Coexisting Shapes and Precision Tests of Monte-Carlo Shell-Model Calculations in ^{96}Zr

LNL experiments: N. Marchini[1,2], F. Ercolano[3], M. Rocchini[2], A. Nannini[1,2], D.T. Doherty[4], M. Zielińska[5], K. Hadyńska-Klęk[6], A. Goasduff[7,8,9], M. Balogh[7], D. Testov[8,9], P. Aguilera[7], F. Angelini[7], G. Benzoni[10], F. Camera[10,11], S.D. Bakes[4,7,8], D. Bazzacco[8,9], J. Benito[7,8], T. Berry[4], D. Brugnara[7,8], M.H.V. Brunet[4], S. Buck[12], G. Carozzi[7,8], W.N. Catford[4], R. Coleman[12], R. Escudeiro[7,8], A. Ertoprak[7], G. de Angelis[7], M. De Rizzo[7,8], F. Galtarossa[7], P.E. Garrett[12], N. Gelli[2], A. Gottardo[7], A. Gozzelino[7], B. Gongora[7], A. Illana[7], D. Kalaydjieva[5], W. Korten[5], J. Keatings[13], A.R.L. Kennington[4], Md.S.R. Laskar[10], M. Matejska-Minda[14], D. Mengoni[8,9], L. Morrison[4], D.R. Napoli[7], M. Ottanelli[2], P. Ottanelli[1,2], G. Pasqualato[8,9,15], J. Pellumaj[7], R.M. Perez-Vidal[7], S. Pigliapoco[7,8], E. Pilotto[7], F. Recchia[8,9], K. Rezynkina[8], S. Riccetto[16], M. Scheck[13], M. Siciliano[7,8], G. Sighinolfi[9], J. Sinclair[13], K. Stoychev[15], J.J. Valiente Dobon[7], K. Wrzosek-Lipska[6], L. Zago[7], G. Zhang[8], I. Zanon[7], T. Zidar[12]

MLL experiments: M. Zielińska[5], P.E. Garrett[12], A. Bergmaier[17], H. Bidaman[12], V. Bildstein[12], A. Diaz Varela[12], D.T. Doherty[4], T. Fästermann[18], R. Hertenberger[19], A.T. Laffoley[12], A.D. MacLean[12], S. Pannu[12], M. Rocchini[2,12], P. Spagnoletti[13], M. Vandebrouck[5], and K. Wrzosek-Lipska[6]

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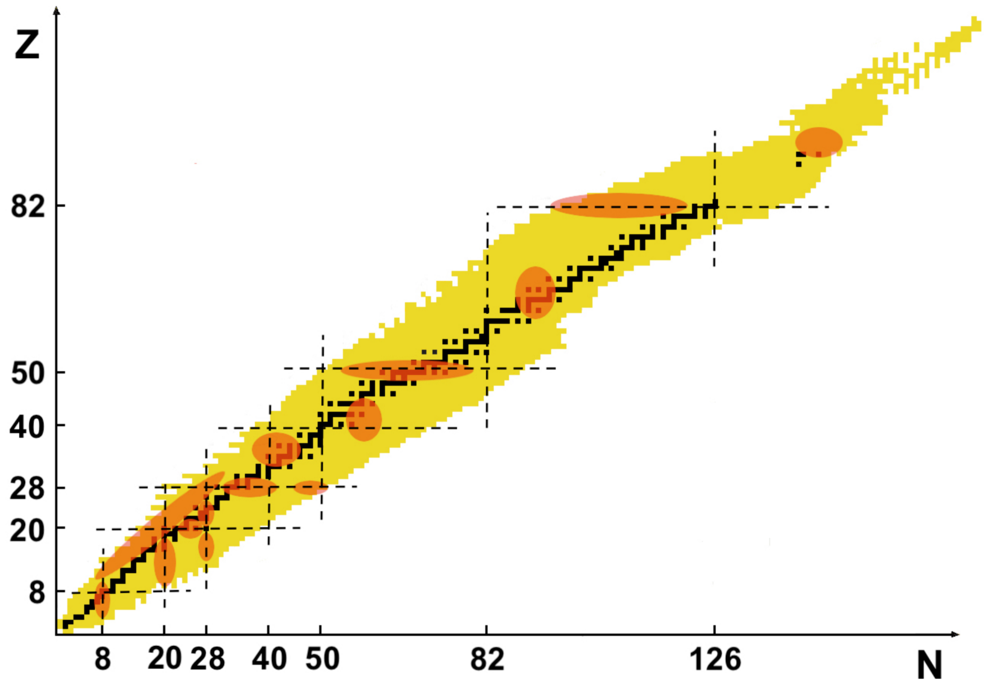
Shape coexistence around Z=40

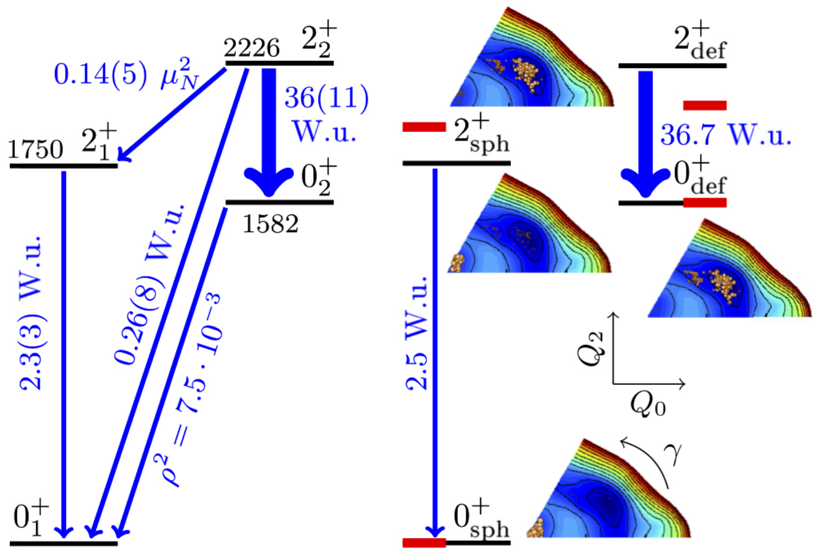
K. Heyde and J. Wood, Rev. Mod. Phys. 83, 1467 (2011)

P. Garrett, MZ and E. Clément, Prog. Part. Nucl. Phys. 124, 103931 (2022)

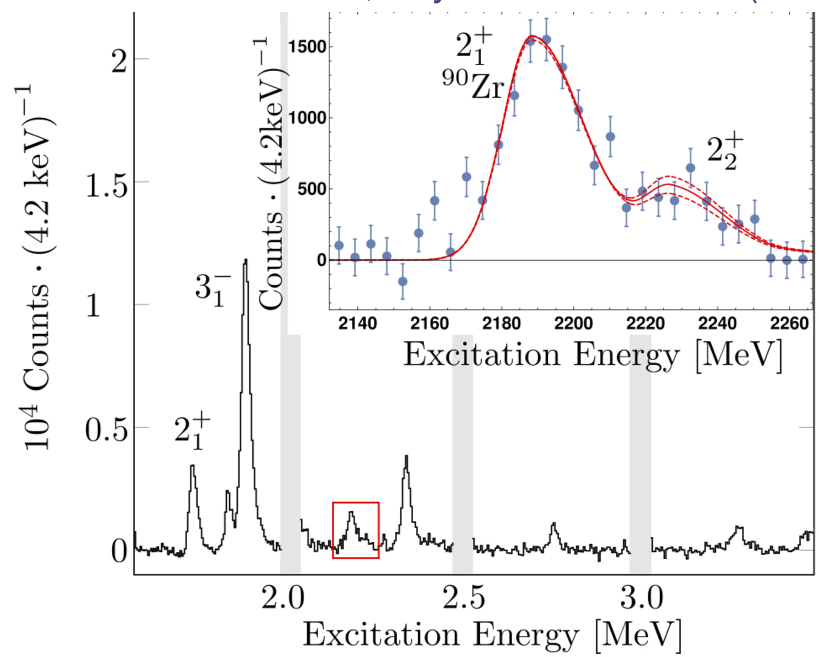


- islands of shape coexistence observed in the vicinity of shell closures
- Z=40 only a sub-shell closure, but strong evidence for shape coexistence in:
  - ^{96,98}Sr (E. Clément et al, Phys. Rev. Lett. 116, 022701 (2016))
  - ^{96}Zr (C. Kremer et al, Phys. Rev. Lett. 117, 172503 (2016))
  - ^{94}Zr (A. Chakraborty et al, Phys. Rev. Lett. 110, 022504 (2013))

Shape coexistence in ^{96}Zr – experimental information

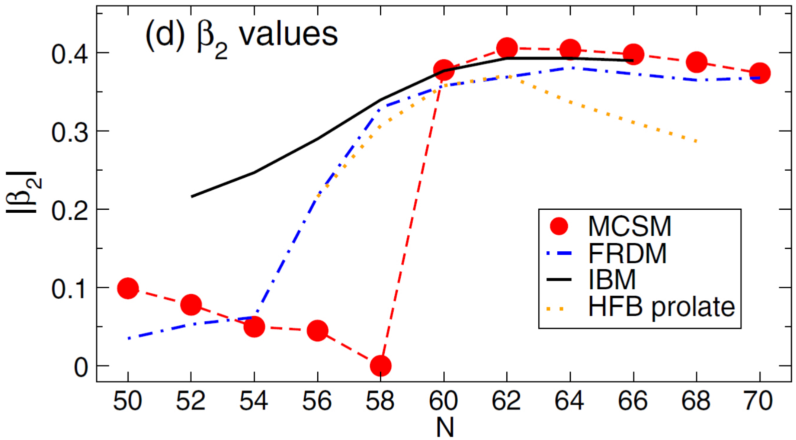


S. Kremer et al, Phys. Rev. Lett. 117 (2017) 172503



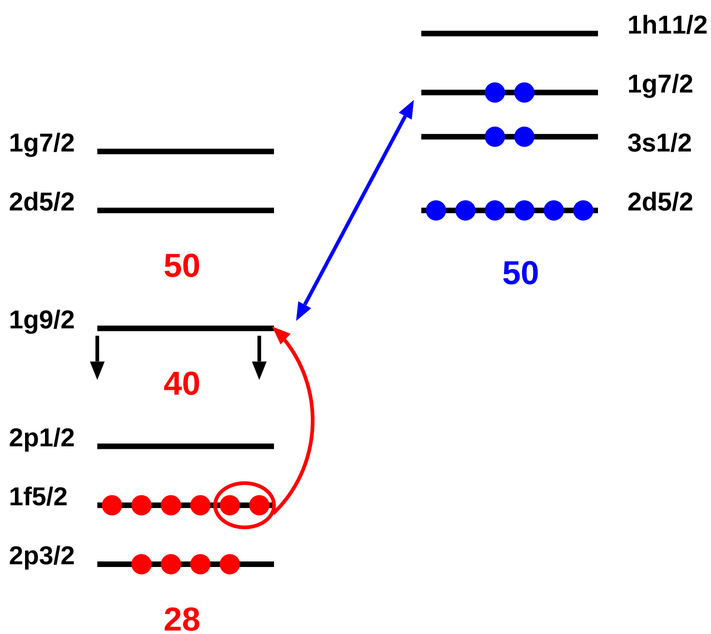
- B(E2; $2_2^+ \rightarrow 0_1^+$) measured using electron scattering, combined with known branching and mixing ratios:
  $\rightarrow$transition strengths from the 2_2^+ state
- B(E2; $2_1^+ \rightarrow 0_1^+$) = 2.3(3) Wu vs B(E2; $2_2^+ \rightarrow 0_2^+$) = 36(11) Wu: nearly spherical and a well-deformed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

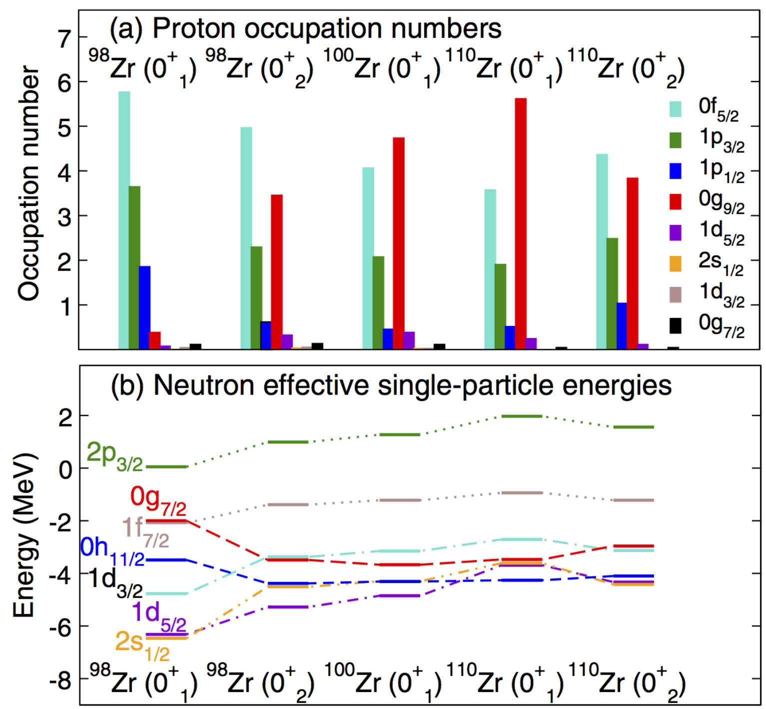
Shape coexistence and type-II shell evolution in Zr isotopes



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

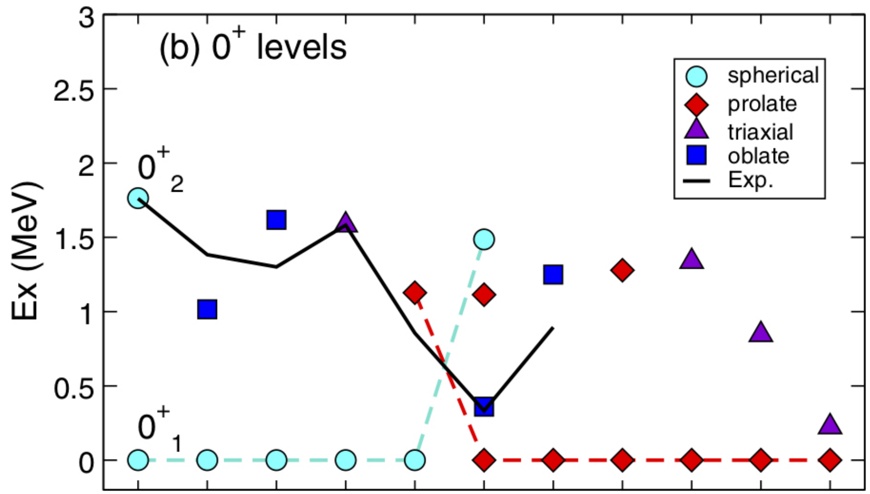
- p-n tensor interaction reduces the Z=40 gap when $\nu g_{7/2}$ is being filled
- 0_2^+ states created by 2p-2h (+ 4p-4h...) excitation across Z=40
- very different configurations and small mixing of 0_1^+ and 0_2^+



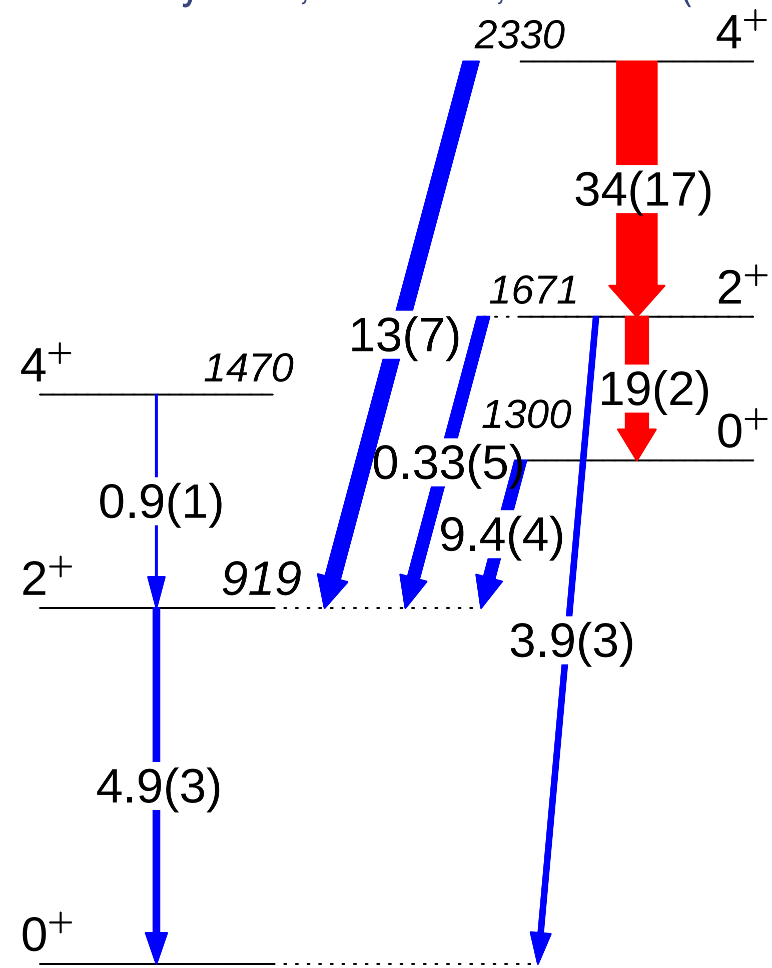


Shape coexistence in ^{94}Zr

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



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

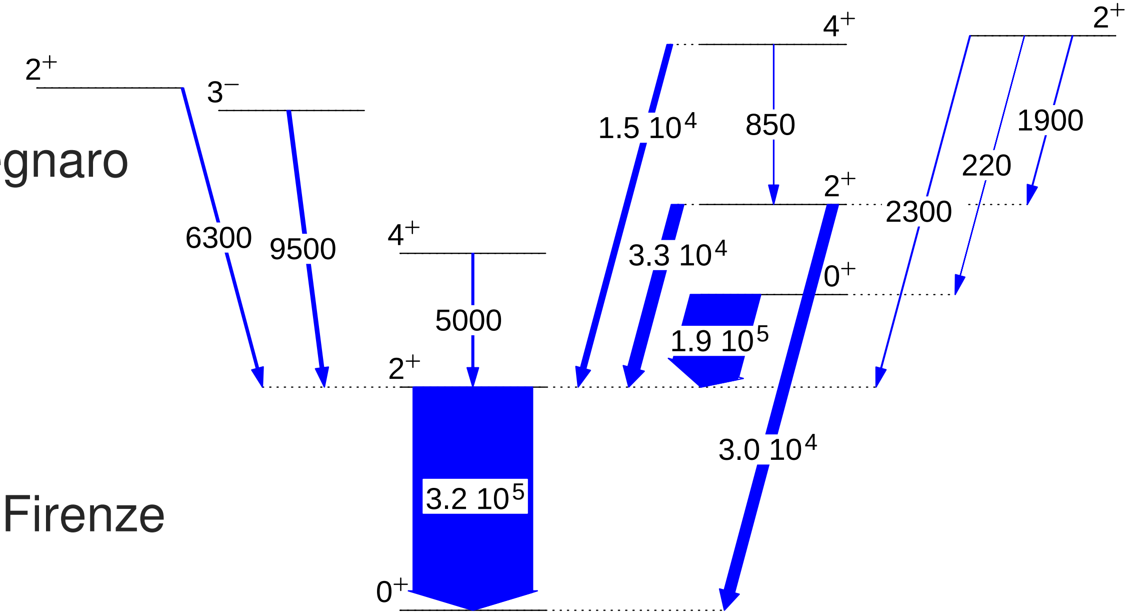


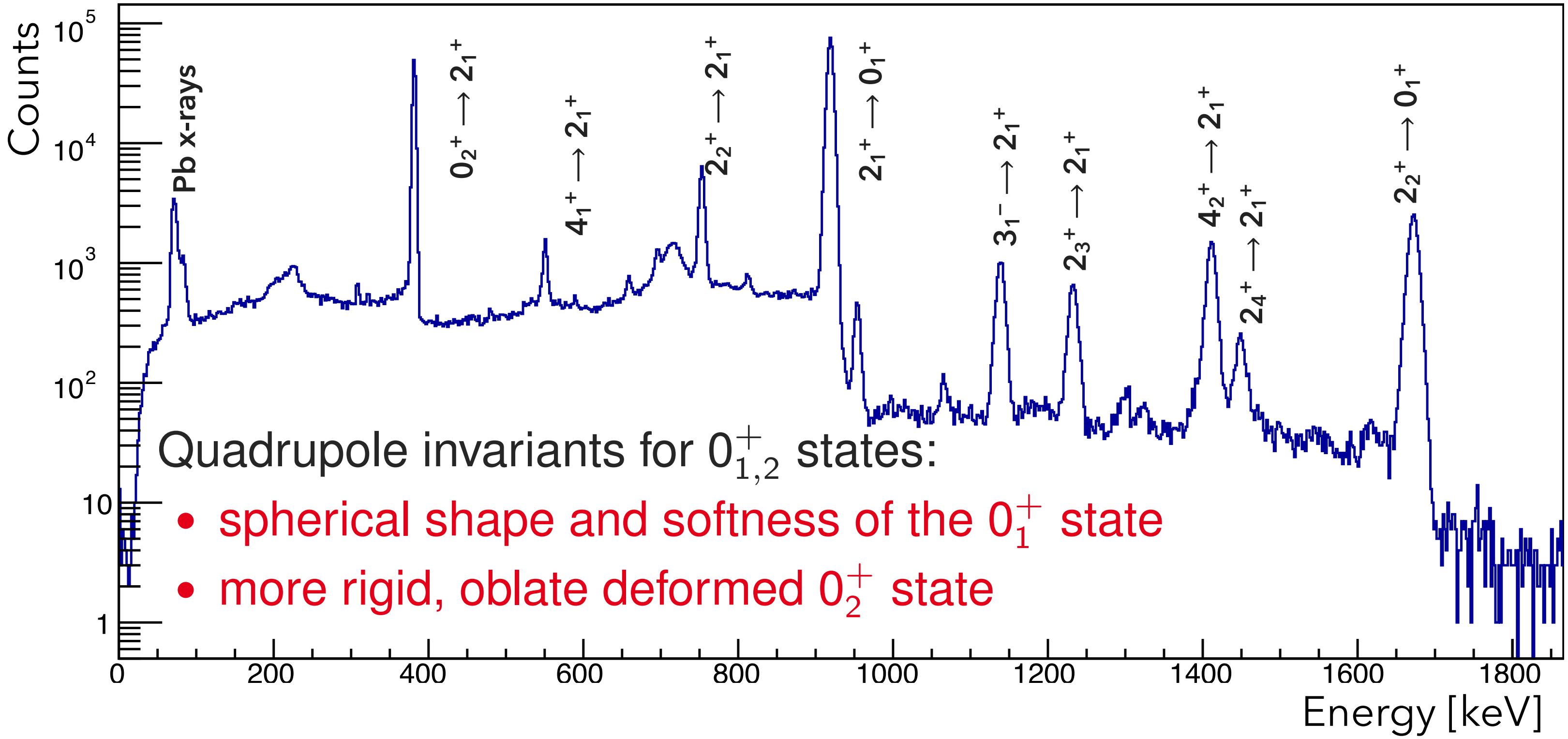
- MCSM calculations suggest a variety of shapes appearing at low excitation energy in Zr nuclei
- ^{94}Zr selected as the first candidate for a detailed experimental investigation
- oblate deformed structure predicted to be built on the 0^+_2 state

- high-statistics β-decay study at TRIUMF: observation of a strong $2^+_2 \rightarrow 0^+_2$ transition (19 W.u.) – a deformed band built on 0^+_2

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





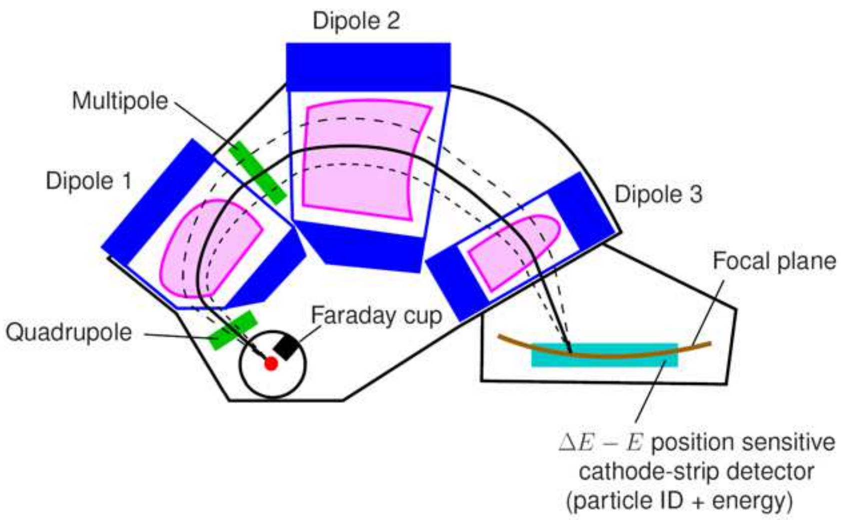
Quadrupole invariants for $0^+_{1,2}$ states:

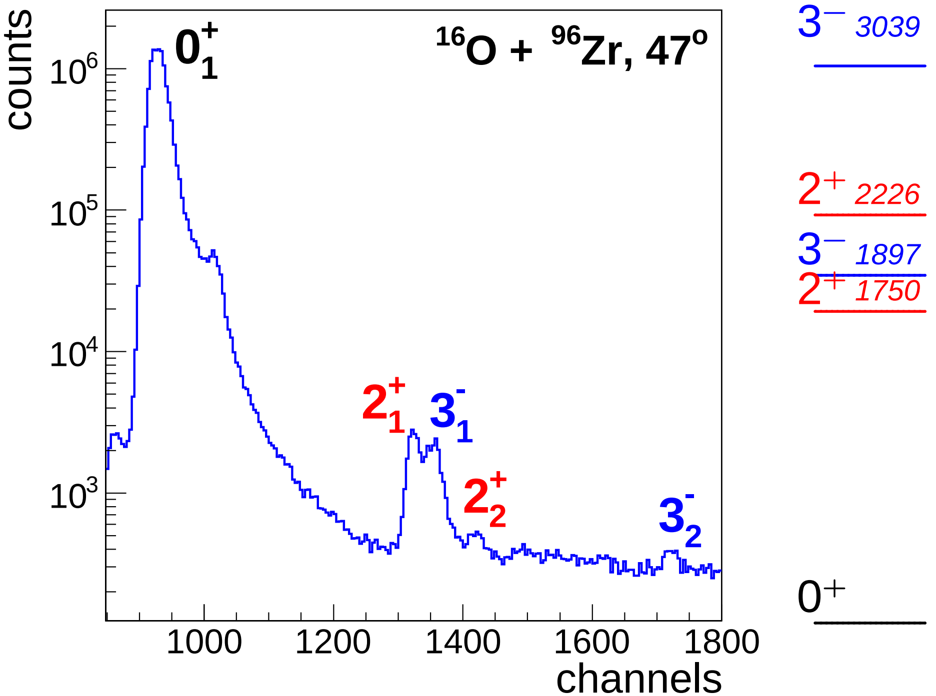
- spherical shape and softness of the 0^+_1 state
- more rigid, oblate deformed 0^+_2 state

Coulomb excitation of ^{96}Zr at MLL

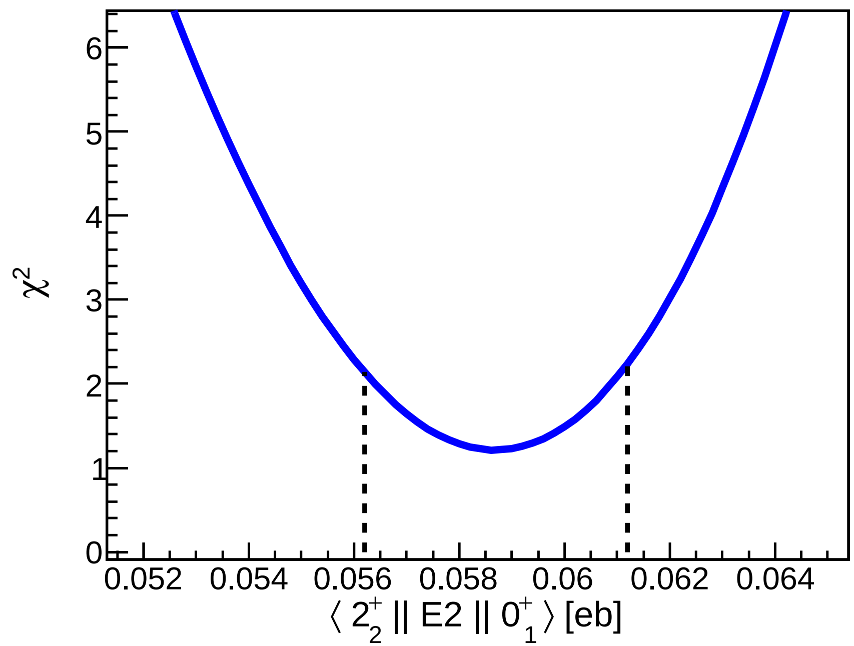
- Coulomb-excitation measurements with magnetic spectrometers common in 1970s, but completely abandoned in favour of γ-ray spectroscopy
- still a very attractive option, especially to populate higher-lying low-spin states: very high beam intensities ($\sim$100 pnA) can compensate for low cross sections
- ^{12}C, ^{16}O beams: direct measurement of population of 2^+ and 3^- states $\rightarrow$ precise B(E2; $2^+_i \rightarrow 0^+_1$) and B(E3; $3^-_i \rightarrow 0^+_1$) values
- Coulomb-excitation campaign in January and August 2019

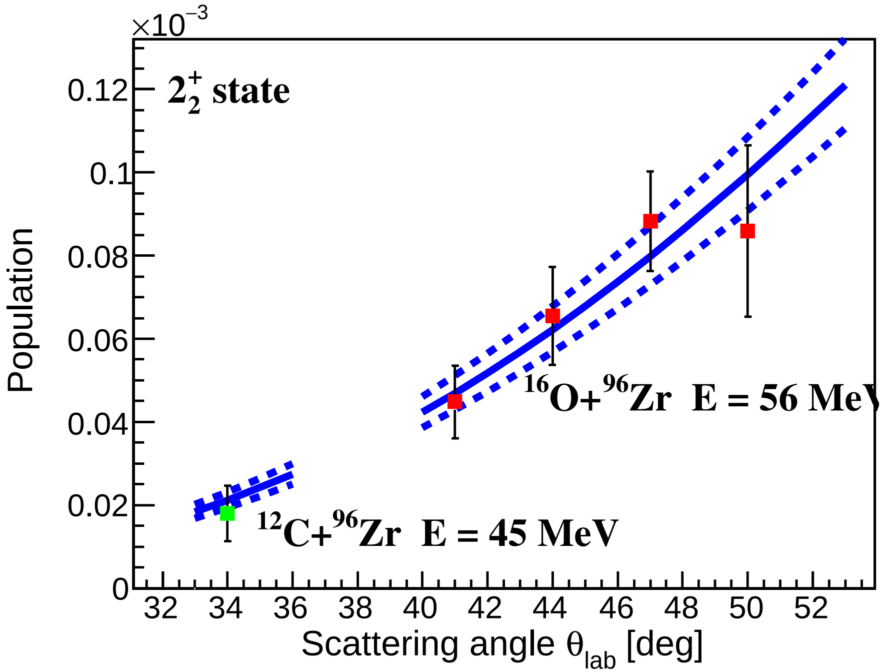
Q3D magnetic spectrometer, MLL





Results: collectivity in the band built on 0_2^+ in ^{96}Zr

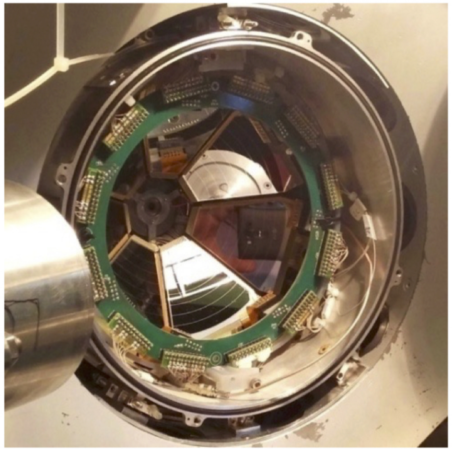


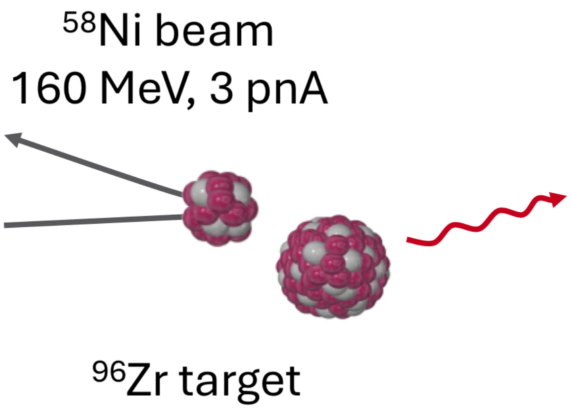


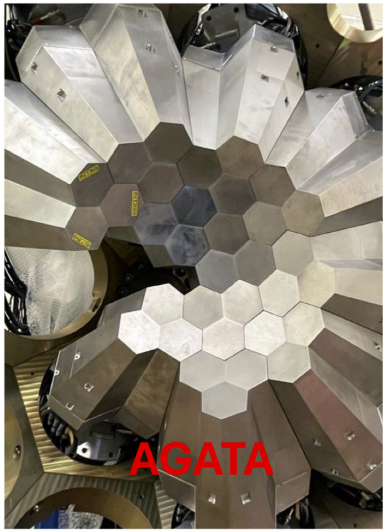
- $B(E2; 2_2^+ \to 0_1^+)$ = 0.270(27) W.u., versus 0.26(8) W.u. from Kremer et al (fully consistent, but 3 $\times$ better precision))
  - $B(E2; 2_2^+ \to 0_2^+)$ = 36(4) W.u.
- for comparison: $B(E2; 2_1^+ \to 0_1^+)$ agrees within 1σ with the literature value (2.74(15) W.u. vs 2.3(3) W.u.))

Coulomb excitation of ^{96}Zr with AGATA at LNL

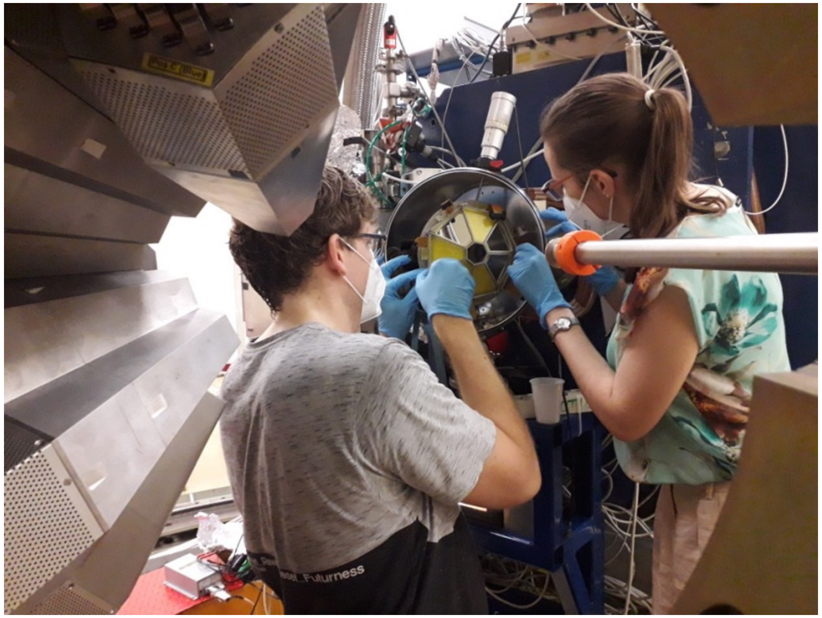
SPIDER







- AGATA array (11 ATCs), close-up position
- SPIDER: modular array of Si detectors segmented into 8 annular strips (junction side)
  $\theta_{\mathrm{LAB}} = 124^\circ - 161^\circ$ (detection of back-scattered ^{58}Ni ions)
- data taking: October 21-25, 2022



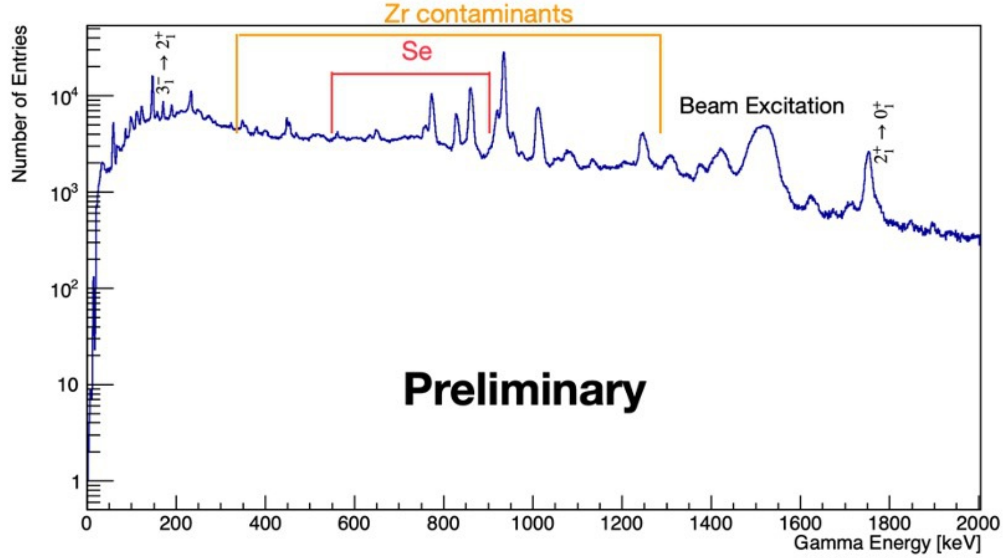
Coulomb excitation of ^{96}Zr with AGATA at LNL

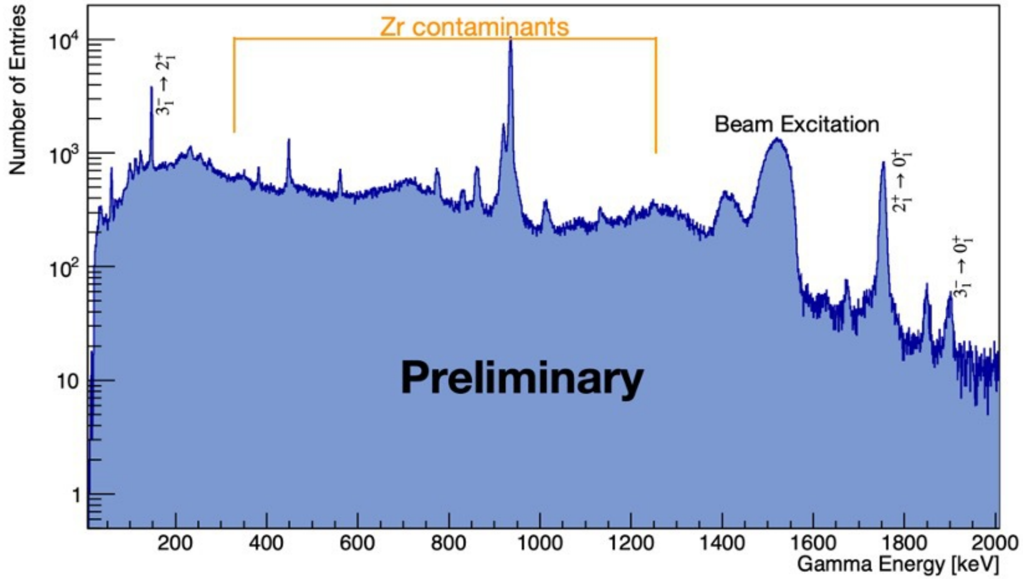
- problems to get the ^{96}Zr material for the targets due to the Russia-Ukraine war; obtained targets with lower isotopic enrichement than reported

- data analysis: cut on excitation energy to remove the fusion-evaporation background

- analysis in progress (N. Marchini, F. Ercolano)

- aim: extraction of quadrupole moments in ^{96}Zr

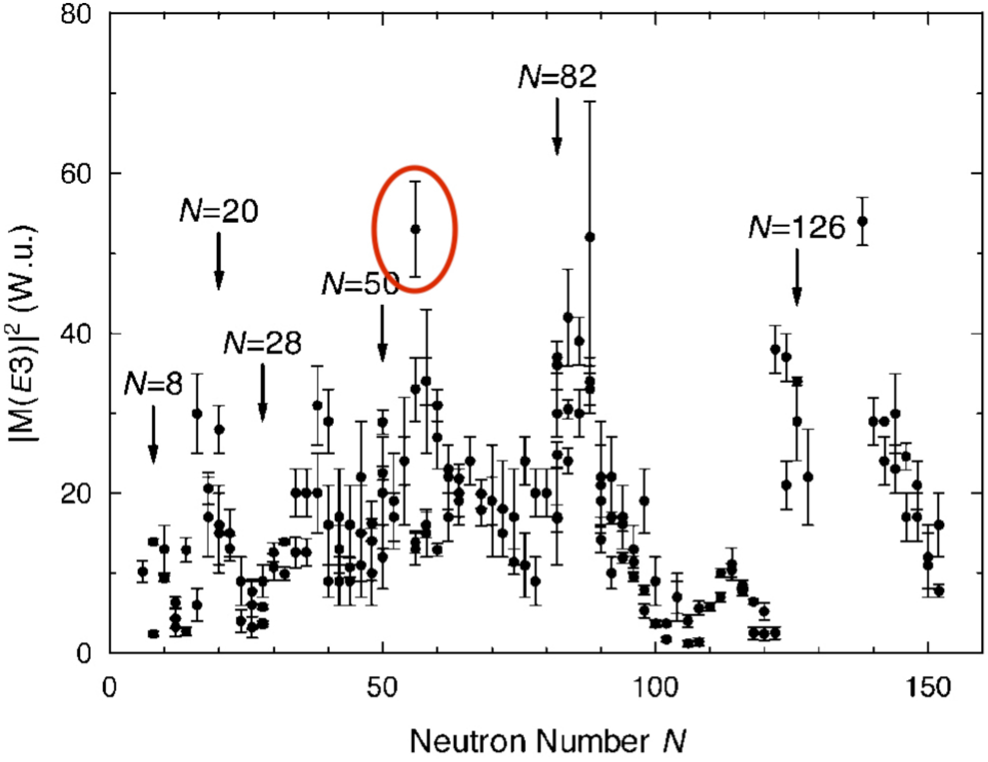




Octupole collectivity in Zr isotopes: anomalous value for ^{96}Zr

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

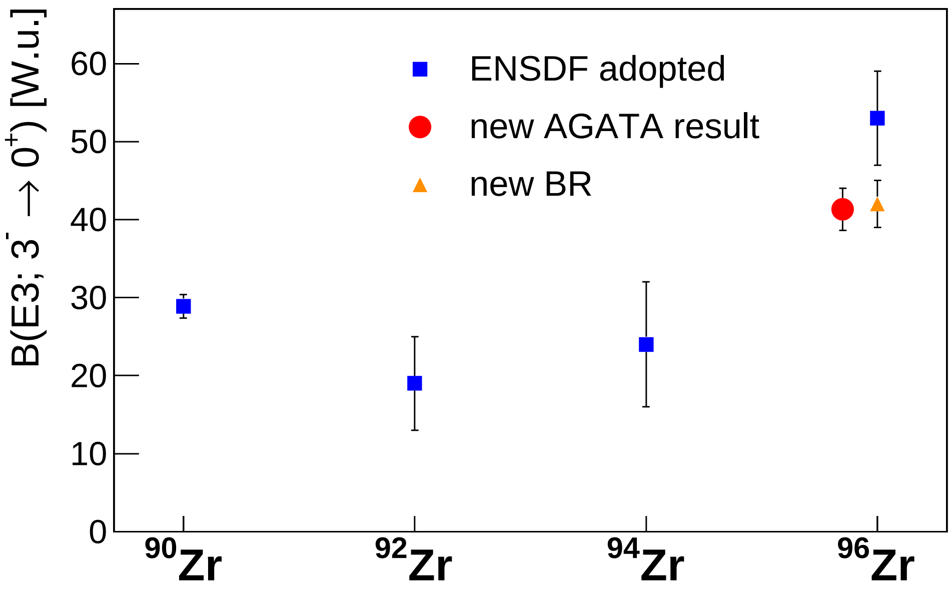
- long-standing challenge for theory

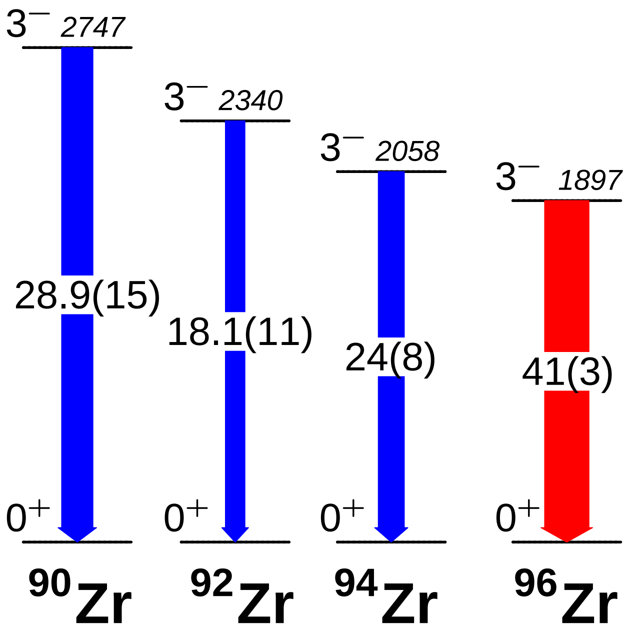


T. Kibédi and R.H. Spear, At. Data Nucl. Data Tables 80, 35 (2002)

Octupole collectivity in ^{96}Zr: AGATA result

- our preliminary result (F. Ercolano, MSc thesis, 2023) points to lower octupole collectivity in ^{96}Zr



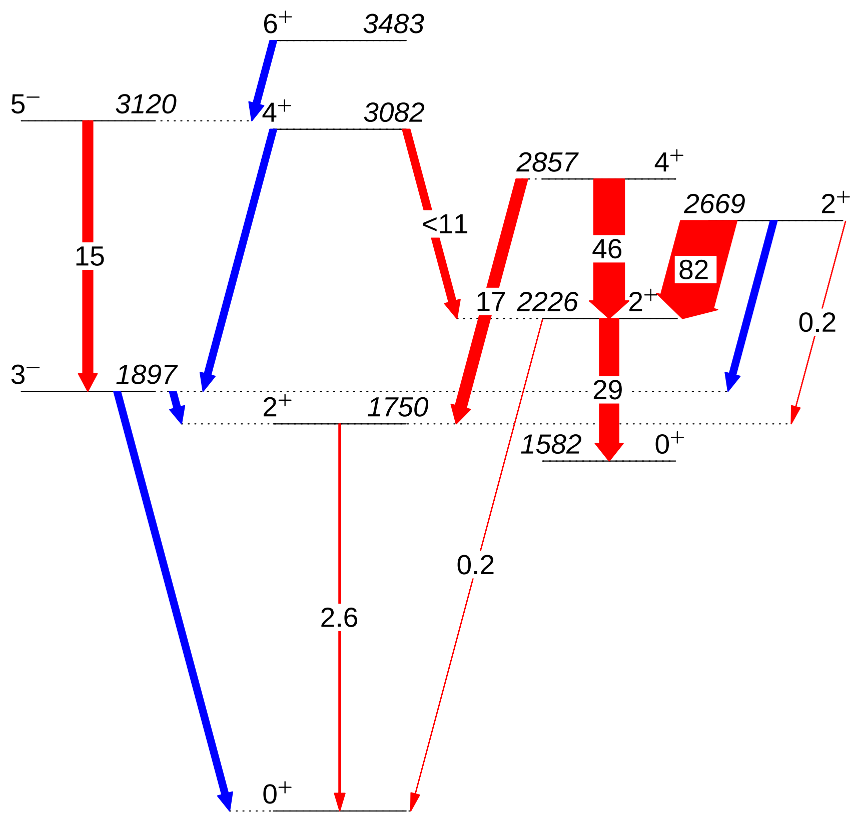


- obtained value in excellent agreement with E3 strength resulting from a new measurement of E1/E3 branching ratio in ^{96}Zr (Ł. Iskra et al, Phys. Lett. B 788 (2019) 396)

Remaining questions

Revised branching and mixing ratios in ^{96}Zr: J. Wiśniewski et al, Phys. Rev. C 108, 024302 (2023)

- which 4^+ belongs to which band? if 4_1^+ is part of the deformed structure, why is its decay to the 2_1^+ so strong (mixing between bands should be weak)?
- the $2_3^+ \rightarrow 2_2^+$ decay seems surprisingly enhanced
- E1 transitions from presumably collective states compete with E2 ones; in particular, the 6^+ state decays predominantly via E1; is it related to a two-phonon octupole vibration?



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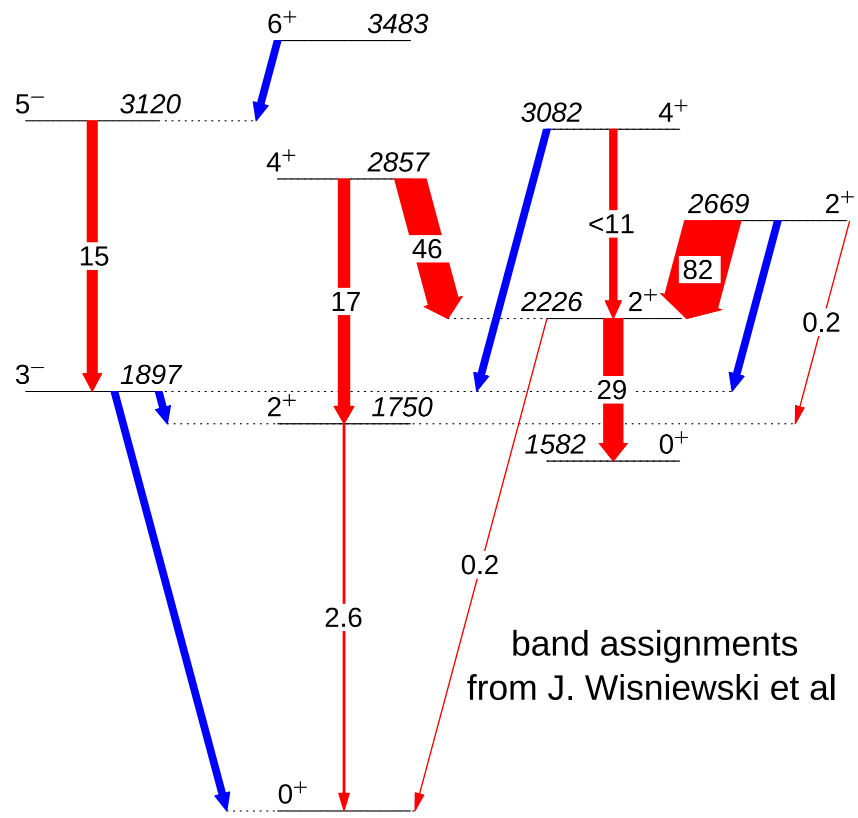

band assignments from J. Wisniewski et al

Outlook: complementary measurements on ^{96}Zr

- combination of a lifetime study with safe and unsafe Coulomb-excitation cross-section measurement with a ^{96}Zr beam (AGATA@LNL, MZ, N. Marchini et al) – presented at LNL PAC meeting this morning
- (p,p’) on ^{96}Zr (AGATA@LNL, November 2023, D. Stramaccioni et al) – search for the direct $6^+ \rightarrow 3^-$ decay in order to verify the hypothesis of the 6^+ state being a double octupole phonon state
- β decay into ^{96}Zr (TRIUMF, December 2023, M. Rocchini, MZ et al) – precise measurement of branching and mixing ratios in the decay of spin-0,1,2,3 states