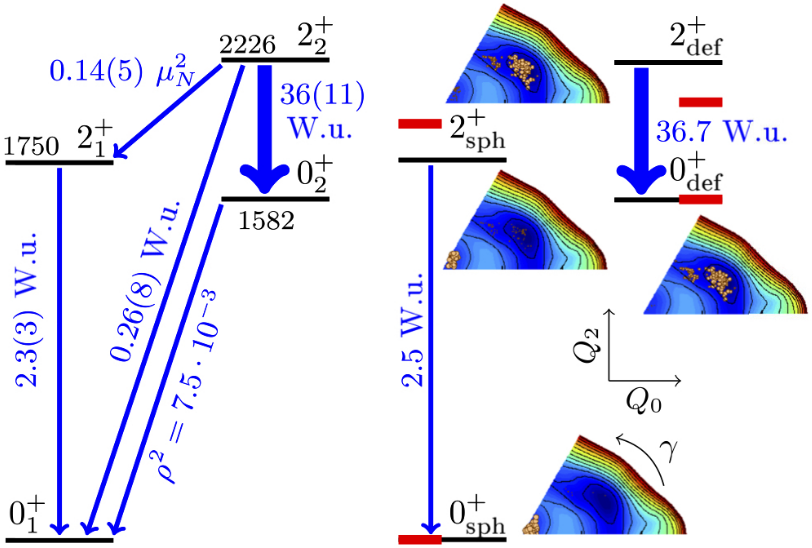
Combined lifetime and transition-probability measurements in ^{96}Zr via unsafe Coulomb excitation

Magda Zielińska, Marco Rocchini, Naomi Marchini,
Jose Javier Valiente Dobón,...

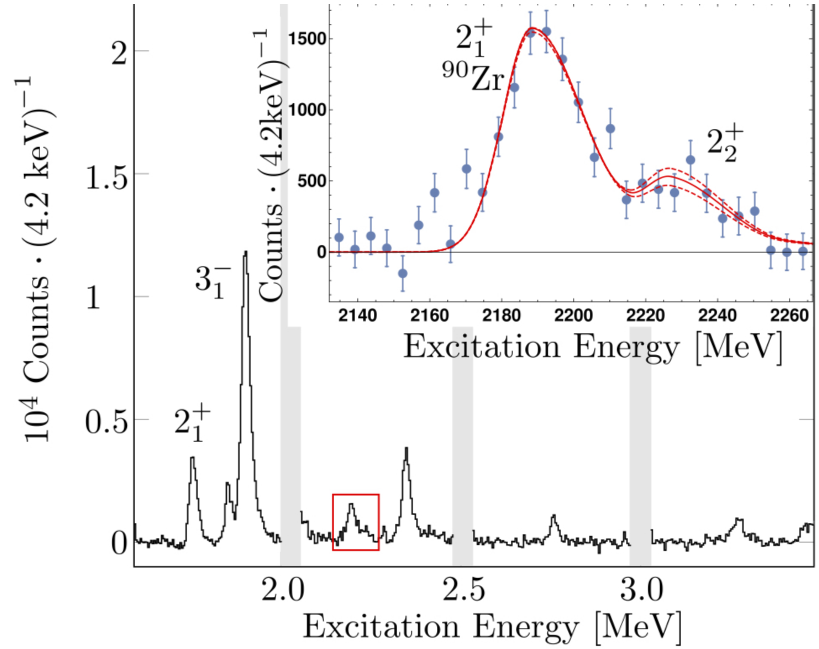
Physics case:

quadrupole and octupole collectivity in ^{96}Zr

Shape coexistence in ^{96}Zr – experimental information

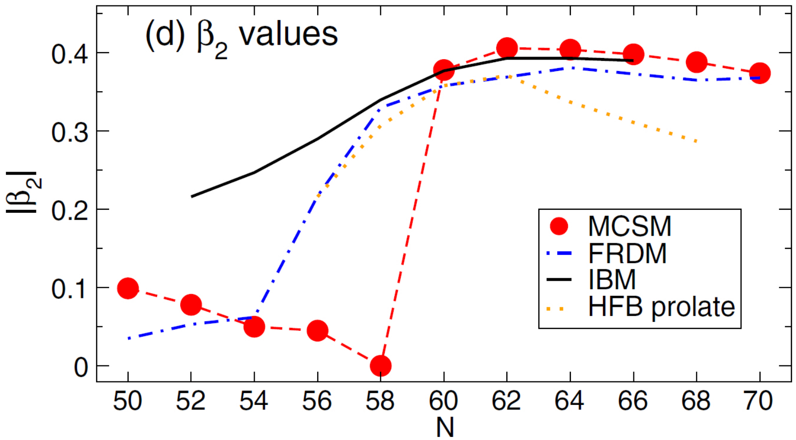


S. Kremer et al, Phys. Rev. Lett. 117 (2017) 172503



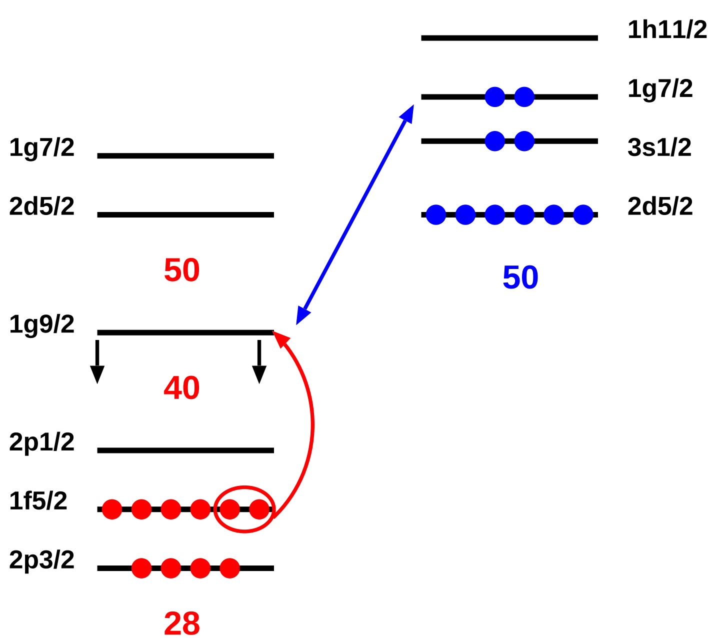
- B(E2; $2_2^+ \to 0_1^+$) measured using electron scattering, combined with known branching and mixing ratios:
  $\rightarrow$transition strengths from the 2_2^+ state
- B(E2; $2_1^+ \to 0_1^+$) = 2.3(3) Wu vs B(E2; $2_2^+ \to 0_2^+$) = 36(11) Wu: nearly spherical and a well-deformed structure ($\beta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

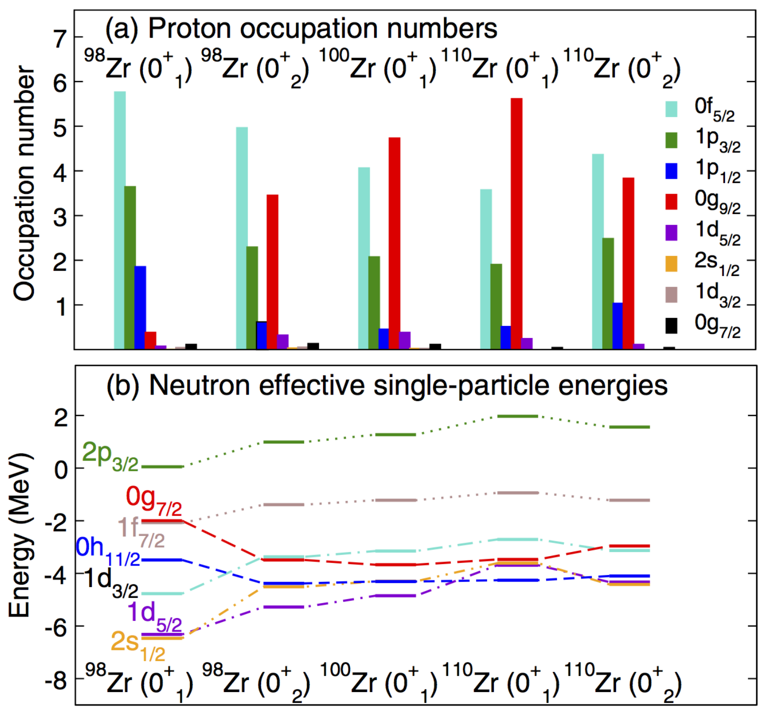
Shape coexistence and type-II shell evolution in Zr isotopes



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

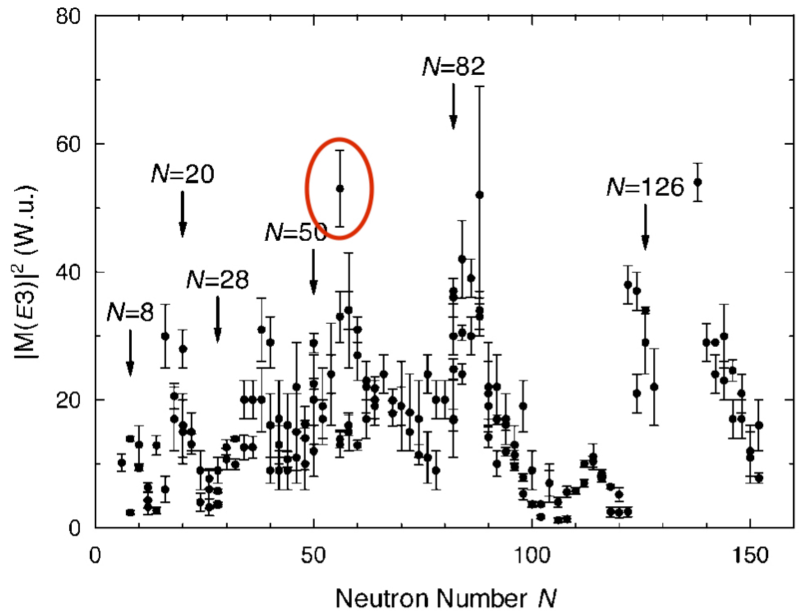




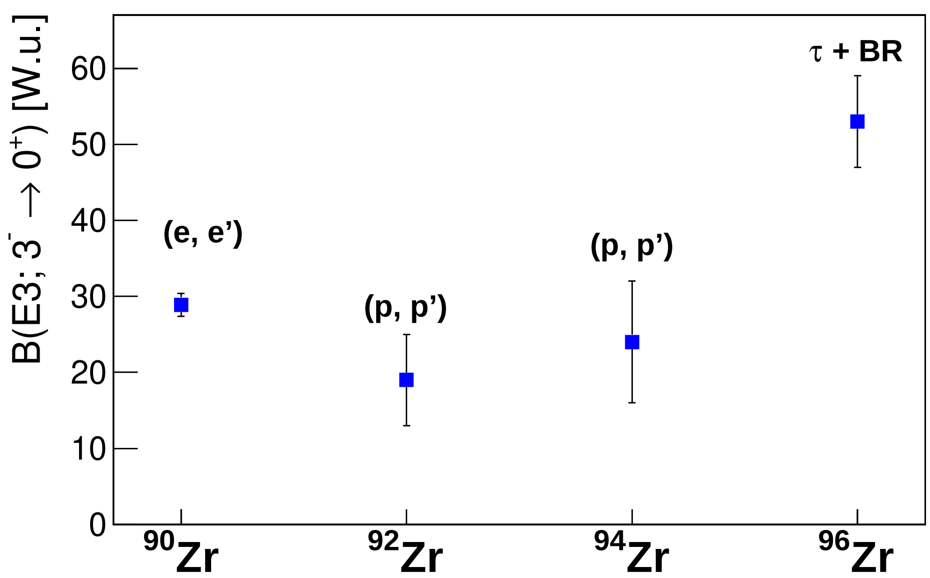
Octupole collectivity in Zr isotopes: anomalous value for ^{96}Zr

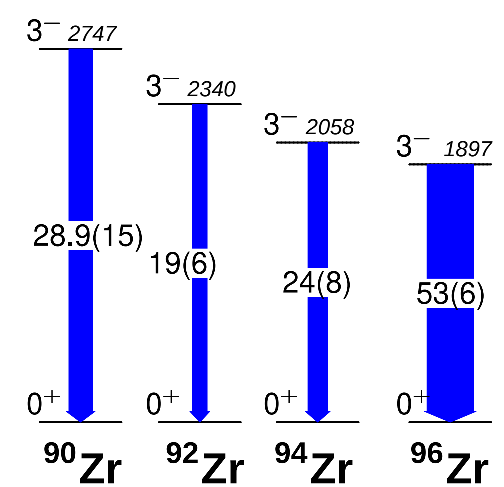
- evaluated B(E3; $3^-_1 \rightarrow 0^+_1$) strength for ^{96}Zr strikingly high (53(6) W.u.), comparable with those known for nuclei with rigid pear shapes

- observed trend of B(E3; $3^-_1 \rightarrow 0^+_1$) values in Zr isotopes inconsistent with 3^-_1 energies and hard to explain



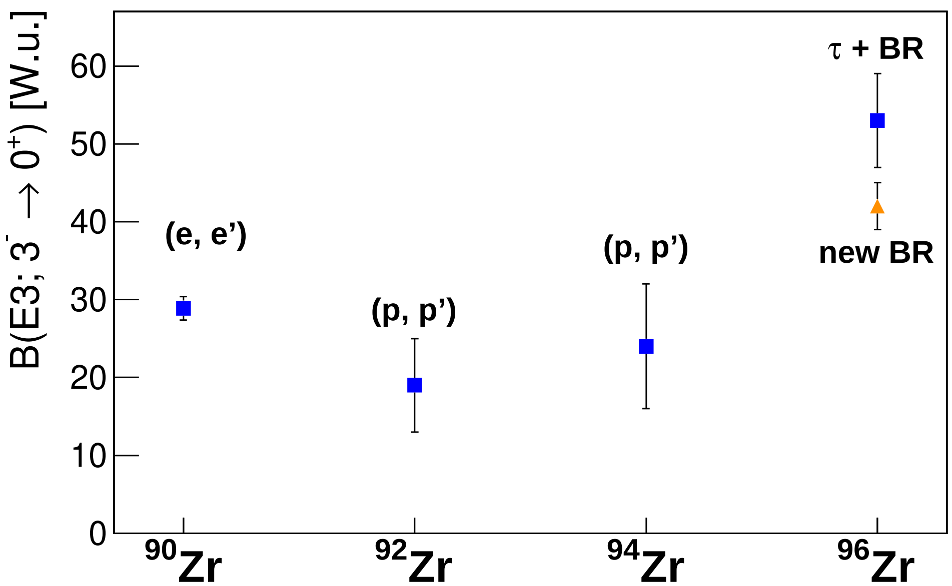
T. Kibédi and R.H. Spear, At. Data Nucl. Data Tables 80, 35 (2002)

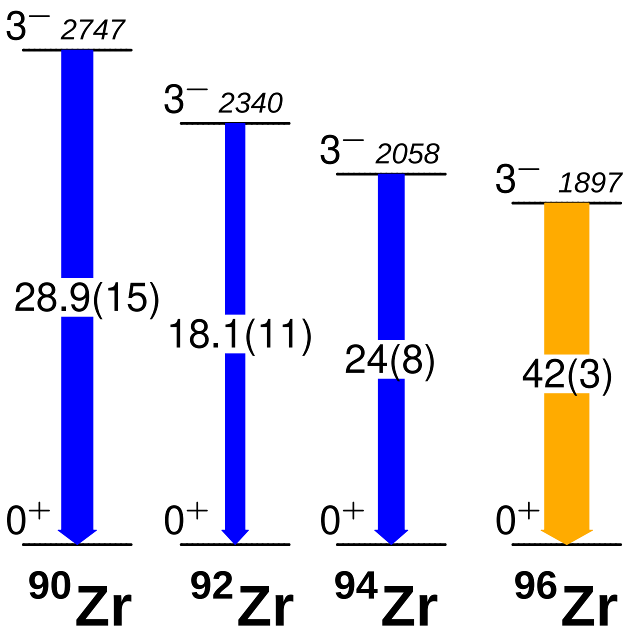




Octupole collectivity in Zr isotopes: new BR measurement for ^{96}Zr

- new measurement of E1/E3 branching ratio in ^{96}Zr (Ł. Iskra et al, Phys. Lett. B 788 (2019) 396) points to lower octupole collectivity, but the overall trend remains puzzling



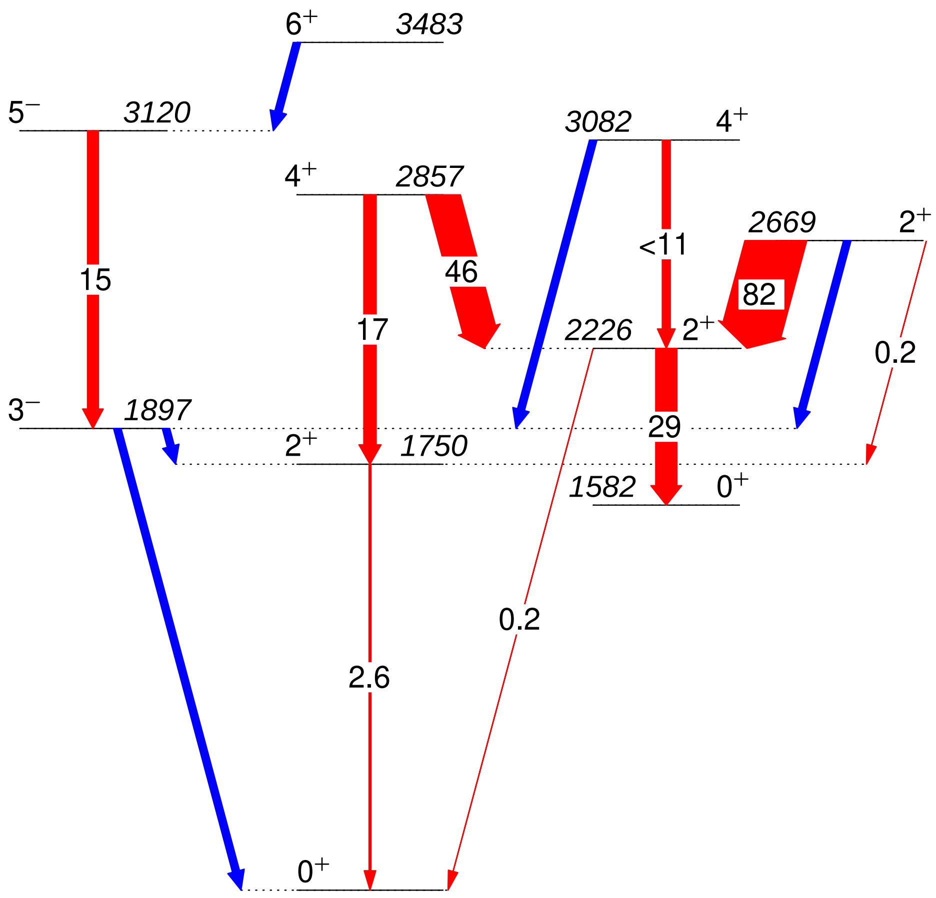


- need to verify the 3^- lifetime

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; in particular, the 6^+ state decays predominantly via E1; is it related to a two-phonon octupole vibration?



Method:

unsafe Coulomb excitation combined with RDDS

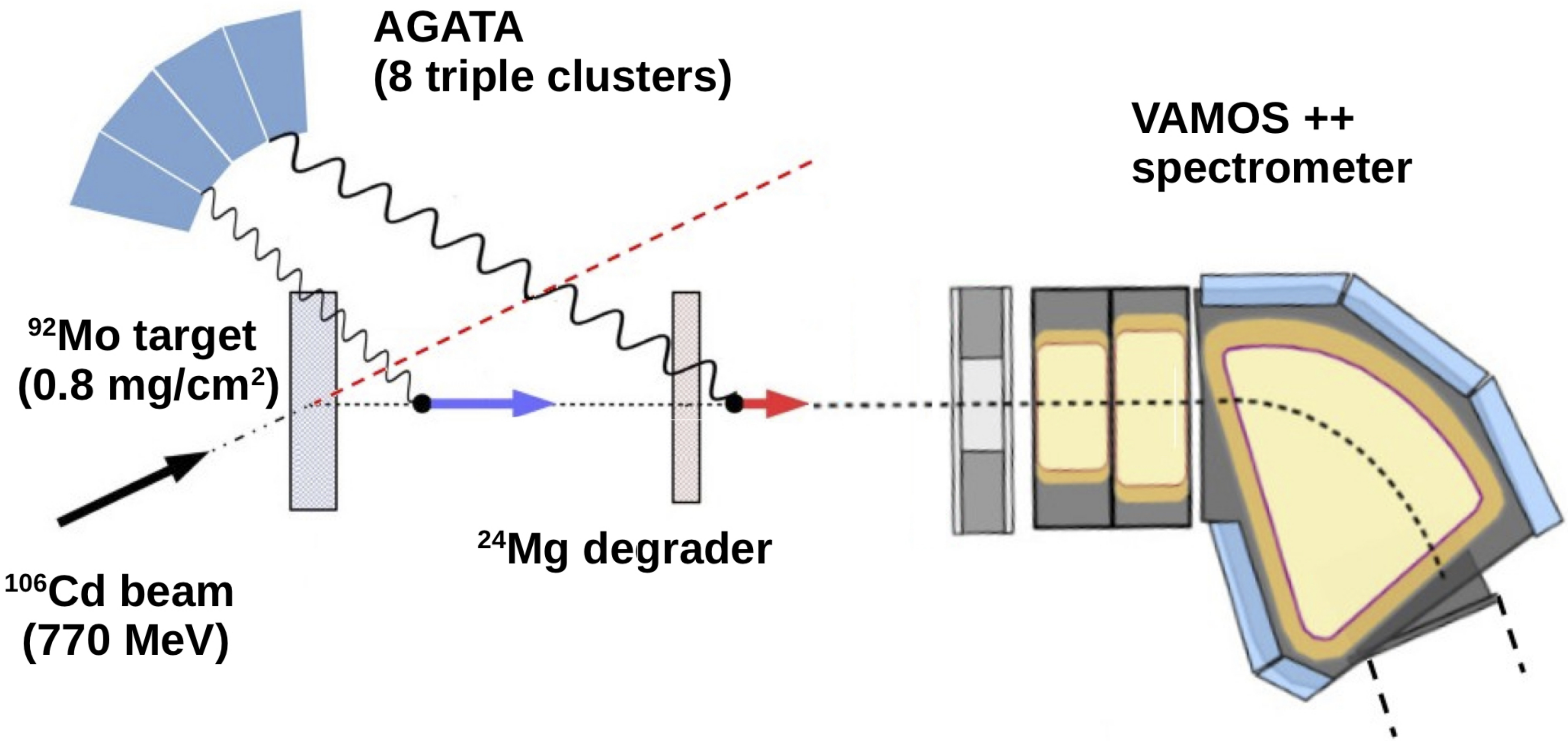
(^{106}Cd at GANIL: proof of principle)

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)

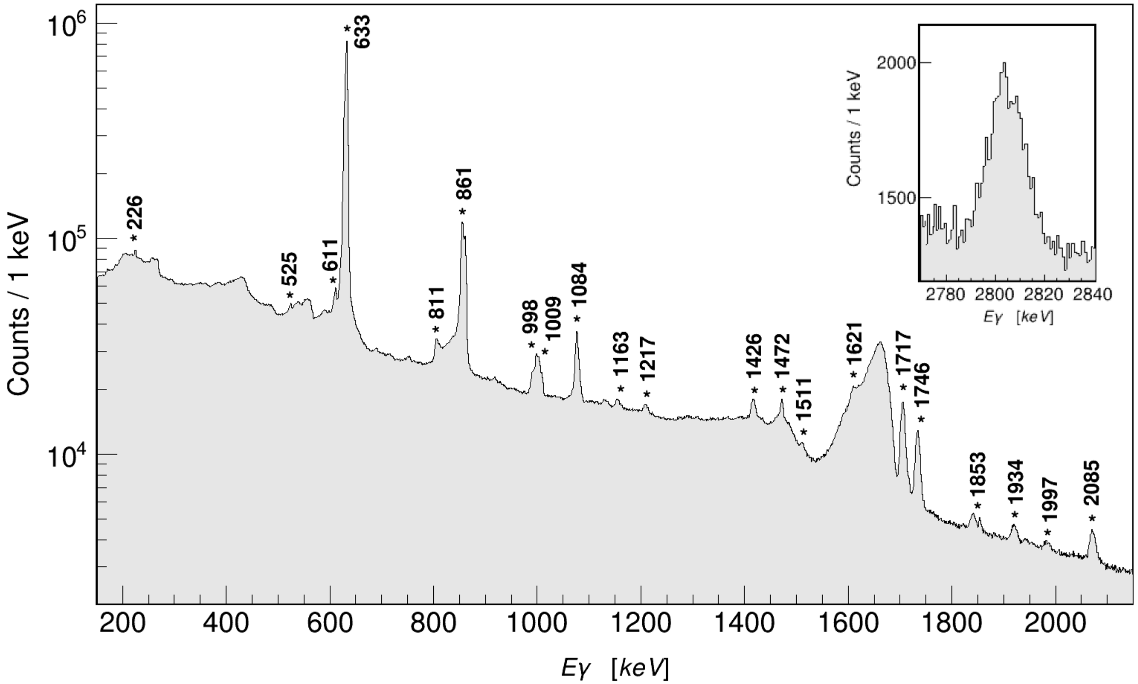
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021)

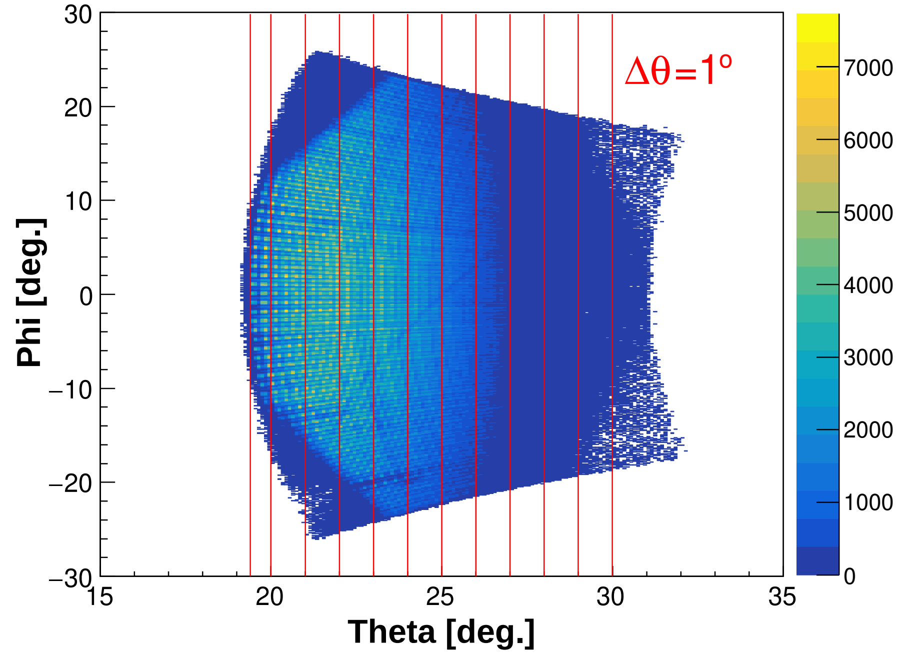


- VAMOS at grazing angle (25°); lowest observed scattering angle (19.4°) corresponding to 107% of Cline's safe energy

Experiment

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

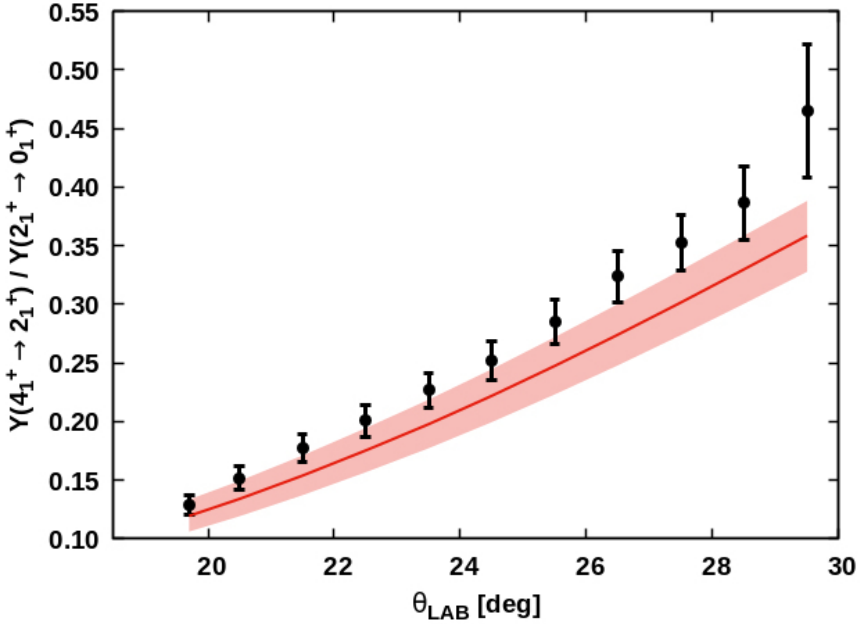




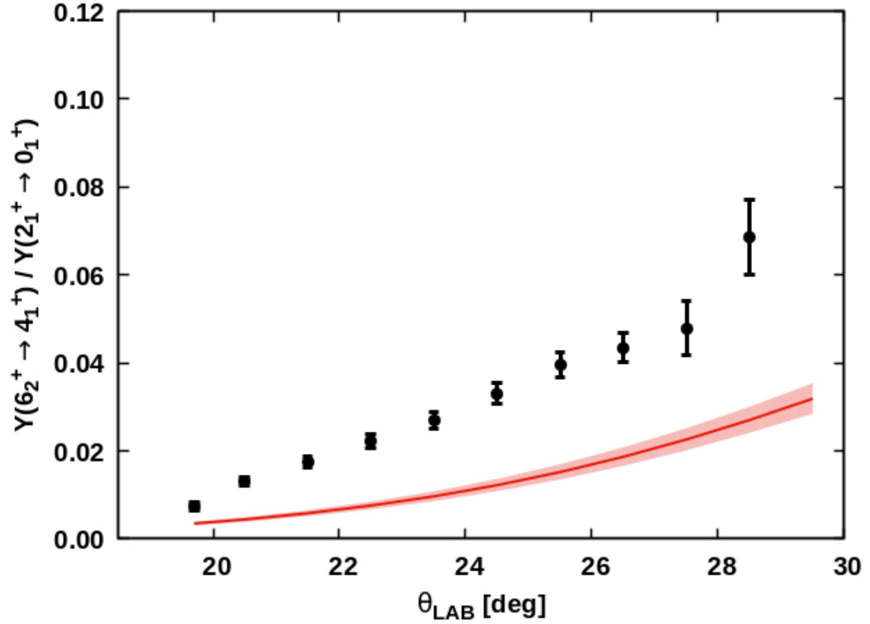
- ^{106}Cd ions identified in VAMOS with $19.4^{\circ} \leq \theta_{\mathrm{LAB}} \leq 30^{\circ}$ (Cline's criterion fulfilled for $\theta_{\mathrm{LAB}} \leq 18^{\circ}$)
- we apply gates on θ_{LAB} with 1° width to study the dependence of the excitation cross sections on scattering angle
- due to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

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



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

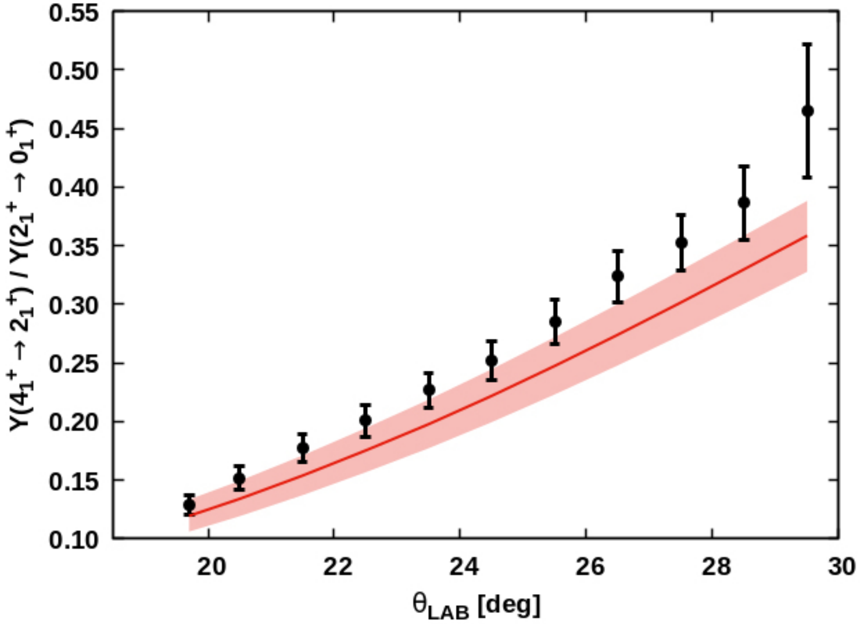


- reasonable agreement with literature data for 4_1^+ (weighted average of measured lifetimes)
- lifetime of the 6_2^+ state deduced from the same data as our transition intensities (M. Siciliano et al., Phys. Rev. C 104, 034320 (2021) is not consistent with the measured intensity ratios

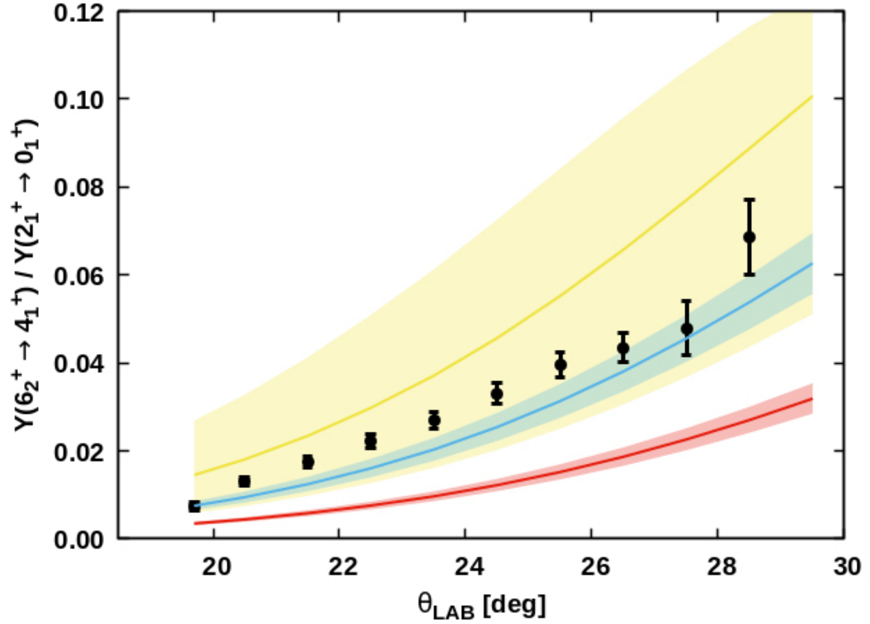
D. Kalaydjieva, PhD thesis, 2023

Sample results (strongly populated states)

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



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

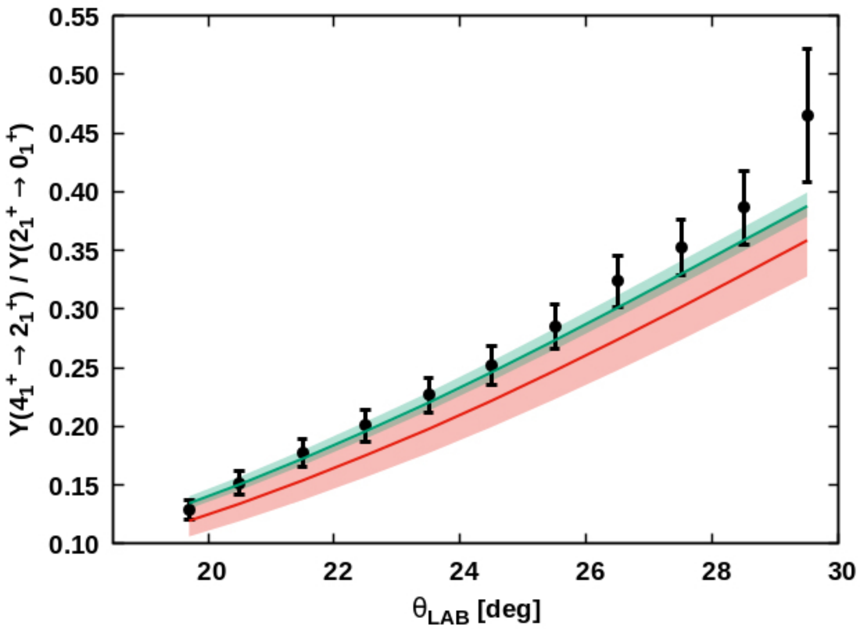


- much better agreement for the 6^+_2 state if we assume:
  - $\langle 6^+_2 \| E2 \| 4^+_1 \rangle$ matrix element from Coulomb excitation (D. Rhodes et al., Phys. Rev. C 103, L051301 (2021))
  - or 6^+_2 lifetime from (n,n'γ) (A. Linnemann, PhD thesis, University of Cologne, 2005 – but here the uncertainty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

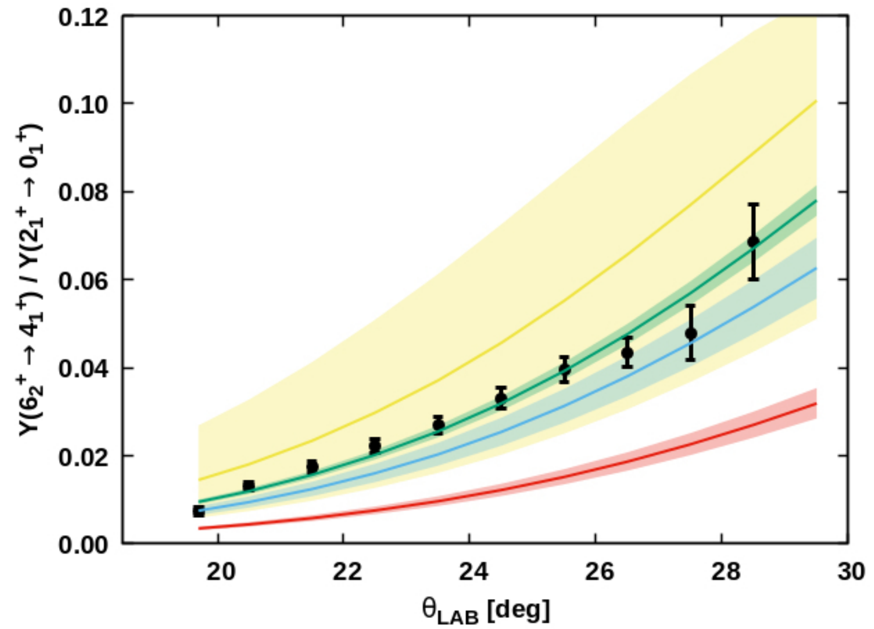
D. Kalaydjieva, PhD thesis, 2023

Sample results (strongly populated states)

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



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



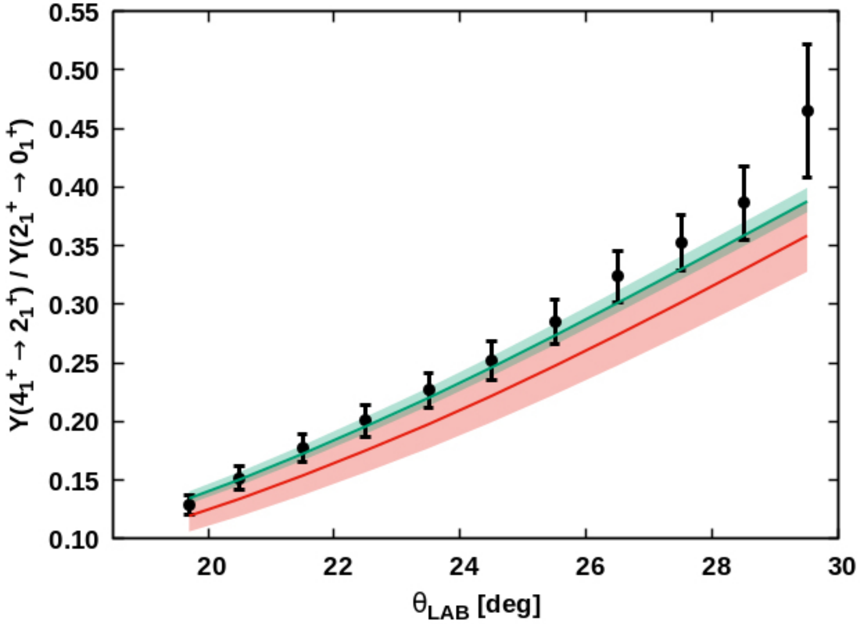
- finally, we can try to fit a set of matrix elements to the first few points of the cross-section distribution, and compare the resulting lifetimes:

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

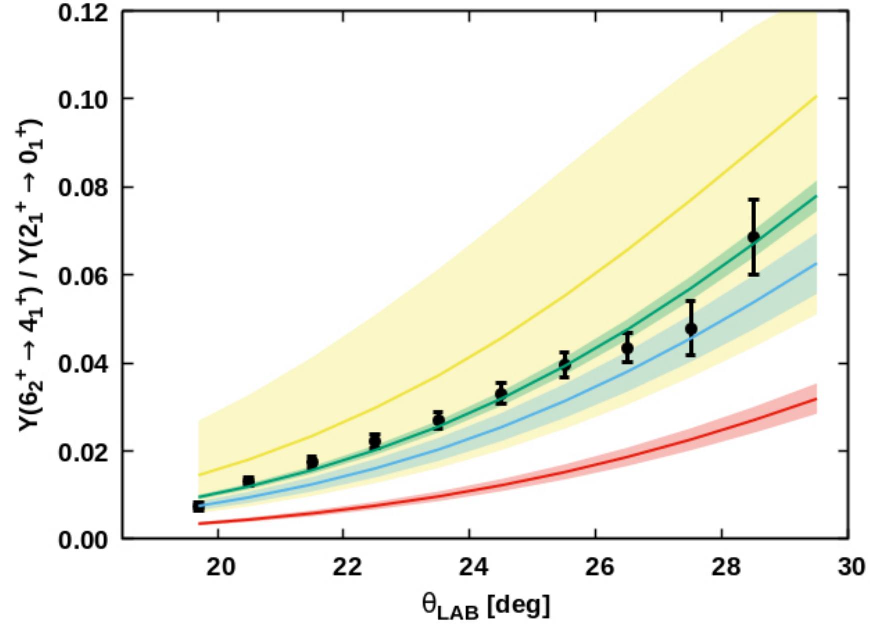
6_2^+ – GOSIA fit: 0.48(3) ps
M. Siciliano et al., Phys. Rev. C 104, 034320 (2021): 1.22(15) ps
D. Rhodes et al., Phys. Rev. C 103, L051301 (2021): 0.54(8) ps

Sample results (strongly populated states)

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



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



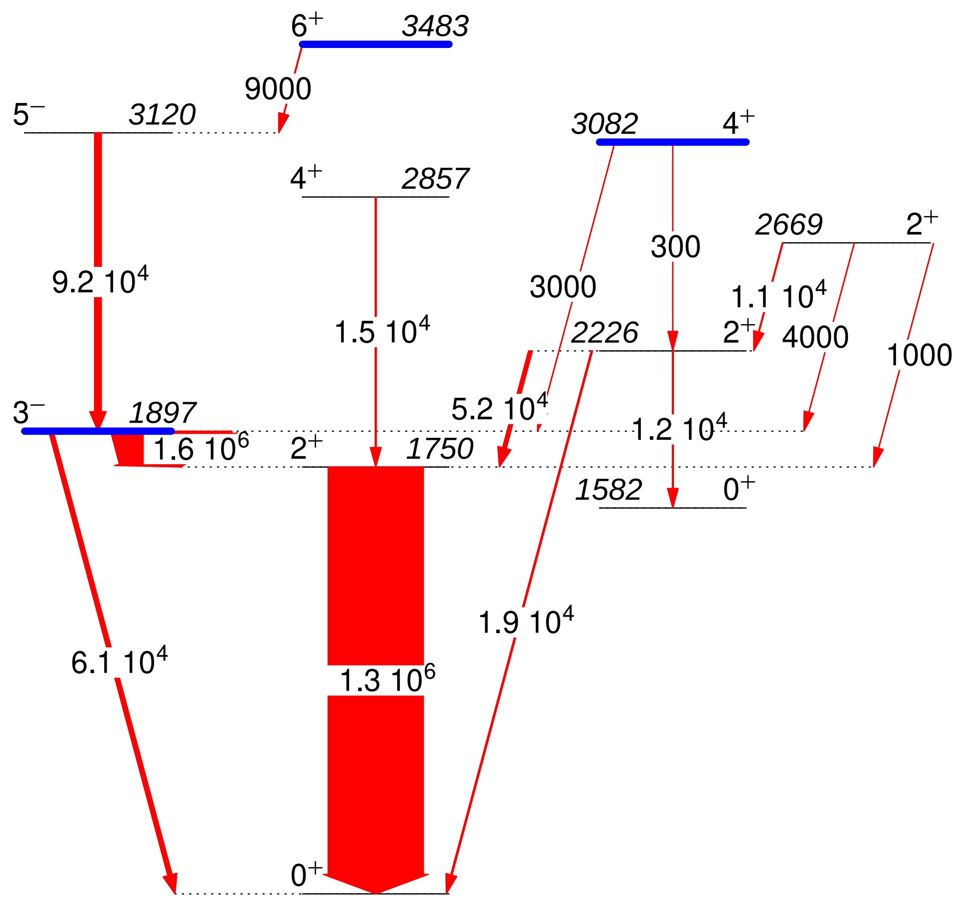
- similar analysis has been applied to all observed states, yielding B(E2) values complementary to those obtained from the RDDS analysis of the same date
- contrary to RDDS, it was possible to obtain B(E2) values for the decay of states that have lifetimes shorter than 1 ps

D. Kalaydjieva, PhD thesis, 2023

Proposed experiment

Counting rates

- PRISMA at 30°; 24°–27° “safe” Coulomb excitation, 27°–36° enhanced cross sections (up to 19% over Cline’s “safe” energy)
- 1 mg/cm^2 ^{116}Sn target on a light backing (^{24}Mg?) Light degrader (again ^{24}Mg?)
- grazing angle 40° – we do not want to open other reaction channels; rate of ^{96}Zr ions in PRISMA – 6kHz, 600 gamma-particle coincidences.



rates per day; blue – states within reach of a RDDS measurement

Expected results and complementary measurements

- Lifetimes of 6^+, 3^- states – octupole collectivity, testing the two-phonon vibration hypothesis in conjunction with the measured E3/E1 branching ratio (23.011)
- Lifetime of 4_2^+, E2 and E3 strengths involving 2_2^+, 2_3^+, 4_1^+, 4_2^+, 6_1^+, 3_1^-, 5_1^- – testing the above + type-II shell-evolution scenario
- Cross-section evolution in the ^{96}Zr + ^{116}Sn system over the “safe” energy – can we apply this method in the future to radioactive beams?

- Complementarity:
  - “safe” Coulomb excitation of ^{96}Zr (22.18) – current project is not sensitive to quadrupole moments, but will offer enhanced cross sections for higher-lying states
  - (p,p’) on ^{96}Zr (23.011) – we aim to measure the 6^+ lifetime, 23.011 will search for the direct $6^+ \rightarrow 3^-$ decay
  - β decay into ^{96}Zr (TRIUMF, December 2023) – precise measurement of branching and mixing ratios in the decay of spin-0,1,2,3 states (we will reach higher in spin)