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Recognizing structure in the $Z = 50$ region

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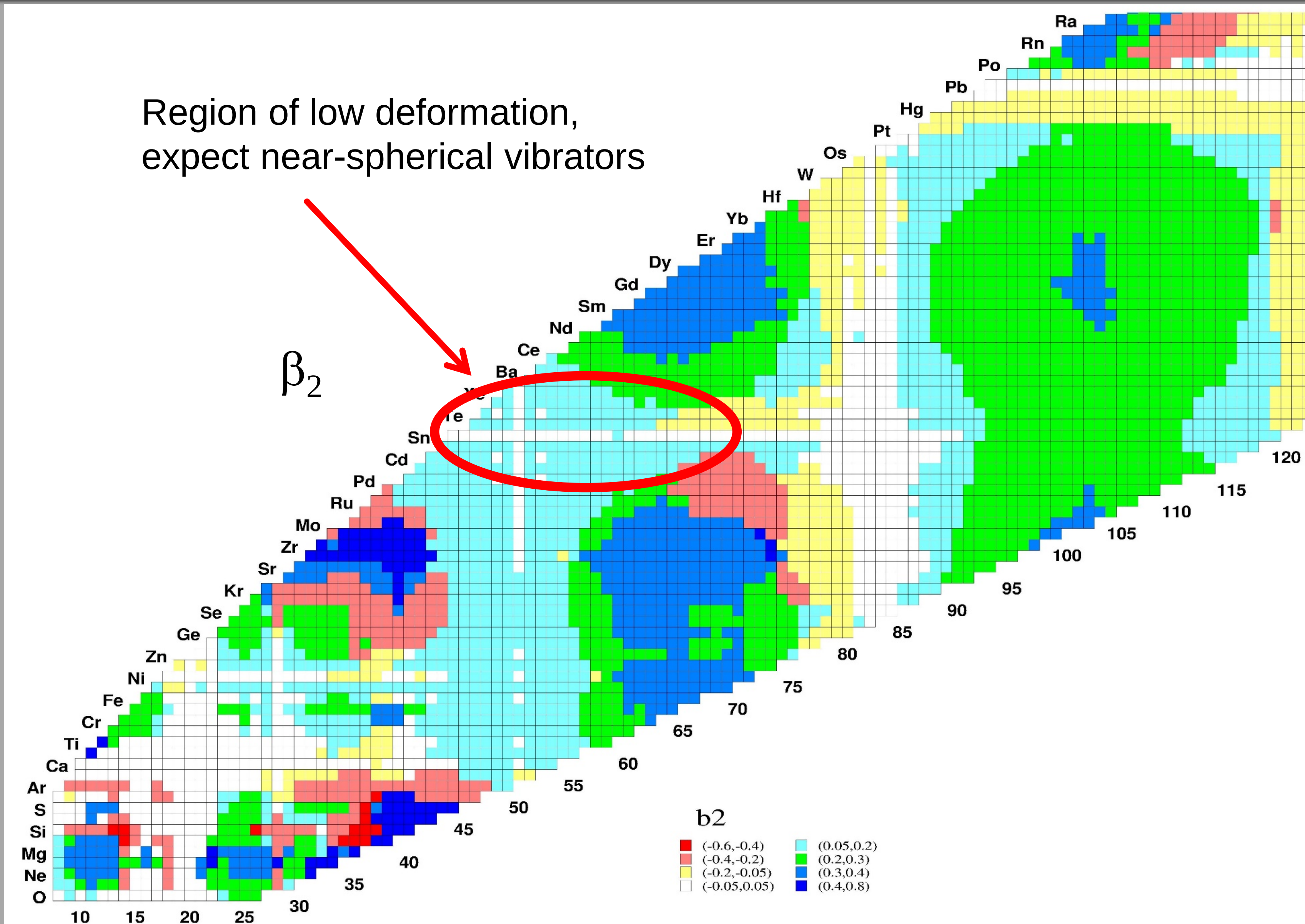
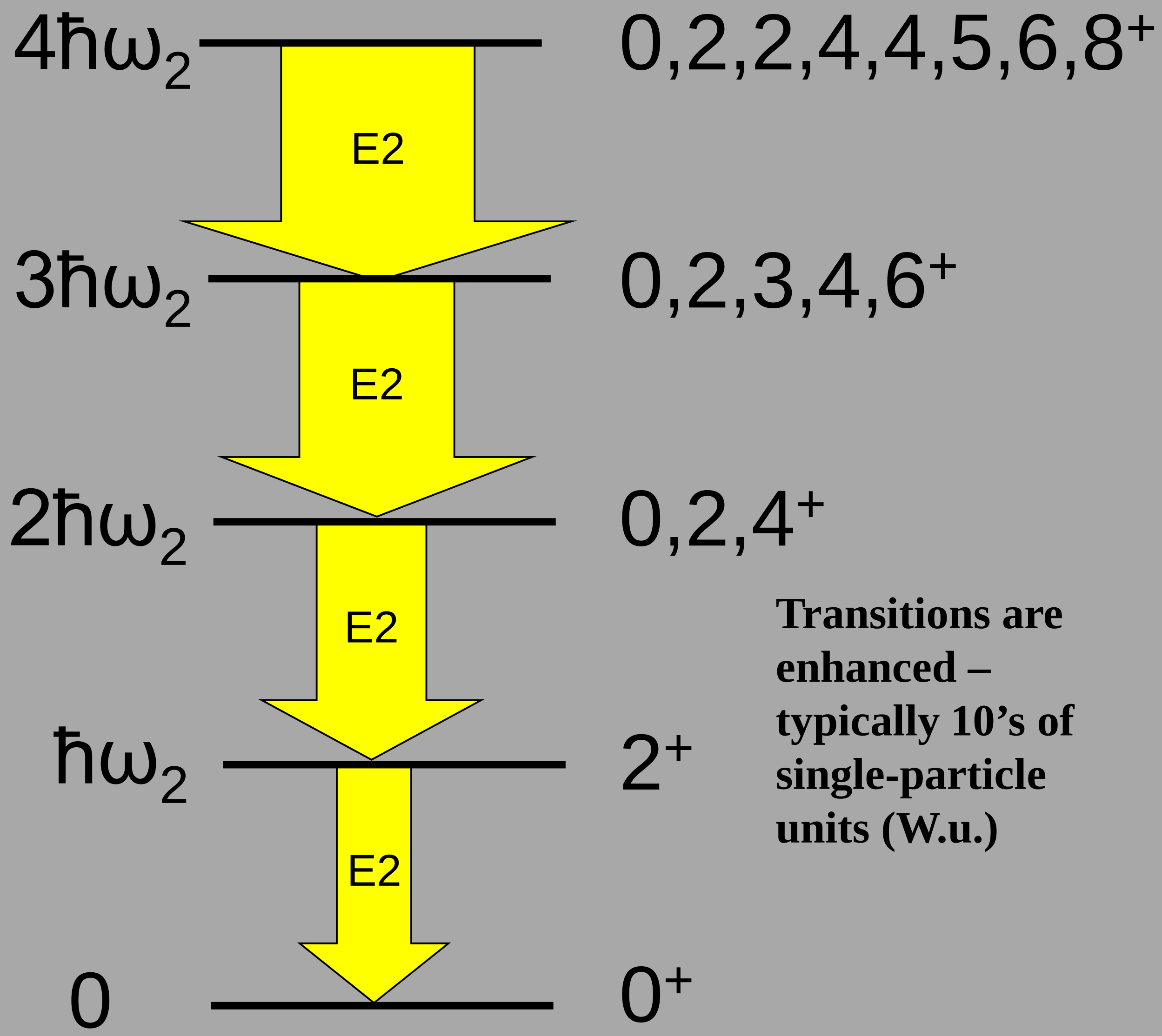
What structure might we expect for even-even nuclei in the $Z = 50$ region?

Region of low deformation, expect near-spherical vibrators

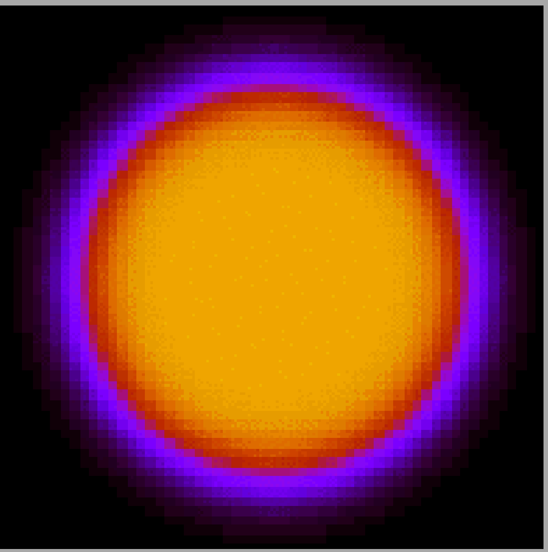


Spherical quadrupole harmonic vibrations



$\Delta n = \pm 1$

Transitions are enhanced – typically 10's of single-particle units (W.u.)



Courtesy of M. Itoh and Y. Fujita

Candidates for near harmonic vibrational motion (or U(5) symmetry) near Z=50

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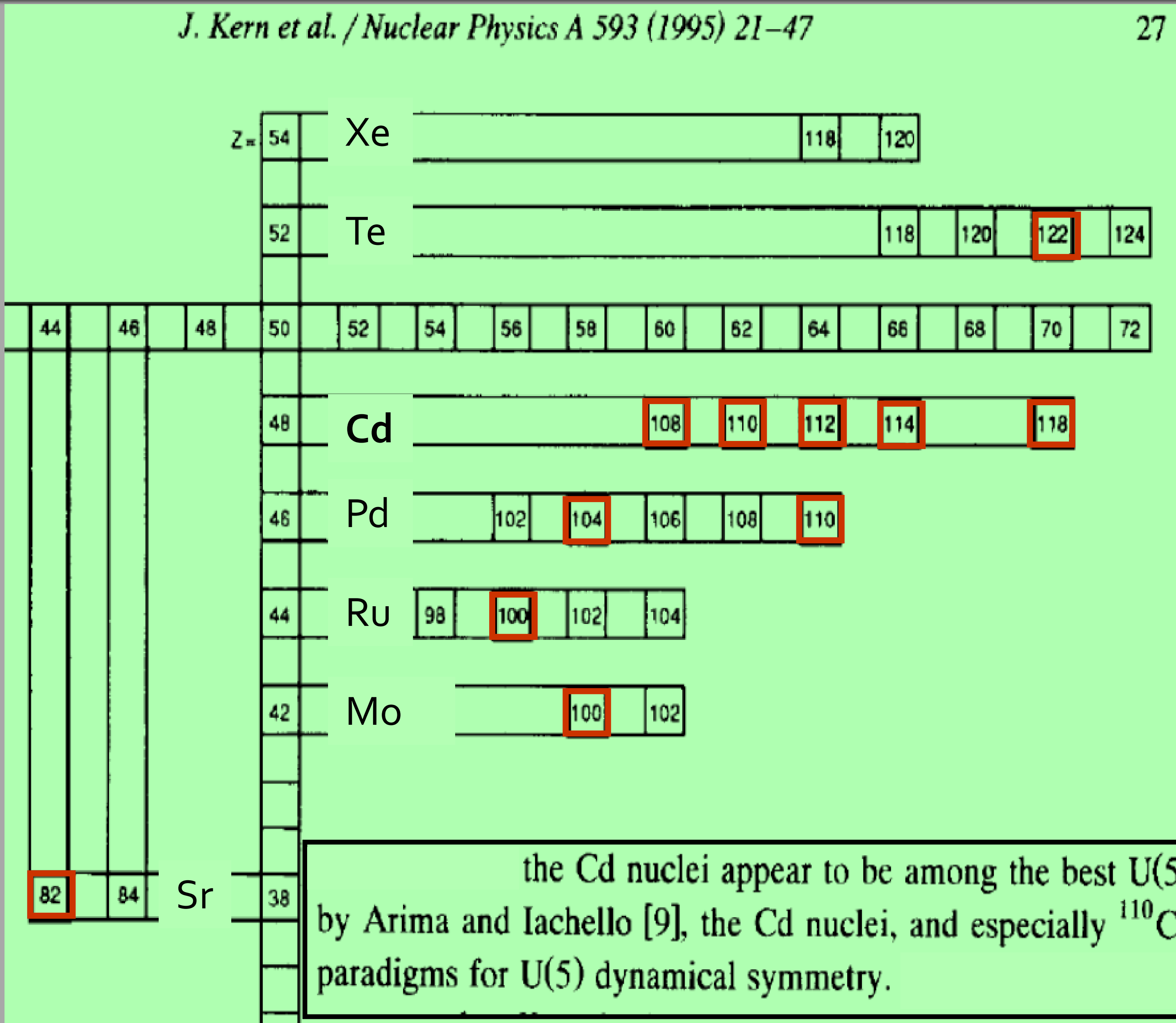


the Cd nuclei appear to be among the best U(5) candidates. As proposed by Arima and Iachello [9], the Cd nuclei, and especially ^{110}Cd, can still be regarded as paradigms for U(5) dynamical symmetry.

Criteria for valid vibrational multiphonon state

For good U(5) candidates, Kern *et al*. considered:

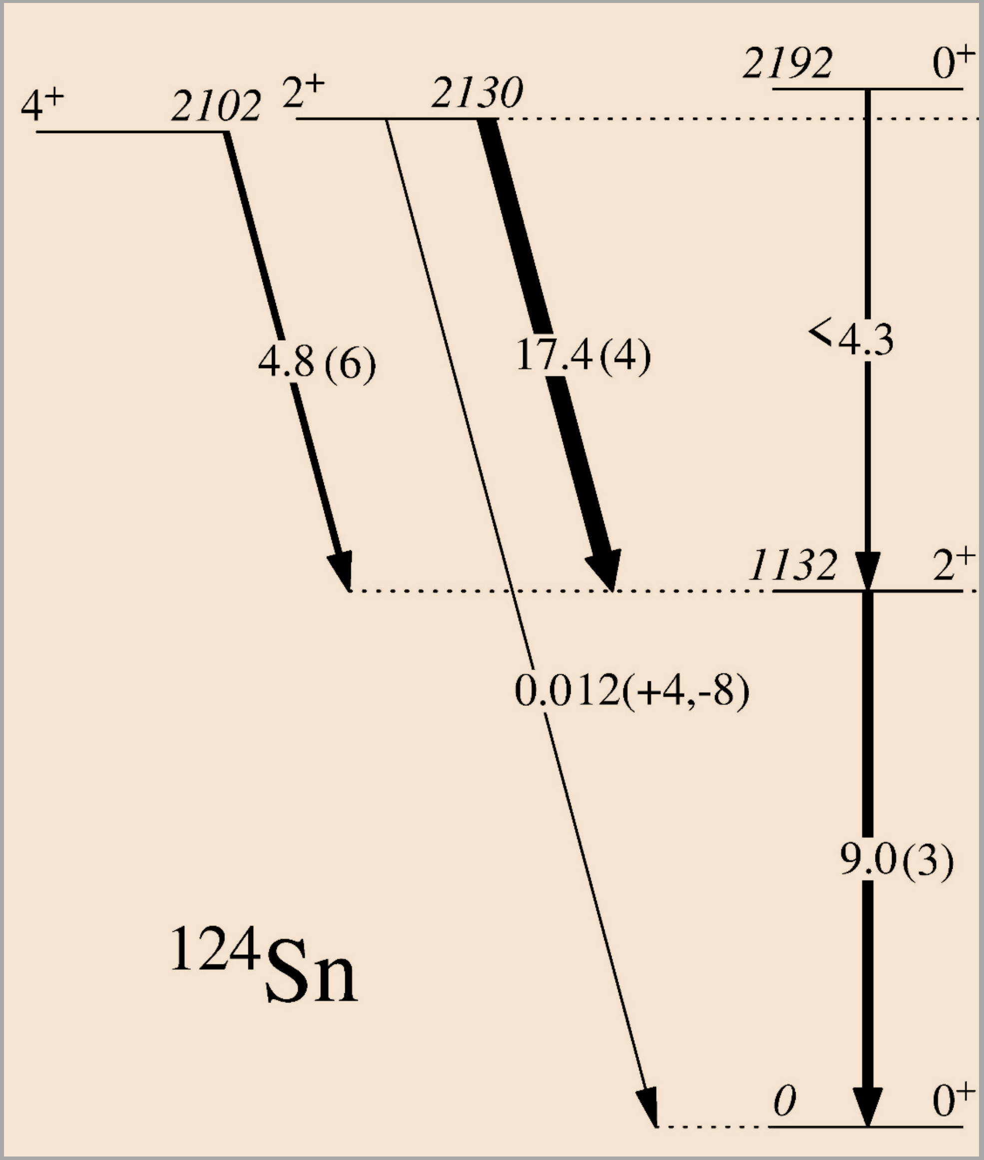
- **Excitation spectrum – existence of a *full* set of two-phonon states, and perhaps even 3-phonon states**
- **E_4/E_2 ratio approximately 2**
- **Energies could be fit with the U(5) energy formula**
- **The $\Delta N = 1$ *E*2 transitions strongly favoured over possible decays**

Now consider expanded criteria:

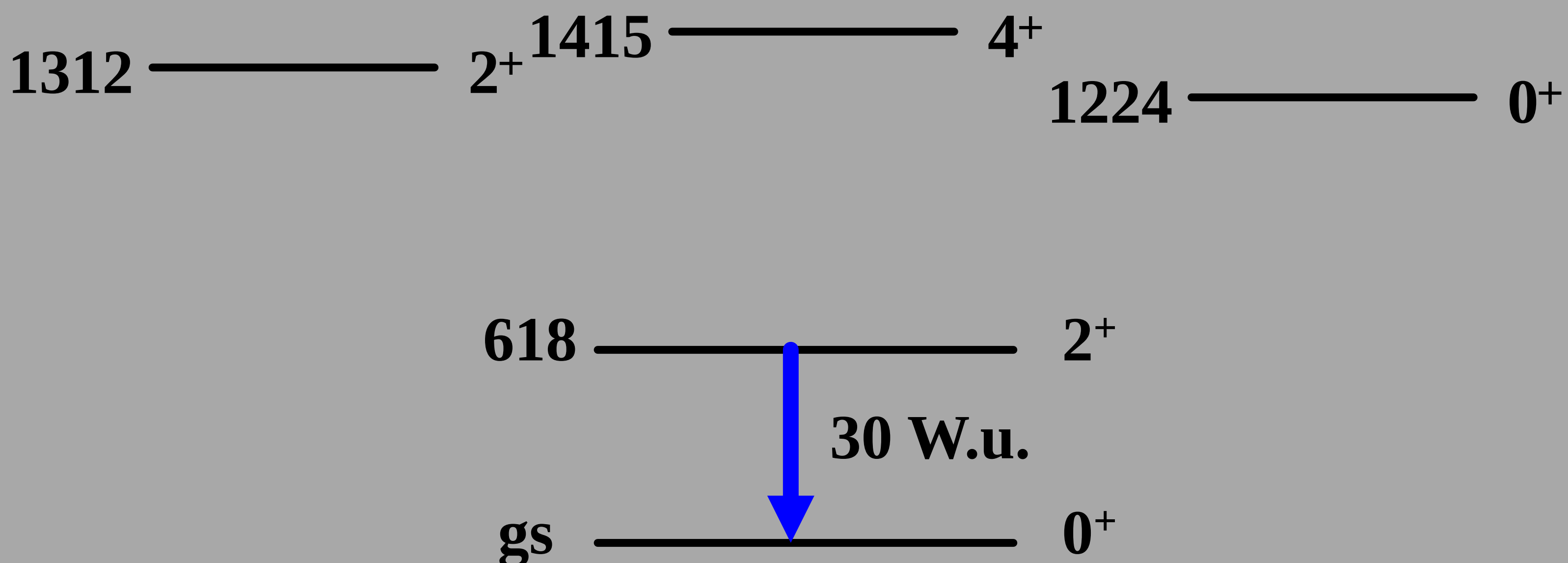
- **Smooth evolution of states as a function of *A***
- **Enhanced set of *B*(*E*2) values between phonon states**
- **Deformation parameters extracted from Coulomb excitation or inelastic scattering follow expectations**
- **Consistent transfer results**
  - **One-phonon states may be strongly populated in SNT, but multiphonon should have (ideally) zero spectroscopic strengths**
  - **Weak populations in two-nucleon transfer**

Why are more stringent criteria needed?

- **Considering only energies and branching ratios would lead to conclusion that ^{124}Sn is a good harmonic vibrational nucleus**
  - **E(4^+)/E(2^+) ratio is 1.86**
  - **Energy spread of 2-phonon triplet is only 90 keV**
  - **Relative *B*(*E*2) strongly favour decay to one-phonon 2^+ state**
- **Absolute *B*(*E*2) values immediately rule out harmonic vibrations**

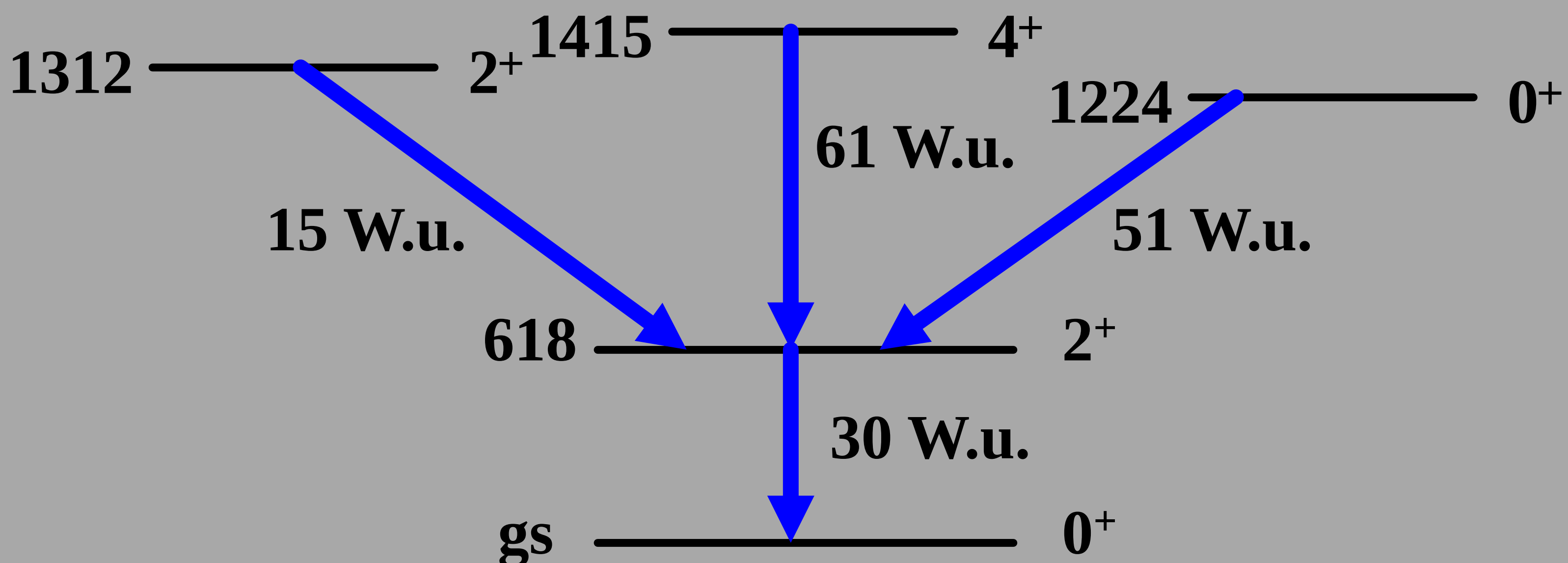


e.g. levels near 1.3 MeV in ^{112}Cd – U(5) candidate



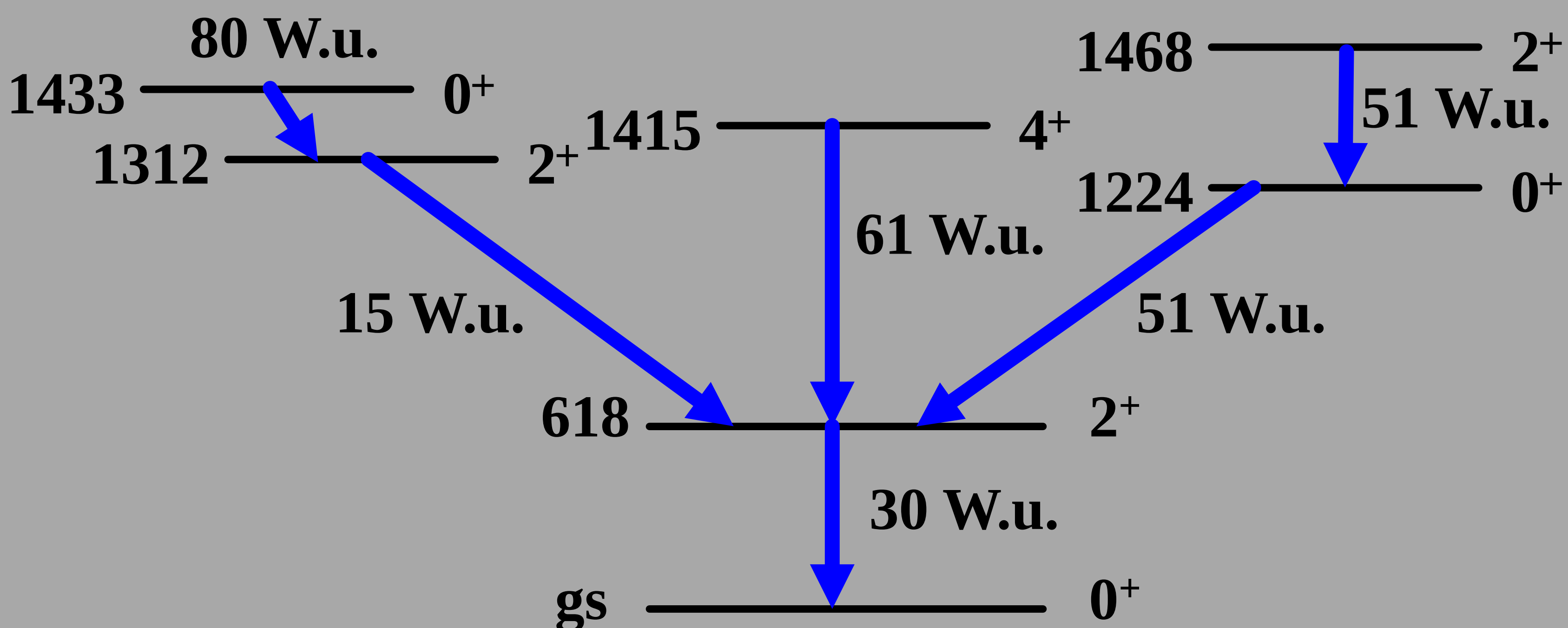
e.g. levels near 1.3 MeV in ^{112}Cd – U(5) candidate

- **Appear to have the right levels and decays**



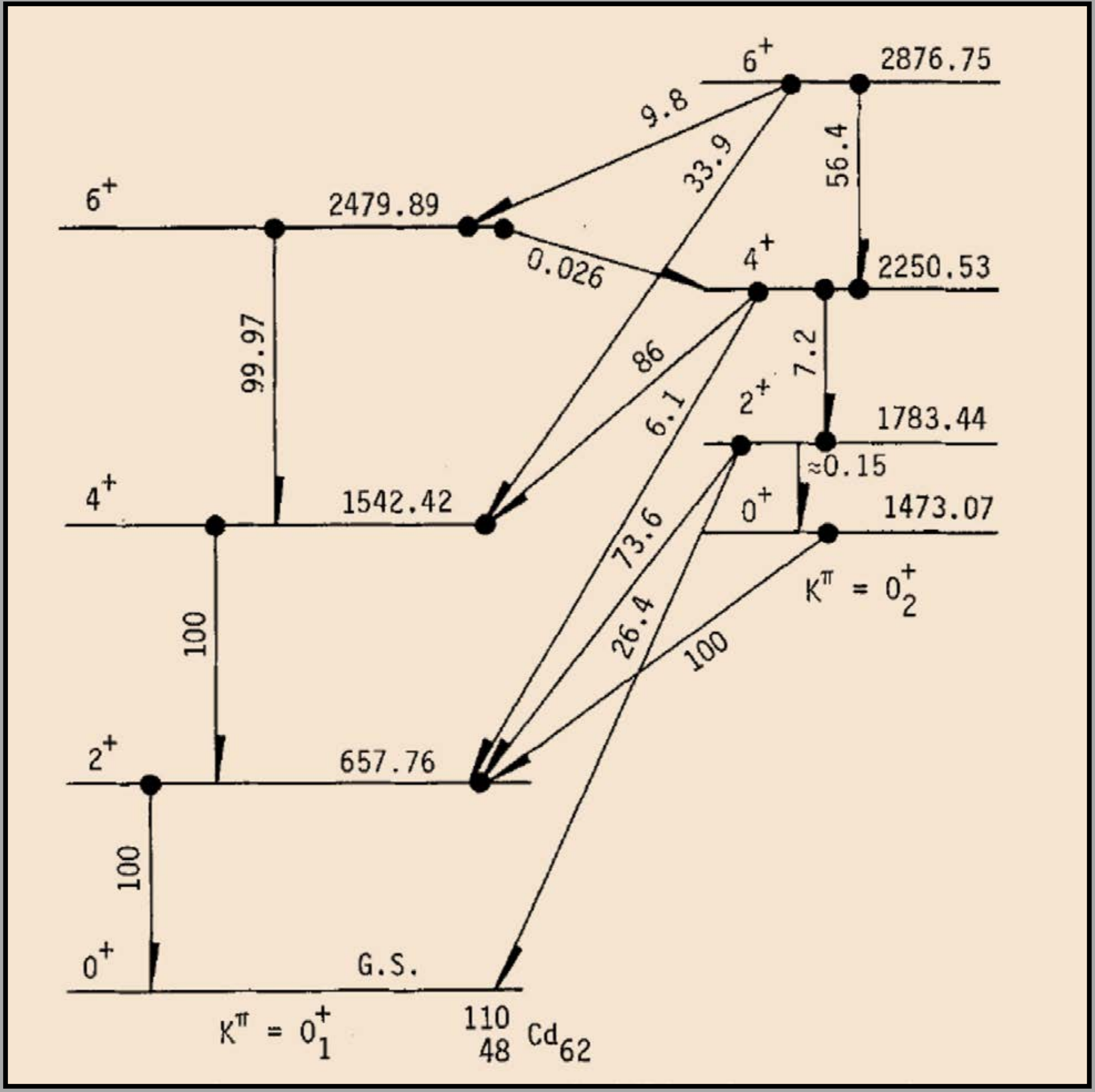
But there are extra states in the vicinity of 2-phonon states… e.g. ^{112}Cd – U(5) candidate

- Appearance of additional 0^+ and 2^+ states with enhanced *E*2 decays systematic in Cd isotopes near midshell



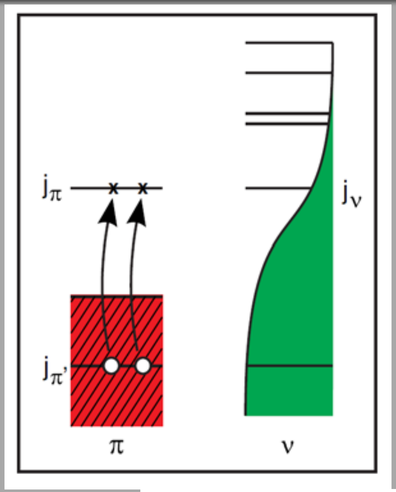
First firm evidence for deformed coexisting band in Cd isotopes – observed with β-decay

- **Detailed spectroscopy on ^{110}Cd via β-decay reveals in-band transitions**
- **"Extra" states in vicinity of 2-phonon triplet explained as part of "intruder" band**

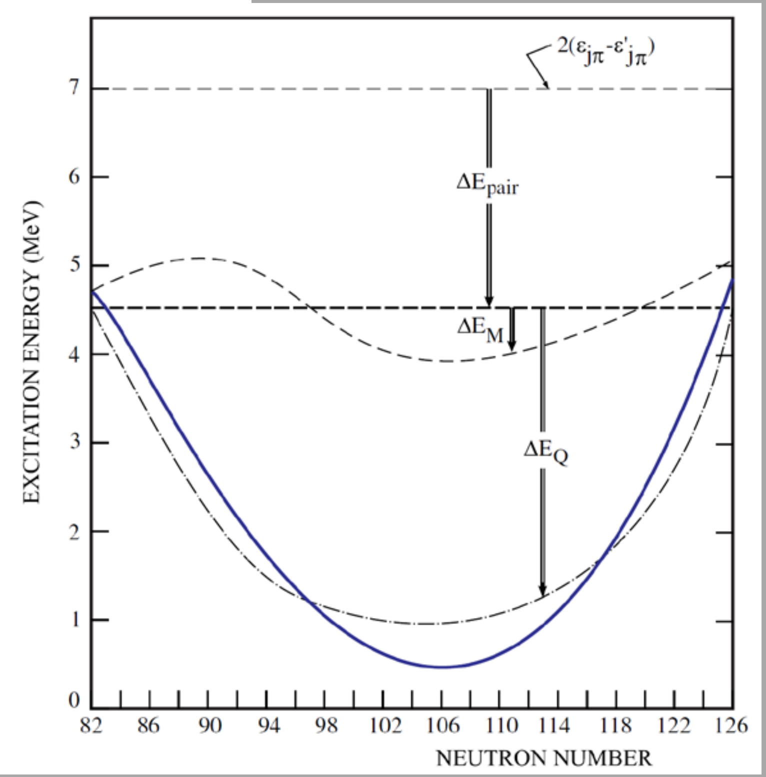


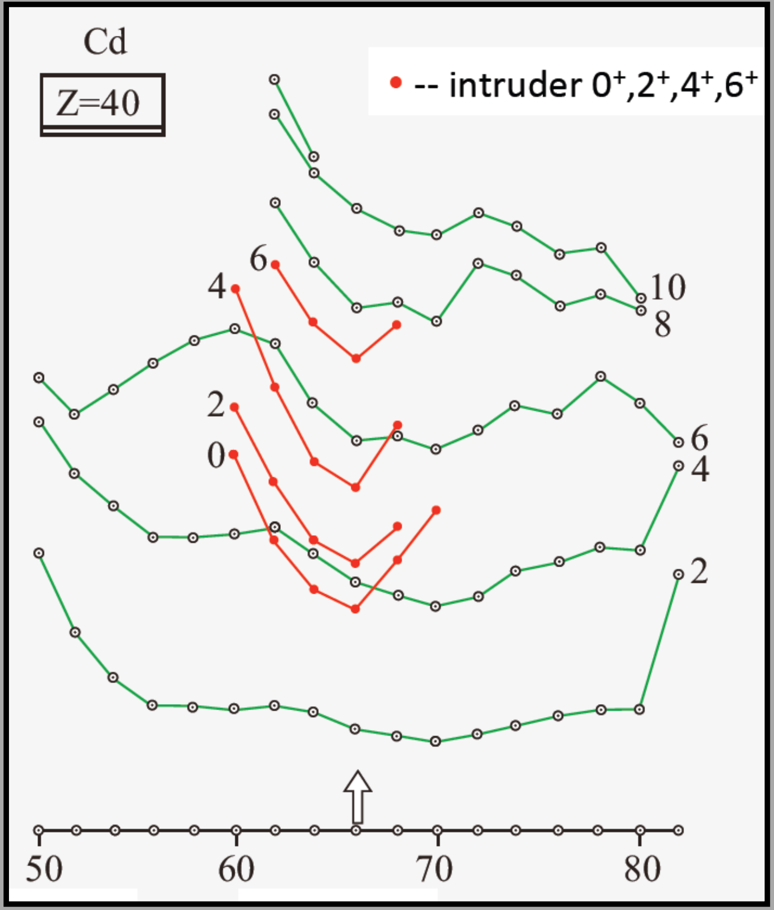
R. Meyer and L. Peker, Z.Phys. **A283**, 379 (1977)

Systematic studies of Cd isotopes revealed intruder states based on $\pi 2p\text{-}4h$ configuration



Evidence for *2p-2h* proton excitations from strong populations of 0^+ band heads in Pd(^{3}He,n) reactions
To understand the structure of the "normal" collective states, we have to be able to identity and separate the intruder structures requiring detailed spectroscopy and systematic studies





Possible $\pi 4p\text{-}2h$ intruder states in the Te isotopes – $^{118-124}$Te U(5) candidates

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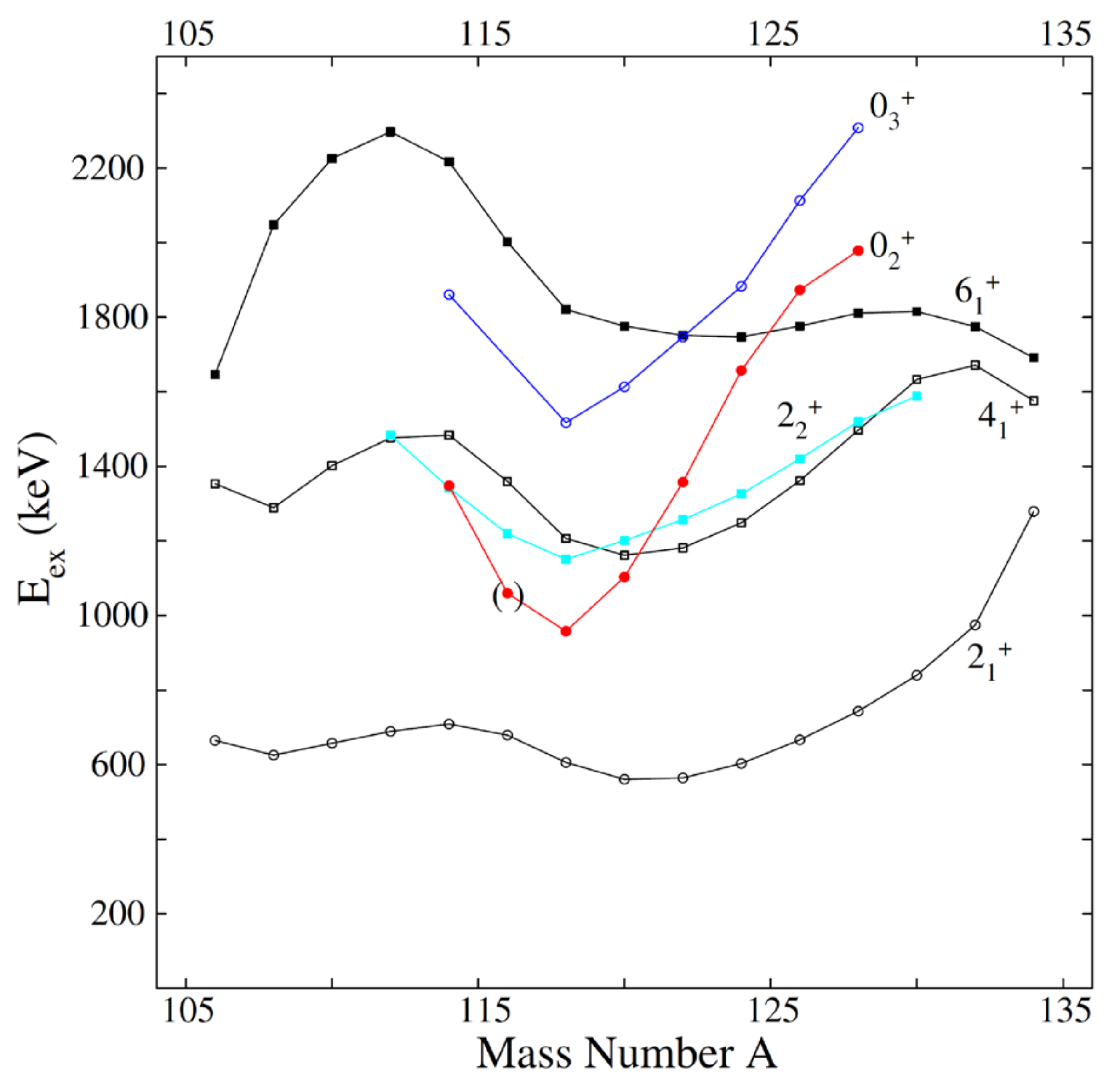
- **Energy systematics of excited states in the Te isotopes suggest intruder origin – or possibly just a changing overall structure?**

- **Is there any real evidence for intruders?**



Strong similarity in structure of Cd and Te nuclei – properties of 0_2^+ states in Te match intruder 0^+ states in Cd

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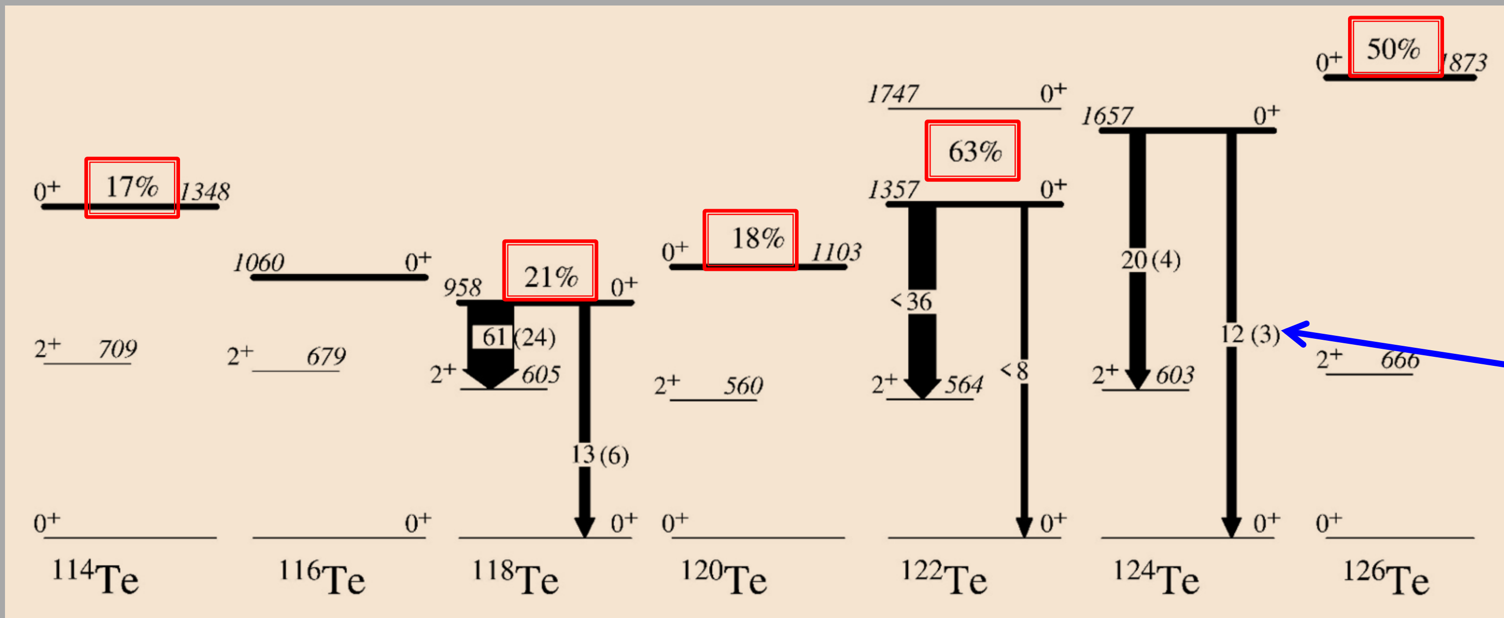
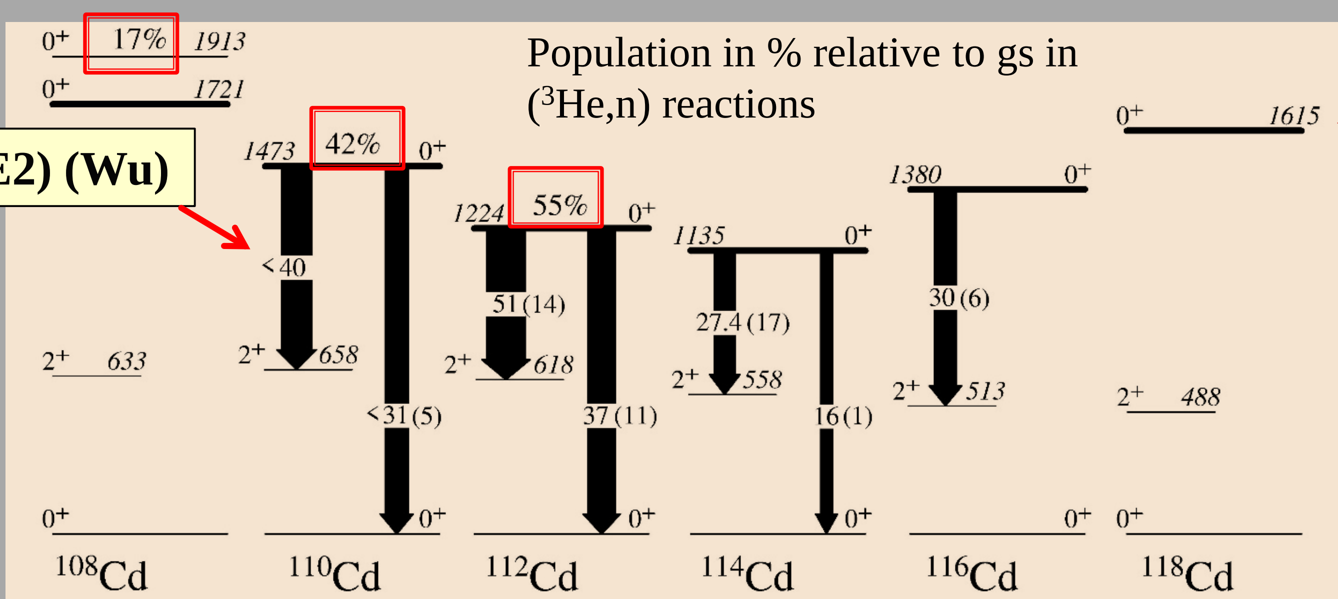


Suggested intruder band heads in the Te isotopes

$10^3\rho^2(E0)$



B(E2) (Wu)

0^+ states identified as intruder band heads in the Cd isotopes

PG, J. Phys. G 43, 084002 (2016).

To establish deformed intruder structures, need detailed spectroscopy – e.g. ^{123}Te(n,γ) @ FIPPS

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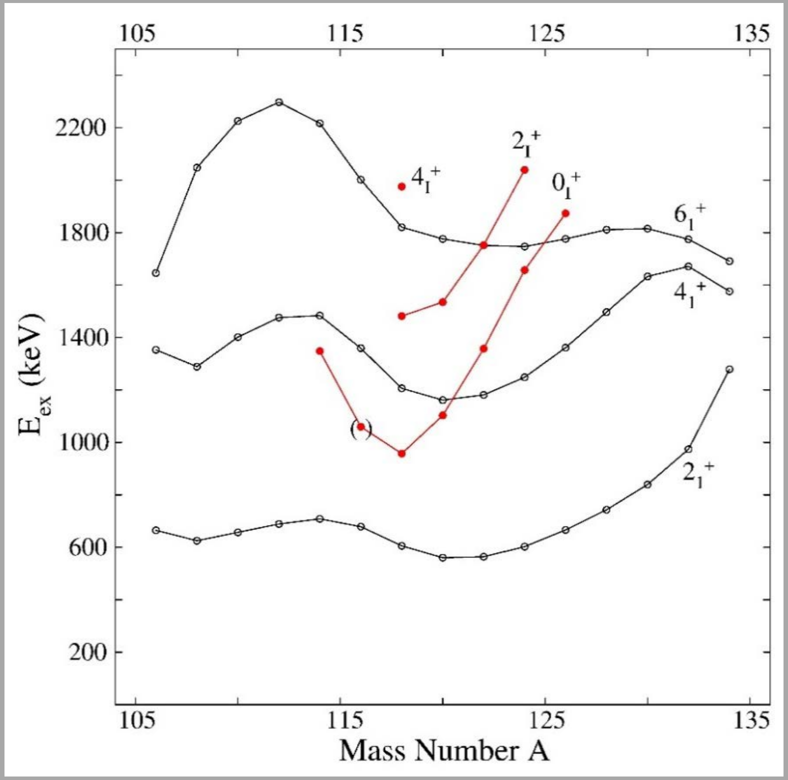
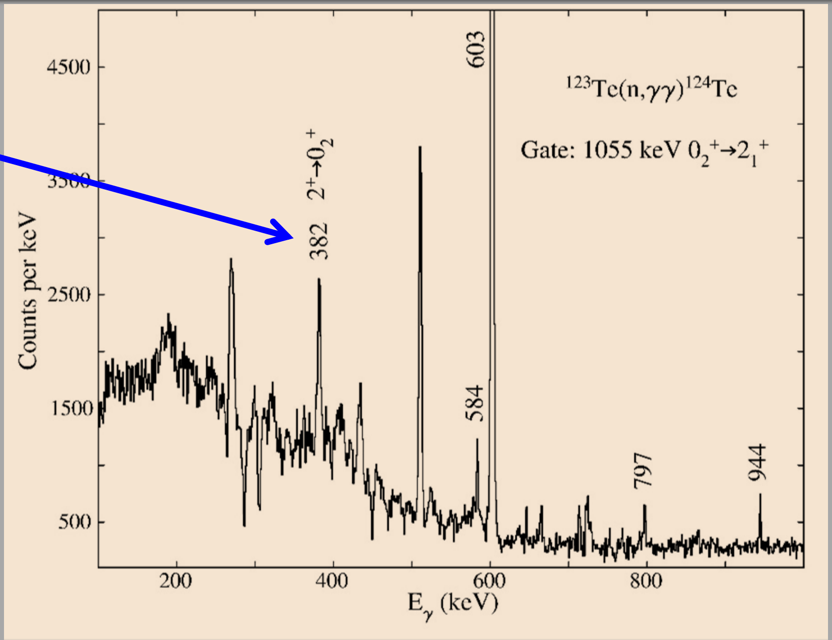
Energy systematics in the Te isotopes

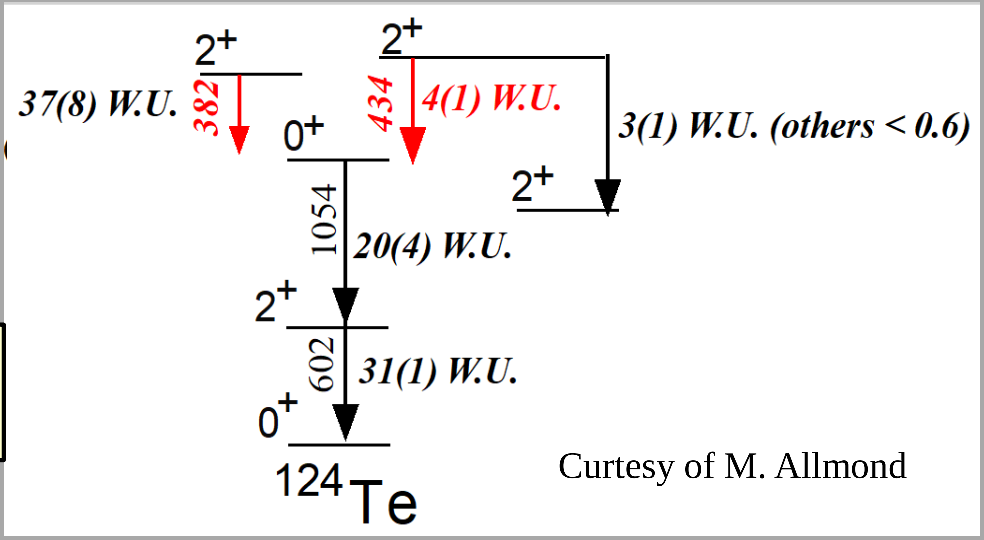


γ decay from suggested 2^+ member of intruder band

Branch observed in ^{124}Sb decay (M. Allmond)



In-band $B(E2;2^+ \to 0^+)$ in ^{122}Te = 194(25) W.u. Hicks *et al*, PRC **71** 034307 (2005)



Energy systematics of low-lying levels in the Pd isotopes – $^{102\text{-}110}$Pd U(5) candidates

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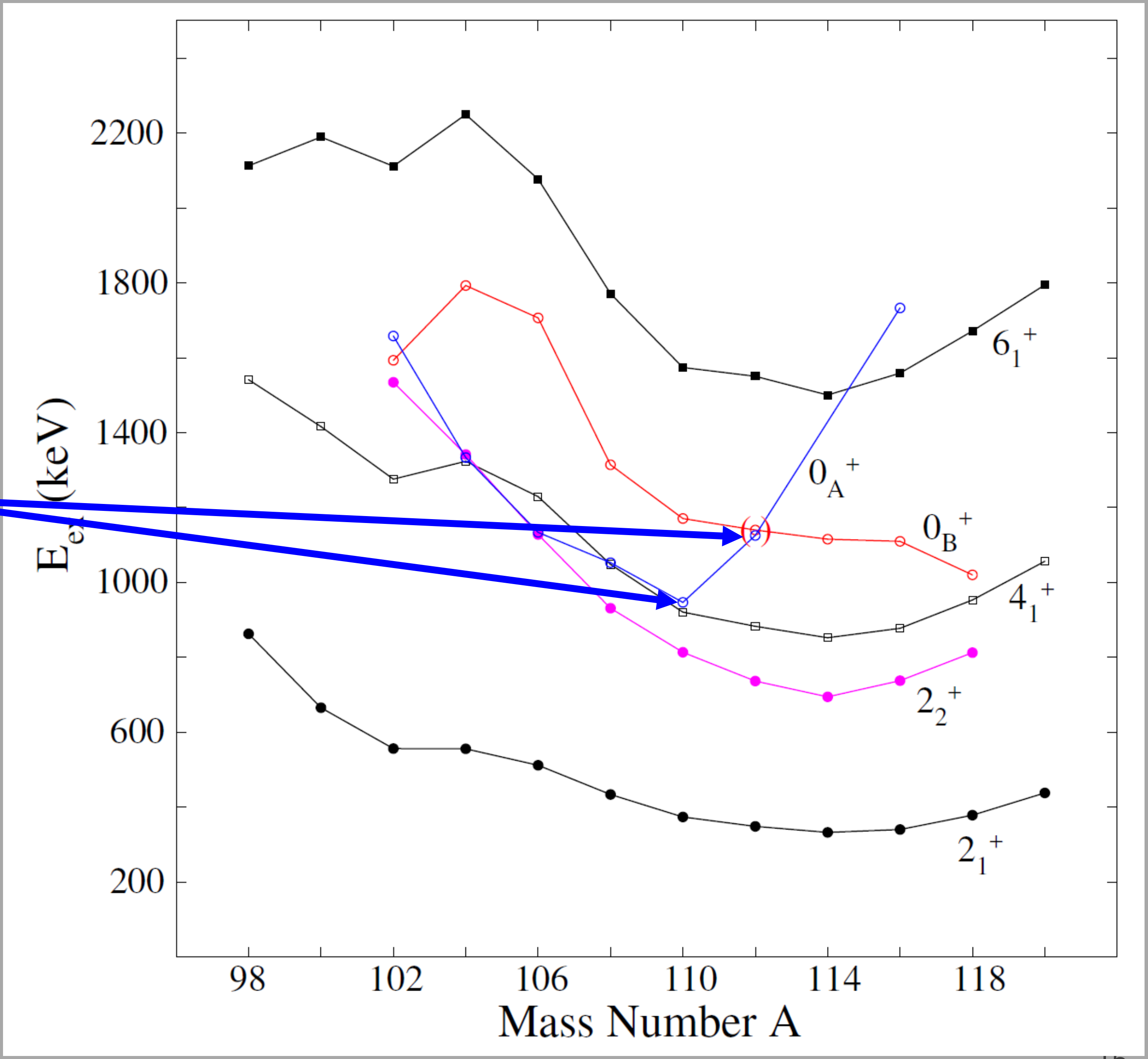
States assigned as intruder Lhersonneau *et al*, PRC 60, 014315 (1999)

0_A^+ state has characteristic "V"-shaped pattern



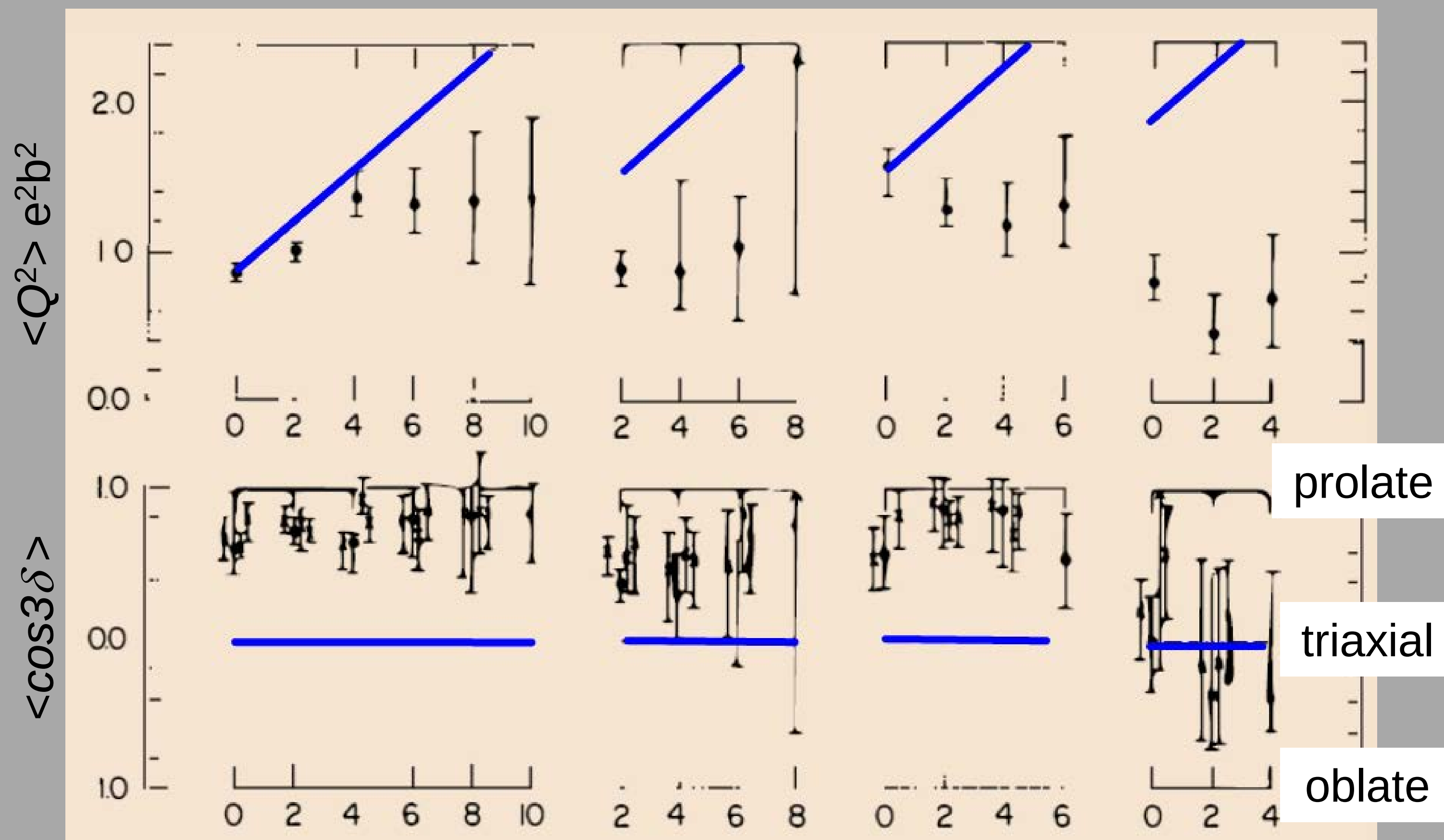
Evidence for shape coexistence in Pd isotopes from rotational invariants in Coulomb excitation

Pd behave as (approx.) prolate rotors – at spin 4^+ in gsb shape has stabilized

0_2^+ band rotor-like from spin 0

0_3^+ band also appears to be shape coexistence band

Rotational invariants for ^{110}Pd



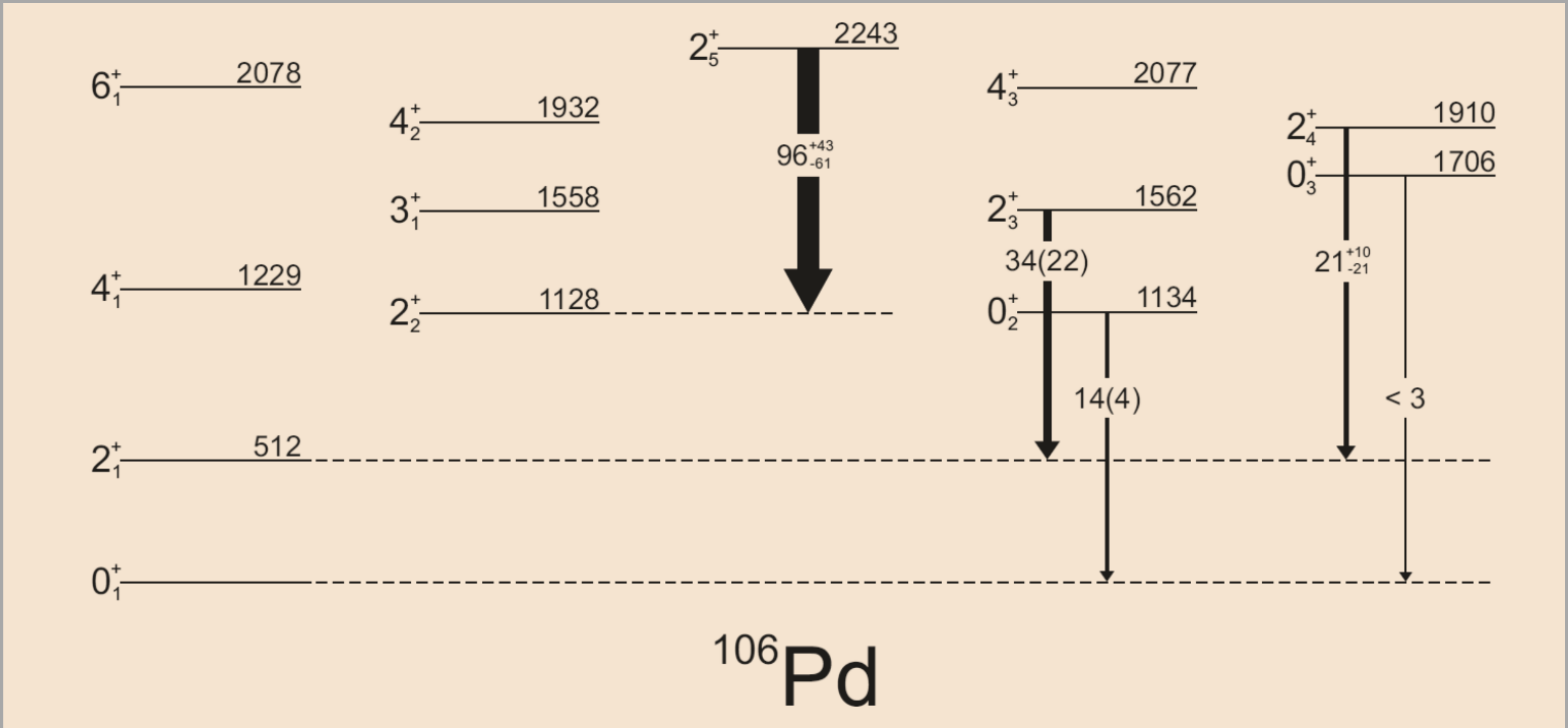
Ground state band γ band 0_2^+ band 0_3^+ band

harmonic vibrator value

D. Cline, Ann. Rev. Nucl. Part. Sci. 36, 683 (1986)

$E0$'s in ^{106}Pd: evidence for shape coexistence in 'K=0' and 'K=2' bands

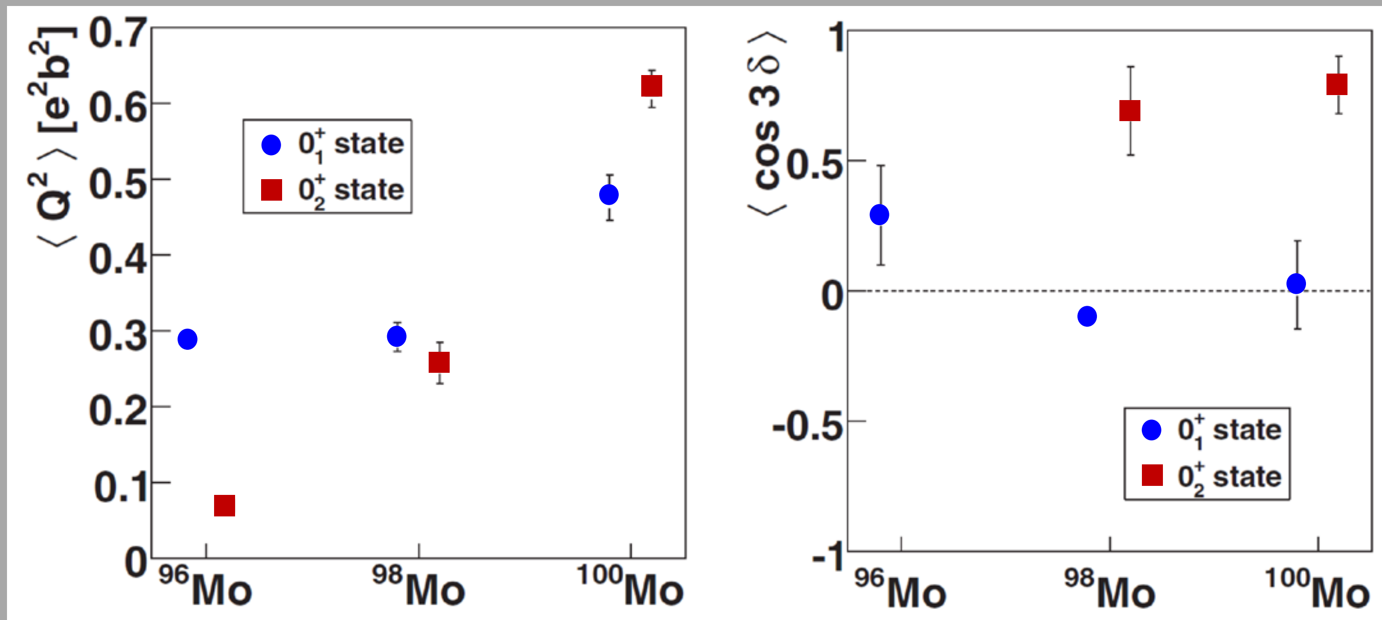
1000×ρ^2(E0) values



E. Peters et al., EPJ **A52**, 96 (2016)

Extending towards Z=40 subshell – $^{100\text{-}102}$Mo U(5) candidates show clear shape coexistence

- **Detailed Coulomb excitation studies enable extraction of shape-invariants clearly indicating different shapes for 0_1^+ and 0_2^+ states**

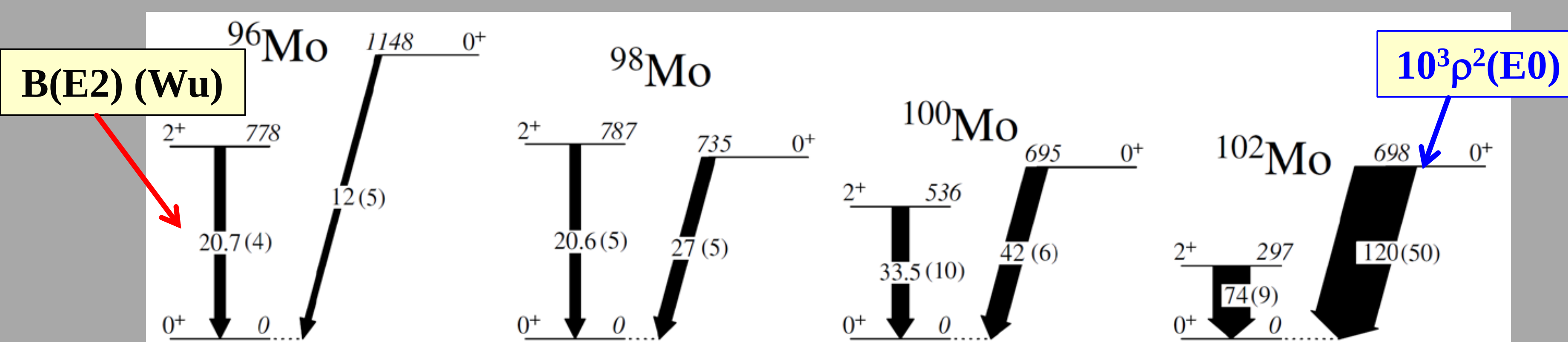


prolate

triaxial

oblate

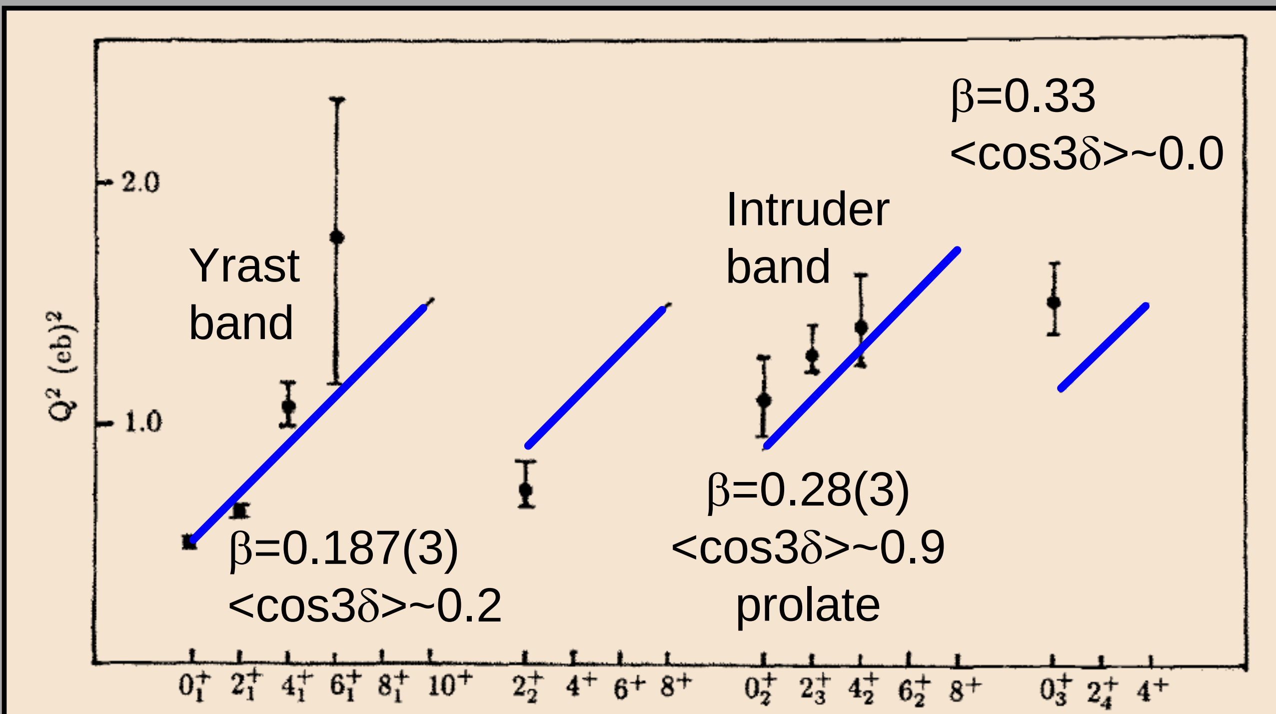
Zielinska et al., NPA 712, 3 (2002), Wrzosek-Lipska et al., PRC 86 064305 (2012)

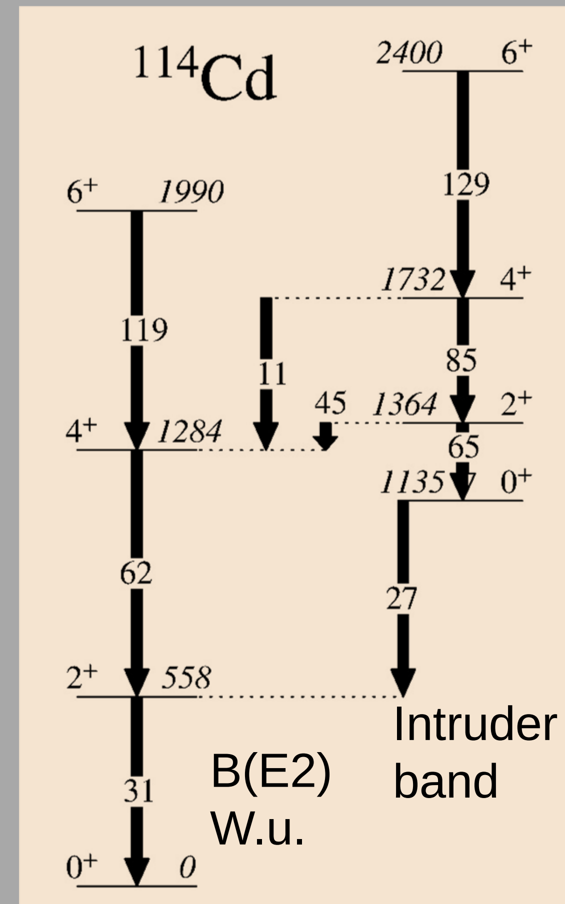


- **In nearly all cases of U(5) candidates in *Z*=50 region, additional data has shown that previously assigned 0^+ member of two-phonon triplet *is, or very likely to be*, a shape coexisting structure**
- **In most of these cases, it's the shape coexisting structure that possess an enhanced *B*(*E*2) value to the 2_1^+ state – why?**

^{114}Cd deformation parameters from rotational invariants

- **Most detailed Coulex study to date on Cd isotopes [Fahlander, NPA 485, 317 (1988)] ^{16}O, ^{40}Ca, ^{58}Ni, ^{208}Pb on ^{114}Cd**





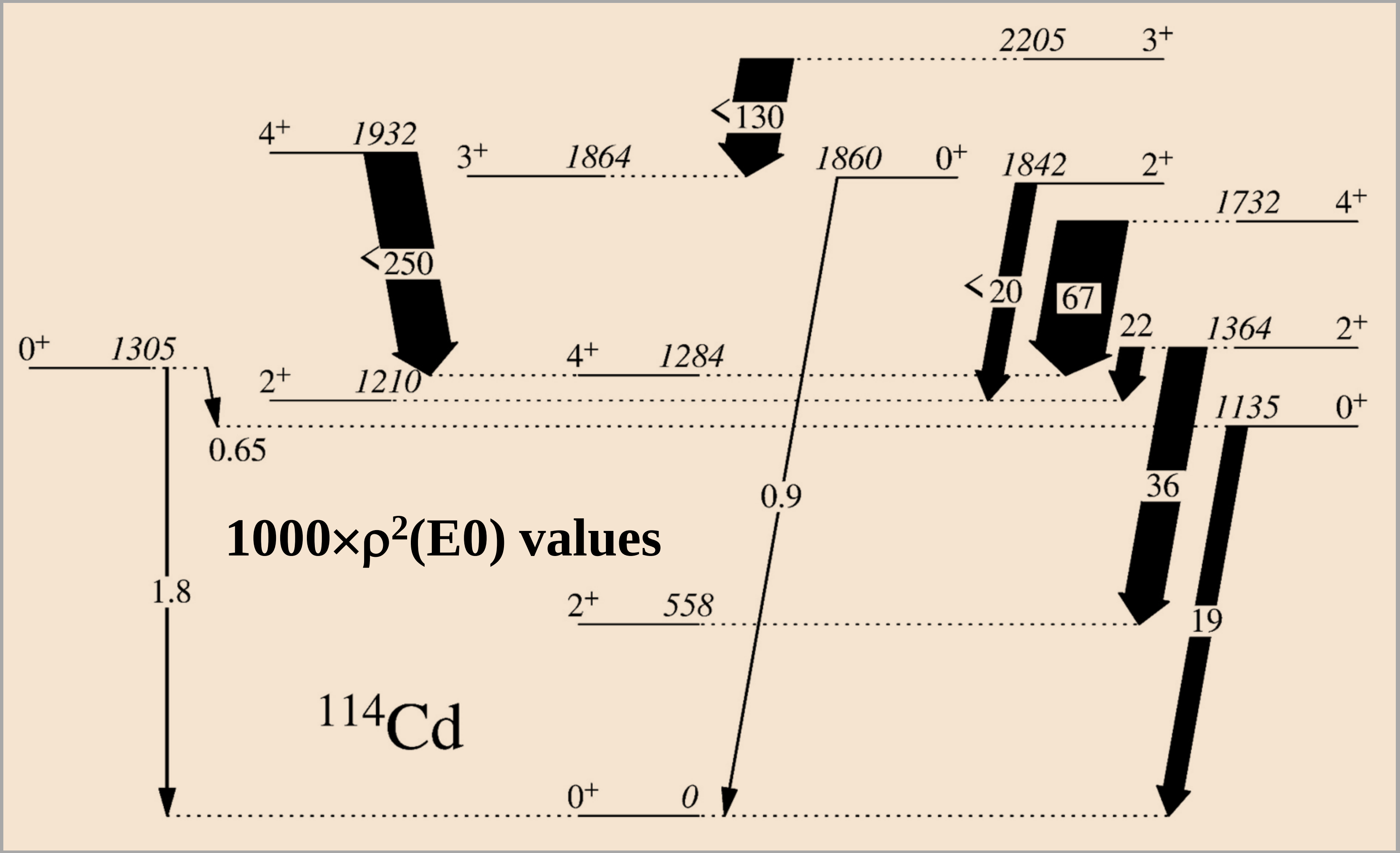
$$\frac{1}{\sqrt{5}}Q^2=\sum_i \langle 0\|M(E2)\|2_i\rangle\langle 2_i\|M(E2)\|0\rangle \begin{Bmatrix} 2 & 2 & 0 \\ 0 & 0 & 2 \end{Bmatrix}$$

$$Q^2 \approx \left(\frac{3}{4\pi}ZR_0^2\right)^2 \beta_0^2$$

harmonic vibrator value

Extensive $\rho^2(E0)$'s also known in ^{114}Cd

- ***E*0's extracted from α coefficients and evaluated lifetimes (Wood et al, NPA 651, 323 (1999) & Kibedi and Spear, At. Data Nucl. Data Tab. 80, 35 (2002))**



Extracting mixing amplitude from shape parameters and $\rho^2(E0)$ values

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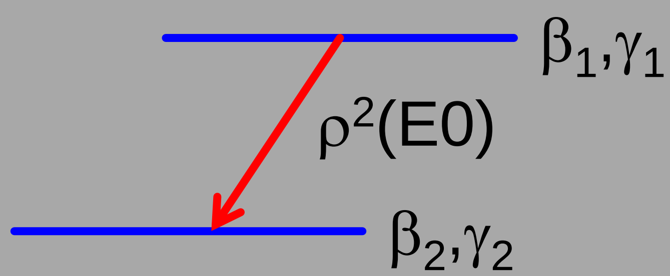
- **Assume 2-level mixing model – may not always be appropriate**
- **Describe levels using β, γ shape parameters, mixing amplitude *a***

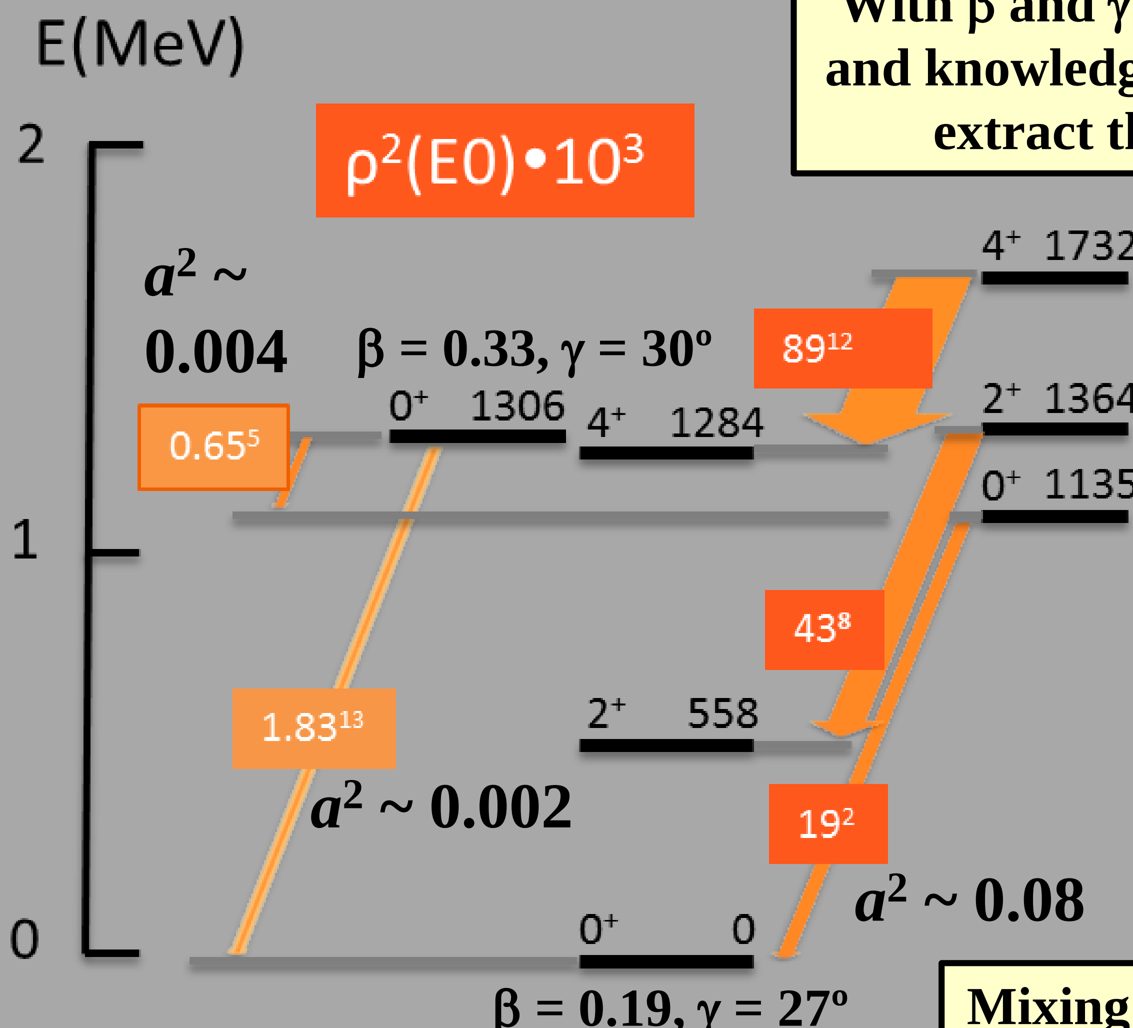


$$\rho^2(E0) = a^2(1-a^2)\left(\frac{3Z}{4\pi}\right)^2\left[(\beta_1^2-\beta_2^2) \quad \sim 0 \quad \right]^2$$

- **If shape parameters are known, the mixing amplitude can be determined**
- **Use the results from detailed Coulomb excitation**

Analysis of 0$^+$ ρ^2(E0) values in ^{114}Cd

With β and γ established from Coulex, and knowledge of ρ^2(E0) values, we can extract the mixing amplitudes



β = 0.27, γ = 9.5º

Conv. Elec. ILL BILL/GAMS
Mheemeed NP A412 113 1984

β,γ values Fahlander NP A485, 317 (1988)

Mixing between configurations (generally) weak

What is the origin of the enhanced $E2$ strength from the 0^+ intruder band head?

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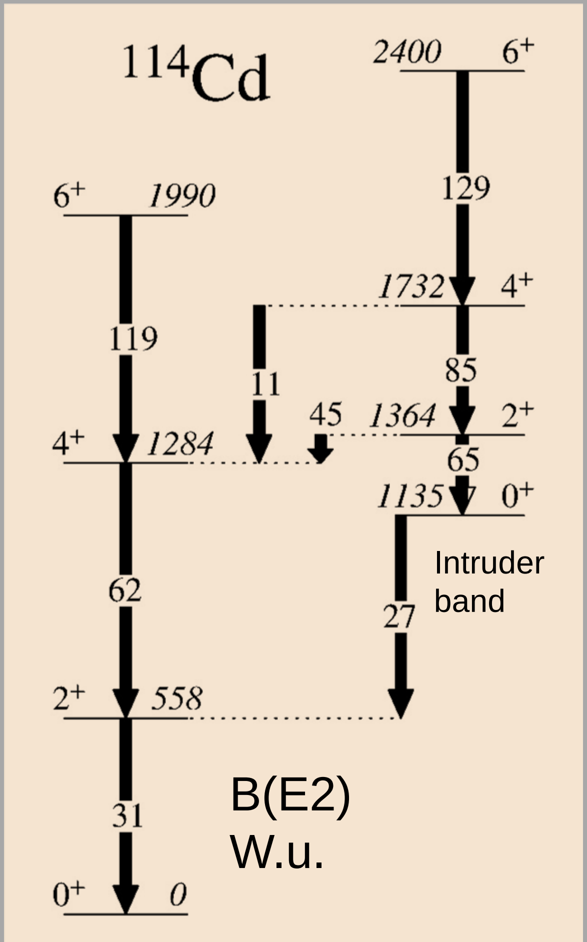
- **While mixing is small, important consequences: Consider ^{114}Cd**



- **Write 0^+ wave functions**

$$|0_{gs}^+> = a|0_A^+> + b|0_B^+>$$

$$|0_I^+> = -b|0_A^+> + a|0_B^+>$$

- **Assume:**
  - **inband $2^+ \rightarrow 0^+$ transitions equal the observed values (since weak mixing) $2_B^+ \rightarrow 0_B^+ = 65 \pm 9$ W.u.**
  - **$2_B^+ \rightarrow 0_A^+ = 0$**

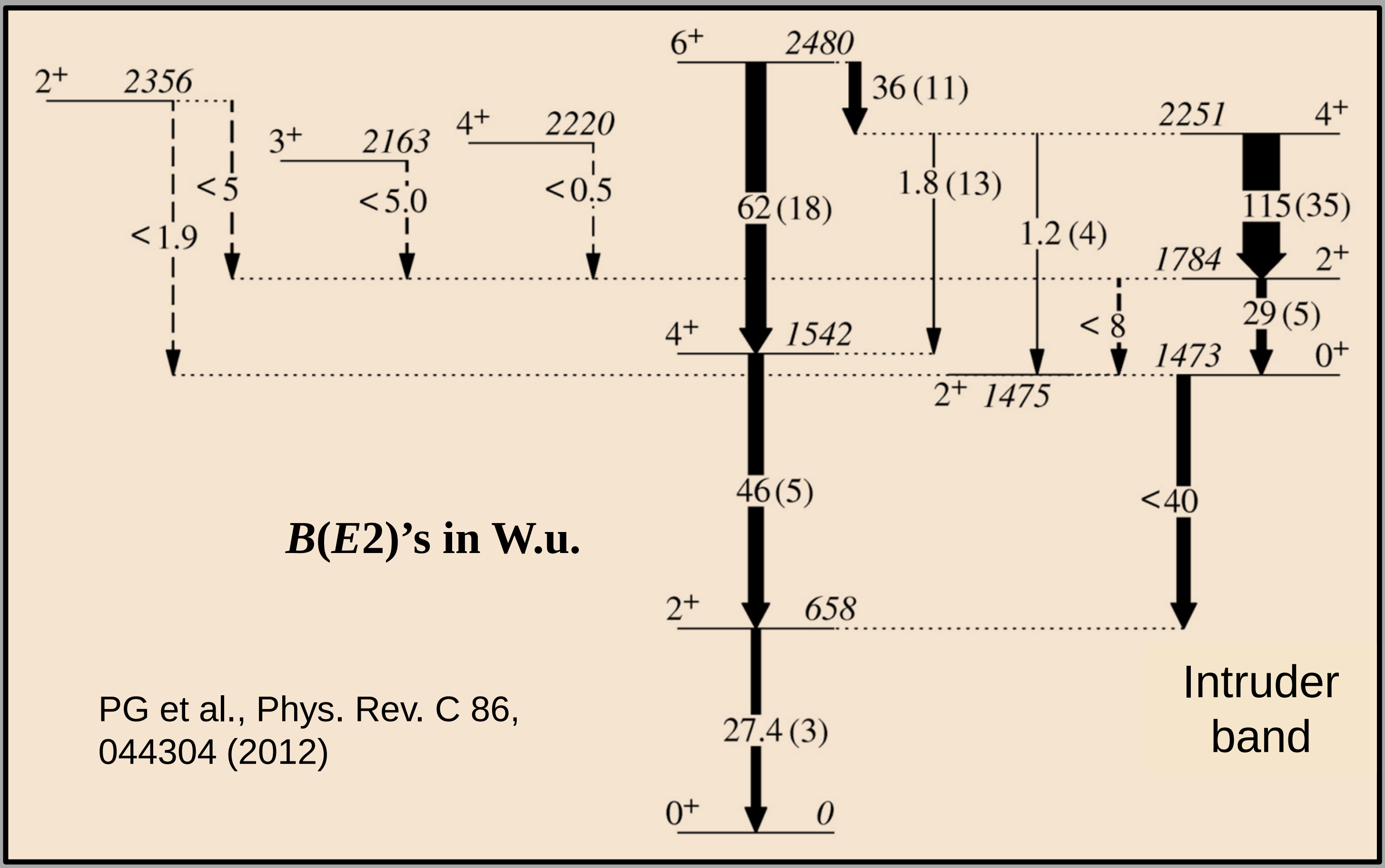
with admixture of 8% results in calculated $B(E2;0_2^+ \rightarrow 2_1^+) = 26 \pm 4$ W.u. consistent with observed value of 27.4 ± 1.7 W.u.

Important contribution to $0_2^+ \rightarrow 2_1^+$ $E2$ strength from mixing

Pulling apart the configurations

- Result for ^{114}Cd 0^+ states consistent with evidence for weak mixing in ^{110}Cd

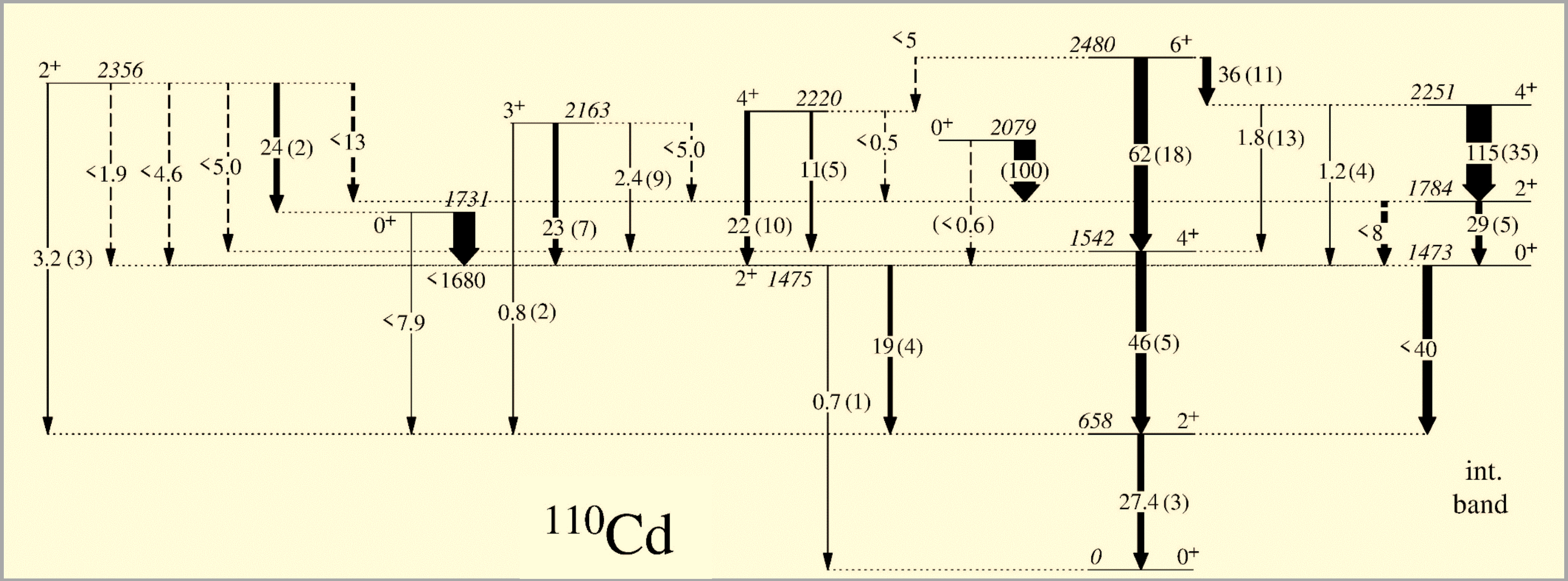
Cross-configuration E2 transitions in ^{110}Cd are generally weak or unobserved



PG et al., Phys. Rev. C 86, 044304 (2012)

Pulling apart the configurations – e.g. ^{110}Cd

Detailed spectroscopy via β-decay and (n,n′γ) enabled observation of, or stringent limits on, nearly all possible decays

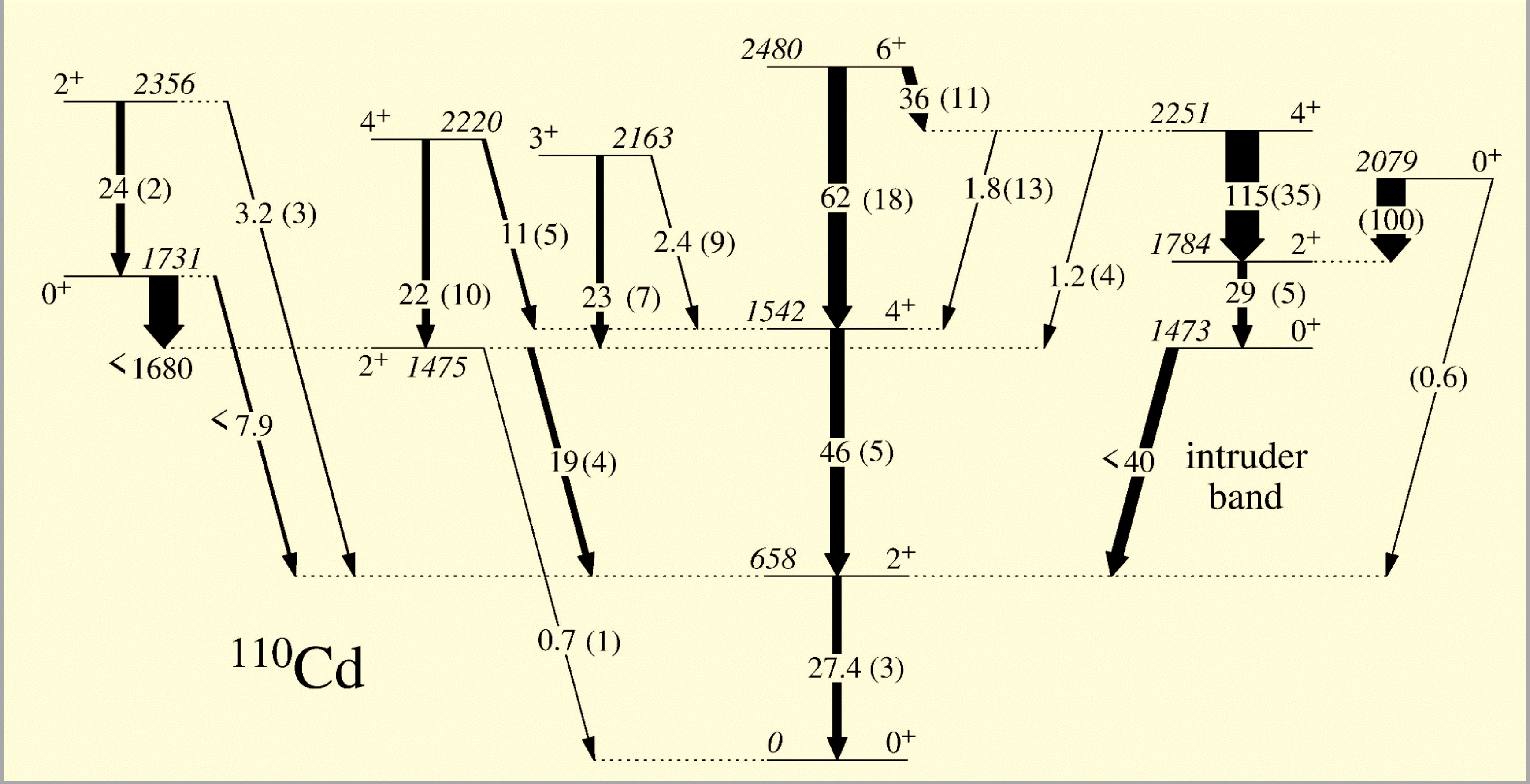


PG et al., Phys. Rev. C 86, 044304 (2012)

Transitions labelled in W.u.
Relative B(E2) in parenthesis
Dashed lines: unobserved transitions

Pulling apart the configurations – e.g. ^{110}Cd

Levels rearranged and limits on unobserved transitions removed

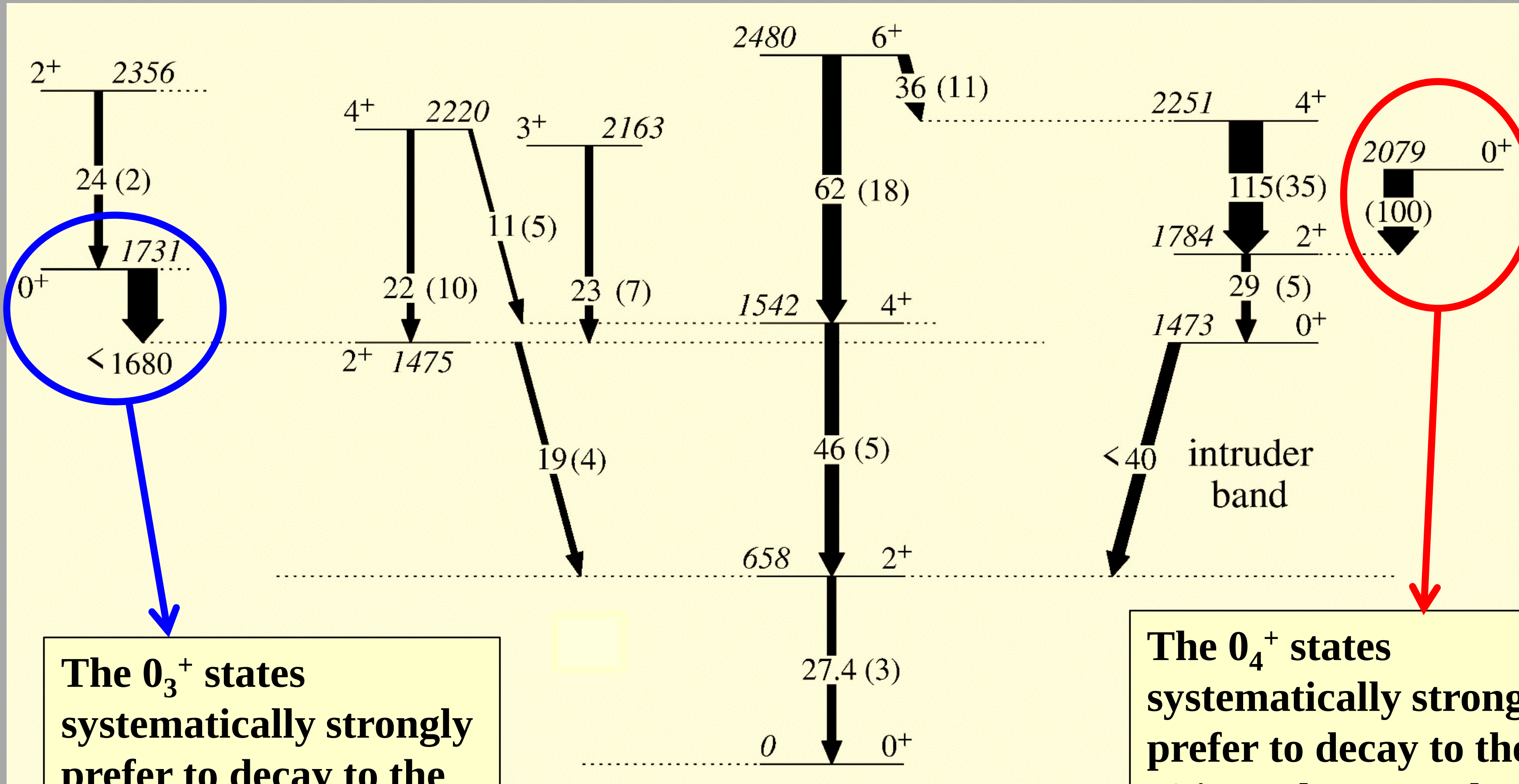


PG et al., Phys. Rev. C 86, 044304 (2012)

Transitions labelled in W.u.
Relative B(E2) in parenthesis

Revealing the underlying structure – e.g. ^{110}Cd

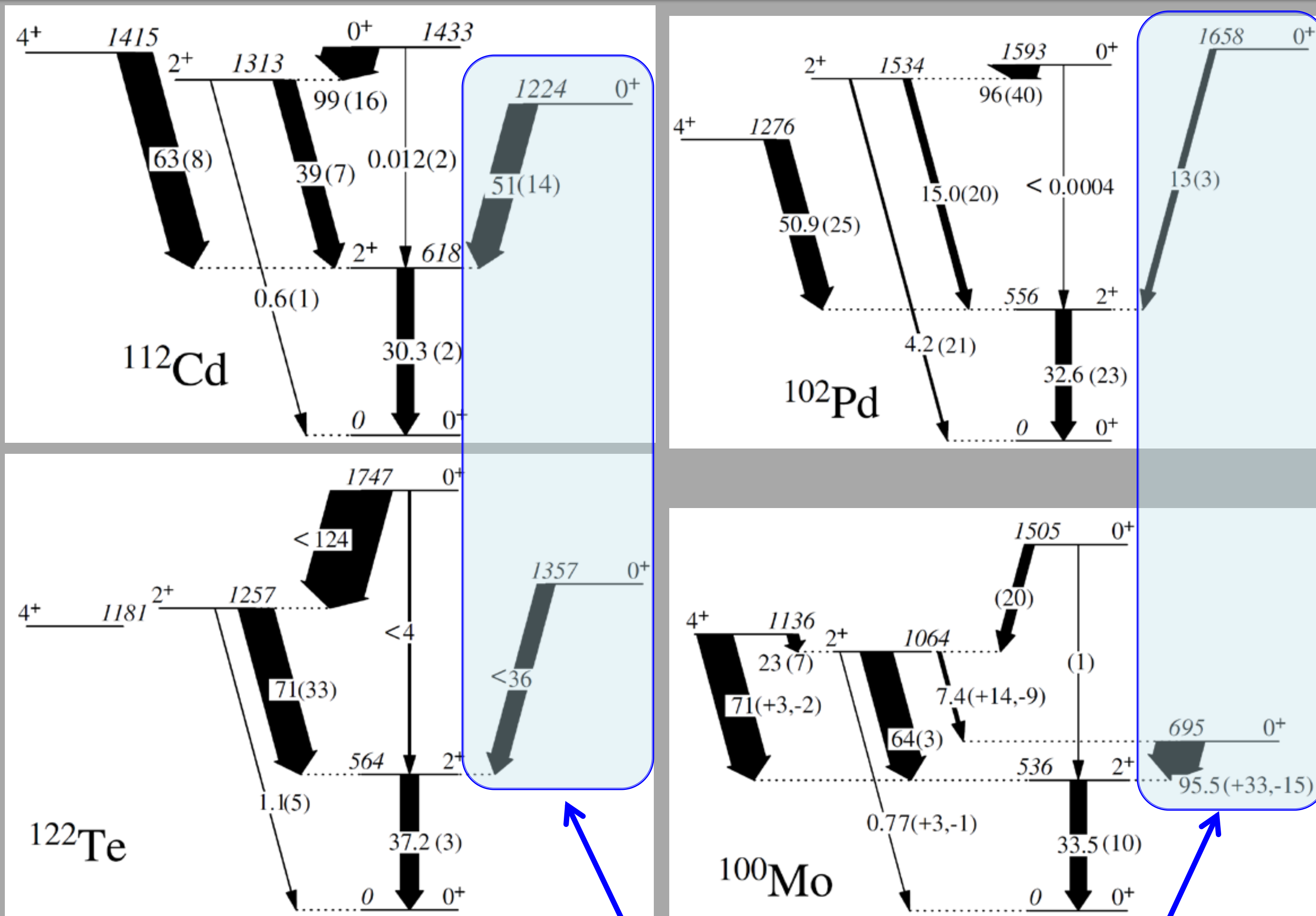
Transitions labelled in W.u.
Relative B(E2) in parenthesis
Weak transitions removed for clarity



The 0_3^+ states systematically strongly prefer to decay to the 2_2^+ "γ-band" head

The 0_4^+ states systematically strongly prefer to decay to the 2^+ intruder – another "K=0" intruder band head?

Revealing the underlying structure



The favoured and enhanced decay of the excited non-intruder 0^+ state to the 2_2^+ state, rather than 2_1^+ state, common feature in Cd, Te, Pd, Ru, Mo, Xe,…

Structure of non-intruder states not that of a spherical vibrator

***B*(*E*2) in W.u.**

Shape coexisting structure

Are their any surviving candidates for near harmonic vibrational motion near $Z = 50$?

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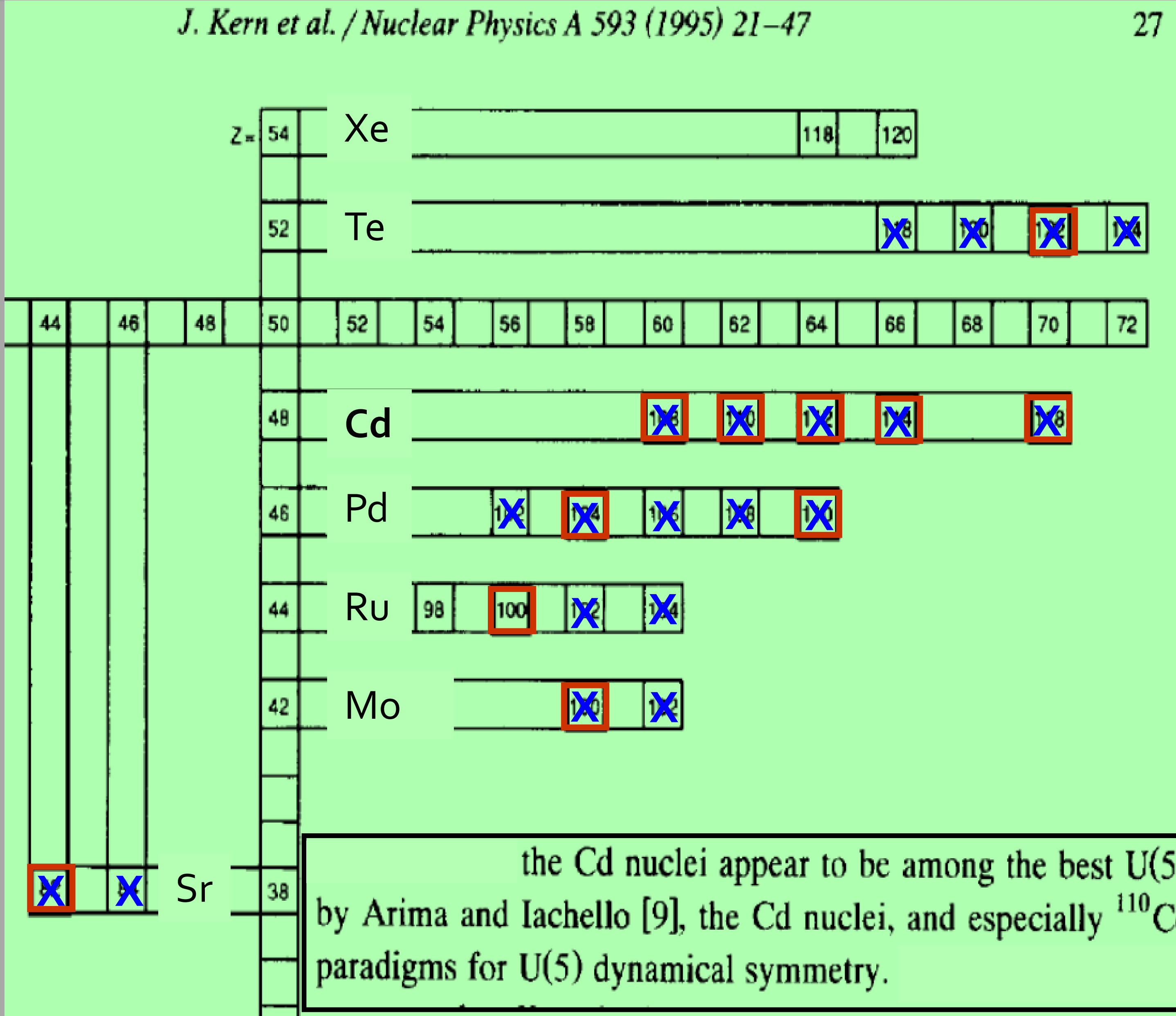
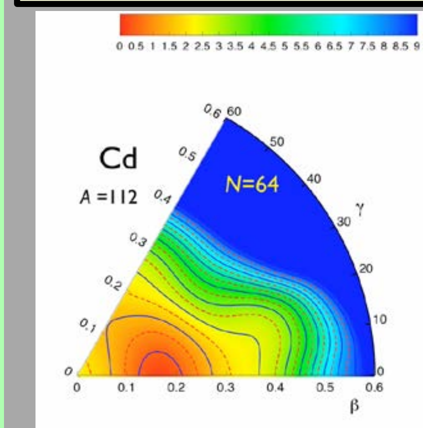


Where detailed Coulomb excitation data exists, consistent with deformed γ-soft or triaxial structure



the Cd nuclei appear to be among the best U(5) candidates. As proposed by Arima and Iachello [9], the Cd nuclei, and especially ^{110}Cd, can still be regarded as paradigms for U(5) dynamical symmetry.

Special thanks to

Steve Yates – Kentucky
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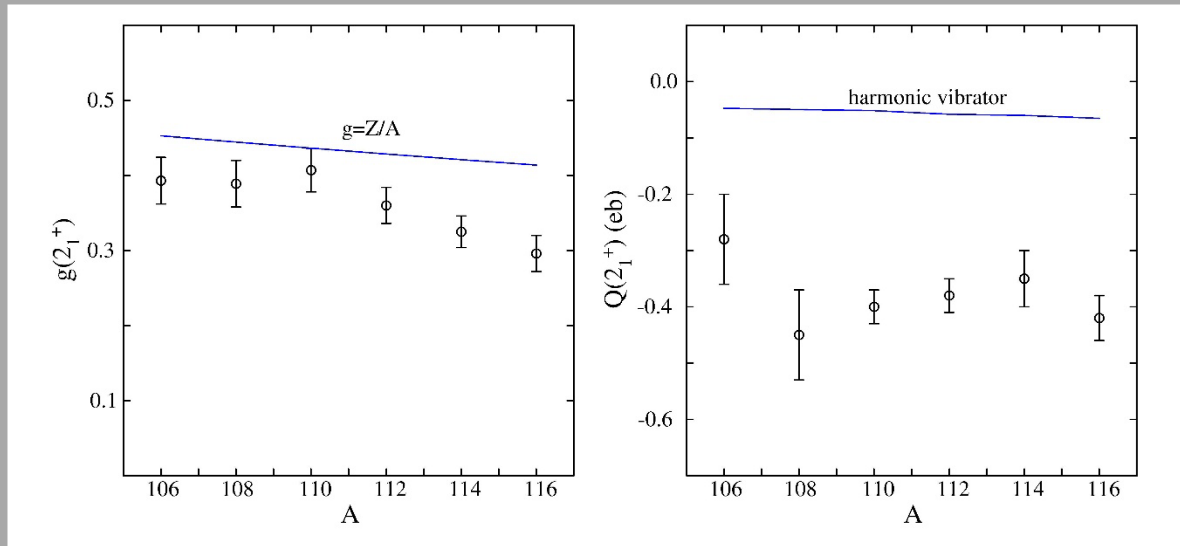
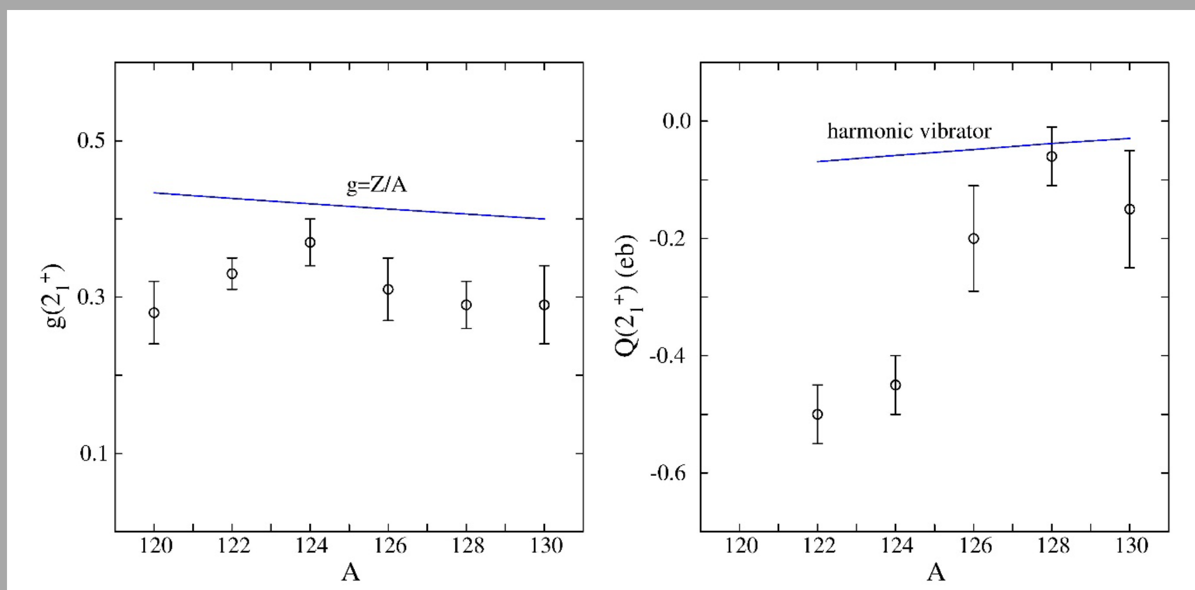
Kasia Wrzosek-Lipska – Warsaw
Mitch Allmond – ORNL
…and the Guelph Nuclear Physics Group



Cd g-factors and quadrupole moments



Te g-factors and quadrupole moments