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Studies of the structures of ^{118,120}Cd using ^{118,120}Ag β-decay of laser-selected isomers

Paul Garrett[1,2], Thomas Cocolios[2],
Adriana Nannini[3], Magda Zielinska[4]
[1]University of Guelph
[2]KU Leuven
[3]INFN Firenze
[4]CEA Saclay

The “evolution” of the structure of the Cd isotopes

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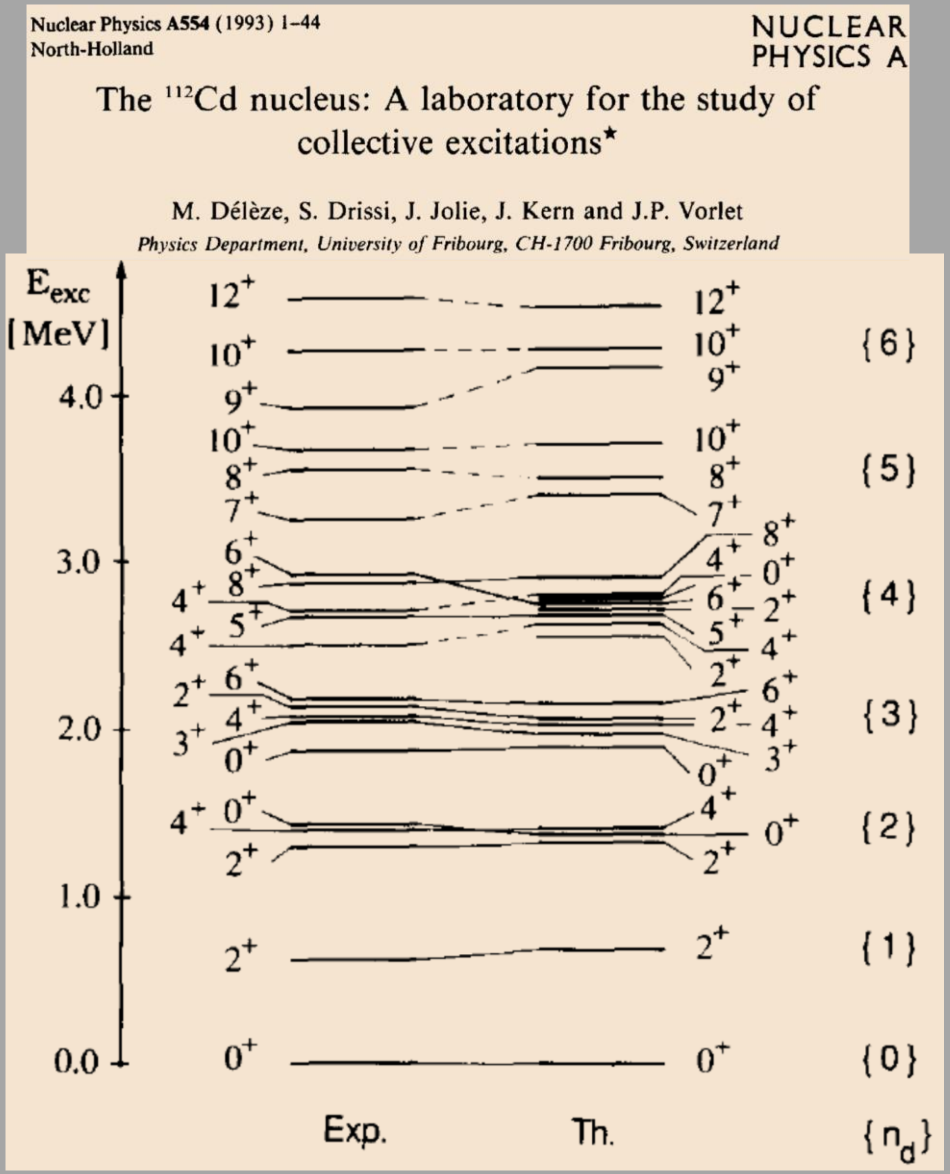
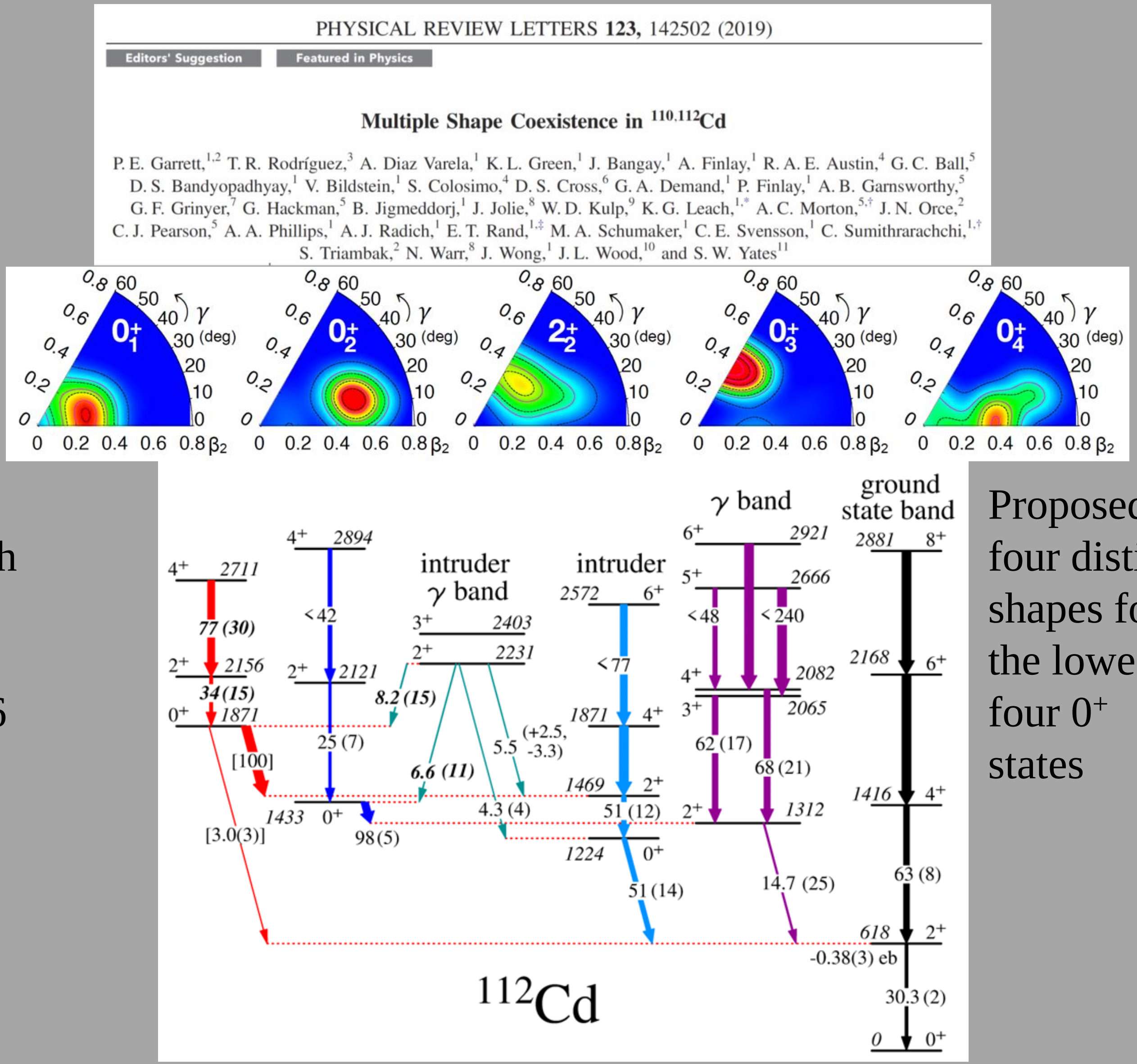
- From spherical vibrators….

…to deformed with multiple shapes

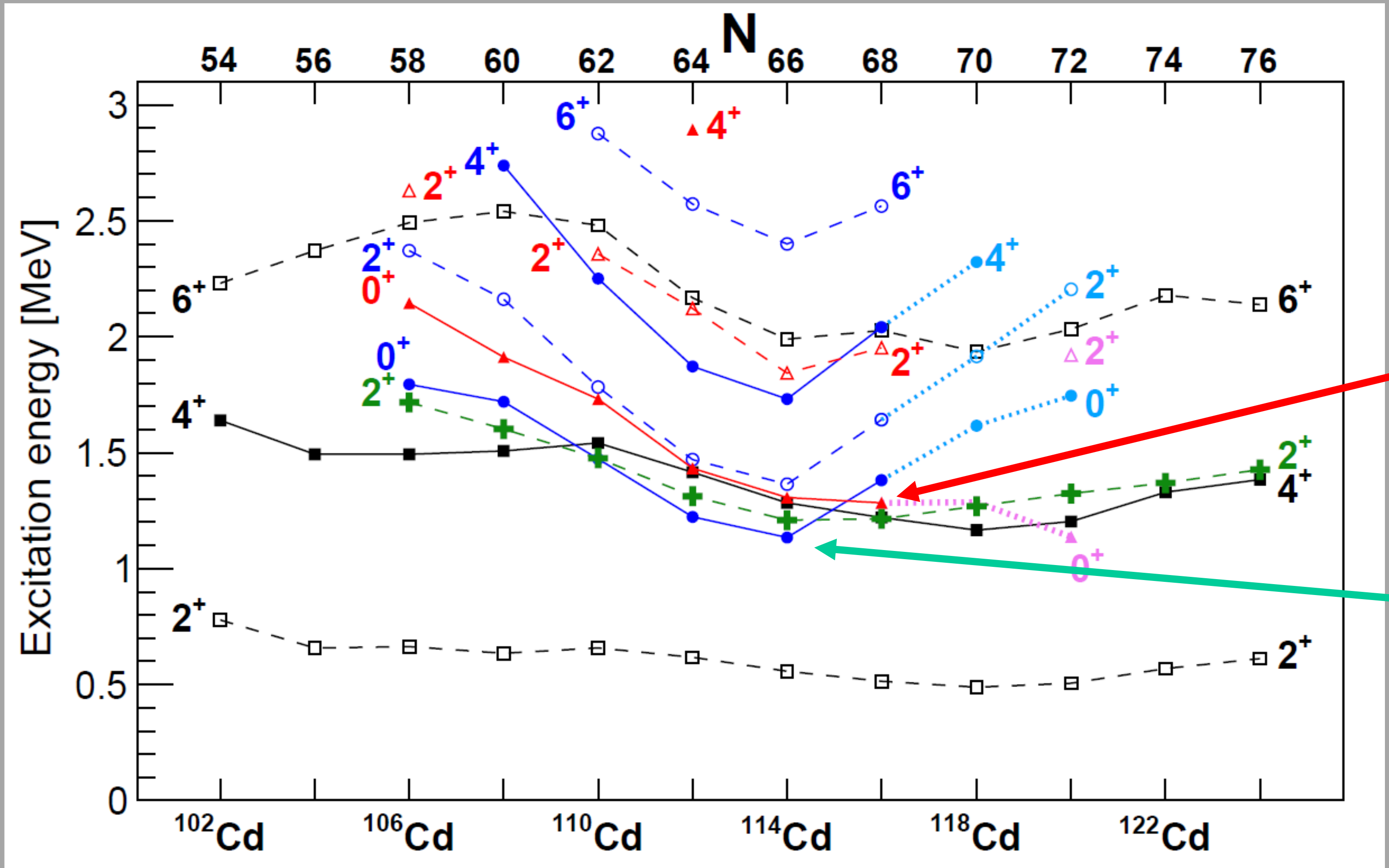


Proposed states with phonon number up to N=6



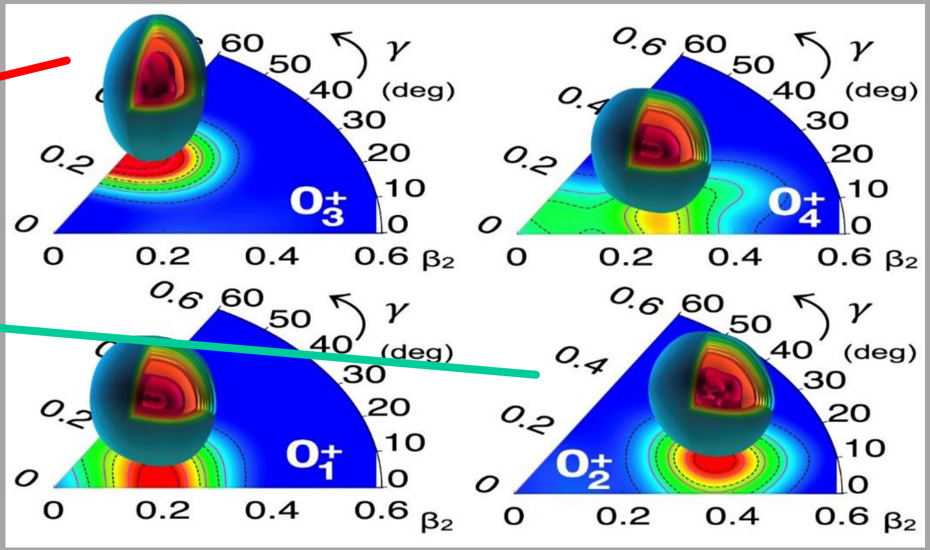
Proposed four distinct shapes for the lowest four 0^+ states

Energy systematics Cd isotopes



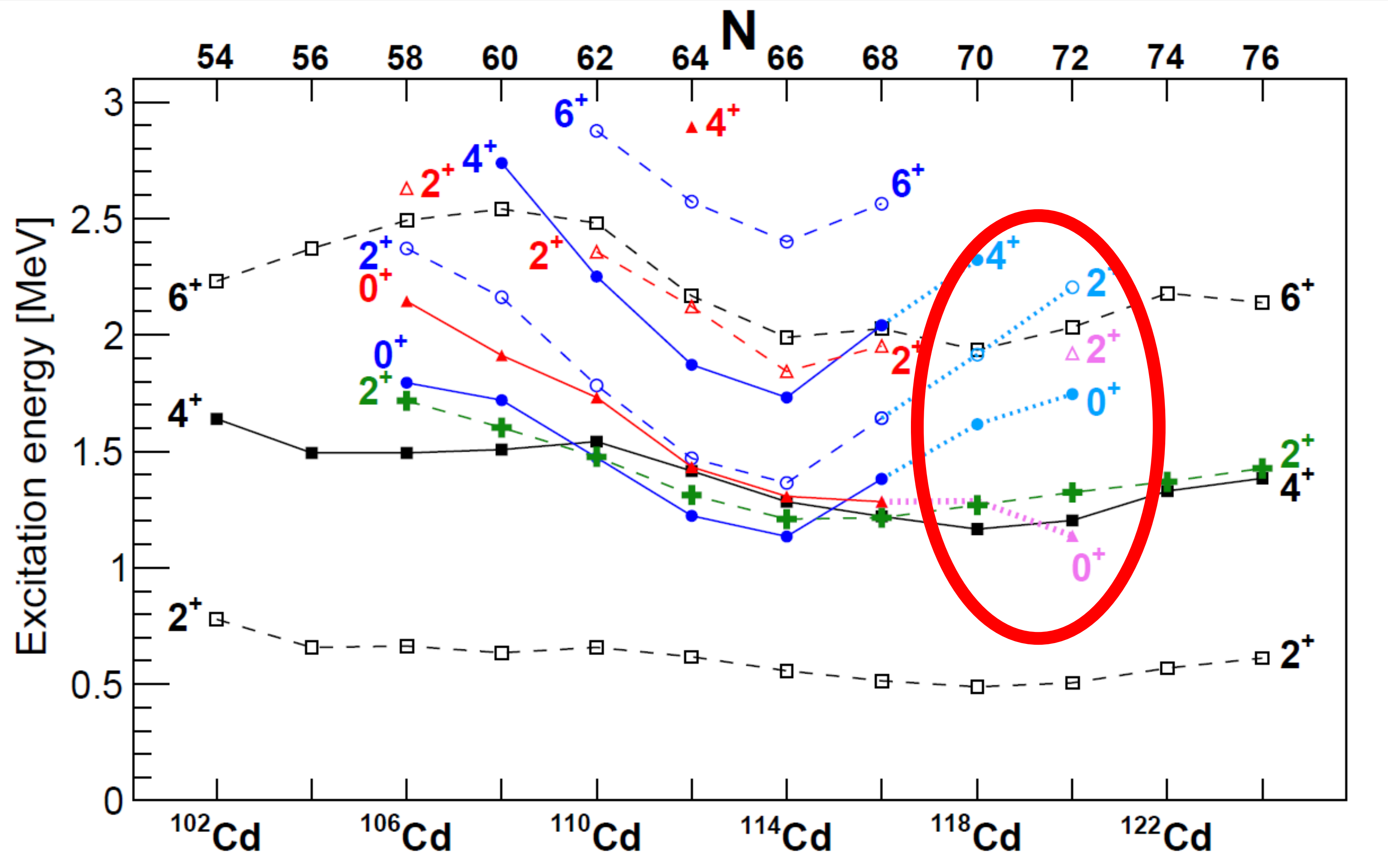
"Blue" states – the original "intruder" band, triaxial shape in ^{110,112}Cd from BMF calculations

"Red" states – oblate band in ^{110,112}Cd from BMF calculations



The presumed shapes are based on systematics and similarities of decay properties – but become increasingly uncertain towards the neutron rich isotopes

Energy systematics Cd isotopes



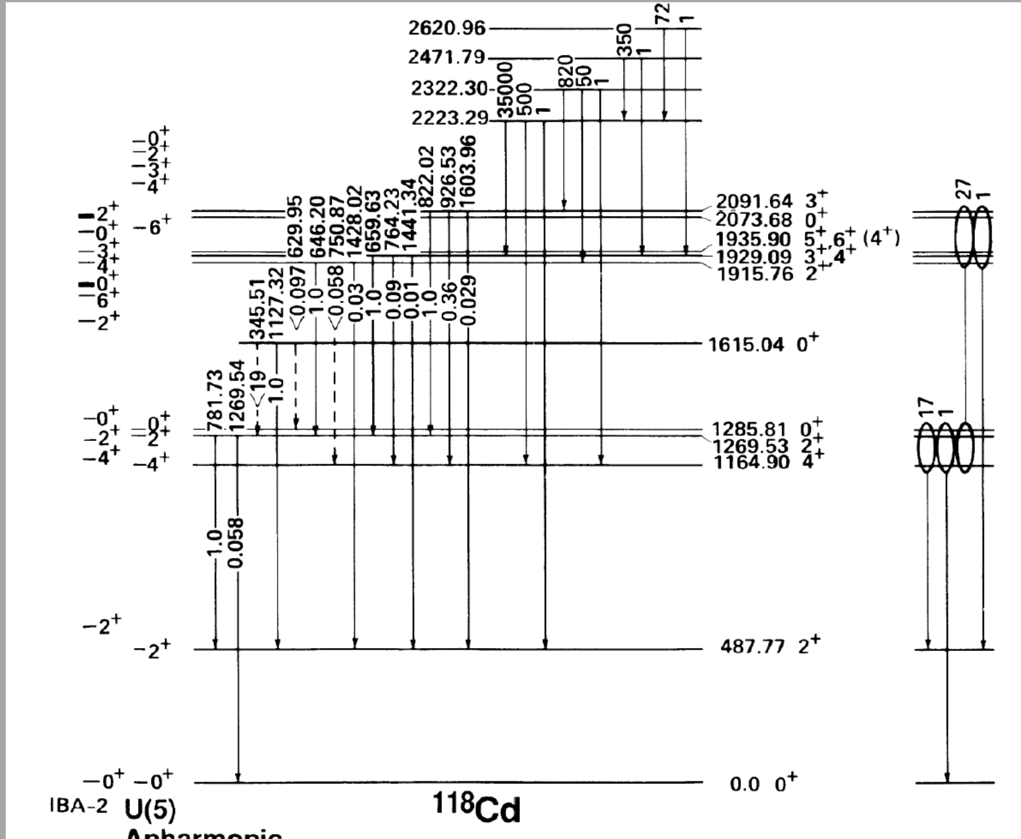
What is happening with the 0_2^+ state in ^{120}Cd? If the recent measurement is correct, it undergoes a significant drop in energy in ^{120}Cd.

There is no good candidate for the 2^+ state built on the 0_2^+ state in ^{118}Cd, implying that it remains unobserved, or other states must be re-interpreted.

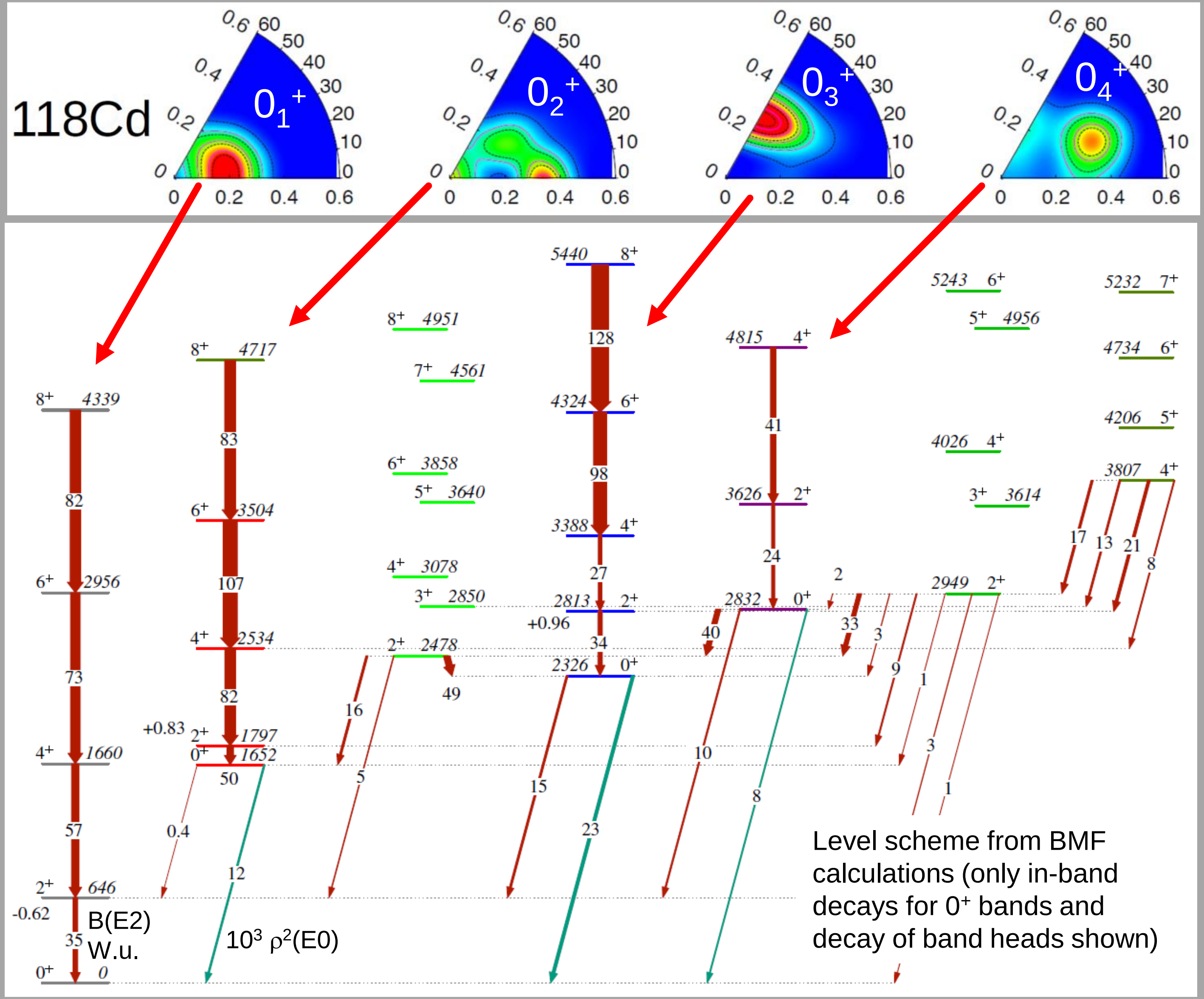
Just off stability, and we do not have a good understanding of the structure

^{118}Cd – a “nearly harmonic nucleus”, or multiple shape coexistence?

- ^{118}Cd has been cited in texts (e.g., R.F. Casten “*Nuclear Structure from a Simple Perspective*”) as an example of spherical vibrational motion

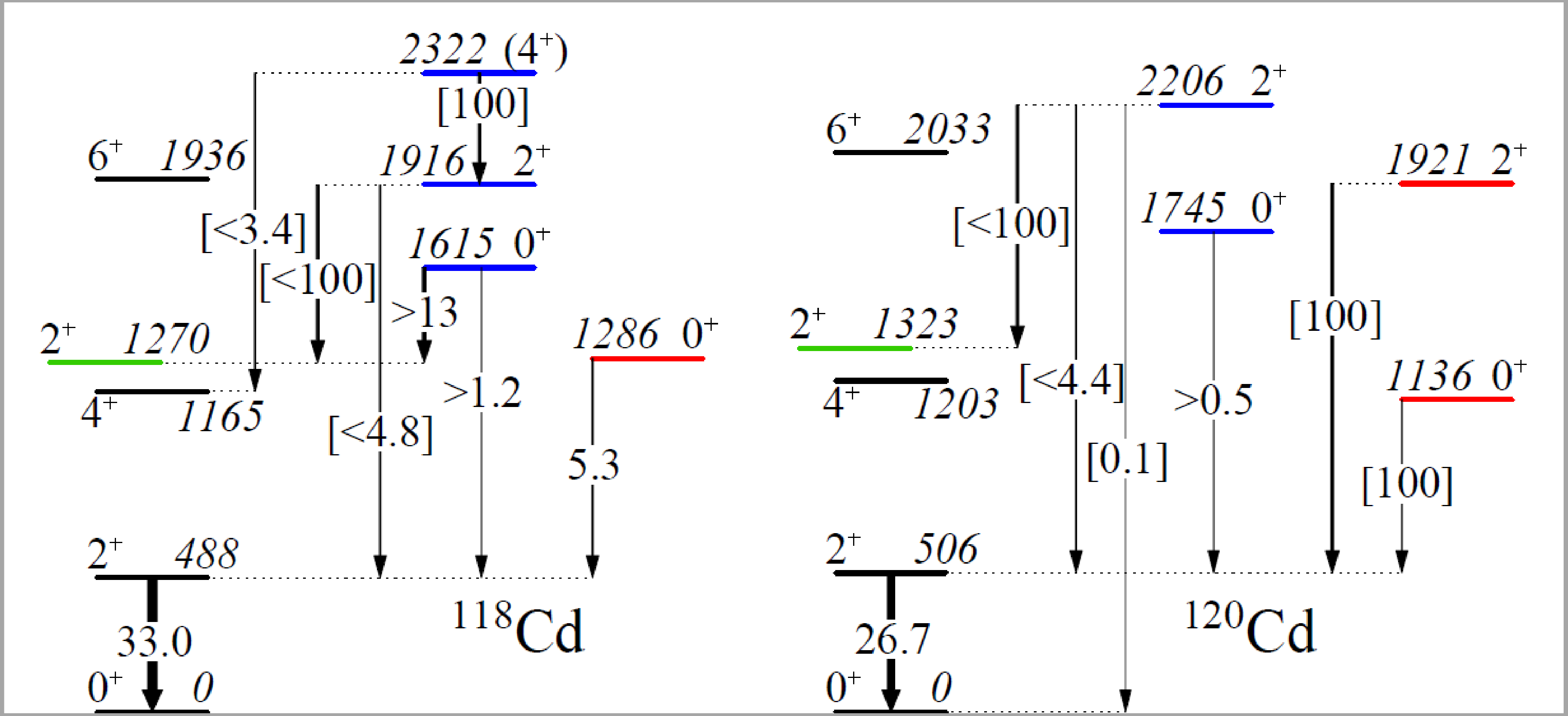


A. Aprahamian et al., PRL 59, 535 (1987).



Level schemes of ^{118,120}Cd not firmly established

- Knowledge of ^{118}Cd has not substantially improved since the 1980s, when it was assigned as a “nearly harmonic” vibrational nucleus
- ^{120}Cd recently studied at ORNL – refuted the previous 0_2^+ state at 1339 keV, and suggested a new 0^+ state at 1136 keV



Transitions labelled with B(E2) values (W.u.) or relative values in [ ]

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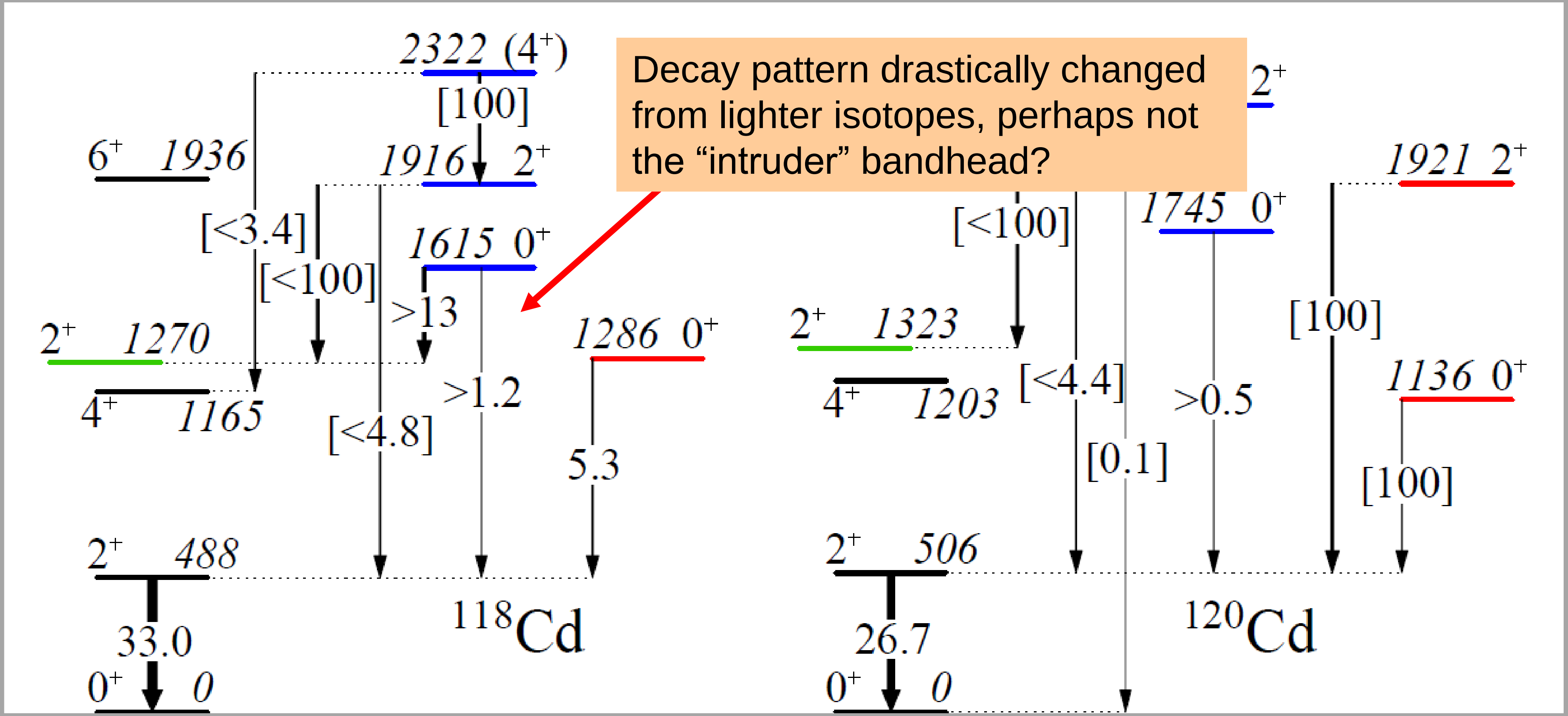

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Level schemes of ^{118,120}Cd not firmly established

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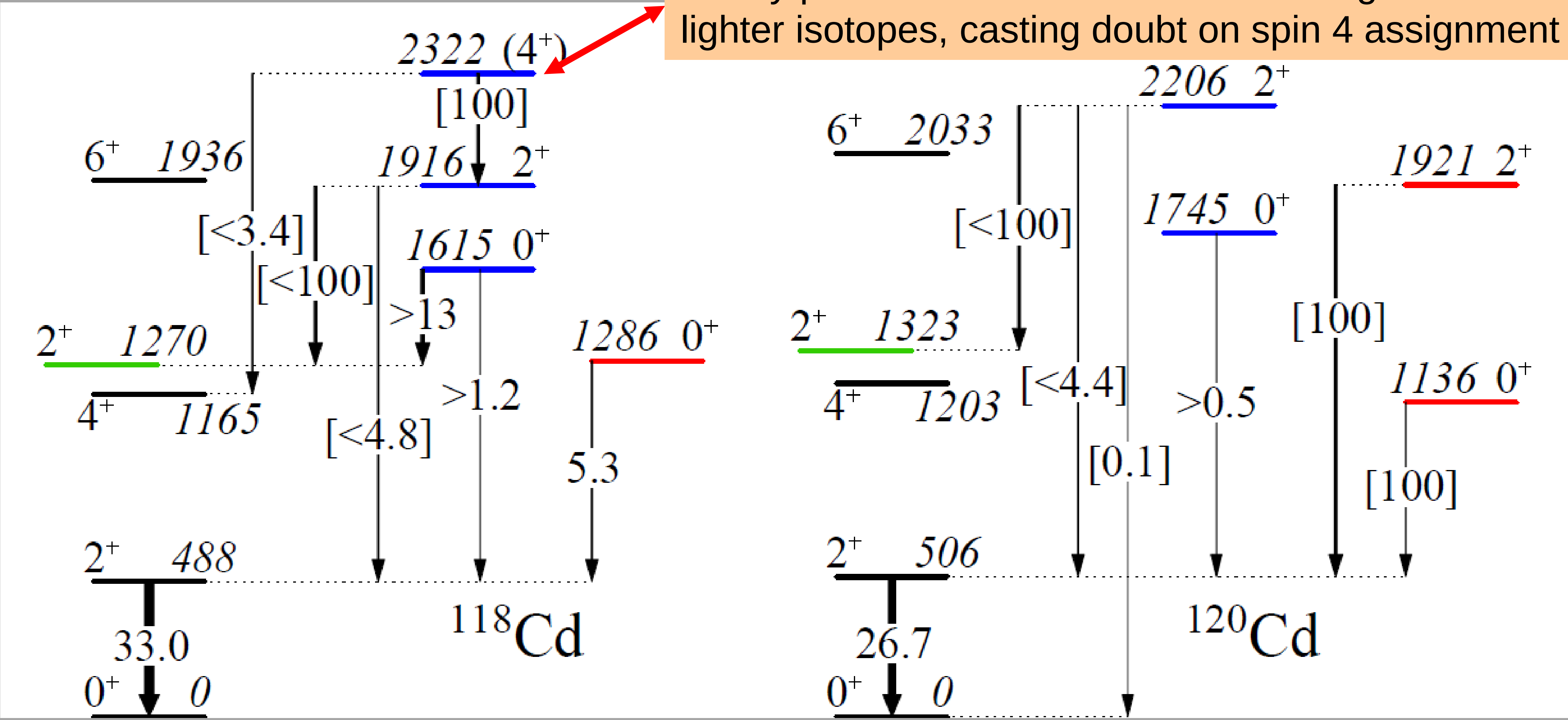
Decay pattern of 4+ band member changed from lighter isotopes, casting doubt on spin 4 assignment



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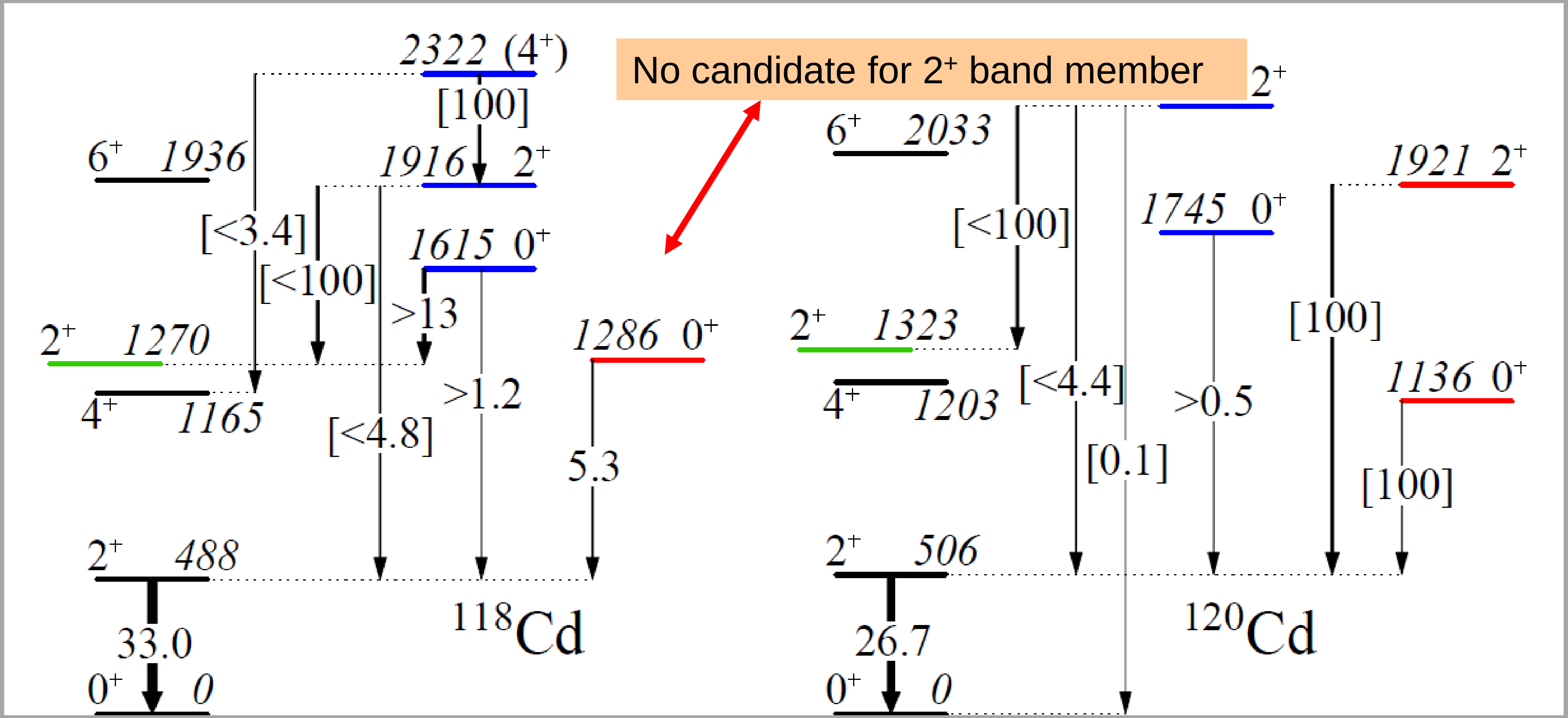

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Level schemes of ^{118,120}Cd not firmly established

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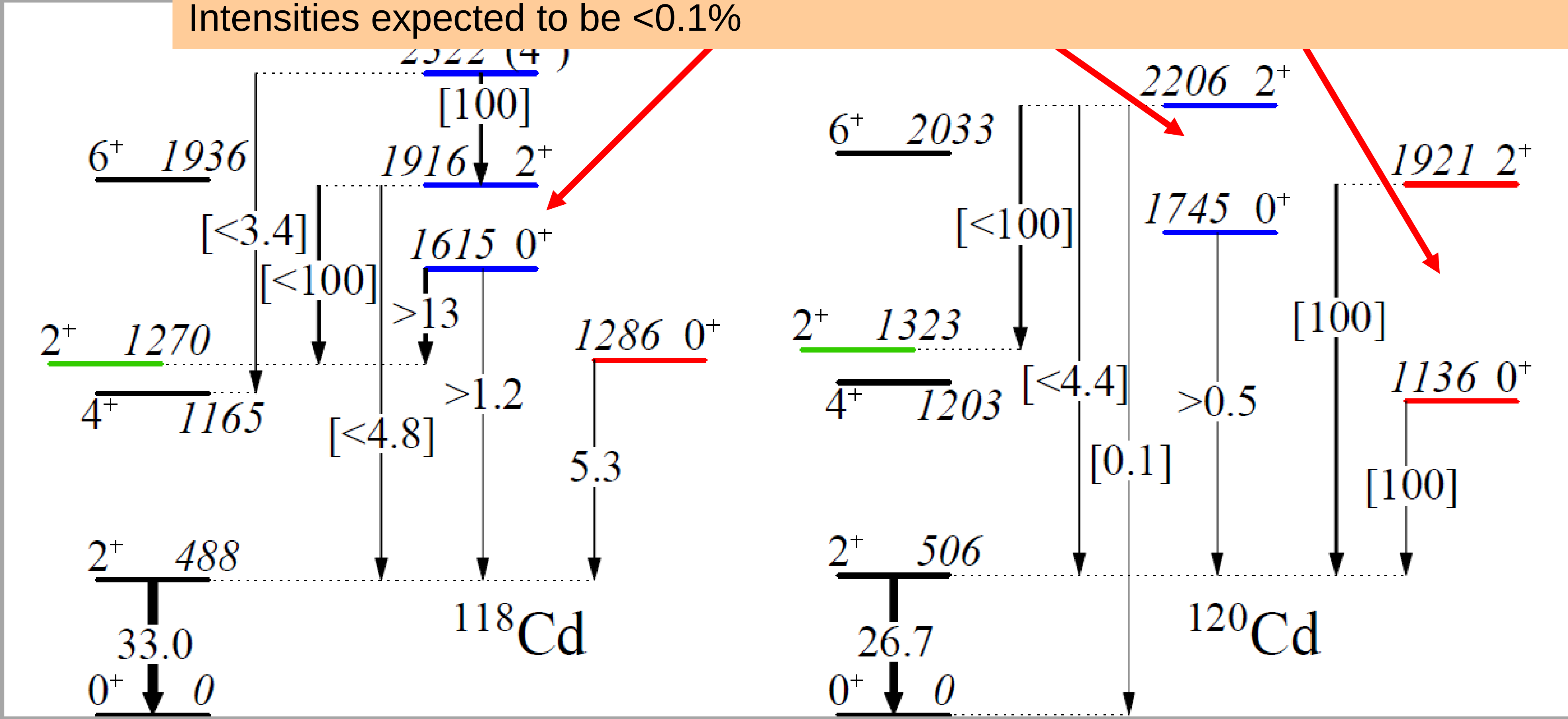
- ^{120}Cd recently studied at ORNL – refuted the previous 0^+ state at 1339 keV, and suggested a new 0^+ state at 11

In-band transitions not observed
Perhaps the 2^+ we are currently associating with the 0^+ intruder band head is incorrect? It would imply a drastic change in structure….
Intensities expected to be <0.1%



Transitions labelled with B(E2) values (W.u.) or relative values in [ ]

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Our proposed experiments

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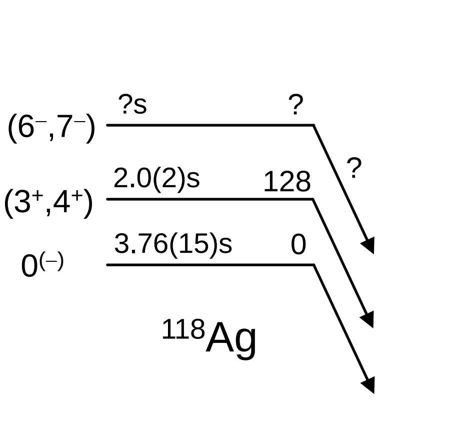
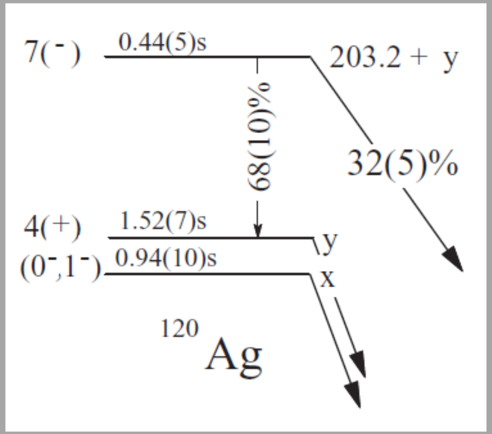
- Populate excited states in $^{118,120}Cd$ via β decay of $^{118,120}Ag$



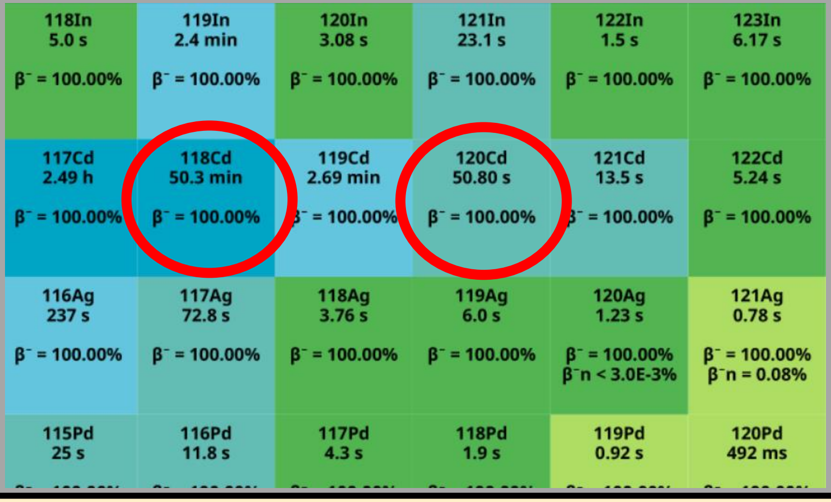
R.P. de Groote et al., Jyvaskyla

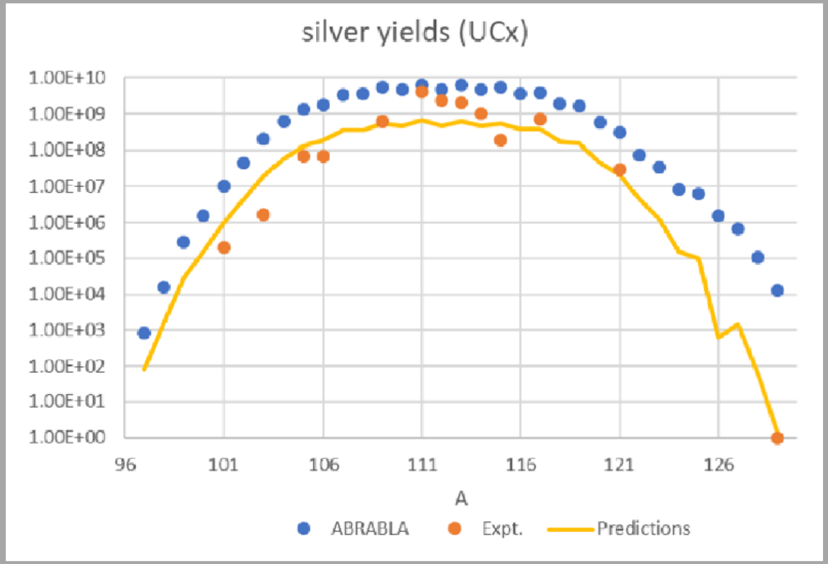


J. Batchelder et al., PRC 86, 064311 (2012)

Presence of multiple β decaying isomeric states cover wide spin range in daughters

Cd daughters long-lived, enabling straightforward separation of decay lines





R.P. de Groote et al., INTC-P-551

Measured yields – from UC_x target with RILIS (Köster, 1999)

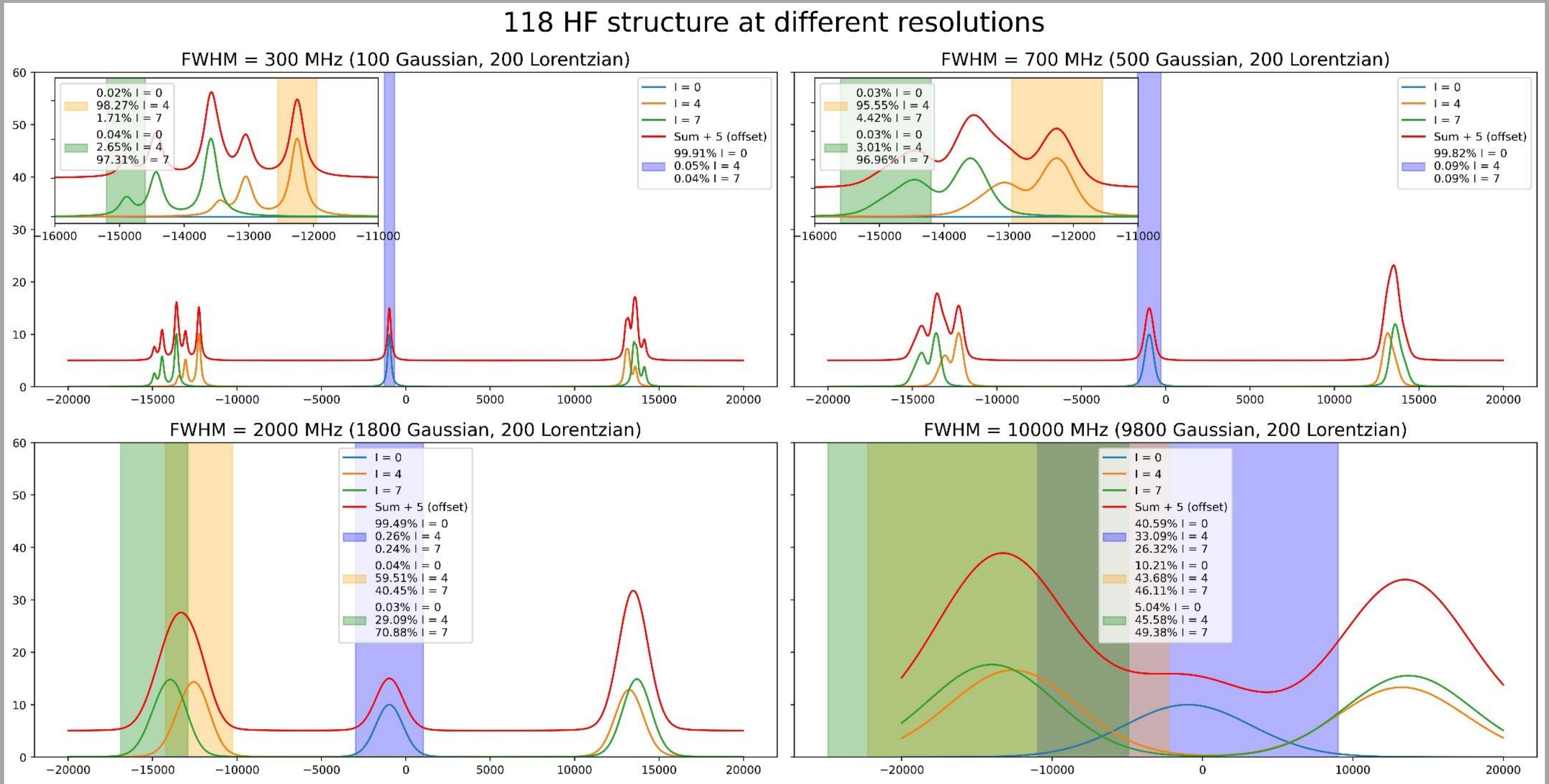
Predicted yields taking into account $t_{½}$

Expected ion beam rate of ~$10^4 – 10^5$/s

- **Identify weak, unobserved transitions, pushing γ-ray intensity sensitivity to better than $1×10^{−5}$ per decay**
- **Use γ-γ coincidences to track the bands, especially for those weak transitions**
- **Study angular correlations in decay cascades to firmly establish the spins of all the intermediary states, and multipolarities to extract mixing ratios δ**
- **Measure conversion electrons, using combination of singles and γ-ray coincidences to extract conversion coefficients: note to extract J→J *E*0 components, we need the mixing ratios δ, since the transition can be E2+M1+E0!**

Use of PI-LIST to achieve separation of isomers

- Use hyperfine structure of *m1* (spin 0), *m2* (spin 3 or 4), and *m3* (spin 6 or 7) states to enhance selectivity
- Compromise between selectivity and beam rate – we will sacrifice the separation of *m2* and *m3* in order to optimise coincidence rate – achieved with 2 GHz resolution
  - Take advantage of proposal I285 approved at JYFL (M. Stryjczyk et al.) using laser and trap purified beams that will unambiguously assign γ-rays to specific isomer decays down to ~1% relative intensity



Decay measurement to be performed at IDS

- Already possible with the 5 clover HPGe detectors in geometry optimized for γ-γ angular correlations

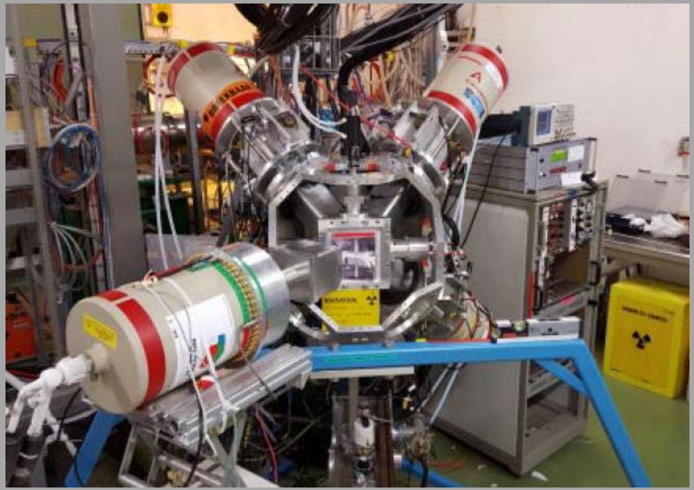
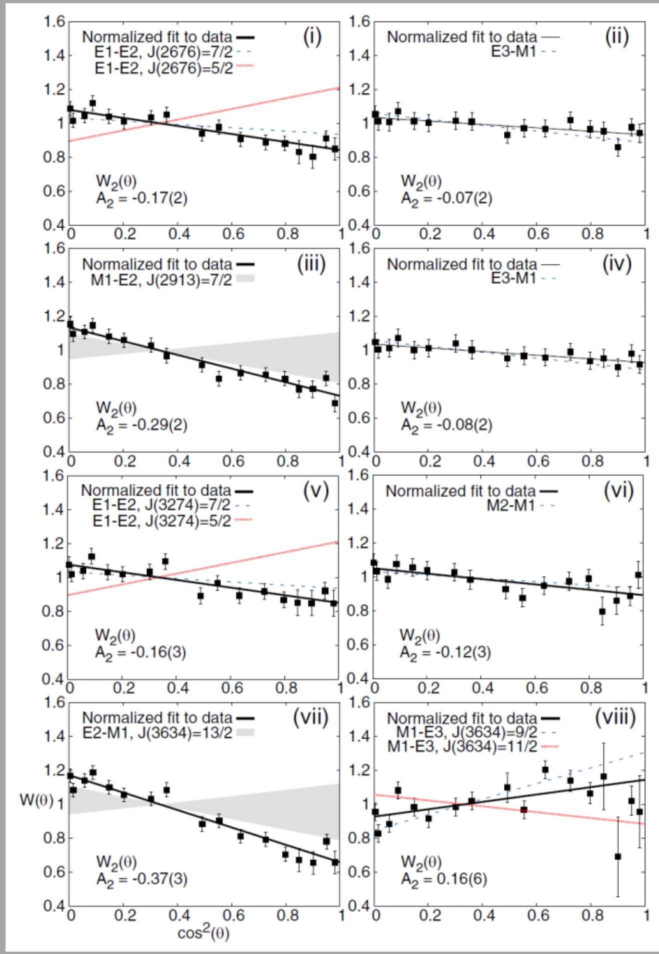


TABLE I. Number of crystal-crystal pairs per 5° angular bin for the asymmetric five-clover detector configuration at IDS, used here for angular correlation measurements. Angles are symmetric around 90°, so, e.g., 0°–5° also includes 175°–180°.

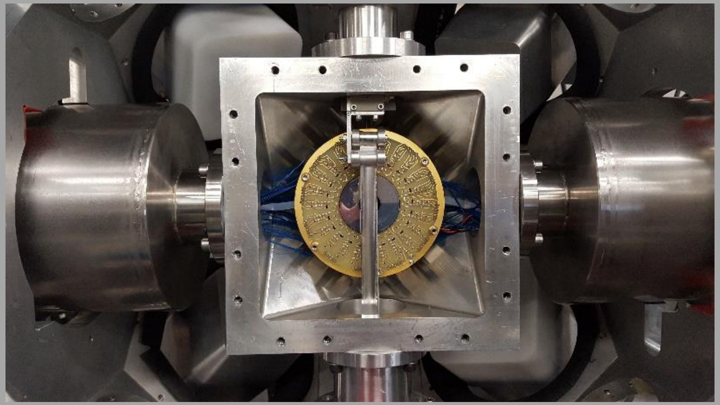
Angle	0°–5°	5°–10°	10°–15°	15°–20°	20°–25°	25°–30°
Pairs	0	1	2	1	1	3
	30°–35°	35°–40°	40°–45°	45°–50°	50°–55°	55°–60°
	3	7	10	2	14	12
	60°–65°	65°–70°	70°–75°	75°–80°	80°–85°	85°–90°
	15	8	19	24	18	20

Angular correlations in ^{207}Tl

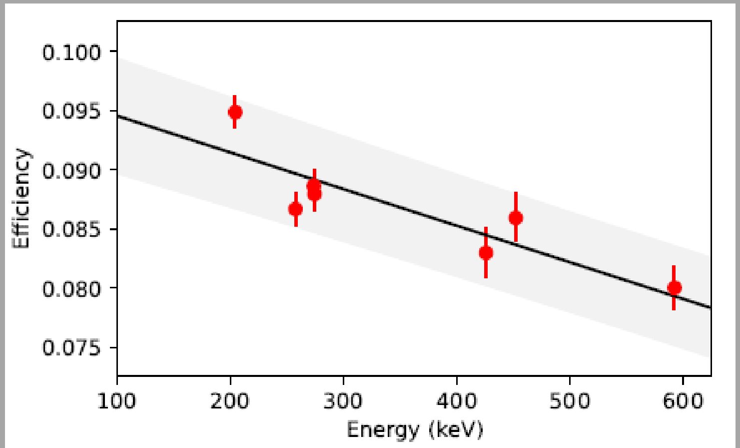


T.A. Berry et al., PRC 101, 054311 (2020)

- **Use of SPEDE for conversion electrons**



PhD thesis M. Stryjczyk (KU Leuven, 2021)



- **Use of $LaBr_3$ detectors for fast timing (at a further radial distance so as to not compromise HPGe efficiency, may not provide sufficient statistics)**

Variation of beam rates

IF AN ORDER OF MAGNITUDE LESS

- In ^{118}Ag, observation of $2^+ \rightarrow 0^+$ transition in intruder band should still be possible (~500 counts in photopeak) but with considerable uncertainty on intensity
- Seek additional 2^+ candidates in level scheme
- Perform angular correlation analysis for transitions for transitions at level of few % intensity, e.g., $2_2^+ \rightarrow 2_1^+$ with unknown mixing ratio δ and 4.5% relative intensity – important to extract relative B(E2)
- In ^{120}Ag, confirm candidate 0_2^+ level at 1133 keV

IF AN ORDER OF MAGNITUDE MORE

- Extend sensitivity in angular correlation analysis to transitions with 0.01% intensity
  - Obtain mixing ratios for most low-lying transitions
- Extend sensitivity for weaker in-band transitions in higher-lying 0^+ bands
  - In ^{112}Cd, $2_5^+ \rightarrow 0_4^+$ transition at level of $\sim 4\times10^{-7}$ per decay
- Enhance statistics in conversion electron spectra, permitting a far more accurate extraction of the E0 components of J→J transition (we must subtract the M1+E2 contributions)

Collaboration

P.E. Garrett[1,2], T.E. Cocolios[2], A. Nannini[3], M. Zielińska[4], Z. Ahmed[1], A. Algora[5], M. Athanasakis-Kaklamanakis[2], S. Bara[2], C. Bernerd[2,6], H. Bidaman[1], V. Bildstein[1], S. Buck[1], A. Camaiani[2], A. Ceulemans[2], K. Chrysalidis[6], A. Claessens[2], R. de Groote[2], H. De Witte[2], Z. Favier[6], F. Dunkel[7], K. Flanagan[8], L. Fraile[9], R.F. Garcia Ruiz[10], D. Hanstorp[1]1, M. Heines[2], R. Heinke[6], J.D. Johnson[2], J. Jolie[7], A. Koszorus[6], S. Kujanpää[2], L. Lalanne[2], R. Lica[12], N. Marchini[3], K. Mastakov[1], C. Mihai[12], E. Nacher[5], G. Neyens[2], B. Olaizola[6], J. Pakarinen[13], S. Pannu[1], O. Poleshchuk[2], R. Raabe[2], J.-M. Regis[7], M. Rocchini[1], T. Rodríguez[9], S. Triambak[14], S. Valbuena[1], B. van den Borne[2], P. Van Duppen[2], N. Warr[7], W. Wojtaczka[2], K. Wrzosek-Lipska[15], X. Yang[16], A. Youssef[2]

[1] *University of Guelph, Guelph, Canada*
[2] *KU Leuven, IKS, Leuven, Belgium*
[3] *INFN Firenze, Italy*
[4] *CEA Saclay, France*
[5] *CSIC, University of Valencia, Valencia, Spain*
[6] *CERN, Geneva, Switzerland*
[7] *IKP, Universität zu Köln, Köln, Germany*
[8] *University of Manchester, Manchester, UK*
[9] *Universidad Complutense de Madrid, Madrid, Spain*
[10] *Massachusetts Institute of Technology, Cambridge, USA*
[11] *University of Gothenburg, Gothenburg, Sweden*
[12] *IFIN-HH, Bucharest, Romania*
[13] *University of Jyväskylä, Jyväskylä, Finland*
[14] *University of the Western Cape, Bellville, South Africa*
[15] *HIL, University of Warsaw, Warsaw, Poland*
[16] *Peking University, Beijing, China*

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Table 1: Yield estimates for ^{118,120}Ag

Species	Yield μC^{-1}	current μA	isomer fraction	LIST eff	duty factor	ions s^{-1}
$^{118}Ag^{m1}$	1.7×10^8	1.7	0.1	10^{-3}	0.67	1.94×10^4
$^{118}Ag^{m2}$	1.7×10^8	1.7	0.45	10^{-3}	0.67	8.7×10^4
$^{118}Ag^{m3}$	1.7×10^8	1.7	0.45	10^{-3}	0.67	8.7×10^4
$^{120}Ag^{m1}$	4.3×10^7	1.7	0.1	10^{-3}	0.67	4.9×10^3
$^{120}Ag^{m2}$	4.3×10^7	1.7	0.45	10^{-3}	0.67	2.2×10^4
$^{120}Ag^{m3}$	4.3×10^7	1.7	0.45	10^{-3}	0.67	2.2×10^4

Complementarity of ISOLDE and existing JYFL proposal

JYFL (M. STRYJCZYK ET AL.)

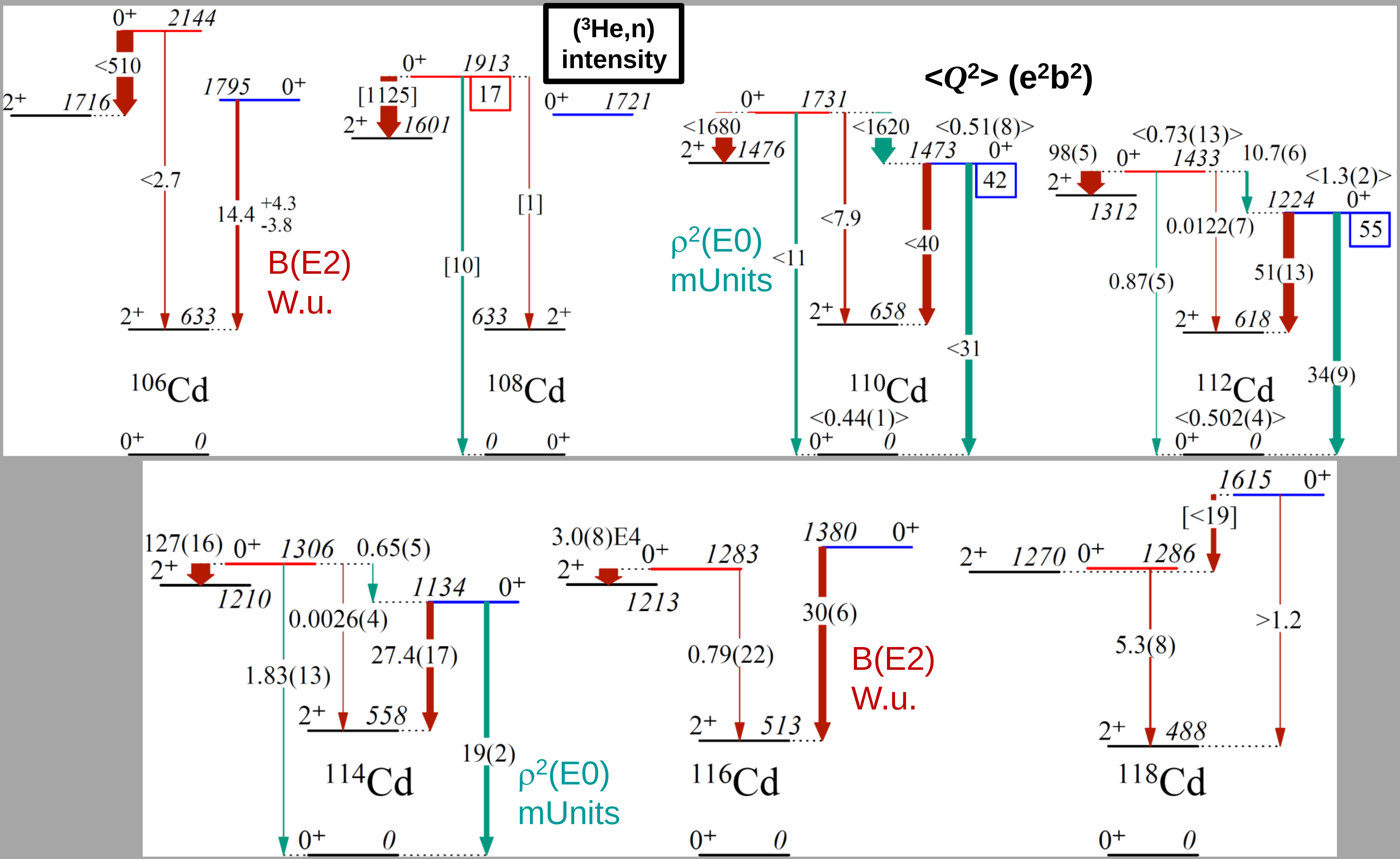
- Use of trap and laser purified beams (in flight) at IGISOL to achieve nearly 100% separation of *m1*, *m2*, and *m3*
- Assign γ ray transitions to specific isomers, with β-γ-γ coincidences, for γ-rays down to level of 1% intensity – important for close lying doublets of levels with different spins (appearance of doublets of states within 1 keV in Cd isotopes not uncommon)
- Aim for decay of 2×10^6 ions for each isomer
- Use of BEGe + coaxial HPGe detectors provides superior energy resolution

ISOLDE

- Use of PI-LIST for beam purification, nearly 100% separation of *m1*, little or no separation of *m2* and *m3*
- Rely on coincidences for assignment to specific isomer decays, using knowledge from JYFL data, to level of 0.01 – 0.001% intensity
- Perform γ-γ angular correlation analysis for sufficiently strong cascades (~0.5%)
- Aim for decay of $(1.4 – 10)\times10^9$ ions (amount depends on specific goals for each isomer)
- Use of HPGe clover enhances high-energy efficiency, $LaBr_3$ detectors for timing

Known data of shape-coexisting Cd candidates

- Very similar decay properties observed for low-lying 0^+ states, until ^{118}Cd
- The BMF calculations predict multiple shape coexistence across much of the Cd isotopic chain



4 distinct shapes predicted for 0^+ bands

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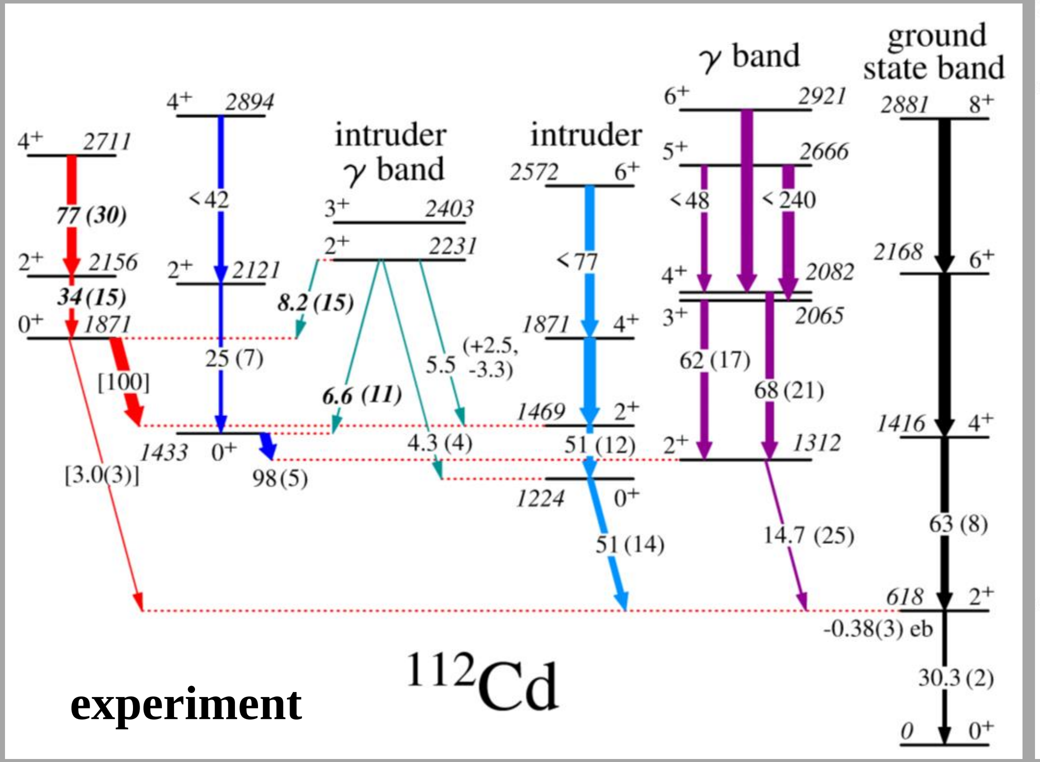
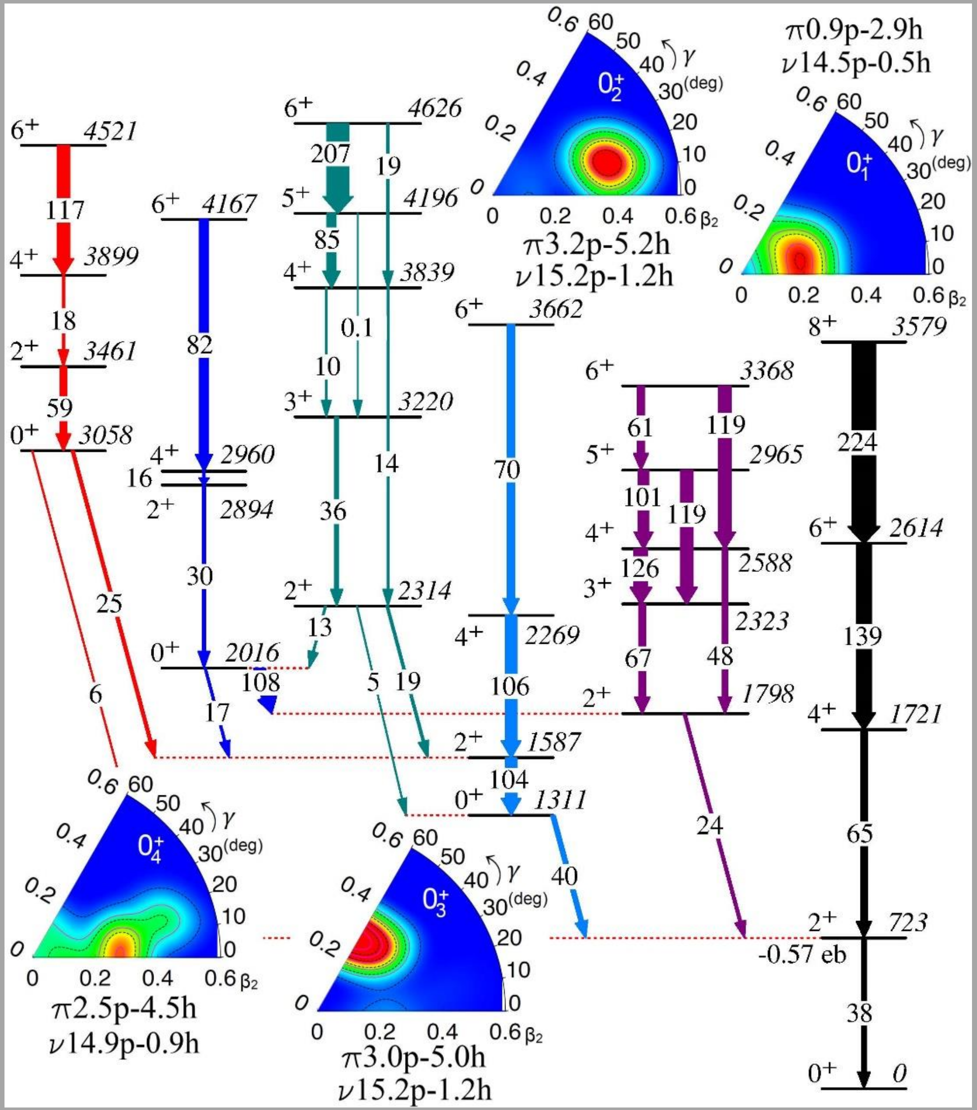
- 0_1^+ – $\beta \approx 0.20$ prolate
- 0_2^+ – $\beta \approx 0.4$, $\gamma \approx 20°$
- 0_3^+ – $\beta \approx 0.30$ oblate
- 0_4^+ – $\beta \approx 0.25$ prolate
- Favoured decays of $0_2^+ \rightarrow 2_1^+$, $0_3^+ \rightarrow 2_2^+$, $0_4^+ \rightarrow 2_3^+$ reproduced





P.E. Garrett et al., PRL 123 (2019) 142502

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Recent facilities that have investigated the structure of Cd isotopes

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PHYSICAL REVIEW LETTERS 123, 142502 (2019)

Editors' Suggestion | Featured in Physics

8π@ISAC

Multiple Shape Coexistence in ^{110,112}Cd

P. E. Garrett,[1,2] T. R. Rodríguez,[3] A. Diaz Varela,[1] K. L. Green,[1] J. Bangay,[1] A. Finlay,[1] R. A. E. Austin,[4] G. C. Ball,[5] D. S. Bandyopadhyay,[1] V. Bildstein,[1] S. Colosimo,[4] D. S. Cross,[6] G. A. Demand,[1] P. Finlay,[1] A. B. Garnsworthy,[5] G. F. Grinyer,[7] G. Hackman,[5] B. Jigmeddorj,[1] J. Jolie,[8] W. D. Kulp,[9] K. G. Leach,[1,*] A. C. Morton,[5,†] J. N. Orce,[2] C. J. Pearson,[5] A. A. Phillips,[1] A. J. Radich,[1] E. T. Rand,[1,‡] M. A. Schumaker,[1] C. E. Svensson,[1] C. Sumithrarachchi,[1,†] S. Triambak,[2] N. Warr,[8] J. Wong,[1] J. L. Wood,[10] and S. W. Yates[11]

PHYSICAL REVIEW C 104, 034320 (2021)

AGATA+VAMOS@GANIL

Lifetime measurements in the even-even $^{102-108}$Cd isotopes

M. Siciliano,[1,2,3,*] J. J. Valiente-Dobón,[2] A. Goasduff,[2,3,4] T. R. Rodríguez,[5] D. Bazzacco,[4] G. Benzoni,[6] T. Braunroth,[7] N. Cieplicka-Oryńczak,[6,8] E. Clément,[9] F. C. L. Crespi,[6,10] G. de France,[9] M. Doncel,[11,12] S. Ertürk,[13] C. Fransen,[7] A. Gadea,[14] G. Georgiev,[15] A. Goldkuhle,[7] U. Jakobsson,[16] G. Jaworski,[2,17] P. R. John,[3,4,18] I. Kuti,[19] A. Lemasson,[9] H. Li,[16] A. Lopez-Martens,[15] T. Marchi,[2] D. Mengoni,[3,4] C. Michelagnoli,[9,20] T. Mijatović,[21] C. Müller-Gatermann,[7,22] D. R. Napoli,[2] J. Nyberg,[23] M. Palacz,[17] R. M. Pérez-Vidal,[14,2] B. Sayği,[2,24,25] D. Sohler,[19] S. Szilner,[21] and D. Testov[3,4,26]

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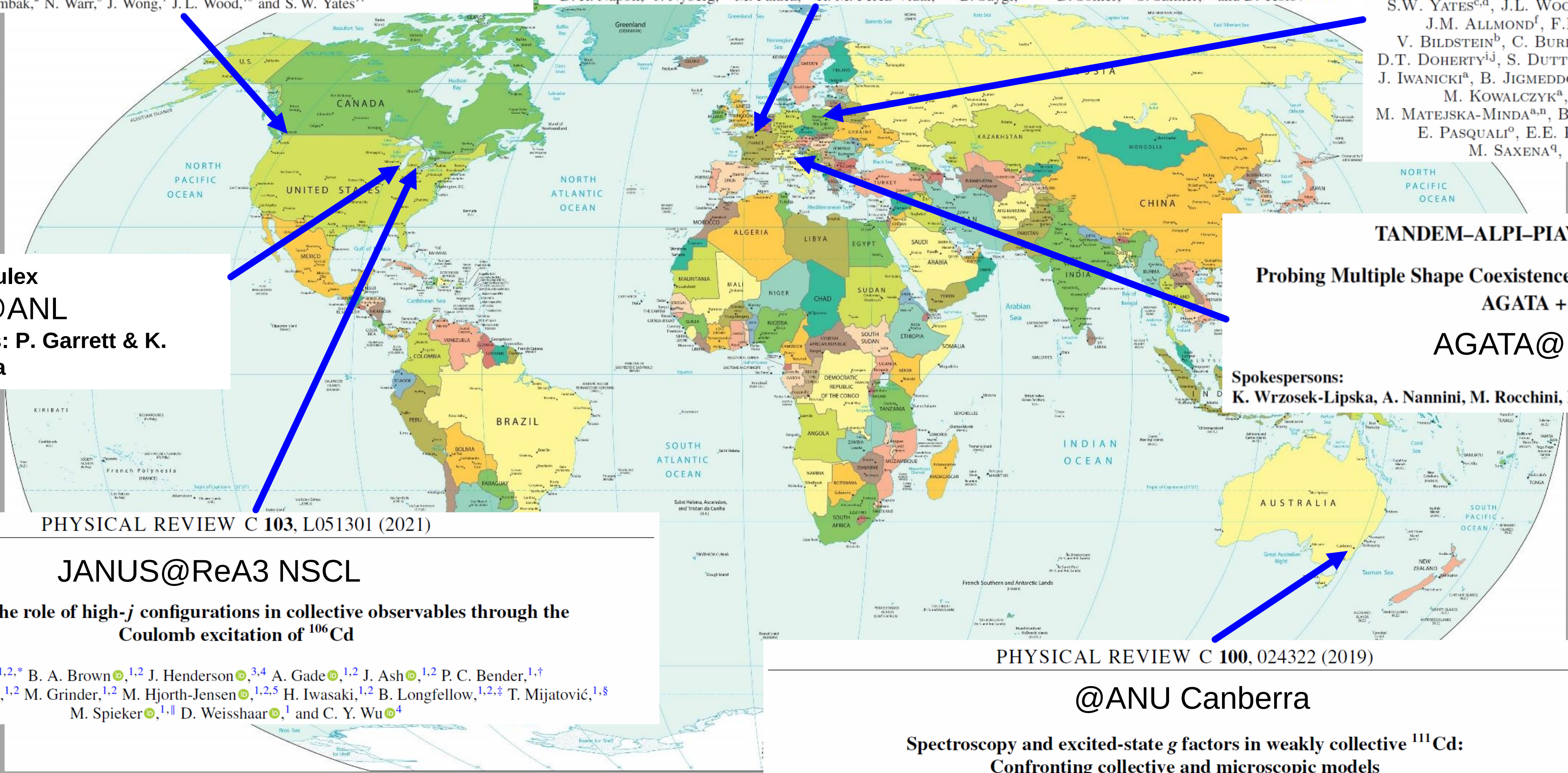
EAGLE@HIL Warsaw

QUADRUPOLE DEFORMATION OF ^{110}Cd STUDIED WITH COULOMB EXCITATION*

K. Wrzosek-Lipska[a], L. Próchniak[a], P.E. Garrett[b] S.W. Yates[c,d], J.L. Wood[e], P.J. Napiorkowski[a], T. Abraham[a] J.M. Allmond[f], F.L. Bello Garrote[g], H. Bidaman[b] V. Bildstein[b], C. Burbadge[b], M. Chiari[h], A. Diaz Varela[b] D.T. Doherty[i,j], S. Dutt[k], K. Hadyńska-Klęk[a,g], M. Hlebowicz[l] J. Iwanicki[a], B. Jigmeddorj[b], M. Kisieliński[a], M. Komorowska[a] M. Kowalczyk[a], R. Kumar[m], T. Marchlewski[a] M. Matejska-Minda[a,n], B. Olaizola[b], F. Oleszczuk[l], M. Palacz[a] E. Pasquali[o], E.E. Peters[d], M. Rocchini[b,p], E. Sahin[g] M. Saxena[q], J. Srebrny[a], A. Tucholski[a]



^{110}Cd+^{208}Pb Coulex

GRETINA@ANL

Spokespersons: P. Garrett & K. Wrzosek-Lipska

TANDEM–ALPI–PIAVE ACCELERATOR

Probing Multiple Shape Coexistence in ^{110}Cd with Coulomb Excitation
AGATA + SPIDER

AGATA@LNL Legnaro

Spokespersons:
K. Wrzosek-Lipska, A. Nannini, M. Rocchini, P.E. Garrett, and M. Zielińska

PHYSICAL REVIEW C 103, L051301 (2021)

Letter

JANUS@ReA3 NSCL

Exploring the role of high-*j* configurations in collective observables through the Coulomb excitation of ^{106}Cd

D. Rhodes,[1,2,*] B. A. Brown,[1,2] J. Henderson,[3,4] A. Gade,[1,2] J. Ash,[1,2] P. C. Bender,[1,†] R. Elder,[1,2] B. Elman,[1,2] M. Grinder,[1,2] M. Hjorth-Jensen,[1,2,5] H. Iwasaki,[1,2] B. Longfellow,[1,2,‡] T. Mijatović,[1,§] M. Spieker,[1,∥] D. Weisshaar,[1] and C. Y. Wu[4]

PHYSICAL REVIEW C 100, 024322 (2019)

@ANU Canberra

Spectroscopy and excited-state *g* factors in weakly collective ^{111}Cd: Confronting collective and microscopic models

B. J. Coombes,[1] A. E. Stuchbery,[1,*] A. Blazhev,[2] H. Grawe,[3] M. W. Reed,[1] A. Akber,[1] J. T. H. Dowie,[1] M. S. M. Gerathy,[1] T. J. Gray,[1] T. Kibédi,[1] A. J. Mitchell,[1] and T. Palazzo[1]