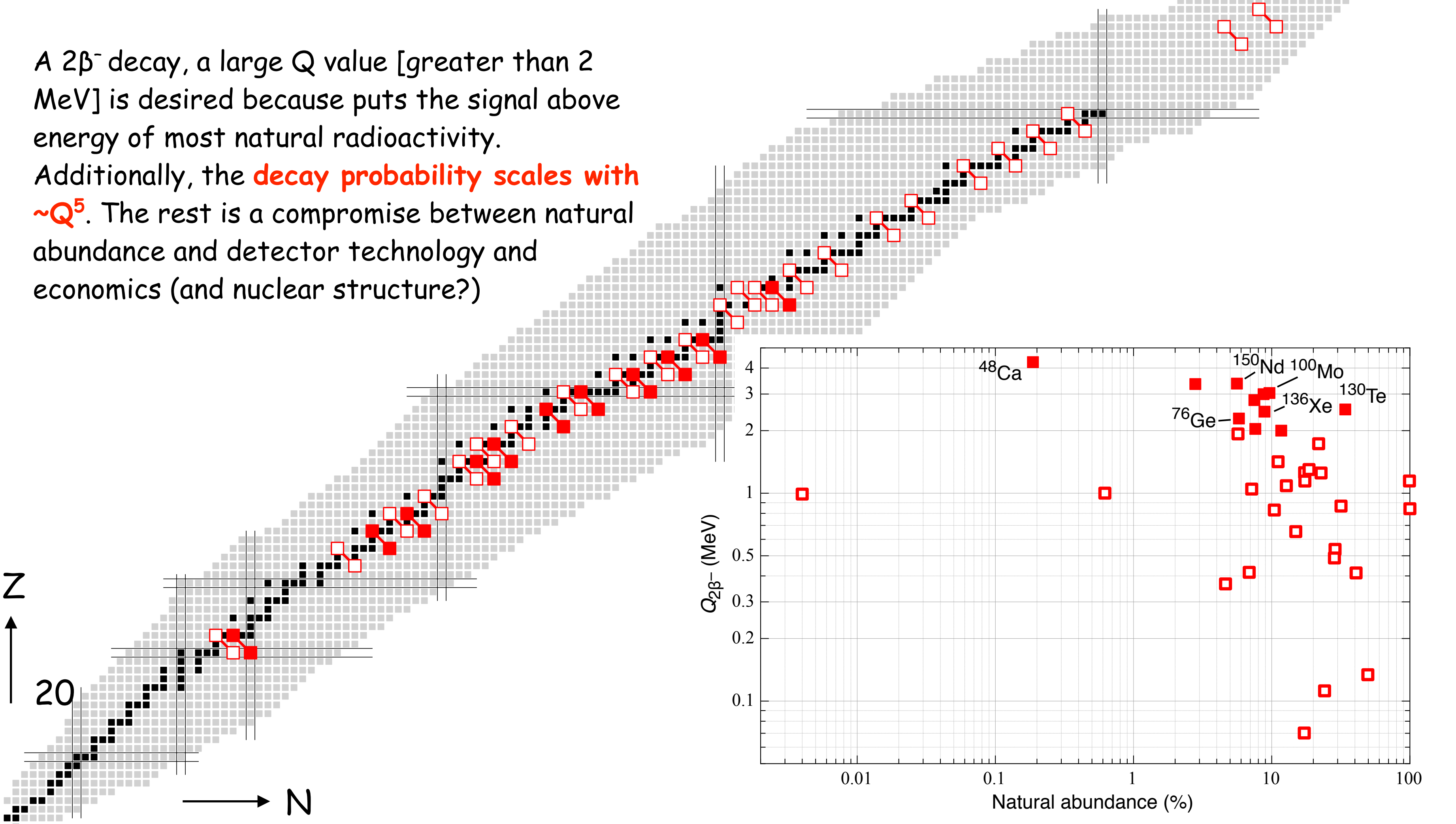
Also, 2ν mode to excited 0^+ states seen in ^{100}Mo, ^{150}Nd.

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

Double β decay on the Segré chart …

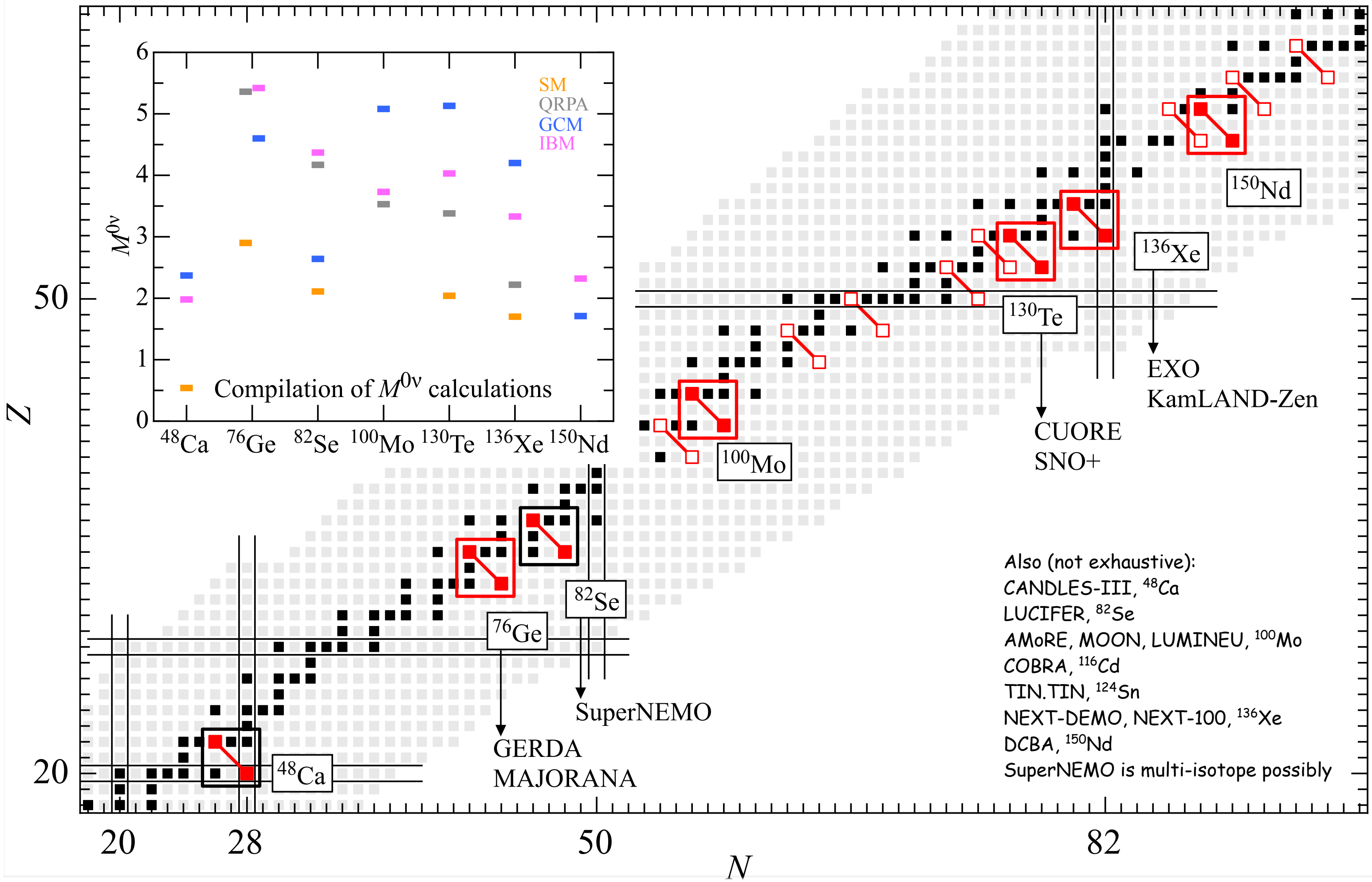
… which isotopes are candidates, which are the best candidates?

A $2\beta^-$ decay, a large Q value [greater than 2 MeV] is desired because puts the signal above energy of most natural radioactivity. Additionally, the **decay probability scales with ~Q^5**. The rest is a compromise between natural abundance and detector technology and economics (and nuclear structure?)



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

Double β decay on the Segré chart …



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

NMEs — "the principal obstacle" (J. Bahcall et al., 2004)

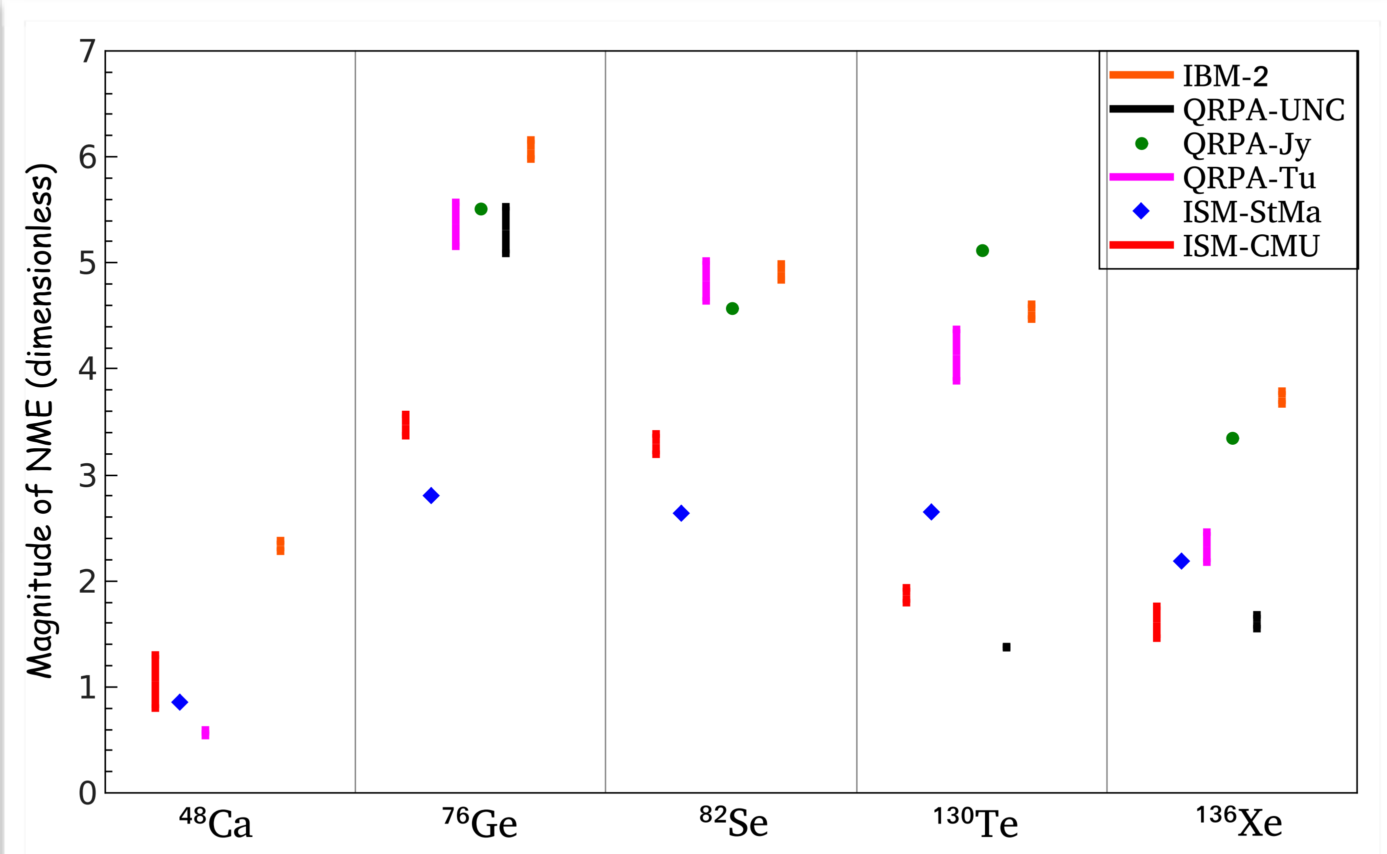


Figure: Neacsu and Horoi, PRC **91**, 024309 (2015)
[countless other papers with similar plots for the 'usual' candidates]

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

NMEs — "the principal obstacle" (J. Bahcall et al., 2004)

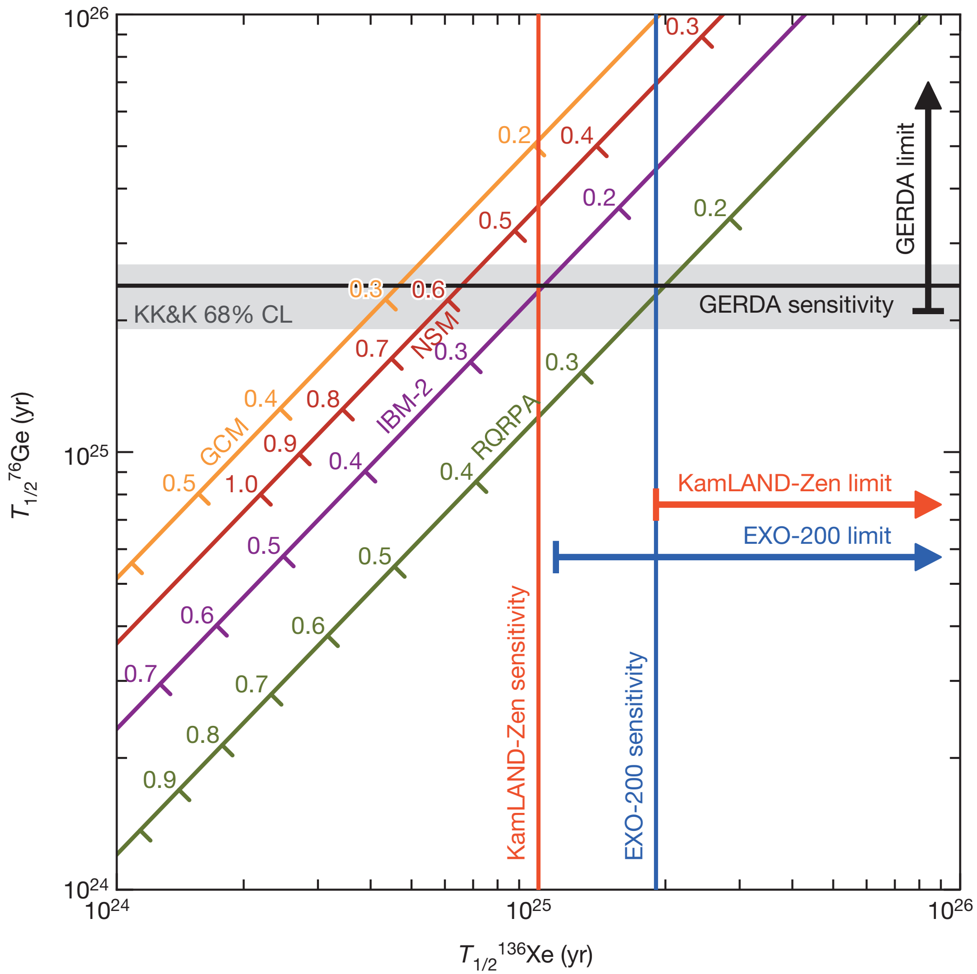


Figure: The EXO-200 Collaboration, Nature 510, 233 (2014)

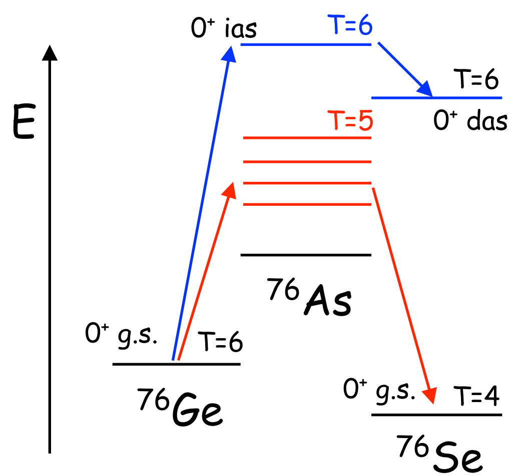
$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta}\rangle|^2$$

NMEs for 2ν2β reasonably well established

What experimentally accessible nuclear-structure properties can be useful?
First a look at the process … and start with what is known and observed, **2ν2β**

2ν2β

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



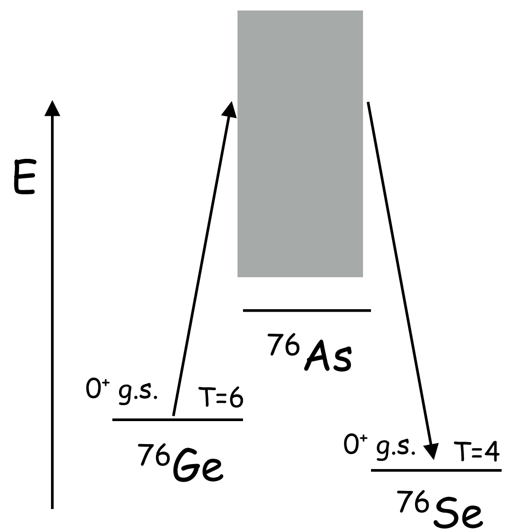
- Dominated by GT transitions via 1^+ states in the intermediate nucleus.
- Nuclear structure effects key (ex. energy / strength of 1^+ states) **AND can be probed experimentally** via charge exchange reactions e.g. $^{76}Ge(^3He,t)^{76}As$, $^{76}Se(t,^3He)^{76}As^*$.

NMEs for 0ν2β less certain

What experimentally accessible nuclear-structure properties can be useful? Not quite so straight forward with **0ν2β**

0ν2β

Probes all intermediate states up to 10's of MeV, any spin (up to 5 to 6 hbar)

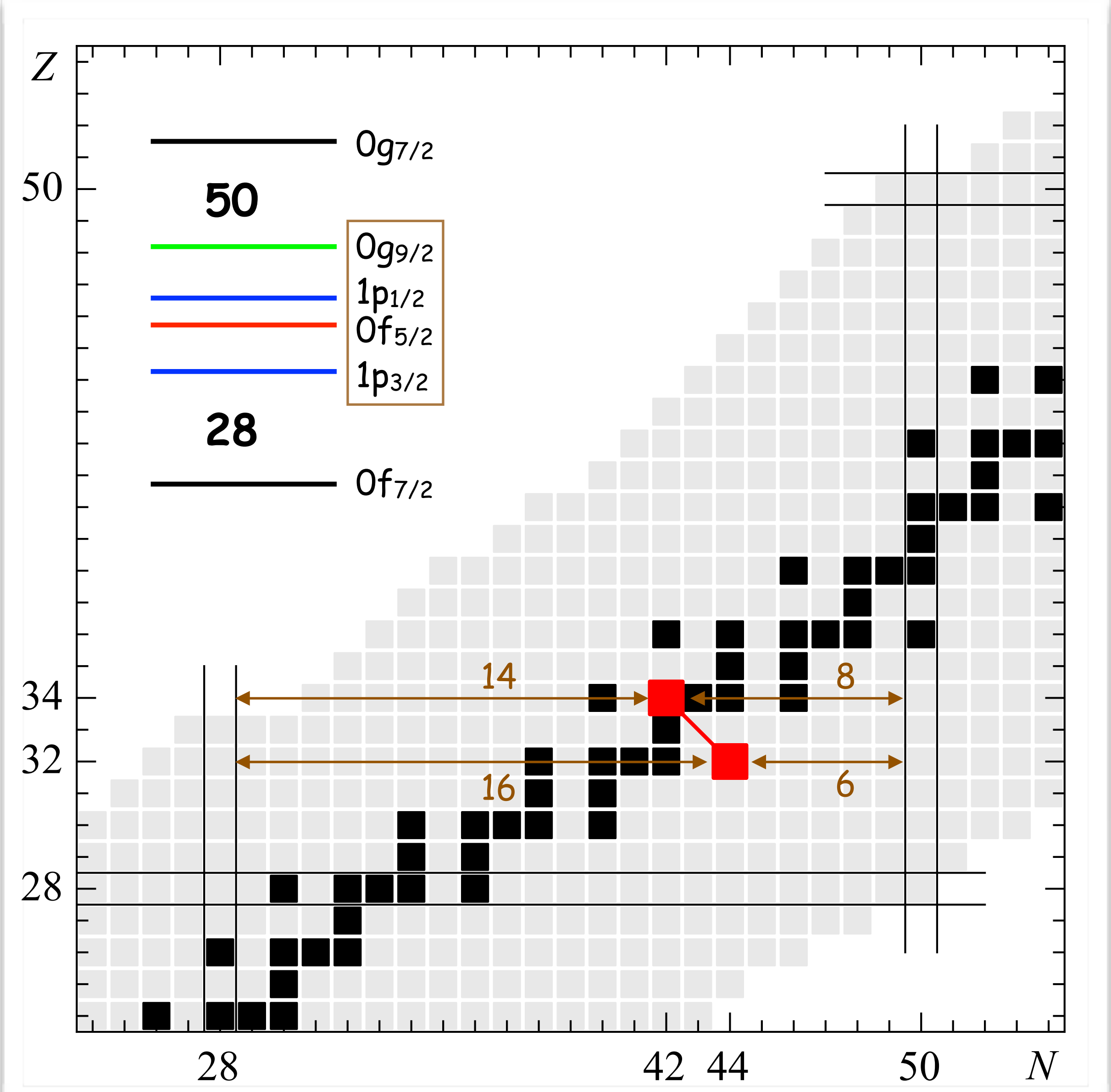


(**Mediation by a virtual neutrino gives different features:**)

- Energy of intermediate states can be large, 10's of MeV cf. a few for 2ν2β … Angular momentum can be large, 5-6 hbar cf. 1 hbar for 2ν2β
- So … it probes essentially all states, and is somewhat insensitive to the details … closure approximation used*
- Not related to 2ν2β, so no short cuts. No obvious probes that connect the **initial and final ground states** e.g., ^{76}Ge(^{18}Ne,^{18}O)^{76}Se.

A look at $^{76}Ge \rightarrow {}^{76}Se$, e.g., neutrons

What is the occupancy and vacancy of the active orbitals? How is the proton/neutron strength distributed (nature of the Fermi surface)? **How does it change from parent to daughter? -- NUCLEON TRANSFER REACTIONS can answer this.**

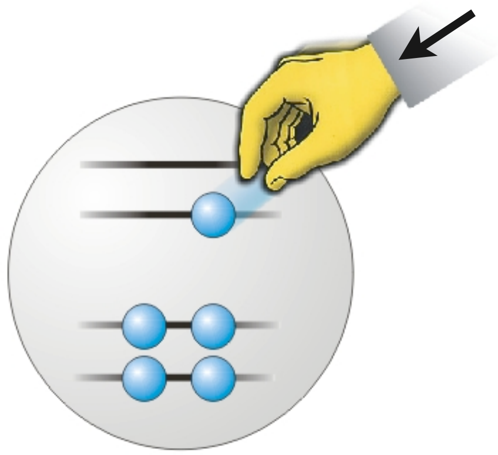


Tools of the trade — transfer reactions

A well understood probe of nuclear structure, much of the formalism developed in the late 50s / early 60s. Exploited to great effect.

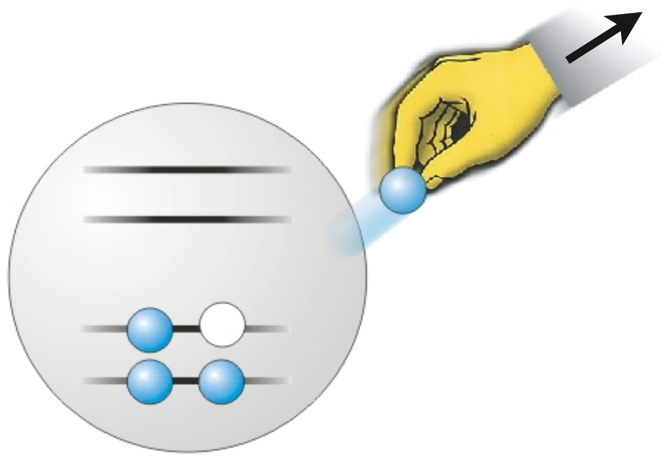
Single-nucleon **ADDING** probes the **EMPTINESS** of the orbital, or the **VACANCY**

(cross section proportional to how many 'spaces' available in the orbital)



Single-nucleon **REMOVAL** probes the **FULLNESS** of the orbital, or the **OCCUPANCY**

(cross section proportional to how many particles that are in the orbital)



From these cross sections, the occupancy and vacancy of orbitals can be determined ...

Tools of the trade — transfer reactions (Convenient example)

^{64}Ni(d,p)

E (keV)	j^π	$(2j+1)S'_{\text{adding}}$
0	$5/2^-$	1.18
63	**ℓ = 1**	**0.91**
310	**ℓ = 1**	**0.1**
693	**ℓ = 1**	**0.36**
1017	$9/2^+$	
1418	**ℓ = 1**	**0.1**
1594	$(7/2^-)$	
1920	$5/2^+$	
2147	**ℓ = 1**	**0.05**
2336	$(9/2^+)$	
2793	$(5/2^+)$	
2829	()	

^{64}Ni(p,d)

E (keV)	j^π	S'_{removing}
0	**ℓ = 1**	**0.25**
87	$5/2^-$	1.47
156	**ℓ = 1**	**1.12**
518	**ℓ = 1**	**0.37**
1001	**ℓ = 1**	**0.23**
1292	$9/2^+$	
2149	**ℓ = 1**	**0.23**
2297	$(5/2^+)$	
2519	$9/2^+$	
2953	$1/2^+$	

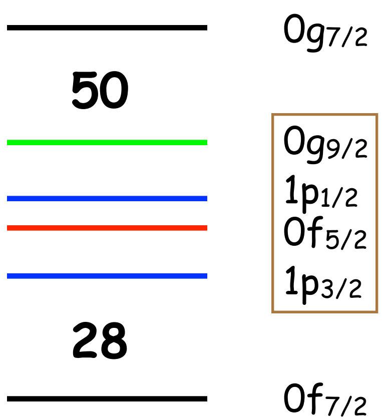
$$F_q \equiv (\Sigma(2j+1)S'_{\text{adding}} + \Sigma S'_{\text{removing}})/(2j+1)$$

$$F_q(\ell=1) \equiv ((0.91+0.10+0.36+0.10+0.05) + (0.25+1.12+0.37+0.23+0.23))/(2+4) = 0.62$$

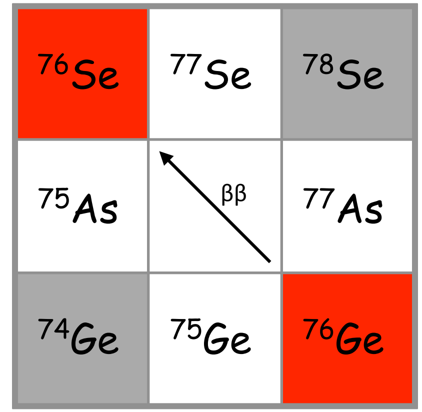
... this normalization is not arbitrary, it is seemingly ubiquitous across all nuclei, reactions, etc. **Key to use this normalization to compare to the calculations**.

Validity, consistency checks …

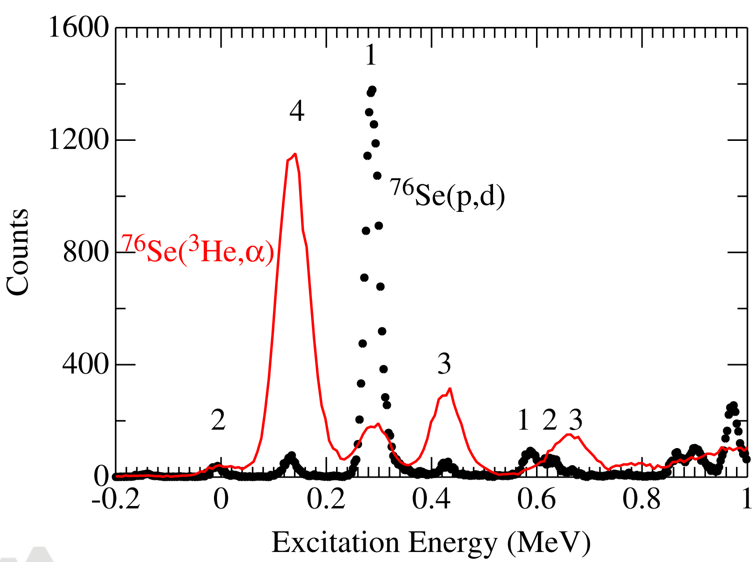
So we have the methodology, but need to ensure the reactions are performed such that they **best satisfy the assumptions made in DWBA**

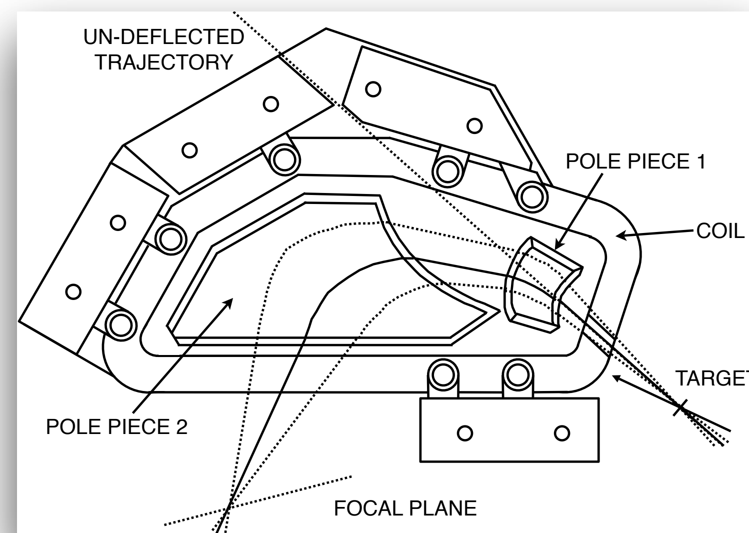


(p,d) for 1p
(^{3}He,α) for 0f, 1g



(d,p) for 1p
(α,^{3}He) for 0f, 1g





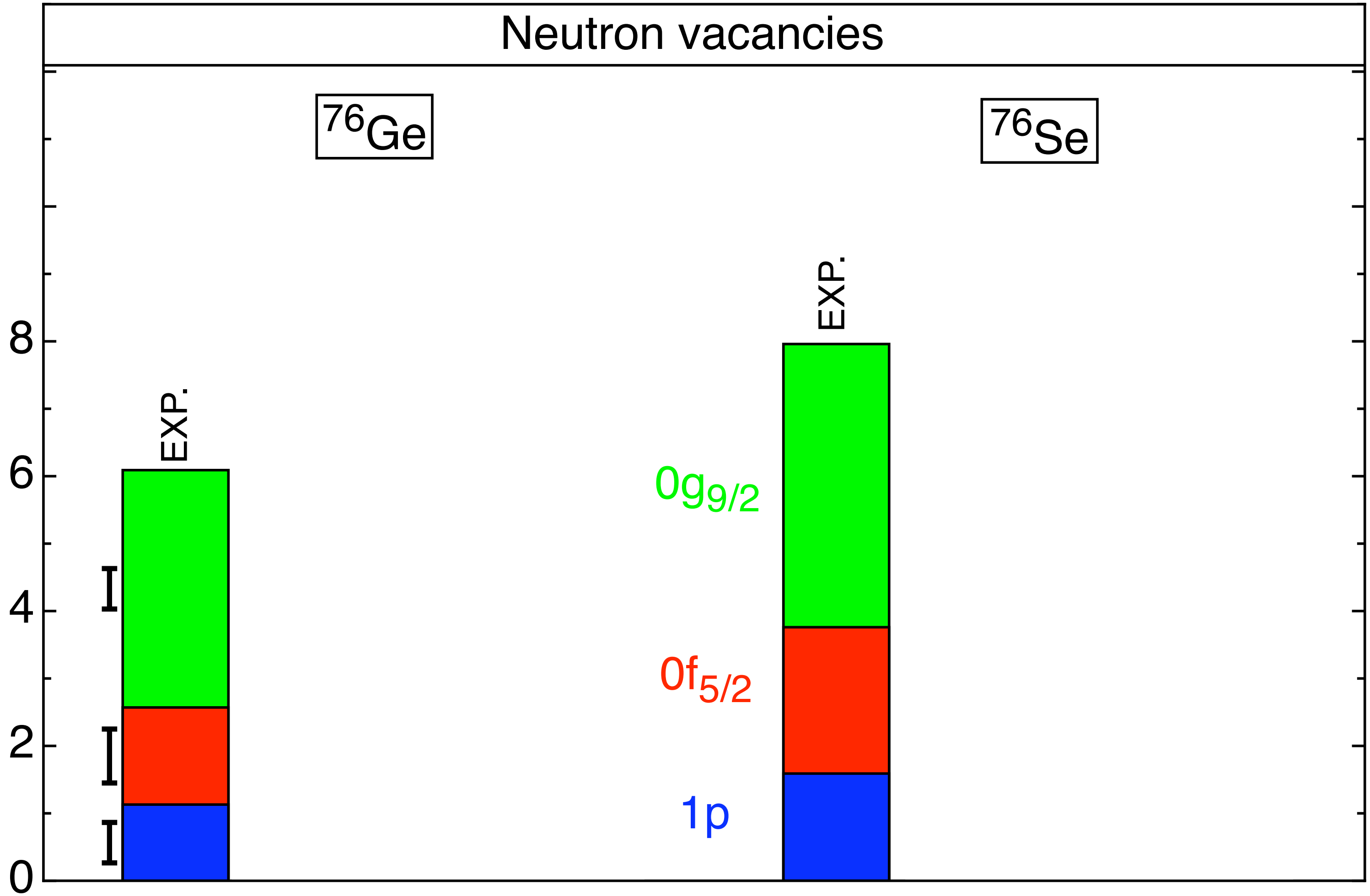
Neutron occupancies, Ge and Se

These measurements carried out at Yale using a tandem accelerator and split-pole spectrograph.

Using an **average normalization factor** – derived from the sum of observed occupancies and vacancy on an orbit-by-orbit in each isotope – the summed occupancies for the valence orbits are as follows:

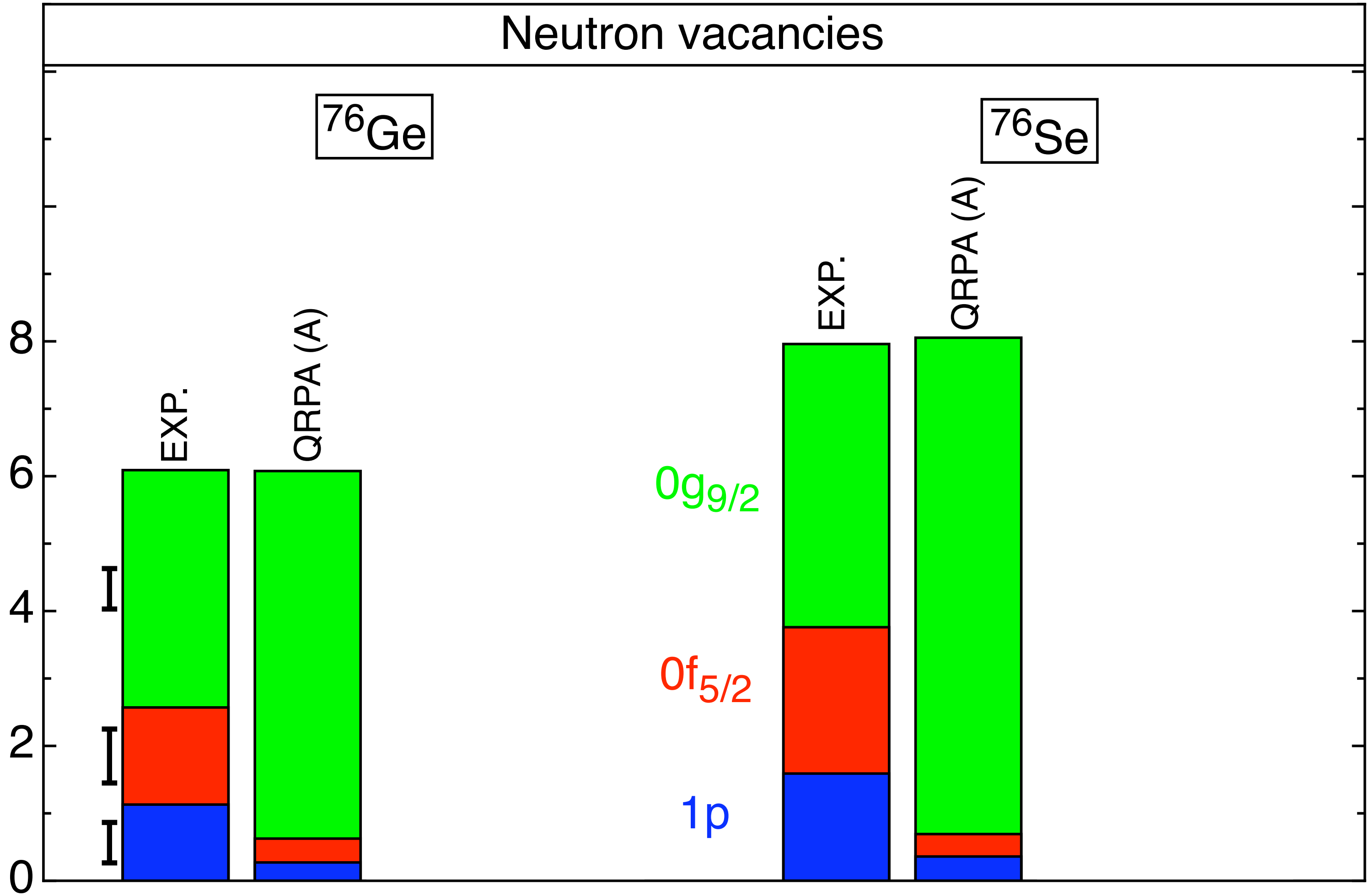
Isotope	$1p_{1/2,3/2}$	$0f_{5/2}$	$0g_{9/2}$	**Sum** **Measured [expected]**
^{74}Ge	4.9(2)	4.2(4)	5.7(3)	14.7(5) [14.0]
^{76}Ge	**4.9(2)**	**4.6(4)**	**6.5(3)**	**15.9(5) [16.0]**
^{76}Se	**4.4(2)**	**3.8(4)**	**5.8(3)**	**14.0(5) [14.0]**
^{78}Ge	5.1(2)	4.4(4)	4.0(3)	16.3(5) [16.0]

Neutron vacancies



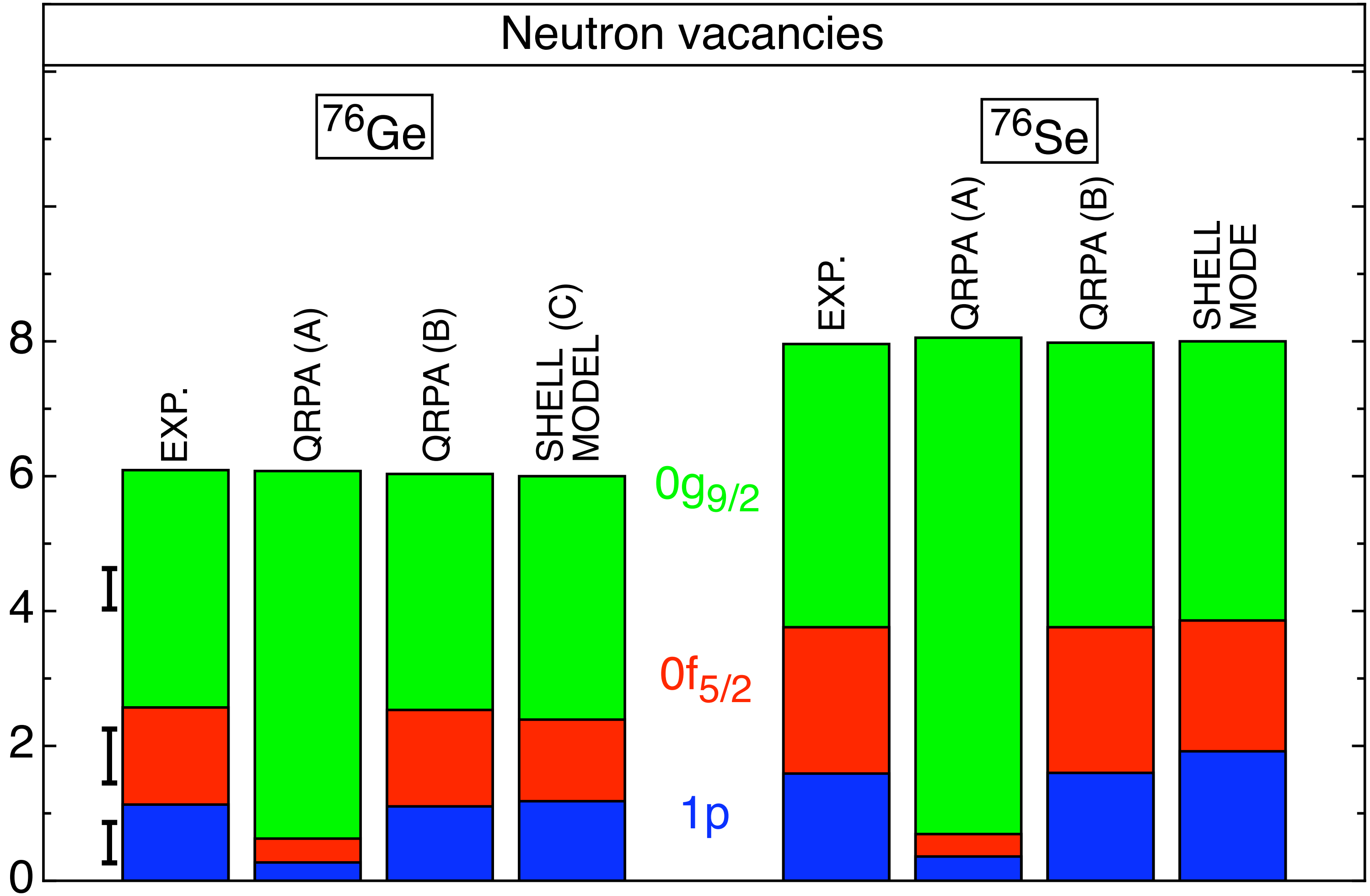
Experiment — Schiffer et al., PRL **100**, 112501 (2008)

Neutron vacancies



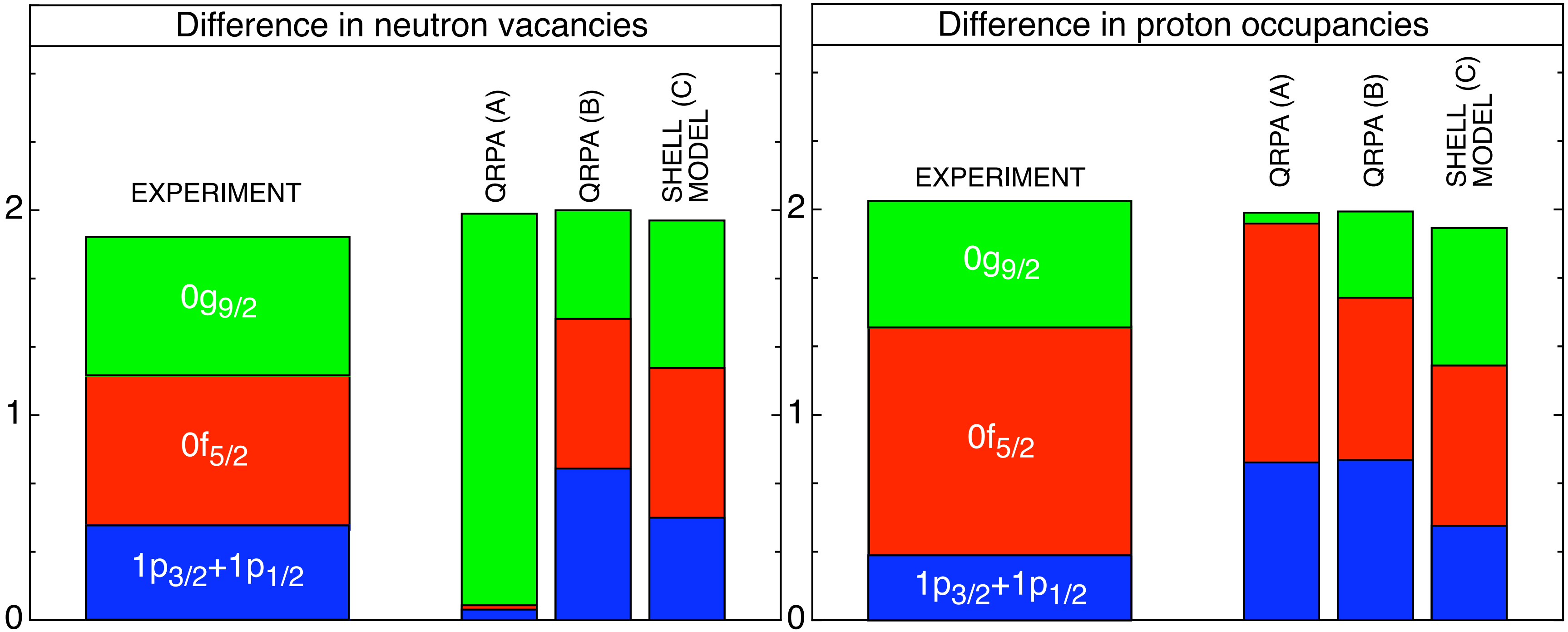
Experiment — Schiffer et al., PRL **100**, 112501 (2008)
A — QRPA calculation, Rodin et al., priv. comm. Method in NPA **766**, 107 (2006)

Neutron vacancies



Experiment — Schiffer et al., PRL **100**, 112501 (2008)
A — QRPA calculation, Rodin et al., priv. comm. Method in NPA **766**, 107 (2006)
B — QRPA calculation, Suhonen et al., priv. comm. Method in PLB **668**, 277 (2008)
C — Shell model, Caurier et al., priv. comm. Method in PRL **100**, 052503 (2008)

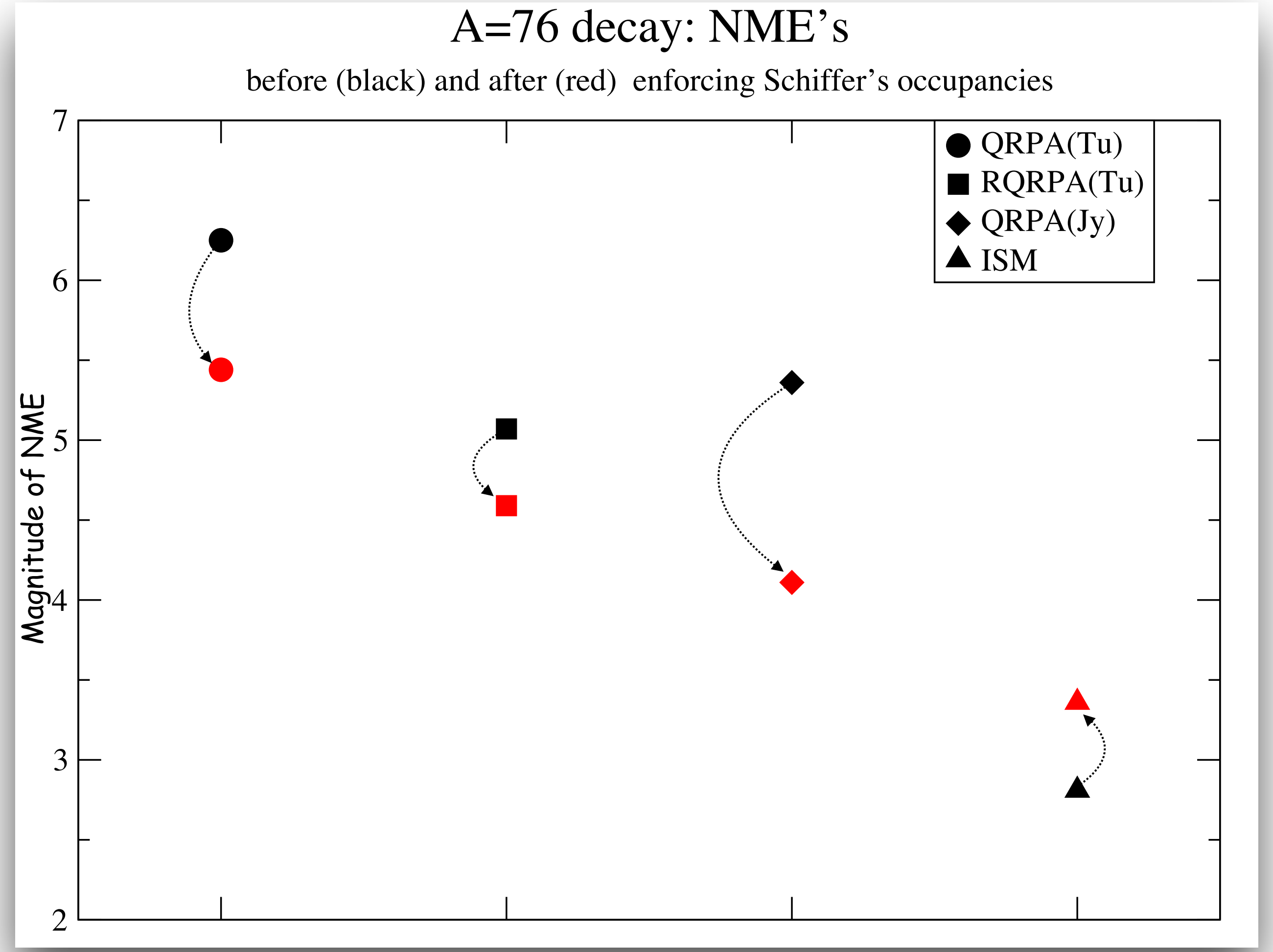
Neutron vacancies, proton occupancies



It is the difference that is important, and here we see the discrepancies more clearly. The theory, before hand, is describing a very different change between the initial and final state.

Schiffer et al., PRL **100**, 112501 (2008), Kay et al., PRC **79**, 021301(R) (2009)

$^{76}Ge \rightarrow ^{76}Se$ … impact?



Menéndez, Poves, Caurier, Nowacki, J. Phys.: Conf. Ser. **312**, 072005 (2011)
(Data from numerous papers)

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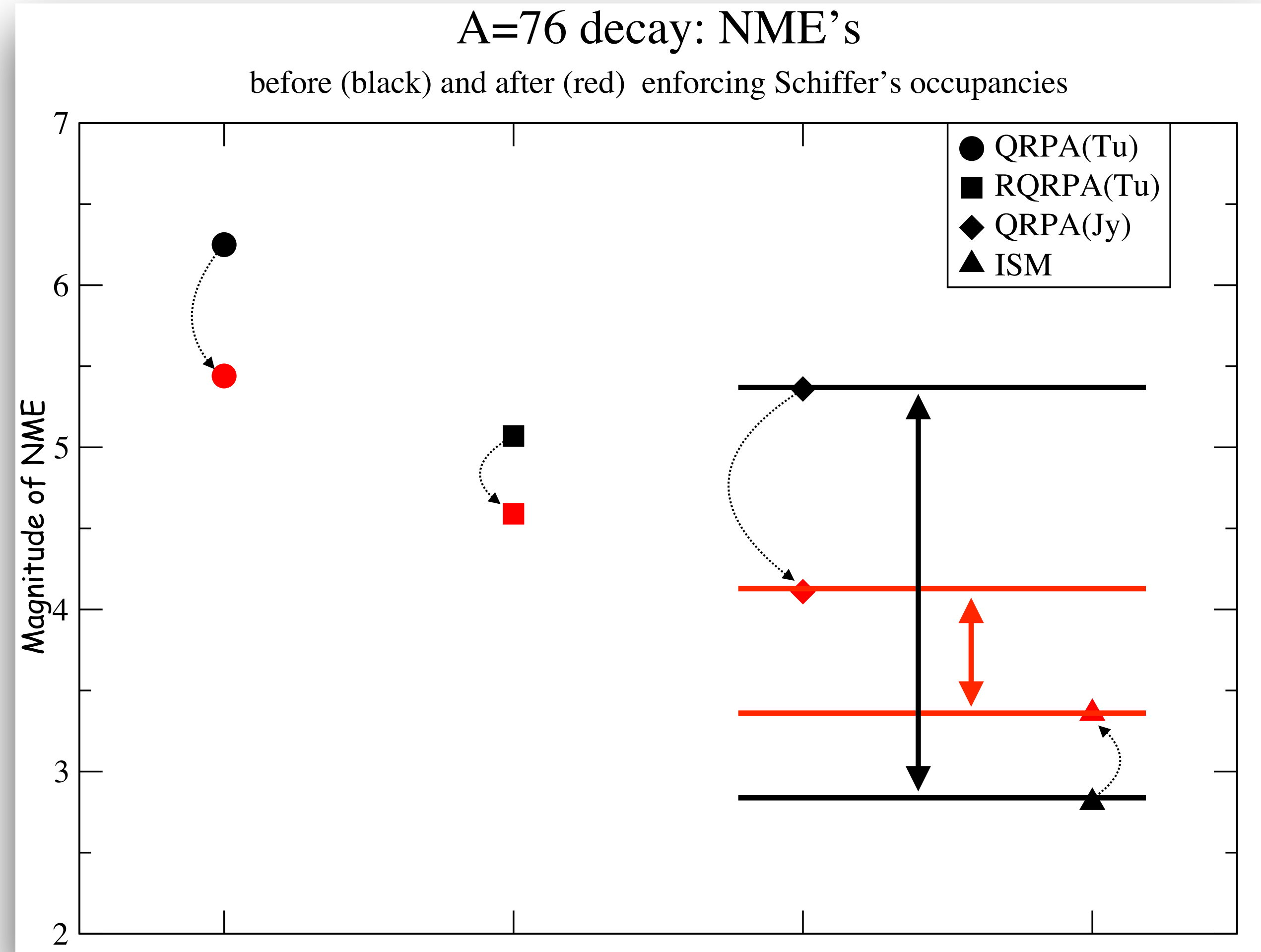
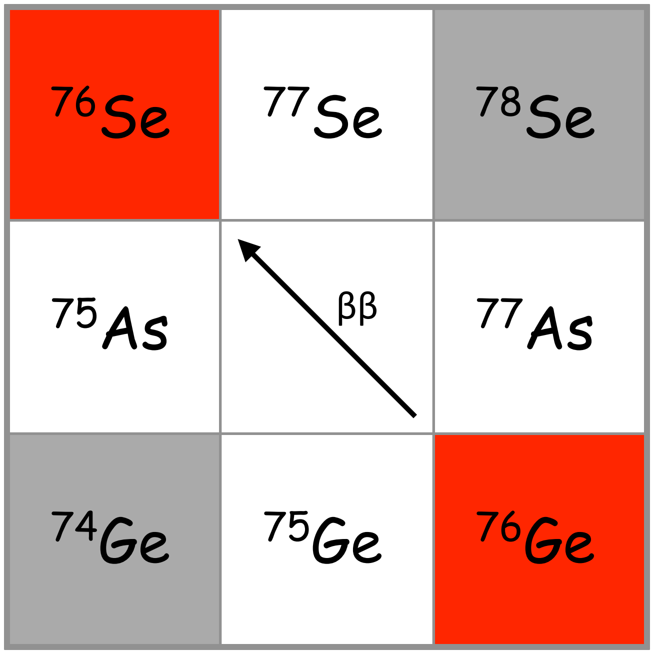


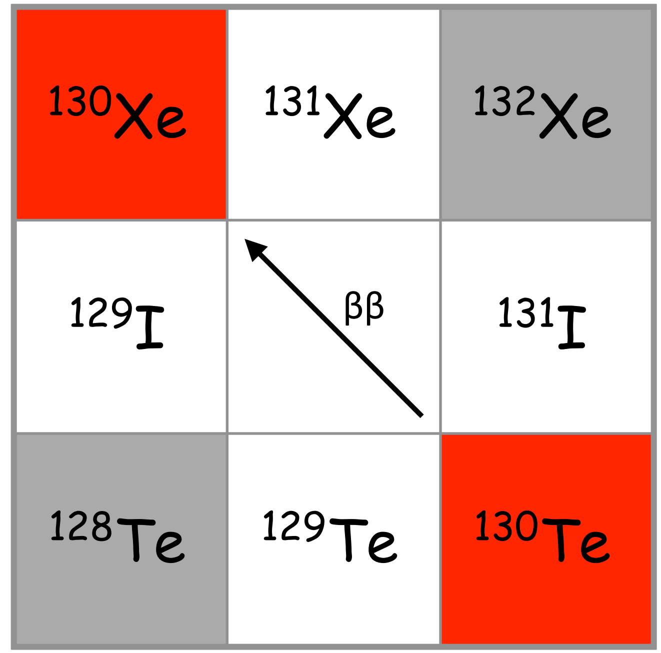
Menéndez, Poves, Caurier, Nowacki, J. Phys.: Conf. Ser. **312**, 072005 (2011)
(Data from numerous papers)

What next?

Buoyed by the success of the $^{76}Ge \rightarrow ^{76}Se$ results, we turned our attention to the subject of the CUORICINO / CUORE experiments, $^{130}Te \rightarrow ^{130}Xe$.
If we were to adopt the same approach, we have to deal with Xe isotopes, which are gaseous. We collaborated with Stuart Freedman's group at Berkeley who developed a cryogenic Xe target for use at Yale.



e.g. Majorana, GERDA

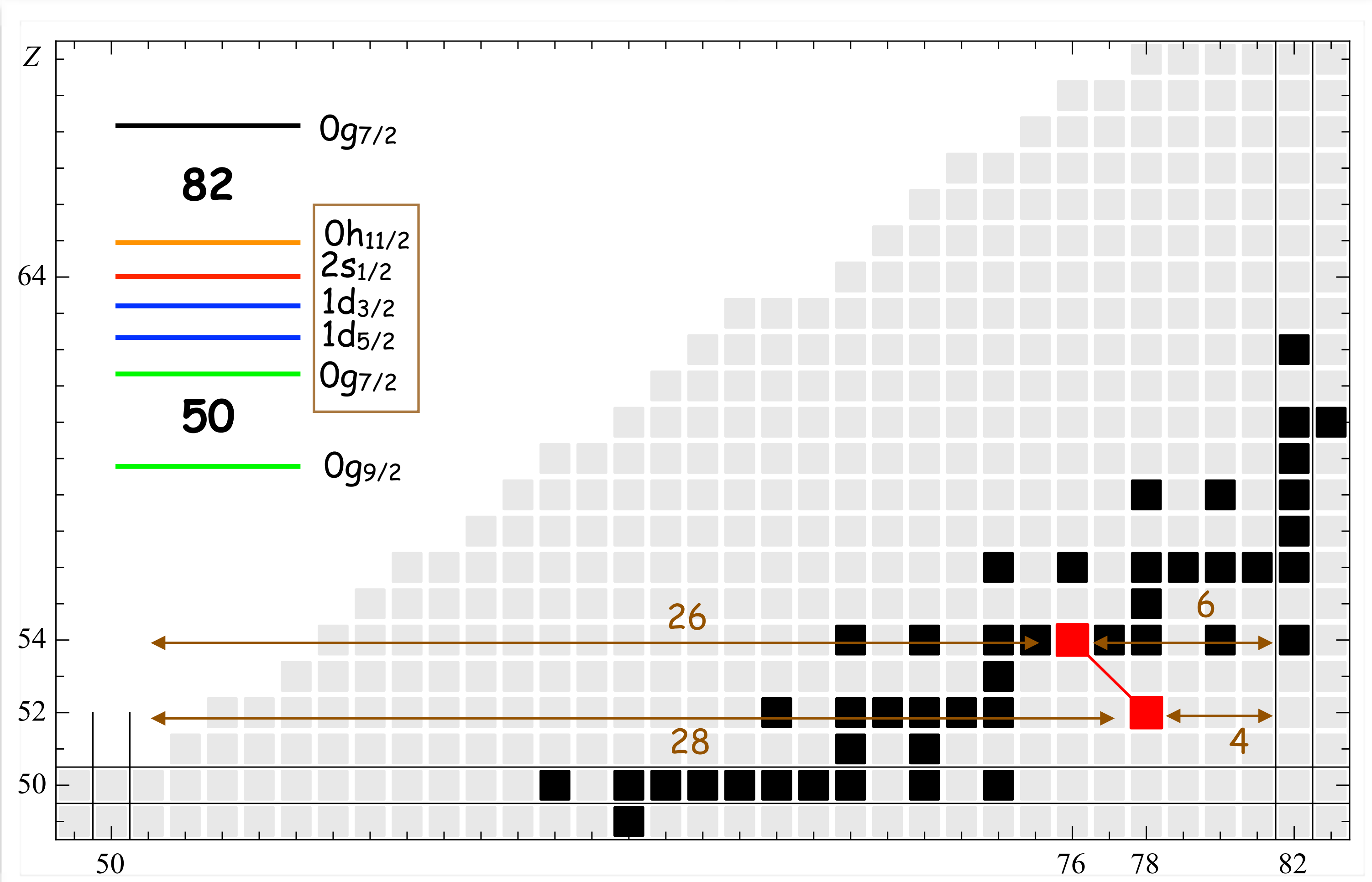


e.g. CUORE

CUORE-0 submitted their first results to PRL just recently (see arXiv last week, 1504.0245v1[nucl-ex])

$^{130}Te \rightarrow ^{130}Xe$ — the landscape

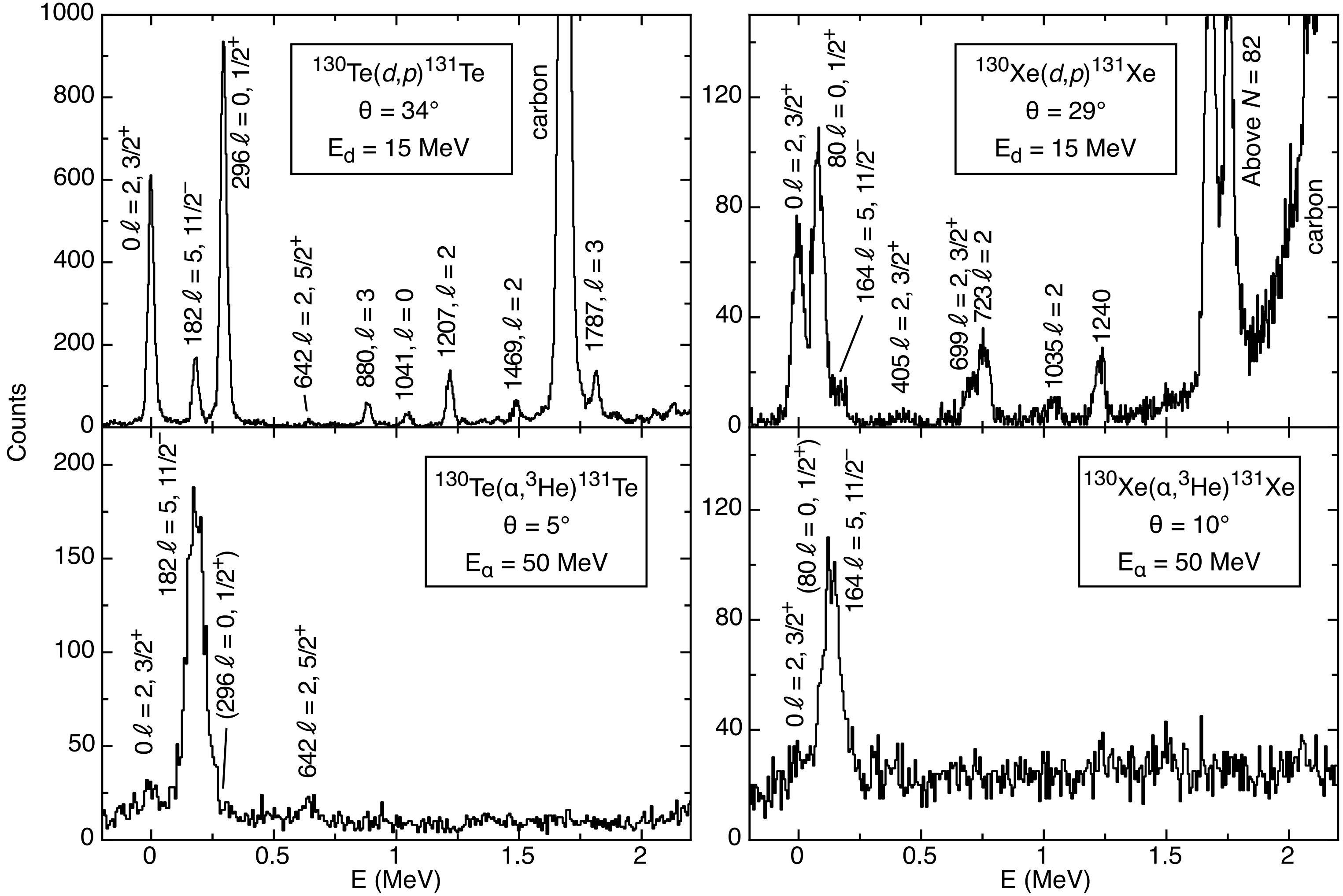
We focused on neutrons first … (lessons learned from the Ge/Se experience)



Neutron adding on Te, Xe

No evidence of $0g_{7/2}$ (ℓ = 4) strength up to 5 MeV (not shown) in the (α,^{3}He) reaction

(ℓ = 4 seen in when probed the occupancies, but is deeply bound / fragmented, so only see limit strength)

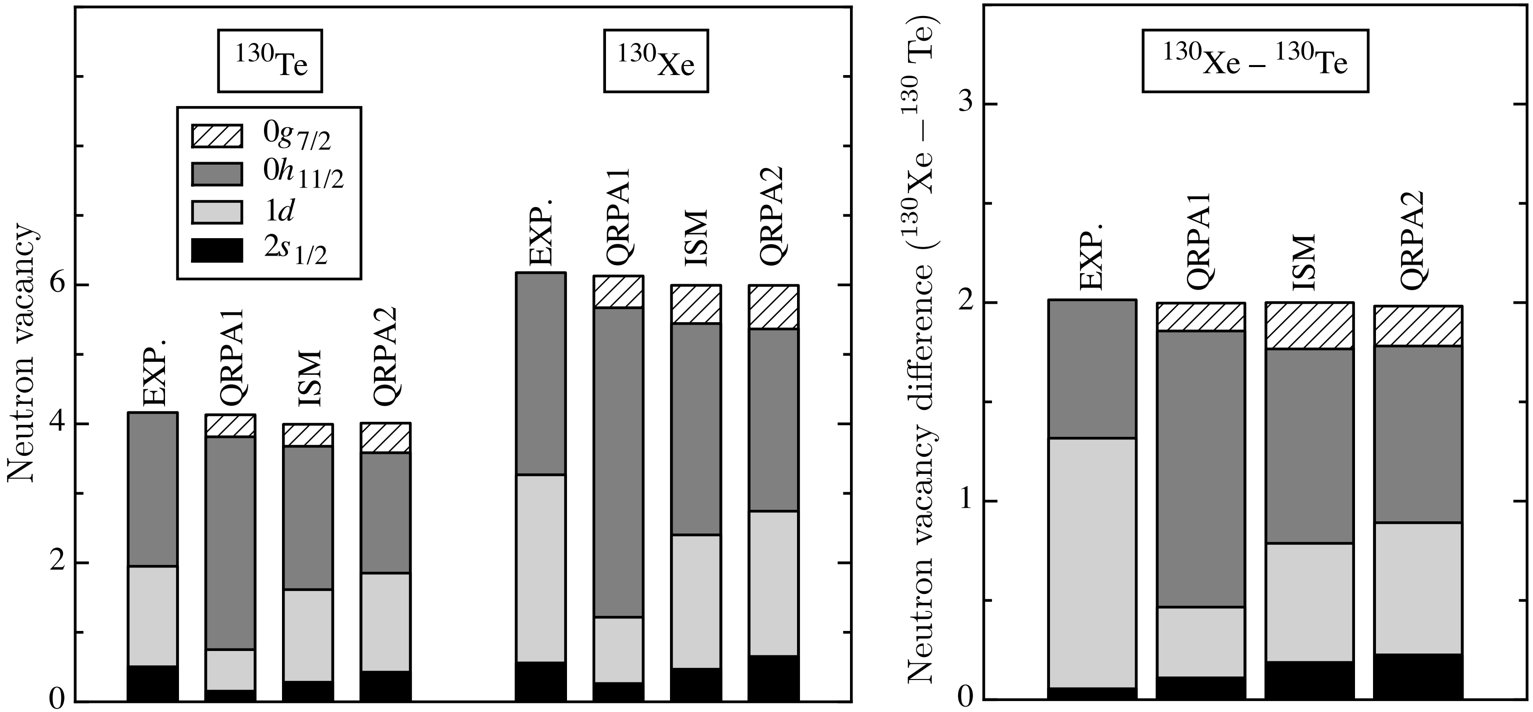


BPK et al., Phys. Rev. C **87**, 011302(R) (2013)

Neutron vacancies, A = 130

TABLE 1. Neutron vacancies.

Target	$2s_{1/2}$	$1d$	$0g_{7/2}$	$0h_{11/2}$	Total [Expected]
^{128}Te	0.72	2.06	0	3.34	6.13 [6]
^{130}Te	0.50	1.45	0	2.21	4.16 [4]
^{130}Xe	0.56	2.71	0	2.99	6.26 [6]
^{132}Xe	0.26	1.96	0	1.77	3.99 [4]



Kay et al., PRC **87**, 011302(R) (2013)
Calculations from Suhonen and Civitarese NPA **847**, 207 (2010).

Neutron vacancies, A = 130 … progress?

(or does it speak to the challenges of using the shell model for heavy systems)

TABLE 1. Neutron vacancies.

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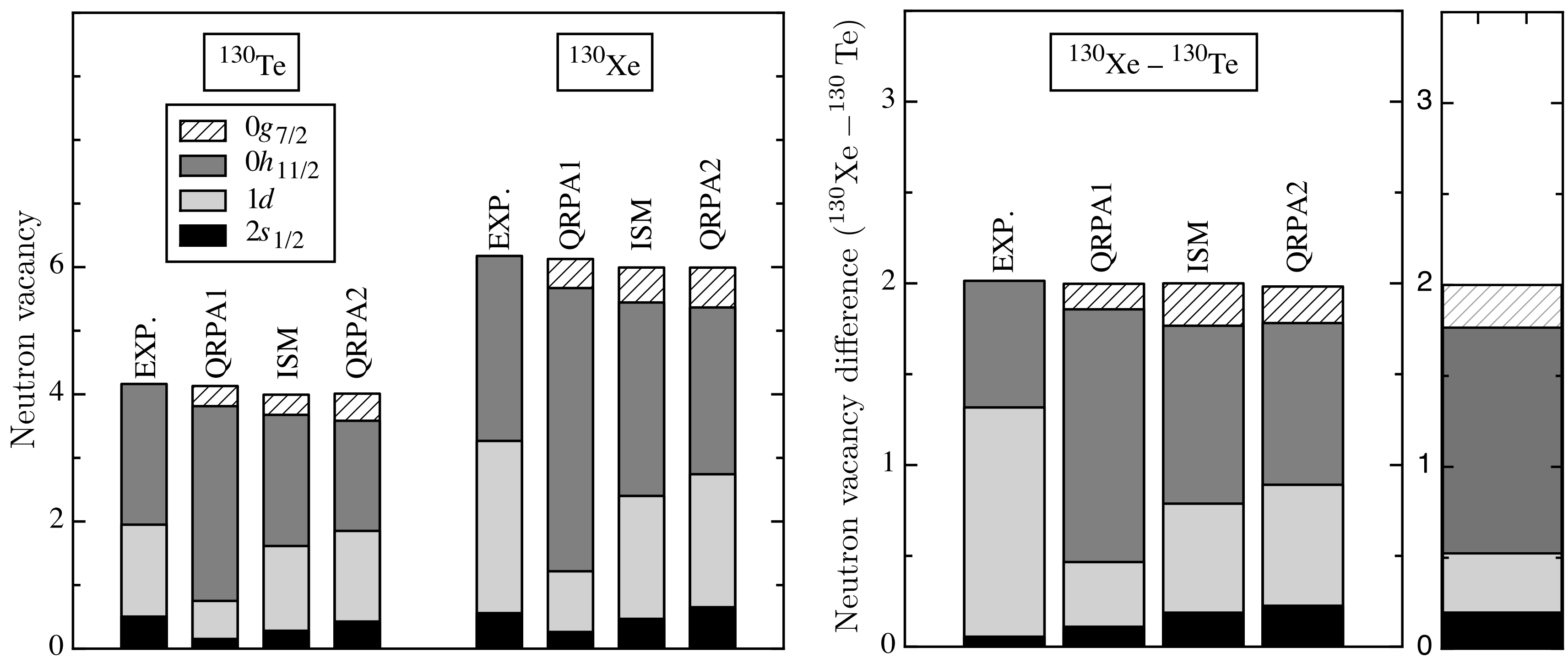


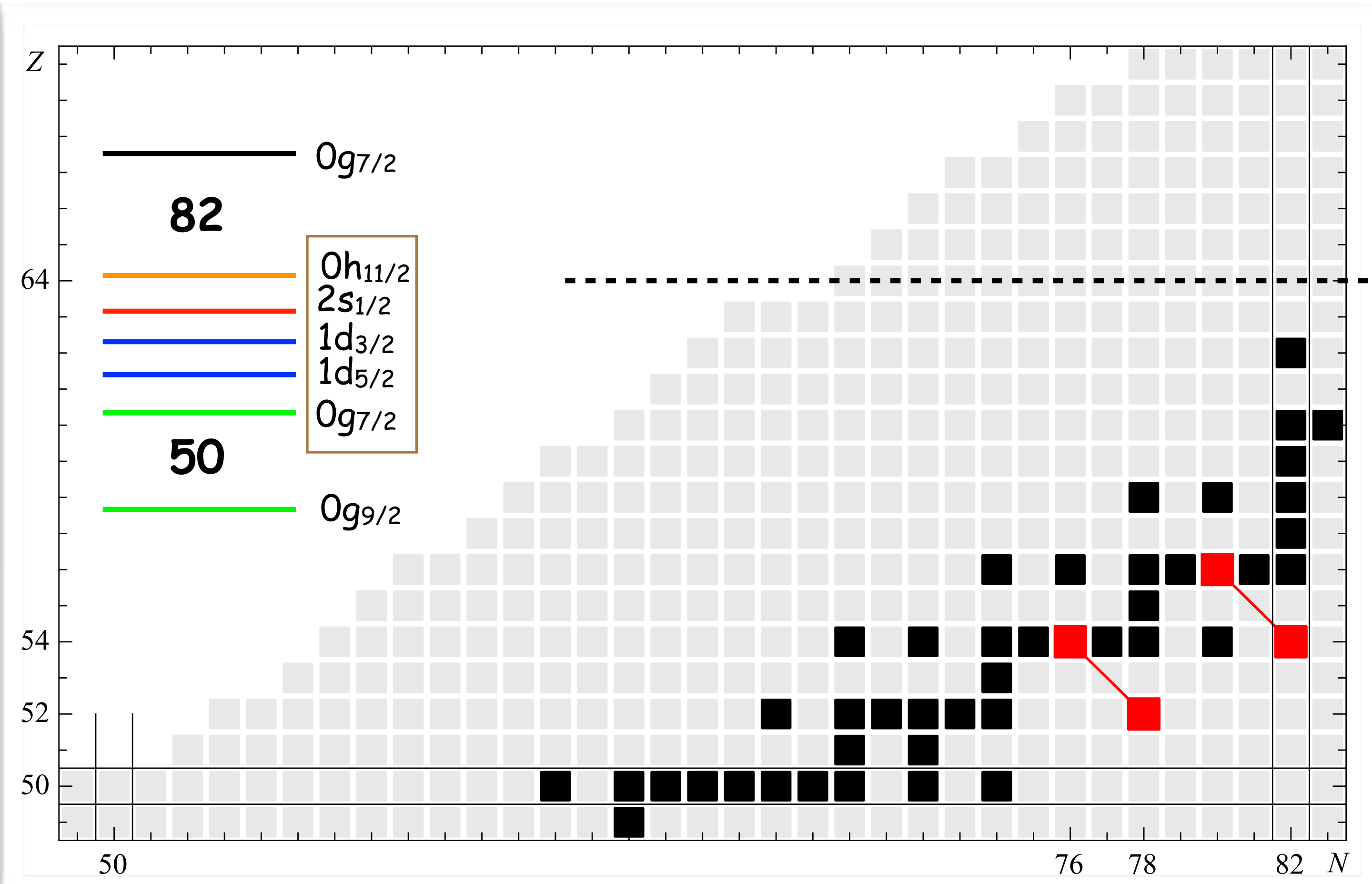
Kay et al., PRC **87**, 011302(R) (2013)

Calculations from Suhonen and Civitarese NPA **847**, 207 (2010).

Neacsu and Horoi, PRC **91**, 024309 (2015)

Protons, $^{130}Te \rightarrow ^{130}Xe$, $^{136}Xe \rightarrow ^{136}Ba$

In the course of our work, **the major successes of the $^{136}Xe \rightarrow ^{136}Ba$ 2/0ν2β experiments, EXO-200 and KamLAND-Zen**, have come about. This system demands attention too.
Here we first tackle the protons as we had already started to plan these measurements for $^{130}Te \rightarrow ^{130}Xe$ system at RCNP (Osaka University), following the success of the Ge/Se measurements.



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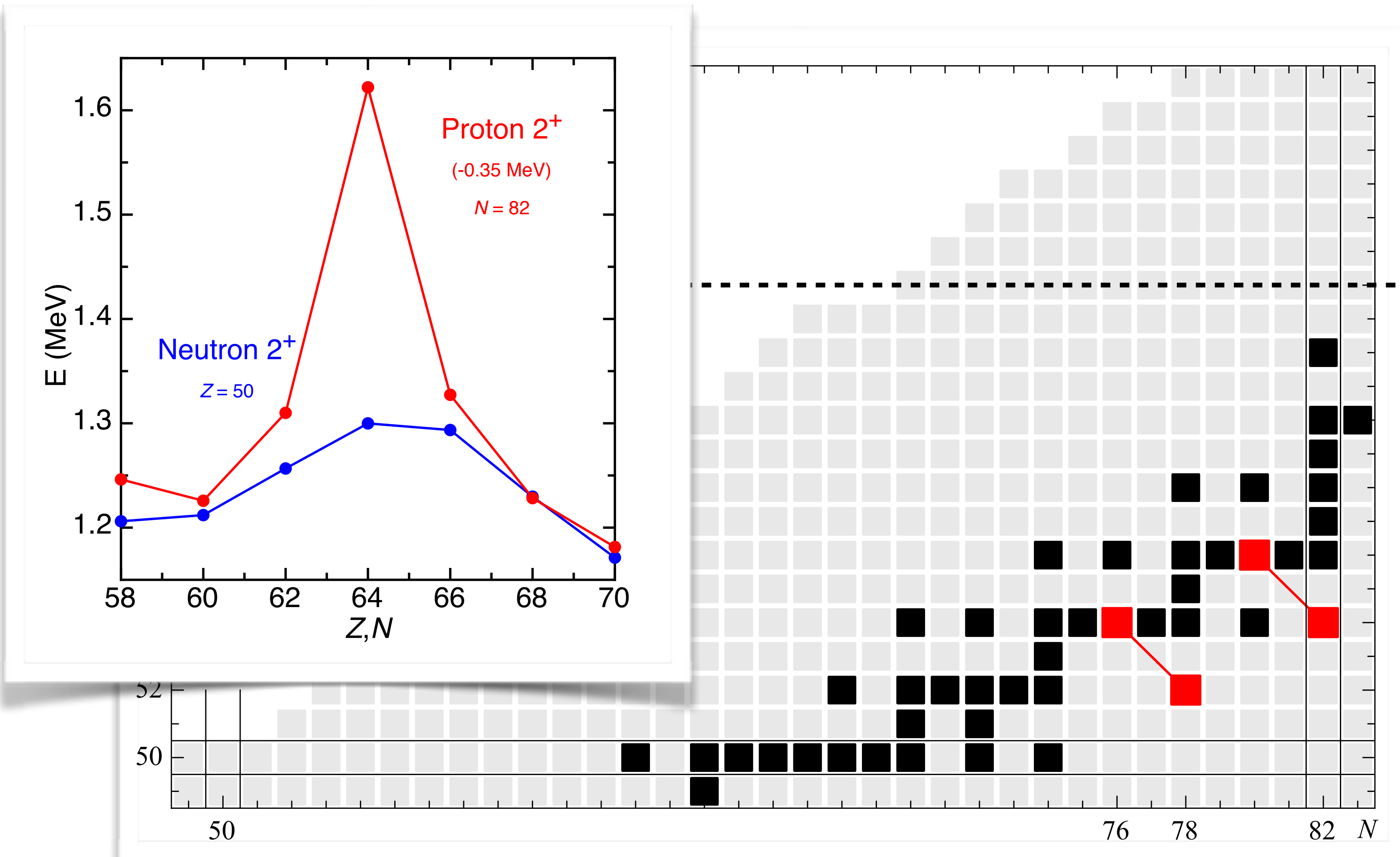
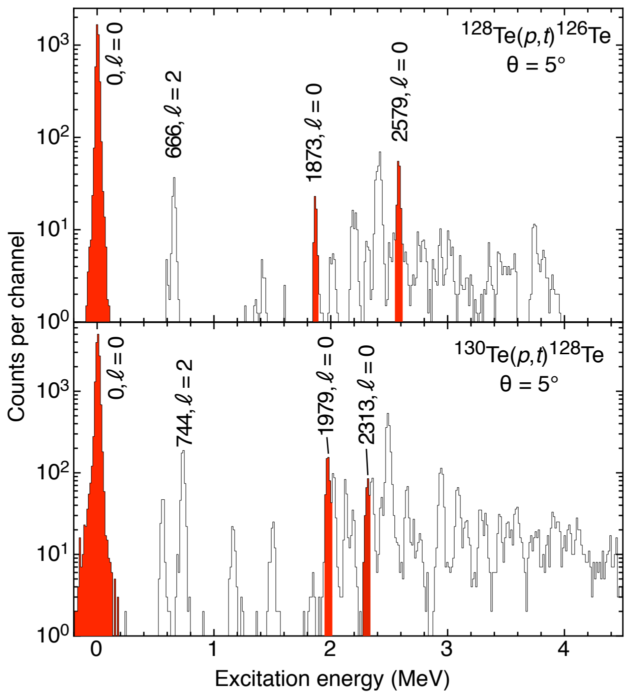


Brief comment on pairing / Z = 64



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

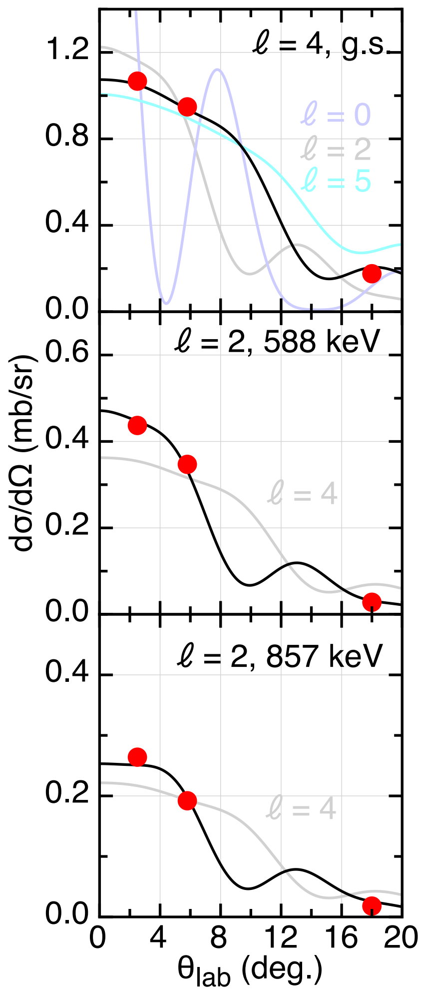
From the proton-pair adding Te(^{3}He,n) reactions by Alford et al., **significant strength is seen in ℓ= 0 transitions to excited states**

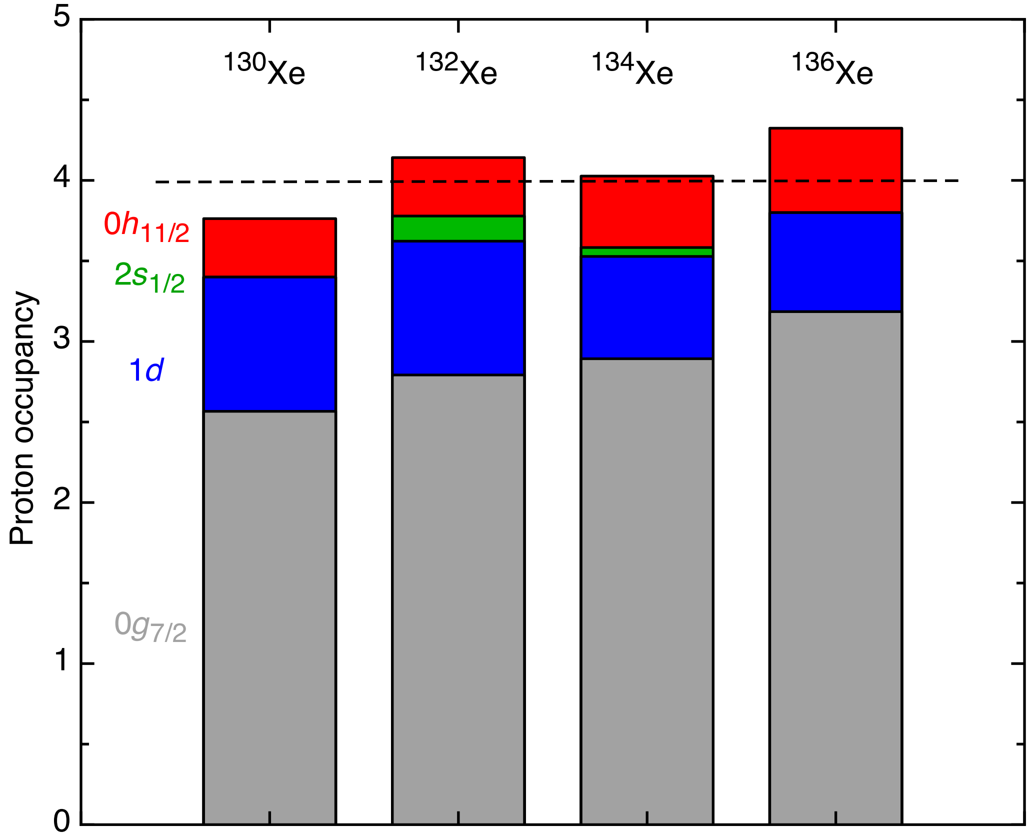
A **classic case of pair vibration** and possibly a consequence of a sub-shell gap at **Z = 64**
Consequences for QRPA? (Does the shell model include this feature also?)

T. Bloxham et al., PRC **82**, 027308 (2010)
W. P. Alford et al., NPA 323, 339 (1979)

(Very) early exploration of the data … encouraging

An experiment which was carried out late in 2014 at RCNP, Osaka University.





J. P. Entwisle, Manchester PhD student, **PRELIMINARY**

So … where do things stand? … ~1 decade in after we started

- The Ge-Se work, mapping out the proton and neutron occupancies, had a major impact on theory …

- (We have also explored the role of pairing vibrations—a nuclear-structure feature that, if present, voids one of the a priori assumptions in one of the leading theory approaches, QRPA.)

- With that said, it is not clear what the answer to the NME 'obstacle' is. They are inherently complex calculations … is there a simple answer?

- Theoretical calculations are now routinely compared to our data (highly cited works).

- The occupancies of the $^{100}Mo \rightarrow ^{100}Ru$, $^{130}Te \rightarrow ^{130}Xe$, $^{136}Xe \rightarrow ^{136}Ba$, $^{150}Nd \rightarrow ^{150}Sm$ systems at various stages of complete.

- Program moving at a rapid pace… others working on different aspects of the problem, and plans to study other systems

Collaborators

This work, initiated by John Schiffer, has been going on for just shy of 10 years now, with measurements made at several labs (WNSL, RCNP, Munich, Orsay, Notre Dame) involving lots of people. (In most instances, targets prepared by J. P. Greene.) (Several people have changed institution.)

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