Exploring quadrupole and octupole collectivity in ^{106}Cd via unsafe Coulomb excitation

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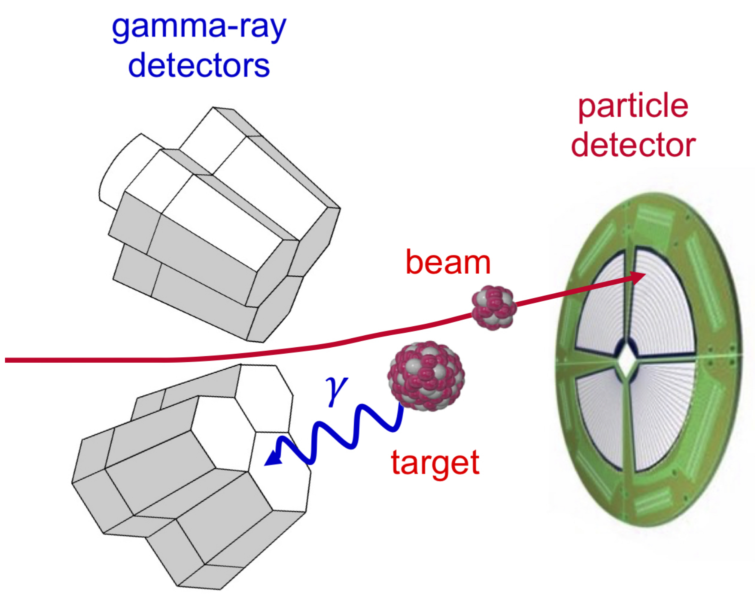
Coulomb excitation

- 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)



more about the method: MZ, Lecture Notes in Physics 1005 (2022), chapter 2

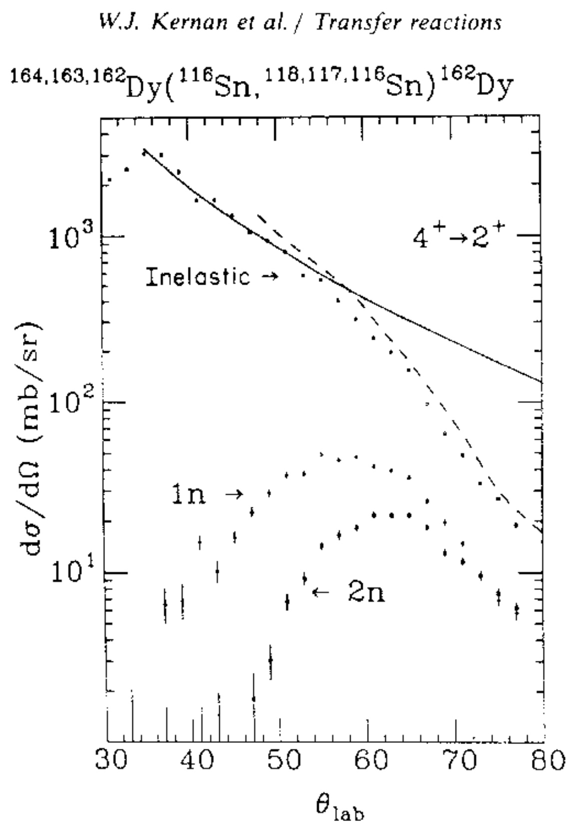
- they are related to the nuclear shape and collectivity – from extensive sets of E2 matrix elements quadrupole invariants can be formed in order to deduce deformation parameters for individual states defined in the intrinsic frame of the nucleus

Where is the border between “safe" and “unsafe" Coulomb excitation?

- Cline’s ”safe energy” criterion: purely electromagnetic interaction if the distance between nuclear surfaces is greater than 5 fm

$$D_{min} = 1.25 \cdot (A_p^{1/3} + A_t^{1/3}) + 5.0 \quad [\mathrm{fm}]$$

- empirical criterion based on systematic studies of inelastic and transfer cross-sections at beam energies of few MeV/A (e.g. W.J. Kernan et al., Nucl. Phys. A 524, (1991) 344)



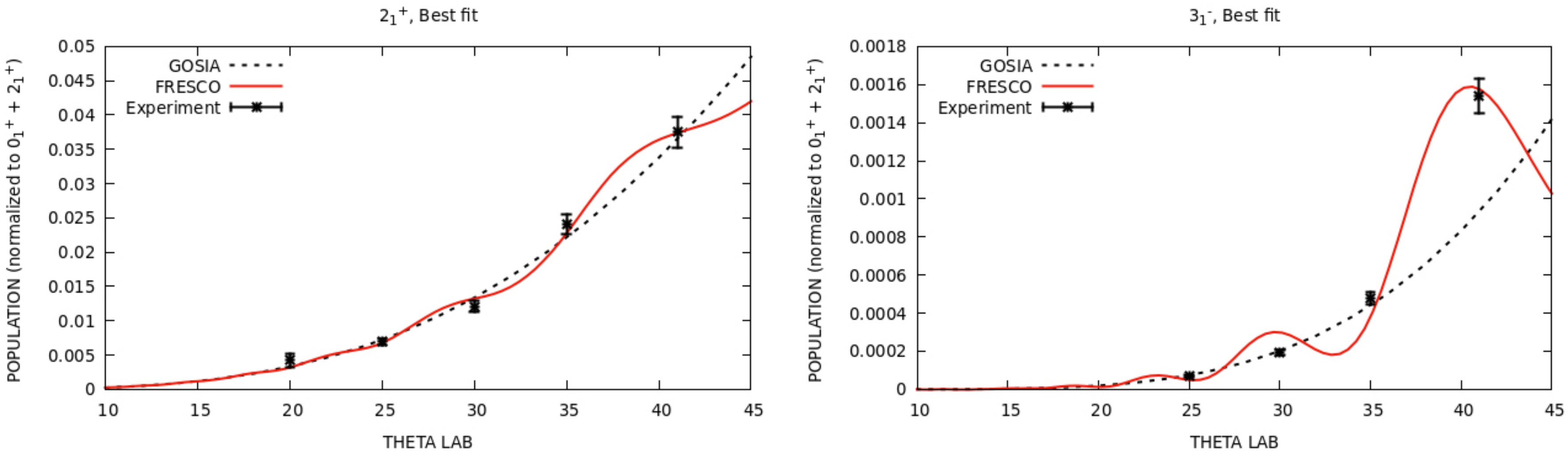
- one-neutron sub-barrier transfer recently observed in Coulomb excitation of ^{42}Ca on ^{208}Pb (K. Hadyńska-Klęk et al, PRC 97, 024326 (2018))

- for light reaction partners (^{12}C, ^{16}O...) deviations from Cline’s criterion observed already at 6.5 fm separation

Why should we care?

- large increase of the excitation cross section! possible application for RIB studies or higher-lying states?

- oscillatory behaviour around the pure Coulomb-excitation cross section due to the nuclear-electromagnetic interference
- deviation from the pure Coulomb-excitation cross section increases with the scattering angle
- multipolarity also plays an important role: much larger effect for E3 than E2



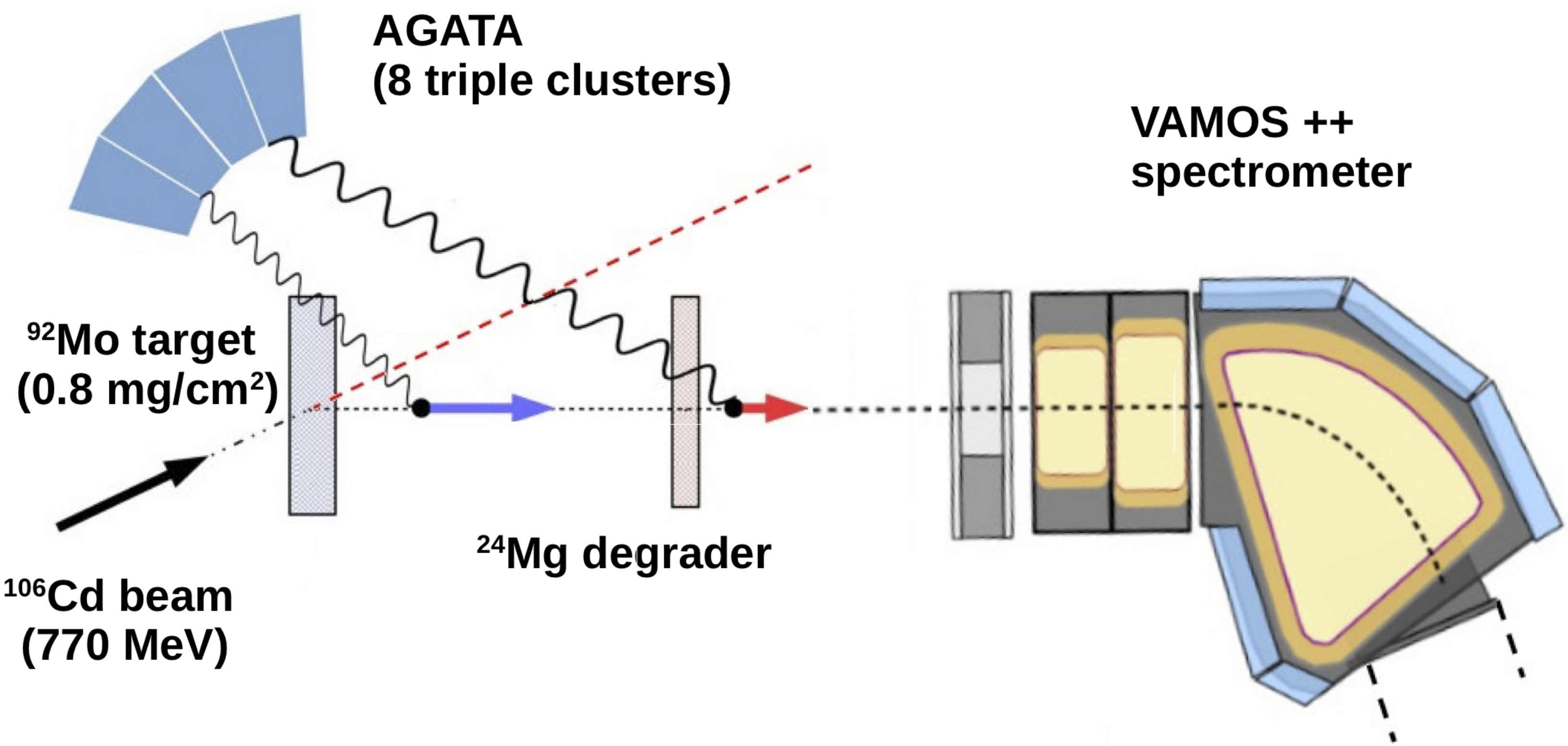
FRESCO calculations: D. Kalaydjieva, N. Keeley.

Data from P. Garrett, MZ et al, PRC 106, 064307 (2022) (^{102}Ru + ^{12}C at 53 MeV)

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

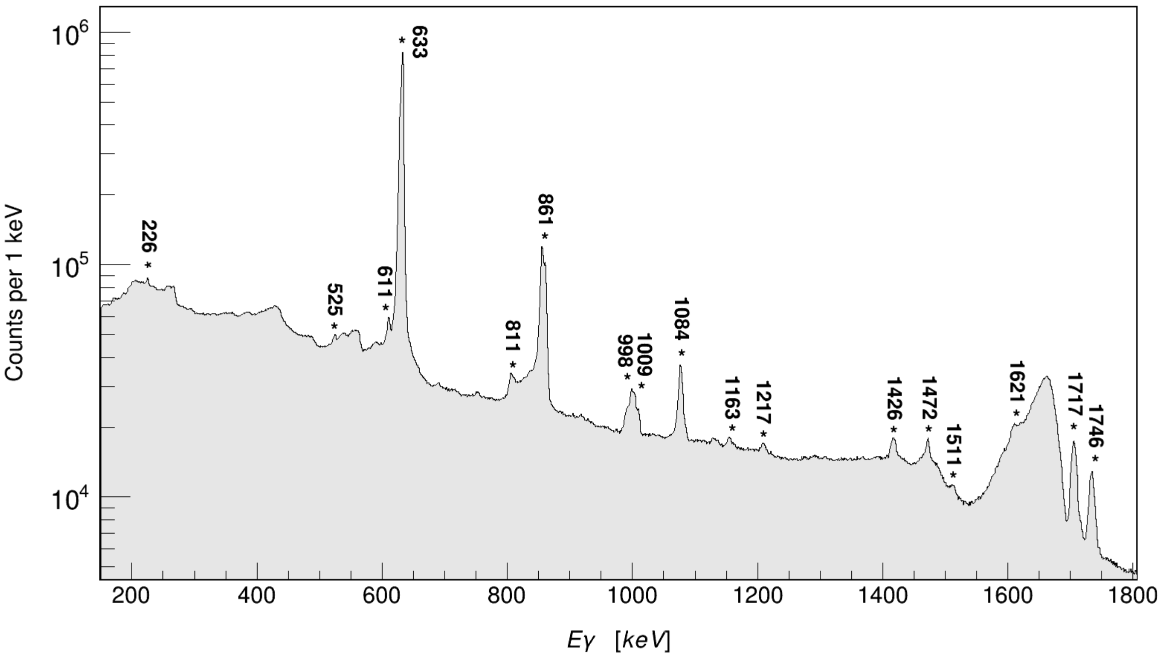
M. Siciliano et al., Phys. Lett. B 806, 135474 (2020)
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021)

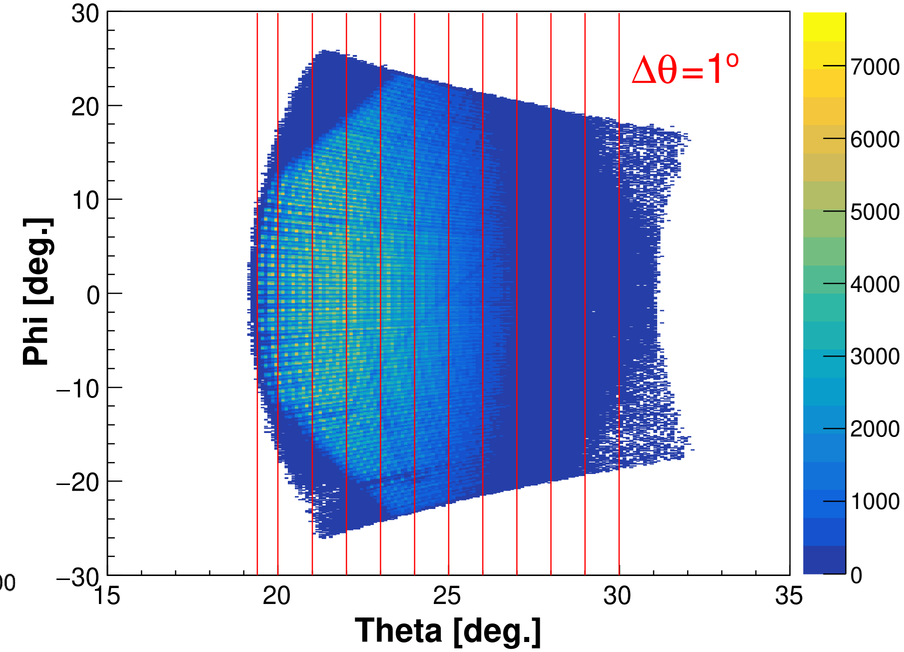


- VAMOS at grazing angle (25°); lowest observed scattering angle (19.4°) corresponding to 107% of Cline's safe energy

Experiment

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

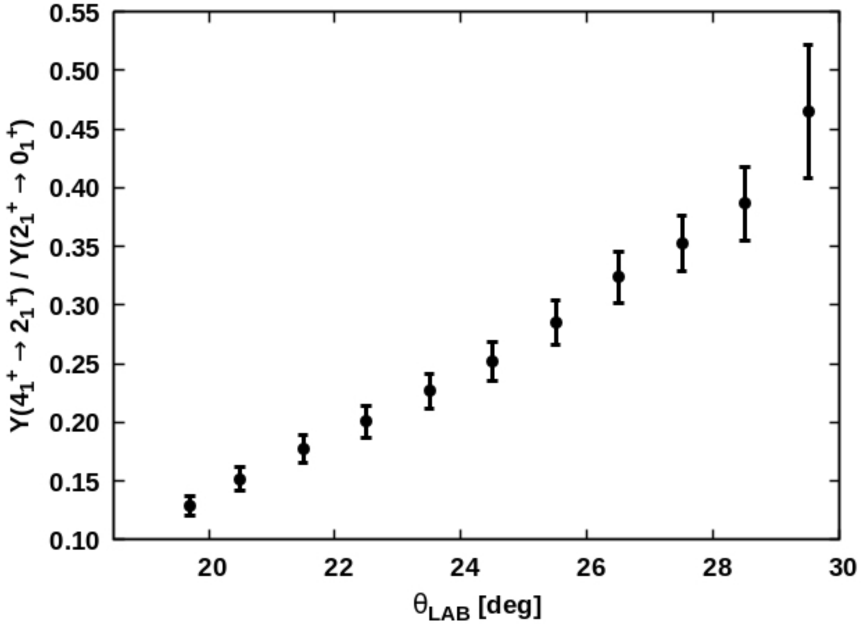




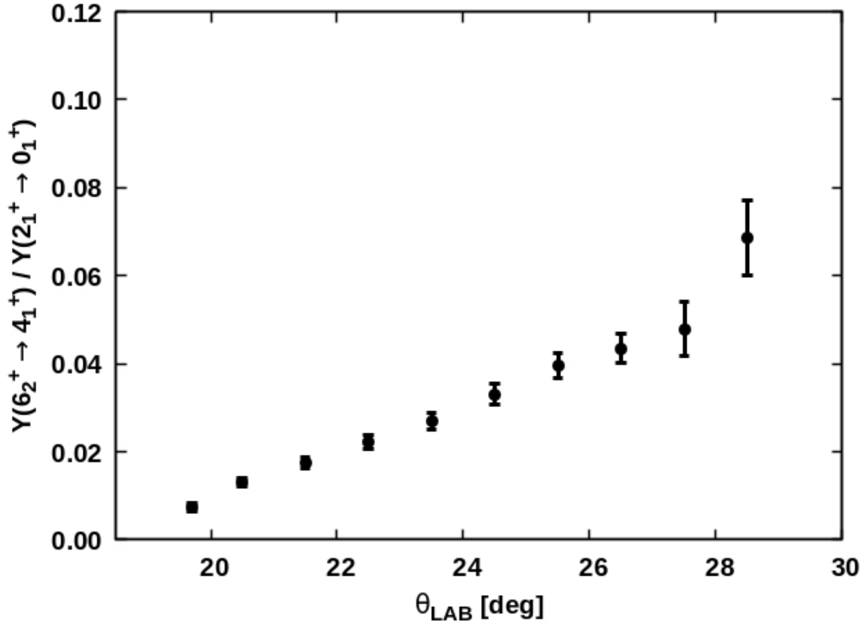
- ^{106}Cd ions identified in VAMOS with $19.4^{\circ} \leq \theta_{\rm LAB} \leq 30^{\circ}$ (Cline's criterion fulfilled for $\theta_{\rm LAB} \leq 18^{\circ}$)
- we apply gates on $\theta_{\rm LAB}$ with 1° width to study the dependence of the excitation cross sections on scattering angle
- due to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

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

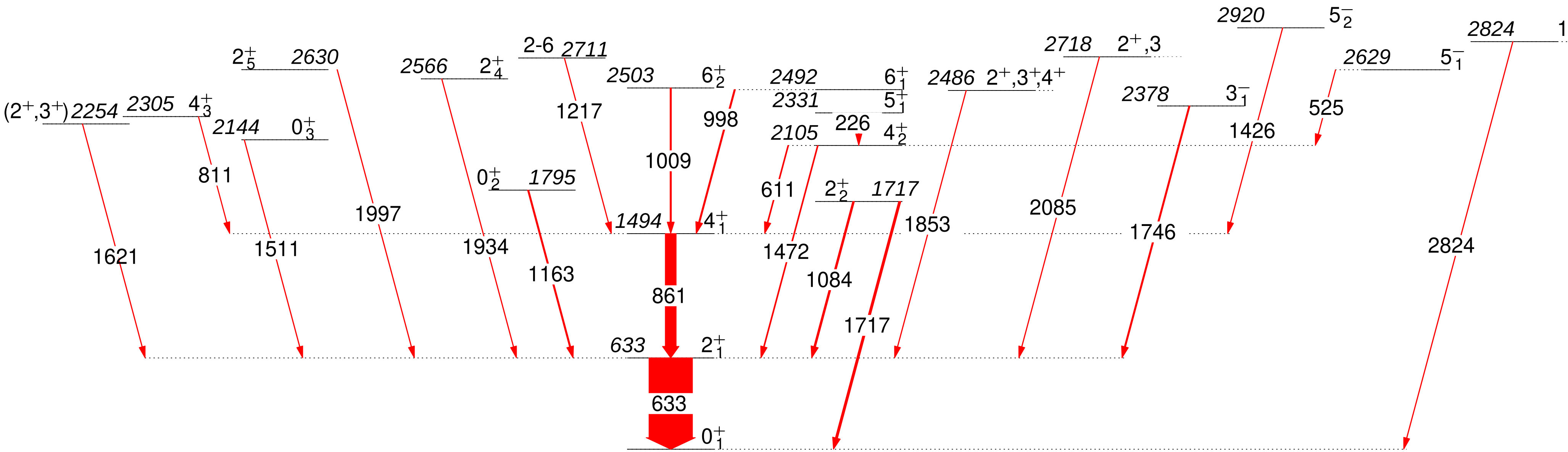


$6_2^+ \rightarrow 4_1^+$



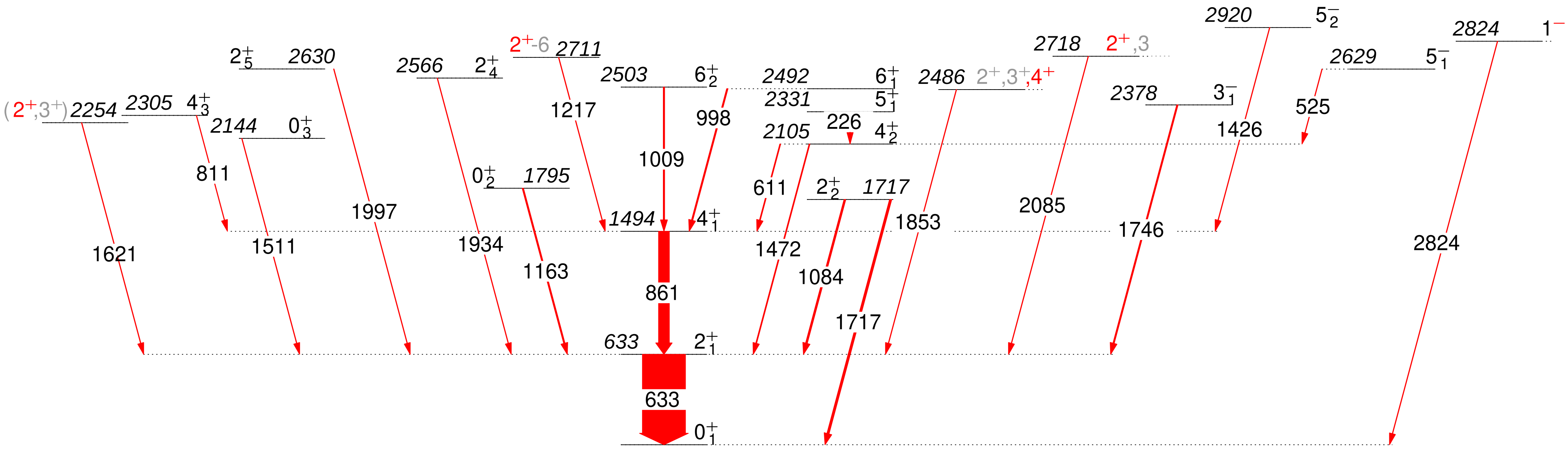
- where are the oscillations? the experimental points line up even for angles where the nuclear surfaces almost touch!
- let's try to assume pure Coulomb-excitation process and see if we can reproduce the measured γ-ray intensities using known spectroscopic data (lifetimes, branching and mixing ratios...)

Level scheme used in the analysis: observed transitions



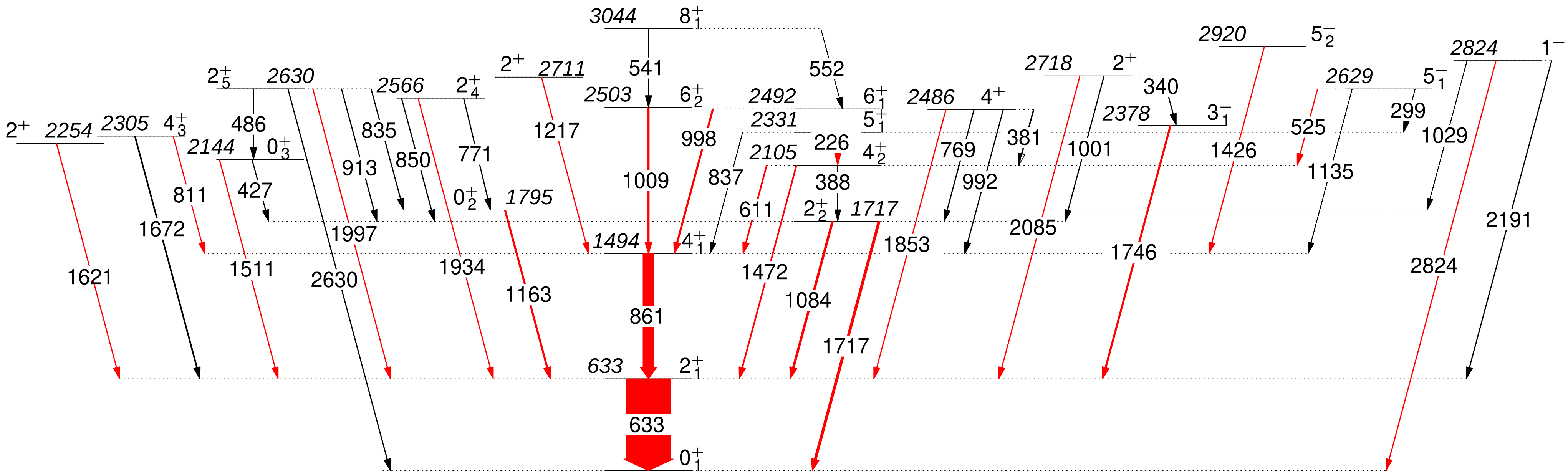
- level spin-parities taken from ENSDF
- assumptions required if there is no firm spin and/or parity assignment (2254 keV, 2486 keV, 2711 keV, 2718 keV, 2824 keV states)

Level scheme used in the analysis: observed transitions



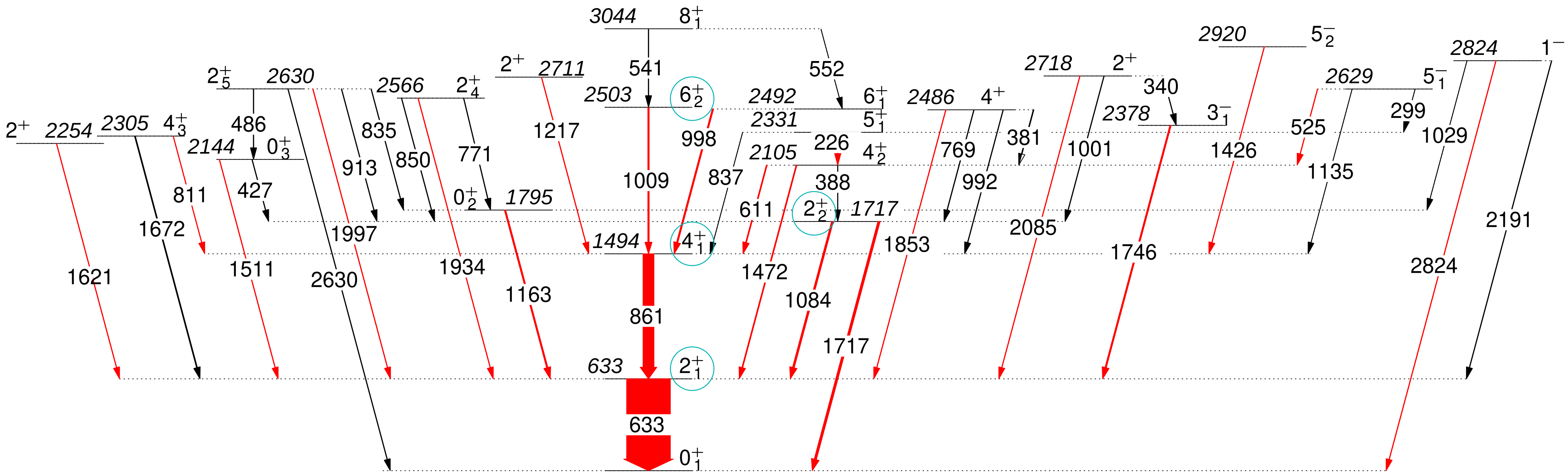
- mostly one- or two-step excitation
- placement of the 1217-keV transition in the level scheme taken from A. Linnemann, PhD thesis, University of Cologne, 2005: in agreement with its observation in the present experiment and with the systematics of heavier Cd isotopes

Level scheme used in the analysis: additional spectroscopic data



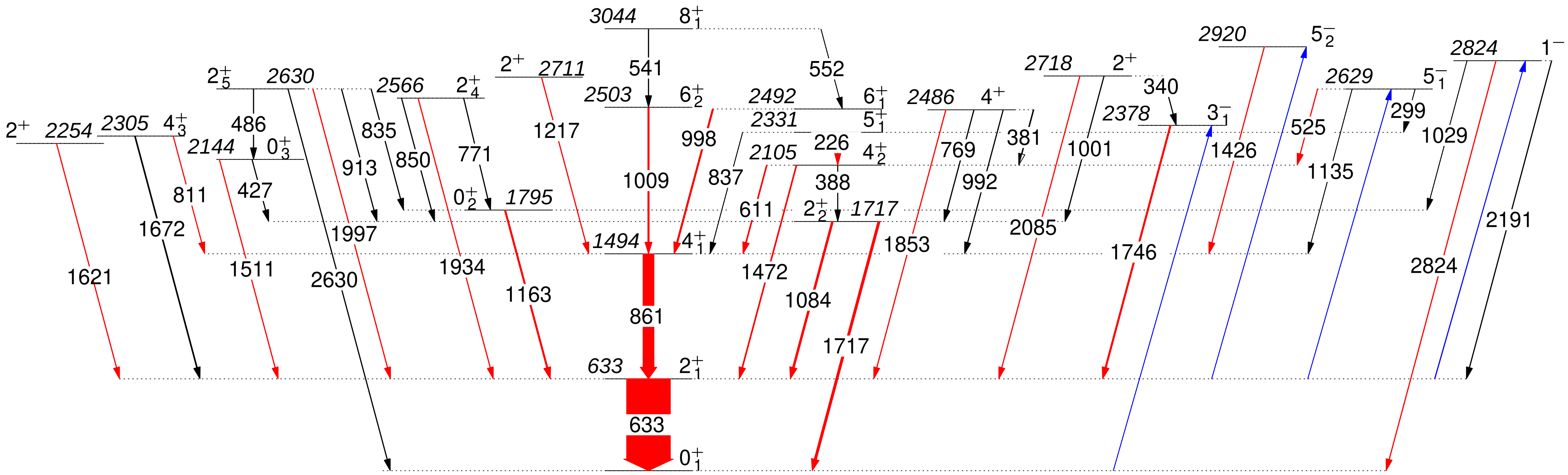
- branching ratios mostly taken from the most recent γ-γ coincidence measurement: (p,p'γ) T. Schmidt, PhD thesis, University of Cologne, 2019
- mixing ratios mostly taken from ENSDF; if they are missing for a $J^+ \rightarrow J^+$ transition – pure E2 assumed
- we note discrepancies in the literature for many branching and mixing ratios

Level scheme used in the analysis: additional spectroscopic data



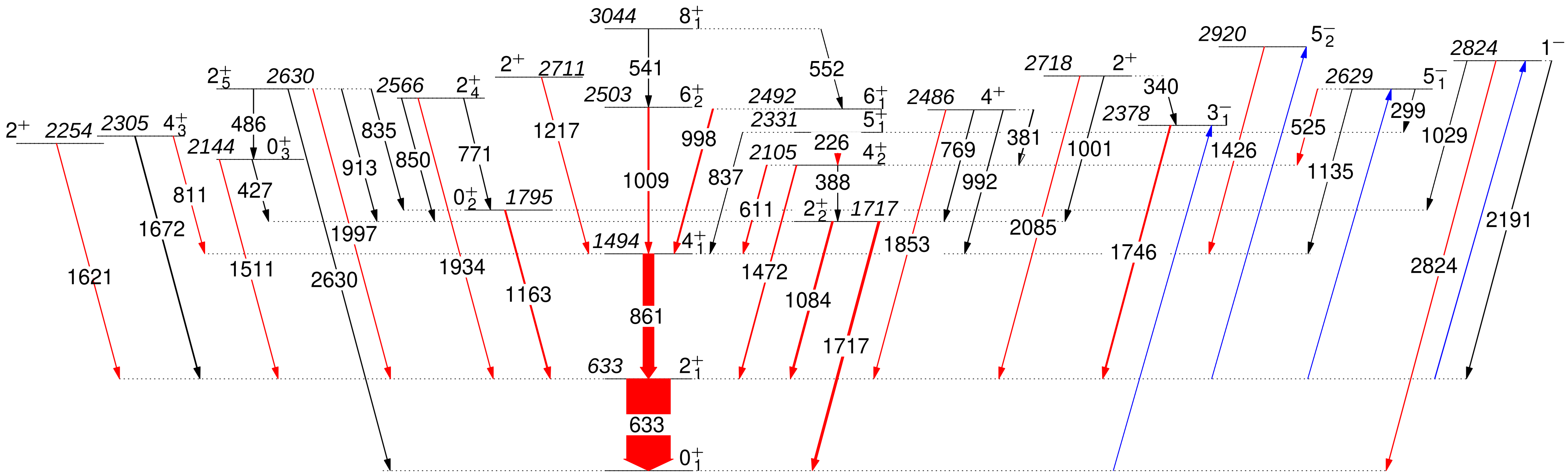
- quadrupole moments: weighted averages of results from D. Rhodes et al., PRC 103, L051301 (2021) and T.J. Gray et al., PLB 834 137446 (2021)

Level scheme used in the analysis: E3 transitions



- initially we assume that only one E3 matrix element is responsible for population of each negative-parity state

Level scheme used in the analysis

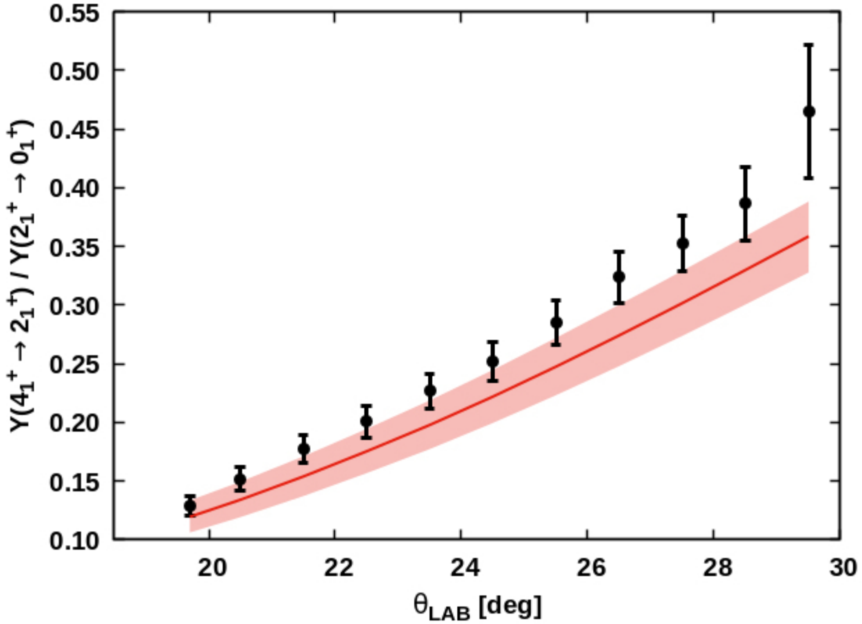


- initially we assume that only one E3 matrix element is responsible for population of each negative-parity state

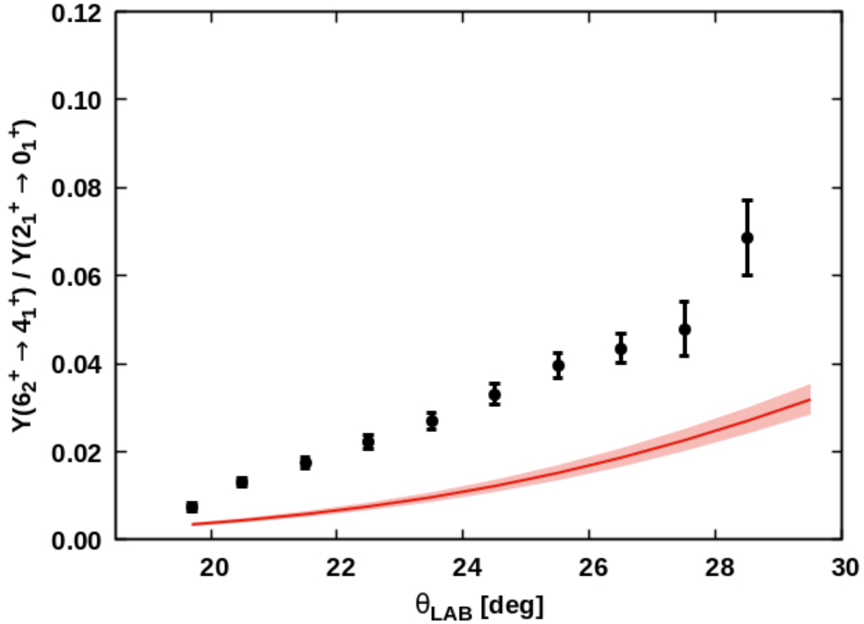
- now that we have a set of electromagnetic matrix elements corresponding to literature data, can we describe our measured transition intensities?

Sample results (strongly populated states)

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



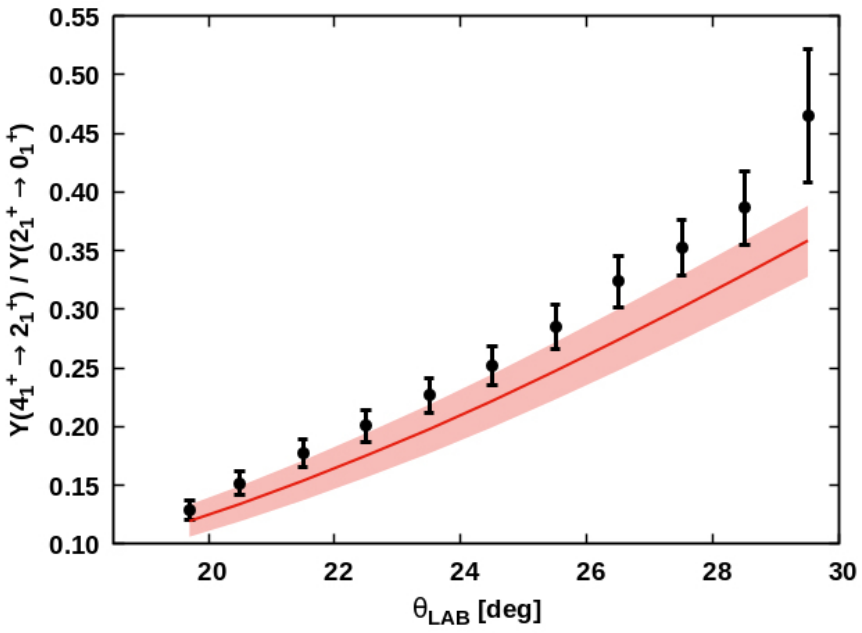
$6_2^+ \to 4_1^+$



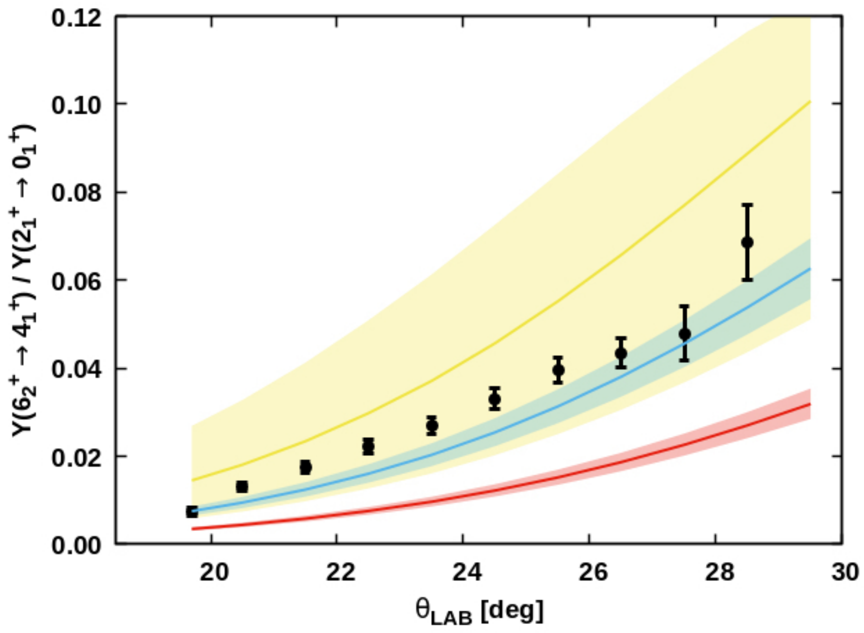
- reasonable agreement with literature data for 4_1^+ (weighted average of measured lifetimes)
- lifetime of the 6_2^+ state deduced from the same data as our transition intensities (M. Siciliano et al., Phys. Rev. C 104, 034320 (2021)) is not consistent with the measured intensity ratios

Sample results (strongly populated states)

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



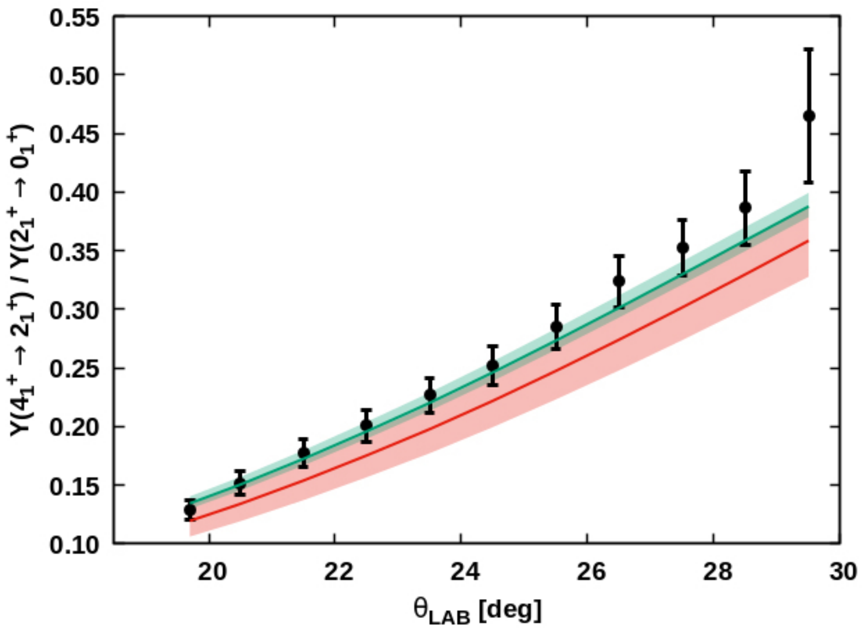
$6_2^+ \rightarrow 4_1^+$



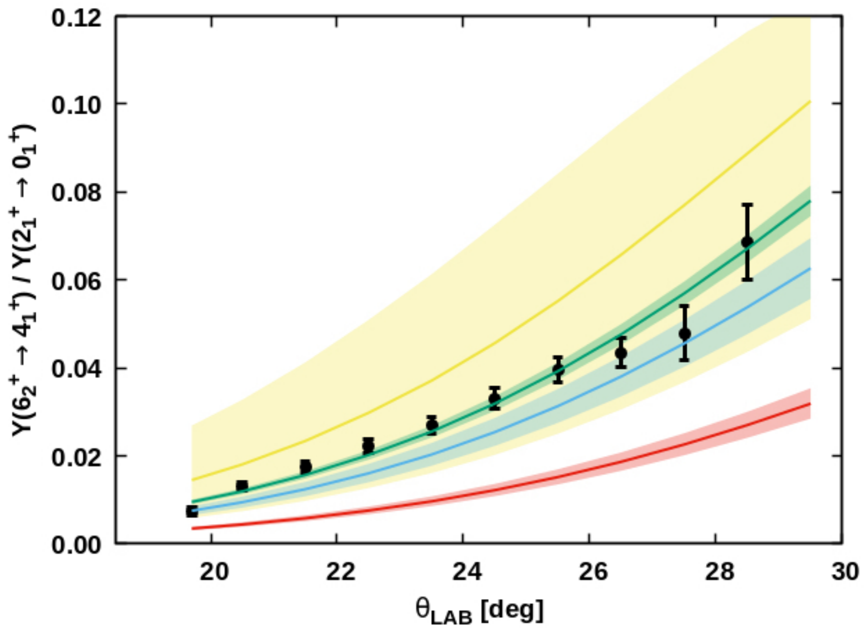
- much better agreement for the 6_2^+ state if we assume:
  - $\langle 6_2^+ \| E2 \| 4_1^+ \rangle$ matrix element from Coulomb excitation (D. Rhodes et al., Phys. Rev. C 103, L051301 (2021))
  - or 6_2^+ lifetime from (n,n'γ) (A. Linnemann, PhD thesis, University of Cologne, 2005 – but here the uncertainty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

Sample results (strongly populated states)

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



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



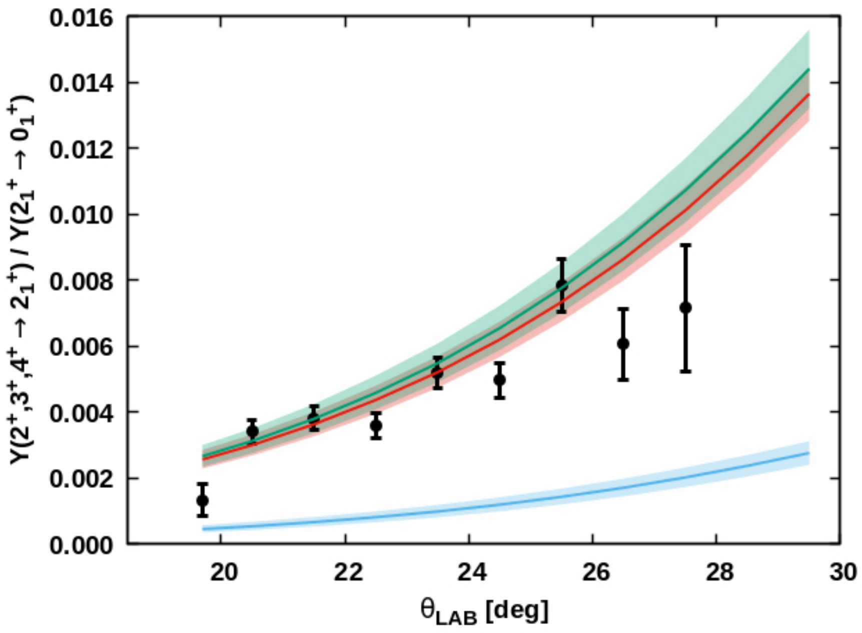
- finally, we can try to fit a set of matrix elements to the first few points of the cross-section distribution, and compare the resulting lifetimes:

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

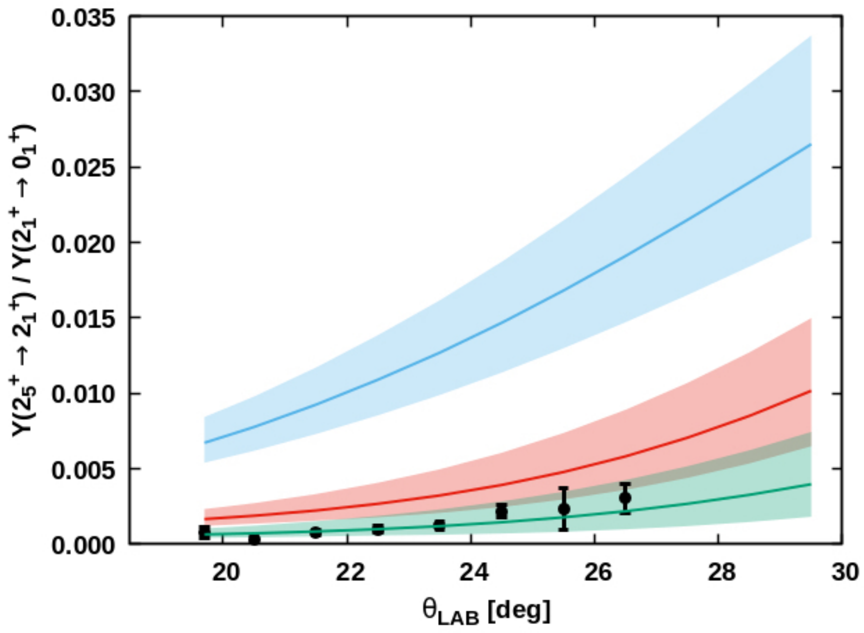
6_2^+ – GOSIA fit: 0.48(3) ps
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021): 1.22(15) ps
D. Rhodes et al., Phys. Rev. C 103, L051301 (2021): 0.54(8) ps

Preference for certain branching or mixing ratios

$2^+, 3^+, 4^+$ (2486 keV) $\rightarrow 2_1^+$



2_5^+ (2630 keV) $\rightarrow 2_1^+$



different decay patterns in the literature:

ENSDF: 51% to 4_1^+, 49% to 2_1^+

T. Schmidt, PhD thesis, University of Cologne, 2019:

63% to 2_1^+, 25% to 4_1^+, 9% to 2_2^+, 3% to 4_2^+

lifetime: $2.12^{+0.21}_{-0.17}$ ps (GOSIA fit)

2.34(17) ps (M. Siciliano, PRC 104, 034320 (2021))

two mixing ratios in ENSDF:

δ=3.2(4) and δ=-0.11(4)

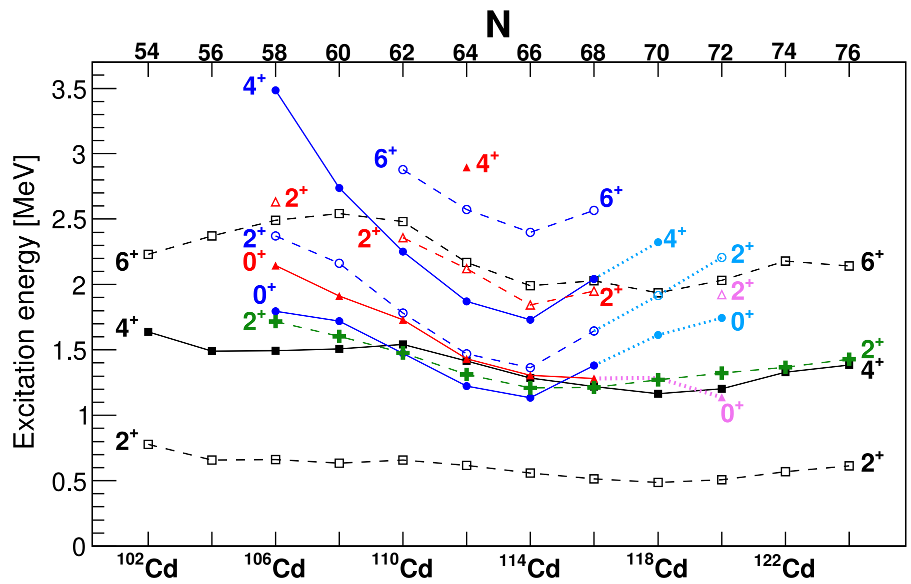
lifetime: $0.45^{+0.19}_{-0.14}$ ps (GOSIA fit)

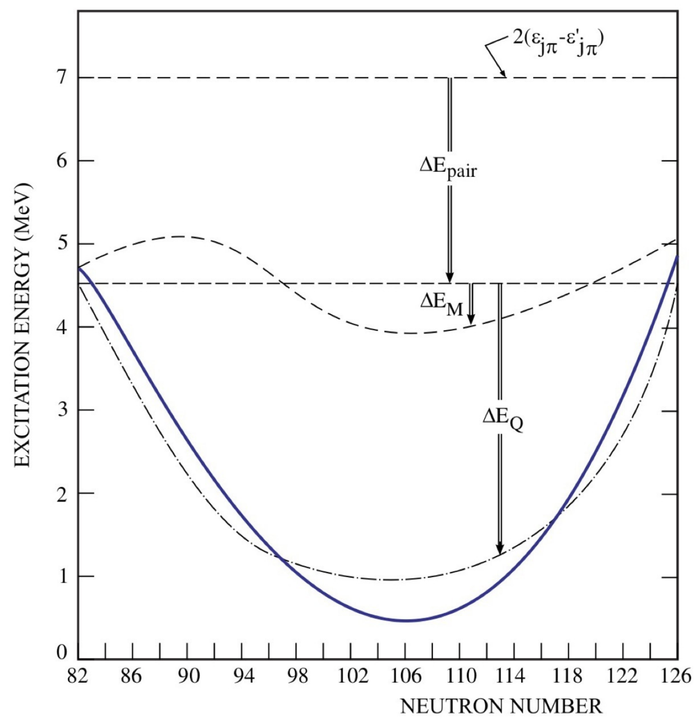
0.19(3) ps (A. Linnemann PhD)

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

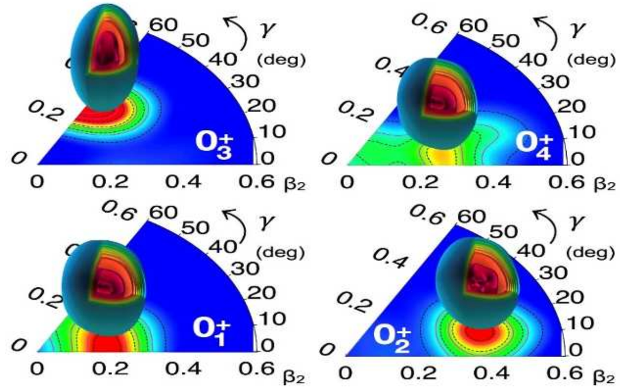
data compilation: P. Garrett, MZ, E. Clément, Prog. Part. Nucl. Phys. 124, 103931 (2022)





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

Shapes of Cd nuclei – context



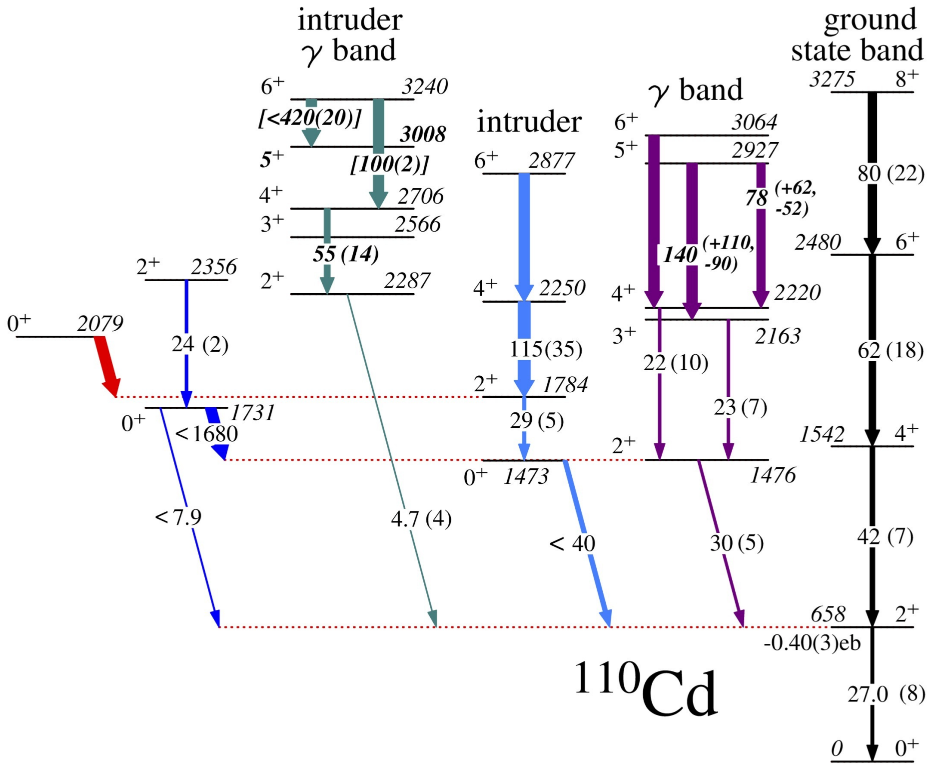
- departure from the surface-vibration paradigm towards a multiple shape-coexistence scenario:
  - β decay (TRIUMF) + DSAM lifetime measurements (Kentucky) in ^{110,112}Cd with guidance from BMF calculations (P.E. Garrett et al, Phys. Rev. Lett. 123, 142502 (2019))

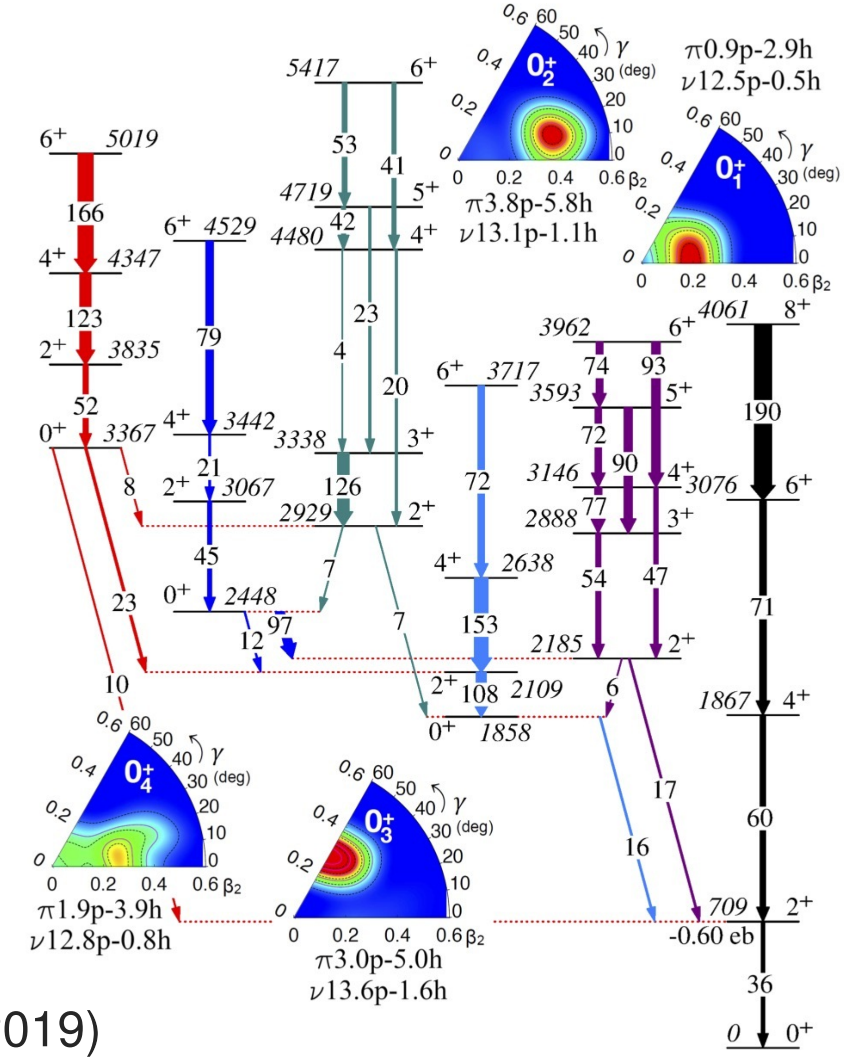
- data can be reconciled with the vibrational picture using partial dynamical symmetry in the IBM (N. Gavrielov et al, Phys. Rev. C 108, L031305 (2023))

- 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)

Shape coexistence in Cd isotopes: BMF predictions



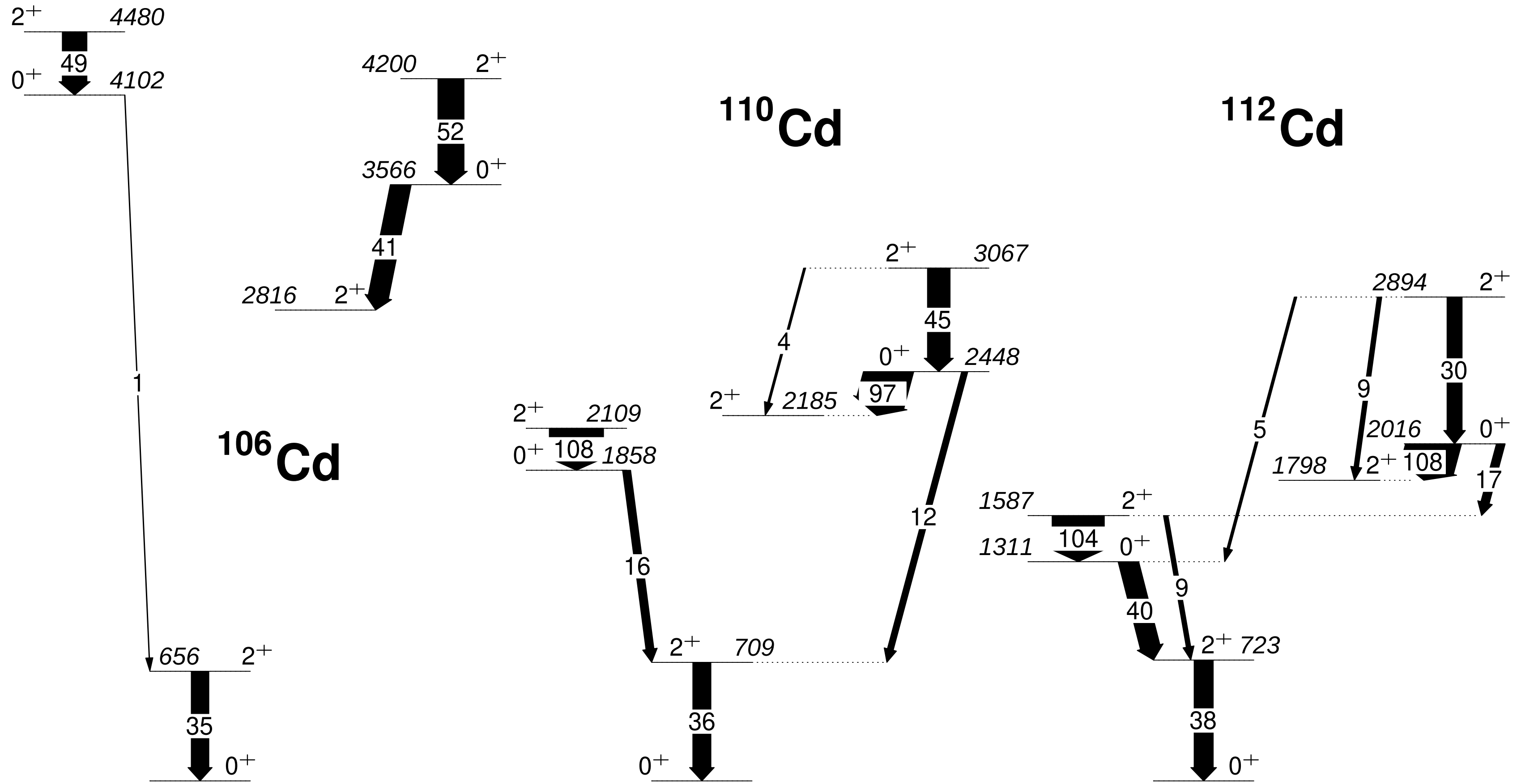


P.E. Garrett et al, Phys. Rev. Lett. 123, 142502 (2019)

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

Shape coexistence in Cd isotopes: BMF predictions

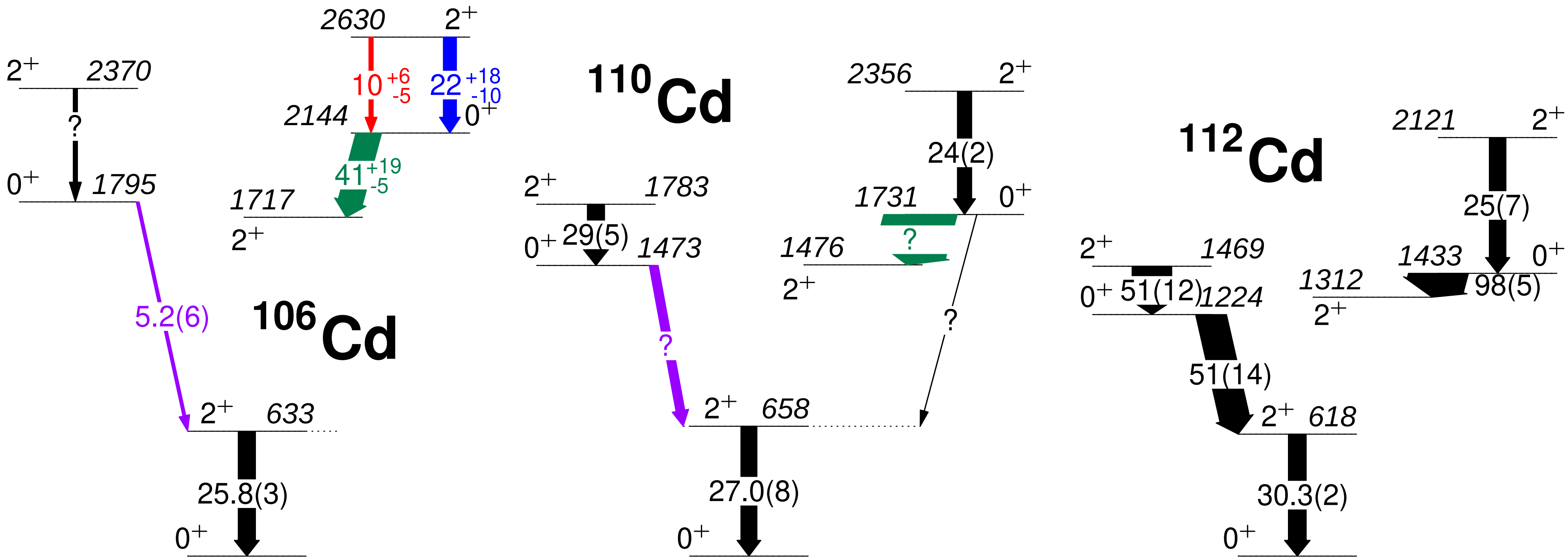
- similar shape-coexisting structures as in ^{110,112}Cd are predicted in ^{106}Cd
- in-band transition strength in the oblate structure predicted to increase with decreasing N, while the B(E2; $0_3^+ \rightarrow 2_2^+$) value decreases



SCCM calculations: T.R. Rodriguez

Coulomb-excitation results: ^{106}Cd (+ ^{110}Cd from HIL!)

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

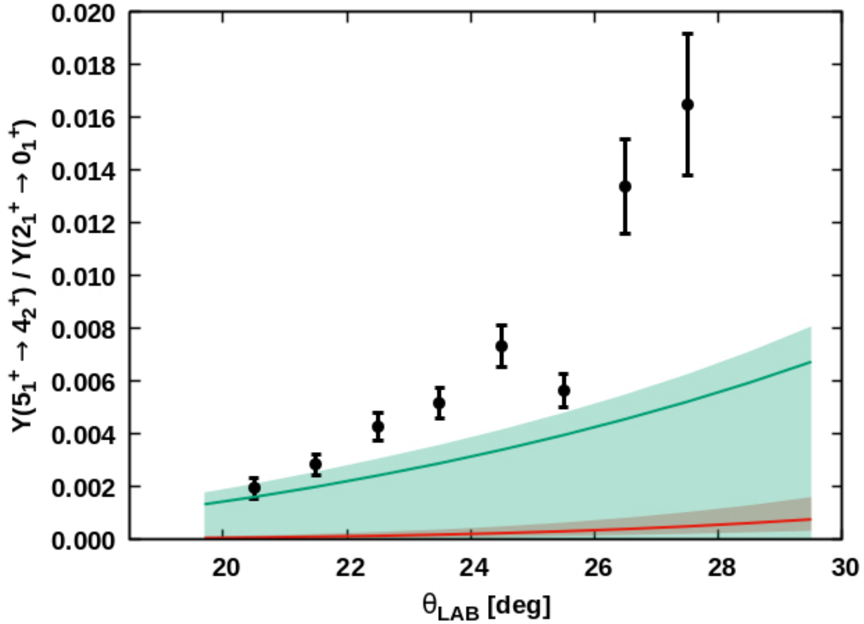


^{106}Cd: D. Kalaydjieva, PhD thesis; ^{110}Cd: new results from HIL (removed from web version)

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

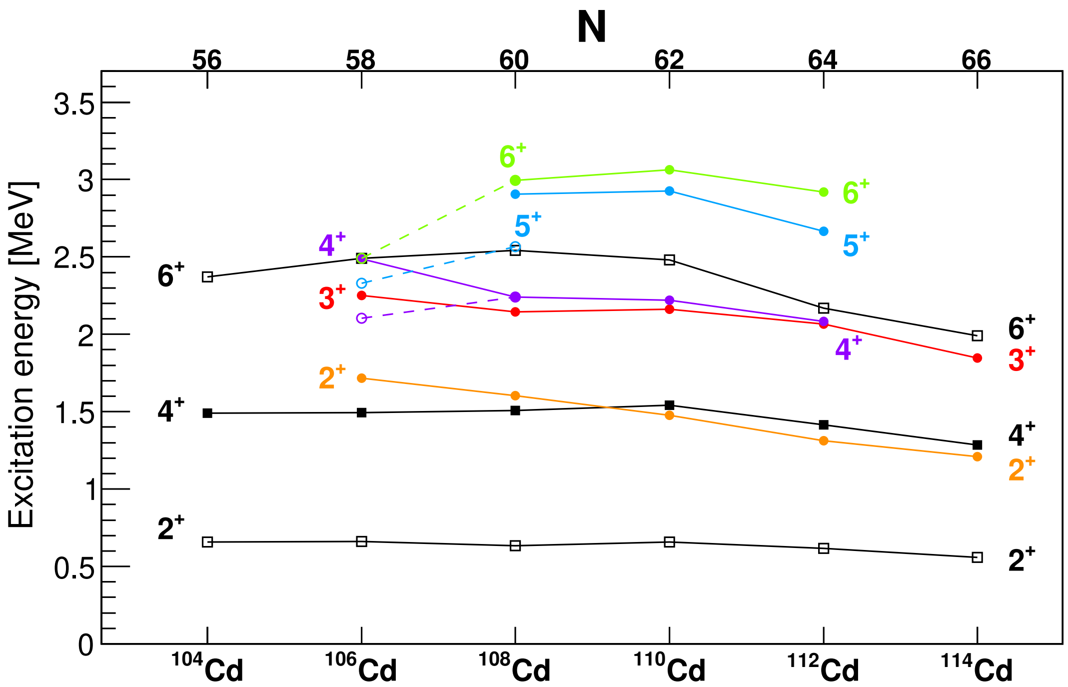
5_1^+ (2331 keV) $\rightarrow 4_2^+$

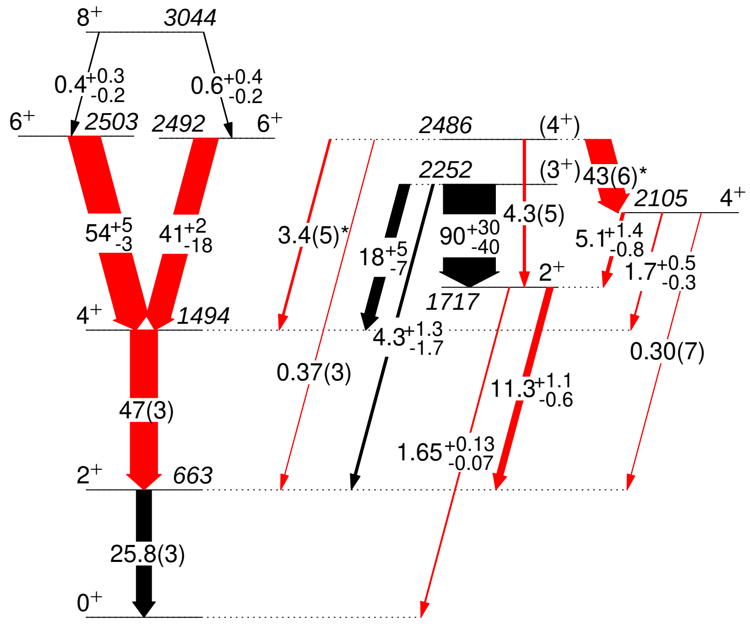
- the observed population of the 5_1^+ state would require B(E2; $5_1^+ \rightarrow 4_2^+$) over 300 W.u.
- lifetime: 9(1) ps (GOSIA fit)
  870(290) ps (ENSDF)
- we suspect the 226-keV $5_1^+ \rightarrow 4_2^+$ transition is part of a doublet



- 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

Proposed reorganisation of the level scheme

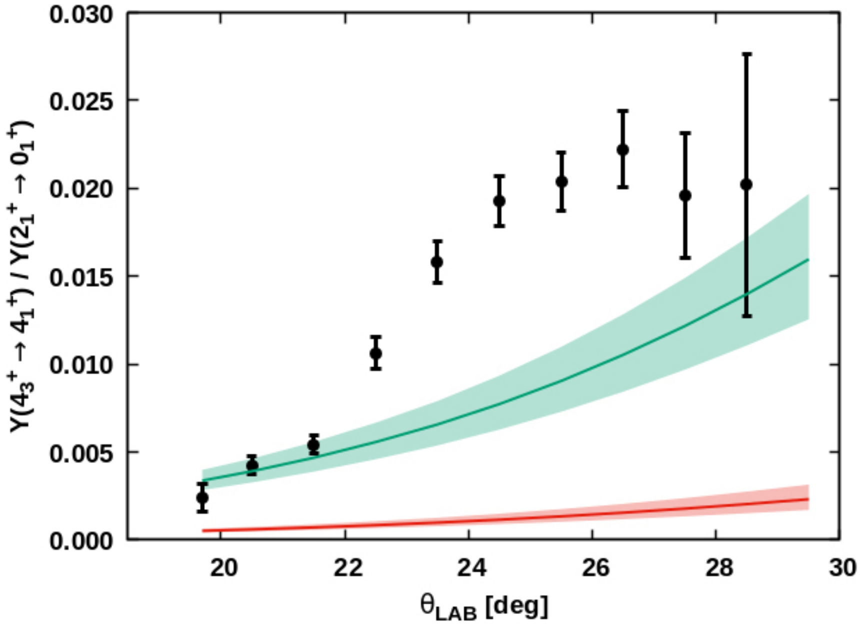


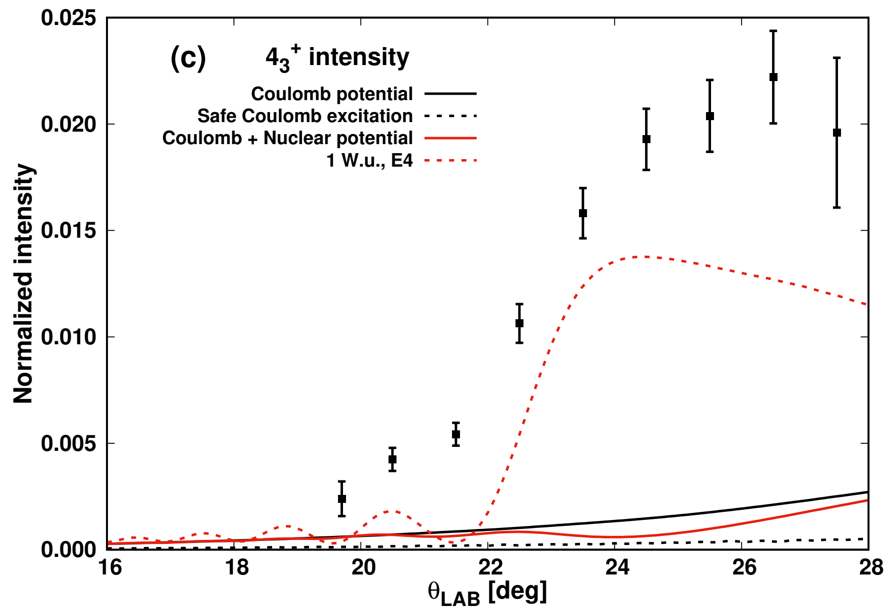


- new K=2 3^+ and 4^+ and K=4 4^+ band members proposed that have expected decay patterns and excitation energies consistent with the systematics
- closely spaced 6^+ states suggested to result from a strong mixing of the rotational band member with a seniority state
- non-observation of the 2252-keV state in the present data supports its 3^+ spin-parity (Coulomb excitation of odd-spin positive parity states is strongly hindered)

More open questions: possible contribution of higher multipolarities?

4_3^+ (2305 keV) $\rightarrow 4_1^+$





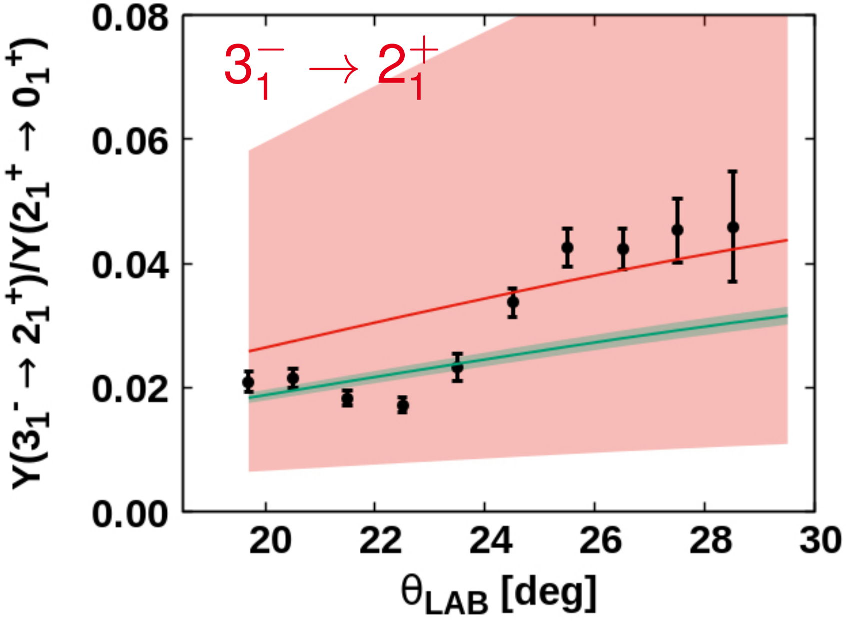
lifetime: 0.18(3) ps (GOSIA fit)

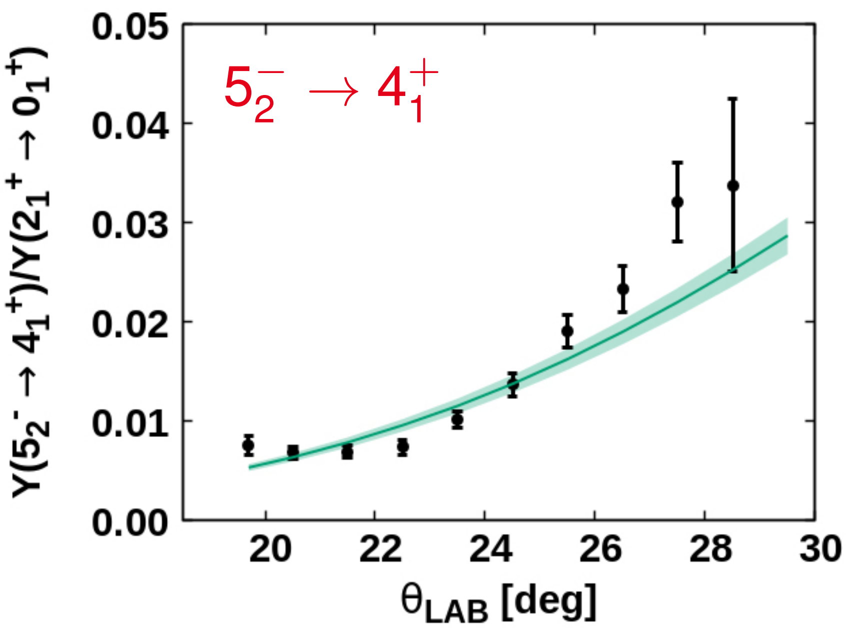
1.1(1) ps (M. Siciliano, PRC 104, 034320)

<0.36 ps ((n,n'γ), A. Linnemann PhD)

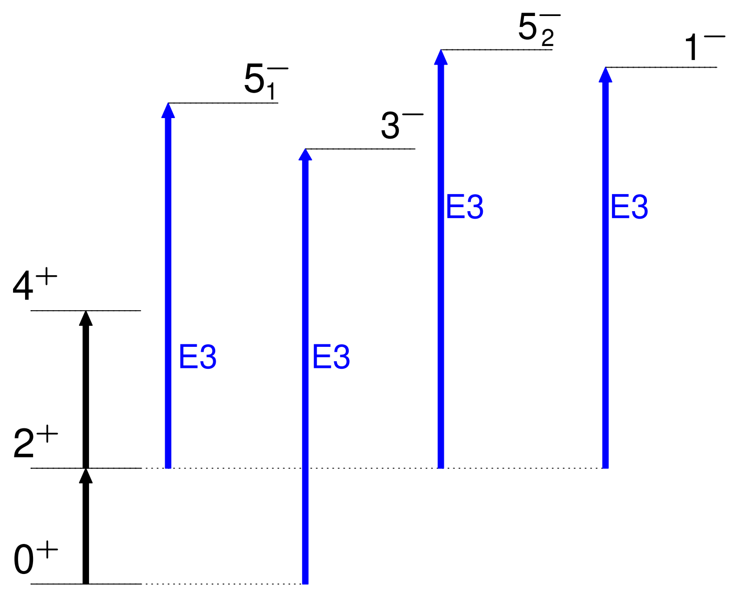
- can the divergence for $\theta > 22^\circ$ be due to direct population via E4?
- strong E4 in this mass region known from inelastic scattering: M. Pignanelli, NPA 540, 27 (1992); strength fragmented between several states around 2.5 MeV

Negative-parity states



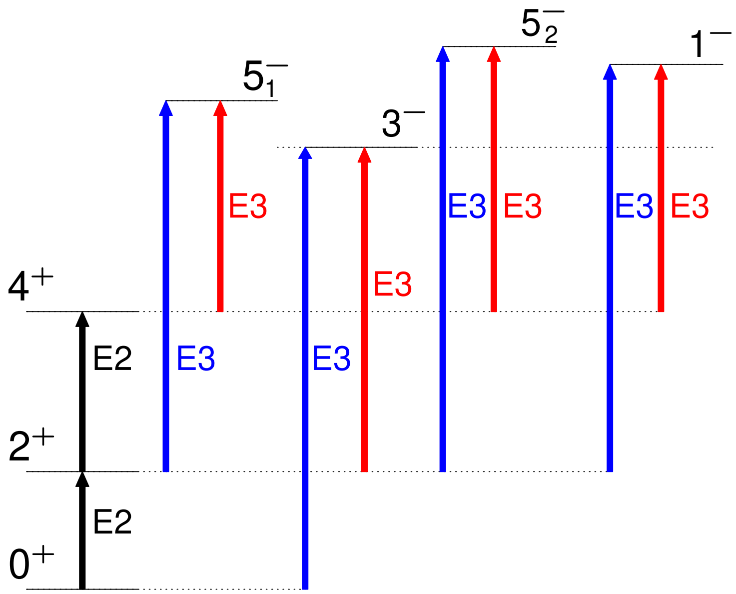


- oscillatory behaviour observed for the 3_1^- and 5_2^- excitation cross sections
- initally only a single E3 matrix element is assumed to be responsible for the population of each of the 3_1^-, 5_1^-, 5_2^- and 1_1^- states



- Results:
  - $B(E3; 3_1^- \to 0_1^+) = 11.6(5)$ W.u.
  - $B(E3; 5_2^- \to 2_1^+) = 57(2)$ W.u. (a lot!)

Negative-parity states



- it is necessary to introduce a more complicated coupling scheme to describe populations of the 5_1^-, 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

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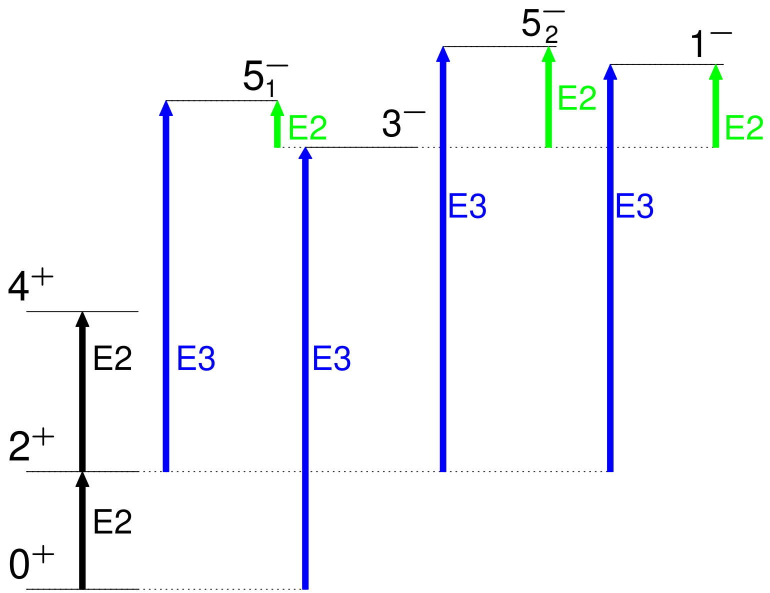
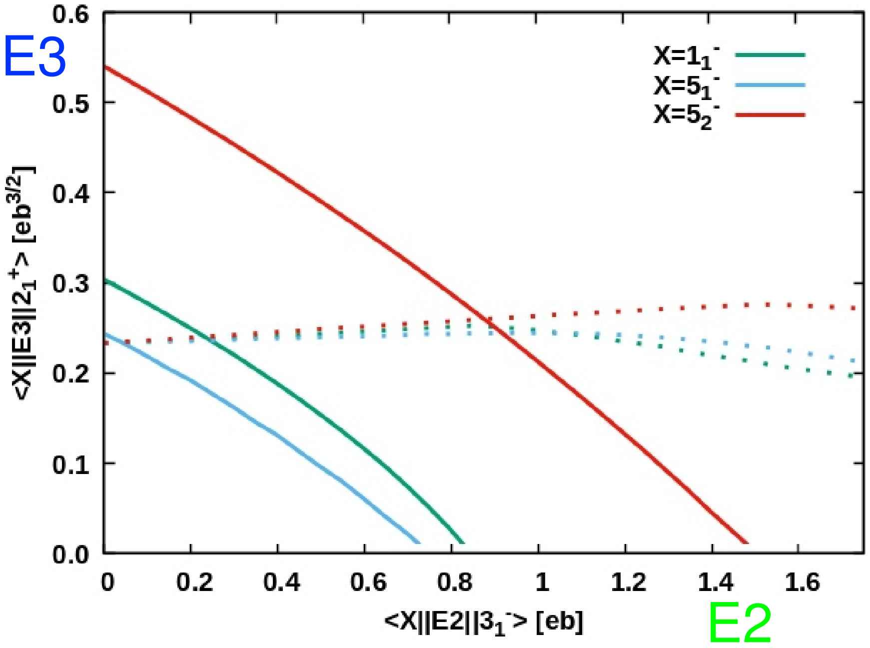
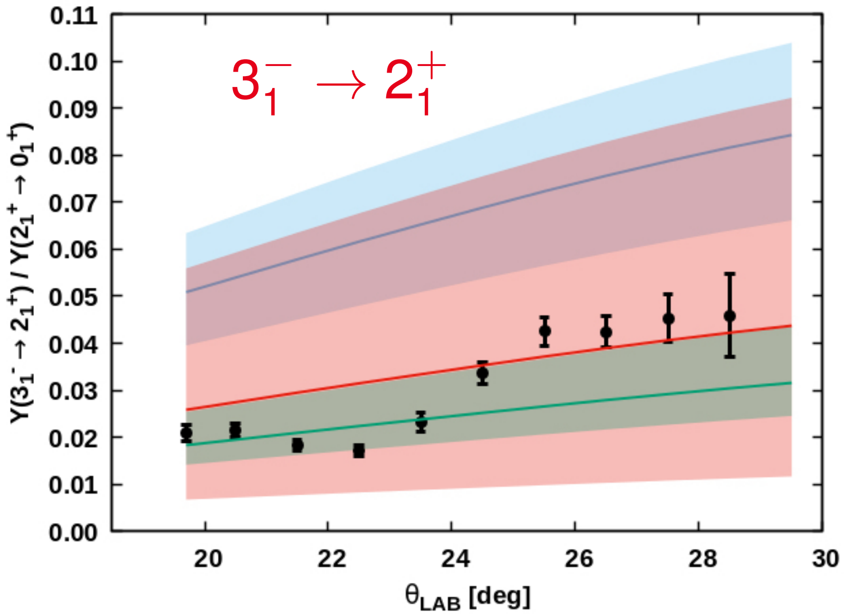
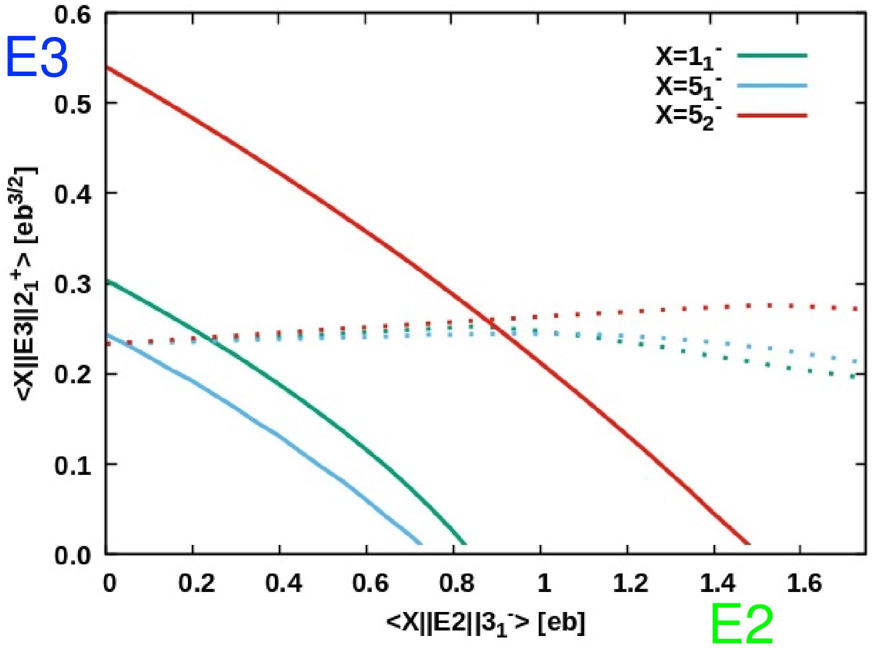




- it is necessary to introduce a more complicated coupling scheme to describe populations of the 5_1^-, 5_2^- and 1_1^- states
- additional E3 transitions change the populations by a few percent, even if values of many tens of W.u. are assumed
- E2 transitions to the 3_1^- state prove to be very important
- we do not know the relevant branching ratios, but we can extract the correlation between the E3 and E2 strength involved in the population of the negative parity states

Negative-parity states: structure results





- $B(E3; 3_1^- \to 0_1^+)$ = 11(4) W.u. in agreement with D. Rhodes et al., PRC 103, L051301 (2021) (red) but in disagreement with the evaluated value of 34(9) W.u. (T. Kibedi and T. Spear, At. Data Nucl. Data Tables 80, 35 (2002))

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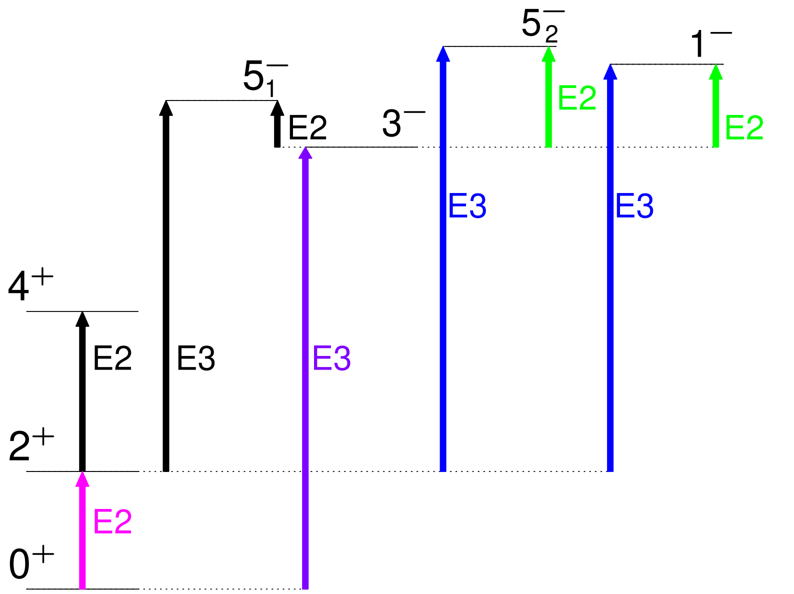

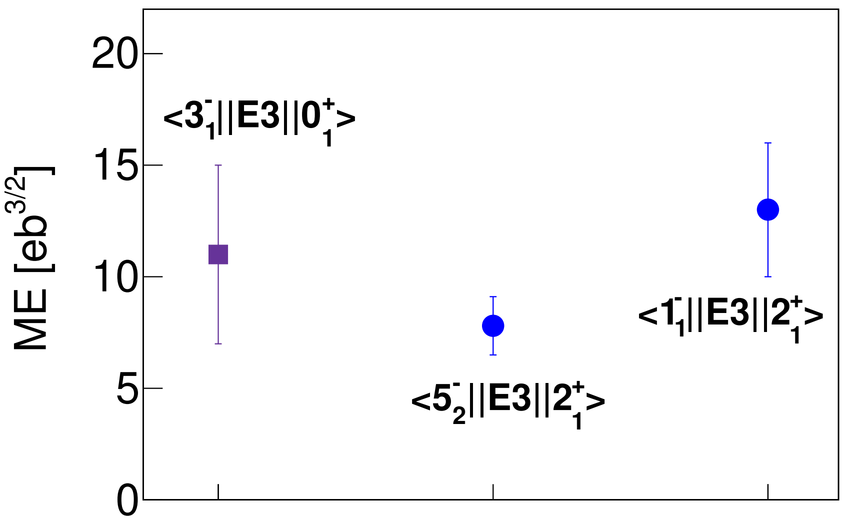

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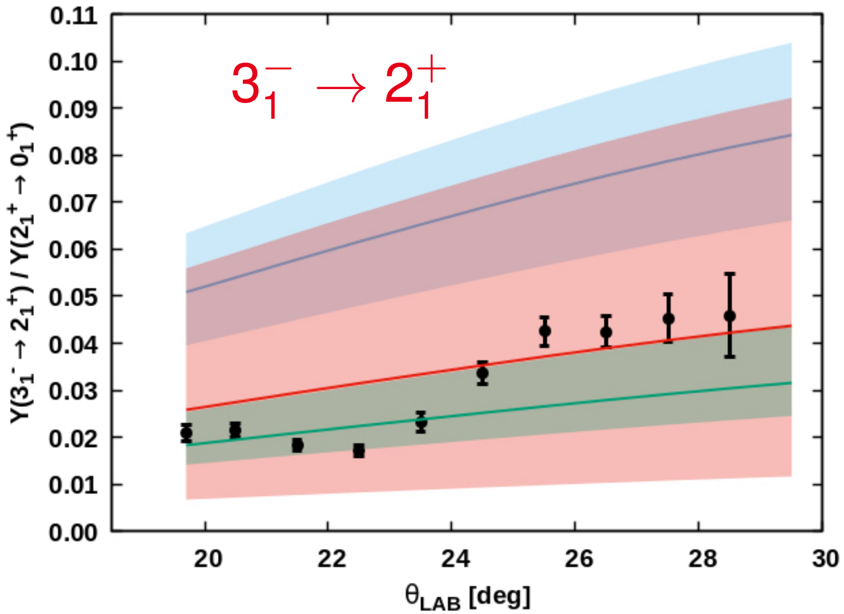
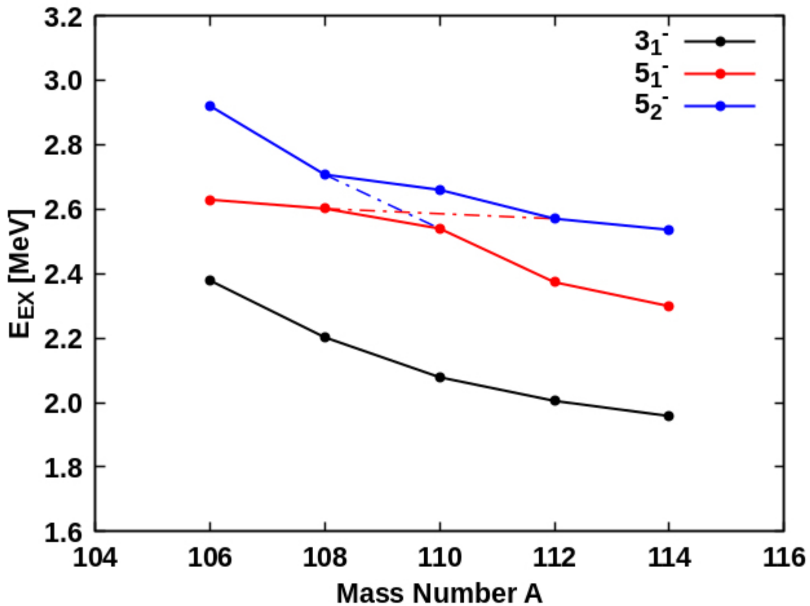
- if one assumes $B(E2; 5_2^- \rightarrow 3_1^-)$ = $B(E2; 1_1^- \rightarrow 3_1^-)$ = $B(E2; 2_1^+ \rightarrow 0_1^+)$, we obtain $B(E3; 5_2^- \rightarrow 2_1^+)$ = 7.8(1.3) W.u. and $B(E3; 1_1^- \rightarrow 2_1^+)$ = 13(3) W.u, equal within error bars to $B(E3; 3_1^- \rightarrow 0_1^+)$
- 5_2^- seems to be either a member of a rotational structure built on the 3_1^- state or result from quadrupole-octupole vibrational coupling

Negative-parity states: structure results





- B(E3; $3_1^- \rightarrow 0_1^+$) = 11(4) W.u. in agreement with D. Rhodes et al., PRC 103, L051301 (2021) (red) but in disagreement with the evaluated value of 34(9) W.u. (T. Kibedi and T. Spear, At. Data Nucl. Data Tables 80, 35 (2002))

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- 5_2^- seems to be either a member of a rotational structure built on the 3_1^- state or result from quadrupole-octupole vibrational coupling, which is also consistent with energy systematics

Can we do anything to verify our speculations?

We need:

- firm spin assignments (the presumed 3^+ state...)
- resolving closely spaced doublets of states (the story of 5^+_1...)
- reliable branching ratios (the $2^+_5 \rightarrow 0^+_3$ transition in the “oblate” band...)
- observation of very weak decay branches (E2 decays of the 5^-_2, 1^-_1 states)

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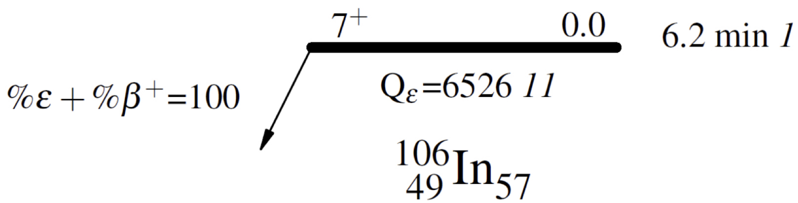
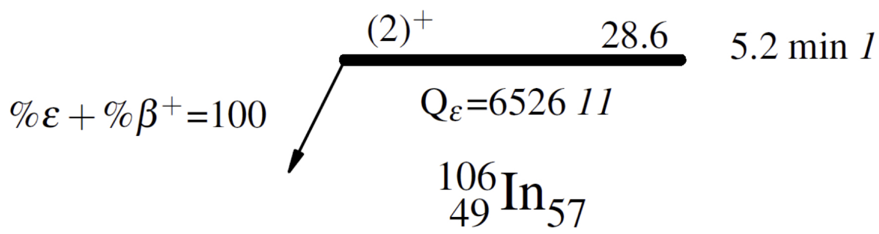
Let's do beta decay!

- ^{106}In decay – two β-decaying states cover wide spin range:

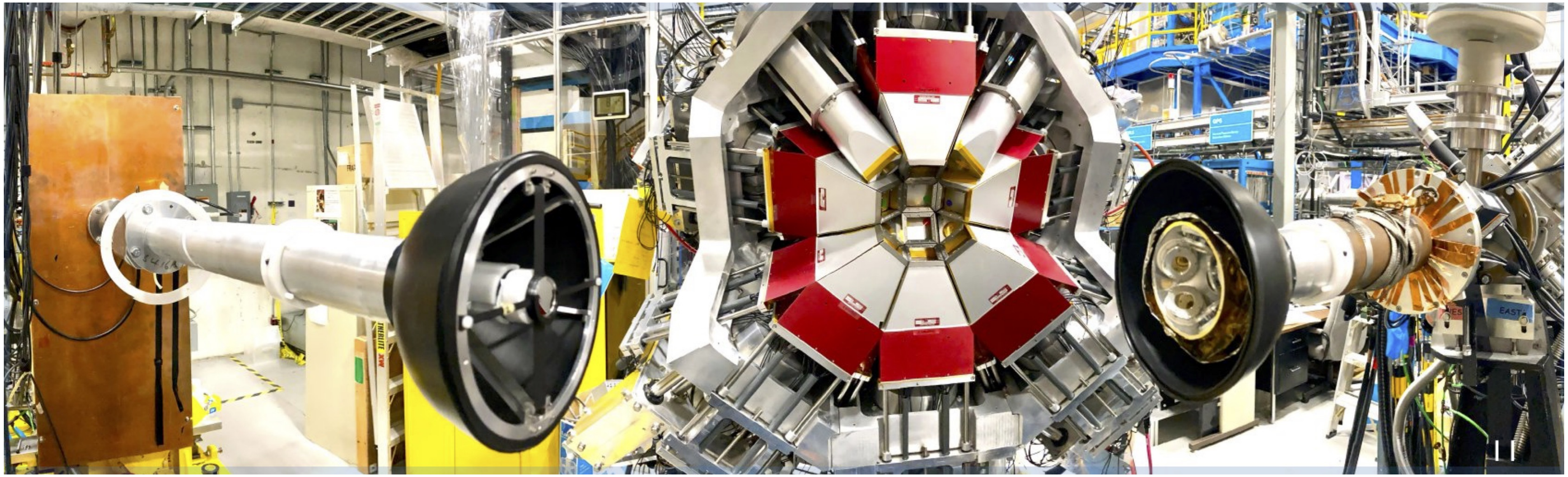




- most detailed decay study performed: B. Roussière et al., Nucl.Phys. A419, 61 (1984) (observation limit: $\sim$0.1% of the $2_1^+ \rightarrow 0_1^+$ transition, only transitions over $\sim$1% placed in the level scheme)
- calculated $5_2^- \rightarrow 3_1^-$ intensity: $5\ 10^{-5}$ of $2_1^+ \rightarrow 0_1^+$ transition – we need to go down two orders of magnitude

S2313 experiment at TRIUMF (to be scheduled – hopefully in 2025!)

Setup: GRIFFIN + PACES + ZDS + $LaBr_3$

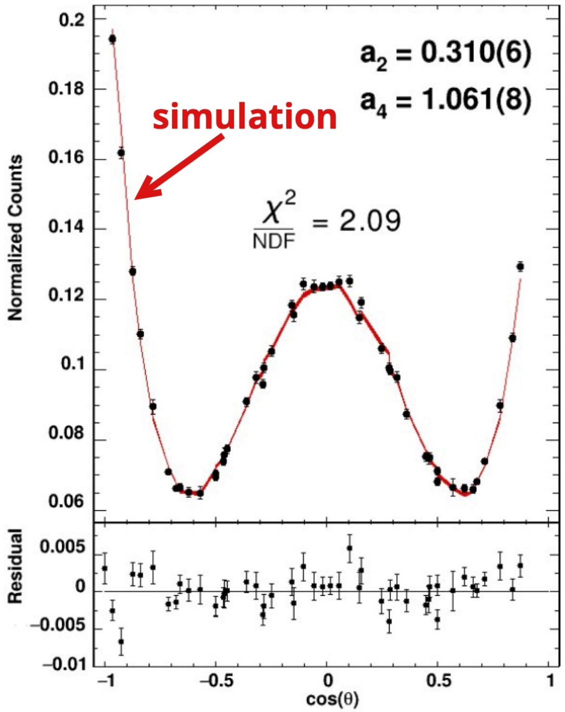


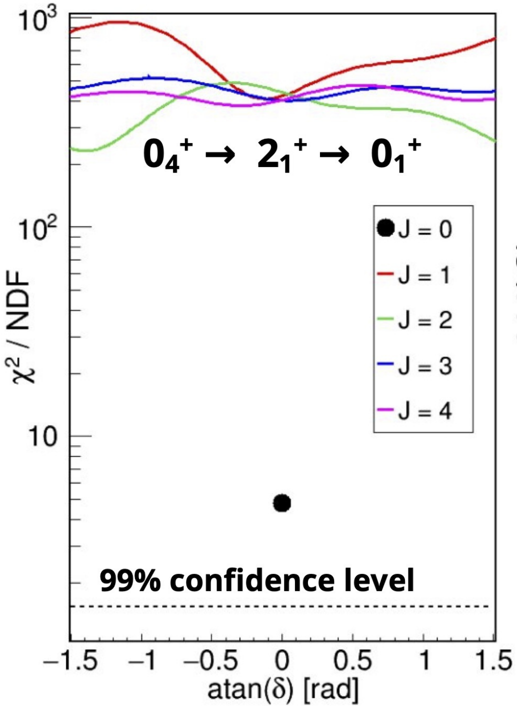
- GRIFFIN: 15 BGO-shielded clovers, 9% efficiency at 1 MeV, 49 unique angles for γ-γ correlations
- 7 $LaBr_3$ detectors – we may be able to obtain an independent measurement of the 0_3^+ lifetime (τ = 13 ps estimated from our B(E2) value)
- total $\sim 10^9$ γ-γ coincidences expected in 10 shifts (10^4 counts in the $5_2^- \rightarrow 3_1^-$ transition in coincidence with $3_1^- \rightarrow 2_1^+$)

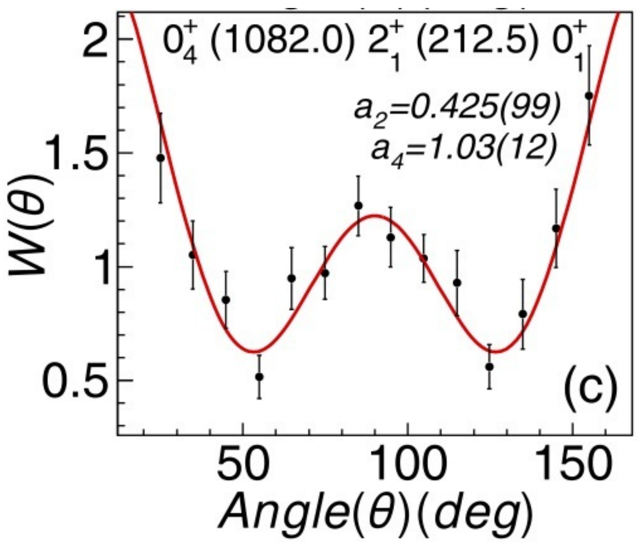
This transition (in coincidence) recently observed in β decay into ^{112}Cd with GRIFFIN

Angular correlations with GRIFFIN – example of ^{100}Zr

correction of a wrong spin assignment for the 1294-keV state in ^{100}Zr (previously assigned as $(2^{-},3)$)







D. Kalaydjieva, PhD thesis, 2023

GRIFFIN+ISAC I
4 10^9 γ-γ coincidences

J. Wu, Phys. Rev. C 109, 024314 (2024)

Gammasphere + CARIBU
4 10^8 γ-γ coincidences

Conclusions and outlook

- for the strongly populated states in ^{106}Cd we have shown that assuming pure Coulomb-excitation process we can well reproduce the experimentally measured transition intensities and extract E2 strengths that are in 1σ agreement with literature values

- there are numerous discrepancies in the level scheme of ^{106}Cd that make conclusions for higher-lying states more difficult: a new β-decay measurement approved at TRIUMF

- we obtained, in particular, new experimental information on the presumably oblate 0^+_3 and 2^+_5 states, as well as on the 3^-_1 and 5^-_2 states

- this method can be applied to analyse byproduct data of lifetime measurements using multinucleon transfer (in particular, to obtain information on states that were beyond sensitivity region of the lifetime measurement – here e.g. 2^+_4, 2^+_5)

- the observed large increase in excitation cross section would also be beneficial for experiments with radioactive beams