Nuclear structure studies from transfer reactions using triton beams

Paul Garrett
University of Guelph

Triton beams at FSU – a very welcome addition!

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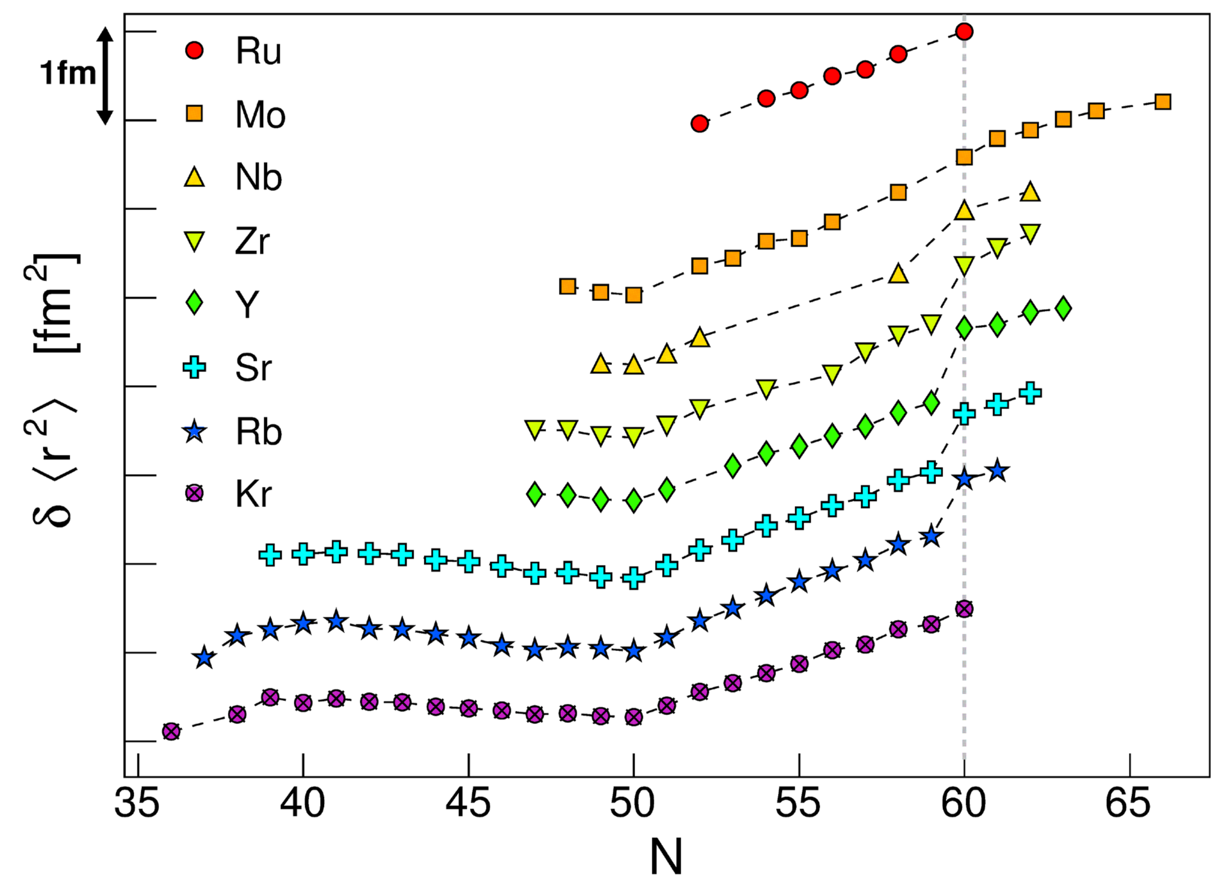
- Mapping proton single-particle states
  - Z=40 – 50 region
- Investigating neutron pairing correlations
  - Pairing vibrations and pairing isomers
- Spectroscopy of selected odd-odd nuclei
  - ^{136}Cs for $0\nu\beta\beta$ and dark matter detection

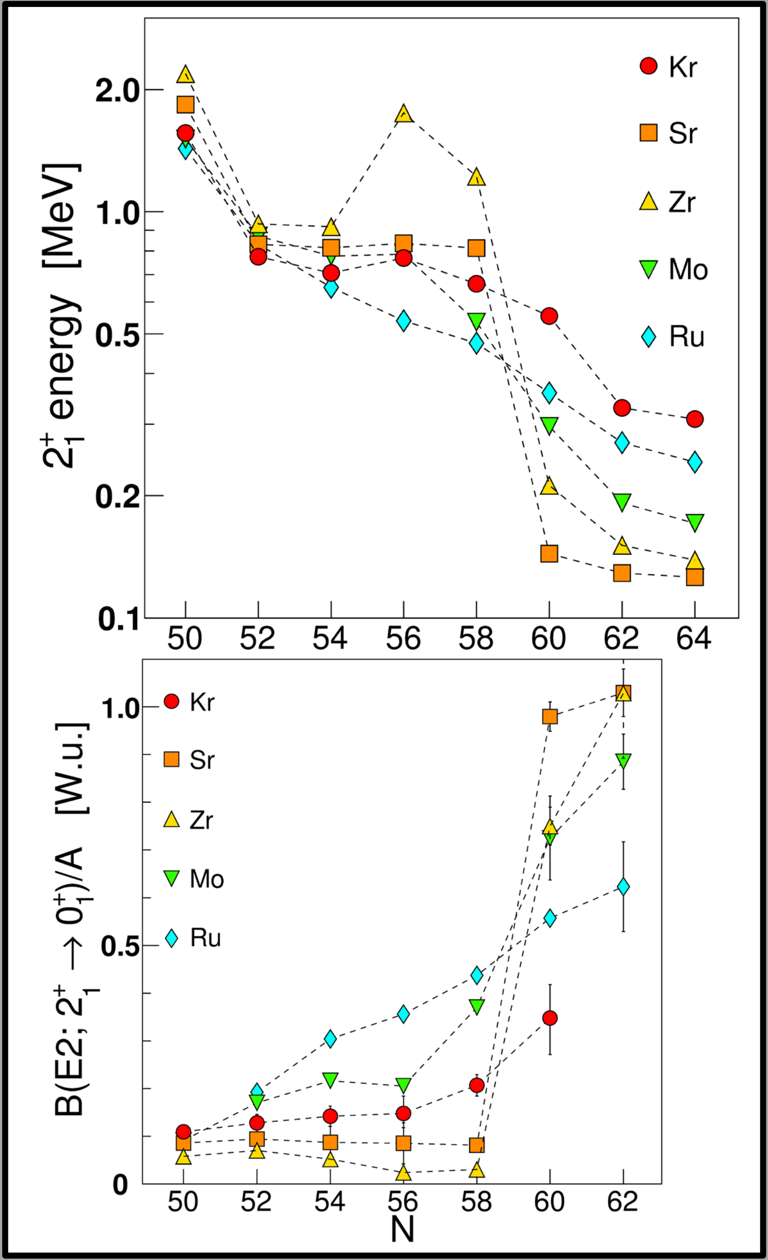
Zr isotopes undergo the most rapid change of ground state structure across the nuclear chart

- **There have been numerous experimental investigations, but firm evidence for shape coexistence has been lacking, and only recently *B(E2)*s determined for deformed states**



Measured isotope shifts

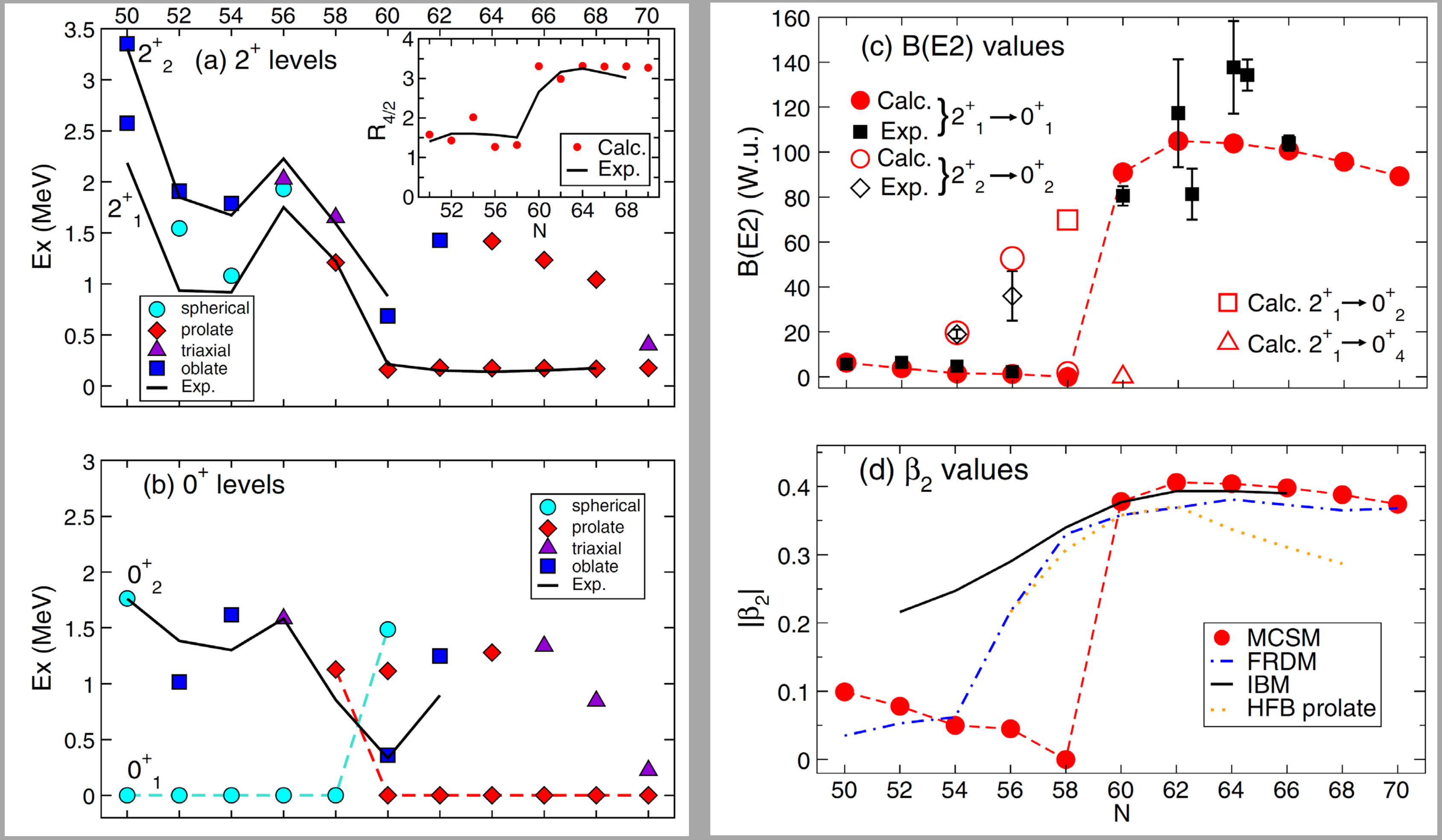
PG, M. Zielinska, and E. Clement, PPNP 124, 123931 (2022)



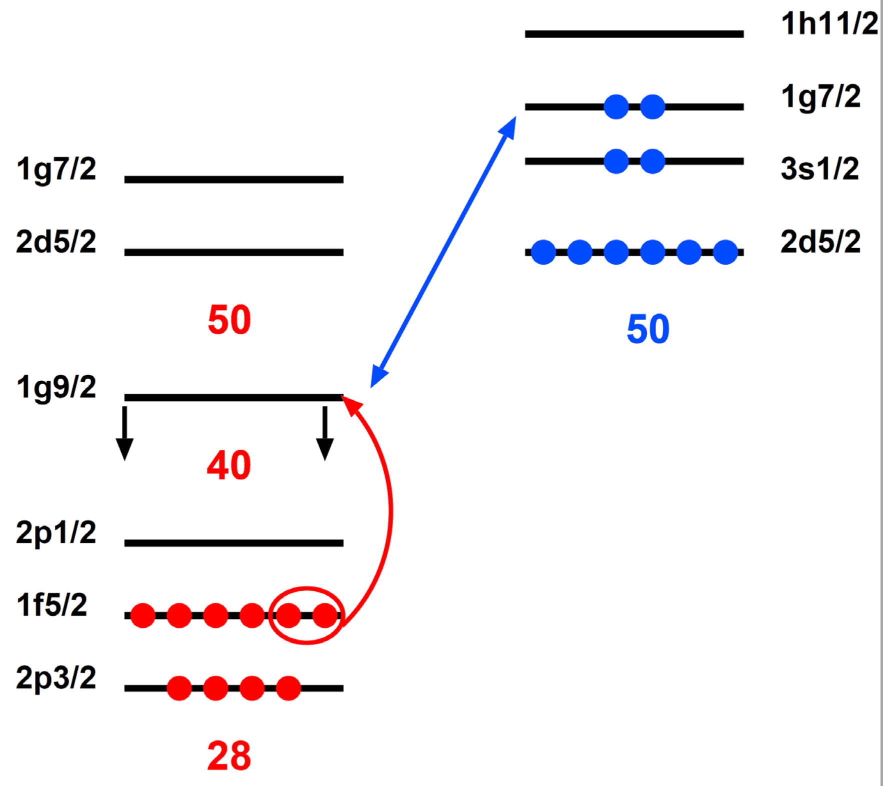
MCSM calculations – shape coexistence in the Zr isotopes

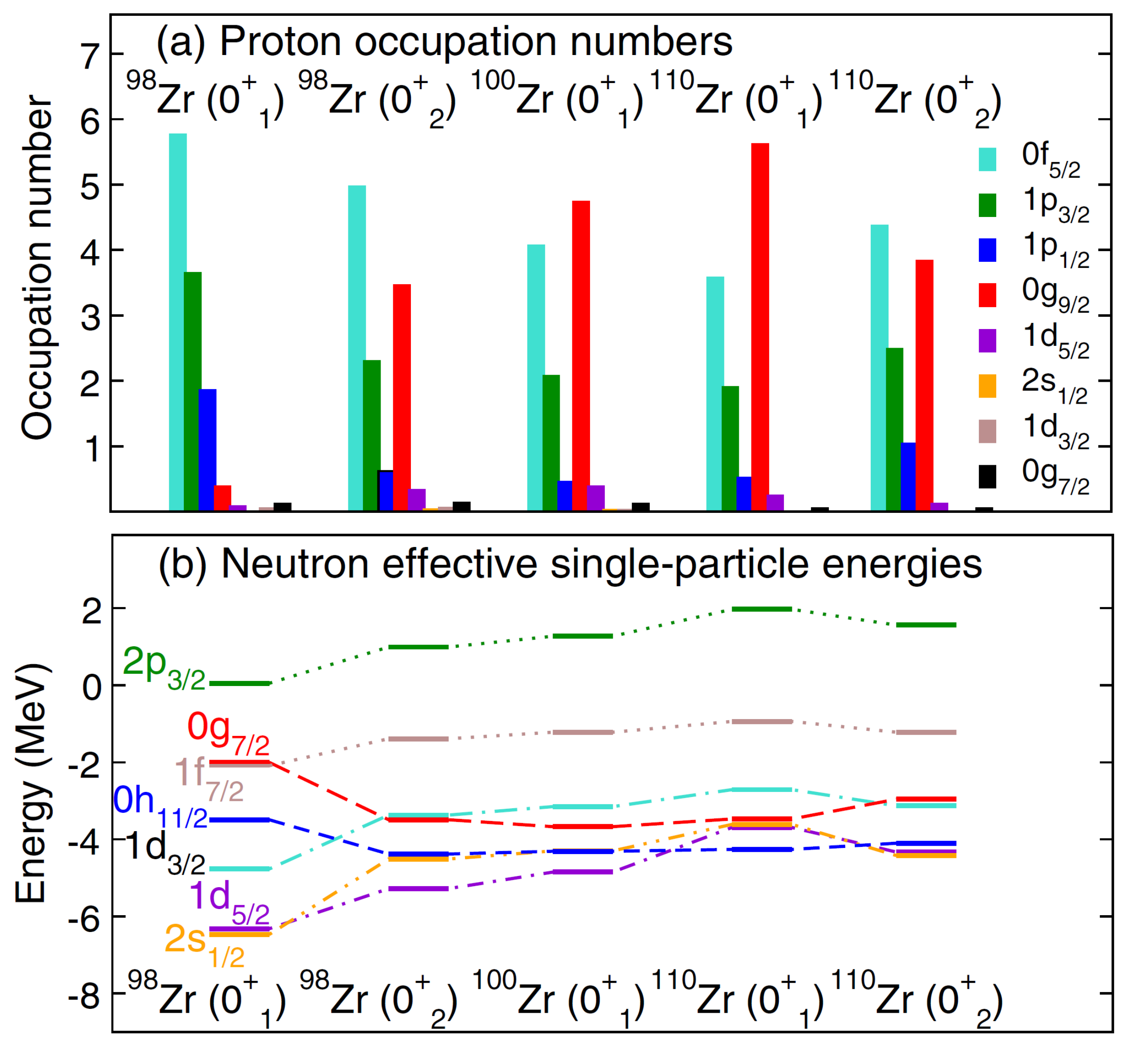
- ***p-n*** **tensor interaction reduces** ***Z*****=40 gap when** $\nu g_{7/2}$ **shell is filled**
- $\mathbf{0_2^+}$ **states configuration includes 2*****p*****-2*****h*** **(+4*****p*****-4*****h*****, …) excitations across** ***Z*****=40 gap**
- **Very different configurations and (generally) weak mixing between** $\mathbf{0_1^+}$ **(spherical) and** $\mathbf{0_2^+}$ **(deformed) until** ***N*****=60 is reached**
- **Type-II shell evolution – self reinforcing mechanism modifies SPEs**

Togashi et al., PRL 117 172502 (2016)



Recent MCSM calculations – shape coexistence and type-II shell evolution in the Zr isotopes





- ***p-n* tensor interaction reduces Z=40 gap when $\nu g_{7/2}$ shell is filled**
- **0_2^+ states configuration includes 2*p*-2*h* (+4*p*-4*h*, …) excitations across Z=40 gap**
- **Very different configurations and (generally) weak mixing between 0_1^+ (spherical) and 0_2^+ (deformed) until N=60 is reached**

Togashi et al., PRL 117 172502 (2016)

How to *prove* type-II shell evolution?

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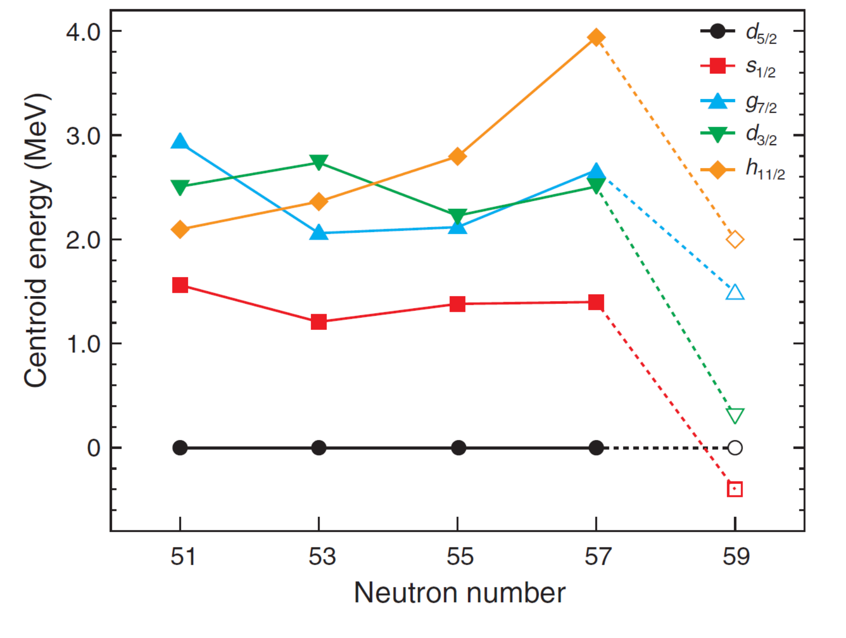
PHYSICAL REVIEW LETTERS **124**, 112501 (2020)

g Factor of the ^{99}Zr $(7/2^+)$ Isomer: Monopole Evolution in the Shape-Coexisting Region

F. Boulay,[1,2,3] G. S. Simpson,[4] Y. Ichikawa,[2] S. Kisyov,[5] D. Bucurescu,[5] A. Takamine,[2] D. S. Ahn,[2] K. Asahi,[2,6] H. Baba,[2] D. L. Balabanski,[2,7] T. Egami,[2,8] T. Fujita,[2,9] N. Fukuda,[2] C. Funayama,[2,6] T. Furukawa,[2,10] G. Georgiev,[11] A. Gladkov,[2,12] M. Hass,[13] K. Imamura,[2,14] N. Inabe,[2] Y. Ishibashi,[2,15] T. Kawaguchi,[2,8] T. Kawamura,[9] W. Kim,[12] Y. Kobayashi,[16] S. Kojima,[2,6] A. Kusoglu,[11,17] R. Lozeva,[11] S. Momiyama,[18] I. Mukul,[13] M. Niikura,[18] H. Nishibata,[2,9] T. Nishizaka,[2,8] A. Odahara,[9] Y. Ohtomo,[2,6] D. Ralet,[11] T. Sato,[2,6] Y. Shimizu,[2] T. Sumikama,[2] H. Suzuki,[2] H. Takeda,[2] L. C. Tao,[2,19] Y. Togano,[6] D. Tominaga,[2,8] H. Ueno,[2] H. Yamazaki,[2] X. F. Yang,[20] and J. M. Daugas[1,2]

- One signature – look for dramatic change in single-particle energies
- Boulay *et al.*, measured *g*-factors of low-lying levels in ^{99}Zr, reproduced results with IBFM calculations
- Compared empirical SPEs with SPEs used in IBFM calculations

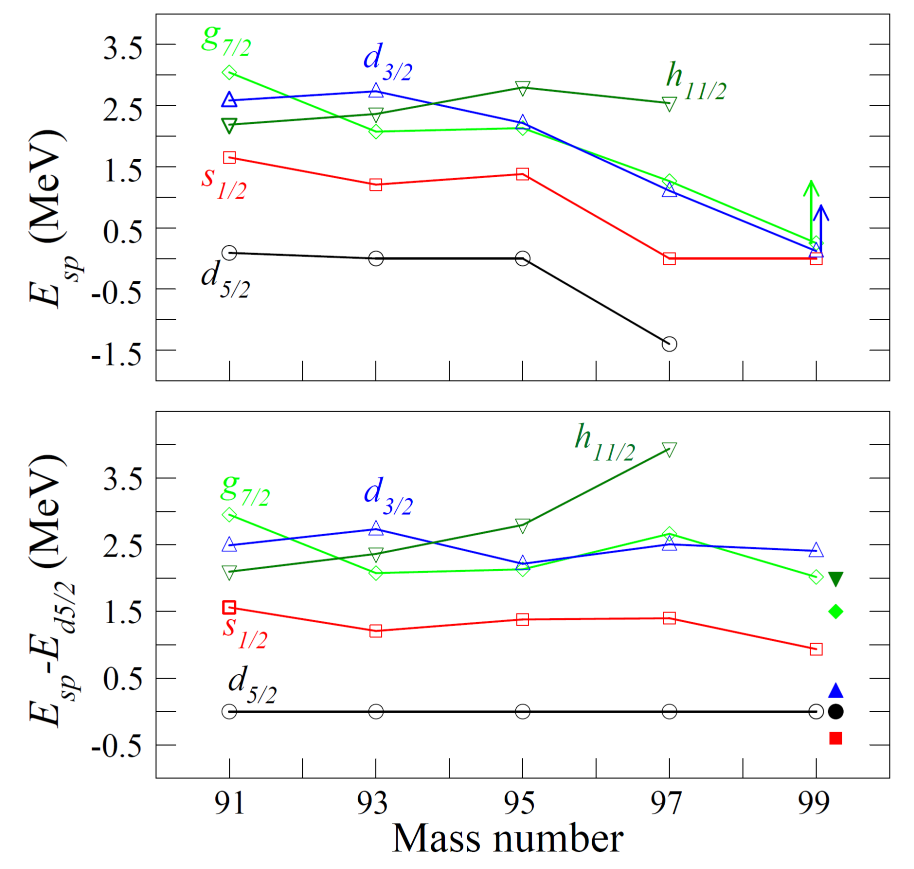


How to prove type-II shell evolution?

- **Unfortunately, Boulay et al. overlooked *identical* magnetic moments of ½$^+$ ground state of ^{97}Zr (–0.937(4) μ_N^2) and ^{99}Zr (–0.930(4) μ_N^2)**
- **^{97}Zr has $s_{1/2}$ firmly assigned from ^{96}Zr(*d,p*) with $S_{1/2}$=1.0**

TABLE I. Amplitudes of the components in the neutron wave functions of the first few IBFM-1 calculated positive-parity states in ^{99}Zr.

J^π	E_{expt} (keV)	E_{th} (keV)	$d_{5/2}$ (%)	$g_{7/2}$ (%)	$s_{1/2}$ (%)	$d_{3/2}$ (%)
$1/2^+$	0.0	0.0	55.7	1.0	1.5	41.8
$3/2^+$	121.7	29.9	85.2	2.1	2.2	10.6
$7/2^+$	252.0	441.9	60.6	11.1	14.9	13.4

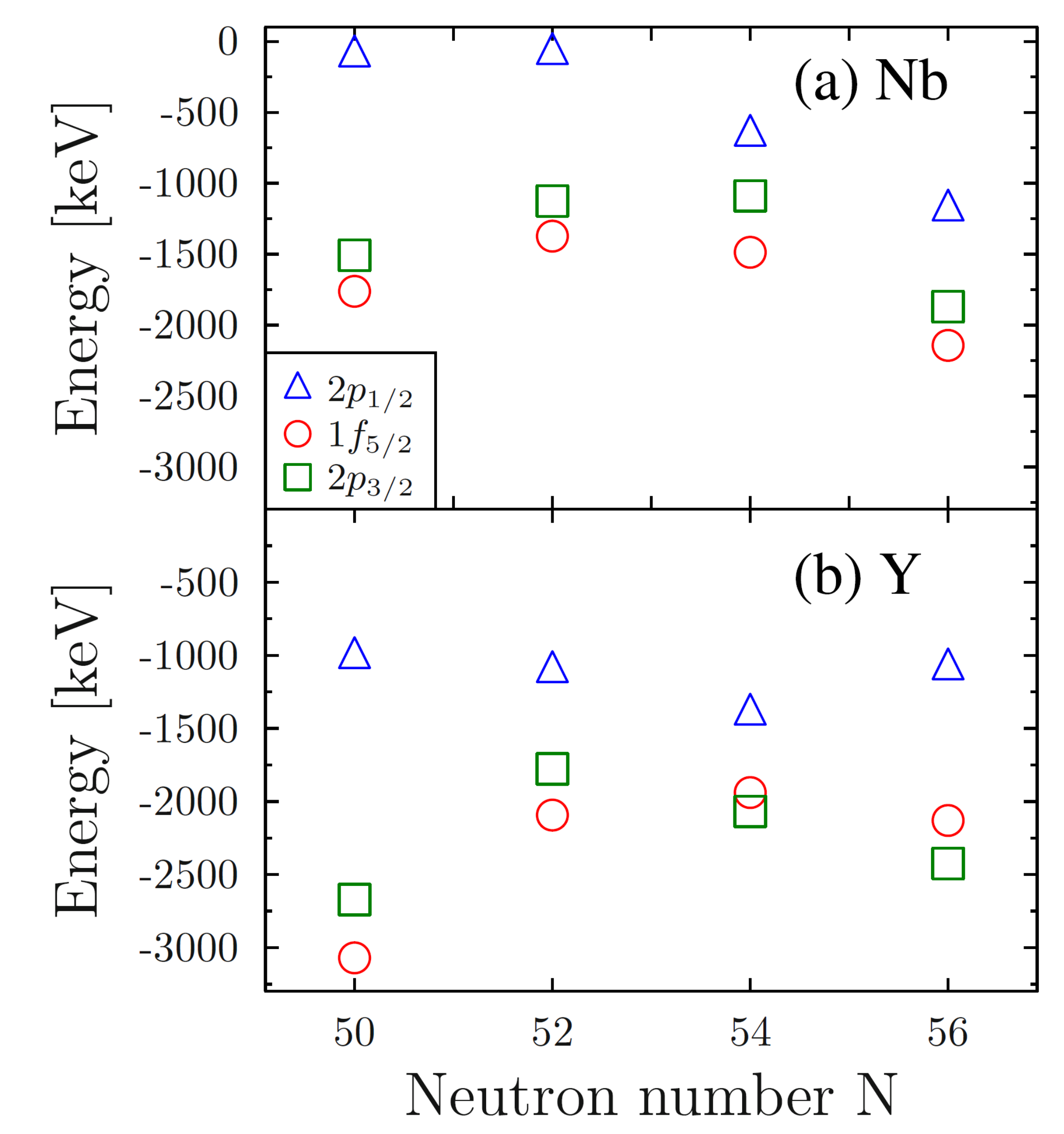


- **A different set of IBFM calculations used vastly different SPEs, and gave wave functions consistent with magnetic moments and transfer results**

PG, *Comment*, PRL 127, 169201 (2021).

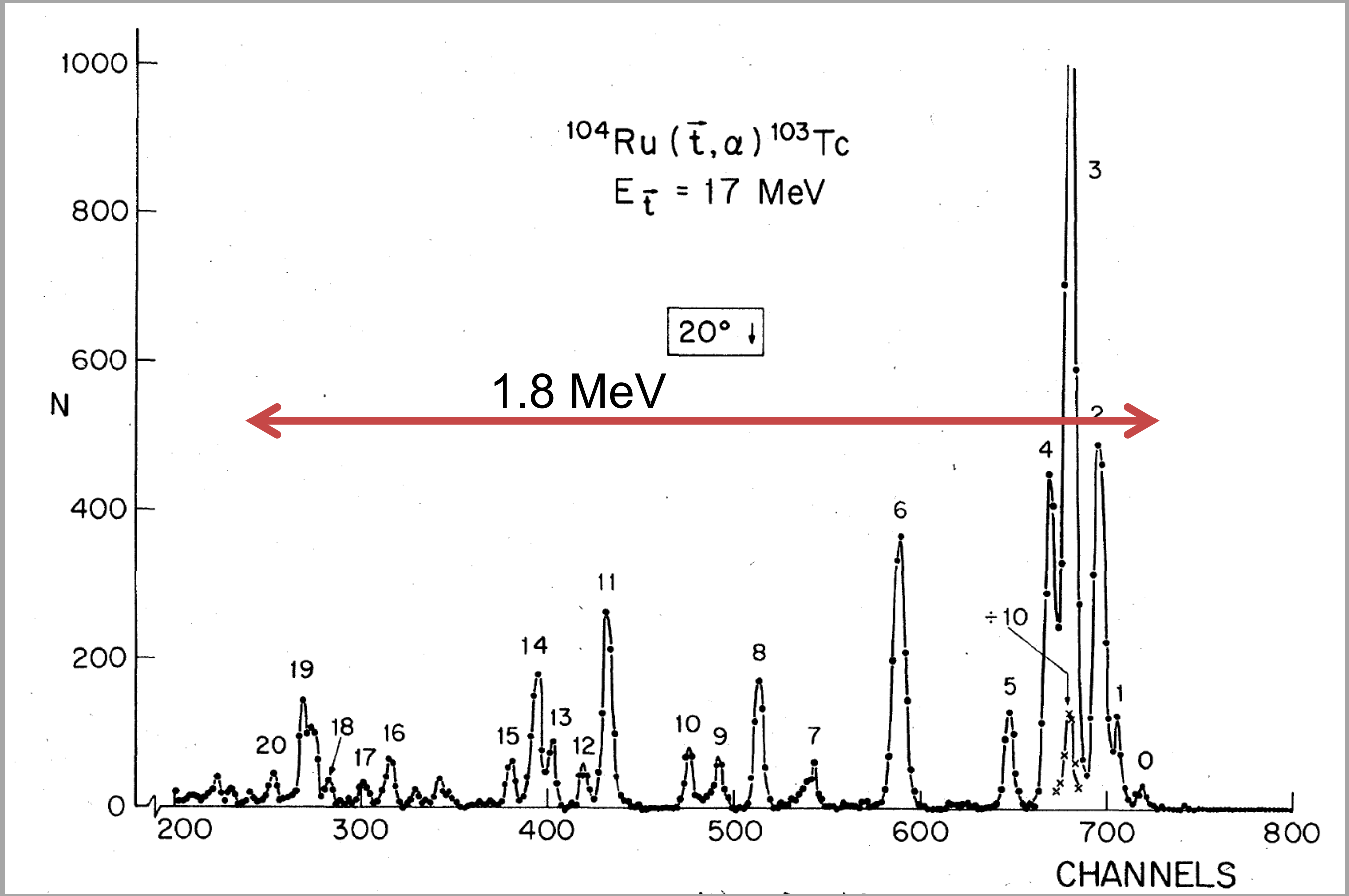
How to prove type-II shell evolution?

- **Approach to examine SPEs is a valid one**
  - **Need reliable SPEs for both neutrons and protons across *N*=60, in Sr, Zr (neutron SPEs) and Nb, Y (proton SPEs)**
  - **Ideally, contrast with data on Tc, Br (outside region of ground state phase transition).**
  - **Tc can be reached with Ru(t,α) or (d,^{3}He), but largely unexplored.**
  - **Only ^{103}Tc probed with single-proton transfer**
- **Map proton single-particle states in ^{95}Tc – ^{101}Tc via Ru(t,α)**
- **Strength centroids in Nb and Y may not be firm – some nuclei should be reinvestigated to higher sensitivity**

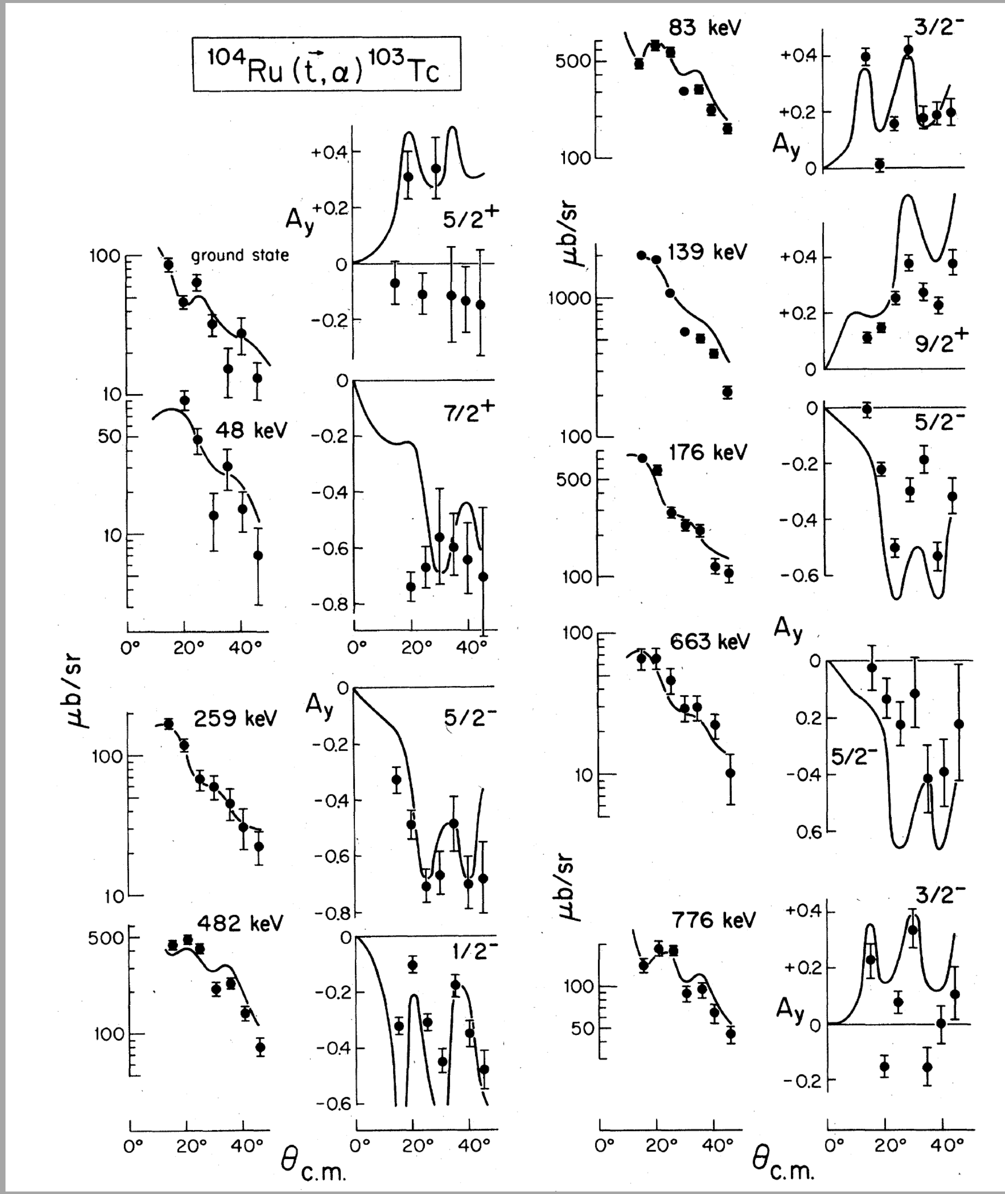


^{103}Tc from (t,α)

- **Study from LANL using 20-50 nA triton beam ~ 60 μC exposures**
- **10% precision on 10 μb/sr X-sec with 20 nA beam in ~ 7.5 hours**

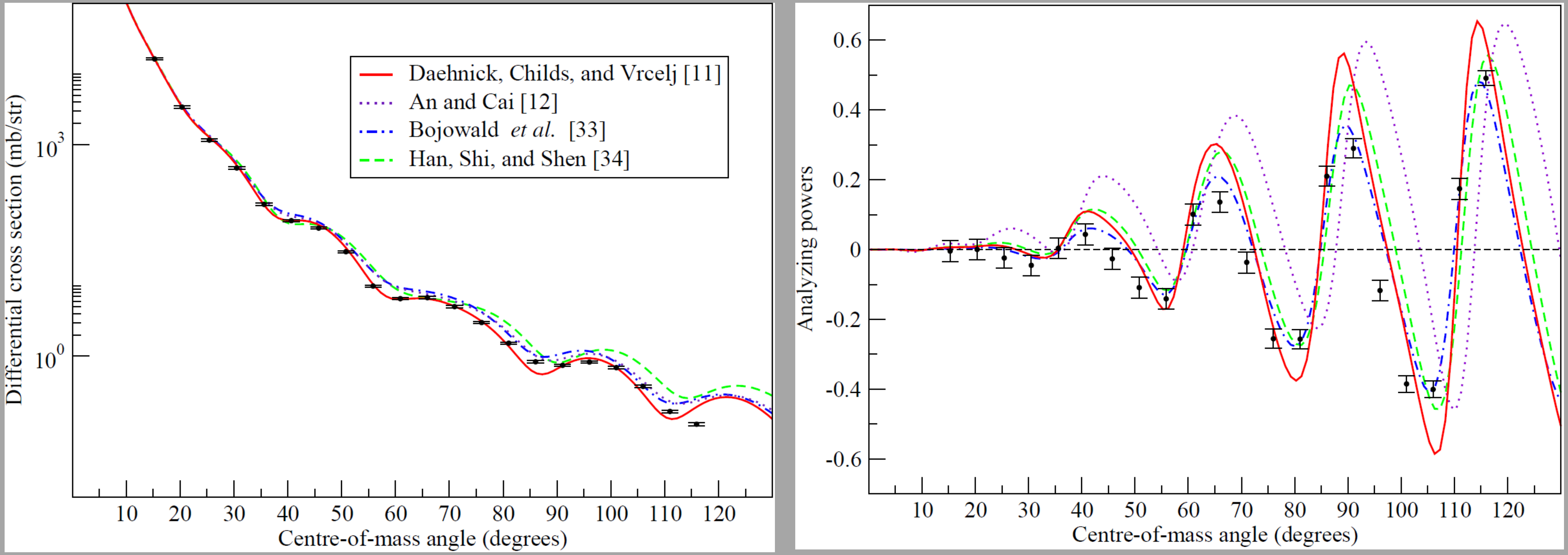


Flynn et al., PRC 24, 902 (1981).



Tests of OMPs

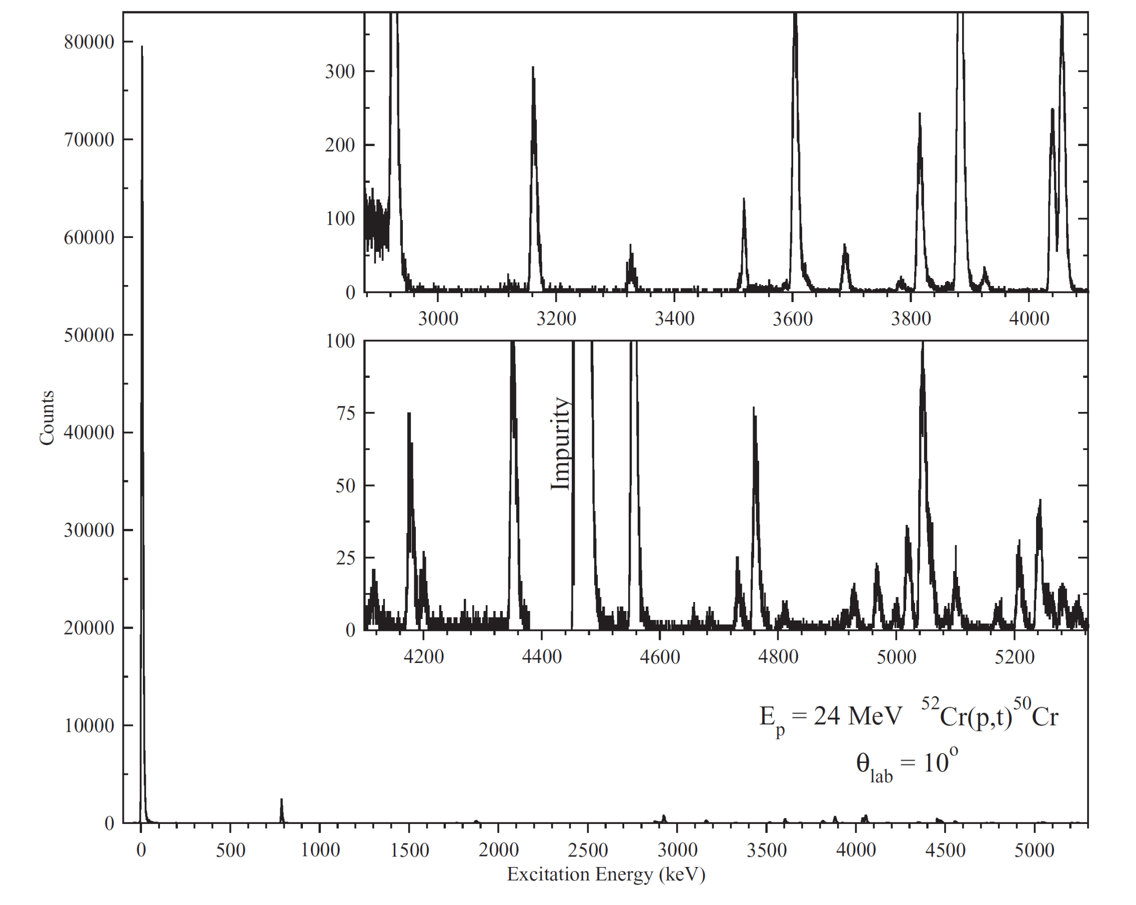
- **Important to map the elastic X-sec for OMPs – triton global OMPs not as well determined as p, d**
- **Ex: polarized d+^{112}Cd @ 22 MeV**



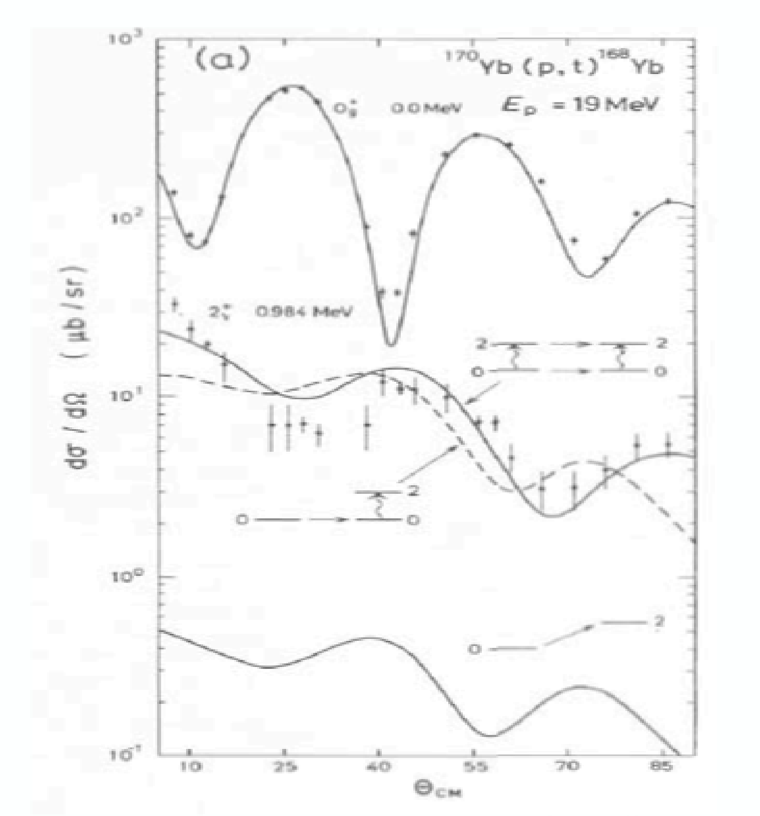
D. Jamieson, PG et al., PRC 98, 044309 (2018)

Two-nucleon transfer reactions – (p,t), (t,p), (^{3}He,n)

- **For even-even nuclei, pairing correlations that lower the ground state energy also result in constructive interference of the transition amplitudes and thus a strongly-enhanced ground-state population.**
- ***L*=0 transitions can be easily identified by the characteristic diffraction pattern in their angular distributions.**



K.G. Leach et al., PRC 100, 014320 (2019)



[Phys. Lett. **44B**(1973)425]

- **In spherical nuclei *L* = 2 and *L* = 4 transitions can also be identified using DWBA analysis,**
- **In deformed nuclei the angular distributions for L≠ 0 are often distorted by multistep excitations which can be described by couple-channels calculations.**

Single-particle dependence of form factor: shape of angular distributions practically independent of *j* of transferred neutron

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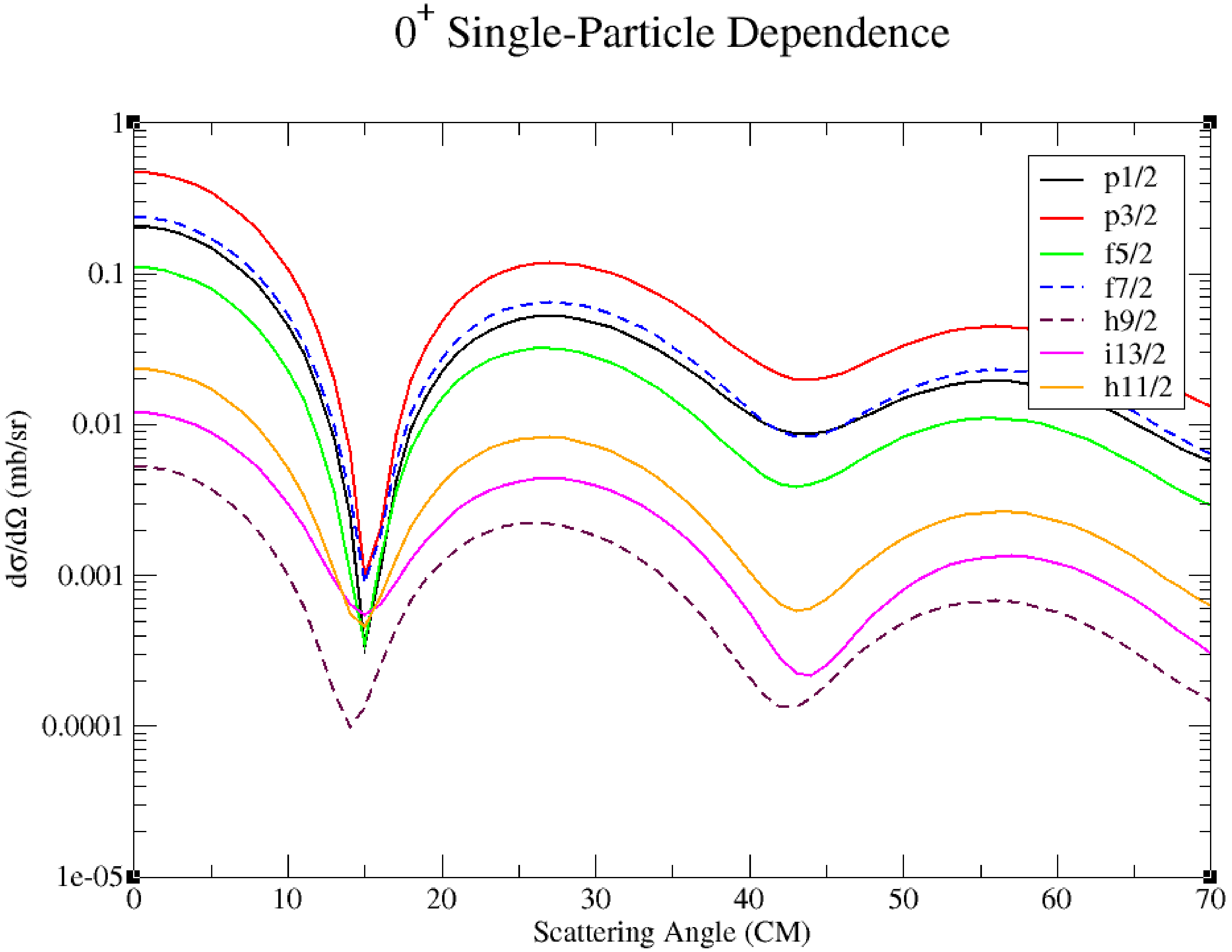

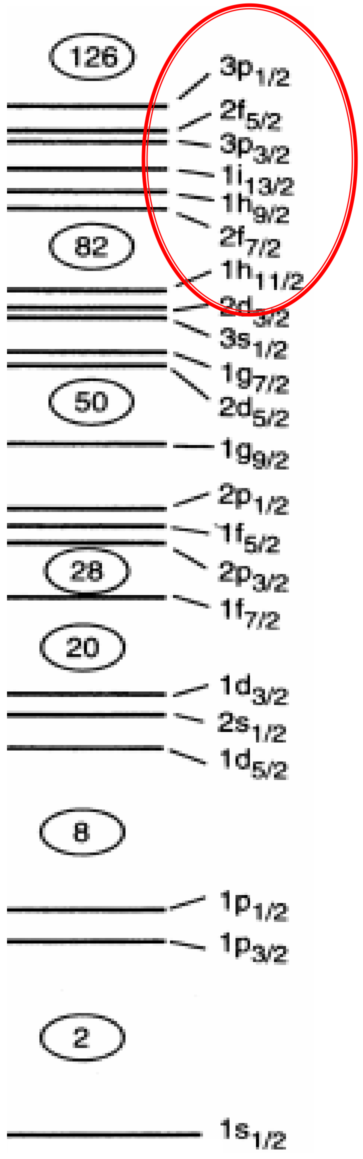

Relative population of 0^+ states

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- **Shape of angular distribution in two-nucleon transfer rather insensitive to individual particle *j*-value involved in pair transfer**

- **Ratio of excited 0^+ to gs cross sections normally expected to be on order of few % for 2QP excitation**

- **0^+ state cross section in (p,t) reaction** $\sigma \propto \left(\sum (a_i V_i^2)\right)^2$,

  and for the (t,p) reaction $\sigma \propto \left(\sum (a_i U_i^2)\right)^2$

- **Relative population on order of 10% or greater indicative of an enhanced transition – a *collective pairing* transition – at least in conventional wisdom**
  - **Even 5% indicates some pairing collectivity, unless we have "hot" orbitals involved**

Excited 0^+ states at closed shells: neutron "pairing vibration" in ^{208}Pb

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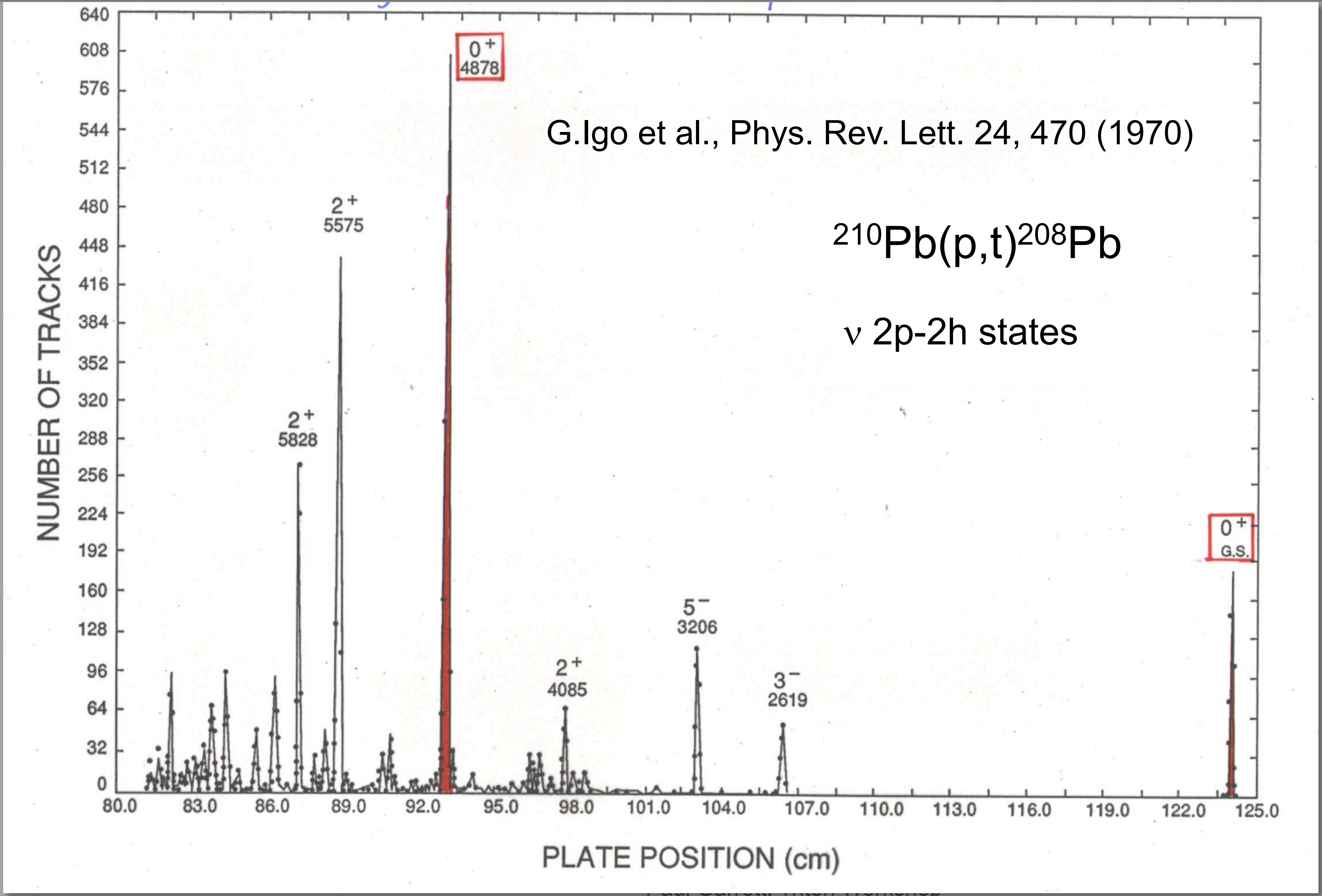


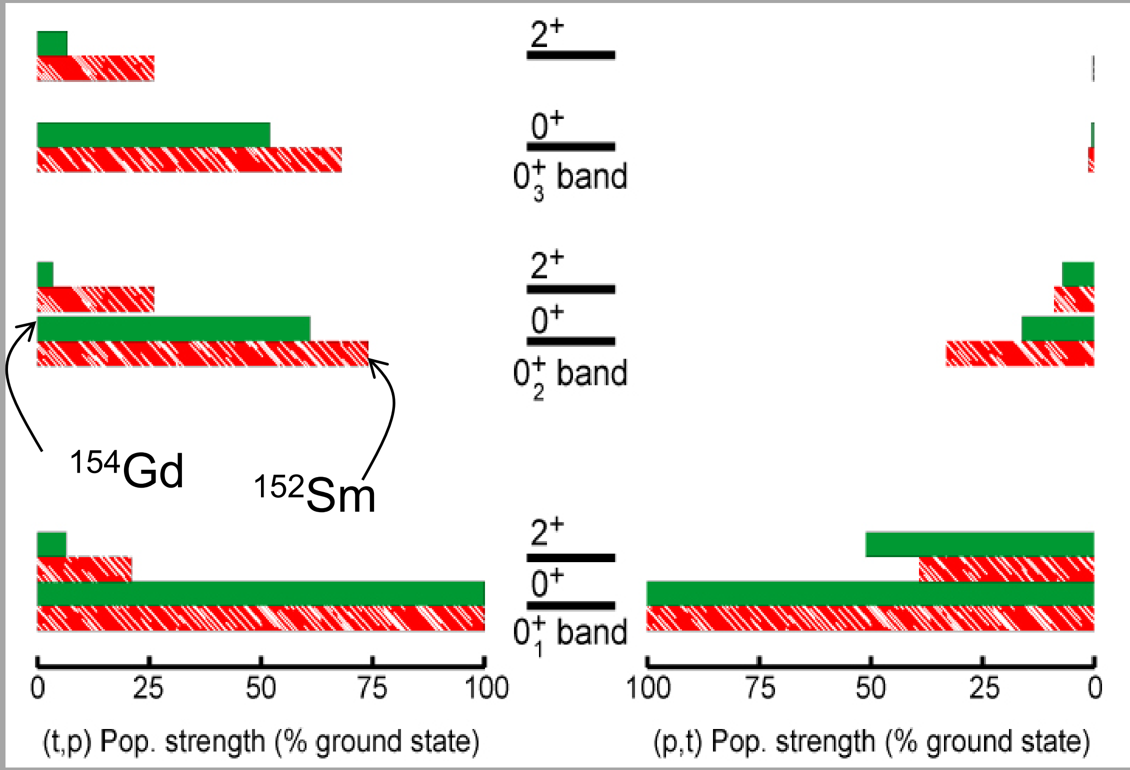
G.Igo et al., Phys. Rev. Lett. 24, 470 (1970)

^{210}Pb(p,t)^{208}Pb

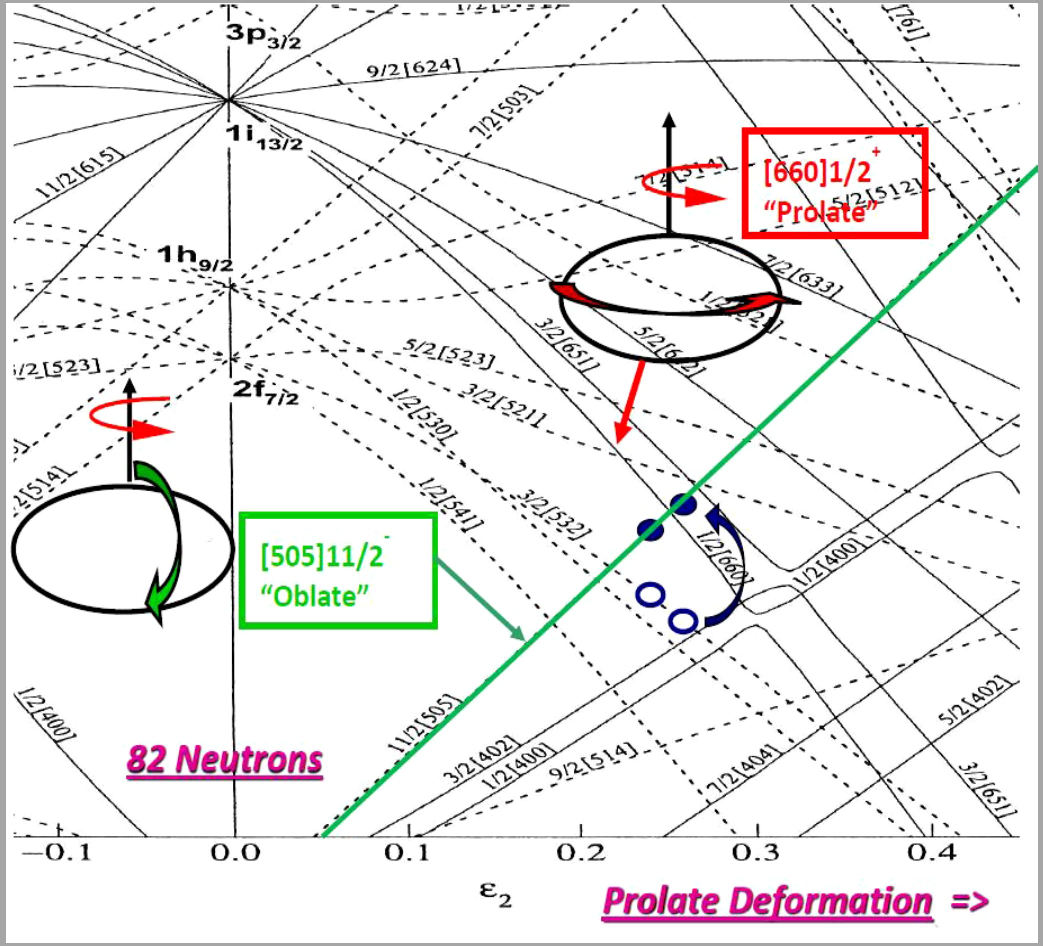
ν 2p-2h states

Investigation of "pairing isomers"

- Predicted to occur when we have a grouping of Nilsson orbitals involving "prolate" and "oblate" orbitals such that the pairing matrix elements $|G_{oo}| \approx |G_{pp}| >> |G_{op}|$
- A dynamic decoupling of single-particle levels occurs (scattering between levels largely suppressed)
- Population of 0^+ states can be highly asymmetric in (p,t) and (t,p) due to difference in V^2 and U^2 factors of Nilsson orbitals.



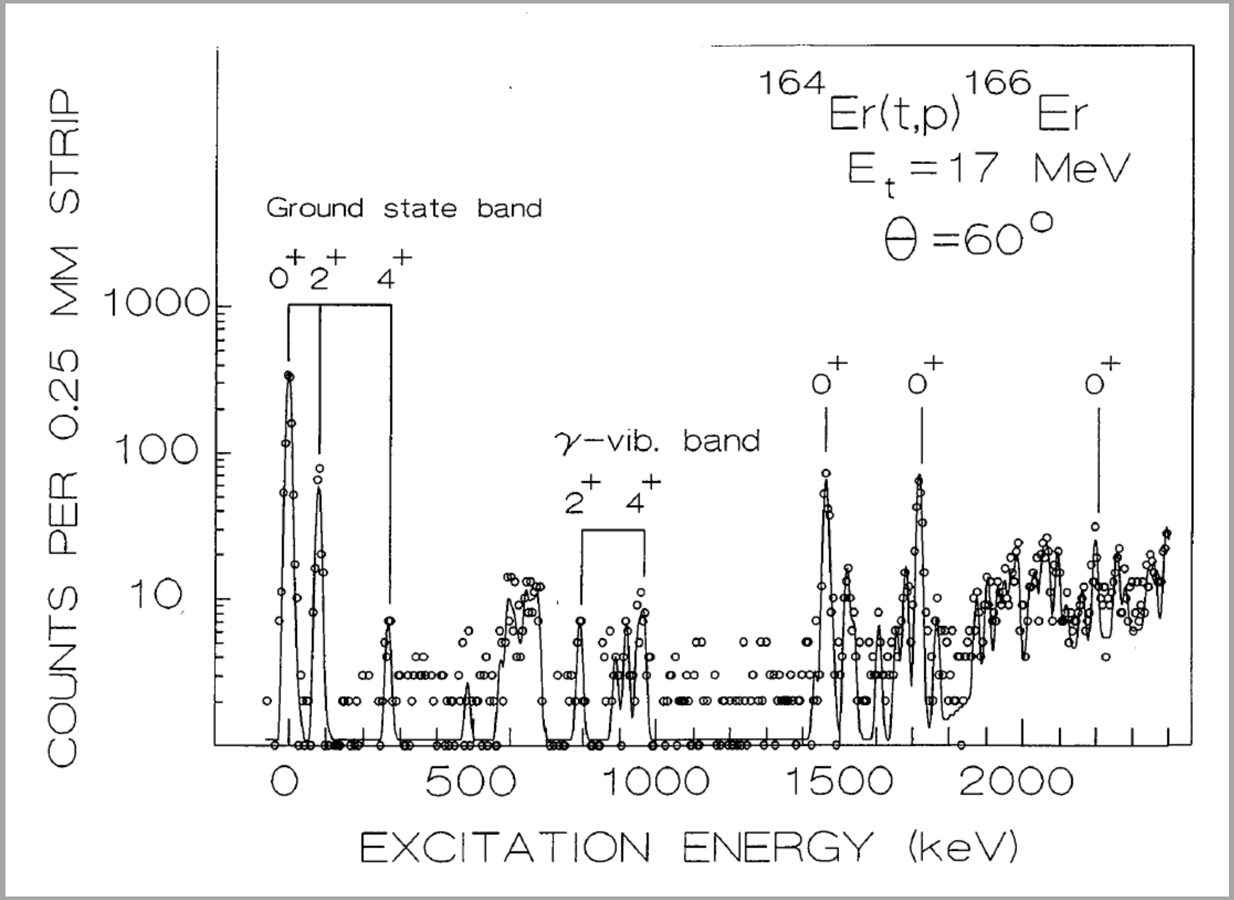
W.D. Kulp et al. PRC **71**, 041303(R) (2005)

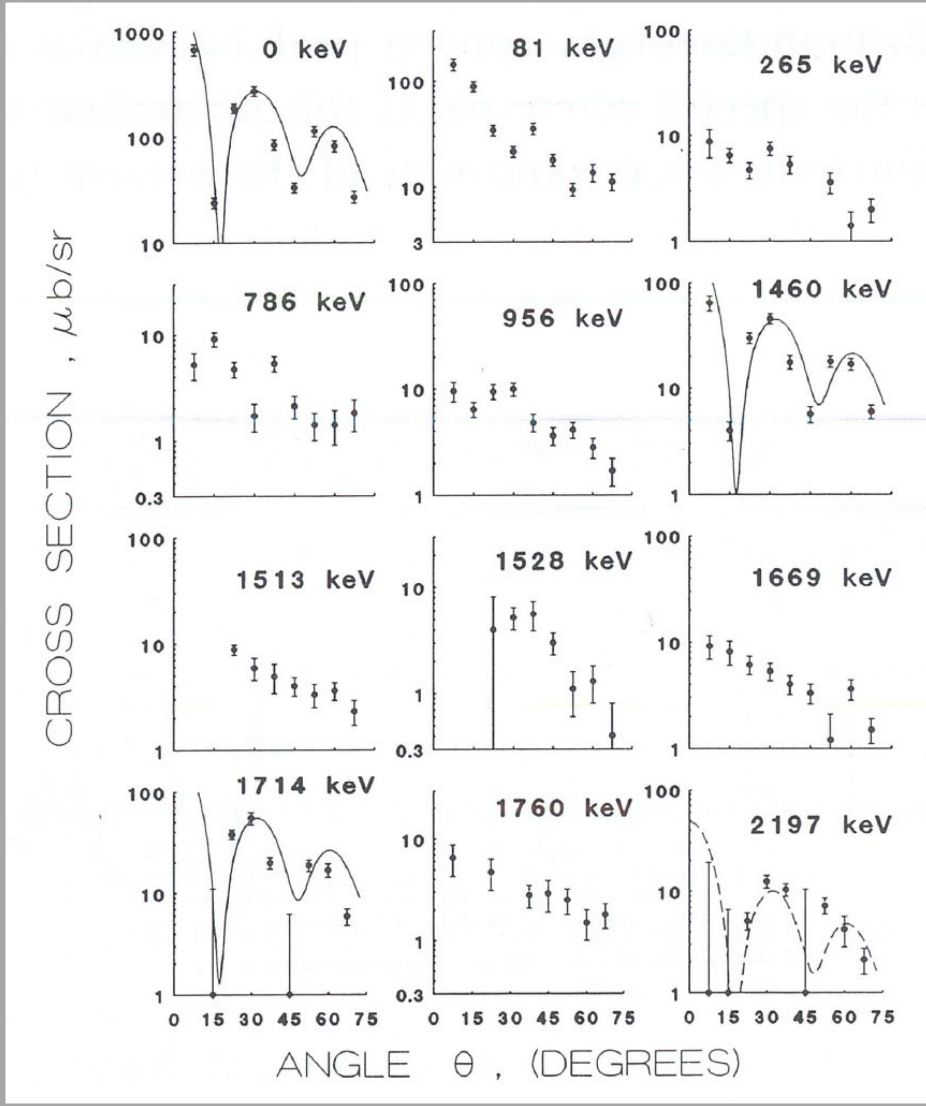


J.F. Sharpey-Schafer et al., EPJ **A55**, 15 (2019)

Investigation of Er isotopes: e.g. ^{166}Er

- **Data from McMaster – the last facility with t beams – Burke and Garrett, NPA 550, 21 (1992)**





Investigation of Er isotopes: e.g. ^{166}Er

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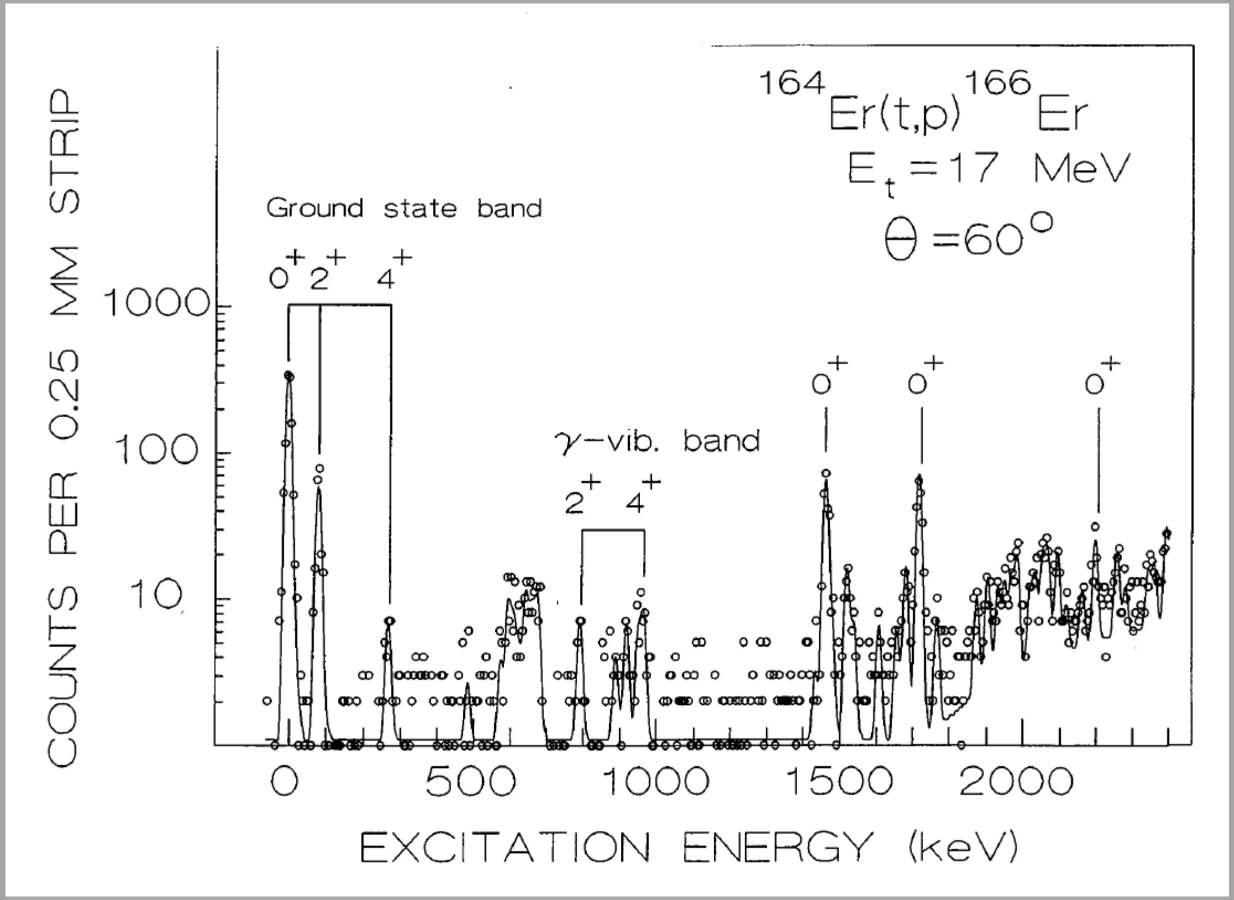
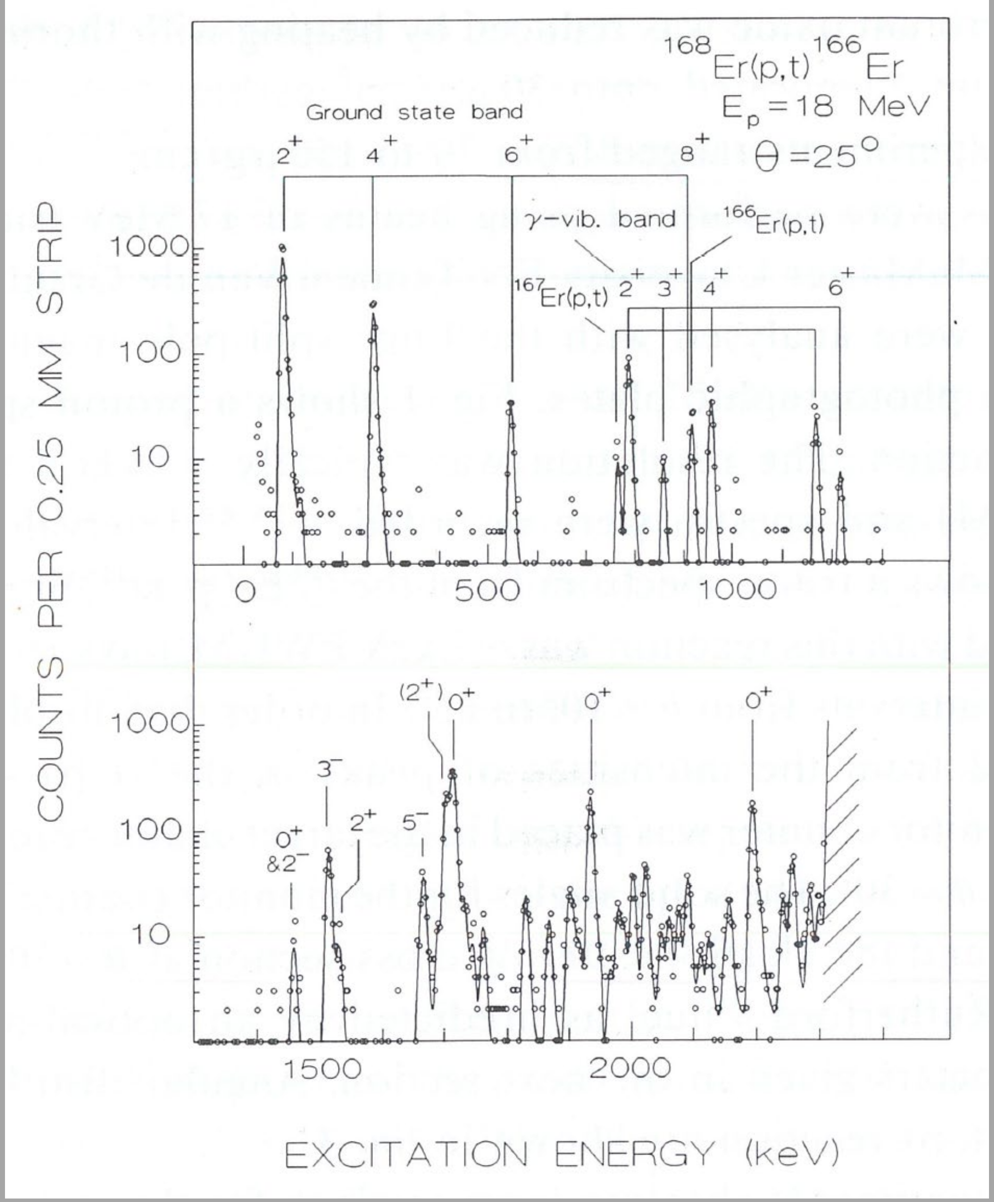
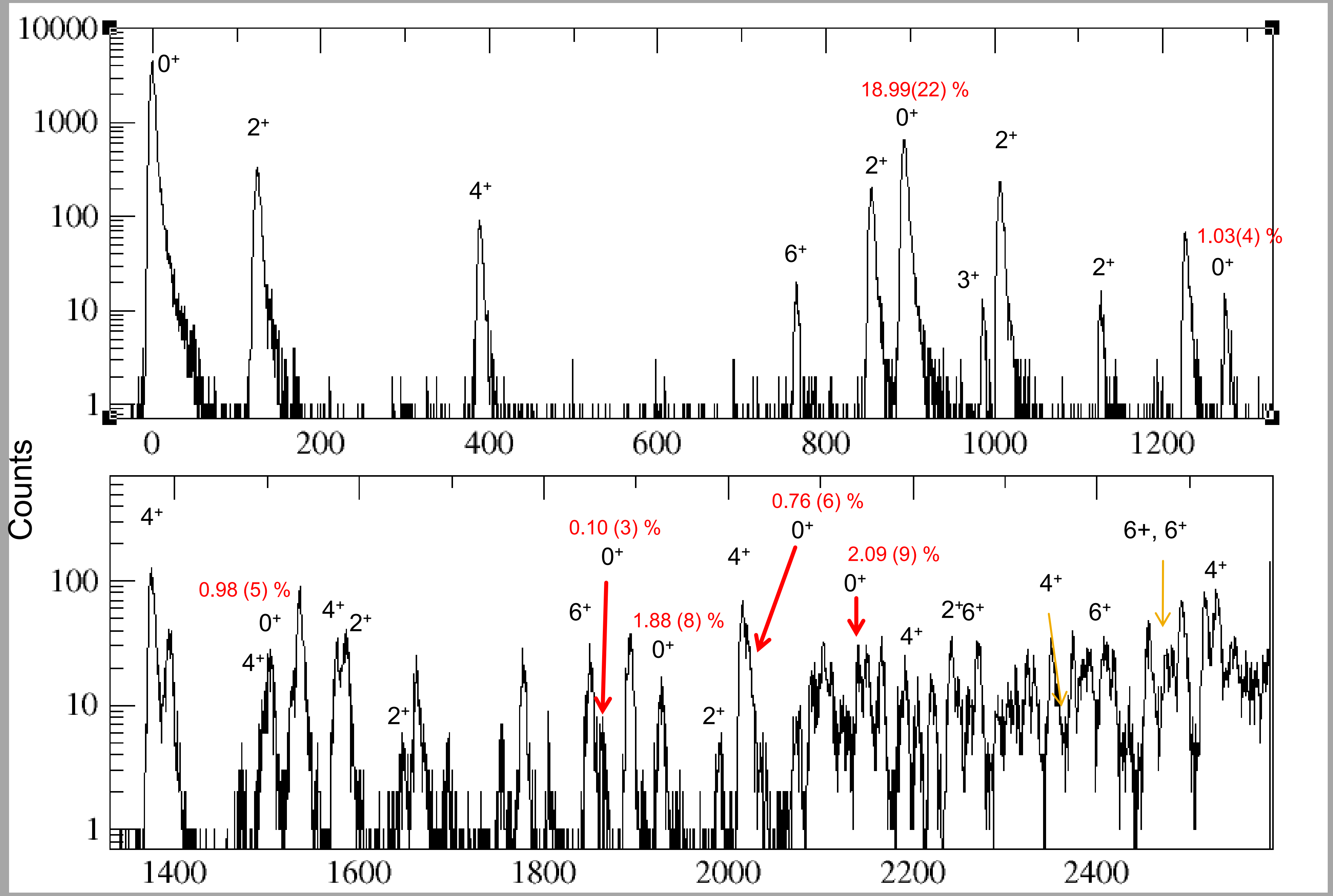


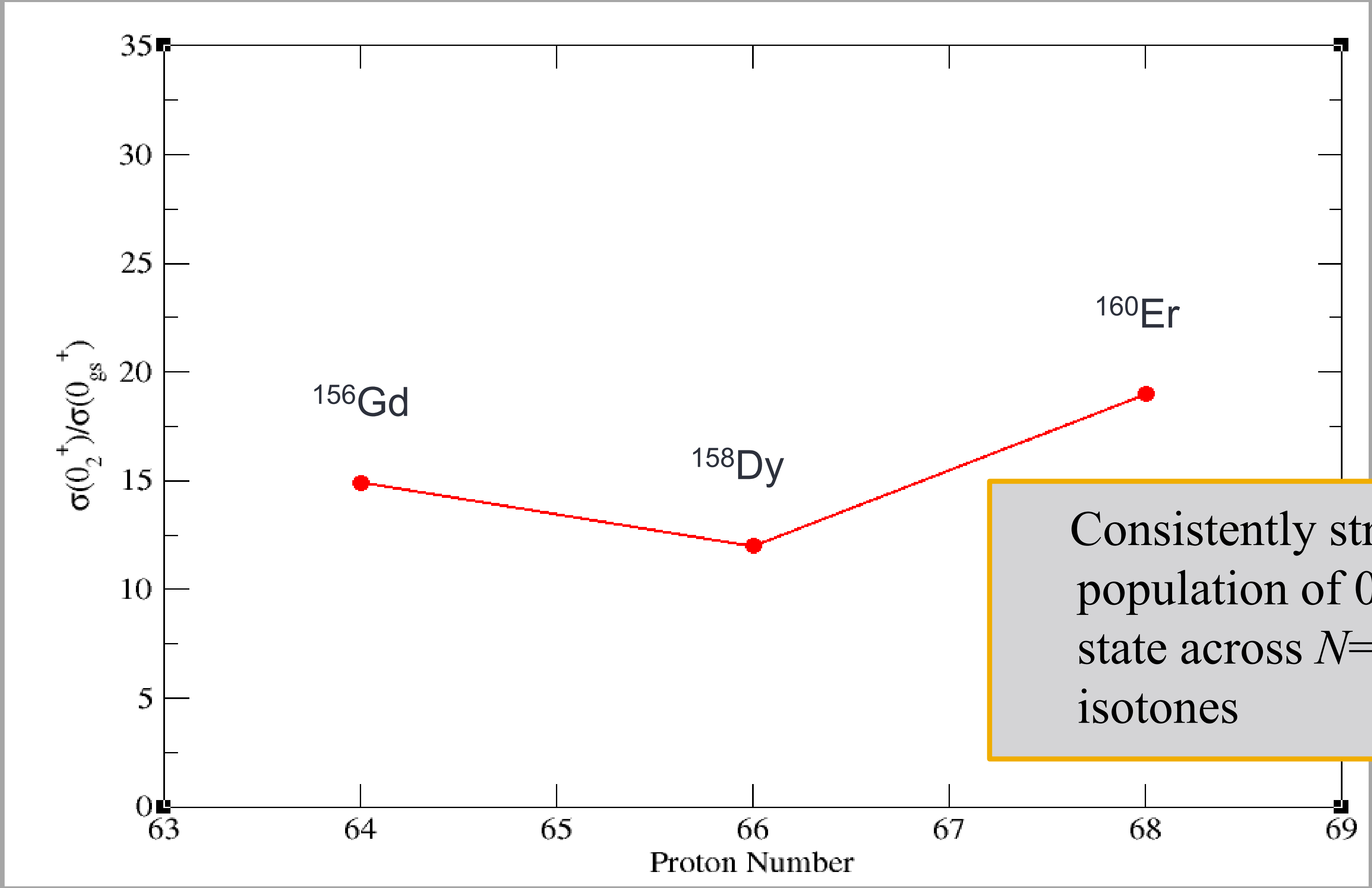


Asymmetric population of excited 0^+ states

Investigation of 0^+ states at *N*=92: $^{162}Er(p,t)^{160}Er$ spectrum



0_2^+ (p,t) population strength in *N*=92 isotones



Consistently strong population of 0_2^+ state across *N*=92 isotones

Consistent properties of 0_2^+ states points to common structure

Er isotopes trend in (p,t) population of 0^+ states

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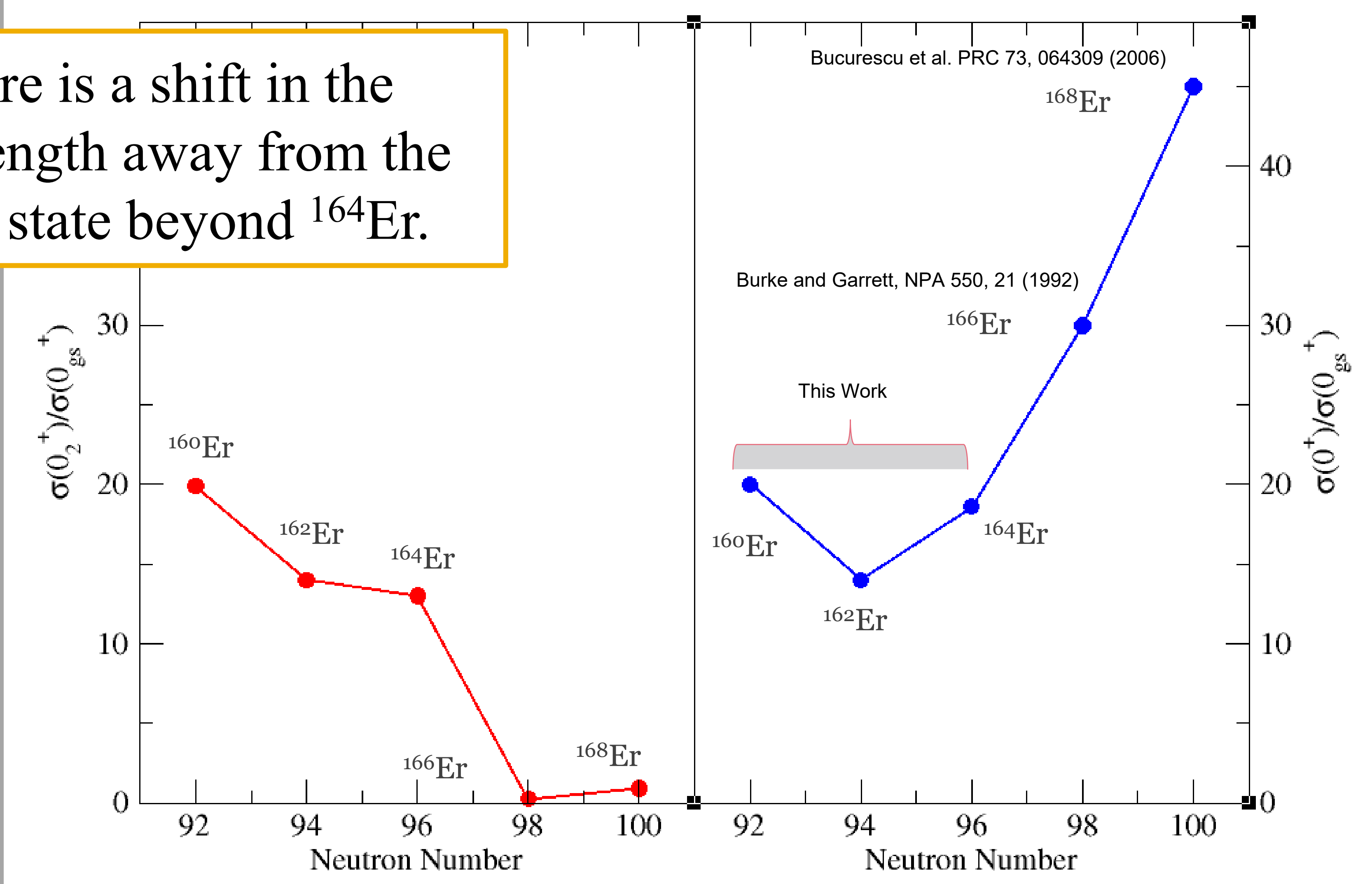
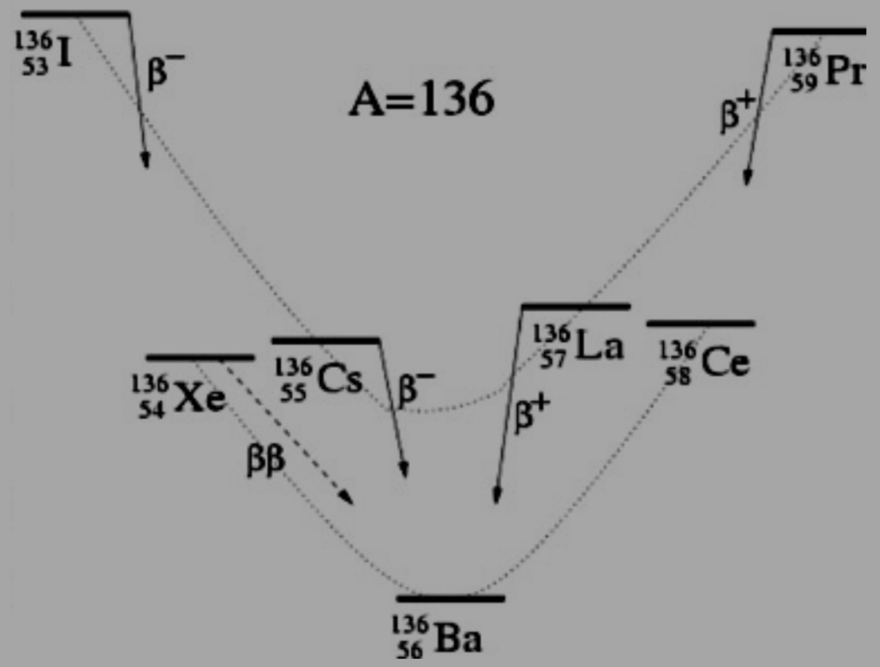
There is a shift in the strength away from the 0_2^+ state beyond ^{164}Er.

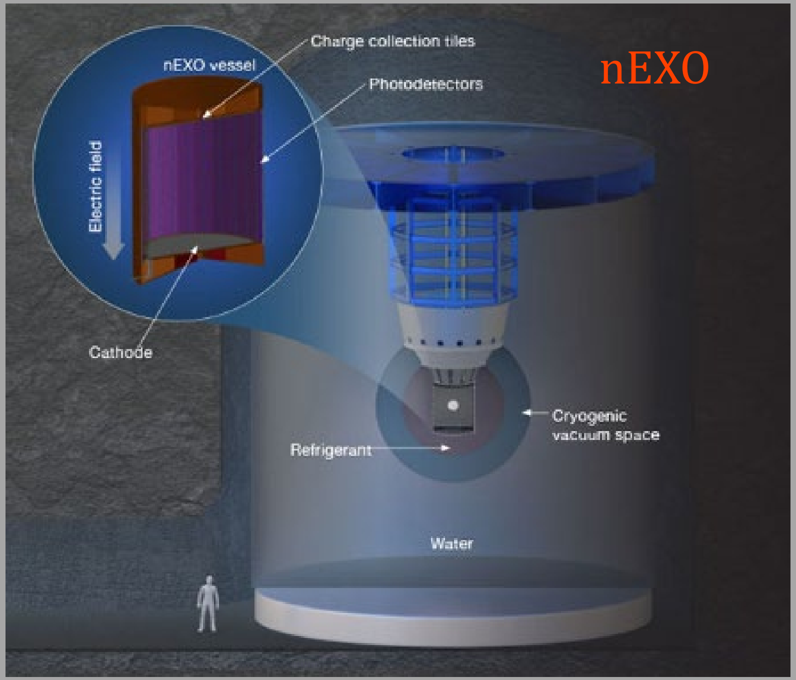


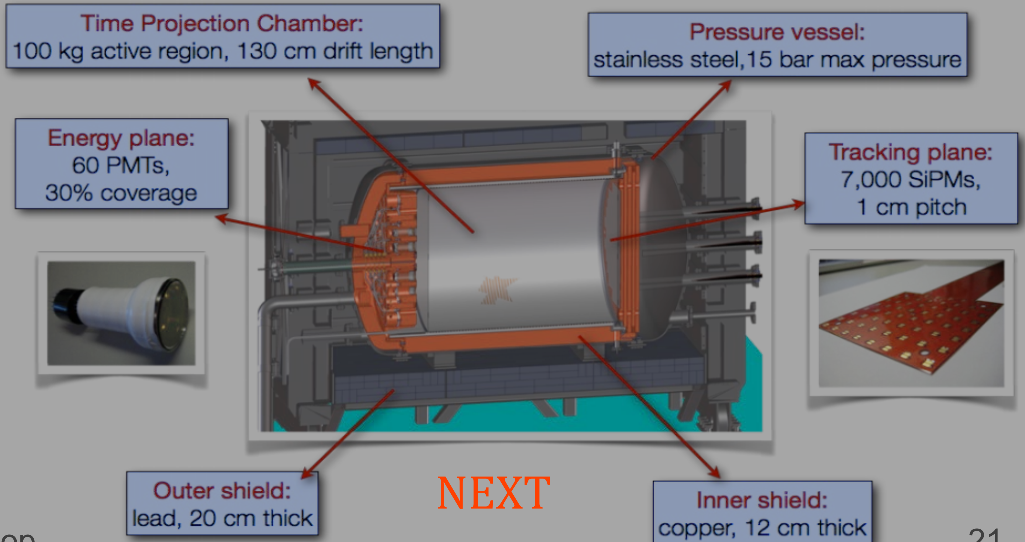
Many of the previous reactions involving t beams were done using photographic emulsions – practical limitations of 1000 “tracks per strip” limiting dynamic range, and often excitation energy range was limited

It would be of great interest to (re)investigate the (t,p) reactions in this region

The 0νββ decay of ^{136}Xe







- **SM-allowed 2ν background is low for ^{136}Xe ββ decay**
- **^{136}Xe has singly closed shell ($N = 82$) → nearly spherical shape**

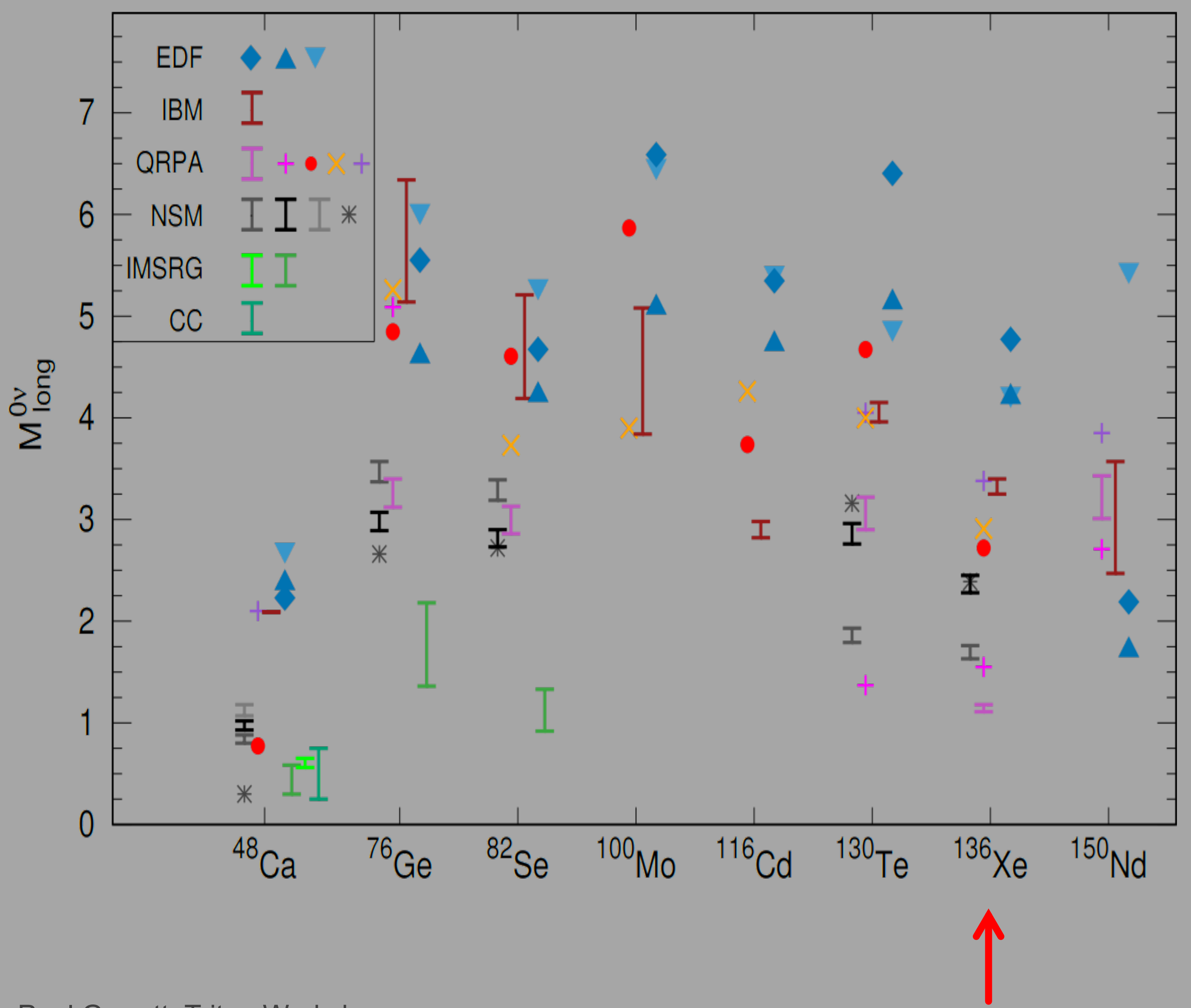
The 0νββ decay of ^{136}Xe

- **Half life of double β decay process depends on square of nuclear matrix elements (NME), *M***

$$\frac{1}{T_{1/2}} = G\, g_A^4\, \mathcal{M}^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

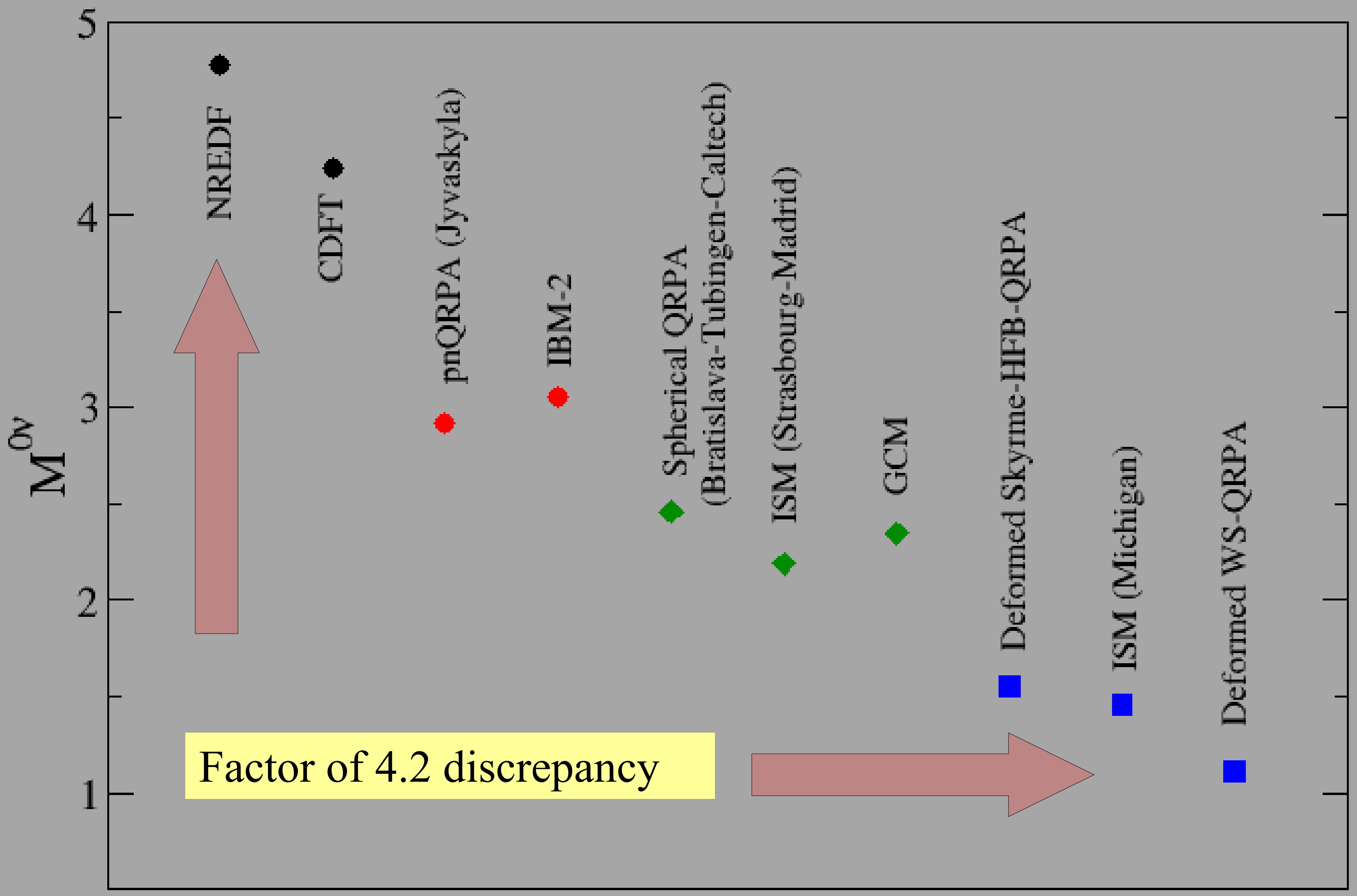
- **If signal is observed, the NME must be known to extract properties of neutrino**
- **Large variation in magnitude of NME from models**

arXiv:2202.01787, Agostini, Benato et al.

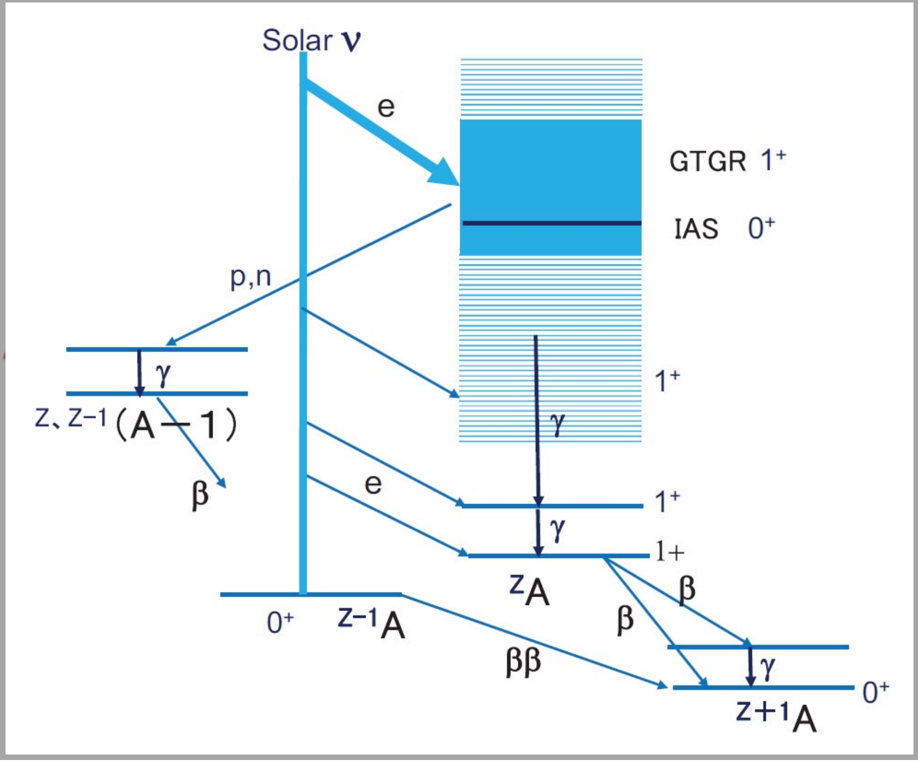


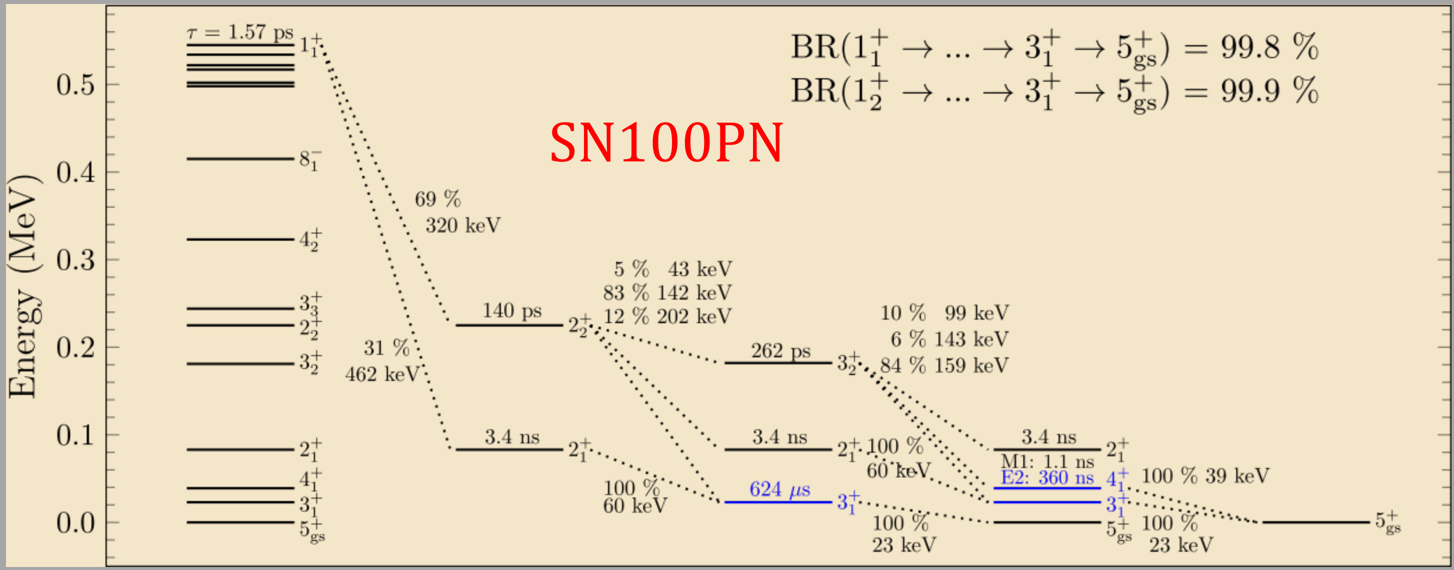
The NME for ^{136}Xe 0νββ decay

- A closer look at the ^{136}Xe NMEs
- Generally, the greater the degree of deformation of ^{136}Ba predicted by the calculations, the smaller the NME



- Promise for CNO neutrino detection
- The ^{7}Be ν line-shift (Bachall, 1994)
- Fermionic Dark Matter absorption (Dror, Elor, and McGehee, 2020)





Charged current neutrino cross section for solar neutrinos, and background to $\beta\beta(0\nu)$ experiments

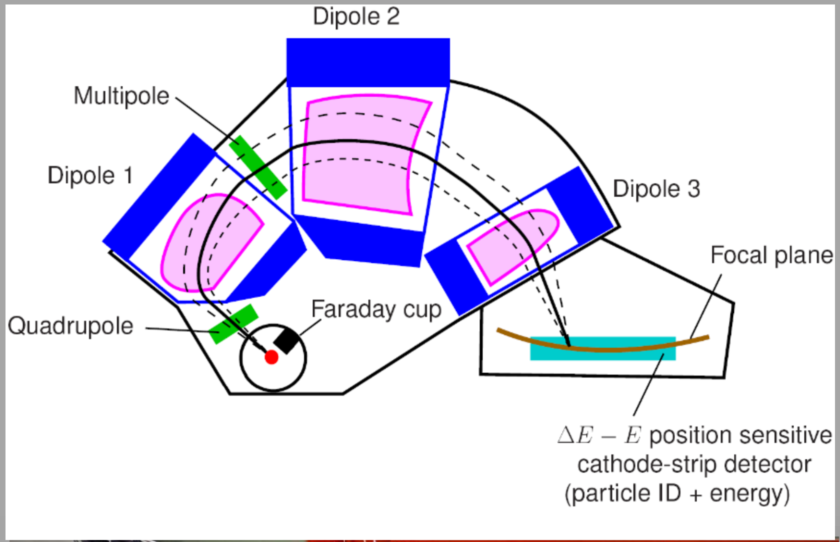
H. Ejiri and S. R. Elliott
Phys. Rev. C **89**, 055501 – Published 8 May 2014

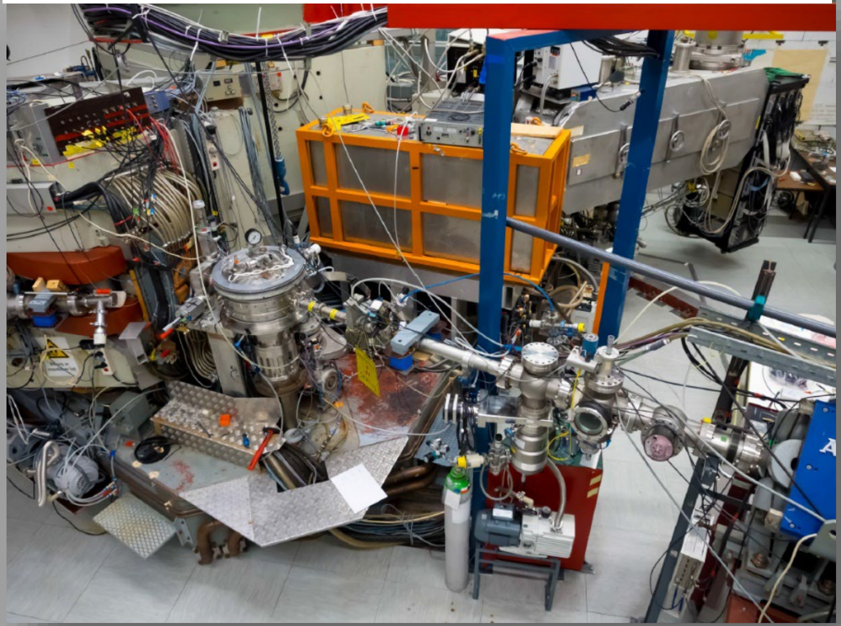
Open Access

Solar neutrino detection in liquid xenon detectors via charged-current scattering to excited states

Scott Haselschwardt, Brian Lenardo, Pekka Pirinen, and Jouni Suhonen
Phys. Rev. D **102**, 072009 – Published 29 October 2020

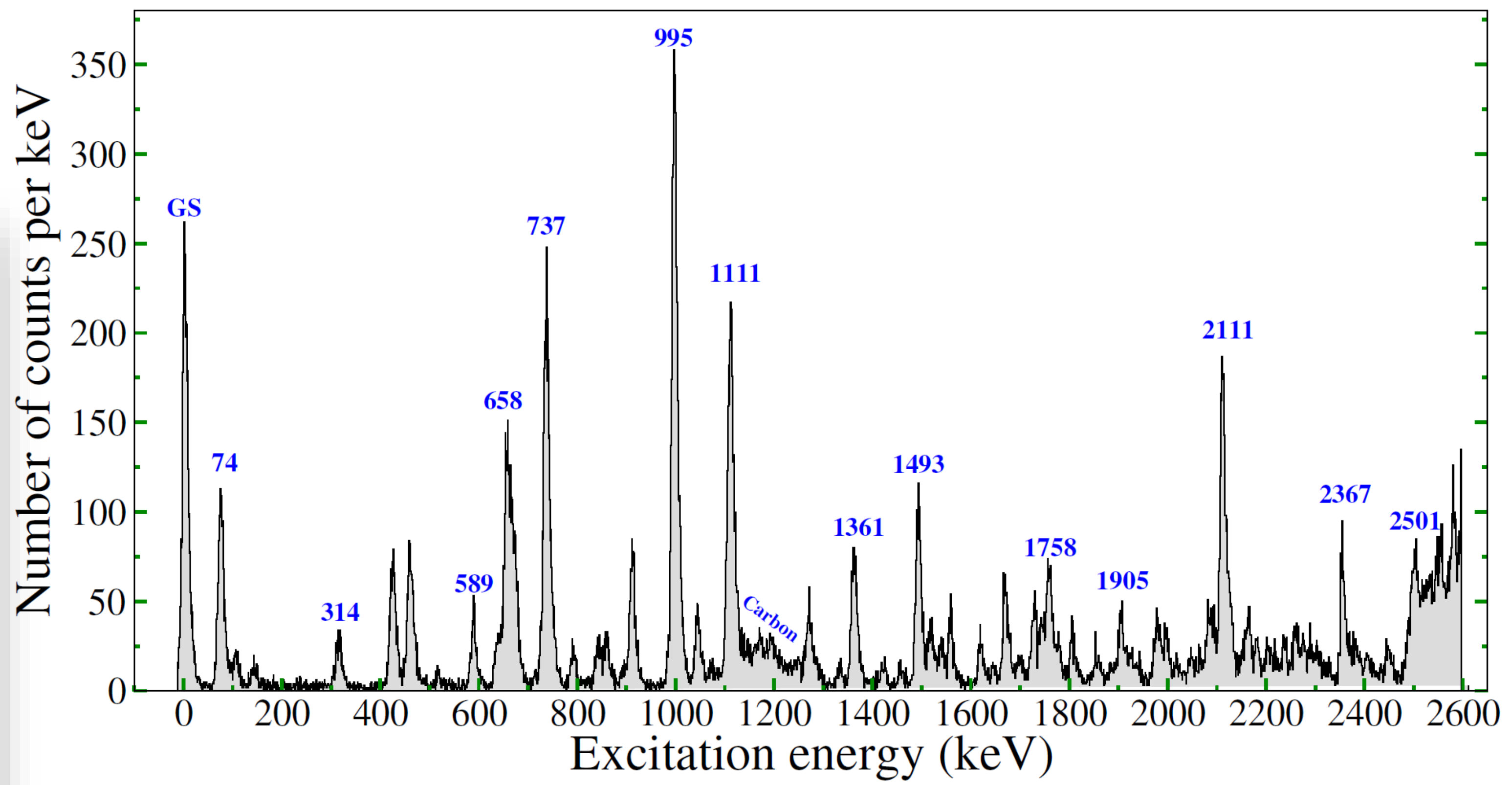
Our study of the $^{138}Ba(d,\alpha)^{136}Cs$ reaction





- **We used the Q3D magnetic spectrograph of the MLL Munich to study the $^{138}Ba(d,\alpha)$ reaction**
  - **22 MeV d beam, ~10 keV resolution FWHM**

B.M. Rebeiro, S. Triambak, PG, *et al.*, PRL 131, 052501 (2023).



Results from ^{138}Ba(d,α) reaction – comparison to predictions

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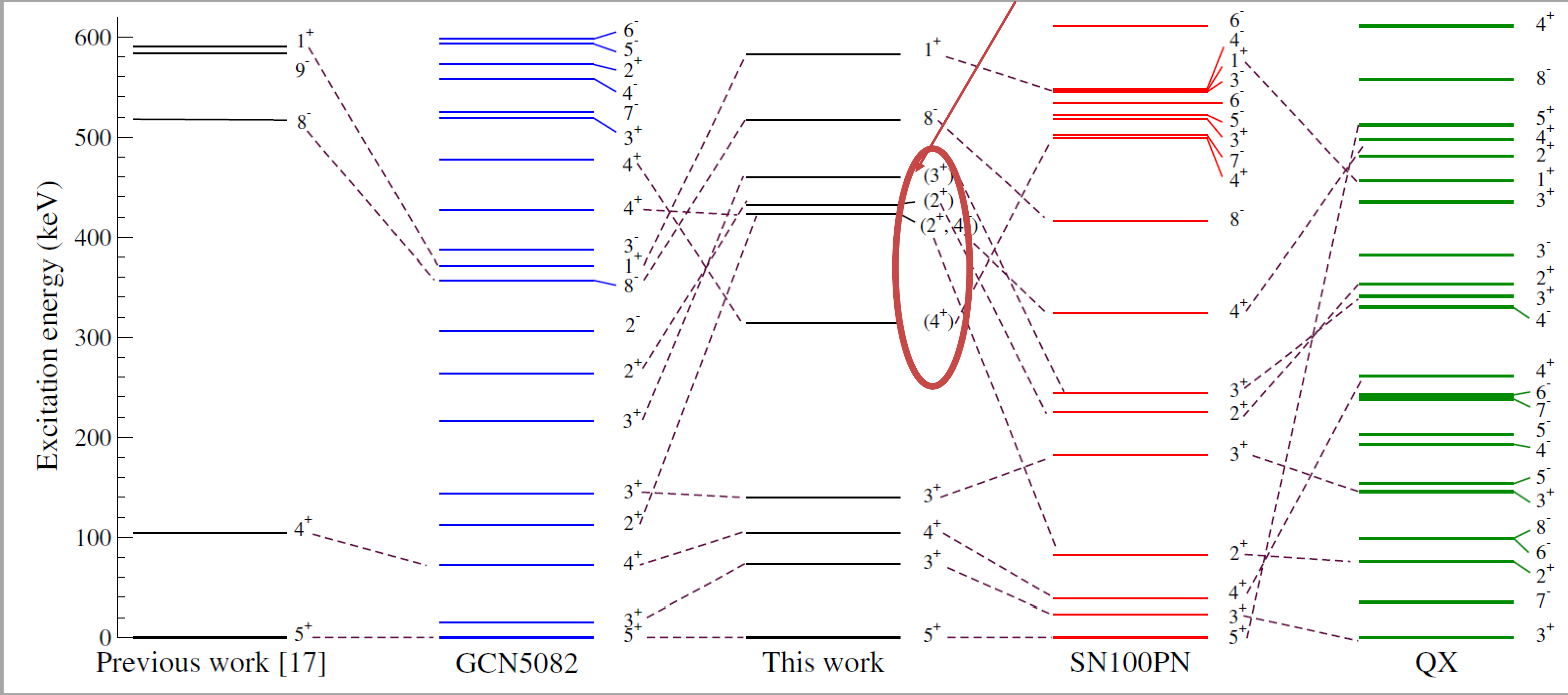
- Transfer results appear to rule out the QX interaction, but cannot distinguish between GCM5082 and SN100PN

Many spins assignments uncertain



Angular distribution from (d,α) reaction – contradiction with spin of 104-keV state?

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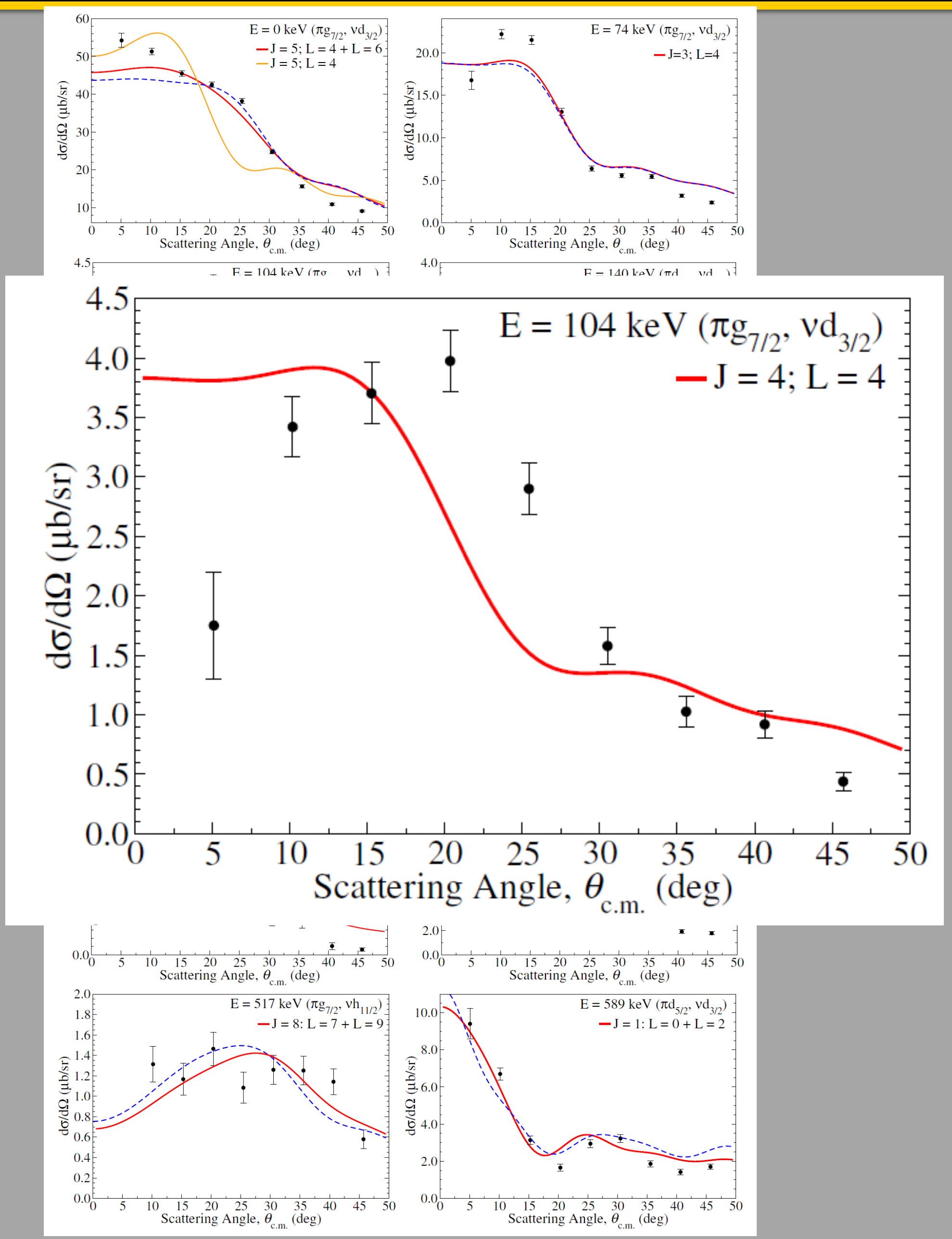
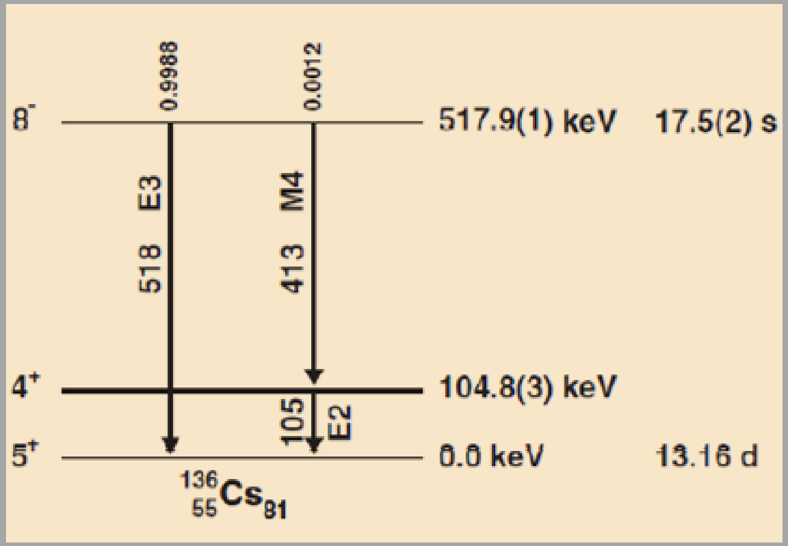


- **Angular distribution of 104-keV 4$^+$ state shows a significant discrepancy that doesn't appear for *any* other state – appears to favour a higher *L* transfer**
- **But, higher *L* would be incompatible with isomer decay results**



- **A ^{137}Ba(t,α) measurement would provide complementary data for assignment of J^{π} values of levels**
- **X-sec to individual levels is small – fragmentation in odd-odd nuclei – but information is important**
- **Ideally, we should have a much large beam intensity – 200 nA?**

- **A broad program of (t,α) and (t,p) measurements can be envisioned; resolution and sensitivity to small cross sections is paramount**
  - **My opinion – perform high-quality measurements; complete angular distributions, sensitivity to weak cross sections**
  - **Many other measurements I am personally interested in; In(t,α), ^{103}Rh(t,α), ^{82}Se(t,p)**

- **Many of these proposed experiments would benefit from higher beam currents, especially the studies of odd-odd intermediate $0\nu\beta\beta$ nuclei; e.g., ^{137}Ba(t,α) which will have very small X-secs – but the physics payoff is worth the investment**

- **Encourage *t* elastic scattering measurements – this is "bread&butter", but important data for global OMP developments, and data comes quickly.**

Measurements using the late, great Q3D at MLL (Munich)

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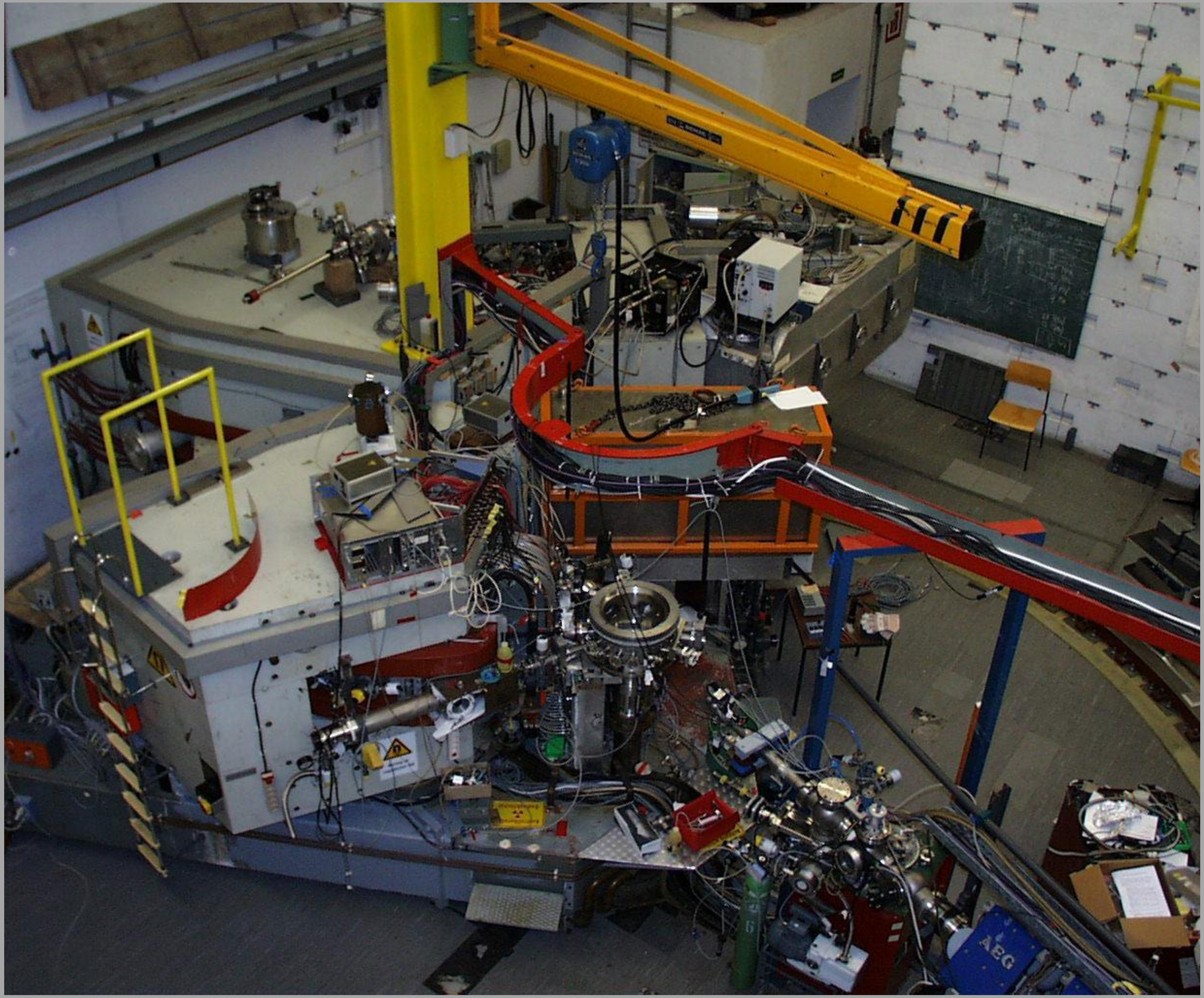
- Until the closure of the Maier Leibnitz Laboratory in Munich at the end of 2019, its Q3D was (my opinion) *the* premier facility for performing nucleon transfer reactions with stable beams

- Wide variety of beams available with currents of μA for light ions, and hundreds of pnA for heavier ions like ^{12}C or ^{16}O.

- Requirement of well-focused beams (< 1 mm wide beam spots) and extremely thin targets (tens – 100 of μg/cm^2)

- Typical resolution (FWHM) ~ $(2\text{-}4)\times10^{-4}$ of outgoing particle energy
  - Higher resolutions could be obtained



Mapping proton single-particle strength in Tc isotopes

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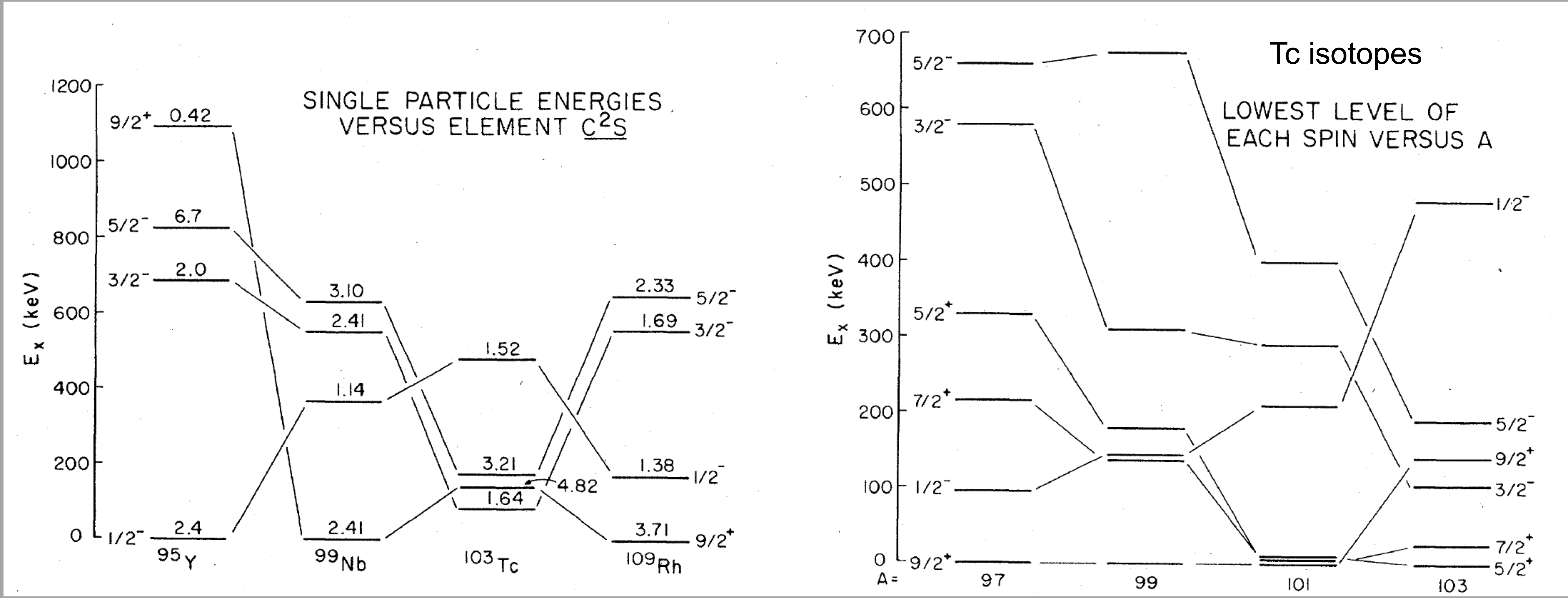

E.R. Flynn et al., PRC 24, 902 (1981)

Data used for SPEs

Nucleus	$1g_{9/2+}$		$2p_{1/2-}$		$1f_{5/2-}$		$2p_{3/2-}$		Reaction and reference
	E	C^2S or S	E	C^2S or S	E	C^2S or S	E	C^2S or S	
^{89}Y	910	6.34	0	0.72	−1745	2.77	−1507	1.86	^{90}Zr$(e,e'p)$ [56];
	2610	0.41			−5040	0.29	−4000	0.12	^{88}Sr(d,n) [57]
^{91}Y	550	1.09	0	1.33	−922	1.5	−653	0.84	^{92}Zr$(d,{}^3$He$)$; [58];
			−2569	0.37	−1552	5.28	−1481	1.9	^{92}Zr(t,α) [59]
					−1974	0.21	−2475	0.38	
					−2205	1.21			
^{93}Y	775	0.81	0	1.58	−890	1.7	−599	0.89	^{94}Zr$(d,{}^3$He$)$ [58]
			−1280	1.51	−1280	4	−2530	0.5	
^{95}Y	1090		0	2.7	−827	9.9	−686	2.4	^{96}Zr$(d,{}^3$He$)$; [58];
					−1887	2.5	−2041	2.2	^{96}Zr(t,α) [60]

Large TNT cross sections to excited 0^+ states observed at N=90

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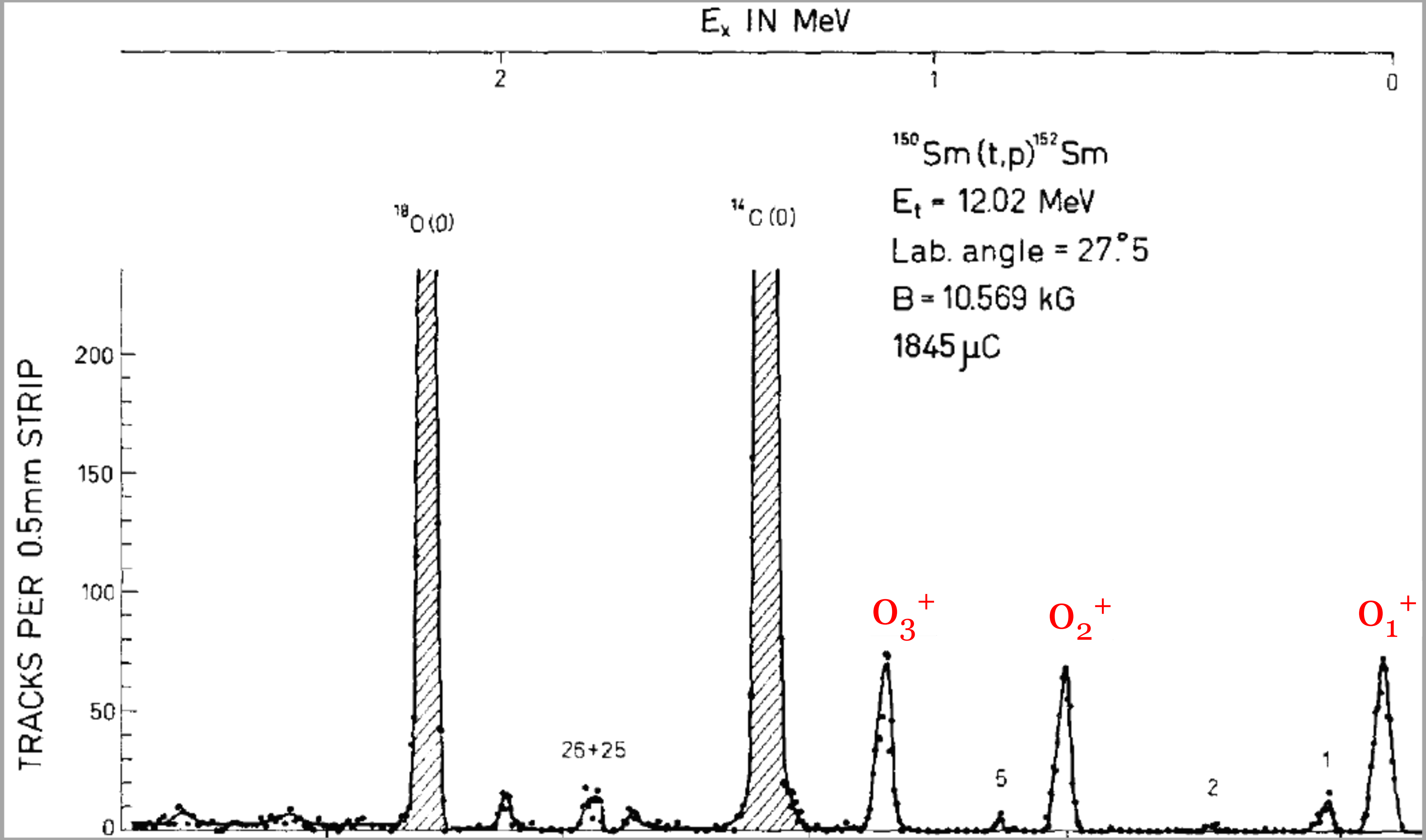
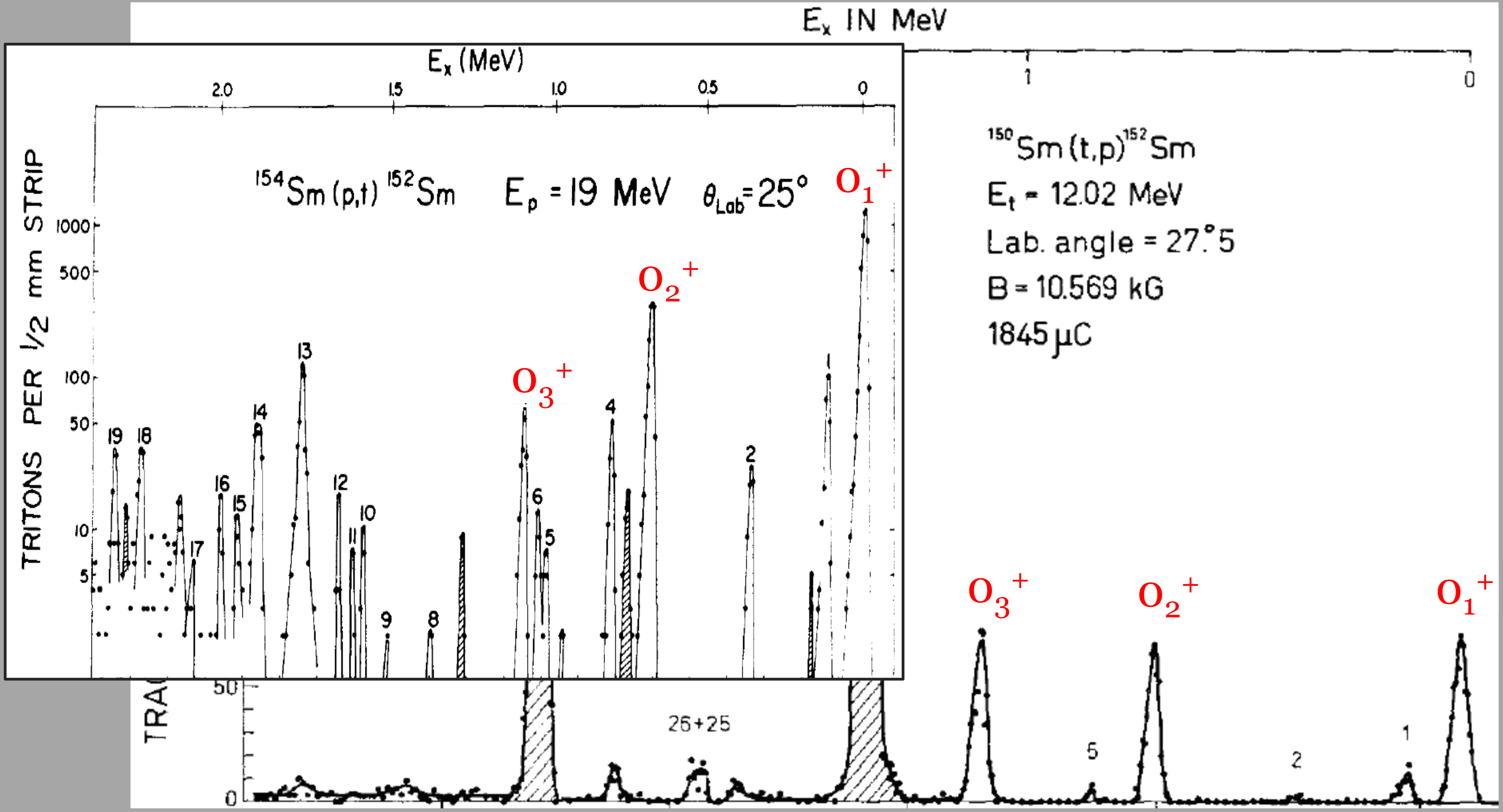


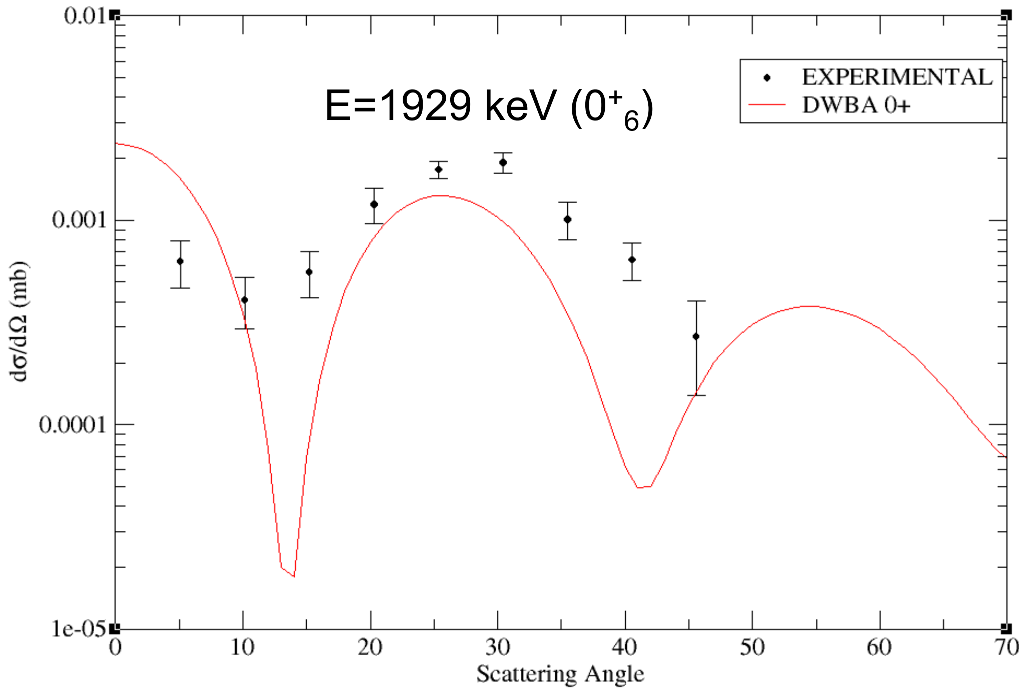
Large TNT cross sections to excited 0^+ states observed at N=90

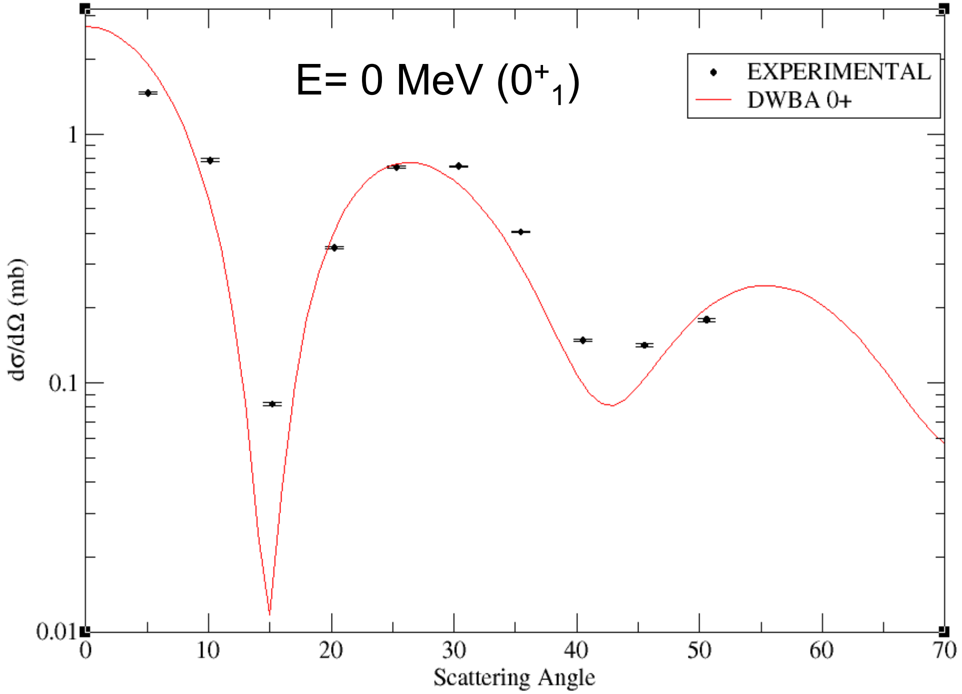


Relative Cross Section

$$\left(\frac{d\sigma}{d\Omega}\right)_{rel} = \frac{\left(\frac{d\sigma}{d\Omega}\right)^{lab}_{0^+_{ex}}}{\left(\frac{d\sigma}{d\Omega}\right)^{dwba}_{0^+_{ex}}} \Bigg/ \frac{\left(\frac{d\sigma}{d\Omega}\right)^{lab}_{0^+_{gs}}}{\left(\frac{d\sigma}{d\Omega}\right)^{dwba}_{0^+_{gs}}}$$

- **Ratio of Exp/DWBA cross sections will provide a Q-value correction for kinematics**





Prior knowledge of ^{136}Cs

Proton (Z) # \ Neutron (N) #	77	78	79	80	81	82	83	84
57	134La 6.45 min ε = 100.00%	135La 19.5 h ε = 100.00%	136La 9.87 min ε = 100.00%	137La 6E+4 y ε = 100.00%	138La 1.02E+11 y 0.08881% ε = 65.60% β^- = 34.40%	139La STABLE 99.9119%	140La 1.67855 d β^- = 100.00%	141La 3.92 h β^- = 100.00%
56	133Ba 10.551 y ε = 100.00%	134Ba STABLE 2.417%	135Ba STABLE 6.592%	136Ba STABLE 7.854%	137Ba STABLE 11.232%	138Ba STABLE 71.698%	139Ba 83.06 min β^- = 100.00%	140Ba 12.7527 d β^- = 100.00%
55	132Cs 6.480 d ε = 98.13% β^- = 1.87%	133Cs STABLE 100%	134Cs 2.0652 y β^- = 100.00% ε = 3.0E-4%	135Cs 2.3E+6 y β^- = 100.00%	136Cs 13.04 d β^- = 100.00%	137Cs 30.08 y β^- = 100.00%	138Cs 33.41 min β^- = 100.00%	139Cs 9.27 min β^- = 100.00%
54	131Xe STABLE 21.232%	132Xe STABLE 26.9086%	133Xe 5.2475 d β^- = 100.00%	134Xe > 5.8E+22 y 10.4357% 2β^-	135Xe 9.14 h β^- = 100.00%	136Xe > 2.4E+21 y 8.8573% 2β^-	137Xe 3.818 min β^- = 100.00%	138Xe 14.14 min β^- = 100.00%
53	130I 12.36 h β^- = 100.00%	131I 8.0252 d β^- = 100.00%	132I 2.295 h β^- = 100.00%	133I 20.83 h β^- = 100.00%	134I 52.5 min β^- = 100.00%	135I 6.58 h β^- = 100.00%	136I 83.4 s β^- = 100.00%	137I 24.5 s β^- = 100.00% β^-n = 7.14%
52	129Te 69.9 min β^- = 100.00%	130Te ≥ 3.0E+24 y 34.08% 2β^- = 100.00%	131Te 25.0 min β^- = 100.00%	132Te 3.204 d β^- = 100.00%	133Te 12.5 min β^- = 100.00%	134Te 41.8 min β^- = 100.00%	135Te 19.0 s β^- = 100.00%	136Te 17.63 s β^- = 100.00% β^-n = 1.31%

- ^{136}Cs lies adjacent to stable Ba and Xe nuclei, but surprisingly little is known on its excited states

2009 ^{136}Cs Levels

E(level)	Jπ†	$T_{1/2}$	Comments
0.0	5		μ=+3.71 2 (1981Th06).
x	8	19 s 2	$T_{1/2}$: from 1975Ra03. μ=+1.319 7 (1989Ra17,1981Th06); Q=+0.74 10 (1989Ra17,1981Th06). %IT>0. Q: includes polarization correction. %IT: Suggested by evaluator from the observation of Cs x-rays by 1975Ra03.

K. WIMMER *et al.* PHYSICAL REVIEW C **84**, 014329 (2011)

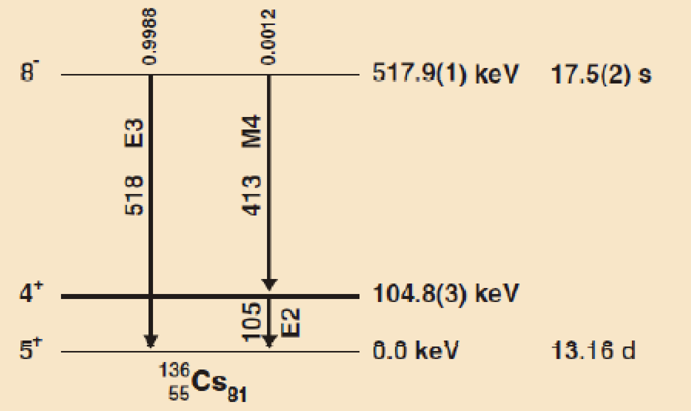
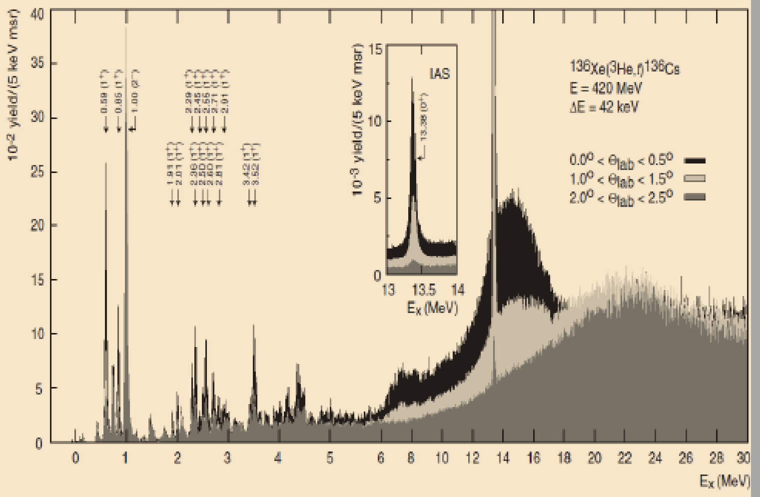


FIG. 3. Proposed level scheme of ^{136}Cs. Previously known were only the spins of the ground state and the isomeric state as well as the half-life of ^{136}Cs.

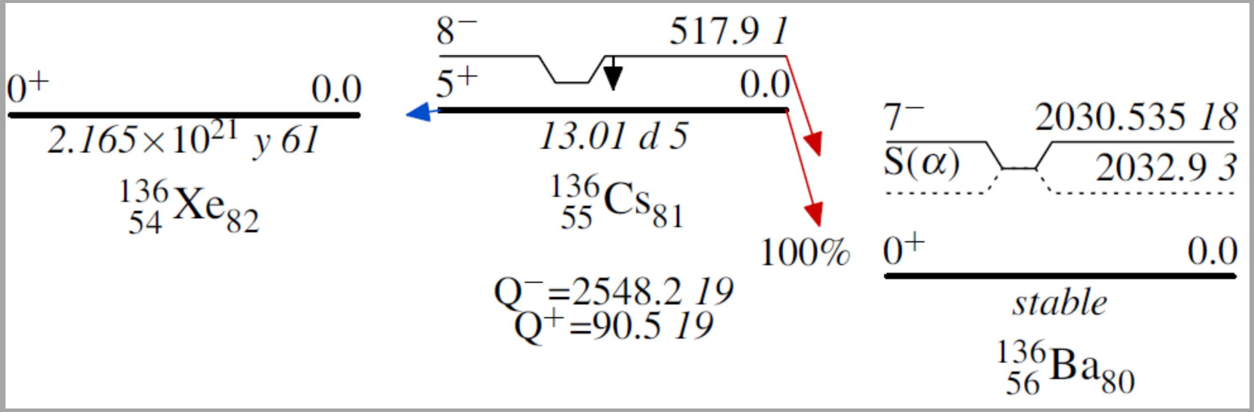
PHYSICAL REVIEW C **84**, 051305(R) (2011)



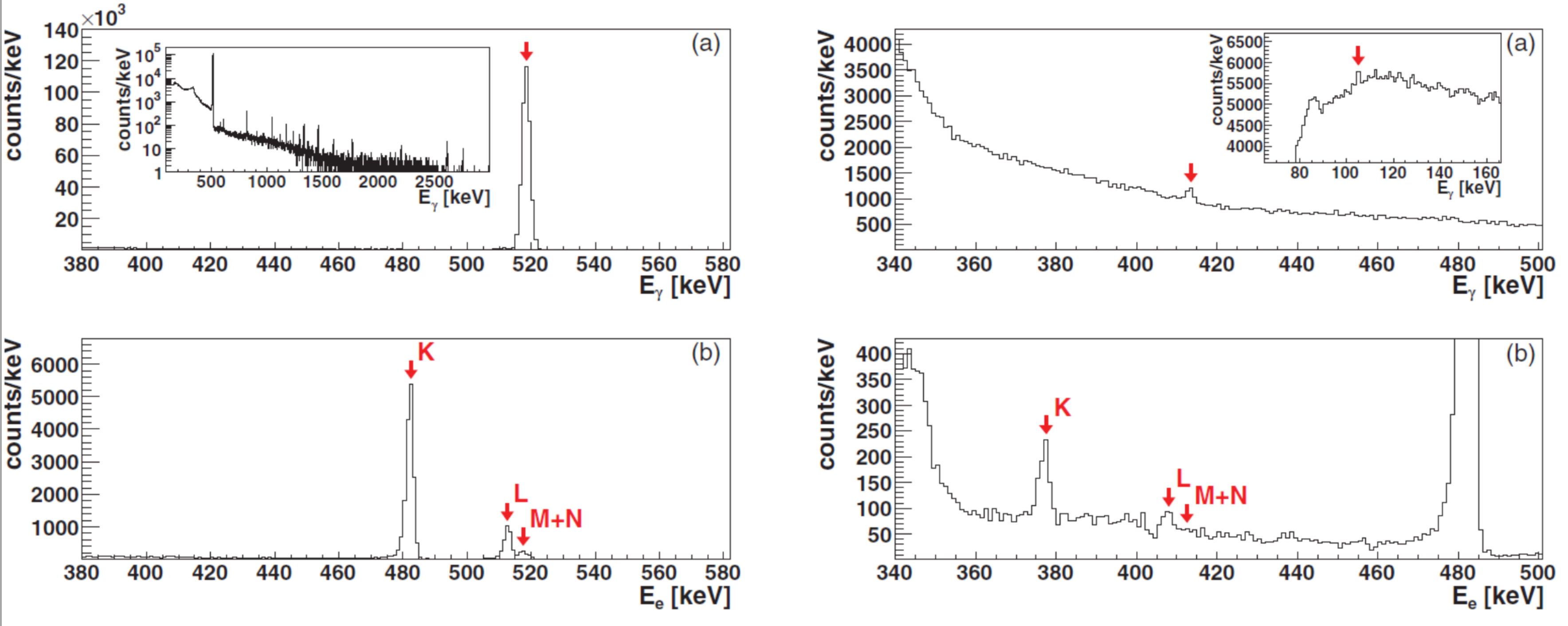
PHYSICAL REVIEW C **95**, 034619 (2017)

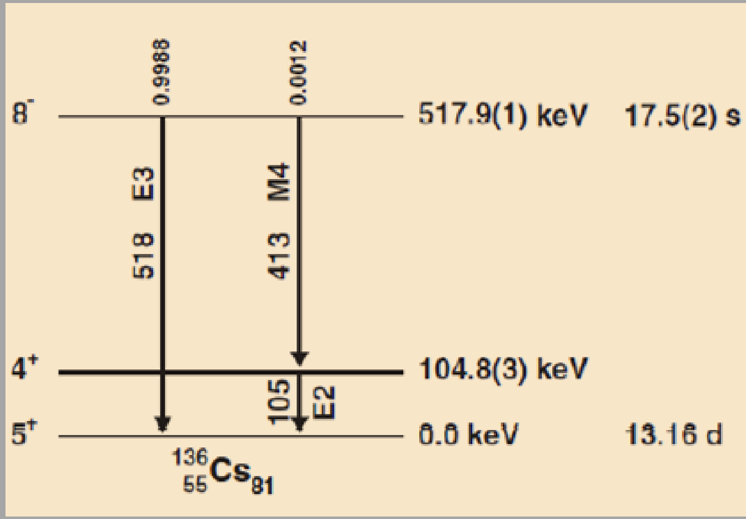
Prior investigation of decay of 8^- isomer in ^{136}Cs

- ^{136}Cs has known 8^- isomer
  - Decay investigated at ISOLDE with γ and e^- spectroscopy
  - Two branches observed: 518-keV *E*3, 413-keV *M*4
  - Multipolarities determined from $I(e^-)/I(\gamma)$, subshell ratios
  - Spins involved seem to be firmly established

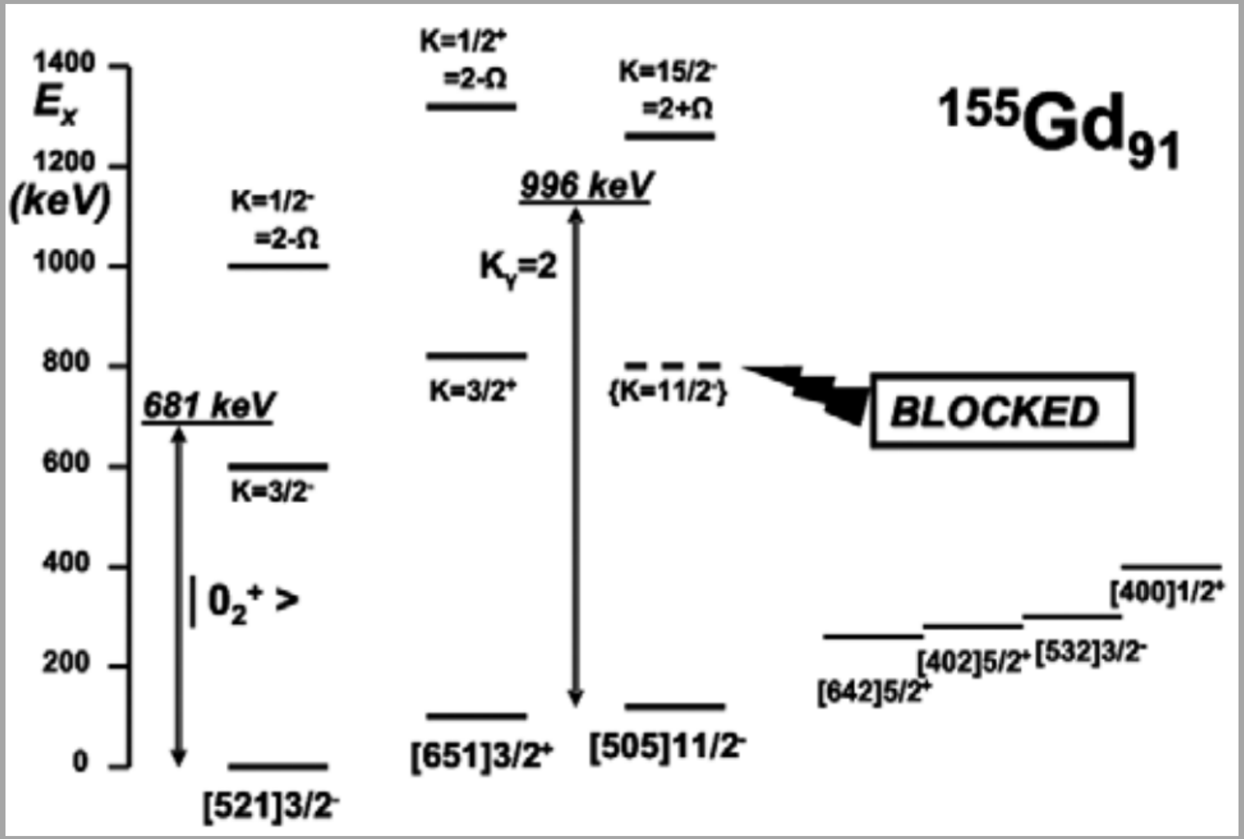


K. Wimmer *et al.*, PRC 84, 014329 (2011)

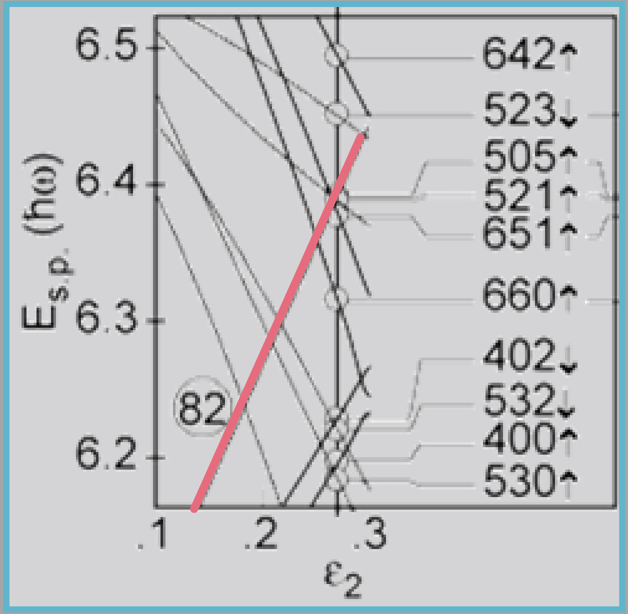




Blocked $\nu h_{11/2}$ orbital in ^{155}Gd



- Extensive searches for a second $K = 11/2^-$ band in ^{155}Gd failed
- The ν11/2[505] orbital built on the 0_2^+ state appears to be blocked in ^{155}Gd



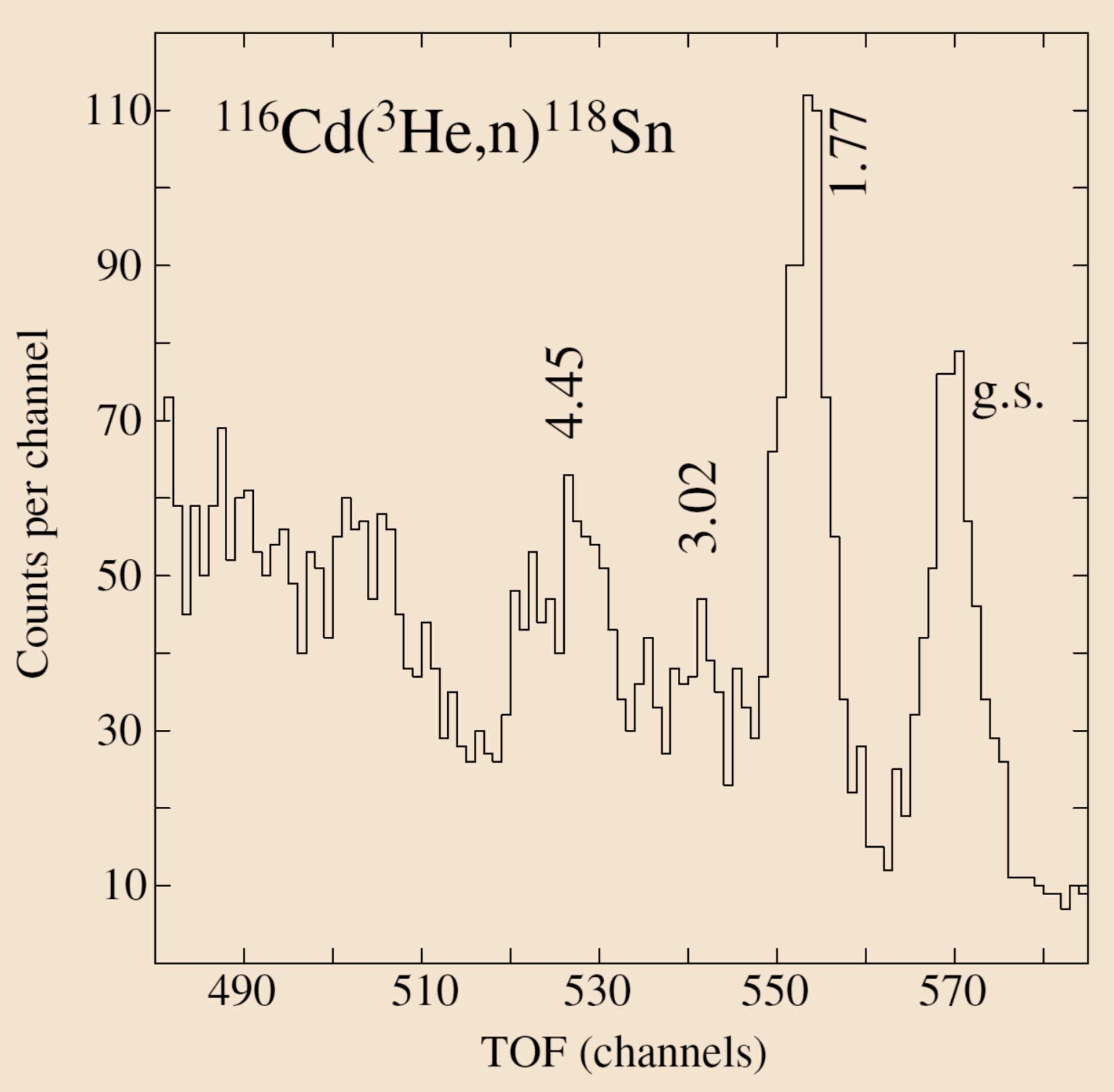
ν11/2[505] believed to be a dominant configuration in the 0_2^+ state at $N = 90$

J.F. Sharpey-Schafer. Eur. Phys. J. A (2011) **47**: 6

Evidence for 'intruder' states in Sn isotopes – *2p-2h* proton excitations

- **In normal or superfluid nuclei, the two-nucleon-transfer should be dominated by ground-state-to-ground-state transitions – typically >95% of $L = 0$ total strength goes to the ground state**

- **Near Z=50, two-proton transfer strongly populates excited 0^+ state – reminiscent of proton pairing vibration – consistent with 2p-2h excitation across $Z = 50$ closed shell**



Fielding et al., Nucl. Phys. **A281**, 392 (1977)

Shape-coexisting "intruder" 0^+ states in Sn populated very weakly in two-neutron transfer

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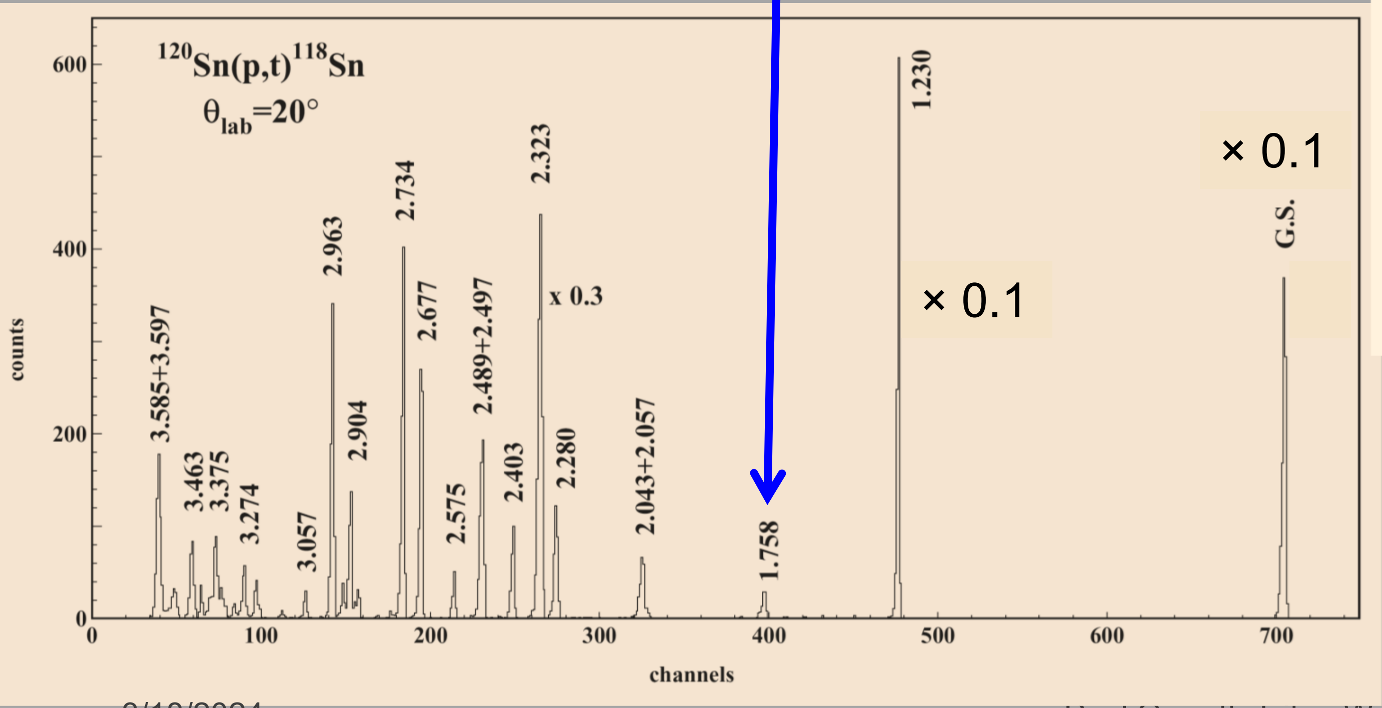
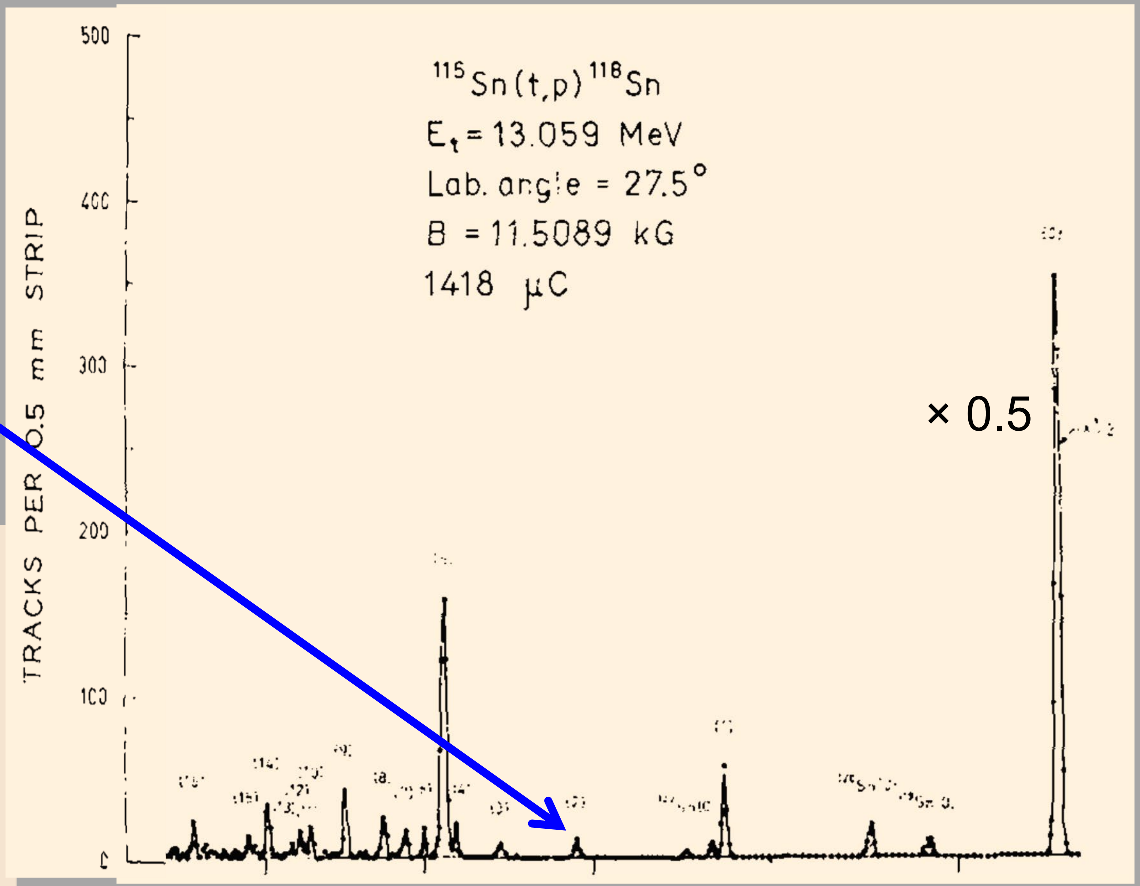
- *π2p-2h* excitation very weak in (p,t) and (t,p)

Guazzoni et al., PRC **78**, 064608 (2008)

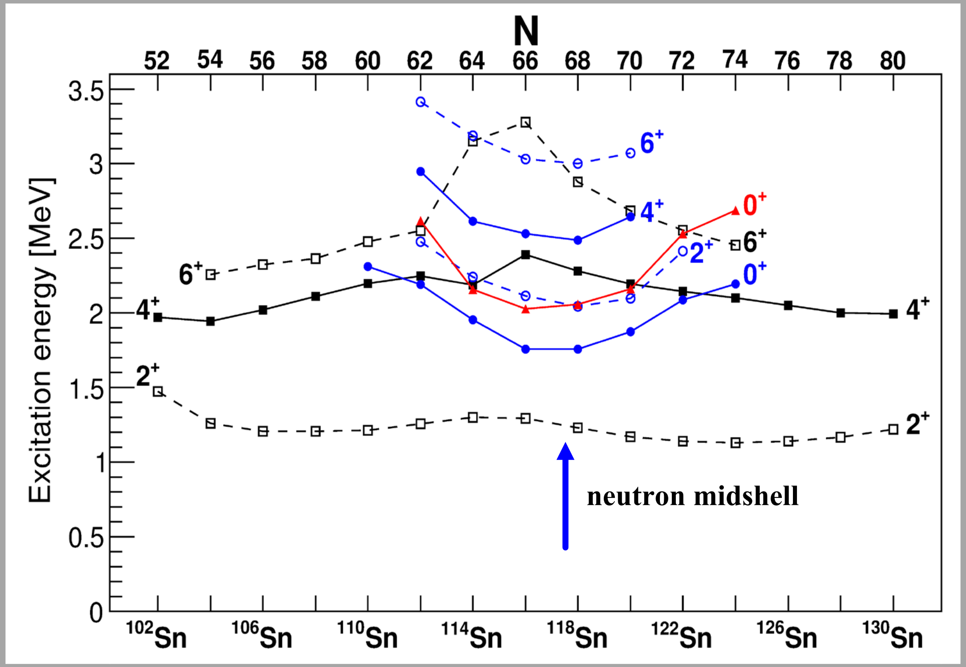




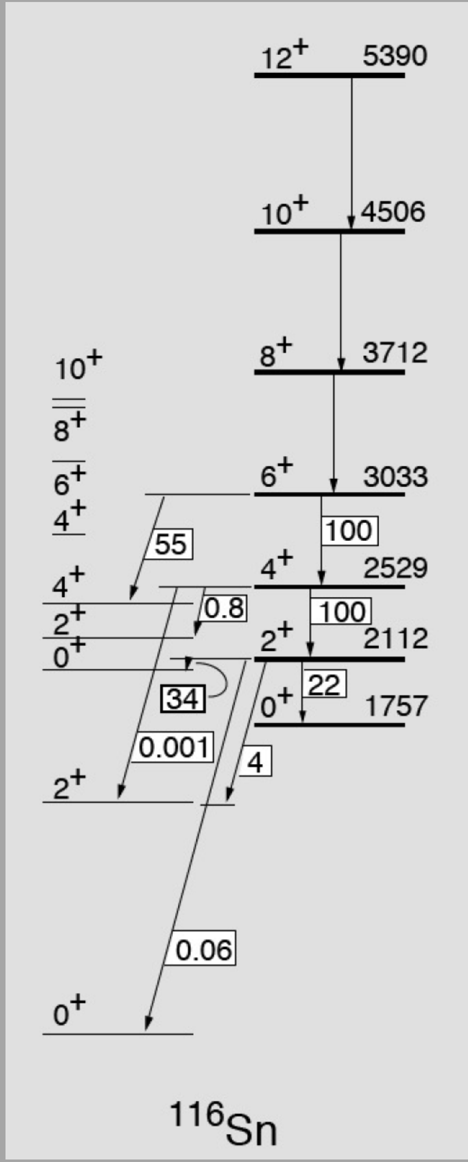
Bjerregaard et al., NPA **110**, 1 (1968)

Example of the data for deformed 2p-2h "intruder" bands at closed shells – ^{116}Sn

Sn isotopes have characteristic parabolic pattern to excitation energies



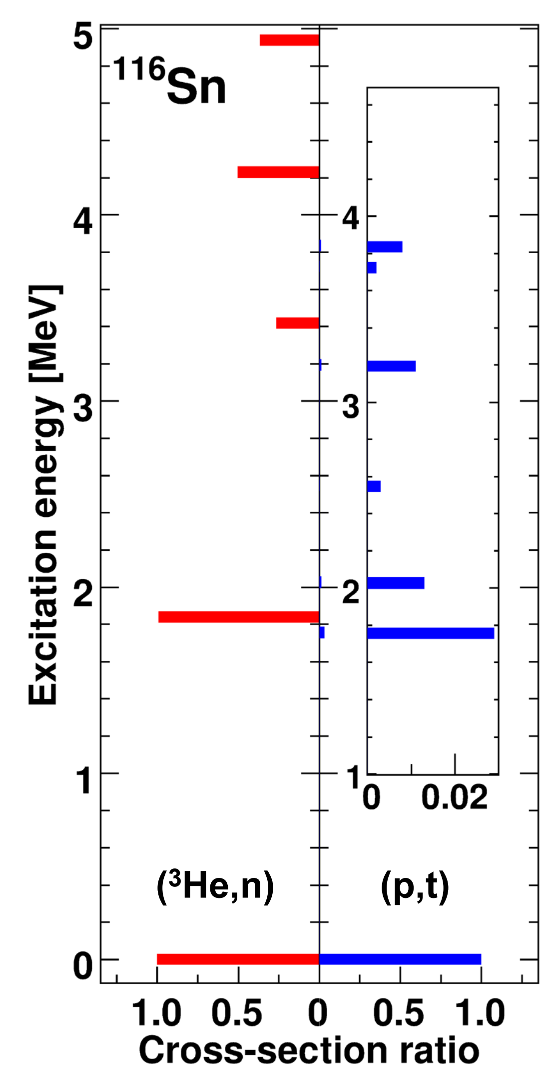
Garrett, Zielińska, & Clément, PPNP **124**, 103931 (2022)



Appearance of rotational-like bands, with enhanced in-band B(E2) values, that stand out amongst spherical "shell-model" states

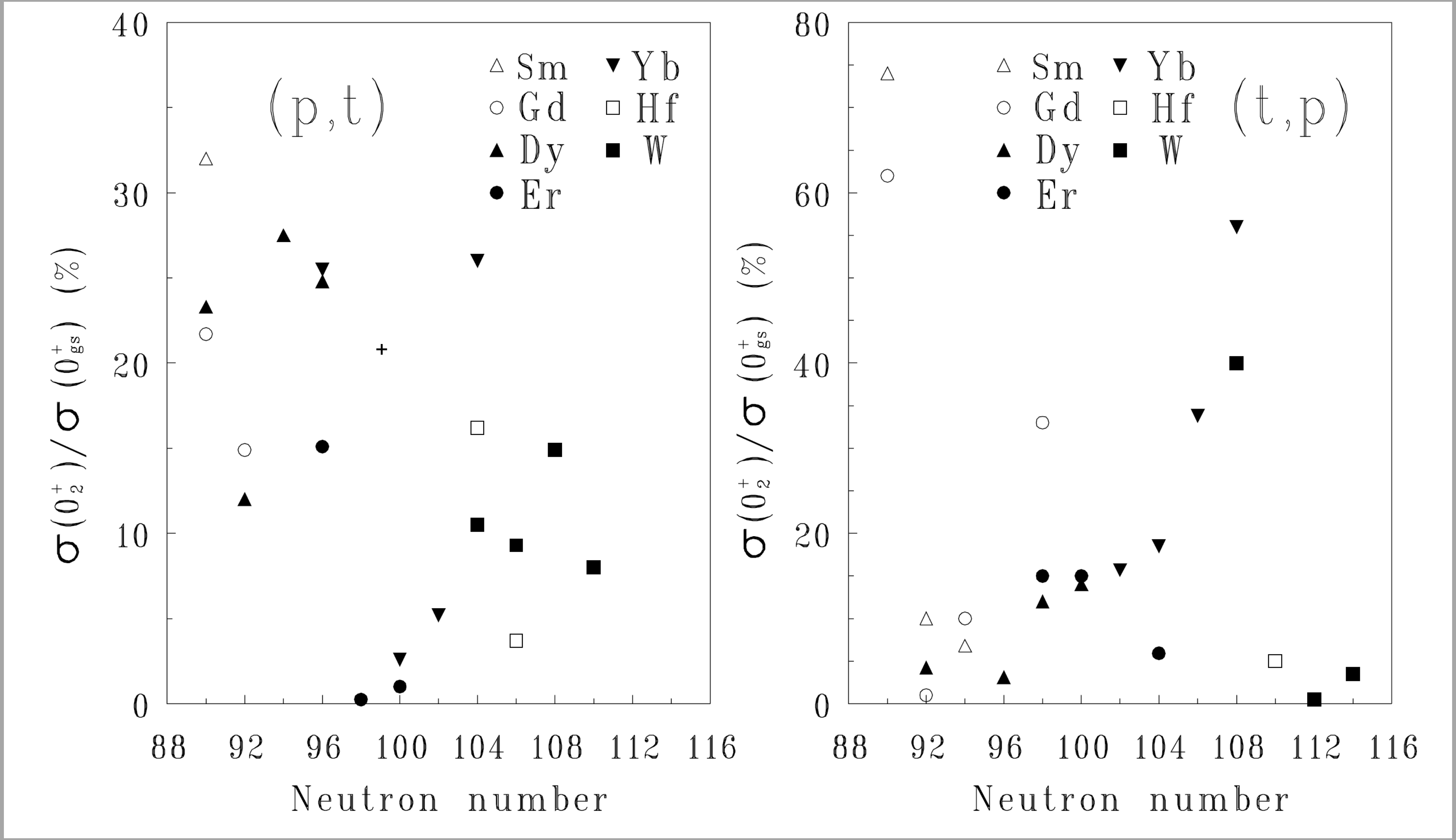
Normally, the two-nucleon-transfer is dominated by gs-to-gs transitions – typically > 95% of L=0 strength

Near $Z = 50$, two-proton transfer strongly populates the 0_2^+ state



Garrett, Zielińska, & Clement, PPNP **124**, 103931 (2022)

Asymmetric population of 0_2 state observed in many rare-earth nuclei



PG, JPG **27,** R1 (2001).

Similarity of energy centroid of 0^+ strength to energy of ν11/2[505] orbital

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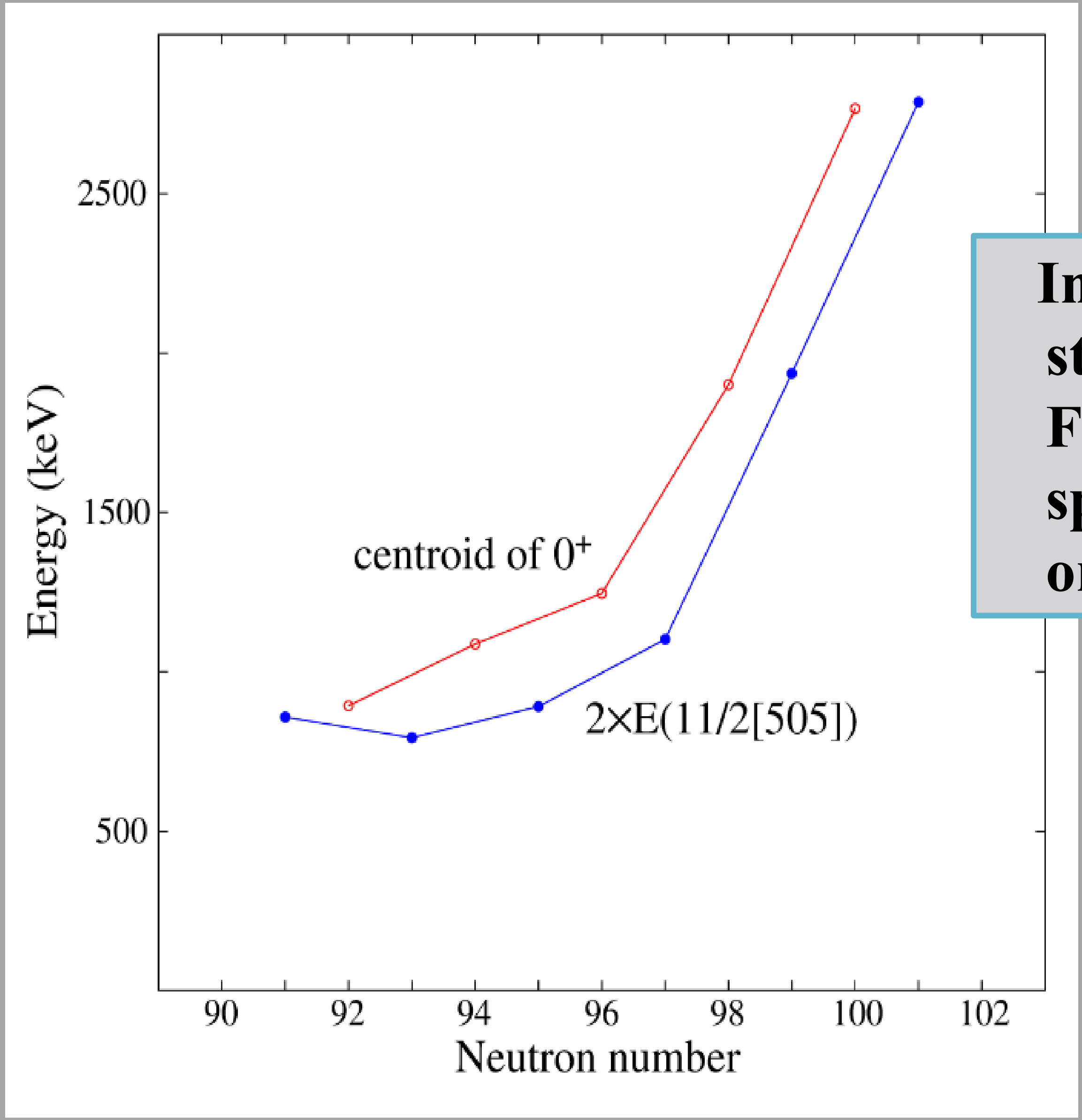

Indication that the 0^+ strength tracks with the Fermi surface, and specifically the 11/2[505] orbital

Complementing the data with (t,p) results on the lighter Er isotopes would complete the picture

The role of the intermediate nucleus

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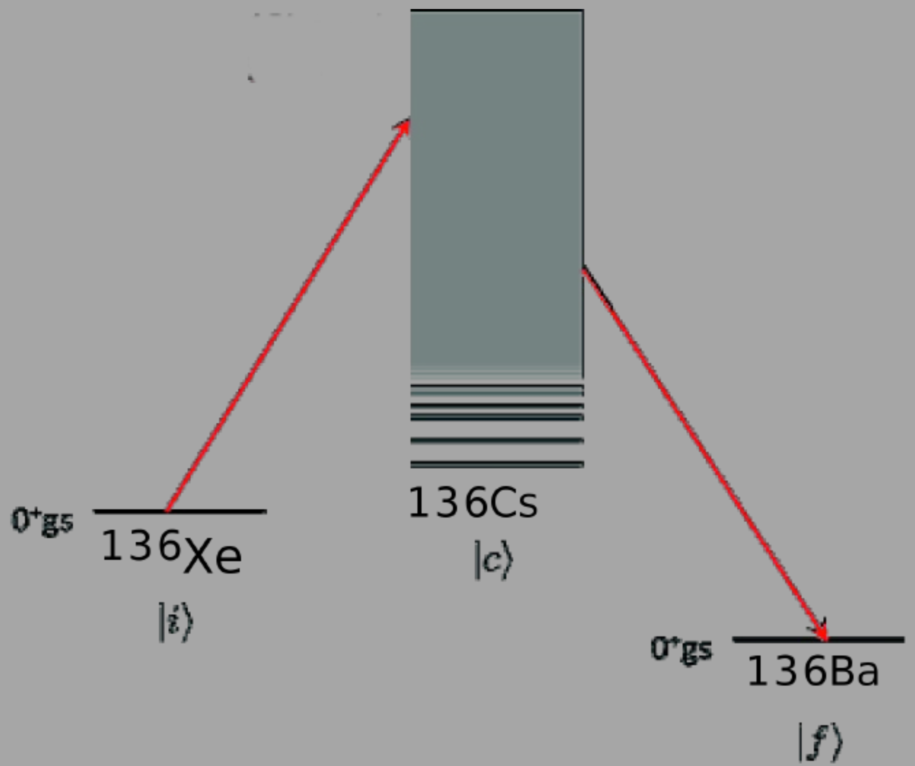

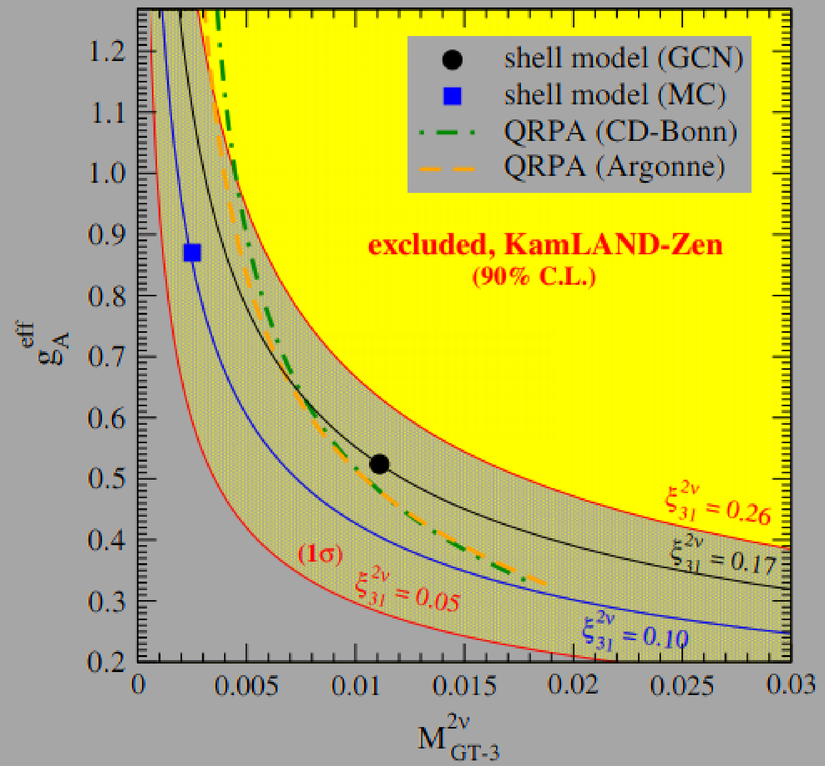

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R. A. Sen'kov, M. Horoi, and B. A. Brown

Phys. Rev. C **89**, 054304 – Published 5 May 2014

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Precision Analysis of the ^{136}Xe Two-Neutrino $\beta\beta$ Spectrum in KamLAND-Zen and Its Impact on the Quenching of Nuclear Matrix Elements

A. Gando *et al.* (KamLAND-Zen Collaboration)

Phys. Rev. Lett. **122**, 192501 – Published 13 May 2019