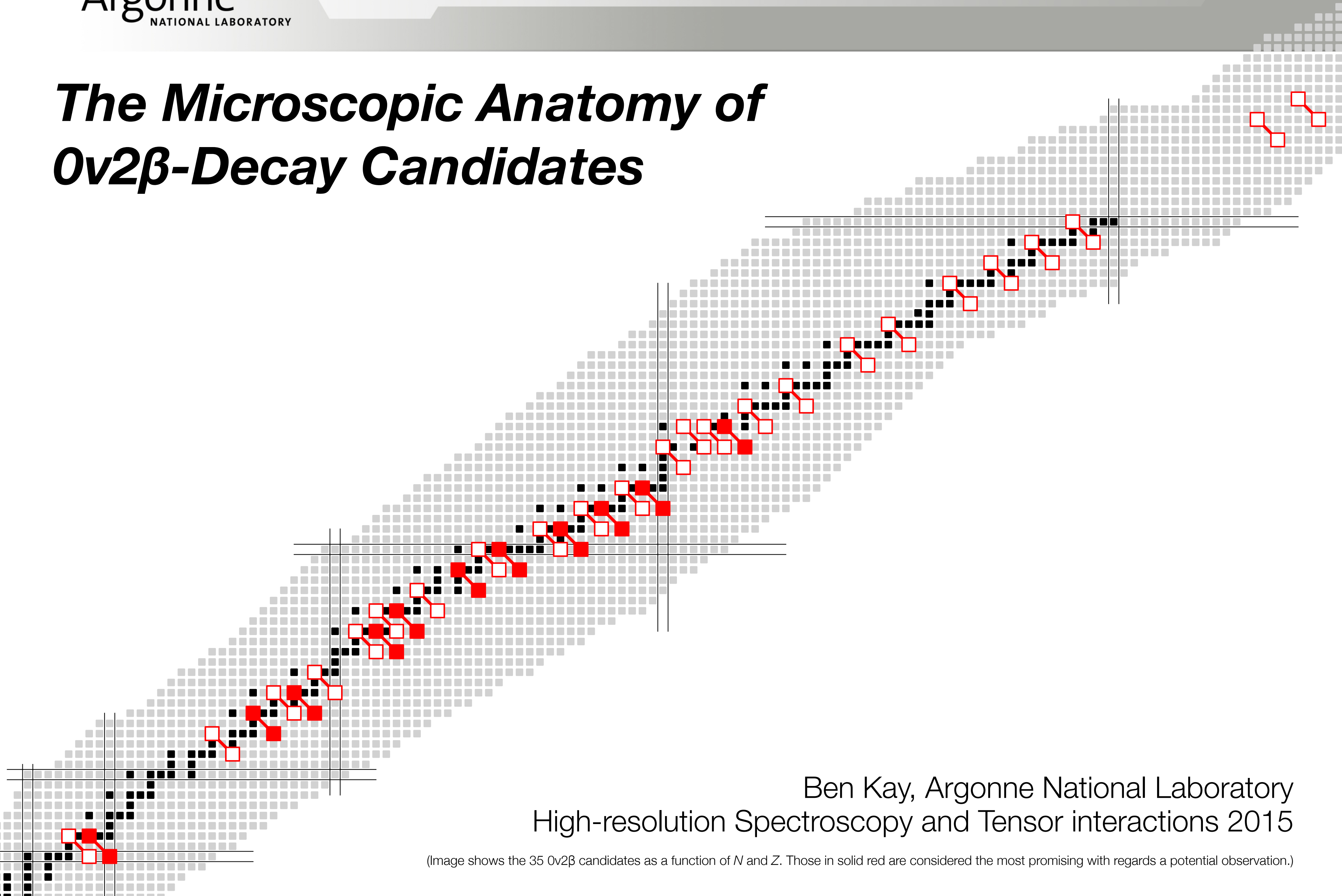
The Microscopic Anatomy of 0v2β-Decay Candidates



Ben Kay, Argonne National Laboratory
High-resolution Spectroscopy and Tensor interactions 2015

(Image shows the 35 0v2β candidates as a function of *N* and *Z*. Those in solid red are considered the most promising with regards a potential observation.)

Overview

- ***A brief introduction***
  - *double beta decay, the candidates, nuclear matrix elements, transfer reactions*
- ***The ^{76}Ge→^{76}Se system*** (work from 2008 and 2009, a recap)
  - *results and impact*
- ***The ^{130}Te→^{130}Xe and ^{136}Xe→^{136}Ba systems*** (2013 and 2015)
  - *Overview of the landscape*
  - *Existing data on the neutron vacancies for the A = 130 system*
  - ***New data** on the proton occupancies for A = 130 and 136*
  - ***New data** on the neutron occupancies for A = 136*

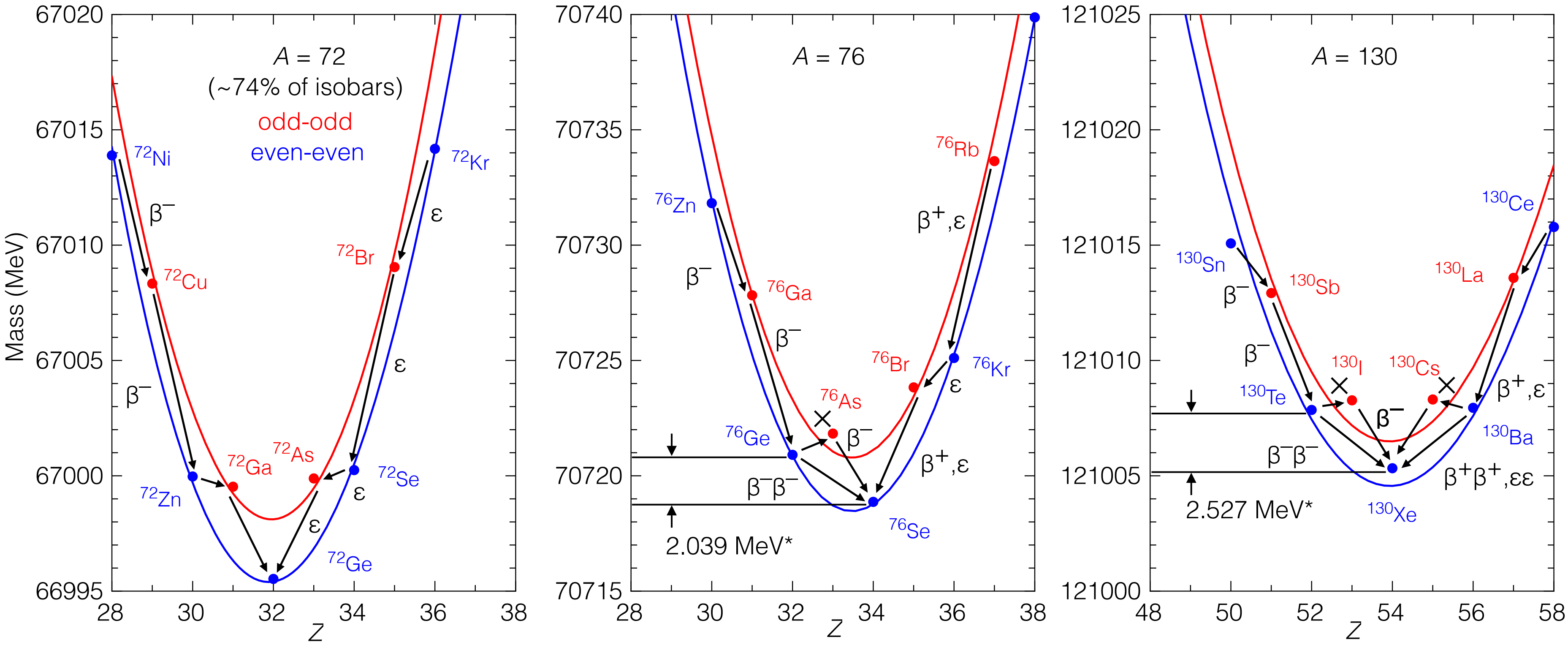
RCNP

- ***Comparison with available calculations***
  - *Detailed comparisons with recent results from the CMU group (2015)*
- ***Outlook and conclusions***
  - *Moving towards complete data sets for key isotopes including the **^{100}Mo→^{100}Ru and ^{150}Nd→^{150}Sm** systems*
  - *Data soon to be available for the **^{82}Se→^{82}Kr** system*
  - *Summary*

RCNP

General discussions on this topic: S. J. Freeman and J. P. Schiffer, J. Phys. G: Nucl. Part. Phys. **39**, 124004 (**2012**)

Beta decay, double beta decay



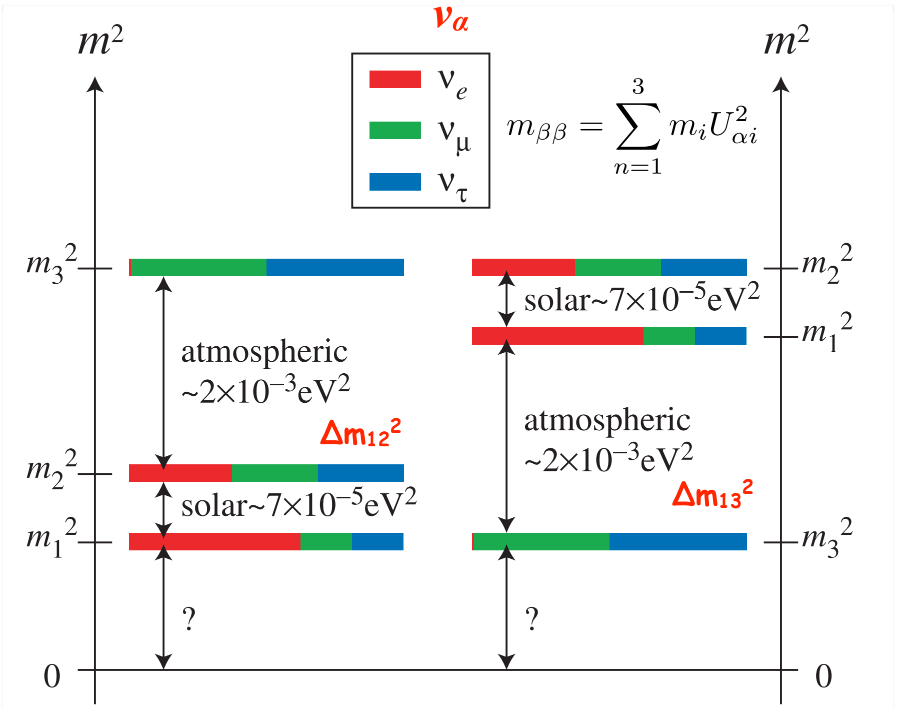
Pairing in nuclei results in a displacement of even-even and odd-odd mass parabolas for given isobars. Data from AME 2012. **Precise masses ⇒ precise Q value.**

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

Double beta decay

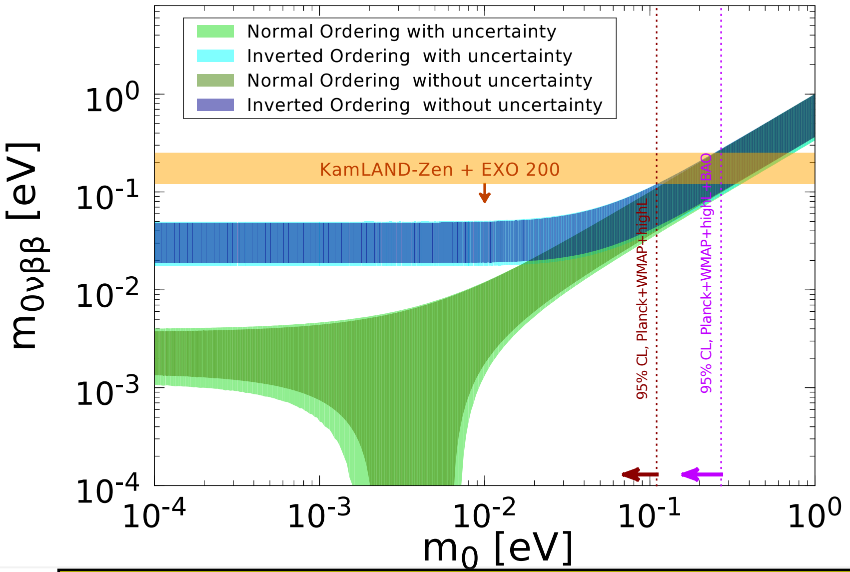
Elucidating the nature of neutrinos is one of the major challenges to contemporary science —

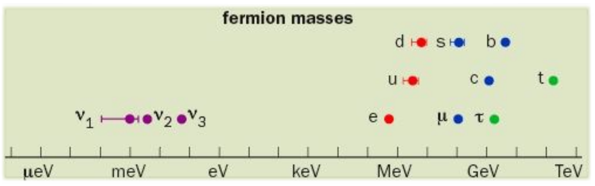
- *Majorana or Dirac?*
- *Lepton number conservation?*
- *Absolute mass scale?*
- *Mass mechanisms?*
- *Matter-antimatter asymmetry?*
- *…*



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

From King et al., Rep. Prog. Phys. 76, 056201 (2013)



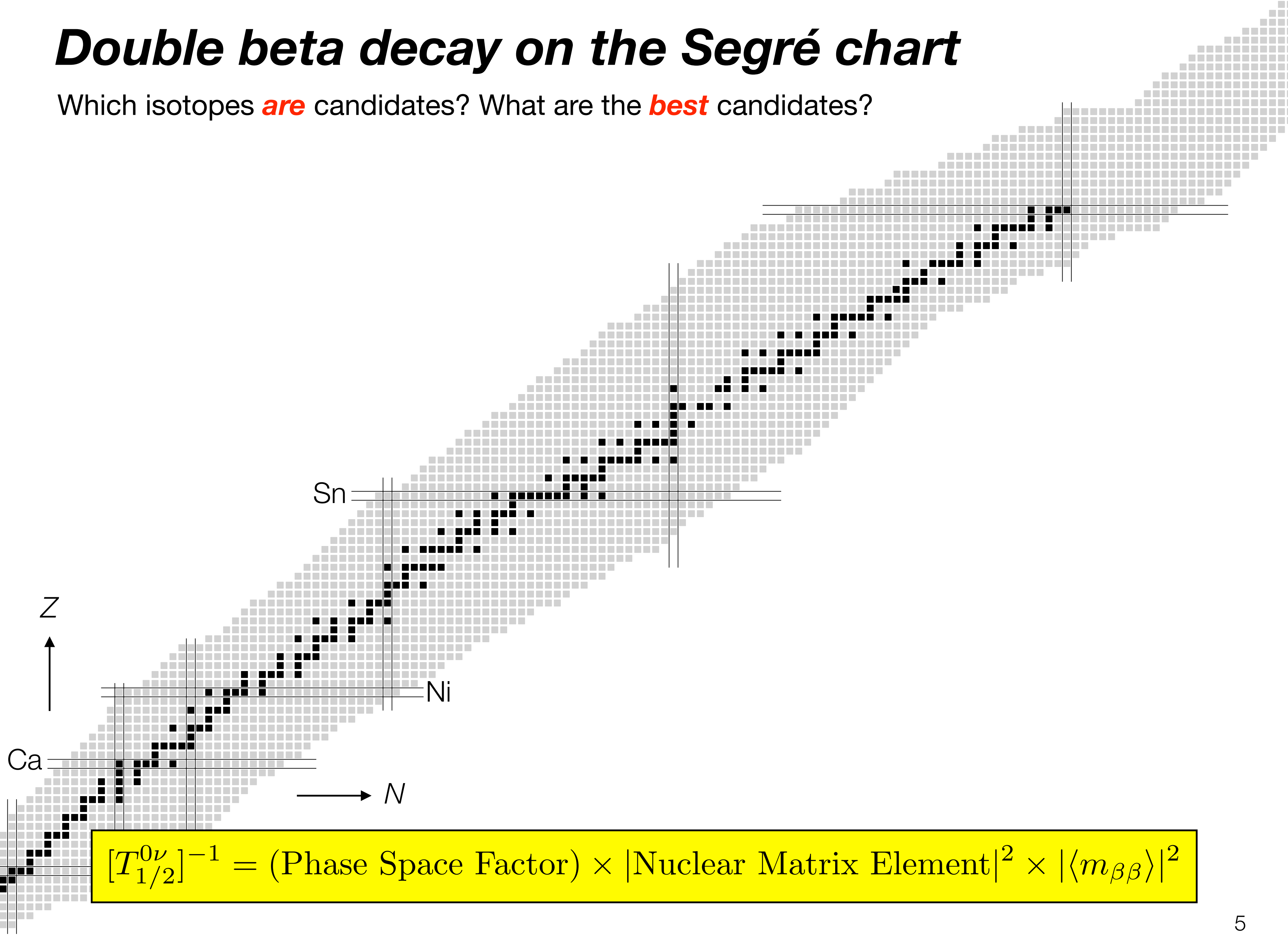


http://ctp.berkeley.edu/neutrino/neutrino5.html

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

Double beta decay on the Segré chart

Which isotopes ***are*** candidates? What 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 beta decay on the Segré chart

Which isotopes ***are*** candidates? What are the ***best*** 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%*.*

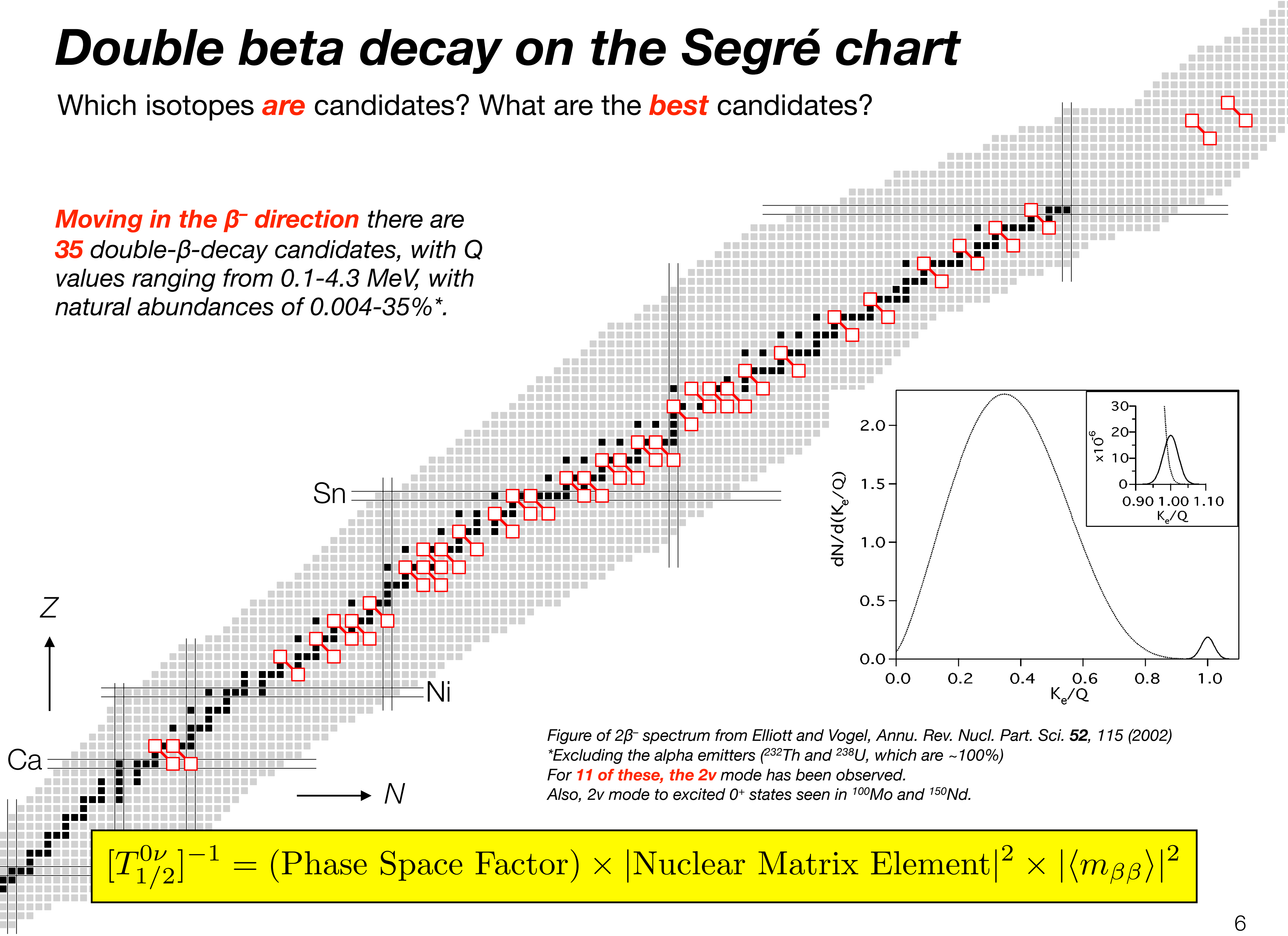


Figure of 2β⁻ spectrum from Elliott and Vogel, Annu. Rev. Nucl. Part. Sci. ***52****, 115 (2002)*

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

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

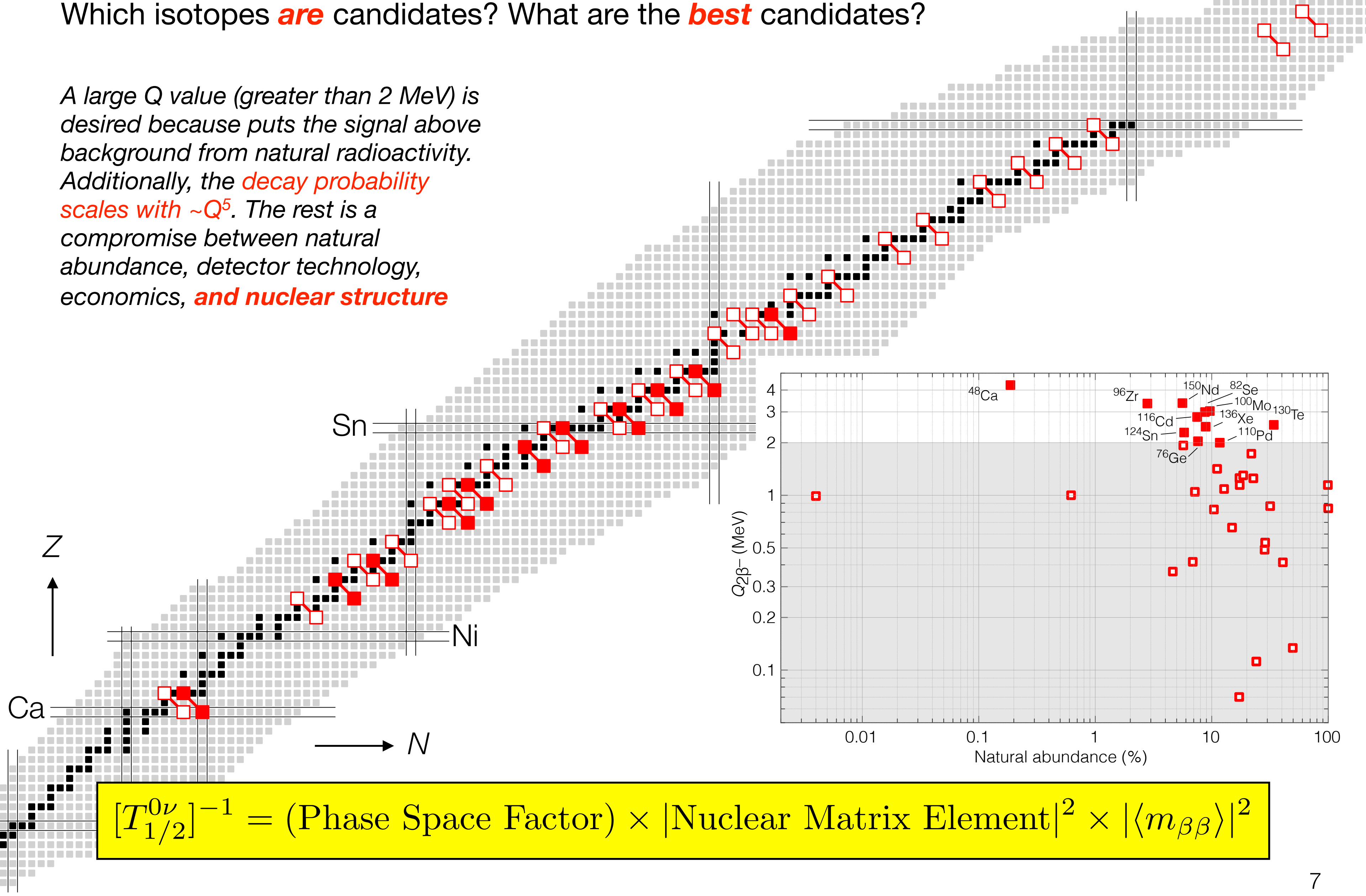
Also, 2ν mode to excited 0^+ states seen in ^{100}Mo and ^{150}Nd.

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

Double beta decay on the Segré chart

Which isotopes ***are*** candidates? What are the ***best*** candidates?

A large Q value (greater than 2 MeV) is desired because puts the signal above background from natural radioactivity. Additionally, the decay probability scales with ~Q^5. The rest is a compromise between natural abundance, detector technology, economics, ***and nuclear structure***



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

Nuclear matrix elements *(uncertainties here)*

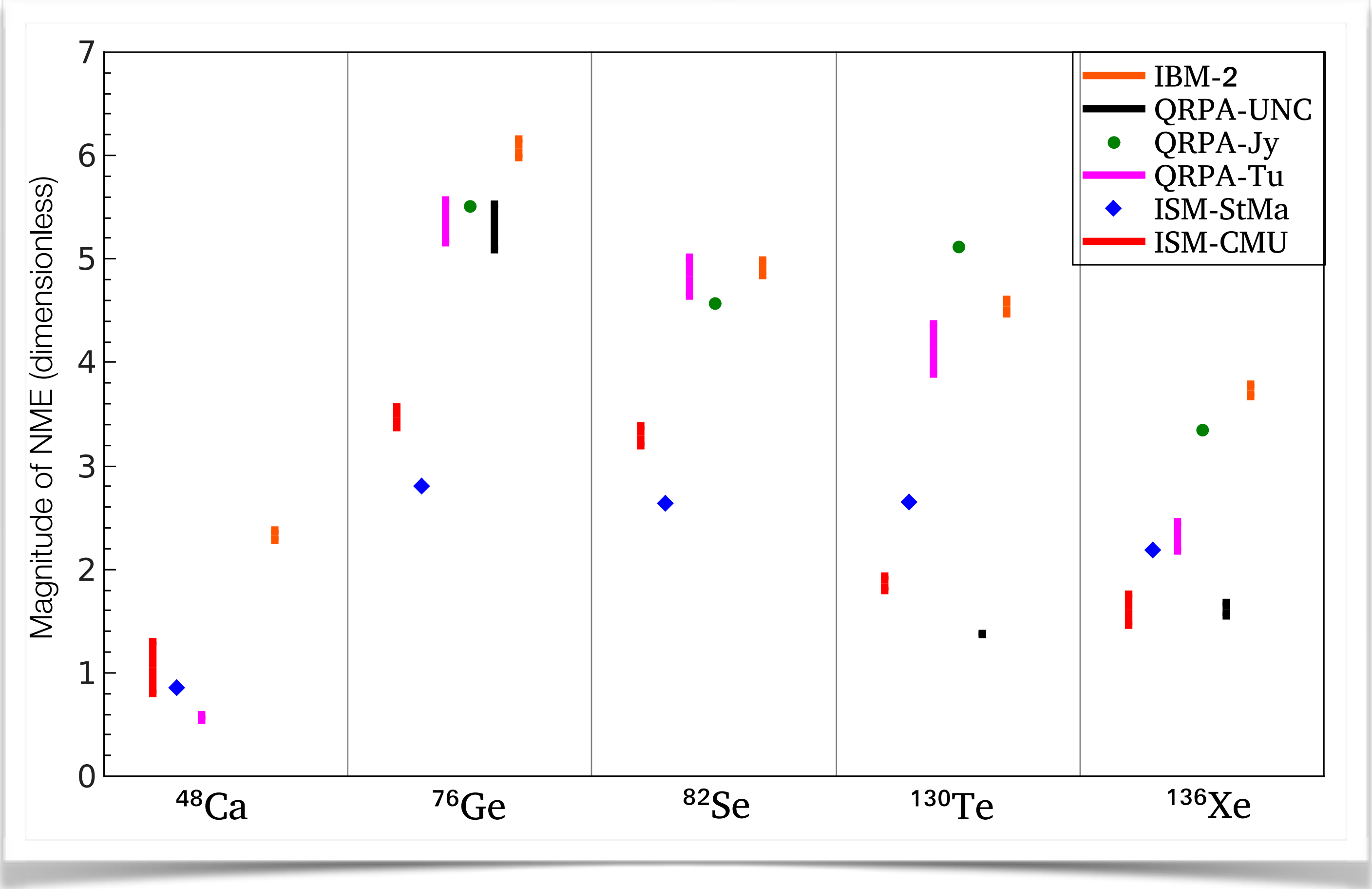


Figure: A. Neacsu and M. Horoi, Phys. Rev. C **91**, 024309 (2015)

Tremendous efforts have been put into the exploration of what may remedy this uncertainty. Our focus is on experimental nuclear-structure data to constrain the calculations.

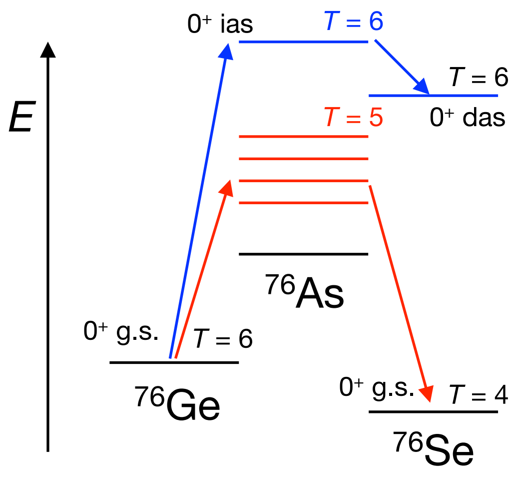
$$\boxed{[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta} \rangle|^2}$$

NMEs for 2v2β 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) in **2v2β***

2v2β

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.

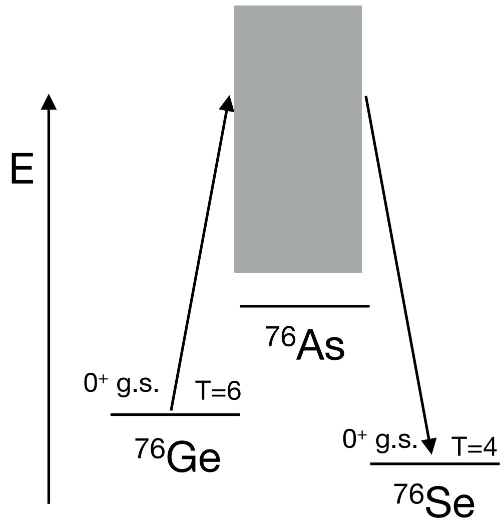
Nuclear structure effects key (excitation energy and strength of 1^+ states) AND can be probed experimentally via charge exchange reactions e.g.:
^{76}Ge(^{3}He,t)^{76}As, ^{76}Se(t,^{3}He)^{76}As.

NMEs for 0v2β less so

*What experimentally accessible nuclear-structure properties can be useful? Not quite so straight forward with **0v2β***

0v2β

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



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

Energy of intermediate states can be large, 10's of MeV cf. a few for 2v2β … Angular momentum can be large, 5-6 hbar cf. 1 hbar for 2v2β

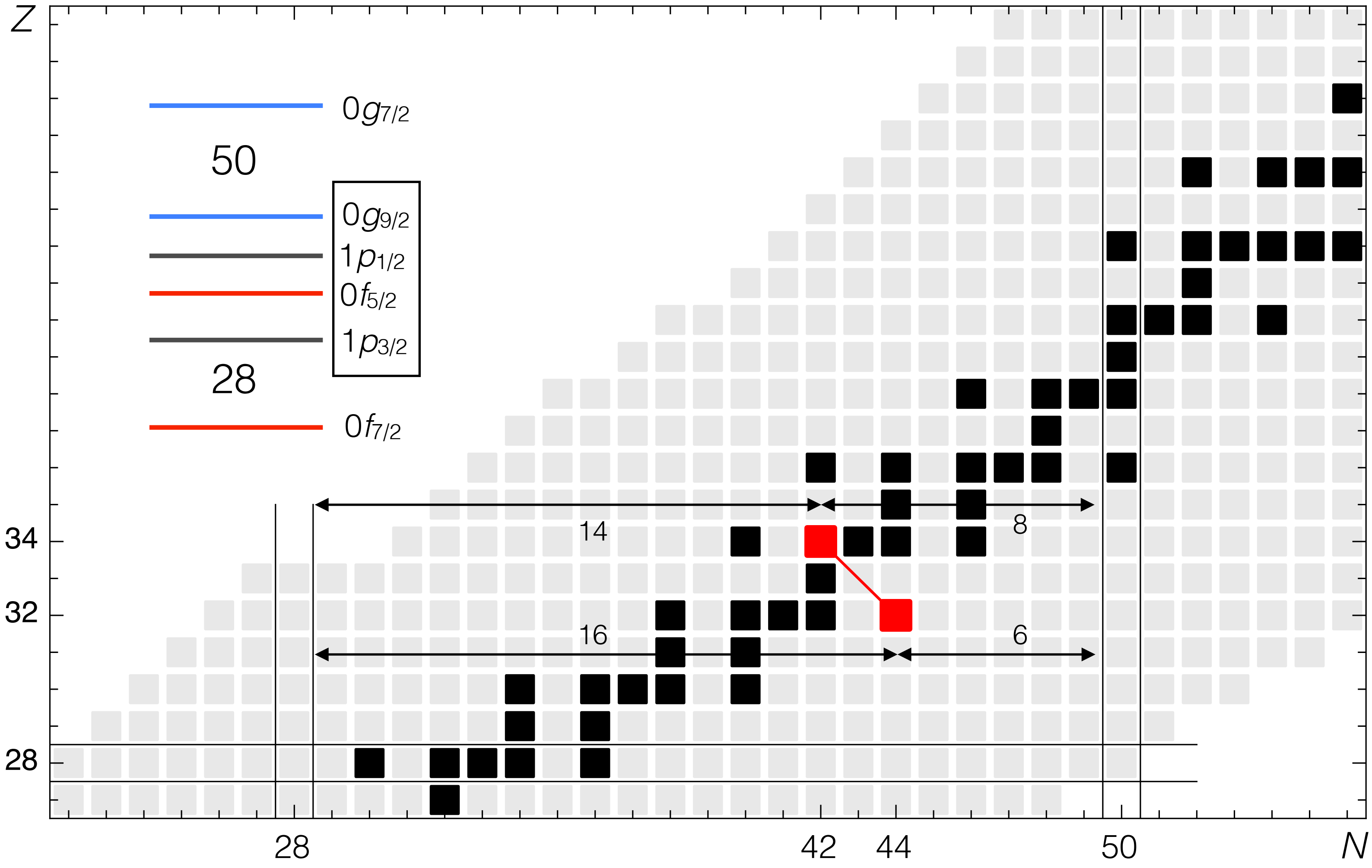
So … it probes essentially all states, and is somewhat insensitive to the details … closure approximation used*

Not related to 2v2β, 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.

---

*Often considered good to 10% or better, see e.g., Sen'kov and Horoi, Phys. Rev. C **90**, 051301(R) (**2014**)

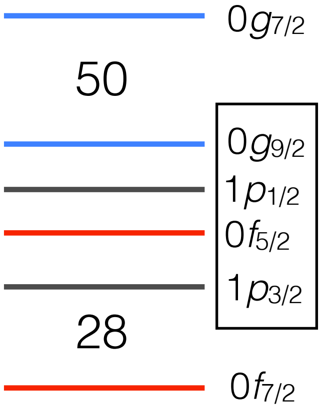
The ^{76}Ge→^{76}Se system *(a recap)*



What is the occupancy and vacancy of the active orbitals? ***How does it CHANGE from initial to final state?—the MICROSCOPIC anatomy can be probed with NUCLEON TRANSFER reactions.***

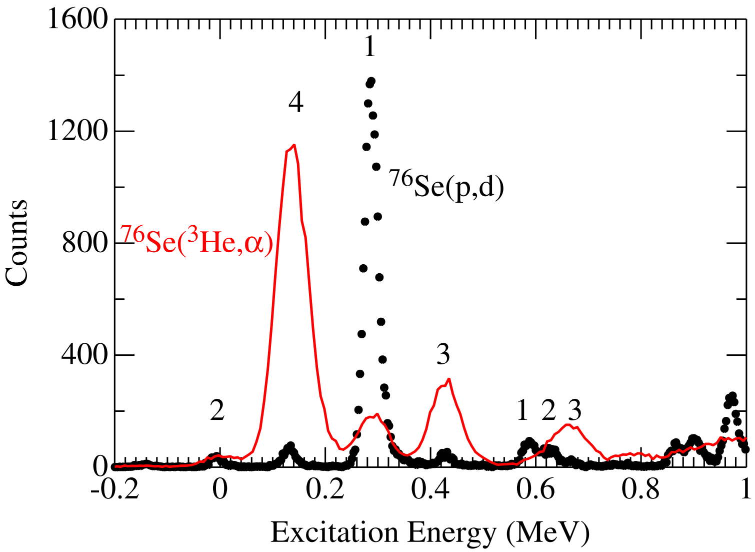
Tools of the trade — transfer reactions

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



Approach

- Careful choice of reactions for adding and removing protons and neutrons
- Consistent experimental approaches
- Consistent analyses (DWBA)



The facilities

- MLL Munich (tandem, Q3D)
- IPN Orsay (tandem, Enge split pole)
- ***RCNP Osaka (cyclotron, Grand Raiden)***
- WNSL Yale (tandem, Enge split pole)

Sum rules, normalization (*cross sections→occupancy*)

^{76}Ge(p,d)

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

^{76}Ge(d,p)

E	ℓ	$(2j+1)S'$	$(2j+1)S$
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		

$$N_j \equiv S'/S$$

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

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

The value of this normalization is not arbitrary (reflects quenching of single-particle motion).
Normalizing is essential compare experiment data to calculations.

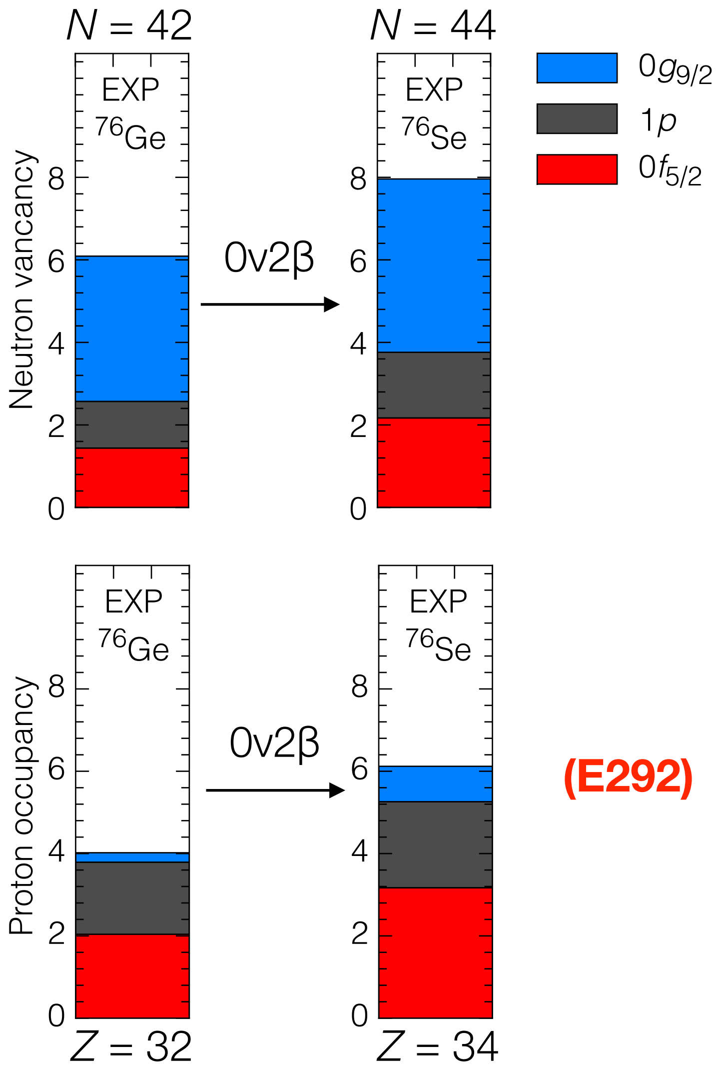
A look back at the Ge/Se results *(WNSL Yale, 2006/7, RCNP 2007)*

e.g., Neutron occupancies

Isotope	$0f_{5/2}$	$1p_{1/2,3/2}$	$0g_{9/2}$	Sum	Expect
^{74}Ge	1.8(4)	1.1(2)	4.3(3)	7.2(5)	8
^{76}Ge	***1.4(3)***	***1.1(2)***	***3.5(2)***	***6.0(5)***	***6***
^{76}Se	***2.2(3)***	***1.6(2)***	***4.2(2)***	***8.0(5)***	***8***
^{78}Se	2.3(4)	0.9(2)	2.8(3)	6.1(5)	6

The (*d*,*p*) and (*p*,*d*) reactions used for the **1*p*** strength and the (α,^{3}He)+(^{3}He,α) used for the **0*f*$_{5/2}$** and **0*g*$_{9/2}$**.

A similar table can be made for the proton occupancies.



(E292)

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

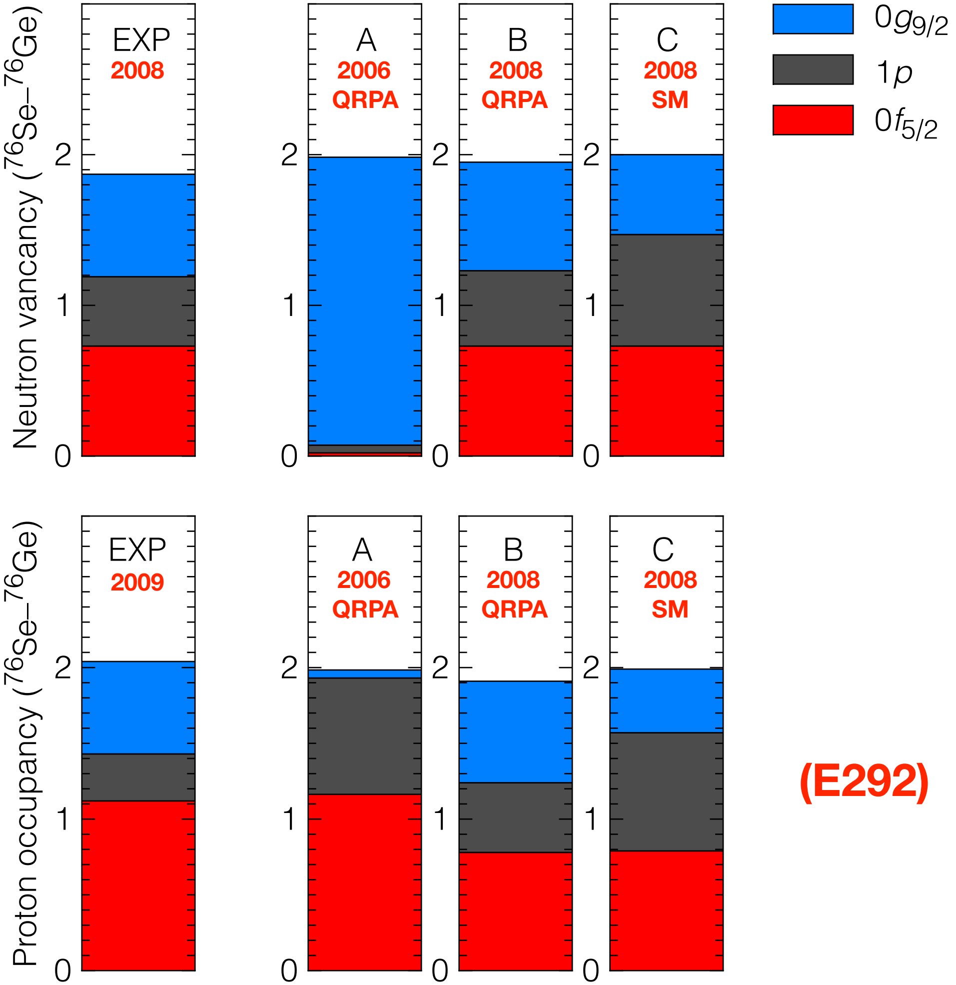
CHANGE in vacancy/occupancy: A = 76

This rearrangement must occur in the decay process

For neutrons, significant changes in the vacancy of all ‘active’ orbitals—seemingly described quite well

What about uncertainties?

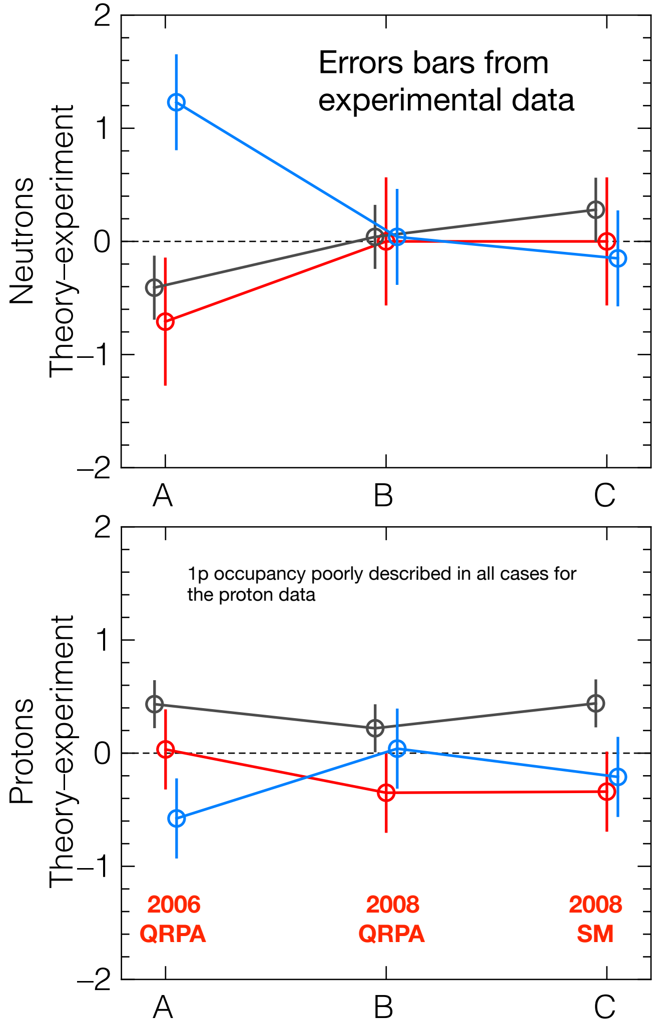
(N.B. no data from IBM at this point)



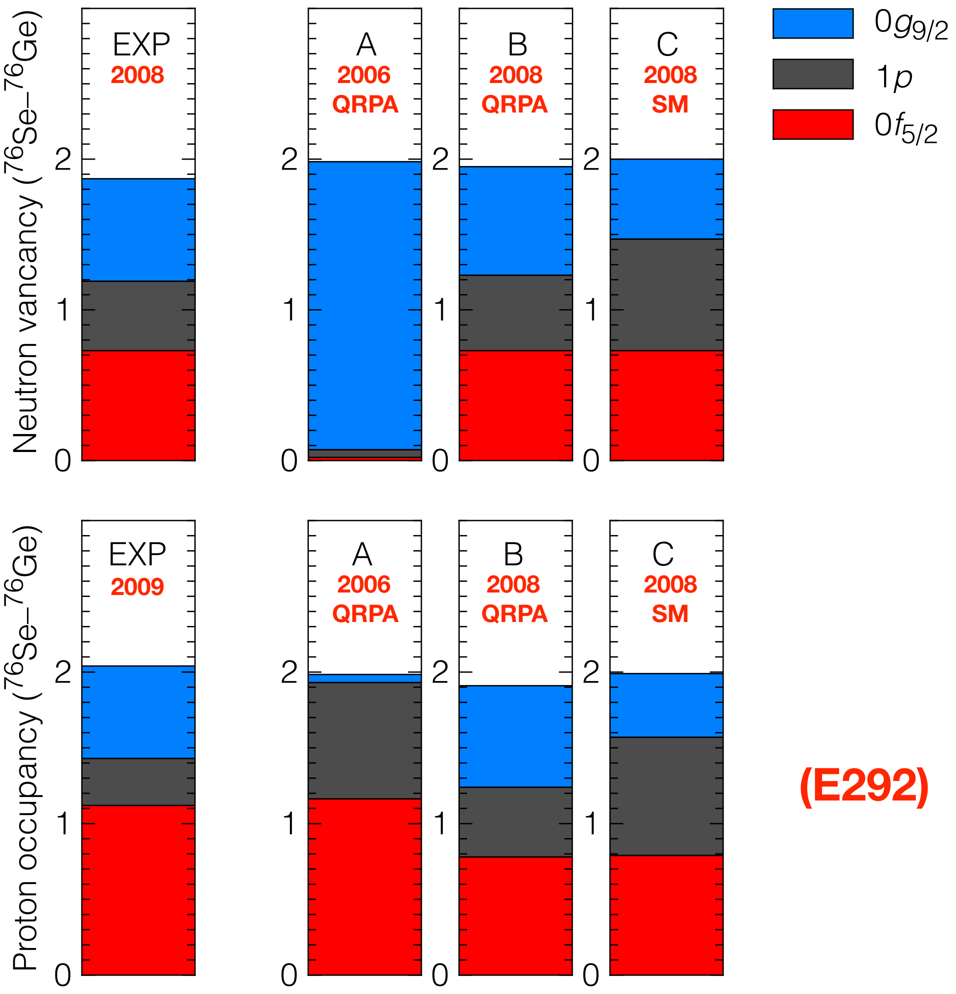
(E292)

EXP — J. P. Schiffer *et al*., Phys. Rev. Lett. **100**, 112501 (2008); BPK *et al*., Phys. Rev. C **79**, 021301(R) (2009)
A — QRPA by Rodin *et al*., priv. com., Nucl .Phys. A **766**, 107 (2006)
B — QRPA by Suhonen *et al*., priv. com., Phys. Lett. B **668**, 277 (2008)
C — ISM by Caurier *et al*., priv. com., Phys. Rev. Lett. **100**, 052503 (2008)

CHANGE in vacancy/occupancy: A = 76


Errors bars from experimental data

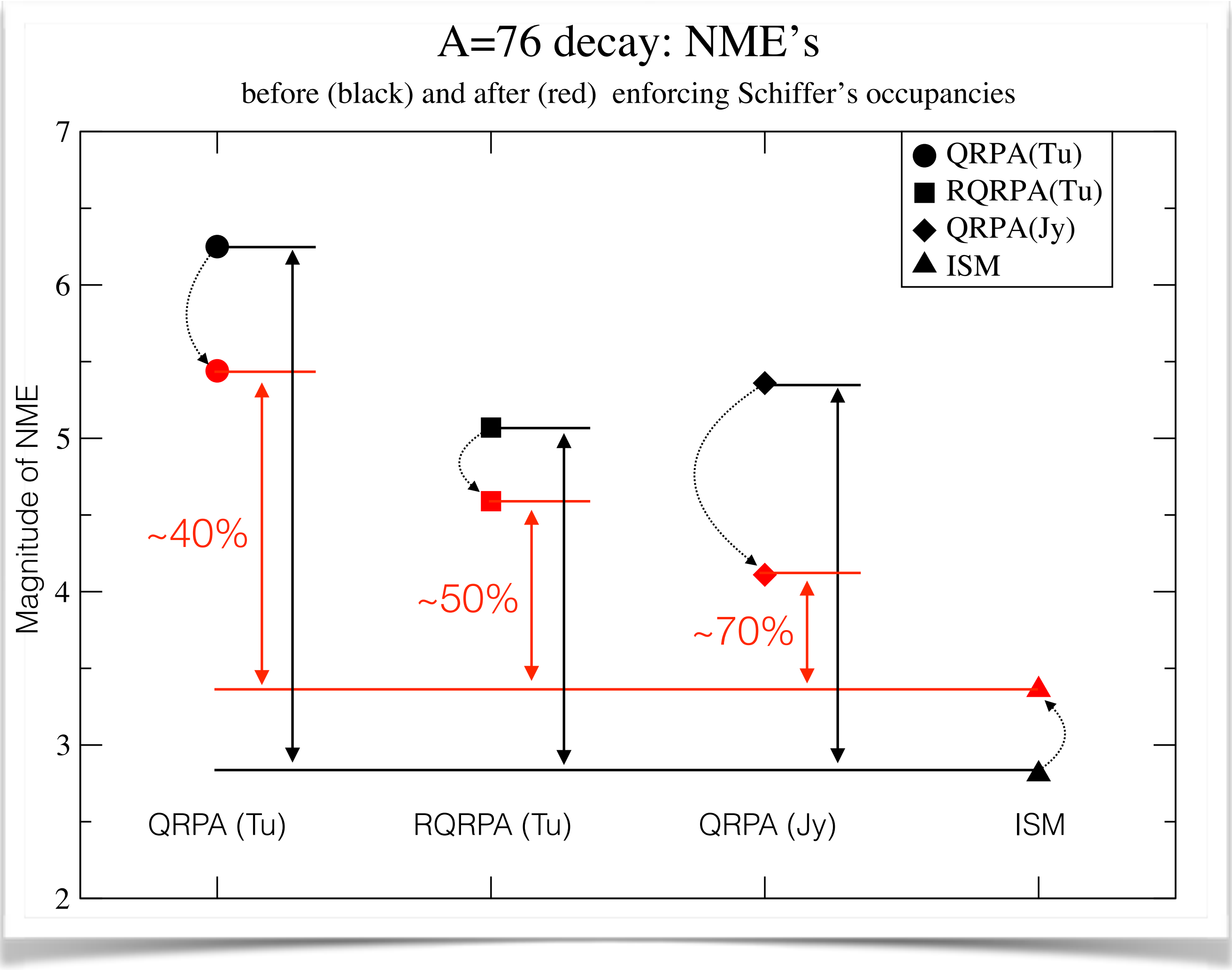
1p occupancy poorly described in all cases for the proton data



(E292)

EXP — J. P. Schiffer *et al*., Phys. Rev. Lett. **100**, 112501 (2008); BPK *et al*., Phys. Rev. C **79**, 021301(R) (2009)
A — QRPA by Rodin *et al*., priv. com., Nucl .Phys. A **766**, 107 (2006)
B — QRPA by Suhonen *et al*., priv. com., Phys. Lett. B **668**, 277 (2008)
C — ISM by Caurier *et al*., priv. com., Phys. Rev. Lett. **100**, 052503 (2008)

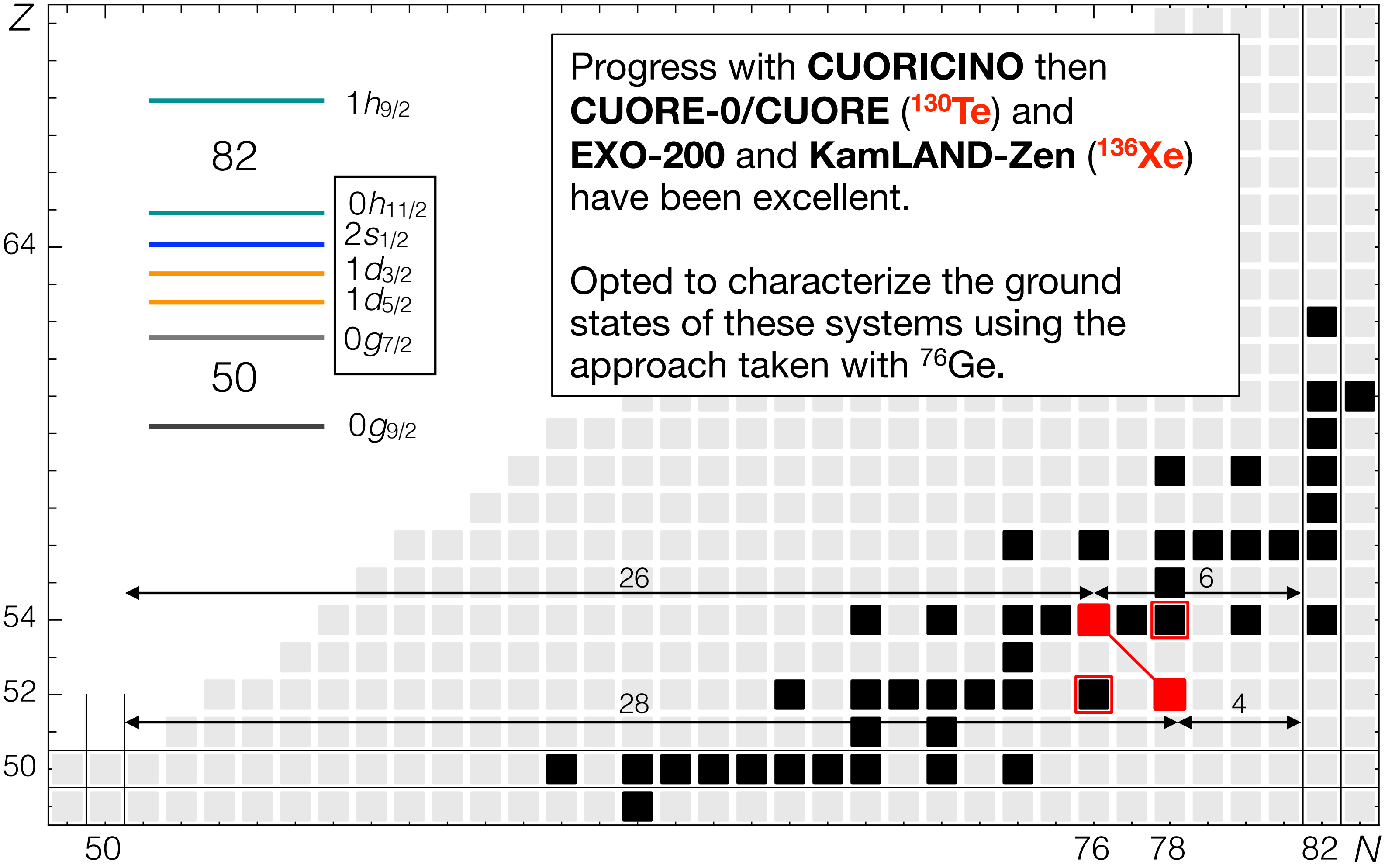
The Ge system: impact on the NMEs?



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

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

***The ^{130}Te→^{130}Xe neutron vacancies** (a recap)*



Progress with **CUORICINO** then **CUORE-0/CUORE** (^{130}Te) and **EXO-200** and **KamLAND-Zen** (^{136}Xe) have been excellent.

Opted to characterize the ground states of these systems using the approach taken with ^{76}Ge.

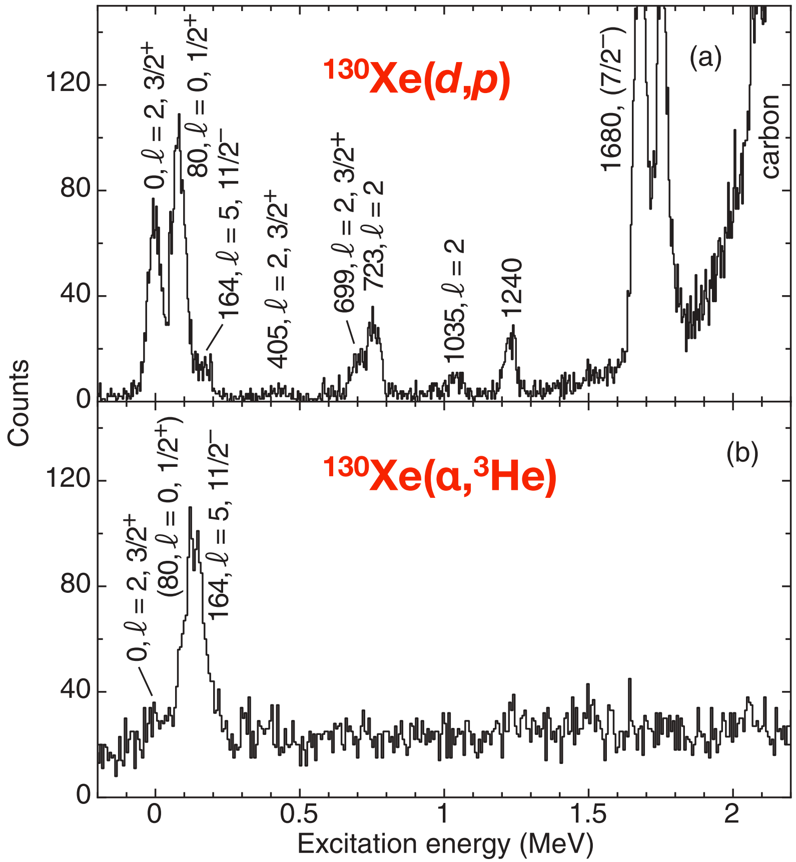
Would one expect the $0g_{7/2}$ orbit to play a role? It is deeply bound at N = 76/78 …

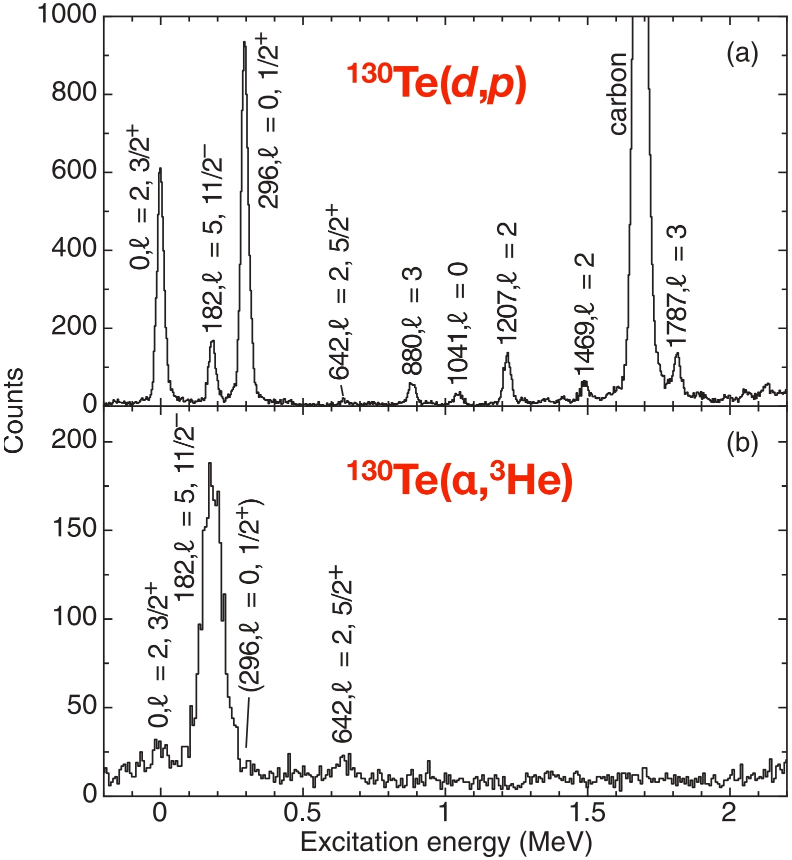
Challenges

Both ^{130}Te→**^{130}Xe** and **^{136}Xe**→^{136}Ba involve a gaseous species—complex targets

The ^{130}Te→^{130}Xe neutron vacancies ***(WNSL Yale, 2013)***

Used a ***frozen*** Xe target for the ^{130,132}Xe isotopes. Conventional solid targets for the ^{128,130}Te isotopes.



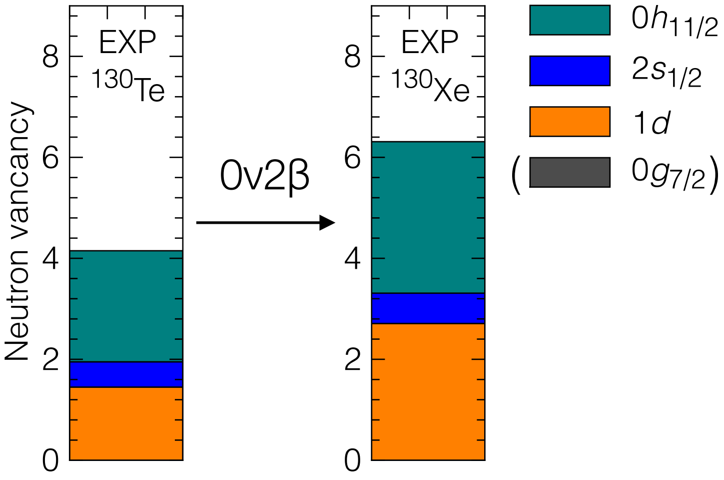


BPK *et al*., Phys. Rev. C **87**, 011302(R) (**2013**)

The ^{130}Te→^{130}Xe neutron vacancies (WNSL Yale, 2013)

Neutron vacancies

Isotope	$0g_{7/2}$	$1d$	$2s_{1/2}$	$0h_{11/2}$	Sum	Expect
^{128}Te	0.0(2)	2.1(2)	0.7(2)	3.3(3)	6.1(5)	6
^{130}Te	*0.0(2)*	*1.5(2)*	*0.5(2)*	*2.2(3)*	***4.2(5)***	***4***
^{130}Xe	*0.0(2)*	*2.7(2)*	*0.6(2)*	*3.0(3)*	***6.3(5)***	***6***
^{132}Xe	0.0(2)	2.0(2)	0.3(2)	1.8(3)	4.0(5)	4



Key point: we saw **no evidence for the $0g_{7/2}$** in the adding reaction which probes the vacancy.

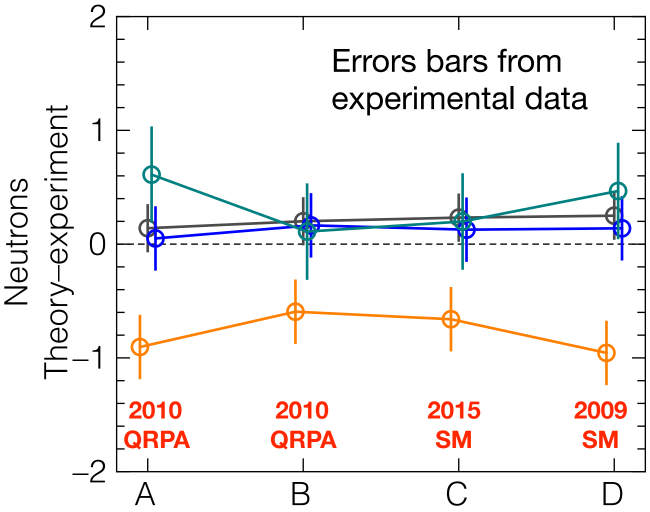
EXP — BPK *et al.*, Phys. Rev. C **87**, 011302(R) (**2013**)

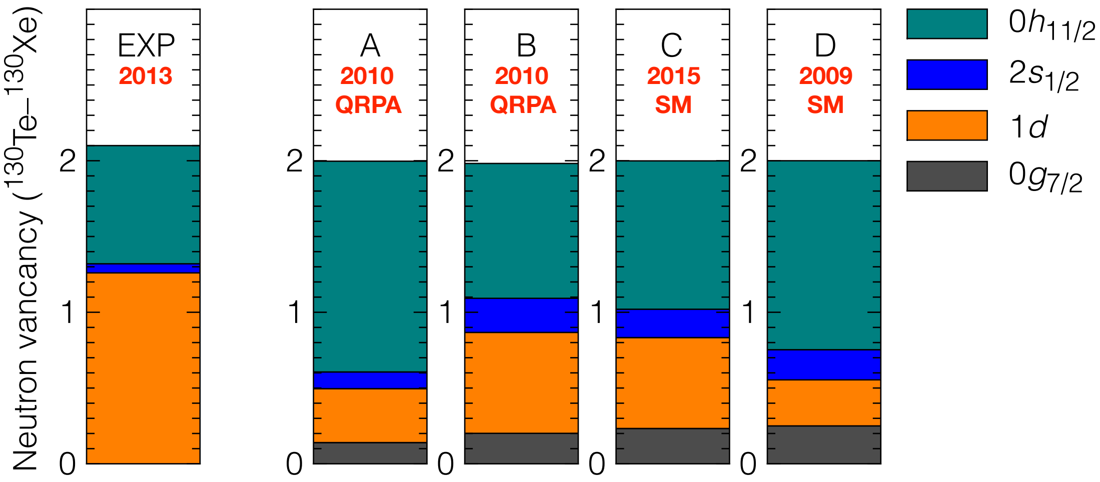
Detailed comparison

New theory 2015

Can the $0g_{7/2}$ be "turned off"?

Beyond this, the main discrepancies between theory and calculations are the **$1d$, the vacancy changing too little**, and the **$0h_{11/2}$, the vacancy changing too much**.

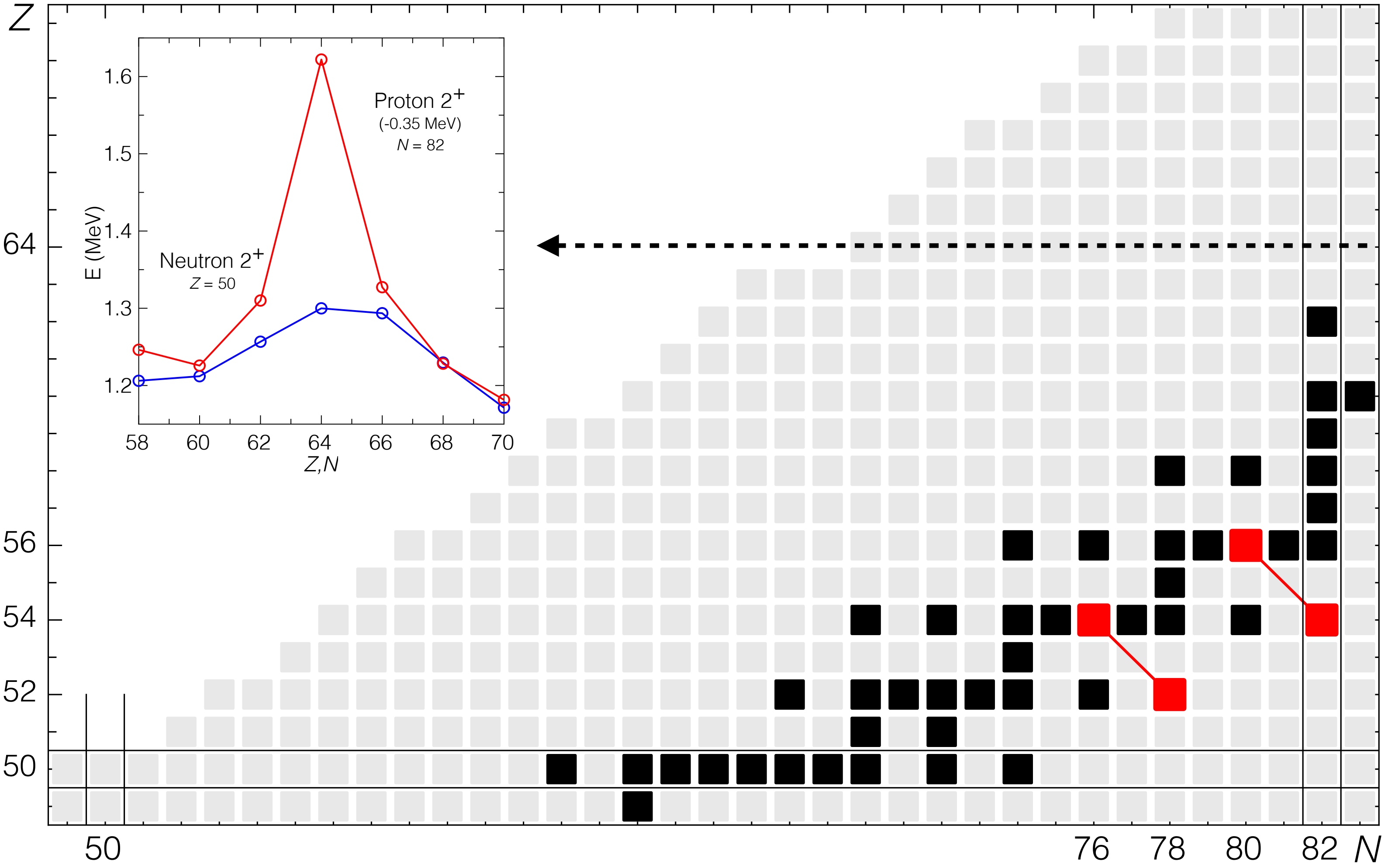




There ***must*** be a quantitative impact on the NMEs were the calculations to be modified to reproduce the experimental data.

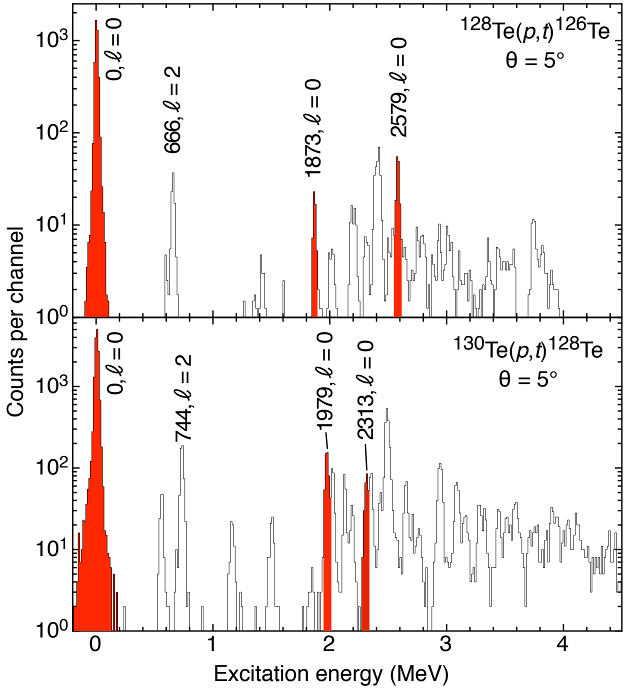
EXP — BPK *et al*., Phys. Rev. C **87**, 011302(R) (**2013**)
A,B — J. Suhonen and O. Civitarese, Nucl. Phys. A **847**, 207 (**2010**)
C — A. Neacsu, priv. com.; A. Neascu and M. Horoi, Phys. Rev. C **91**, 024309 (**2015**)
D — J. Menéndez, priv. com.; J. Menéndez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A **818**, 139 (**2009**)

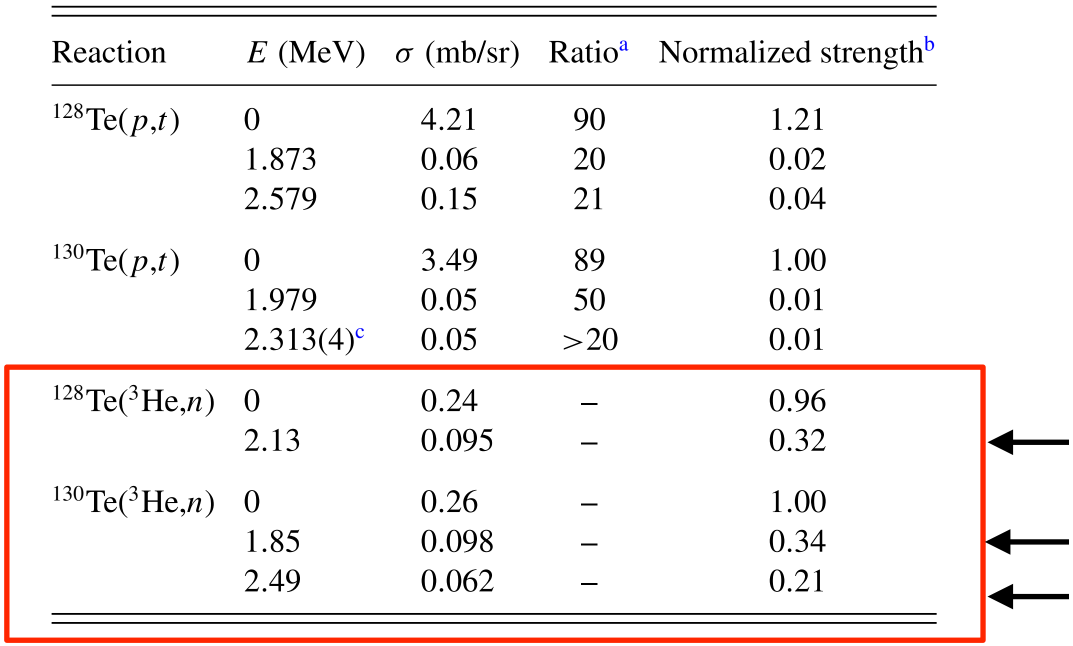
Comment on *PAIRING*



Does the Z = 64 sub-shell gap play a role here? (No sub-shell gap for neutrons.)

Comment on *PAIRING*





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

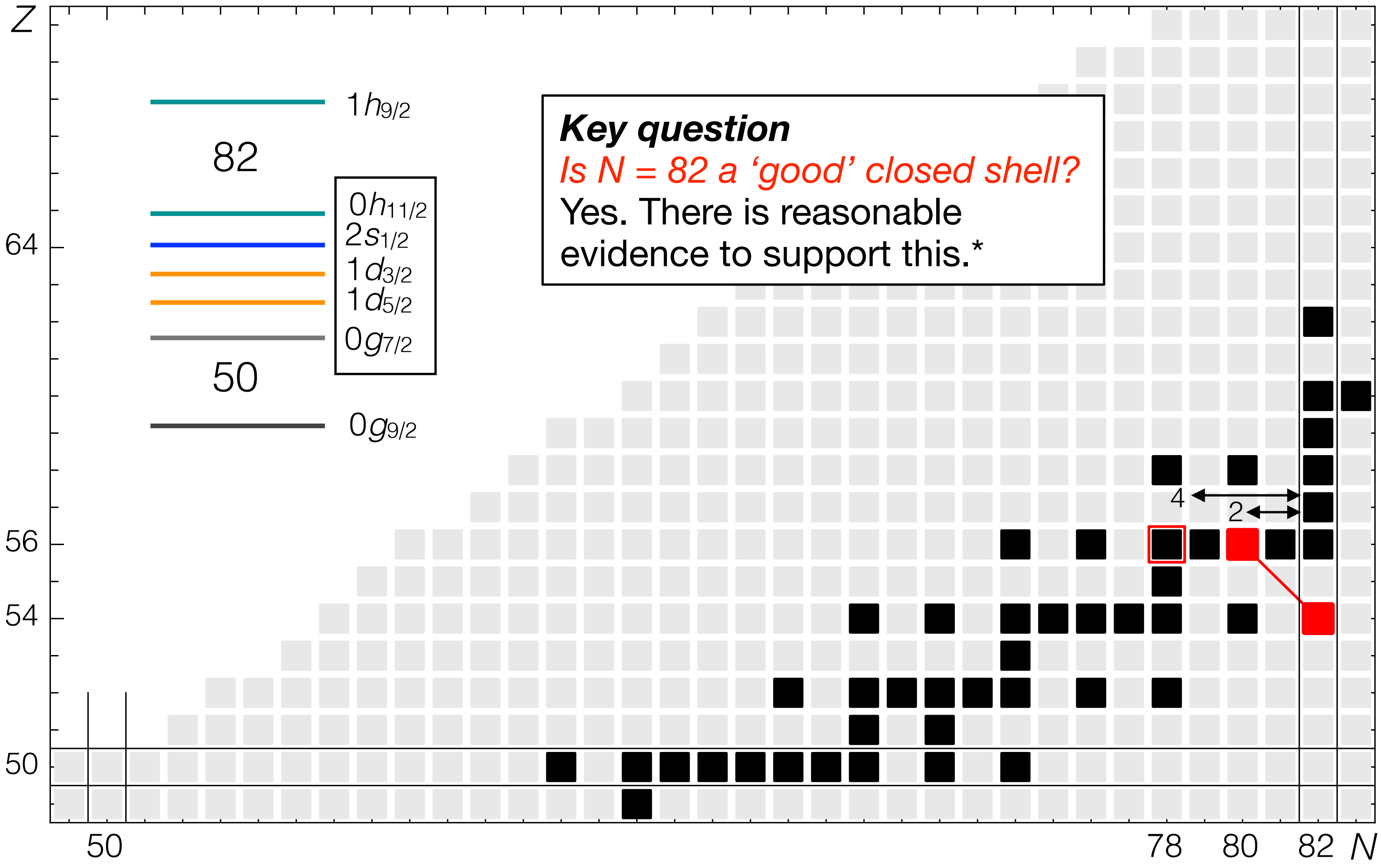
From the proton-pair adding Te(^{3}He,n) reactions by Alford *et al*., ***significant strength is seen in ℓ= 0 transitions to excited states***

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*., Phys. Rev. C **82**, 027308 (**2010**)
W. P. Alford *et al*., Nucl.Phys. A **323**, 339 (**1979**)

The ^{136}Xe→^{136}Ba neutrons

New
Preliminary



Key question

Is N = 82 a 'good' closed shell?

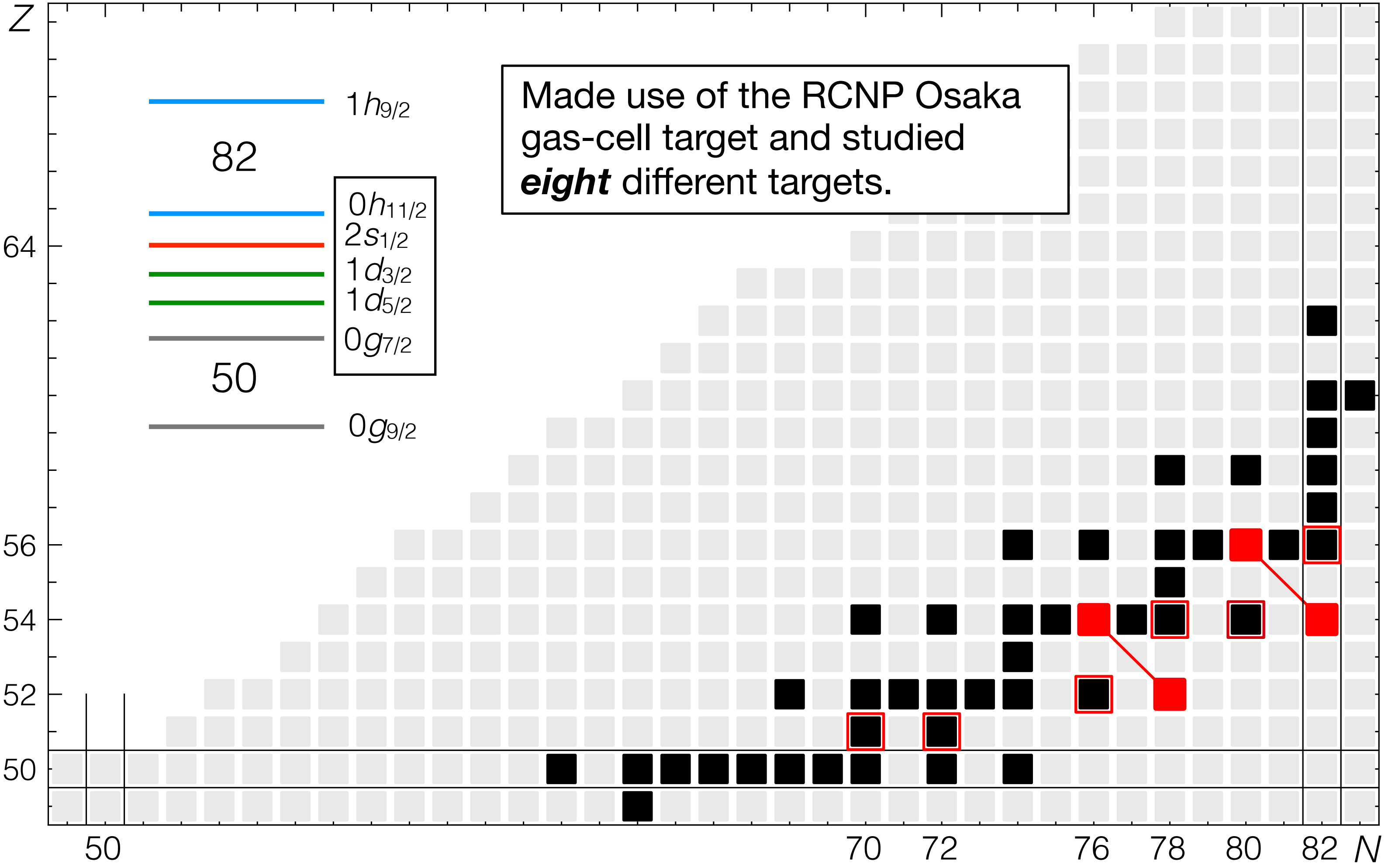
Yes. There is reasonable evidence to support this.*

Experiments completed, but not discussed here.

BPK, S. V. Szwec et al., preliminary; under analysis (experiment in **May and Oct 2015**)

The A = 130 and 136 protons (RCNP, Oct/Nov 2014)

New Preliminary

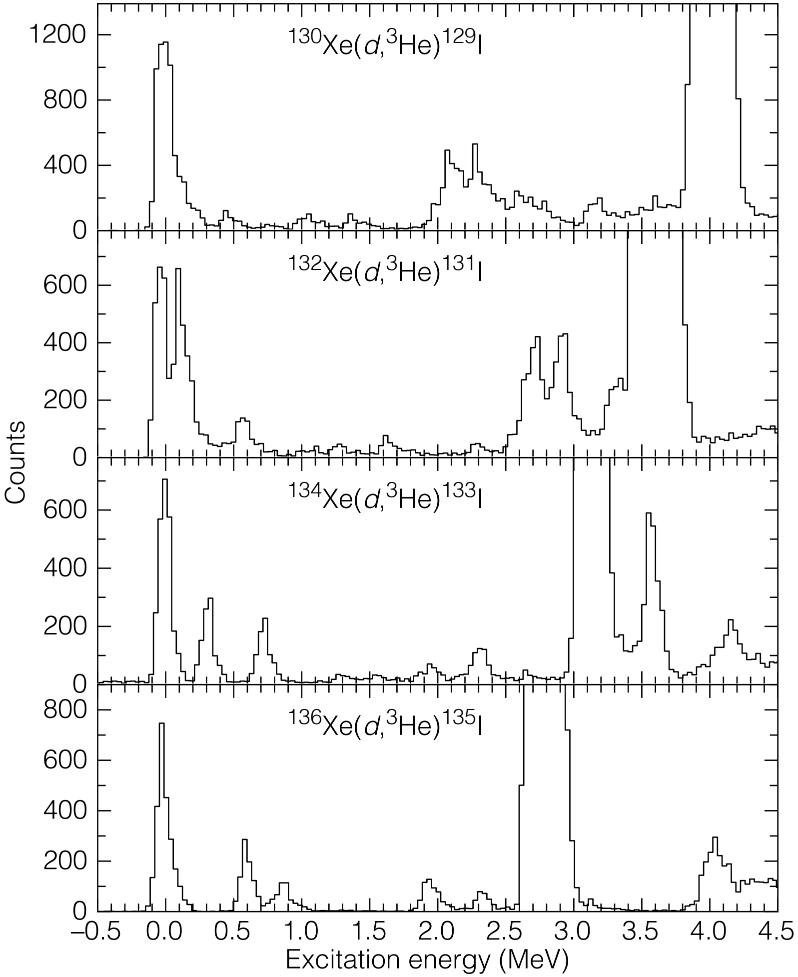


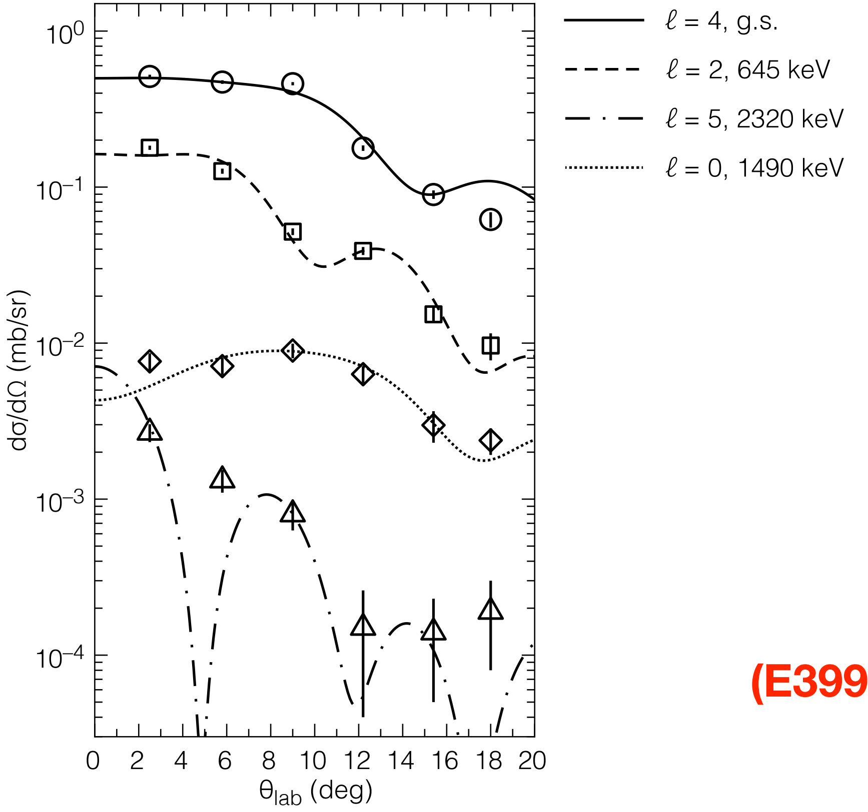
Made use of the RCNP Osaka gas-cell target and studied ***eight*** different targets.

Being close to the start of a major shell, only the proton-removing (d,^{3}He) reaction used (probing the 2, 4, and 6, proton occupancies above N = 50).

The A = 130 and 136 protons (**RCNP, Oct 2014**)

New Preliminary





(E399)

No dispersion matching, Grand Raiden and RCNP gas target, beam energy of 101 MeV, spectra at 5.8°
H. Matsubara et al., Nucl. Instrum. Methods Phys. Res. A 678, 122 (2012).
P. Puppe et al., Phys. Rev. C 84, 051305(R) (2011).

EXP — J. P. Entwisle, BPK *et al*., preliminary (**experiment in Oct 2014**).

The A = 130 and 136 protons (RCNP, Oct 2014)

New
Preliminary

At a glance … consistent results across all targets with the exception of **^{138}Ba**, where there were some anomalies with the electronics set up.

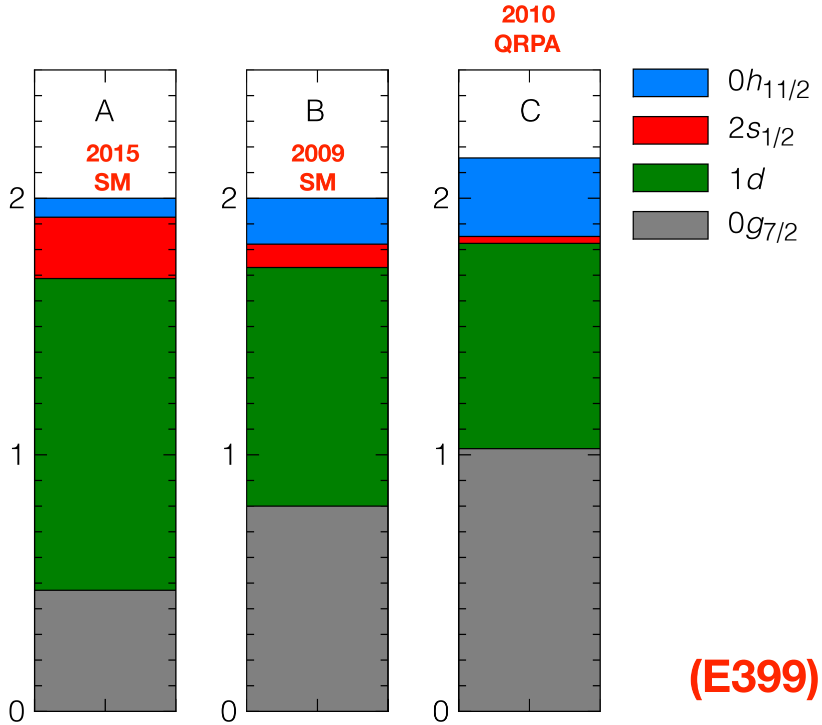
EXP — J. P. Entwisle, BPK *et al*., preliminary (**experiment in Oct 2014**).

CHANGE *in proton occupancies (A = **130**)*

New Preliminary

A = 130

Most notable is the large change in the ***1d*** strength in the theory, contrasting with the experimental data.



(E399)

EXP — J. P. Entwisle, BPK *et al*., preliminary: under analysis (**experiment in Oct 2014**)
A — A. Neacsu, priv. com.; A. Neascu and M. Horoi, Phys. Rev. C **91**, 024309 (**2015**)
B — J. Menéndez, priv. com.; J. Menéndez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A **818**, 139 (**2009**)
C — J. Suhonen and O. Civitarese, Nucl. Phys. A **847**, 207 (**2010**)

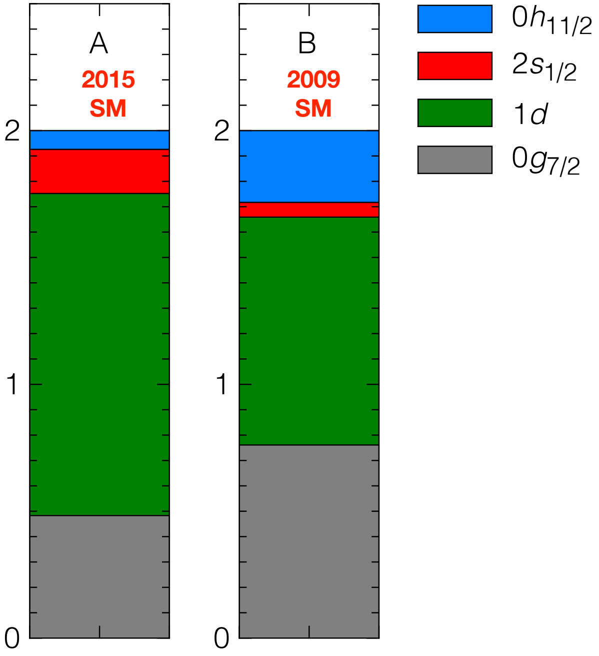
CHANGE in proton occupancies (A = 136)

New Preliminary

A = 136

Moving further away from ***Z* = 50** seems to result in a more '***diffuse***' change. Seems intuitive.

The Menéndez *et al*. results seem to be in close(r) agreement.

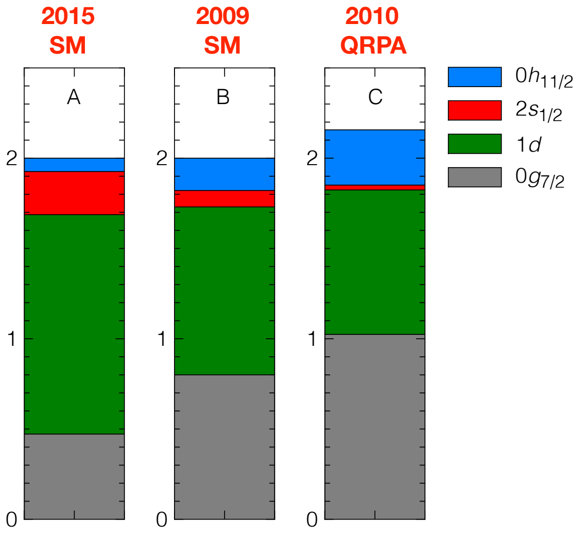


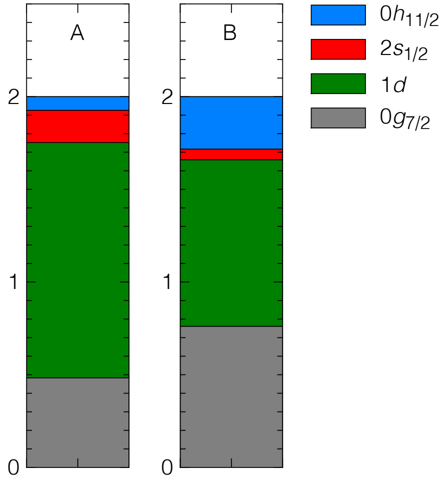
(E399)

EXP — J. P. Entwisle, BPK *et al*., preliminary: under analysis (**experiment in Oct 2014**)
A — A. Neacsu, priv. com.; A. Neascu and M. Horoi, Phys. Rev. C **91**, 024309 (**2015**)
B — J. Menéndez, priv. com.; J. Menéndez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A **818**, 139 (**2009**)
C — J. Suhonen and O. Civitarese, Nucl. Phys. A **847**, 207 (**2010**)

Detailed comparison

New Preliminary





(E399)

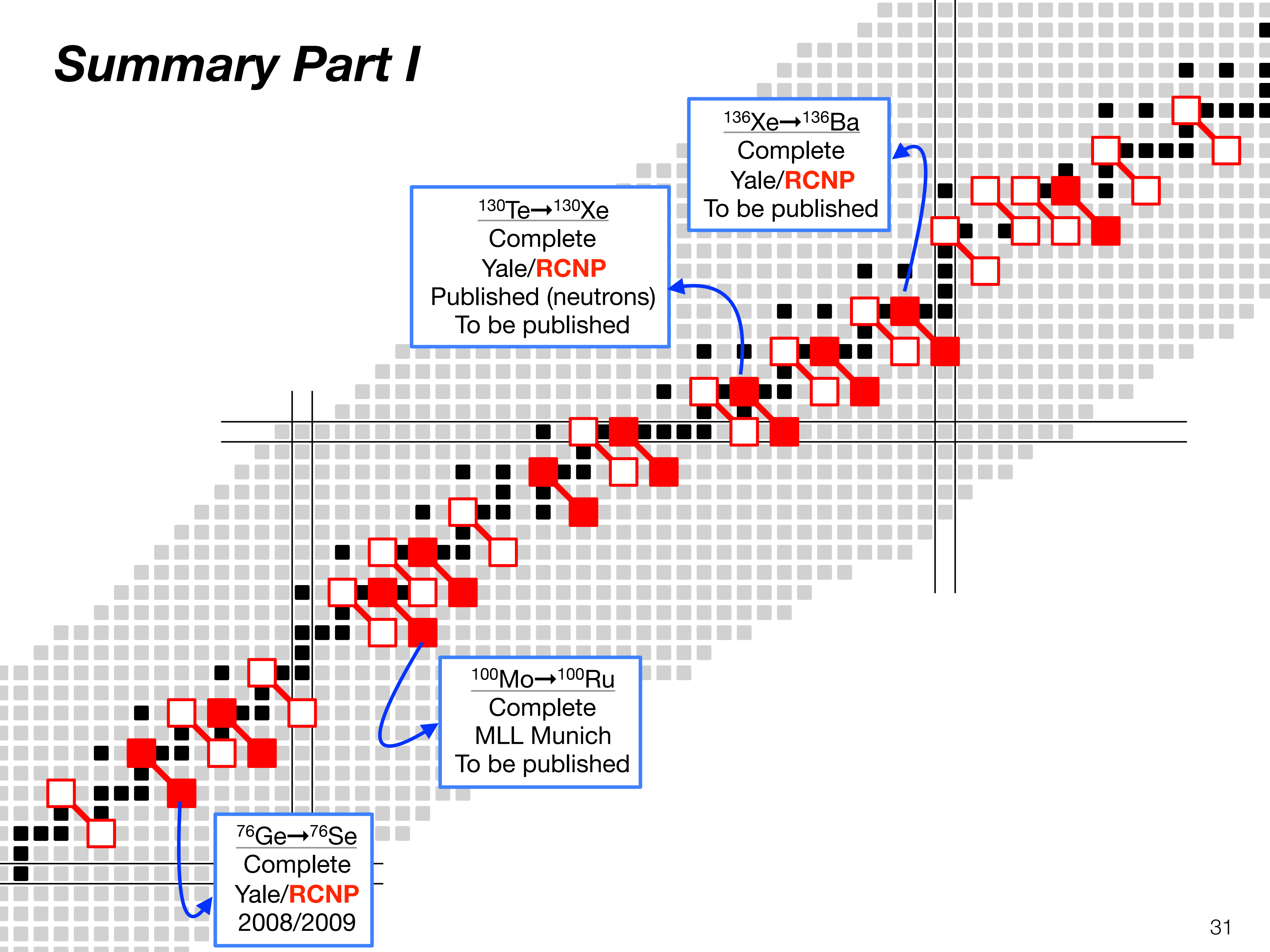
EXP — J. P. Entwisle, BPK *et al*., preliminary: under analysis (**experiment in Oct 2014**)

A — A. Neacsu, priv. com.; A. Neascu and M. Horoi, Phys. Rev. C **91**, 024309 (**2015**)

B — J. Menéndez, priv. com.; J. Menéndez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A **818**, 139 (**2009**)

C — J. Suhonen and O. Civitarese, Nucl. Phys. A **847**, 207 (**2010**)

Summary Part I



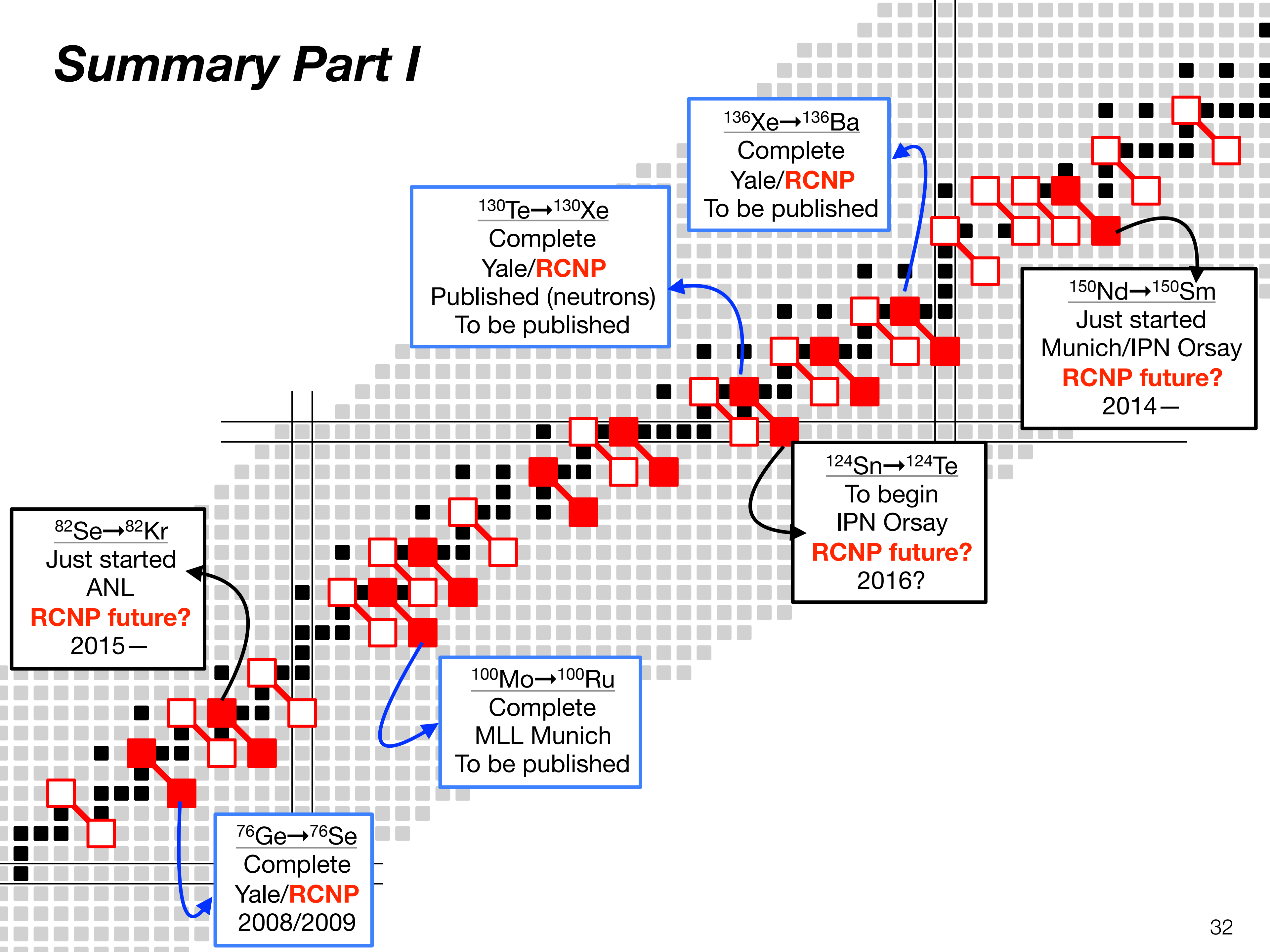
$^{130}\mathrm{Te}\rightarrow{}^{130}\mathrm{Xe}$
Complete
Yale/**RCNP**
Published (neutrons)
To be published

$^{136}\mathrm{Xe}\rightarrow{}^{136}\mathrm{Ba}$
Complete
Yale/**RCNP**
To be published

$^{100}\mathrm{Mo}\rightarrow{}^{100}\mathrm{Ru}$
Complete
MLL Munich
To be published

$^{76}\mathrm{Ge}\rightarrow{}^{76}\mathrm{Se}$
Complete
Yale/**RCNP**
2008/2009

Summary Part I



$^{136}\text{Xe}\rightarrow{}^{136}\text{Ba}$
Complete
Yale/**RCNP**
To be published

$^{130}\text{Te}\rightarrow{}^{130}\text{Xe}$
Complete
Yale/**RCNP**
Published (neutrons)
To be published

$^{150}\text{Nd}\rightarrow{}^{150}\text{Sm}$
Just started
Munich/IPN Orsay
RCNP future?
2014—

$^{124}\text{Sn}\rightarrow{}^{124}\text{Te}$
To begin
IPN Orsay
RCNP future?
2016?

$^{82}\text{Se}\rightarrow{}^{82}\text{Kr}$
Just started
ANL
RCNP future?
2015—

$^{100}\text{Mo}\rightarrow{}^{100}\text{Ru}$
Complete
MLL Munich
To be published

$^{76}\text{Ge}\rightarrow{}^{76}\text{Se}$
Complete
Yale/**RCNP**
2008/2009

Summary Part II

All data, when analysis is complete, is published either in papers or at NNDC. Cross sections, energies, etc.

We are close to having four key systems complete in ***^{76}Ge, ^{100}Mo, ^{130}Te, and ^{136}Xe*** — a wealth of data collected over the last decade. Work on ***^{82}Se and ^{150}Nd*** in the early stages.

Ge was explored very closely by theorists—the impact appears quite significant though ***no real conclusions … yet***.

Comparisons of recent calculations with the A = 130 and 136 shows significant disagreement (***role the g7/2, dominant changes at odds with data***)

Other recent discussion suggest a closer exploration of pairing / knockout / etc. Interesting avenues to pursue.

In several cases the calculations cannot describe the experimental data, at least within the experimental uncertainties.

It has to be important, as this is precisely what changes in the decay. Can a reassessment of some of the calculations be made in light of these data? How does it effect the lifetimes (NMEs)?

Collaborators (from earlier works and the [not discussed] ^{100}Mo and ^{150}Nd)

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.)

J. A. Clark, C. M. Deibel, C. R. Hoffman, and K. E. Rehm
Argonne National Laboratory, Illinois, USA

S. J. Freeman, S. A. McAllister, A. J. Mitchell, A. M. Howard, D. K. Sharp, and J. S. Thomas
Schuster Laboratory, University of Manchester, UK

A. Heinz, A. Parikh, P. D. Parker, V. Werner, C. Wrede
WNSL, Yale University, Connecticut, USA

A. C. C. Villari, D. Hirata, GANIL, France,
P. Grabmayr, Universitat Tubingen, Germany

K. Hatanaka, **A. Tamii**, T. Adachi, H. Fujita, Y. Fujita, M. Hirata, Y. Meada, H. Matsubara, H. Okumura, Y. Sakemi, Y. Shimizu, H. Shimoda, K. Suda, Y. Tameshige
RCNP, Osaka University, Japan **(E292)**

T. Bloxham, K. Han, S. J. Freedman
Lawrence Berkeley National Laboratory, California, USA

T. Faestermann, H.-F. Wirth
Technische Universitat Munchen

A. Roberts, A. M. Howard, J. J. Kolata, Notre Dame
I. Stefan, N. de Serevile, IPN Orsay

Collaborators (from more recent runs)

The WNSL Yale Runs (A = 130 Neutrons, May 2011)
T. Bloxham, S. A. McAllister, J. A. Clark, C. M. Deibel, S. J. Freedman, S. J. Freeman, K. Han, A. M. Howard, A. J. Mitchell, P. D. Parker, J. P. Schiffer, D. K. Sharp, J. S. Thomas.
Argonne National Laboratory, Lawrence Berkeley National Laboratory, University of Manchester

The RCNP Osaka Runs (A = 130 and 136 Protons, Oct 2014) (E399)
S. Adachi, N. Aoi, J. A. Clark, J. P. Entwisle, S. J. Freeman, H. Fujita, Y. Fujita, T. Furuno, T. Hashimoto, C. R. Hoffman, O. H. Jin, E. Ideguchi, T. Ito, C. Iwamoto, T. Kawabata, B. Liu, M. Miura, J. P. Schiffer, D. K. Sharp, G. Süsoy, T. Suzuki, S. V. Szwec, M. Takaki, **A. Tamii**, M. Tsumura, T. Yamamoto.
Argonne National Laboratory, RCNP-Osaka, University of Manchester

The IPN Orsay Runs (A = 136 Neutrons, May and Oct 2015)
T. E. Cocolios, J. P. Entwisle, S. J. Freeman, L. P. Gaffney, V. Guimaraes, F. Hammache, P. P. McKee, E. Parr, C. Portail, J. P. Schiffer, N. de Séréville, D. K. Sharp, J. F. Smith, I. Stefan, S. V. Szwec.
Argonne National Laboratory, University of Manchester, IPN-Orsay, University of the West of Scotland

Thank you to Andrei Neascu for theoretical data for A = 130 and 136 data and J. Menéndez for data on A = 76, 82, 130, and 136.

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 and the U.K. Science and Technology Facilities Council.