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
- multiple shape coexistence in ^{110}Cd and ^{74}Se:
  data under analysis (HIL Warsaw, CEA Saclay)

Shape coexistence

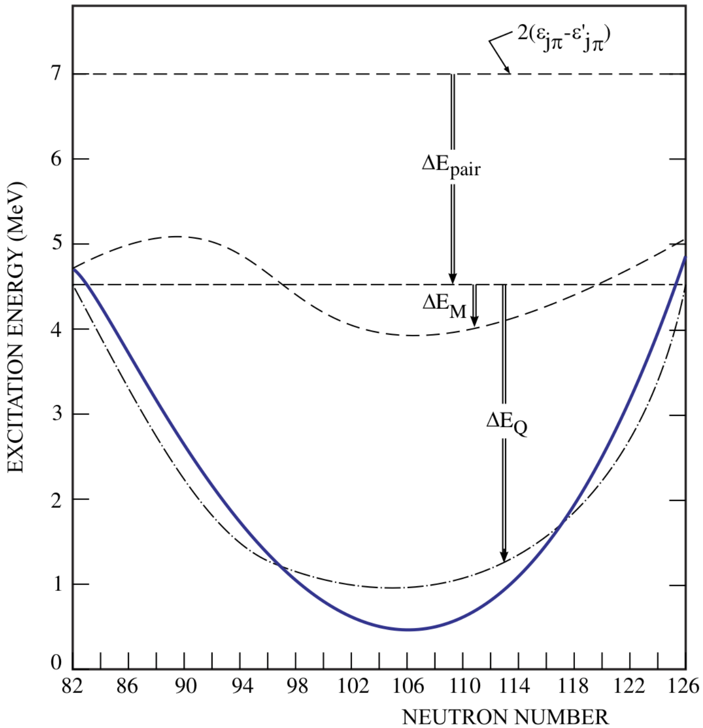
K. Heyde and J. Wood, Rev. Mod. Phys. 83, 1467 (2011)

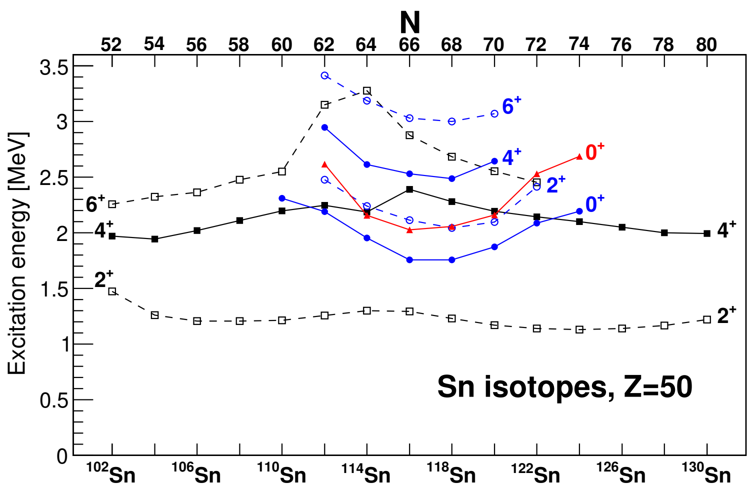
- appearance of states characterised by different shapes closely lying in energy

- 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

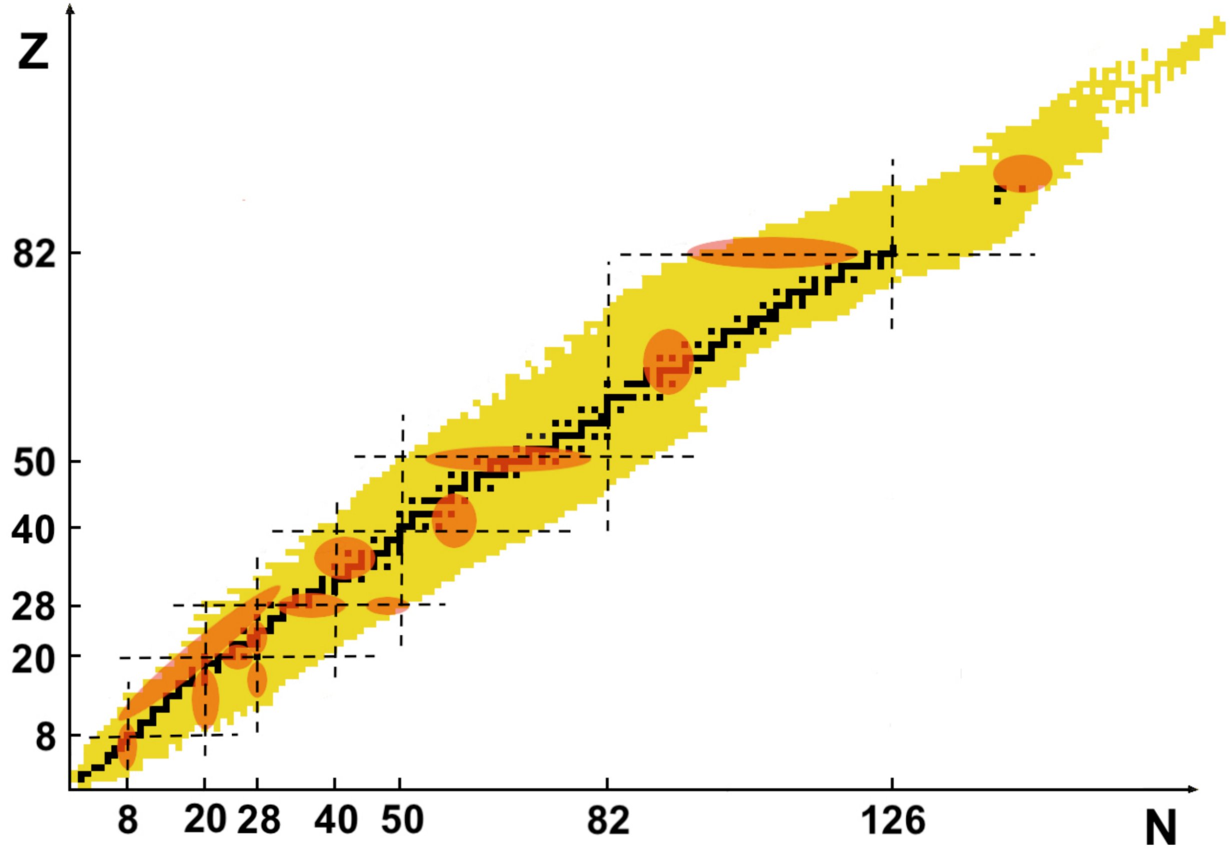
- depends on a delicate balance of macroscopic, liquid-drop-like properties of the nuclear matter and microscopic shell effects – provides stringent tests of modern nuclear structure models





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

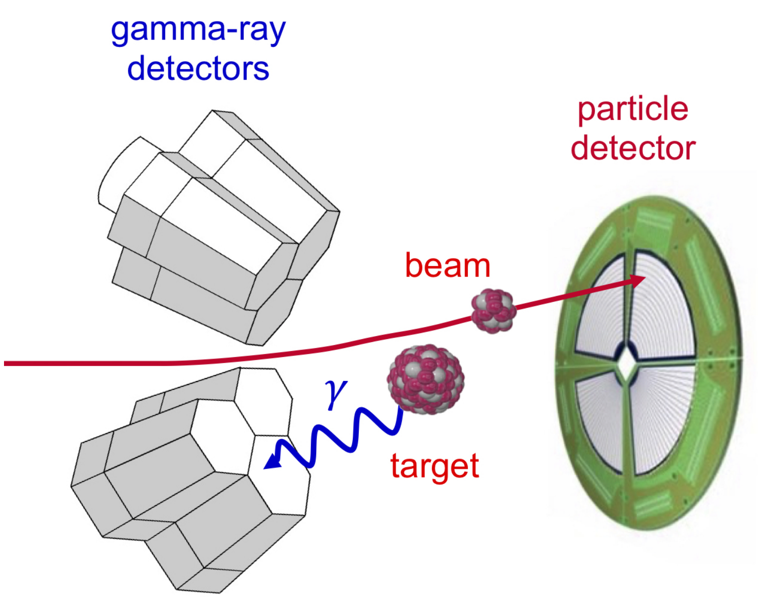
- Coulomb excitation: perfect tool to study shape coexistence as it is the only technique sensitive to charge distribution in excited nuclear states

Coulomb excitation

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

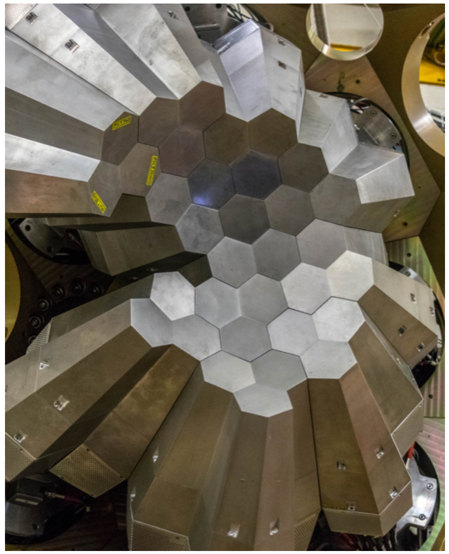
- we observe gamma-ray decay of Coulomb-excited states in coincidence with scattered beam ions or target recoils

- 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

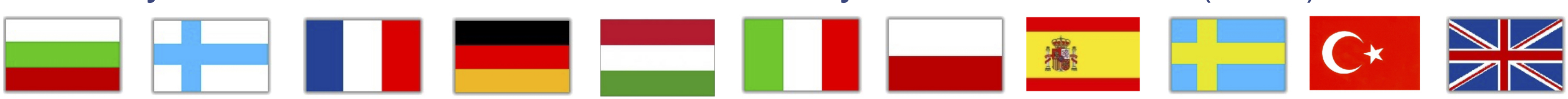


11 ATC, Feb 2022

- new-generation gamma-ray tracking array developed by a 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

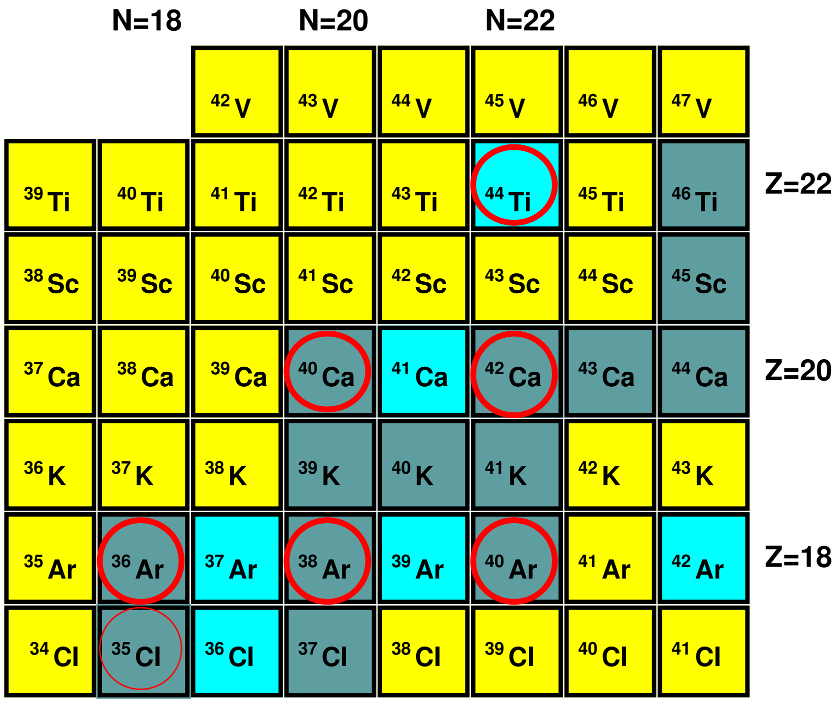
S. Akkoyun et al., Nucl. Instrum. Methods Phys. Res. A 668, 26 (2012).



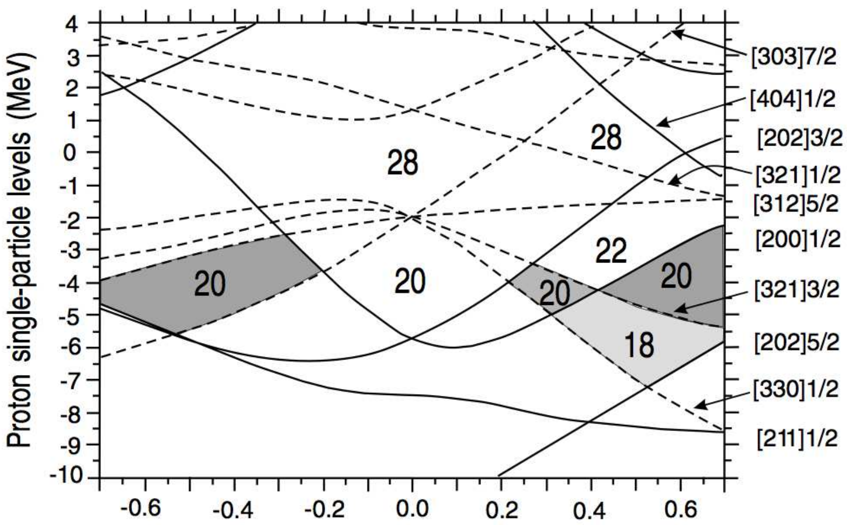
Part I: AGATA Demonstrator at LNL

superdeformation in ^{42}Ca

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

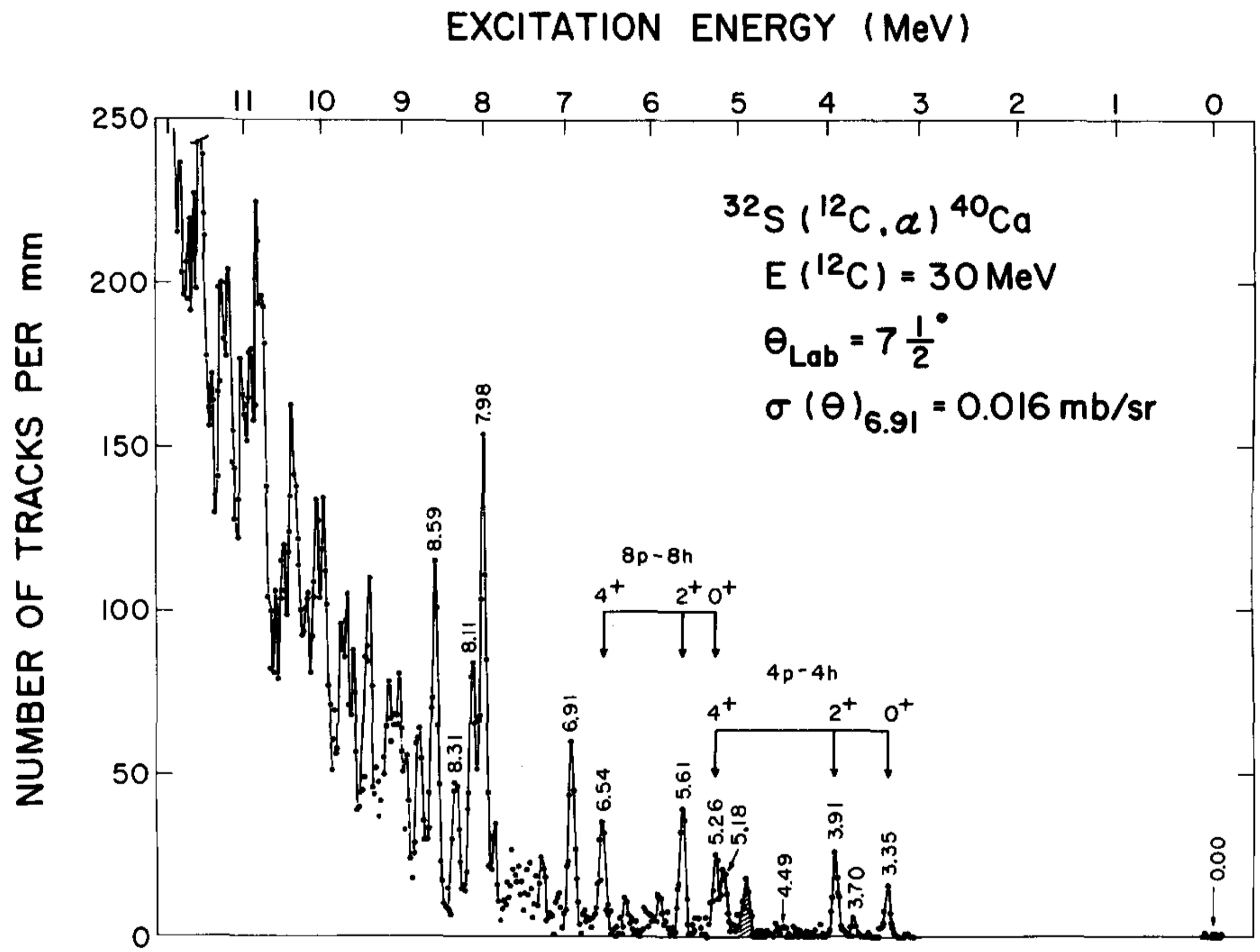


E. Ideguchi et al., PRL 81 (2001) 222501



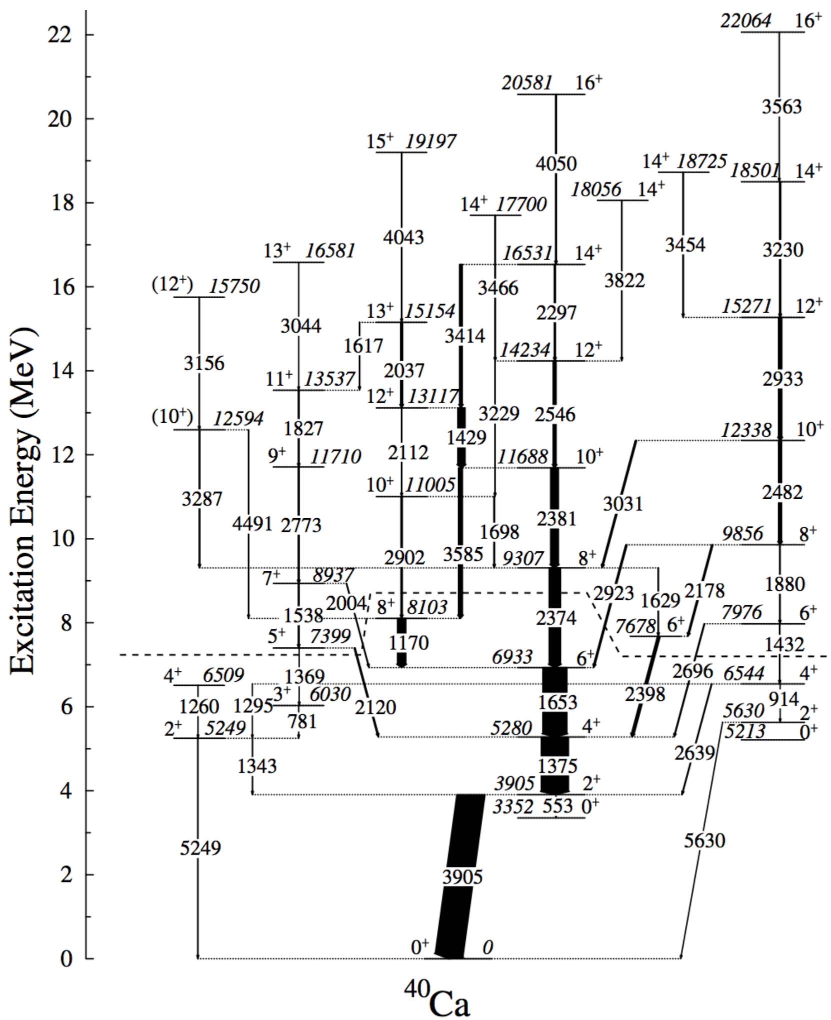
- spherical and highly-deformed magic numbers appear at similar particle numbers – dramatic shape coexistence

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



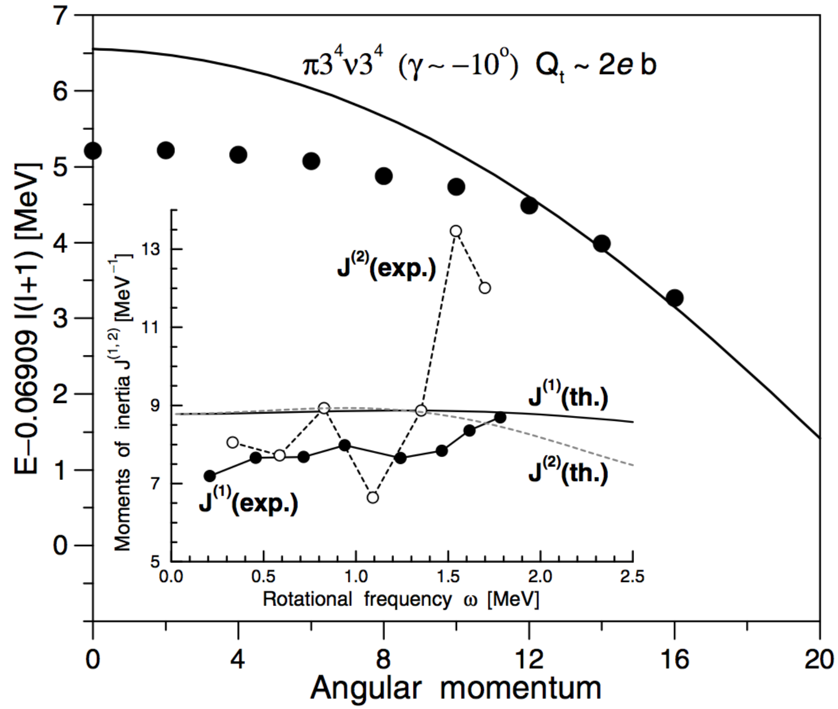
R. Middleton et al, Phys. Lett. 39B (1972) 339

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, ...

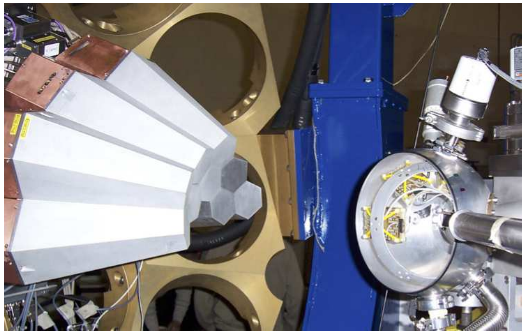
E. Ideguchi et al., PRL 81 (2001) 222501

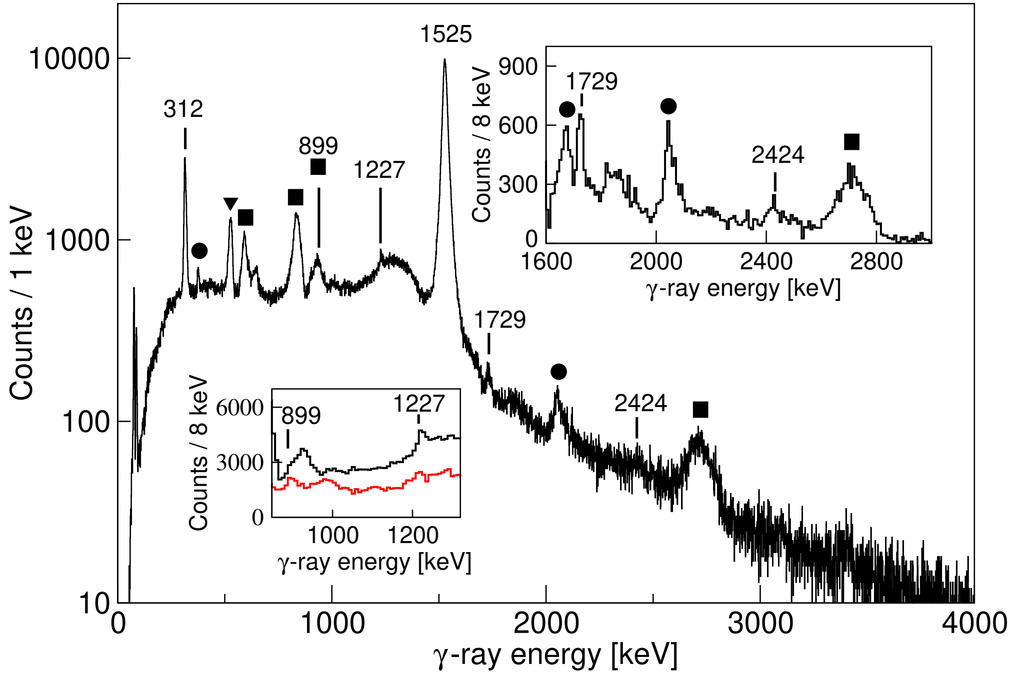


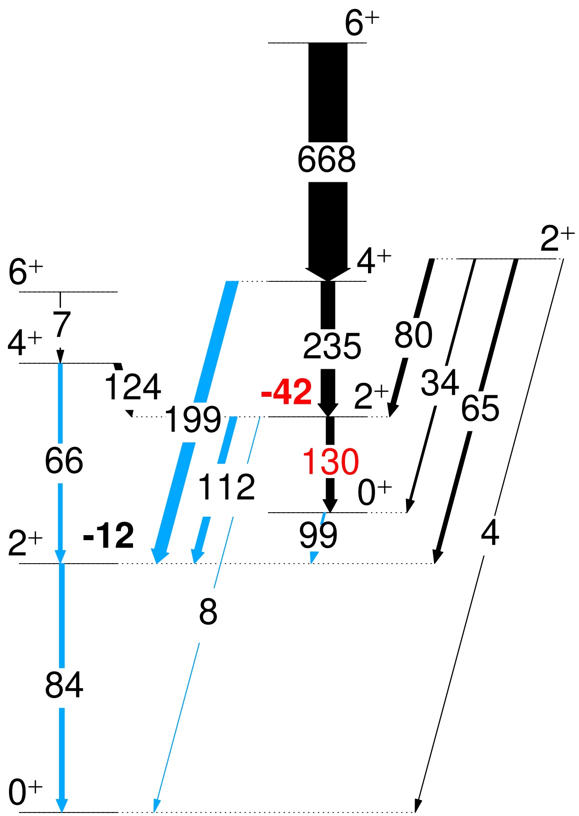
- intense transitions linking very deformed structures to ground-state bands – mixing of configurations

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°







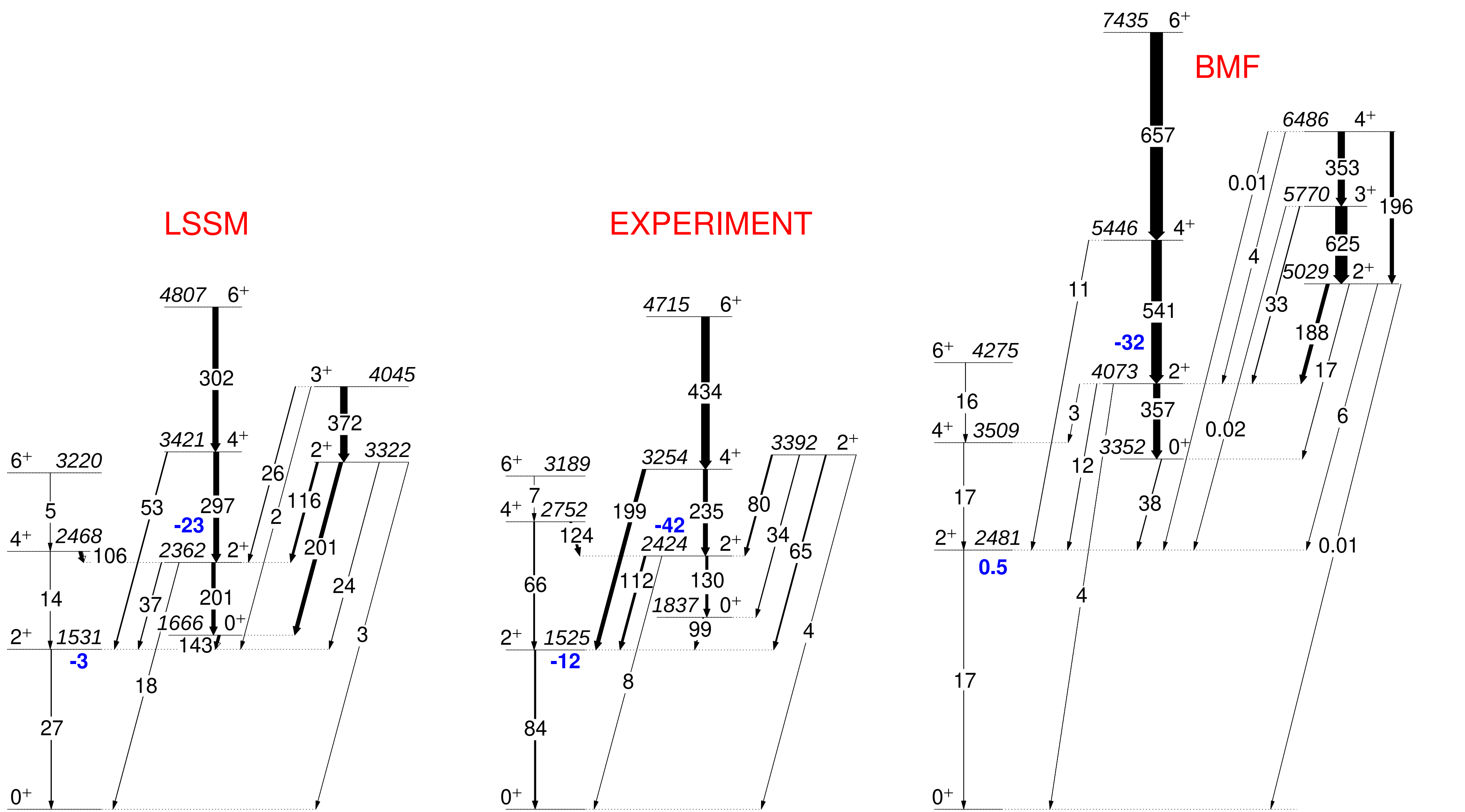
- first population of a superdeformed band in Coulomb excitation
- measured quadrupole moment of 2_2^+ corresponds to $\beta = 0.48(14)$

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

Comparison with theoretical calculations

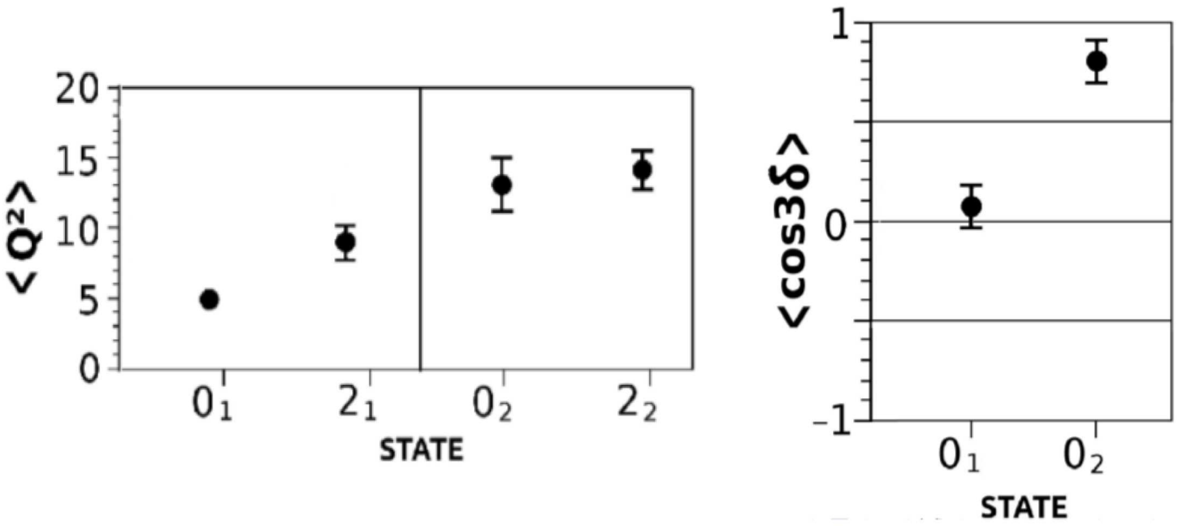
K. Hadyńska-Klęk,
PRL 117 (2016) 062501

- 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



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

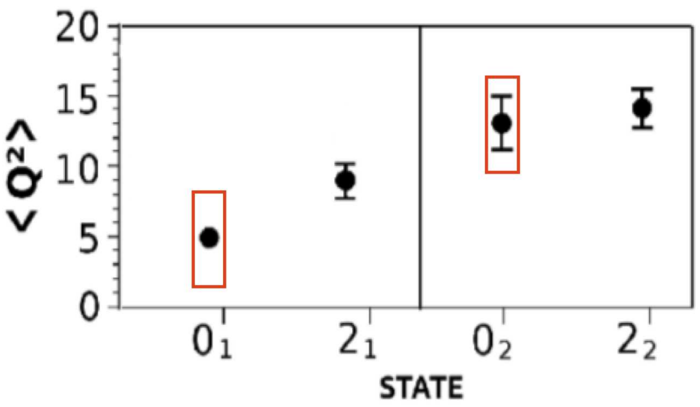
$$\bar{\gamma} = \arccos\langle \cos(3\delta) \rangle$$

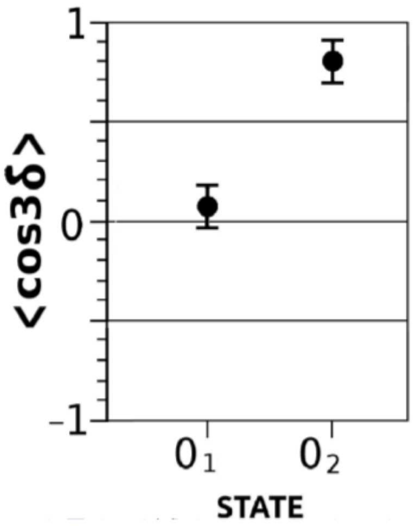
- deformation parameters:
  - side band: $\bar{\beta}$=0.43(4), $\bar{\gamma}$=13(6)°
  - ground-state band: $\bar{\beta}$=0.26(2), $\bar{\gamma}$=29(2)° (?)
- are these static deformations, or fluctuations?
  - what about softness in β: $\sigma(Q^2) = \sqrt{\langle Q^4 \rangle - \langle Q^2 \rangle^2}$?

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

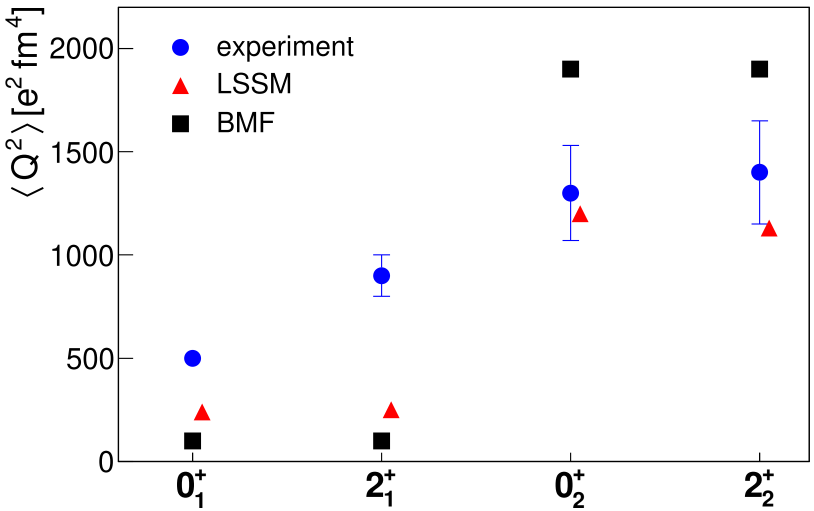
$\rightarrow$ fluctuations about a spherical shape; $\langle\cos(3\delta)\rangle$=0 resulting from averaging over all possible quadrupole shapes ranging from prolate to oblate

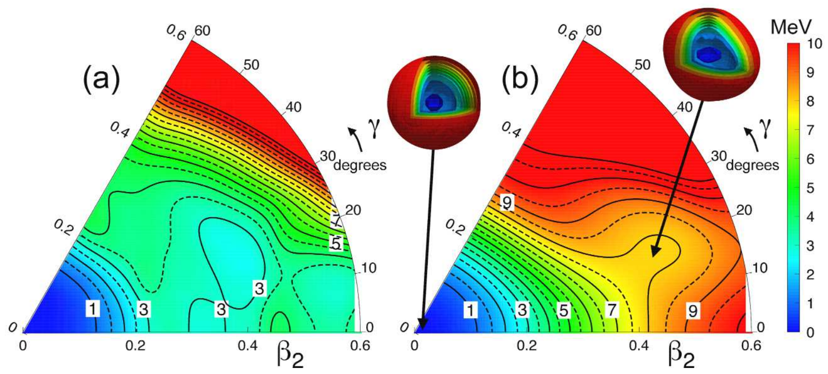
excited band: $\sigma(Q^2)$ few times lower than $\langle Q^2\rangle$

$\rightarrow$ static deformation

Comparison with theoretical calculations

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



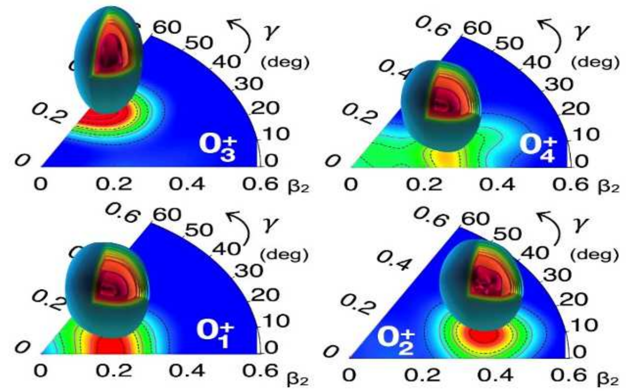


- coexistence of two very different structures reproduced by both theories, slightly triaxial SD minimum present in both potential maps
- deformation in the ground-state band increases with spin contrary to theoretical predictions → mixing seems to be underestimated by calculations

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

- decisive arguments: β-decay study (8π, TRIUMF) + DSAM lifetime measurements (Kentucky) in ^{110,112}Cd with guidance from beyond-mean-field calculations (P.E. Garrett et al, Phys. Rev. Lett. 123, 142502 (2019))

- 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)

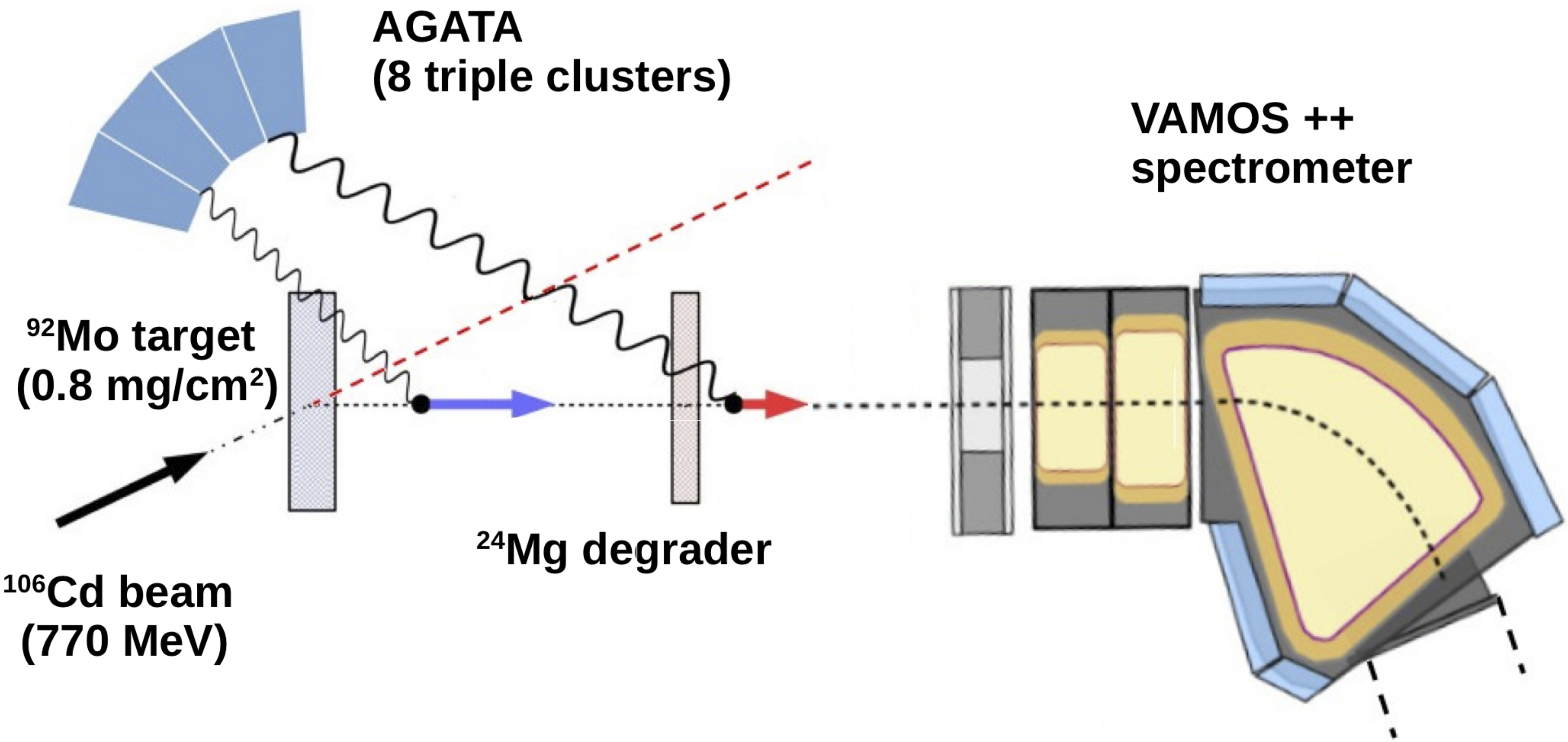
- also for neighbouring nuclei, in particular ^{106}Cd:
  - Coulomb excitation of ^{106}Cd: (ReA3, MSU – D. Rhodes et al, Phys. Rev. C 103, L051301 (2021); GRETINA, ANL – T. Gray et al, Phys. Lett. B 834, 137446 (2022))
  - RDDS lifetime measurement in $^{102-108}$Cd: (AGATA, GANIL – M. Siciliano et 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)

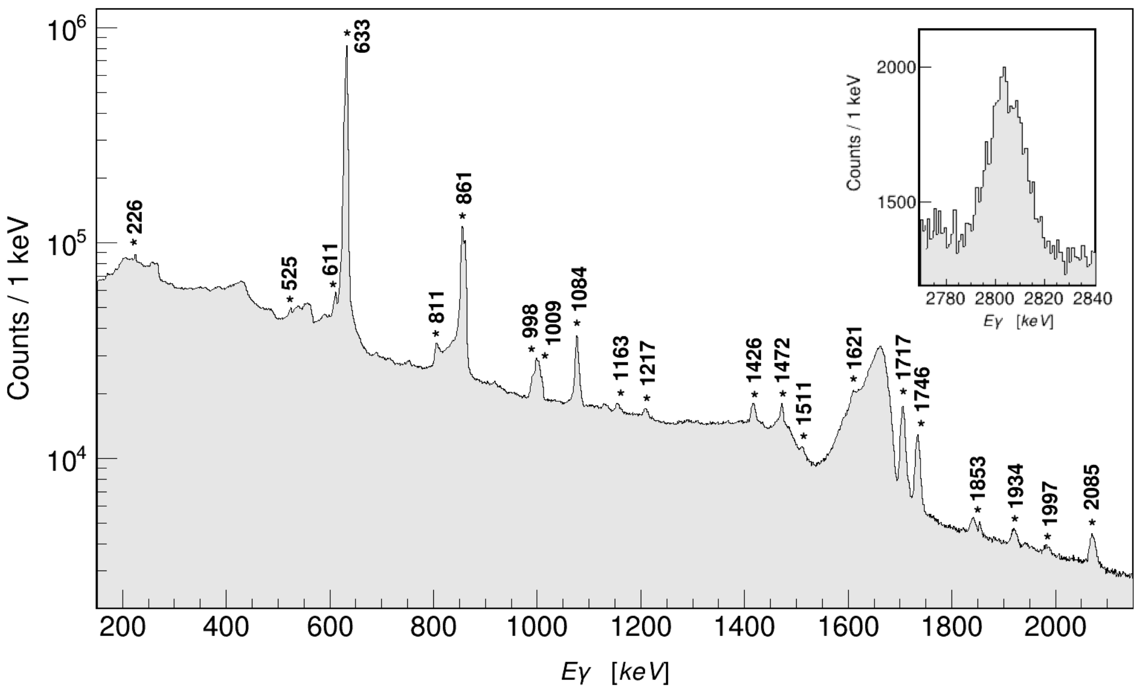
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021)

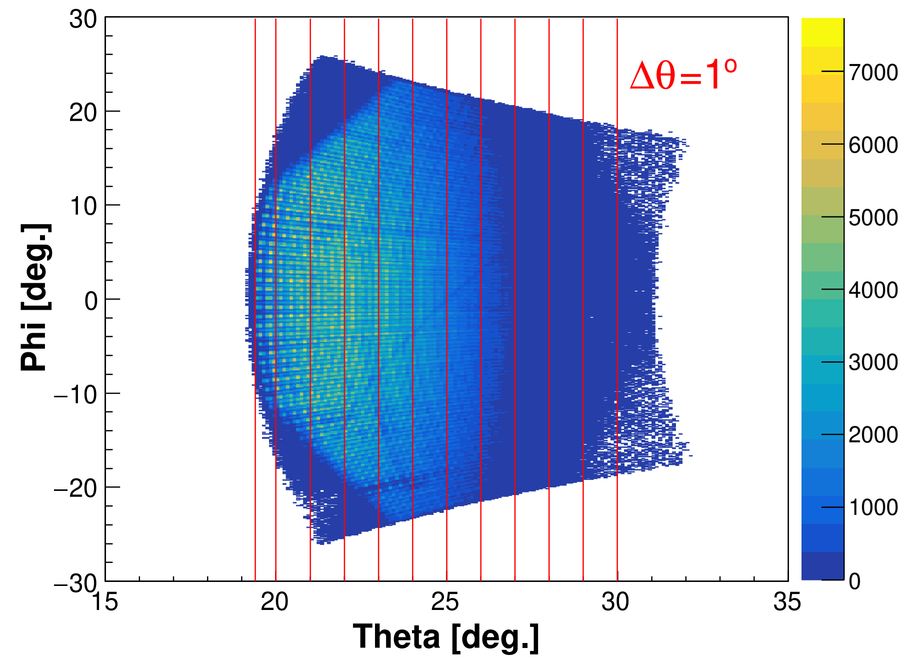


- VAMOS at grazing angle (25°); lowest observed scattering angle (19.4°) corresponding to 107% of Cline's safe energy

Experiment

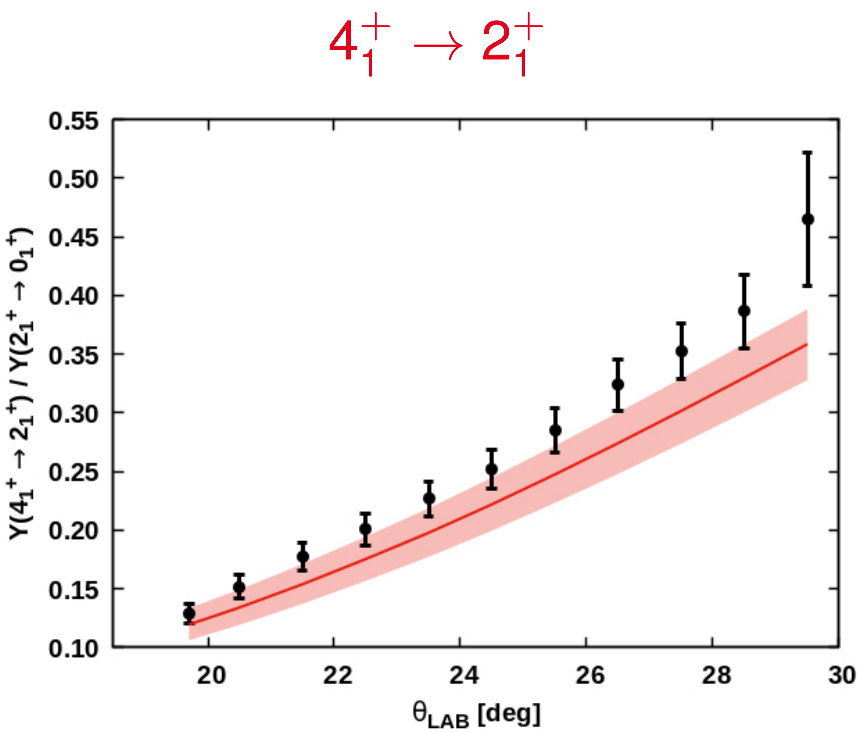
- population of 21 excited states observed (up to spin 6^+)

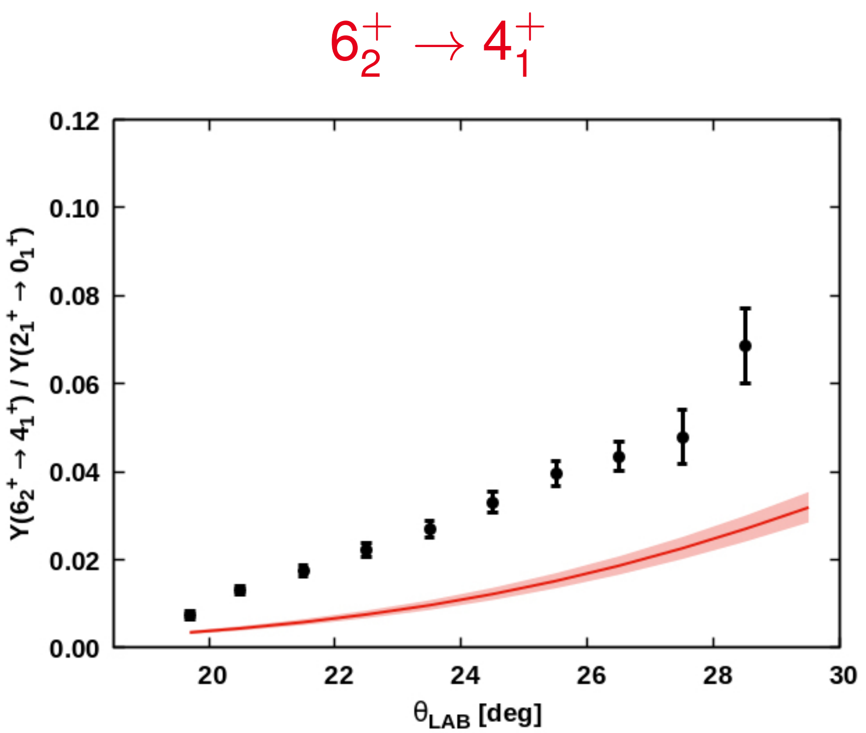




- ^{106}Cd ions identified in VAMOS with $19.4^{o} \leq \theta_{\text{LAB}} \leq 30^{o}$ (Cline's criterion fulfilled for $\theta_{\text{LAB}} \leq 18^{o}$)
- we apply gates on θ_{LAB} with 1^{o} width to study the dependence of the excitation cross sections on scattering angle
- due to complicated acceptance 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)



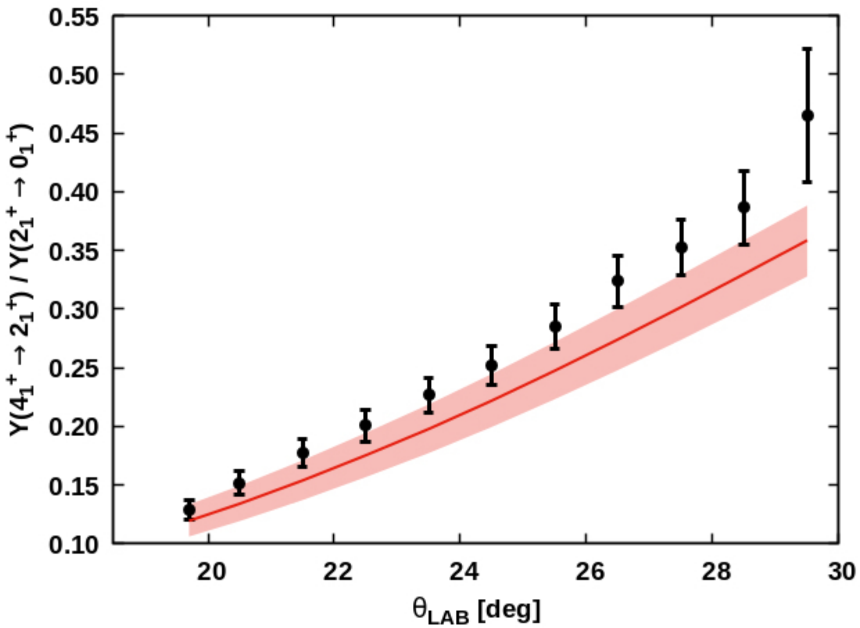


- reasonable agreement with literature data for 4_1^+ (weighted average of measured lifetimes)
- lifetime of the 6_2^+ state deduced from the same data as our transition intensities (M. Siciliano et al., Phys. Rev. C 104, 034320 (2021)) is not consistent with the measured intensity ratios

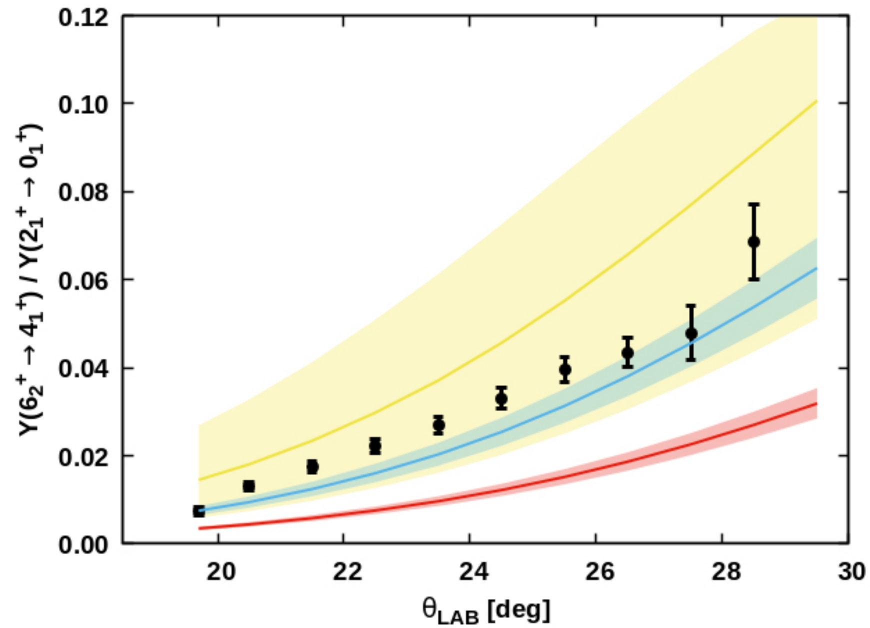
D. Kalaydjieva, PhD thesis, 2023

Sample results (strongly populated states)

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



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

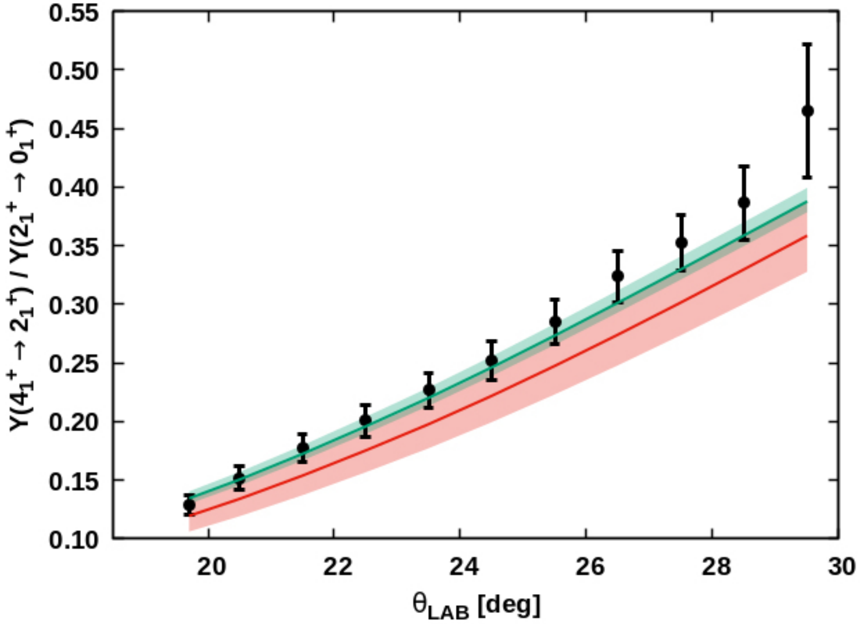


- much better agreement for the 6_2^+ state if we assume:
  - $\langle 6_2^+ \| E2 \| 4_1^+ \rangle$ matrix element from Coulomb excitation (D. Rhodes et al., Phys. Rev. C 103, L051301 (2021))
  - or 6_2^+ lifetime from (n,n'γ) (A. Linnemann, PhD thesis, University of Cologne, 2005 – but here the uncertainty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

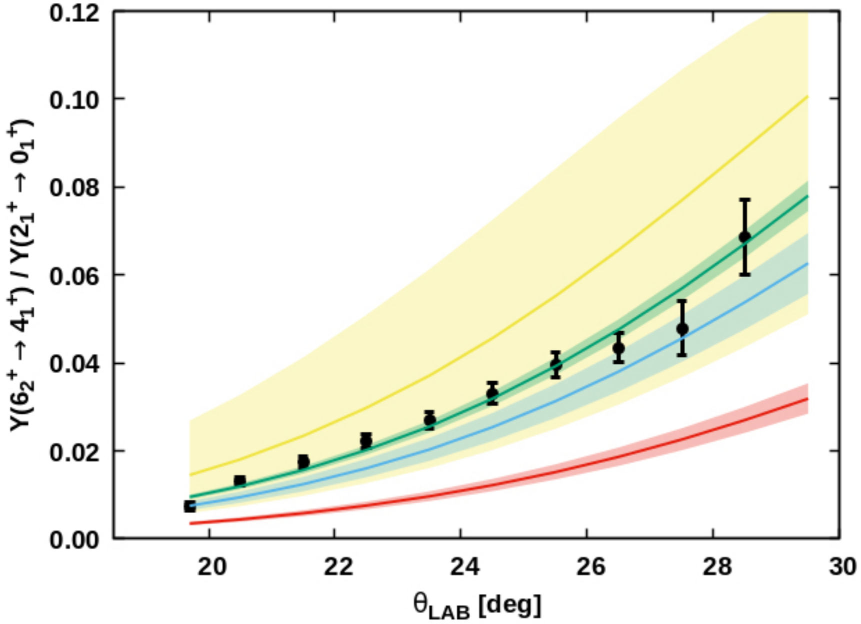
D. Kalaydjieva, PhD thesis, 2023

Sample results (strongly populated states)

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



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



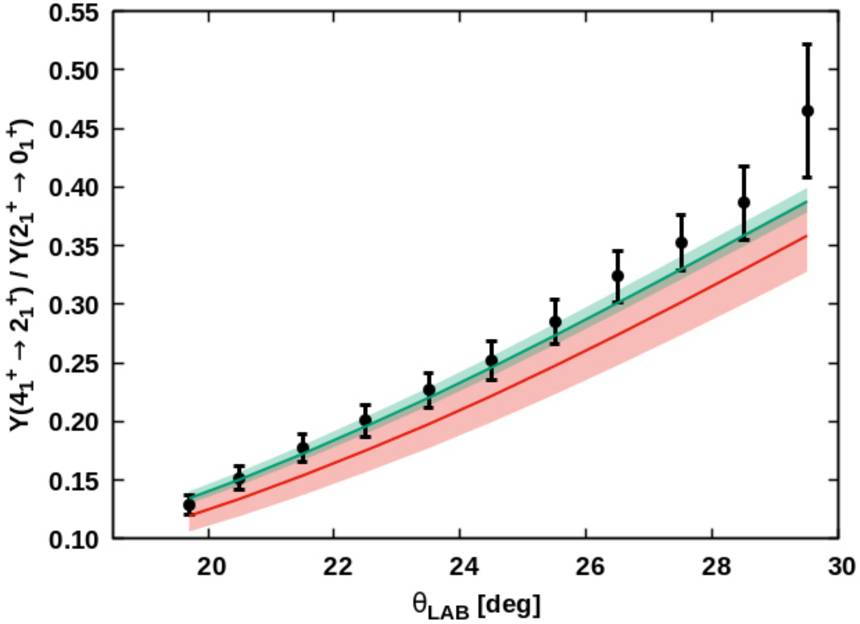
- finally, we can try to fit a set of matrix elements to the first few points of the cross-section distribution, and compare the resulting lifetimes:

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

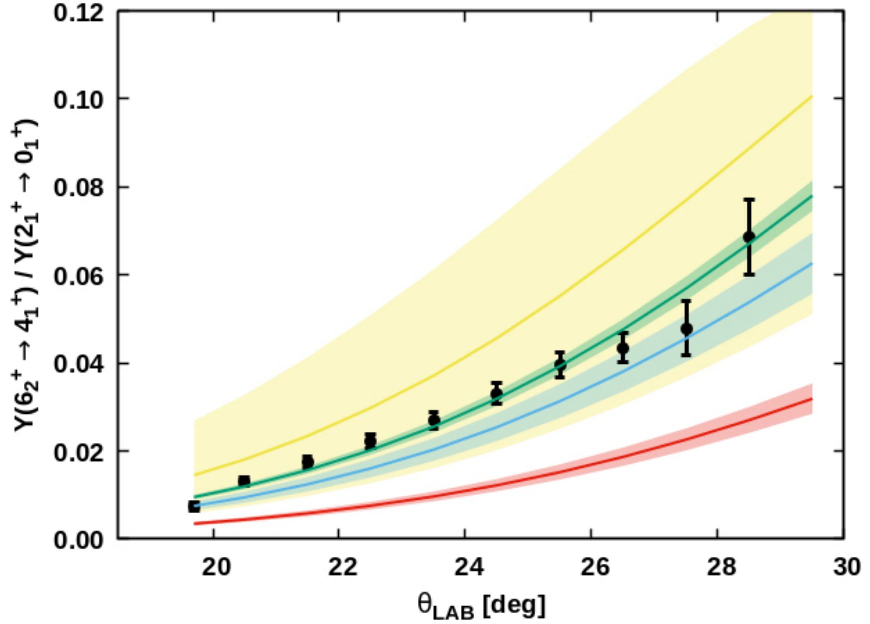
6_2^+ – GOSIA fit: 0.48(3) ps
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021): 1.22(15) ps
D. Rhodes et al., Phys. Rev. C 103, L051301 (2021): 0.54(8) ps

Sample results (strongly populated states)

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



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

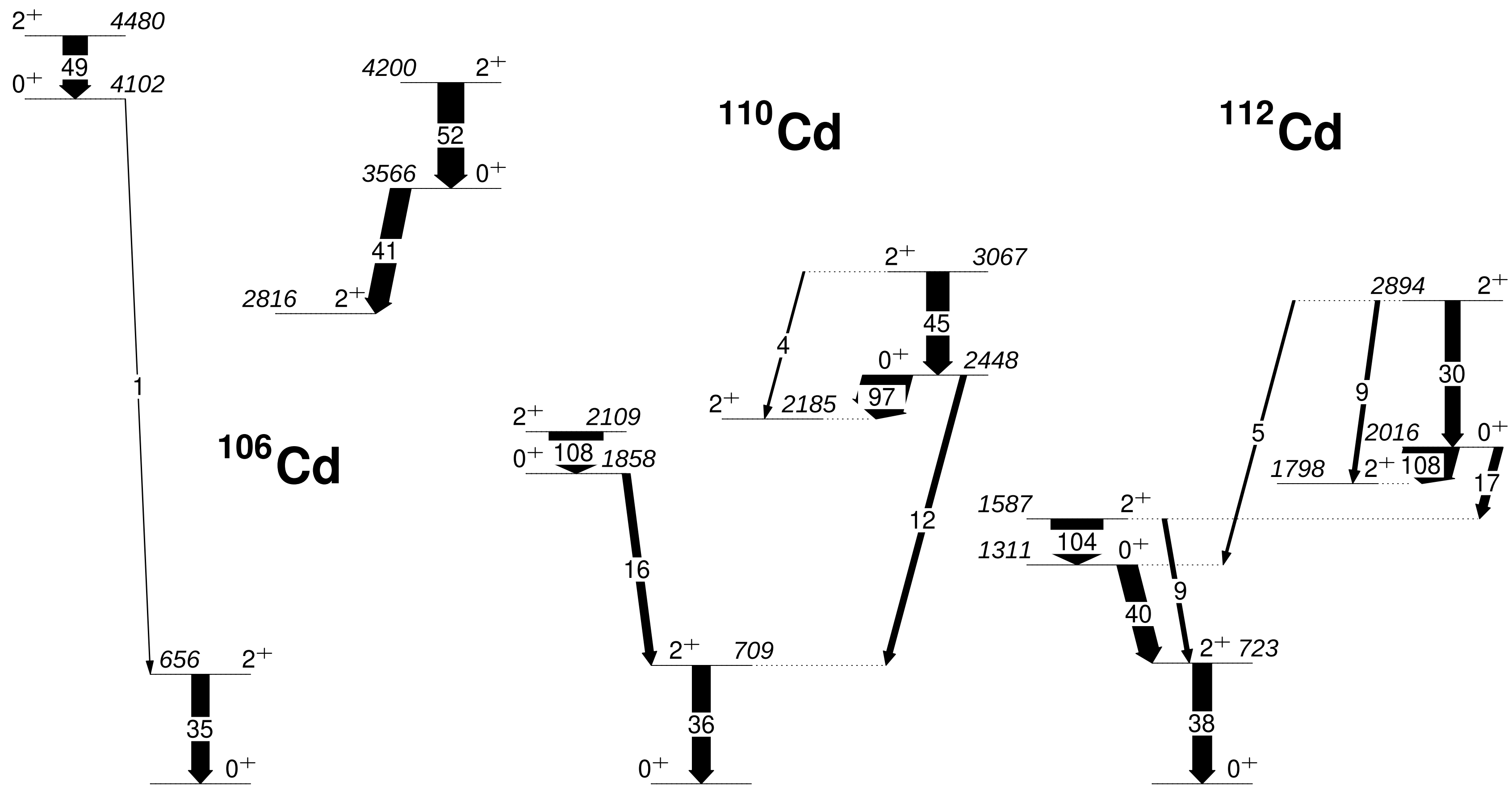


- similar analysis has been applied to all observed states, yielding B(E2) values complementary to those obtained from the RDDS analysis of the same date
- contrary to RDDS, it was possible to obtain B(E2) values for the decay of states that have lifetimes shorter than 1 ps

D. Kalaydjieva, PhD thesis, 2023

Shape coexistence in Cd isotopes: BMF predictions

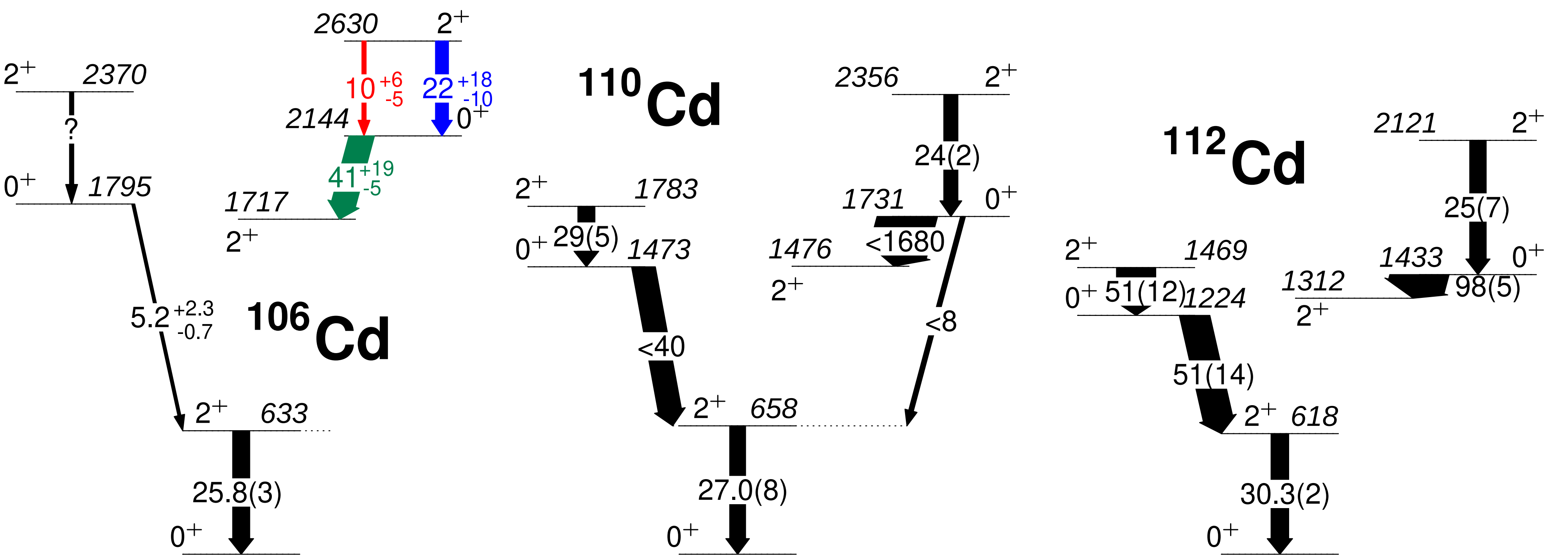
- similar shape-coexisting structures as in ^{110,112}Cd are predicted in ^{106}Cd
- in-band transition strength in the oblate structure predicted to increase with decreasing N, while the $B(E2; 0_3^+ \rightarrow 2_2^+)$ value decreases



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)



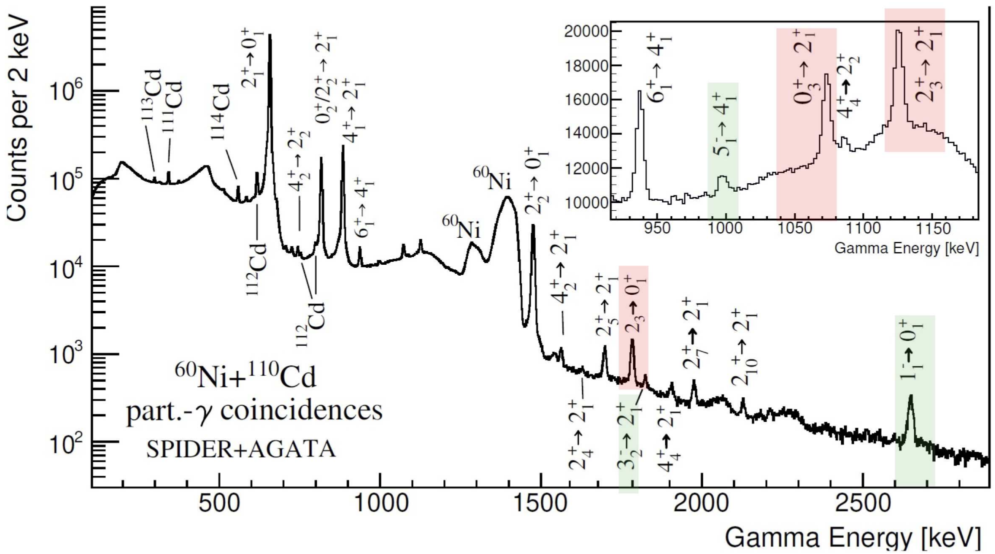
106Cd: D. Kalaydjieva, PhD thesis, 2023

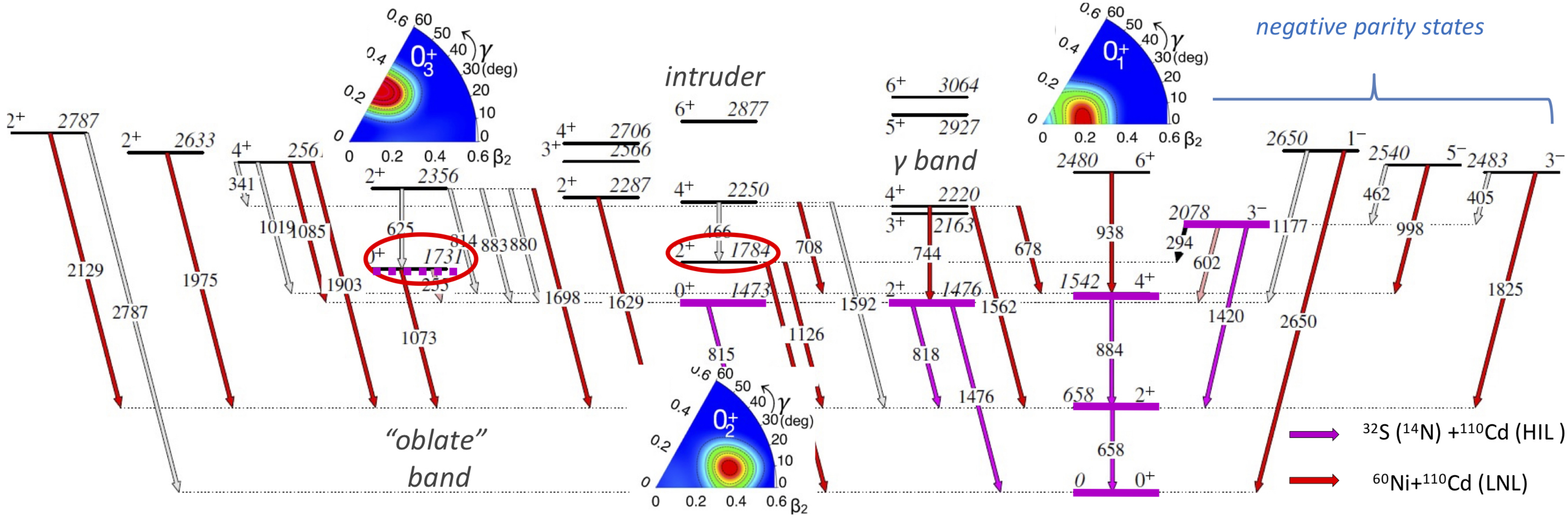
Present and future: AGATA at LNL

multiple shape coexistence in ^{110}Cd, ^{74}Se, ...

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))



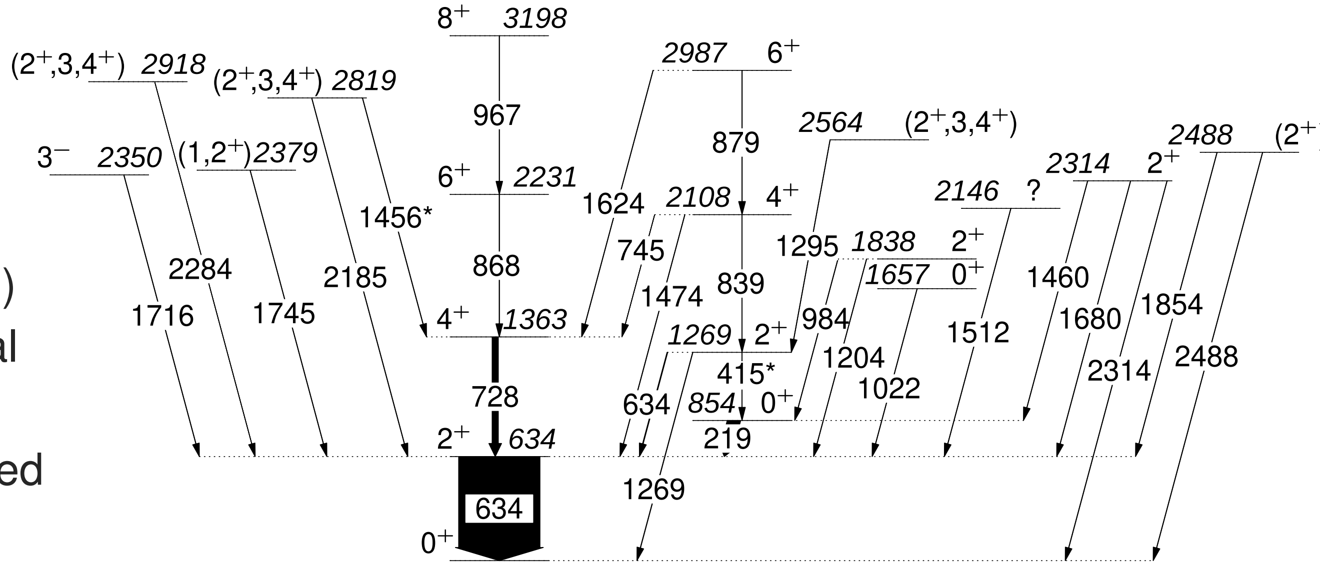


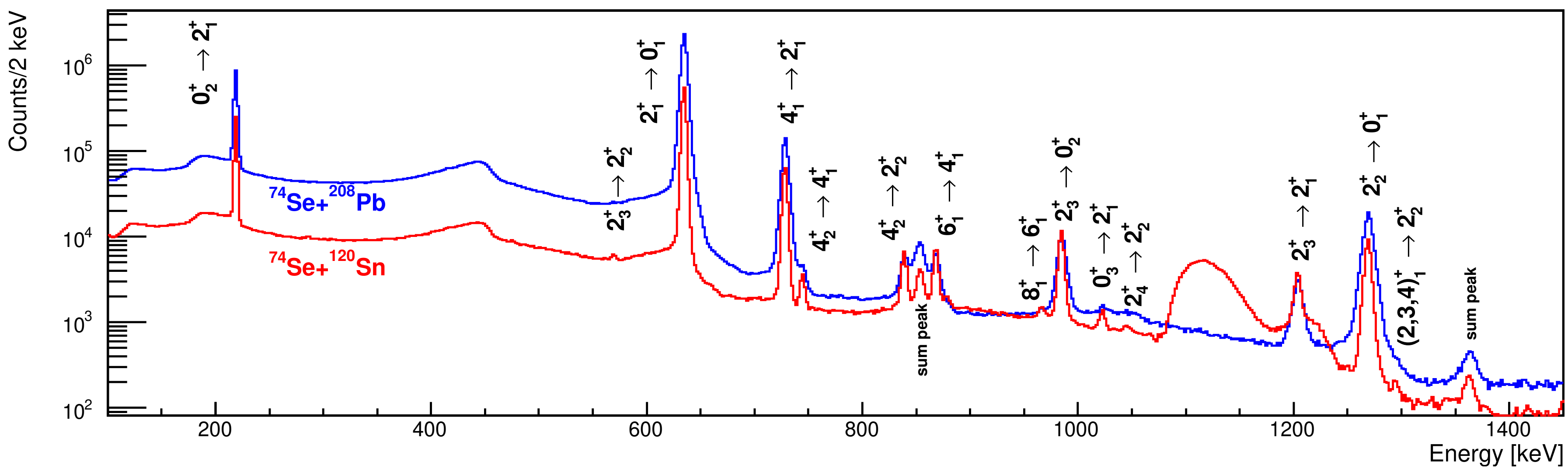
5 days of ^{58}Ni beam with AGATA in 2022, complementary measurements at HIL Warsaw

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

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

Summary

- 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 in ^{42}Ca
- $\langle\cos(3\delta)\rangle$ 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
- we obtained new experimental information on the presumably oblate 0_3^+ and 2_5^+ states in ^{106}Cd
- we populated structures built on the 0_1^+, 0_2^+ and 0_3^+ states in ^{110}Cd and ^{74}Se and on this basis will address the question of multiple shape coexistence in these nuclei