Collective excitations and shape co-existence in the Cd/Sn region

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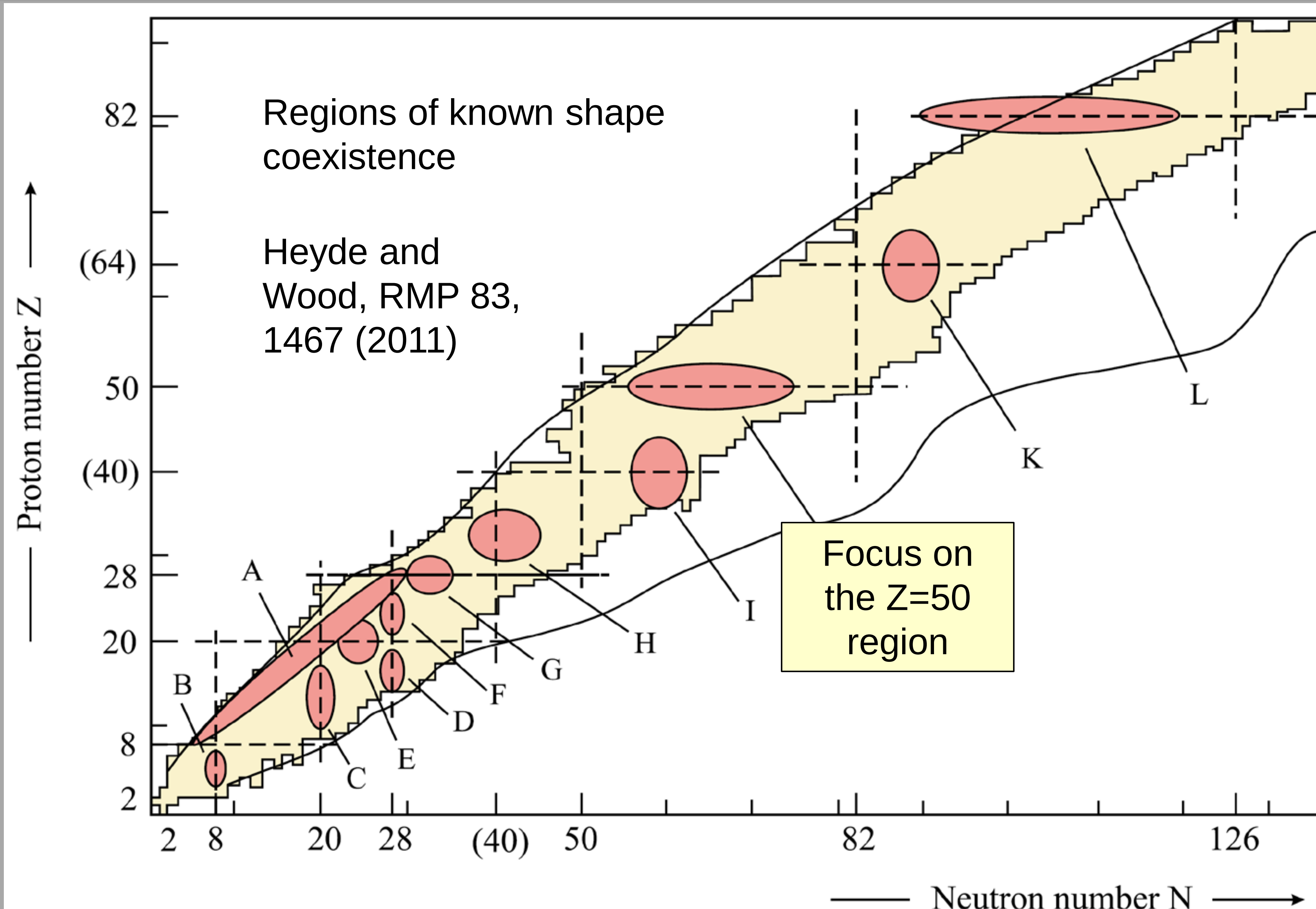
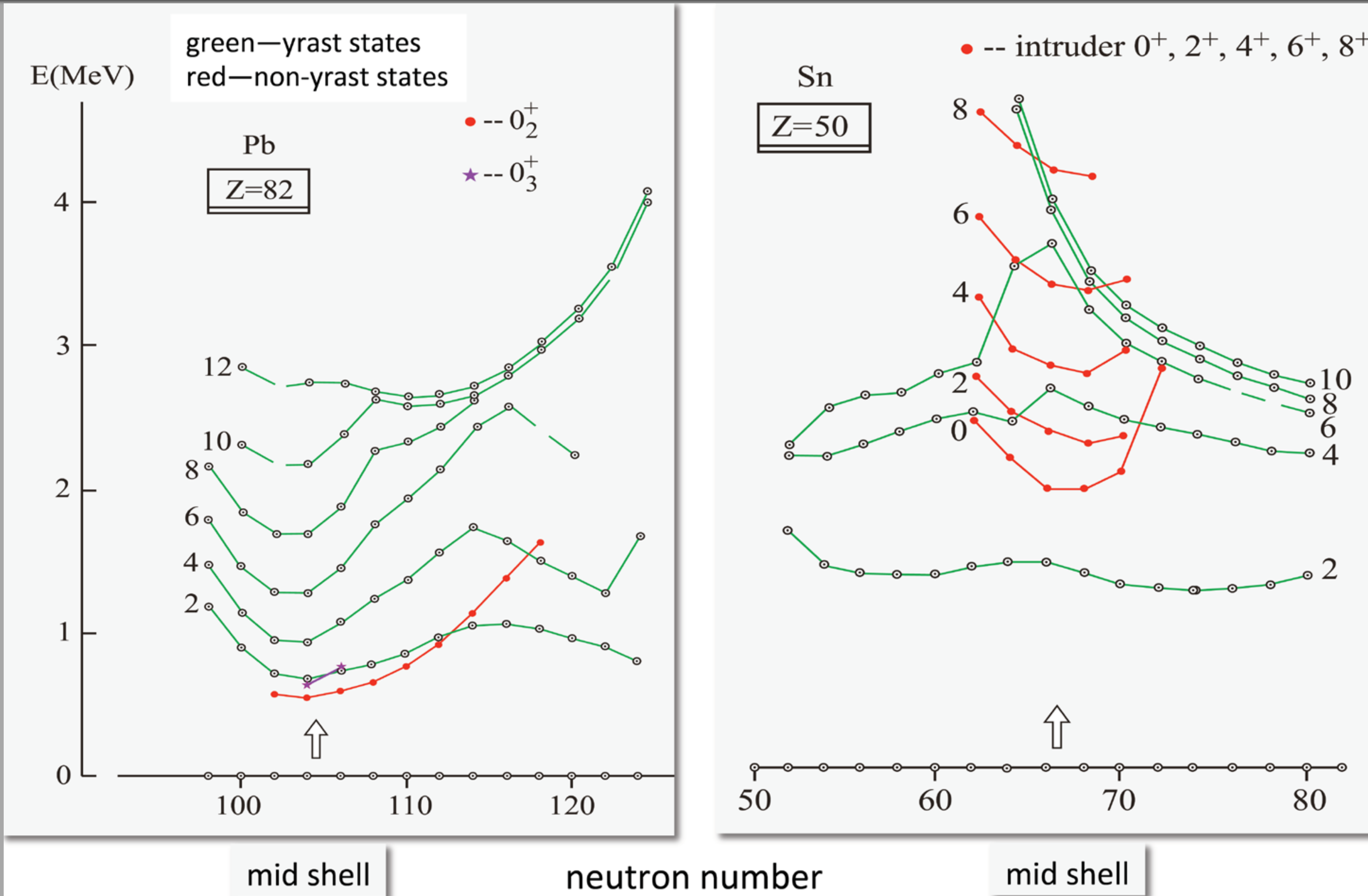
Shape coexistence pervasive throughout nuclear chart

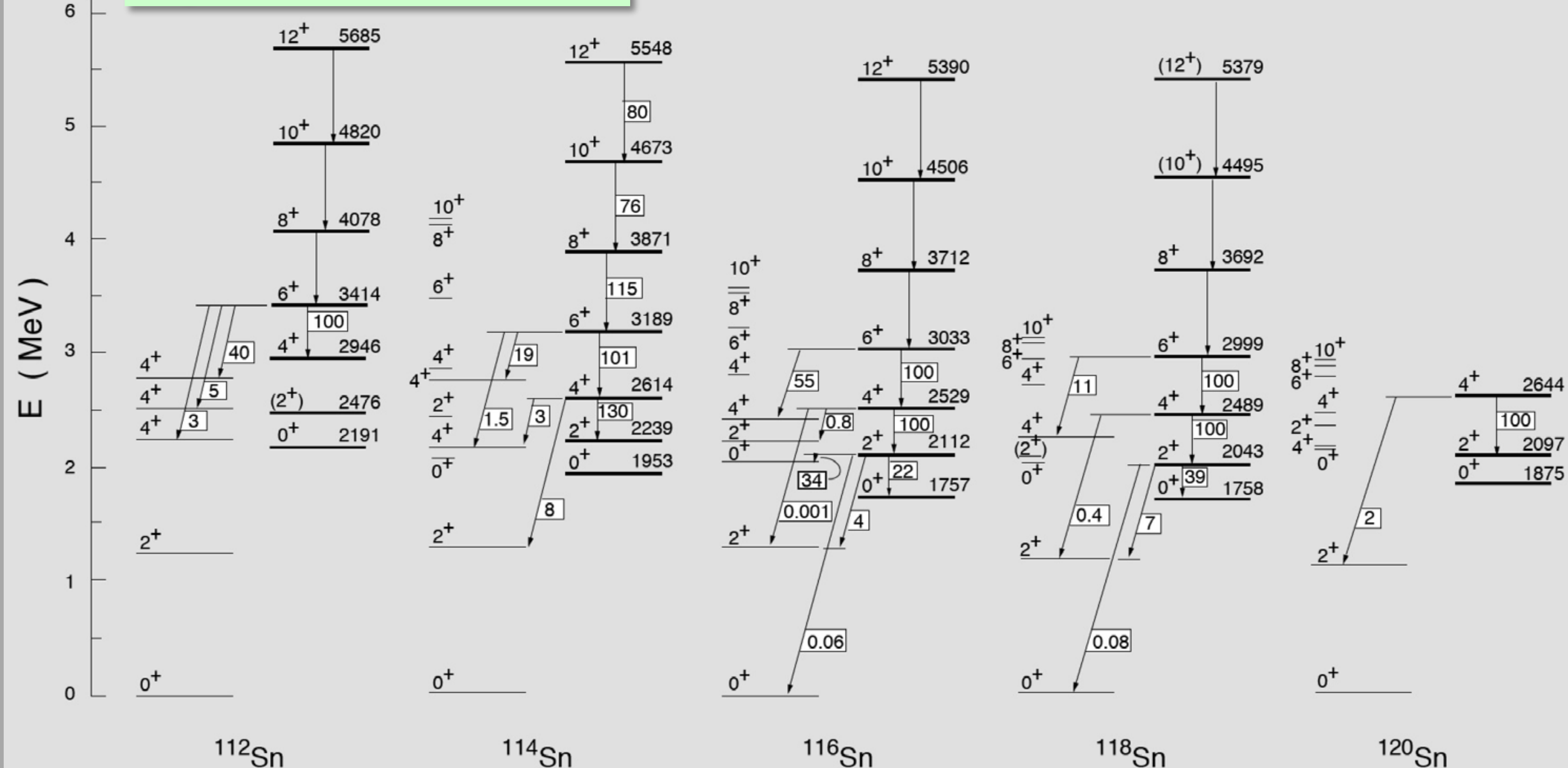


Characteristic pattern of deformed intruder bands at closed shells



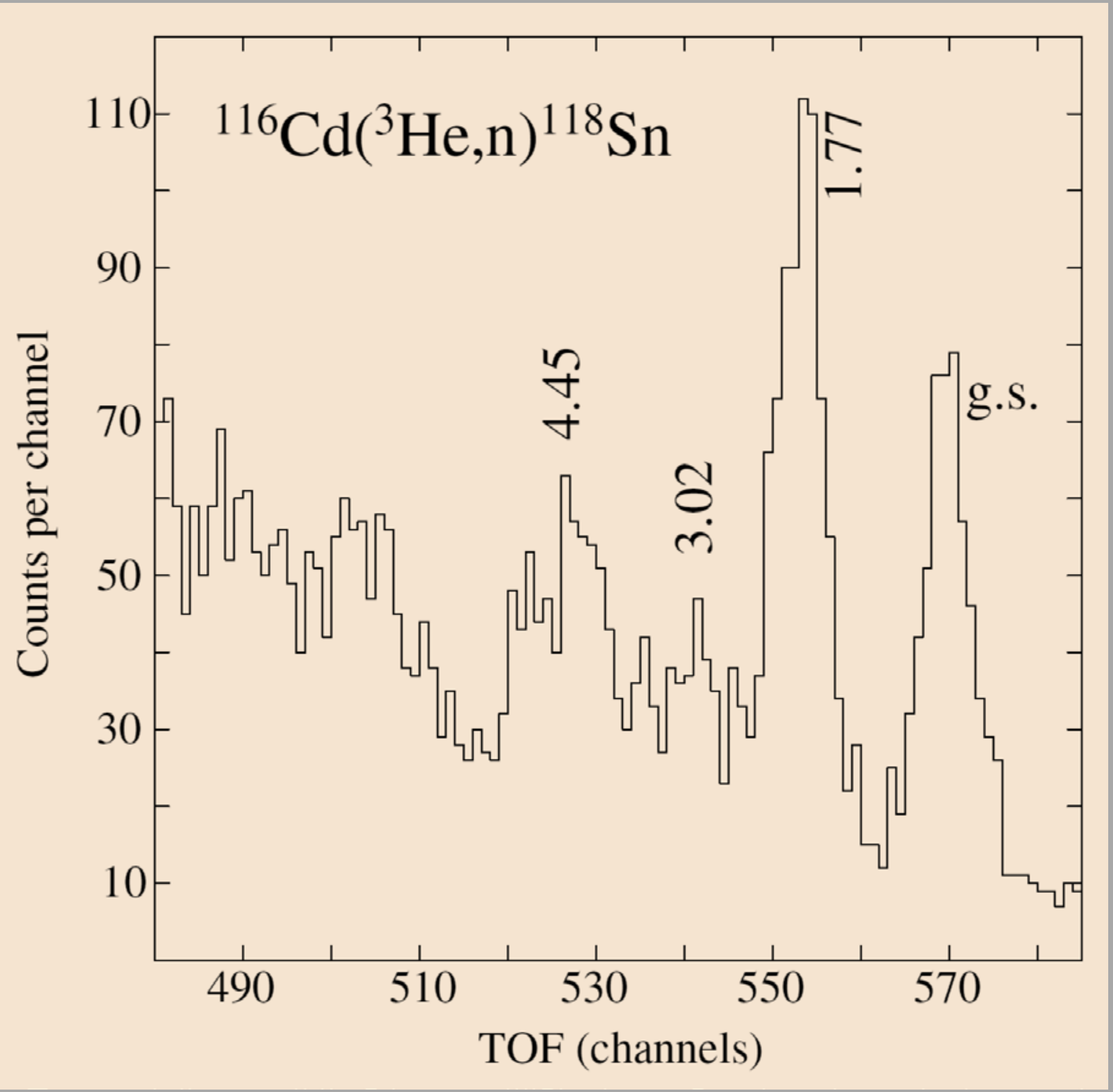
Deformed bands in the even-even Sn isotopes

Figure from Rowe & Wood



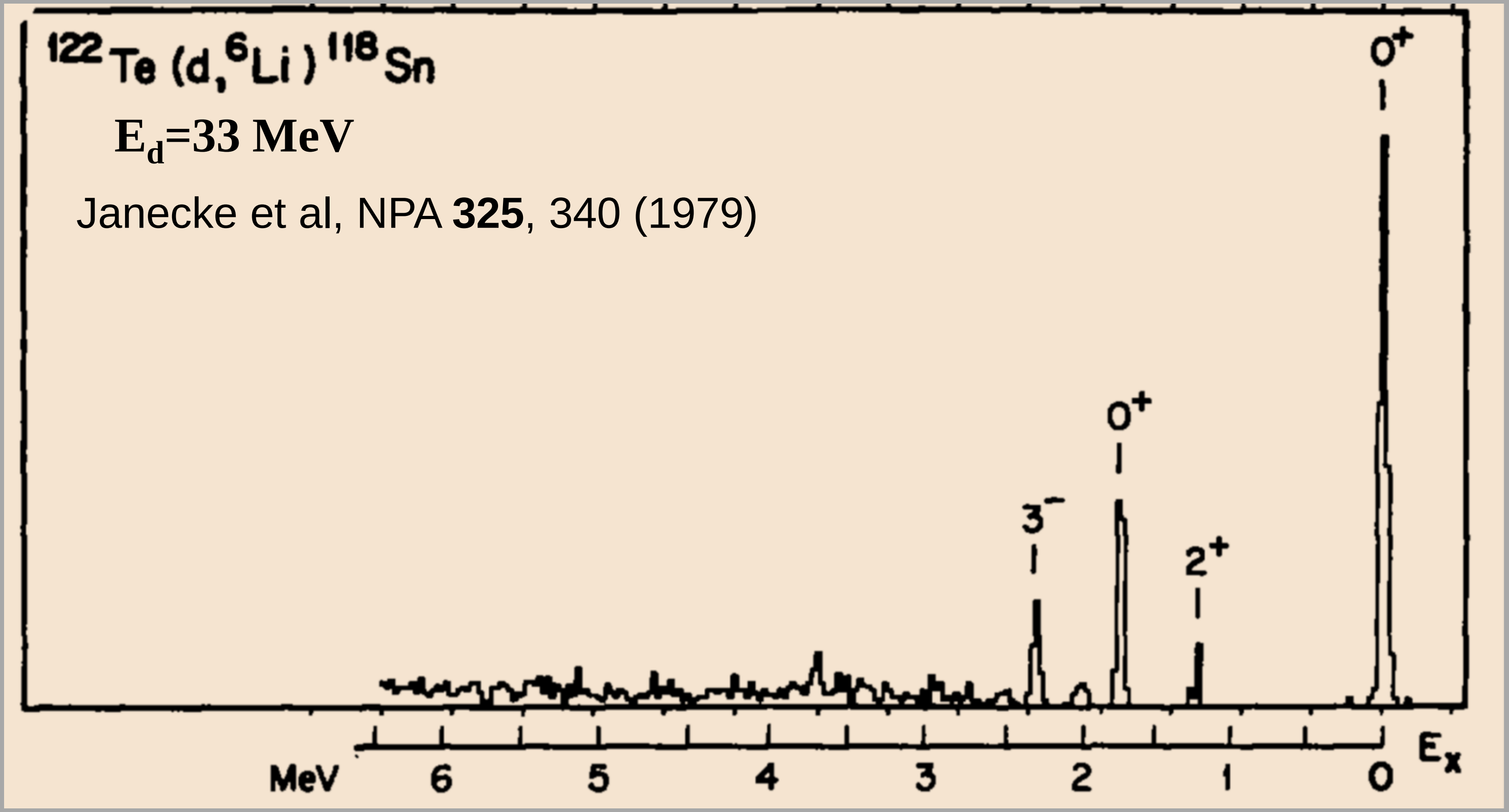
- **Two-proton transfer strongly populates excited 0^+ state – reminiscent of proton pairing vibration – assigned as 2*p*-2*h* excitation across *Z*=50 closed shell**

Fielding et al., Nucl. Phys. **A281**, 392 (1977)



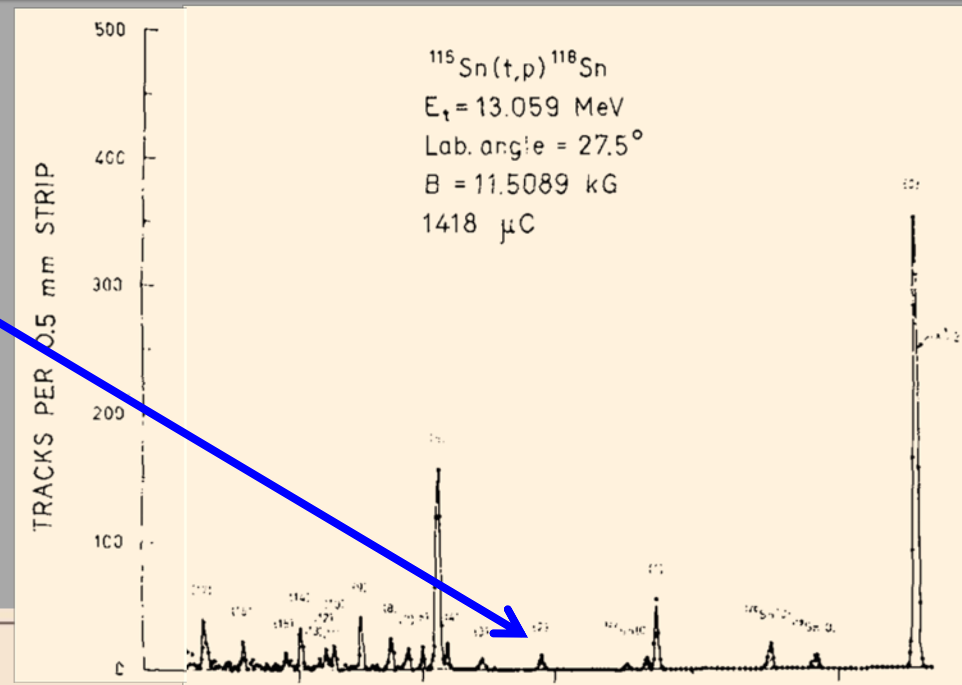
Further evidence for proton *2p-2h* character from α-particle transfer

- **Te target – protons in 2*p* state**
- **Removal of α particle favours population of 0*p*-0*h* (gs) or 2*p*-2*h* state (intruder)**



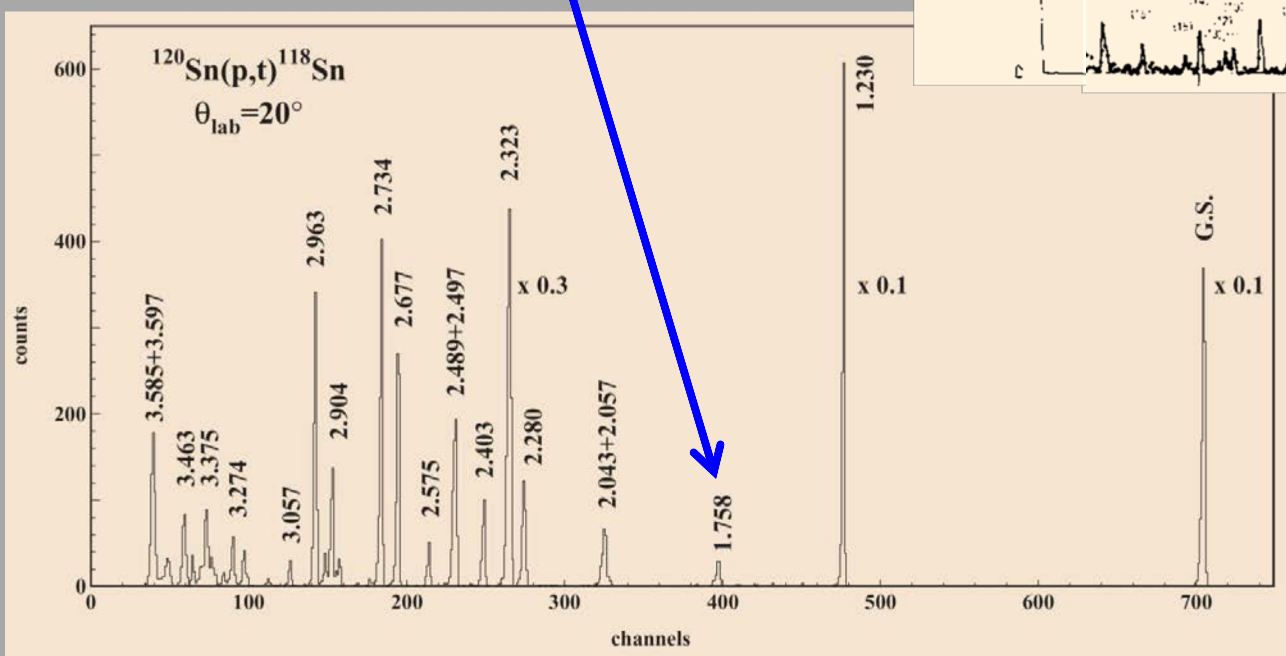
Intruder 0$^+$ states in Sn populated very weakly in two-neutron transfer

- ***π2p-2h*** **excitation very weak in (p,t) and (t,p)**

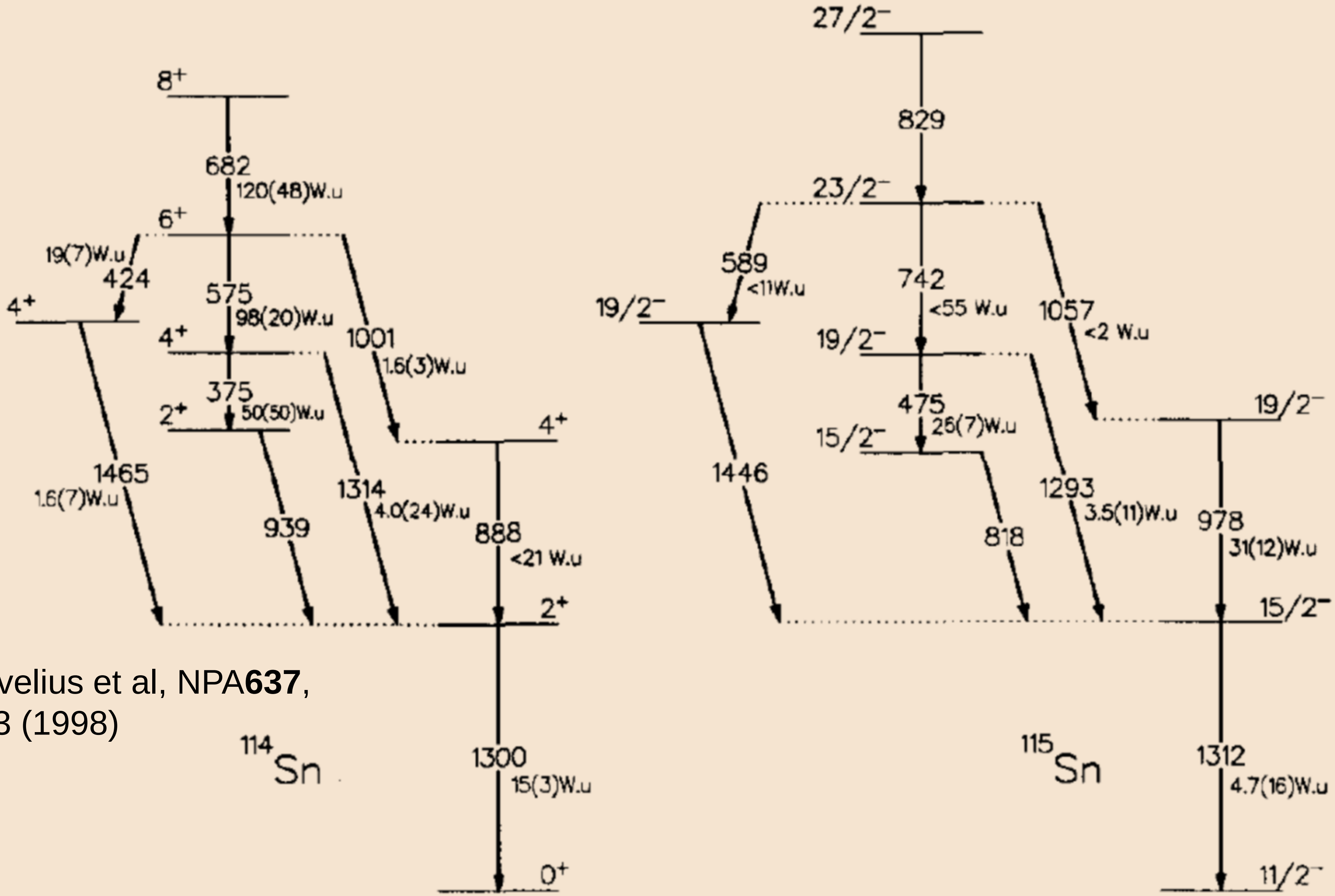


Bjerregaard et al., NPA **110**, 1 (1968)

Guazzoni et al., PRC **78**, 064608 (2008)



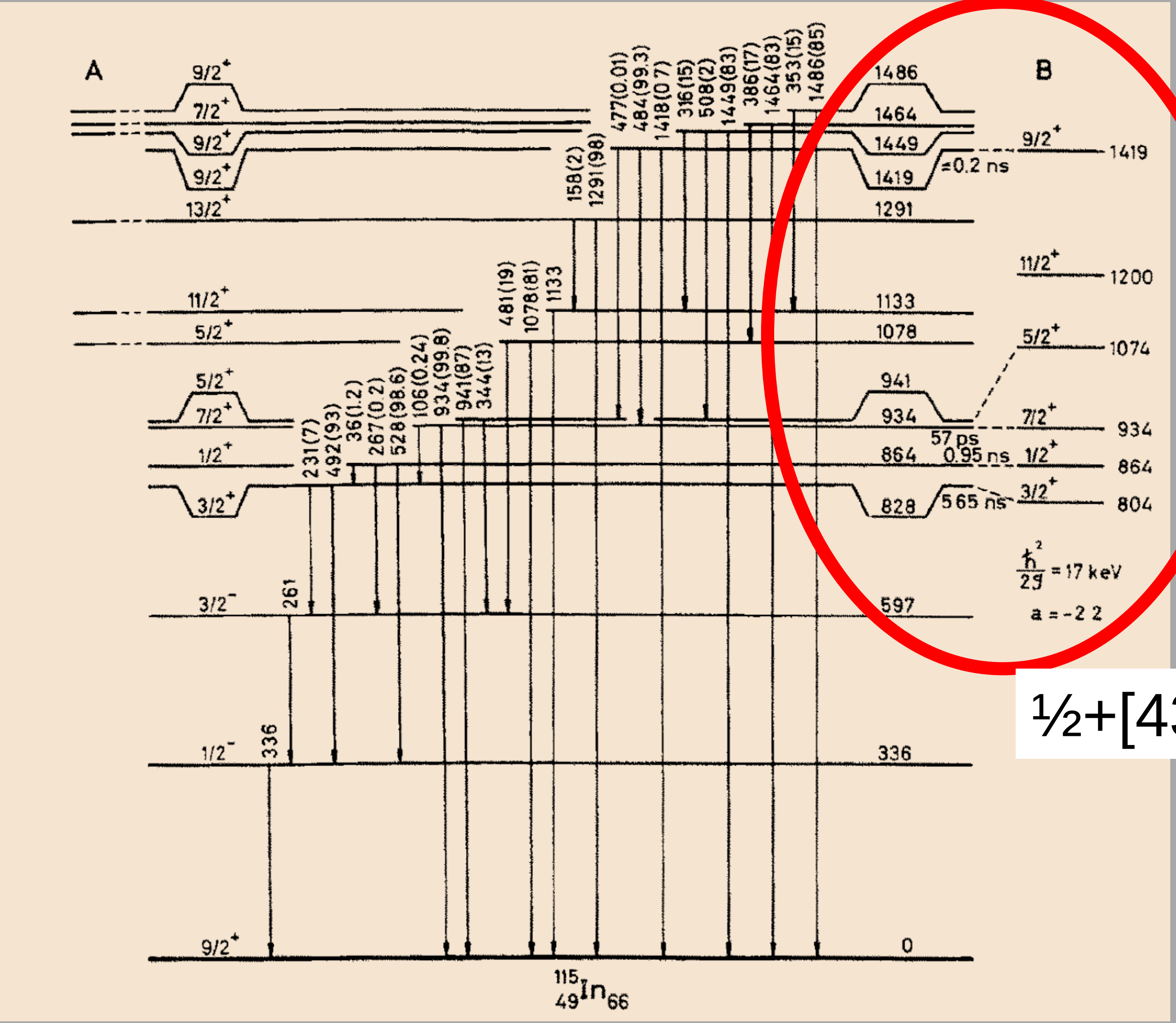
Strong evidence for persistence of intruder states in odd-mass Sn isotopes



Savelius et al, NPA**637**, 513 (1998)

Similar structures observed in $^{109,111,113}Sn$

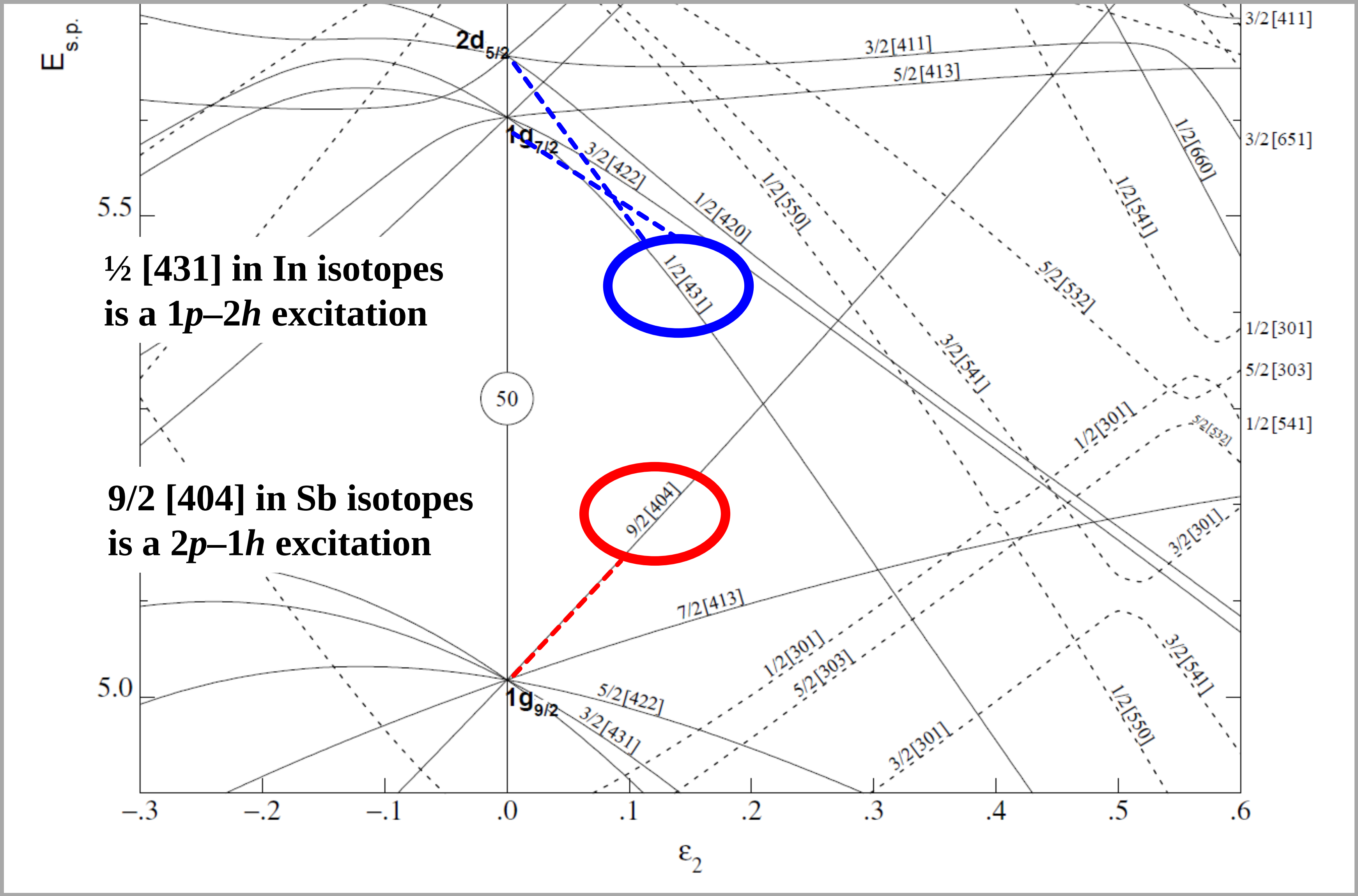
Intruder states in odd mass In isotopes



McDonald et al., Nucl. Phys. **A224** 13 (1974)

½+[431]

Nilsson states near *Z*=50

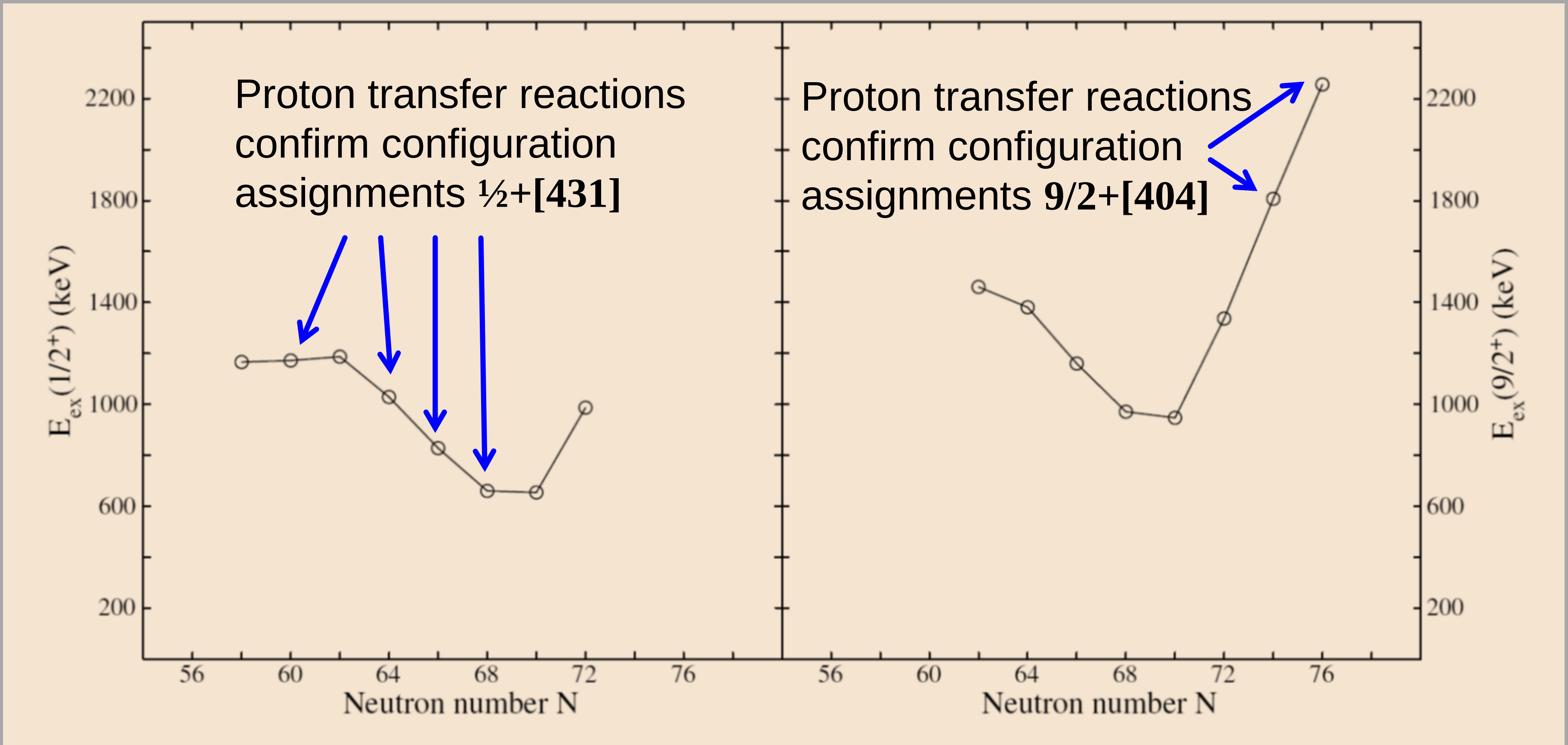


½ [431] in In isotopes is a 1*p*–2*h* excitation

9/2 [404] in Sb isotopes is a 2*p*–1*h* excitation

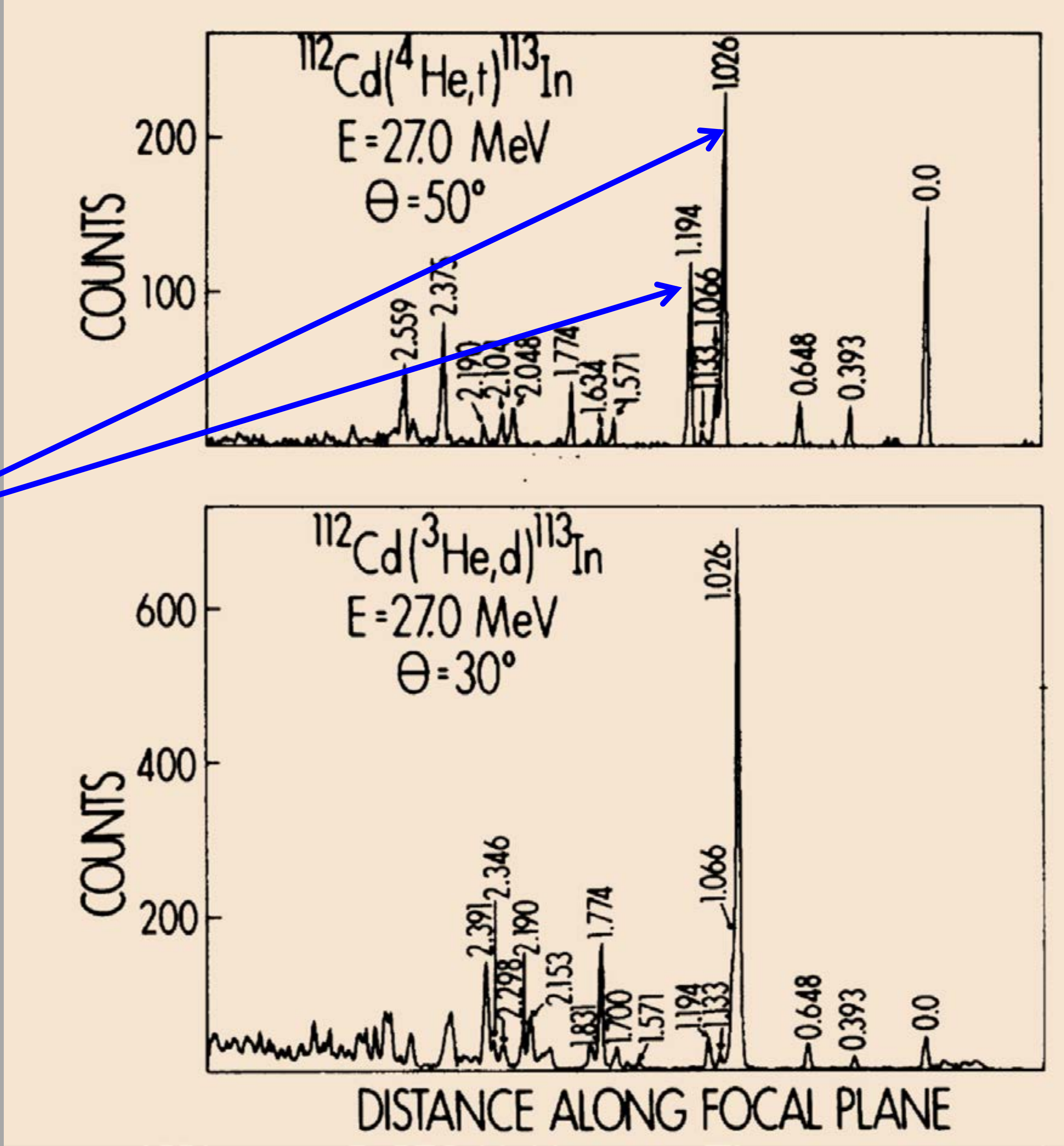
Systematics of intruder bands in In and Sb

In isotopes 1*p* – 2*h* states | **Sb isotopes 2*p* – 1*h* states**



Single-proton transfer results

- **Proton stripping reactions on Cd targets (2*h*) preferentially populate 1*h* or 1*p*-2*h* states in final nucleus**
  - **½ + [431] has large components d5/2 and g7/2**
  - **Fingerprint pattern confirms Nilsson assignment**



Markham and Fulbright, Phys. Rev. C **9**, 1633 (1974)

Systematic studies of Cd isotopes reveal intruder configuration evolution

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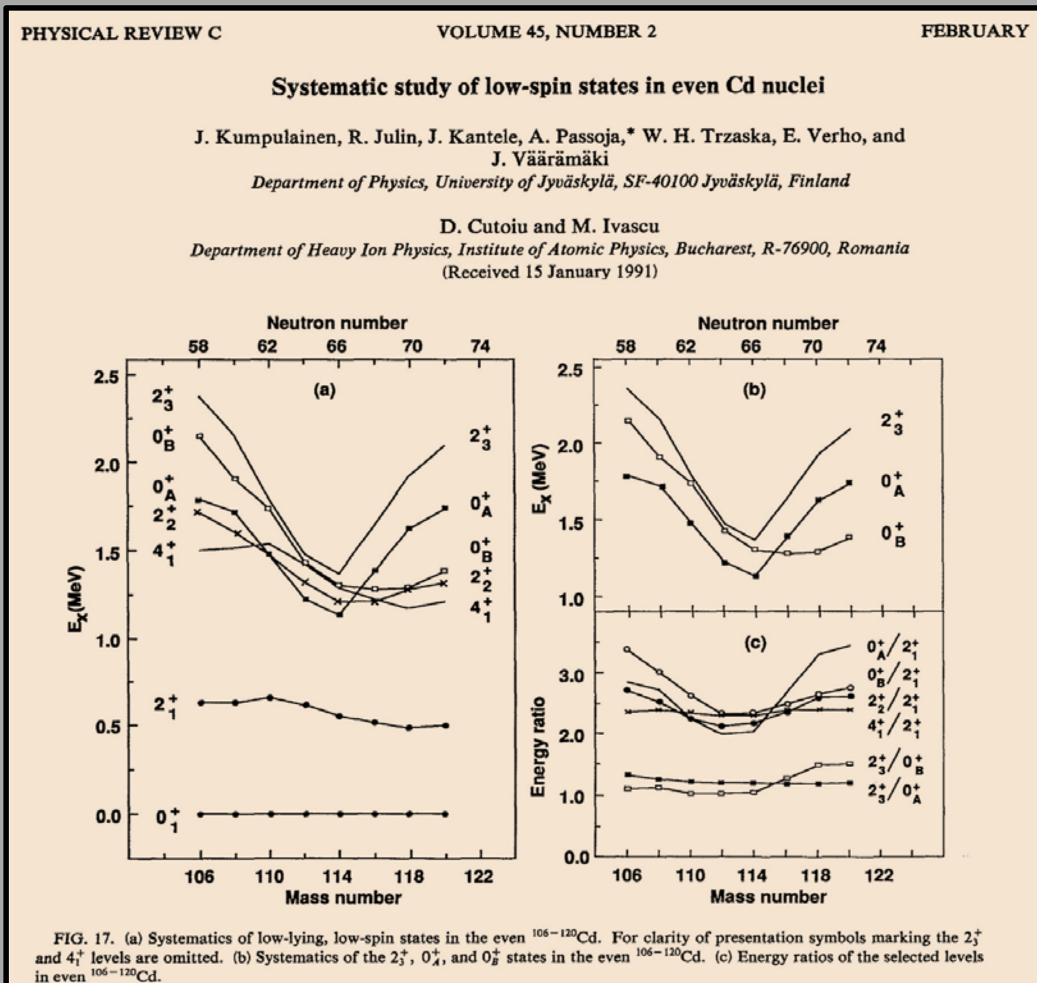
PHYSICAL REVIEW C VOLUME 45, NUMBER 2 FEBRUARY

Systematic study of low-spin states in even Cd nuclei

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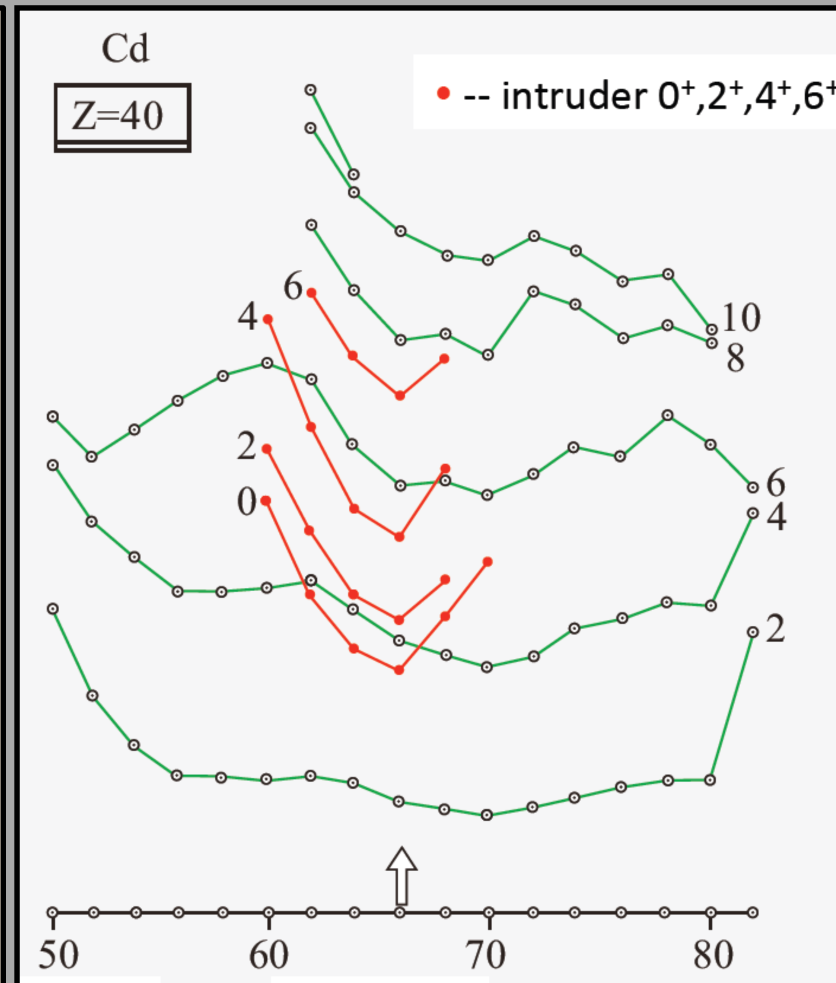
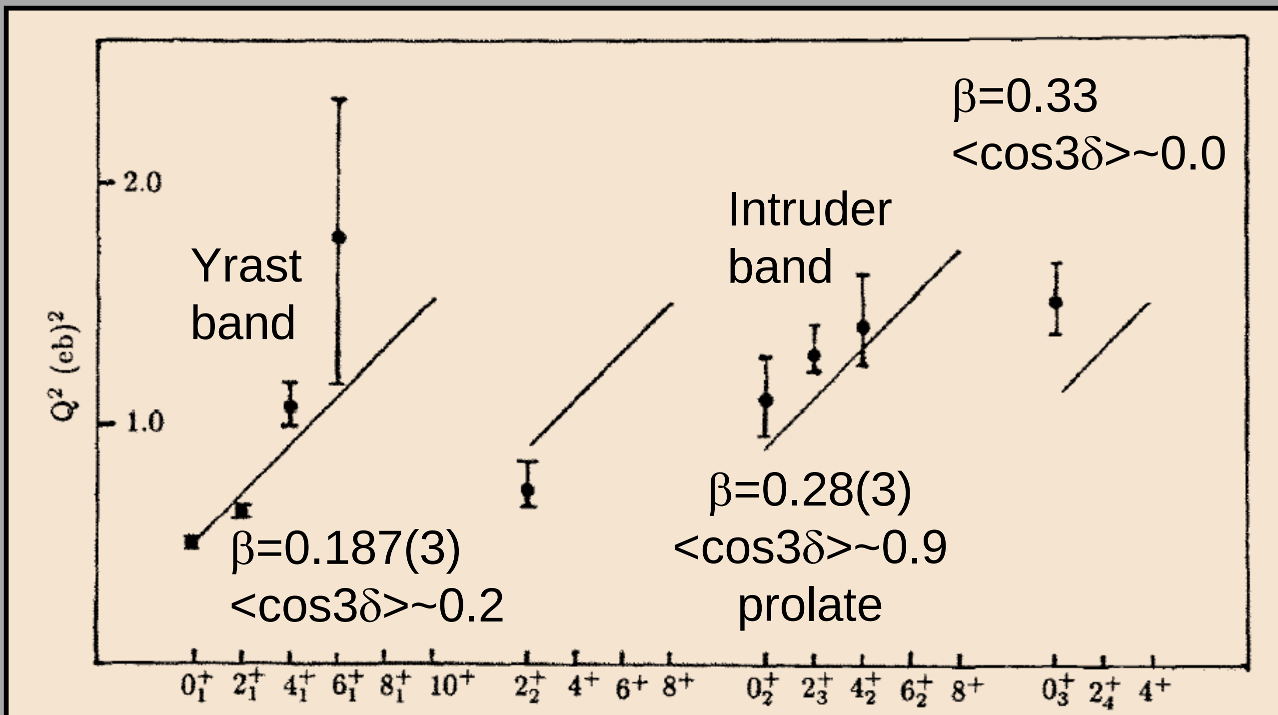
(Received 15 January 1991)

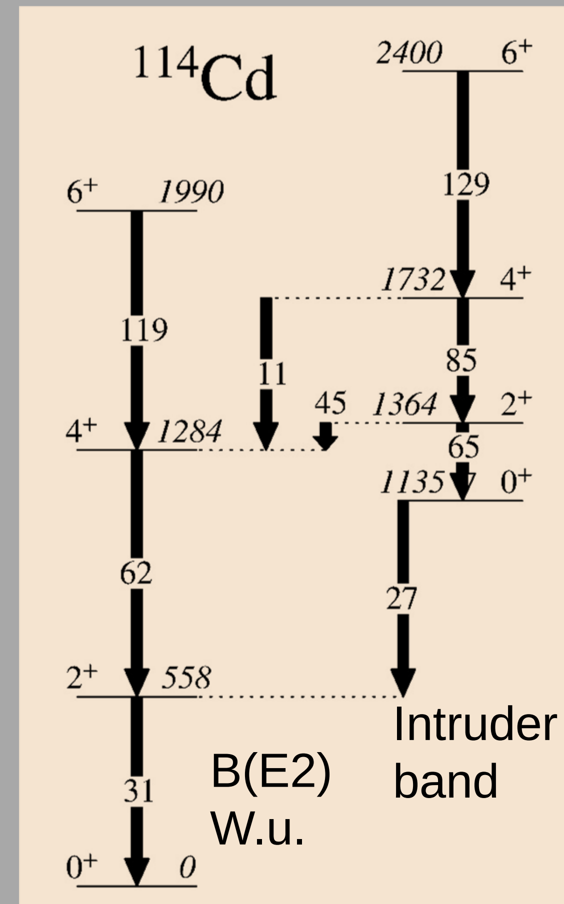
FIG. 17. (a) Systematics of low-lying, low-spin states in the even $^{106-120}$Cd. For clarity of presentation symbols marking the 2_3^+ and 4_1^+ levels are omitted. (b) Systematics of the 2_3^+, 0_A^+, and 0_B^+ states in the even $^{106-120}$Cd. (c) Energy ratios of the selected levels in even $^{106-120}$Cd.



How well determined is the deformation of the intruder band? Best evidence is from Coulex!

- **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**





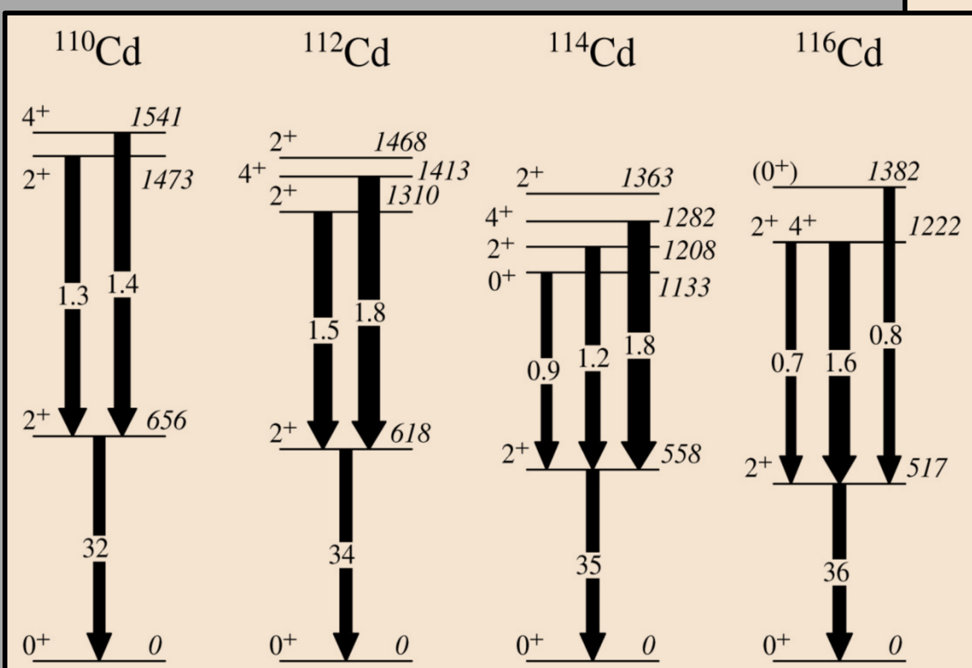
$$\frac{1}{\sqrt{5}} Q^2 = \sum_i \langle 0 \| M(E2) \| 2_i \rangle \langle 2_i \| M(E2) \| 0 \rangle \begin{Bmatrix} 2 & 2 & 0 \\ 0 & 0 & 2 \end{Bmatrix}$$

$$Q^2 \approx \left(\frac{3}{4\pi} Z R_0^2 \right)^2 \beta_0^2$$

Remarkably few nuclei studied in detail by Coulomb excitation with modern spectrometers

- **Coulex is one of the most powerful methods to explore collectivity – but few nuclei have been explored with modern spectrometers**

$2_1^+ \rightarrow 0^+$ absolute $B(E2)$ in W.u.; others relative to $B(E2;2_1^+ \rightarrow 0^+)$



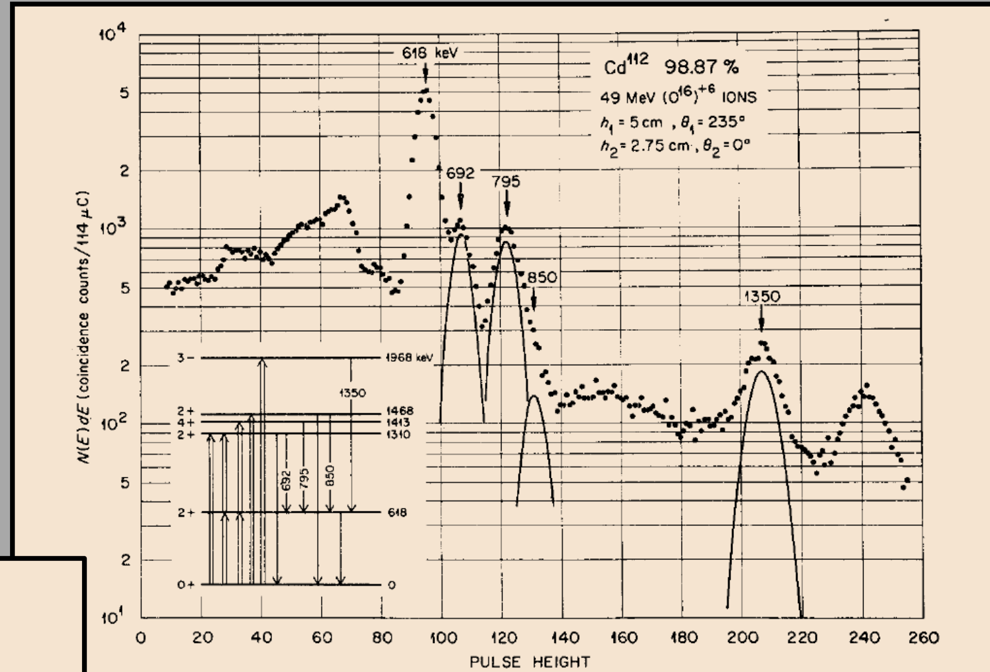


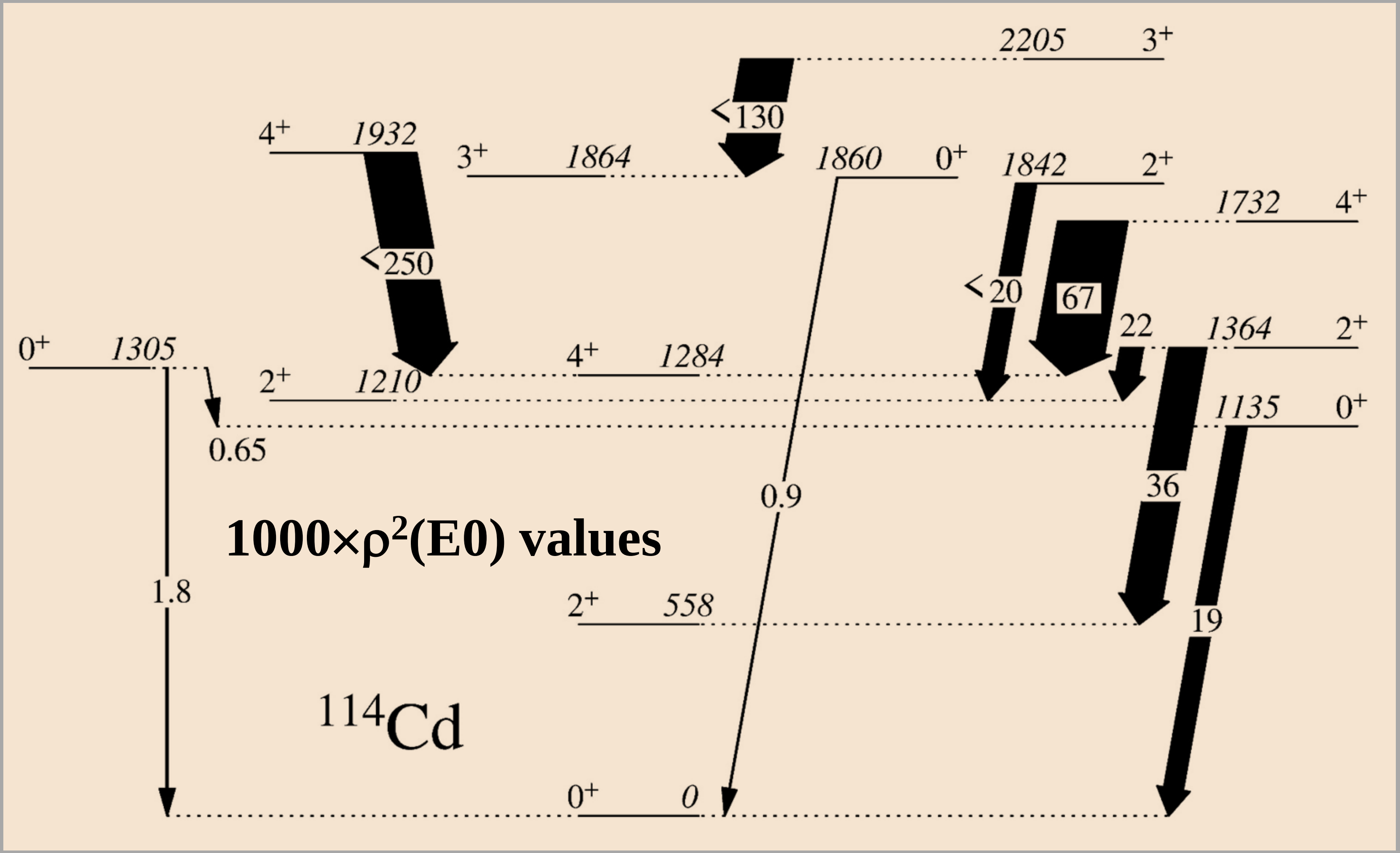
Fig. 4. Coincidence pulse-height spectrum of the γ rays for ^{16}O ions on a ^{112}Cd target.

- Apart from ^{114}Cd, the remaining Cd nuclei were studied with heavy-ion Coulex with state-of-the-art equipment circa 1965

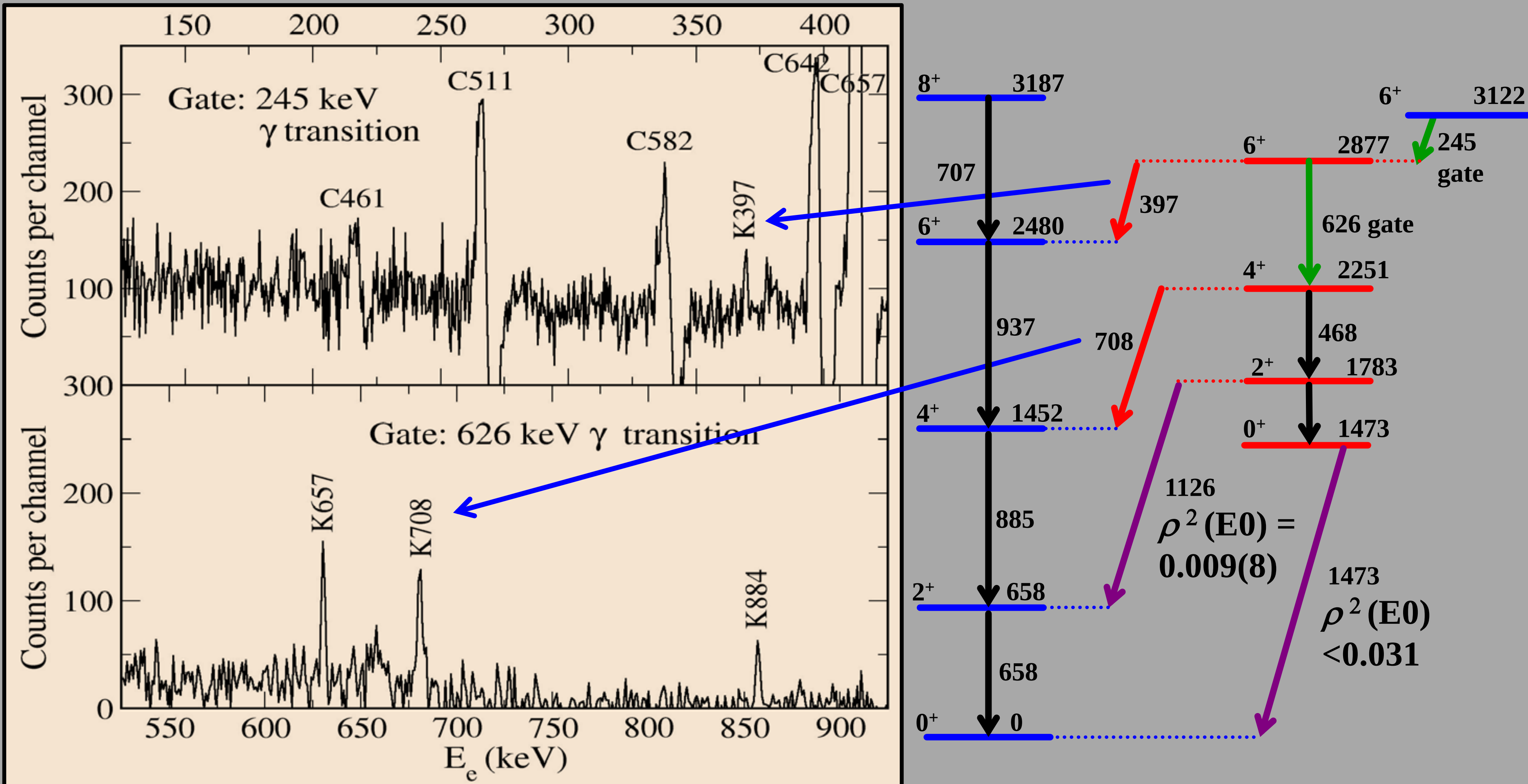
McCowan et al., NP 66, 97 (1965), Milner et al., NPA 129, 687 (1969)

Consequence of shape coexistence – ρ^2(E0)'s

- **E0'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))**



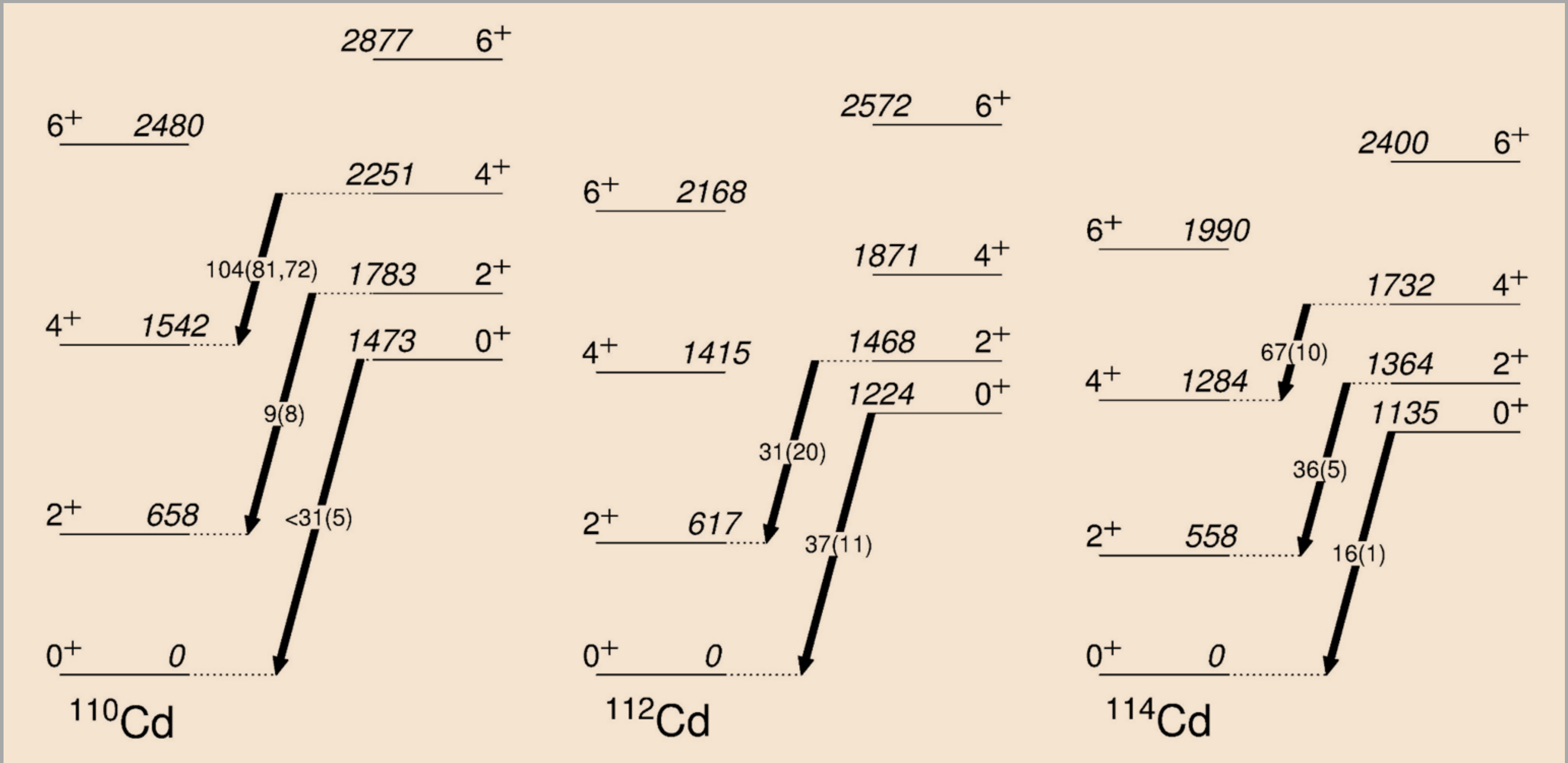
New *E0* transitions in ^{110}Cd through γ-gated e^- spectroscopy



708-keV 4$^+$(intruder) → 4$^+$(gsb) $\rho^2(E0) = 0.104^{+81}_{-72}$

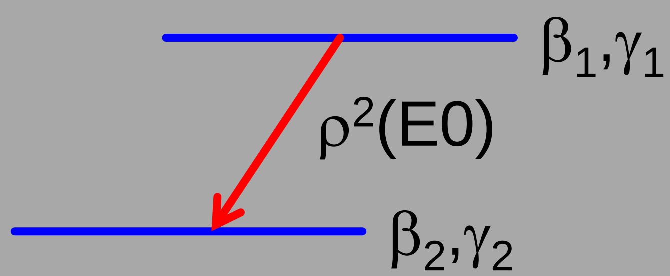
Jigmeddorj *et al.*, EPJ **A 52**, 36 (2016)

Systematics of 1000×ρ^2(E0) values in Cd isotopes



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

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

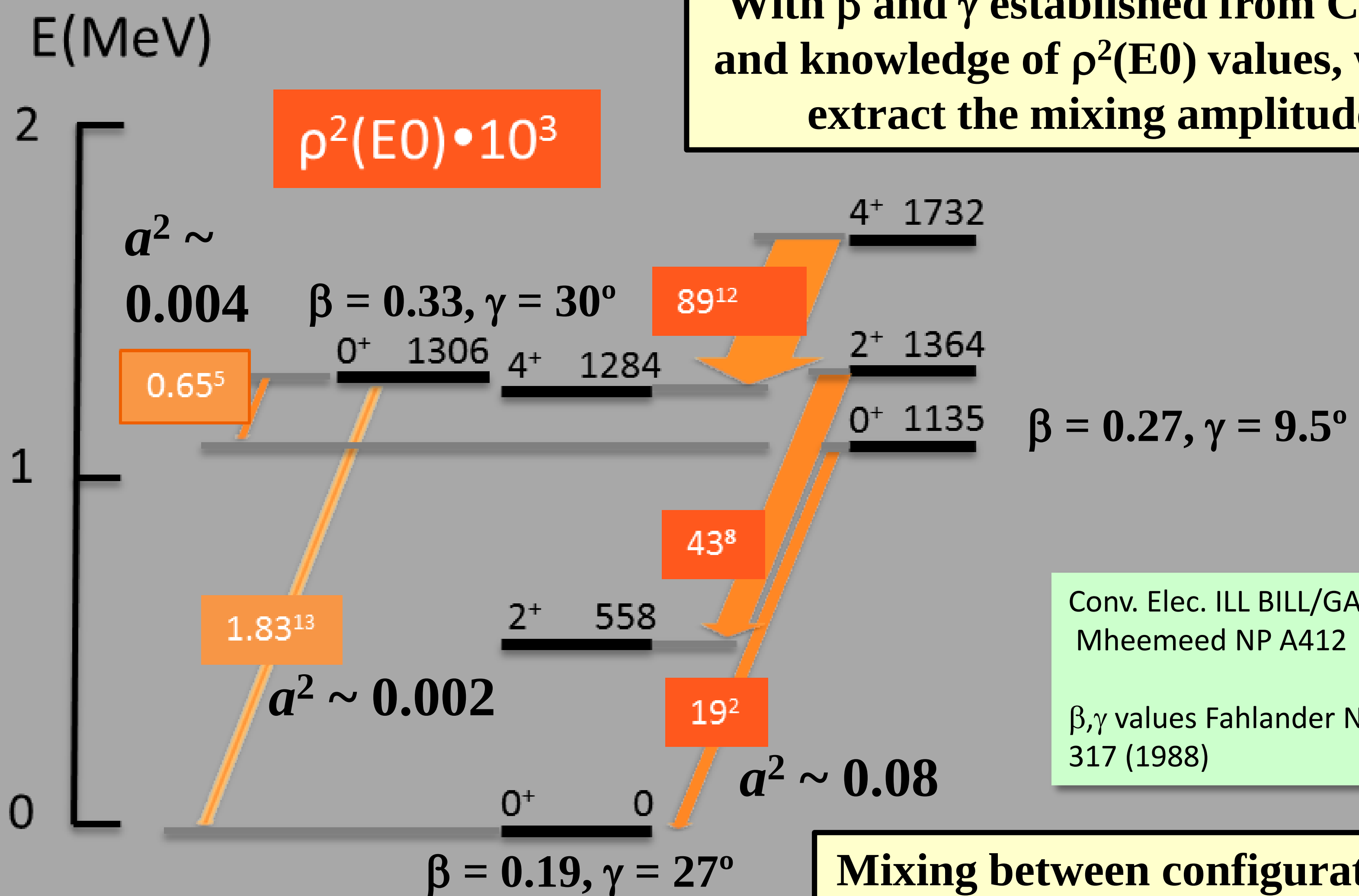


$$\rho^2(E0)$$
$$= a^2(1-a^2)\left(\frac{3Z}{4\pi}\right)^2\left[(\beta_1^2-\beta_2^2) \qquad \sim 0 \qquad \right]^2$$

- **If shape parameters are known, the mixing amplitude can be determined**
- **Use the results from Coulomb excitation (available for ^{114}Cd)**

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



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?

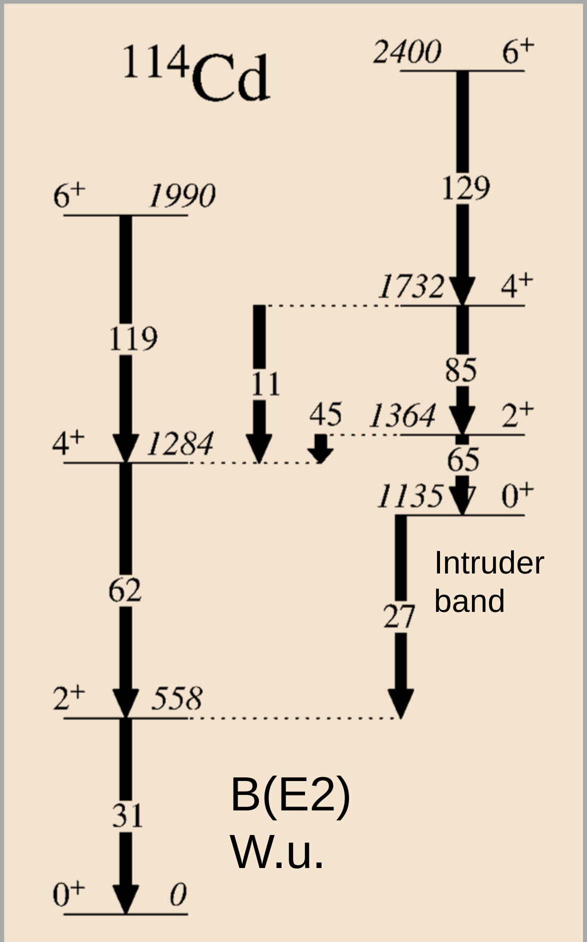
- **While mixing is small, important consequences: Consider ^{114}Cd**
- **Write 0^+ wave functions**

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

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

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

with admixture of 8% results in 26 ± 4 W.u. consistent with observed value of 27.4 ± 1.7 W.u.

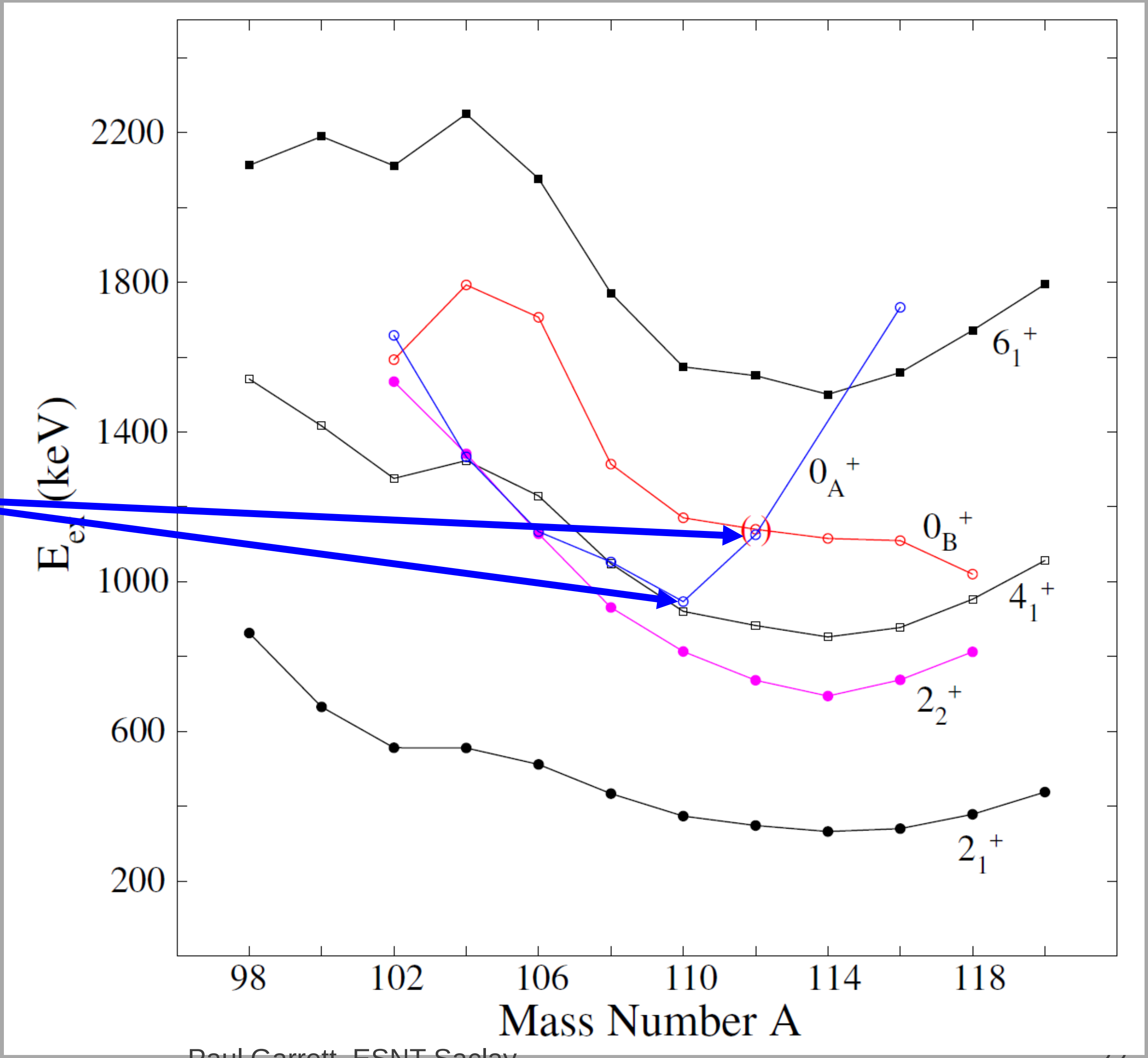


Important contribution to $0_2^+ \rightarrow 2_1^+$ E2 strength from mixing

Energy systematics of low-lying levels in the Pd isotopes

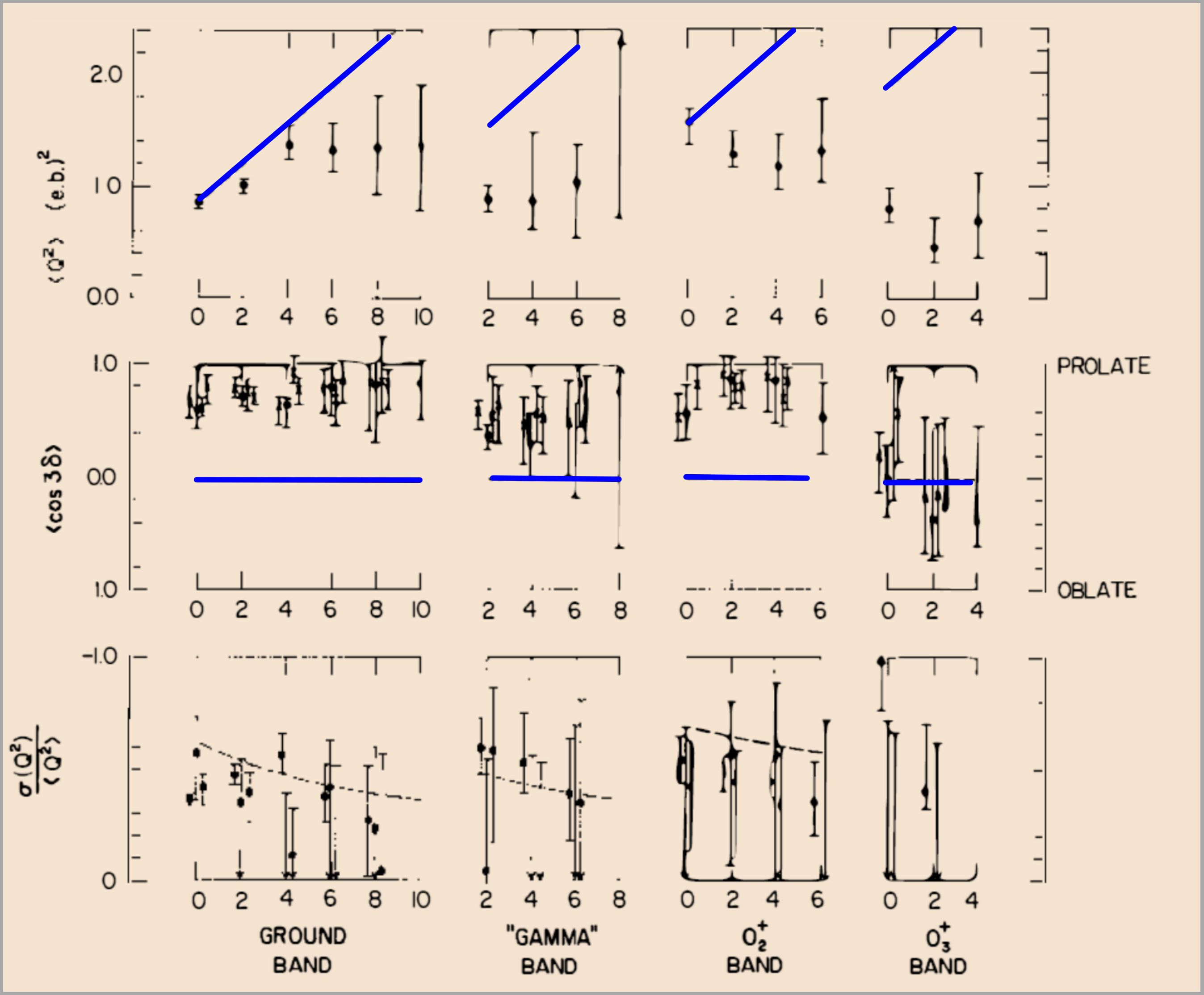
States assigned as intruder 2*p*-4*h* Lhersonneau *et al*, PRC 60, 014315 (1999)

0_A^+ state has characteristic “V”-shaped pattern



Invariants for ^{110}Pd from Coulomb excitation

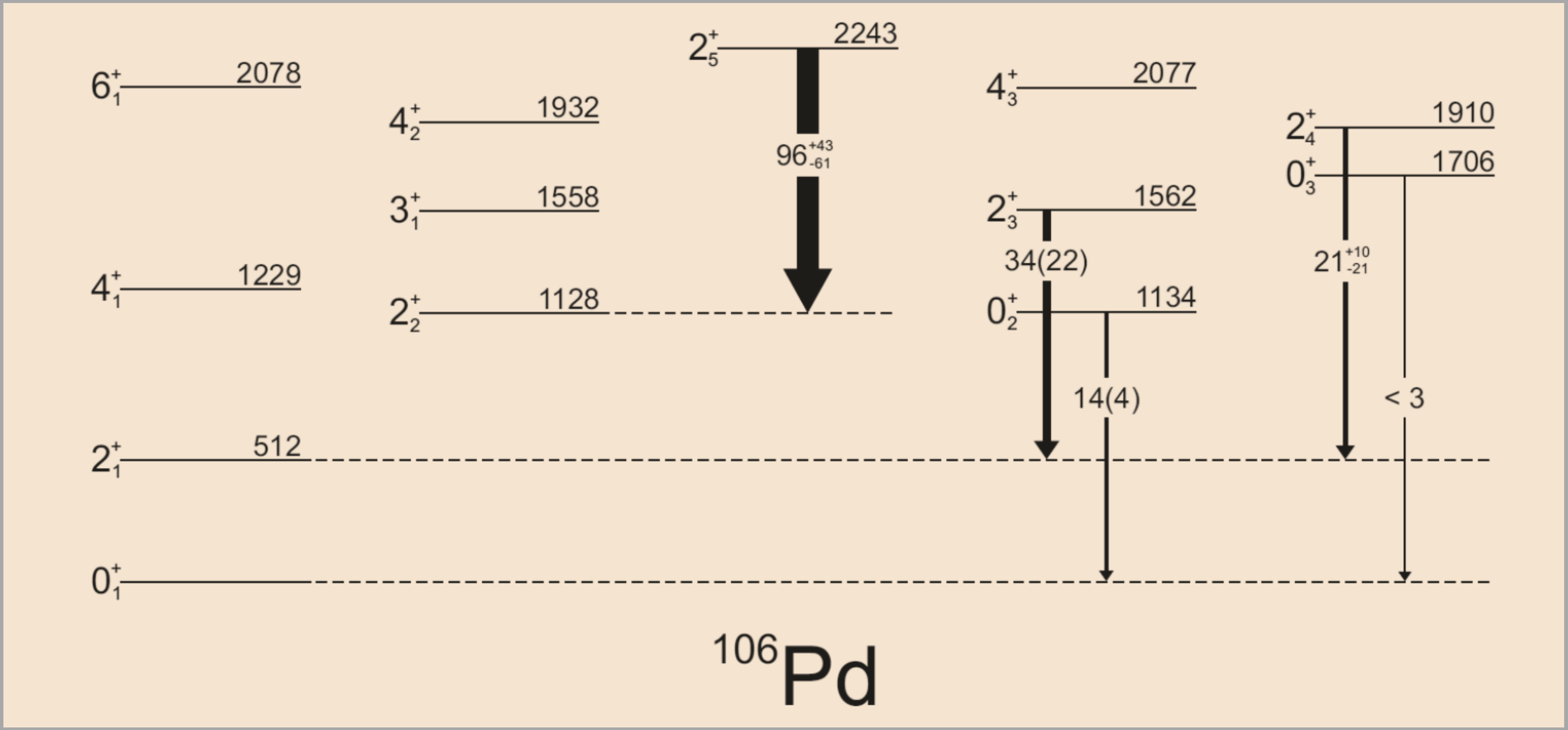
- **Pd behave as (approx.) prolate rotors – at spin 4$^+$ in gsb shape has stabilized**
- **0_2^+ band rotor-like from spin 0**
- **0_3^+ band also appears to be shape coexistence band**



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

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

1000×ρ^2(E0) values



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

Possible intruder states in the Te isotopes

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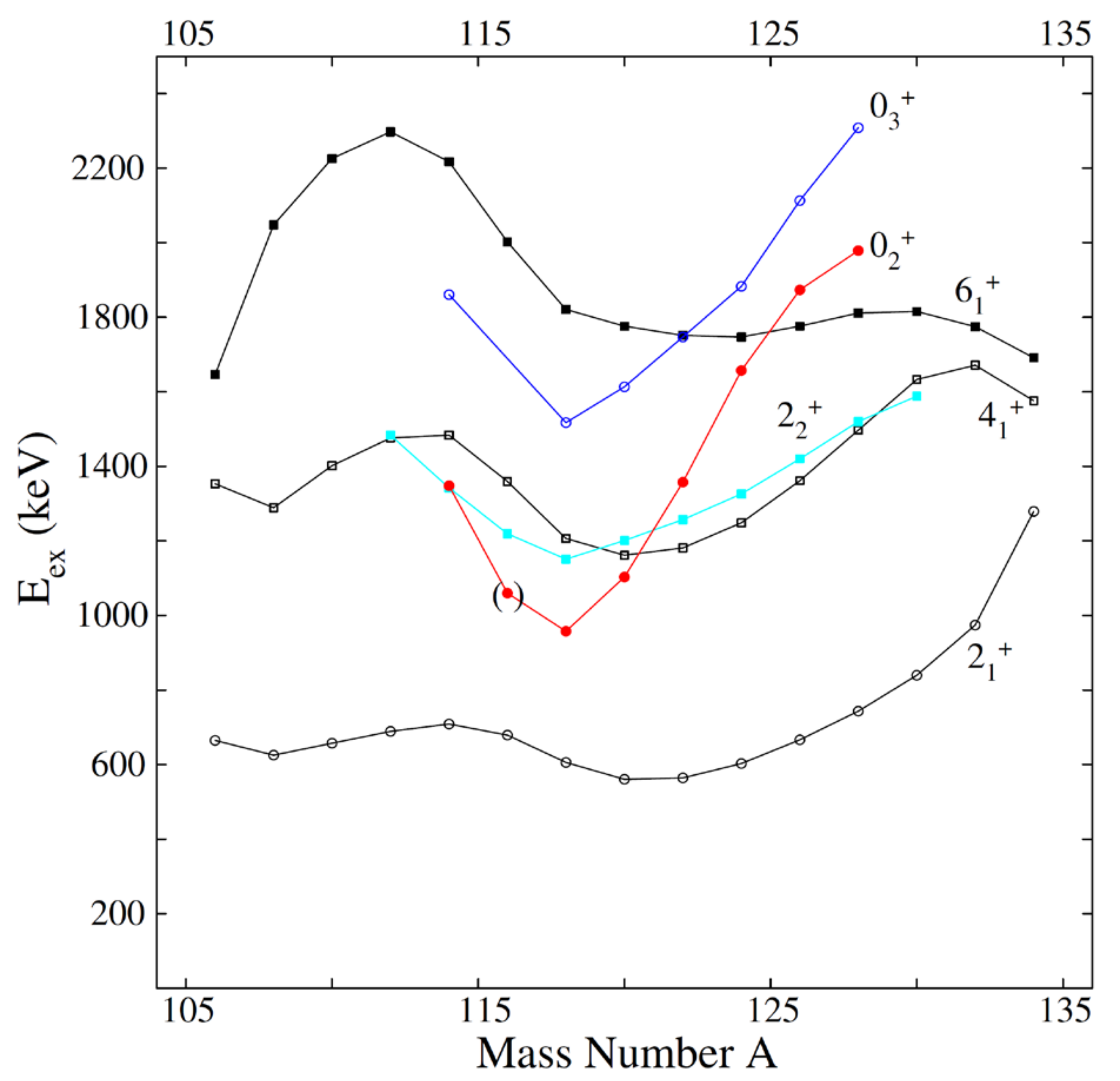
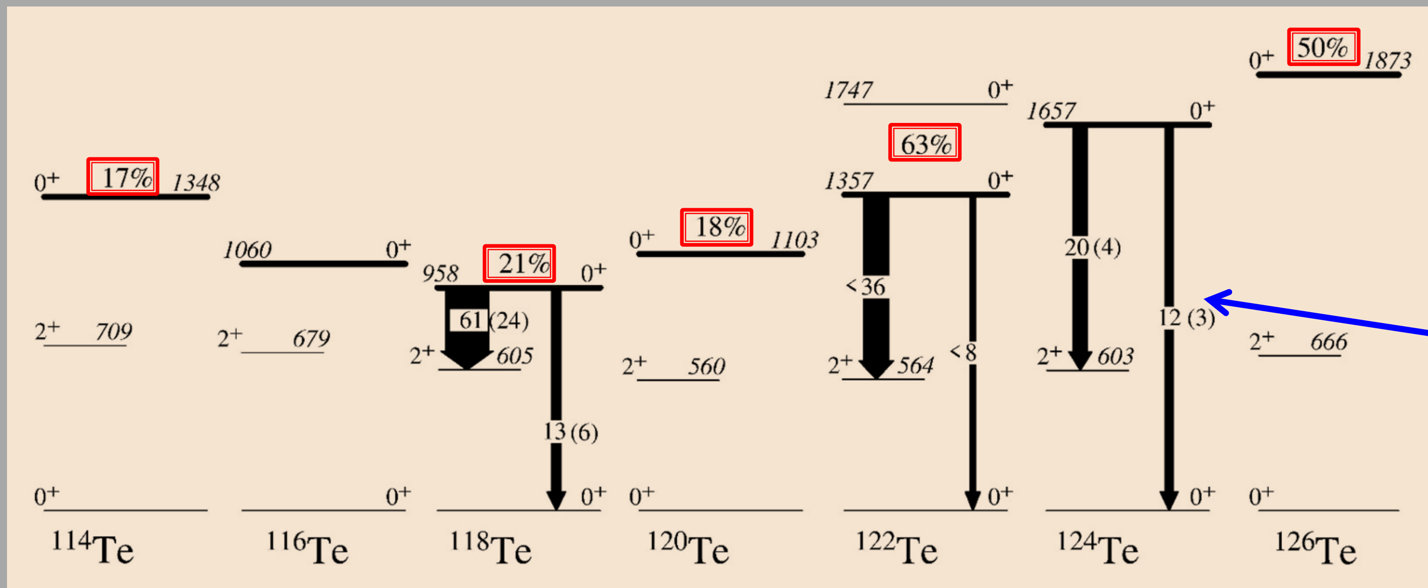
- Energy systematics of excited states in the Te isotopes suggest intruder origin – or possibly just a changing overall structure?

- Is there any real evidence for intruders?



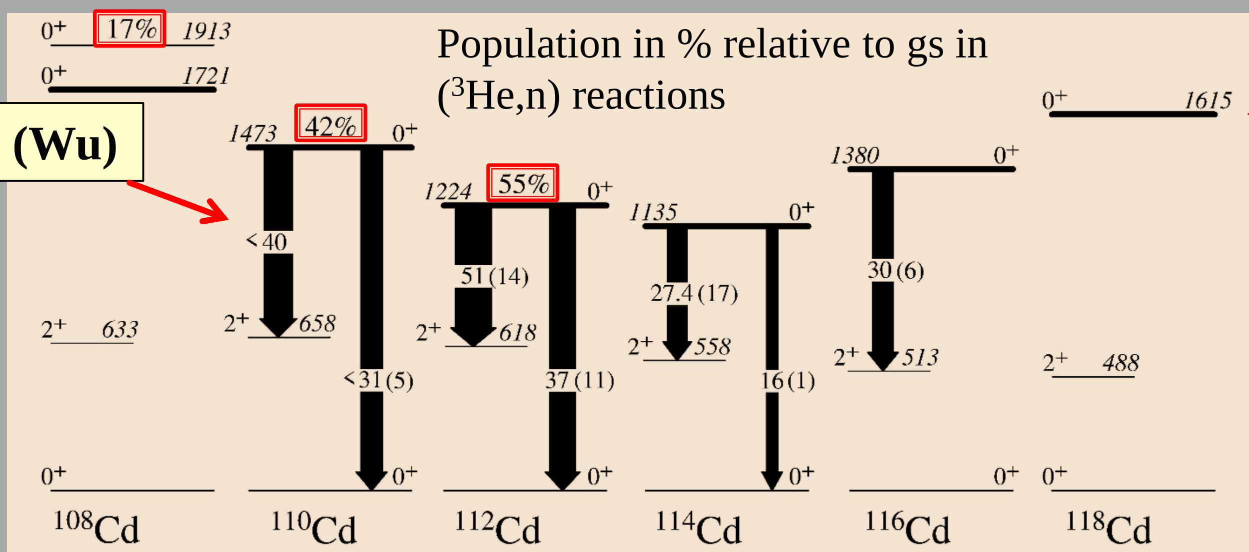
Strong similarity in structure of Cd and Te nuclei – properties of 0_2^+ states in Te match intruder 0^+ states in Cd



Suggested intruder band heads

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

B(E2) (Wu)

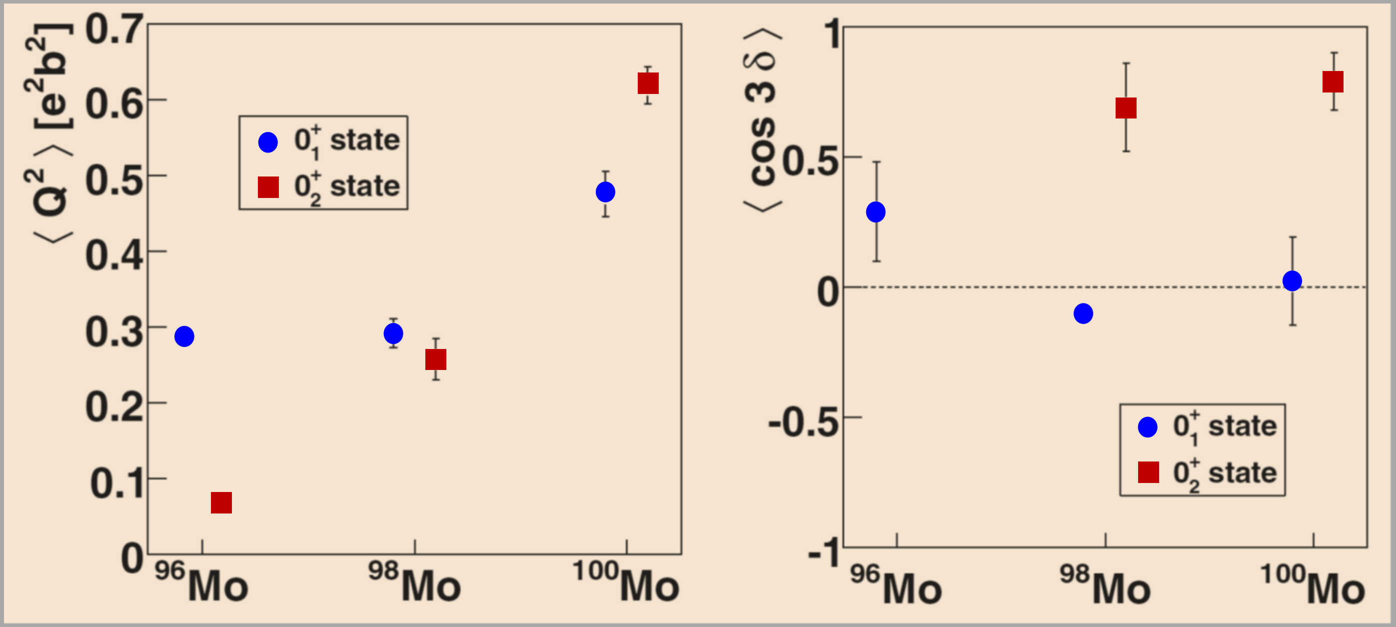


0^+ states identified as intruder band heads

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

Extending towards $Z = 40$ subshell – Mo isotopes show clear shape coexistence

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

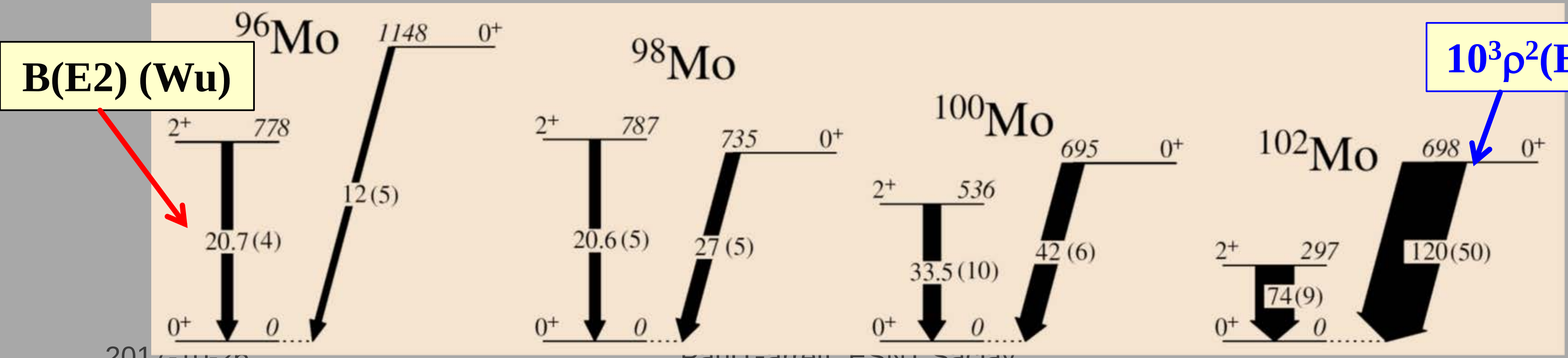


prolate

Triaxial/
spherical

oblate

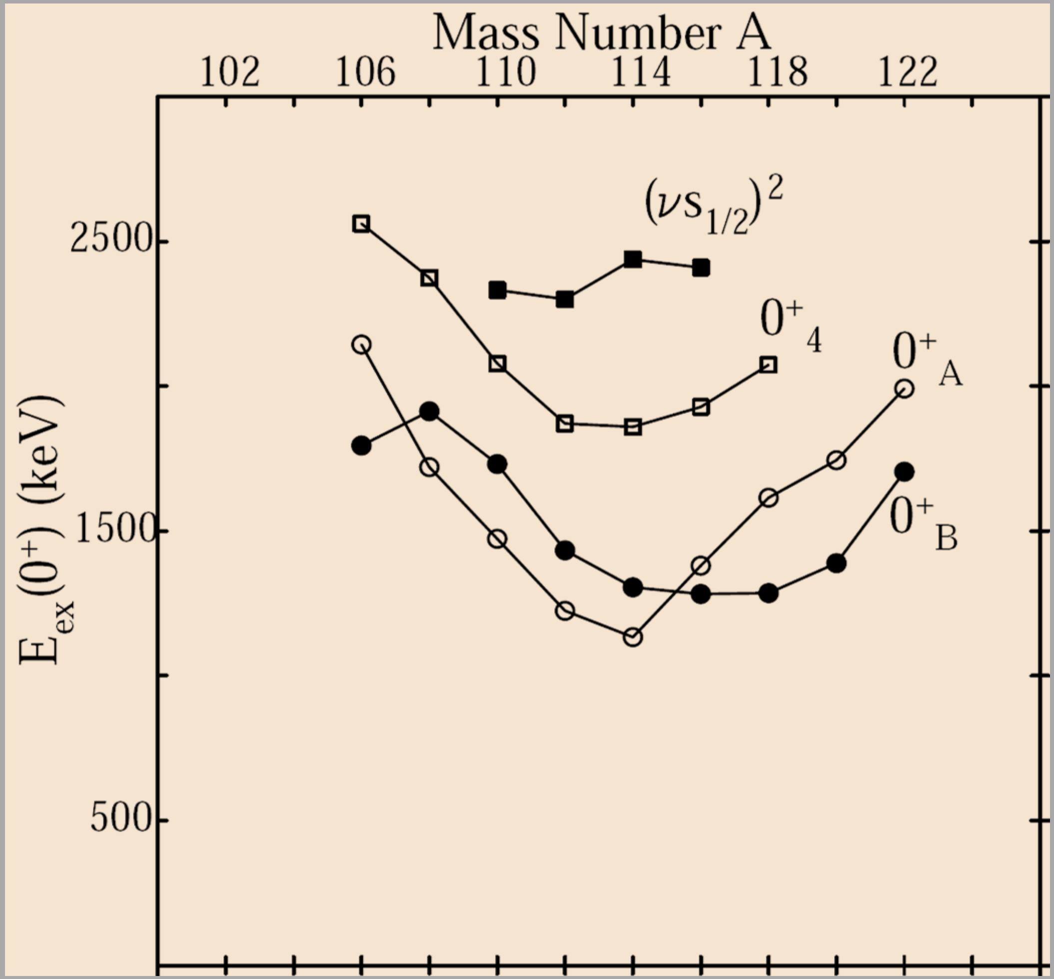
Zielinska et al., NPA 712, 3 (2002), Wrzosek-Lipska et al., PRC 86 064305 (2012)



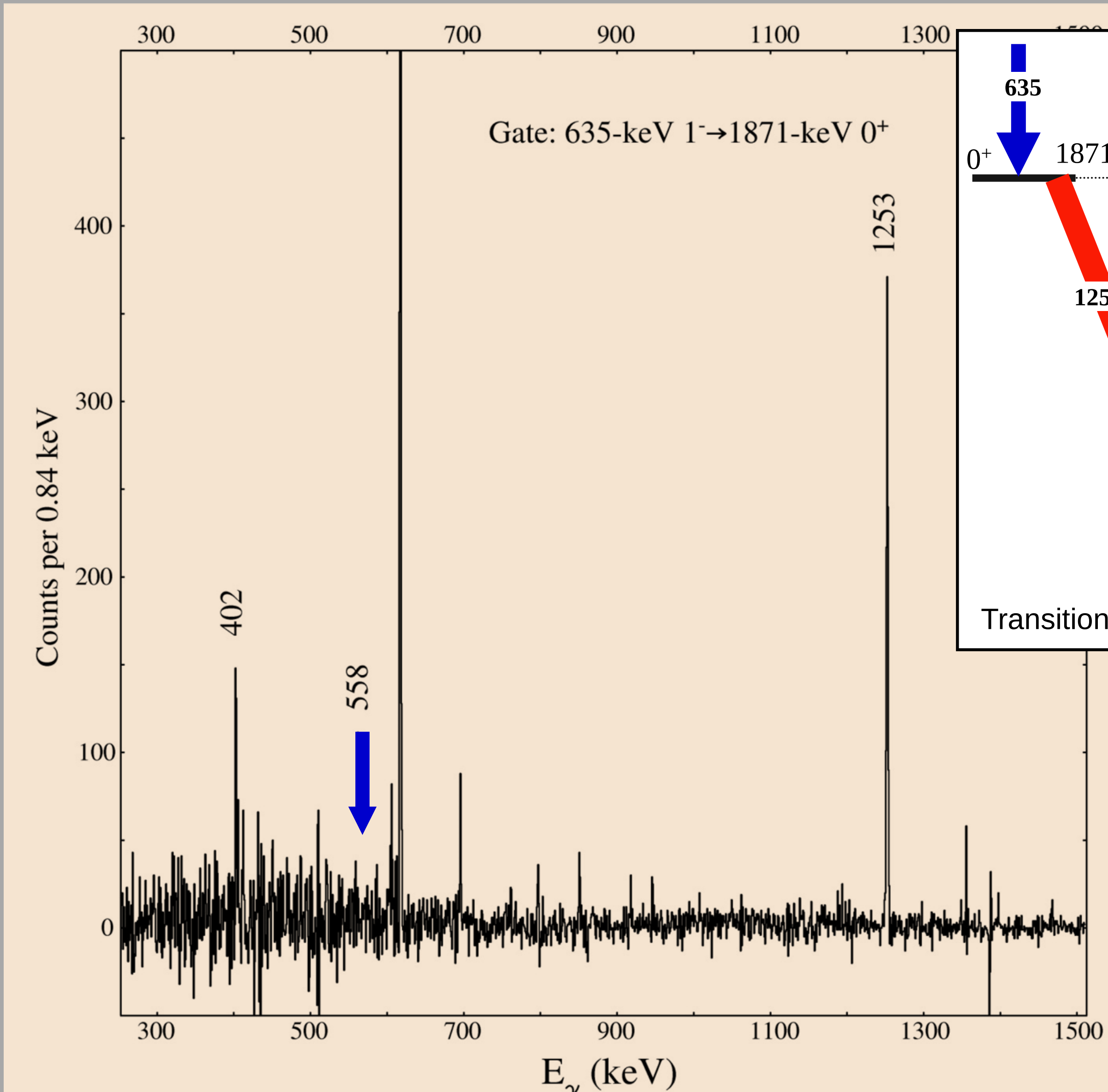
Beyond lowest intruder configuration

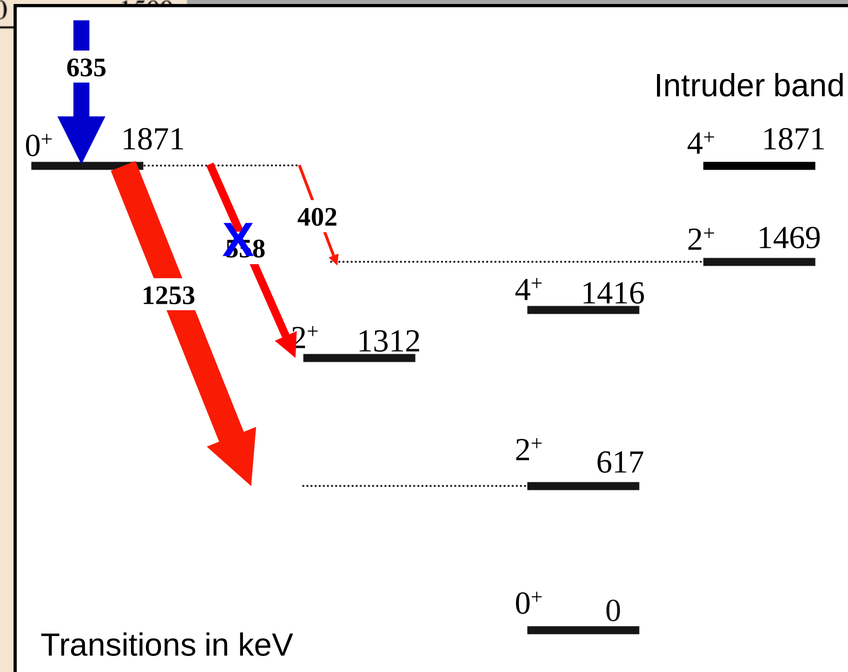
- Evidence to date strong for 2*p*-2*h* excitation across Z=50 closed shell – evidence for higher excitations?

- Systematics in energy of 0^+_4 level in mid-shell Cd nuclei, combined with favored decay to intruder 2^+ level, suggest an intruder assignment



Eg. ^{112}Cd decay of 0_4^+ state



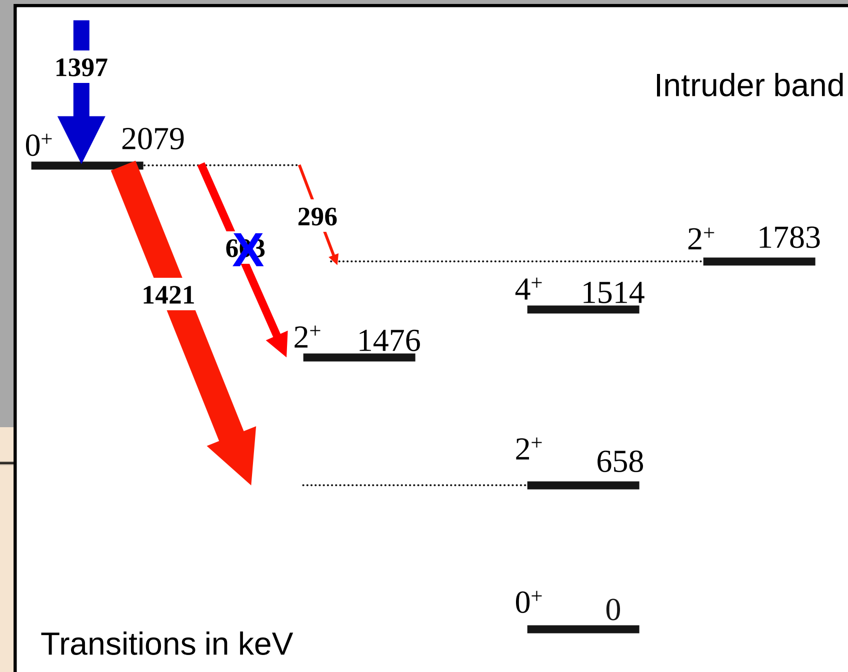


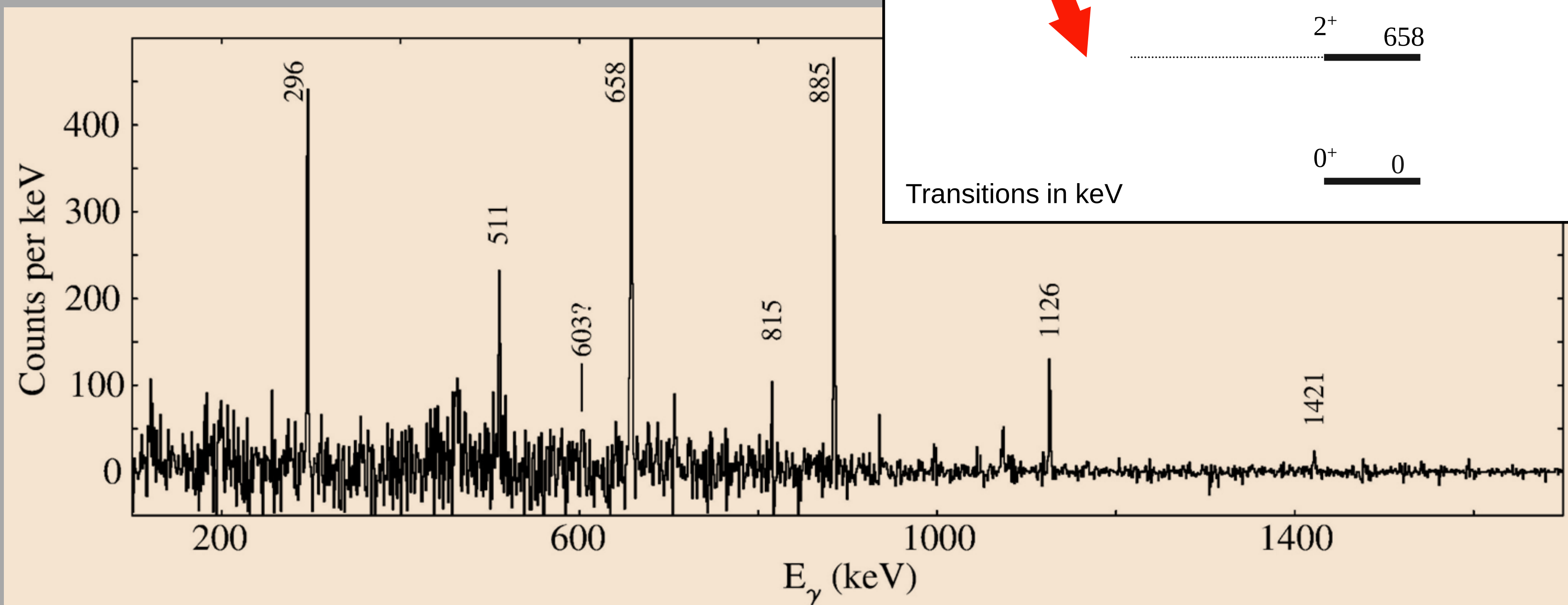
The 1871-keV 0^+ state has no observed decay to 2^+ state at 1312 keV, but strongly favoured decay to 2^+ intruder band member

Green *et al.*, PRC **80**, 032502(R) (2009).

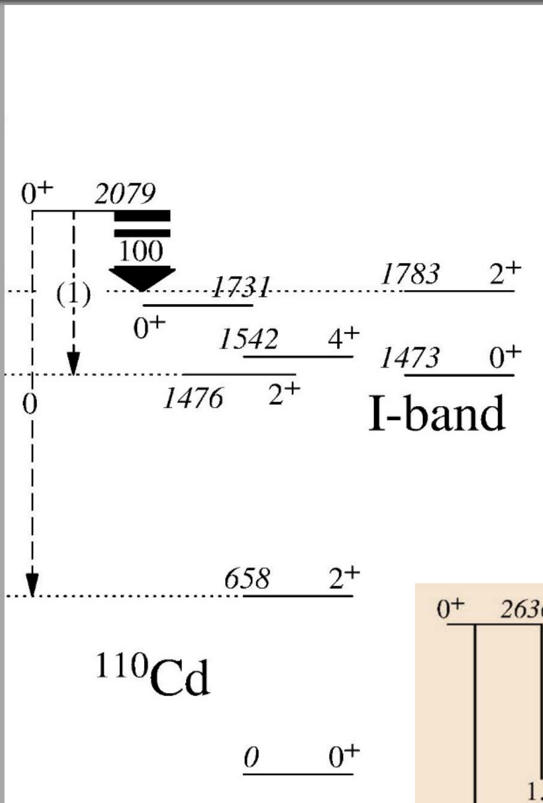
Similar situation in decay of 0_4^+ state in ^{110}Cd

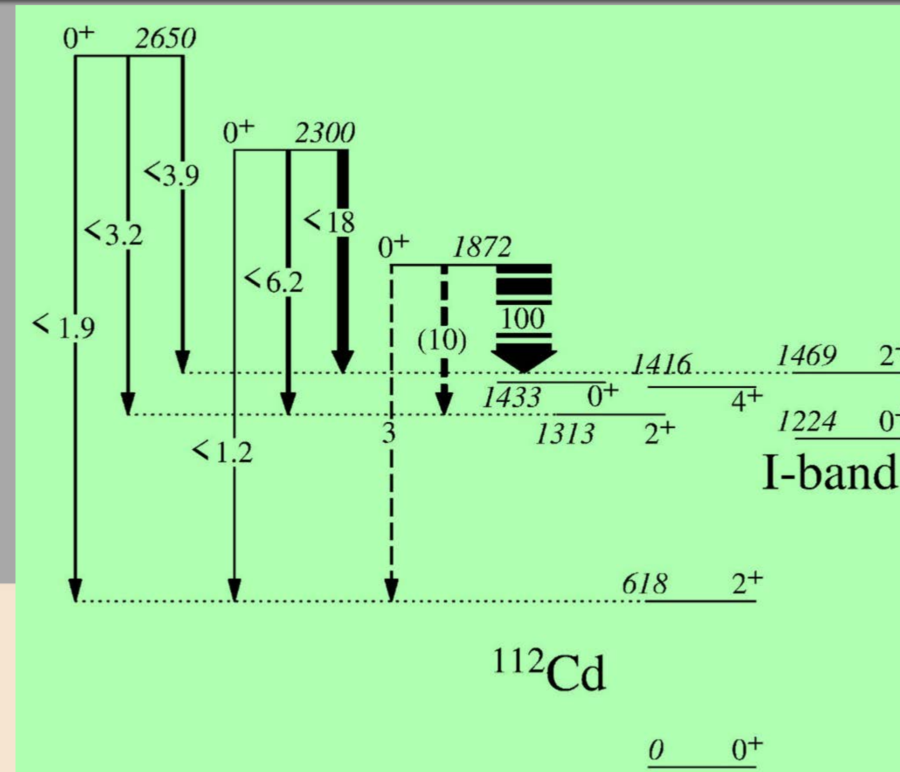
The 2079-keV 0^+ state has no observed decay to 2^+ state at 1476 keV, but strongly favoured decay to 2^+ intruder band member

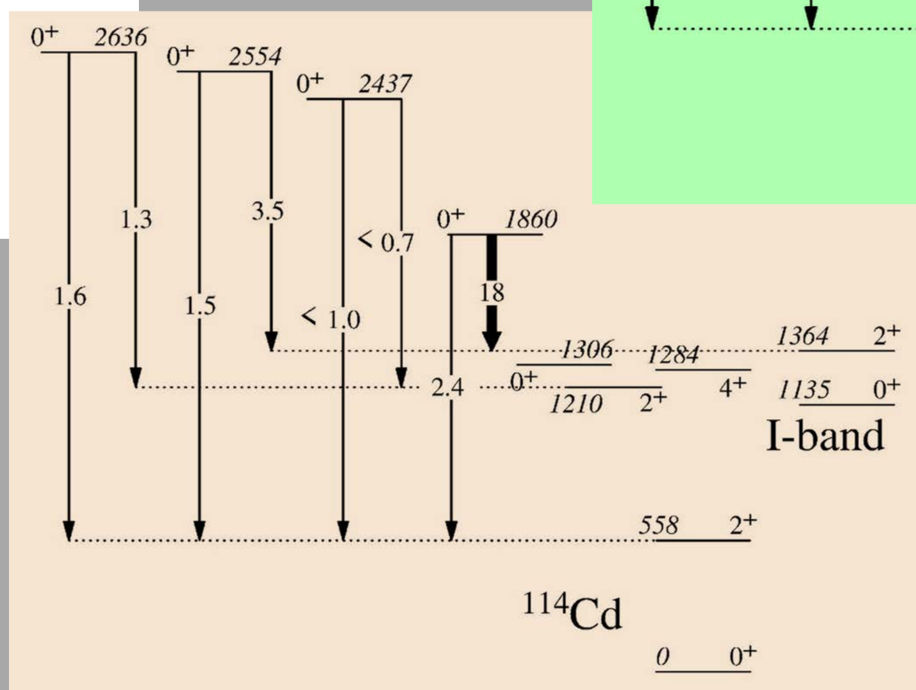




Enhanced relative or absolute *B(E2)* values for decay to 2^+ intruder band members in $^{110,112,114}Cd$



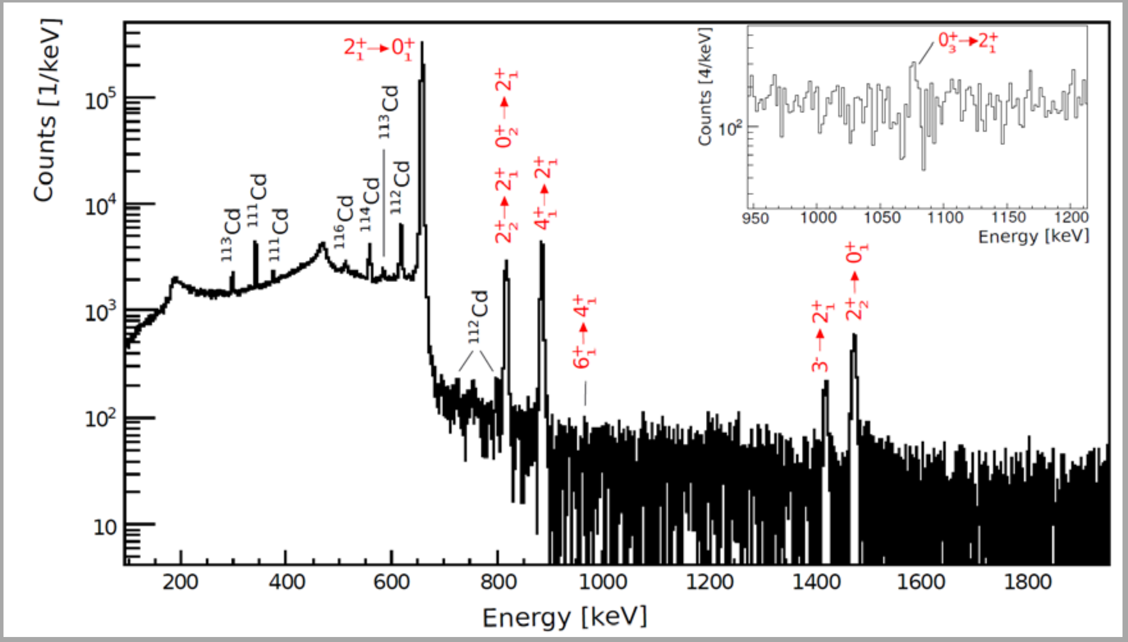




Dashed lines: relative *B(E2)* values
Full lines: absolute *B(E2)* values in W.u.

Searching for *np-mh* states in the Z=50 region – How to establish their nature?

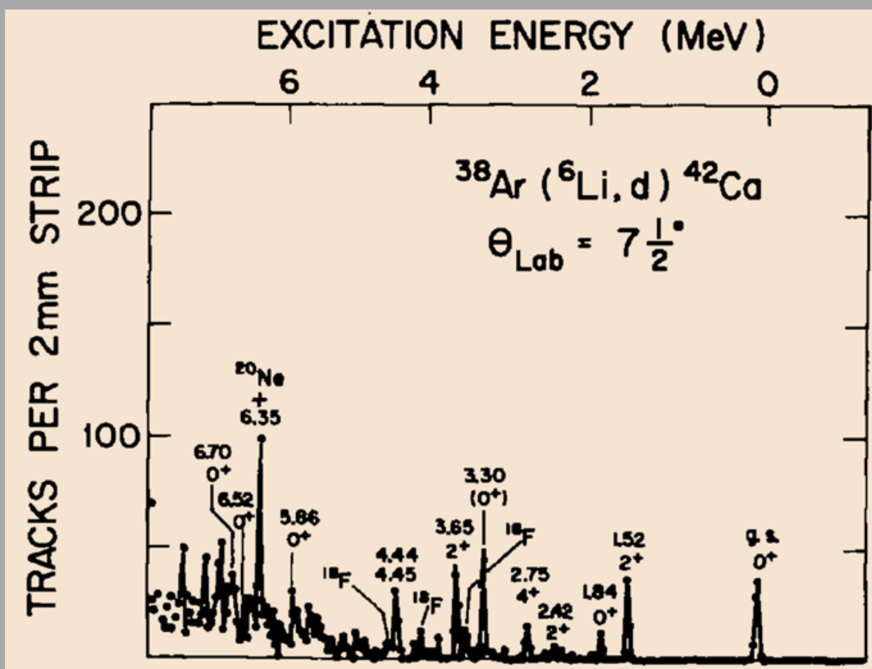
- **Observe low-energy transitions, e.g., the missing $2^+ \rightarrow 0^+$ transitions**
  - **β decay may be the best technique to use: LOI with GRIFFIN@TRIUMF to do this in Cd isotopes, extend to Te isotopes, Xe, etc…**
  - **Proposal at iThemba to study ^{98,100}Rh decay to Ru**
  - **(n,γ) reactions with FIPPS@ILL: ^{111,113}Cd(n,γ) and ^{125}Te(n,γ) approved**
- **Measure in Coulex – extract rotational invariants <Q^2> and, ideally, <cos3δ>**
  - **^{114}Cd is the only Cd studied in detail by Coulex – only recently has work commenced on other stable Cd: eg. ^{110}Cd with ^{32}S at HIL, Warsaw (K. Wrzosek-Lipska et al.), Cd on ^{208}Pb at ANL (M. Allmond)**

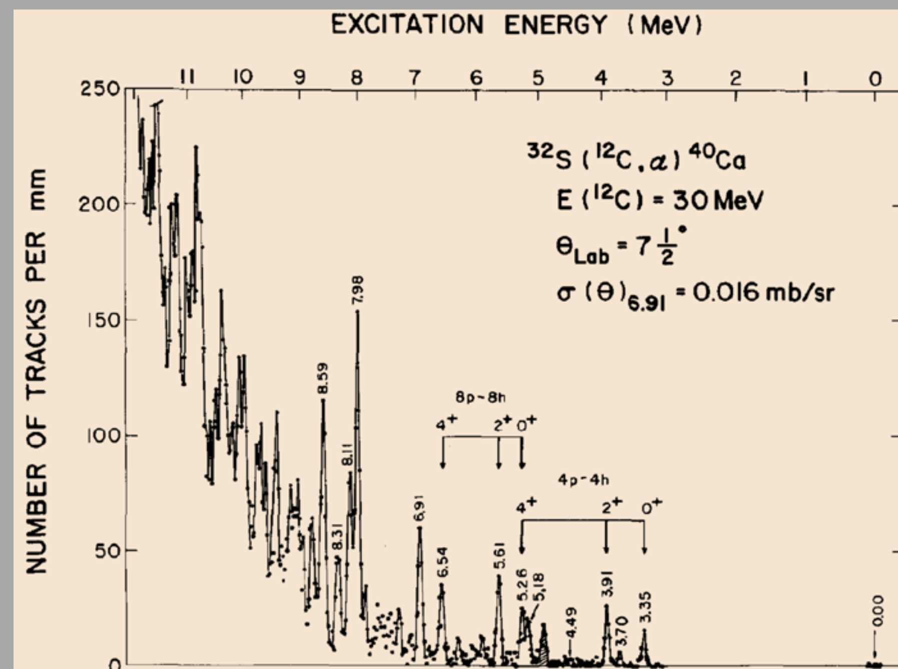


^{32}S+^{110}Cd @ 91 MeV, K. Wrzosek-Lipska

Searching for *np-mh* states in the Z=50 region – How to establish their nature?

- **Probe nature with transfer reactions**
  - ***2p-2h* in Sn may be populated in (^{6}Li,d) reactions from Cd isotopes, *2p-4h* in Cd with Pd targets, *2p-6h* in Pd with Ru targets, etc. Feasible, and we will do this in Munich with the Q3D**
  - ***2p-2h* states in Sn with (d,^{6}Li) reactions on Te (has been done). To populate *4p-2h* states in Te requires Xe targets**
  - **(^{12}C,α) reactions may populate higher *np-mh* configurations, ex. ^{108}Pd to ^{116}Sn to populate *4p-4h* state. (Our attempt in Munich was unsuccessful)**





  - **Two neutron and two-proton transfer reactions, e.g. (^{3}He,nγ) at iThemba**