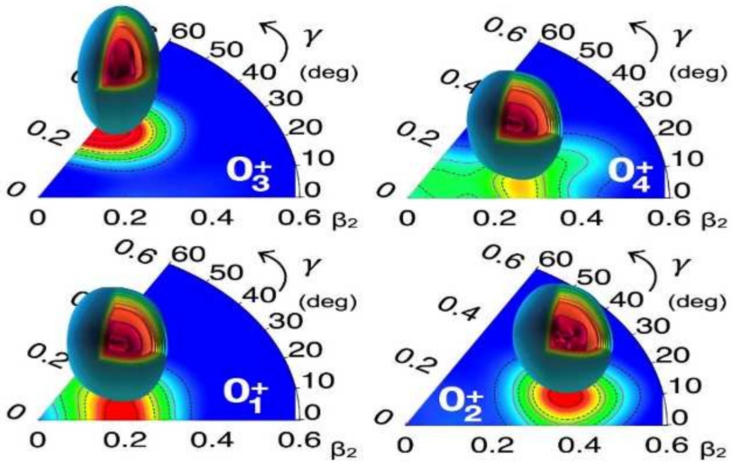
Nuclear deformation in excited states: Shape coexistence in A∼100 nuclei

project coordinators: K. Wrzosek-Lipska, M. Zielińska



Physics cases studied within the project

- Unsafe Coulomb excitation of ^{106}Cd with AGATA at GANIL
  - PhD thesis of D. Kalaydjieva under supervision of M. Zielińska and W. Korten (Université Paris-Saclay, October 2023)
  - Final publication to be submitted to Eur. Phys. J. A in the coming weeks

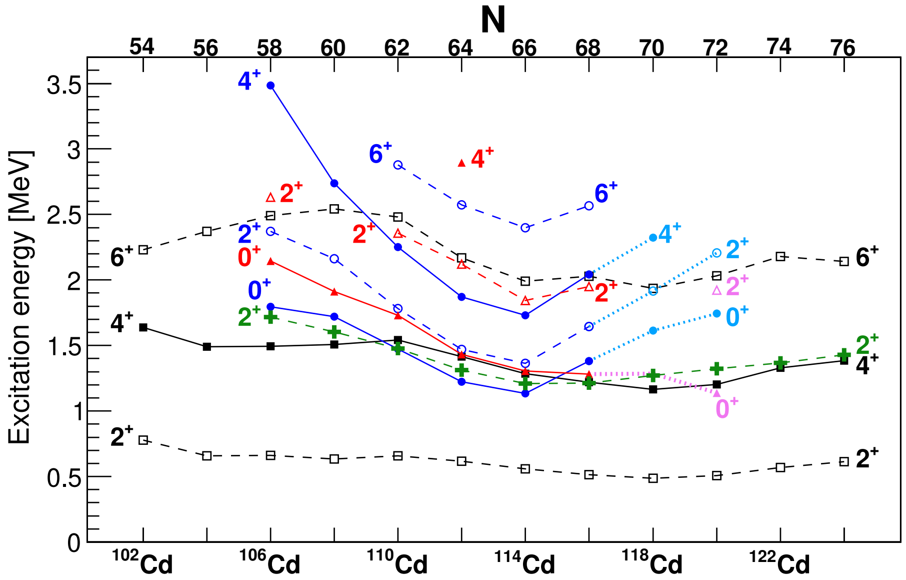
- "Standard" Coulomb excitation of ^{110}Cd at:
  - HIL (EAGLE, ^{32}S and ^{14}N beams)
    - MSc project of I. Piętka under supervision of K. Wrzosek-Lipska (University of Warsaw, September 2023)
    - Final publication to be submitted to Phys. Lett. B in the coming weeks
  - LNL (AGATA, ^{60}Ni beam)
    - PhD thesis of I. Piętka under supervision of K. Wrzosek-Lipska and L. Próchniak (University of Warsaw, ongoing)

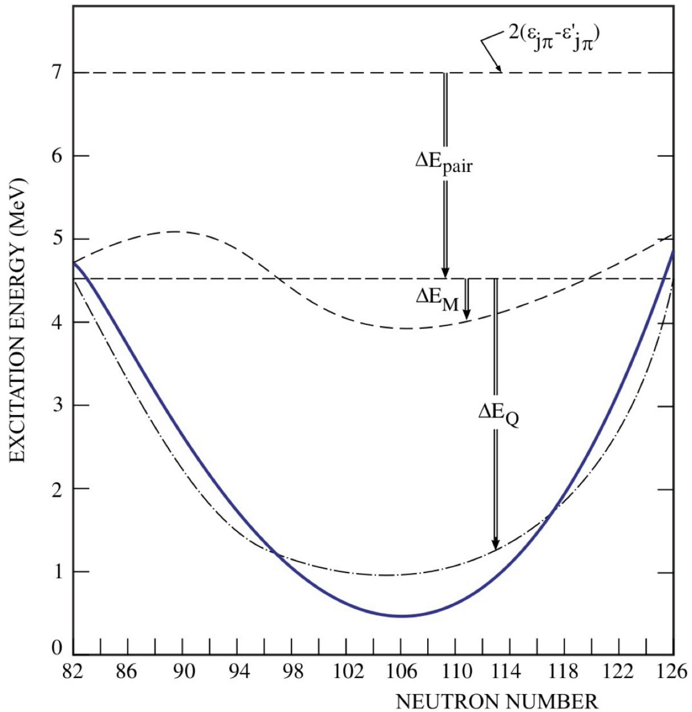
- "Standard" Coulomb excitation of ^{100}Ru at HIL (EAGLE, ^{32}S beam)
  - Internship of F.-e. Demyani (PHELMA Grenoble) under supervision of M. Zielińska (Université Paris-Saclay, summer 2024)

Shapes of Cd nuclei – context

- mid-neutron-shell Cd isotopes used to be considered textbook candidates for spherical vibrational motion based on their energy level schemes that can be arranged into multi-phonon multiplets
- when put into a context of broader systematics, parabolic pattern of level energies is revealed, characteristic for multiparticle-multihole excitations through a shell gap

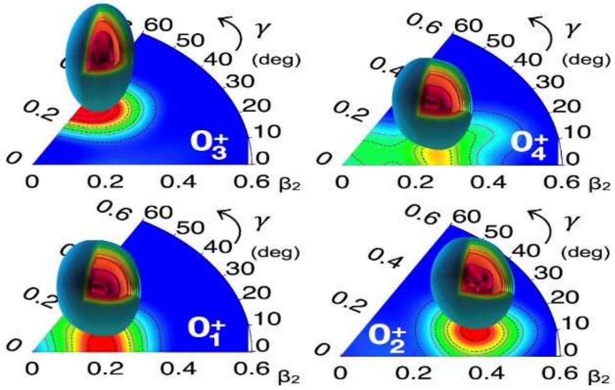
data compilation: P. Garrett, MZ, E. Clément, Prog. Part. Nucl. Phys. 124, 103931 (2022)





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

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)

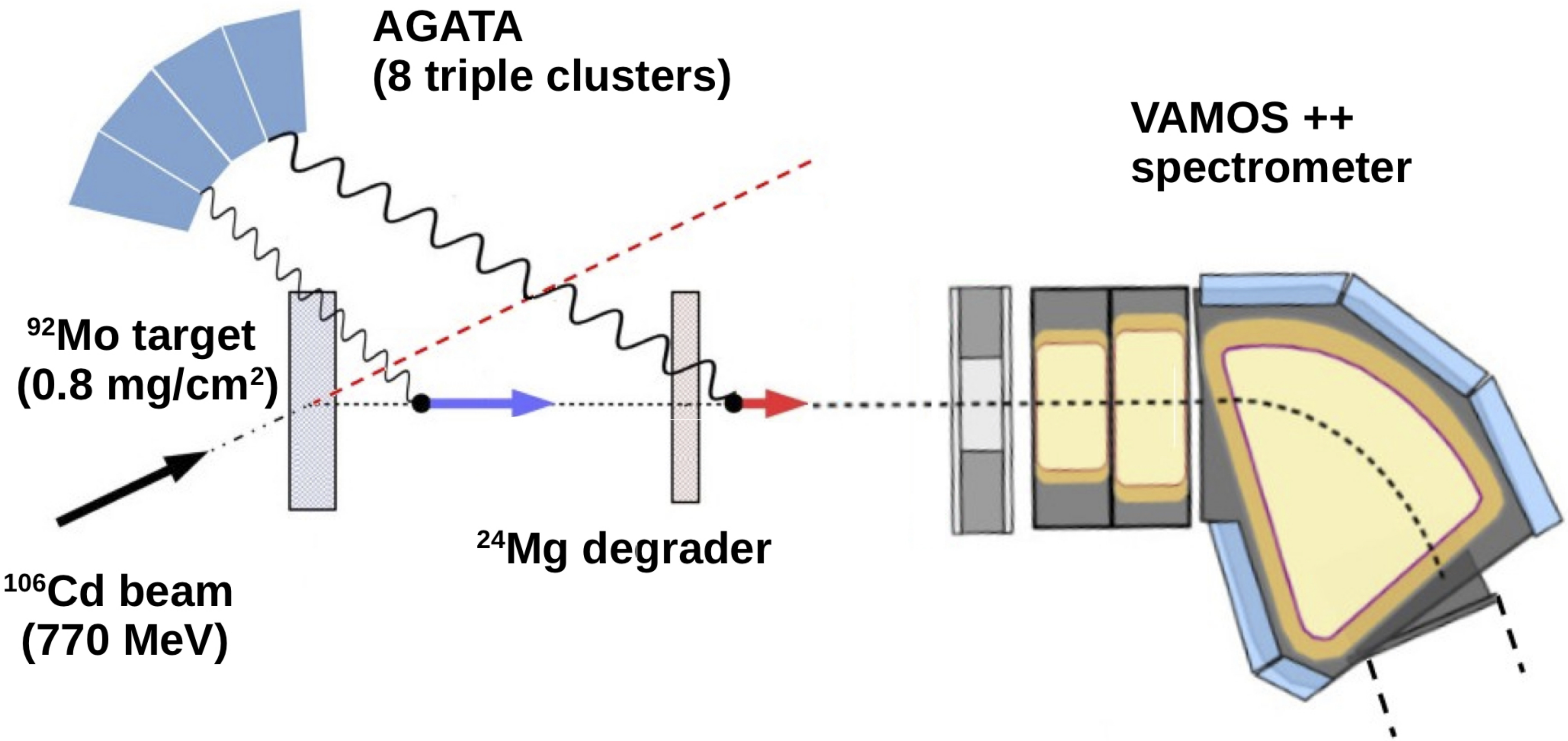
- triggered a multitude of new measurements:
  - high-precision beta decay into ^{110}Cd (GRIFFIN, TRIUMF – 2022)
  - Coulomb excitation of ^{110}Cd (AGATA, LNL; GRETINA, ANL – 2022)

- 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)

Unsafe Coulomb excitation of ^{106}Cd at GANIL

- 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

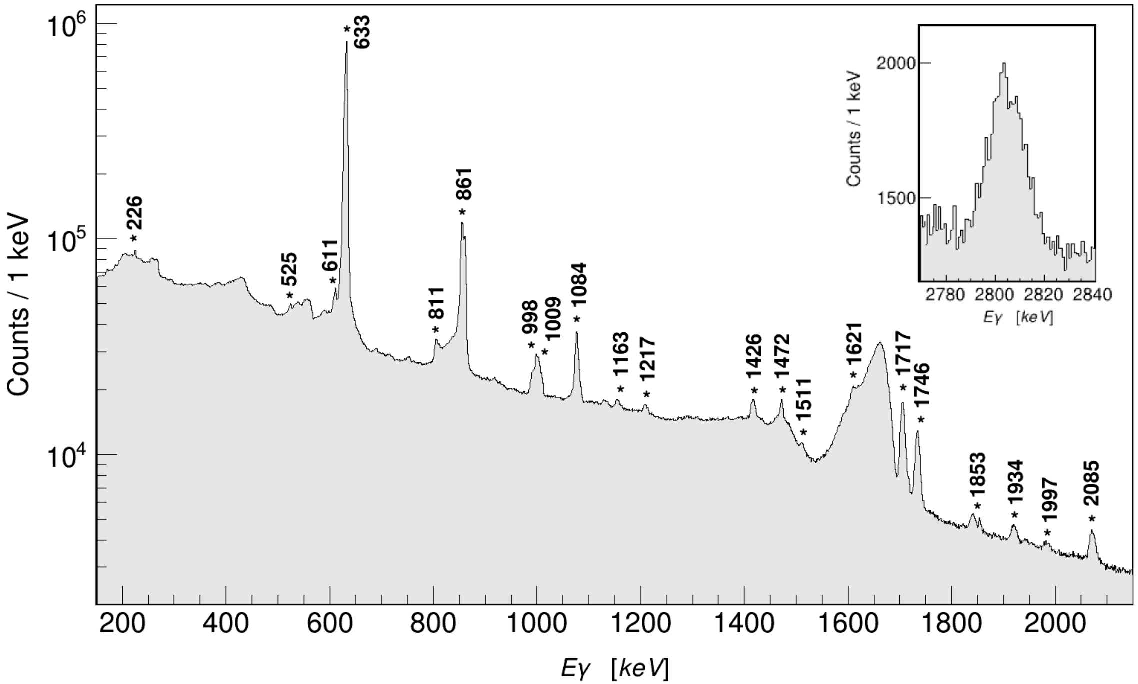
M. Siciliano et al., Phys. Lett. B 806, 135474 (2020)
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021)

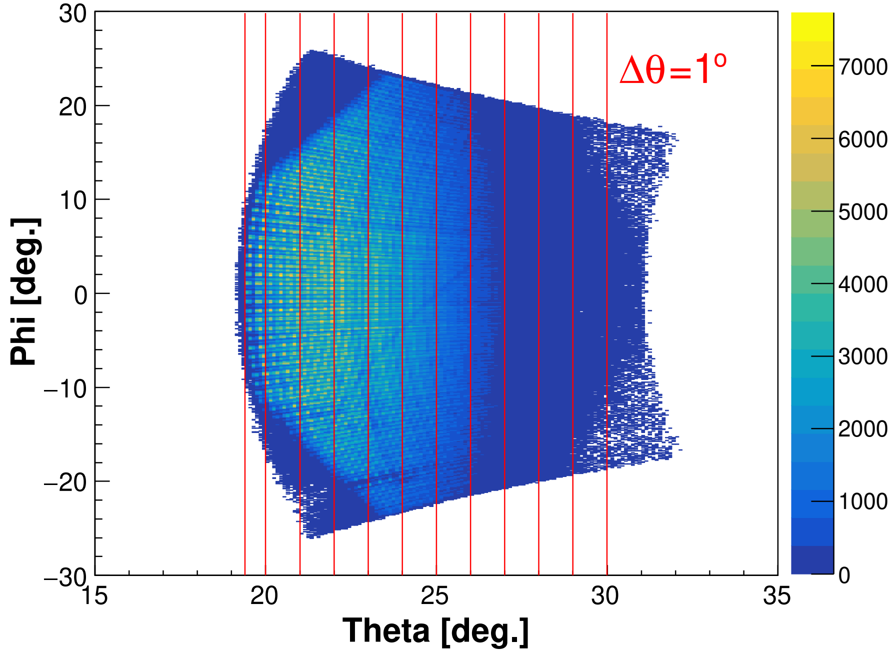


- VAMOS at grazing angle (25°); lowest observed scattering angle (19.4°) corresponding to 107% of Cline's safe energy

Unsafe Coulomb excitation of ^{106}Cd at GANIL

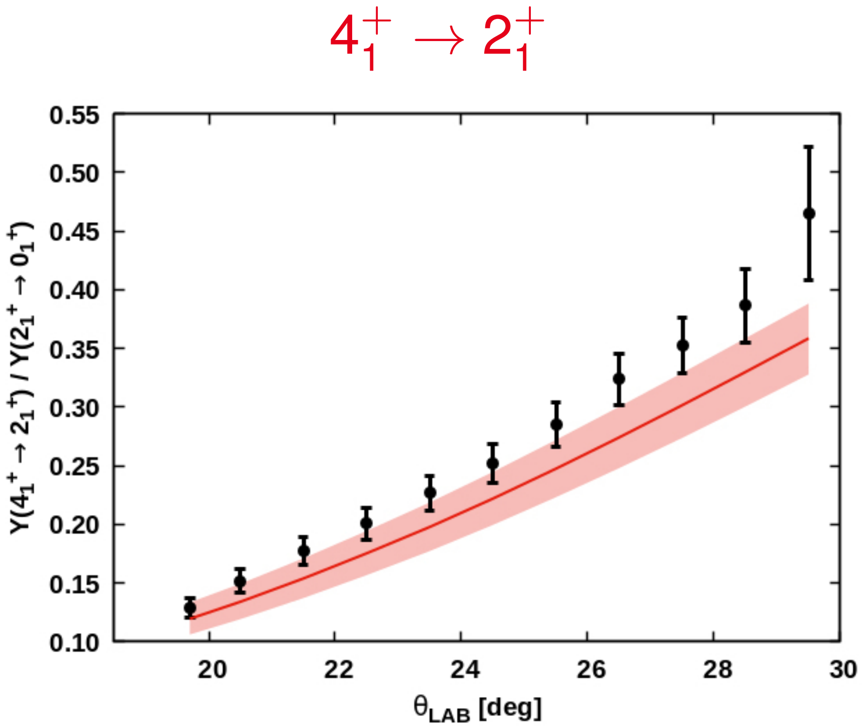
- population of 21 excited states observed (up to spin 6^+)

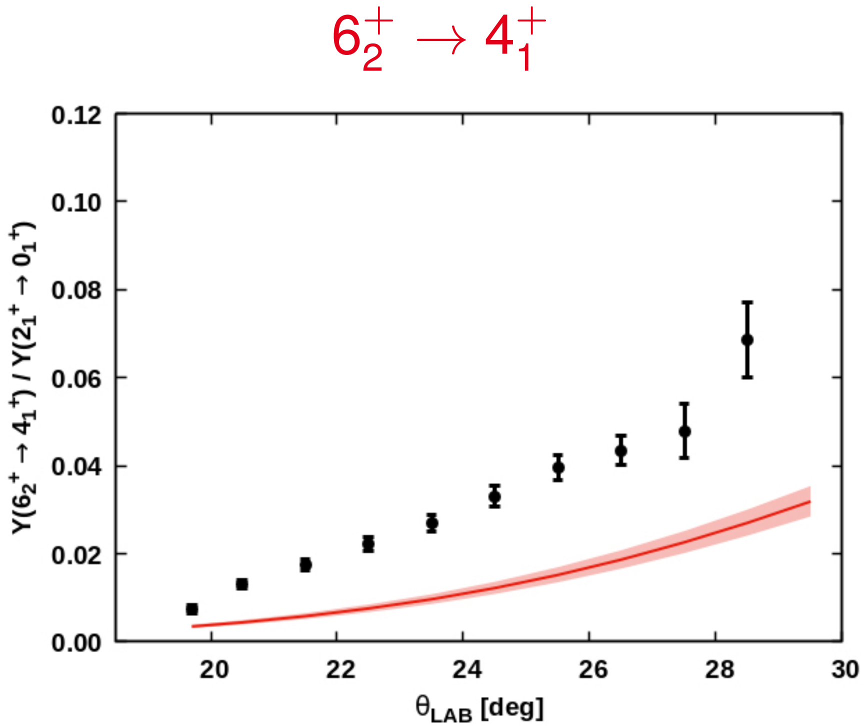




- ^{106}Cd ions identified in VAMOS with 19.4° $\leq \theta_{\mathrm{LAB}} \leq$ 30° (Cline's criterion fulfilled for $\theta_{\mathrm{LAB}} \leq$ 18°)
- we apply gates on θ_{LAB} with 1° width to study the dependence of the excitation cross sections on scattering angle
- due to complicated acceptance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



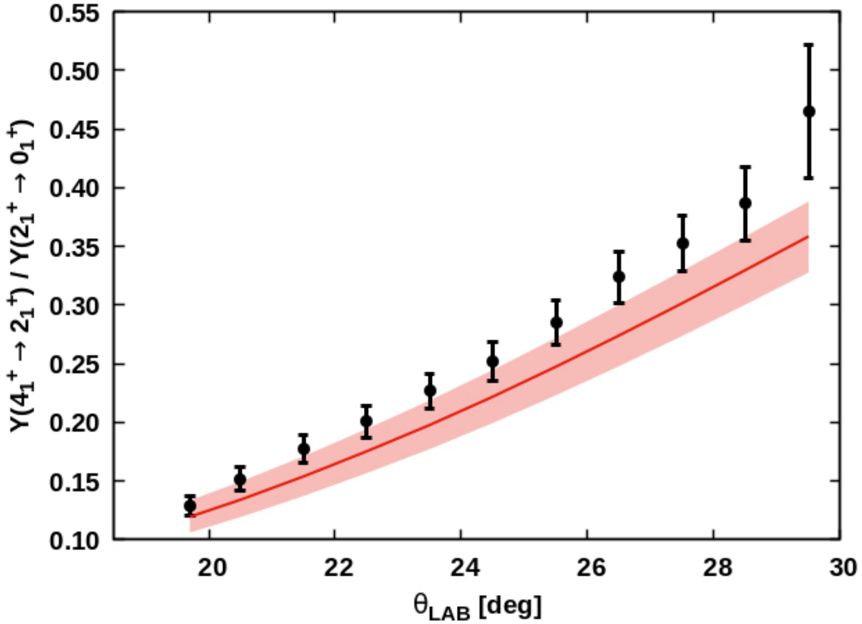


- reasonable agreement with literature data for 4_1^+ (weighted average of measured lifetimes)
- lifetime of the 6_2^+ state deduced from the same data as our transition intensities (M. Siciliano et al., Phys. Rev. C 104, 034320 (2021)) is not consistent with the measured intensity ratios

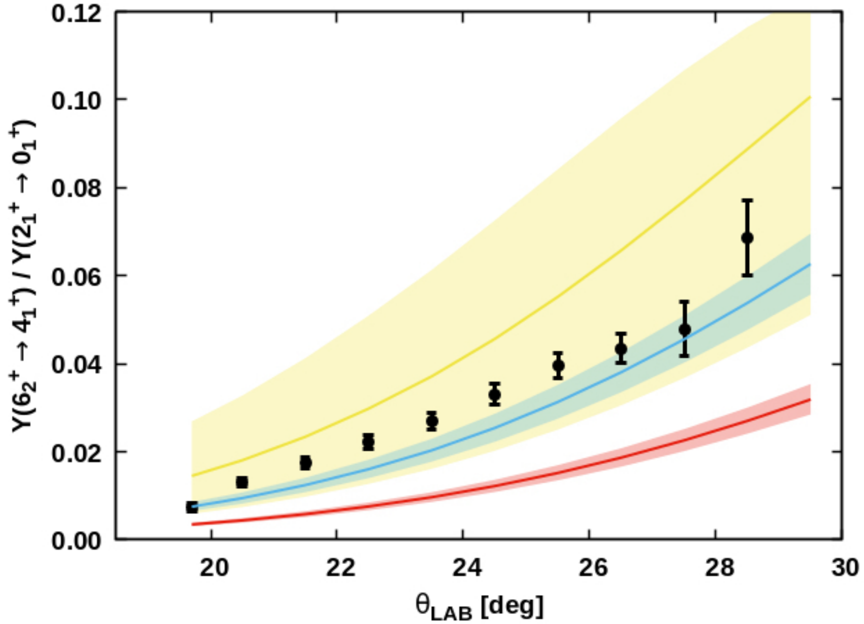
D. Kalaydjieva, PhD thesis, 2023

Sample results (strongly populated states)

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



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

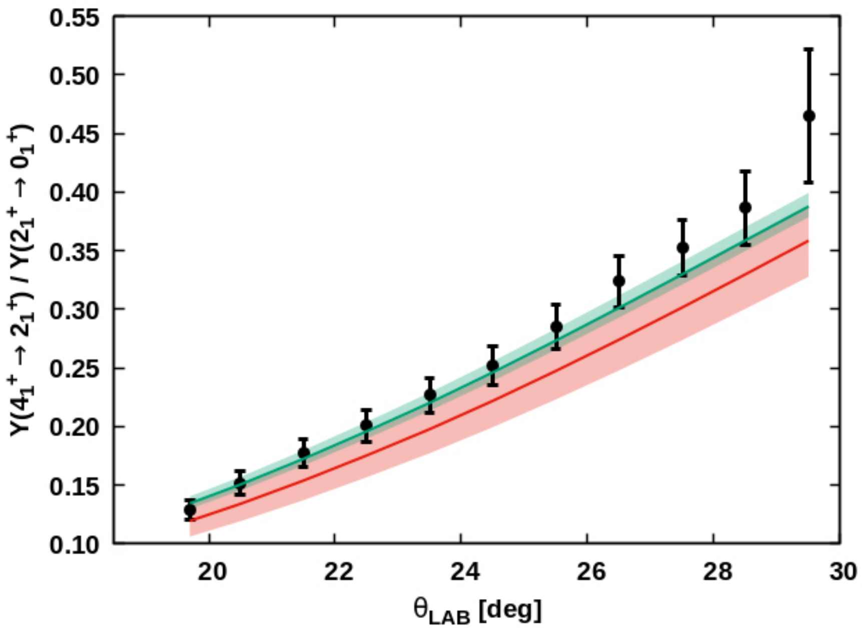


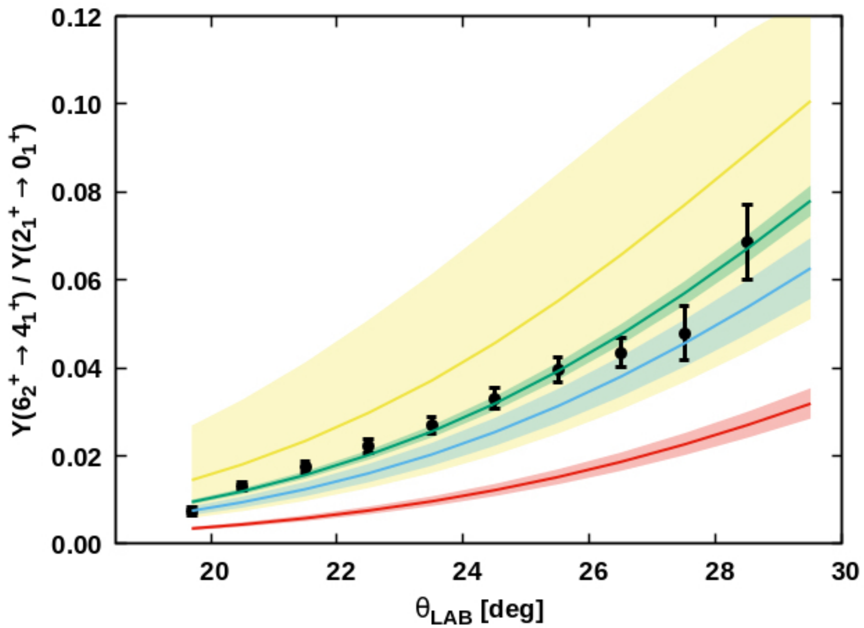
- much better agreement for the 6_2^+ state if we assume:
  - $\langle 6_2^+ \| E2 \| 4_1^+ \rangle$ matrix element from Coulomb excitation (D. Rhodes et al., Phys. Rev. C 103, L051301 (2021))
  - or 6_2^+ lifetime from (n,n'γ) (A. Linnemann, PhD thesis, University of Cologne, 2005 – but here the uncertainty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

D. Kalaydjieva, PhD thesis, 2023

Sample results (strongly populated states)

$4^+_1 \rightarrow 2^+_1$ $6^+_2 \rightarrow 4^+_1$





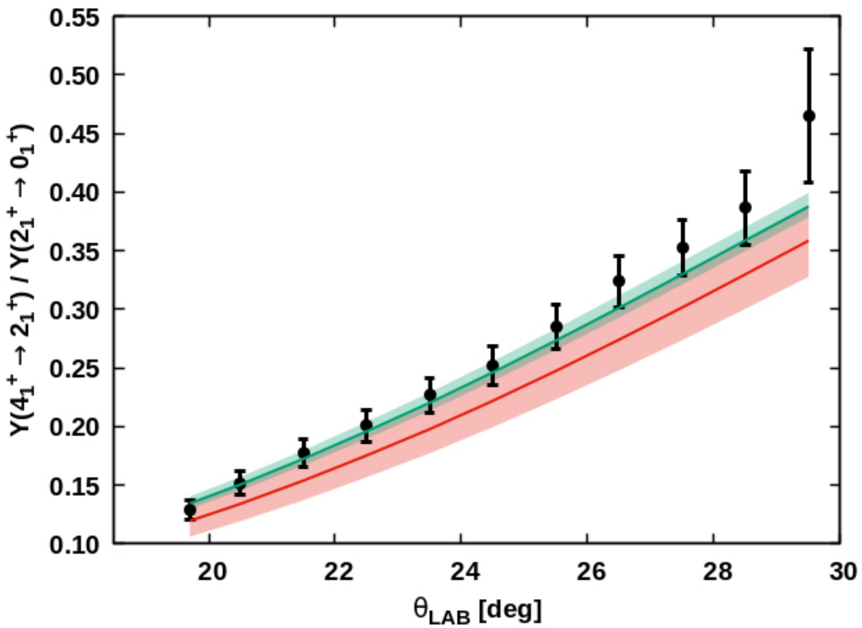
- finally, we can try to fit a set of matrix elements to the first few points of the cross-section distribution, and compare the resulting lifetimes:

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

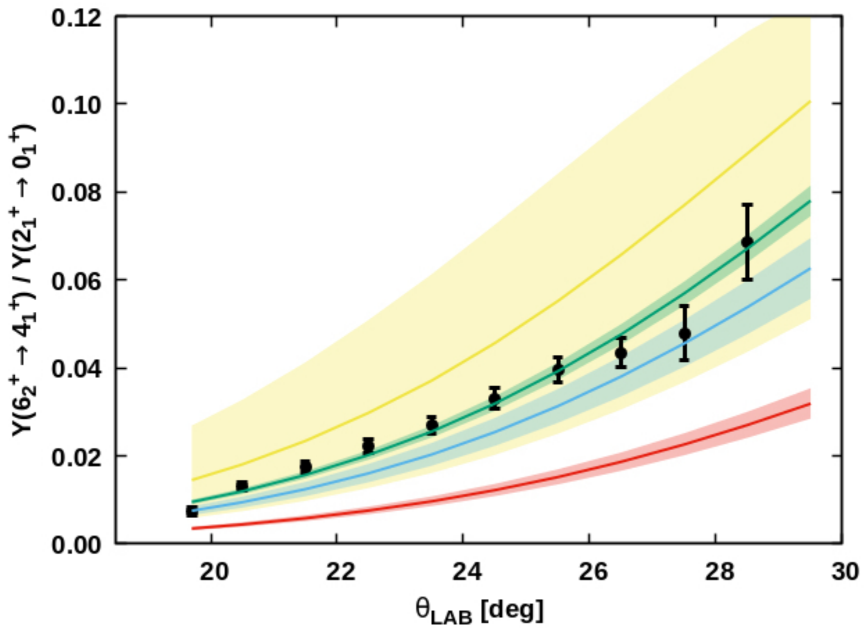
6^+_2 – GOSIA fit: 0.48(3) ps
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021): 1.22(15) ps
D. Rhodes et al., Phys. Rev. C 103, L051301 (2021): 0.54(8) ps

Sample results (strongly populated states)

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



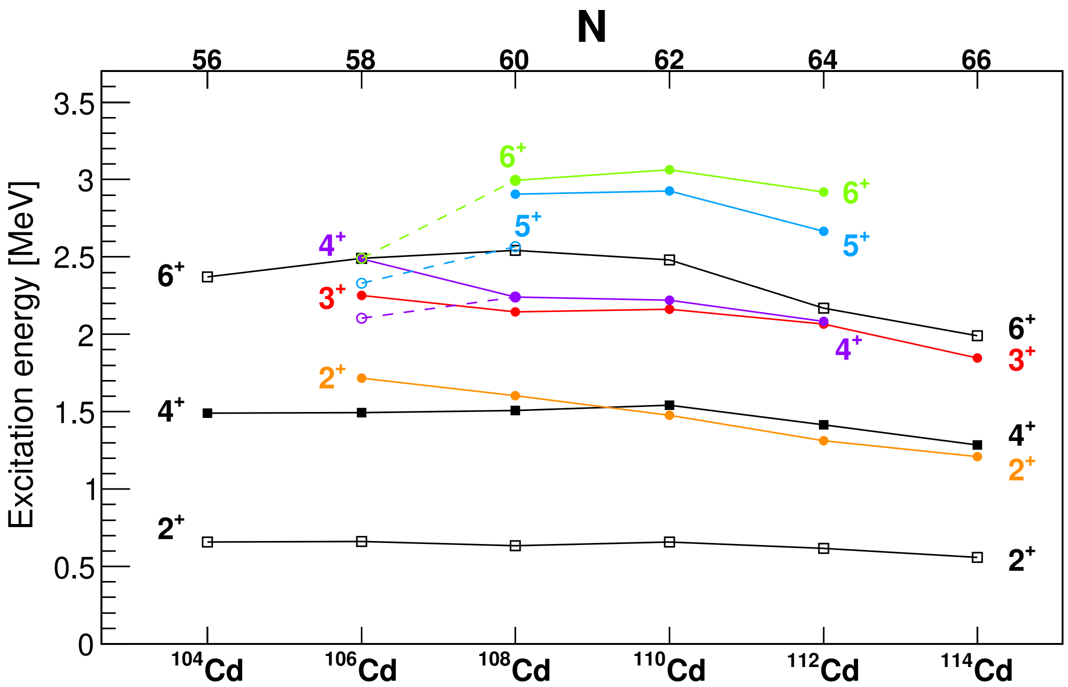
$6_2^+ \rightarrow 4_1^+$

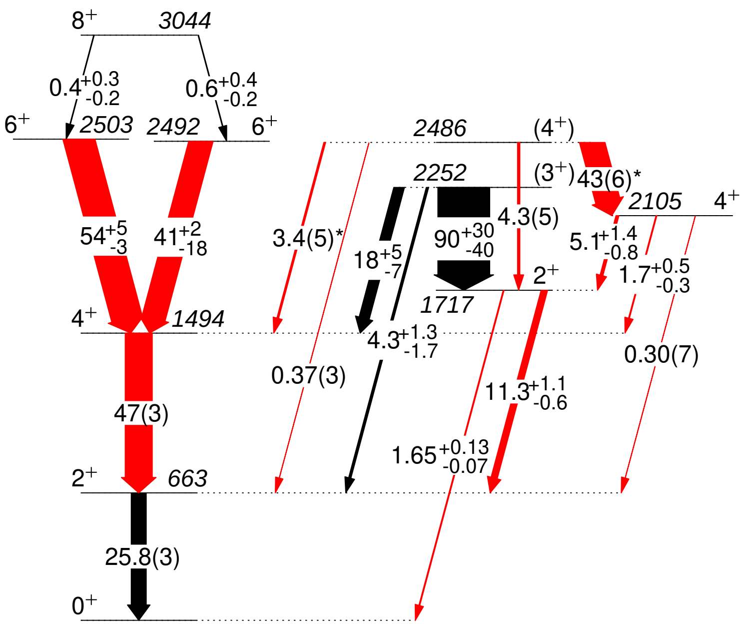


- similar analysis has been applied to all observed states, yielding B(E2) values complementary to those obtained from the RDDS analysis of the same date
- contrary to RDDS, it was possible to obtain B(E2) values for the decay of states that have lifetimes shorter than 1 ps

D. Kalaydjieva, PhD thesis, 2023

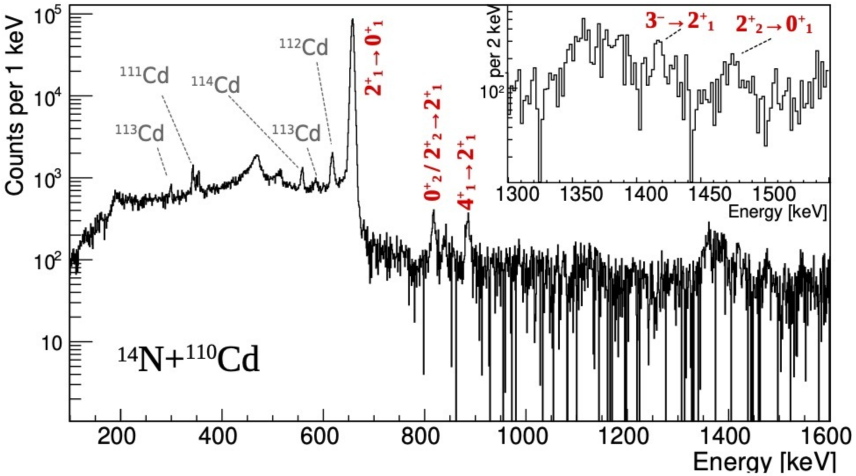
Proposed reorganisation of the ^{106}Cd level scheme

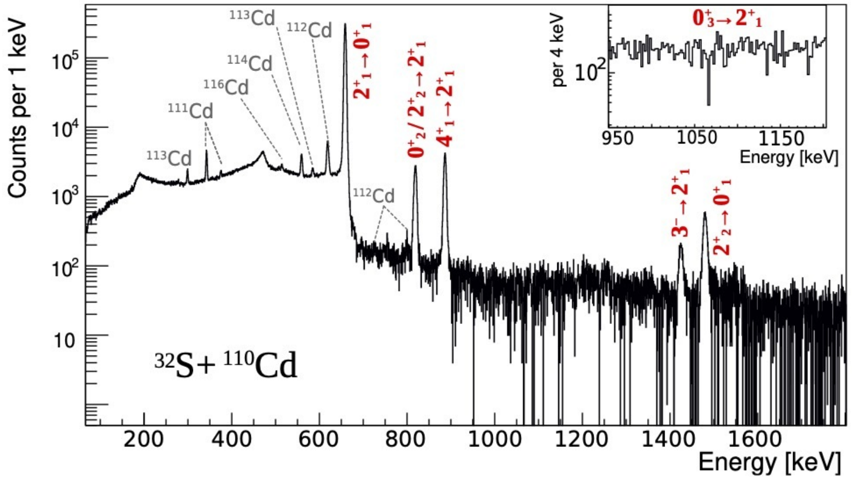


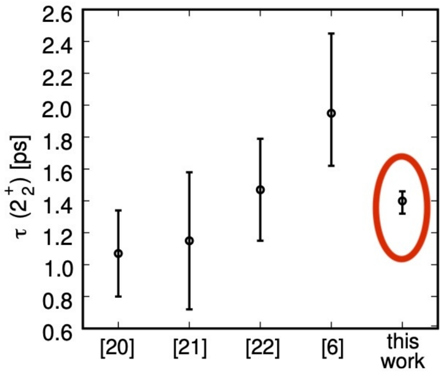


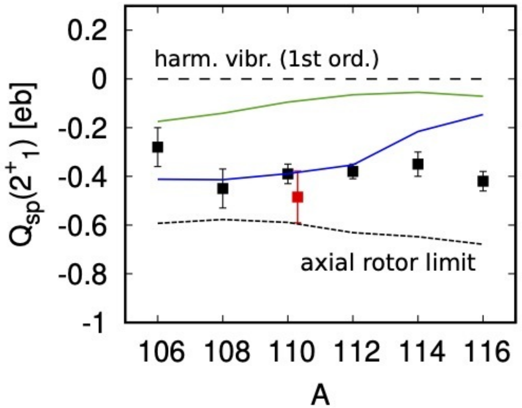
- new K=2 3^+ and 4^+ and K=4 4^+ band members proposed that have expected decay patterns and excitation energies consistent with the systematics
- closely spaced 6^+ states suggested to result from a strong mixing of the rotational band member with a seniority state
- non-observation of the 2252-keV 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

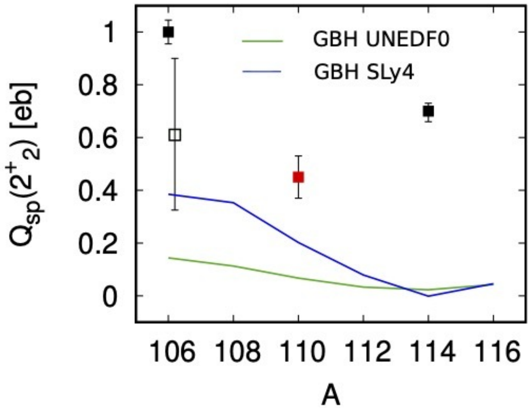
Coulomb excitation of ^{110}Cd at HIL Warsaw: EAGLE + 48 PIN diodes





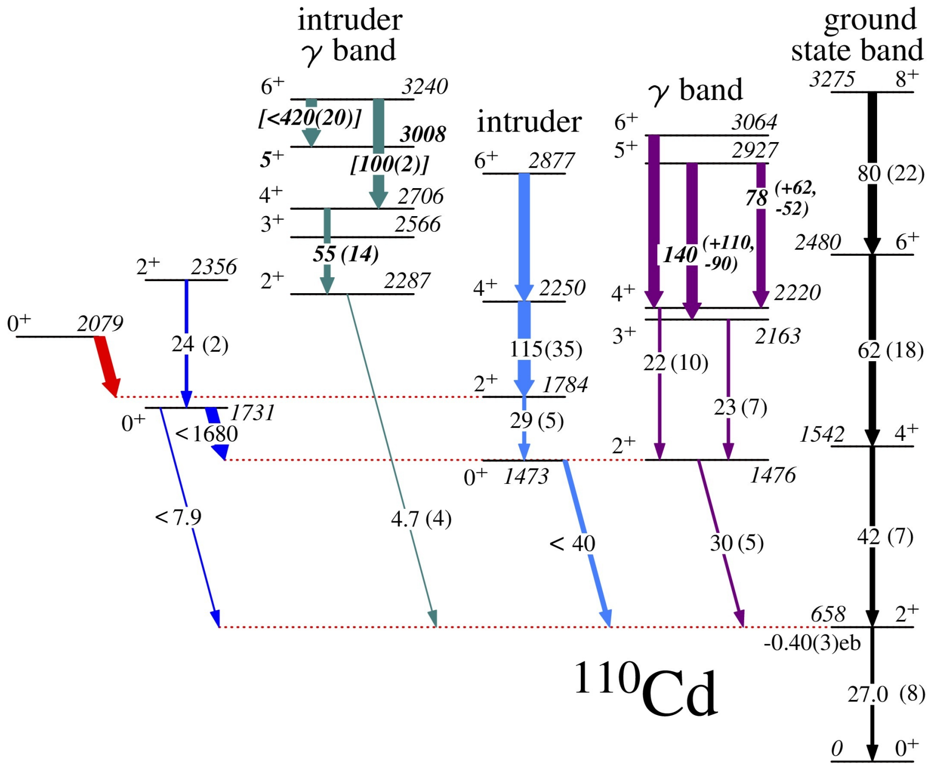


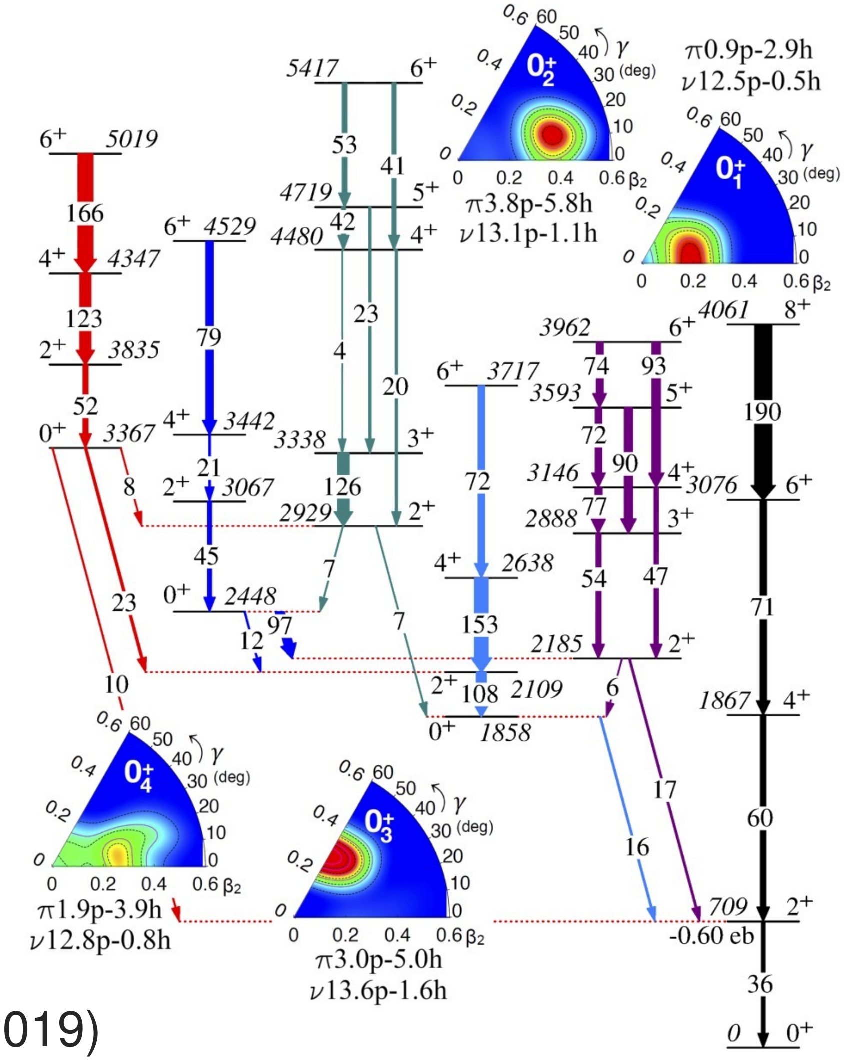




- precise 2_2^+ lifetime (I. Piętka et al, to be submitted to Acta Phys. Pol. B)
- first determination of the 2_2^+ quadrupole moment – value inconsistent with a two-phonon structure (K. Wrzosek-Lipska et al, to be submitted to Phys. Lett. B)

Shape coexistence in Cd isotopes: BMF predictions



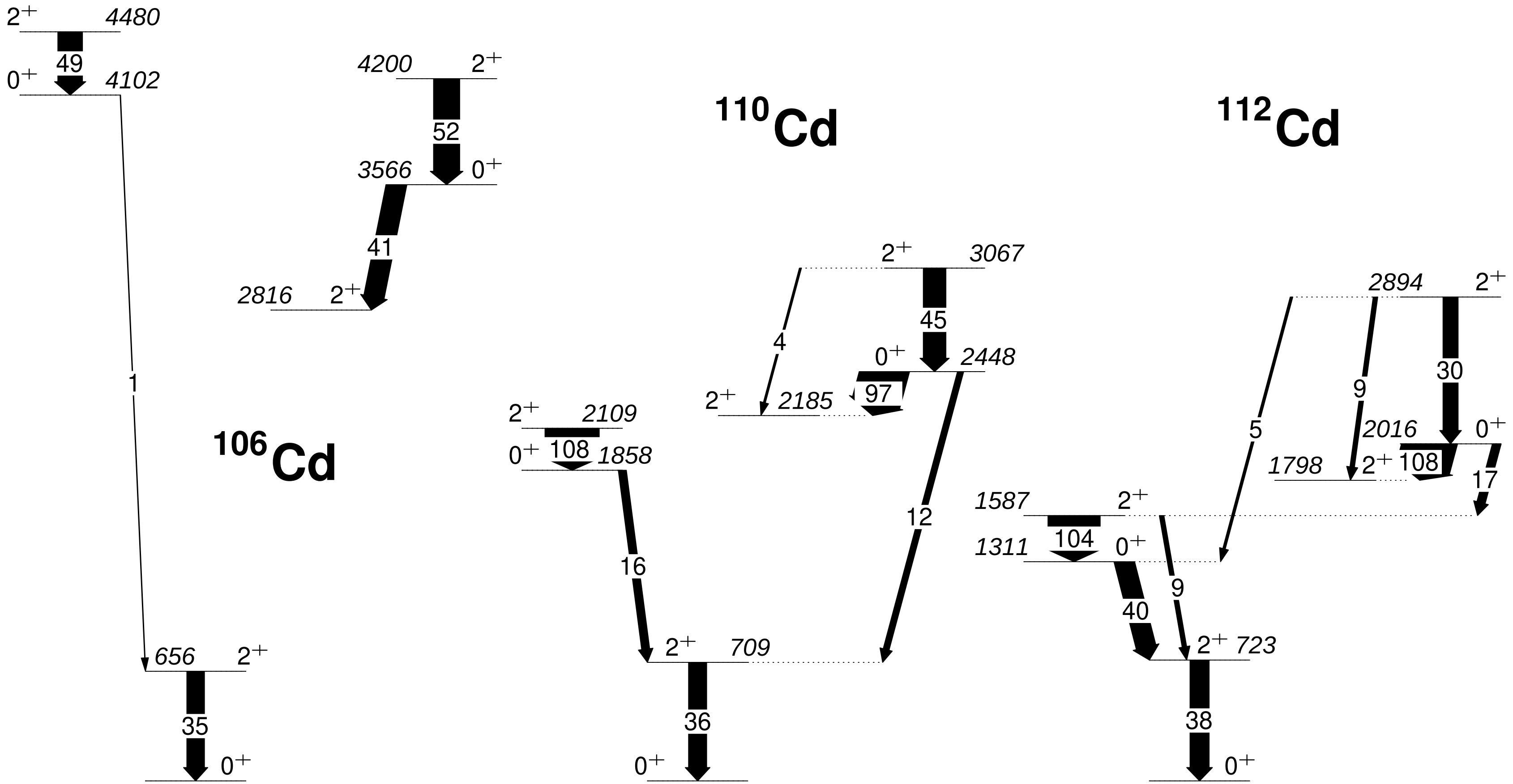


P.E. Garrett et al, Phys. Rev. Lett. 123, 142502 (2019)

calculations: T.R. Rodriguez, symmetry-conserving configuration-mixing method (SCCM) with Gogny D1S

Shape coexistence in Cd isotopes: BMF predictions

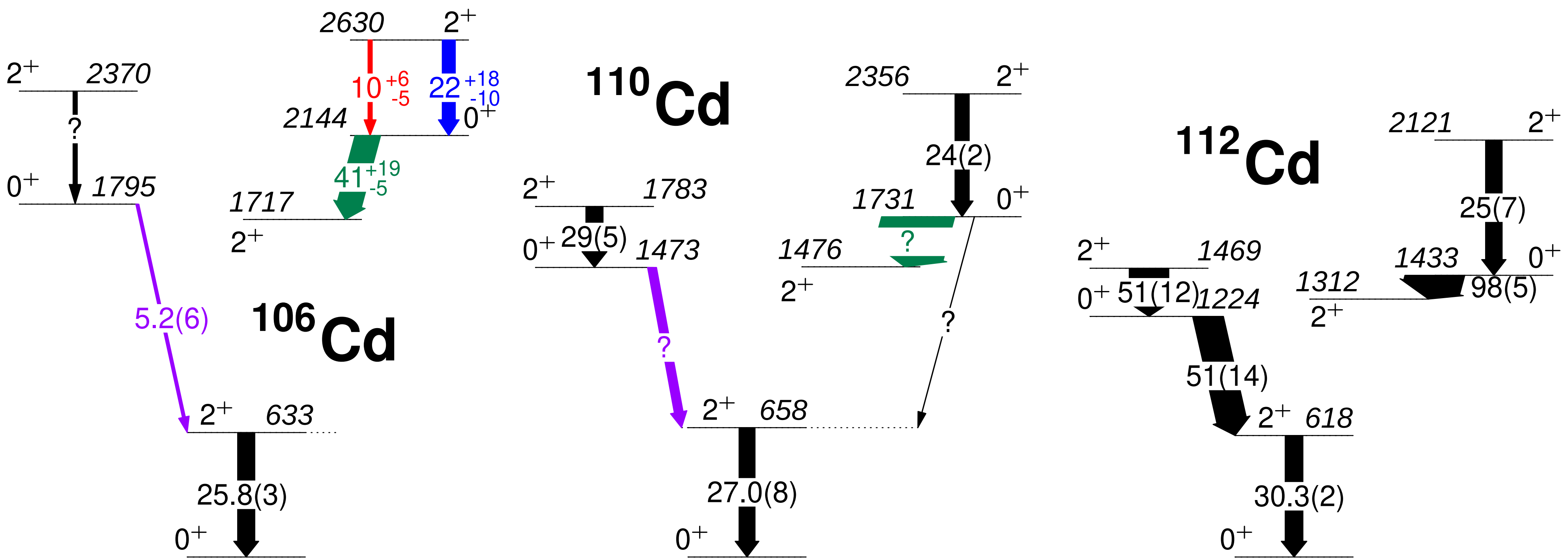
- similar shape-coexisting structures as in ^{110,112}Cd are predicted in ^{106}Cd
- in-band transition strength in the oblate structure predicted to increase with decreasing N, while the B(E2; $0_3^+ \rightarrow 2_2^+$) value decreases



SCCM calculations: T.R. Rodriguez

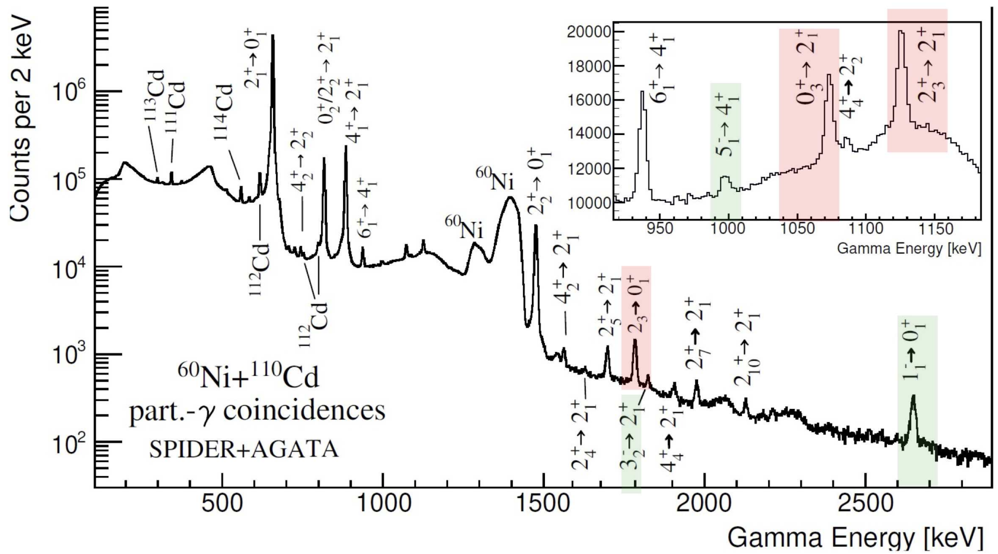
Coulomb-excitation results

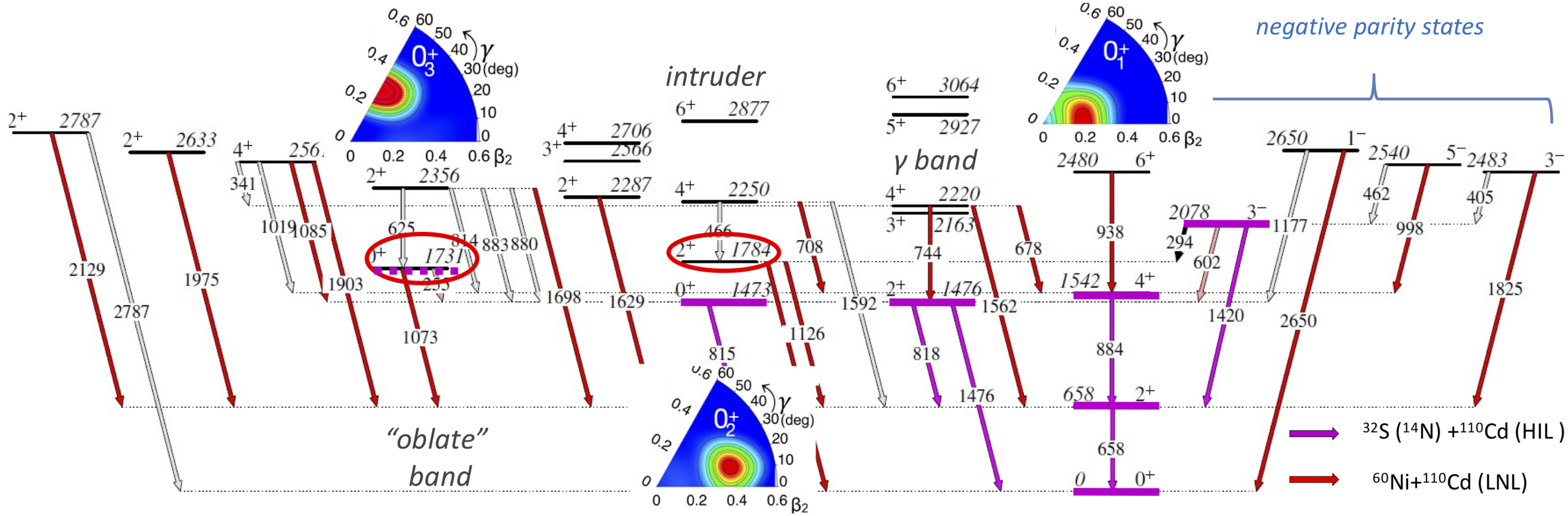
- decay of the presumably prolate 0_2^+ state in ^{106,110}Cd agrees well with the SCCM prediction
- similar for the decay of the presumably oblate 0_3^+ state in ^{106,110}Cd, but the in-band transition strength has a different trend
  - larger B(E2; $2_5^+ \rightarrow 0_3^+$) (similar to that in the 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)



AGATA experiment on ^{110}Cd (LNL)

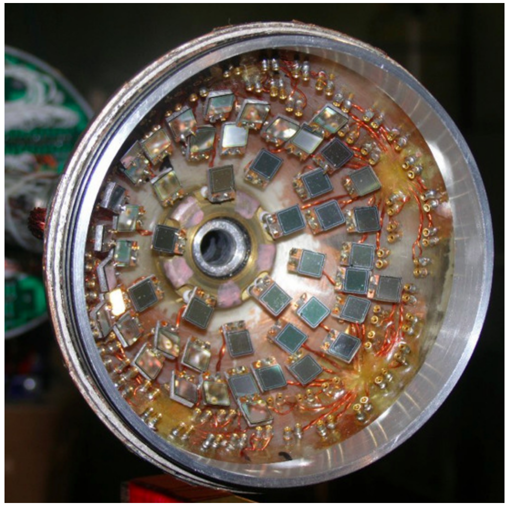
- 5 days of ^{60}Ni beam with AGATA + SPIDER (May + October 2022)
- aim: determination of β and γ parameters of 0_1^+, 0_2^+ and 0_3^+ states in ^{110}Cd using quadrupole sum rules





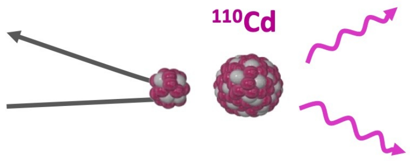
data analysis: PhD thesis of I. Piętka, University of Warsaw, ongoing

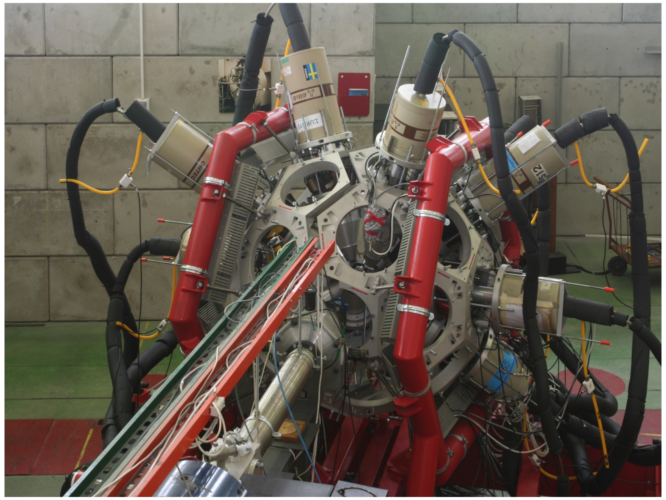
Coulomb excitation of ^{100}Ru at HIL Warsaw



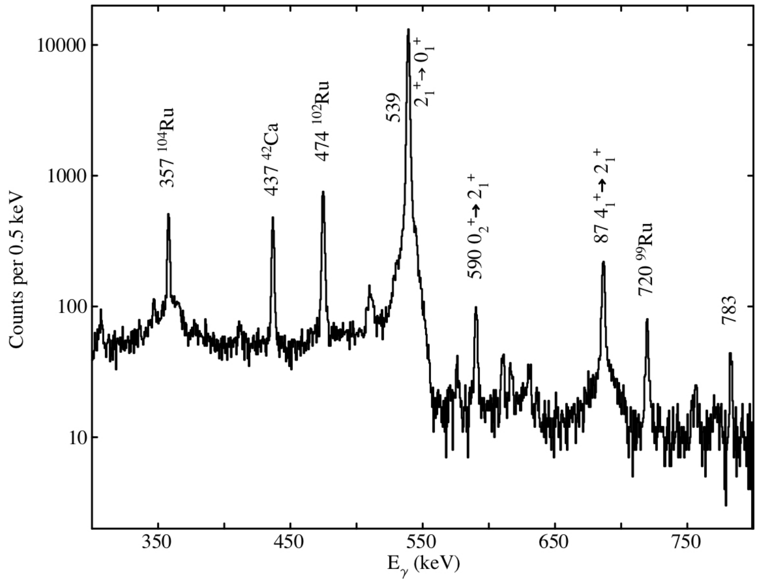
EAGLE + 48 PIN diodes

^{32}S beam at 83 MeV



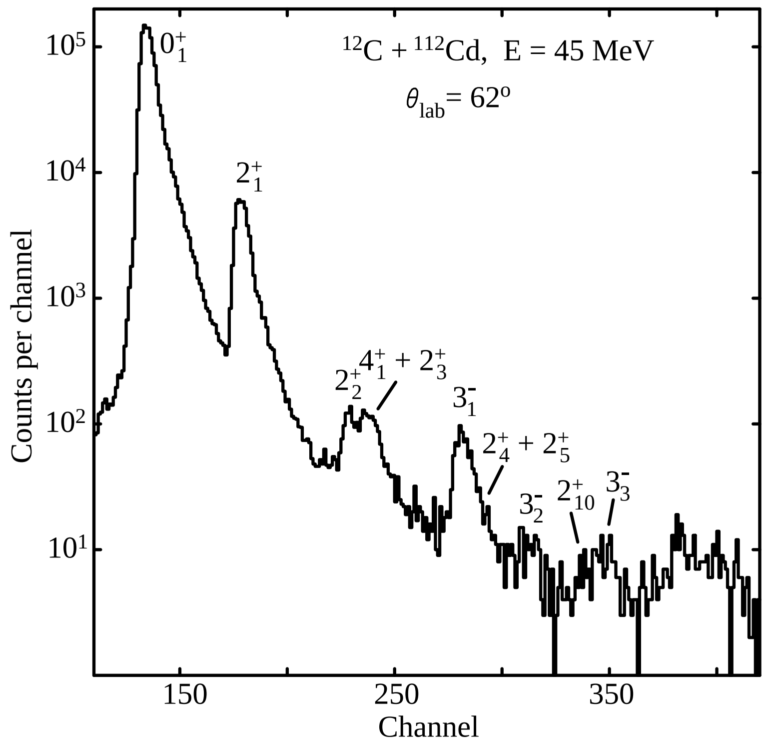


- analysis: internship of F.-e. Demyani at CEA
- preliminary results:
  - $Q_s(2_1^+)$ compatible with one of conflicting literature values
  - first determination of $B(E2; 0_2^+ \to 2_1^+)$



Outlook: studies of ^{112}Cd

- Coulomb-excitation study of ^{112}Cd at the Maier-Leibnitz Laboratory (Munich, Germany) using a ^{12}C beam and a Q3D magnetic spectrograph (analysis completed): verification of lifetimes of 2^+ states and B(E3; $3_1^- \to 0_1^+$) strength
- β decay of ^{112}Ag and ^{112}In into ^{112}Cd (TRIUMF, approved; ^{112}Ag decay scheduled next week): precision branching ratios and E2/M1 transition mixing ratios



- Coulomb-excitation study of ^{112}Cd with a ^{60}Ni beam (AGATA at LNL – presented at the recent pre-PAC workshop, will be submitted to the PAC in the coming weeks)
- complementary measurement at HIL with a ^{32}S beam under consideration