Shape coexistence studied with Coulomb excitation and AGATA

Magda Zielińska

Legnaro
2010 - 2011

GSI
2012 - 2014

GANIL
2015 - 2021

Legnaro
2022 -

- superdeformation in ^{42}Ca:
  K. Hadyńska-Klęk *et al.*, Phys. Rev. Lett. 117 (2016) 062501
  K. Hadyńska-Klęk *et al.*, Phys. Rev. C 97 (2018) 024326
- shape coexistence in ^{106}Cd:
  D. Kalaydjieva, PhD thesis, Université Paris-Saclay, 2023
- quadrupole shapes in ^{96}Zr:
  data under analysis (Uni Guelph, INFN Firenze)

Shape coexistence

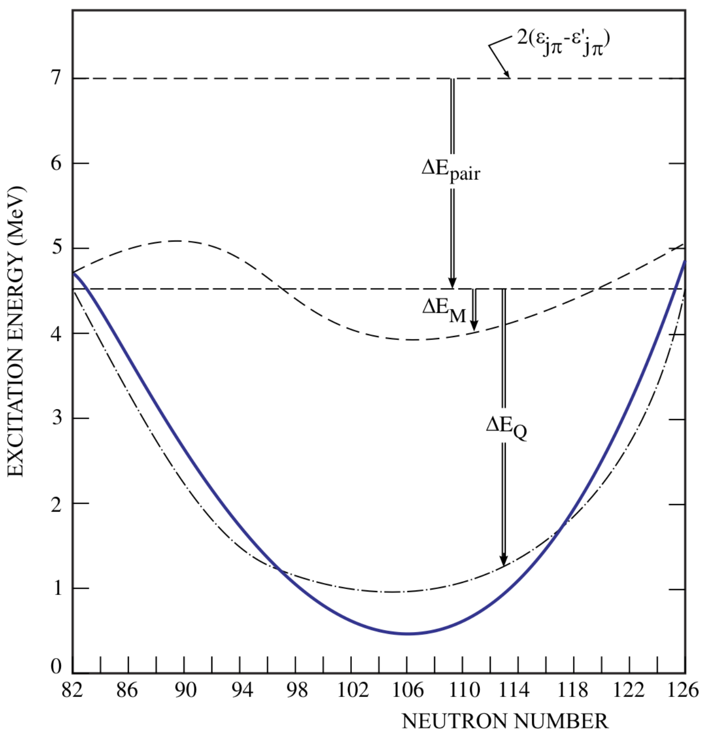
K. Heyde and J. Wood, Rev. Mod. Phys. 83, 1467 (2011)

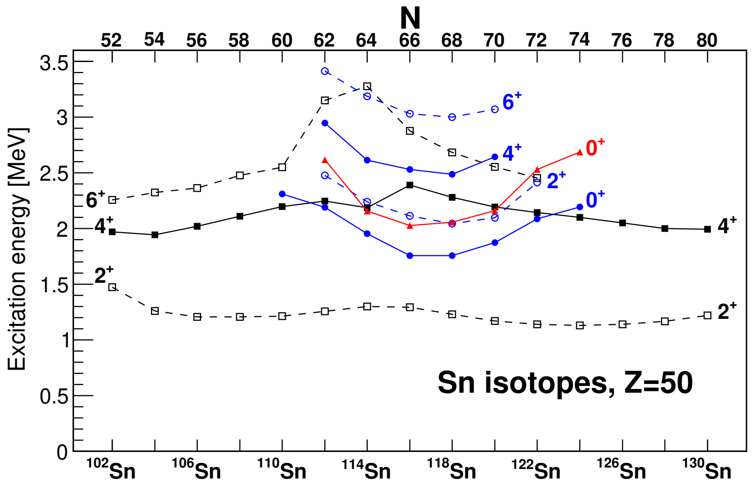
- appearance of states characterised by different shapes closely lying in energy

- proposed mechanism: gain from correlations offsets the shell gap and multiparticle-multihole excitations go down in excitation energy

- effect increases towards mid shell – characteristic parabolic behaviour of intruder states energies

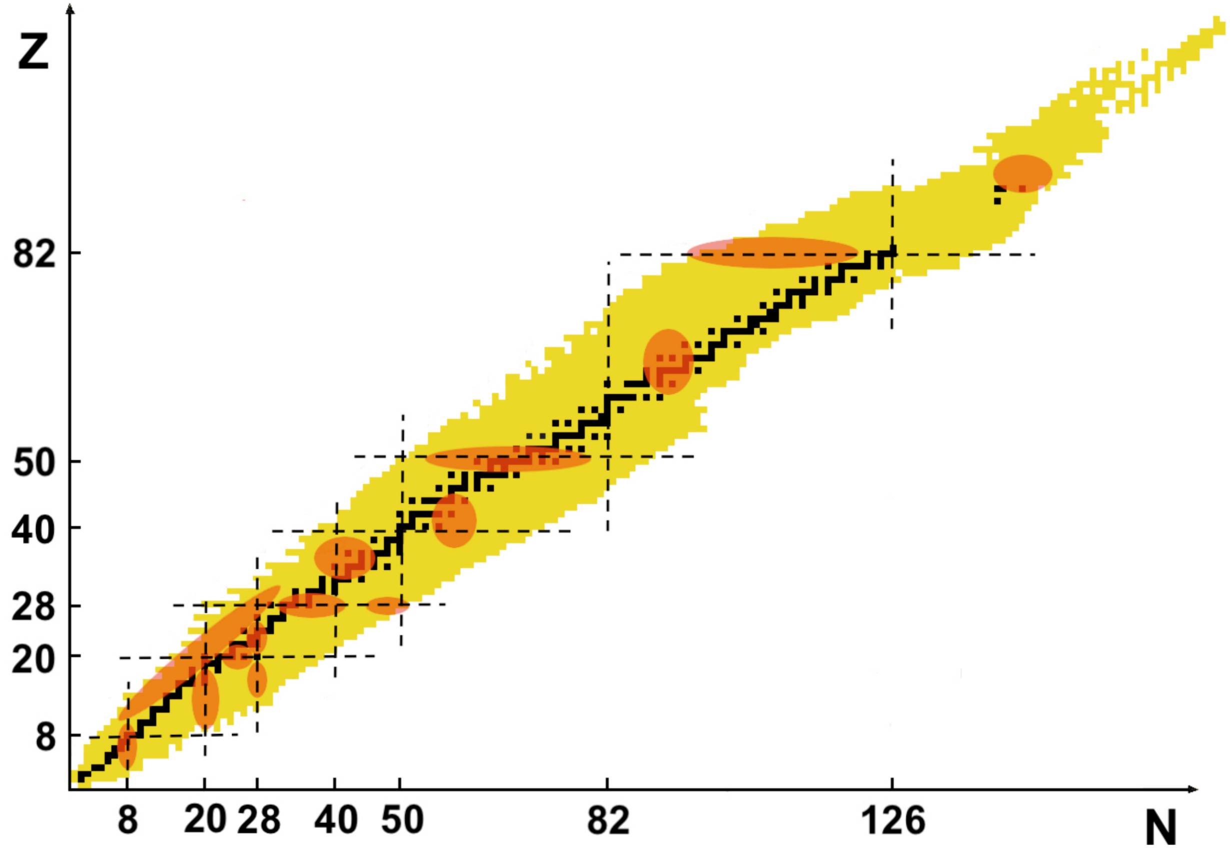
- depends on a delicate balance of macroscopic, liquid-drop-like properties of the nuclear matter and microscopic shell effects – provides stringent tests of modern nuclear structure models





Shape coexistence

- a widespread phenomenon in areas close to proton and neutron shell closures



- difficult to establish experimentally as nuclear shape is not an observable

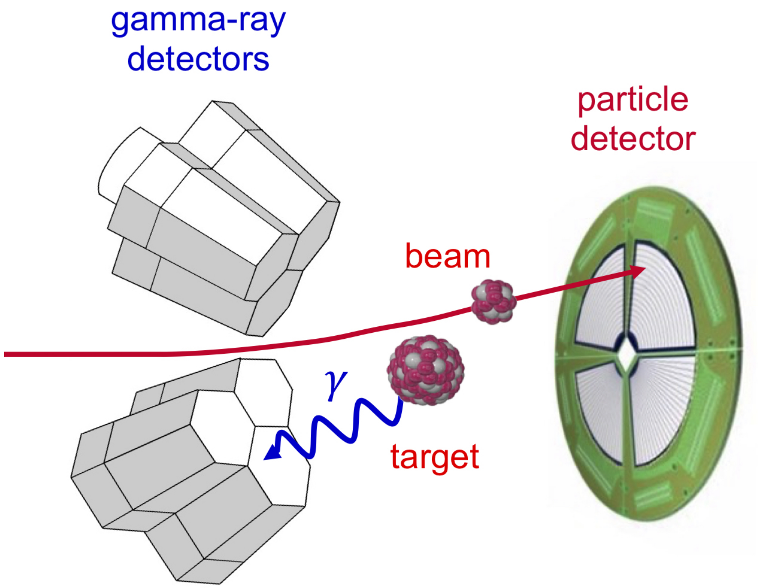
- Coulomb excitation: perfect tool to study shape coexistence as it is the only technique sensitive to charge distribution in excited nuclear states

Coulomb excitation

• population of excited states via purely electro-magnetic interaction between the collision partners in the process of quasi-elastic scattering

• we observe gamma-ray decay of Coulomb-excited states in coincidence with scattered beam ions or target recoils

• the decay intensities, measured as a function of particle scattering angle, are related to reduced transition probabilities and spectroscopic quadrupole moments determined via a multi-dimensional fit performed using dedicated analysis codes (e.g. GOSIA)



• they are related to the nuclear shape and collectivity – from extensive sets of E2 matrix elements quadrupole invariants can be formed in order to deduce deformation parameters for individual states defined in the intrinsic frame of the nucleus

AGATA

Legnaro
2010 - 2011

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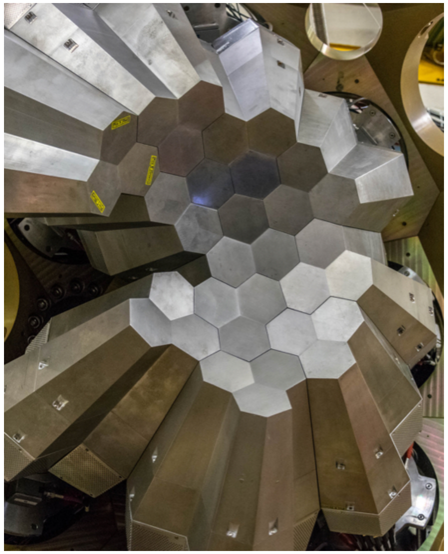
GANIL
2015 - 2021

Legnaro
2022 -



11 ATC, Feb 2022

- new-generation gamma-ray tracking array developed by a European collaboration involving 13 countries and over 40 institutions
- currently at LNL after campaigns at GANIL and GSI
- angular resolution: $\sim 1^\circ$
- large inner radius to accommodate ancillary devices
- final configuration: 180 segmented crystals (60 ATC), 35% efficiency

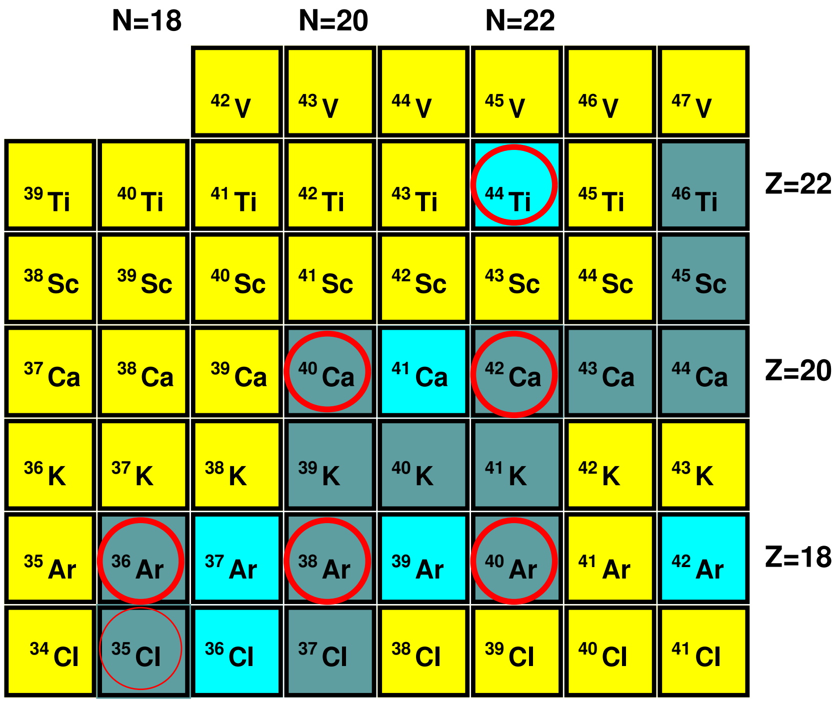
http://www.agata.org

S. Akkoyun et al., Nucl. Instrum. Methods Phys. Res. A 668, 26 (2012).

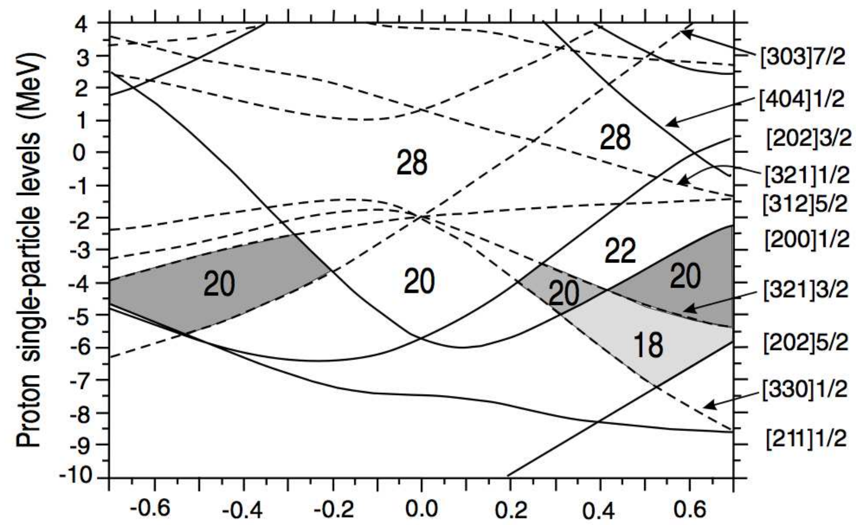
Part I: AGATA Demonstrator at LNL

superdeformation in ^{42}Ca

Highly-deformed structures in the A $\sim$ 40 region

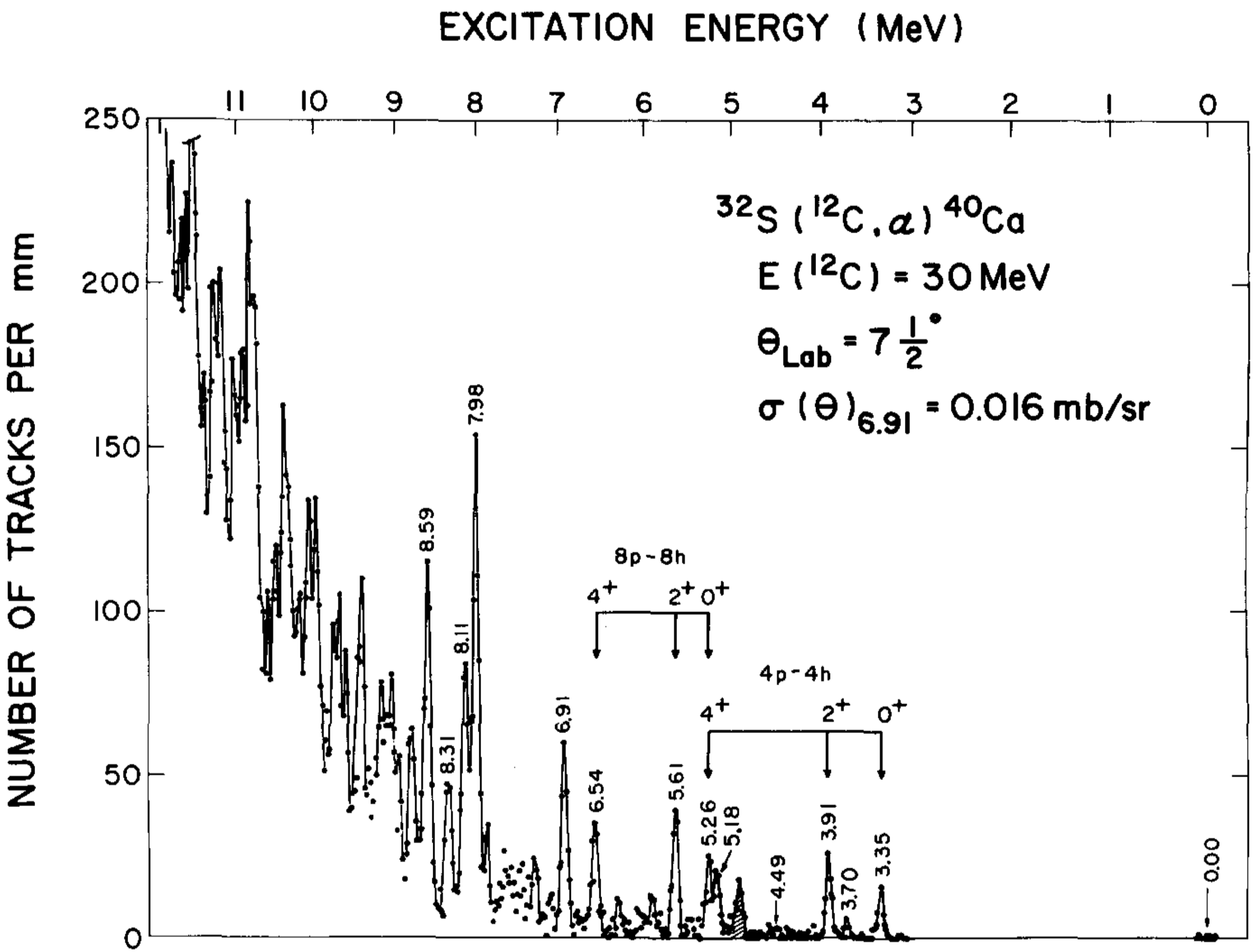


E. Ideguchi et al., PRL 81 (2001) 222501



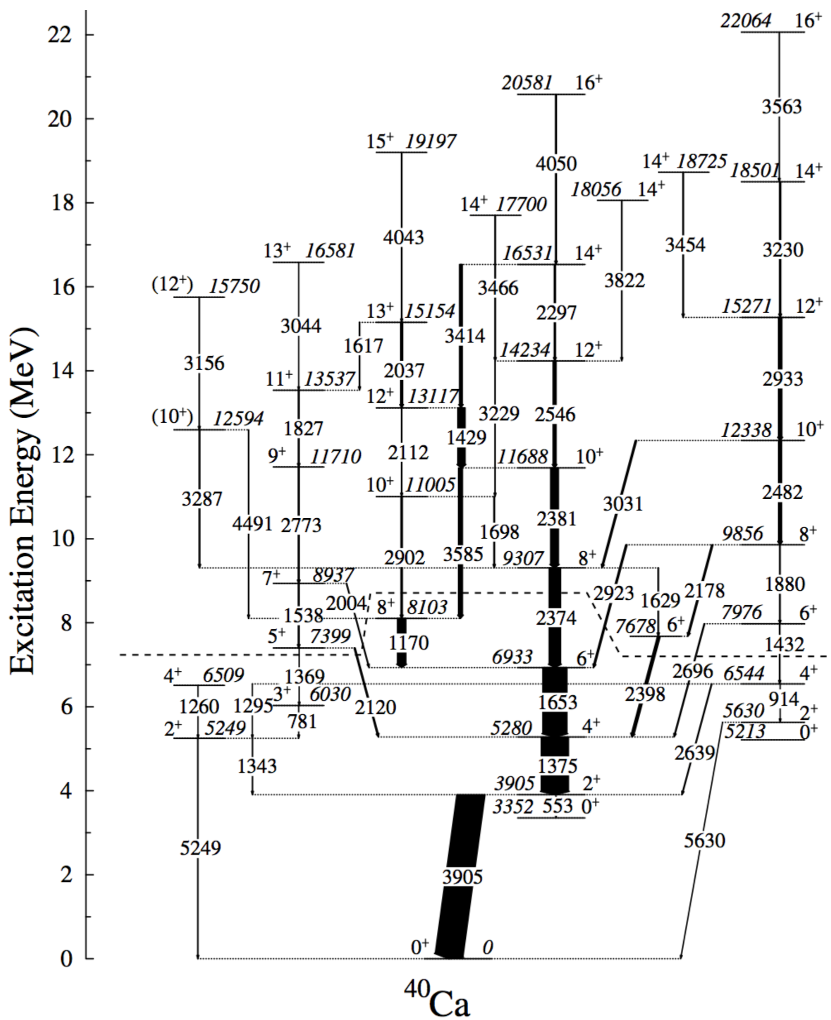
- spherical and highly-deformed magic numbers appear at similar particle numbers – dramatic shape coexistence

Identfication of 4p-4h and 8p-8h structures in ^{40}Ca



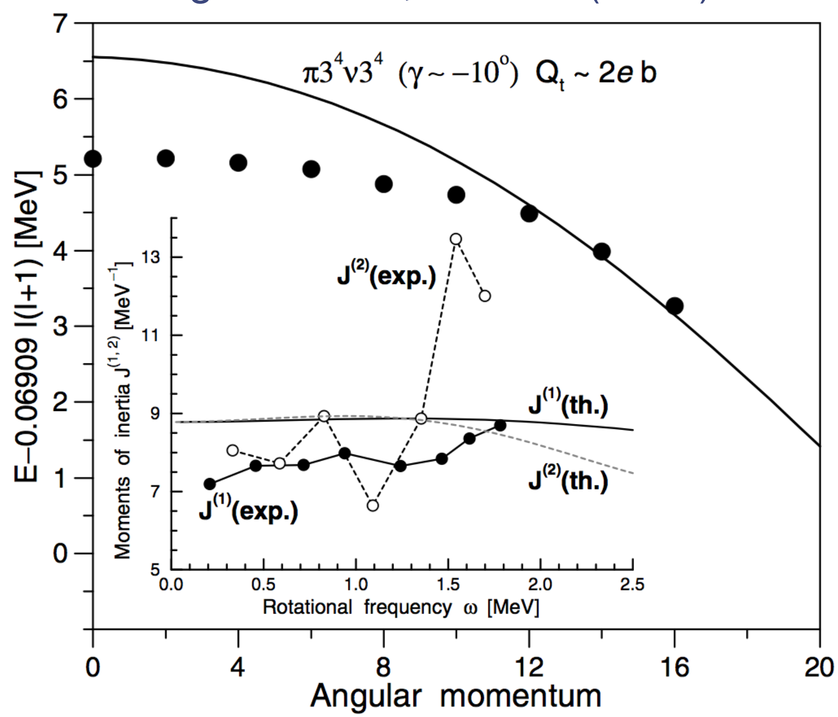
R. Middleton et al, Phys. Lett. 39B (1972) 339

High-spin spectroscopy around ^{40}Ca



- regular rotational bands built on 0^+ states observed up to spin $14^+ - 16^+$ in ^{40}Ca, ^{36,38,40}Ar, ...

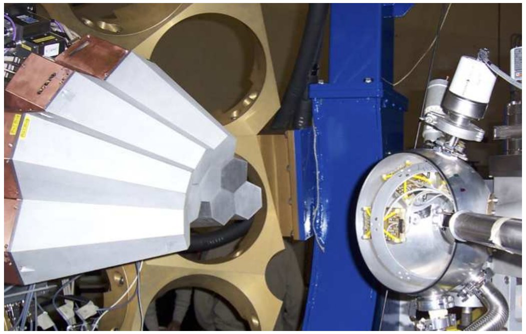
E. Ideguchi et al., PRL 81 (2001) 222501

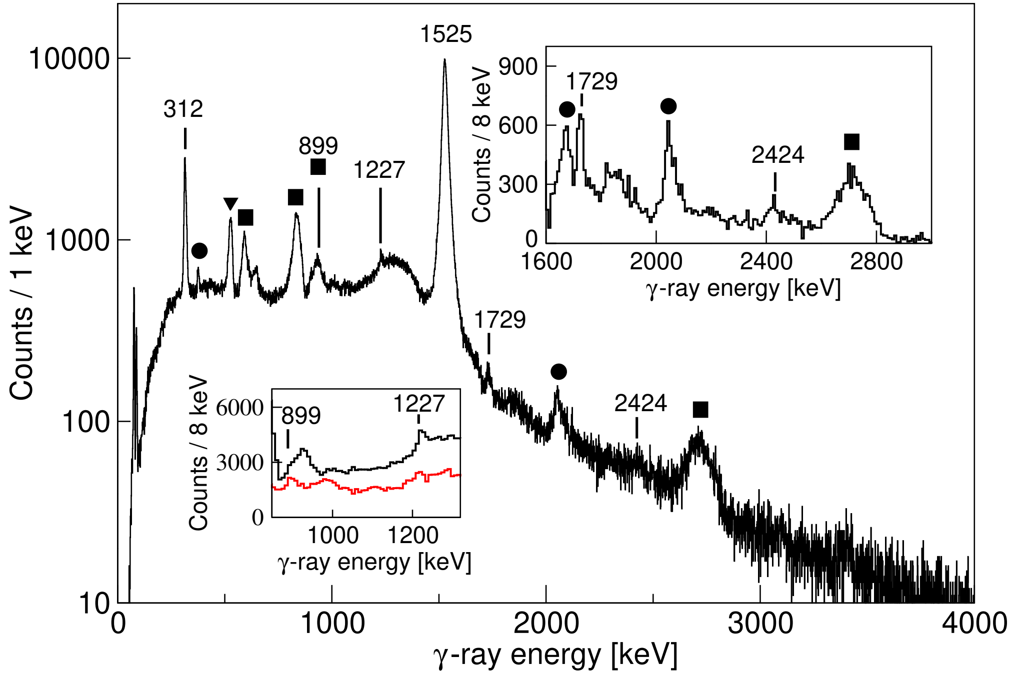


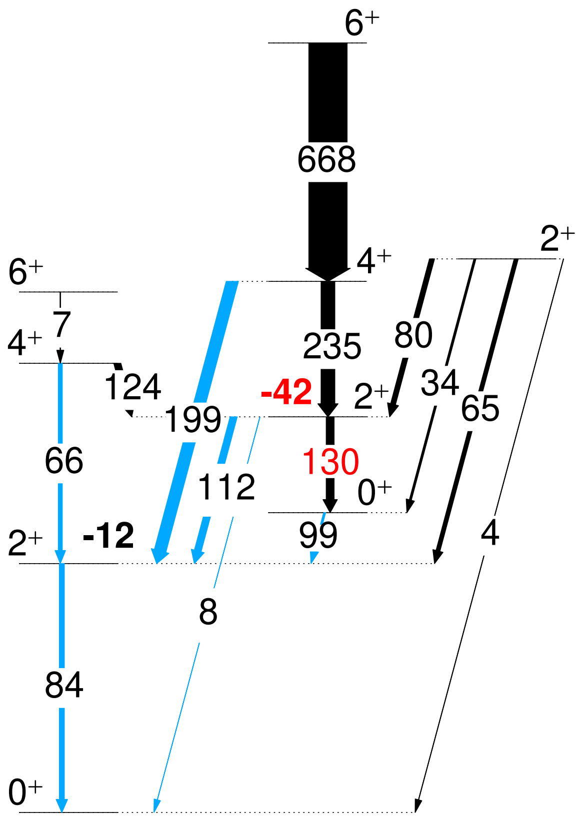
- intense transitions linking very deformed structures to ground-state bands – mixing of configurations

Coulomb excitation of ^{42}Ca at LNL

- Targets: ^{208}Pb, ^{197}Au, 1mg/cm^2
- AGATA: 3 triple clusters
- DANTE: 3 MCP detectors, θ range: 100-144°







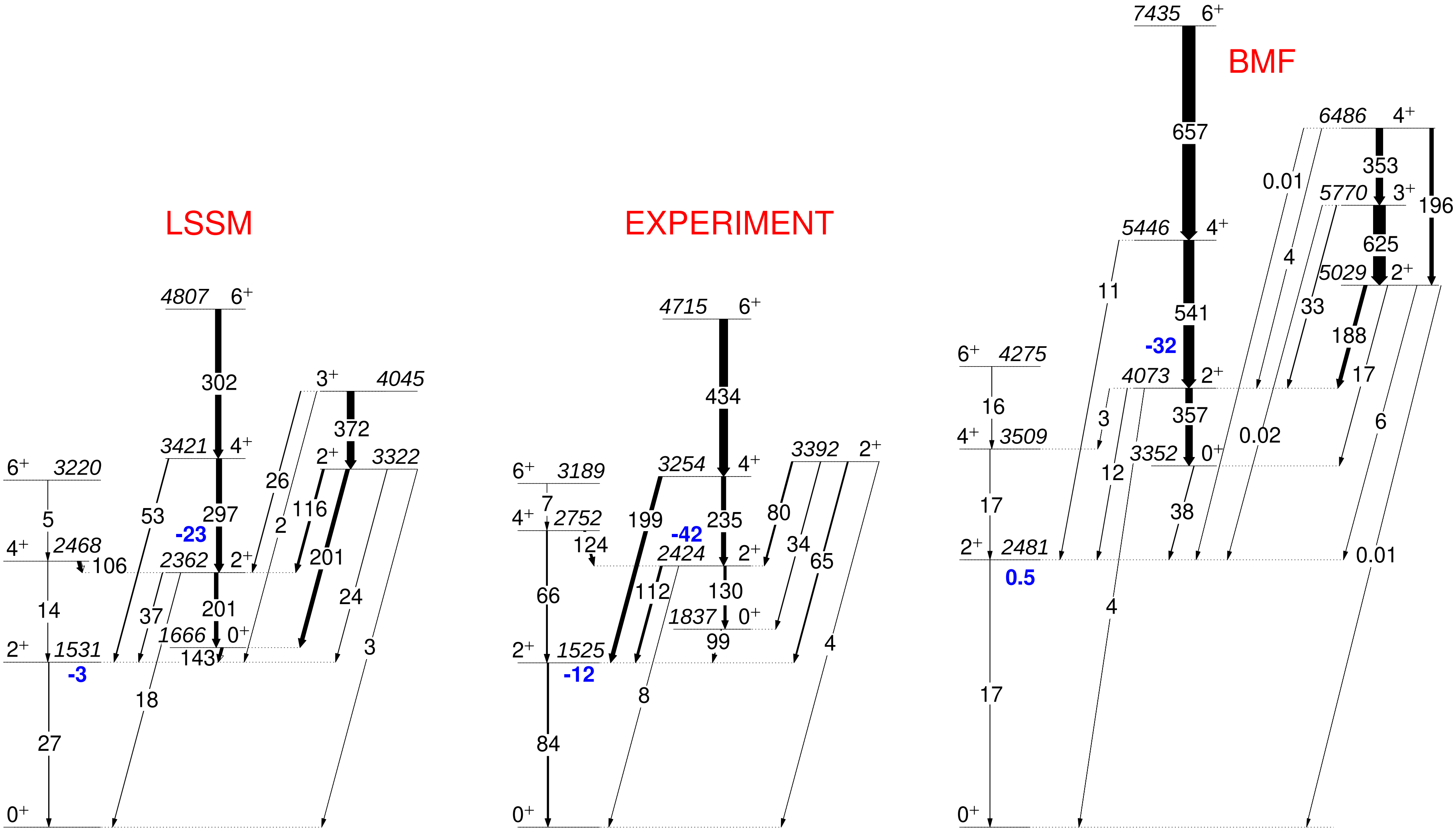
- first population of a superdeformed band in Coulomb excitation
- measured quadrupole moment of 2_2^+ corresponds to $\beta = 0.48(14)$

K. Hadyńska-Klęk et al, PRL 117 (2016) 062501

Comparison with theoretical calculations

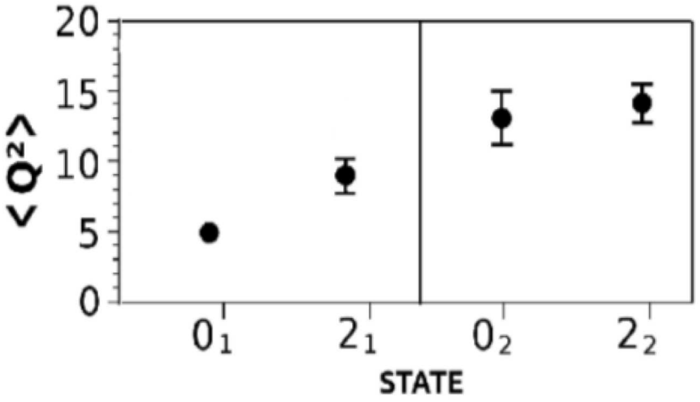
K. Hadyńska-Klęk,
PRL 117 (2016) 062501

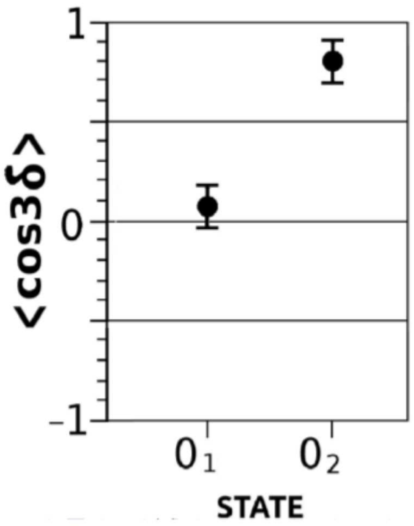
- Large-Scale Shell Model: F.Nowacki, H.Naïdja, B.Bouthong (Strasbourg)
- Beyond Mean Field calculations with Gogny D1S: T. R. Rodriguez (Madrid)



Shape parameters of 0^+ and 2^+ states in ^{42}Ca

K. Hadyńska-Klęk, PRC 97 (2018) 024326





$$\bar{\beta} = \sqrt{\langle\beta^2\rangle} = \sqrt{\frac{\langle Q^2\rangle}{q_0^2}}$$

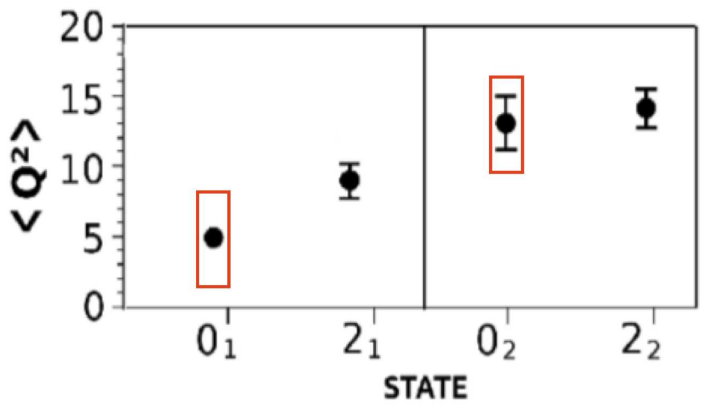
$$\bar{\gamma} = \arccos\langle\cos(3\delta)\rangle$$

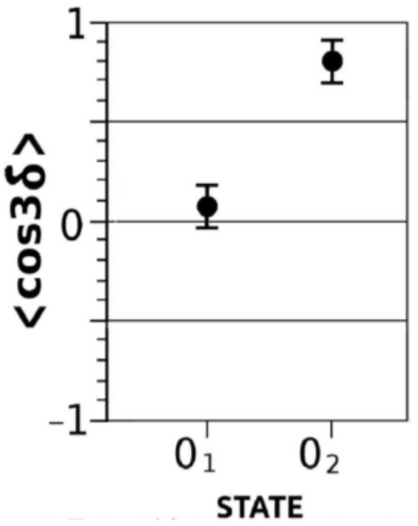
- deformation parameters:
  - side band: $\bar{\beta}$=0.43(4), $\bar{\gamma}$=13(6)°
  - ground-state band: $\bar{\beta}$=0.26(2), $\bar{\gamma}$=29(2)° (?)
- are these static deformations, or fluctuations?
  - what about softness in β: $\sigma(Q^2) = \sqrt{\langle Q^4\rangle - \langle Q^2\rangle^2}$?

Shape parameters of 0^+ and 2^+ states in ^{42}Ca

K. Hadyńska-Klęk, PRC 97 (2018) 024326

red rectangles: $\sigma(Q^2)$





$$\bar{\beta} = \sqrt{\langle\beta^2\rangle} = \sqrt{\frac{\langle Q^2\rangle}{q_0^2}}$$

$$\bar{\gamma} = \arccos\langle\cos(3\delta)\rangle$$

$\sigma(Q^2)$ comparable with $\langle Q^2\rangle$ for the ground-state band

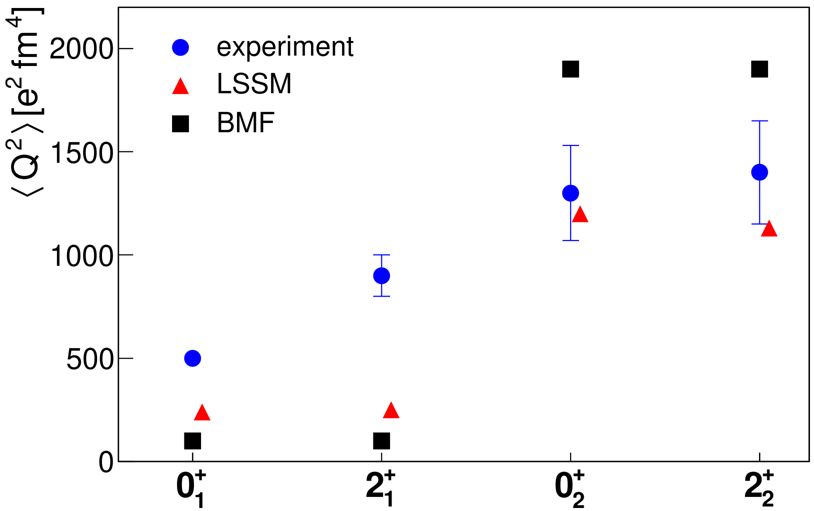
$\rightarrow$ fluctuations about a spherical shape; $\langle\cos(3\delta)\rangle$=0 resulting from averaging over all possible quadrupole shapes ranging from prolate to oblate

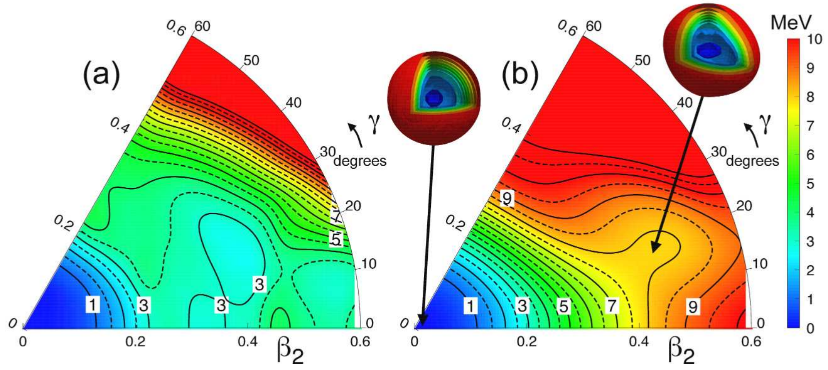
excited band: $\sigma(Q^2)$ few times lower than $\langle Q^2\rangle$

$\rightarrow$ static deformation

Comparison with theoretical calculations

K. Hadyńska-Klęk, PRL 117 (2016) 062501





- coexistence of two very different structures reproduced by both theories, slightly triaxial SD minimum present in both potential maps
- deformation in the ground-state band increases with spin contrary to theoretical predictions → mixing seems to be underestimated by calculations

Two-states mixing model applied to ^{42}Ca

• mixing of the underlying configurations can be deduced from measured E2 matrix elements, or alternatively for 0^+ states from E0 strengths:

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

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

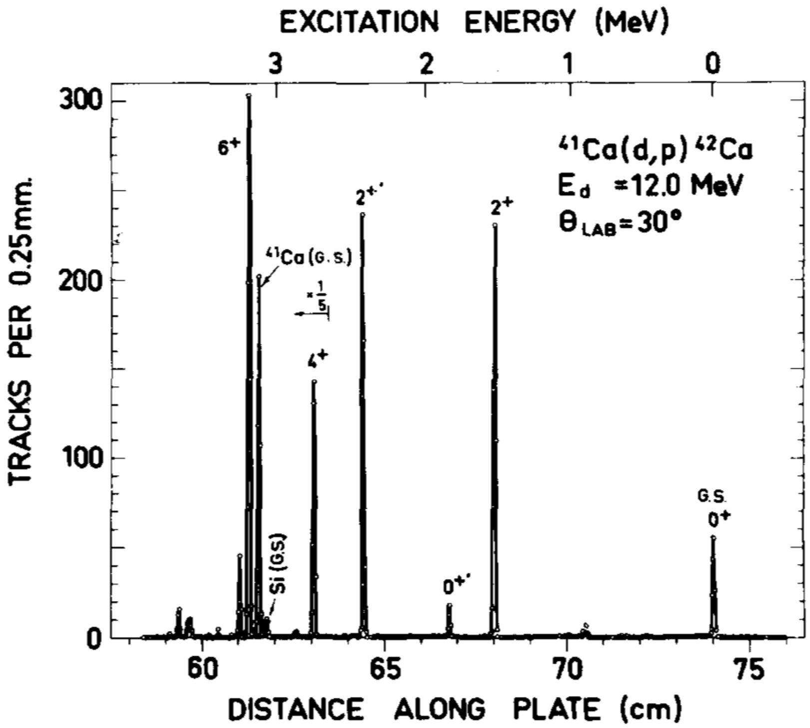
J.L. Wood *et al.*, NPA 651, 323 (1999)

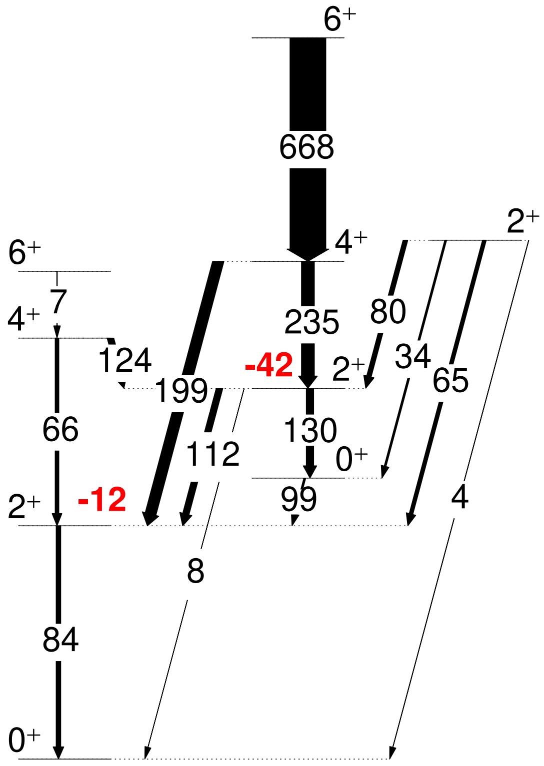
K. Hadyńska-Klęk *et al.*, PRC 97 (2018) 024326 (Coulomb excitation),
J.L. Wood *et al.*, NPA 651, 323 (1999) (E0)

	from E2 matrix elements [KHK]	from $\rho^2(E0)$ [JLW] + sum rules results [KHK]	SM	BMF
$\cos^2(\theta_0)$	0.88(4)	0.84(4)	0.85	0.96
$\cos^2(\theta_2)$	0.39(8)	-	0.83	0.97

- 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

Population of the deformed structure in one-neutron transfer





C. Ellegaard *et al.*, Phys. Lett. 40B (1972) 641

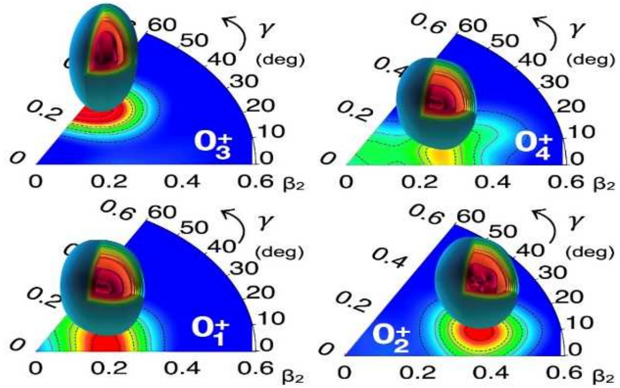
- equal population of 2_1^+ and 2_2^+ in ^{41}Ca(d,p)^{42}Ca – the same admixture of $(f_{7/2})^2$, while the quadrupole moments are very different!

→ the remaining admixtures to the 2_1^+ and 2_2^+ wave functions must be different → another configuration must enter the mixing

Part II: AGATA at GANIL

shape coexistence in ^{106}Cd

Shapes of Cd nuclei – context



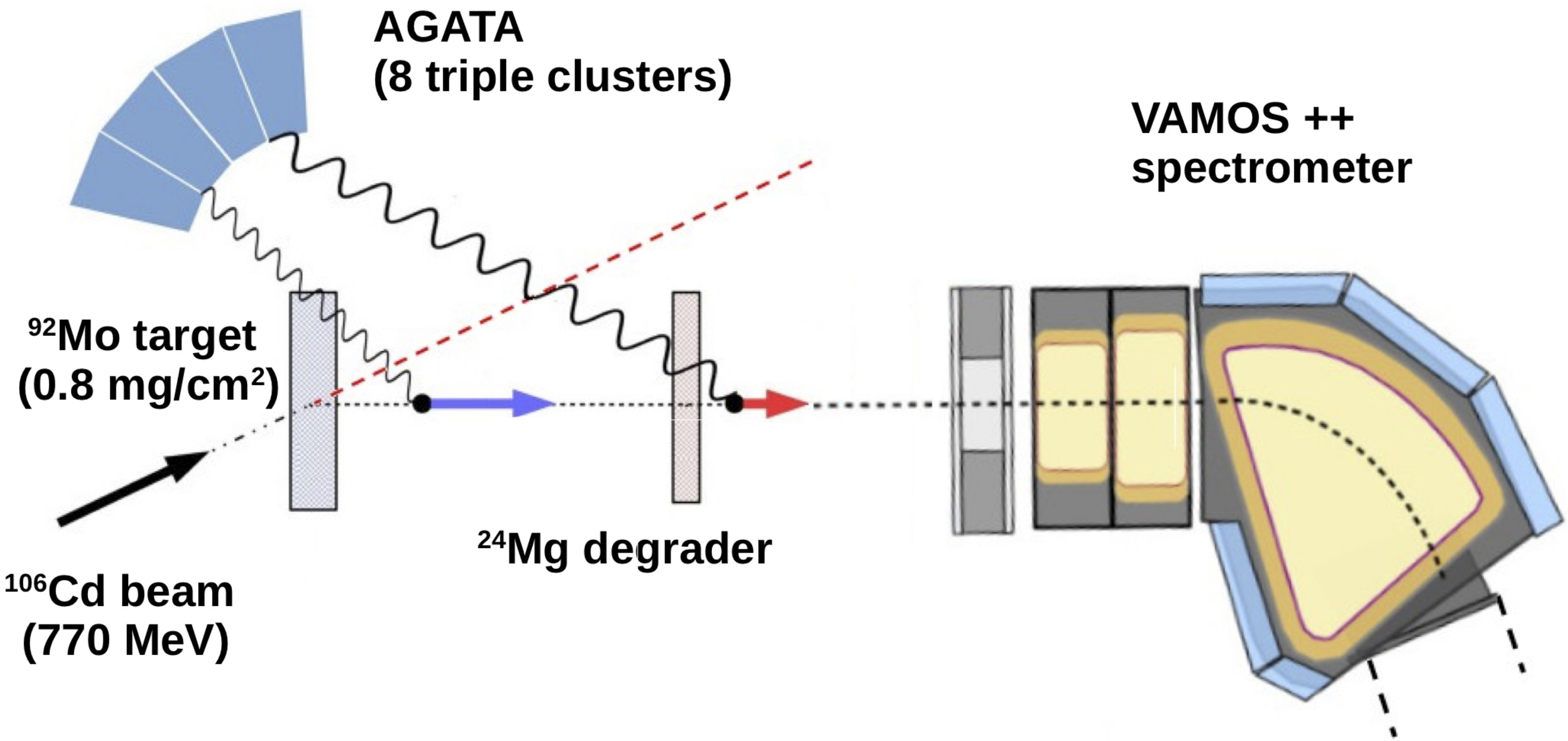
- departure from the surface-vibration paradigm towards a multiple shape-coexistence scenario
  - β decay (TRIUMF) + DSAM lifetime measurements (Kentucky) in ^{110,112}Cd with guidance from BMF calculations (P.E. Garrett et al, Phys. Rev. Lett. 123, 142502 (2019))
- data can be reconciled with the vibrational picture using partial dynamical symmetry in the IBM (N. Gavrielov et al, Phys. Rev. C 108, L031305 (2023))
- triggered a multitude of new measurements:
  - high-precision beta decay into ^{110}Cd (GRIFFIN, TRIUMF – 2022)
  - Coulomb excitation of ^{110}Cd (AGATA, LNL; GRETINA, ANL – 2022)
- also for neighbouring nuclei, in particular ^{106}Cd:
  - Coulomb excitation of ^{106}Cd: (ReA3, MSU – D. Rhodes et al, Phys. Rev. C 103, L051301 (2021); GRETINA, ANL – T. Gray et al, Phys. Lett. B 834, 137446 (2022))
  - RDDS lifetime measurement in $^{102-108}$Cd: (AGATA, GANIL – M. Siciliano et al, Phys. Rev. C 104, 034320 (2021))

Experiment

- inelastic scattering data on ^{106}Cd: byproduct of a RDDS lifetime measurement following multinucleon transfer in the ^{106}Cd + ^{92}Mo reaction at 7 MeV/A

M. Siciliano et al., Phys. Lett. B 806, 135474 (2020)

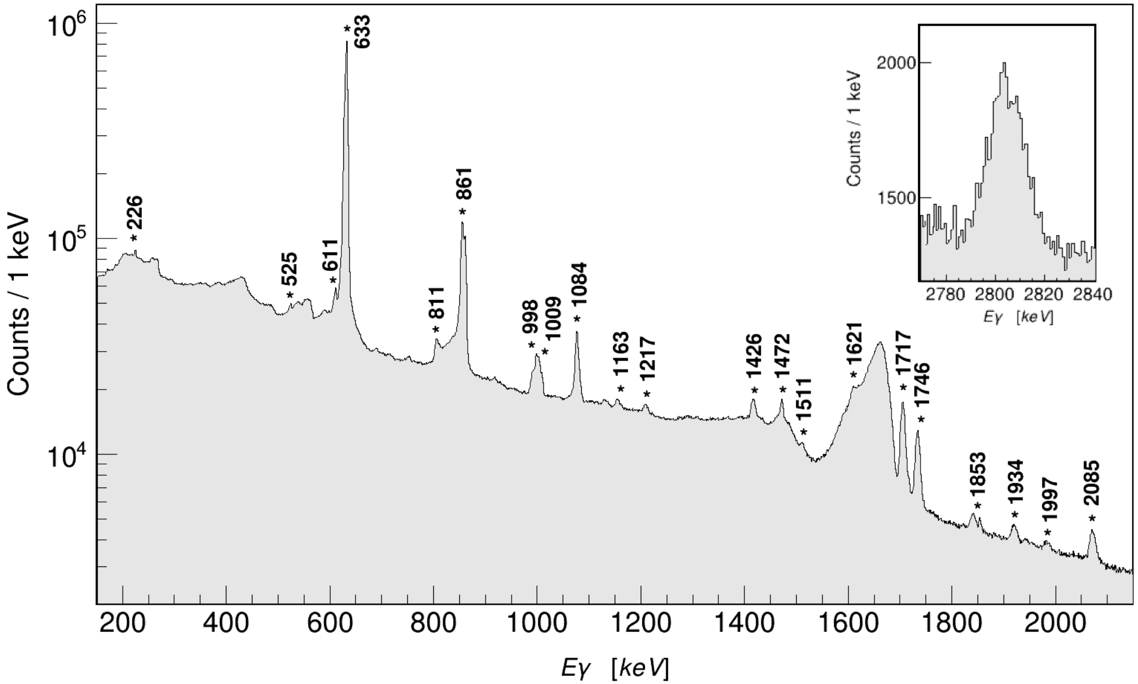
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021)

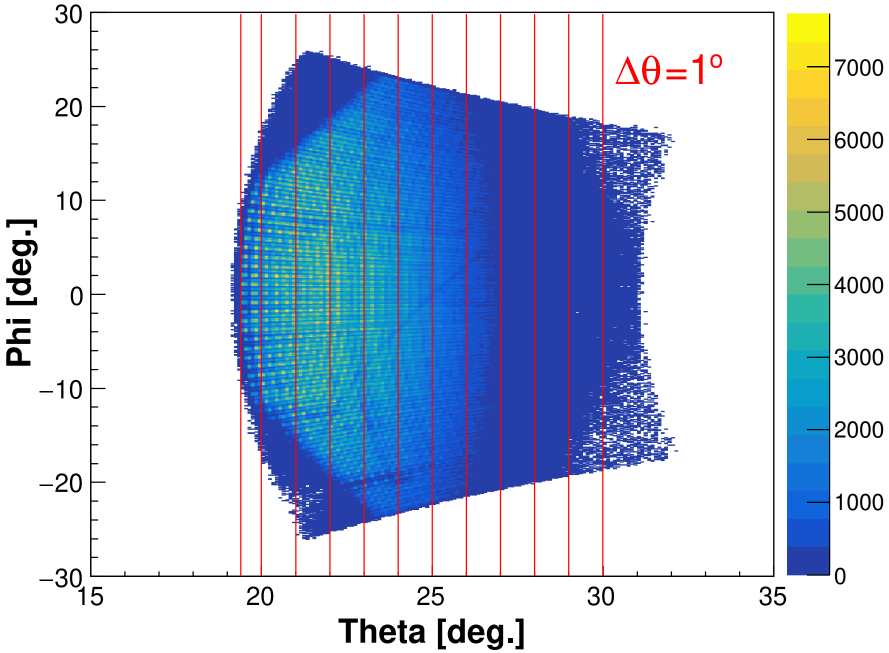


- VAMOS at grazing angle (25°); lowest observed scattering angle (19.4°) corresponding to 107% of Cline's safe energy

Experiment

- population of 21 excited states observed (up to spin 6^+)

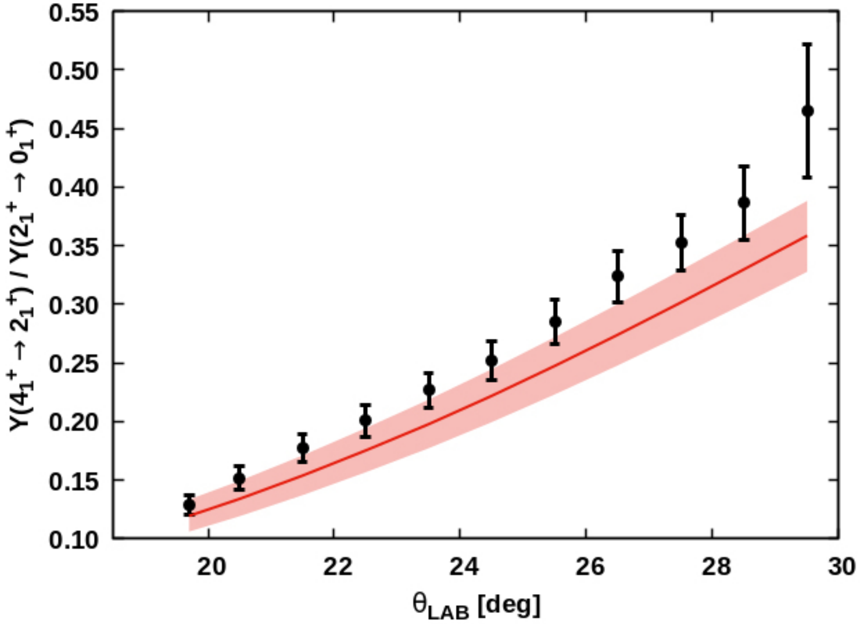




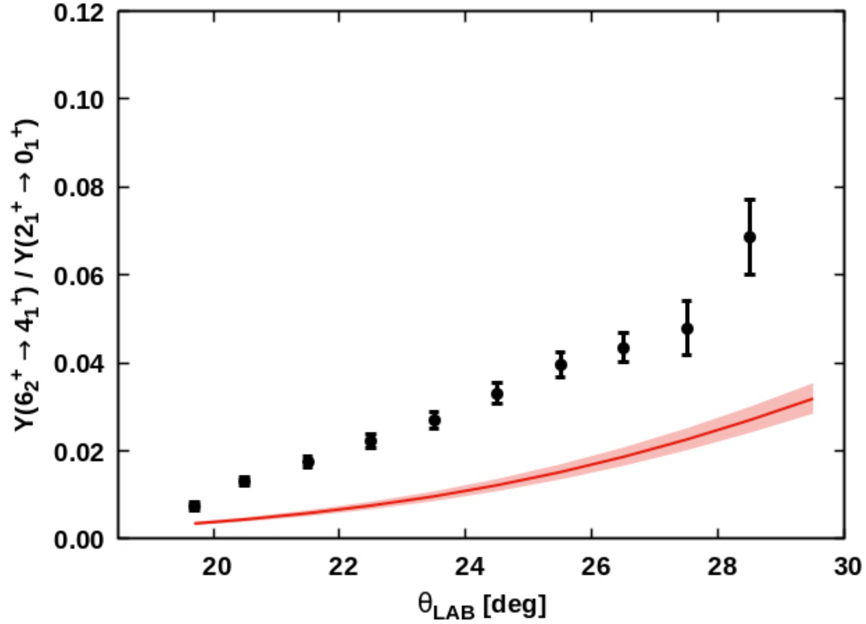
- ^{106}Cd ions identified in VAMOS with 19.4° $\leq \theta_{\text{LAB}} \leq$ 30° (Cline's criterion fulfilled for $\theta_{\text{LAB}} \leq$ 18°)
- we apply gates on θ_{LAB} with 1° width to study the dependence of the excitation cross sections on scattering angle
- due to complicated acceptance of the spectrometer as a function of θ, we normalise the measured γ-ray intensities to that of the $2^+_1 \rightarrow 0^+_1$ transition

Sample results (strongly populated states)

$4_1^+ \to 2_1^+$



$6_2^+ \to 4_1^+$

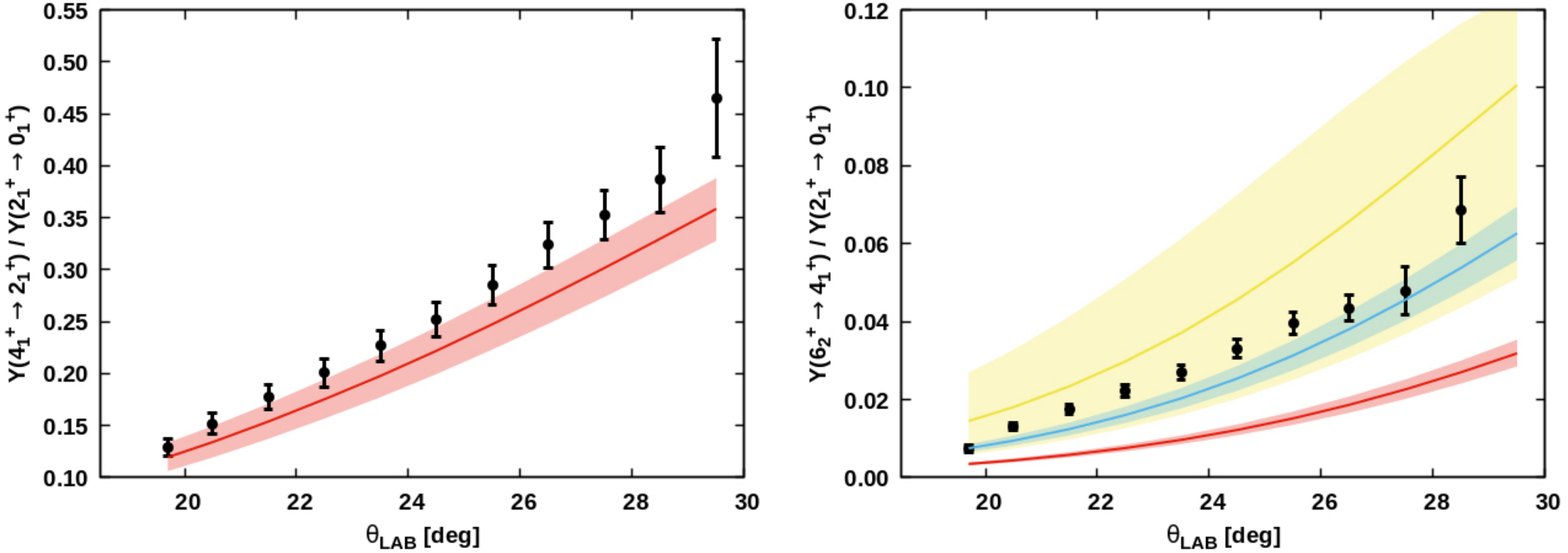


- reasonable agreement with literature data for 4_1^+ (weighted average of measured lifetimes)
- lifetime of the 6_2^+ state deduced from the same data as our transition intensities (M. Siciliano et al., Phys. Rev. C 104, 034320 (2021)) is not consistent with the measured intensity ratios

D. Kalaydjieva, PhD thesis, 2023

Sample results (strongly populated states)

$4_1^+ \to 2_1^+$ $\qquad$ $6_2^+ \to 4_1^+$

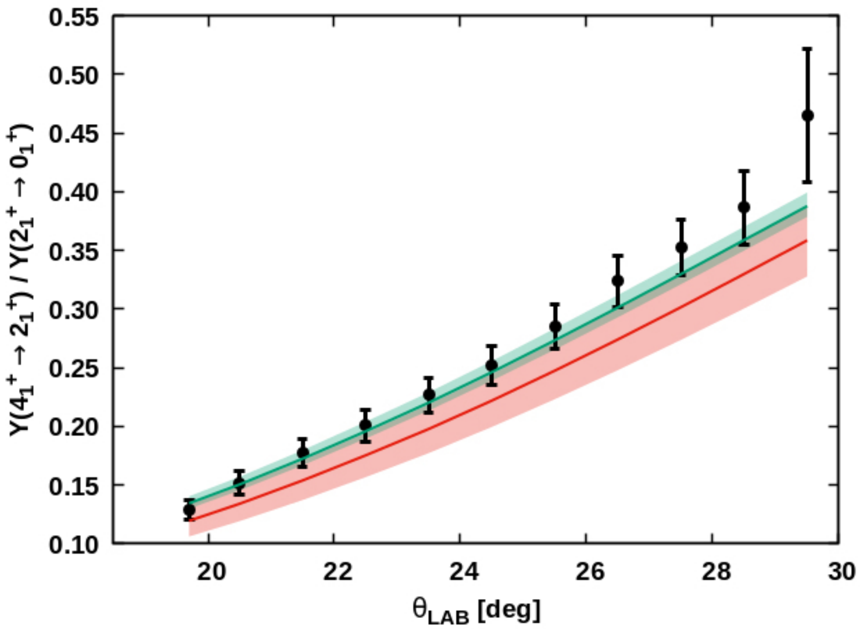


- much better agreement for the 6_2^+ state if we assume:
  - $\langle 6_2^+ \| E2 \| 4_1^+ \rangle$ matrix element from Coulomb excitation (D. Rhodes et al., Phys. Rev. C 103, L051301 (2021))
  - or 6_2^+ lifetime from (n,n'γ) (A. Linnemann, PhD thesis, University of Cologne, 2005 – but here the uncertainty is very large ($\tau = 0.26^{+0.44}_{-0.14}$ ps)

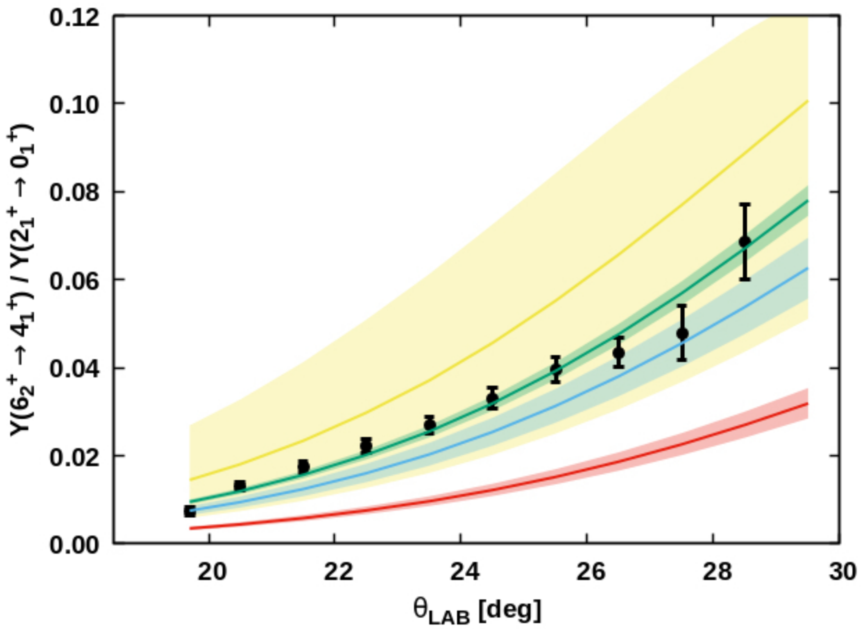
D. Kalaydjieva, PhD thesis, 2023

Sample results (strongly populated states)

$4_1^+ \rightarrow 2_1^+$



$6_2^+ \rightarrow 4_1^+$



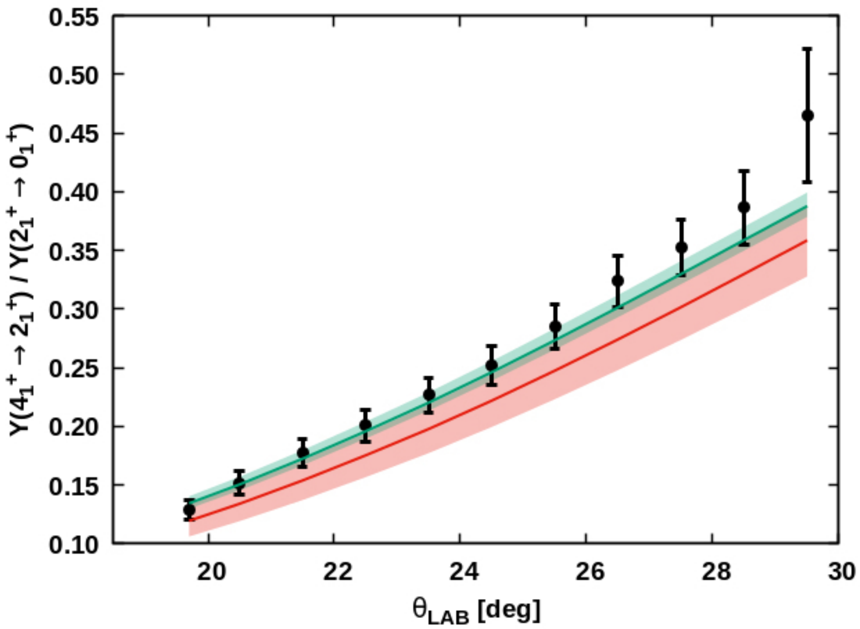
- finally, we can try to fit a set of matrix elements to the first few points of the cross-section distribution, and compare the resulting lifetimes:

4_1^+ – GOSIA fit: 1.23(7) ps
weighted average of lifetimes: 1.32(12) ps

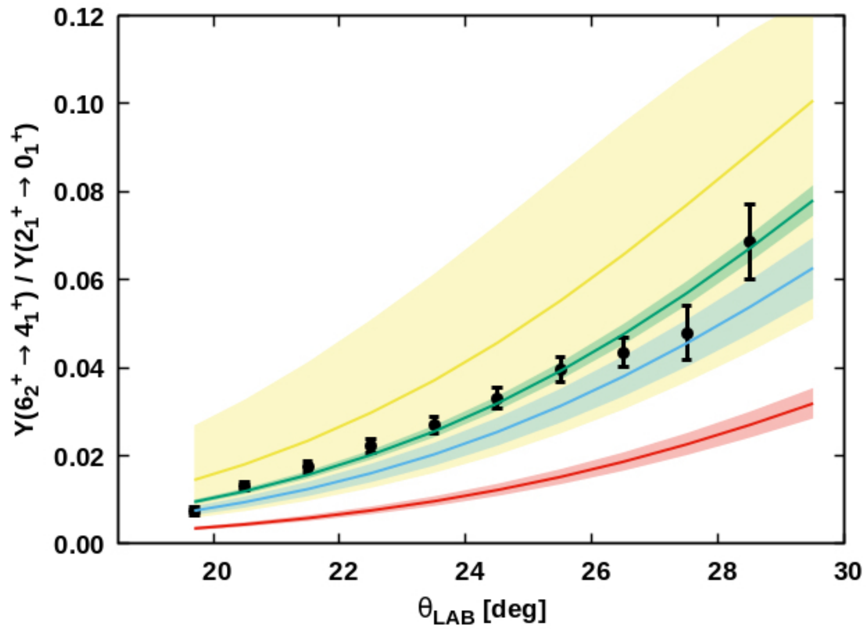
6_2^+ – GOSIA fit: 0.48(3) ps
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021): 1.22(15) ps
D. Rhodes et al., Phys. Rev. C 103, L051301 (2021): 0.54(8) ps

Sample results (strongly populated states)

$4_1^+ \to 2_1^+$



$6_2^+ \to 4_1^+$

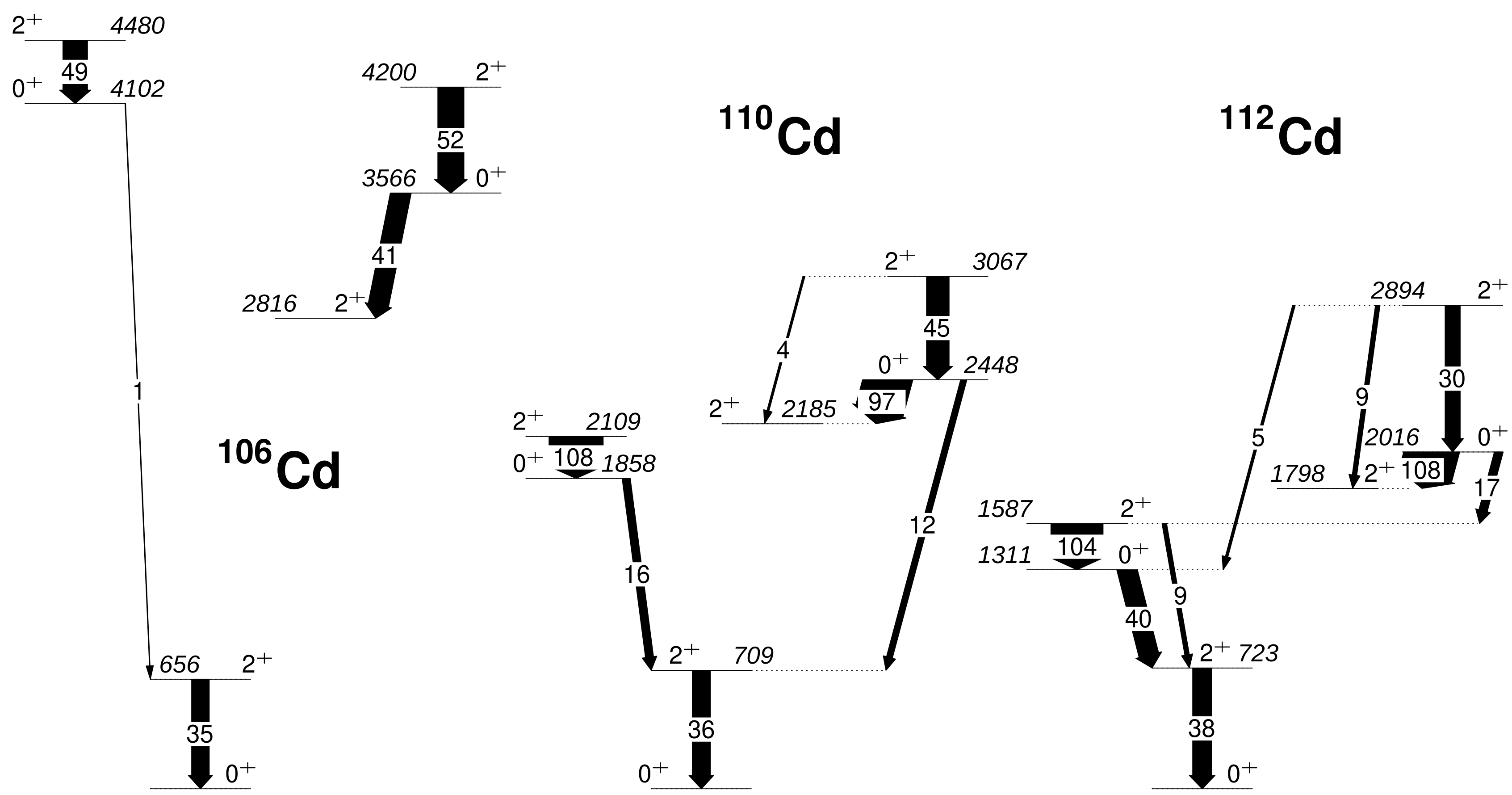


- similar analysis has been applied to all observed states, yielding B(E2) values complementary to those obtained from the RDDS analysis of the same date
- contrary to RDDS, it was possible to obtain B(E2) values for the decay of states that have lifetimes shorter than 1 ps

D. Kalaydjieva, PhD thesis, 2023

Shape coexistence in Cd isotopes: BMF predictions

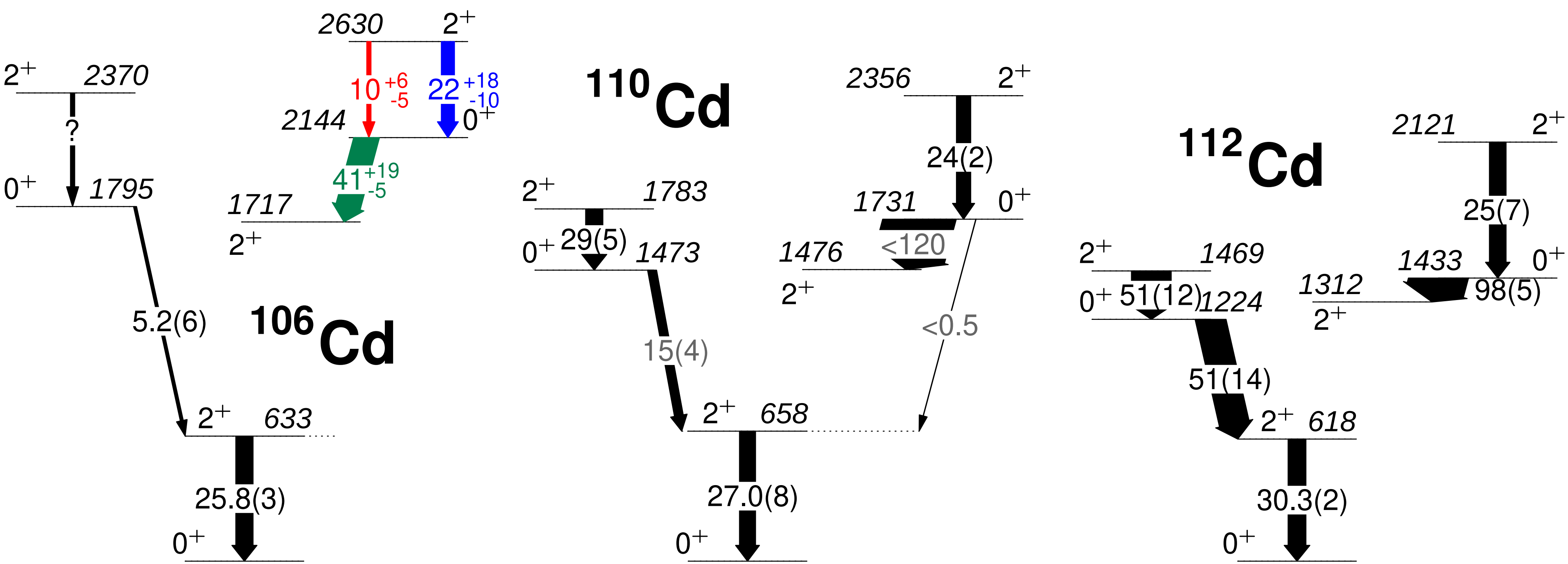
- similar shape-coexisting structures as in ^{110,112}Cd are predicted in ^{106}Cd
- in-band transition strength in the oblate structure predicted to increase with decreasing N, while the $B(E2; 0_3^+ \rightarrow 2_2^+)$ value decreases



SCCM calculations: T.R. Rodriguez

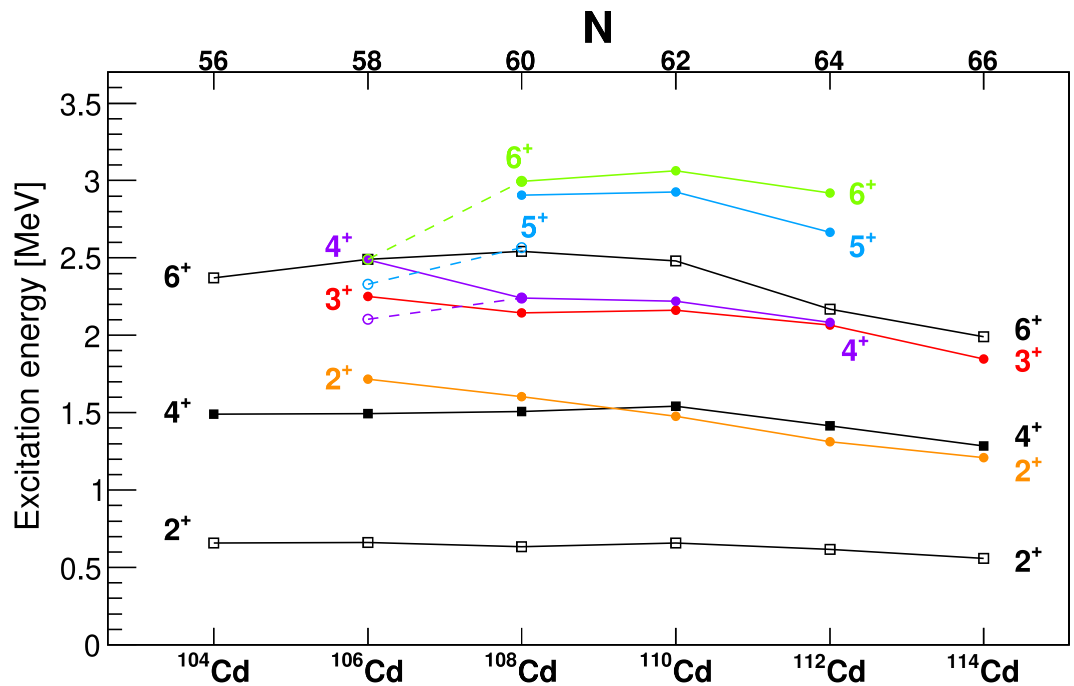
Unsafe Coulomb-excitation results

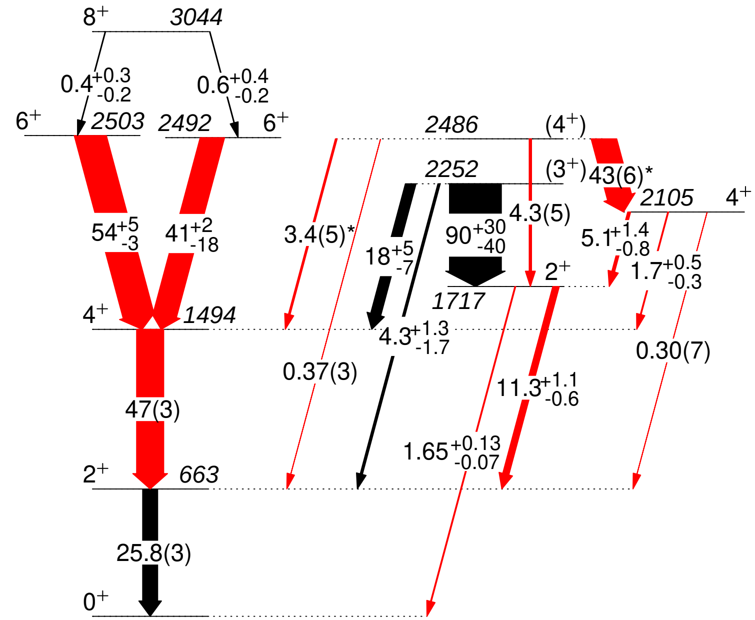
- decay of the presumably oblate 0_3^+ state agrees well with the SCCM prediction, but the in-band transition strength has a very different trend
- larger B(E2; $2_5^+ \rightarrow 0_3^+$) (similar to that in the ground-state band) if the branching ratio from A. Linnemann PhD (Cologne, 2005) is assumed instead of the more precise value from T. Schmidt PhD (Cologne, 2019)



^{106}Cd: D. Kalaydjieva, PhD thesis, 2023; ^{110}Cd: preliminary values (K. Wrzosek-Lipska) in gray

Proposed reorganisation of the level scheme



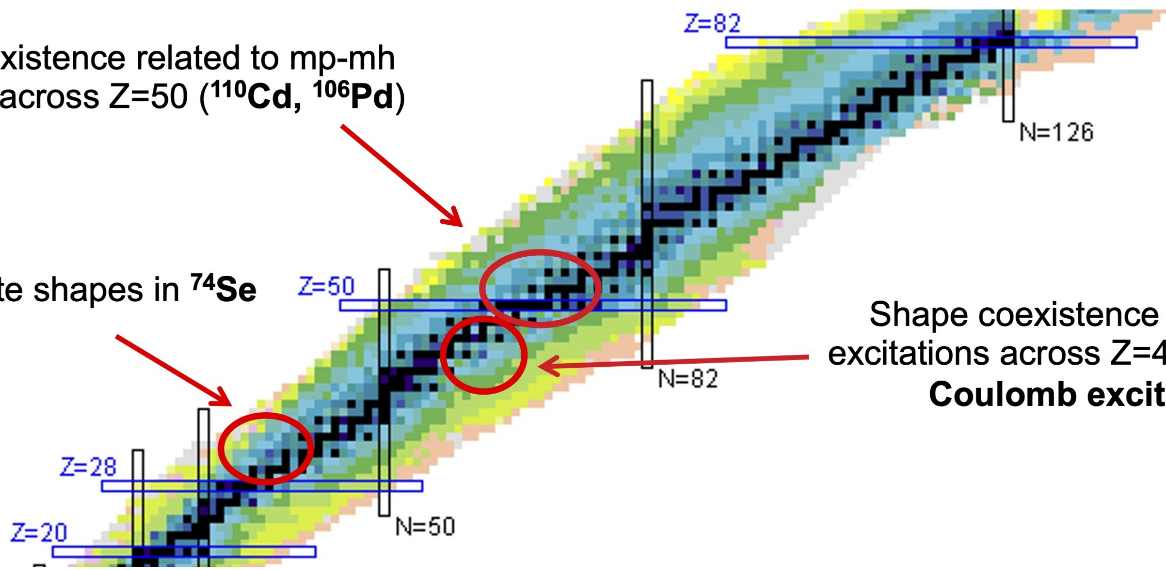


- new K=2 3^+ and 4^+ and K=4 4^+ band members proposed that have expected decay patterns and excitation energies consistent with the systematics
- closely spaced 6^+ states suggested to result from a strong mixing of the rotational band member with a seniority state
- non-observation of the 2252-keV state in the present data supports its 3^+ spin-parity (Coulomb excitation of odd-spin positive parity states is strongly hindered)
- firm spin assignments will be obtained from a high-statistics β decay study into ^{106}Cd recently approved at TRIUMF

Present and future: AGATA at LNL

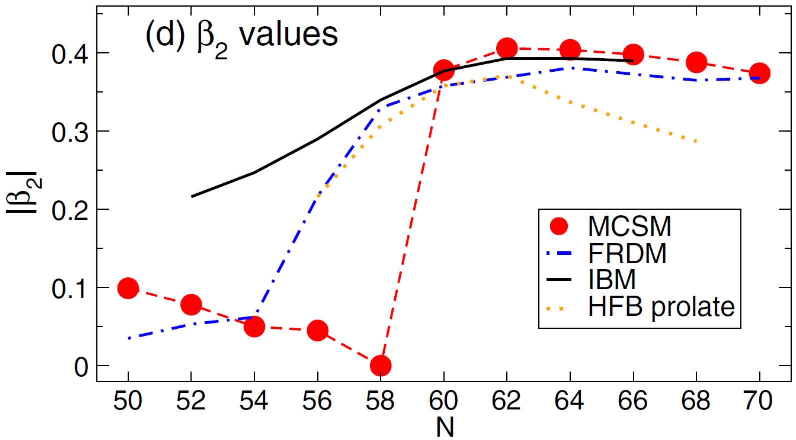
Shape coexistence related to mp-mh excitations across Z=50 (^{110}**Cd**, ^{106}**Pd**)

Prolate and oblate shapes in ^{74}**Se**



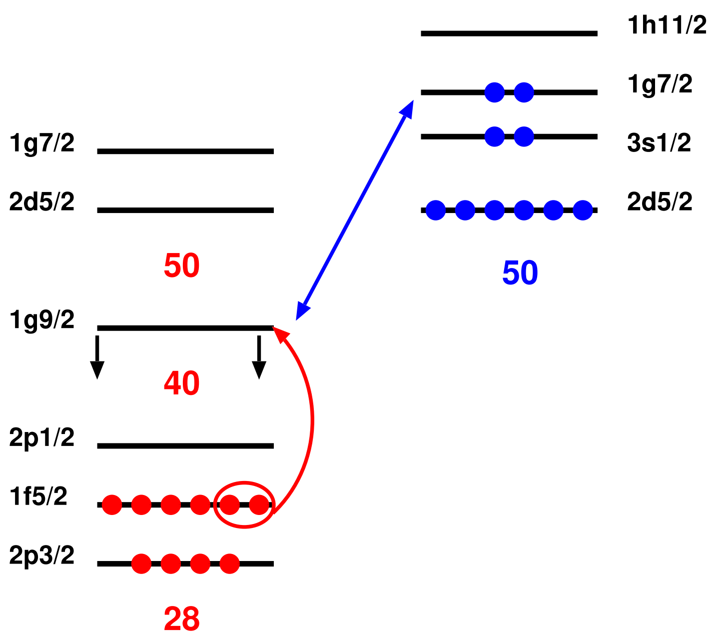
Shape coexistence related to mp-mh excitations across Z=40 (**safe and unsafe Coulomb excitation of** ^{96}**Zr**)

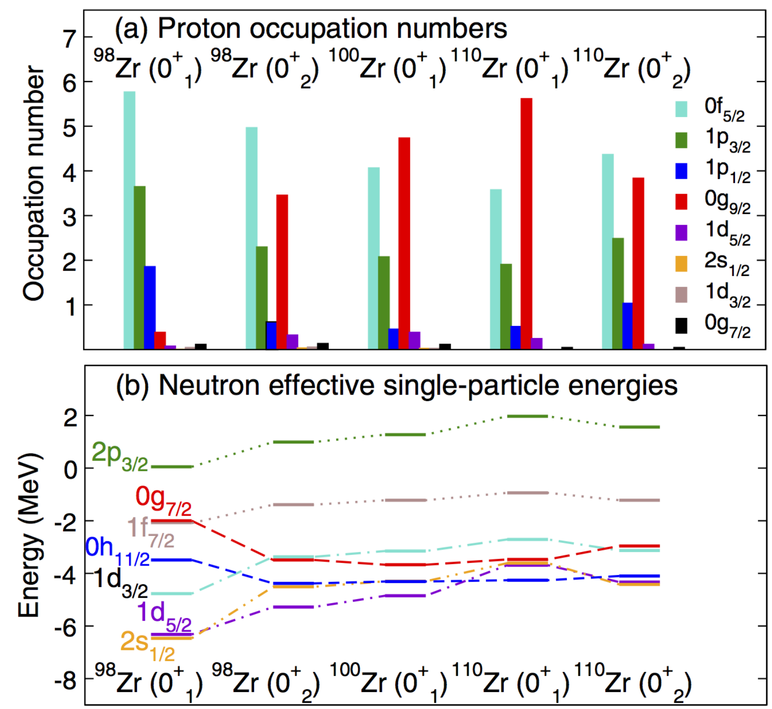
Shape coexistence and type-II shell evolution in Zr isotopes



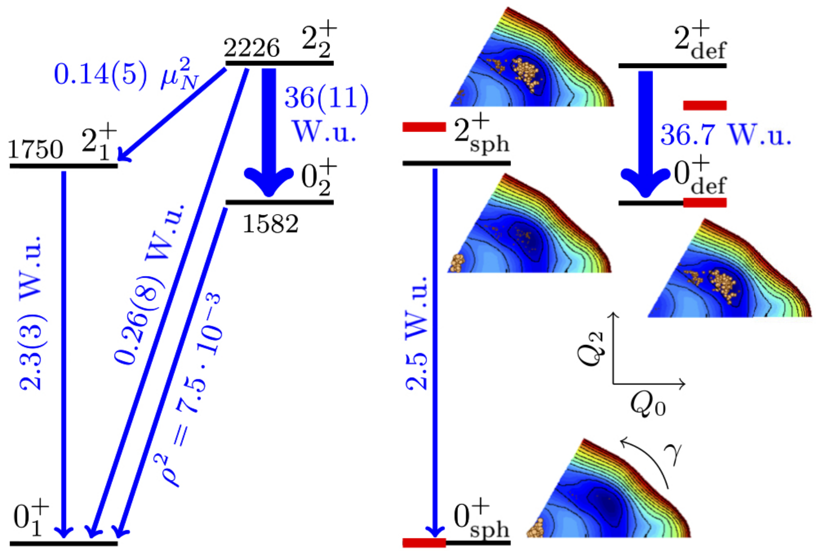
T. Togashi et al, PRL 117, 172502 (2016)

- 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^+

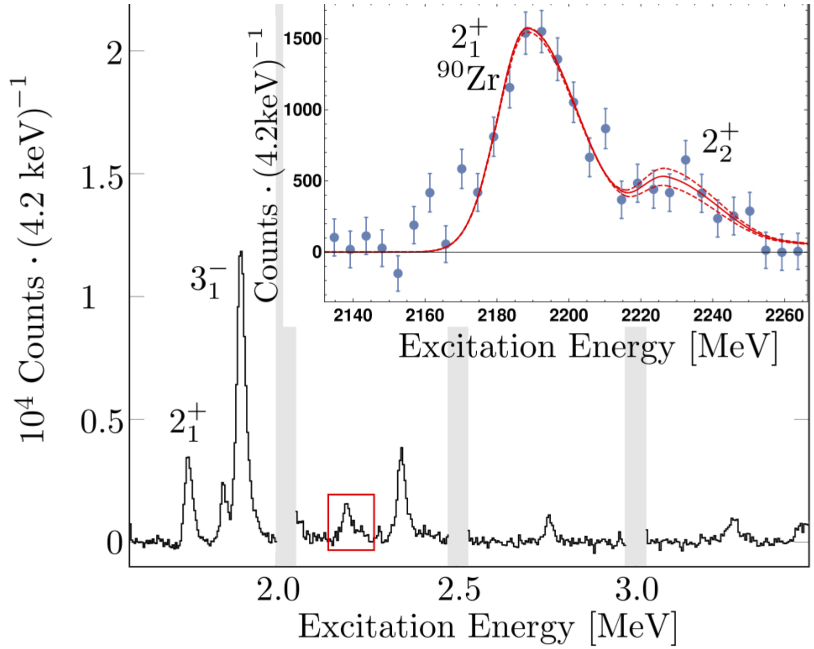




Shape coexistence in ^{96}Zr – experimental information



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

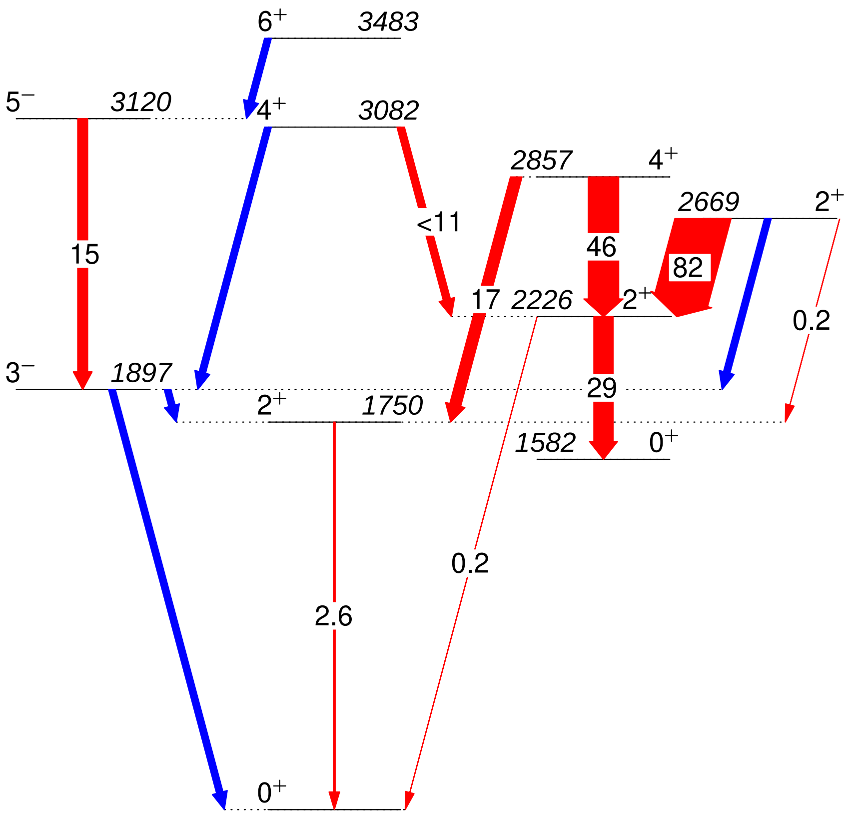


- B(E2; $2_2^+ \rightarrow 0_1^+$) measured using electron scattering, combined with known branching and mixing ratios:
  $\rightarrow$transition strengths from the 2_2^+ state
- B(E2; $2_1^+ \rightarrow 0_1^+$) = 2.3(3) Wu vs B(E2; $2_2^+ \rightarrow 0_2^+$) = 36(11) Wu: nearly spherical and a well-deformed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

^{96}Zr decay scheme with revised branching and mixing ratios

J. Wiśniewski et al, Phys. Rev. C 108, 024302 (2023)

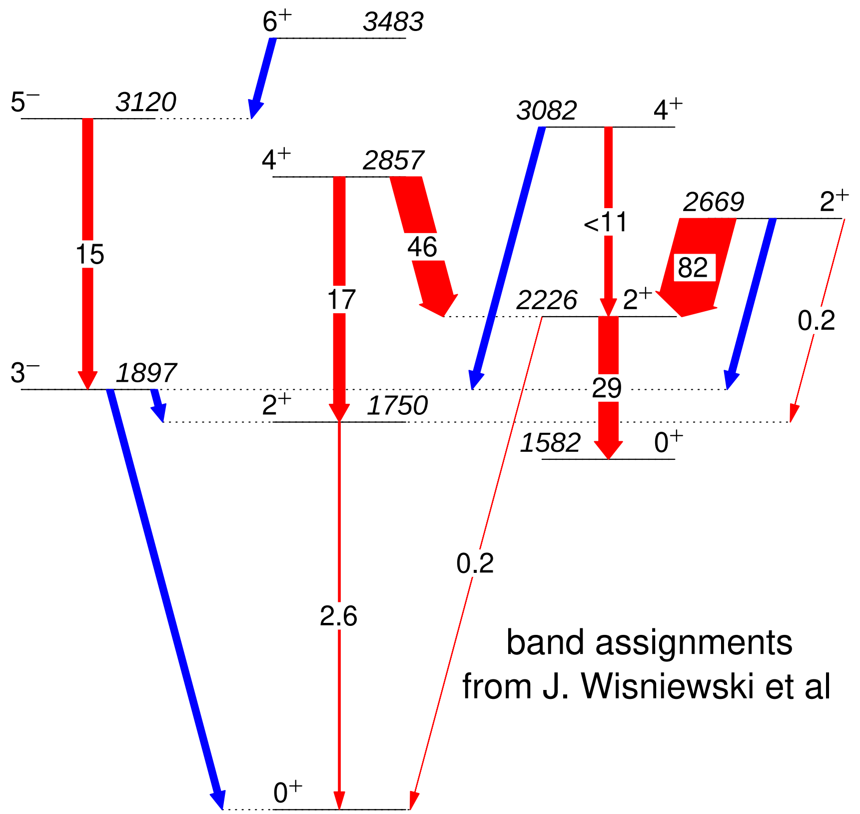
- which 4^+ belongs to which band? if 4_1^+ is part of the deformed structure, why is its decay to the 2_1^+ so strong (mixing between bands should be weak)?
- the $2_3^+ \rightarrow 2_2^+$ decay seems surprisingly enhanced
- E1 transitions from presumably collective states compete with E2 ones



^{96}Zr decay scheme with revised branching and mixing ratios

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



^{96}Zr decay scheme with revised branching and mixing ratios

J. Wiśniewski et al, Phys. Rev. C 108, 024302 (2023)

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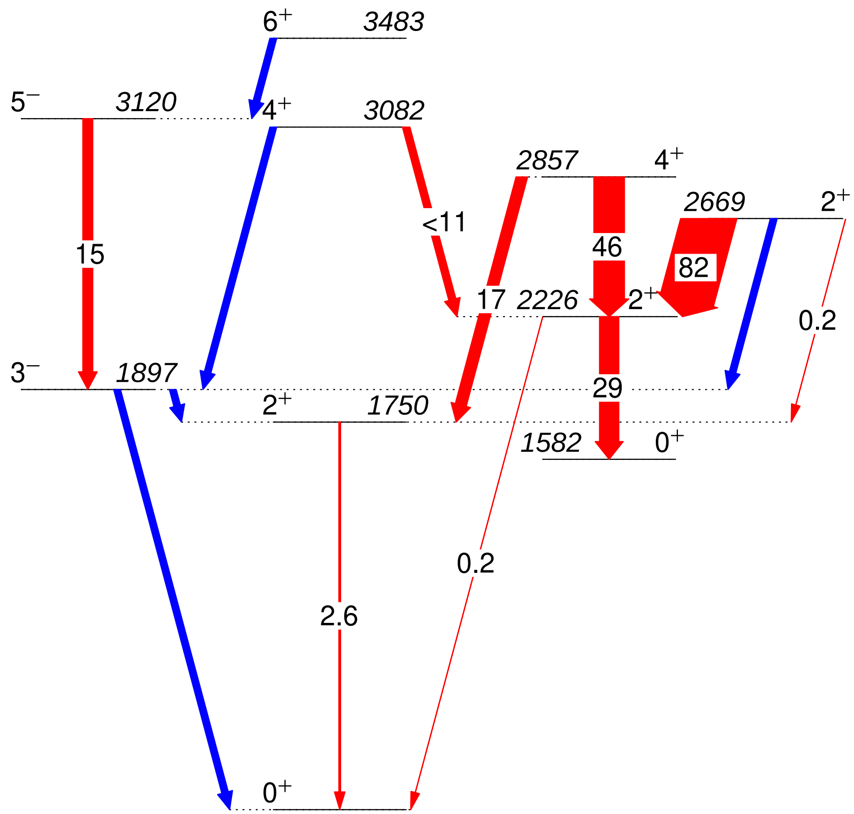


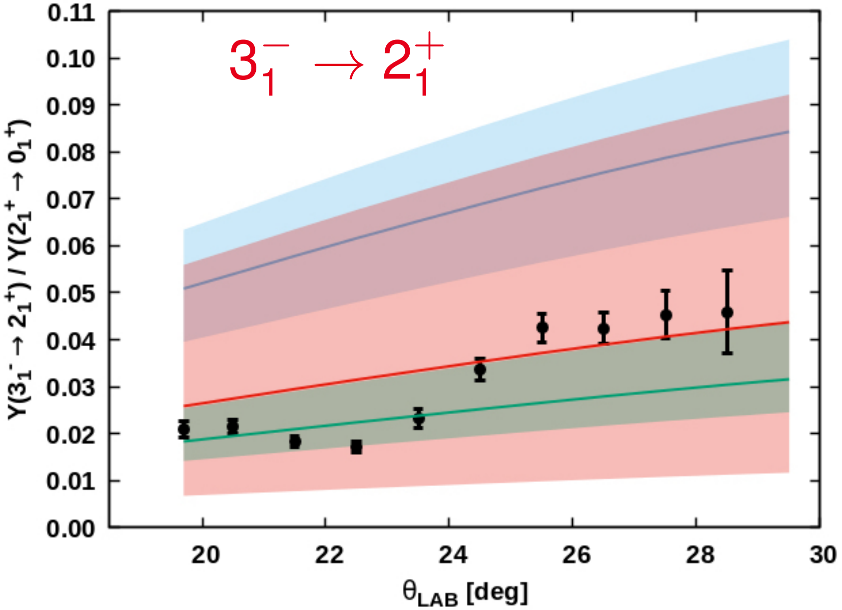
- “unsafe” Coulomb-excitation experiment with AGATA coupled to PRISMA magnetic spectrometer (May 2024)
- notable result: unexpectedly strong population of the 4^+_1 state – consistent with mixing of $4^+_{1,2}$ states

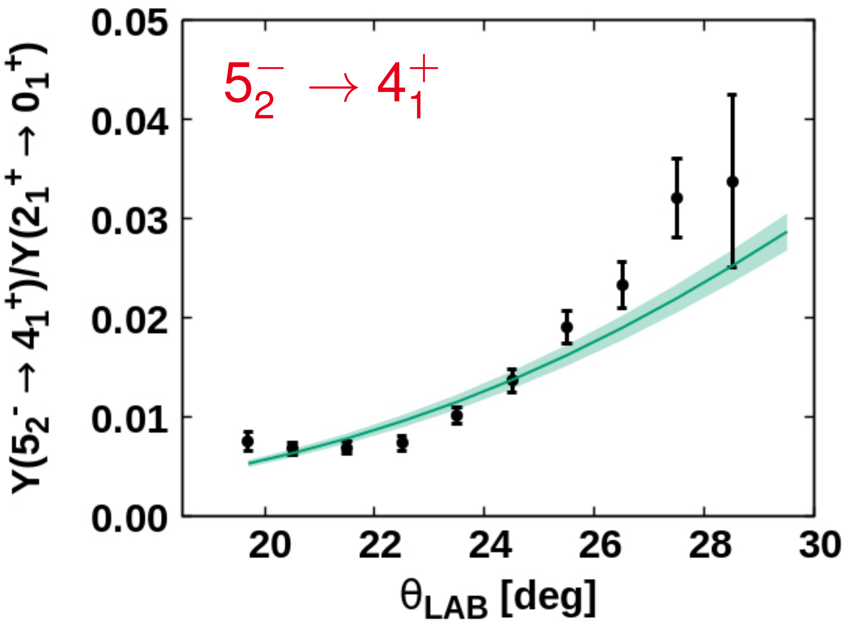
data analysis: Z.T. Ahmed, University of Guelph

Summary

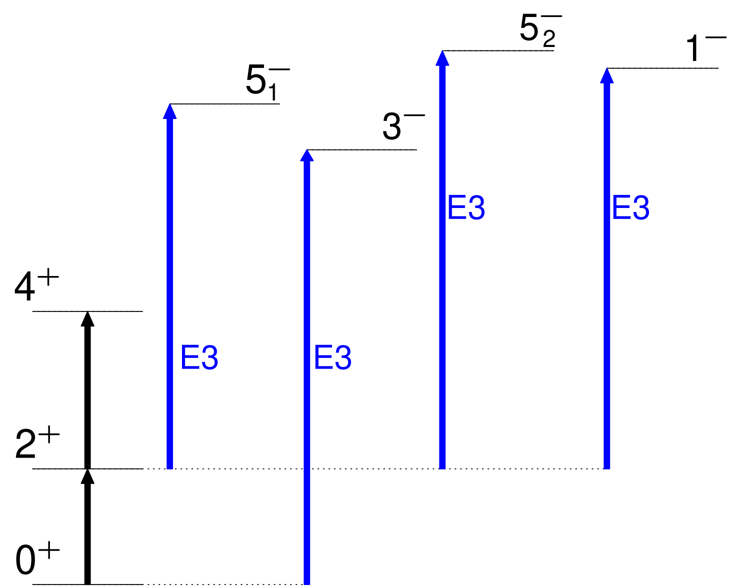
- ^{42}Ca: large static deformation of $\beta(0_2^+)$=0.43(4) and $\beta(2_2^+)$=0.45(4) is consistent with the superdeformed character of the side band
- $\langle \cos(3\delta) \rangle$ obtained for the 0_2^+ state in ^{42}Ca brings the first experimental evidence for the non-axial character of SD structures in the A$\sim$40 mass region
- ^{106}Cd: we obtained new experimental information on the presumably oblate 0_3^+ and 2_5^+ states and proposed a rearrangement of the level scheme involving K=2 and K=4 structures
- ^{96}Zr (preliminary!): we observed a surprisingly strong population of the 4_1^+ state, important in the context of shape coexistence with weak mixing postulated for this nucleus

Negative-parity states





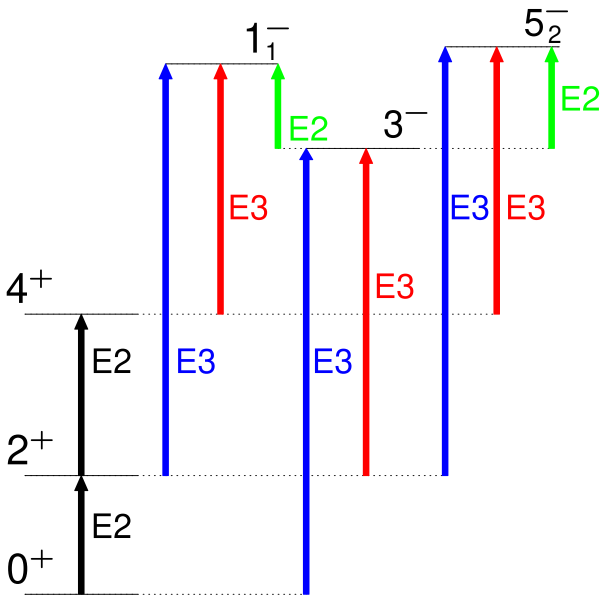
- oscillatory behaviour observed for the 3^-_1 and 5^-_2 excitation cross sections
- initally only a single E3 matrix element is assumed to be responsible for the population of each of the 3^-_1, 5^-_1, 5^-_2 and 1^-_1 states



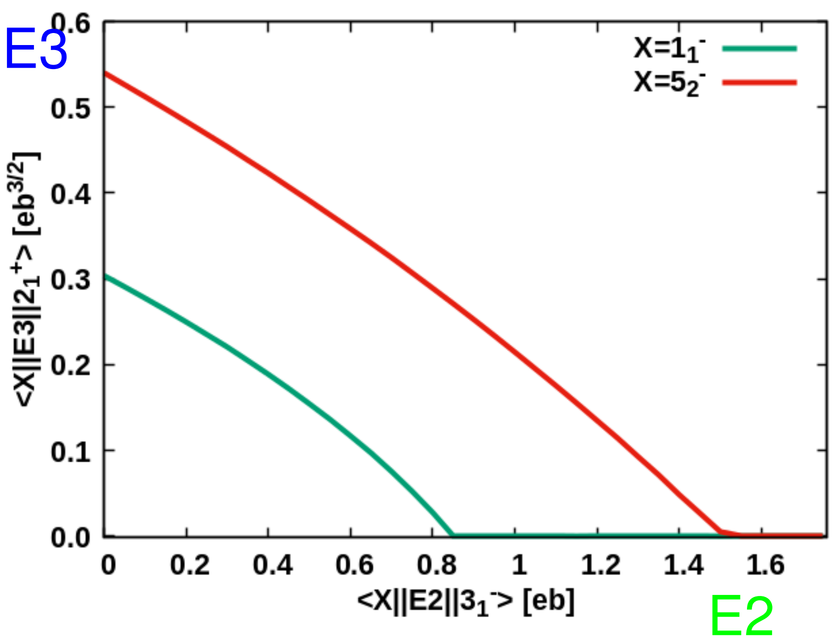
Results:

- $B(E3; 3^-_1 \to 0^+_1) = 11^{+4}_{-3}$ W.u.
- $B(E3; 5^-_2 \to 2^+_1) = 40(3)$ W.u. (a lot!)
- $B(E3; 1^-_1 \to 2^+_1) = 45(6)$ W.u. (also a lot!)

Negative-parity states: quadrupole-octupole coupling



- it is necessary to introduce a more complicated coupling scheme to describe populations of the 5_2^- and 1_1^- states
- additional E3 transitions change the populations by a few percent, even if values of many tens of W.u. are assumed
- E2 transitions to the 3_1^- state prove to be very important

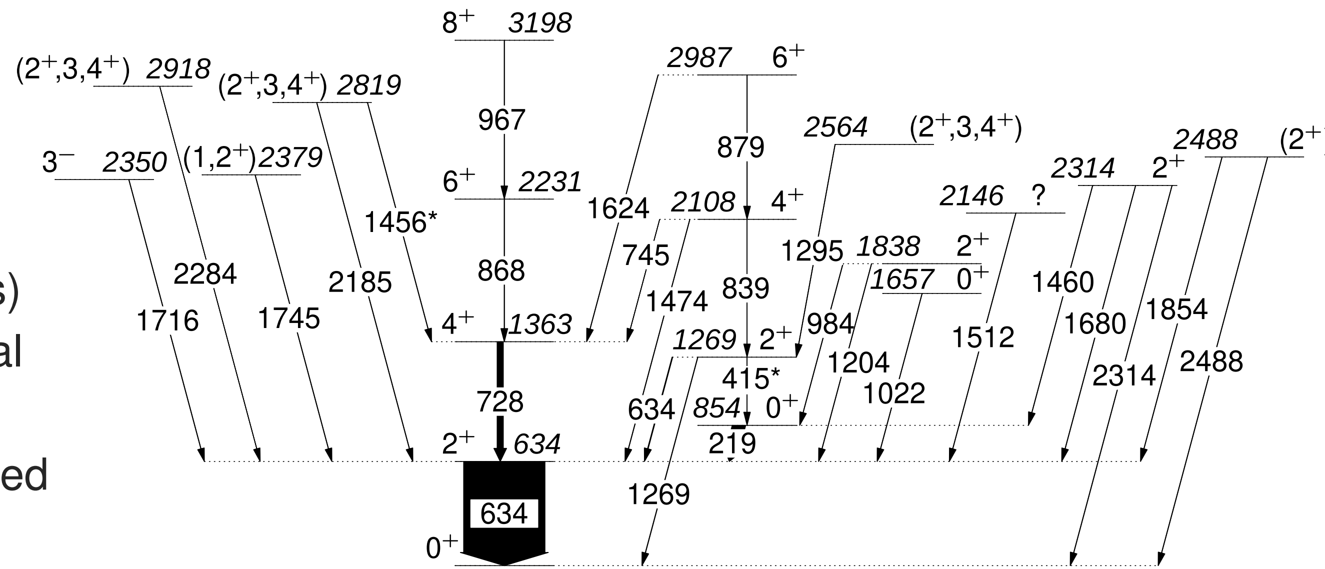


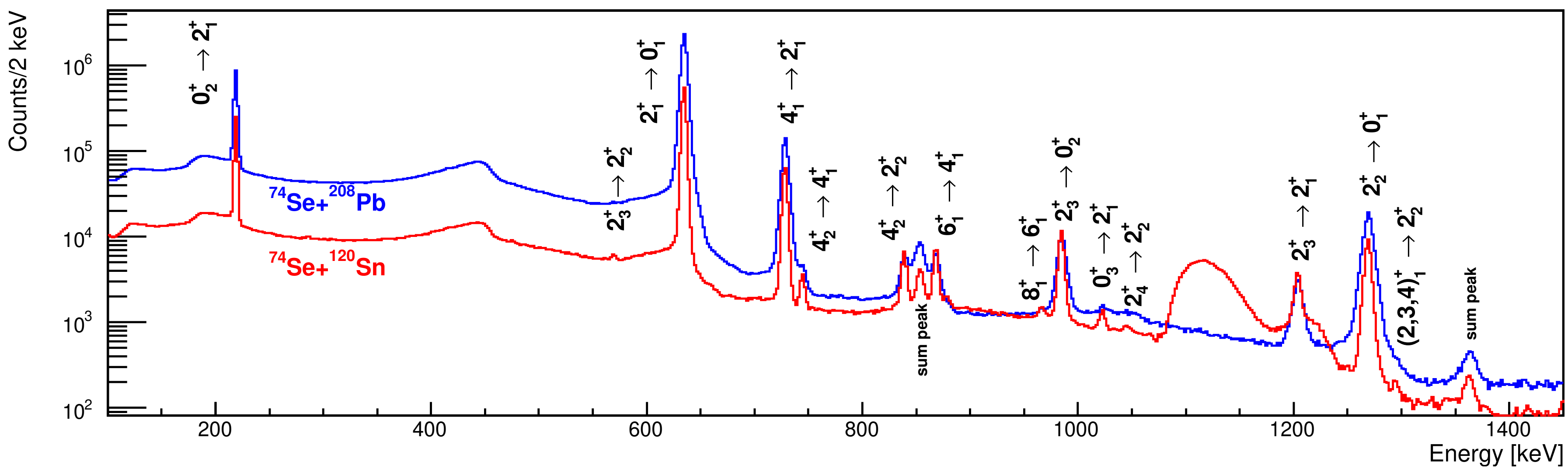
- we can extract the correlation between the E3 and E2 strength involved in the population of the negative parity states
- assuming $B(E2; 5_2^- \rightarrow 3_1^-) = B(E2; 1^- \rightarrow 3_1^-) = B(E2; 2_1^+ \rightarrow 0_1^+) = 26$ W.u. we obtain:
  - $B(E3; 5_2^- \rightarrow 2_1^+) = 7.8(1.3)$ W.u
  - $B(E3; 1_1^- \rightarrow 2_1^+) = 13(3)$ W.u.

  while $B(E3; 3_1^- \rightarrow 0_1^+) = 11^{+4}_{-3}$ W.u.

Shapes in ^{74}Se

- two interpretations:
  - prolate-oblate shape coexistence (0_1^+, 0_2^+ states)
  - weakly deformed vibrational (ground-state band, 0_2^+) coexisting with well deformed states (0_3^+, 2_4^+)



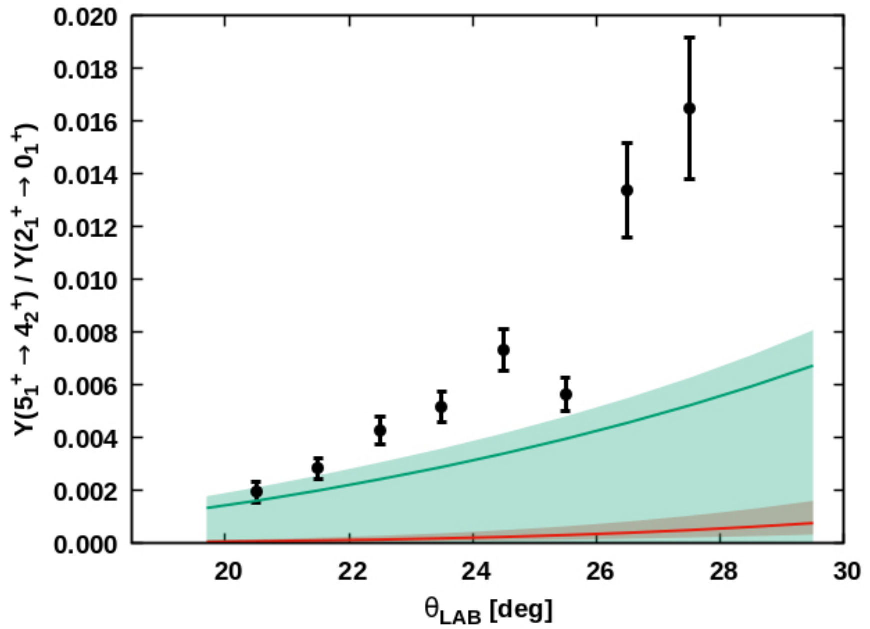


^{120}Sn and ^{208}Pb targets used to enhance sensitivity to the $0_3^+ \to 2_4^+$ excitation path

data analysis: R. Kjus, MZ, CEA Saclay

Ambiguities regarding the K=2 structure in ^{106}Cd

5_1^+ (2331 keV) $\rightarrow 4_2^+$



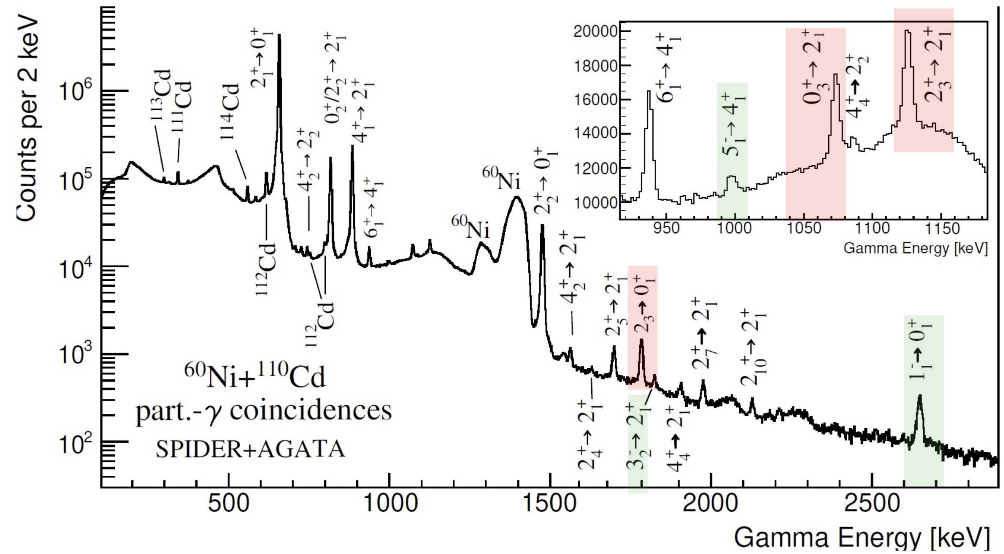
- the observed population of the 5_1^+ state would require B(E2; $5_1^+ \rightarrow 4_2^+$) over 300 W.u.
- lifetime: 9(1) ps (GOSIA fit)
  870(290) ps (ENSDF)
- we suspect the 226-keV $5_1^+ \rightarrow 4_2^+$ transition is part of a doublet

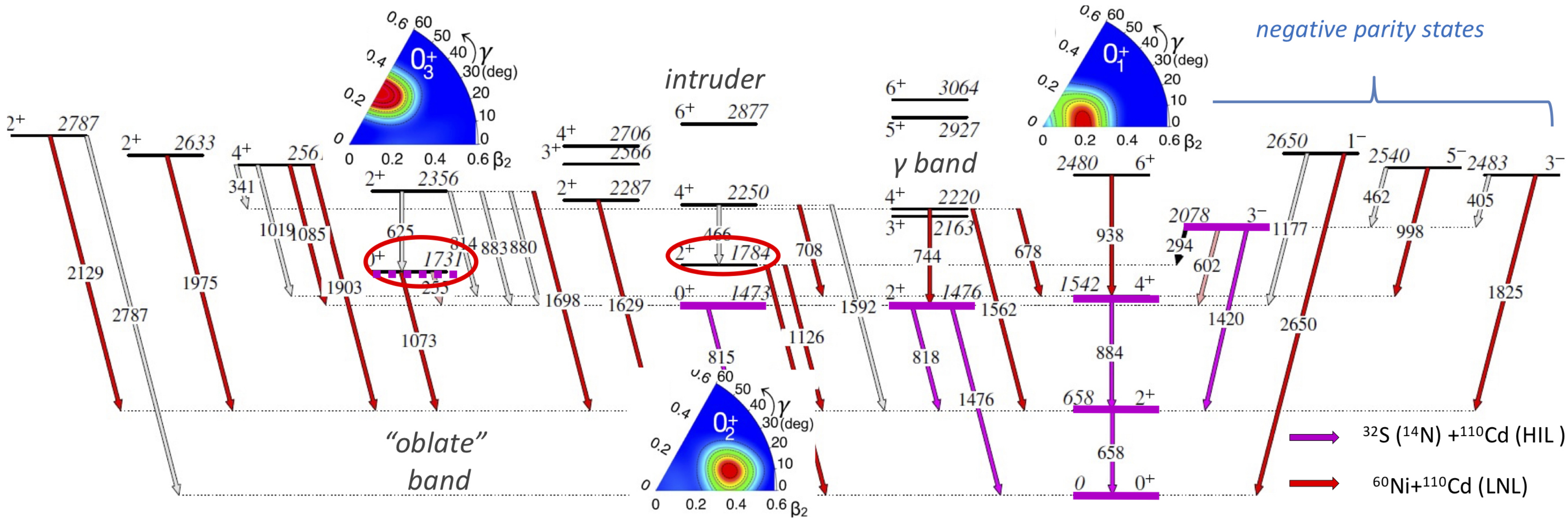
- K=2 band proposed in M. Siciliano et al., Phys. Rev. C 104, 034320 (2021) has a much more narrow energy spacing than those in heavier Cd nuclei
- multiple 3^+ candidates (2252, 2254, 2710, 2718-keV), none of them with a firm spin assignment
- strong discrepancies in the literature regarding branching ratios in the 4_2^+ and 2_2^+ decay

D. Kalaydjieva, PhD thesis, 2023

Multiple shape coexistence in ^{110}Cd

- aim: determination of β and γ parameters of 0_1^+, 0_2^+ and 0_3^+ states in ^{110}Cd using quadrupole sum rules
- verification of the multiple shape-coexistence scenario (P.E. Garrett et al, Phys. Rev. Lett. 123, 142502 (2019))





5 days of ^{58}Ni beam with AGATA in 2022, complementary measurements at HIL Warsaw

data analysis: I. Piętka, K. Wrzosek-Lipska, HIL Warsaw