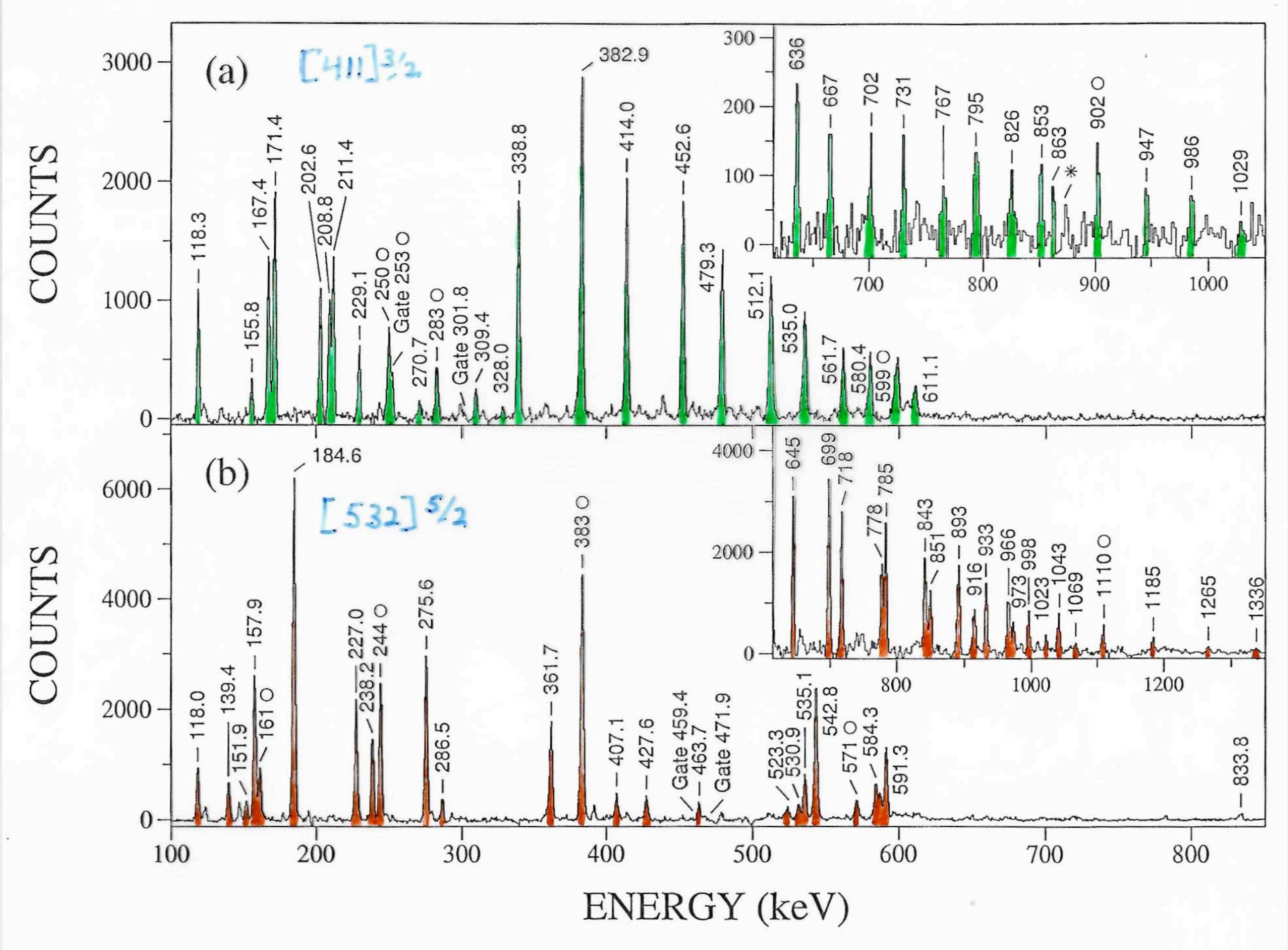
A High-Spin Journey with Robert

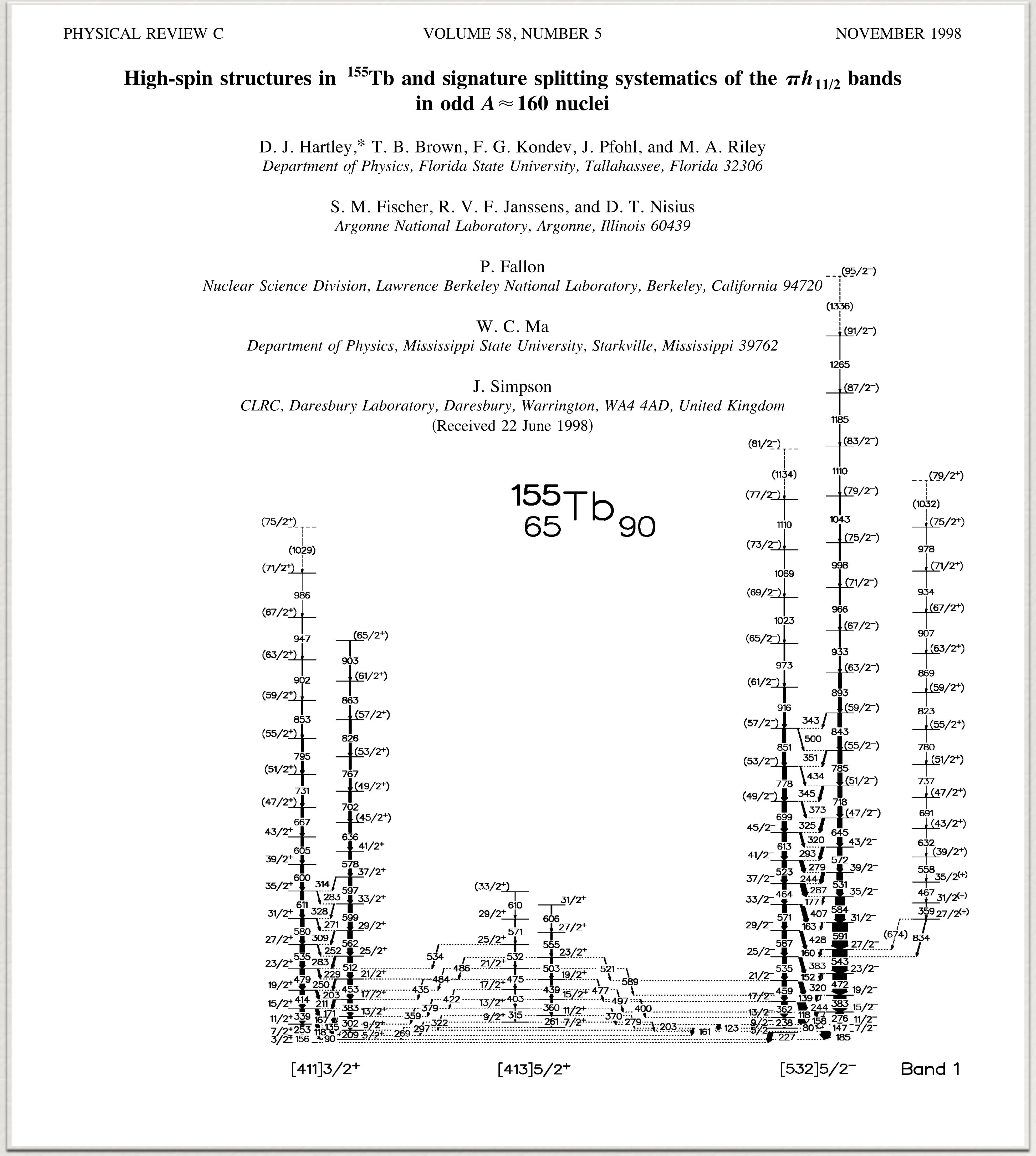
Daryl Hartley
U.S. Naval Academy

In the beginning (for me)...

- *First met in Tallahassee, circa 1995*
- *Robert taught me a thing or two about properly setting up a Compton-Suppressed system (in less than 2 minutes)*

In the beginning (for me)...





PHYSICAL REVIEW C VOLUME 58, NUMBER 5 NOVEMBER 1998

High-spin structures in ^{155}Tb and signature splitting systematics of the $\pi h_{11/2}$ bands in odd $A \approx 160$ nuclei

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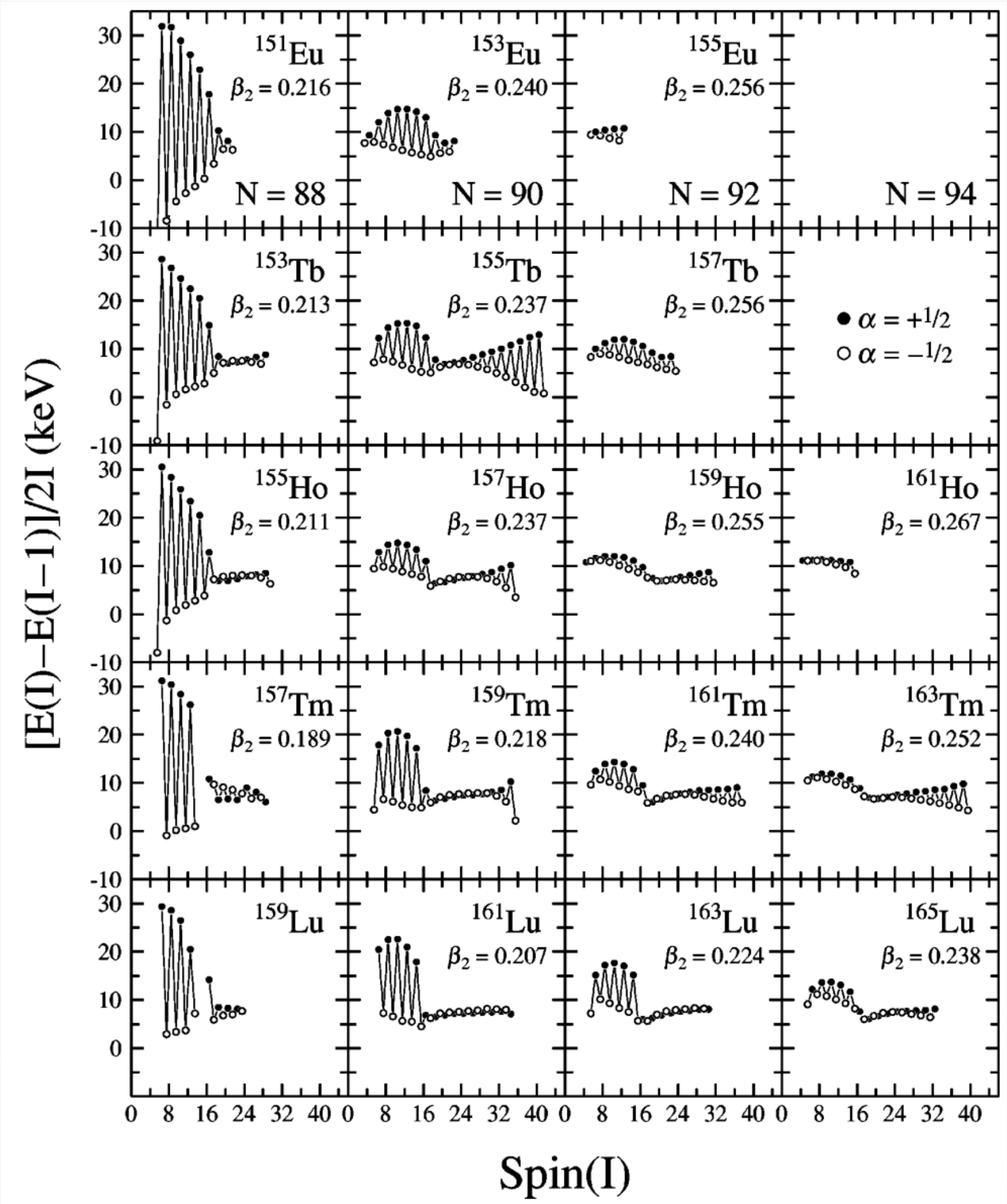
(Received 22 June 1998)

In the beginning (for me)...

- *Systematic study of signature splitting*
- *Likely associated with triaxial deformation at low spin*



In the beginning (for Robert)…

Z. Physik A 274, 113–119 (1975)

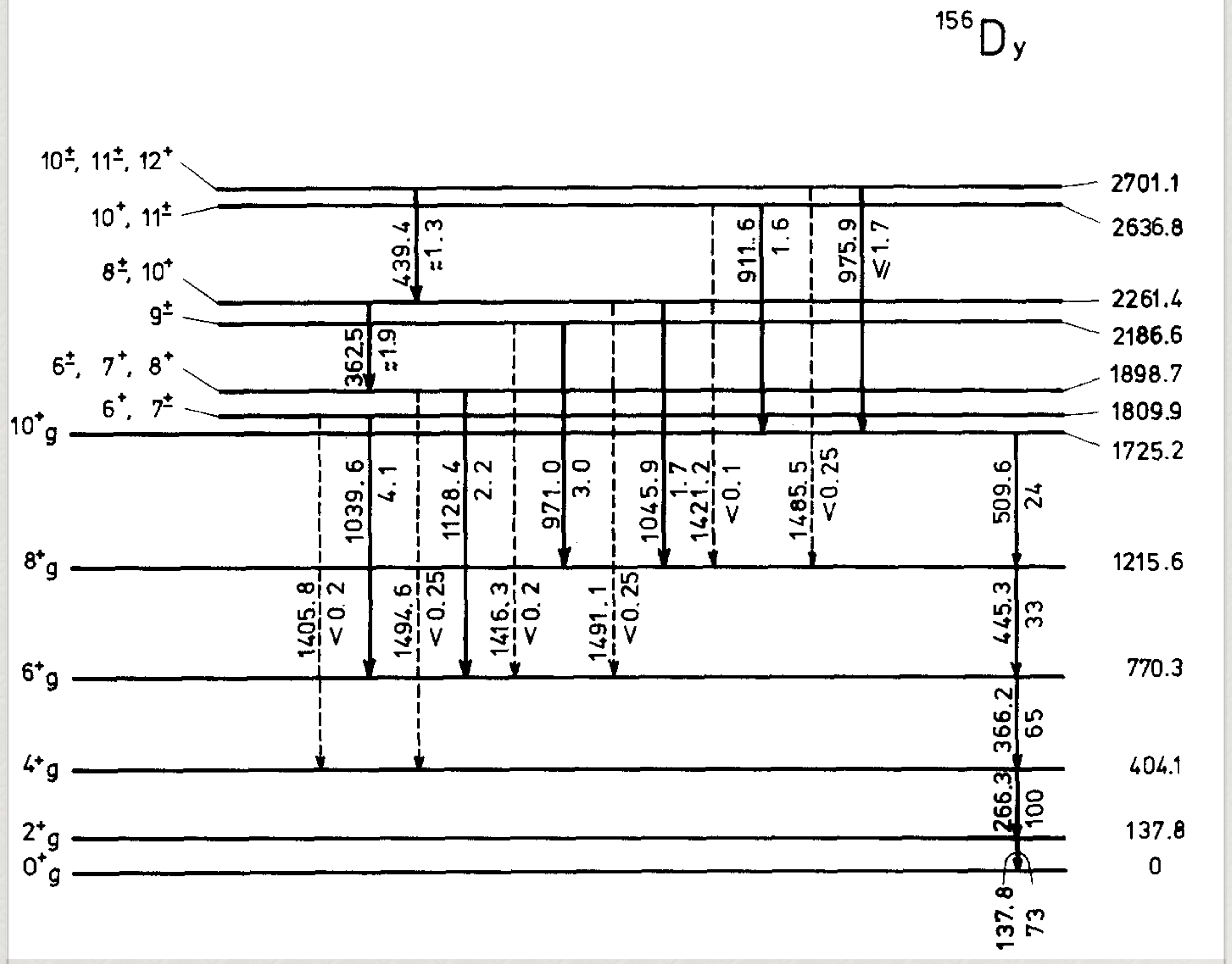
Experimental Evidence for Low-Spin Members of "Upper" Bands in ^{156}Dy

Y. El Masri, R. Janssens, C. Michel, P. Monseu, J. Steyaert, and J. Vervier

Institut de Physique Corpusculaire, Louvain-la-Neuve, Belgium

Received May 26, accepted June 16, 1975

Abstract. Study of the energy levels of ^{156}Dy through the ^{159}Tb$(p, 4n)^{156}$Dy reaction has revealed the existence of six states with excitation energies between 1.8 and 2.8 MeV and spins between 6 and 12. Some of them can tentatively be assigned as low-spin members of "upper" bands which are thought to be responsible for the backbending phenomenon experimentally observed in the ground-state and β-vibrational bands of this nucleus. Others could be levels of a negative-parity octupole band.



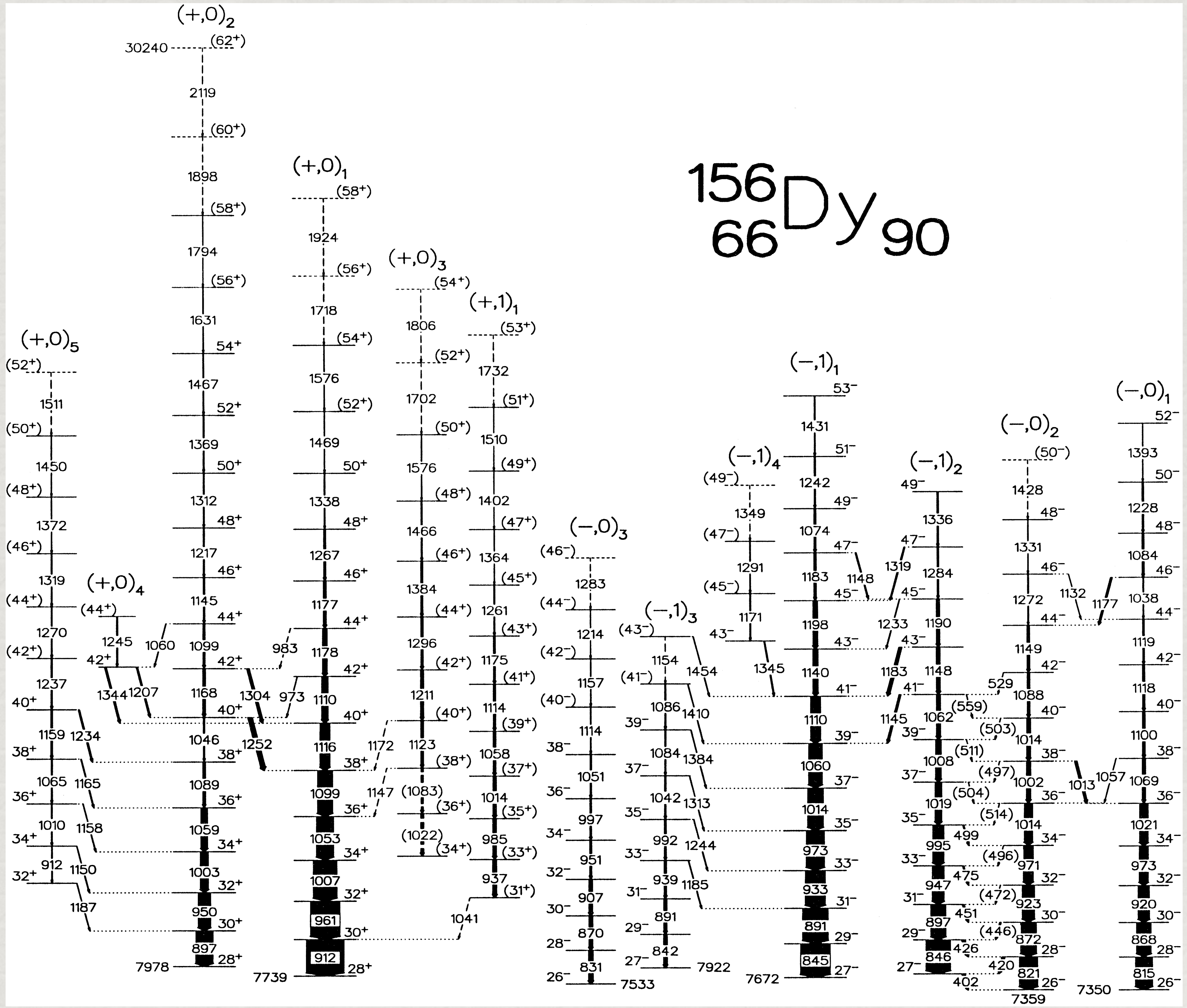
In the beginning (for Robert)…

ELSEVIER

Physics Letters B 437 (1998) 35–43

Spin ∼ 60 ℏ in ^{156}Dy: competition between collective and terminating structures at very high-spin

F.G. Kondev [a,1], M.A. Riley [a], R.V.F. Janssens [b], J. Simpson [c], A.V. Afanasjev [d,2], I. Ragnarsson [d], I. Ahmad [b], D.J. Blumenthal [b], T.B. Brown [a], M.P. Carpenter [b], P. Fallon [e], S.M. Fischer [b], G. Hackman [b], D.J. Hartley [a], C.A. Kalfas [f], T.L. Khoo [b], T. Lauritsen [b], W.C. Ma [g], D. Nisius [b], J.F. Sharpey-Schafer [h], P.G. Varmette [g]



In the beginning (for Robert)…

PHYSICAL REVIEW C **95**, 014321 (2017)

Investigation of negative-parity states in ^{156}Dy: Search for evidence of tetrahedral symmetry

D. J. Hartley,[1] L. L. Riedinger,[2] R. V. F. Janssens,[3] S. N. T. Majola,[4] M. A. Riley,[5] J. M. Allmond,[6,7] C. W. Beausang,[6] M. P. Carpenter,[3] C. J. Chiara,[3,8,9,*] N. Cooper,[10] D. Curien,[11,12] B. J. P. Gall,[11,12] P. E. Garrett,[13] F. G. Kondev,[9] W. D. Kulp,[14] T. Lauritsen,[3] E. A. McCutchan,[3,15] D. Miller,[2,†] S. Miller,[5] J. Piot,[11,12] N. Redon,[16] J. F. Sharpey-Schafer,[17] J. Simpson,[18] I. Stefanescu,[3,8] X. Wang,[5,‡] V. Werner,[10,§] J. L. Wood,[14] C.-H. Yu,[7] S. Zhu,[3] and J. Dudek[11,19]

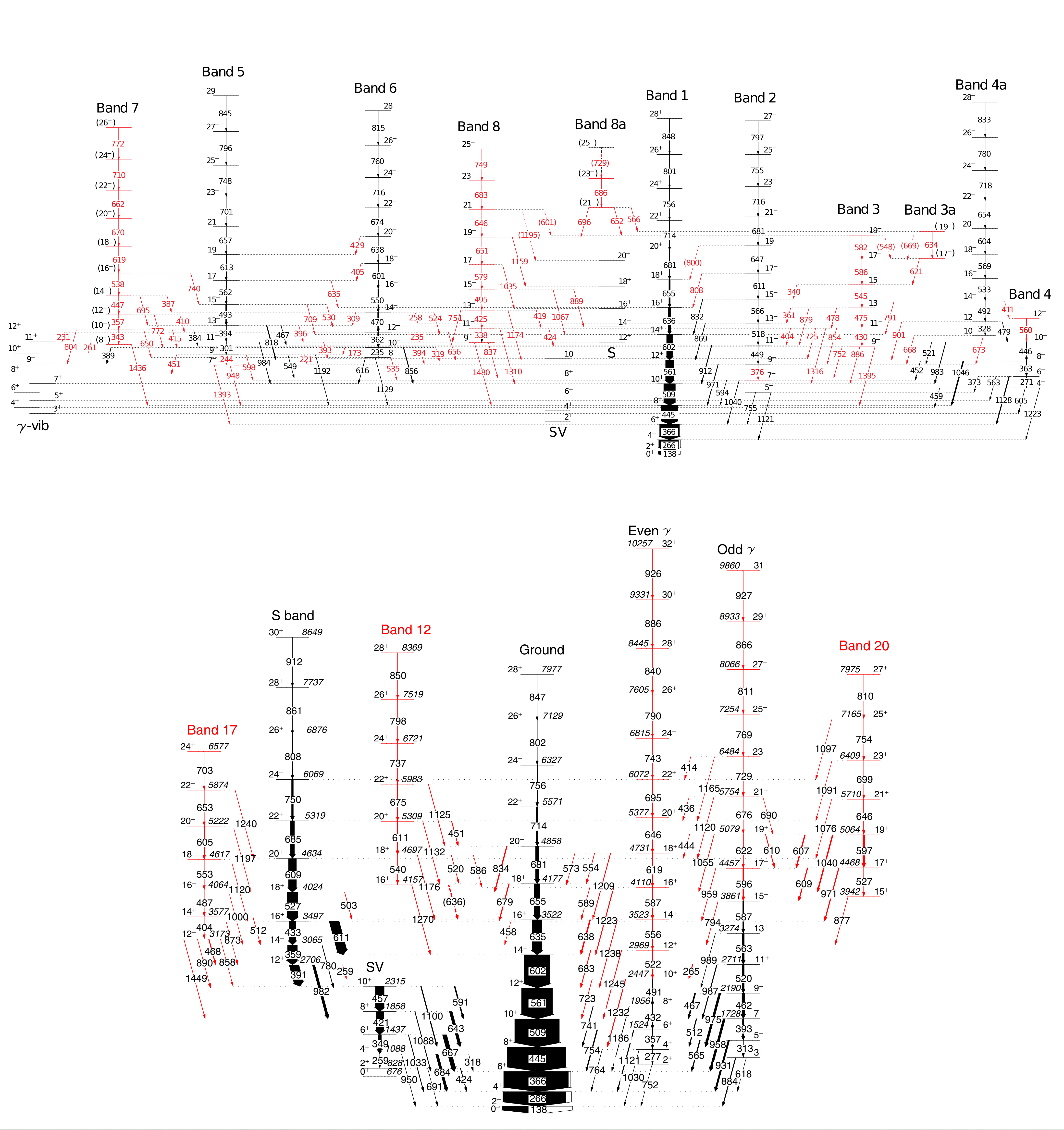
PHYSICAL REVIEW C **91**, 034330 (2015)

Observation of γ vibrations and alignments built on non-ground-state configurations in ^{156}Dy

S. N. T. Majola,[1,2,*] D. J. Hartley,[3] L. L. Riedinger,[4] J. F. Sharpey-Schafer,[5] J. M. Allmond,[6,17] C. Beausang,[6] M. P. Carpenter,[7] C. J. Chiara,[8] N. Cooper,[9] D. Curien,[10] B. J. P. Gall,[10] P. E. Garrett,[11] R. V. F. Janssens,[7] F. G. Kondev,[8] W. D. Kulp,[12] T. Lauritsen,[7] E. A. McCutchan,[7,13] D. Miller,[4] J. Piot,[10] N. Redon,[14] M. A. Riley,[15] J. Simpson,[16] I. Stefanescu,[7] V. Werner,[9] X. Wang,[15] J. L. Wood,[12] C.-H. Yu,[17] and S. Zhu[7]

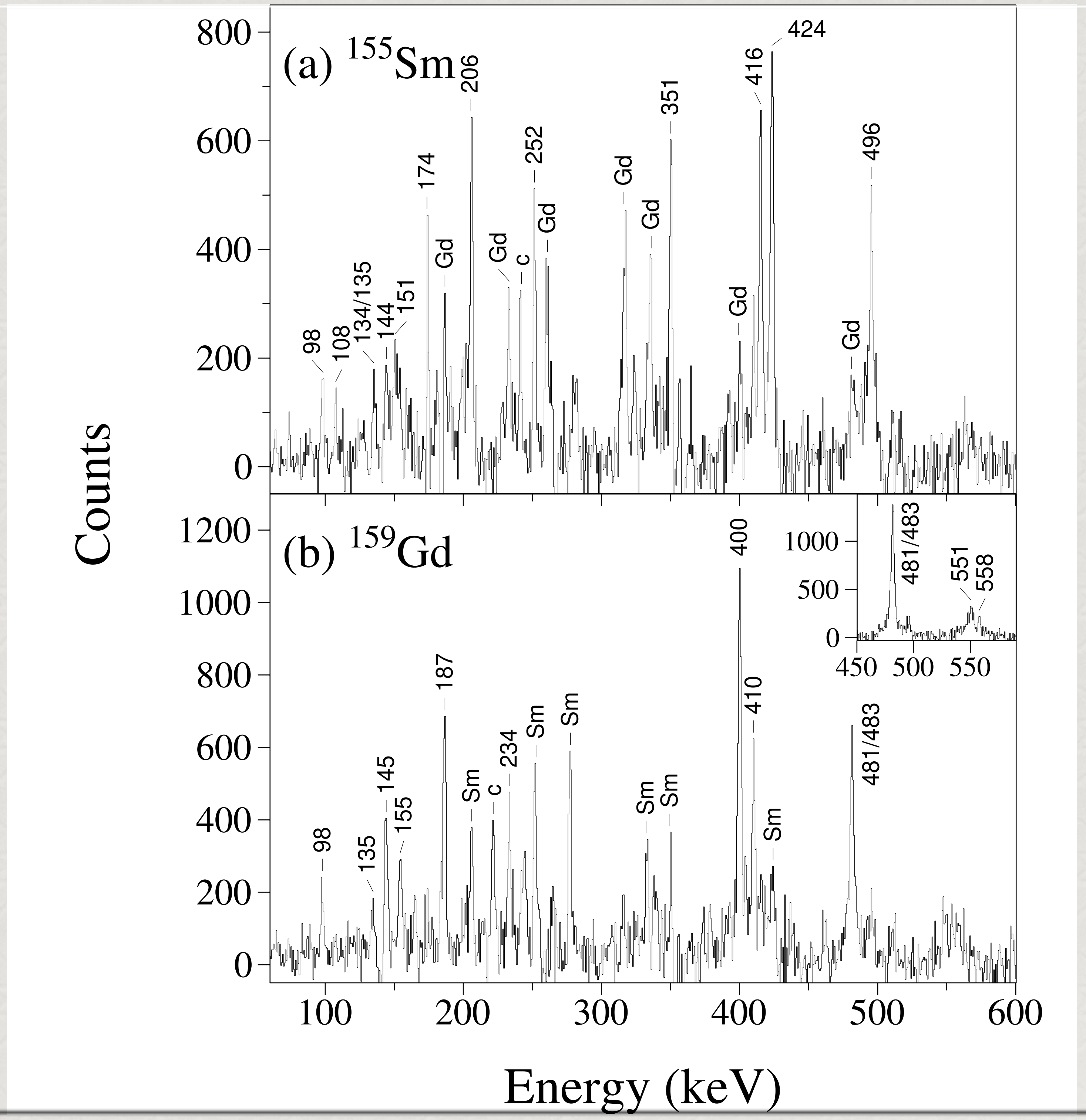
Robert's Golden Rule:

Always do an experiment on ^{156}Dy every 15-20 years



Onto to More Recent Work…

- *Mutli-nucleon transfer reactions allow for the observance of neutron-rich nuclei*
- *Produce large variety of nuclei with moderately high spin that come in pairs*
- $^{160}Gd + {}^{154}Sm$ *reaction at* 1000 *MeV*
- *Gammasphere had* 73 *detectors - focus on prompt spectroscopy*



Onto to More Recent Work…

- *Mutli-nucleon transfer reactions allow for the observance of neutron-rich nuclei*
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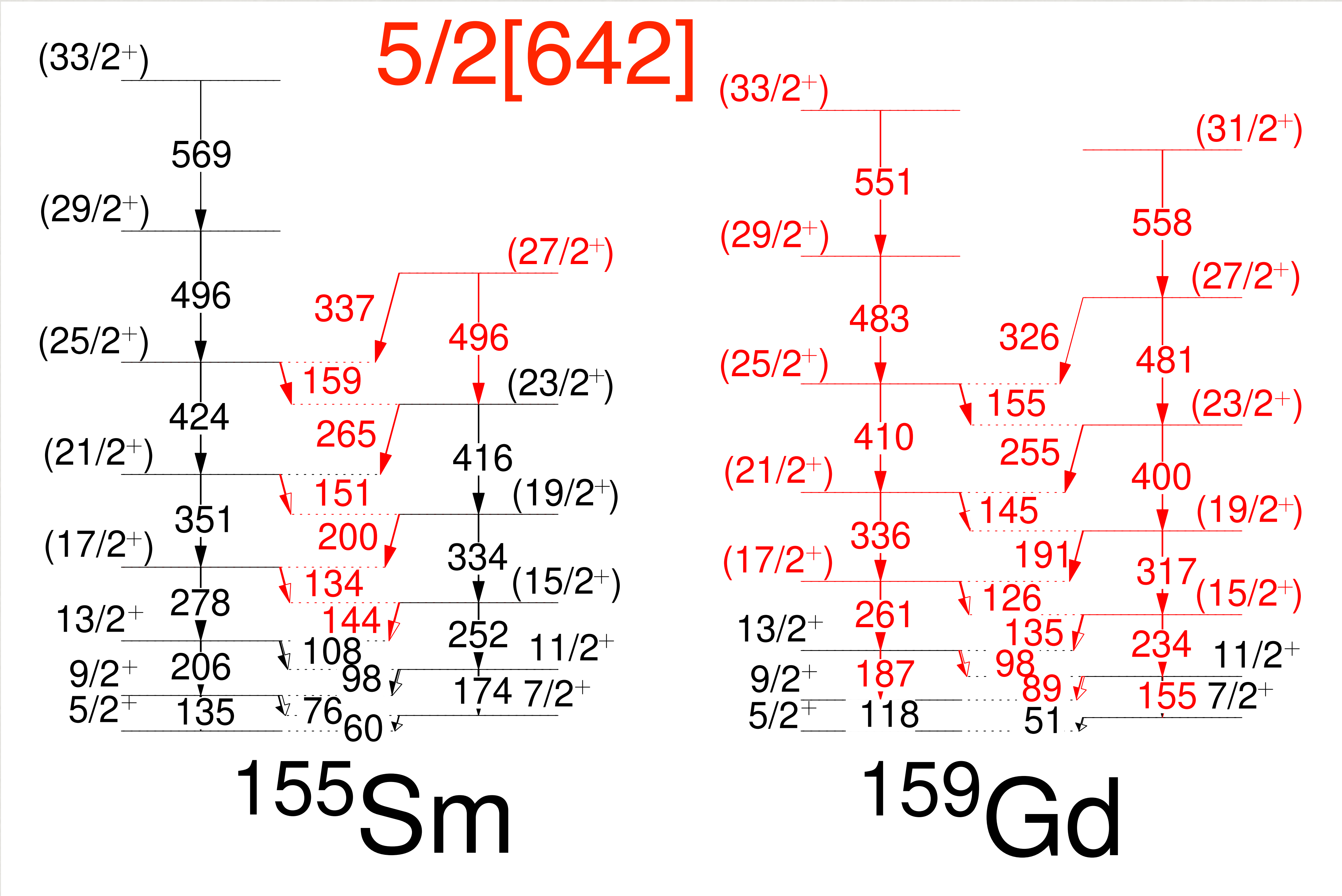
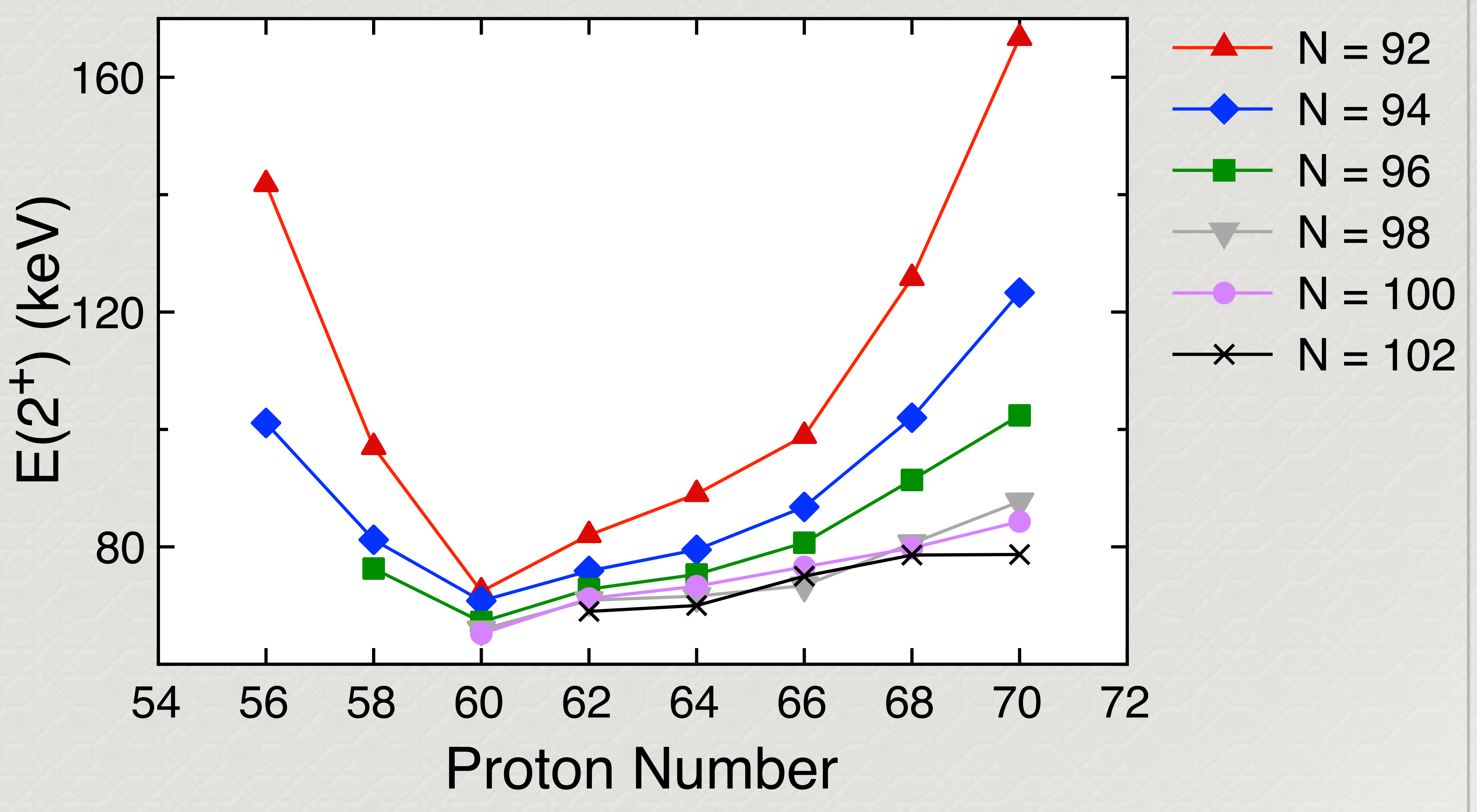


Evidence of Z = 60 Subshell Gap

- *A low energy of the first* 2^+ *state [E*(2^+)*] in even-even nuclei is associated with large deformation*
- *Note that for each isotone group, Z* = 60 *(Nd) has lowest E*(2^+)
- *Indicates high-deformation subshell gap at Z* = 60*, rather than at midshell, Z* = 66 *(Dy)*

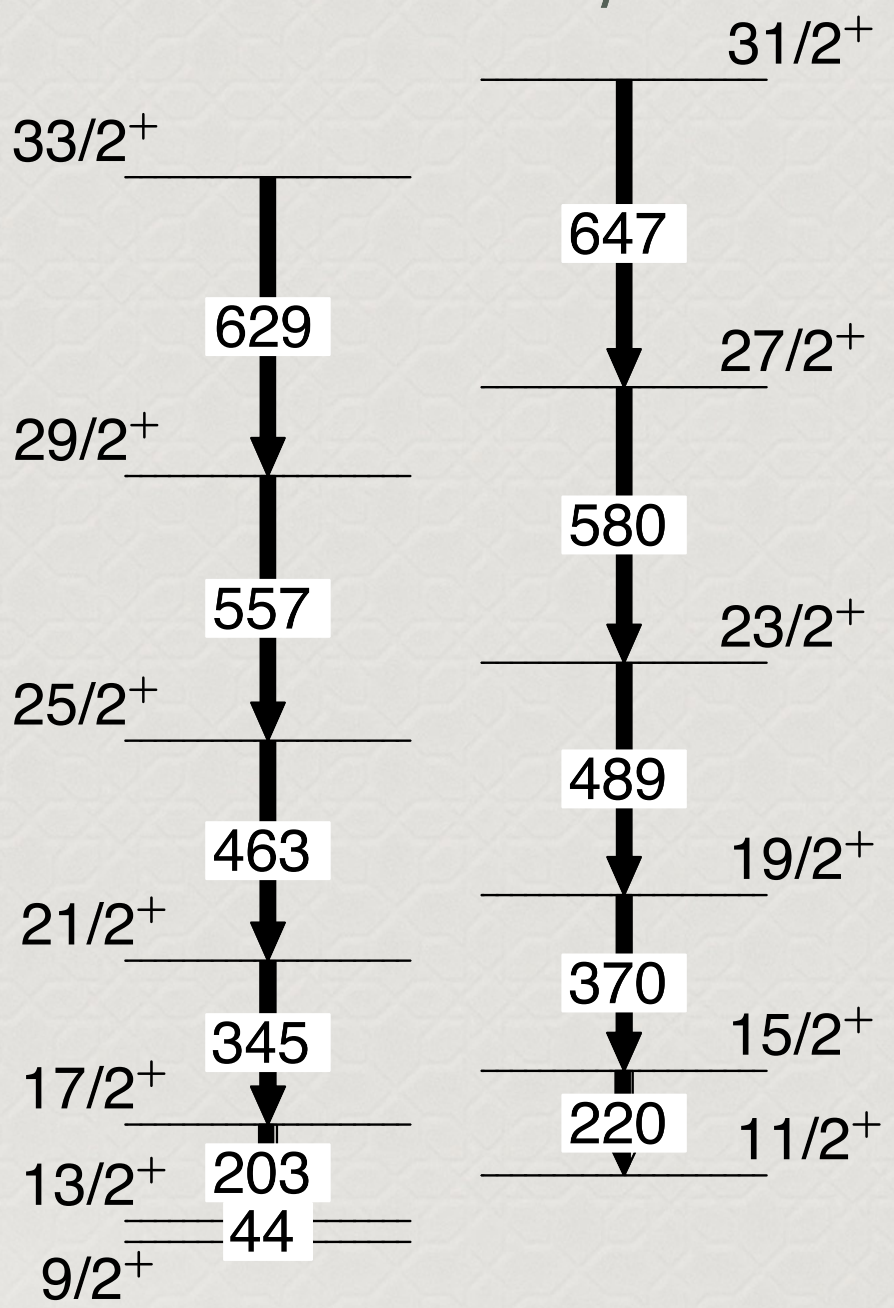


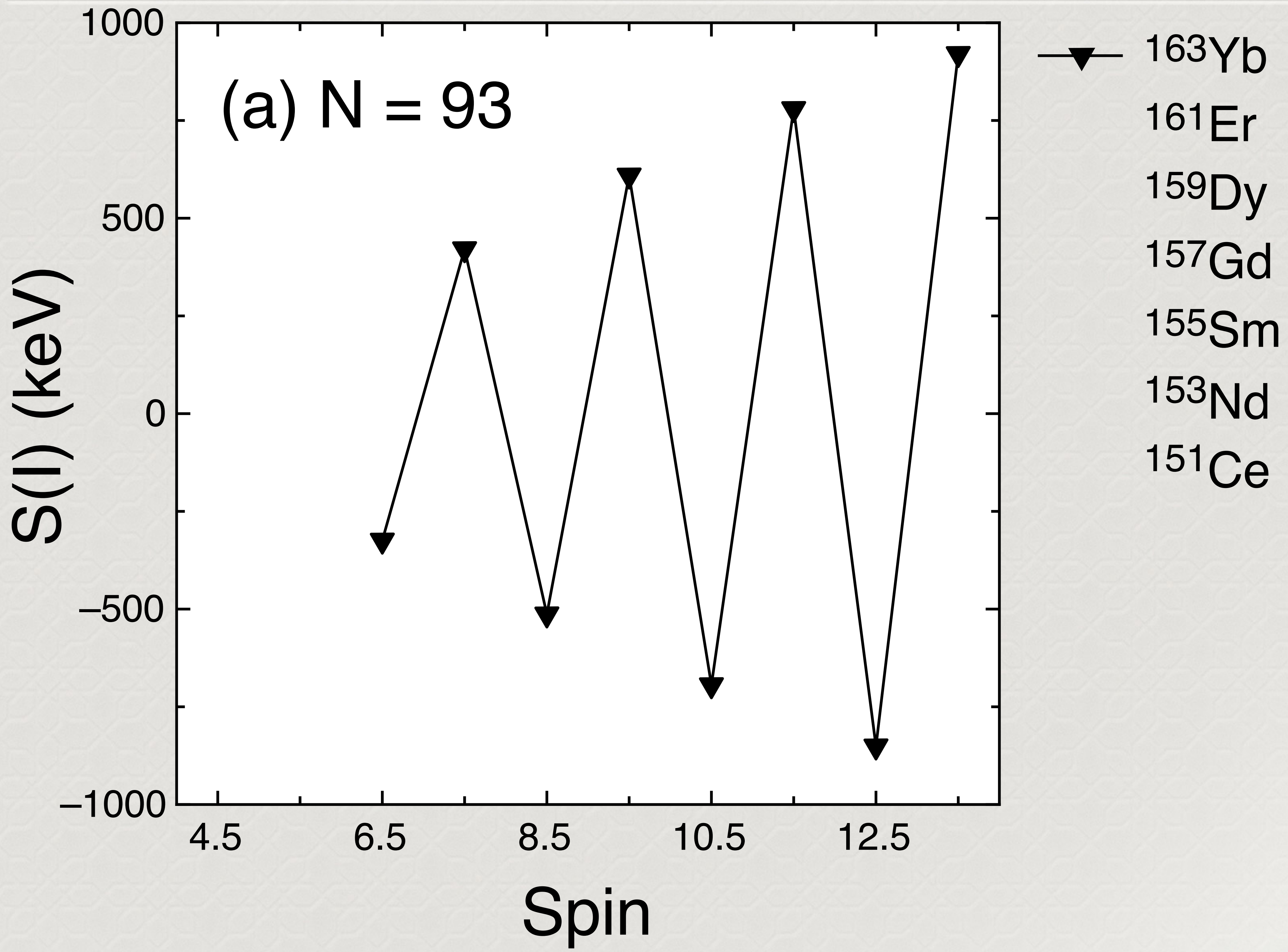
Origin of Energy Staggering

Signature $\alpha = +1/2$ $-1/2$

^{163}Yb

5/2[642]





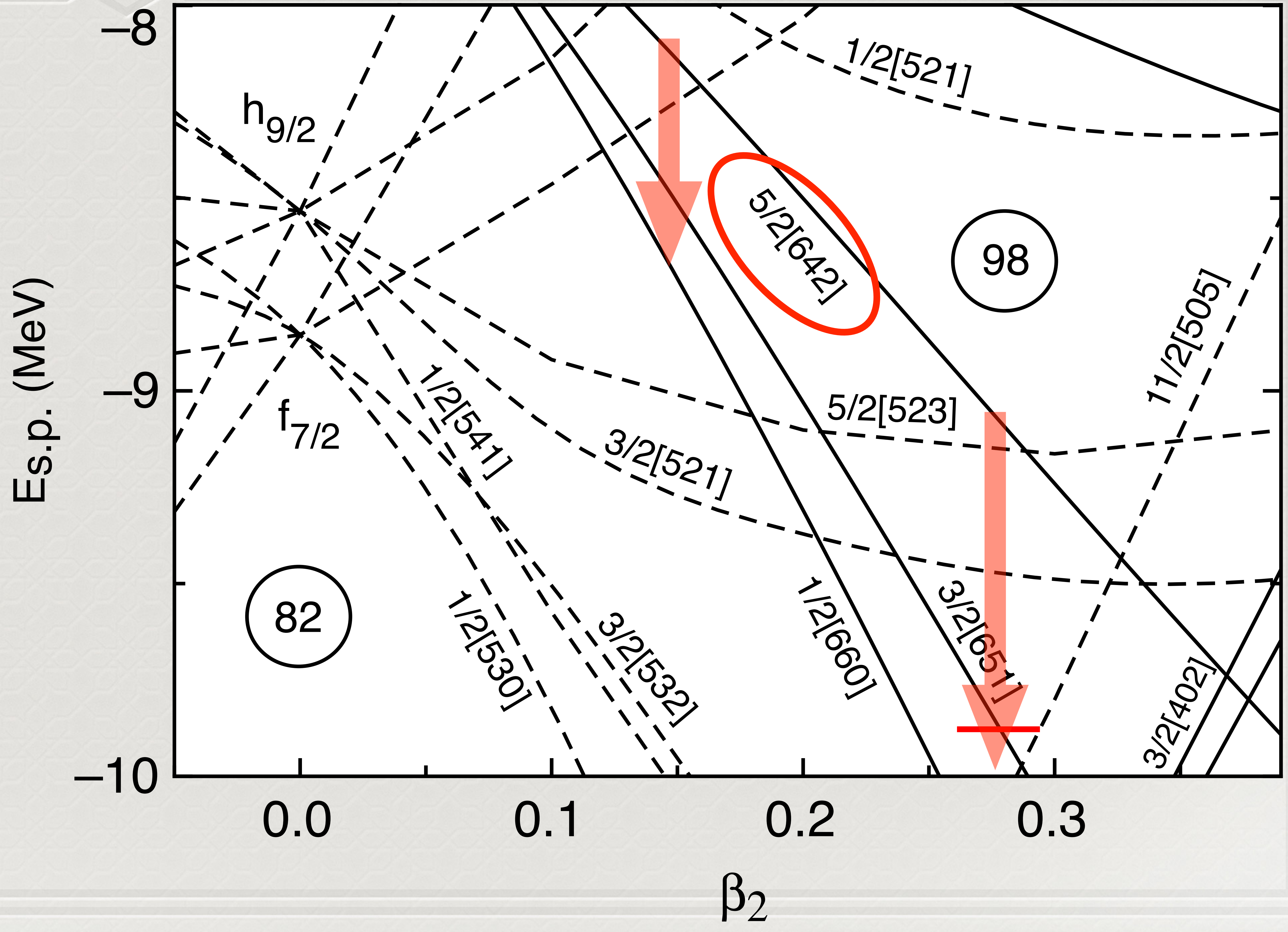
$$E_{K=1/2}(I) = \frac{\hbar^2}{2\mathcal{J}}[I(I+1) + a(-1)^{I+1/2}(I+1/2)]$$

Creates energy staggering

$$S(I) = E(I) - (E-1) -1/2[E(I+1) - E(I) + E(I-1) - E(I-2)]$$

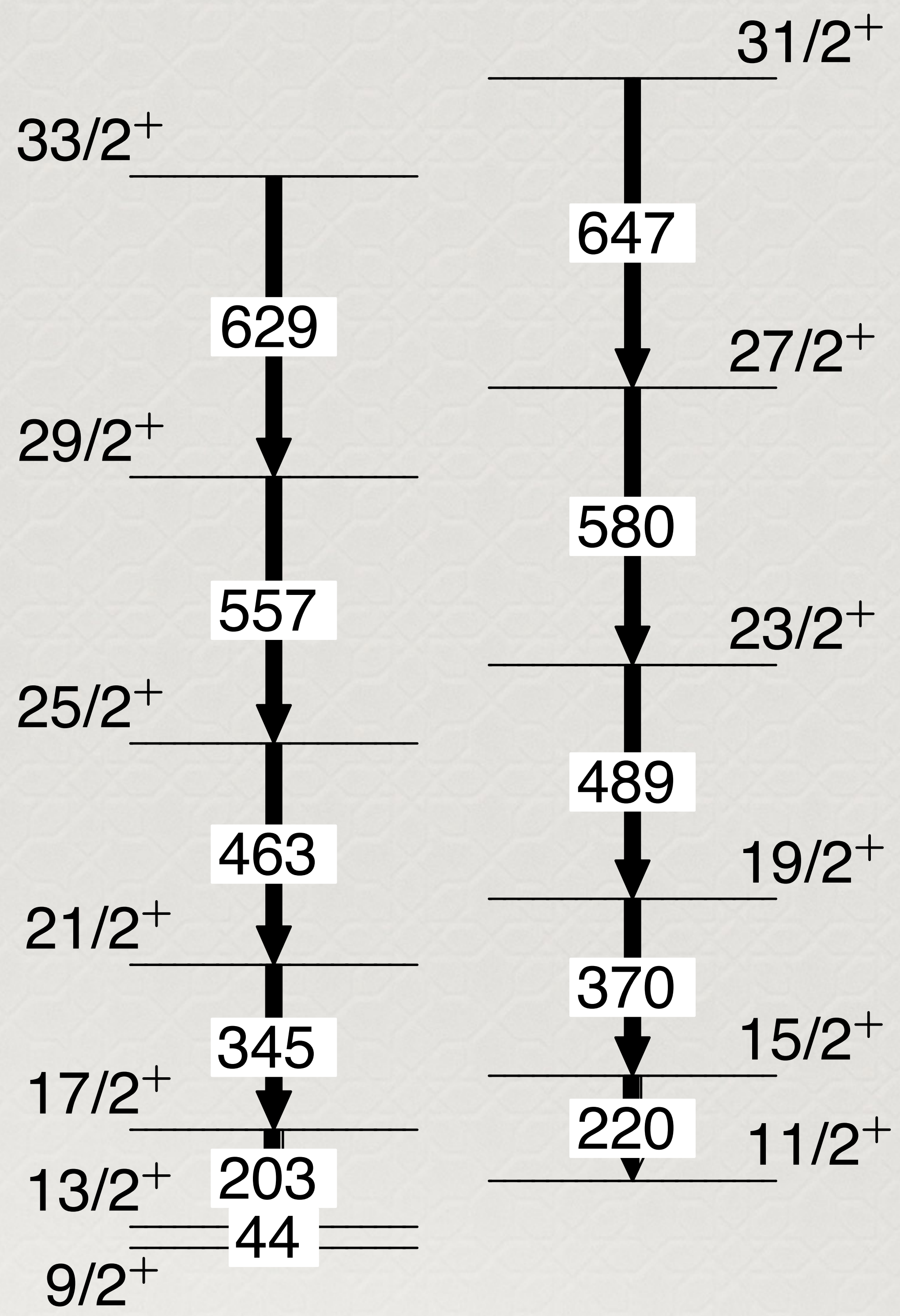
Origin of Energy Staggering

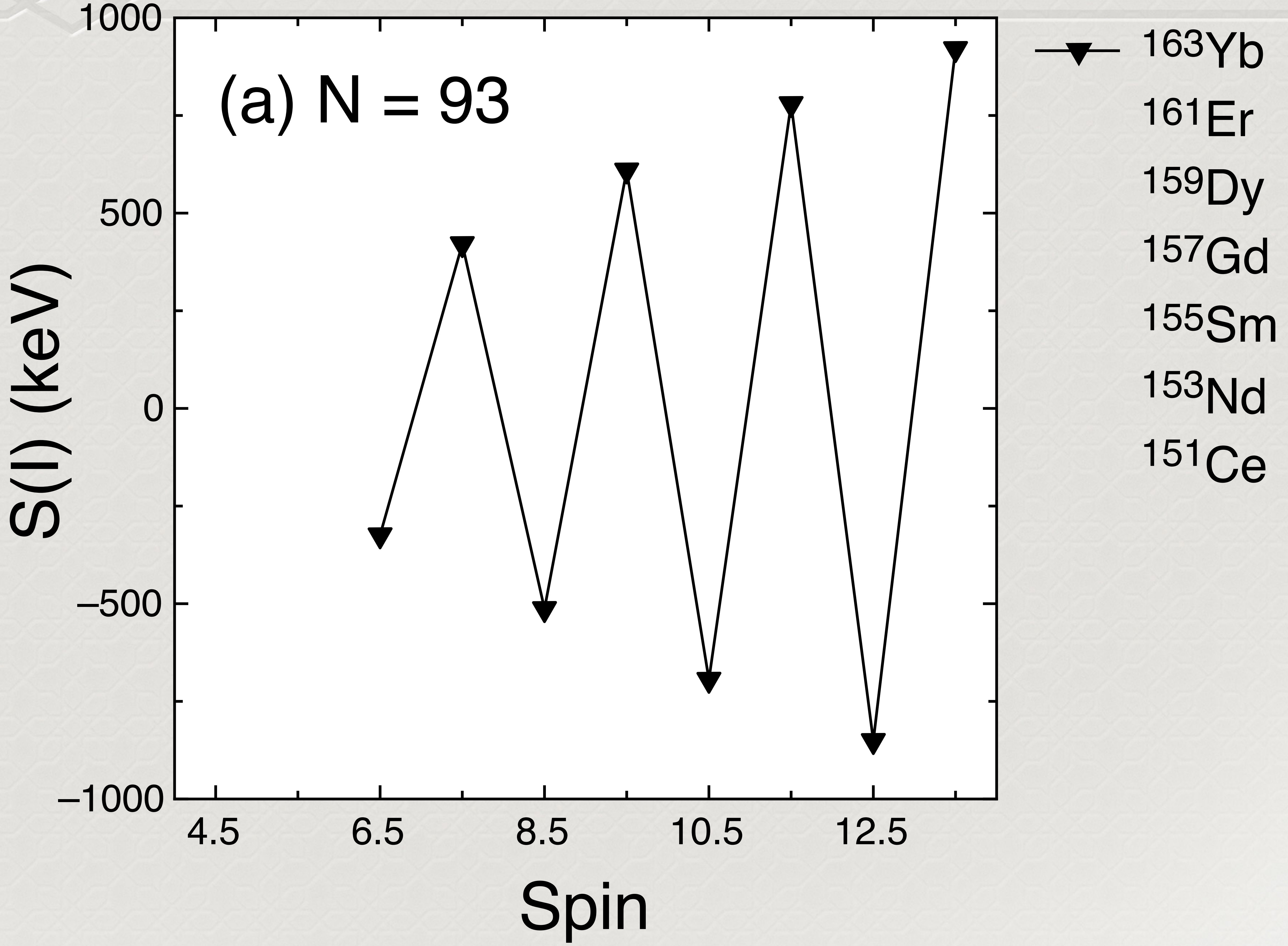
- *Only K* = 1/2 *orbital has decoupling constant, a, that produces energy staggering*
- *Higher K orbitals are mixed and will have K* = 1/2 *component*
- *The amount of K* = 1/2 *admixture is dependent on the location of the Fermi surface*
- *Low β_2 = large K mix = large splitting*
  High β_2 = low K mix = low splitting



Energy Staggering in 5/2[642] Band

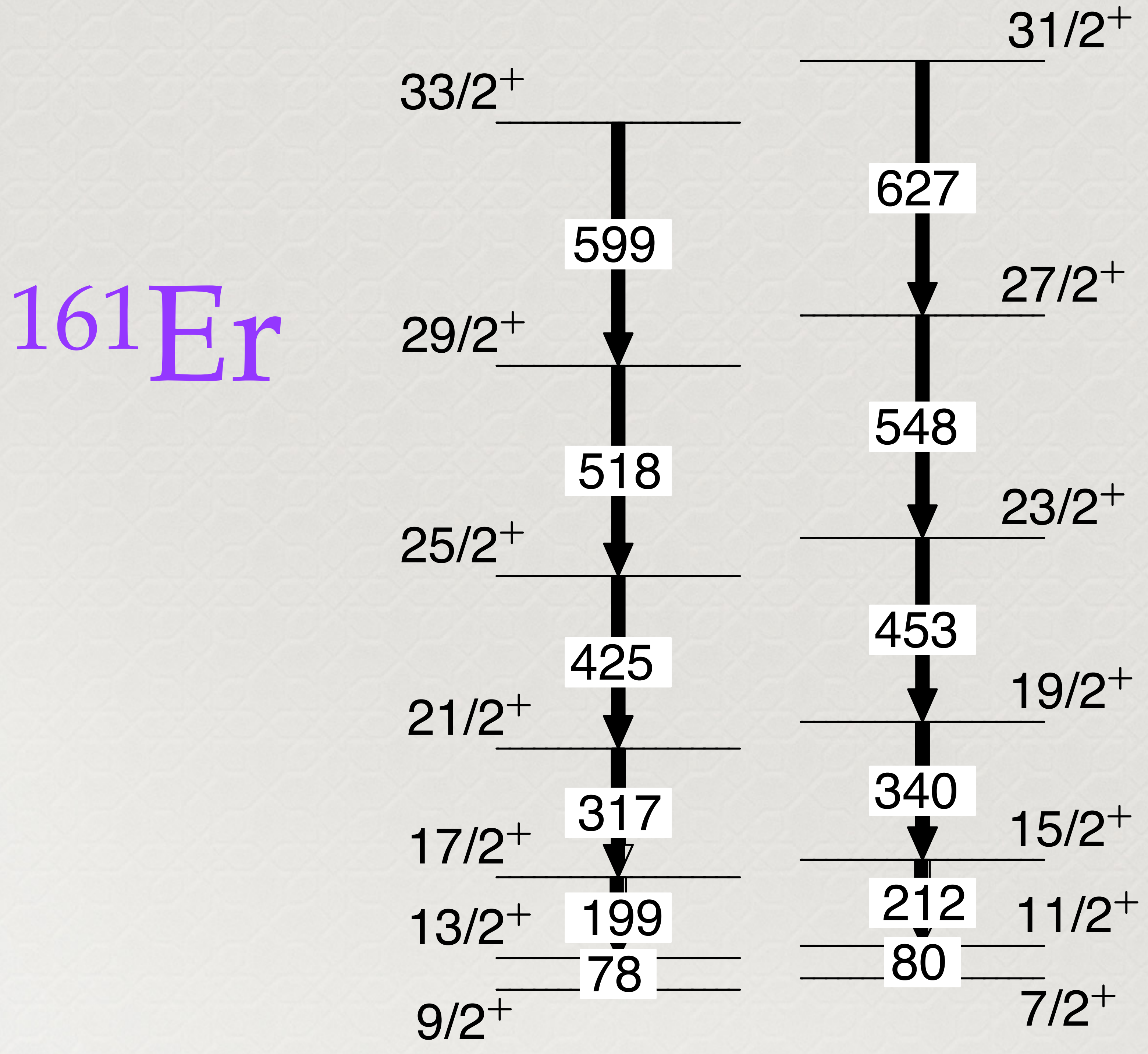
^{163}Yb

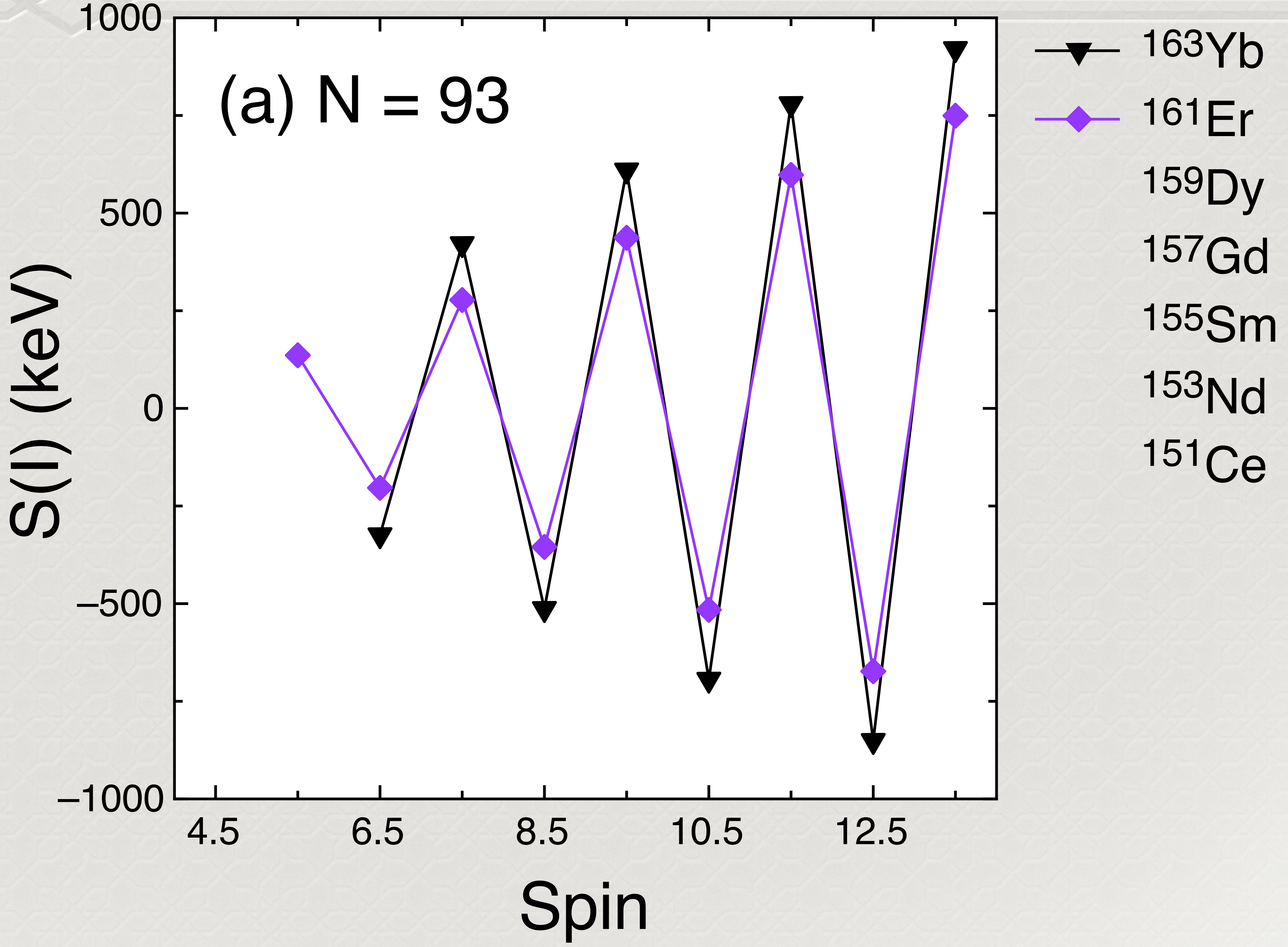




J. Kownacki *et al.*, NPA **394**, 269 (1983)

Energy Staggering in 5/2[624] Band

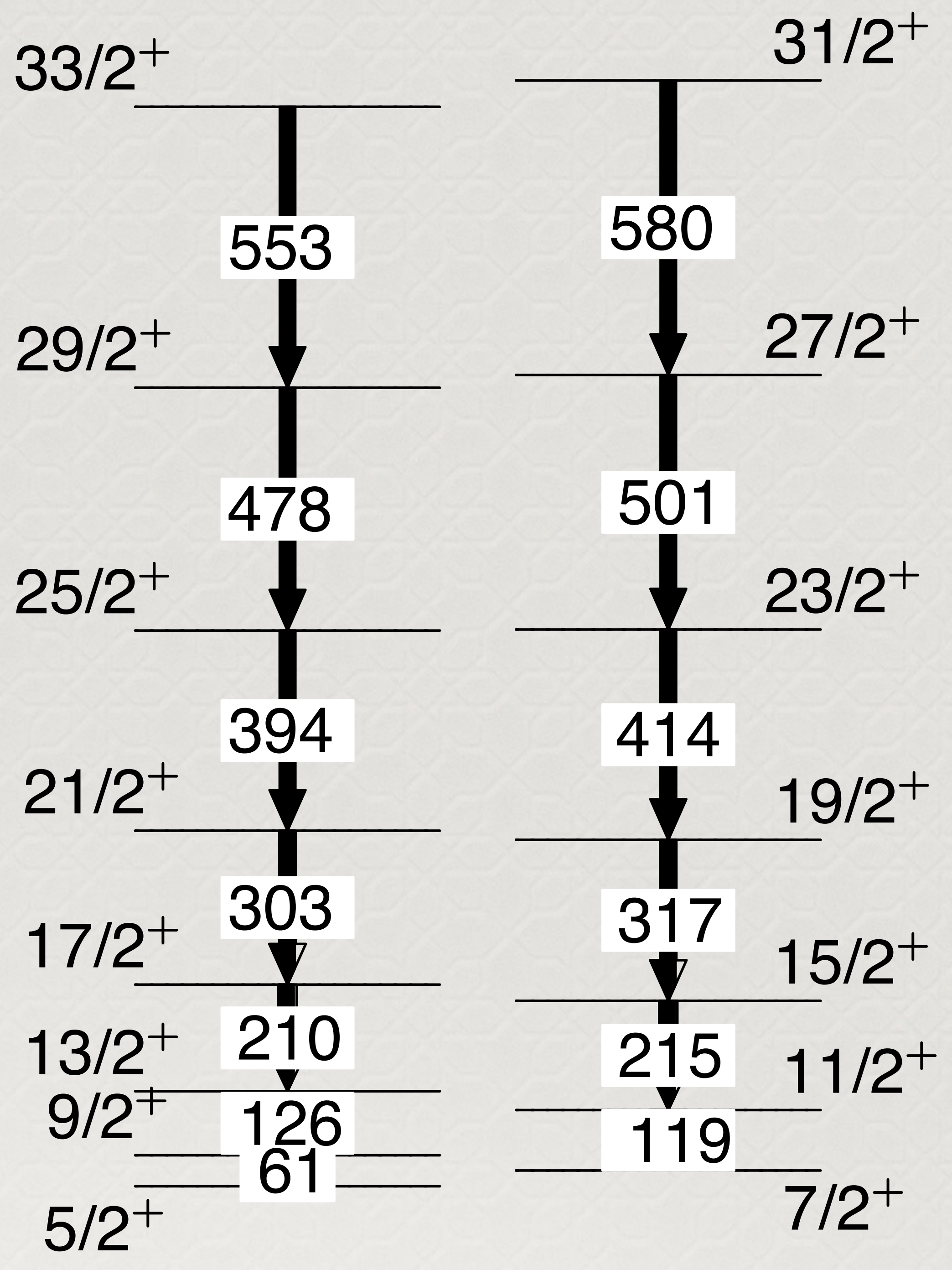


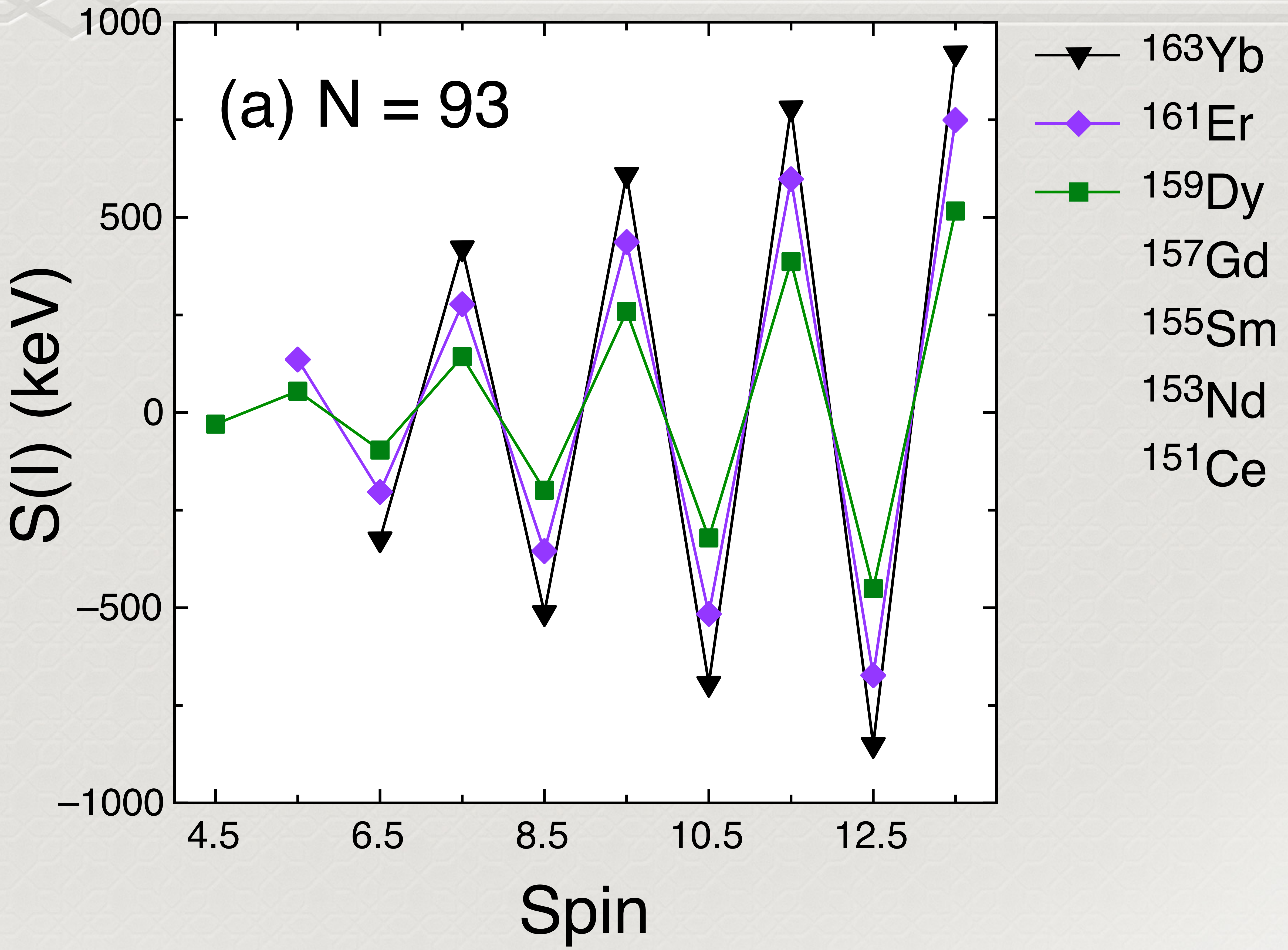


J. D. Garrett *et al.*, PLB **118**, 297 (1982)

Energy Staggering in 5/2[624] Band

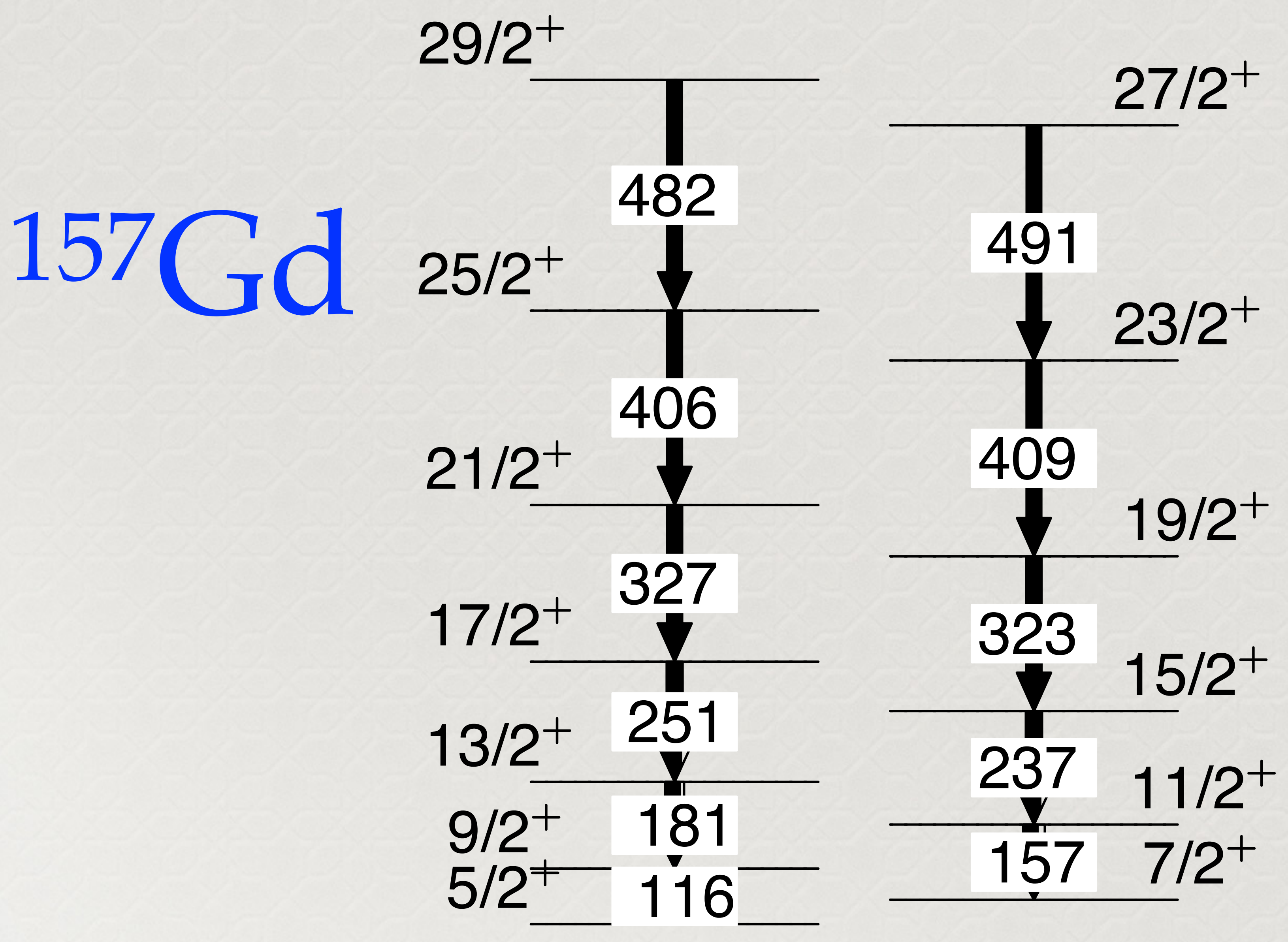
^{159}Dy

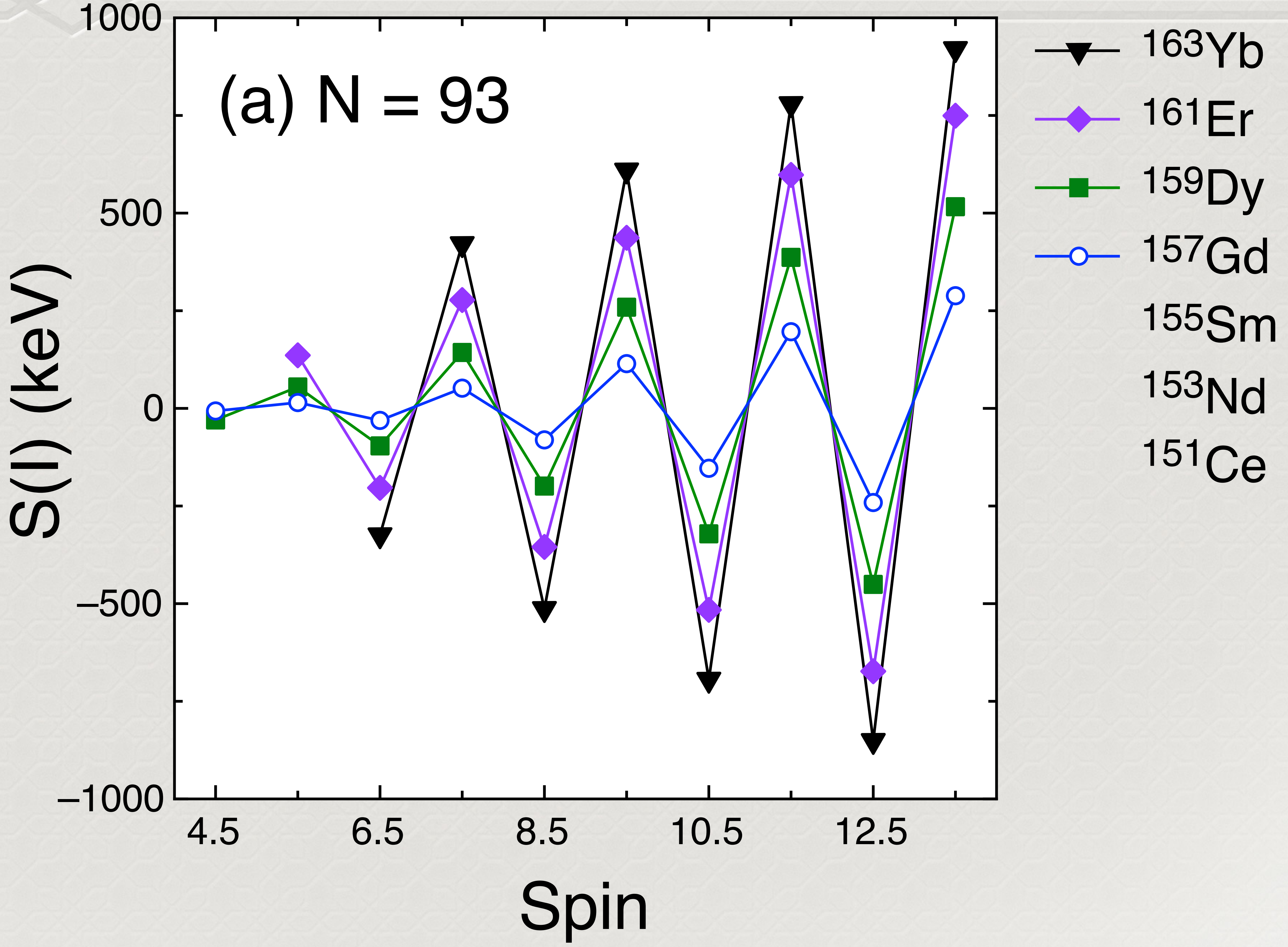




A. Jungclaus *et al.*, PRC **67**, 034302 (2003)

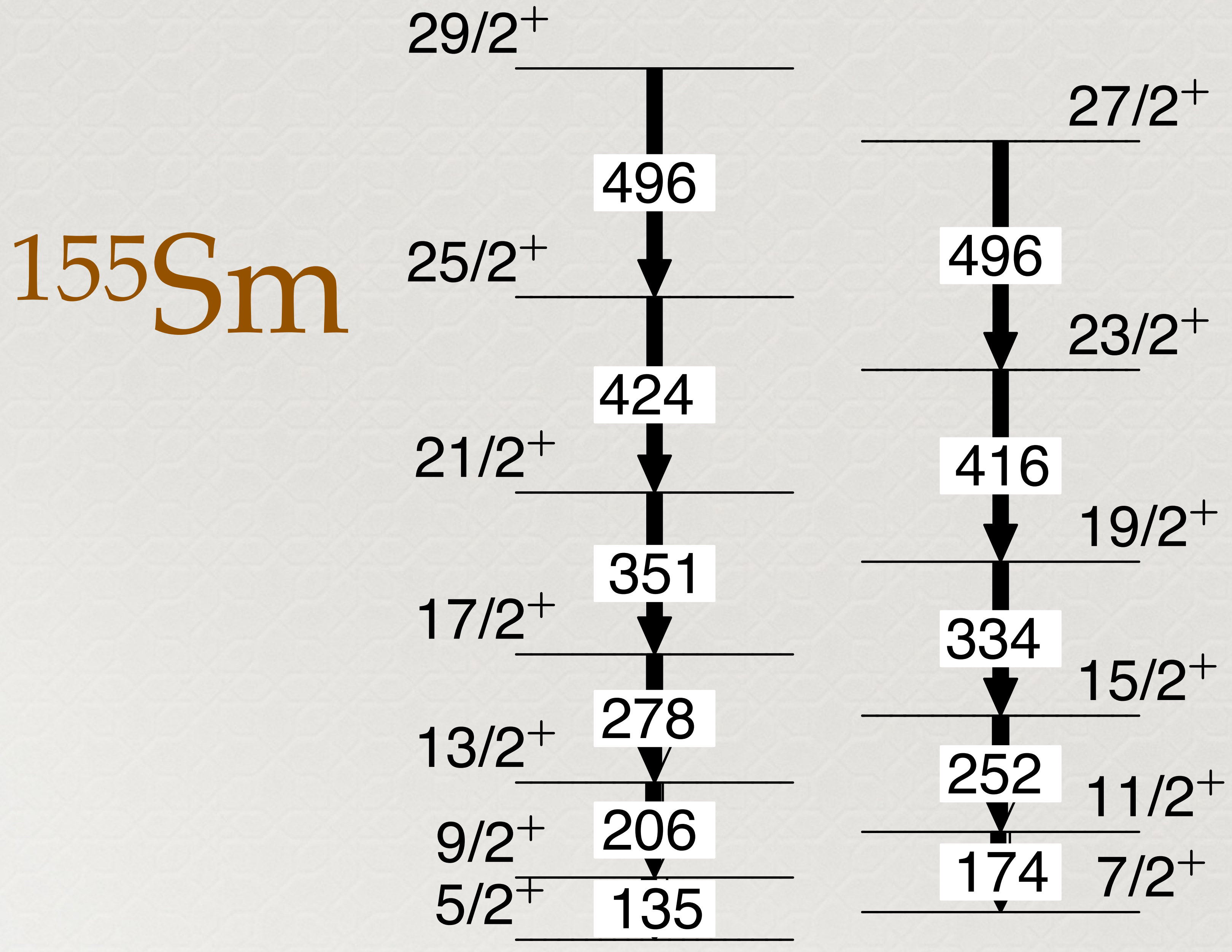
Energy Staggering in 5/2[624] Band



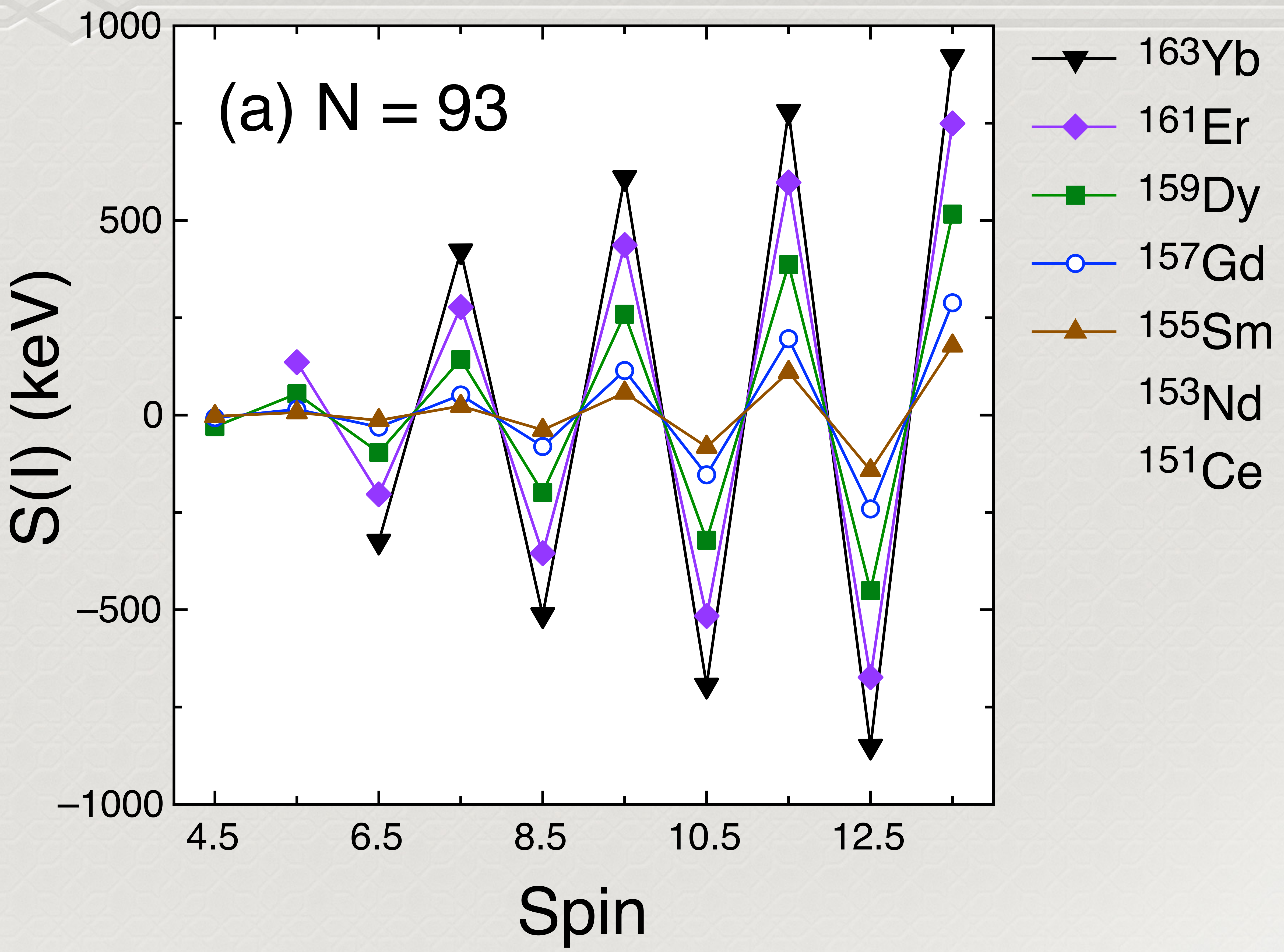


T. Hayakawa *et al.*, PLB **551**, 79 (2003)

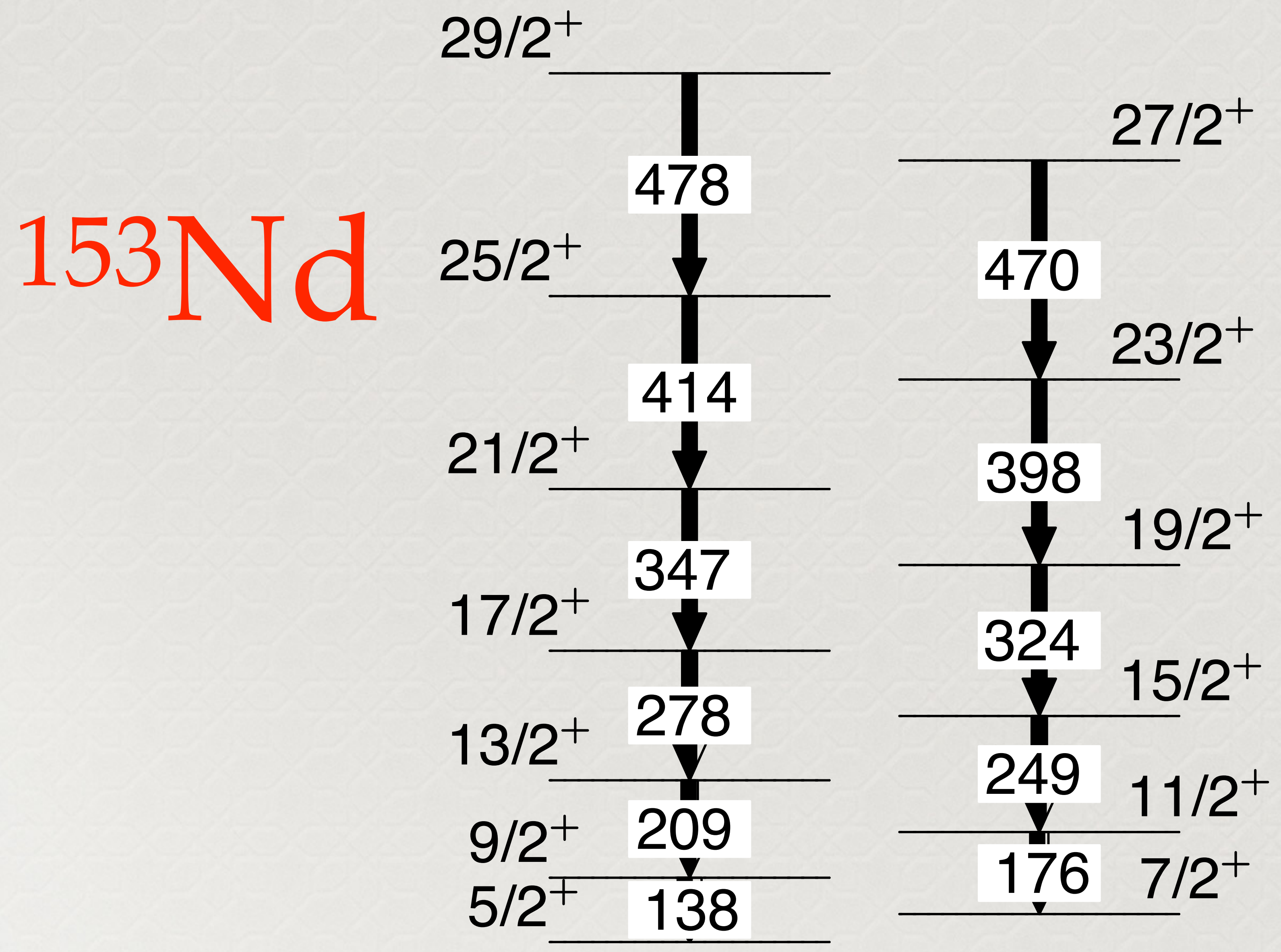
Energy Staggering in 5/2[624] Band

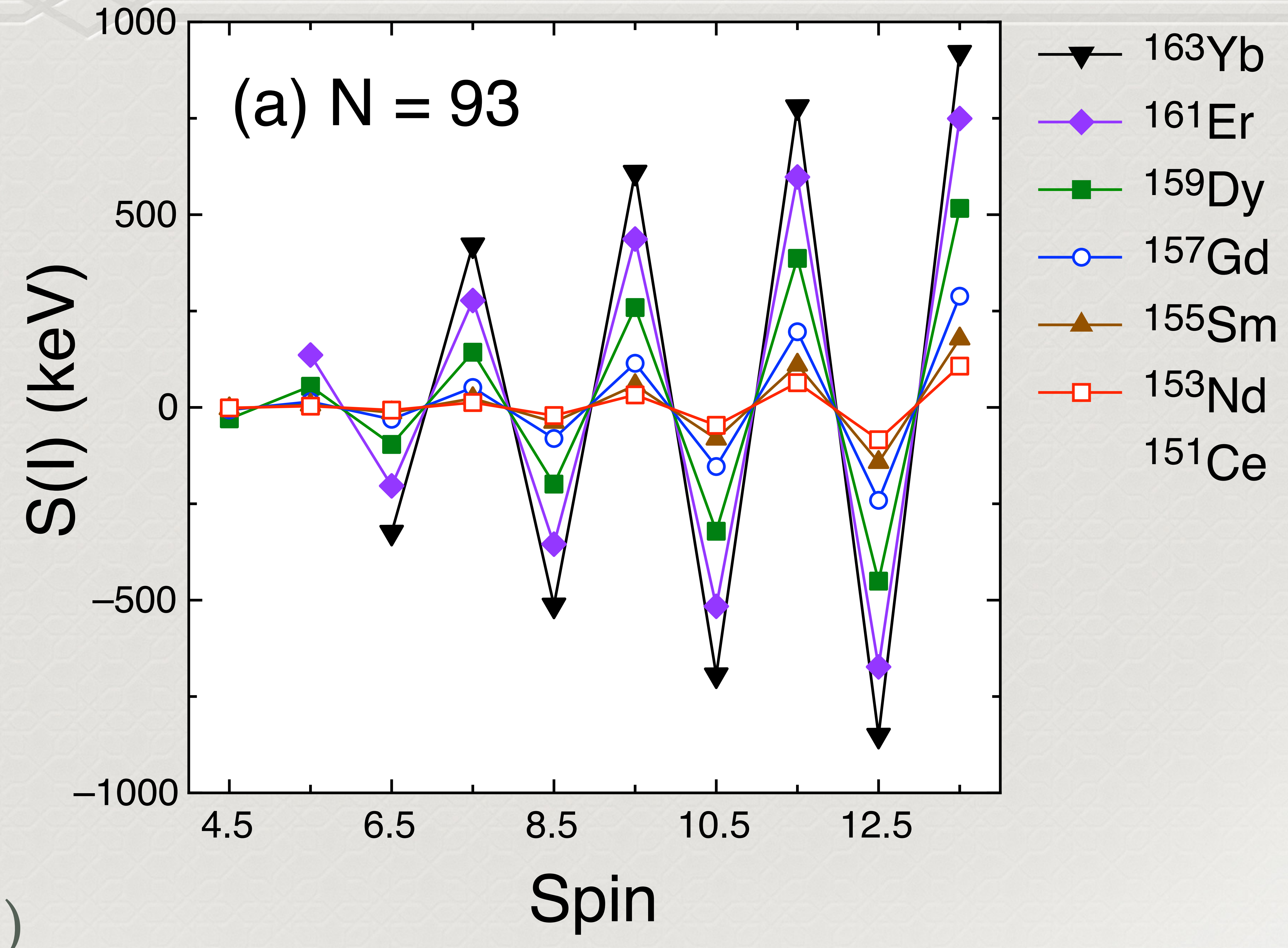


S. J. Asztalos *et al.*, PRC **60**, 044307 (1999)



Energy Staggering in 5/2[624] Band

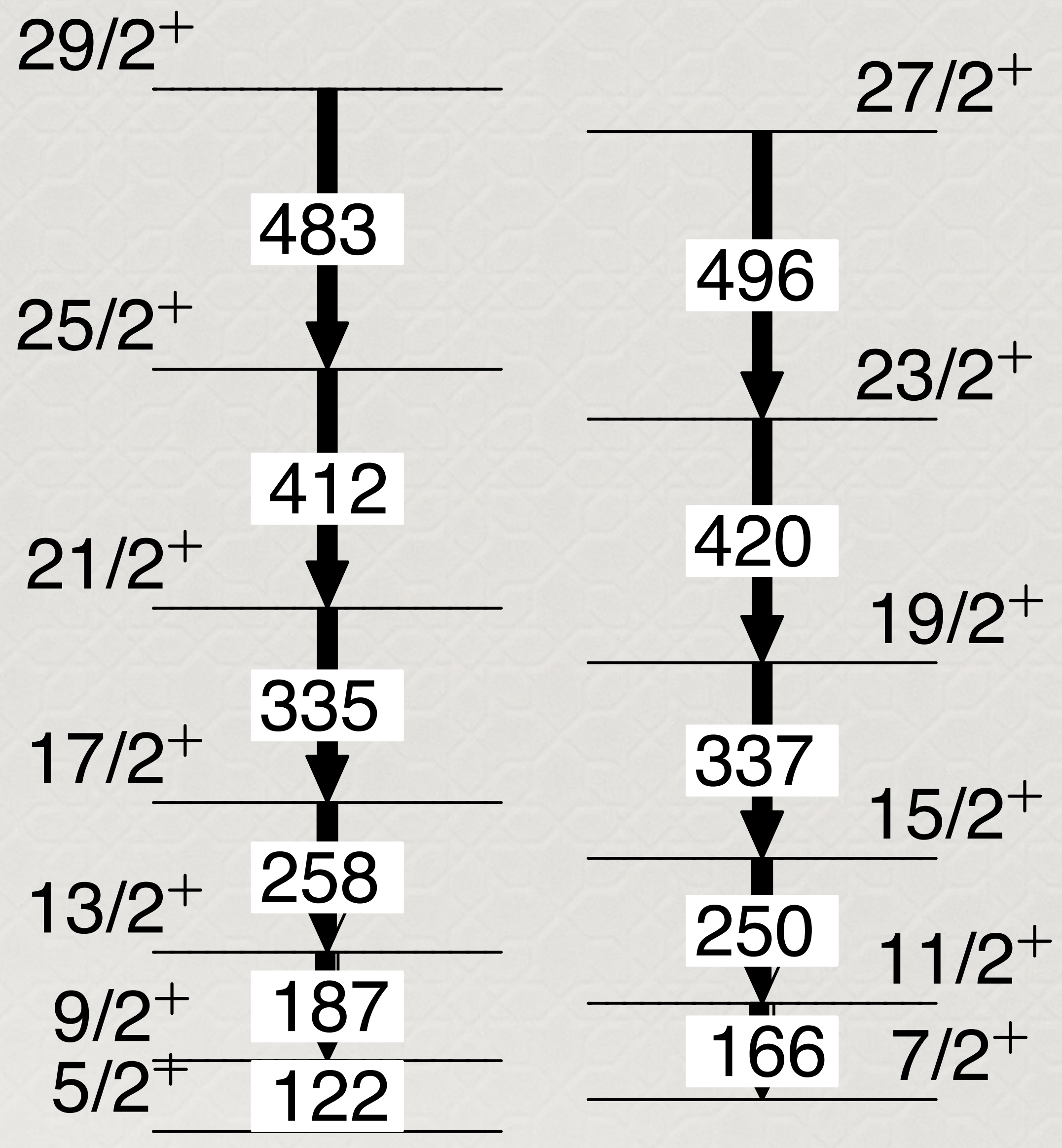


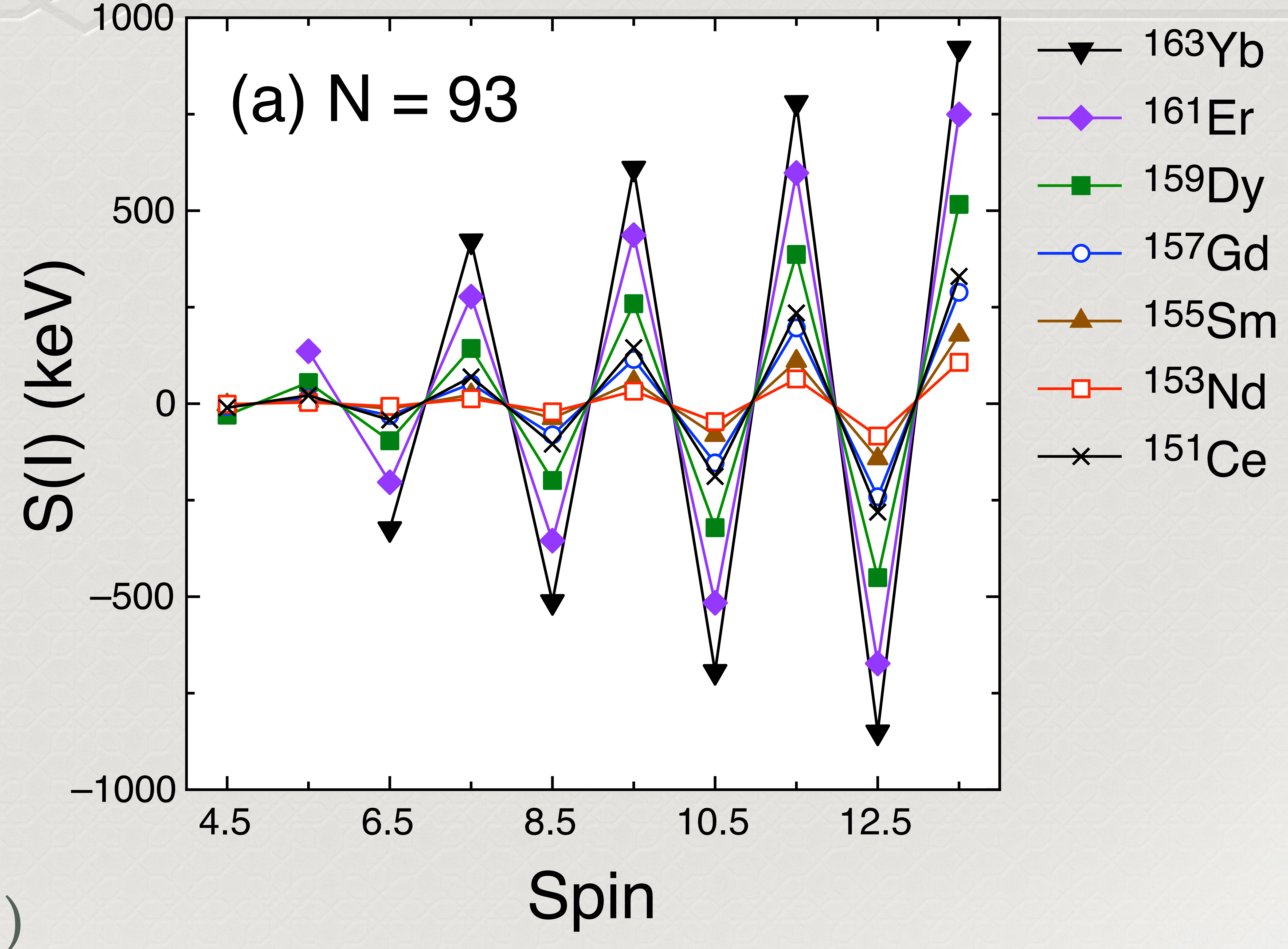


G. S. Simpson *et al.*, PRC **81**, 024313 (2010)

Energy Staggering in 5/2[624] Band

^{151}Ce

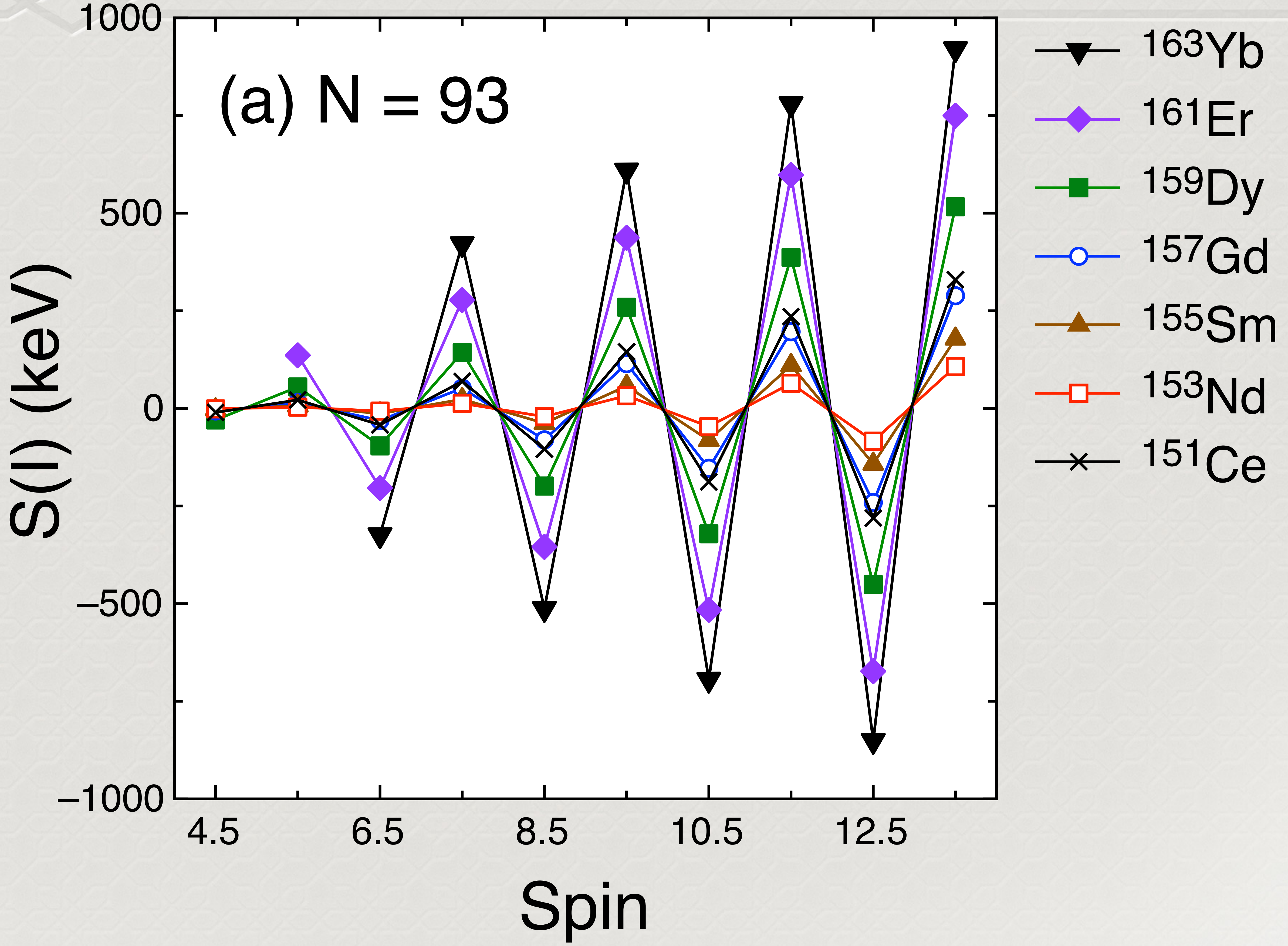




G. S. Simpson *et al.*, PRC **81**, 024313 (2010)

Energy Staggering in 5/2[624] Band

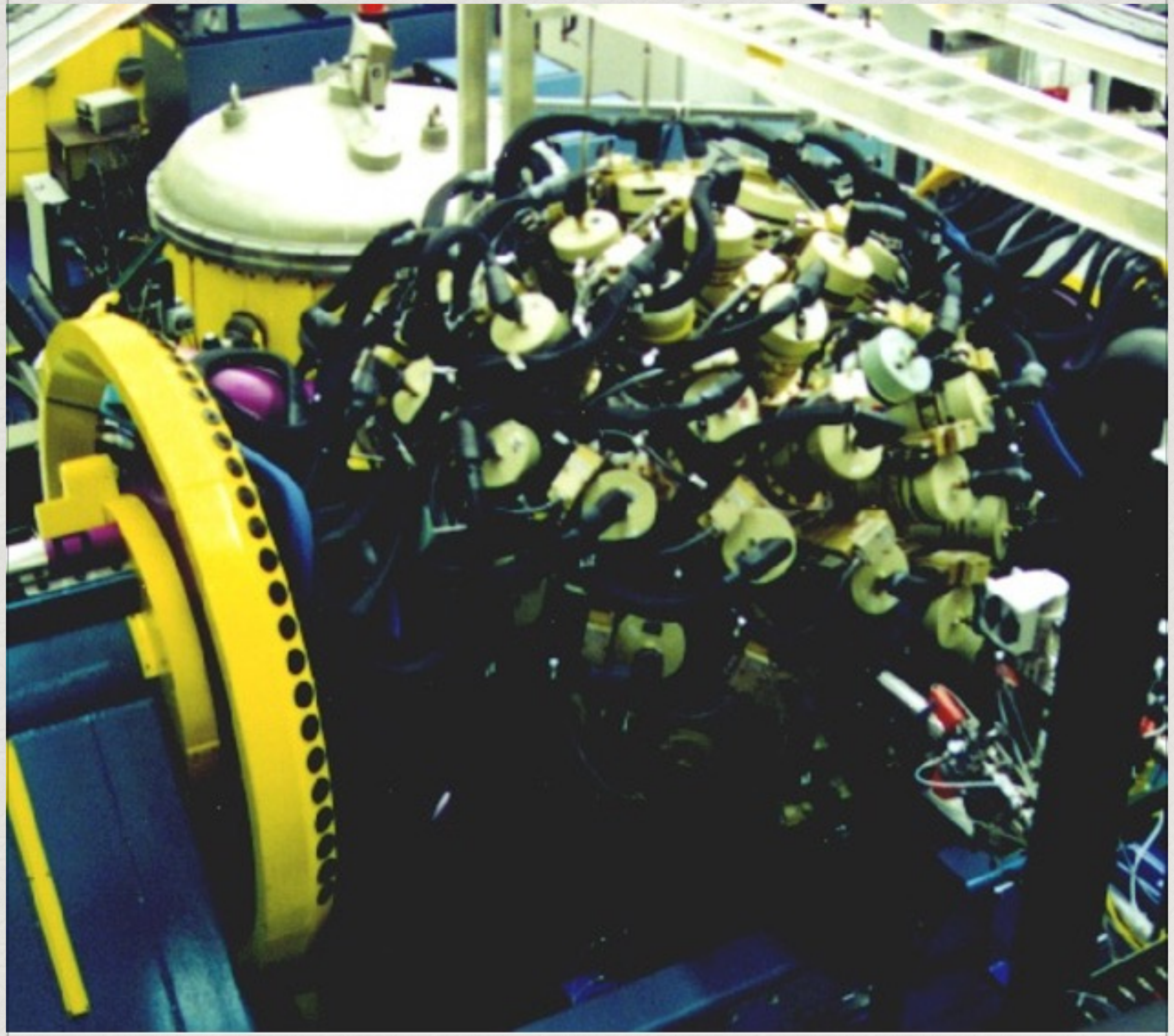
- *Energy staggering of the* 5/2[642] *band in this region is an indicator of deformation*
- *See same trend in N* = 95 *nuclei*
- *Maximum deformation is not at midshell (Z* = 66*, Dy), but appears to be located at Z* =60 *(Nd)*
- *Consistent with E*(2+) *systematics*



DJH *et al.*, PRC **105**, 014301 (2022)

Isomers in Neutron-Rich, Rare-Earth Nuclei

- ~20 years ago, Dracoulis, Kondev, & Lane ran a series of multi-nucleon transfer reactions to produce neutron-rich nuclei that are likely to have isomers
- ^{136}Xe + ^{176}Yb at 820 MeV, performed at ATLAS
- 1/10 pulsing (825 ns between beam bursts)
- Gammasphere had 101 detectors operating - focus on out-of-beam

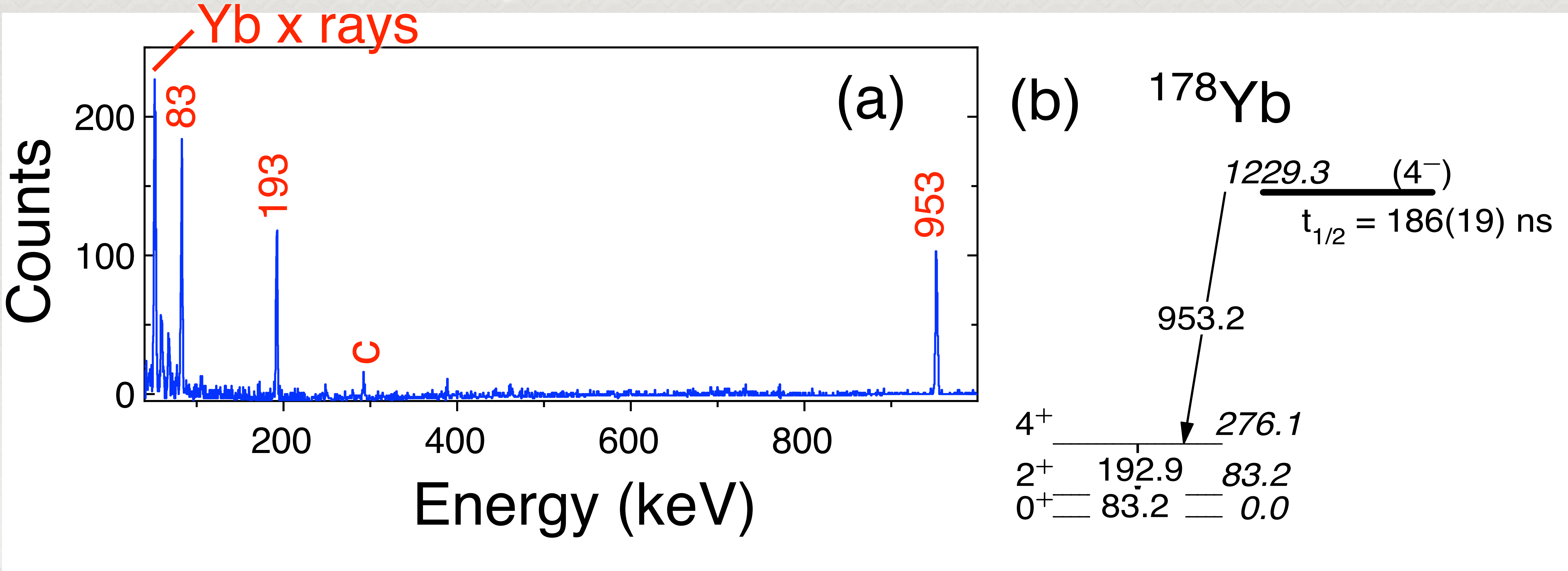


What was made...

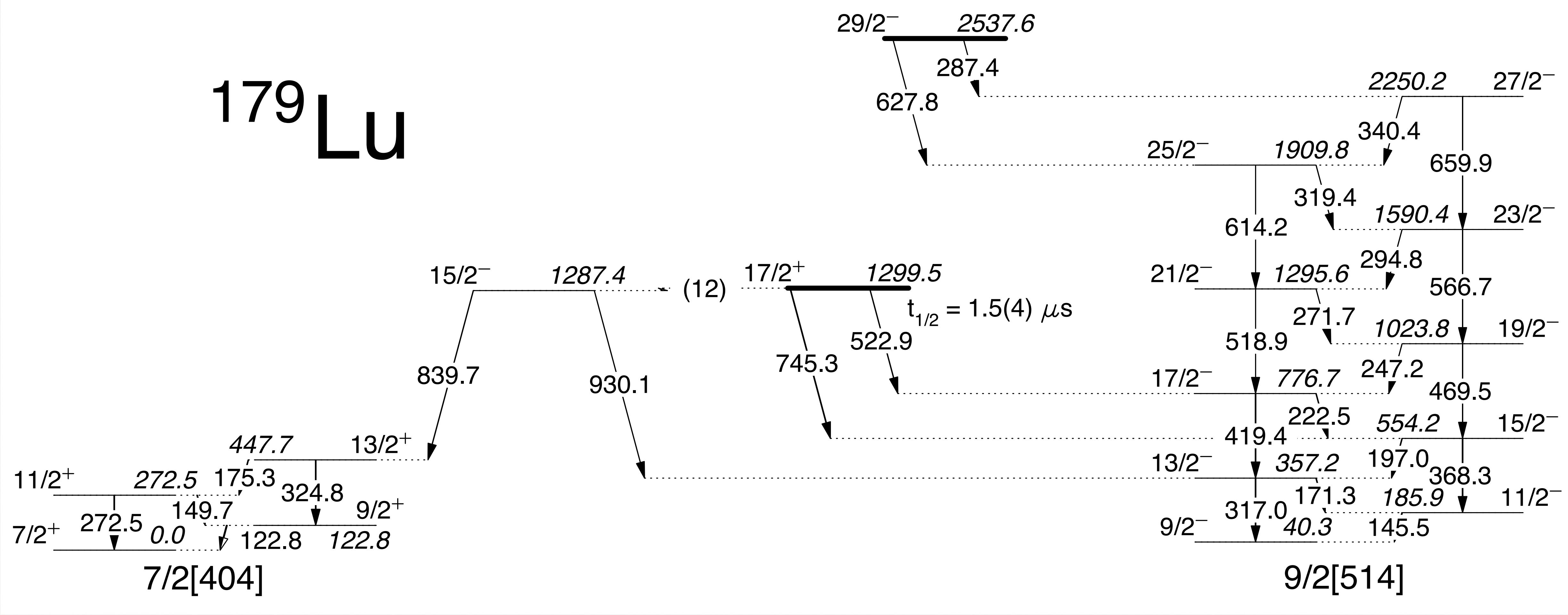
Neutrons	102	103	104	105	106	107	108	109	110
W					^{180}W	^{181}W	^{182}W		^{184}W
Ta			^{177}Ta	^{178}Ta	^{179}Ta		^{181}Ta		^{183}Ta
Hf	^{174}Hf		^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf	^{181}Hf	^{182}Hf
Lu			^{175}Lu	^{176}Lu	^{177}Lu	^{178}Lu	^{179}Lu	^{180}Lu	
Yb	^{172}Yb		^{174}Yb	^{175}Yb	^{176}Yb	^{177}Yb	^{178}Yb		
Tm	^{171}Tm	^{172}Tm	^{173}Tm	^{174}Tm	^{175}Tm				
Er	^{170}Er		^{172}Er	^{173}Er	^{174}Er				

Two-quasiparticle Isomer in ^{178}Yb

- Most neutron-rich Yb nucleus with known excited states
- Spectra are from cube resulting from data between beam bursts
- Sum of the 83/193, 83/953, and 193/953 gates
- Observed coincident x rays are from Yb

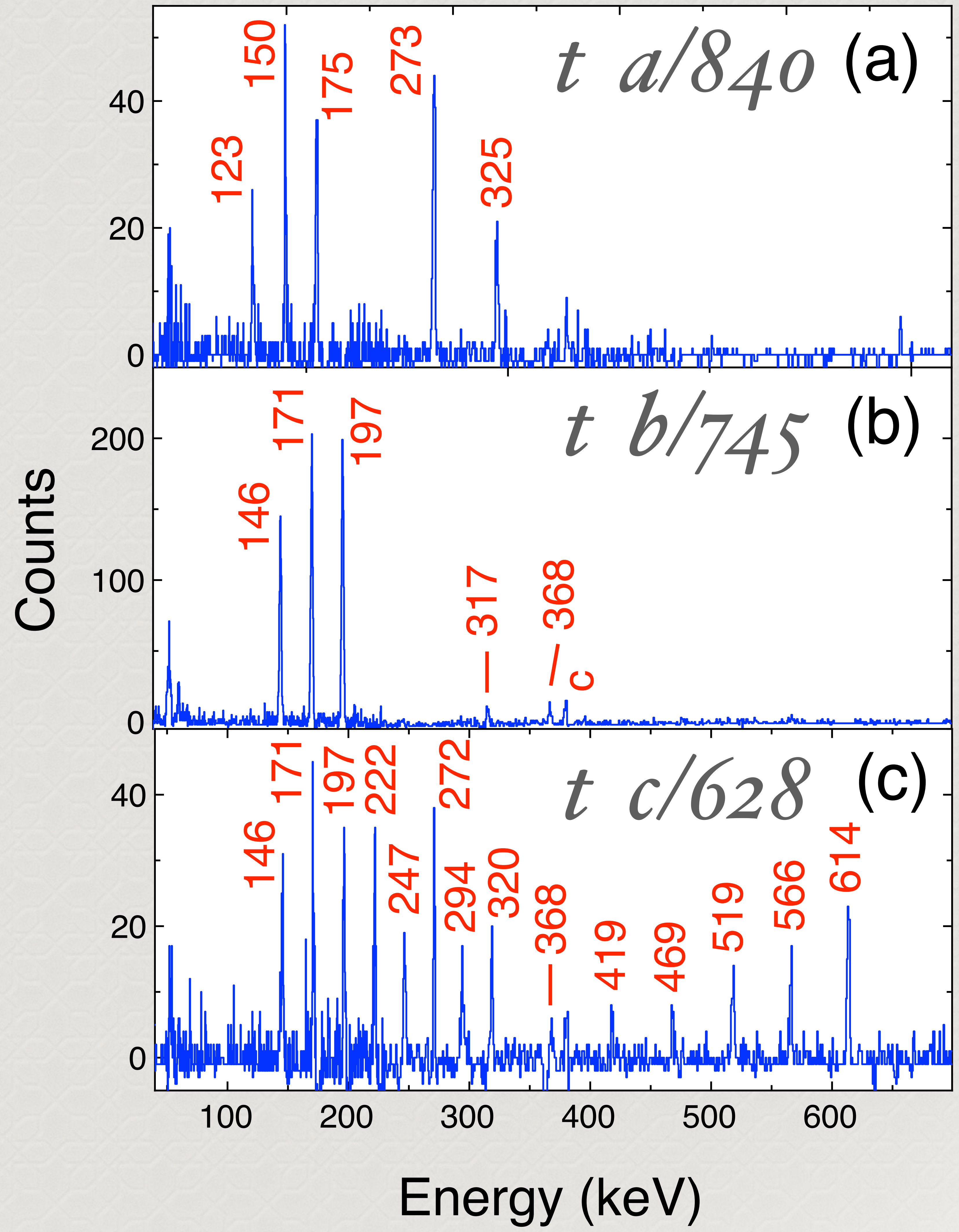


Multiple 3-quasiparticle isomers in ^{179}Lu

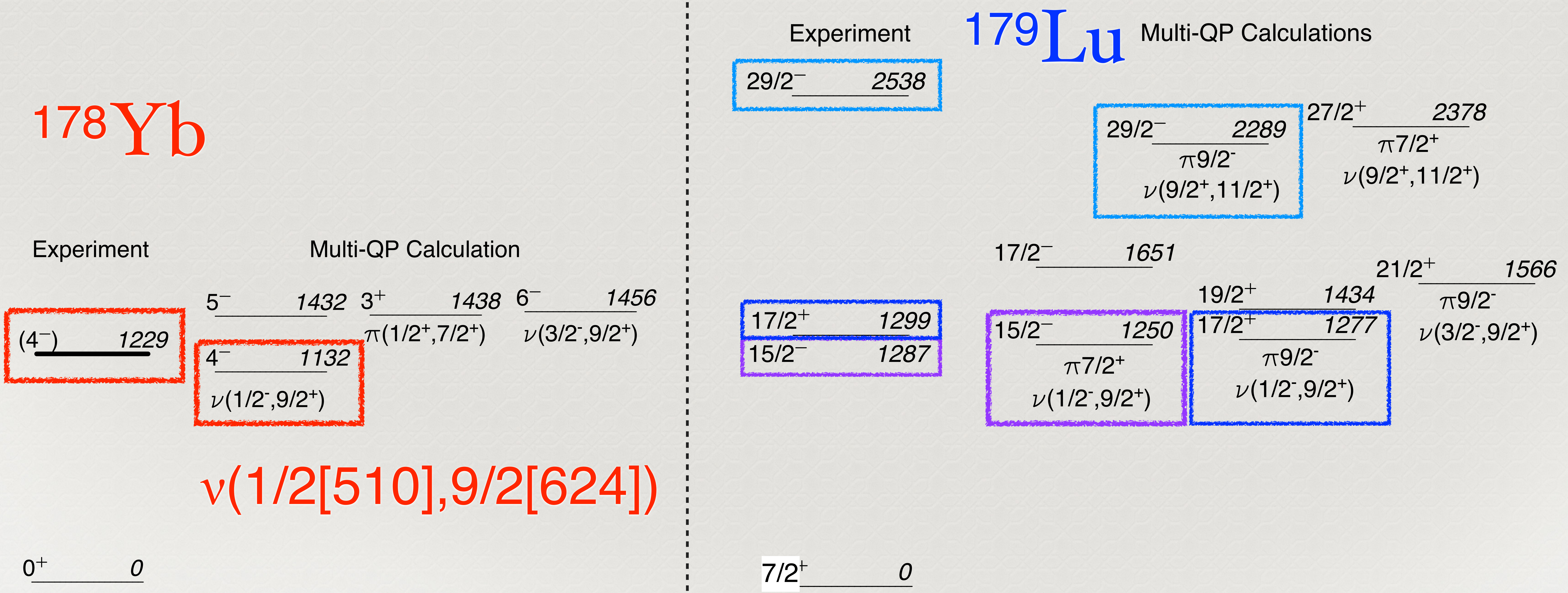


- *Most neutron-rich, odd-A Lu*
- *No γ's previously known, excited states up to* 13/2 *from proton spectra*

Burke & Garrett, NPA **550**, 179 (1992)



Multi-Quasiparticle Calculations



Thank You, Robert!!

- *Have had a terrific time exploring rare-earth nuclei at high spin and not-so-high spin together*
- *You have greatly aided me in my scientific and professional endeavors*
- *You have been an advocate, a mentor, and a friend throughout the years*
- *Congratulations on your retirement!!*

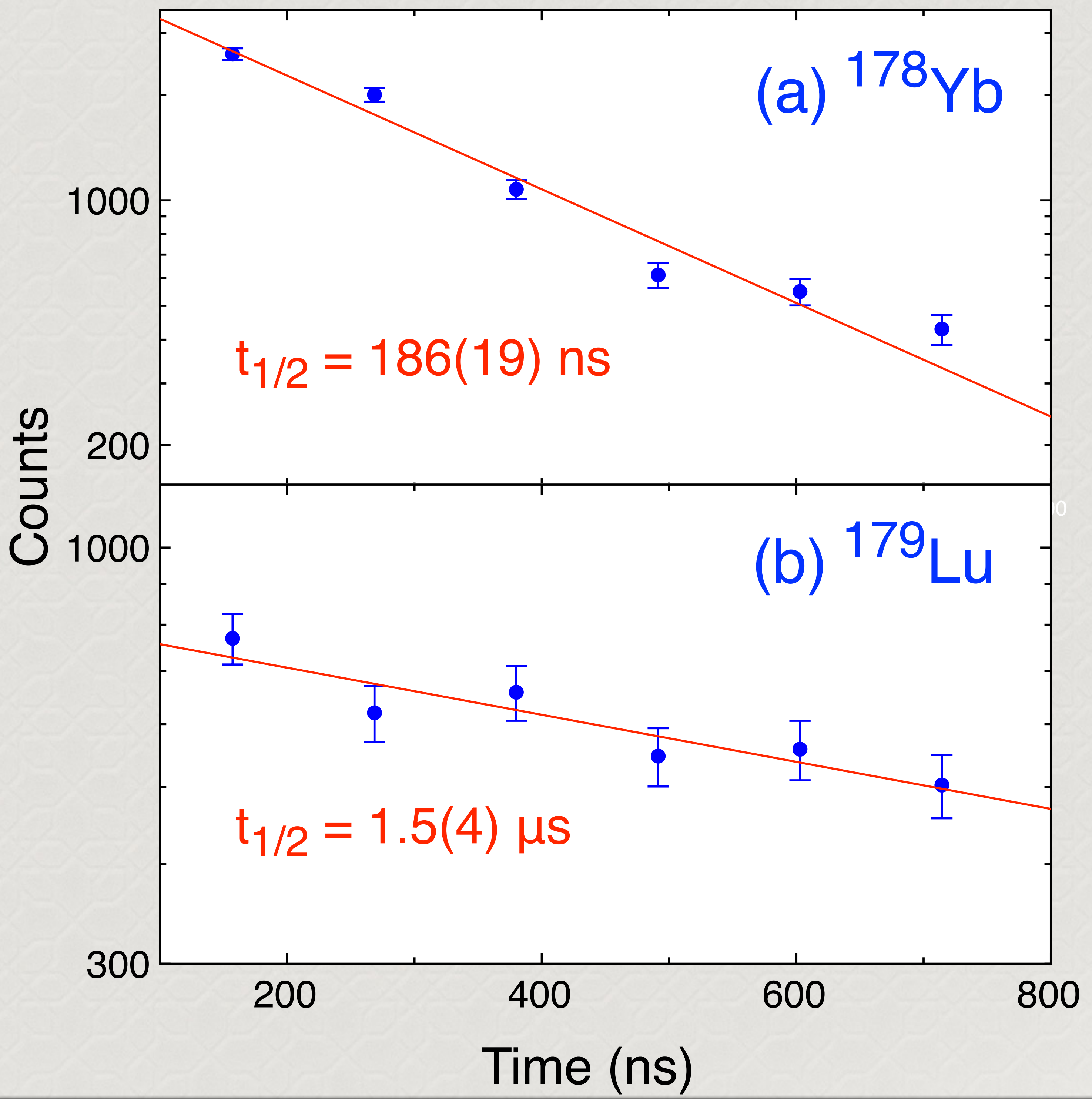
This work was supported by various grants from the NSF (PHY-2208137) and DOE (DE-AC02-06CH11357, DE-FG02-97ER41041, DE-FG02-97ER41033)

Thank you to my many collaborators

F. G. Kondev, M. A. Riley, L. L. Riedinger, M. P. Carpenter, G. J. Lane, G. D. Dracoulis, T. B. Brown, J. Pfohl, S. M. Fischer, D. T. Nisius, P. Fallon, W. C. Ma, J. Simpson, S. N. T. Majola, J. M. Allmond, C. W. Beausang, C. J. Chiara, N. Cooper, D. Curien, B. J. P. Gall, P. E. Garrett, W. D. Kulp, T. Lauritsen, E. A. McCutchan, D. Miller, S. Miller, J. Piot, N. Redon, J. F. Sharpey-Schafer, I. Stefanescu, X. Wang, V. Werner, J. L. Wood, C.-H. Yu, S. Zhu, J. Dudek, K. Villafana, K. Auranen, A. D. Ayangeakaa, J. S. Baron, A. J. Boston, J. A. Clark, J. P. Greene, J. Heery, C. R. Hoffman, J. Li, E. S. Paul, D. Seweryniak, S. Stolze, G. L. Wilson, J. Wu, A. P. Byrne, P. Chowdhury, H. Watanabe

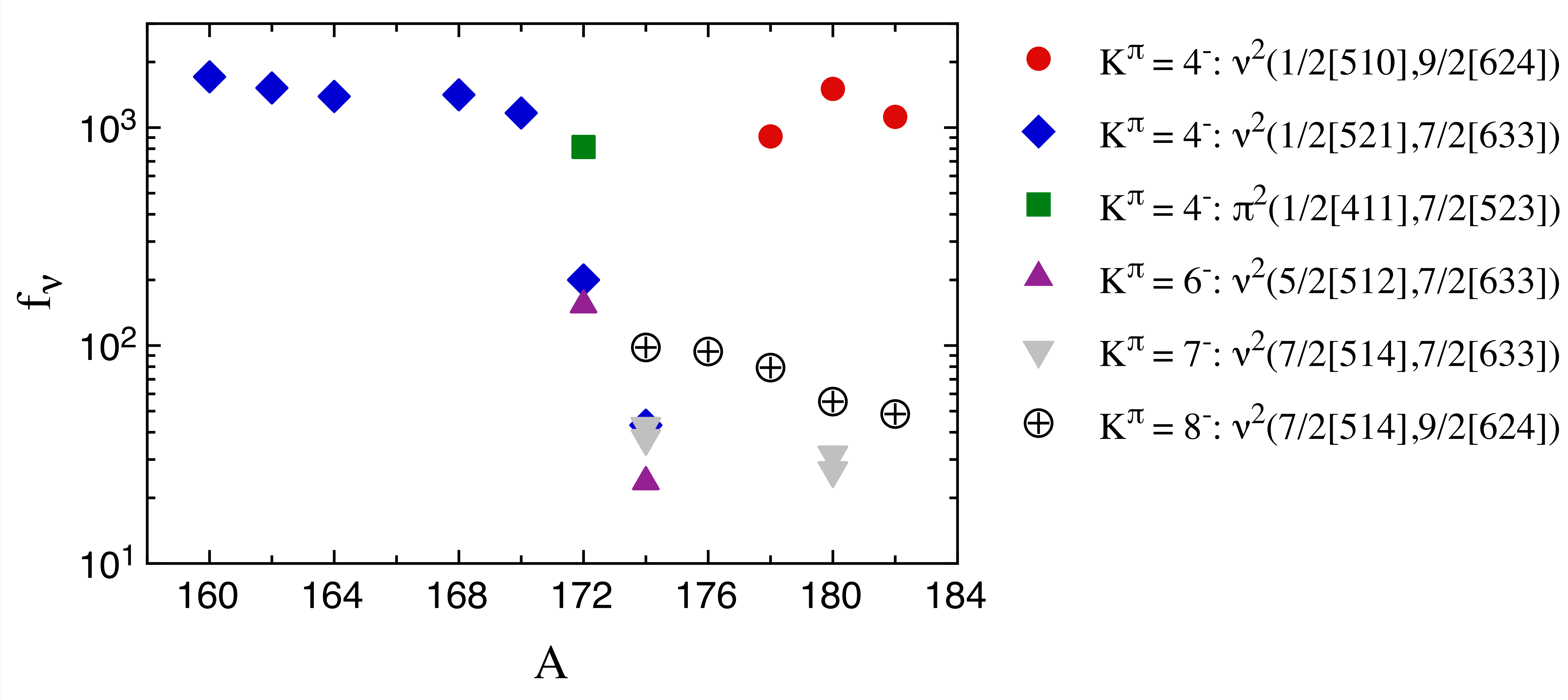
Half lives

- *Six cubes were constructed dividing the out-of-beam period into ~110 ns intervals*
- *To obtain enough statistics, a single (clean) gate was placed to track the intensity of a γ in the decay sequence*



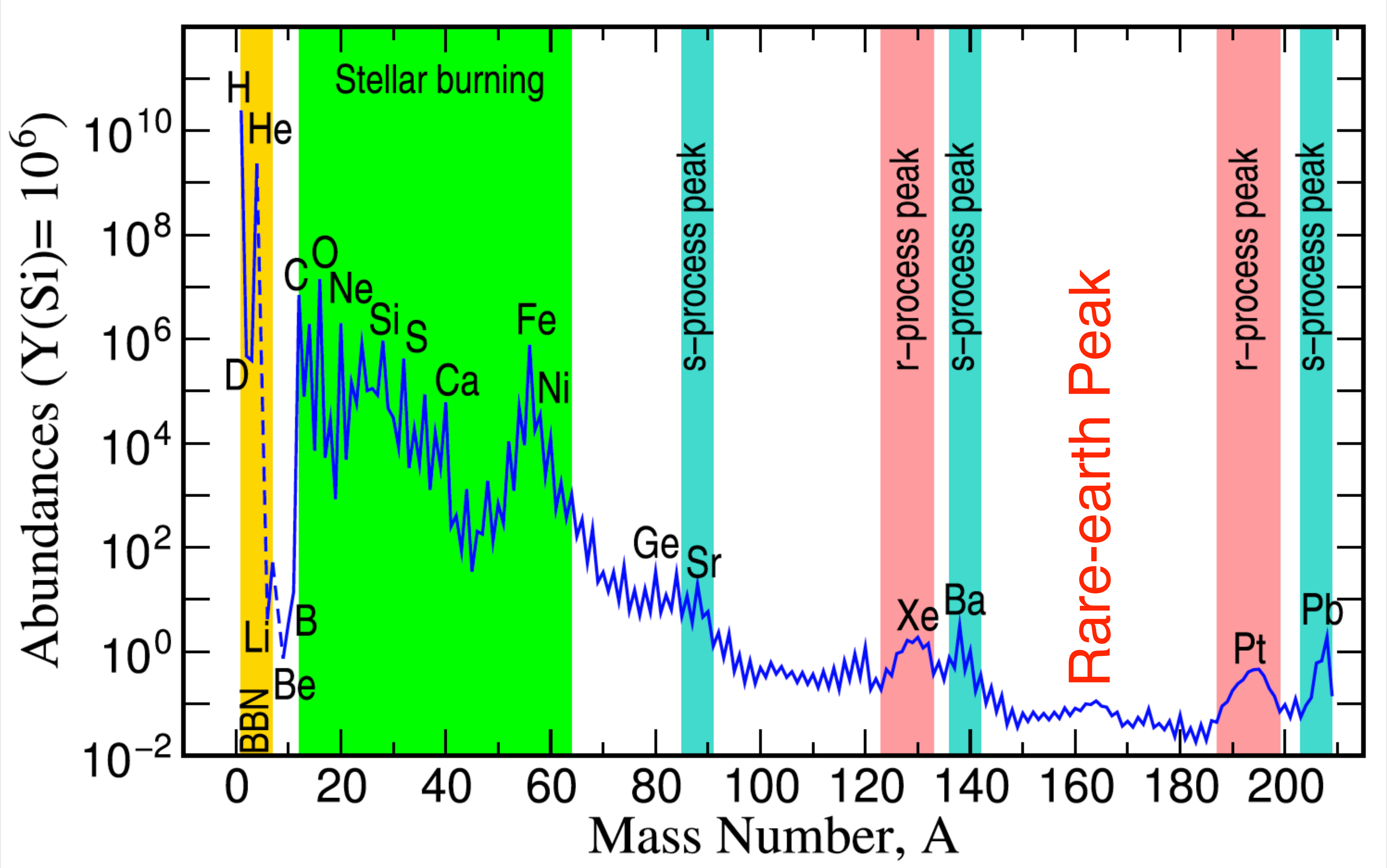
Systematics of E1 Reduced Hindrance Factors

- $f_\nu = (t^{\gamma}_{1/2}/t^{W}_{1/2})^{1/\nu}$
- *Note that the K = 4 isomers are a factor of 10 higher*
- *The re-coupling of particles is an effective* 1/2[510] —> 9/2[624] *transition*
- *This ΔK=ΔΛ=4 transition is greatly hindered by Alaga*



On to (kinda) new things

- *Understand conditions to sustain r-process*
- *Reproducing the rare-earth peak may be a key component to this understanding*
- *~20 years ago, Dracoulis, Kondev, & Lane ran a series of multi-nucleon transfer reactions to produce neutron-rich nuclei that are likely to have isomers*



J. J. Cowan et al., Rev. Mod. Phys. 93, 015002 (2021)