Constraining Neutrinoless Double Beta Decay Matrix Elements using Transfer Reactions

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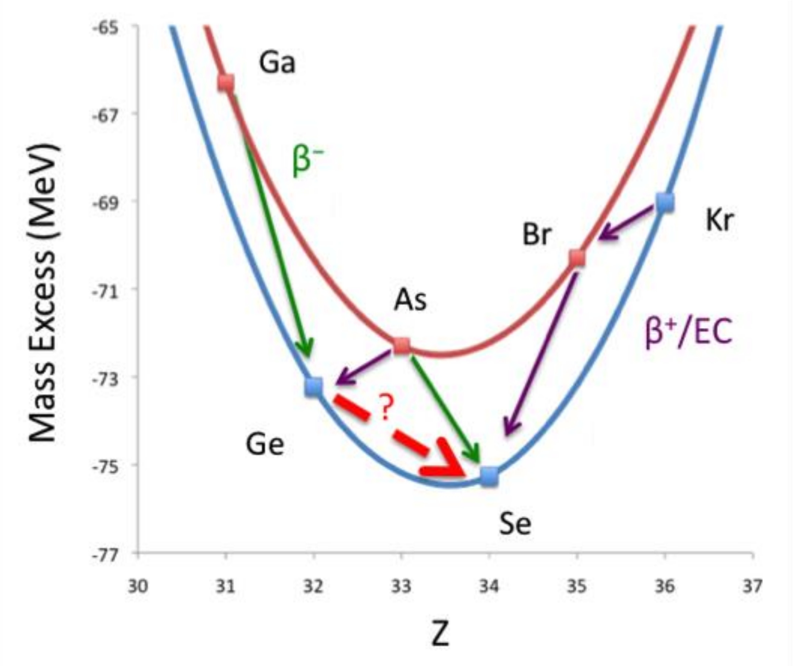
Review what we know about the nuclear physics influence on neutrinoless double beta decay.
Results of an experimental programme to help address the issue of the nuclear matrix elements.
Stick to one-nucleon transfer measurements.

What is double beta decay?

Two neutrons, bound in the ground state of an even-even nucleus, transform into two bound protons, typically in the ground state of a final nucleus.

Observation of rare decays is only possibly when other radioactive processes don't occur… a situation that often arises naturally, usually thanks to pairing.



Accompanied with emission of:

- Two electrons and two neutrinos (2νββ) observed in 10 species since 1987.
- Two electrons only (0νββ) for which a convincing observation remains to be made.

[Sometimes to excited bound states; sometimes protons to neutrons with two positrons; positron and an electron capture; perhaps resonant double electron capture.]

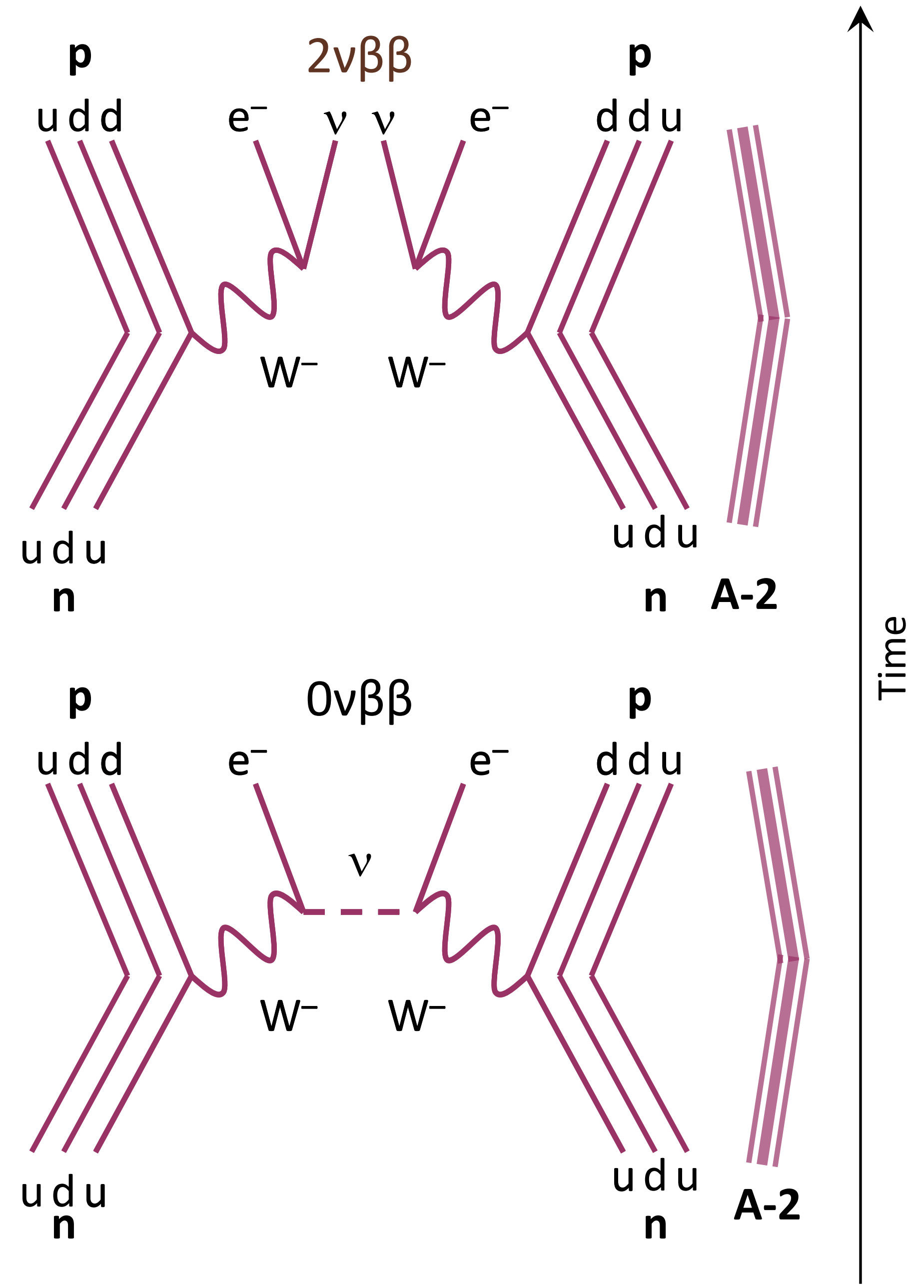
Double beta decay with neutrinos:

- simultaneous ordinary beta decay.
- lepton number conserved and SM allowed.
- observed in around 10 nuclei with $T_{1/2} \approx 10^{19-21}$ years.

Double beta decay without neutrinos:

- lepton number violated and SM forbidden.
- no observations, $T_{1/2}$ limits are 10^{24-25} years.
- simplest mechanism: exchange of a light massive Majorana neutrino
  i.e. neutrino and antineutrino are identical.

Other proposed mechanisms, but all imply massive Majorana neutrino via Schechter-Valle theorem.

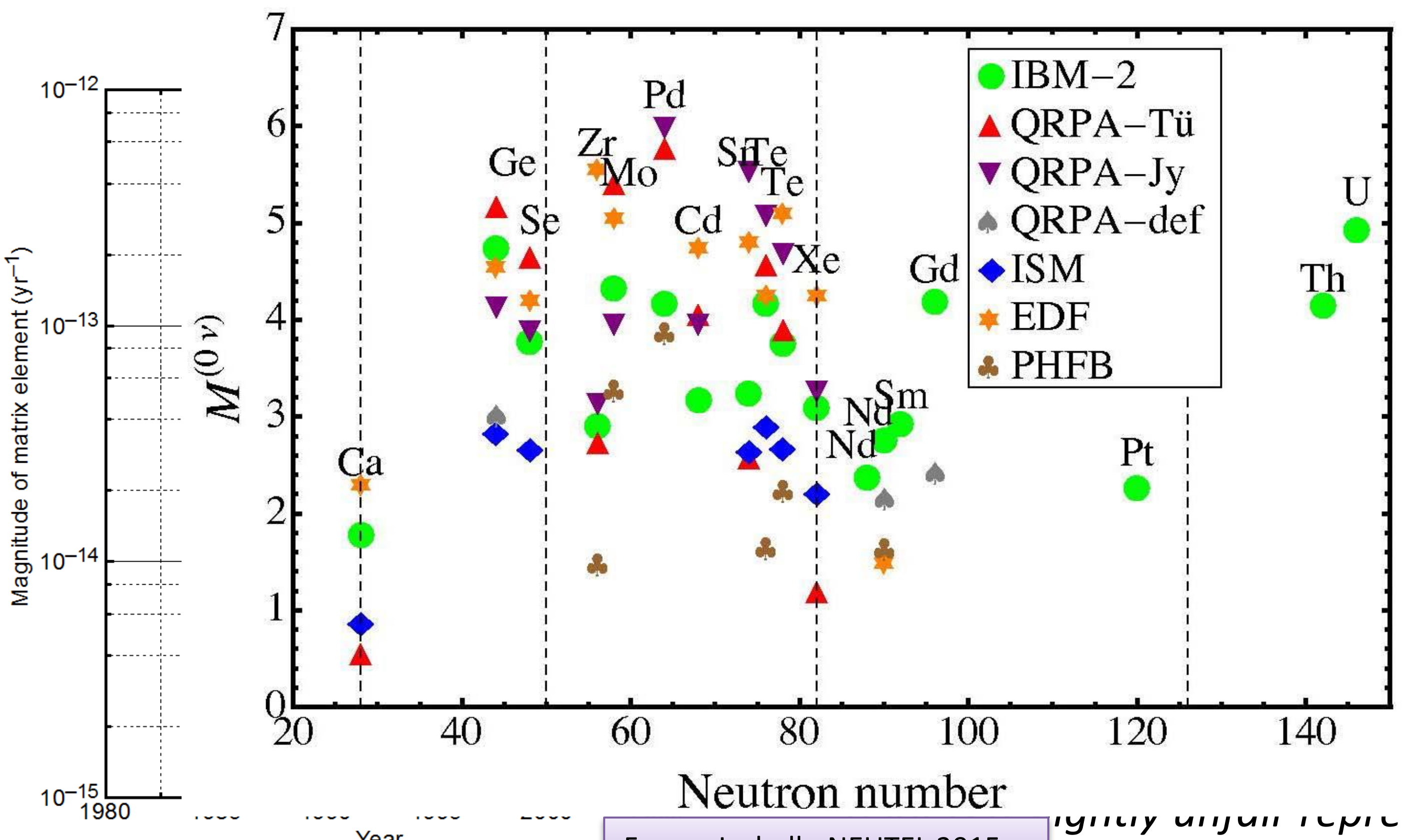


Neutrino Masses

For neutrinoless double beta decay mediated by a light massive neutrino:

$$\text{Rate } = G^{0\nu}\,|M^{0\nu}_{\rm GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_{\rm F}|^2\,\langle m_\nu\rangle^2$$

Convincing observation: Majorana neutrinos and their absolute mass scale?



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slightly unfair representation!)

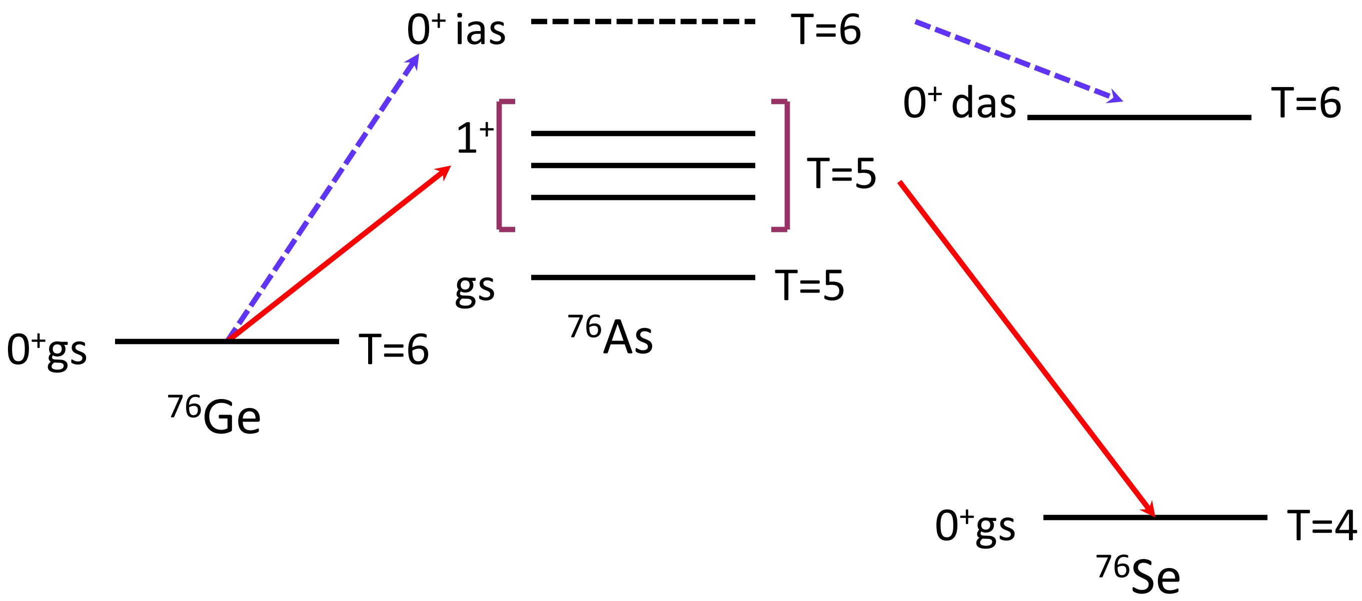
Franco Iachello NEUTEL 2015.

Double beta decay with neutrinos, 2νββ

Often viewed as via virtual excitation of states in the intermediate nucleus.

Fermi part: $\Delta J=0$; super allowed if $T_i=T_f$ (can neglect)
GT part: $\Delta J=\pm1,0$, except no J=0 to J=0

Essentially GT transitions via 1^+ states in the intermediate nucleus



Effects of nuclear structure in intermediate nucleus is high, depends critically on specific locations of *low-lying* 1+ states
i.e. GT strength function in the intermediate system and the initial/final states.

Neutrinoless double beta decay, 0νββ

Mediation by a virtual neutrino gives different features:

$$q \sim \hbar/r_{nn} \sim 50 - 100\mathrm{MeV/c}$$

A: Energy of intermediate excited states can be large up to several tens of MeV *(compare with few MeV for 2νββ).*

B: Angular momentum transfer is also large, up to 7-8 *ħ* (compare with *1ħ for 2νββ).*

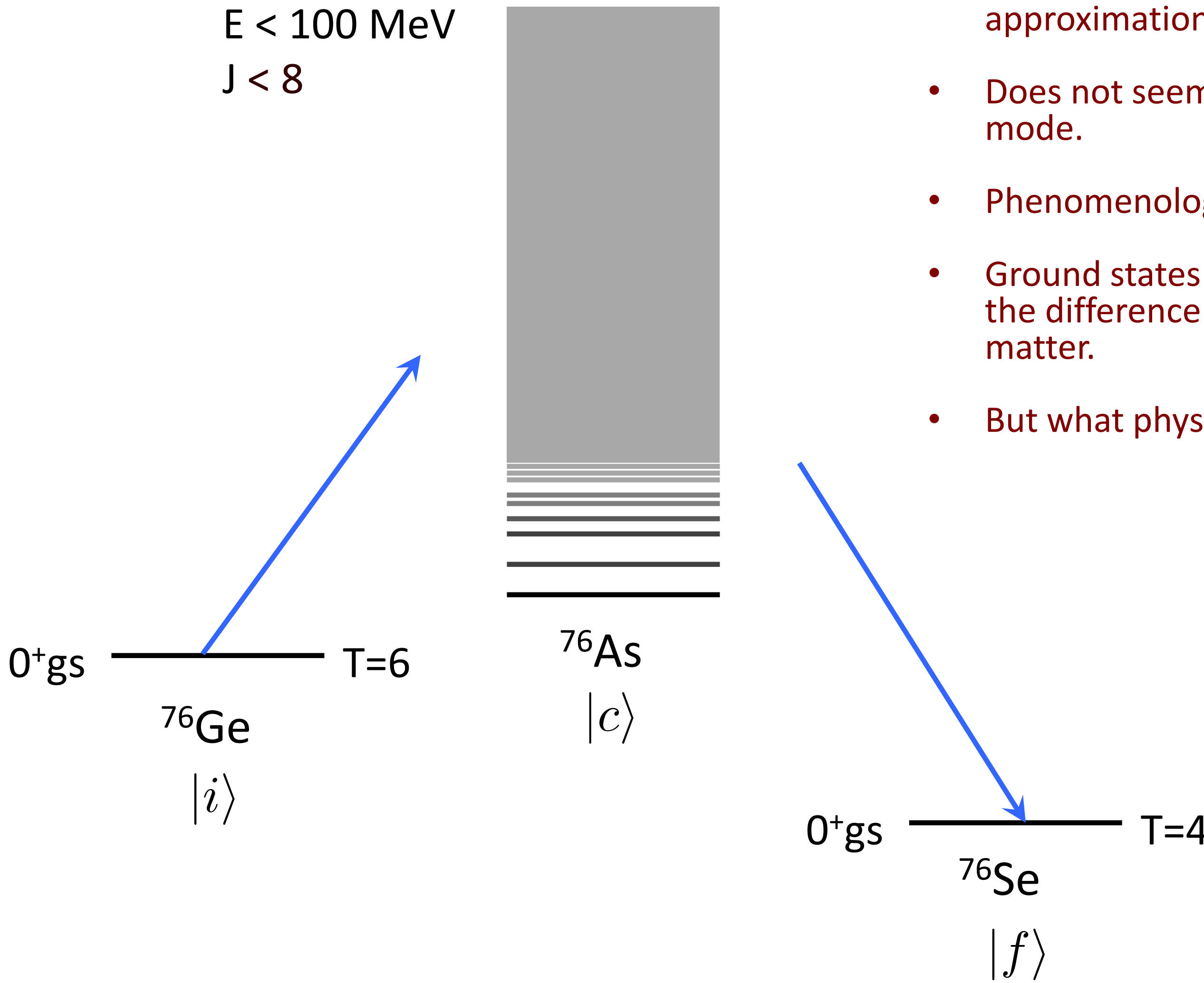
$$M^{0\nu} \approx \langle f | \sum_{lk} H(r_{lk}, E) \tau_l \tau_k \left(\sigma_l \sigma_k - \left(\frac{g_V}{g_A} \right)^2 \right) |i\rangle$$

Both F and GT transitions.

"Neutrino potential": depends on position of nucleons and (weakly) on the energy of intermediate state, due to A can replace by average (CLOSURE).

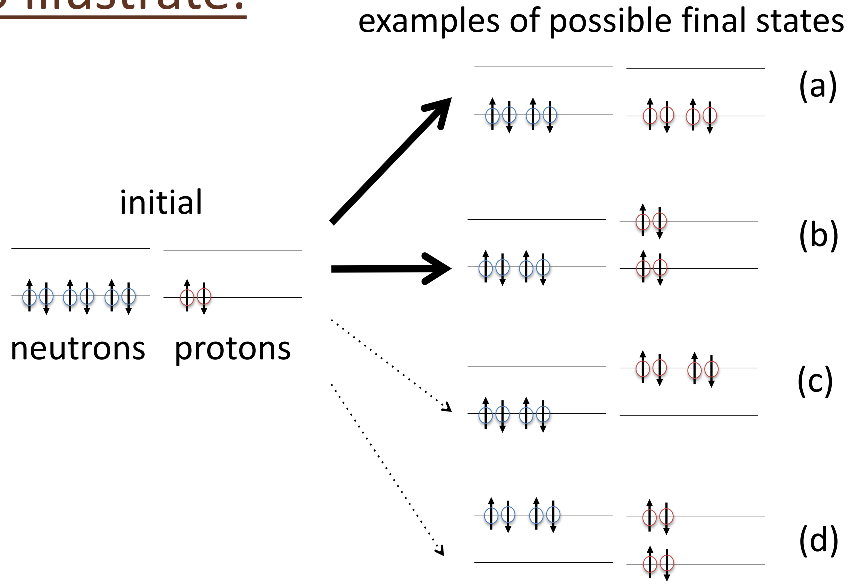
When expanding H into multipoles expect contributions up to 7-8.

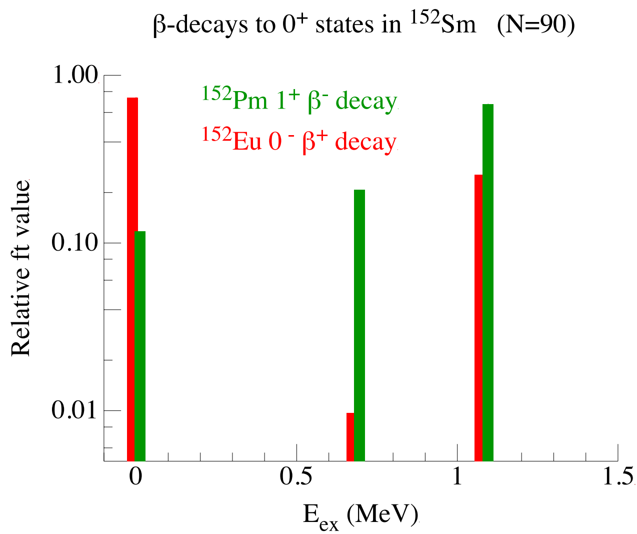
Neutrinoless double beta decay, 0νββ



- Given the shear number of states involved, would appear less sensitive to details of intermediate nucleus; tests of closure approximation show this.
- Does not seem simply related to 2νββ mode.
- Phenomenology is unlikely to work!
- Ground states of parent and daughter (or the difference between them) must matter.
- But what physics is important?

Naïve caricature to illustrate:



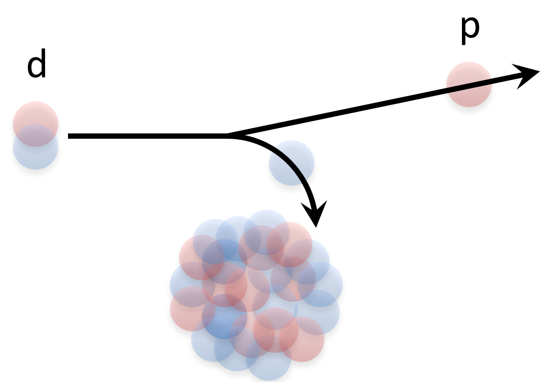


- Process might be facilitated if the parent/daughter ground states are related by simple changes of neutrons to protons, such as if in the decay $2\nu \Rightarrow 2\pi$ in same orbital (a) or different orbital (b).
- Significant rearrangements of nucleons other than the direct participants, as in (c) and (d), is likely to inhibit process: e.g. very different structures or deformation in parent and daughter.

Comparison of experimentally deduced occupancies and those implied by models used to calculate the nuclear matrix elements likely to be a useful in addressing the efficacy of the calculations.

<u>Experimental Probe</u>: single-nucleon transfer reactions e.g. (d,p)

Arrange experimental conditions to favour single-step transfer of a nucleon to/from target.



Angular distribution indicative of ℓ transferred

Caricature version:
Empty orbit: can't remove, but can add.
Full orbit: can't add, but can remove.
Partially occupied: reduced cross section.

Define a spectroscopic overlap or factor: $SF = |\langle \Phi_{J_B}^{M_B} | \mathcal{A}[\Phi_{J_A} \phi_j]_{J_B}^{M_B} \rangle|^2$

"How much does the final state look like the target plus a nucleon in a specific orbit"

Extract from experimental cross sections by comparison with reaction model of cross section expected for an IPM state: $SF = \sigma_{\rm expt}/\sigma_{\rm IPM}$

Effectively 'reduced cross sections"

Macfarlane and French Sum Rules:

Number of vacancies = $\sum (2j+1) SF_{\text{adding}}$

Number of occupancies = $\sum SF_{\text{removing}}$

Sums over all states populated via transfer of nucleon from the relevant orbit.

Doing both adding AND removal reactions on the same target provides a check:

$$2j+1 = \sum SF_{\text{removing}} + \sum (2j+1) SF_{\text{adding}}$$

Experimental Methods

Light-ion induced reactions under conditions where a direct mechanism dominates.
[10-20 MeV/u, forward angles, 1st peak]

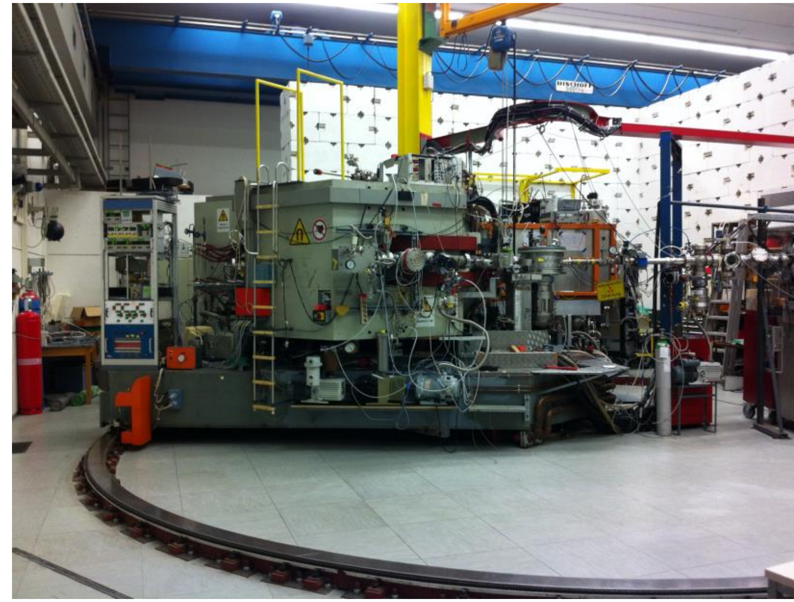
Often two sets of reactions needed to meet "matching conditions" for low and high ℓ.
[e.g. neutron transfer by both (d,p) and (α,^{3}He)]

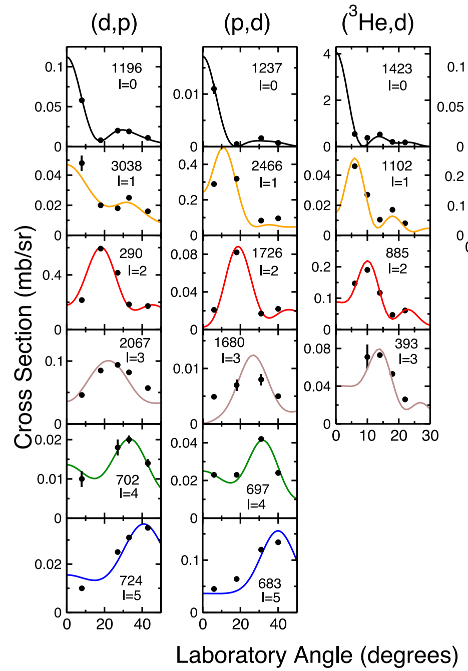
Identify outgoing ions on the basis of their momentum, dispersed using a magnetic spectrometer, and energy-loss characteristics in gas-filled focal plane detector.

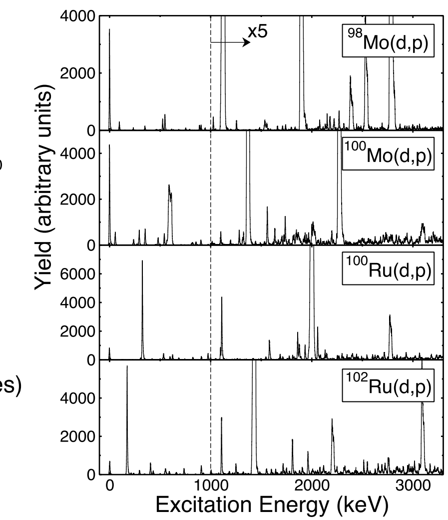
Measure cross sections to final states as a function of angle.
[Absolute scale by comparison with elastic scattering in Rutherford regime.]

Assign spin-parities of final states; although many already known.

Yale, Osaka, Munich and Orsay.







“Every man, woman and their dogs did transfer reactions in the 60’s and 70’s, doesn’t the data exist?”

“You’re not going to learn anything new!”

- C20 data preservation was poor: cross sections often not published.
- Reaction modeling developed alongside experimental work: approaches were not consistent and variety of approximations used to get around computing speed problems of full calculations.
- Very few systematic measurements made: different experimental approaches, different beam energies, different ranges in angle and excitation, different approaches to absolute cross section, difference in analytical procedures.

Very useful technological advances (e.g. excellent high intensity ion sources available, ASCI wire-by-wire readout in focal plane detectors) improve data rates to enable systematic measurements across a range of targets (DBBD nuclei and some neighbors for checks).

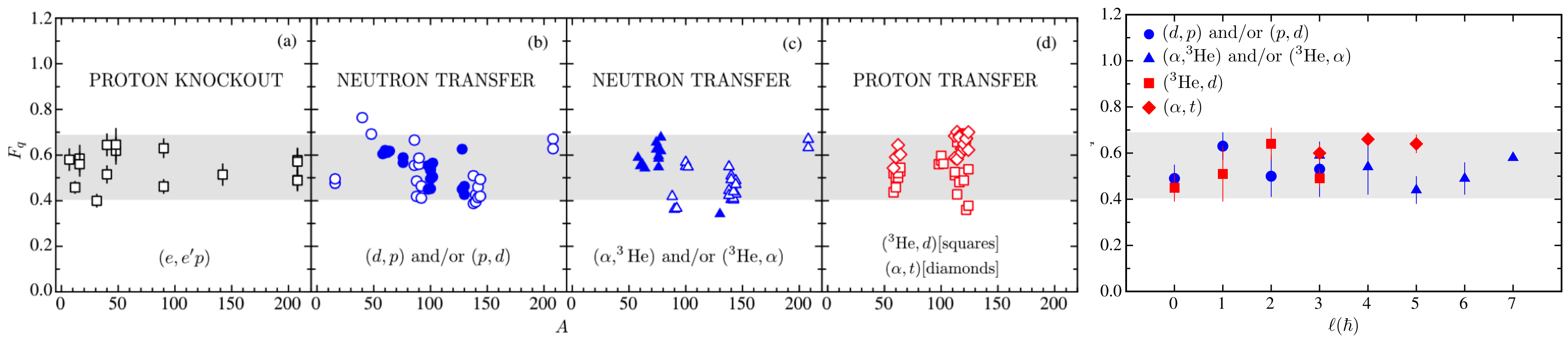
Reaction modeling is mature and fast calculations allow better understanding of individual cases….and some interesting global trends..

Many states now studied in different ways….assignments firmer.

Global Trends in SF: Quenching of Cross Sections

$$2j+1=\sum SF_{\text{removing}}+\sum(2j+1)SF_{\text{adding}}$$

Cross sections appear quenched: 50-60% of total expected occupancy.



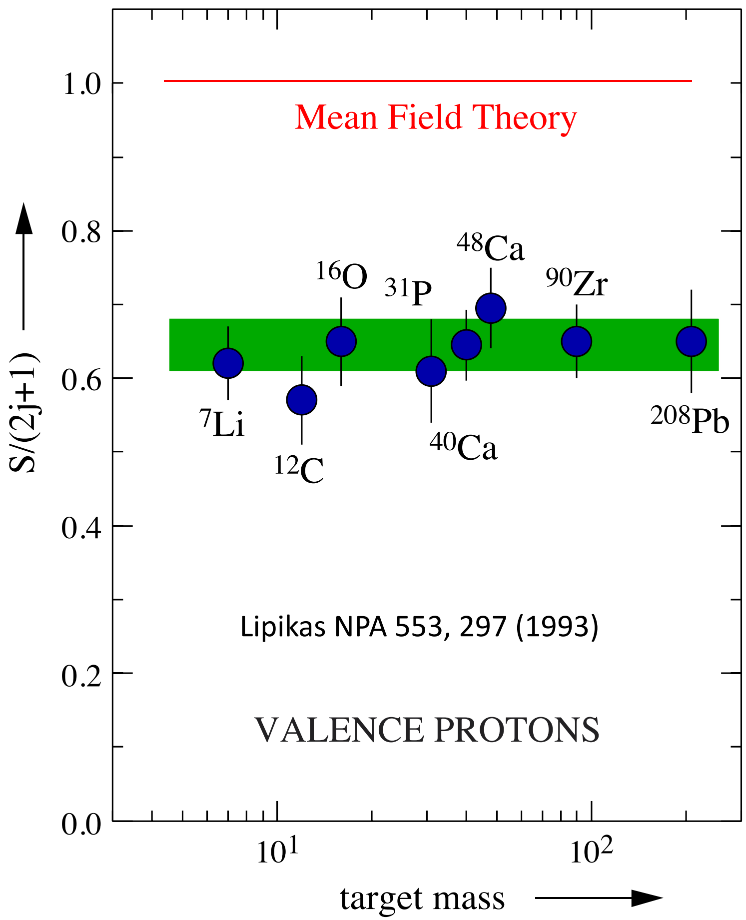
Kay, Schiffer, Freeman PRL 042502 (2013)

Analysis of 124 cases between ^{16}O and ^{208}Pb, induced by variety of reactions and orbital angular momentum: quenching of 0.55.

[Consistent reaction DWBA modelling with modern global optical potentials, projectile wave functions from ab-initio calculations, target bound state adopted from (e,e'p) studies. Other reaction models, e.g. ADWA, give similar results.]

Global Trends in SF: Quenching of Cross Sections

Confirm and extends an effect identified in (e,e'p) studies at NIKEF in 1990's…



Our analyses show it is independent of whether nucleon added or removed, type of nucleon transferred, nuclear mass, reaction type or angular momentum transfer.

It *does* appear to be a uniform property in large part thought to be due to the effects of short-range correlations (SRC).

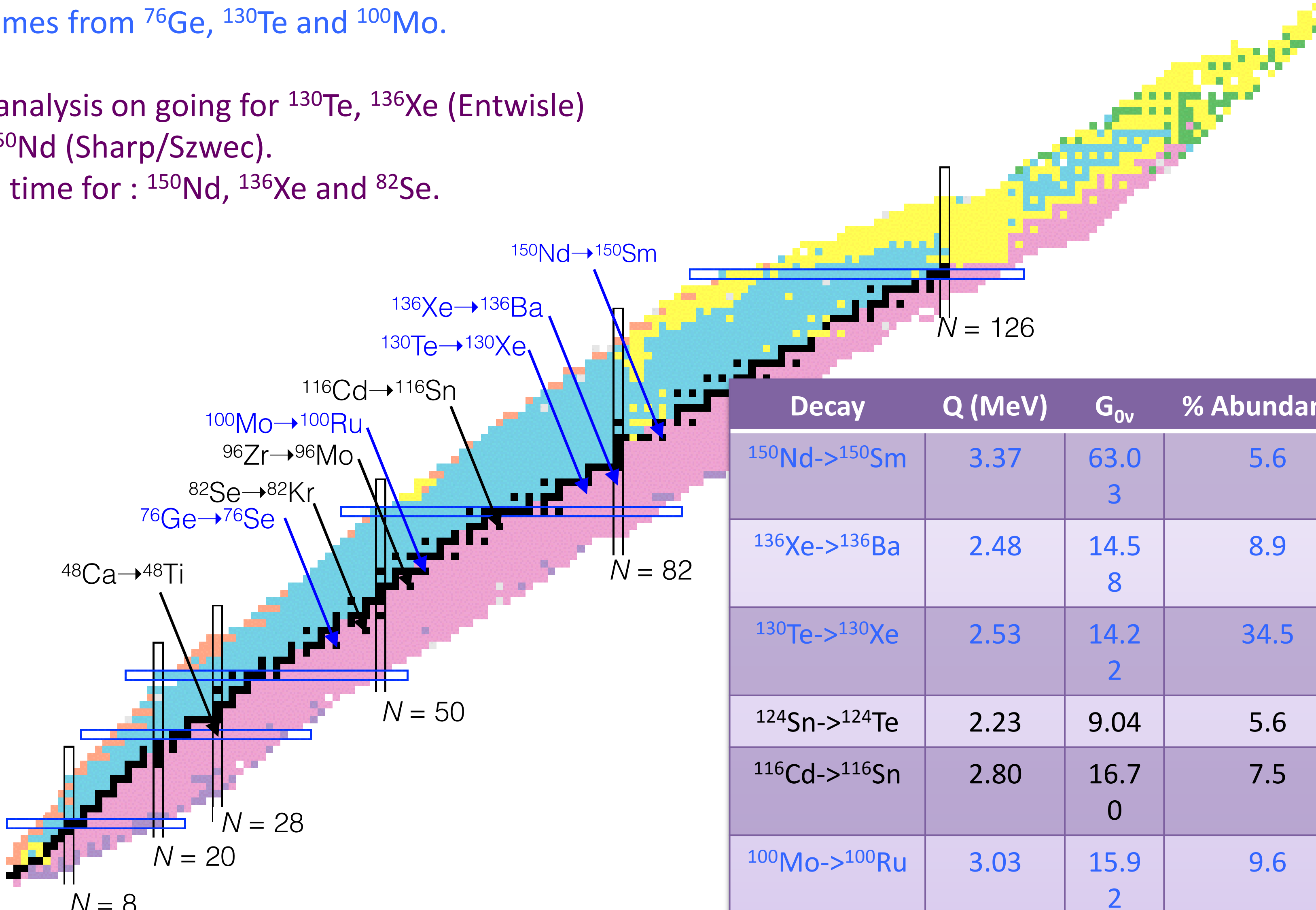
In what follows, *choose* to normalise the observed population of the valence orbitals to *(2j+1)* using the individually deduced quenching factors.

- Somewhat conventional; since uniform property should not matter..
- Internal normalisation adopted has some more global consistency.
- SRC are taken into account in calculations of NME.

Status of Our Programme of Measurements

Measurements on likely candidates, the product and some neighbouring nuclei: outcomes from ^{76}Ge, ^{130}Te and ^{100}Mo.

Data analysis on going for ^{130}Te, ^{136}Xe (Entwisle) and ^{150}Nd (Sharp/Szwec).
Beam time for : ^{150}Nd, ^{136}Xe and ^{82}Se.



Decay	Q (MeV)	$G_{0\nu}$	% Abundance
^{150}Nd->^{150}Sm	3.37	63.03	5.6
^{136}Xe->^{136}Ba	2.48	14.58	8.9
^{130}Te->^{130}Xe	2.53	14.22	34.5
^{124}Sn->^{124}Te	2.23	9.04	5.6
^{116}Cd->^{116}Sn	2.80	16.70	7.5
^{100}Mo->^{100}Ru	3.03	15.92	9.6
^{96}Zr->^{96}Mo	3.35	20.58	2.8

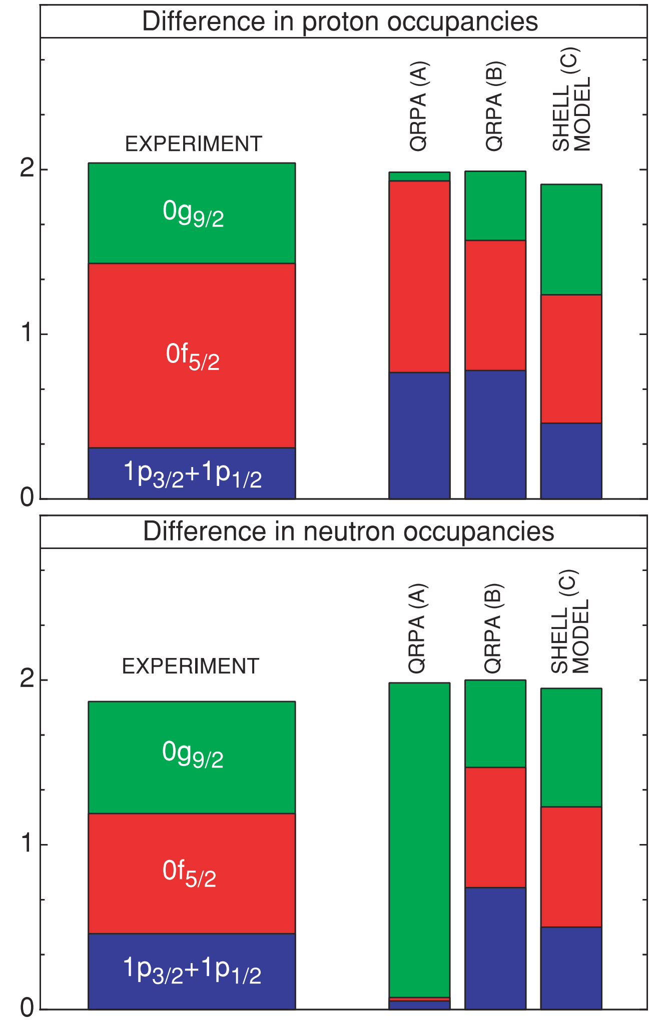
Valence Nucleon Occupancies Relevant to 76Ge

Neutron and proton adding and removal reactions on ^{76,74}Ge and ^{76,78}Se targets.

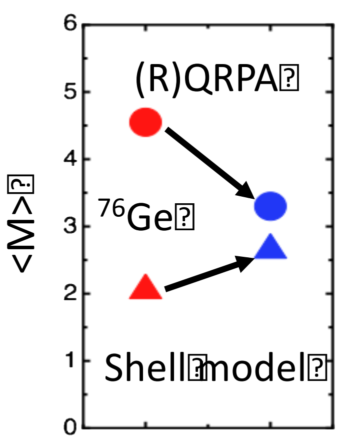
Both proton and neutron Fermi surfaces in shell that includes: $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$.

Experimentally deduced changes in a putative 0νββ decay compared to prior theoretical calculations (A) suggest:

- $0g_{9/2}$ protons considerably more involved.
- $0g_{9/2}$ neutrons considerably less involved.
- Both Fermi surfaces more diffuse.



PRL 100 112501 and PRC 79 021301(R)



Calculations with adjusted mean fields (B) and (C) :

- In QRPA, $M^{0\nu}$ fell by around 30%.
- In SM, $M^{0\nu}$ increased by 15%.
- Discrepancy reduced by factor two.

Facilities used at:

Yale University

OSAKA UNIVERSITY

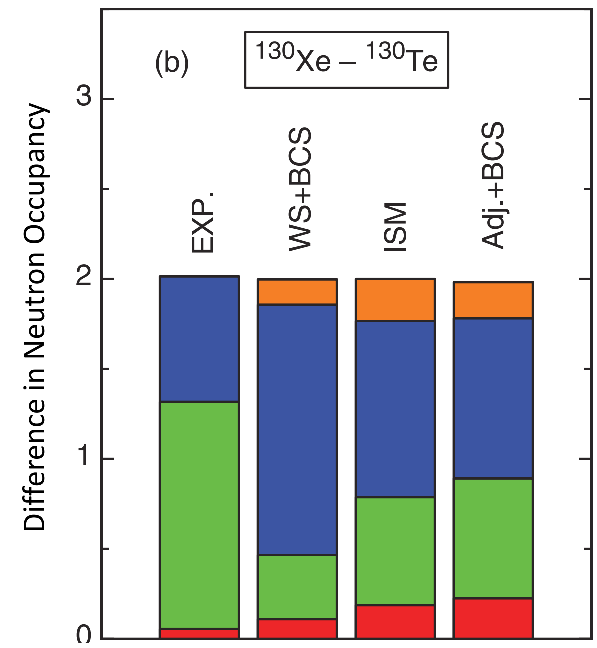
Valence Nucleon Occupancies Relevant to 130Te

Neutron adding and removal reactions on ^{128,130}Te and frozen ^{130,132}Xe targets.

Neutron Fermi surfaces in shell that includes: $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$ and $0h_{11/2}$.

Experimentally deduced changes in a putative 0νββ decay compared to prior theoretical calculations (A) suggest:

- $0g_{7/2}$ fully occupied and inactive; no evidence for population at low excitation energy.
- Relative roles of other orbitals differs from that assumed in the calculations of 0νββ matrix elements.



PRC 87 011302(R)

Facilities used at:

Yale University

Protons:

- Old data for Te targets only suggests no proton $0h_{11/2}$ strength despite playing a role in calculations of 0νββ; a consequence of the Z=64 subshell gap?
- Recent experiment: data from proton transfer on solid Te and Ba targets and Xe gas cells under analysis.

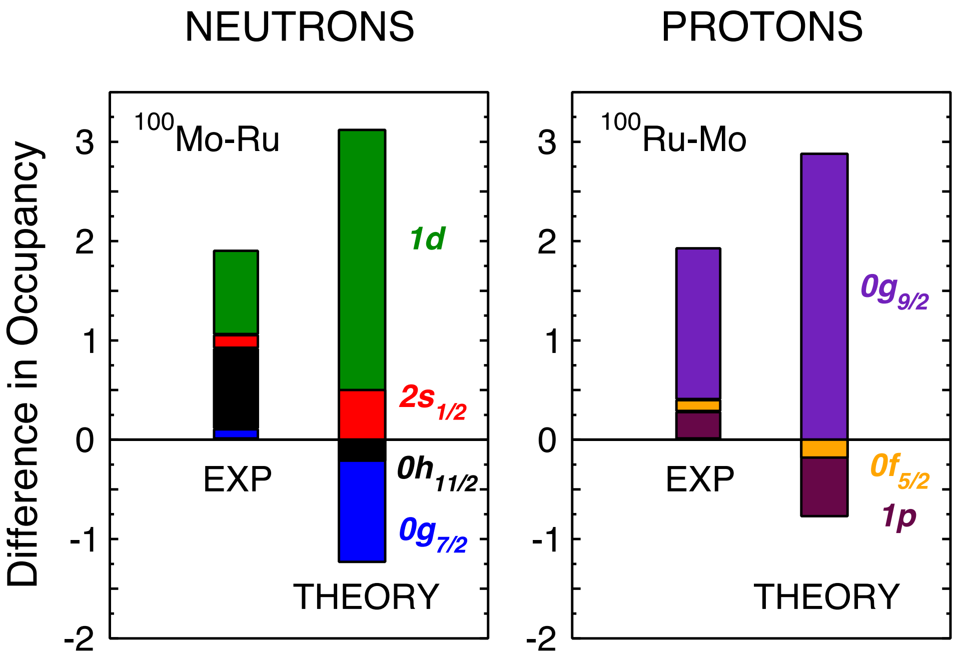
Valence Nucleon Occupancies Relevant to 100Mo

Neutron and proton adding and removal reactions on ^{98,100}Mo and ^{100,102}Ru targets.

Proton Fermi surfaces in shell that includes: $1p_{3/2}$, $0f_{5/2}$, $1p_{1/2}$ and $0g_{9/2}$.

Neutron Fermi surfaces in shell that includes: $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$ and $0h_{11/2}$.

Recently published QRPA occupancies look strange by comparison; some neutron orbitals *increasing* and some proton orbitals *decreasing*.



Publication in preparation

Facilities used at:

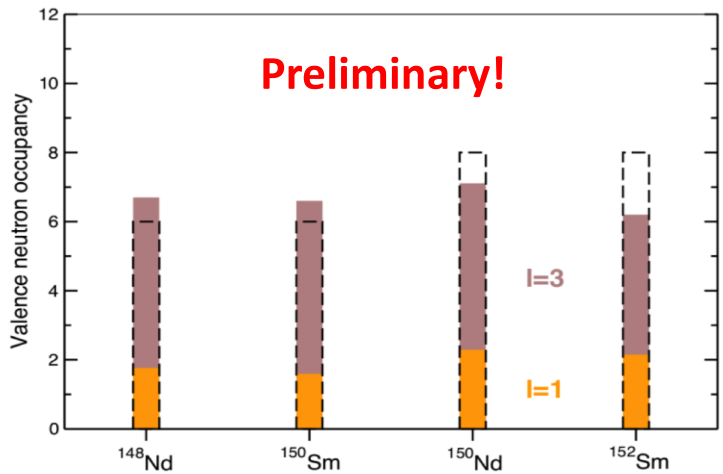
Valence Nucleon Occupancies Relevant to 150Nd

Neutron adding and removal reactions on ^{148,150}Nd and ^{150,152,154}Sm targets.

Parent-product pair of putative 0νββ spans a well-known shape change between N=88 and 90.

Data taken on some neutron-transfer reactions (under analysis) and more experiments planned.

Early results suggest sum rules obeyed at least to 15%, but some puzzles to solve yet...



Facilities used (or will be used) at:

Conclusions and Comments

- New large-scale $0\nu\beta\beta$ experiments may increase the probability that observation is imminent, at least in the inverted mass hierarchy scenario.
- Observation could set the absolute neutrino mass scale, if the nuclear matrix elements can be calculated reliably. Calculation of $M^{0\nu}$ is therefore an important, but difficult task.
- Values of $M^{0\nu}$ from different theoretical methods compare better than perhaps they did. However, the comparability of different theoretical measurements is no guarantee that they are correct.
- Useful checks can be made by measurements of specific nuclear properties, as illustrated here with the changing occupancies of valence nucleon orbits.
- What other nuclear properties have a critical effect on the matrix elements? Pair transfer to test BCS approximations of pairing; single and double charge exchange reactions; single β decay…but not always clear if there is a critical connection with $M_{0\nu}$
- Theoretical calculations, as presented, are not always hygienic enough to disentangle the physics that matters; simple "intuitive" understanding has yet to emerge:

Prospects look good: a lot of work is underway by a rather diverse collection of theorists and experimentalists who have learned how to undertake very productive discussions… …let's hope this is well timed with any impending observation!

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