# Overview of nuclear deformation and shape coexistence around $^{96}$Zr and $^{96}$Ru

- overall quadrupole deformation and shape coexistence
- triaxiality
- octupole collectivity

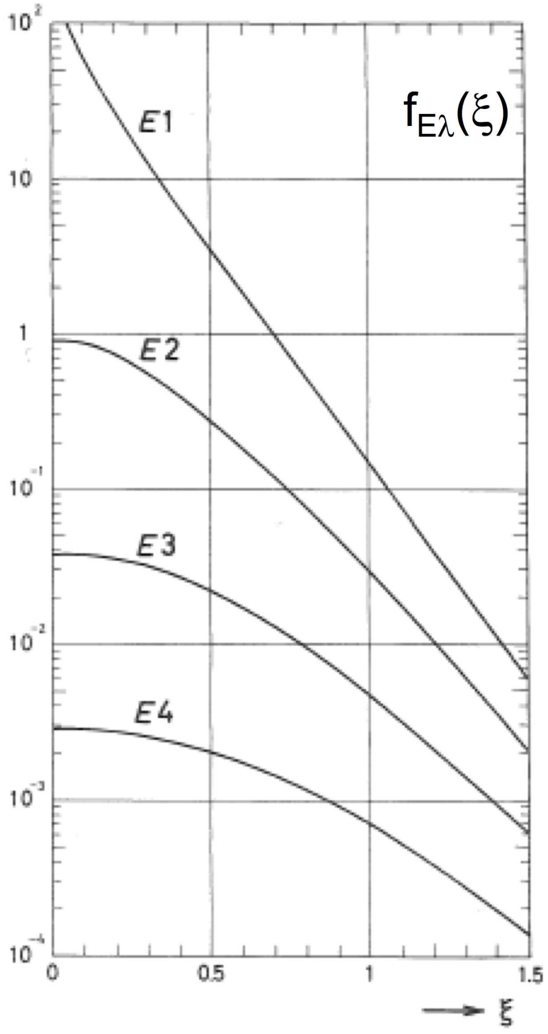
# What observables are related to nuclear shapes?

- differences in root mean square charge radii (determined via laser spectroscopy for ground and isomeric states)
- level energies
  - energy of the first $2^+$ state: the simplest measure of collectivity
- transition probabilities: $B(E2; 0^+ \rightarrow 2^+) = ((3/4\pi)eZR_0^2)^2 \, {\beta_2}^2$
- quadrupole moments: measure of the charge distribution in a given state (always zero for spin 0 and 1/2, even if there is non-zero intrinsic deformation)
  - laser spectroscopy for long-lived states
  - reorientation effect in Coulomb excitation for short-lived states: influence of the quadrupole moment of an excited state on its excitation cross section
- deformation lengths from inelastic scattering: need for accurate potentials to describe the nuclear interaction between collision partners
- complete sets of E2 matrix elements:
  possibility to determine quadrupole invariants and level mixing
- monopole transition strengths: enhancements observed for shape coexistence with strong mixing

## Coulomb excitation cross sections

Dependence on:

- strength of the electromagnetic field: atomic number of the collision partner
- beam energy
- difference in excitation energy between the initial and final levels
- scattering angle
- transition probabilities
- transition multipolarities
  - E2 excitation dominates, followed by E3; other multipolarities (including magnetic transitions) usually negligible in low-energy Coulomb-excitation process



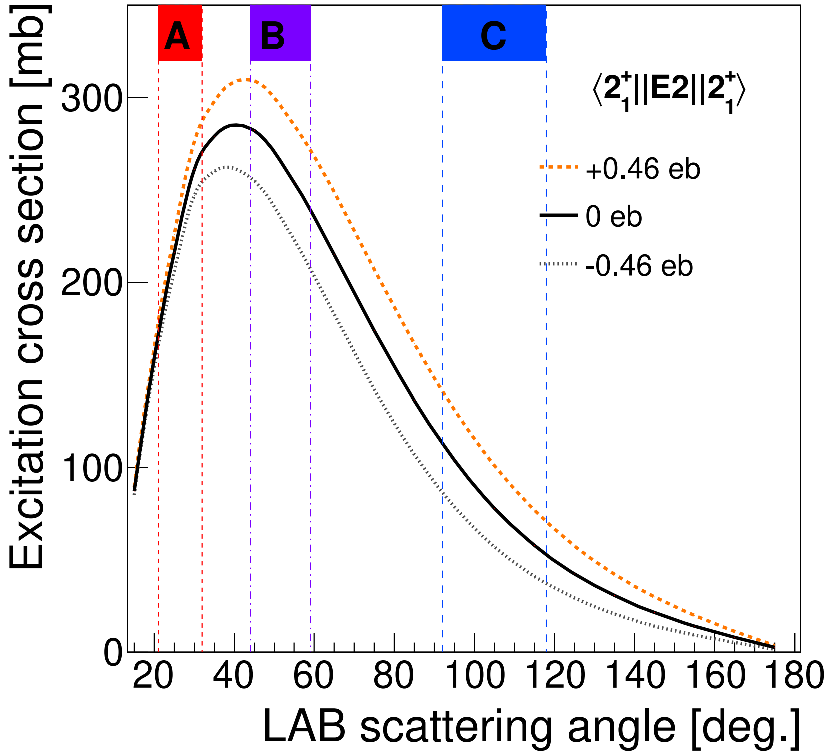
first perturbation: $\sigma = \left(\frac{Z_1 e}{\hbar v}\right)^2 a^{-2(\lambda+1)} B(E\lambda) \cdot f_{E\lambda}(\xi)$

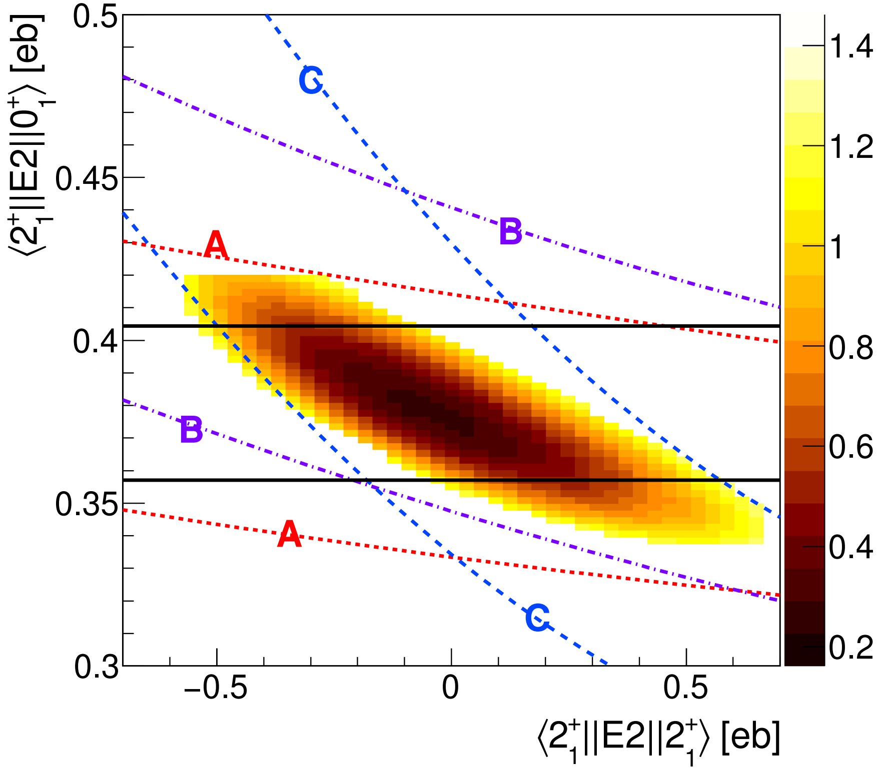
with adiabacity parameter $\xi = \frac{\Delta E a}{\hbar v}$

# Measuring quadrupole moments of excited states

- reorientation effect: influence of the quadrupole moment on the excitation cross section

$^{76}$Zn, HIE-ISOLDE data from: A. Illana, MZ *et al.*, submitted to PRC





- $\chi^2$ comparison of measured cross sections with calculated ones
- independent lifetime measurements increase precision of extracted quadrupole moments

# Quadrupole sum rules

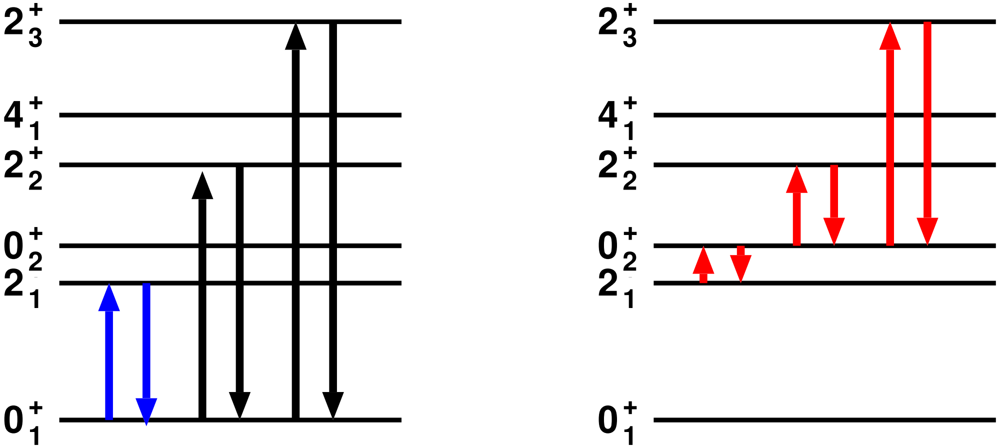
D. Cline, Ann. Rev. Nucl. Part. Sci. 36 (1986) 683
K. Kumar, PRL 28 (1972) 249

- electromagnetic multipole operators are spherical tensors – products of such operators coupled to angular momentum 0 are rotationally invariant

- in the intrinsic frame of the nucleus, the E2 operator may be expressed using two parameters Q and $\delta$ related to charge distribution:

$$\begin{aligned} E(2,0) &= Q\cos\delta \\ E(2,2)=E(2,-2) &= \frac{Q}{\sqrt{2}}\sin\delta \\ E(2,1)=E(2,-1) &= 0 \end{aligned}$$

$$\frac{\langle Q^2\rangle}{\sqrt{5}} = \langle i|\,[E2\times E2]^0\,|i\rangle = \frac{1}{\sqrt{(2I_i+1)}}\sum_t \langle i||E2||t\rangle\langle t||E2||i\rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_i & I_t \end{Bmatrix}$$



$\langle Q^2\rangle$: measure of the overall deformation;
for the ground state – extension of B(E2; $0^+ \to 2^+$) = $((3/4\pi)eZR_0^2)^2\ \beta_2{}^2$

Contributions to $\langle Q^2\rangle$ in $^{100}$Mo: K. Wrzosek-Lipska *et al.*, PRC 86 (2012) 064305

# $\langle Q^2\rangle$ for $^{96}$Zr and $^{96}$Ru ground states

- Extensive lifetime measurements for low-spin states in $^{96}$Zr and $^{96}$Ru:
- $^{96}$Zr: (n,n'$\gamma$) + (e,e') for $2^+_2$; $^{96}$Ru: (p,p'$\gamma$), ($^3$He,2n$\gamma$)

- $^{96}$Zr:
  - B(E2; $2^+_1 \rightarrow 0^+_1$) = 2.3(3) W.u. $\rightarrow \langle\, 2^+_1 \| \,\mathrm{E2}\, \| \,0^+_1 \rangle$ = 0.173(11) eb
  - B(E2; $2^+_2 \rightarrow 0^+_1$) = 0.26(8) W.u. $\rightarrow \langle\, 2^+_2 \| \,\mathrm{E2}\, \| \,0^+_1 \rangle$ = 0.058(9) eb

  - $\langle Q^2\rangle$ = 0.033(5)e$^2$b$^2$, $\beta$=0.06(1)

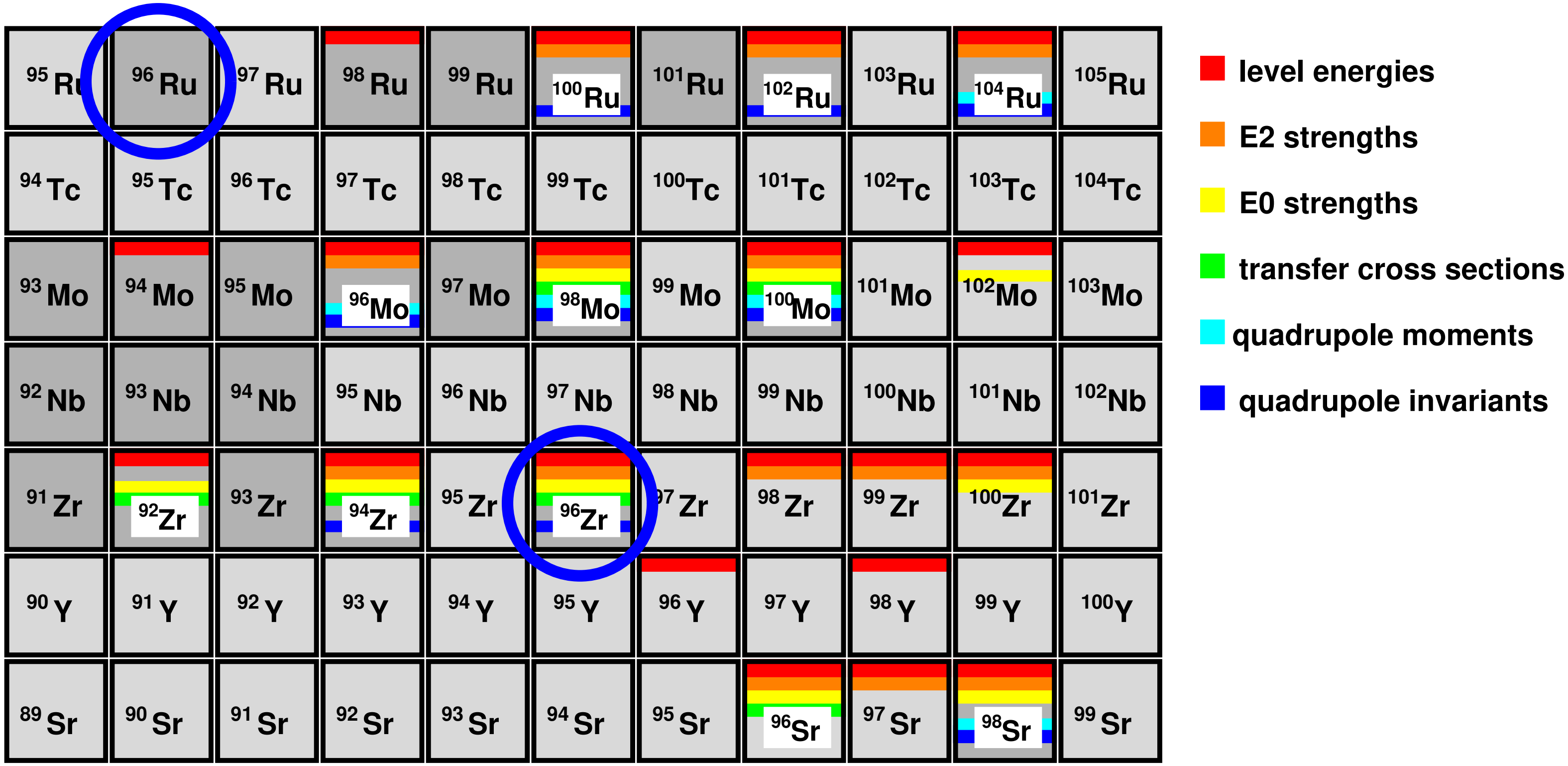
  $^{96}$Ru:
  - B(E2; $2^+_1 \rightarrow 0^+_1$) = 18.4(4) W.u. $\rightarrow \langle\, 2^+_1 \| \,\mathrm{E2}\, \| \,0^+_1 \rangle$ = 0.490(5) eb
  - B(E2; $2^+_2 \rightarrow 0^+_1$) = 0.16(4) W.u. $\rightarrow \langle\, 2^+_2 \| \,\mathrm{E2}\, \| \,0^+_1 \rangle$ = 0.050(6) eb

  - $\langle Q^2\rangle$ = 0.243(6)e$^2$b$^2$, $\beta$=0.155(4)

- $\langle Q^2\rangle = q_0^2\langle\beta_2^2\rangle$; $q_0 = \frac{3}{4\pi}ZeR_0^2$ and $R_0 = 1.2A^{1/3}$ fm
- includes both dynamic and static deformation and assumes that mass and charge distributions are the same
- errors in ENSDF for $^{96}$Ru: wrong B(E2; $2^+_2 \rightarrow 0^+_1$)=35 W.u, $2^+_4$ lifetime 0.15 fs, 15 fs (it is 0.15 ps)

# Shape coexistence: experimental information for A $\approx$ 100

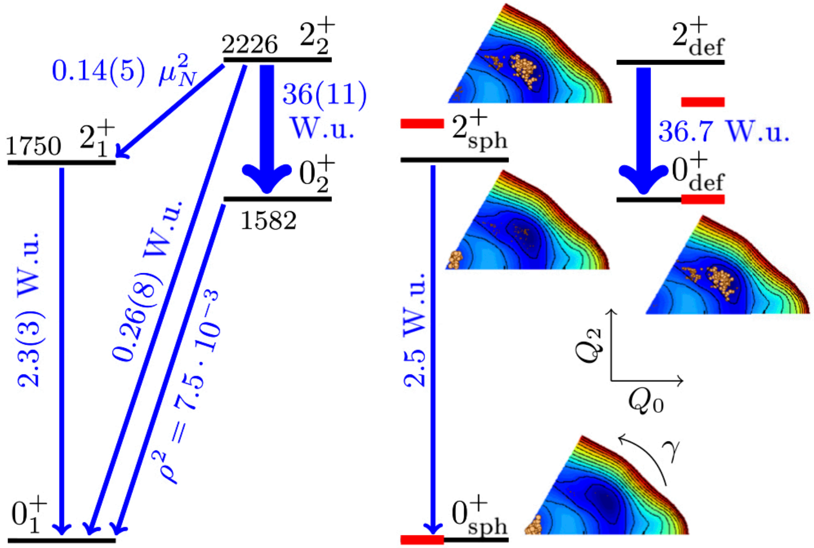
- dramatic increase of ground-state deformation at N=60
- multitude of coexisting shapes predicted by theory



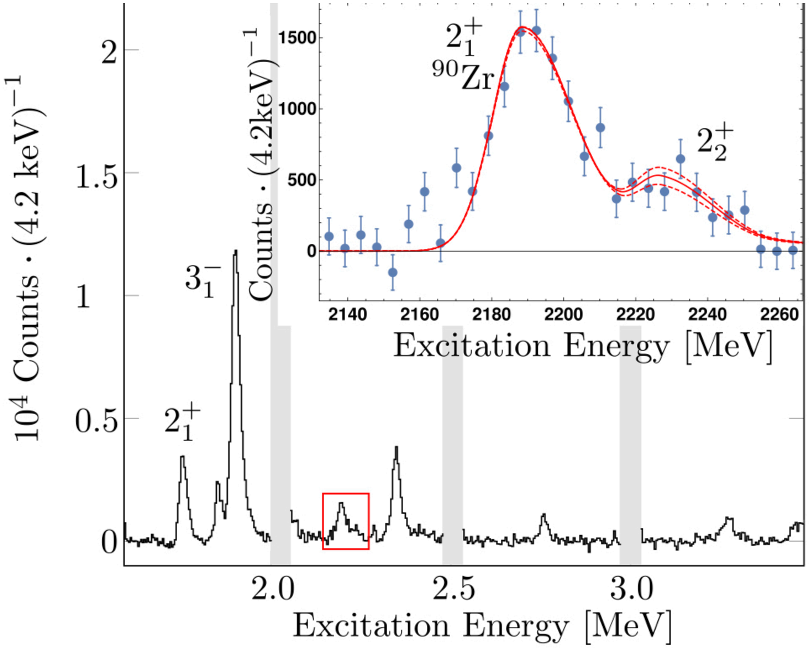
| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $^{95}$Ru | $^{96}$Ru | $^{97}$Ru | $^{98}$Ru | $^{99}$Ru | $^{100}$Ru | $^{101}$Ru | $^{102}$Ru | $^{103}$Ru | $^{104}$Ru | $^{105}$Ru |
| $^{94}$Tc | $^{95}$Tc | $^{96}$Tc | $^{97}$Tc | $^{98}$Tc | $^{99}$Tc | $^{100}$Tc | $^{101}$Tc | $^{102}$Tc | $^{103}$Tc | $^{104}$Tc |
| $^{93}$Mo | $^{94}$Mo | $^{95}$Mo | $^{96}$Mo | $^{97}$Mo | $^{98}$Mo | $^{99}$Mo | $^{100}$Mo | $^{101}$Mo | $^{102}$Mo | $^{103}$Mo |
| $^{92}$Nb | $^{93}$Nb | $^{94}$Nb | $^{95}$Nb | $^{96}$Nb | $^{97}$Nb | $^{98}$Nb | $^{99}$Nb | $^{100}$Nb | $^{101}$Nb | $^{102}$Nb |
| $^{91}$Zr | $^{92}$Zr | $^{93}$Zr | $^{94}$Zr | $^{95}$Zr | $^{96}$Zr | $^{97}$Zr | $^{98}$Zr | $^{99}$Zr | $^{100}$Zr | $^{101}$Zr |
| $^{90}$Y | $^{91}$Y | $^{92}$Y | $^{93}$Y | $^{94}$Y | $^{95}$Y | $^{96}$Y | $^{97}$Y | $^{98}$Y | $^{99}$Y | $^{100}$Y |
| $^{89}$Sr | $^{90}$Sr | $^{91}$Sr | $^{92}$Sr | $^{93}$Sr | $^{94}$Sr | $^{95}$Sr | $^{96}$Sr | $^{97}$Sr | $^{98}$Sr | $^{99}$Sr |

P. Garrett, MZ, E. Clément, Prog. Part, Nucl. Phys. 124, 123931 (2022)

# Shape coexistence in $^{96}$Zr – experimental information



S. Kremer et al, Phys. Rev. Lett. 117 (2017) 172503

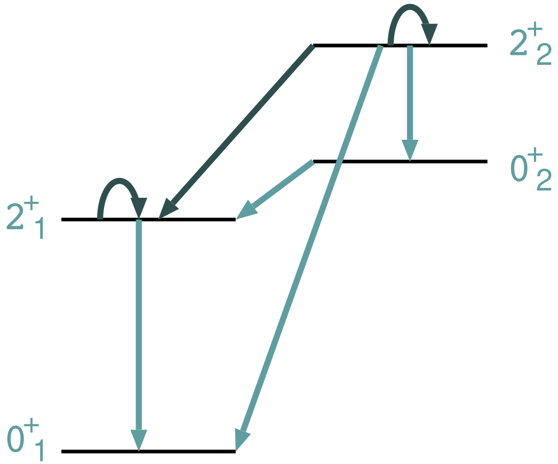


- B(E2; $2_2^+ \rightarrow 0_1^+$) measured using electron scattering, combined with known branching and mixing ratios:
  $\rightarrow$transition strengths from the $2_2^+$ state
- B(E2; $2_1^+ \rightarrow 0_1^+$) = 2.3(3) Wu vs B(E2; $2_2^+ \rightarrow 0_2^+$) = 36(11) Wu: nearly spherical and a well-deformed structure ($\beta \approx$ 0.24)
- very low mixing of coexisting structures: cos$^2\theta_0$=99.8%, cos$^2\theta_2$=97.5%,

# Two-state mixing model

- we assume that physical states are linear combinations of pure spherical and deformed configurations:

$$| I_1^+ \rangle = +\cos\theta_I \times | I_d^+ \rangle + \sin\theta_I \times | I_s^+ \rangle$$
$$| I_2^+ \rangle = -\sin\theta_I \times | I_d^+ \rangle + \cos\theta_I \times | I_s^+ \rangle$$



with transitions between the pure spherical and deformed states forbidden:

$$\langle 2_d^+ \| E2 \| 0_s^+ \rangle = \langle 2_d^+ \| E2 \| 2_s^+ \rangle = \langle 2_s^+ \| E2 \| 0_d^+ \rangle = 0$$

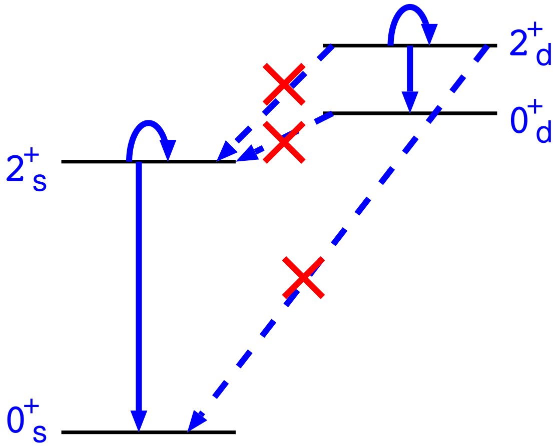
- the measured matrix elements can be expressed in terms of the "pure" matrix elements and the mixing angles:

$$\langle 2_1^+ \| E2 \| 0_1^+ \rangle =$$
$$\sin\theta_0 \sin\theta_2 \, \langle 2_s^+ \| E2 \| 0_s^+ \rangle + \cos\theta_0 \cos\theta_2 \, \langle 2_d^+ \| E2 \| 0_d^+ \rangle$$

$$\langle 2_1^+ \| E2 \| 0_2^+ \rangle =$$
$$\cos\theta_0 \sin\theta_2 \, \langle 2_s^+ \| E2 \| 0_s^+ \rangle - \sin\theta_0 \cos\theta_2 \, \langle 2_d^+ \| E2 \| 0_d^+ \rangle$$

$$\langle 2_2^+ \| E2 \| 0_1^+ \rangle =$$
$$\sin\theta_0 \cos\theta_2 \, \langle 2_s^+ \| E2 \| 0_s^+ \rangle - \cos\theta_0 \sin\theta_2 \, \langle 2_d^+ \| E2 \| 0_d^+ \rangle$$

$$\langle 2_2^+ \| E2 \| 0_2^+ \rangle =$$
$$\cos\theta_0 \cos\theta_2 \, \langle 2_s^+ \| E2 \| 0_s^+ \rangle + \sin\theta_0 \sin\theta_2 \, \langle 2_d^+ \| E2 \| 0_d^+ \rangle$$



# E0 strengths, shape coexistence and mixing

- E0 transitions are sensitive to the changes in the nuclear charge-squared radii

- their strengths depends on the mixing of configurations that have different mean-square charge radii:

$$\rho^2(E0) = \frac{Z^2}{R^4}\cos^2\theta_0\,\sin^2\theta_0\left(\langle r^2\rangle_A - \langle r^2\rangle_B\right)^2$$

$$= \left(\frac{3Z}{4\pi}\right)^2\cos^2(\theta_0)\sin^2(\theta_0)\cdot\left[\left(\beta_1^2-\beta_2^2\right)+\frac{5\sqrt{5}}{21\sqrt{\pi}}\left(\beta_1^3\cos\gamma_1-\beta_2^3\cos\gamma_2\right)\right]^2$$

J.L. Wood *et al.*, NPA 651, 323 (1999)

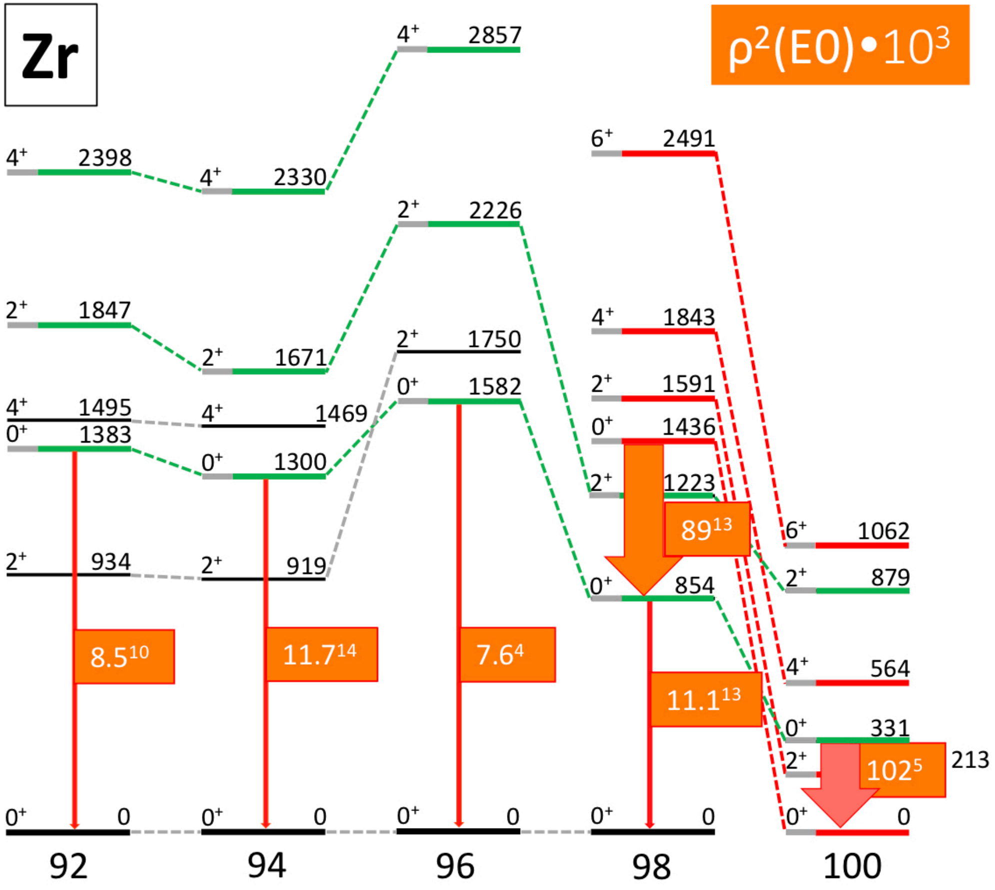
Example of $^{42}$Ca: K. Hadyńska-Klęk *et al.*, PRC 97 (2018) 024326 (Coulomb excitation),
J.L. Wood *et al.*, NPA 651, 323 (1999) (E0)

| | from E2 matrix elements [KHK] | from $\rho^2(E0)$ [JLW] + sum rules results [KHK] |
|---|---|---|
| $\cos^2(\theta_0)$ | 0.88(4) | 0.84(4) |
| $\cos^2(\theta_2)$ | 0.39(8) | - |

- good agreement of the $\cos^2(\theta_0)$ values obtained with the two methods
- $\cos^2(\theta_2)<0.5$: two-state mixing model cannot be applied to $2^+$ states in $^{42}$Ca

# E0 strengths in Zr and Ru isotopes

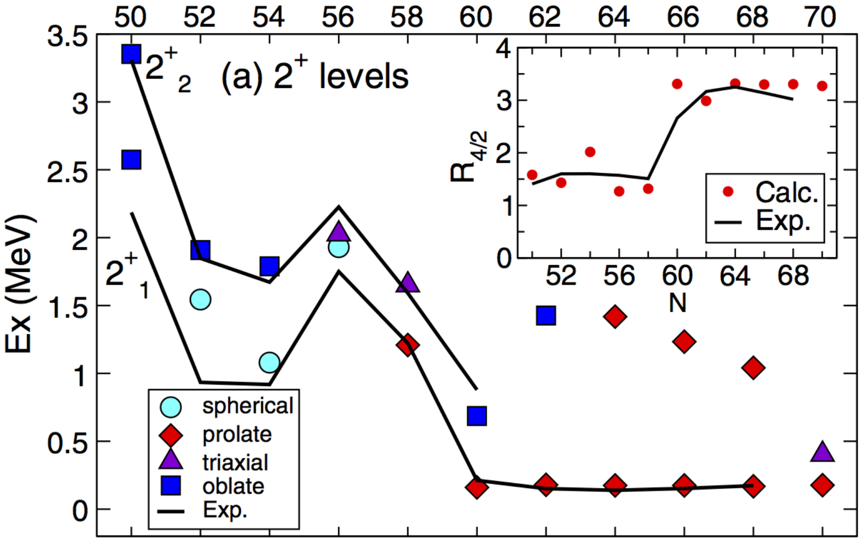
T. Kibedi *et al.*, Prog. Part. Nucl. Phys. 120 (2021)



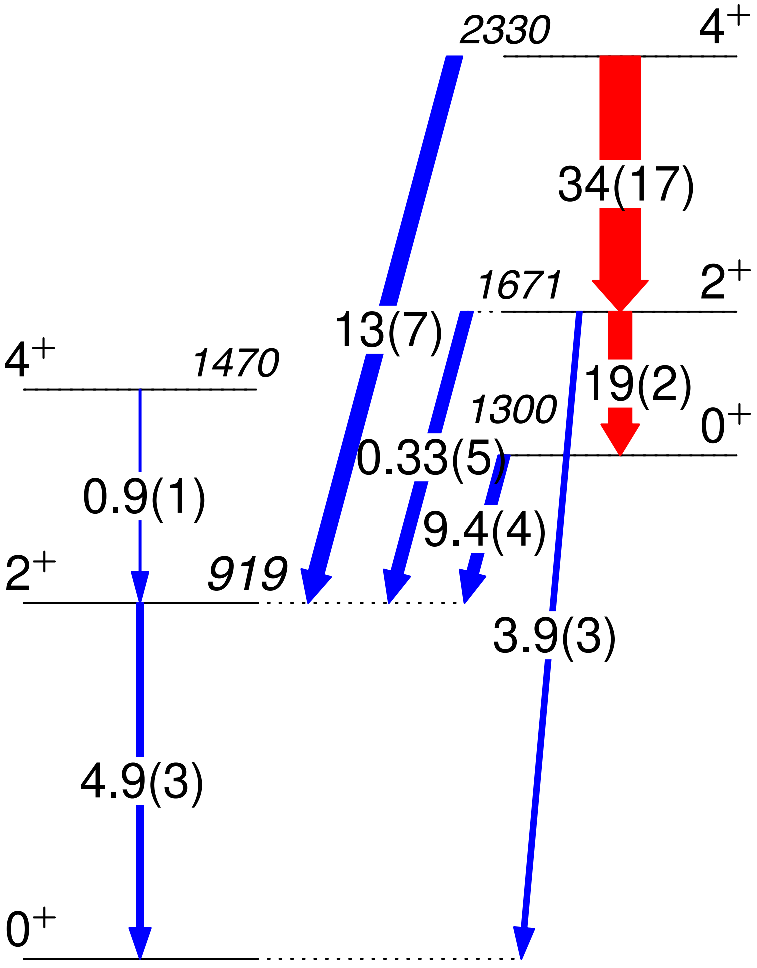
- $^{100}$Ru: 11(2) $10^{-3}$ between $0_2^+$ and $0_2^+$, no data for lighter Ru isotopes

# Shape coexistence in $^{94}$Zr

A. Chakraborty et al, PRL 110, 022504 (2013)



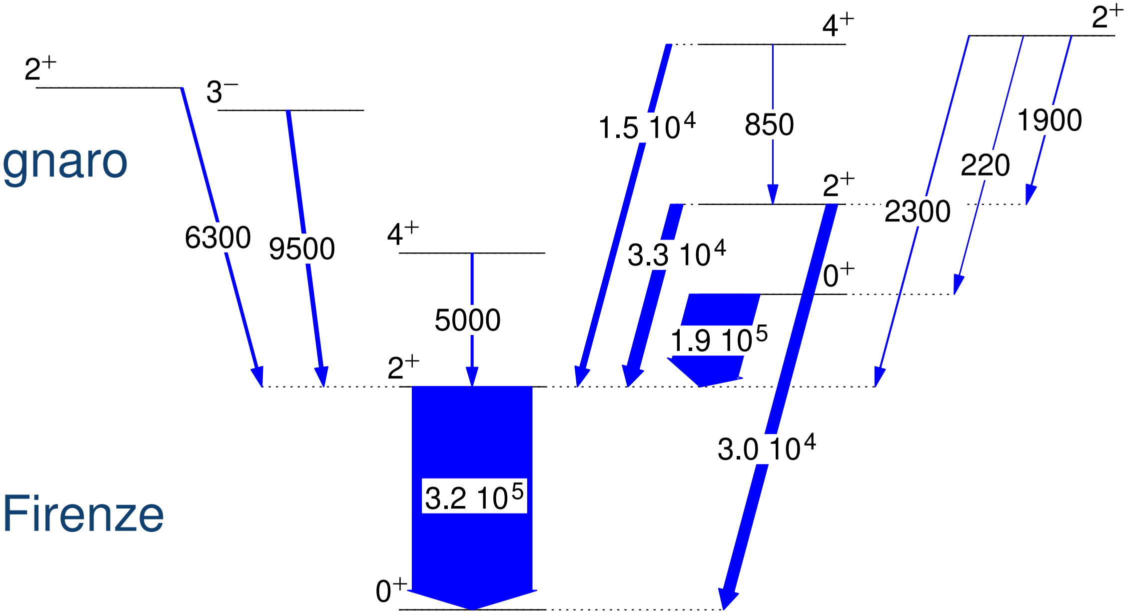
T. Togashi et al, PRL 117, 172502 (2016)

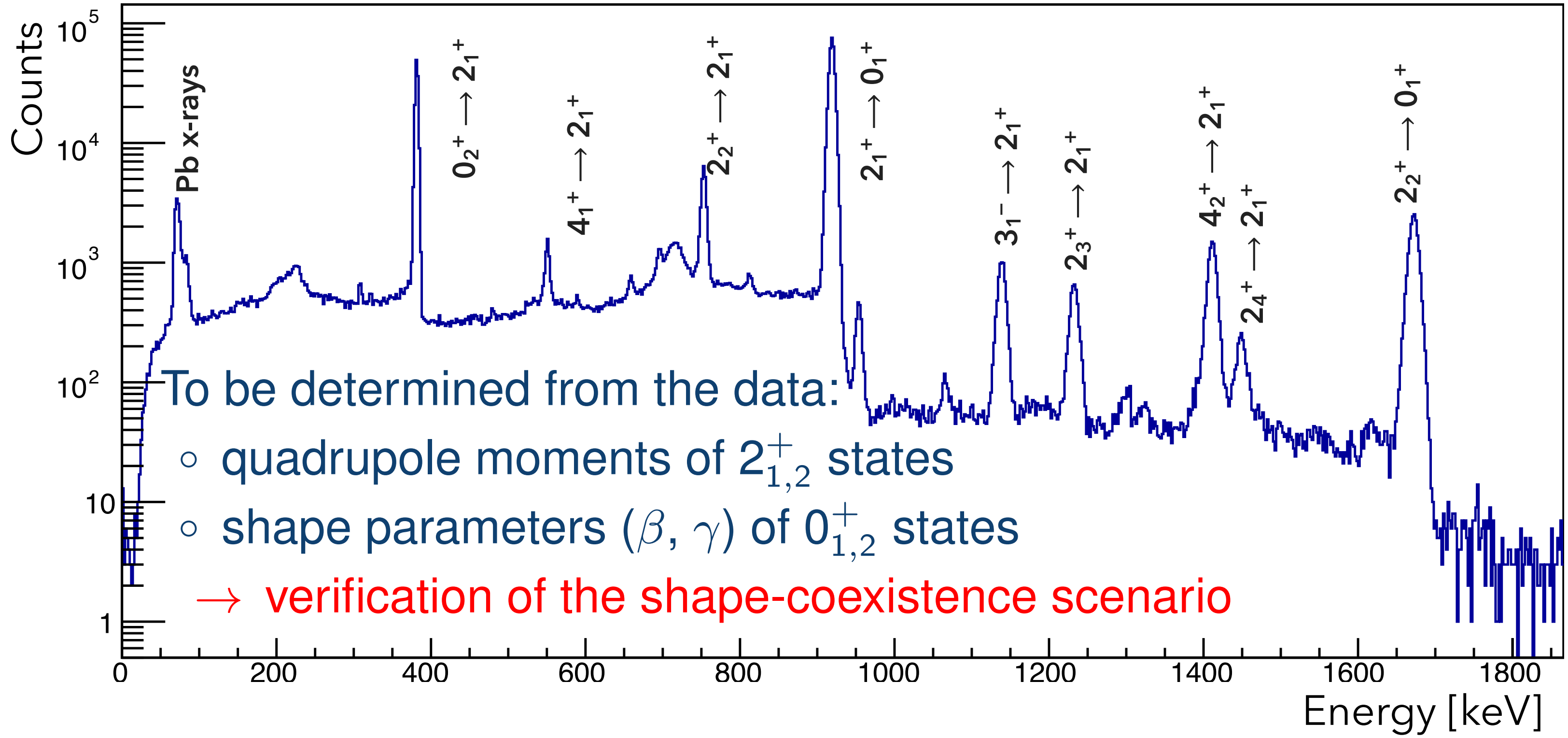


- observation of a strong $2^+_2 \rightarrow 0^+_2$ transition (19 W.u.) – deformed band built on $0^+_2$
- shell model calculations suggest an oblate shape

# Coulomb excitation of $^{94}$Zr

- experiment performed at LNL Legnaro (March 2018)
- GALILEO + SPIDER
- $^{94}$Zr beam on $^{208}$Pb target
- analysis: Naomi Marchini, INFN Firenze





To be determined from the data:

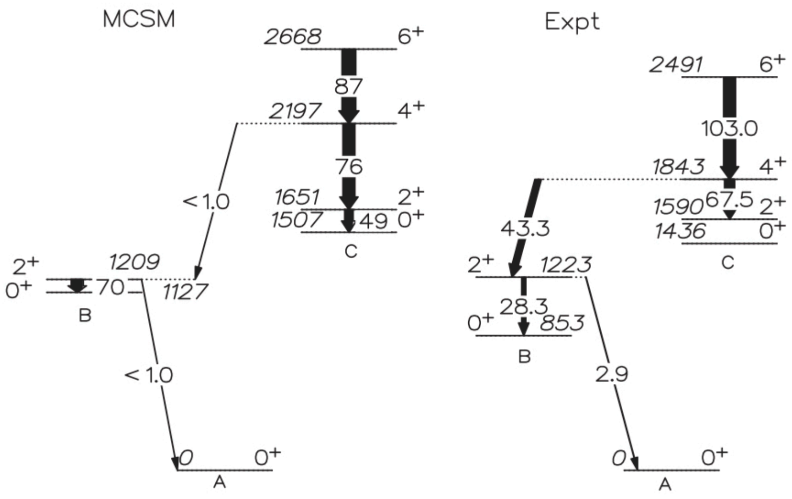
- ◦ quadrupole moments of $2^+_{1,2}$ states
- ◦ shape parameters ($\beta$, $\gamma$) of $0^+_{1,2}$ states

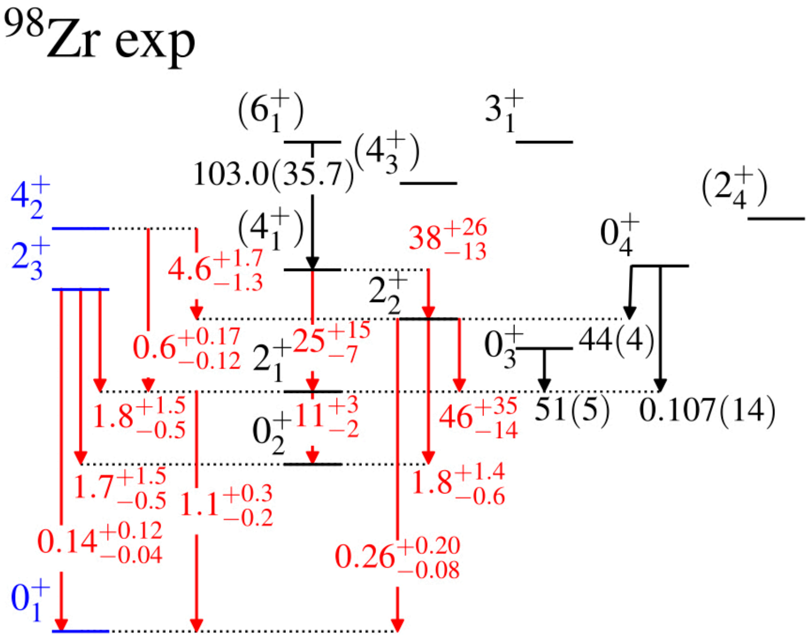
→ verification of the shape-coexistence scenario

# Lifetime measurements in $^{98}$Zr

- Lifetimes measured in $^{9}$Be induced fission of $^{238}$U, and $^{96}$Zr+$^{18}$O 2p transfer

P. Singh et al., PRL 121, 192501 (2018)    V. Karayonchev et al., PRC 102, 064314 (2020)



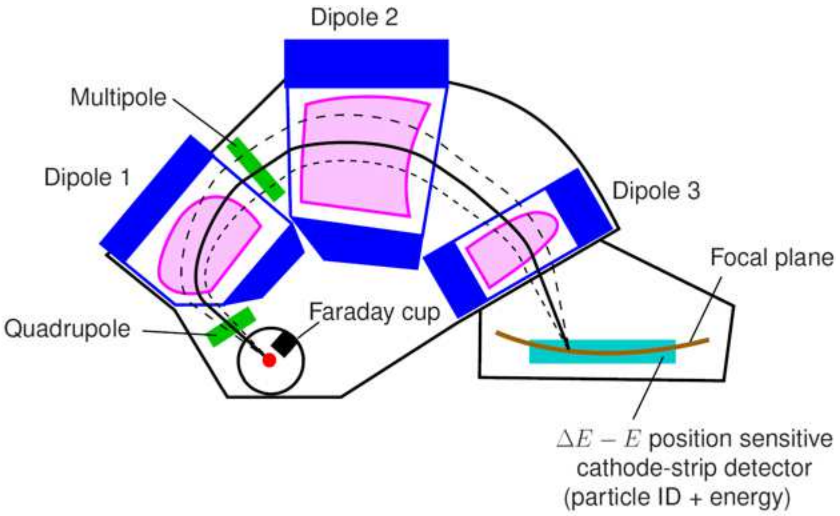


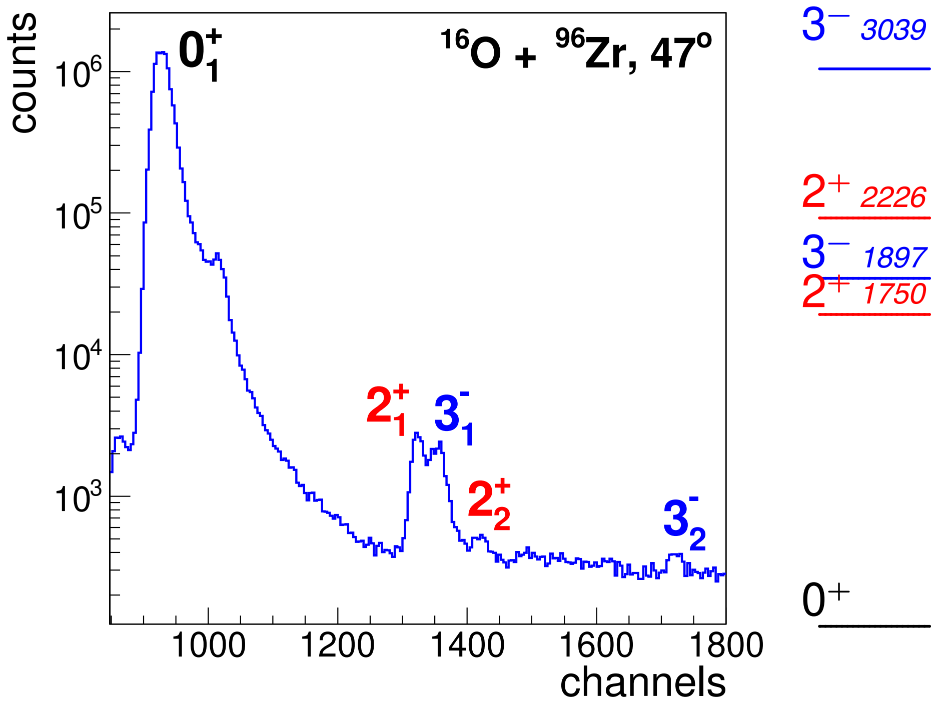
- substantial differences in measured lifetimes and interpretations
- $2_2^+ \rightarrow 0_3^+$ is expected to be either enhanced in-band transition, or a forbidden three- to two-phonon transition
- combination of $2_2^+$ lifetime and branching ratio points to an unphysical value of 500 W.u.
- $\beta$-decay data from TRIUMF (under analysis) expected to resolve this issue

# Coulomb excitation with the Q3D spectrometer

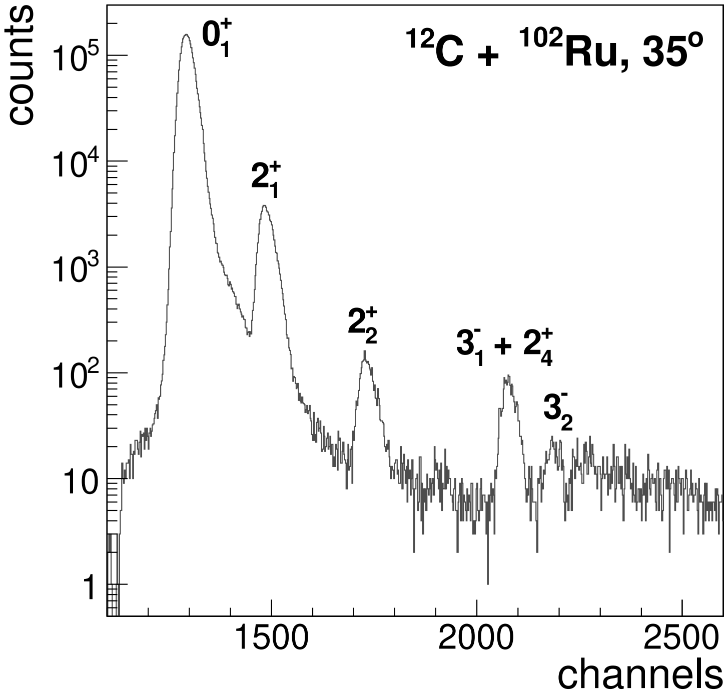
- Coulomb-excitation measurements with magnetic spectrometers common in 1970s, but completely abandoned in favour of $\gamma$-ray spectroscopy
- still a very attractive option, especially to populate higher-lying low-spin states: very high beam intensities ( 100 pnA) can compensate for low cross sections
- campaigns with $^{12}$C, $^{16}$O beams: direct measurement of $2^+$ and $3^-$ population $\rightarrow$ precise B(E2; $2^+_i \rightarrow 0^+_1$) and B(E3; $3^-_i \rightarrow 0^+_1$) values

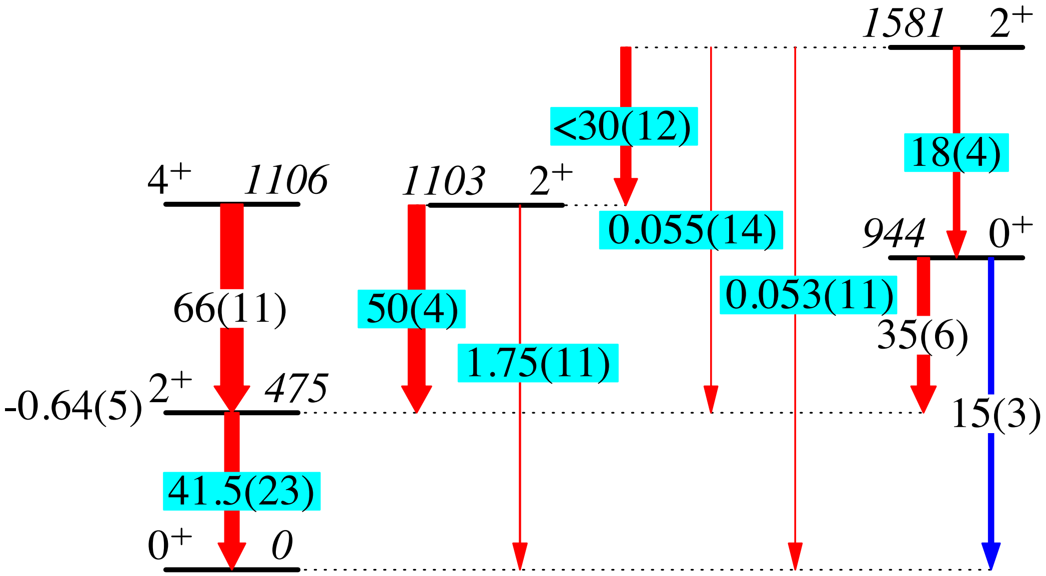
Q3D magnetic spectrometer, MLL





# Results: shape coexistence in $^{102}$Ru

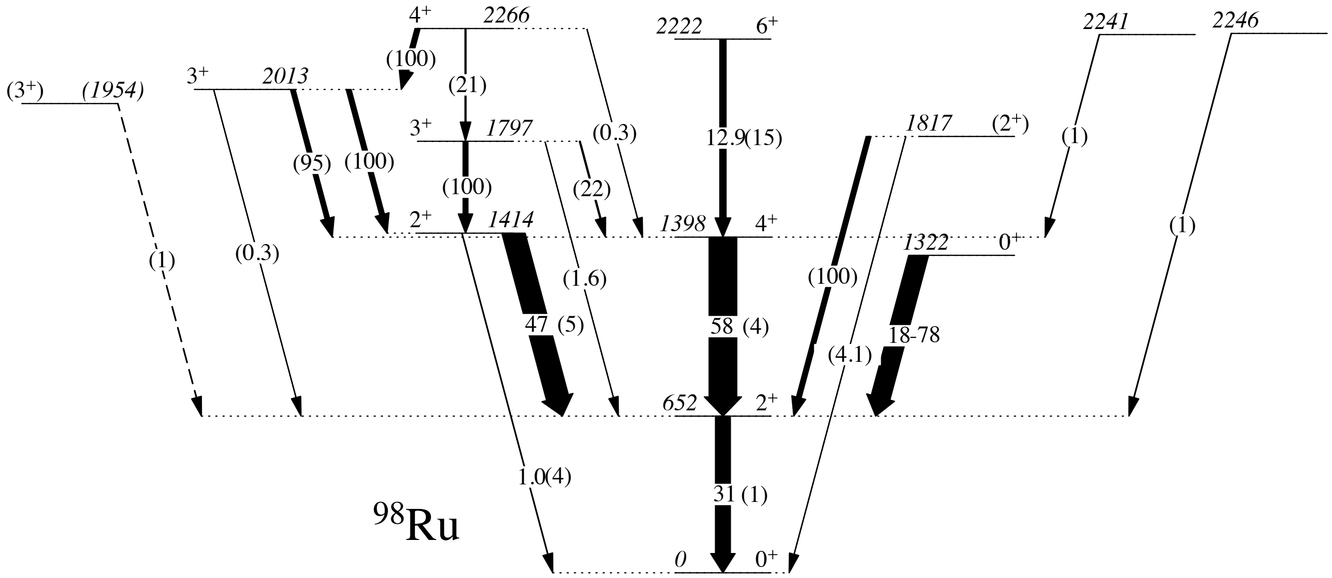




P. Garrett, MZ et al, PRC 106, 064307 (2022)

- first measurement of the B(E2; $2_3^+ \rightarrow 0_1^+$) value
- combined with known branching ratios yields B(E2) values in the two bands differing by a factor of 2
- coexistence of two structures with different overall deformation ($\beta \approx 0.24$ and $\beta \approx 0.18$)

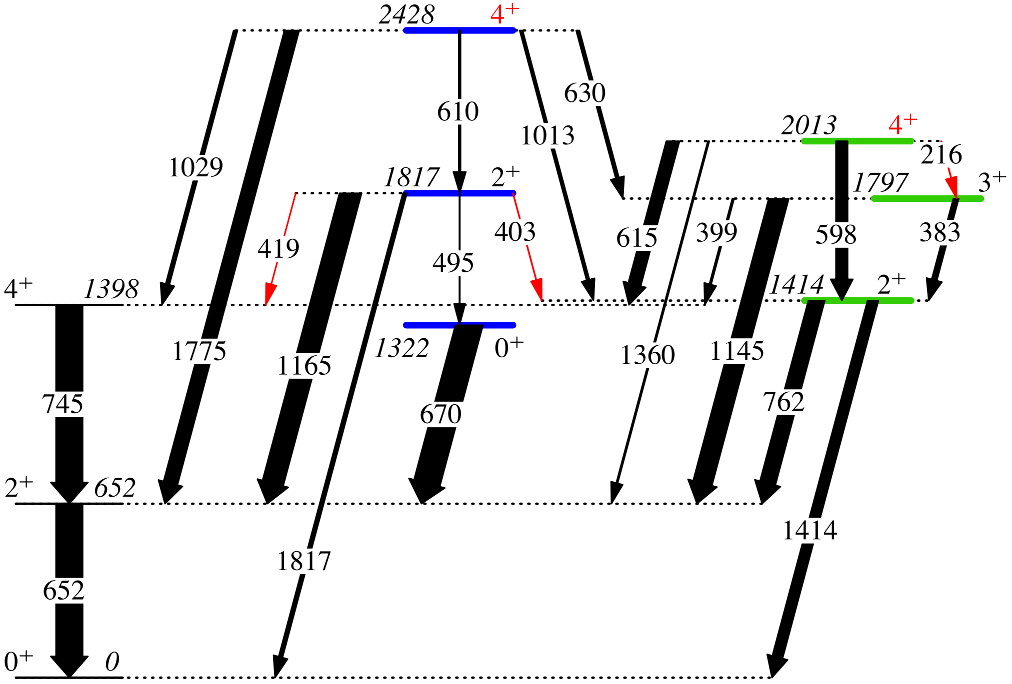
# $^{98}$Ru level scheme a few years ago

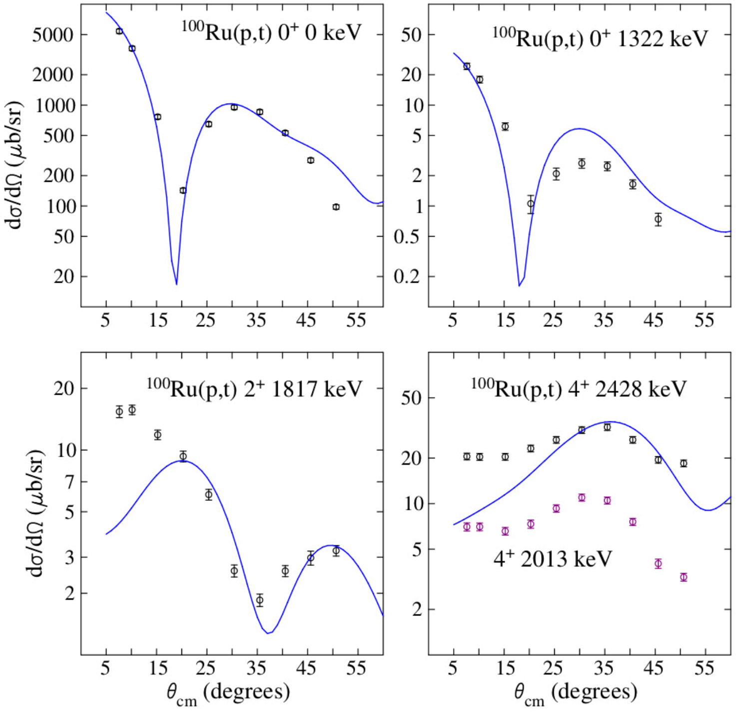


- highly unlikely that there are three closely-lying $3^+$ states
- level scheme incomplete with missing decays and spin assignments

# Reevaluation of $^{98}$Ru level scheme

P. Garrett et al., PLB 809, 135762 (2020)





- combined $\beta$-decay study (iTHEMBA Labs) and (p,t) transfer (MLL)
- resulting level scheme suggestive of shape coexistence and triaxiality

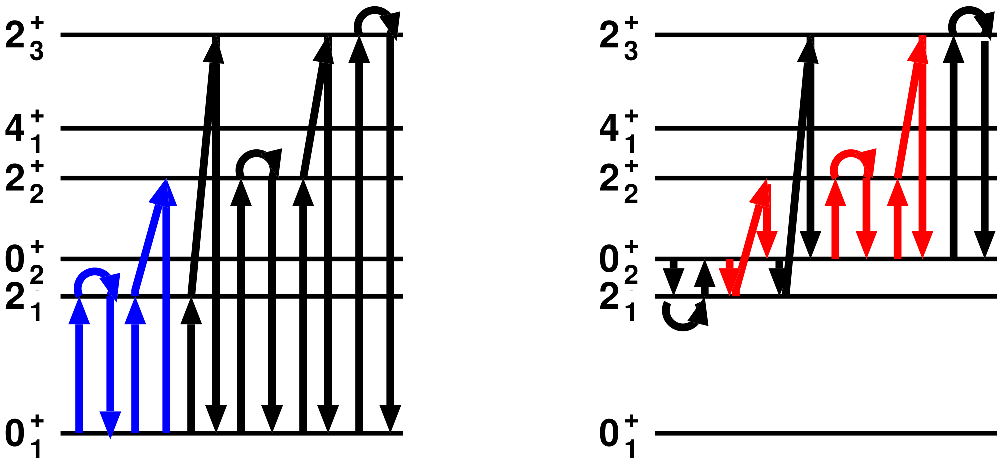
# Quadrupole sum rules: triaxiality

D. Cline, Ann. Rev. Nucl. Part. Sci. 36 (1986) 683

K. Kumar, PRL 28 (1972) 249

$$\sqrt{\frac{2}{35}}\langle Q^3 \cos 3\delta\rangle = \langle i|\{[E2\times E2]^2 \times E2\}^0|i\rangle$$

$$= \frac{1}{(2I_i+1)}\sum_{t,u}\langle i||E2||u\rangle\langle u||E2||t\rangle\langle t||E2||i\rangle \left\{\begin{array}{ccc} 2 & 2 & 2 \\ I_i & I_t & I_u \end{array}\right\}$$



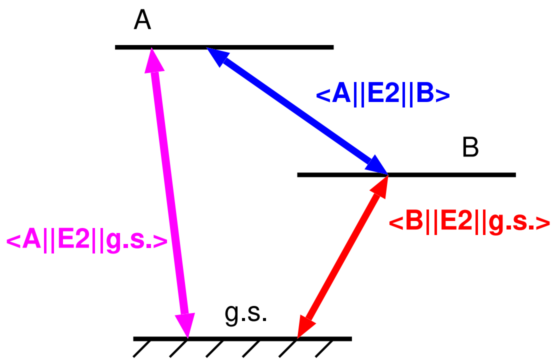
$\langle\cos 3\delta\rangle$: measure of triaxiality

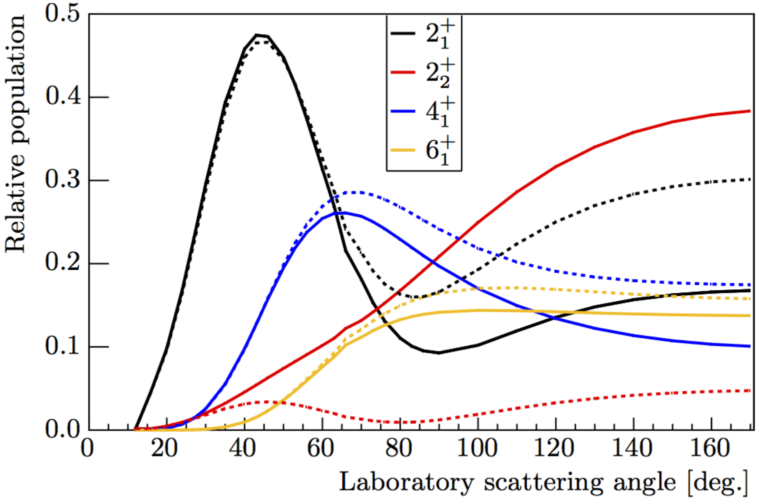
- relative signs of E2 matrix elements are needed: can we get them experimentally?

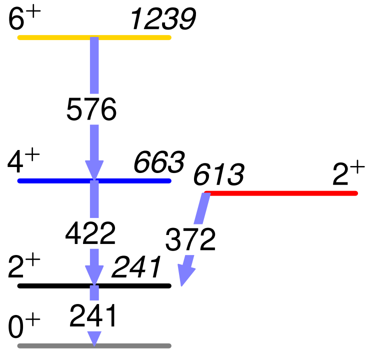
Contributions to $\langle Q^3 \cos 3\delta\rangle$ in $^{100}$Mo: K. Wrzosek-Lipska *et al.*, PRC 86 (2012) 064305

## Relative signs of E2 matrix elements

- Coulomb-excitation cross section are sensitive to relative signs of MEs: result of interference between single-step and multi-step amplitudes
- excitation amplitude of state A: $a_A \sim \langle A||E2||g.s.\rangle + \langle B||E2||g.s.\rangle\langle A||E2||B\rangle$
- excitation probability ($\sim a_A^2$) contains interference terms $\langle A||E2||g.s.\rangle\langle B||E2||g.s.\rangle\langle A||E2||B\rangle$







$^{110}$Ru

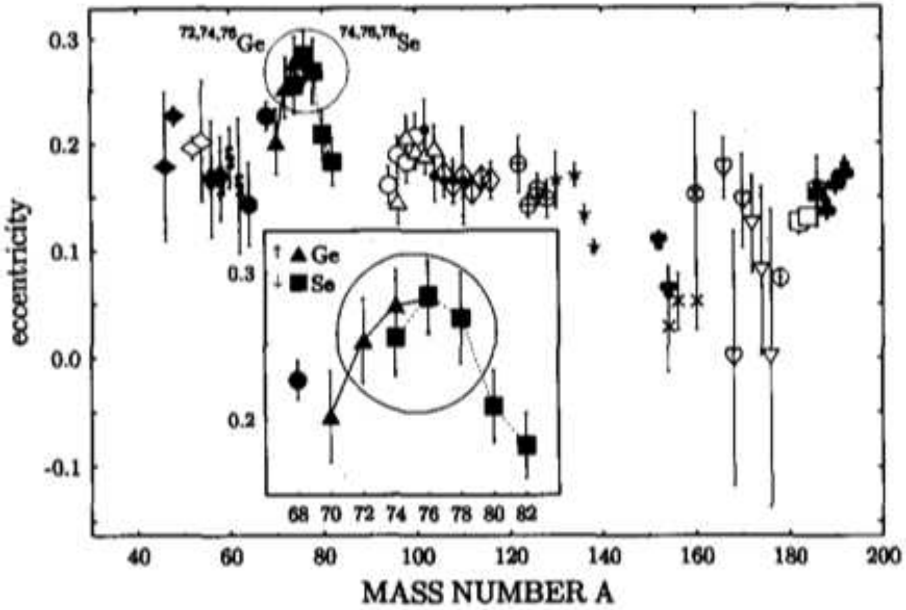
- negative $\langle 2_1^+||E2||2_2^+\rangle$ (solid lines): much higher population of $2_2^+$ at high CM angles
- sign of a product of matrix elements is an observable

# Quadrupole sum rules: triaxiality

A. Andrejtscheff *et al*, Phys. Lett. B 329 (1994) 1

For the ground state, two terms dominate the sum:

$$\langle \cos 3\delta \rangle \approx -\sqrt{\frac{7}{10}}\langle Q^2_{0_1^+}\rangle^{-3/2}\Big( \left|\langle 0_1^+\|E2\|2_1^+\rangle\right|^2 \langle 2_1^+\|E2\|2_1^+\rangle + 2\langle 0_1^+\|E2\|2_1^+\rangle\langle 2_1^+\|E2\|2_2^+\rangle\langle 2_2^+\|E2\|0_1^+\rangle \Big)$$



still, sign of the $\langle 0_1^+\|E2\|2_1^+\rangle\langle 2_1^+\|E2\|2_2^+\rangle\langle 2_2^+\|E2\|0_1^+\rangle$ product is necessary

# Do we know all states that should enter the sum?

- especially for the (E2 x E2 x E2), where terms can cancel out – can we say that terms involving higher lying levels (the $2_4^+$ state etc) do not significantly influence the rotational invariant?
  - if such state were coupled to the state in question via a large E2 matrix element, it would be populated in the experiment
  - comparison with GBH calculations for $^{100}$Mo: $\langle Q^2 \rangle$, $\langle Q^3 \cos(3\delta) \rangle$ calculated by acting with an operator on calculated wave functions and from theoretical values of matrix elements, limited to the same three intermediate states

$\Rightarrow$ difference below 3% for both $0^+$ states

| | GBH | | exp |
|---|---|---|---|
| $0_1^+ : \overline{\beta}$ | 0.20 | 0.20 | 0.22 ±0.01 |
| $0_1^+ : \overline{\gamma}$ | 27° | 27° | 29°±3° |
| $0_2^+ : \overline{\beta}$ | 0.24 | 0.24 | 0.25 ±0.01 |
| $0_2^+ : \overline{\gamma}$ | 18° | 17° | 10°±3° |

K. Wrzosek-Lipska, PRC 86 (2012) 064305

PHYSICAL REVIEW C **86**, 064305 (2012)

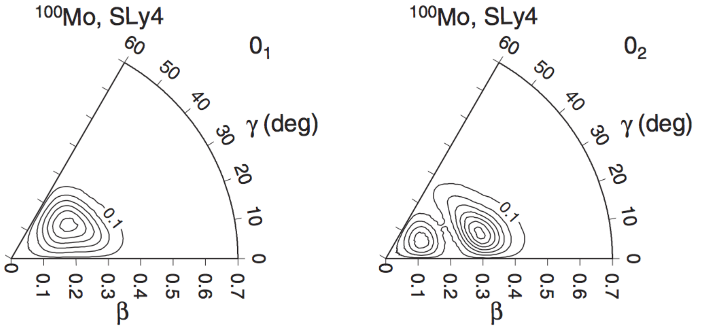
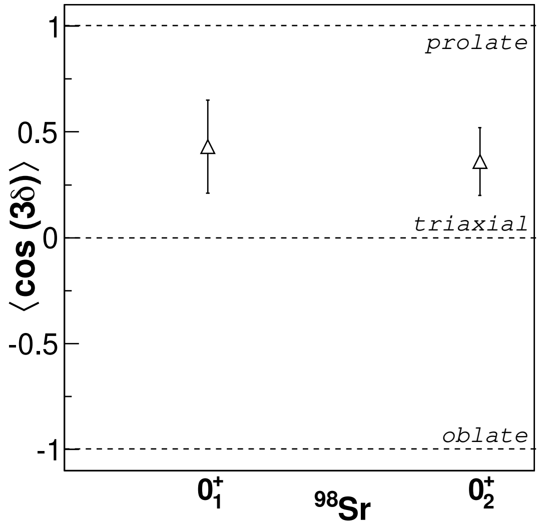
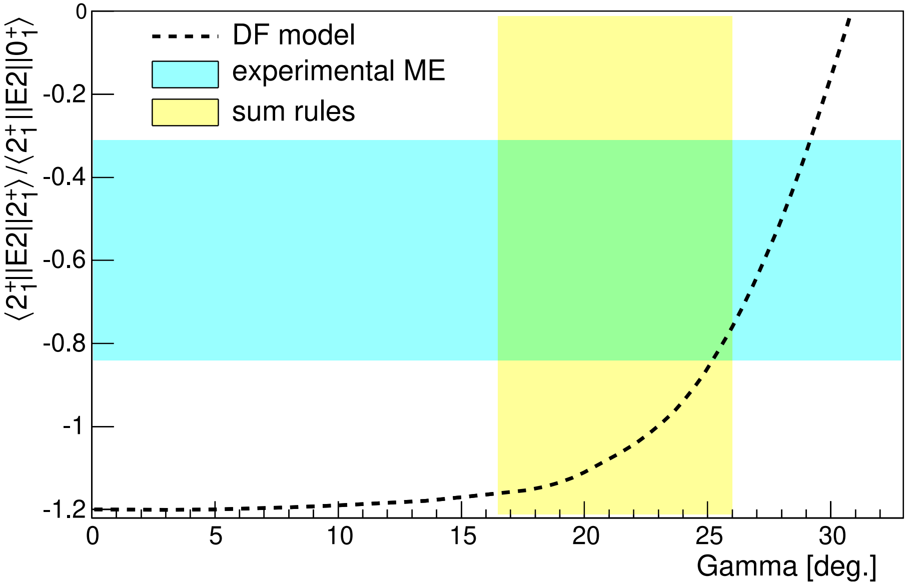


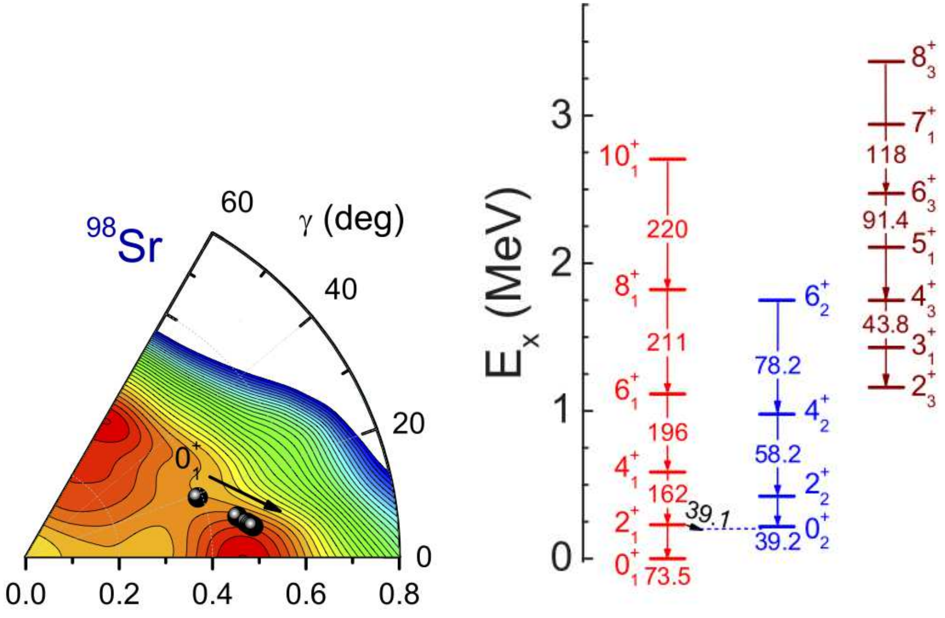
FIG. 15. Probability density [Eq. (26)] for the $0_1^+$ and $0_2^+$ states for the Skyrme SLy4 interaction. The contour interval is 0.3.

# Triaxiality in $^{98}$Sr



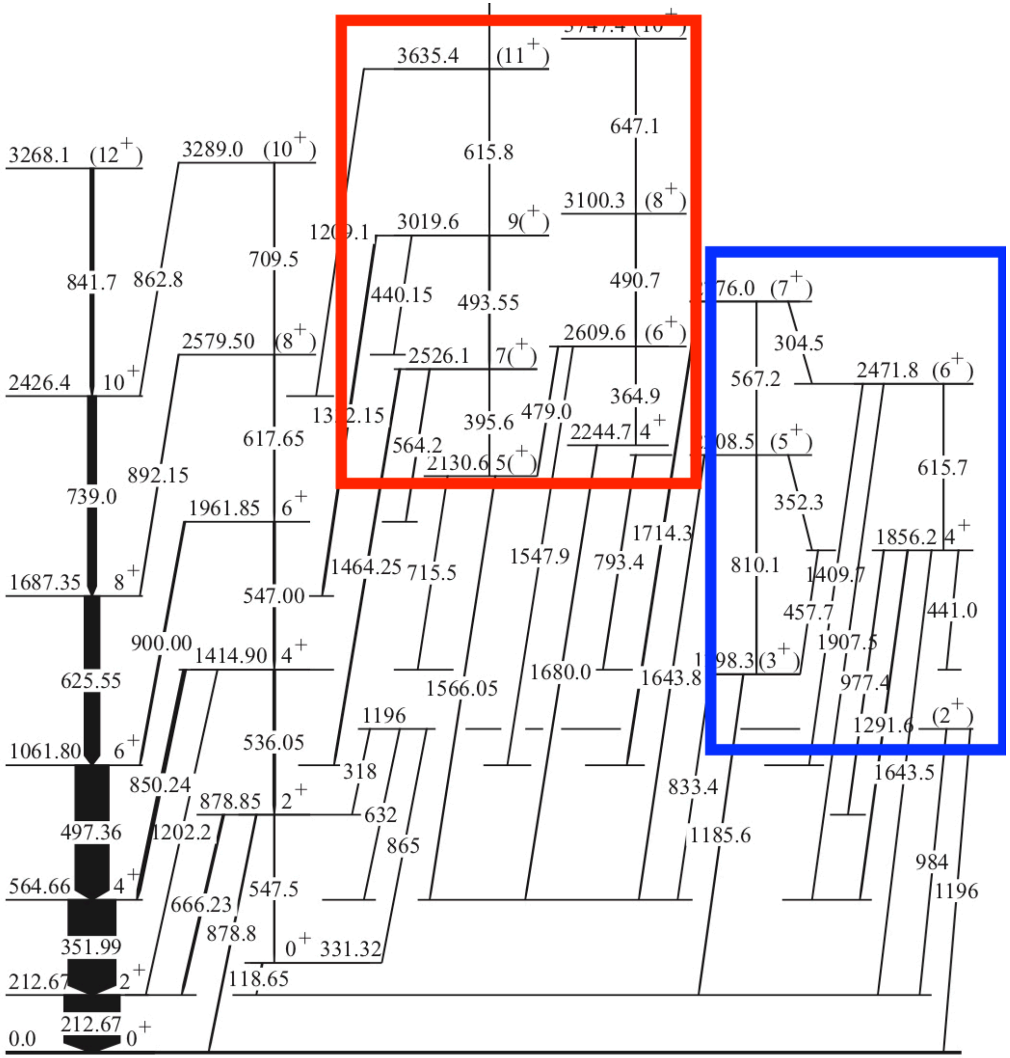


- gamma ≈ 25° would explain the reduction of $Q_s(2^+_1)$ in $^{98}$Sr
- but where is the gamma band?



J. Xiang *et al.,* PRC 93, 054324 (2016), 5DCH with PC-PK1 interaction

# Gamma and ‘triaxial’ structures in $^{100}$Zr



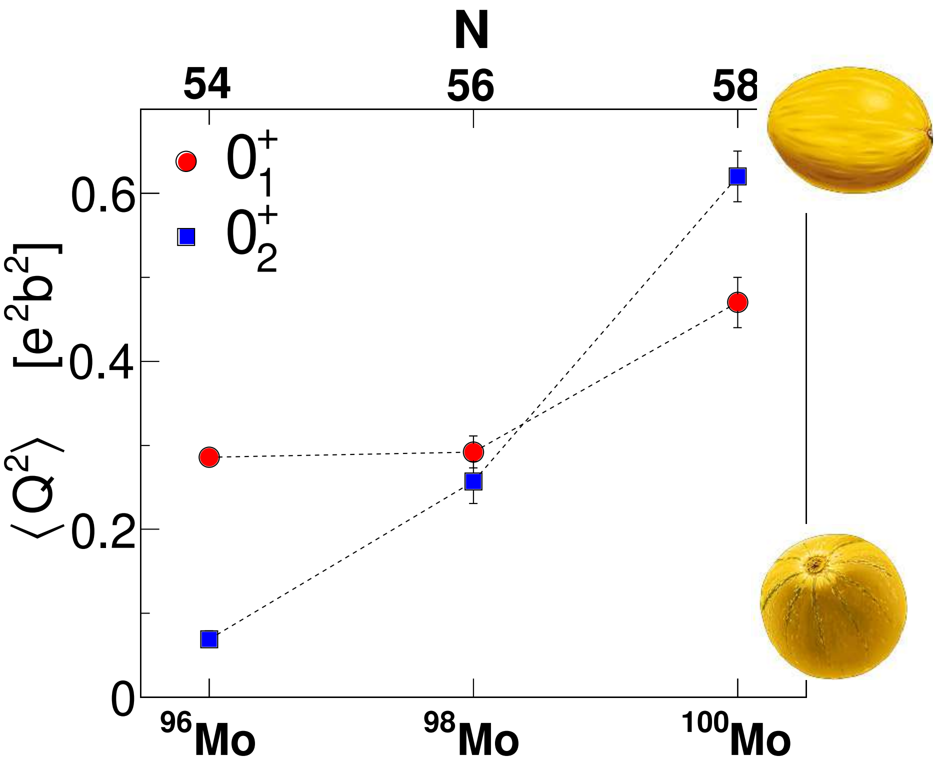
W. Urban et al, PRC 100, 014319 (2019)

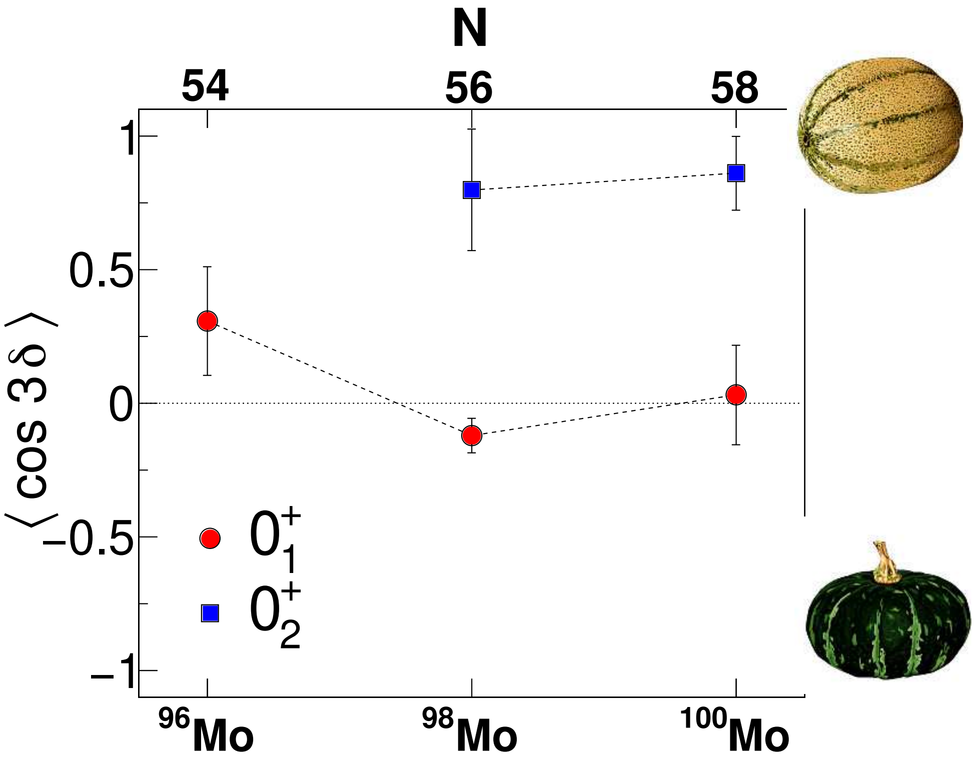
- “gamma” band proposed (related to the softness in the $\gamma$ degree of freedom) and “triaxial” band (related to a rotation of an non-axial shape)
- transitions to low-spin states missing, or even candidates missing

# Shape evolution of $^{96-100}$Mo

MZ *et al.*, Nucl. Phys. A 712 (2002) 3

K. Wrzosek-Lipska *et al.*, PRC 86 (2012) 064305

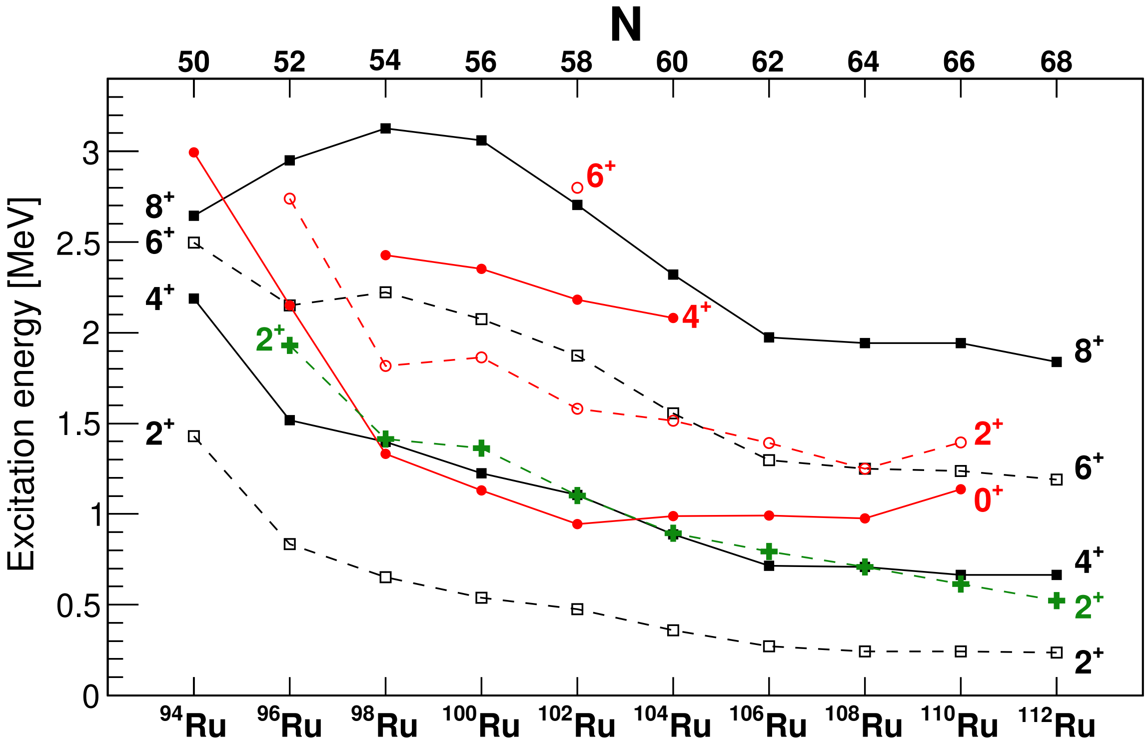




- $^{96}$Mo: coexistence of the deformed ground state with a spherical $0_2^+$
- ground states of the Mo isotopes triaxial (average shape, may result from dynamic effects), deformation of $0_2^+$ increasing with N
- shape coexistence in $^{98}$Mo manifested in a different triaxiality of $0_1^+$ and $0_2^+$

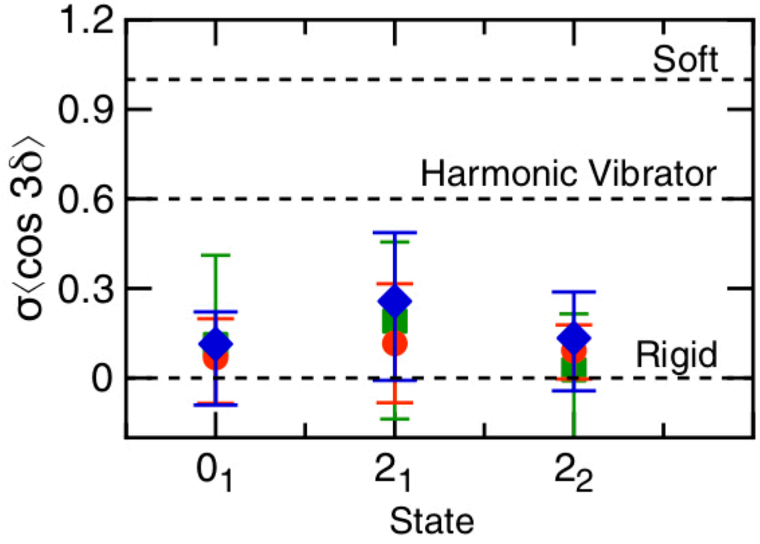
# Energy systematics in Ru isotopes

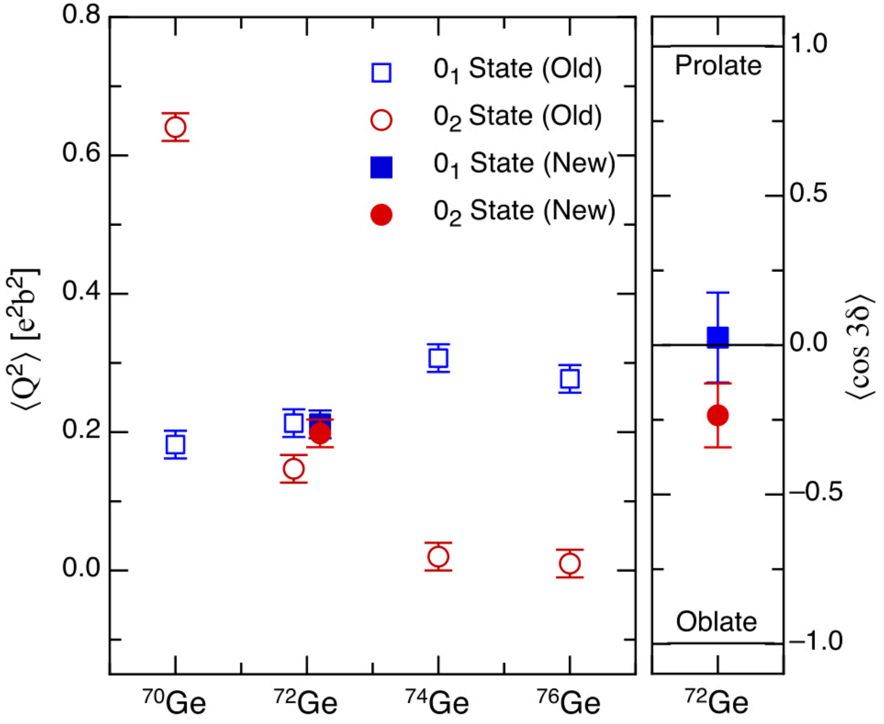
- transition from potentially $\gamma$-rigid $^{110,112}$Ru (D. Doherty et al, PLB 776, 334 (2017)) to $\gamma$-soft nuclei
- parabolic intrusion of potentially shape-coexisting shapes
- experimental data on shape coexistence less detailed than in the Zr, Mo isotopic chains



# Higher-order quadrupole invariants – example of $^{72,76}$Ge

A.D. Ayangeakaa *et al.*,
PRL 123, 102501 (2019)
PLB 754, 254 (2016)





- $^{76}$Ge: unique example of determination of softness in $\gamma$ from experimental data

- $^{72}$Ge: much higher number of transitions observed in a new measurement
→ slight change of the deduced invariants due to extra states entering the sum

# Experimental information on octupole collectivity in even-even nuclei

- energy of the first $3^-$ state (first hint)

- $B(E3; 3_1^- \rightarrow 0_1^+)$ value; $B(E3; I_i \rightarrow I_f) = \frac{7}{16\pi}(I_f 030|I_i 0)^2 Q_3^2$
  $Q_3 = \frac{3}{\sqrt{7\pi}} Z\, e\, R_0^3 \beta_3$

- negative-parity states decay predominantly by fast E1 transitions; large B(E1) values usually correlate with octupole collectivity, but the inverse is not true

- lifetime of a negative-parity state is a very poor indicator of octupole collectivity

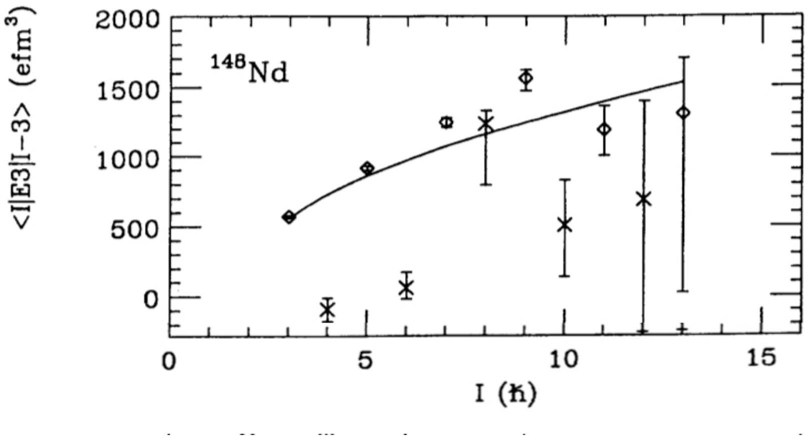
- direct E3 decay is rarely observed

- Coulomb excitation and inelastic scattering are the methods of choice to determine E3 strength

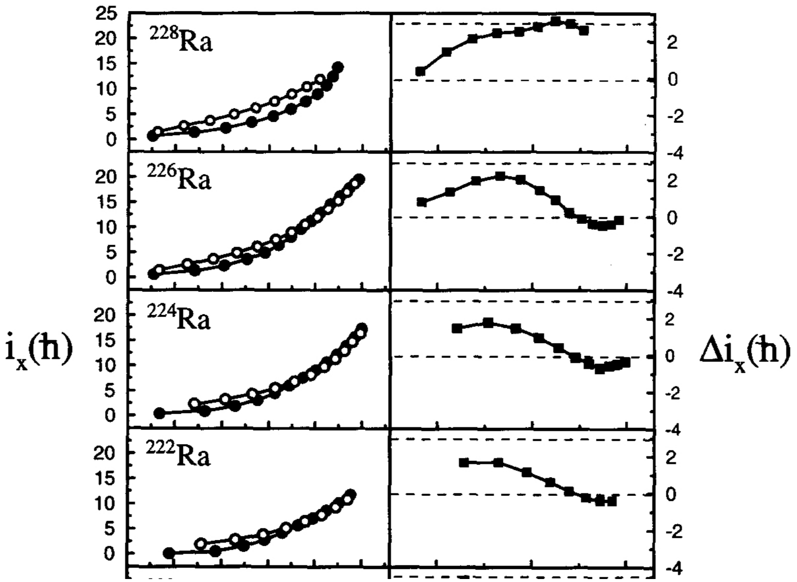
# Rigid octupole deformation versus octupole vibration

- apart from actinides, E3 collectivity is usually attributed to surface vibrations

- rigid octupole deformation can be claimed on the basis of B(E3) values between the ground-state band and the negative-parity band, or identical rotational alignments in these bands (→ interleaving of positive and negative-parity states)



J.F.C. Cocks et al./Nuclear Physics A 645 (1999) 61–91



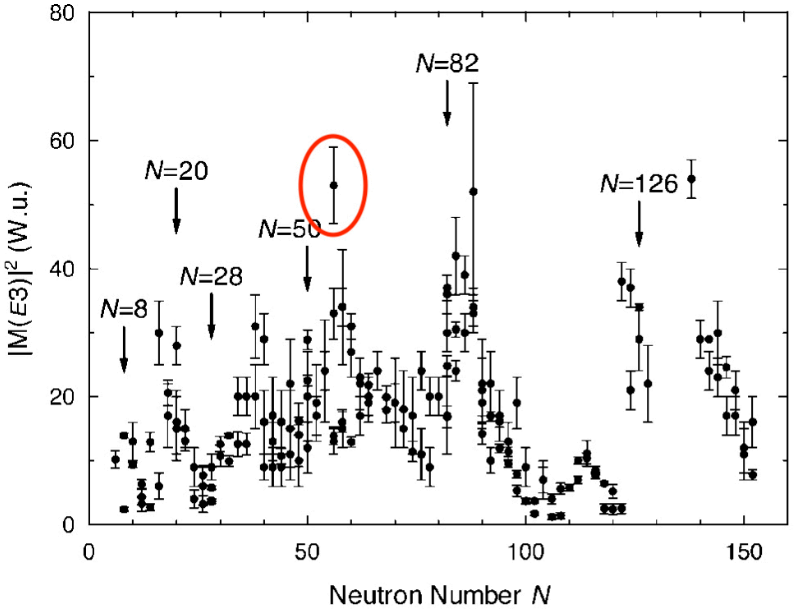
R. Ibbotson et al, PRL 71, 27 (1993)

More info: P. A. Butler and W. Nazarewicz Rev. Mod. Phys. 68, 349 (1996); P. Butler, Proc. R. Soc. A 476, 202 (2020)

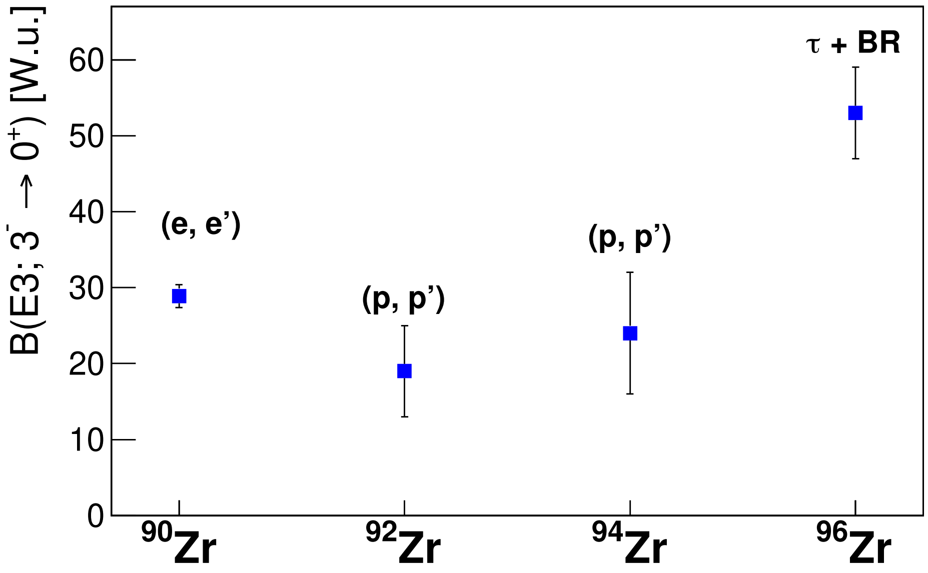
# Octupole collectivity in Zr isotopes: anomalous value for $^{96}$Zr

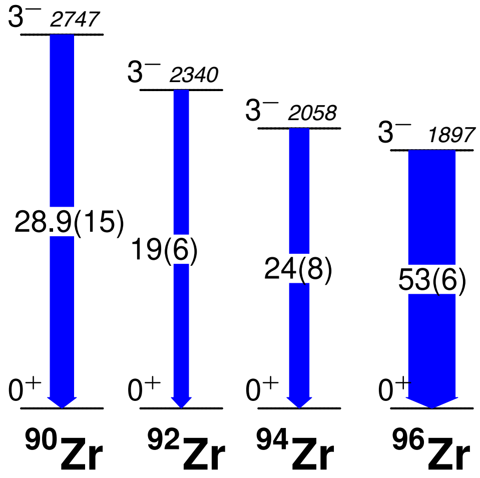
- evaluated B(E3; $3^-_1 \rightarrow 0^+_1$) strength for $^{96}$Zr strikingly high (53(6) W.u.), comparable with those known for nuclei with rigid pear shapes

- observed trend of B(E3; $3^-_1 \rightarrow 0^+_1$) values in Zr isotopes inconsistent with $3^-_1$ energies and hard to explain



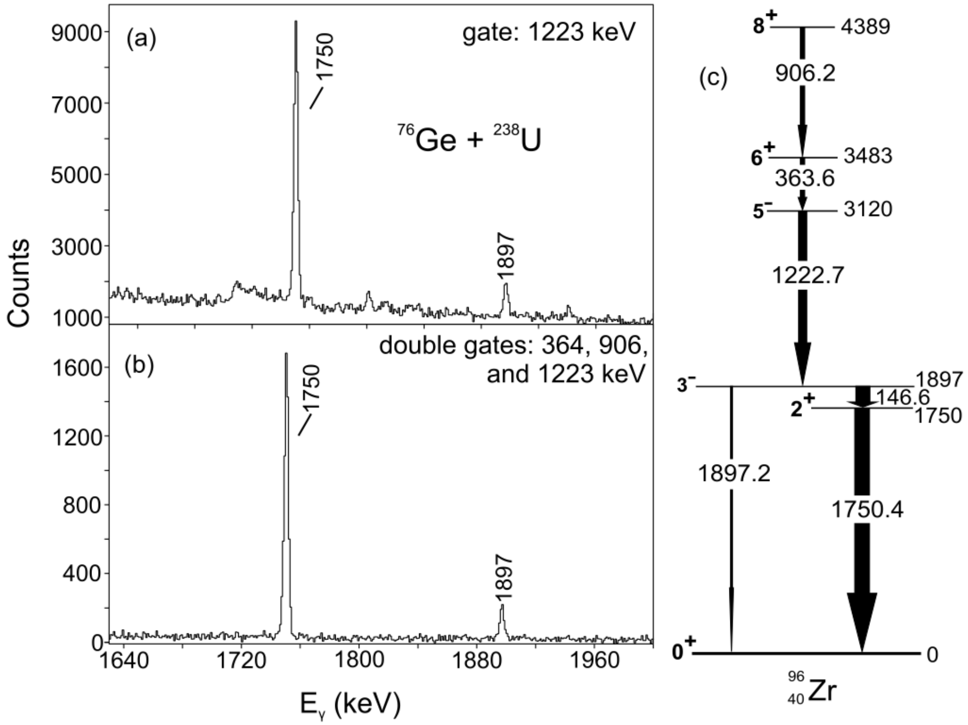
T. Kibédi and R.H. Spear, At. Data Nucl. Data Tables 80, 35 (2002)





# Revision of the E3 strength in $^{96}$Zr

- determination of E3 strength in $^{96}$Zr using gamma-ray spectroscopy requires two measurements:
  - lifetime ($\approx$ 70ps – plunger measurements)
  - branching ratio E3/E1
- if the 147 keV / 1897 keV intensity ratio is directly measured, the efficiency must be known precisely
  - walk effect, conversion at 147 keV

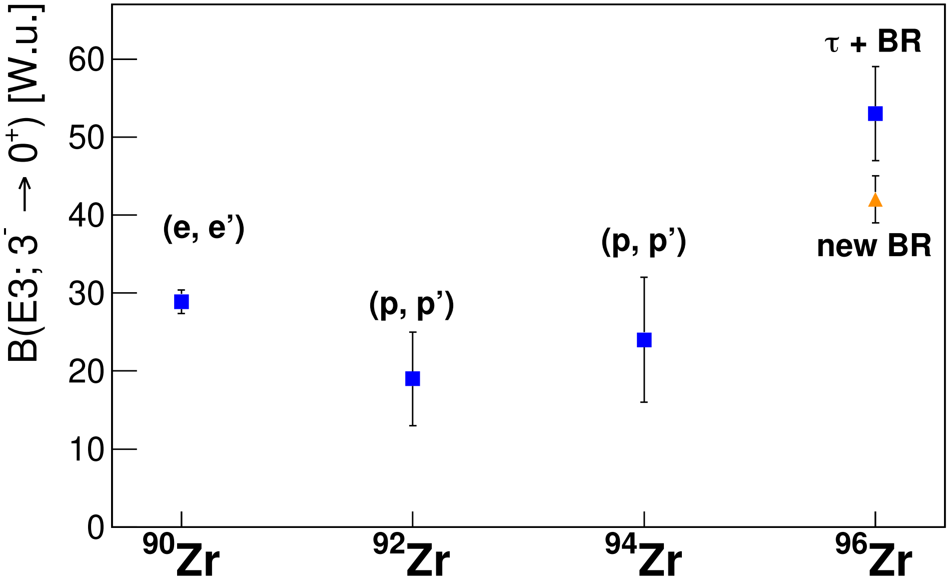


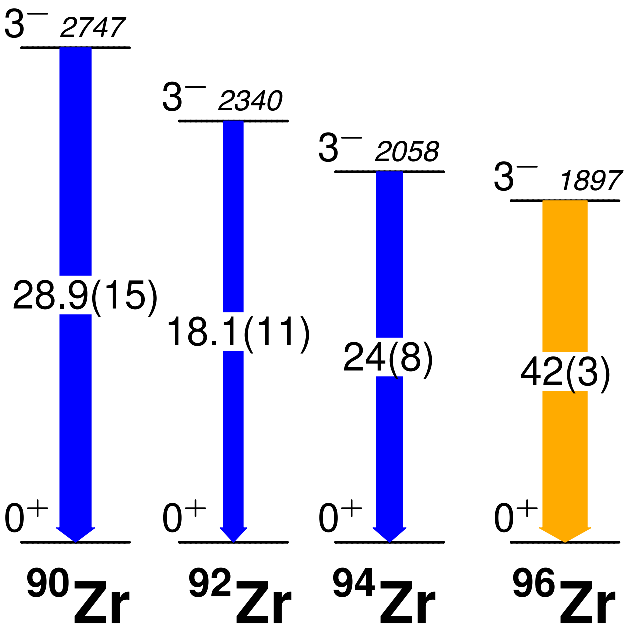
- new measurement – gating from above and comparison of 1750 keV and 1897 keV intensities

Ł. Iskra et al, Phys. Lett. B 788 (2019) 396

# Octupole collectivity in Zr isotopes: new BR measurement for $^{96}$Zr

- new measurement of E1/E3 branching ratio in $^{96}$Zr (Ł. Iskra et al, Phys. Lett. B 788 (2019) 396) points to lower octupole collectivity, but the overall trend remains puzzling

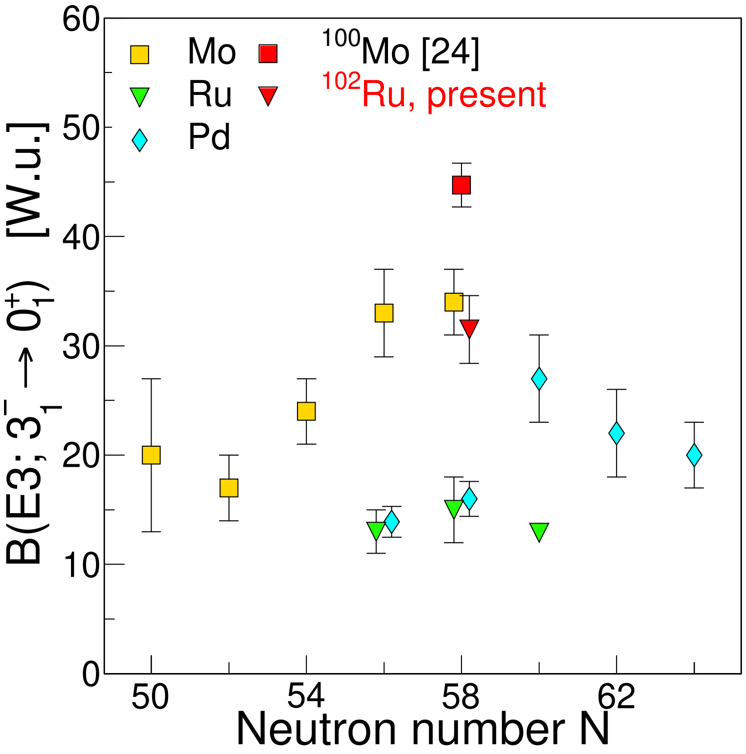


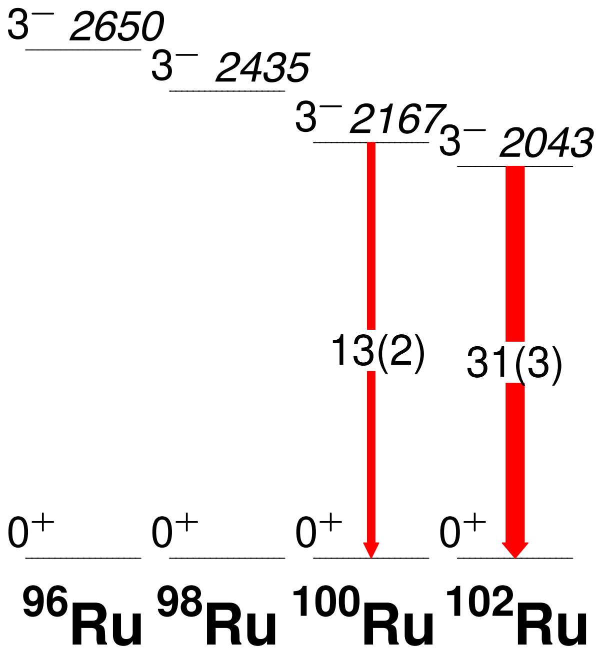


→ new systematic study of quadrupole and octupole collectivity in stable Zr isotopes at MLL

# Octupole collectivity in Ru isotopes

- no B(E3) values for Ru isotopes lighter than $^{100}$Ru
- smooth evolution of $3^-$ energies
- conflicting B(E3) results in Ru and Mo nuclei

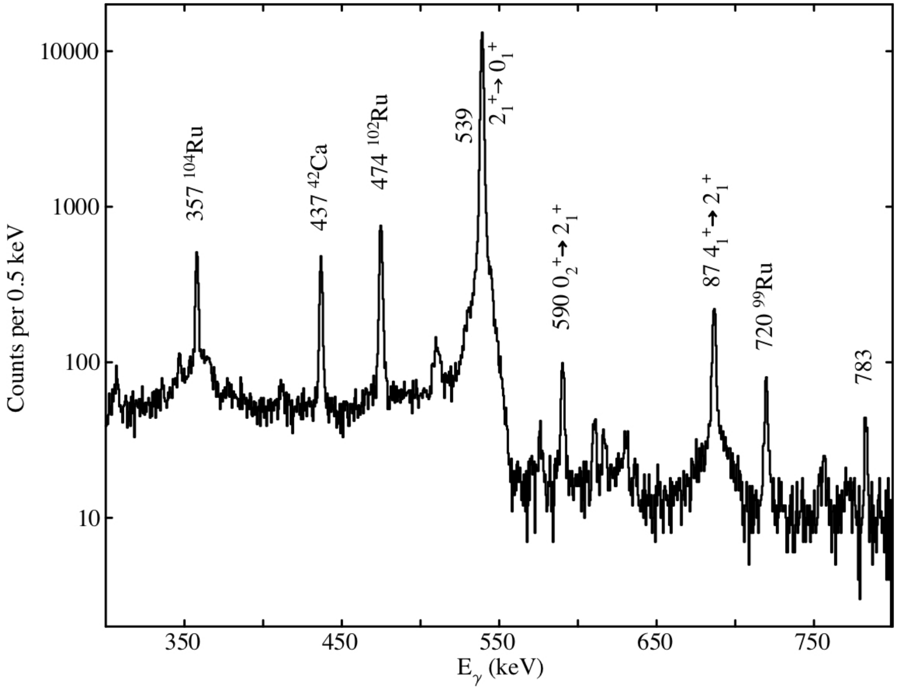




P. Garrett, MZ et al, PRC 106, 064307 (2022)

# Coulomb excitation of $^{100}$Ru

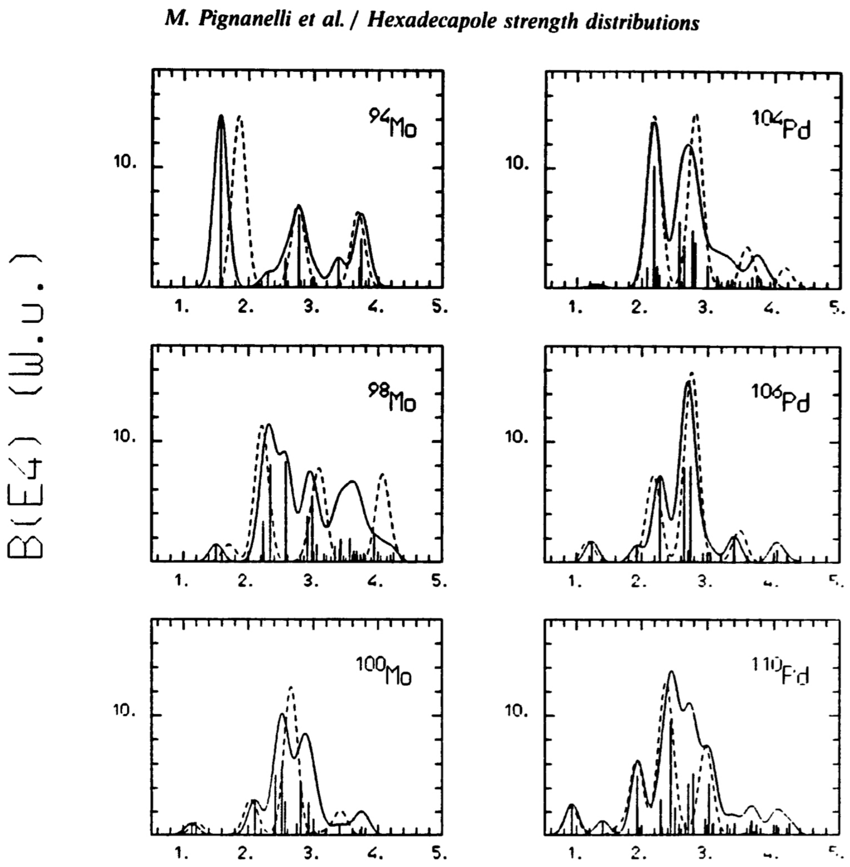
- low-energy Coulomb excitation of $^{100}$Ru with a $^{32}$S beam performed at HIL Warsaw in April 2022 (PI P. Garrett, K. Wrzosek-Lipska, MZ)
- in order to better constrain the properties of the $2_2^+$ state, data will be completed by a second measurement with a $^{14}$N beam
- additional lines in the spectrum due to target oxidation
- decay of the $3_1^-$ state at the observation limit



# Outlook: challenges for future Coulomb-excitation studies

- abundance: 5.54% $^{96}$Ru, 2.80% $^{96}$Zr
- difficult to get material with high enrichment (even more since the war has started); to my knowledge, no suppliers offer $^{96,98}$Ru
- difficult to produce Ru and Zr targets (material often available in oxide form, Ru targets produced by electrodeposition proven very fragile)
- high excitation energies in $^{96}$Zr and $^{96}$Ru with respect to other isotopes make it more difficult to populate levels of interest

# Hexadecapole strength in A$\approx$ 100 nuclei



M. Pignanelli et al, NPA 540, 27 (1992)