Changes in nucleon occupancies in double beta decay systems

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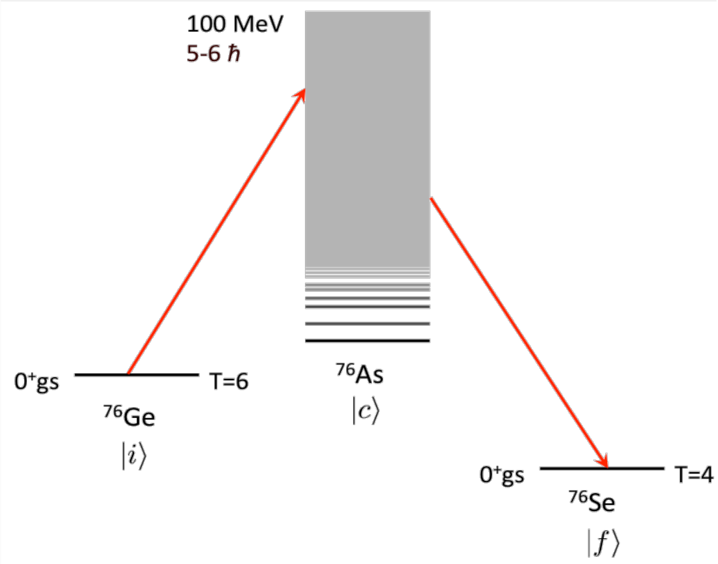
Double beta decay workshop

TRIUMF 11th-13th May 2016

Key Questions

- *What experimental data should theory reproduce so we trust neutrinoless double-beta decay predictions?*
- *What existing experimental data is most useful for constraining the various theory ingredients, and what are the most crucial unmeasured quantities?*

Neutrinoless double beta decay



<u>0νββ distinctly different from 2νββ</u>

Neutrinoless case involves excitations up to 10s of MeV and angular momentum up to ~5-6 ħ.

Details of intermediate nucleus appears to matter less to the 0νββ given the shear number of states involved.

No other process samples the same matrix element as 0νββ. Does not seem simply related to 2νββ case.

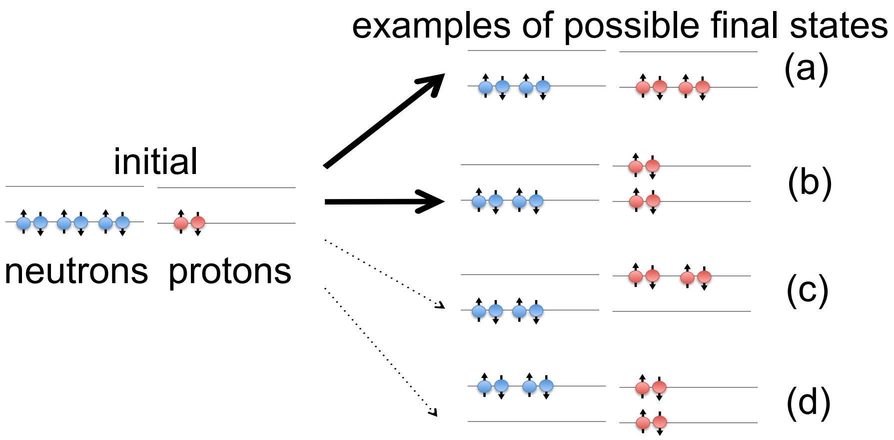
***Initial and final ground state wavefunctions** must be important.*

Why should ground state wavefunctions be important?

Details of the valence single-particle occupancies before and after decay have important consequences.

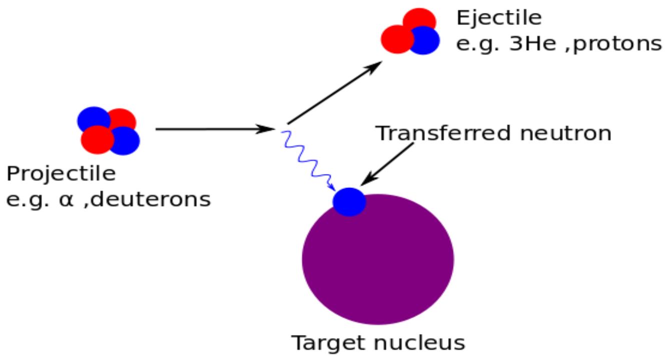
Decay may be facilitated if parent and daughter ground states are related by simple changes of neutrons to protons in (a) same orbital or (b) a different orbital

Any rearrangement of nucleons is likely to hinder the decay rate such as in (c) and (d).



See review article S. J. Freeman and J. P. Schiffer, J. Phys.G: Nucl Part. Phys. **39** 124004 (2012).

Probe - Single nucleon transfer reactions



Experimental conditions arranged to favour single-step transfer of a nucleon to/from target.

Selectively populate single-particle states.

Cross section proportional to emptiness (adding) or fullness (removal) of an orbital.

Due to correlations between nucleons, strength of an independent-particle model (IPM) orbit can be spread over ***many states.***

Spectroscopic factor*: Measure of the overlap between the final and initial state. How much does the final state look like the target plus a nucleon in a particular orbit?*

$$SF = \left| \left\langle \Phi_{J_B}^{M_B} \middle| A[\Phi_{J_A} \phi_j]_{J_B}^{M_B} \right\rangle \right|^2$$

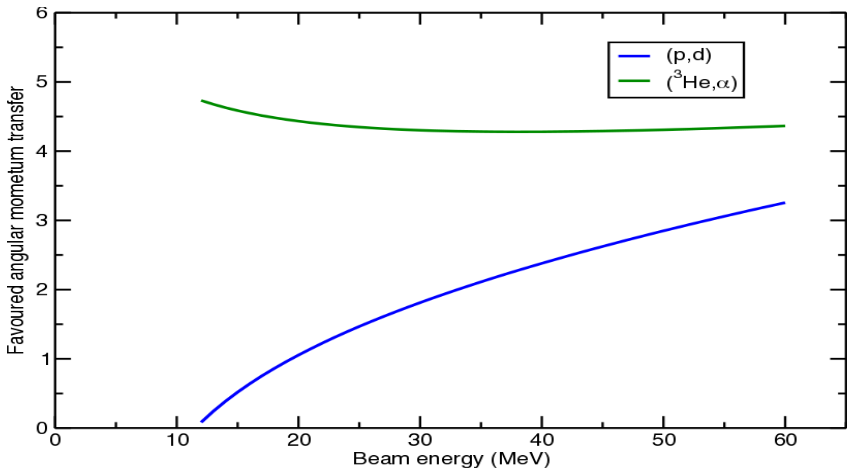
$$SF = \frac{\sigma_{exp}}{\sigma_{IPM}}$$

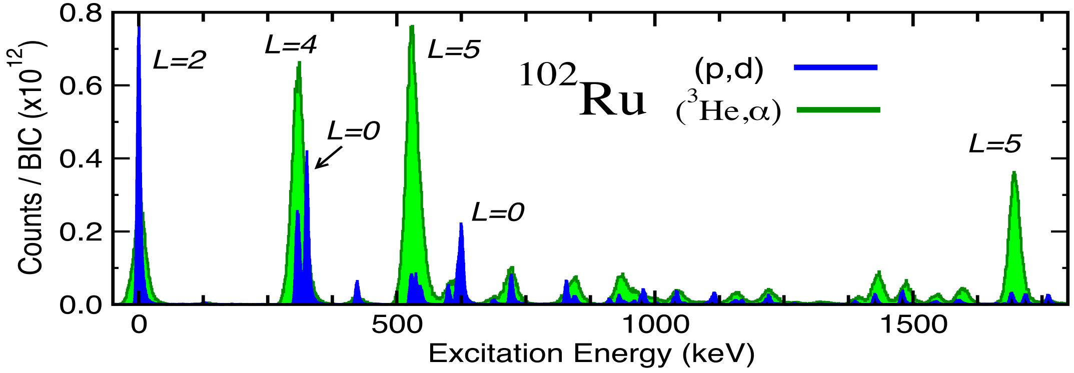
Experimental methods

*Light-ion induced reactions with beam energies of 10-20 MeV/u – **direct mechanism dominates.***

Where possible use two sets of reactions to meet matching conditions for low- and high-ℓ transfer.

Maximise cross section and reduce multi-step contribution.





High-Q value→high-ℓ transfer.
Low-Q value→low-ℓ transfer.

Linear momentum transfer related to angular momentum transfer in a semi-classical model $\ell = \mathbf{r} \times \mathbf{q}$

Experimental methods

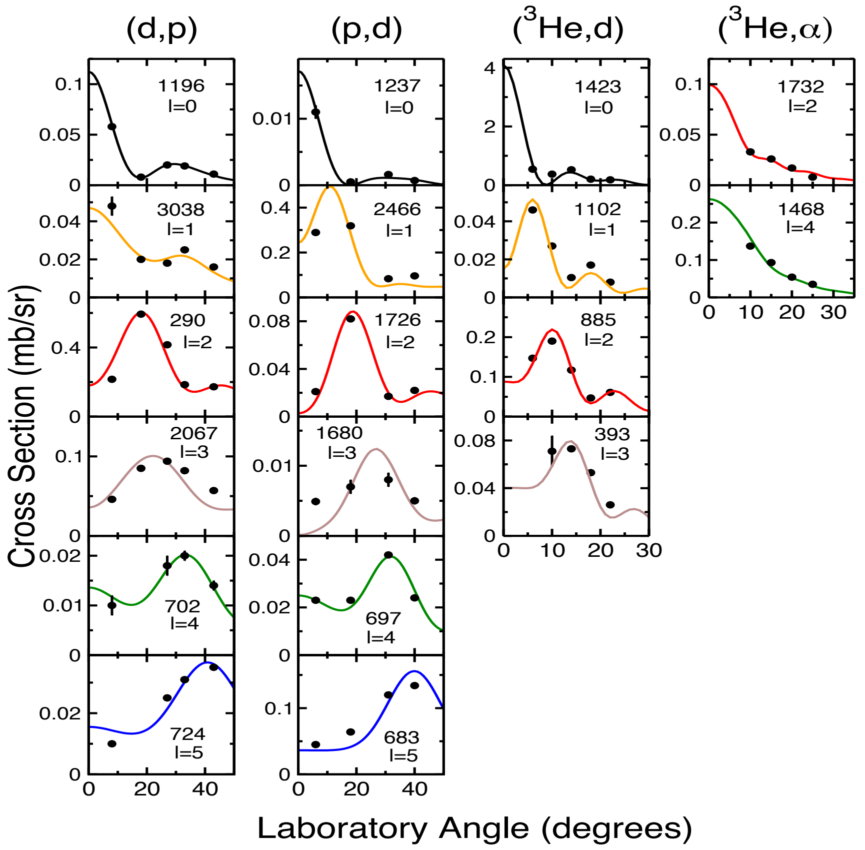
Use magnetic spectrograph to momentum separate outgoing ions and identify using energy loss characteristics in focal plane detector.

Measure cross sections at peaks of distributions where assumptions in DWBA are best met.

Angular distributions allow ℓ *identification*

If polarised measurements available allow ***j*** *identification*

Ensure consistency in both experimental approach and reaction modelling.



Where? - accelerators


Yale tandem, 22 MV

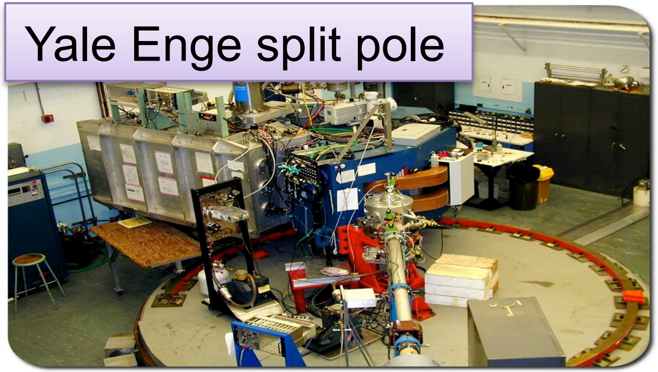

Munich tandem, 14 MV


RCNP cyclotrons

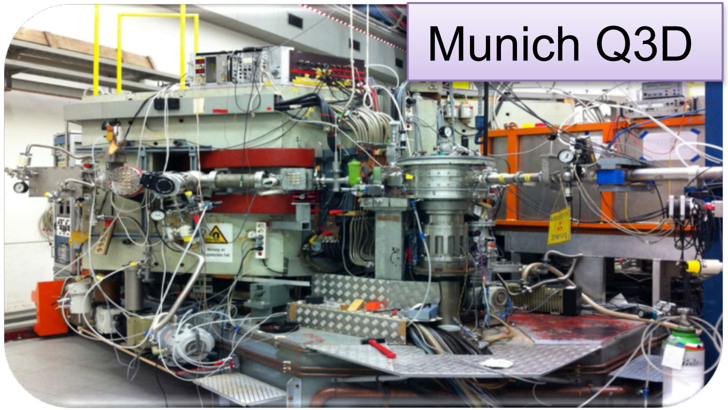

IPN Orsay tandem, 14.8 MV

Where? - spectrographs

Yale Enge split pole



Munich Q3D



RCNP Grand Raiden

IPN Orsay spilt pole

Reaction normalisation

Need to normalise reaction model, remove some uncertainty on absolute numbers due to choices in calculations. Use sum rules.

$$Vacancy = N_j \sum_j (2j+1) C^2 SF_+$$

$$Occupancy = N_j \sum_j C^2 SF_-$$

Can normalise observed strength to expected total number of valence nucleons (removing reactions) or holes (adding reactions) outside closed shell (need to be confident total strength has been observed).

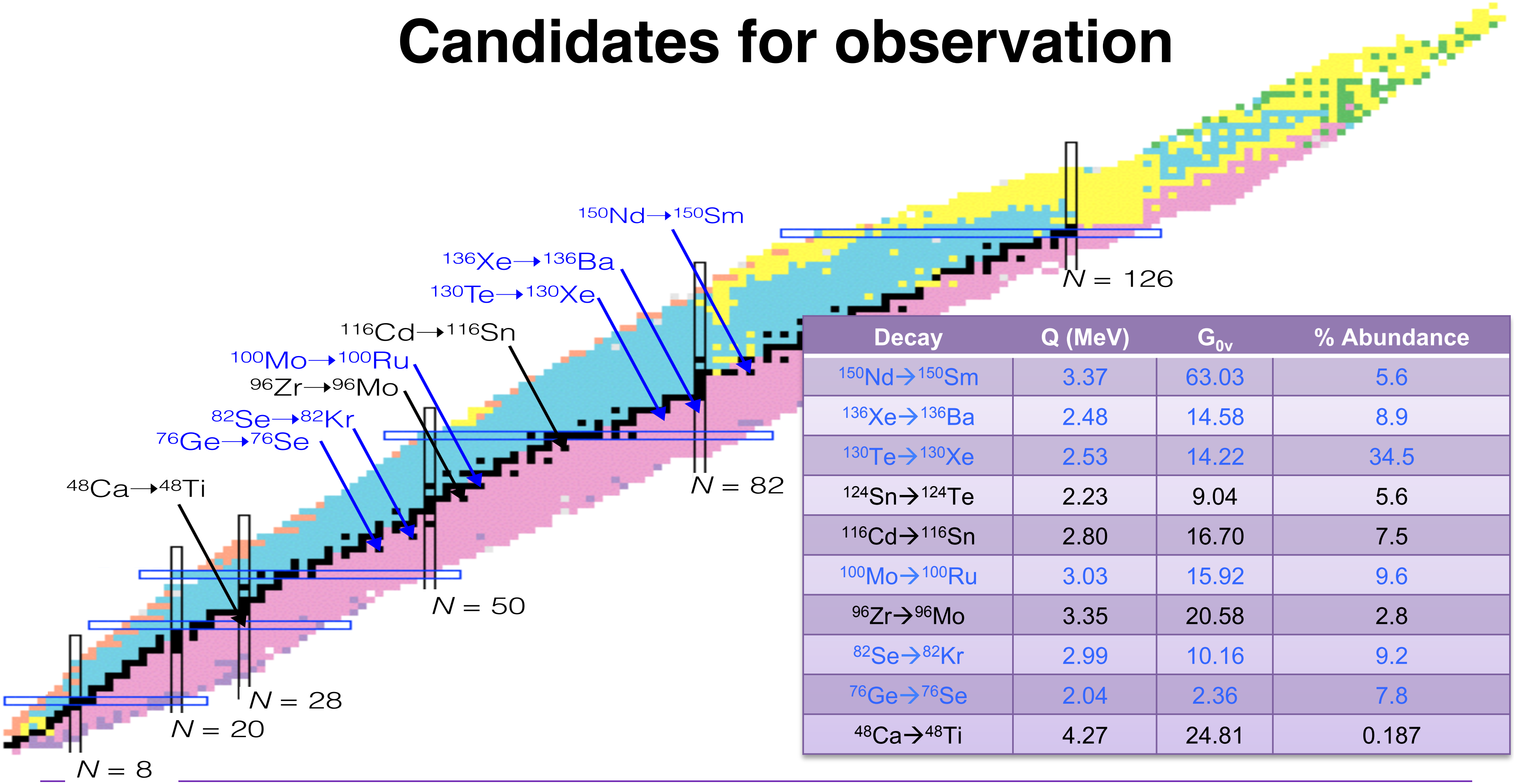
More robust if both adding and removal reactions are available.

$$N_j = ((2j+1)\Sigma C^2 SF_+ + \Sigma C^2 SF_-) / (2j+1)$$

Normalisation deduced for each orbital and we use an average across a number of isotopes then occupancy for each orbital deduced using common normalisation.

M. H. Macfarlane and J. B French, Rev. Mod. Phys. **32**, 567 (1960)

Candidates for observation



Decay	Q (MeV)	G_{0v}	% Abundance
$^{150}Nd \rightarrow {}^{150}Sm$	3.37	63.03	5.6
$^{136}Xe \rightarrow {}^{136}Ba$	2.48	14.58	8.9
$^{130}Te \rightarrow {}^{130}Xe$	2.53	14.22	34.5
$^{124}Sn \rightarrow {}^{124}Te$	2.23	9.04	5.6
$^{116}Cd \rightarrow {}^{116}Sn$	2.80	16.70	7.5
$^{100}Mo \rightarrow {}^{100}Ru$	3.03	15.92	9.6
$^{96}Zr \rightarrow {}^{96}Mo$	3.35	20.58	2.8
$^{82}Se \rightarrow {}^{82}Kr$	2.99	10.16	9.2
$^{76}Ge \rightarrow {}^{76}Se$	2.04	2.36	7.8
$^{48}Ca \rightarrow {}^{48}Ti$	4.27	24.81	0.187

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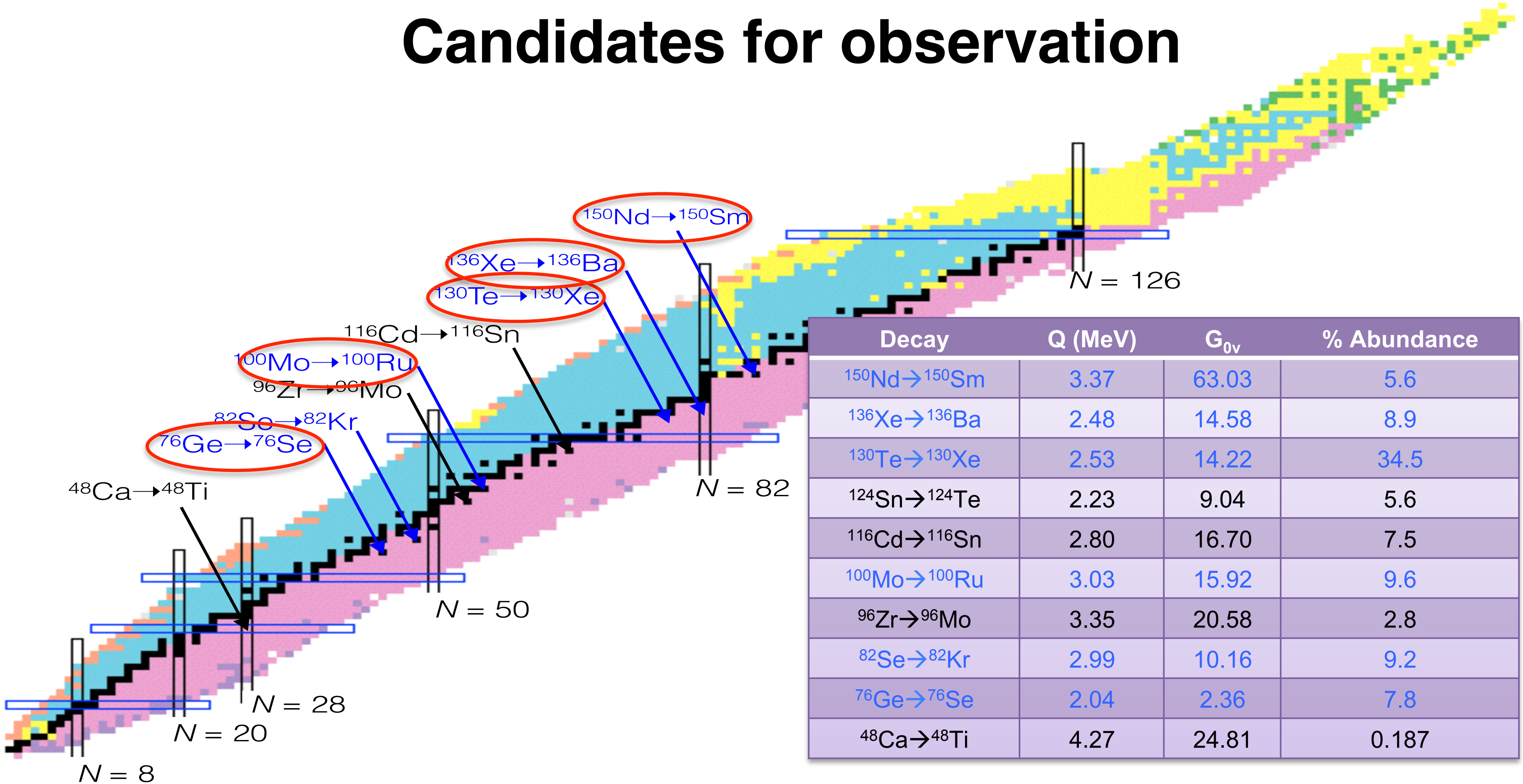

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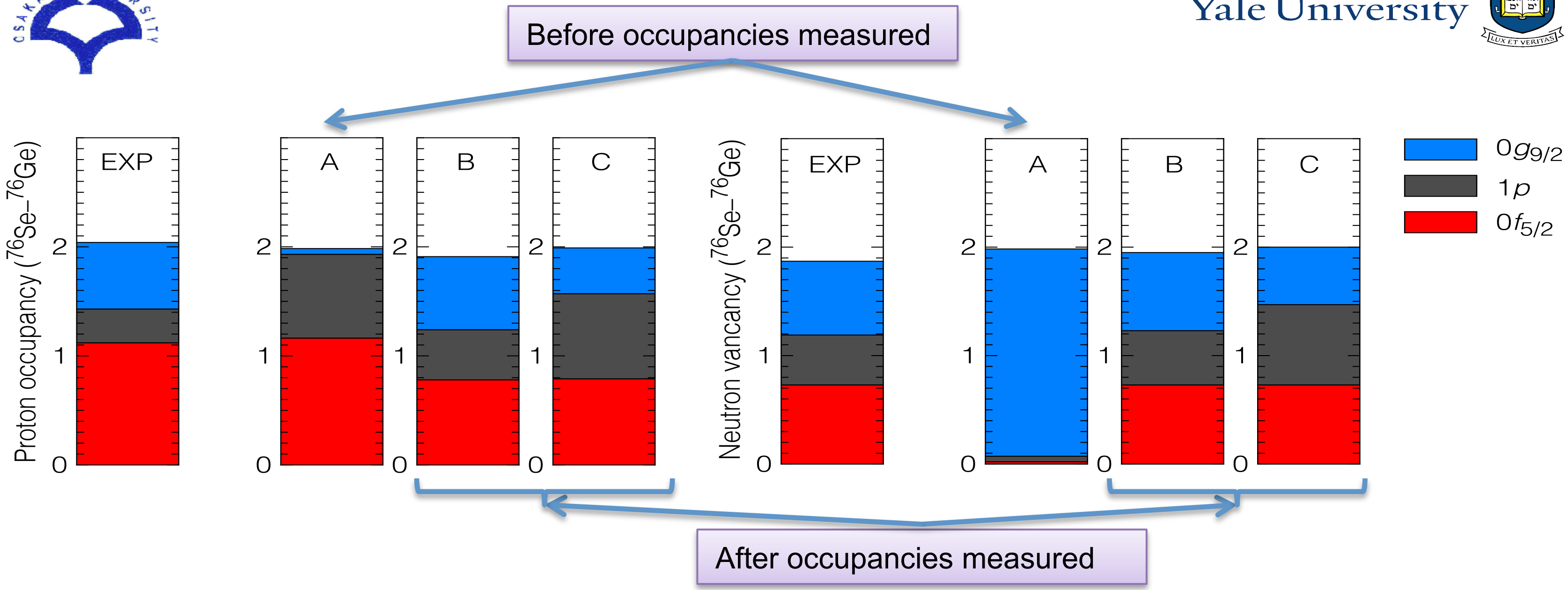
^{76}Ge, ^{130}Te and ^{136}Xe systems

- *In these systems the neutrons and protons occupy the same orbitals*
- *Simple rearrangement of neutrons and protons within the same model space*
- *Neutron transfer measured at Yale and Orsay (Frozen ^{130}Xe target)*
- *Proton transfer measured at Osaka ($^{130,136}Xe$ gas targets)*

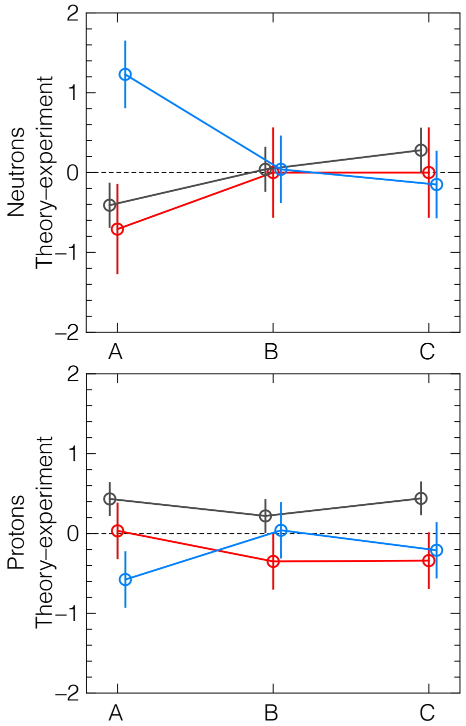
Change in Vacancy/Occupancy: ^{76}Ge

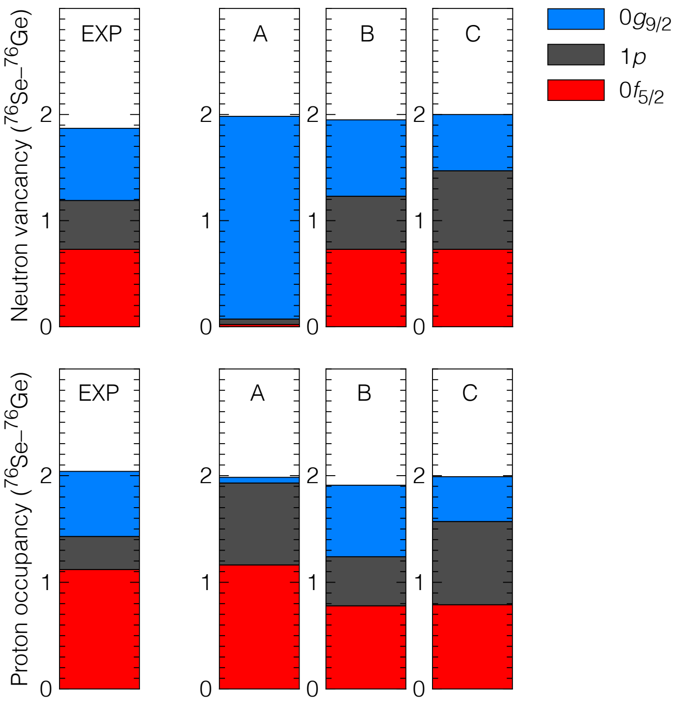


EXP — J. P. Schiffer *et al*., Phys. Rev. Lett. **100**, 112501 (2008); BPK *et al*., Phys. Rev. C **79**, 021301(R) (2009)
A — QRPA by Rodin *et al*., priv. com., Nucl .Phys. A **766**, 107 (2006)
B — QRPA by Suhonen *et al*., priv. com., Phys. Lett. B **668**, 277 (2008)
C — ISM by Caurier *et al*.,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

Change in Vacancy/Occupancy: ^{76}Ge

Yale University





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Impact on NME's

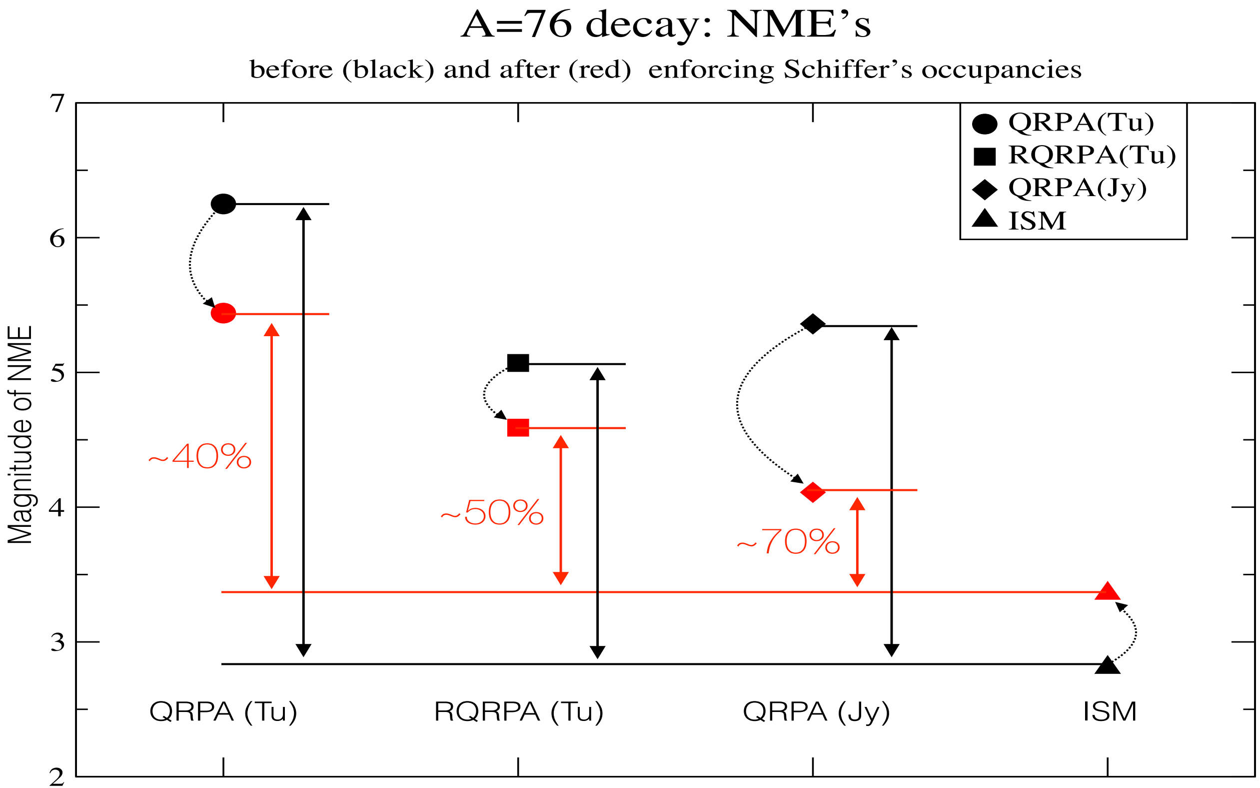
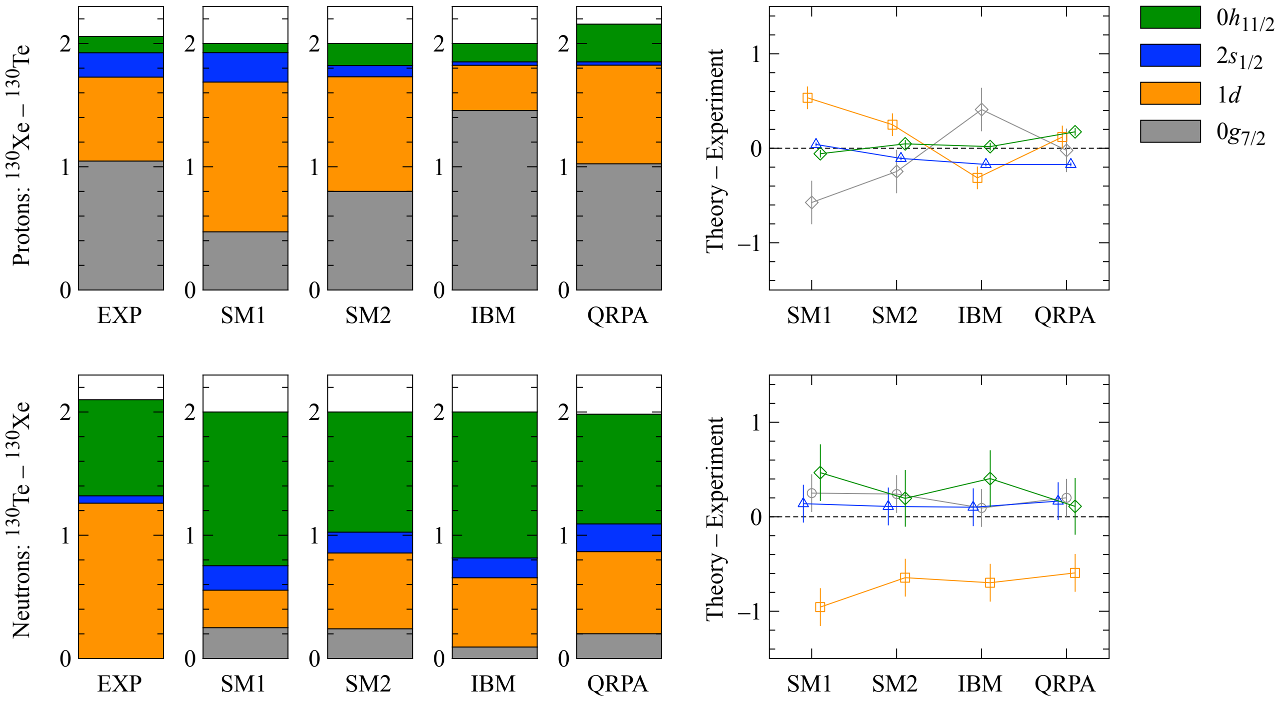


Figure adapted from Menéndez, Poves, Caurier, Nowacki, J. Phys.: Conf. Ser. **312**, 072005 (2011).

Change in Occupancy: $^{130}Te \rightarrow ^{130}Xe$

SM overestimating change in 1d and underestimating $g_{7/2}$. IBM opposite behaviour.

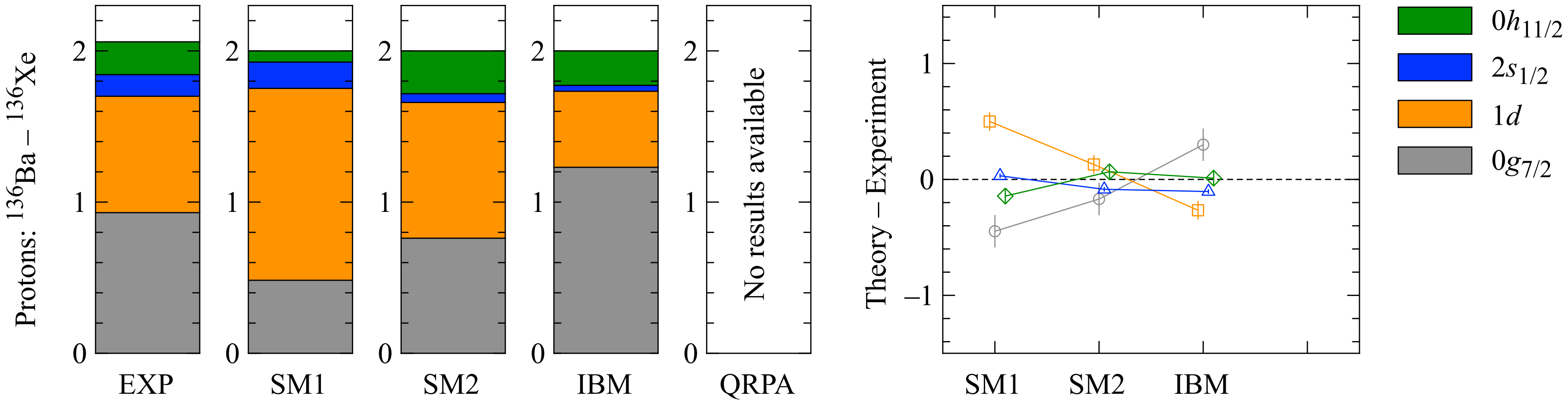
No contribution from $g_{7/2}$ seen experimentally. $h_{11/2}$ overestimated in all models with 1d contribution underestimated



EXP — Neutrons: BPK *et al*., Phys. Rev. C **87**, 011302(R) (2013); Protons: BPK *et al*., Submitted to Phys. Rev. C (2016)
SM1 — A. Neacsu, priv. com.; A. Neascu and M. Horoi, Phys. Rev. C **91**, 024309 (2015)
SM2 — J. Menéndez, priv. com.; J. Menéndez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A **818**, 139 (2009)
IBM -– J. Kotilla, priv. com
QRPA — J. Suhonen and O. Civitarese, Nucl. Phys. A **847**, 207 (2010)

Change in Occupancy: ^{136}Xe→^{136}Ba

SM overestimating change in 1d and underestimating $g_{7/2}$ in A=136 system also. IBM opposite behaviour. SM2 does a good job of reproducing the observed data in this particular case.



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IBM –- J. Kotilla, priv. com

^{100}Mo system

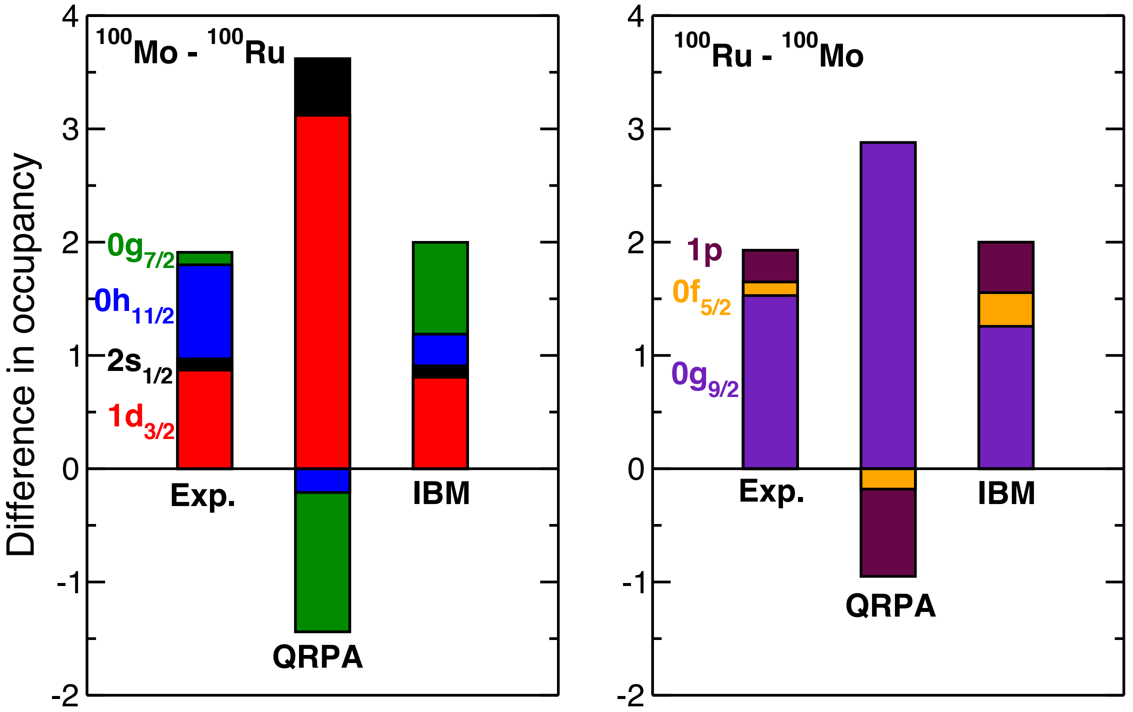
- *Neutrons and protons occupy different valence spaces.*
- *Region of deformation away from closed shells.*
- *More difficult measurements – high degree of fragmentation.*
- *Measurements made at Munich – higher resolution spectrograph*

^{100}Mo→^{100}Ru system – change in occupancies

*Occupancy measurements indicate that the **$0h_{11/2}$** and **1d** neutrons participate significantly in a double β decay process.*

*Smaller contributions from **$2s_{1/2}$** and **$0g_{7/2}$**.*

*Increase in number of protons during decay mainly in the **0g9/2** orbital with **1p** protons playing a lesser role.*



Theory: *QRPA* - J. Suhonen, O. Civitarese., Nucl. Phys. A. **924**, 1, (2014)
IBA – J. Kotilla, *priv. com.*

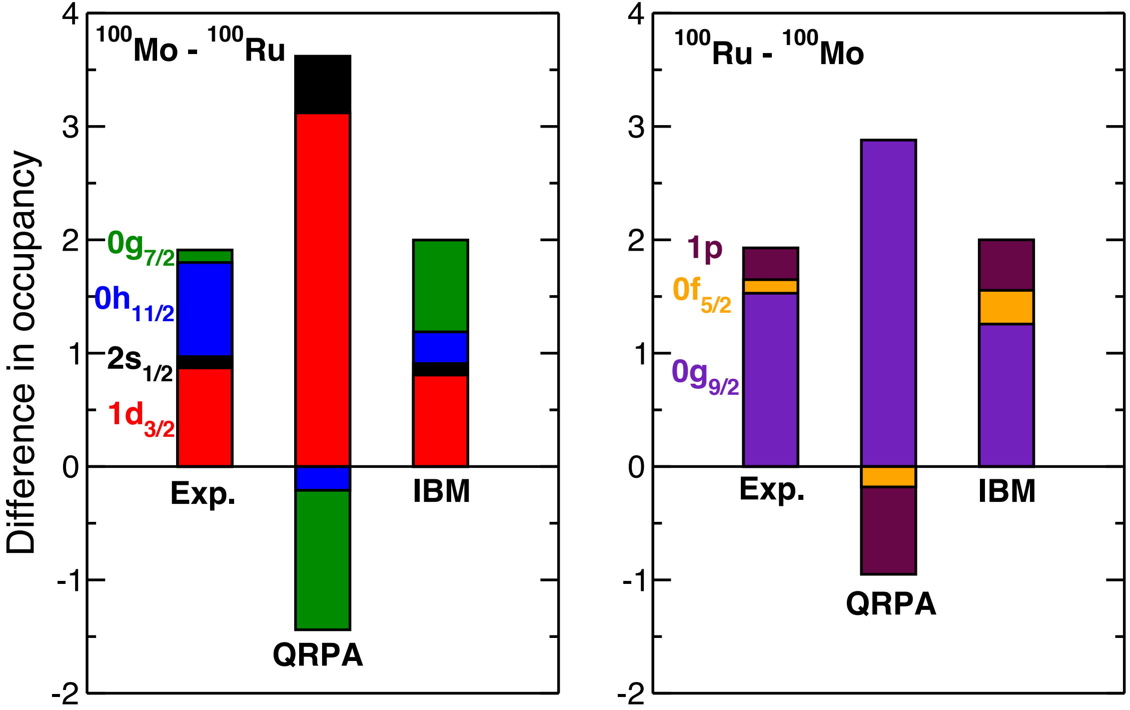
Maier-Leibnitz-Laboratorium für Kern-, Teilchen- & Beschleunigerphysik

^{100}Mo→^{100}Ru system – change in occupancies

Complex rearrangement suggested in a particular QRPA calculation not observed experimentally.

Better agreement with IBM but still large discrepancies in high-ℓ neutron orbitals.

What happens to NME's in both cases if calculations are altered to reproduce these changes in the occupancies?



Theory: *QRPA* - J. Suhonen, O. Civitarese., Nucl. Phys. A. **924**, 1, (2014)
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Conclusions and questions

The observed changes in occupancies in double beta decay systems provide a benchmark for comparison with theory. The work shown here encompasses almost a decade of experimental effort to measure the occupancies of these systems.

Measurements on ^{76}Ge appears to have effected improved agreement between different models.

Does this give us more confidence?

Measurements on other systems show discrepancies between experiment and theory. What happens to NME when theory reproduces the data? The data is or is soon to be available.

Occupancies are one experimental observable that may be of use for benchmarking calculations. What other information is useful to theorists? Can we measure it?

Collaborators

D. K. Sharp, **S. J. Freeman**, S. D. Blot, T. E. Cocolios, J. P. Entwilse, A. M. Howard, S. A. McAllister, A. J. Mitchell, S. V. Szwec and J. S. Thomas
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