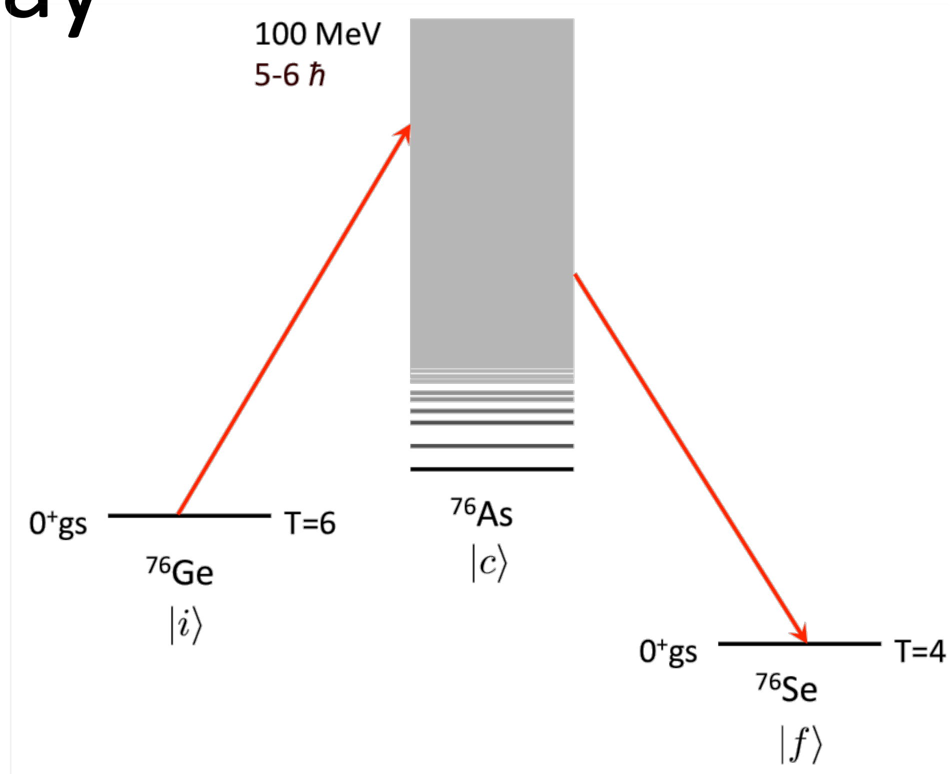
Experiments to probe the pairing properties of double-beta decay candidates.

Speculations from an experimentalist point of view on pairing-related effects that might be important for 0νββ matrix element.



Sean J Freeman

TRIUMF Workshop 2016

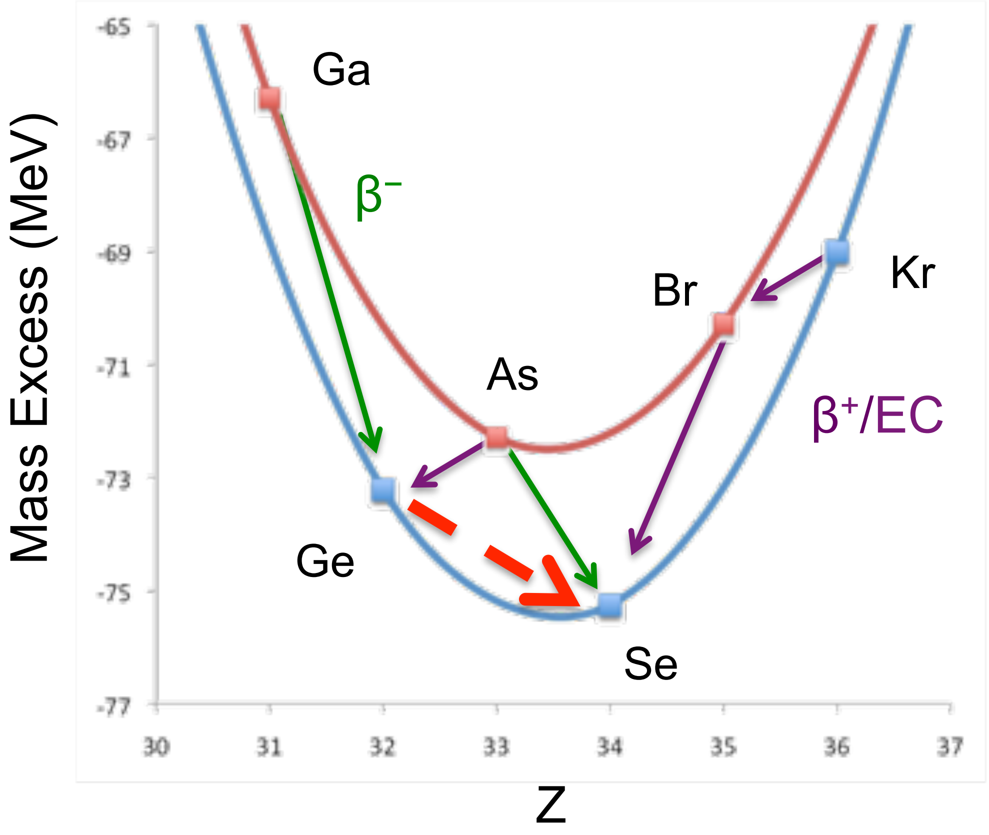
OUTLINE

- Pairing and $0\nu\beta\beta$ matrix elements.
- Departures from BCS pairing.
- Pair transfer reactions.
- Review results of recent experiments:
  ^{76}Ge-Se, ^{130}Te-Xe and ^{100}Mo-Ru.
- What the literature says about:
  ^{150}Nd-Sm, ^{136}Xe-Ba and ^{82}Se-Kr.
- Some closing comments.

Pairing and Double Beta Decay

Some very basic connections between pairing and double beta decay:

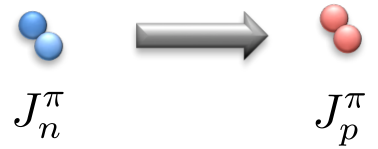
- Pairing is responsible for the viability of double beta decay.
- Smearing of the Fermi surface enables $2\nu\beta\beta$ in nuclei with a neutron excess, where it is otherwise Pauli blocked.
- Conversion of two neutrons into protons – should we expect pairing to be relevant to the matrix elements?



Pairing and Double Beta Decay

If 0νββ NMEs are written as a sum over the angular momentum of the products of pair creation and annihilation operators, contributions from zero-spin pairs can be separated from other J^{π}.

Ubiquitous result: dominant contribution from J=0, but J>0 still significant and of opposite sign.
Cancellation effects seem to diminish the long-range components, leaving a short range peak.

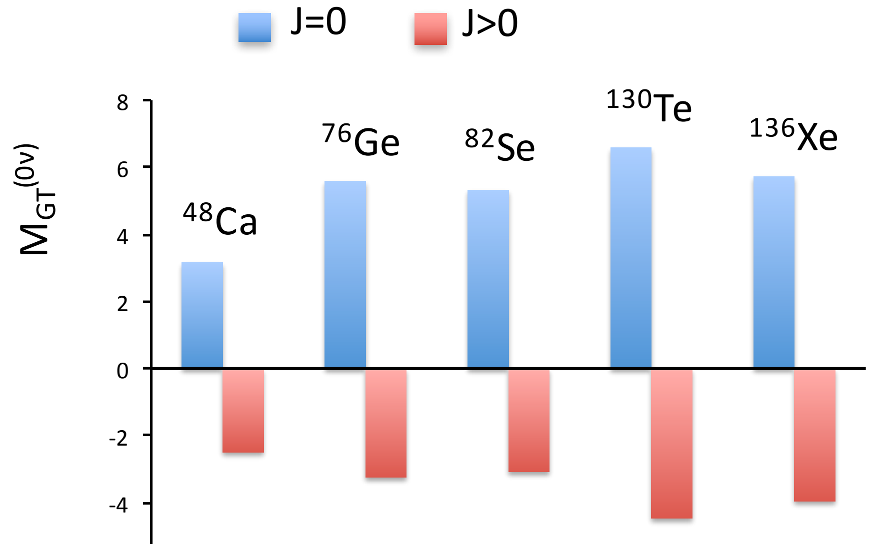


Šimkovic et al. PRC 79, 015502 (2009)

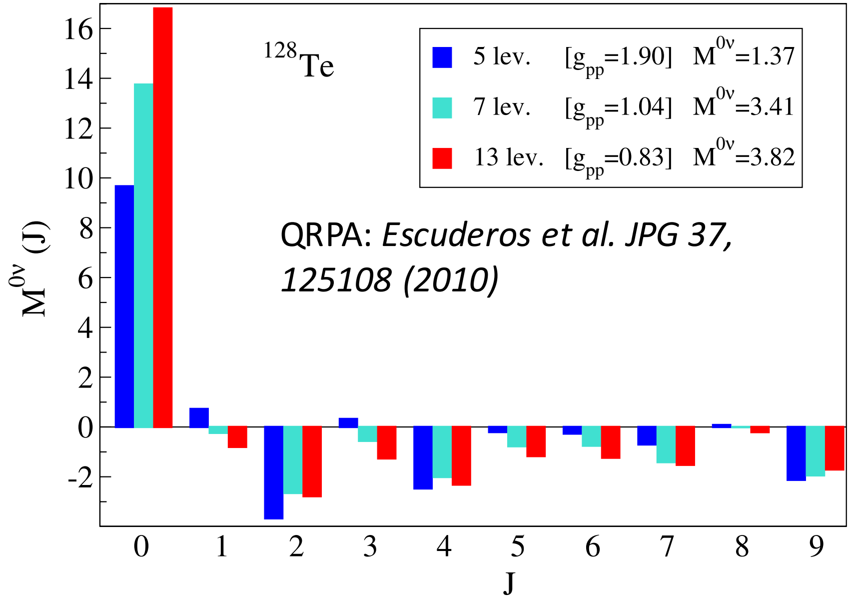
$$\hat{M}^{(0\nu)} = \sum_{J^\pi} \hat{P}^{\dagger}_{J_n^\pi} \hat{P}_{J_p^\pi}$$

A couple of recent examples:

Contributions to the GT matrix element with:



SM: *Caurier et al. PRL 100, 052503 (2008)*

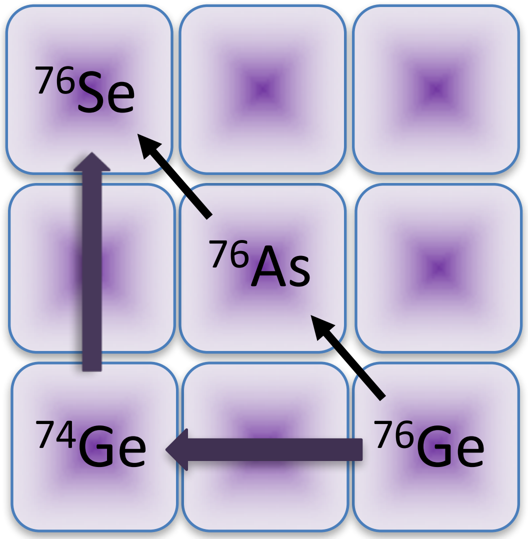


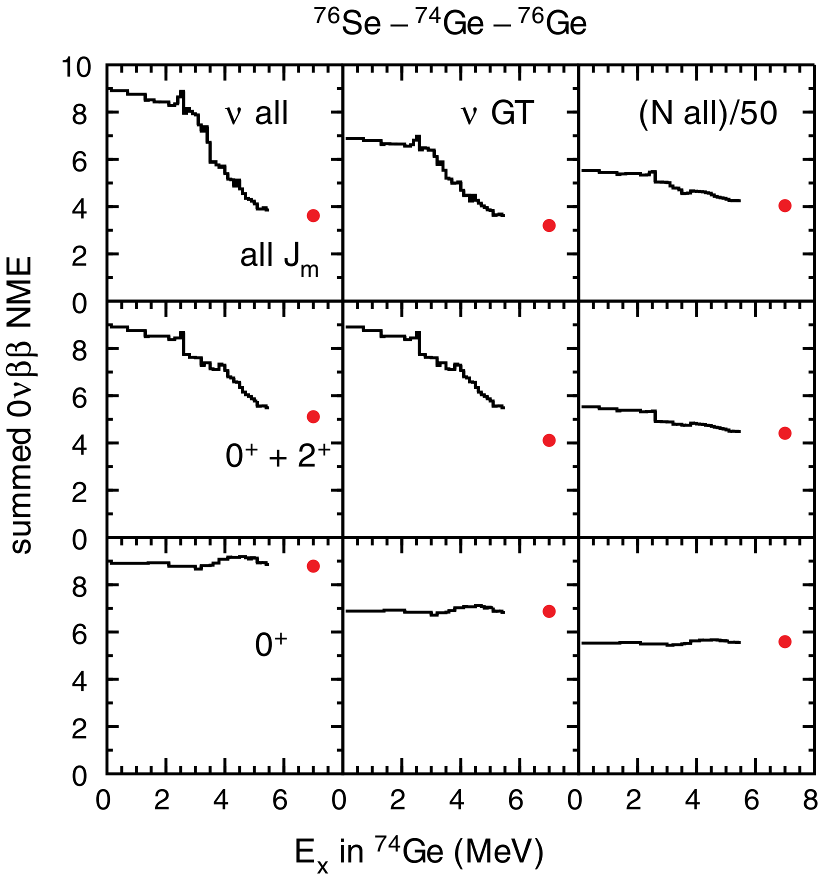
QRPA: *Escuderos et al. JPG 37, 125108 (2010)*

Pairing and Double Beta Decay

Brown et al. PRL 113, 262501 (2014)

$0\nu\beta\beta$ matrix elements as summation over states of different spins J in the A-2 nucleus.





- NME dominated by the contribution through the ground state.
- Cancellations from intermediate states with J>0.
- Pairing enhances the $J=0^+$ contribution.
- Connection to pair transfer reactions via complicated sums over quantities related to two-nucleon transfer amplitudes.

Pairing in Different Nuclear Models Used for 0νββ

In QRPA, pair correlations between like nucleons are treated separately from other effective interactions via the transformation to the quasiparticle regime within the Bardeen-Cooper-Schrieffer (BCS) approximation.

In shell-model treatments, more detailed set of interactions is used than simple pair correlations, albeit within a limited model space.

In IBM treatments, pairing implicit in the bosonisation approach to truncating the model space.

BCS works well in many nuclei to describe pairing correlations for protons and neutrons, but there are some well-established nuclear structure scenarios where it fails.

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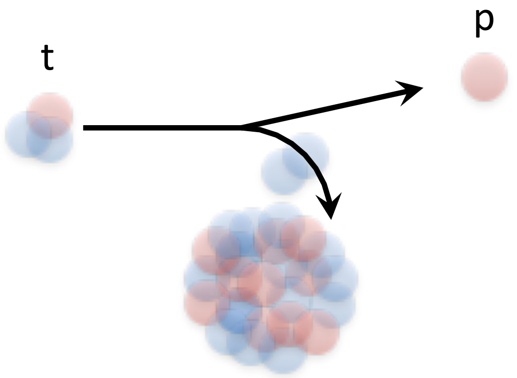
Pair-Transfer Reactions

Most important pair correlations are short-range correlations associated with $J=0^+$ like nucleon pairs — good experimental probe is a reaction transferring two *s*-wave nucleons.

Examples: (*p*,*t*)/(*t*,*p*) neutron and (^{3}He,*n*) proton pair transfer reactions. Both *t* and ^{3}He have a pair of $s_{1/2}$ nucleons, with a strong overlap with pairs of correlated nucleons.



Yoshida NP 33, 685 (1961)

Yoshida first analysed reactions within a Born approximation:

- Spectroscopic amplitudes for transfer of nucleon pairs from single-particle orbitals with j_1 to those with j_2.
- Between states with mixed single-particle configurations, summations in the amplitude over j_1 and j_2.
- Between BCS states, the summation is coherent due to common phase of amplitudes from different *j* values — enhancements of the pair-transfer cross section.

Today, descriptions of the reaction mechanism are more sophisticated, but these essence of Yoshida's insight remains.

See for example, Potel et. al PRL 107, 092501 (2011)

BCS Enhancement in Pair Transfer

Simple estimate (ignoring Q value effects):

$$\frac{\sigma_{\mathrm{gs}\to\mathrm{gs}}}{\sigma_{\mathrm{gs}\to 2\mathrm{qp}}} = \left[\frac{\Delta}{G U_\nu^2}\right]^2 \sim \frac{A}{4}$$

$$\Delta \sim 12 A^{-1/2}\ \mathrm{MeV}$$
$$G \sim 28/A\ \mathrm{MeV}$$
$$U_\nu^2 \sim 1$$

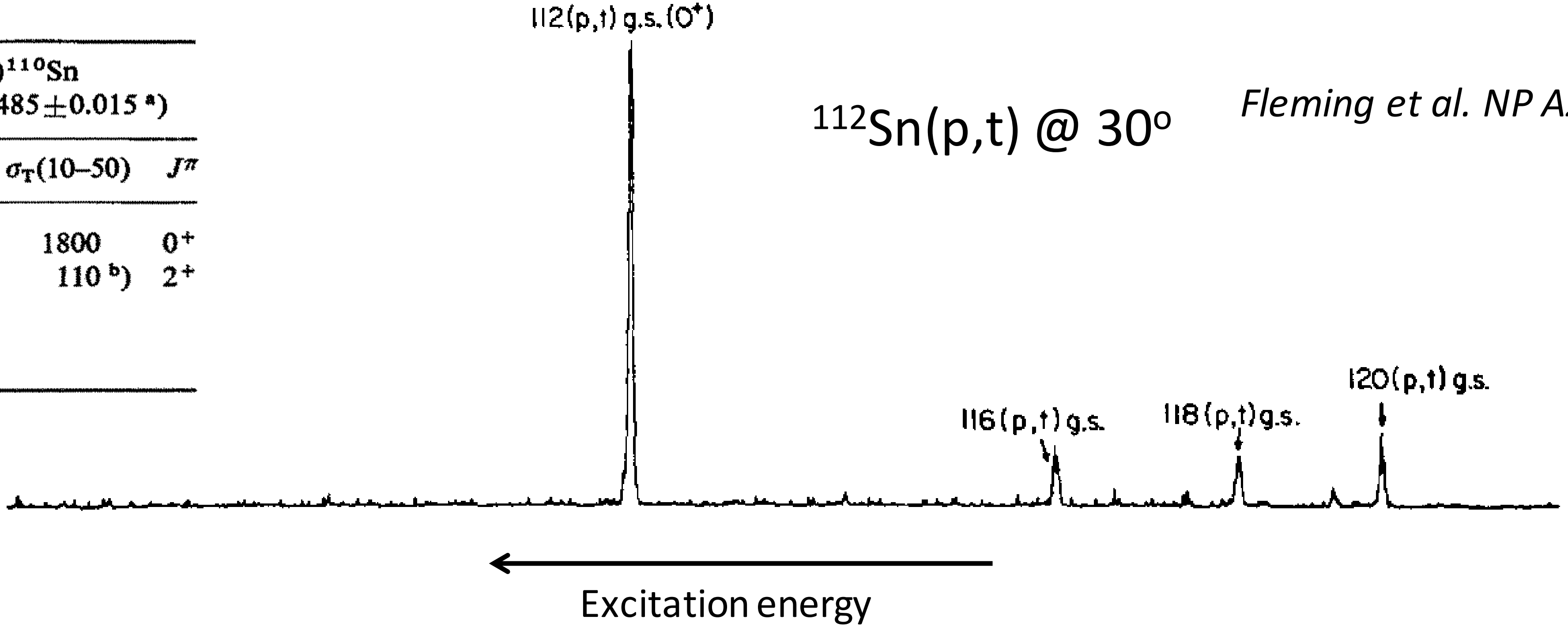
For medium-mass nuclei:
transfer spectrum dominated by gs transition by factors of ~30.

^{112}Sn(p,t)^{110}Sn
$Q_{\mathrm{g.s.}} = -10.485 \pm 0.015$ [a])

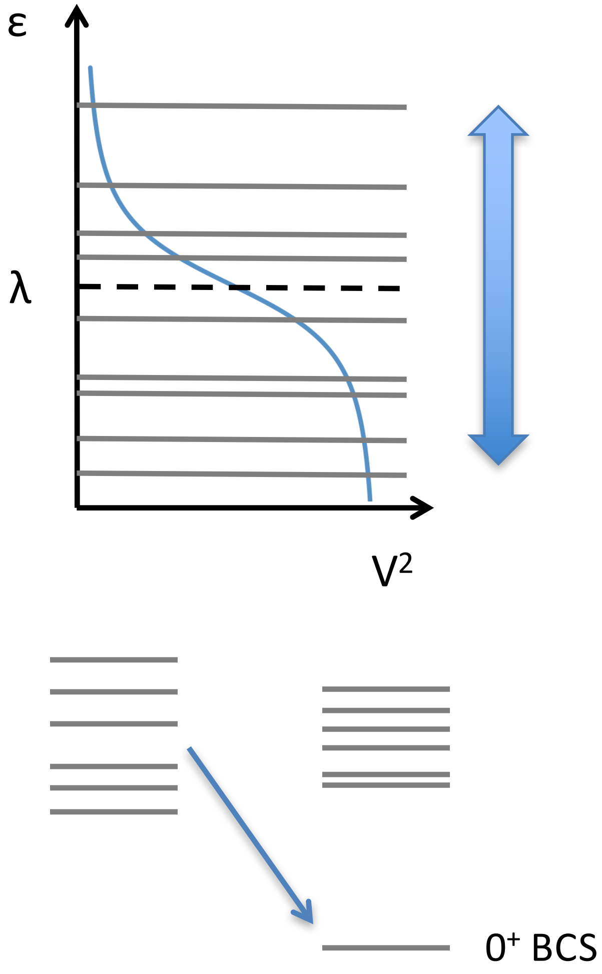
Exc. (MeV)	σ_T(10–50)	J^π
0.0	1800	0^+
1.215 ± 0.010	110 [b])	2^+

^{112}Sn(p,t) @ 30°

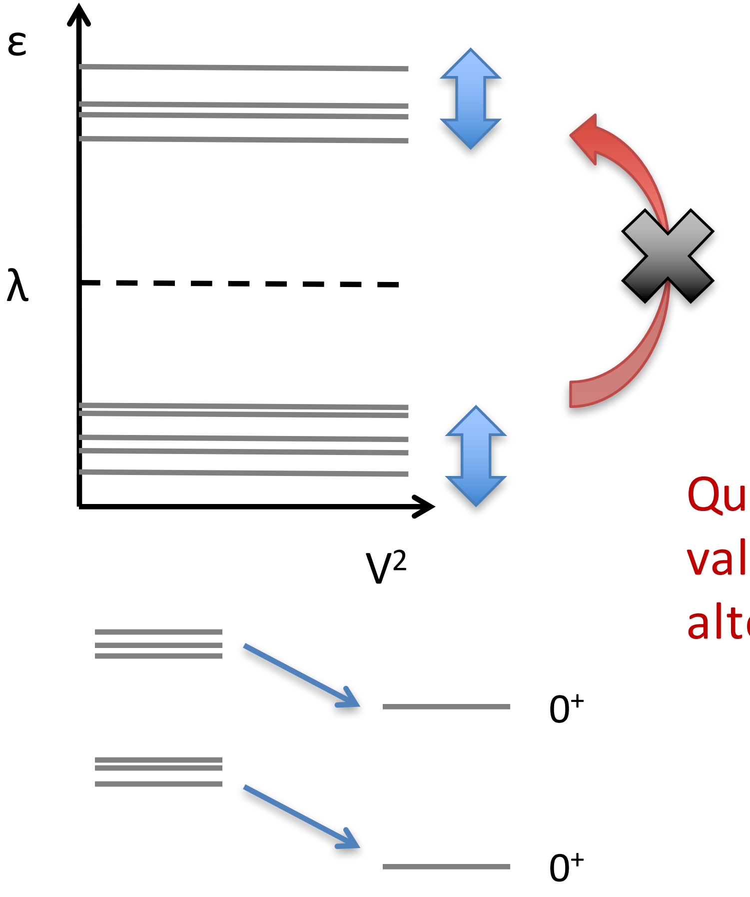
Fleming et al. NP A281, 389 (1977)



Breakdown in BCS: Pairing Vibrations



Gap larger than pairing energy



Quantitative validity of BCS altered

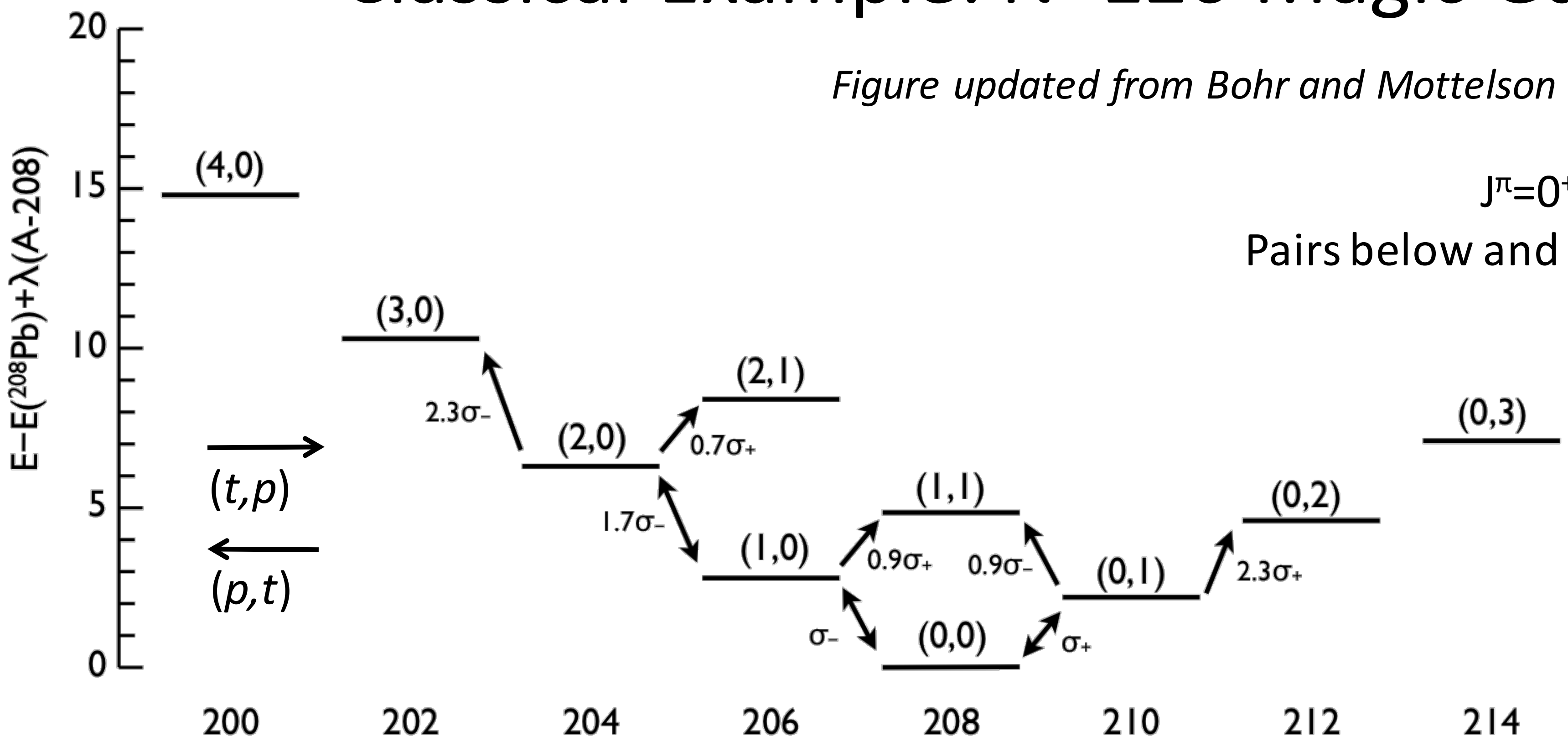
Strong pair transfer to gs.
Other states at few % relative strength.

Pair transfer associated with BCS state fragmented.
Excited states with more significant strength.

Classical Example: N=126 Magic Gap

Figure updated from Bohr and Mottelson Nuclear Structure Volume 2.

$J^{\pi}=0^{+}$ states in Pb isotopes.
Pairs below and above N=126: (n_{-2}, n_{+2})



Large gap in neutron levels associated with N=126.
Pair addition and removal creates pairing vibrations relative to ^{208}Pb "vacuum".
If pairs are identical and interactions between them can be neglected harmonic spectrum results:

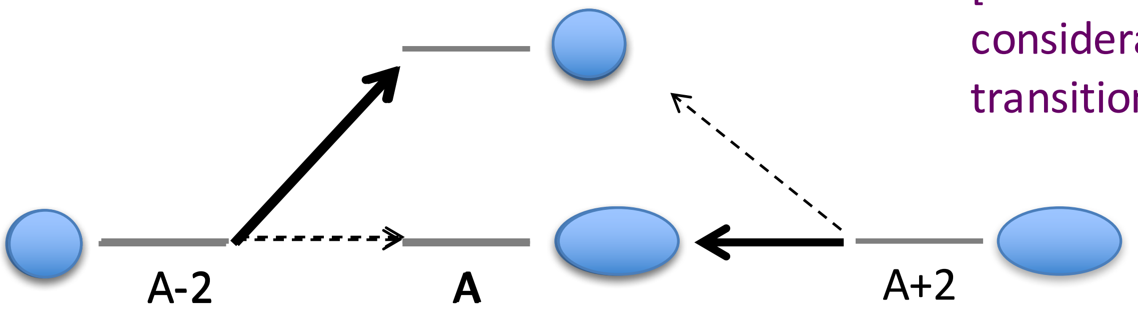
$$E = \hbar\omega_{-2} n_{-2} + \hbar\omega_{2} n_{2}$$

Subshell gaps in spherical and Nilsson schemes also give rise to pairing vibrations.

Transitional Regions

At the onset of a deformed region, two-nucleon transfer from a "spherical" ground state to an excited 0^+ "spherical" state in the residual nucleus, rather than the "deformed" ground state, can be significant due to the larger overlap in wave functions.

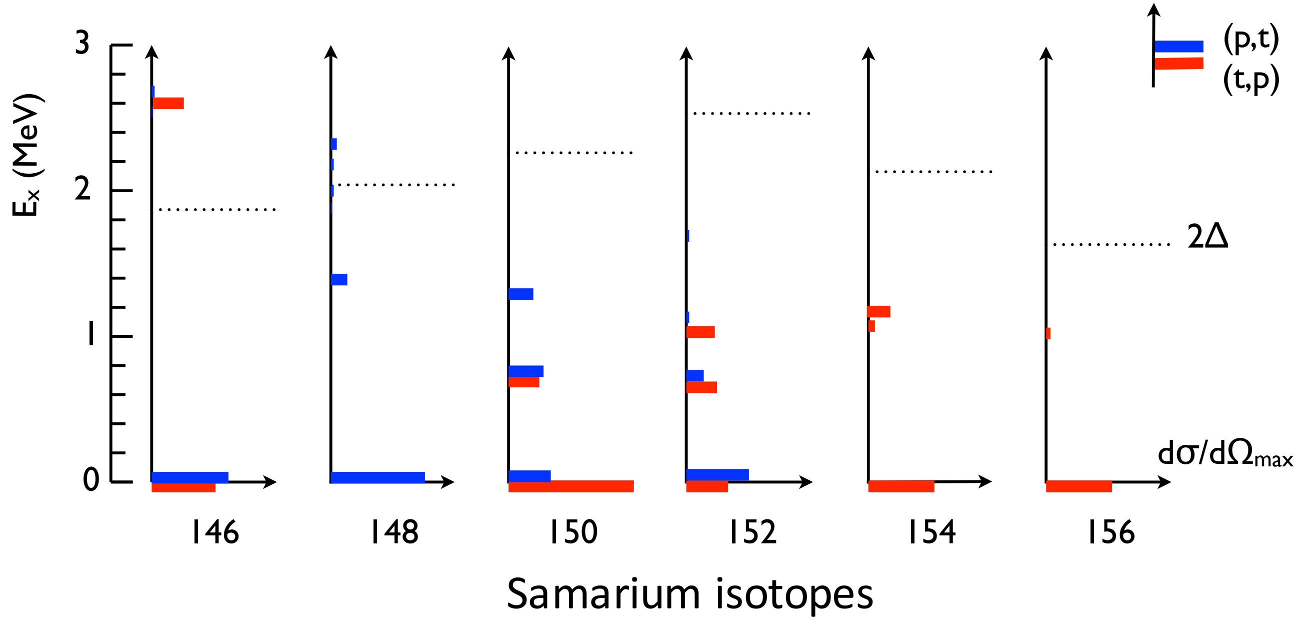
[Generally more complicated since considerable shape mixing common in transitional regions.]



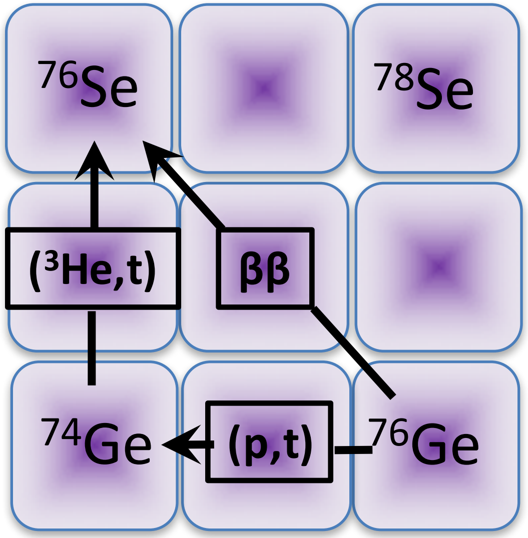
The classical example is relevant to 0νββ:

- N≈88-90 Sm nuclei are the classical example of shape transition effects in pair transfer.
- Population of excited 0+ states indicative of changing shapes.
- A likely issue for calculation of NME.

Bjerregaard NP 86, 145 (1966)
Debenham NP A195, 385 (1972)



Consequences for Double Beta Decay?



ββ: Removal of pair of neutrons and addition of a pair of protons: appears to be enhanced by pairing?

(*p*,*t*): Removal of pair of neutrons. BCS enhancement of gs-gs.

(^{3}He,*n*): Addition of pair of protons. BCS enhancement of gs-gs.

- Measurement of accurate cross sections might be useful as a check on ground-state wave functions.
- If pairing vibrations are revealed by (*p*,*t*), (*t*,*p*) and (^{3}He,*n*), BCS-correlations modified and fragmentation of the pair transfer cross sections between 0^+ states results from this more complicated structure.
- Or indicates the possibility of changing shapes in a transitional region.

Q: Do these pair vibration phenomena arise in double beta decay candidates?

IF they do:

Q: Could there be some corresponding "fragmentation" of the decay probability?

Q: What issues arise with on assuming BCS approximation in QRPA?

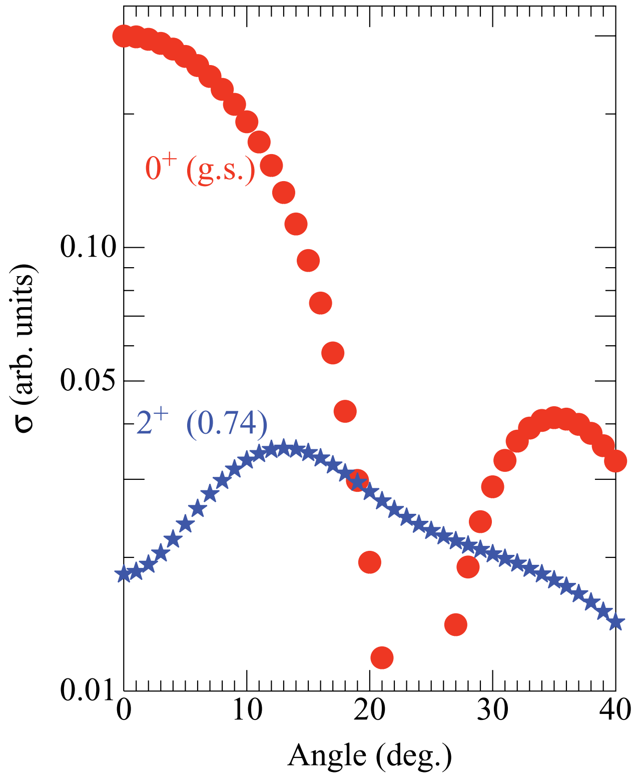
Q: Do other models reproduce these structures?

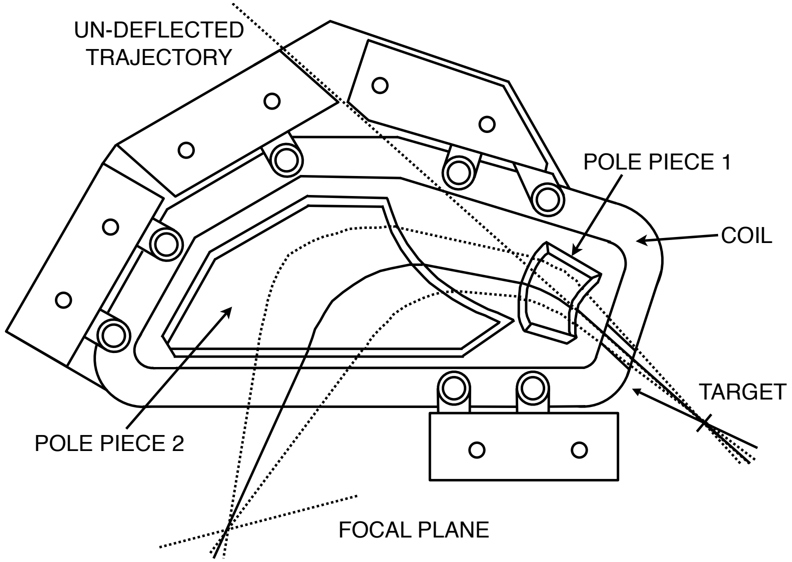
Experimental Comments

(*p,t*): Fairly "routine" charged-particle spectroscopy.
Dwindling facilities: Yale University (GONE!), RCNP Osaka University, IPN Orsay and Maier-Leibnitz Laboratory, Munich.

(*t,p*): Fairly "routine" charged-particle spectroscopy. Troublesome radioactive beam in normal kinematics. Triton beams available 1970-90; studies in the literature.

(^{3}He,*n*): "Troublesome" neutron time-of-flight spectroscopy. Dedicated facilities were available in the past; some recent work at Notre Dame University.

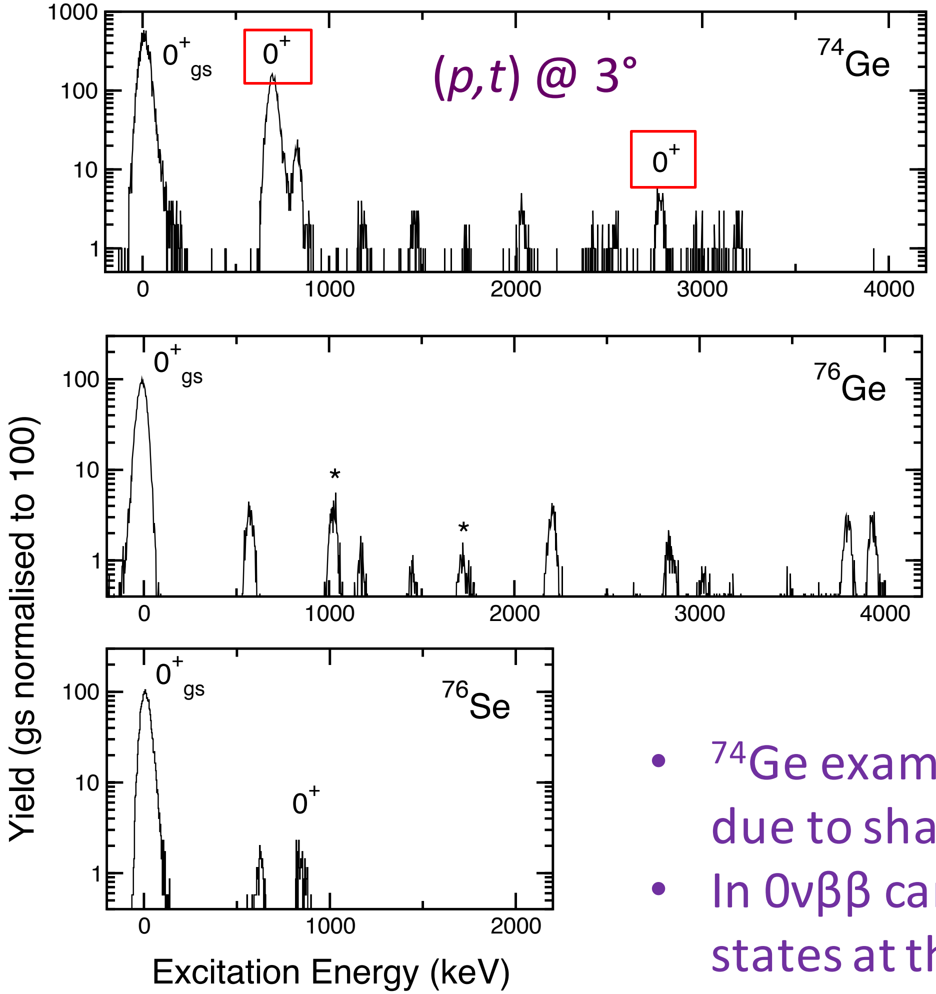




- Measure the energy spectrum of outgoing ions.
- Identify 0^+ states via forward peaked $\ell=0$ transitions.
- Measure cross sections accurately by minimizing systematic effects.
- Useful to make measurements on neighbouring isotopes for consistency.

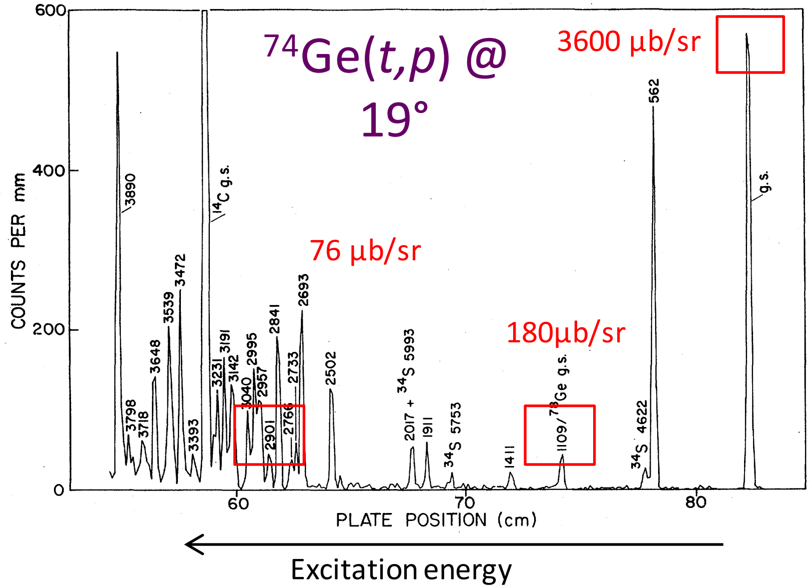
^{76}Ge-Se: neutron pairing

Freeman al. PRC 75, 051301(2007)



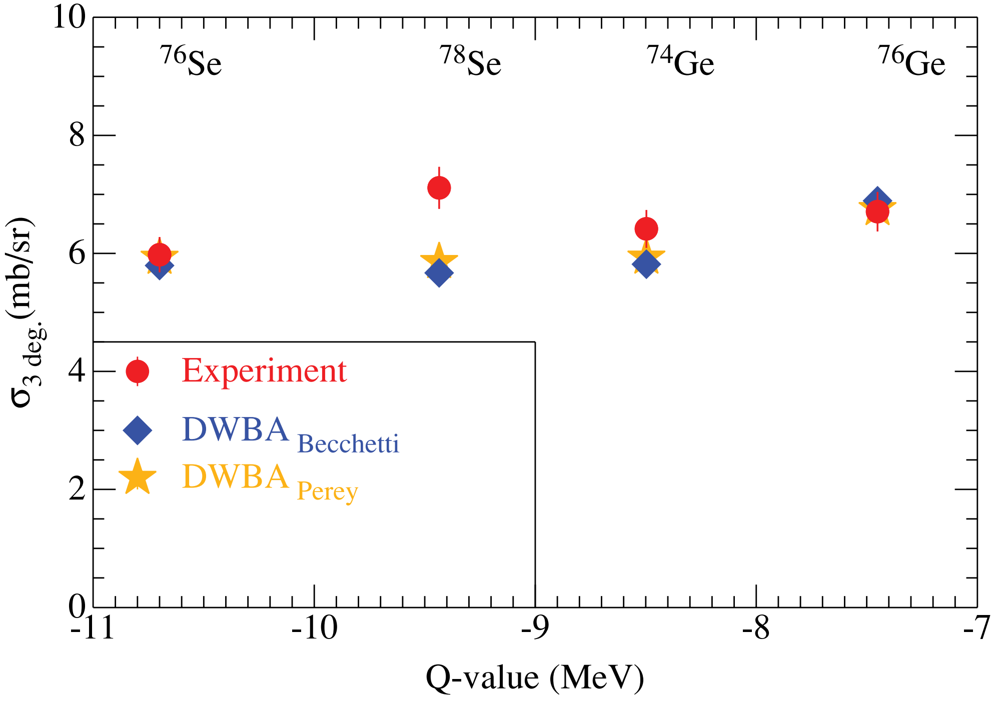
Excitation energy (keV)	$(\sigma/\sigma_{gs})_{3^\circ}$	Ratio(3°/22°)
^{74}Ge$(p,t)^{72}$Ge	σ_{gs}(lab) = 6.4 mb/sr	
0	**100**	**86**
691	**29**	**280**
834	2.8	0.9
1464	0.5	1.5
2024	0.5	4
2762	**0.9**	**130**
^{76}Ge$(p,t)^{74}$Ge	σ_{gs}(lab) = 6.7 mb/sr	
0	**100**	**50**
596	3.2	1.0
1204	1.1	1.6
1463	2.2	0.8
2198	2.9	3
2833	1.7	6
^{76}Se$(p,t)^{74}$Se	σ_{gs}(lab) = 6.0 mb/sr	
0	**100**	**115**
635	1.0	0.4
854	**1.4**	**80**

Mordechai al. PRC 18, 2498 (1974)



- ^{74}Ge example of pairing vibration due to shape coexistence.
- In $0\nu\beta\beta$ candidates, excited 0^+ states at the few % level.

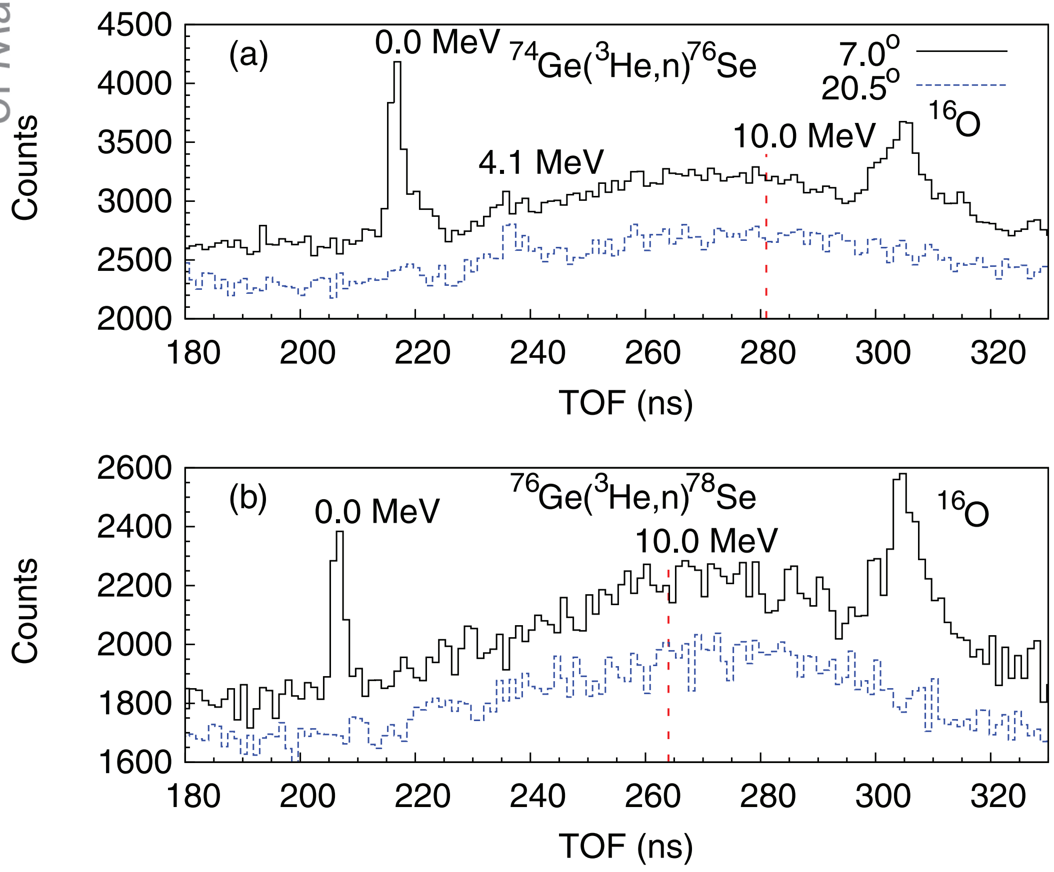
^{76}Ge-Se: neutron pairing



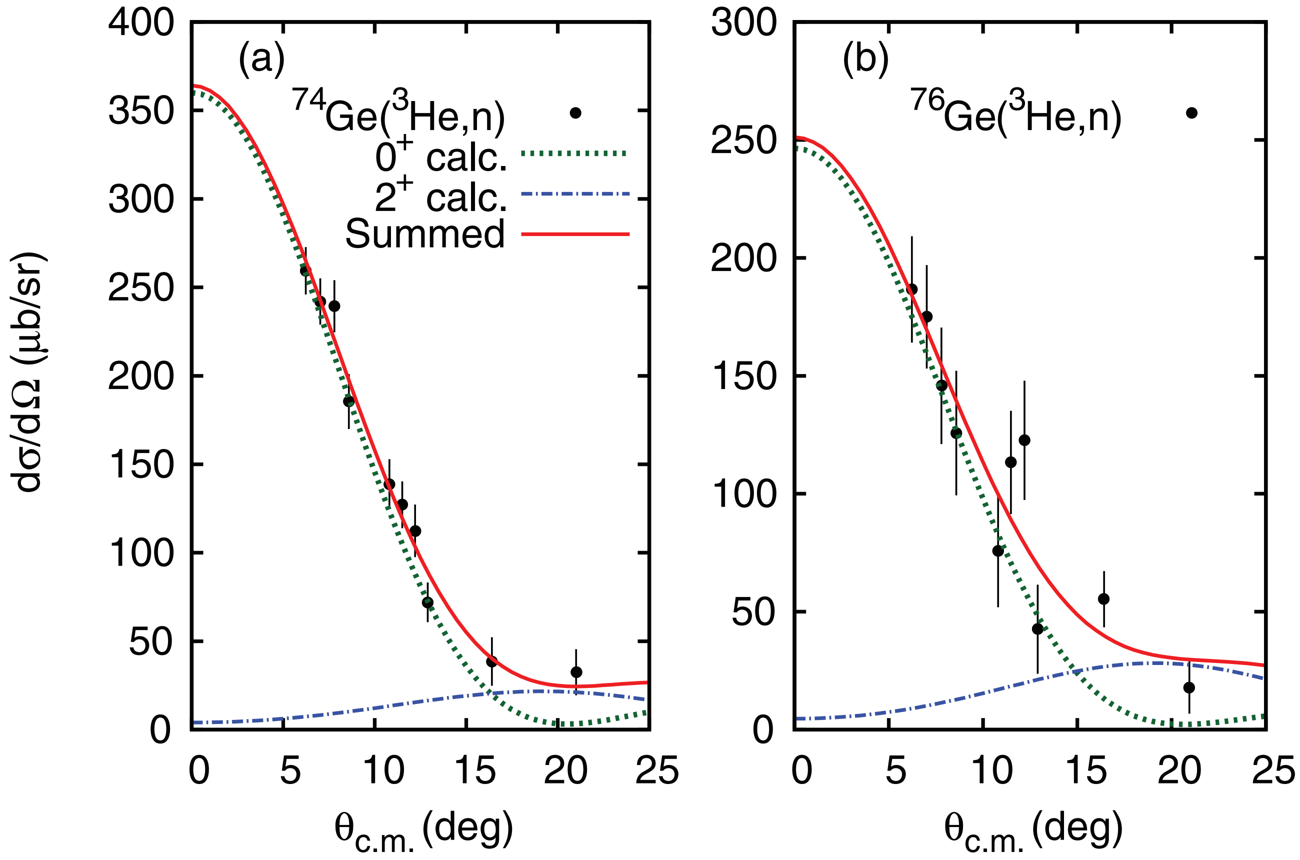
Freeman al. PRC 75, 051301(2007)

- No excited states in (*p*,*t*) or (*t*,*p*) > few % relative to ground-state transition.
- BCS for neutrons appears to be a reasonable approximation.
- Ground-state transitions are surprisingly constant cross section.
- Pairing in parent and daughter nuclei is quantitatively similar.

^{76}Ge-Se: proton pairing

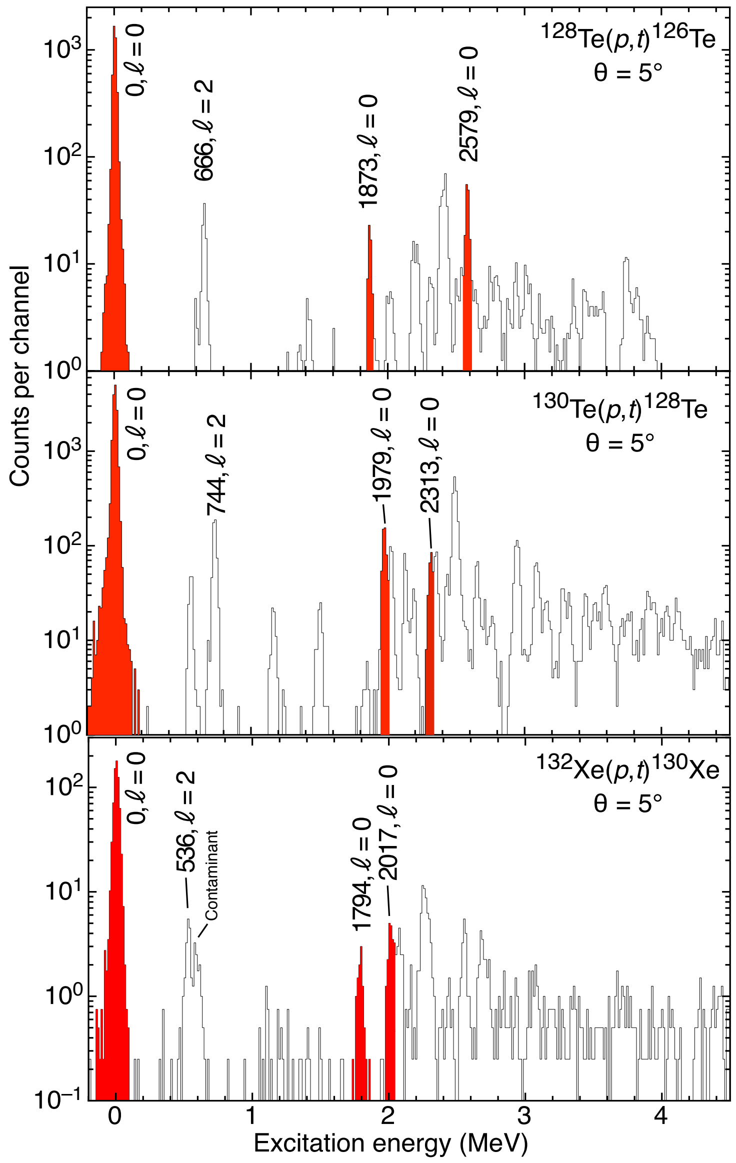


Roberts al. PRC 87, 051305(2013)



- No evidence for breaking of BCS approximation for protons above the 5-7% level.

^{130}Te-Xe: neutron pairing



For ^{130}Te and ^{130}Xe, again no signs of neutron pairing vibrations; excited 0$^+$ states only weakly populated in (p,t).

Experiments at Yale University, using a frozen Xe target.

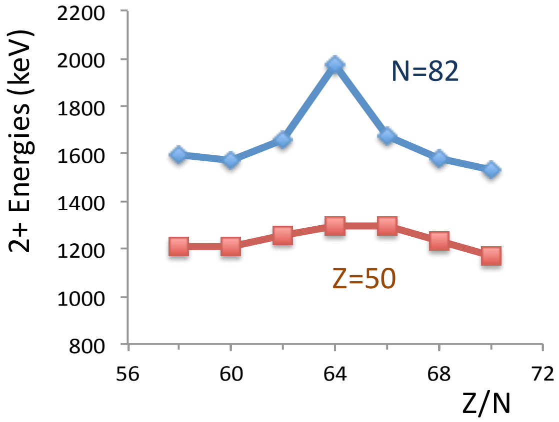
Reaction	E (MeV)	σ (mb/sr)	Ratio[a]	Normalized strength[b]
^{128}Te(p,t)	0	4.21	90	1.21
	1.873	0.06	20	0.02
	2.579	0.15	21	0.04
^{130}Te(p,t)	0	3.49	89	1.00
	1.979	0.05	50	0.01
	2.313(4)[c]	0.05	>20	0.01

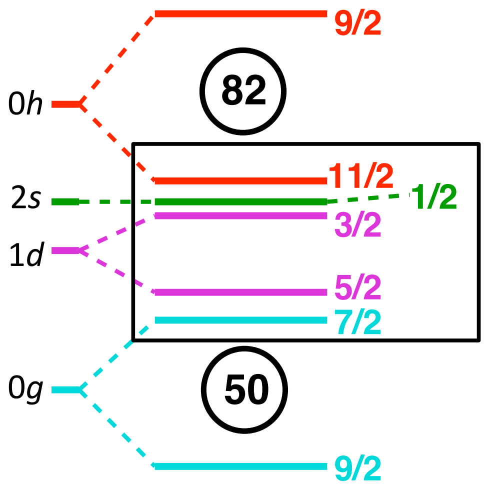
Bloxham al. PRC 82, 027308 (2007)

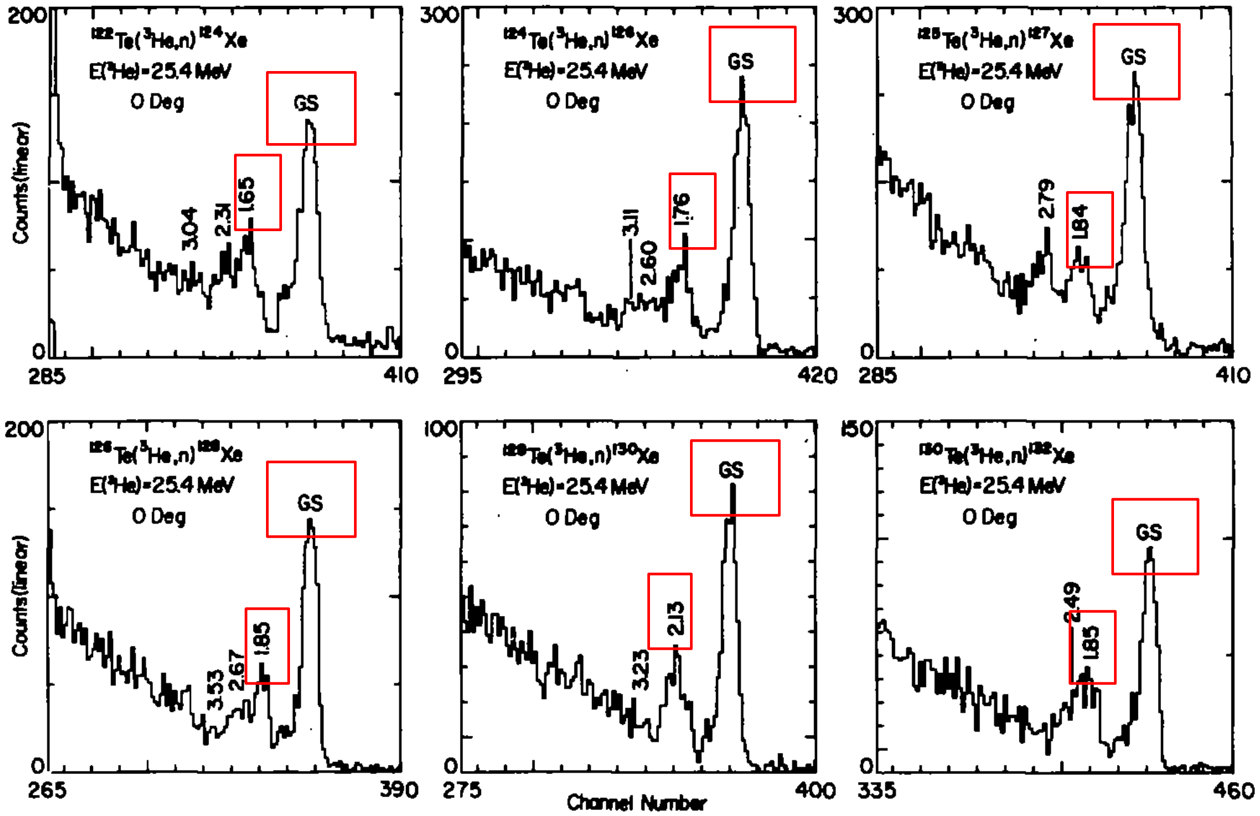
Kay al. PRC 87, 011302 (2013)

^{130}Te-Xe: proton pairing

- Proton pairing vibration evident in (^{3}He,*n*) spectra.
- Associated with gap in proton single-particle levels at *Z*=64.
- Gap observed in other nuclear properties for protons.







Alford al. NP A323, 339 (1979)

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

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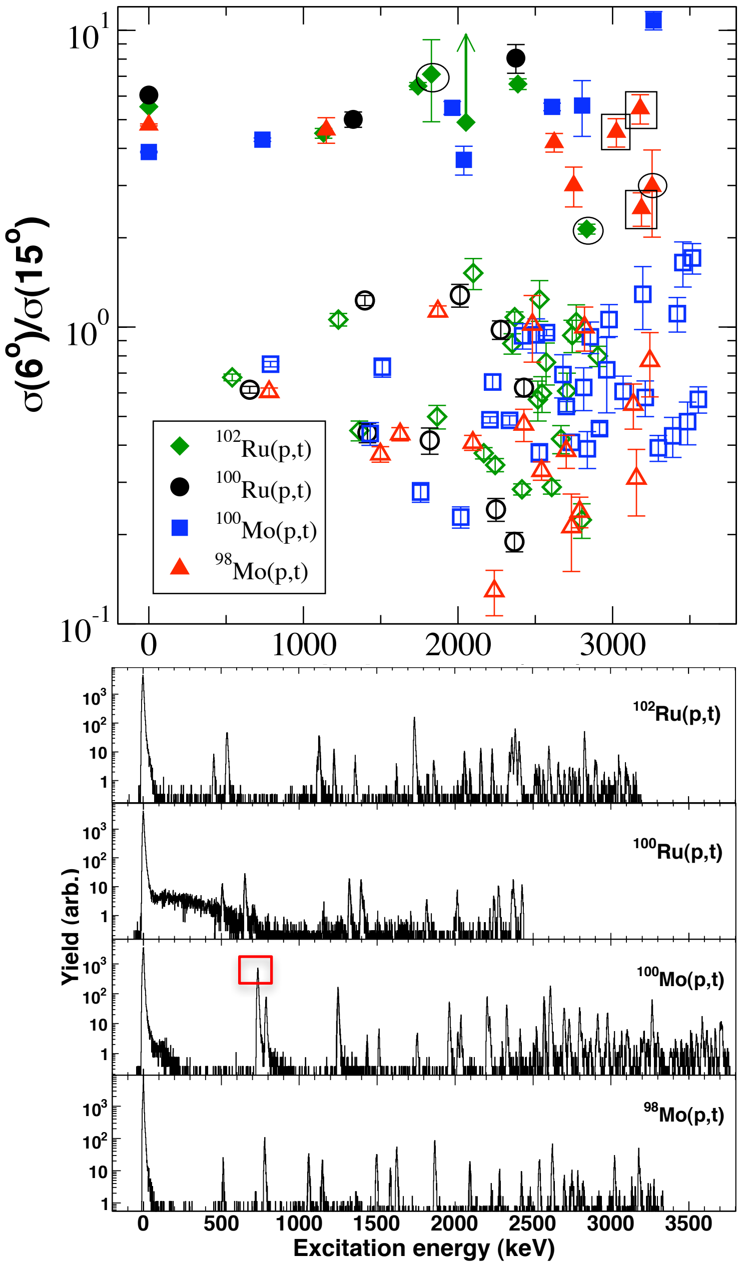
^{100}Mo-Ru: neutron pairing



- Fragmentation of pair transfer strength: 20% to 735 keV in ^{98}Mo.
- Behavior asymmetric for (*p,t*) and (*t,p*).
- Due to the onset of ground-state deformation in Mo isotopes around A=100.
- But clearly some shape mixing in the transitional region.

J.S. Thomas et al. PRC 86, 047304 (2012)

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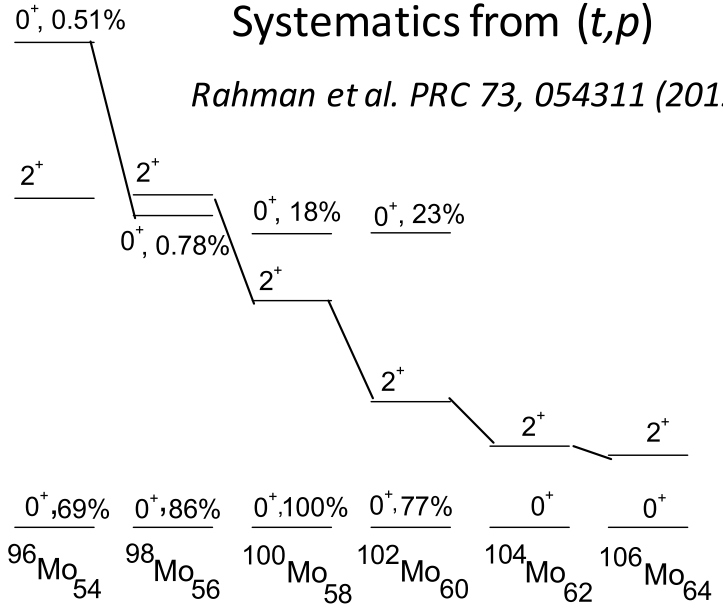
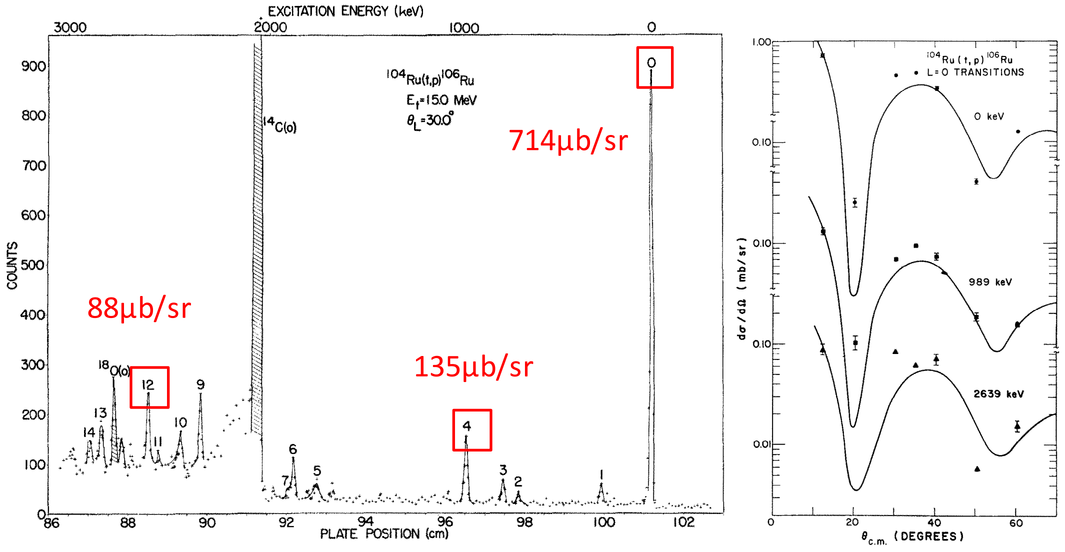
Systematics from (*t,p*)

Rahman et al. PRC 73, 054311 (2012)



Transitions strengths normalised to ^{100}Mo gs.

^{100}Mo-Ru: neutron pairing

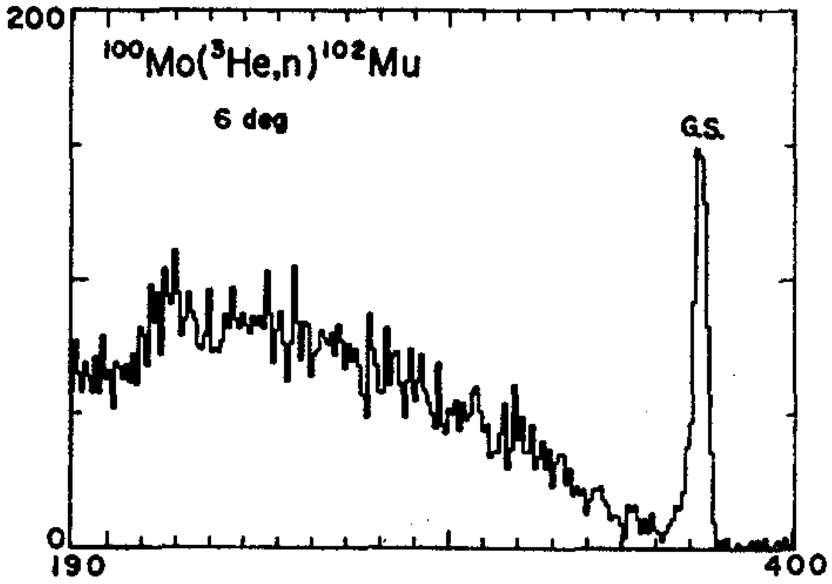


Casten NP A184, 357 (1972)

- Similar transition happens at higher A in Ru.
- For example, evidence in $^{102,\,104}$Ru(t,p).
- Parent and daughter nuclei in double beta decay with differing deformations.
- Although TOTAL pair removal strength consistent at 10% level.

^{100}Mo-Ru: proton pairing

- Limited measurements of(^{3}He,n).
- Reaction on ^{100}Mo does not appear to have evidence for excited 0^{+} states in ^{102}Ru, but less sensitive due to worse background and resolution of neutron time-of-flight spectroscopy.



Fielding NP A269, 125 (1976)

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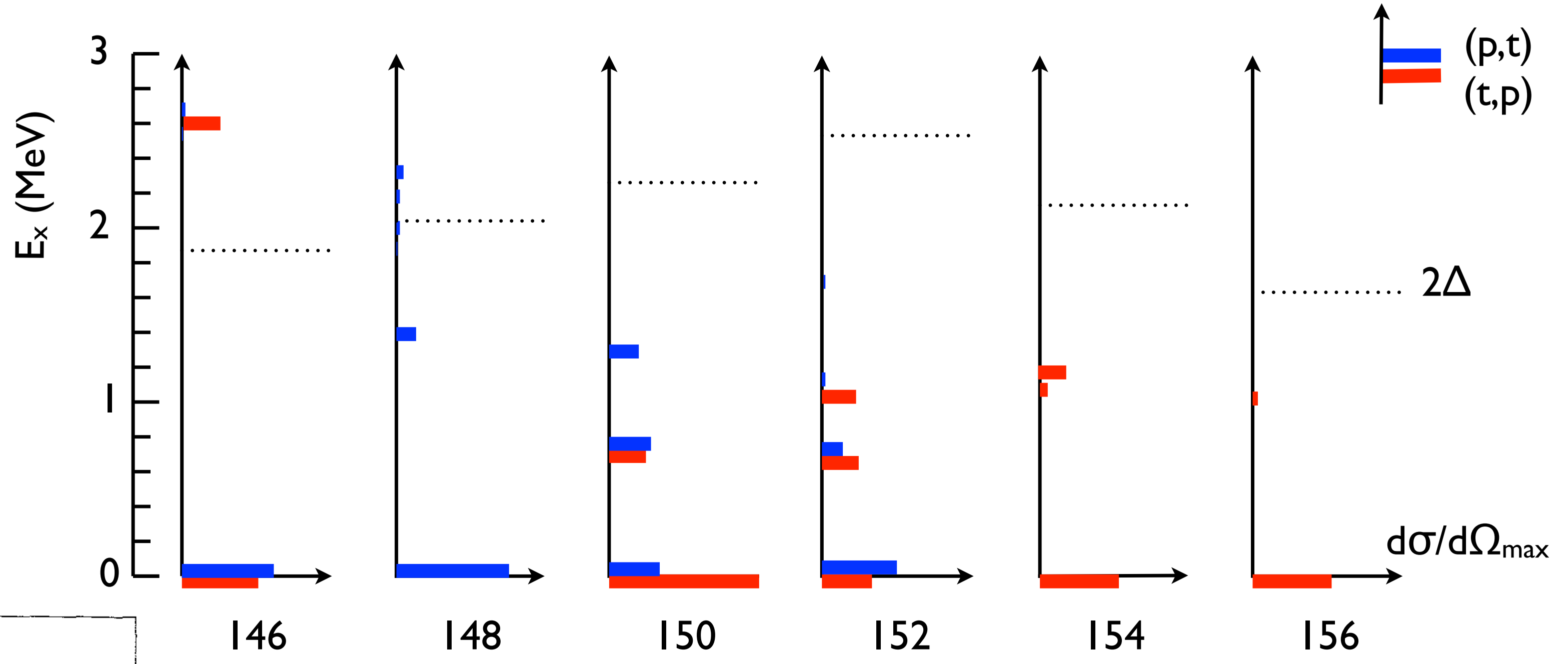
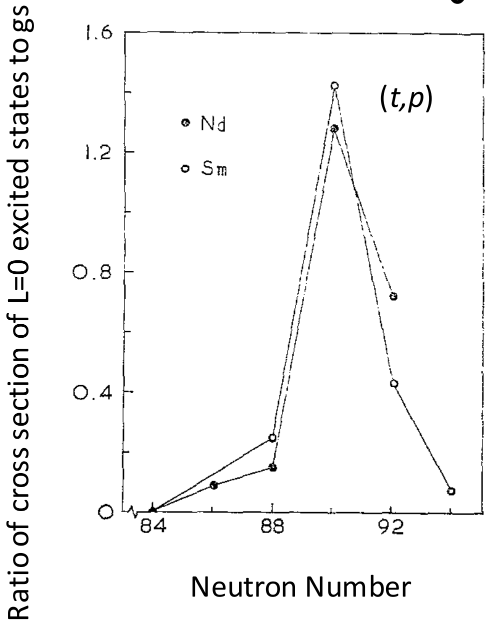
^{150}Nd-Sm: Neutron and Proton Pairing





- N≈90 Sm nuclei are the classical example of shape transition effects in pair transfer.
- Nd nuclei show globally similar effects in (*p*,*t*) and (*t*,*p*), although differs in the detail of the excited states.
- ^{148,150}Nd(^{3}He,*n*)^{150,152}Sm does not populate excited 0^{+} states.

Sm Bjerregaard NP 86, 145 (1966), Debenham NP A195, 385 (1972)
Nd Chapman NP A186, 603 (1972).
Nd protons Alford NP A321, 45 (1979).

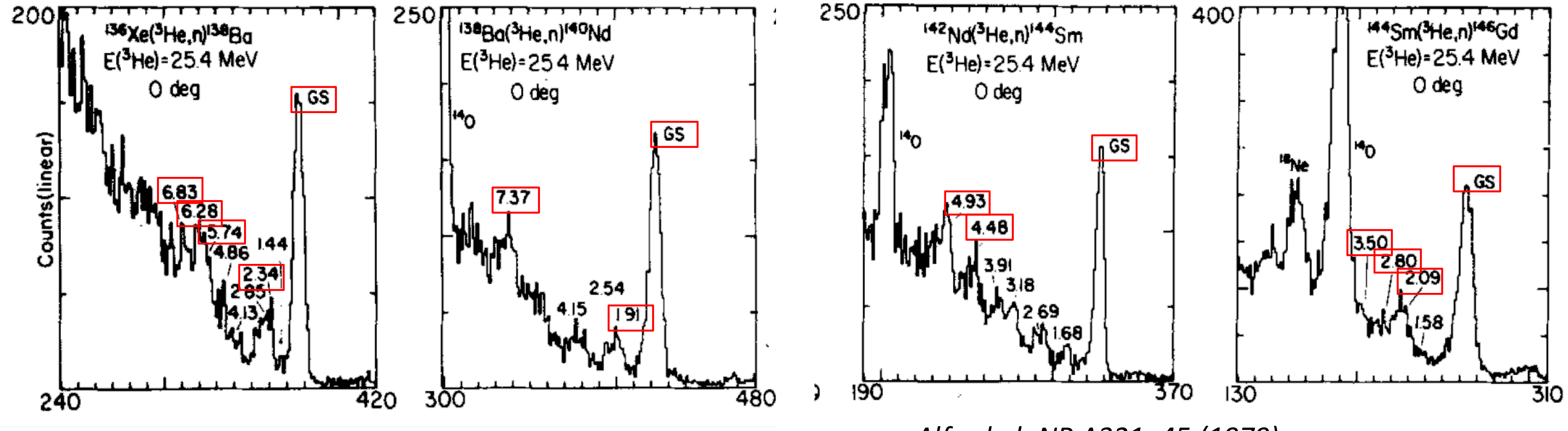
^{136}Xe-Ba: Neutron and Proton Pairing

Both targets are difficult, so not so well studied. But measurements on some neighboring nuclei reveal some interesting features.

^{142}Nd, ^{140}Ce and ^{132,134}Ba(*p,t*): significant population of excited 0^+ states.
^{136,138}Ba(*t,p*): strong population of excited 0^+ states around 3 MeV.

Point to neutron pairing vibrations associated with *N=82*, albeit with some fragmentation across several excited states. But pairing suppressed anyway.

(3He,*n*) reaction on *N=82* sees significant excited 0^+ states, likely associated with the *Z=64* subshell gap as in ^{130}Te.



Alford al. NP A321, 45 (1979)

^{82}Se-Kr

- Some rudimentary (*p*,*t*) measurements on ^{82}Se: difficult to conclude much.
- ^{80,82}Se(*t*,*p*) suggest significantly populated 0^+ states below 1 MeV.
- ^{82,84}Kr(*p*,*t*) performed, but only data/discussion of L=3 transitions in literature.
- No measurements of (^{3}He,*n*).

Summary of experimental situation

SYSTEM	DATA	COMMENTS
^{76}Ge-Se	New data.	BCS approximation good. Pairing similar across parent and daughter.
^{82}Se-Kr	Sparse data: Se(*t*,*p*) only.	Difficult to be definitive, but some evidence of fragmentation in neutron pair removal.
^{100}Mo-Ru	New (*p*,*t*) data.	Fragmentation due to deformation, parent-daughter differences. Overall pairing looks similar across parent and daughter.
^{130}Te-Xe	New (*p*,*t*) data.	Neutron BCS approximation good. Proton pairing vibration associated with *Z*=64.
^{136}Xe-Ba	Some relevant data available.	Apparent influence of pairing vibrations associated with *Z*=64.
^{150}Nd-Sm	Extensive data in literature	Fragmentation due to deformation in neutron transfer.

<u>Some evidence of breaking of BCS in ALL these cases, except for ^{76}Ge-Se.</u>

Summary:

To what extent do pairing correlations really matter for $0\nu\beta\beta$?

In cases with pairing vibrations, there is a reduction in pair transfer strength between ground states. Does a similar reduction in strength occur for $0\nu\beta\beta$? How much might it affect the decay rate?

In these cases, what issues arise with the assumption of the BCS approximation in QRPA?

Are these complicated aspects of nuclear structure reproduced in shell-model or IBM calculations?
Would such a comparisons identify any useful physics for the matrix elements?

Is there a quantitative connection between pair transfer strength and $0\nu\beta\beta$ that might be profitably pursued?

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THANK YOU

To our many collaborators in Yale, Notre Dame and Munich experiments, and also to those who have contributed to the literature over the years. They were unlikely to have realised their data would contribute to this issue.

Ge/Se(p,t): S.J. Freeman, J. P. Schiffer, A. C. C. Villari, J. A. Clark, C. Deibel, S. Gros, A. Heinz, D. Hirata, C. L. Jiang, B. P. Kay, A. Parikh, P. D. Parker, J. Qian, K. E. Rehm, X. D. Tang, V. Werner, and C. Wrede.
Manchester, Argonne, GANIL, Yale, Open University.

Ge/Se(3He,n): A. Roberts, A. M. Howard, J. J. Kolata, A. N. Villano, F. D. Becchetti, P. A. DeYoung, M. Febbraro, S. J. Freeman, B. P. Kay, S. A. McAllister, A. J. Mitchell, J. P. Schiffer, J. S. Thomas, and R. O. Torres-Isea
Notre Dame, Minnesota, Michigan, Hope College, Manchester, York, Argonne.

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