γ-ray spectroscopy for nuclear structure; β-decay studies in the ARIEL era

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What will ARIEL do for us?

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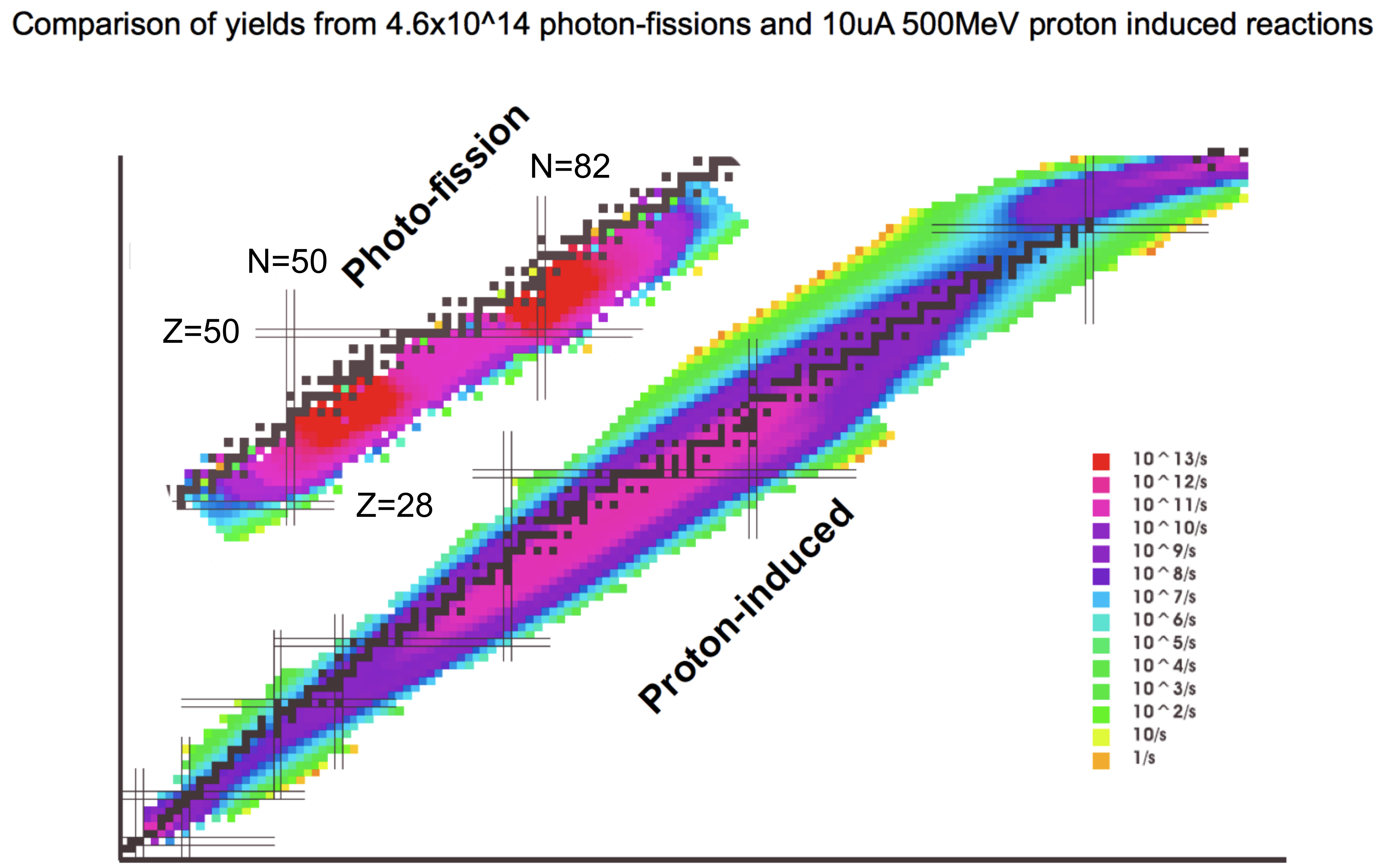
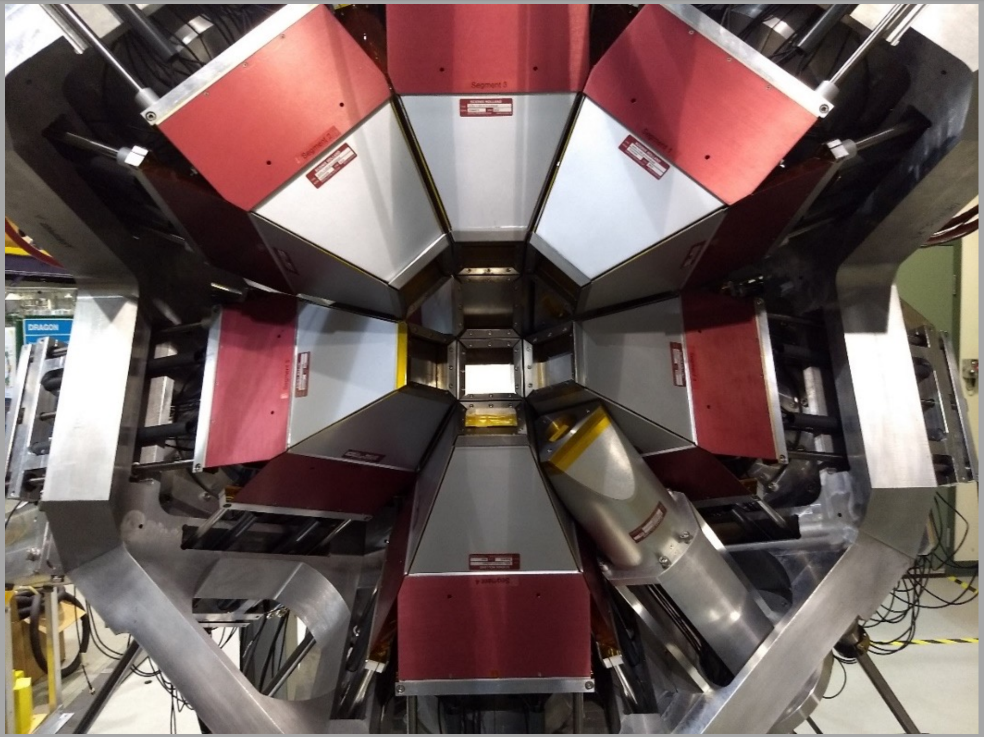
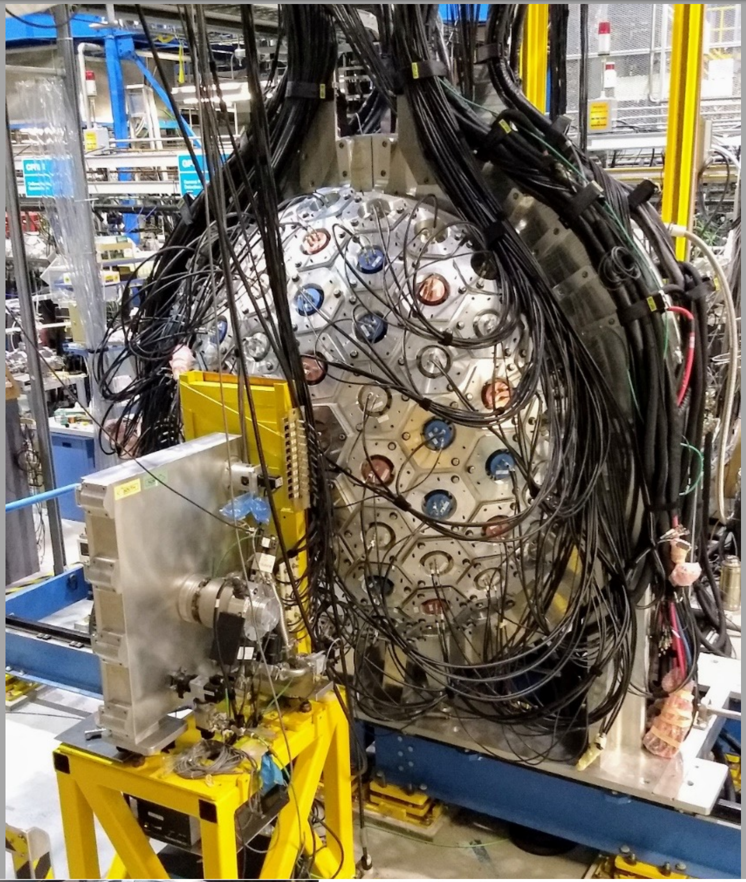
- Excellent yields near the fission peaks
- Multi-user capability that enables experiments of longer duration
- *Both* points are important to our future programme

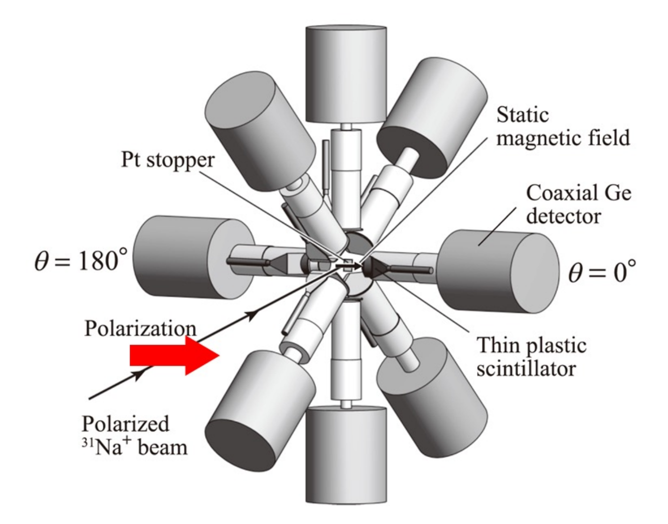


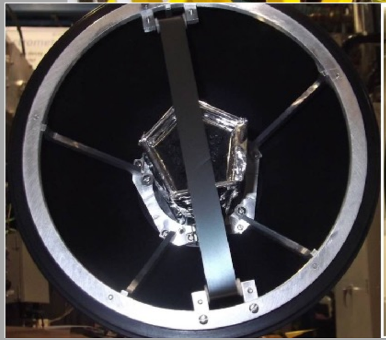
Our workhorse – the GRIFFIN spectrometer

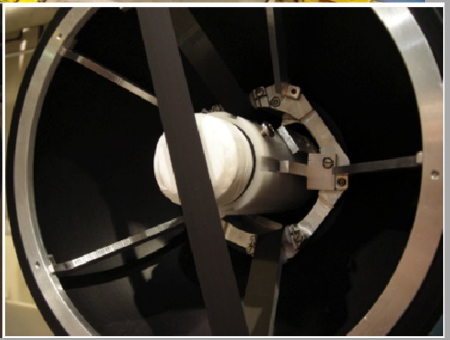




- **Otsaka setup for β-γ angular correlations with spin-polarized beams also produces important results and extend capabilities**







Nuclear structure studies with γ-ray spectroscopy following β-decay

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- Three general themes
  - Studies related to *fundamental symmetries*, e.g. superallowed Fermi β decay, characterized by *high-precision* measurements
    - Structure information on the daughters gathered in the process
  - Studies related to nuclei *far from stability*, characterized by *weak beams* and *low rates*
    - Can be compensated somewhat by GRIFFIN's capabilities or long durations
  - Studies related to nuclei *on or near stability*, characterized by *intense beams* and *high rates*
    - ARIEL can extend the intense-beam envelope into the photofission yield peak region

- My view:
  - Let other facilities pursue the extremes – we should focus on where we have the superior beam+detection efficiency+duration advantage
  - Push the level of statistics – low-statistics experiments lead to high-speculation physics; we should aim for definitive experiments

Focus on shape coexistence – why are they interesting?

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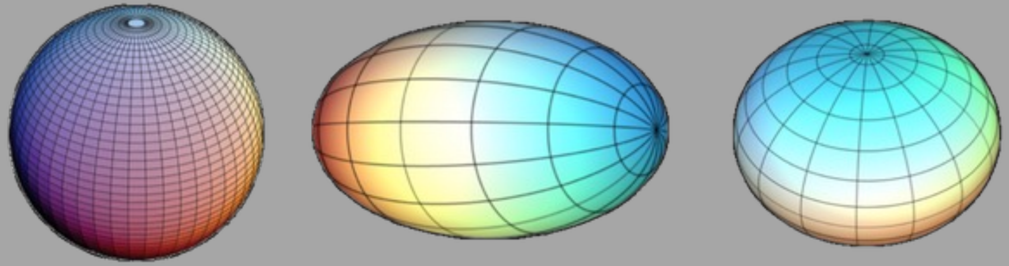
- What do we mean by shape coexistence?
  - presence of states in the same nucleus within a narrow energy range of two (or more) states that have well defined and distinct properties that can be interpreted in terms of different intrinsic shapes

- The shapes we observe, e.g., spherical, prolate, oblate, triaxial



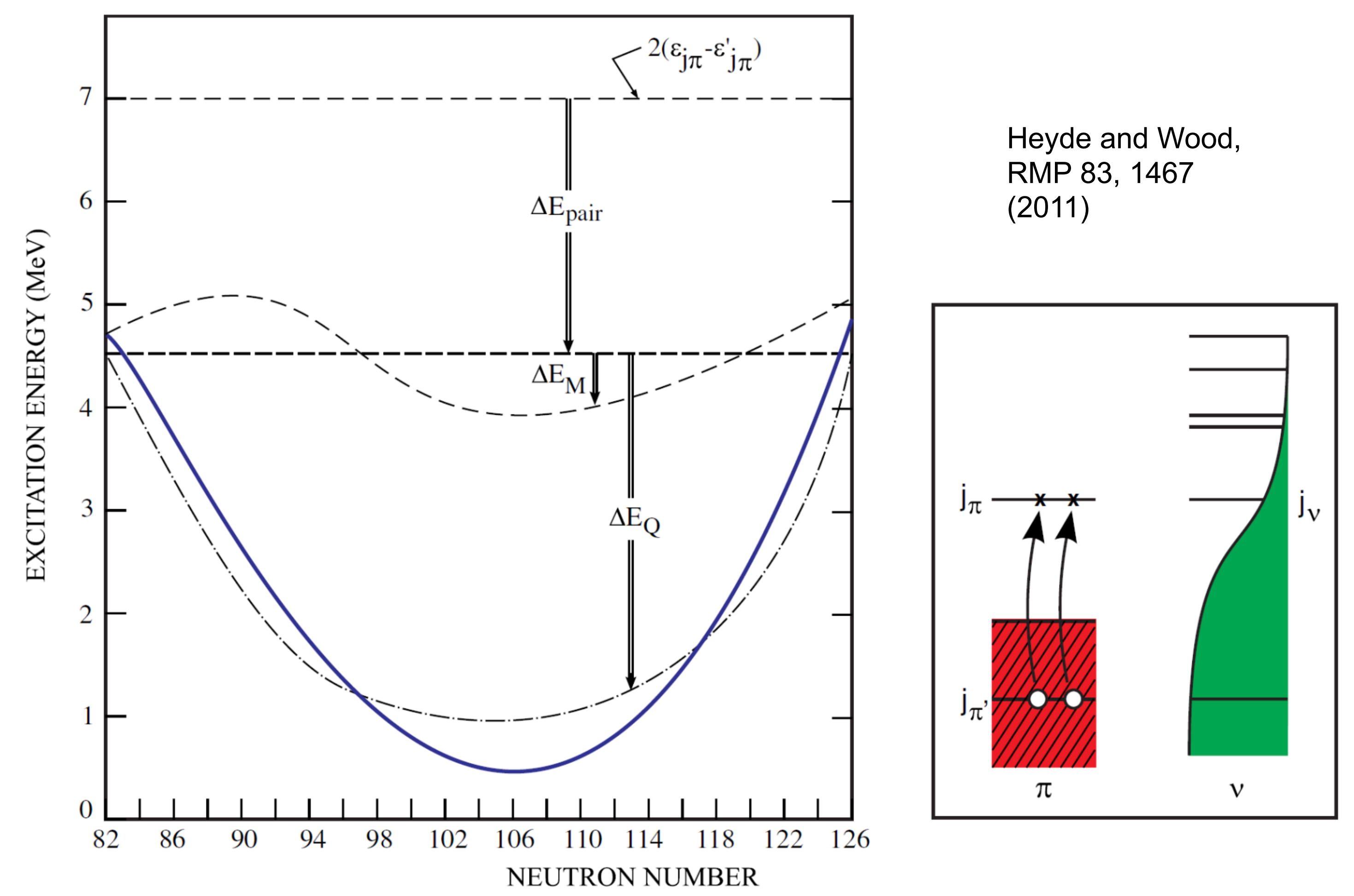
emerge as a consequence of the nucleon-nucleon interaction manifest in a many-body system

- The presence of competing shapes due to effects of correlations, especially pairing and quadrupole-quadrupole correlations amongst nucleons, overcoming cost of energy promoting particles into different orbits – even across major shell gaps

- Studies of shape coexistence enables us to study effects of correlation energies on deformation (or *vice versa*) within a system having the same number of protons and neutrons

Multiparticle-multihole states and shape coexistence

- Deformation is driven by the quadrupole-quadrupole interaction between protons and neutrons – the more valence particles of both types, the greater the deformation (up to a point)
- There can be a substantial gain in energy due to correlations between the particles such that the energy cost for promoting particle across shells can be offset
- The most common mechanism to generate states with different shapes involves the creation of multiparticle-multihole states



Heyde and Wood, RMP 83, 1467 (2011)

We have a strong programme in shape coexistence studies with β decay

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PRL **110,** 022504 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2013

Collective Structure in ^{94}Zr and Subshell Effects in Shape Coexistence

A. Chakraborty,[1,2,*] E. E. Peters,[2] B. P. Crider,[1] C. Andreoiu,[3] P. C. Bender,[4] D. S. Cross,[3] G. A. Demand,[5] A. B. Garnsworthy,[4] P. E. Garrett,[5] G. Hackman,[4] B. Hadinia,[5] S. Ketelhut,[4] Ajay Kumar,[1,2,†] K. G. Leach,[5] M. T. McEllistrem,[1] J. Pore,[3] F. M. Prados-Estévez,[1,2] E. T. Rand,[5] B. Singh,[6] E. R. Tardiff,[4] Z.-M. Wang,[3,4] J. L. Wood,[7] and S. W. Yates[1,2]

PHYSICAL REVIEW LETTERS **123,** 142502 (2019)

Editors' Suggestion Featured in Physics

Multiple Shape Coexistence in ^{110,112}Cd

P. E. Garrett,[1,2] T. R. Rodríguez,[3] A. Diaz Varela,[1] K. L. Green,[1] J. Bangay,[1] A. Finlay,[1] R. A. E. Austin,[4] G. C. Ball,[5] D. S. Bandyopadhyay,[1] V. Bildstein,[1] S. Colosimo,[4] D. S. Cross,[6] G. A. Demand,[1] P. Finlay,[1] A. B. Garnsworthy,[5] G. F. Grinyer,[7] G. Hackman,[5] B. Jigmeddorj,[1] J. Jolie,[8] W. D. Kulp,[9] K. G. Leach,[1,*] A. C. Morton,[5,†] J. N. Orce,[2] C. J. Pearson,[5] A. A. Phillips,[1] A. J. Radich,[1] E. T. Rand,[1,‡] M. A. Schumaker,[1] C. E. Svensson,[1] C. Sumithrarachchi,[1,†] S. Triambak,[2] N. Warr,[8] J. Wong,[1] J. L. Wood,[10] and S. W. Yates[11]

PHYSICAL REVIEW LETTERS **125,** 172501 (2020)

Absence of Low-Energy Shape Coexistence in ^{80}Ge: The Nonobservation of a Proposed Excited 0_2^+ Level at 639 keV

F. H. Garcia,[1,*] C. Andreoiu,[1] G. C. Ball,[2] A. Bell,[1] A. B. Garnsworthy,[2] F. Nowacki,[3,4] C. M. Petrache,[5] A. Poves,[6] K. Whitmore,[1] F. A. Ali,[7,8] N. Bernier,[2,9,†] S. S. Bhattacharjee,[2,‡] M. Bowry,[2] R. J. Coleman,[10] I. Dillmann,[2,11] I. Djianto,[1] A. M. Forney,[12] M. Gascoine,[1] G. Hackman,[2] K. G. Leach,[13] A. N. Murphy,[2] C. R. Natzke,[14,13] B. Olaizola,[14] K. Ortner,[1] E. E. Peters,[15] M. M. Rajabali,[16] K. Raymond,[1] C. E. Svensson,[10] R. Umashankar,[14] J. Williams,[1,§] and D. Yates[14,9]

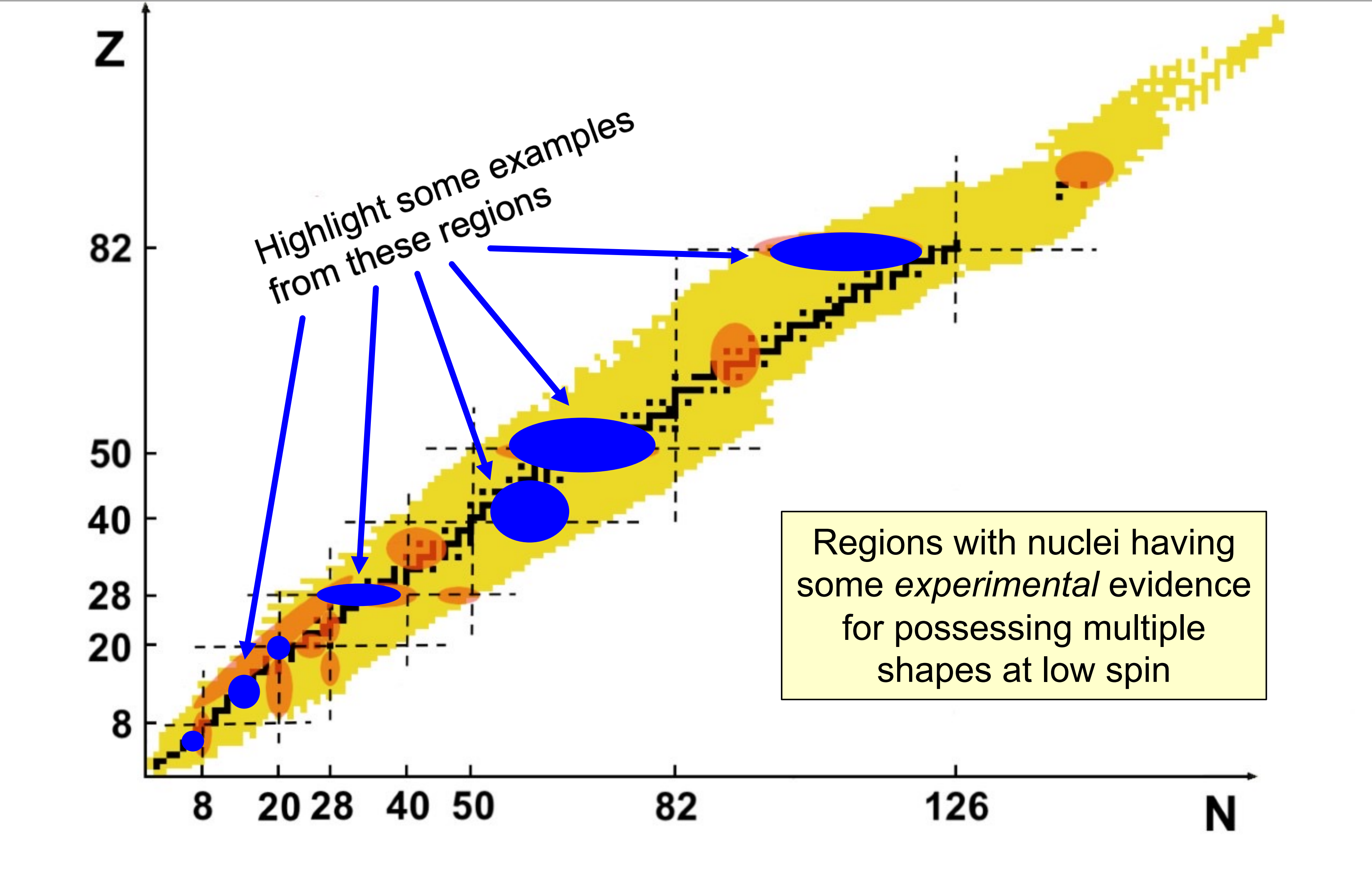
PHYSICAL REVIEW LETTERS **130,** 122502 (2023)

First Evidence of Axial Shape Asymmetry and Configuration Coexistence in ^{74}Zn: Suggestion for a Northern Extension of the $N = 40$ Island of Inversion

M. Rocchini,[1,*] P. E. Garrett,[1] M. Zielińska,[2] S. M. Lenzi,[3,4] D. D. Dao,[5] F. Nowacki,[5] V. Bildstein,[1] A. D. MacLean,[1] B. Olaizola,[6,†] Z. T. Ahmed,[1] C. Andreoiu,[7] A. Babu,[6] G. C. Ball,[6] S. S. Bhattacharjee,[6,‡] H. Bidaman,[1] C. Cheng,[6] R. Coleman,[1] I. Dillmann,[6,8] A. B. Garnsworthy,[6] S. Gillespie,[6] C. J. Griffin,[6] G. F. Grinyer,[9] G. Hackman,[6] M. Hanley,[10] A. Illana,[11] S. Jones,[12] A. T. Laffoley,[1] K. G. Leach,[10] R. S. Lubna,[6,§] J. McAfee,[6,13] C. Natzke,[6,10] S. Pannu,[1] C. Paxman,[6,13] C. Porzio,[6,14,15,∥] A. J. Radich,[1] M. M. Rajabali,[16] F. Sarazin,[10] K. Schwarz,[6] S. Shadrick,[10] S. Sharma,[9] J. Suh,[9] C. E. Svensson,[1] D. Yates,[6,17] and T. Zidar[1]

Shape coexistence in the nuclear landscape

- Regions of shape coexistence are now known to be located throughout the nuclear chart, although still mainly concentrated in the vicinity of closed shell or subshells
  - There has been much activity recently, including areas suggested to possess multiple shape coexistence – C, Si/Mg, Ni, Sr/Zr, Cd, Pb/Hg



What are the experimental signatures of shape coexistence?

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- Level energies
  - Appearance of "unexpected" levels at low energies, e.g., low-lying 0^+ states
  - Appearance of rotational bands, especially in a spherical nucleus
  - Inferred moments of inertia

From γ-γ coincidence measurements with Ge detectors

- Transition rates – vastly different $B(E2)$ values within bands

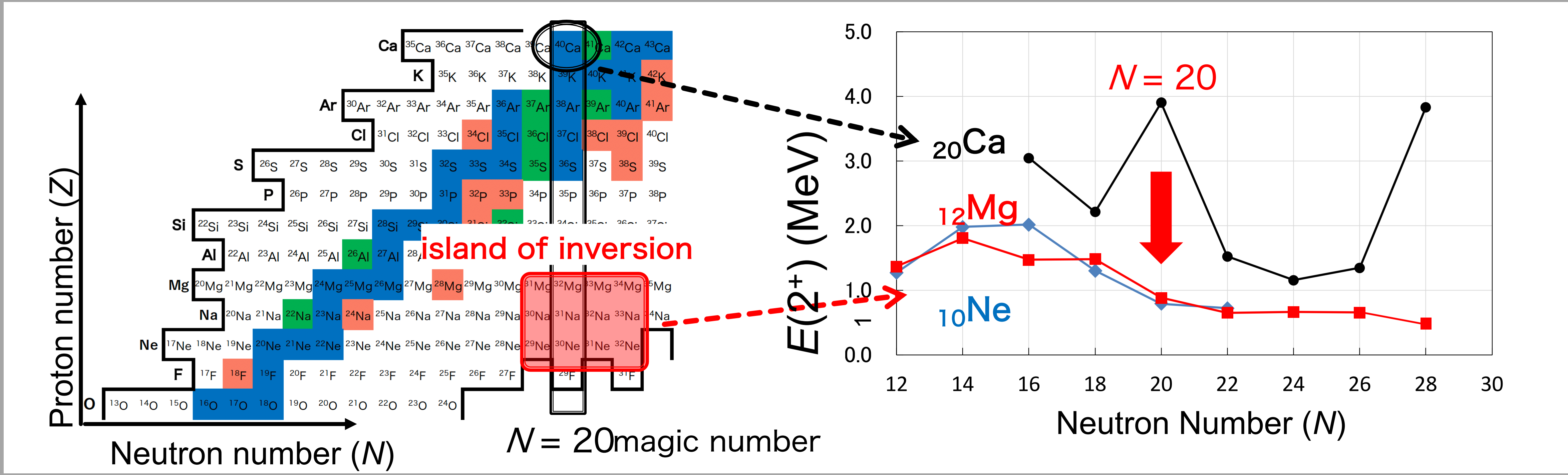
From lifetime measurements with $LaBr_3$ detectors

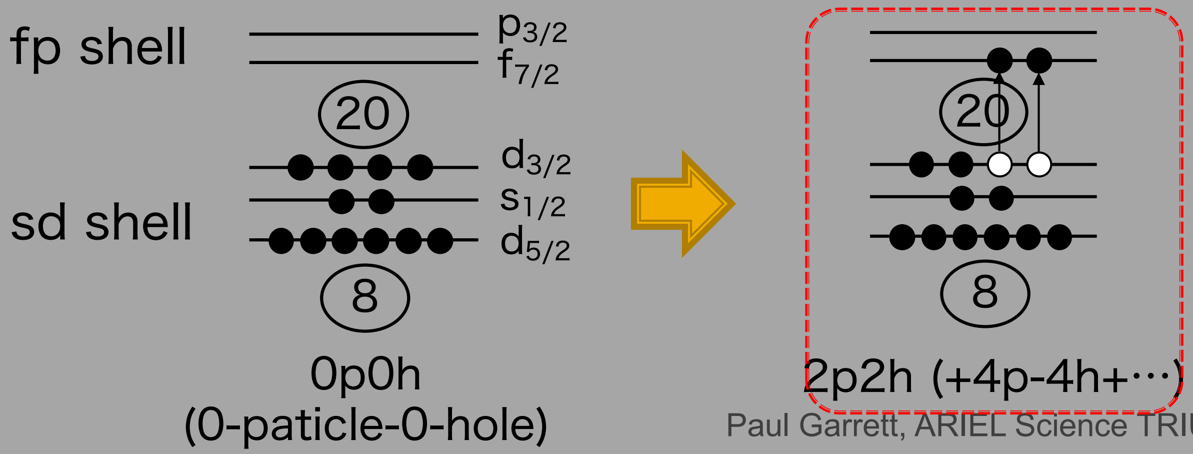
- Transfer reaction cross sections – large enhancements of cross sections, especially to excited 0^+ states
- Quadrupole moments – measure of charge distribution revealing deformation
- Charge radii – directly measuring size of nuclear state
- Sets of EM transition matrix elements to form "invariant" quantities
- $E0$ transition strengths – enhancements to $E0$ transition rates require mixing of states with different deformations

From measurements of conversion electrons using Si(Li) detectors

The *N*=20 "island of inversion"

- **Expected spherical shape for the ground states, but instead they are deformed**



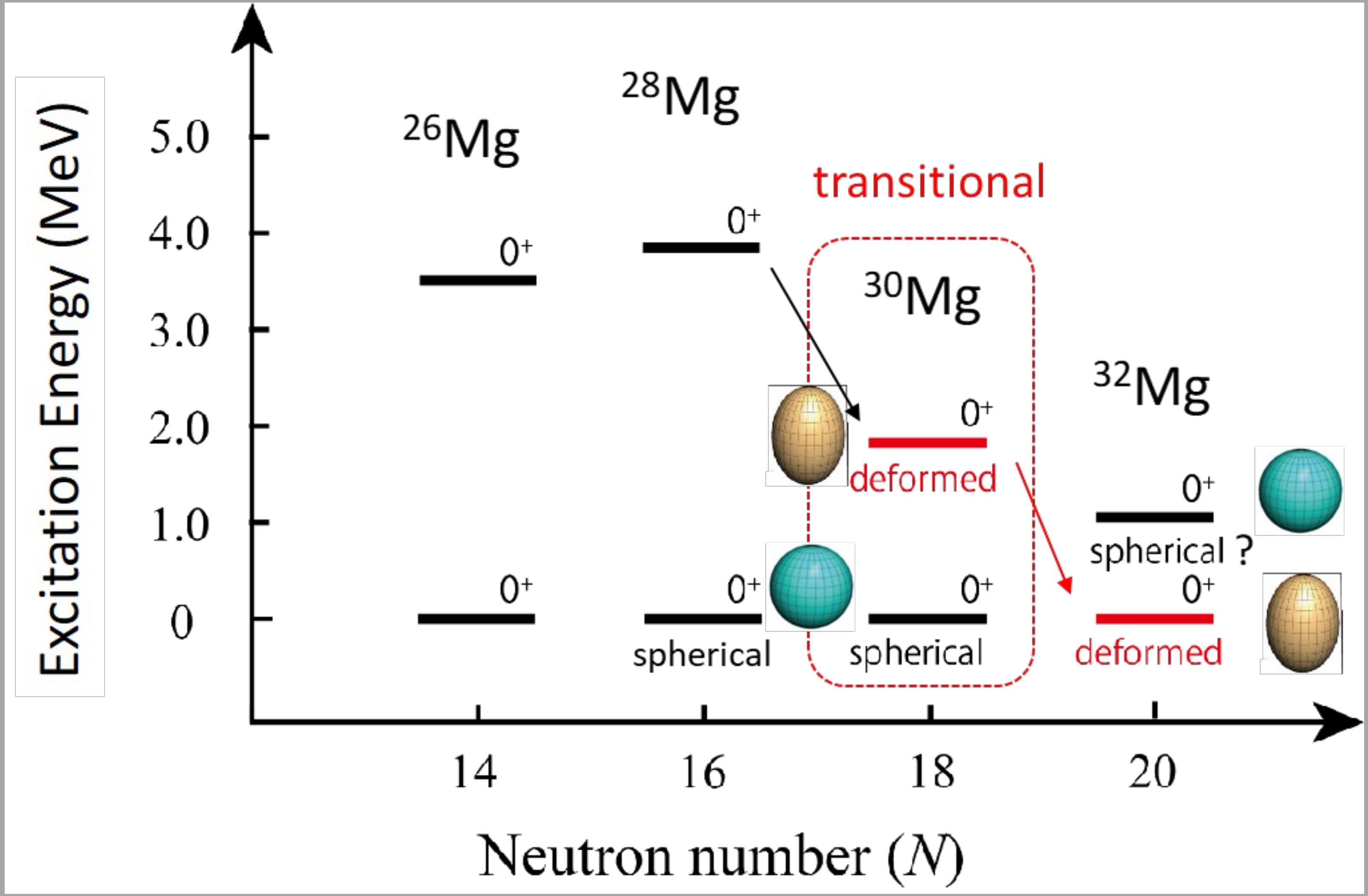


dominant in neutron-rich N~20 region

"island of inversion"

E. Caurier et al., Phys. Rev. C **90**, 014302 (2014).

The N=20 island of inversion region



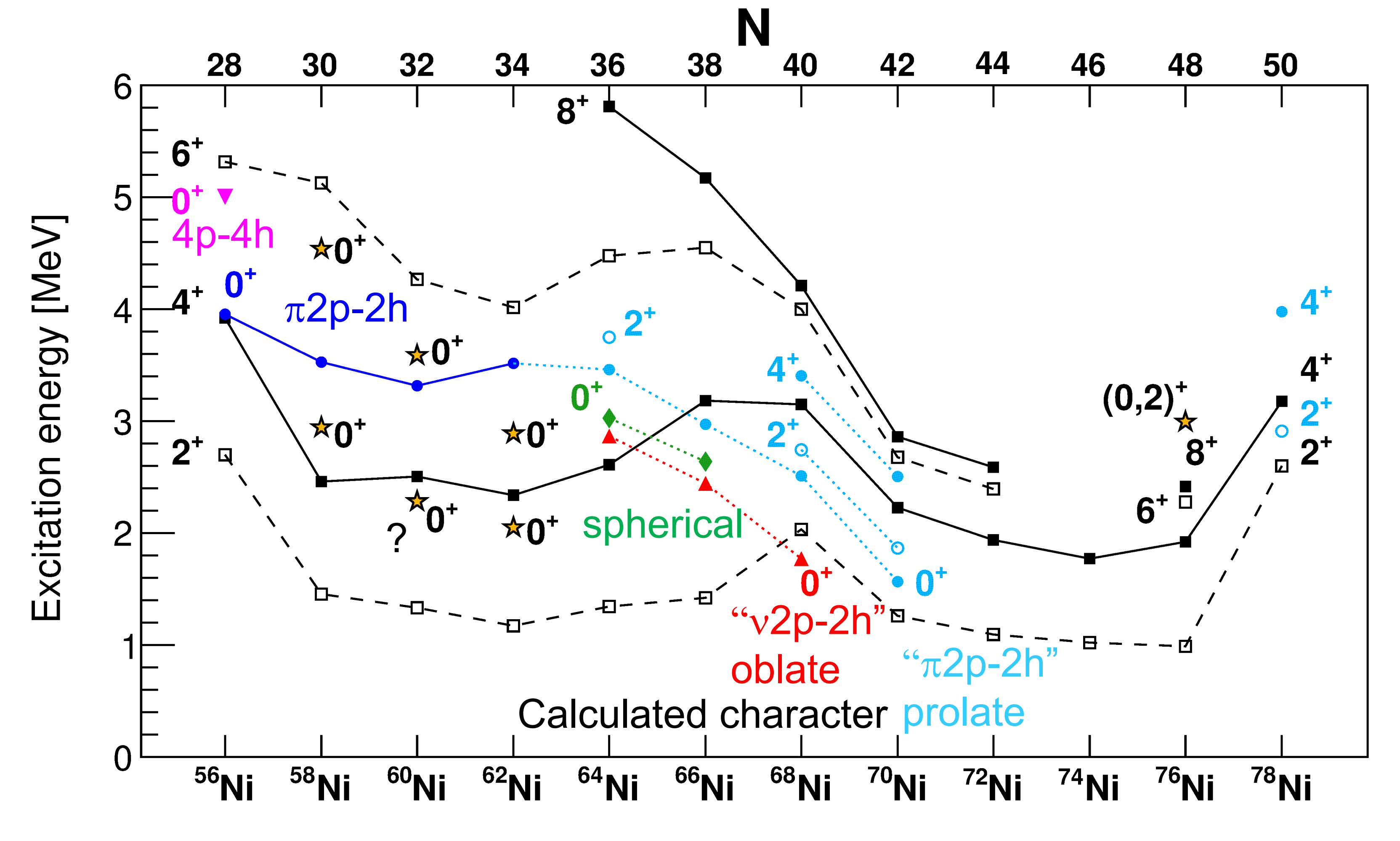
- **Recent 3-level mixing calculations suggested that the ^{30}Mg ground state was a mixture of the normal-ordered 0p-0h and intruder 2p-2h configurations, with the 0_2^+ a mixture of the 2p-2h and 4p-4h configurations, and the existence of an unknown 0_3^+ state that has the dominant 0p-0h configuration**

- **0_2^+ state in ^{32}Mg believed to have $t_{1/2}$ in range of 10 – 38 ns**

Can reach 10^{10} decays of ^{30}Na in ~ 10 days, 10^8 decays of ^{32}Na in ~ 3 weeks

The Ni isotopes

- Variety of highly deformed structures observed in vicinity of ^{56}Ni by Lund group (e.g., ^{56}Ni by D. Rudolf et al., PRL 82, 3763 (1999))

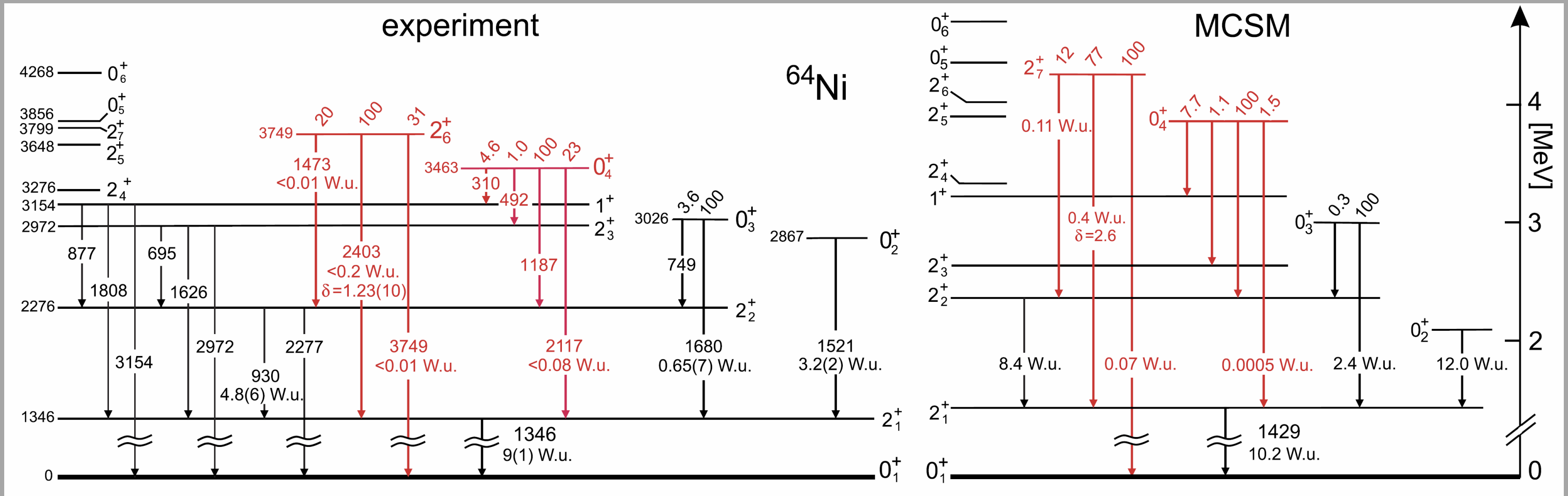


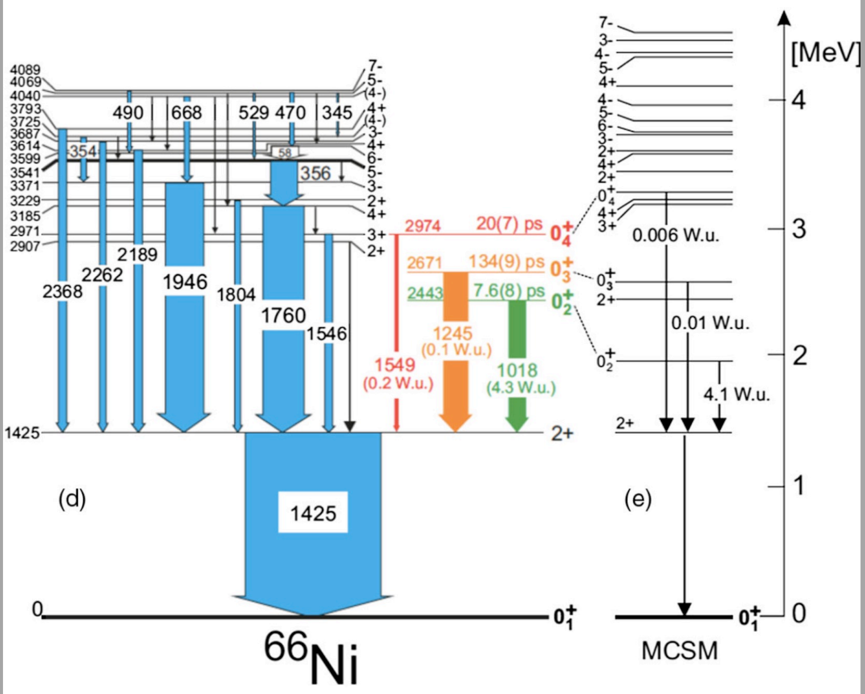
Garrett, Zielinska, and Clement, PPNP 124, 123931 (2022)

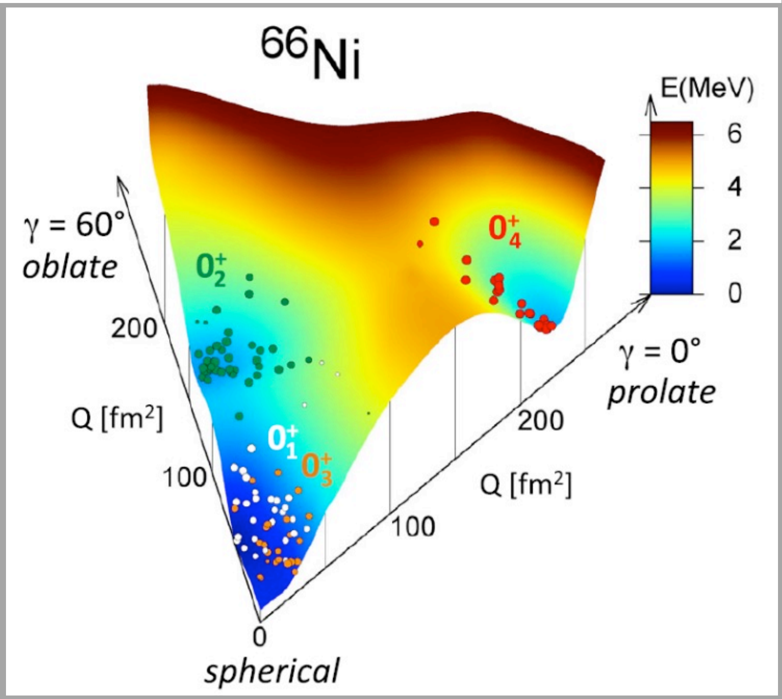
Suggestions for multiple shapes in $^{64-68}$Ni through comparisons with MCSM

- **Suggested shapes need to be confirmed through additional measurements**

S. Leoni et al., PRL 118, 162502 (2017)
N. Mărginean et al., PRL 125, 102502 (2020)







Trouble in paradise for *E*0s – the mysterious case of the Ni isotopes

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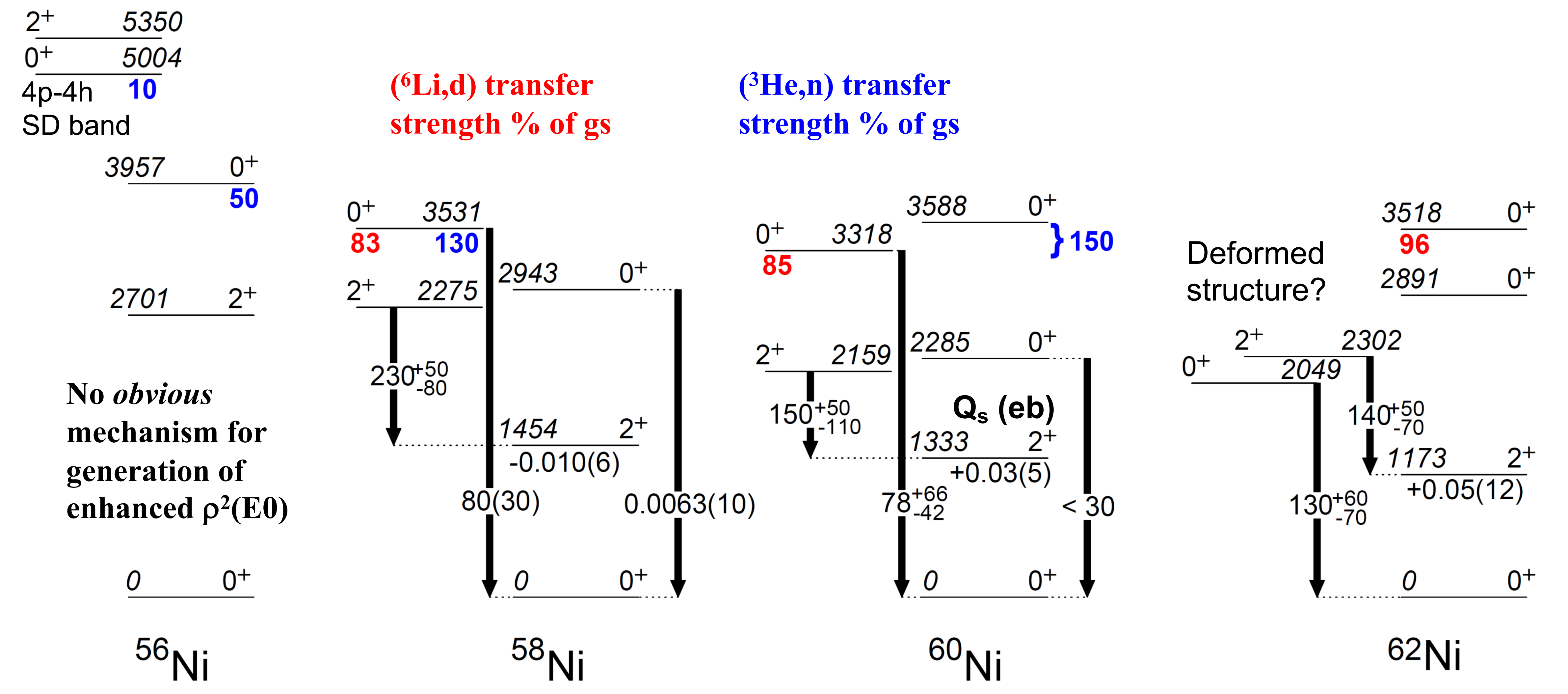
Transitions labelled with $10^3\rho^2(E0)$

E0 data from L. Evitts et al., PRC 99, 024306 (2019)



Garrett, Zielinska, and Clement, PPNP 124, 123931 (2022)

Example – conflicting interpretations in ^{68}Ni

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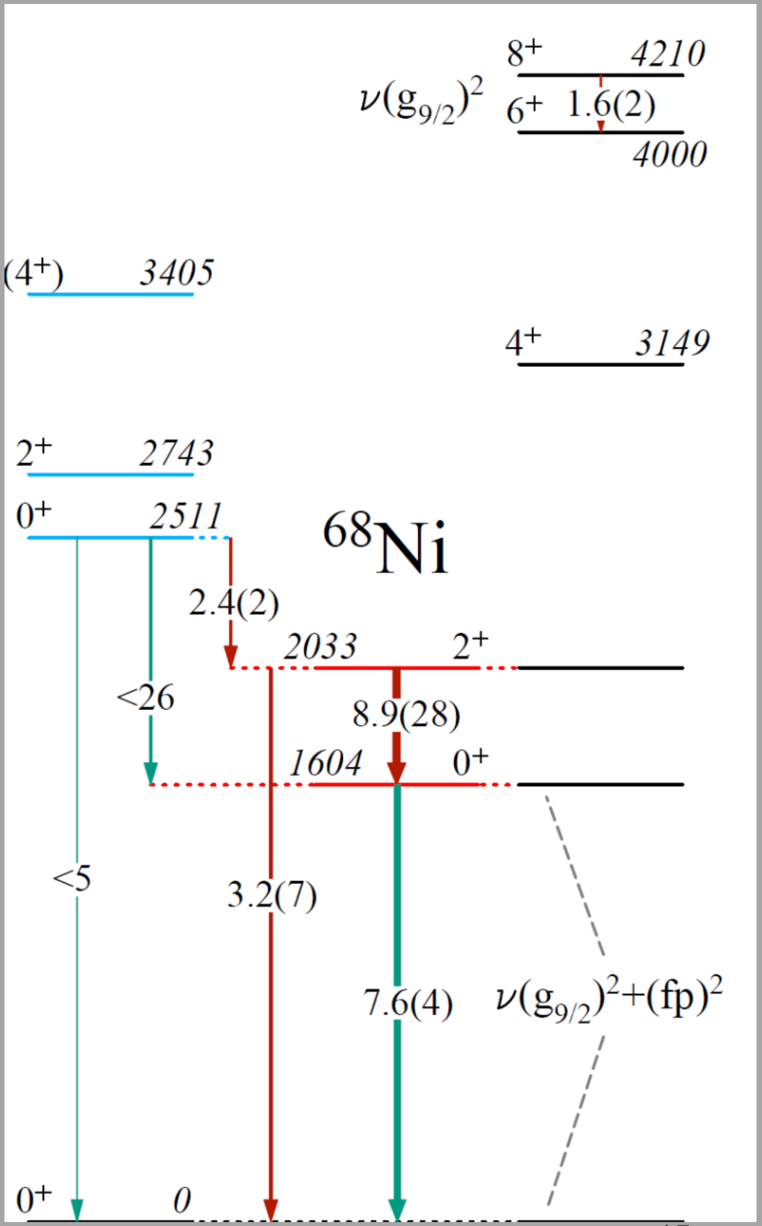
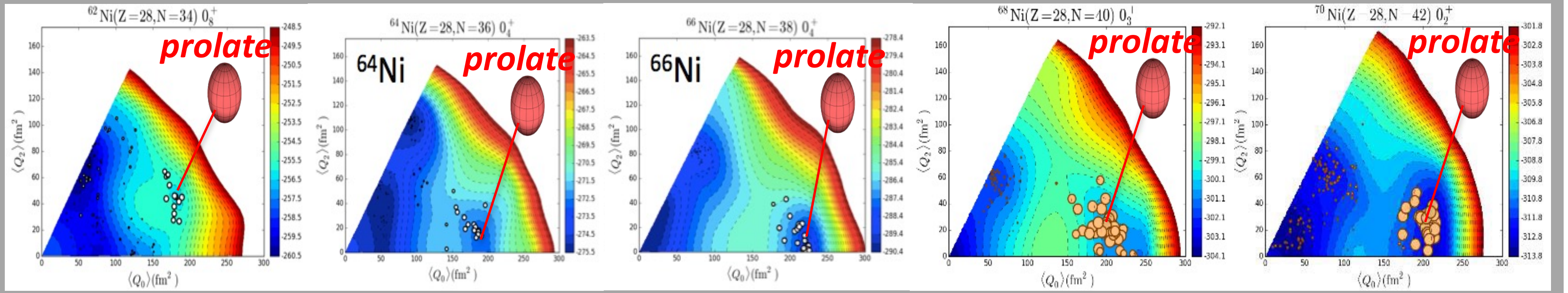
- Key transition $2_1^+ \rightarrow 0_2^+ \sim 9$ W.u. establishes a deformed structure, but was a very weak transition observed in one experiment only
- An alternative interpretation involves a seniority-2 structure, with the ground state and 0_2^+ state involving a mixture of $(g_{9/2})^2+(p_{1/2})^2$ neutrons

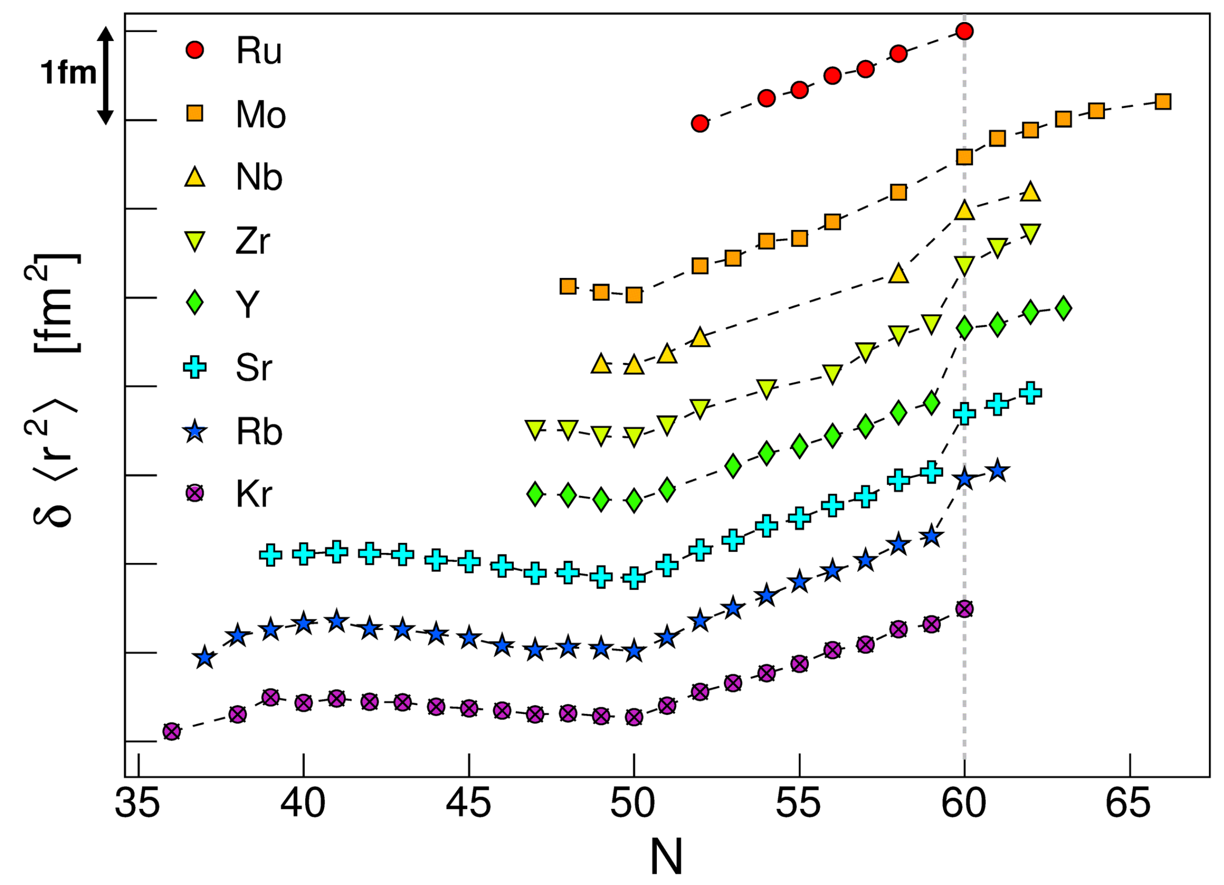
- To study Ni isotopes, ideally extract Co beams (successfully done at ISOLDE); a Co laser scheme for use with TRILIS is ready
- Rates will still be low to reach ^{68}Ni – prime example of extended beam time making use of multi-user capability



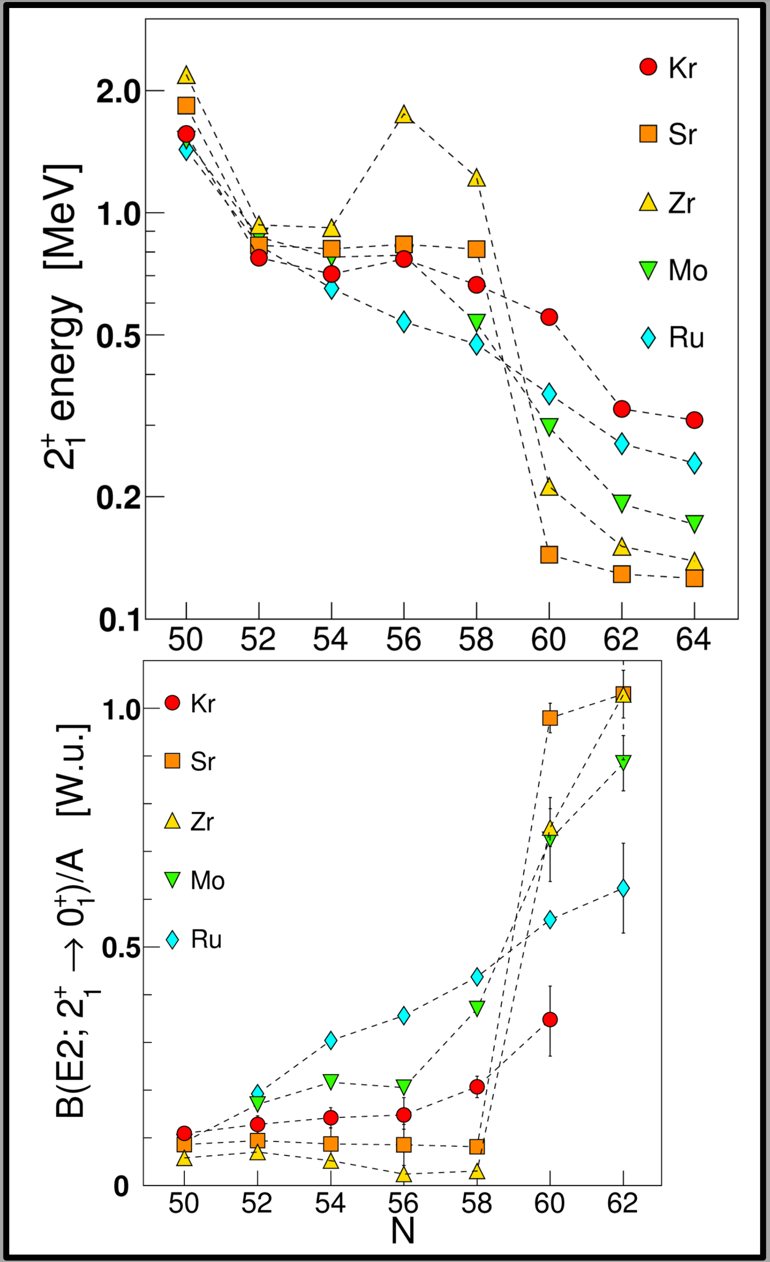


Zr isotopes undergo the most rapid change of ground state structure across the nuclear chart

- **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**

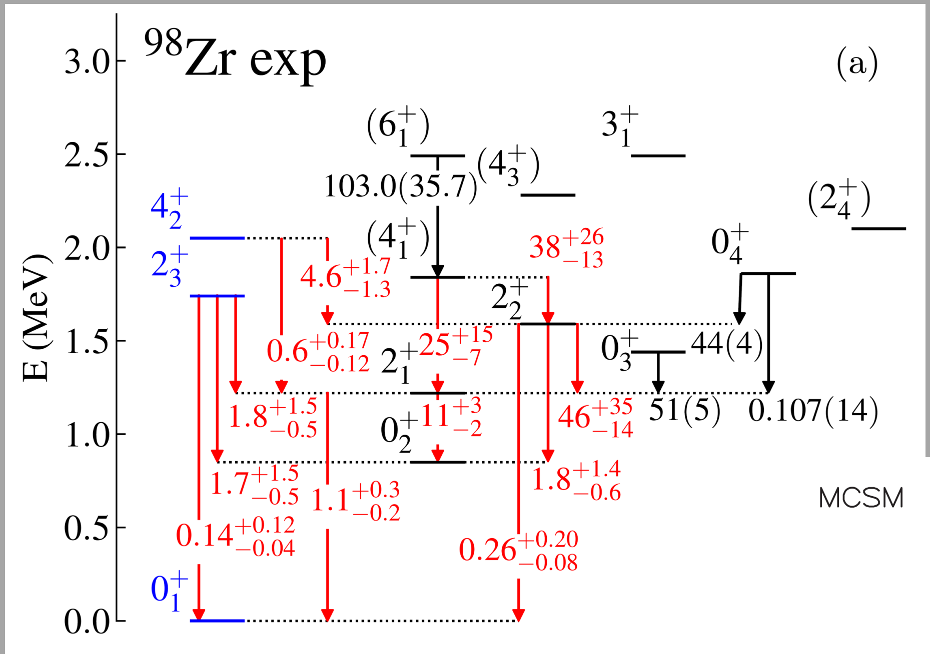


Measured isotope shifts



Insufficient knowledge to distinguish interpretations

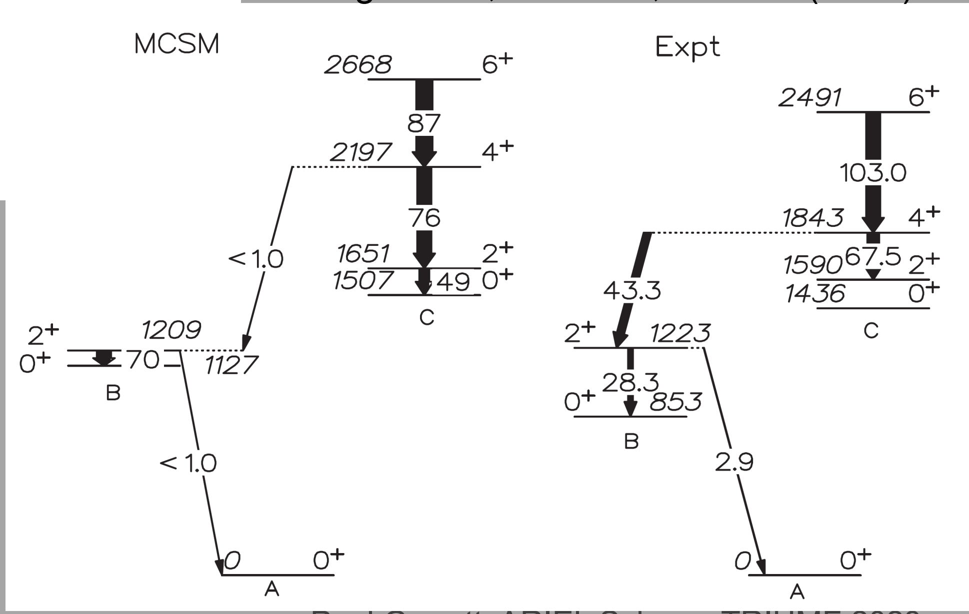
^{98}Zr – lifetimes measured in ^{9}Be induced fission of ^{238}U, and ^{96}Zr+^{18}O 2*p* transfer reaction



V. Karayonchev et al., PRC 102, 064314 (2020)

Substantial differences in both measured lifetimes, and assignments/interpretations

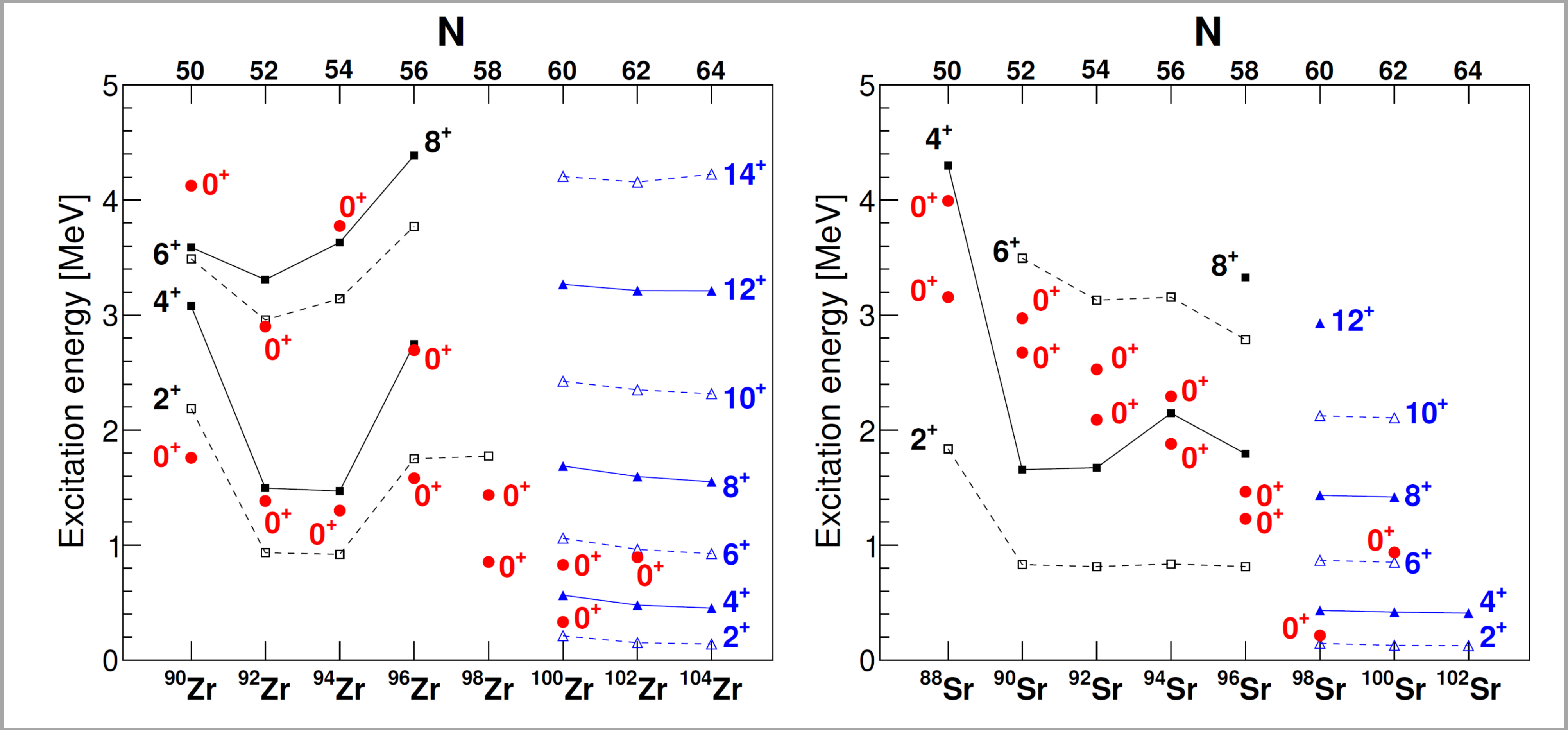
P. Singh et al., PRL 121, 192501 (2018)



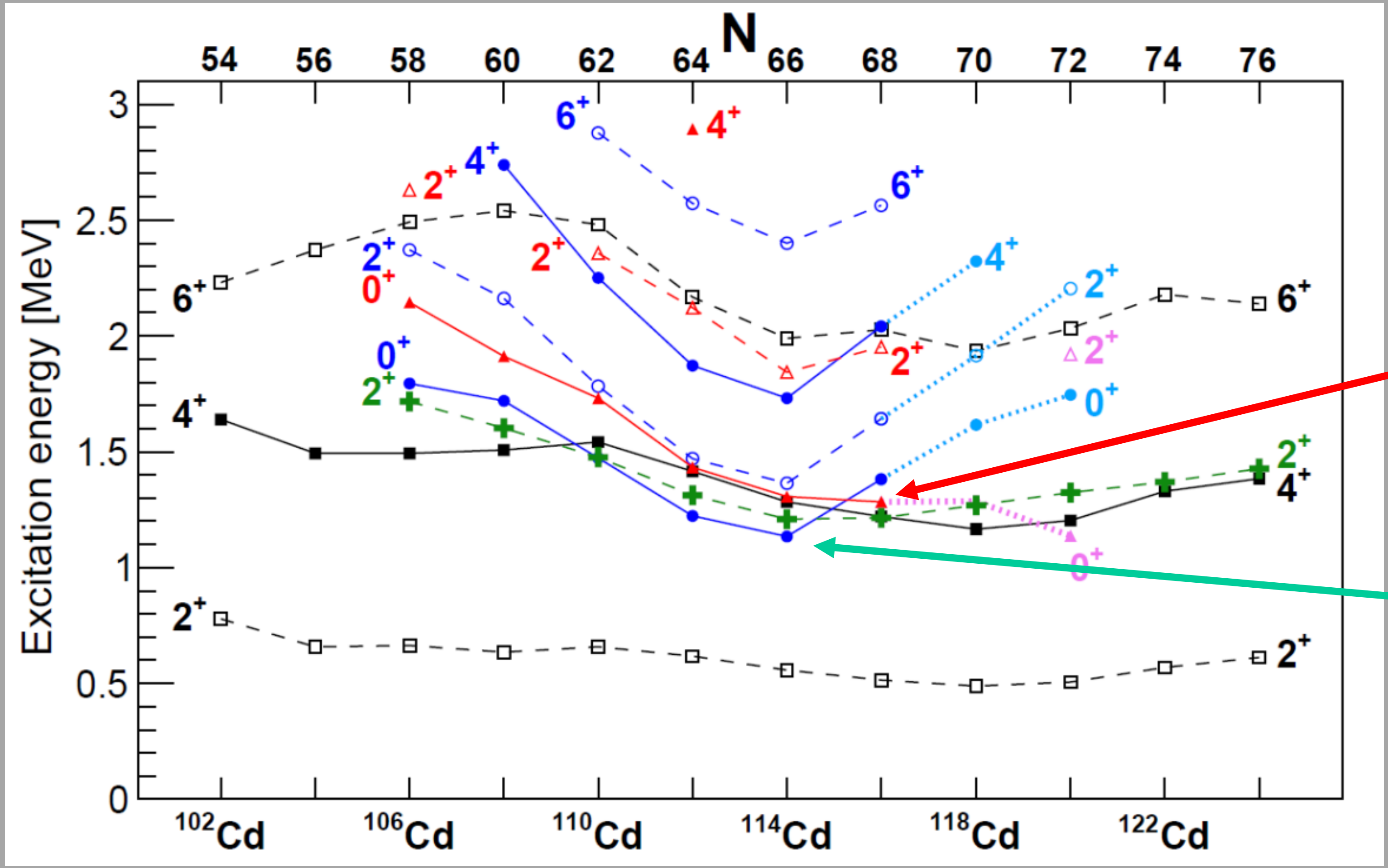
- Singh *et al.* favoured multiple shape coexistence with deformed band structures, Karayonchev *et al.* favoured a multiphonon-like structure with configuration mixing
- Knowledge of excited 0^+ configurations in *N* > 60 Zr and Sr isotopes very limited

Extending studies of the Sr-Zr isotopes

- Need to map the low-spin configurations past N=60 transition point
  - We can reach ^{98}Sr, ^{100}Zr with existing beams and achieve high-statistics data sets
- ARIEL advantage – the required Sr, Rb beams are close to the lower mass fission peak, enabling us to push well past *N*=60

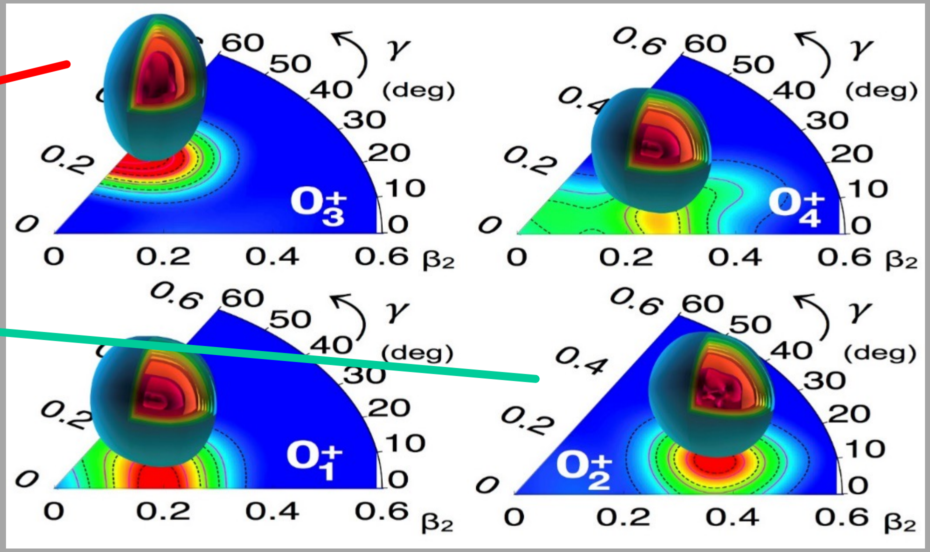


Energy systematics Cd isotopes



"Blue" states – the original "intruder" band, triaxial shape in ^{110,112}Cd from BMF calculations

"Red" states – oblate band in ^{110,112}Cd from BMF calculations



The presumed shapes are based on systematics and similarities of decay properties – but become increasingly uncertain towards the neutron rich isotopes

Energy systematics Cd isotopes

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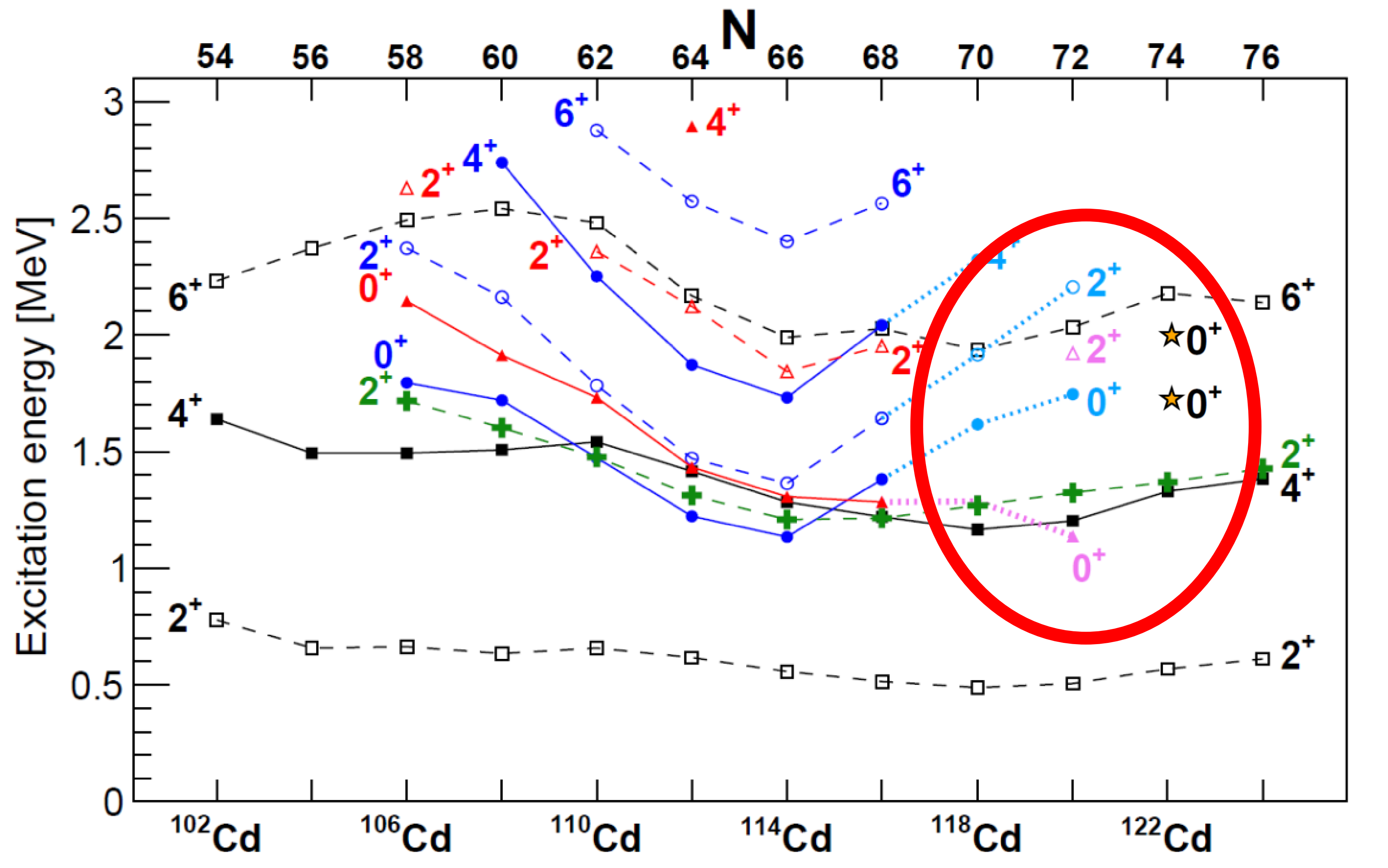

- What is happening with the 0_2^+ state in ^{120}Cd? If a recent measurement is correct, it undergoes a significant drop in energy in ^{120}Cd.
- There are no firm candidates for these configurations beyond ^{120}Cd – the 0_2^+ state in ^{122}Cd would match the energy of the 0_3^+ in ^{120}Cd
- No candidates for excited 0^+ states in ^{124}Cd and heavier

Above mid-neutron-shell we do not have a good understanding of the structure

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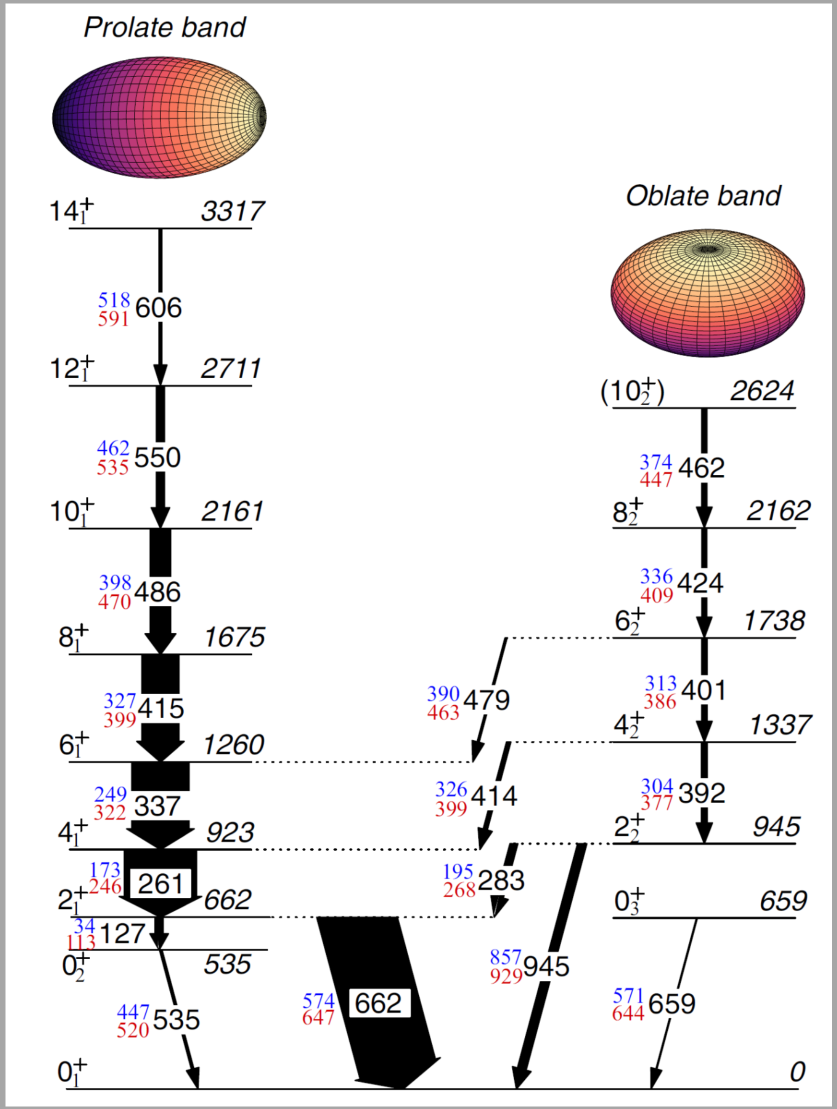
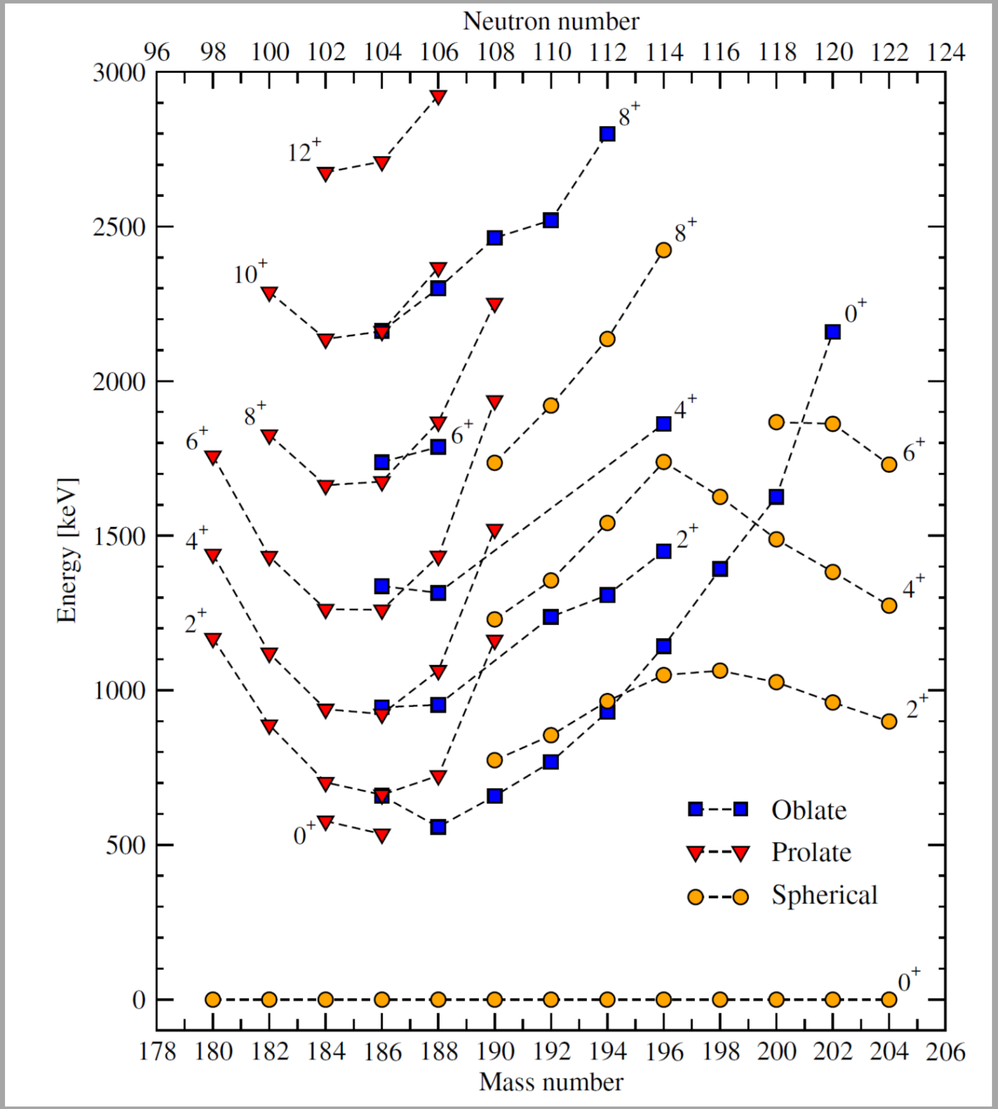
- A spectroscopic *tour de force*, using γγ and γe^- spectroscopy with recoil decay tagging at Jyvaskyla, observed the weak, in-band $2_1^+ \rightarrow 0_2^+$ transition establishing the 0_2^+ state as the head of the prolate band with $B(E2; 2_1^+ \rightarrow 0_2^+) =$ 190(80) W.u.

- Results indicated small mixing of 0_2^+ and 0_3^+ states





Ojala et al, Nature Communications **5**, 213 (2022)

Shape coexistence well established in Hg isotopes

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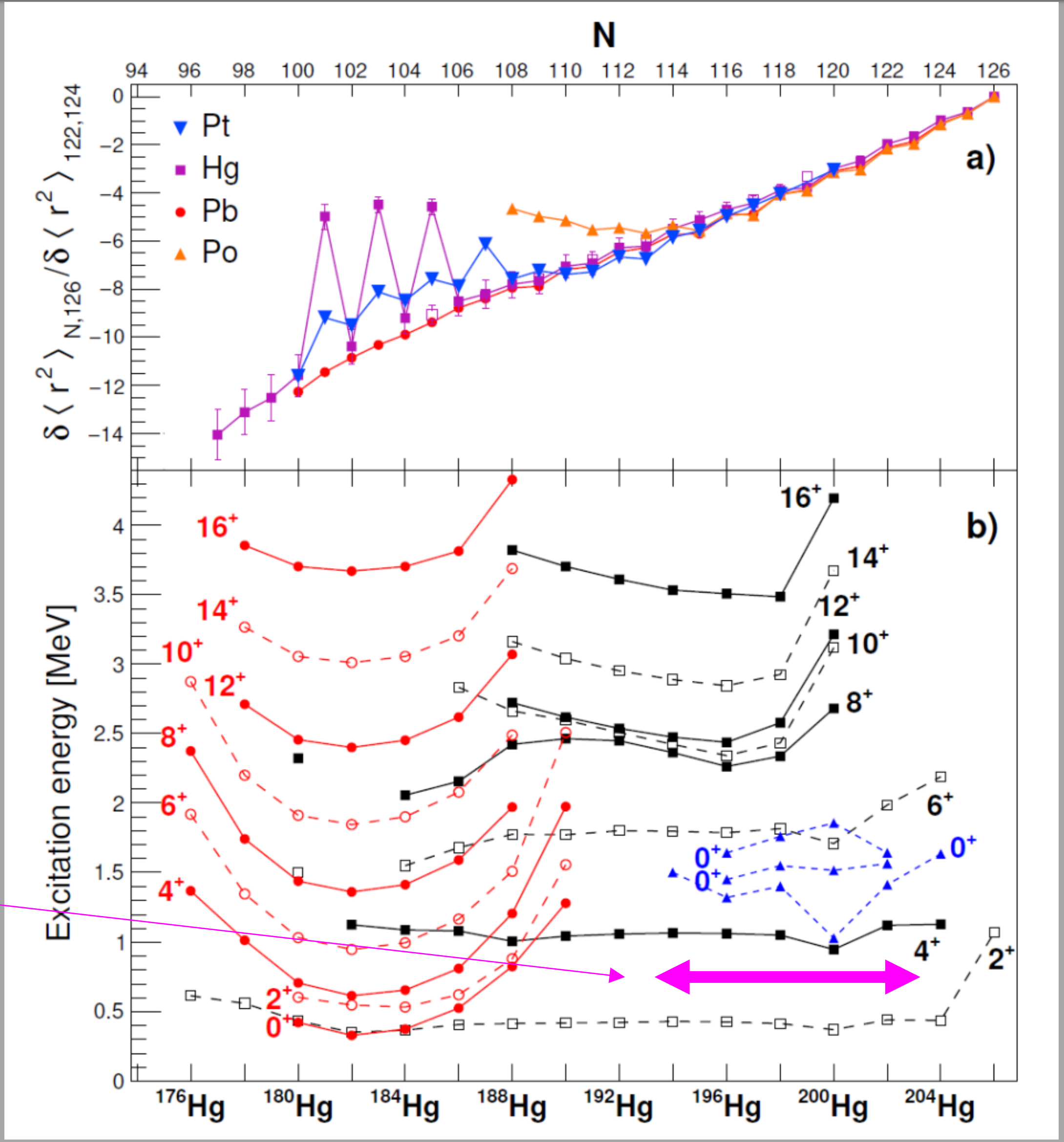
- Difference in mean-squared charge radii for Hg show odd-even staggering – large changes in ground state deformation observed
- Energy systematics of deformed intruder states display "typical" parabolic dependence on valence neutron number
- Information on excited 0^+ states drops dramatically outside region that can be probed with two-nucleon-transfer reactions
  - population cross section in many reactions, especially HI fusion evaporation, often extremely small
  - Is there another configuration as in the Pb isotopes and triple shape coexistence?



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

- **There are a wide variety of open nuclear structure questions – ARIEL facility with increased reach, and especially multi-user capability, will enable studies to address these questions**

- **While my focus was on shape-coexistence in even-even, studies of odd-A vital to establish and track single-particle structures**

- **A coordinated approach with experiments at other facilities (e.g., transfer or Coulomb excitation at TIGRESS, measurements at ISOLDE or FRIB, etc.) will reap enormous benefits**

- **Systematics, systematics, systematics,…**
  - **It's not stamp collecting, this is often where the physics lies!**

- **… but don't get caught up in doing mediocre experiments on a dozen nuclei instead of outstanding measurements on a few**

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

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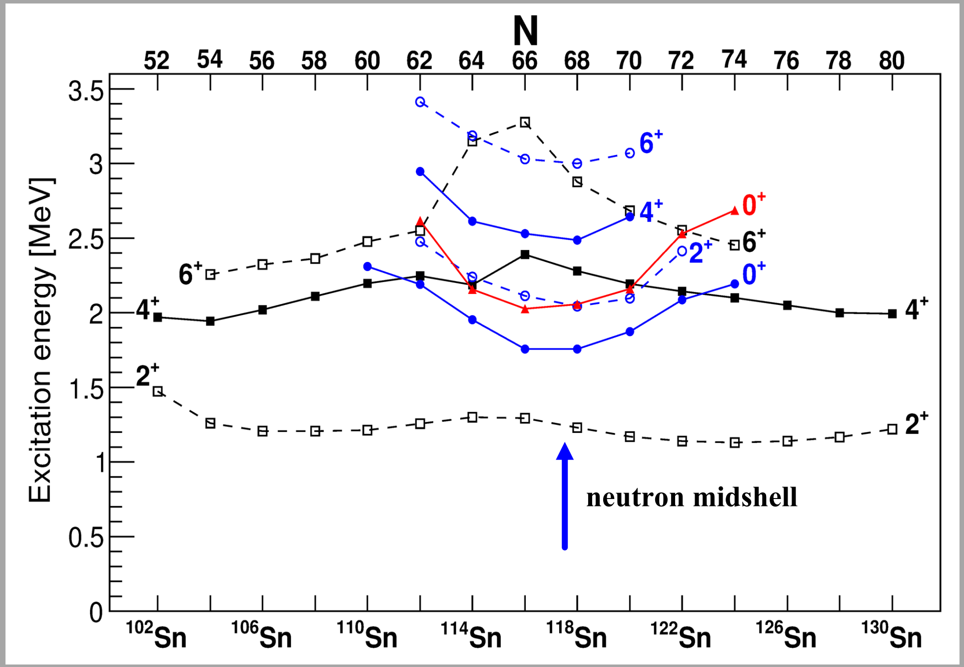
Sn isotopes have characteristic parabolic pattern to excitation energies



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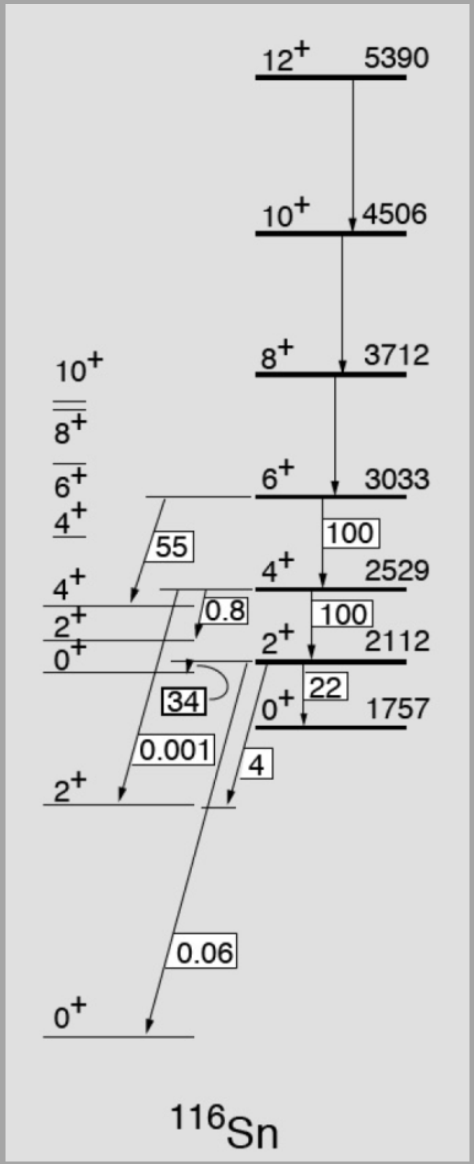
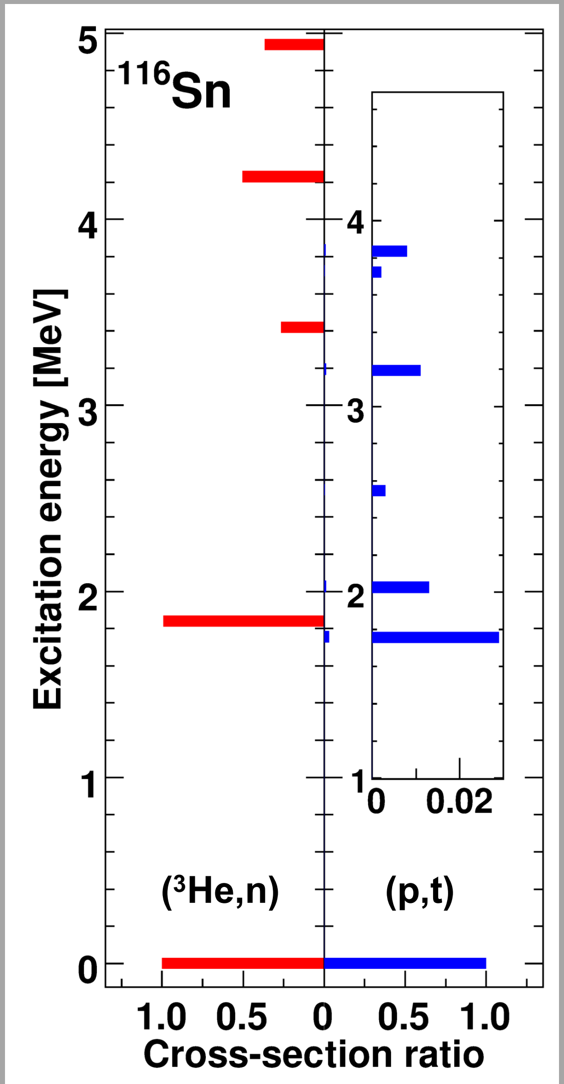


Appearance of rotational-like bands, with enhanced in-band B(E2) values, that stand out amongst spherical “shell-model” states

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)

Similarity of ^{98}Sr, ^{100}Zr structure

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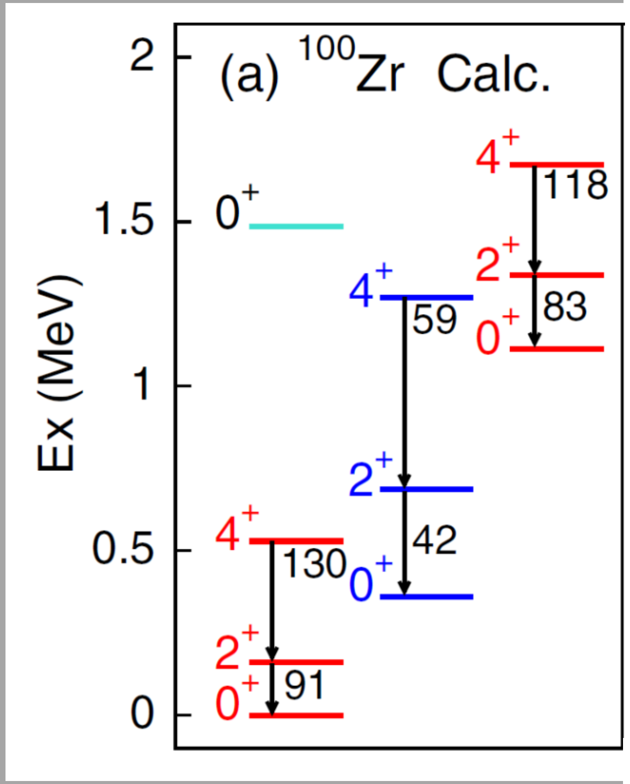
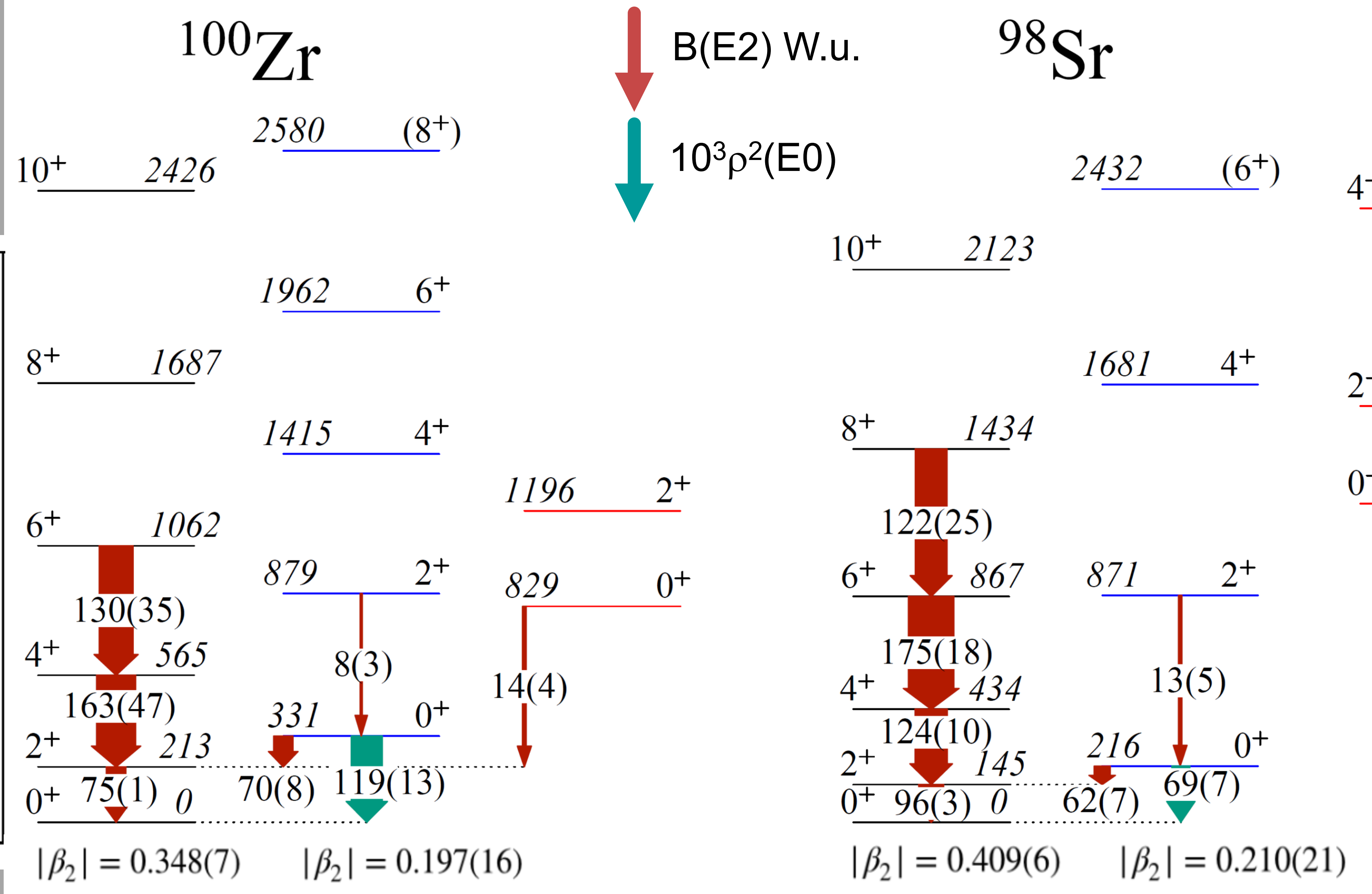
- gsb appears to be well reproduced in MCSM
- Less collectivity in 0_2^+ band than predicted





E. Clement et al., PRL 116, 022701 (2016), PRC 94, 054326 (2016).

Triple shape coexistence in ^{186}Pb

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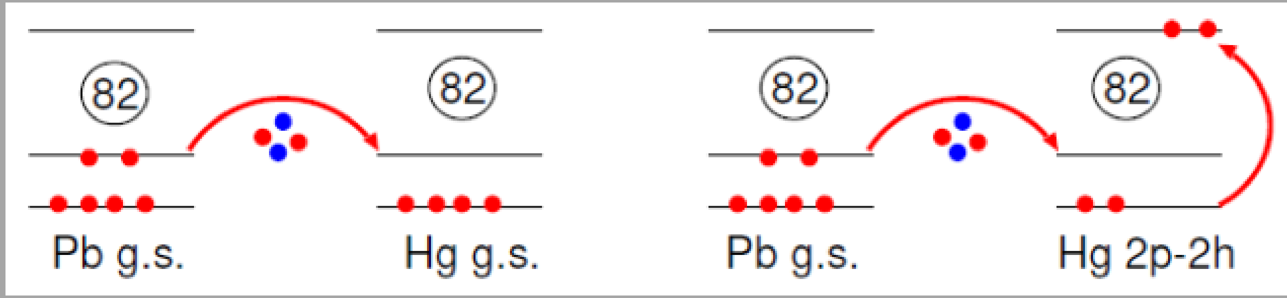
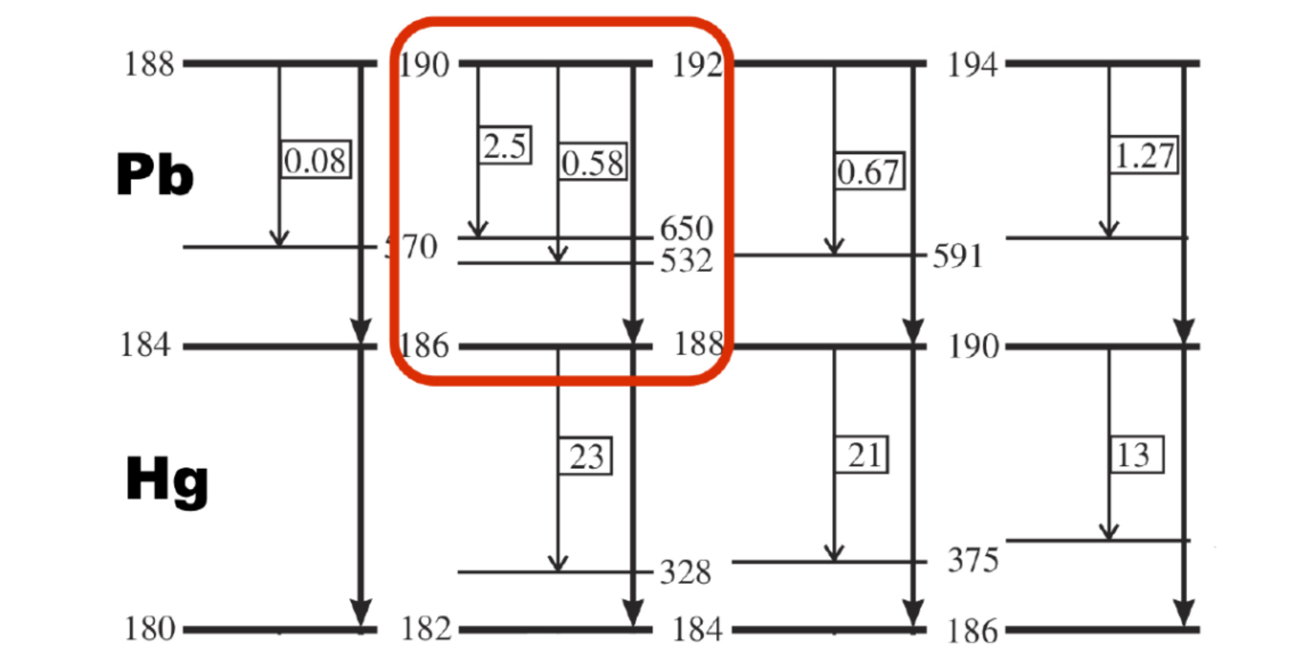
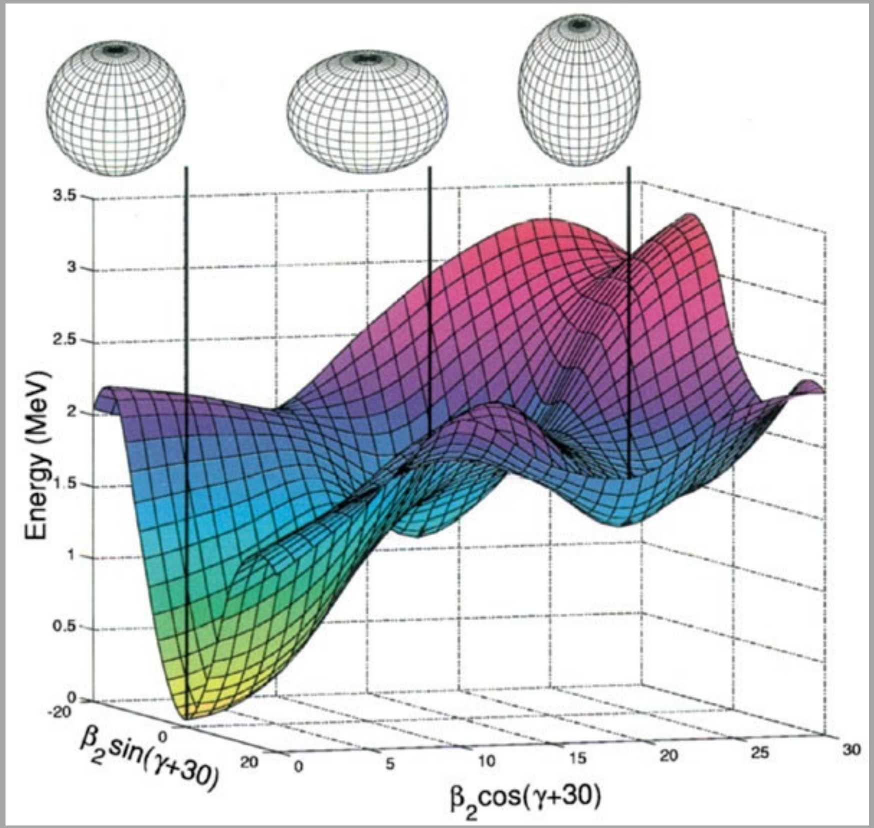
- ^{186}Pb *the* famous example of multiple-shape coexistence



- α-decay similar to α-transfer to gain information on 2*p*-2*h* enhancements



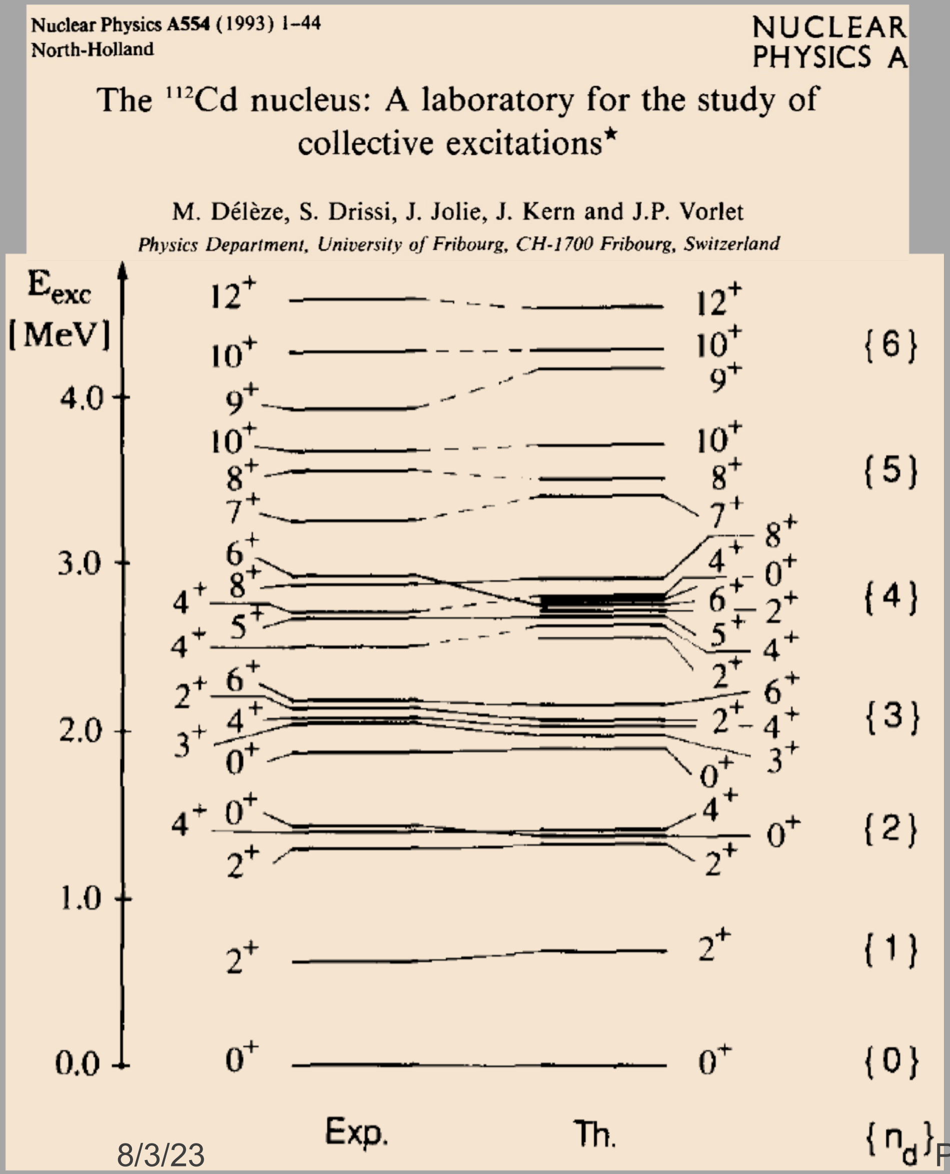


Andreyev et al., Nature **405**, 430 (2000).

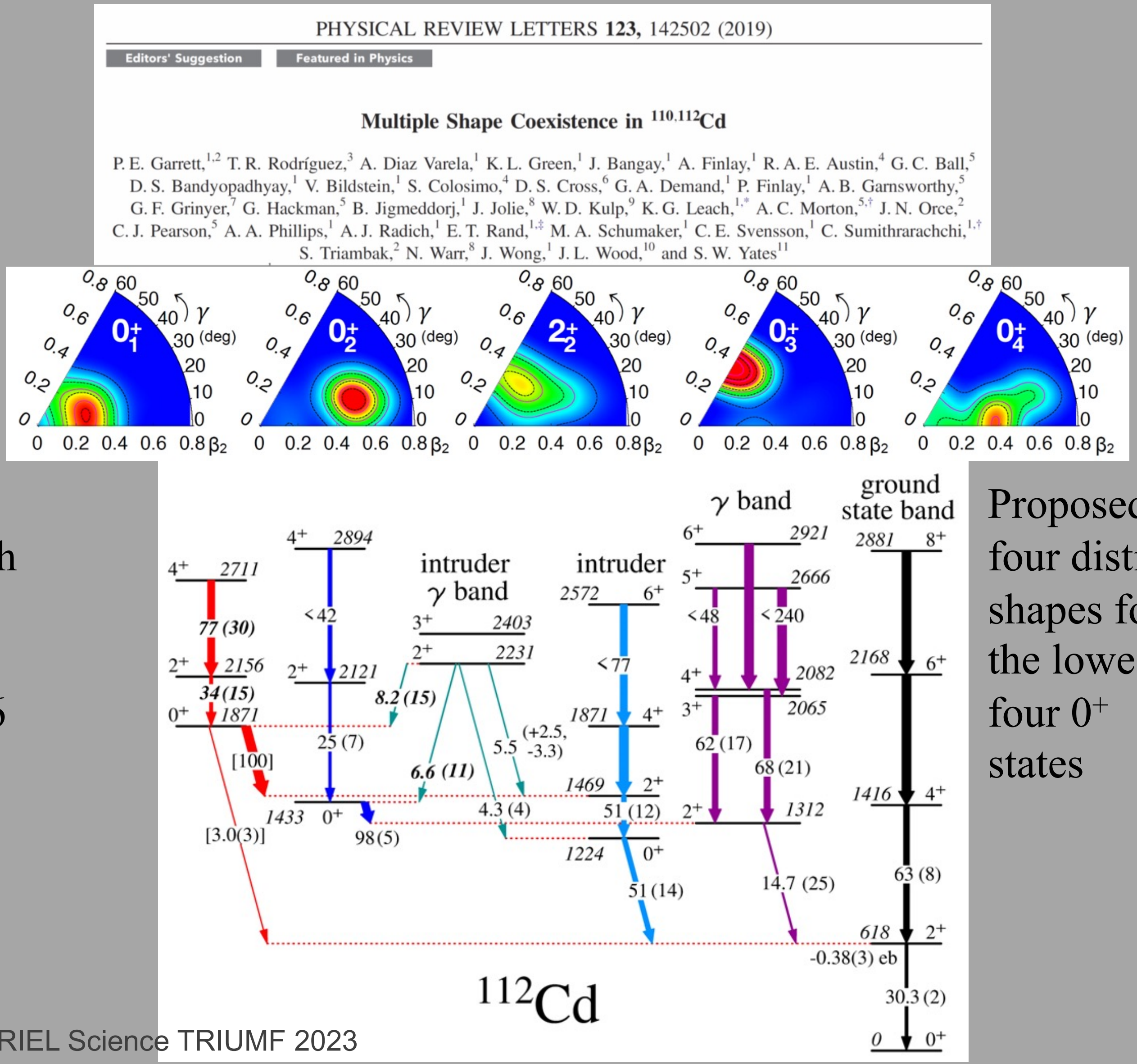
The "evolution" of the structure of the Cd isotopes

- From spherical vibrators….

…to deformed with multiple shapes



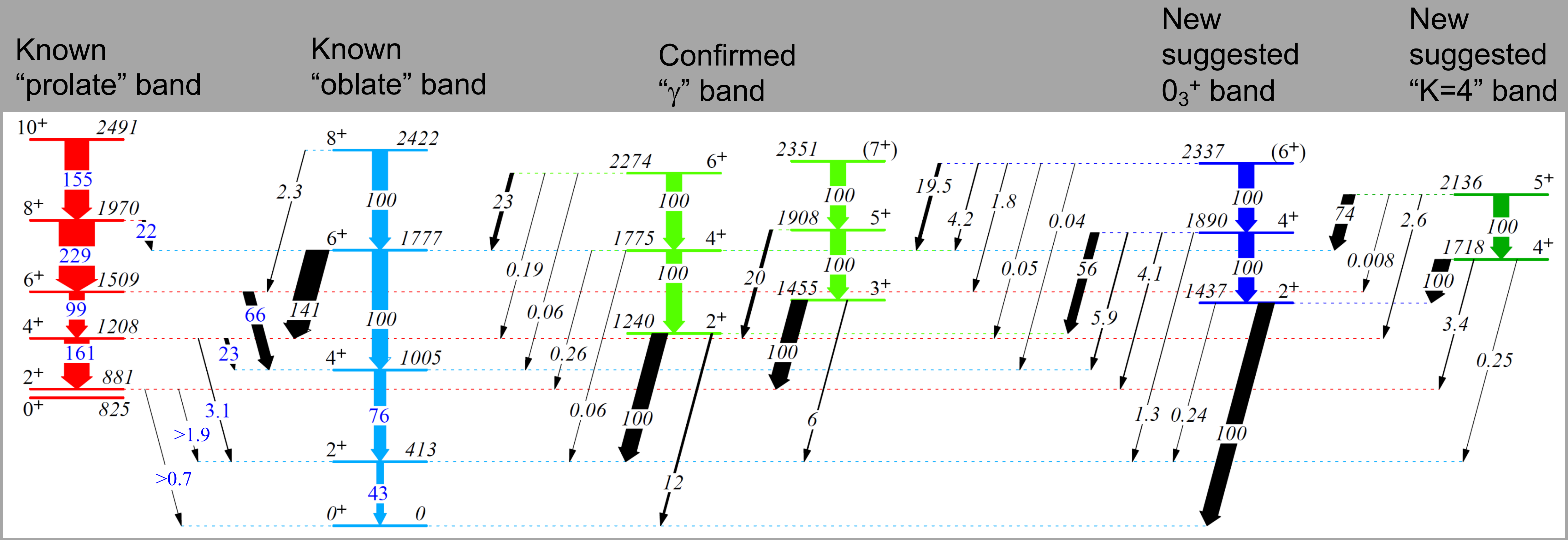
Proposed states with phonon number up to N=6



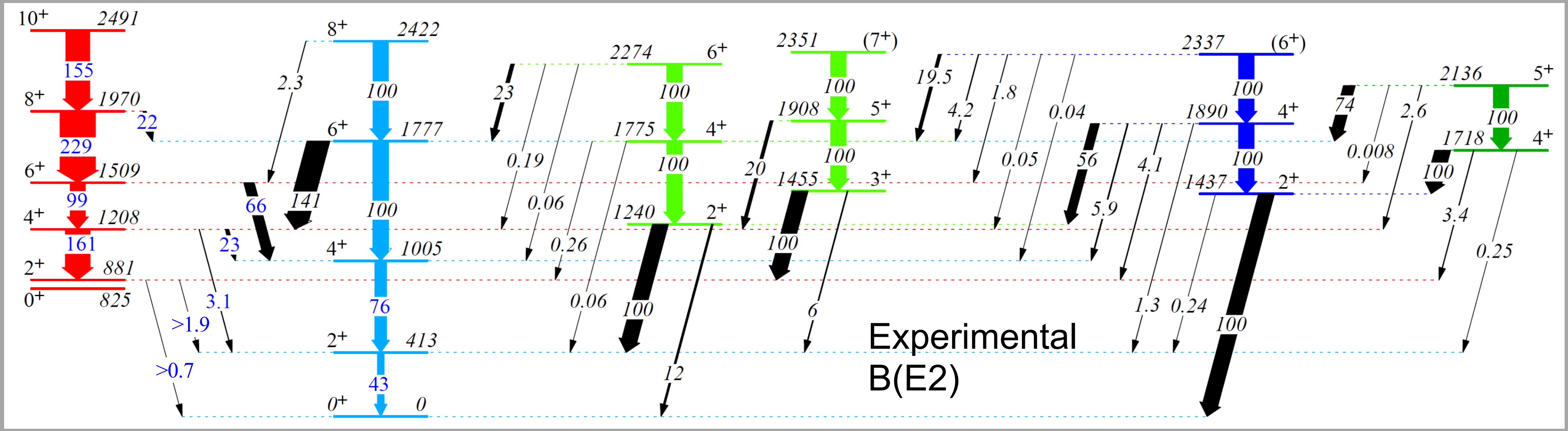
Proposed four distinct shapes for the lowest four 0^+ states

Organization of the ^{188}Hg level scheme

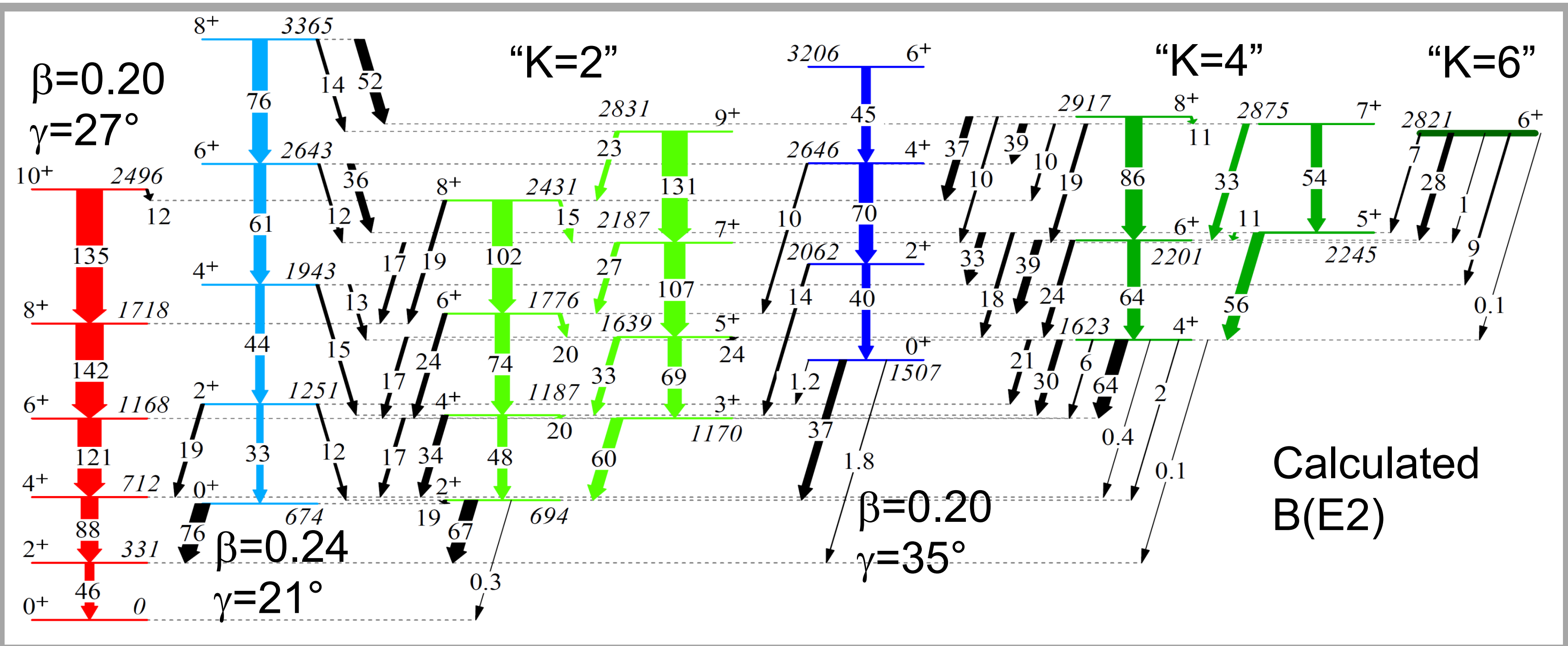
- **Using the extracted branching ratios, *E2/M1* mixing ratios, absolute or relative *B*(*E2*) values determined**
  - **Transitions labelled in absolute *B*(*E2*) in Wu (blue), or relative *B*(*E2*) (black italic), showing clear preference for in-band decays**



Comparison to model calculations: *E2* transitions



Transitions labelled in absolute B(E2) in Wu (blue), or relative B(E2) black italic),



Calculations by S. Peru

Mean field derived from HFB calculation using Gogny D1M interaction

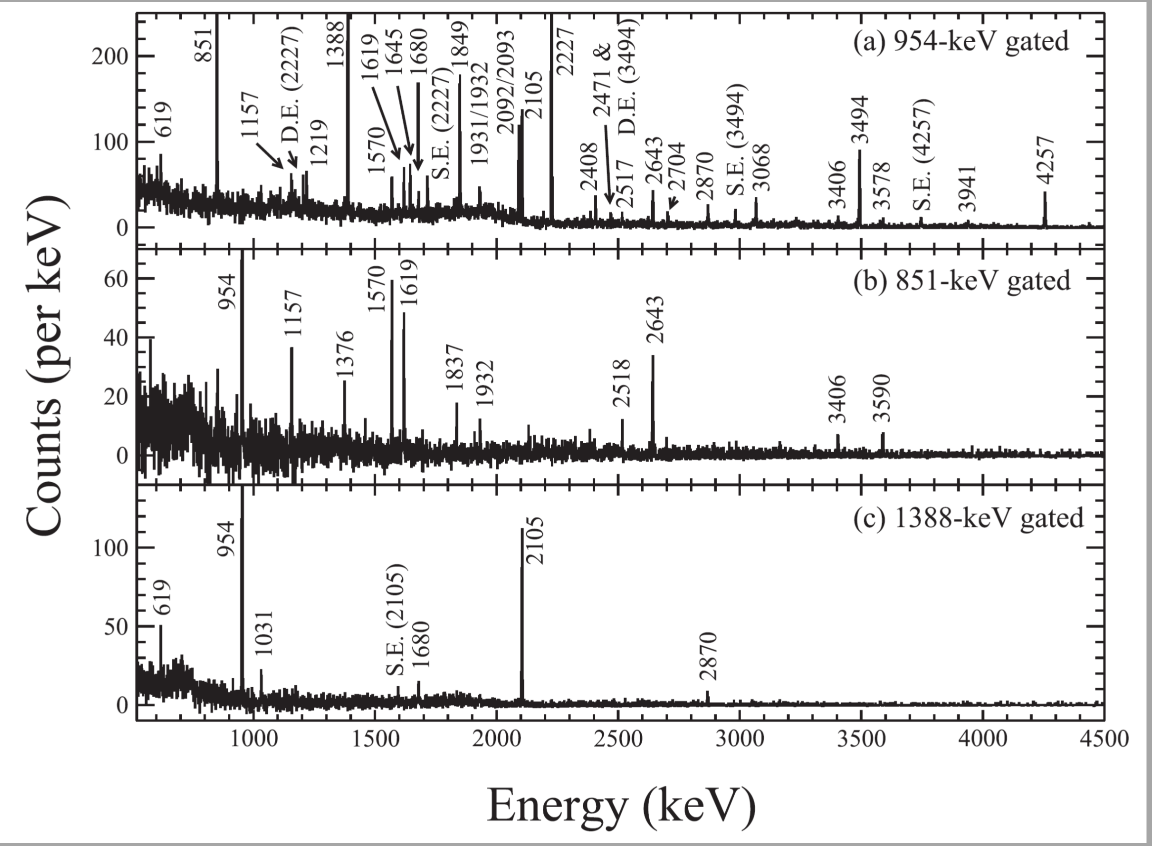
GCM applied to yield 5-dimensional collective Hamiltonian – no restrictions to axial symmetry

States from calculations grouped into bands according to their spectroscopic properties

γ-ray spectroscopy – a very versatile tool

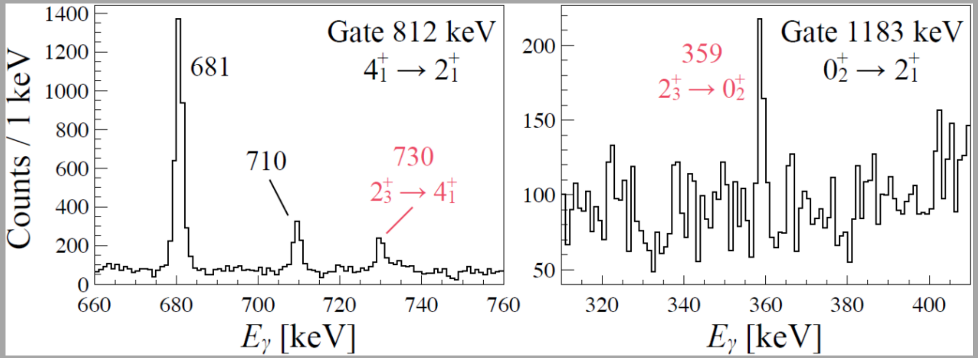
- **Weak interaction tests e.g. studies of Fermi superallowed β-decay**
  - **^{62}Ga decay – beam rate of 6 – 12k/s, placement of γ-rays to 1 ppm level permits very sensitive tests related CKM matrix unitarity**

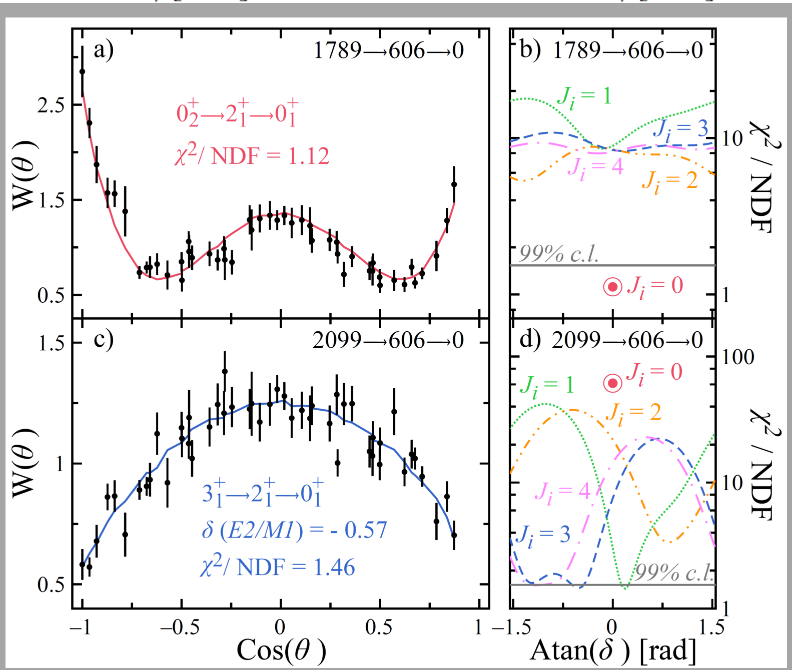
A.D. MacLean et al., PRC 102, 054325 (2020)



- **Nuclear structure investigations e.g. ^{74}Zn and *N*=40 "island of inversion"**

M. Rocchini et al., PRL 130, 122502 (2023)

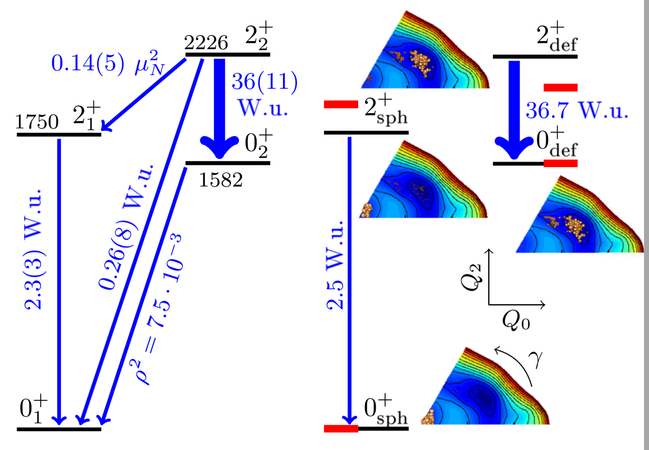




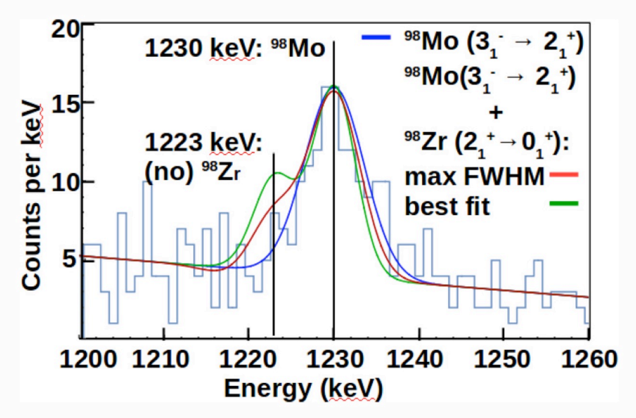
Some recent work on the Zr isotopes

UNIVERSITY of GUELPH

^{96}Zr – high resolution e^- scattering yielding B(E2;$2_2^+ \rightarrow 0_1^+$) and comparisons with MCSM

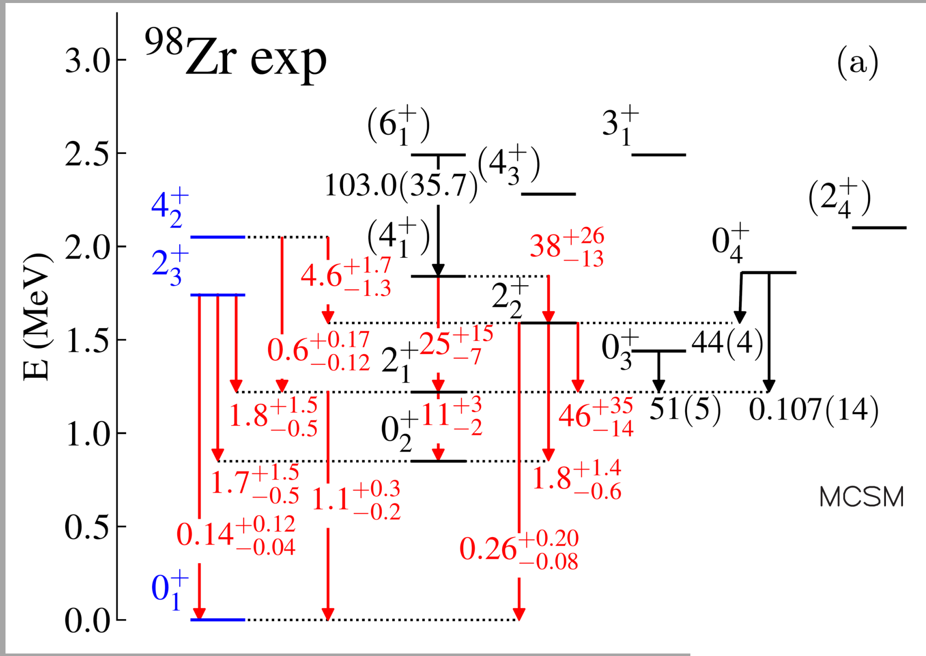


C. Kremer *et al.*, PRL 117, 172503 (2016)



W. Witt *et al.*, PRC 98, 041302(R) (2018)

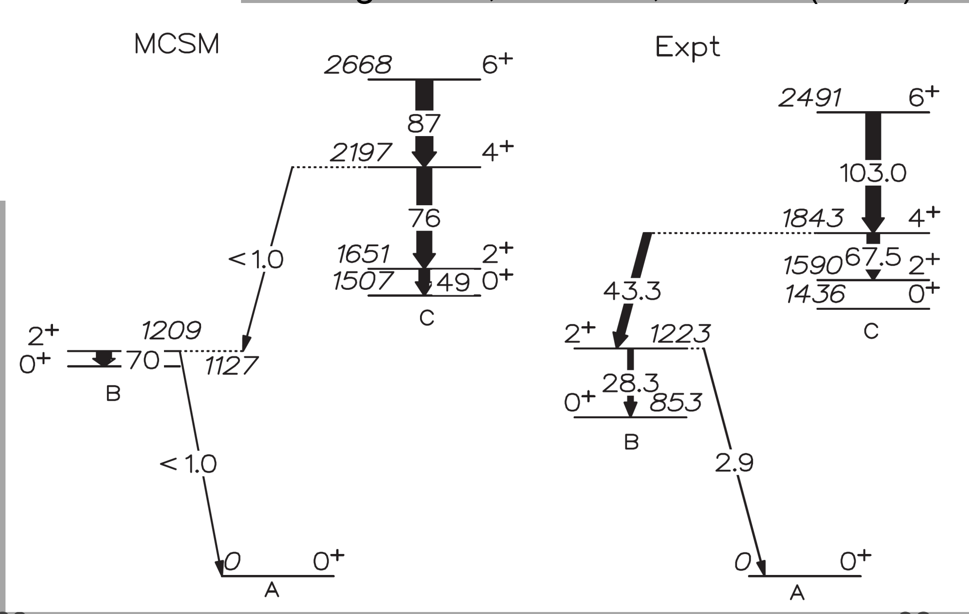
^{98}Zr – lifetimes measured in ^{9}Be induced fission of ^{238}U, and ^{96}Zr+^{18}O 2*p* transfer reaction



V. Karayonchev et al., PRC 102, 064314 (2020)

Substantial differences in both measured lifetimes, and assignments/interpretations

P. Singh et al., PRL 121, 192501 (2018)



^{98}Zr – Coulomb excitation of mass 98 beam placed limit on B(E2;$2_1^+ \rightarrow 0_1^+$) value