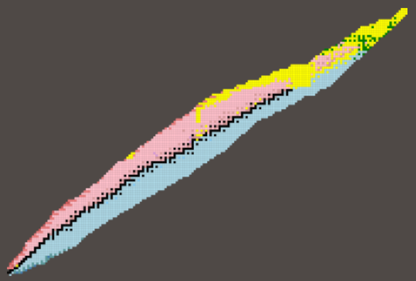
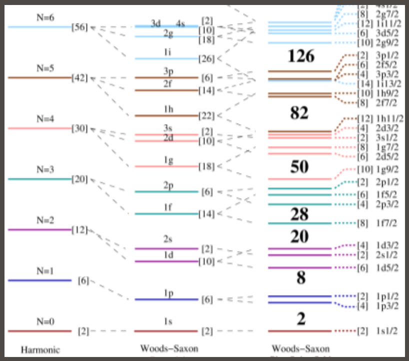
Collective Excitations in Nuclei

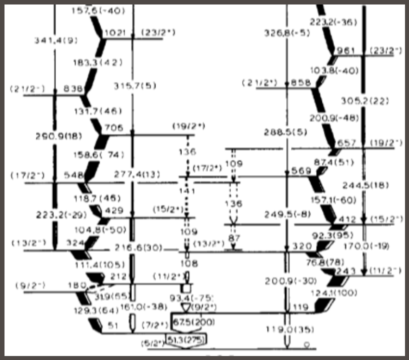
Nuclear Spectroscopy #6

Postdoc Lecture Series, Graduate and Postdoc Society (GAPS)

Mike Bowry and Jack Henderson
Gamma Ray Spectroscopy at ISAC (GRSI) | TRIUMF







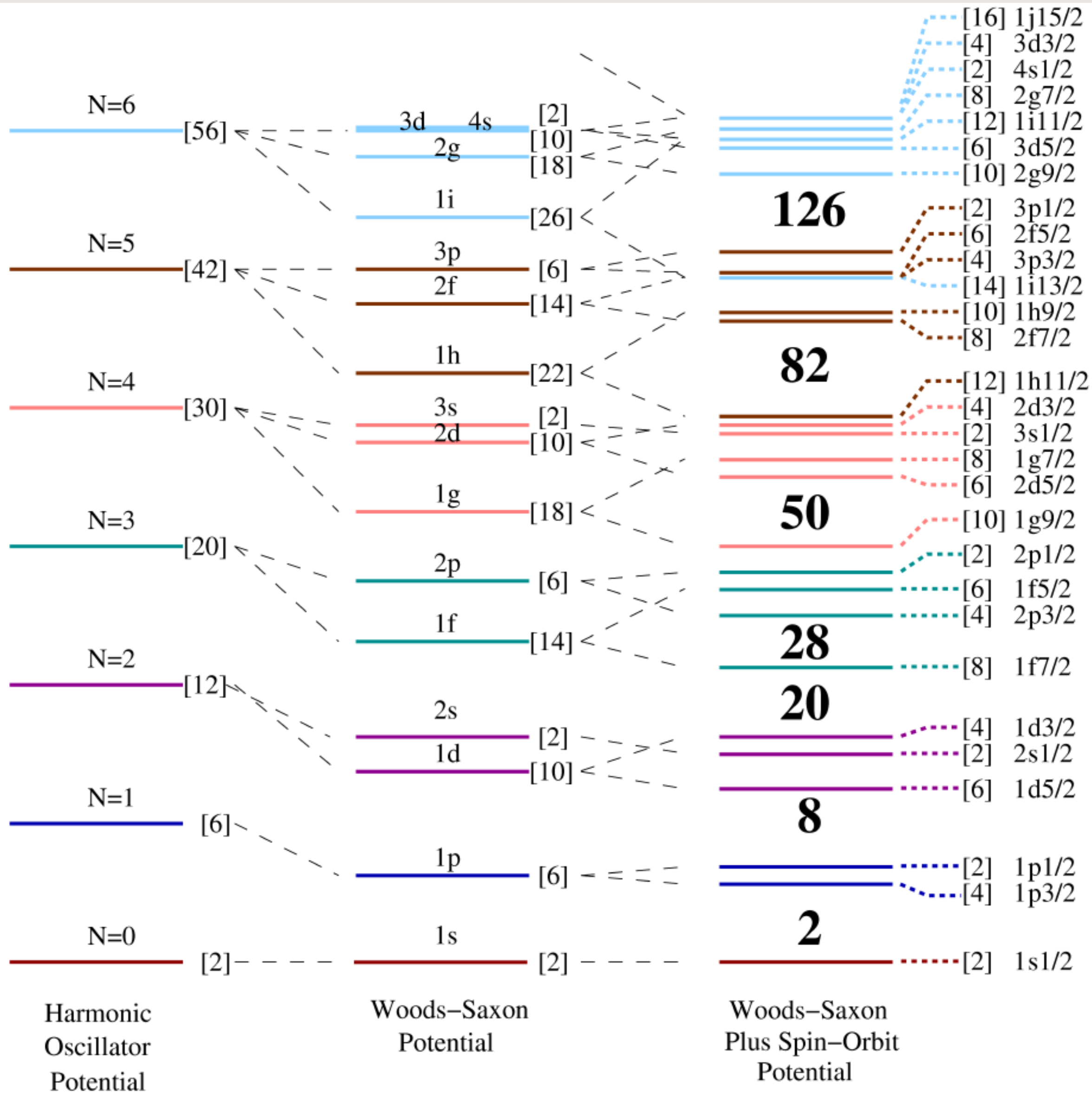
Single-particle versus Collective

- **Nuclear Structure** is concerned with examining the behavior and properties of nuclei

  - Properties of excited states such as their **spin** $\boldsymbol{I}$, **parity** $\boldsymbol{\pi}$, **excitation energy** $\boldsymbol{E_x}$ and **half-life** $\boldsymbol{T_{1/2}}$ reflect the physical mechanism responsible for their manifestation

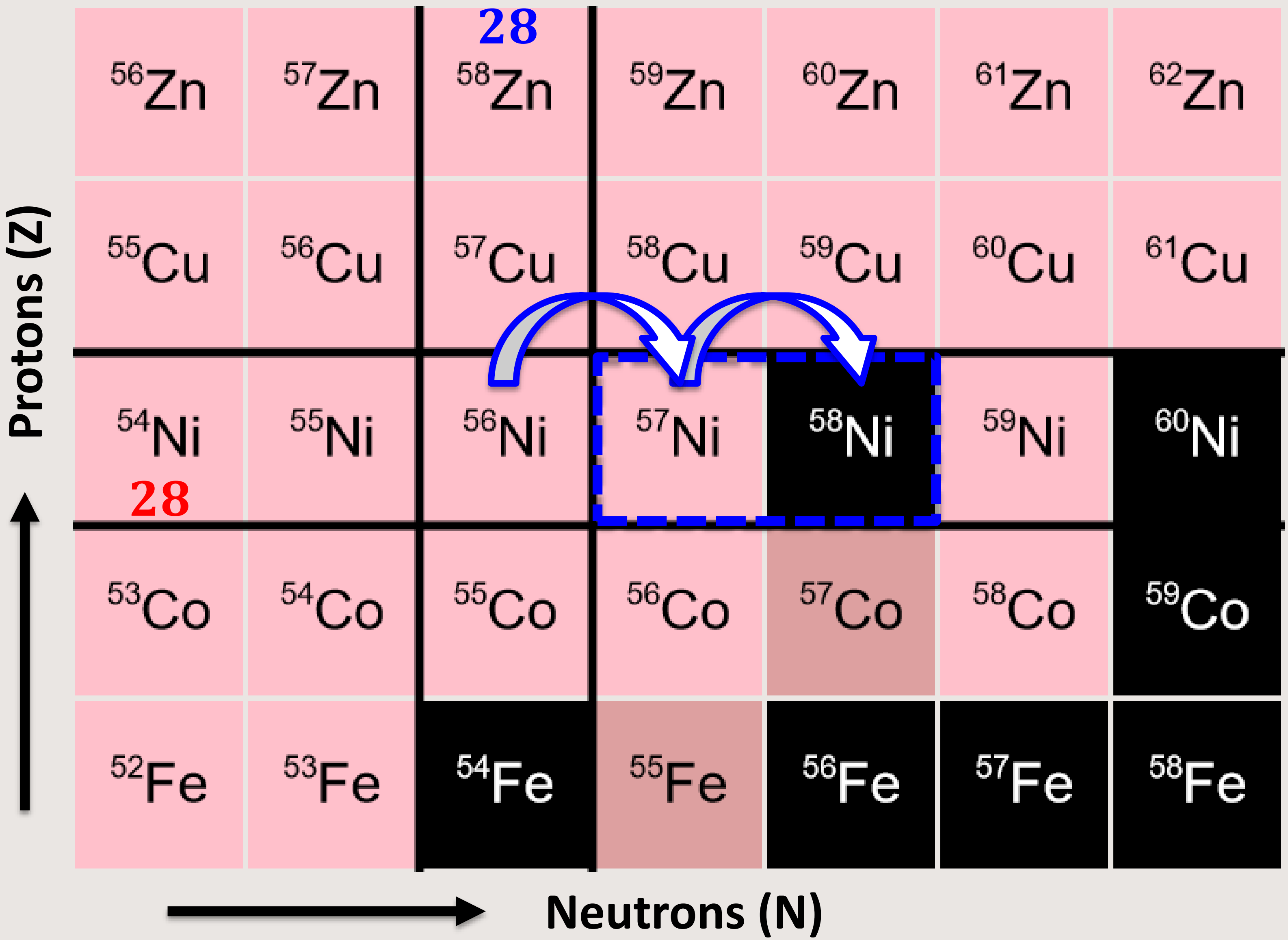
- Nuclear excitations can arise via:
  - **Single-particle motion**
    - ➢ Properties determined by arranging a small number of nucleons
  - **Collective motion**
    - ➢ ‘Bulk’ motion of the nuclear fluid involving many nucleons
  - **…combinations of the above!**

Nuclear Shell Model

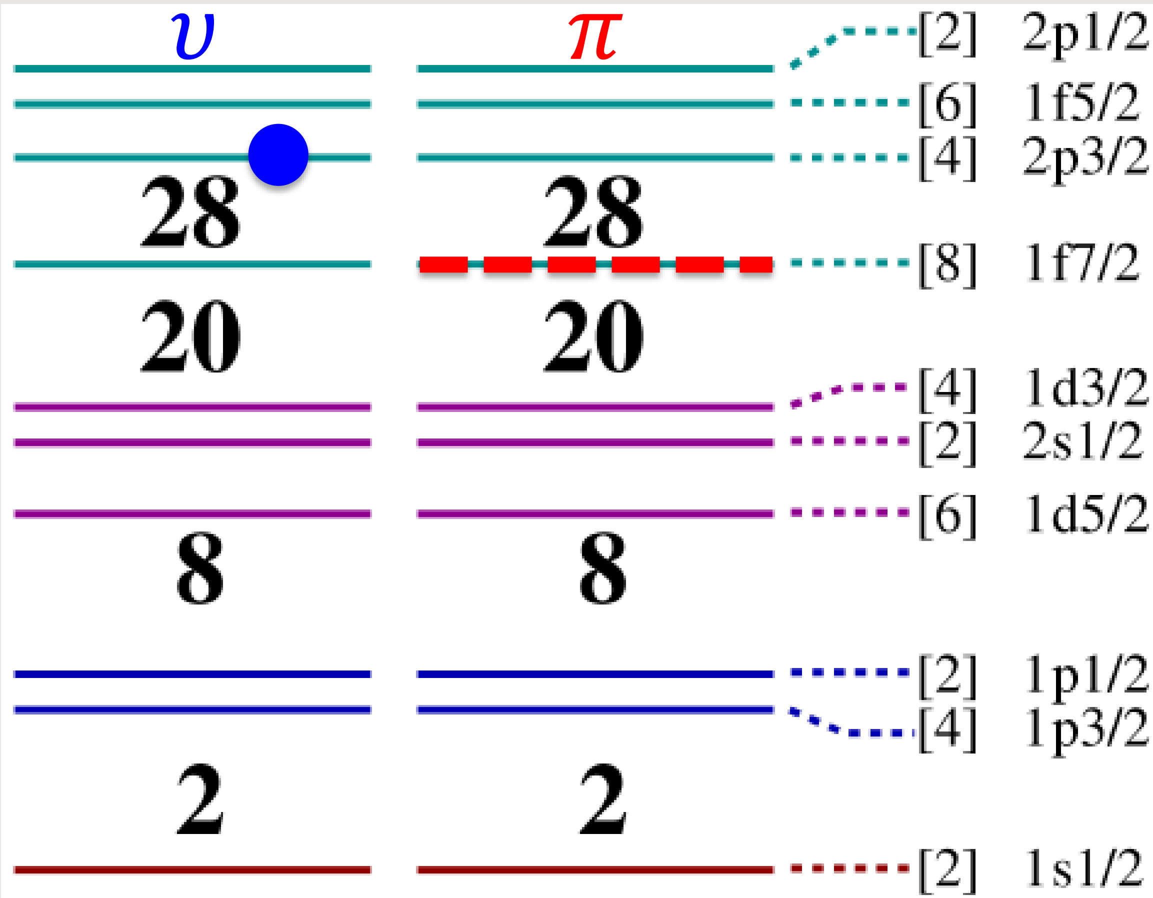


- **Single-particle orbits** defined by quantum numbers $[nlj]$
  - Principal n
  - Orbital angular momentum l
  - Total angular momentum j
  - Occupancy $[2j+1]$
  - Parity $(-1)^l$

Example: nickel isotopes



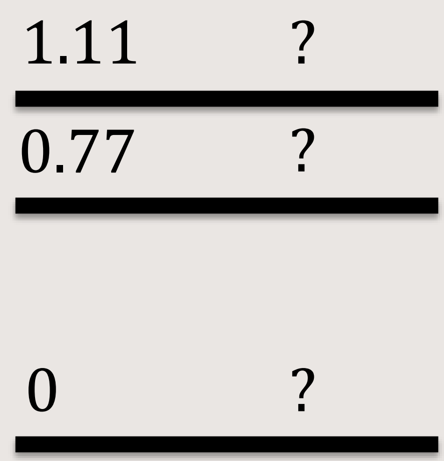
^{57}Ni ("even-odd")



T. Motoba, Progr. Theor. Phys. 54, 429 (1975)

M. R. Bhat, Nucl. Data Sheets 85, 415 (1998)

$E_x(MeV), I^{\pi}(\hbar)$



$^{57}_{28}Ni_{29}$

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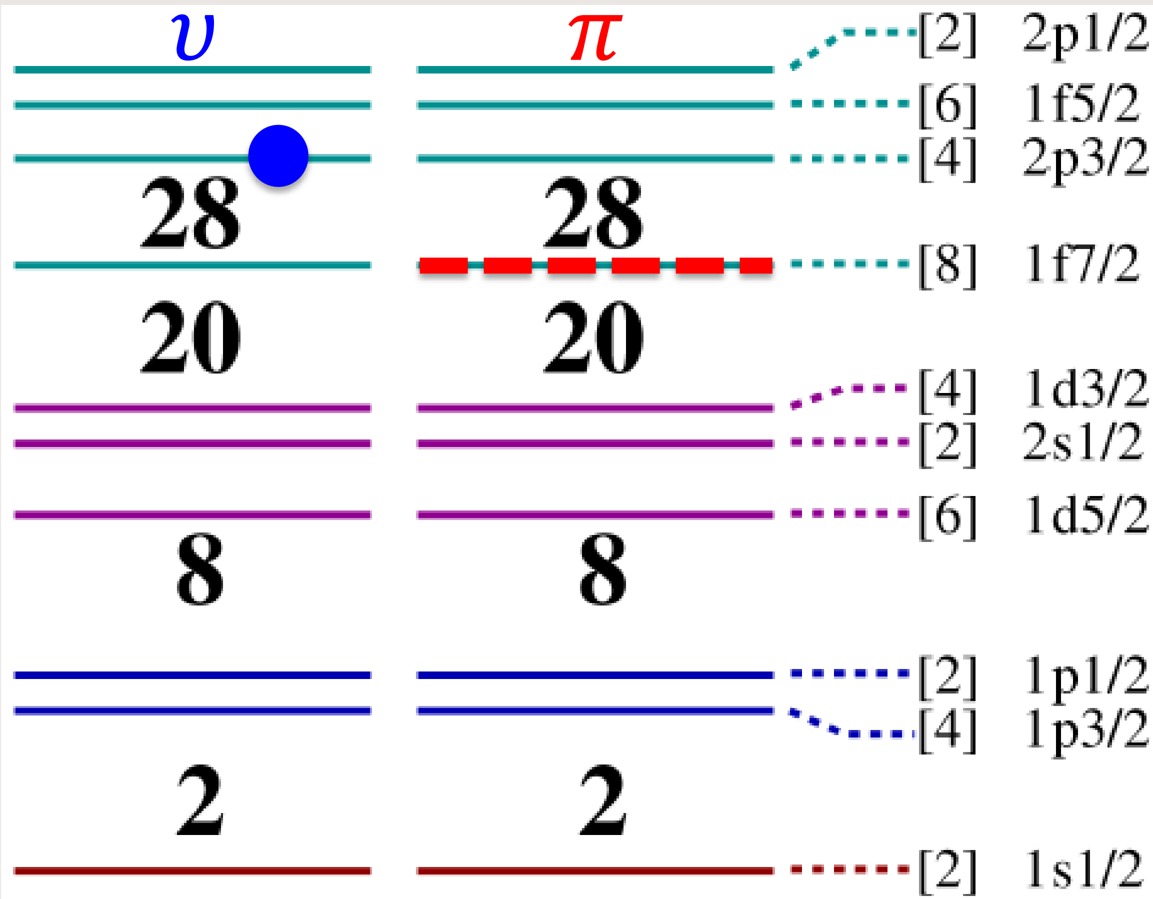
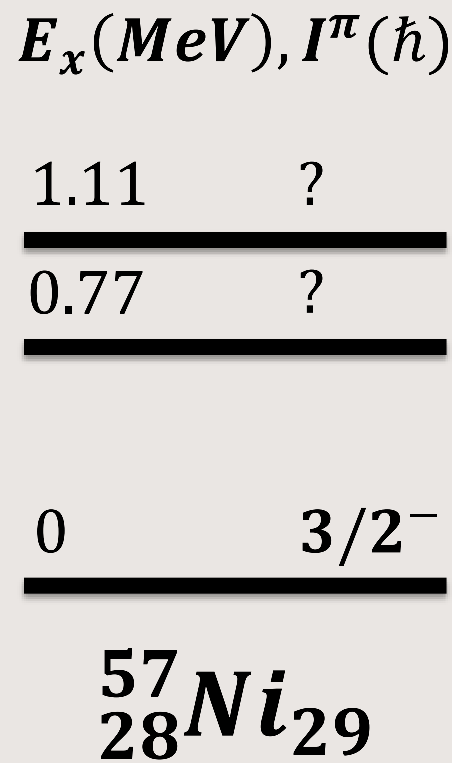
^{57}Ni ("even-odd")





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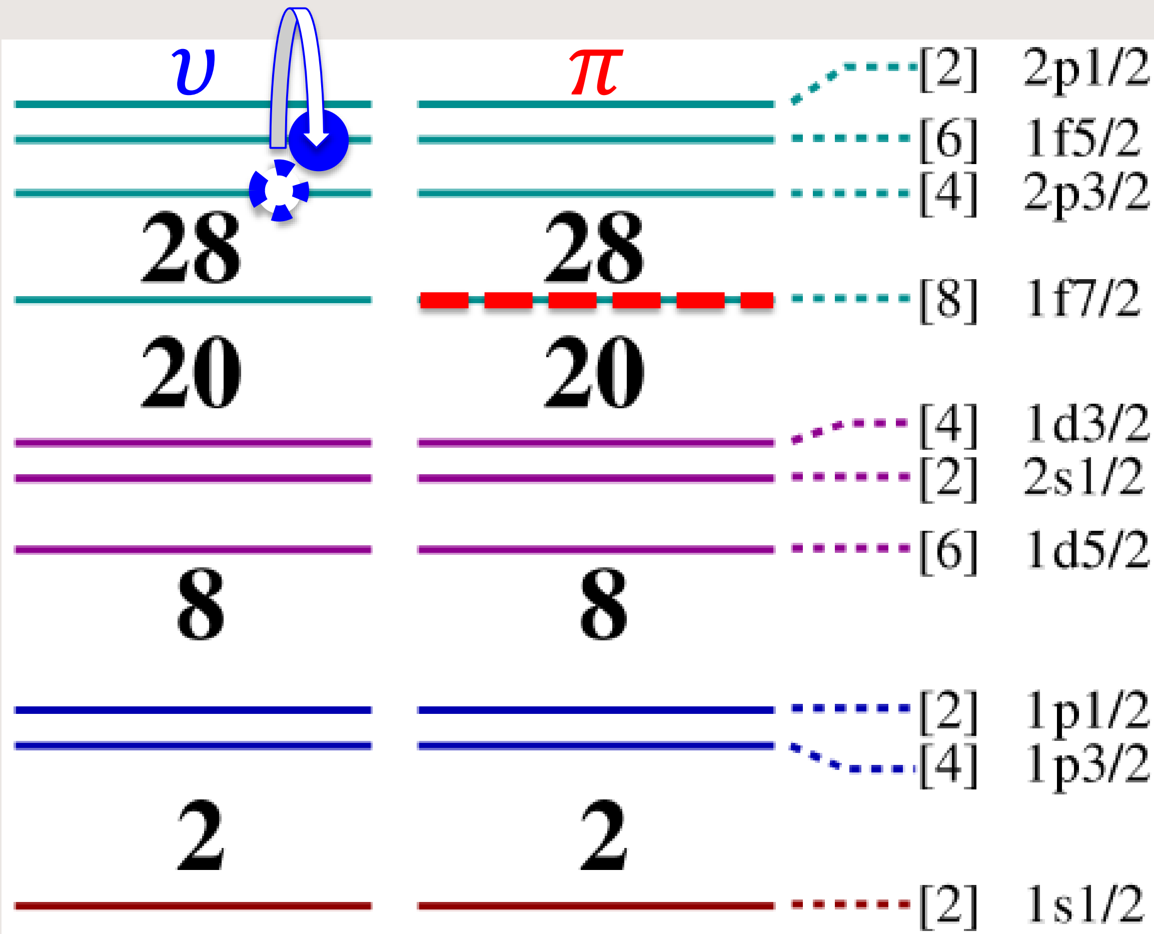

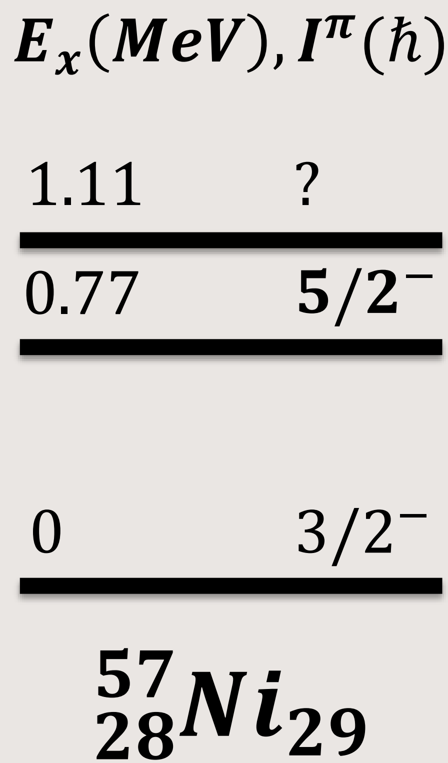

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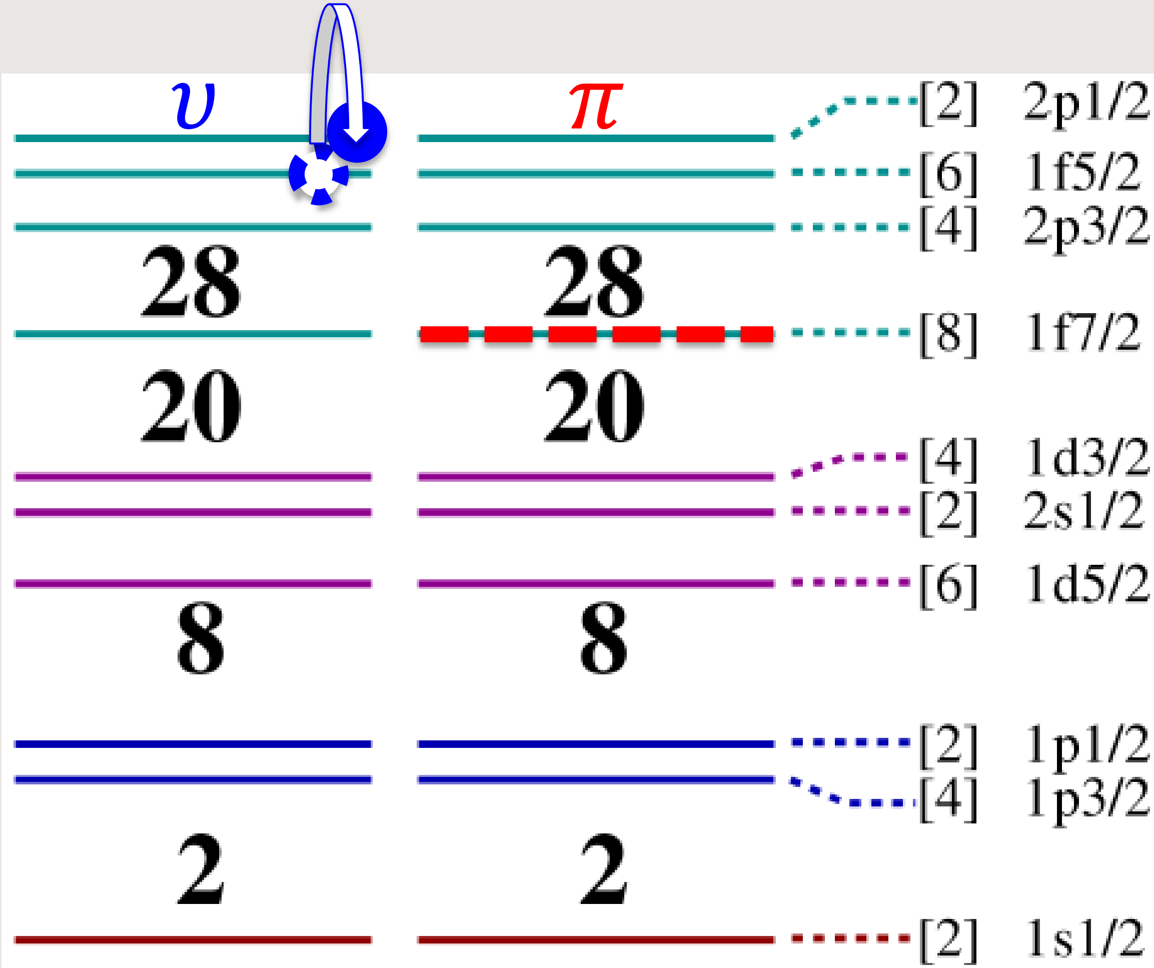

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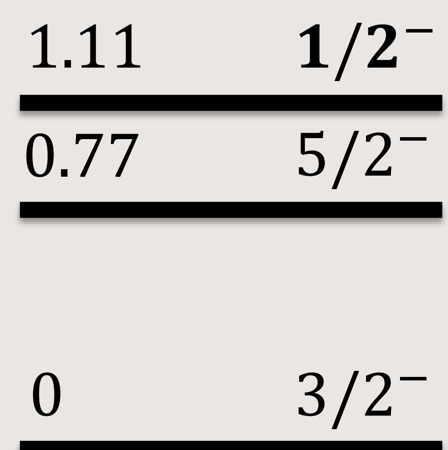

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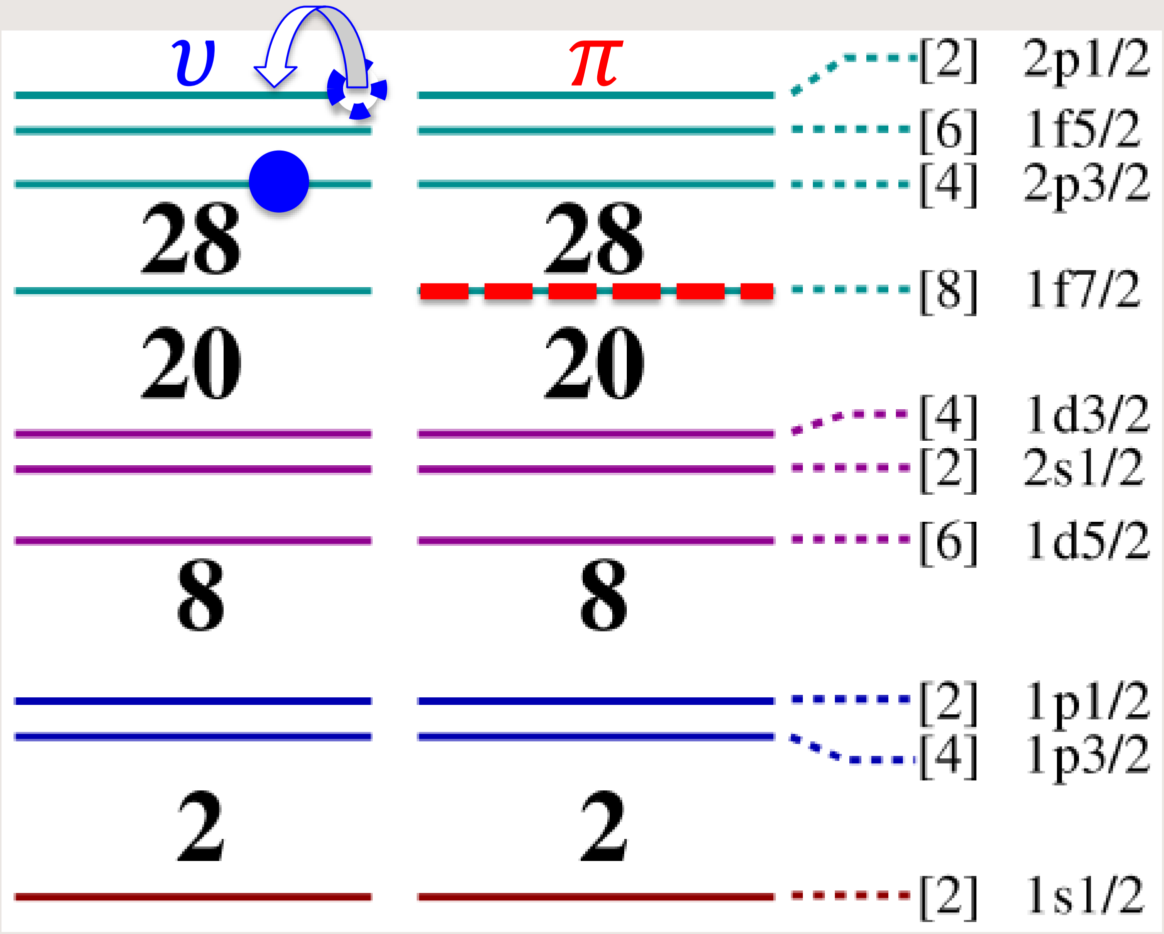
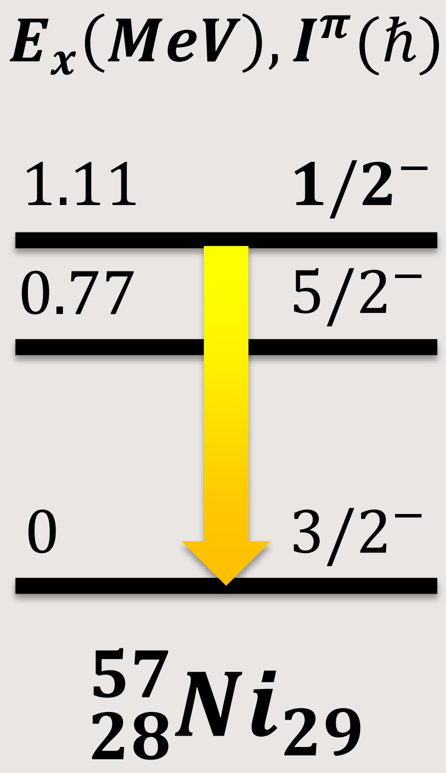
^{57}Ni ("even-odd")

- de-excitation





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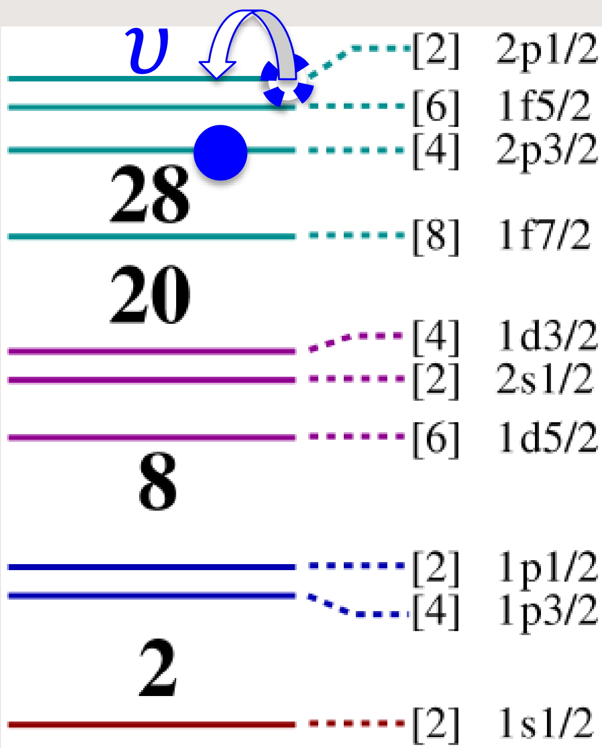

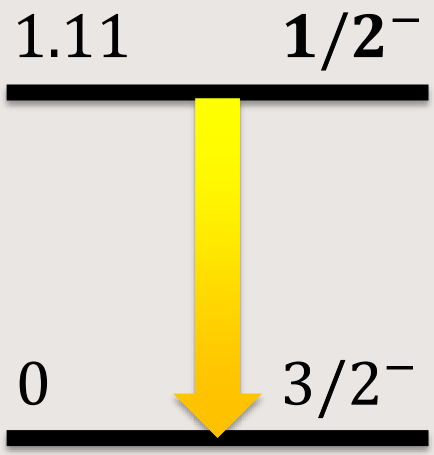

$$^{57}_{28}Ni_{29}$$

$$|I_i + I_f| \geq L \geq |I_i - I_f|$$

$$L = 1, 2$$

$$\pi(E) = -1^L$$

$$\pi(M) = -1^{L+1}$$

$$M1/E2$$

$$(\delta_{exp} = 0.1)$$

T. Motoba, Progr. Theor. Phys. 54, 429 (1975)
M. R. Bhat, Nucl. Data Sheets 85, 415 (1998)

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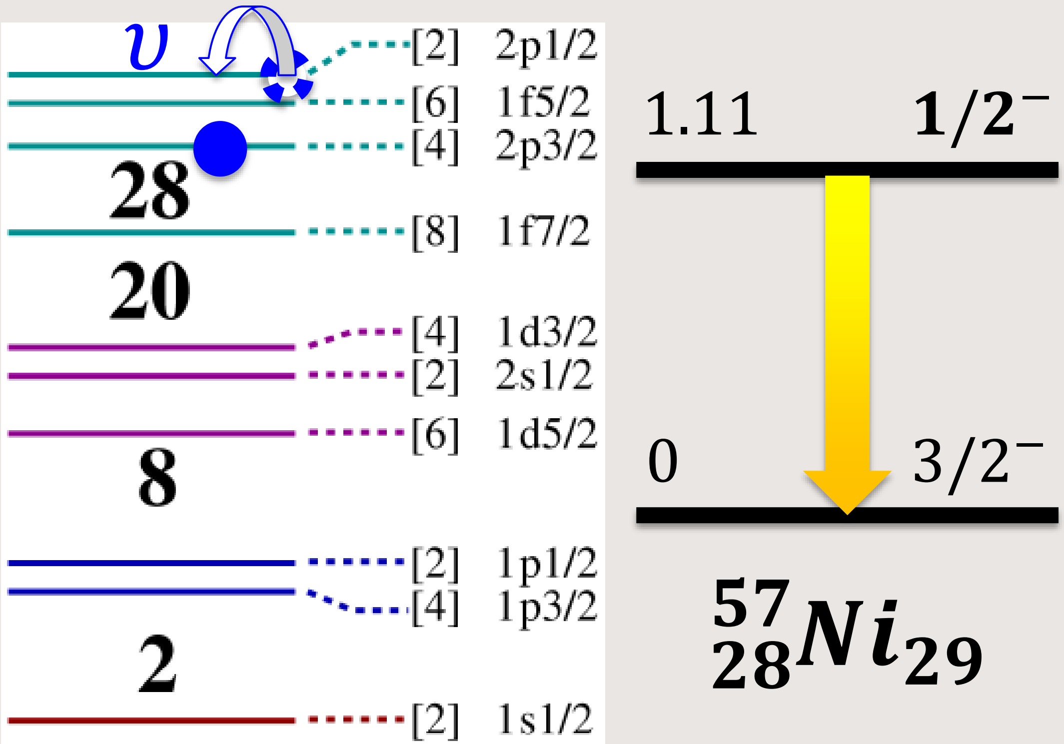

$^{57}_{28}Ni_{29}$

$$\textit{Weisskopf est.}\,(s^{-1})$$
$$\lambda(M1) = 3.15 \times 10^{13} E_\gamma{}^3$$
$$\textit{Experiment}\ (s^{-1})$$
$$\lambda_{exp} = 6.54 \times 10^{12}$$

$$\textit{Transition Prob.}\,(W.u.)$$
$$B(M1) = \frac{\lambda_{exp}}{\lambda(M1)} \sim 0.2$$

T. Motoba, Progr. Theor. Phys. 54, 429 (1975)
M. R. Bhat, Nucl. Data Sheets 85, 415 (1998)

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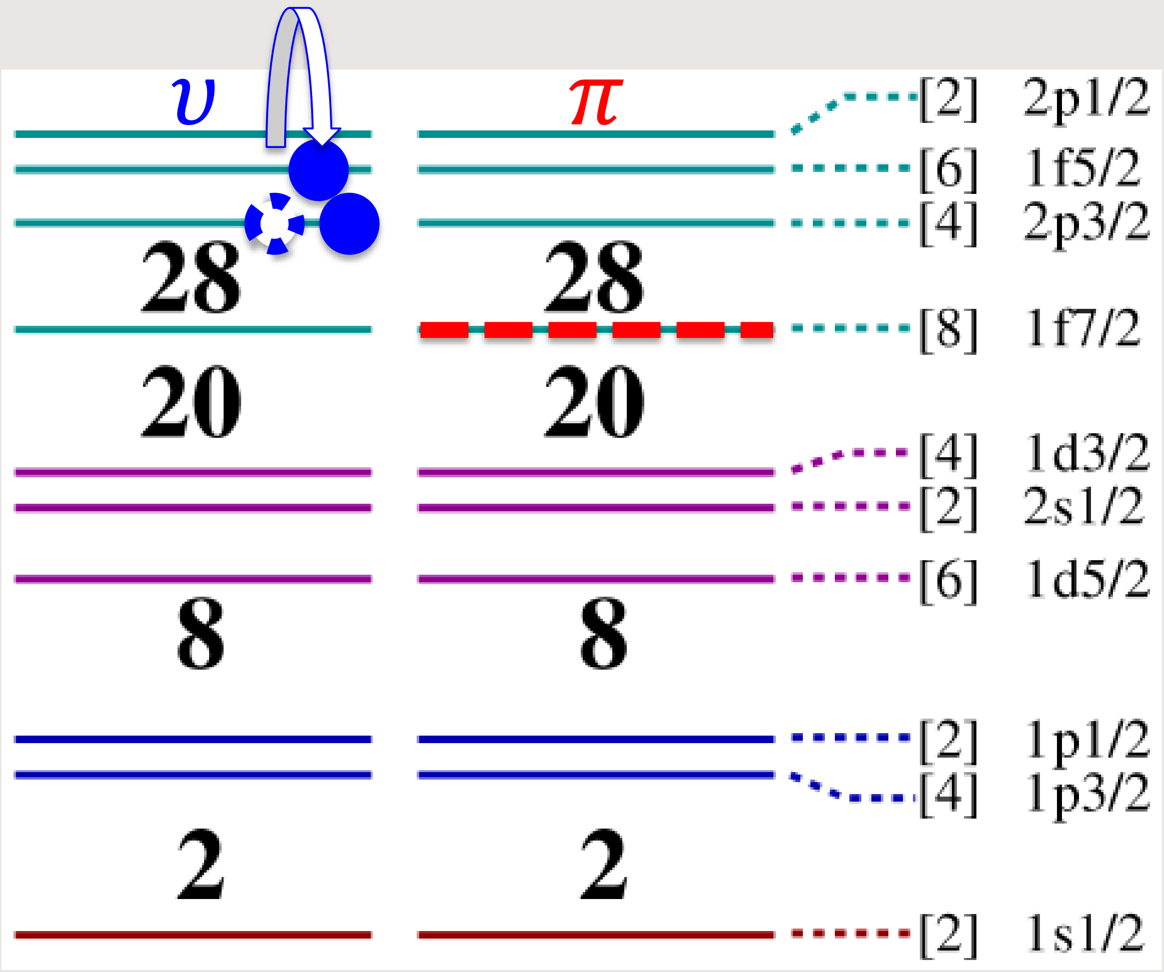
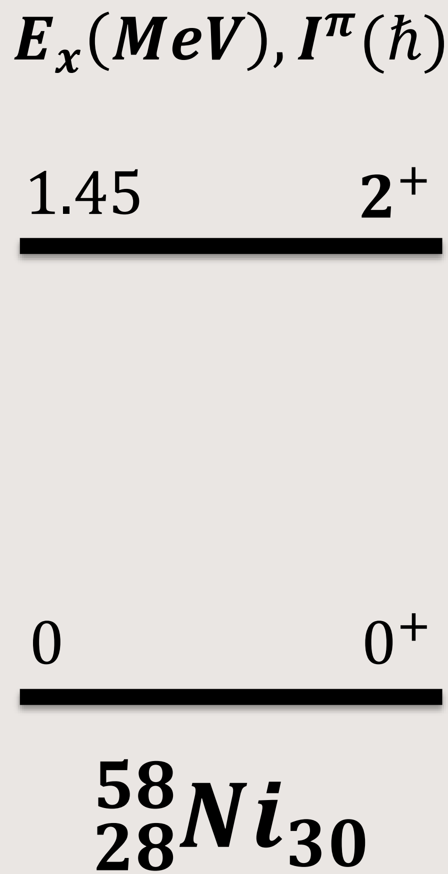
^{58}Ni ("even-even")



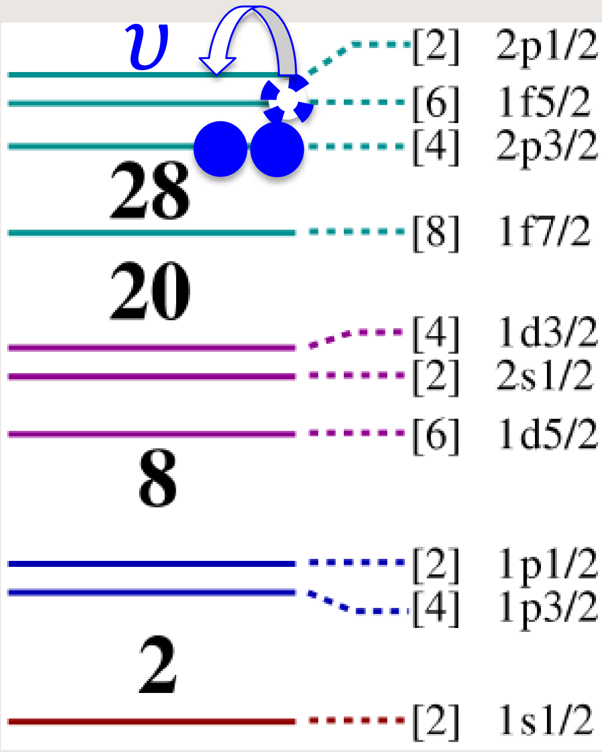


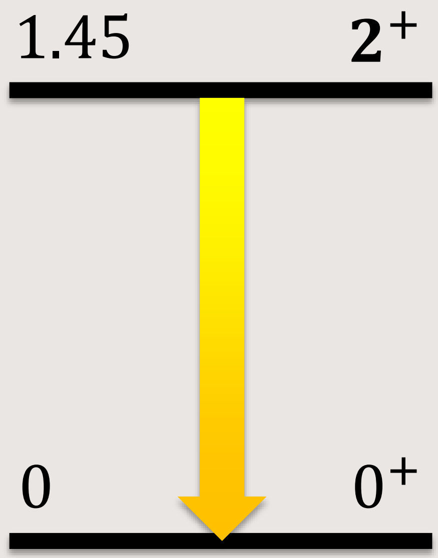
M. C. Bertin et al., Phys. Lett. 26B, 623 (1968)

C. D. Nesaraja et al., Nucl. Data Sheets 111, 897 (2010)

^{58}Ni ("even-even")

- de-excitation





$$^{58}_{28}Ni_{30}$$

$$|I_i + I_f| \geq L \geq |I_i - I_f|$$

$$L = 2$$

$$\pi(E) = -1^L$$

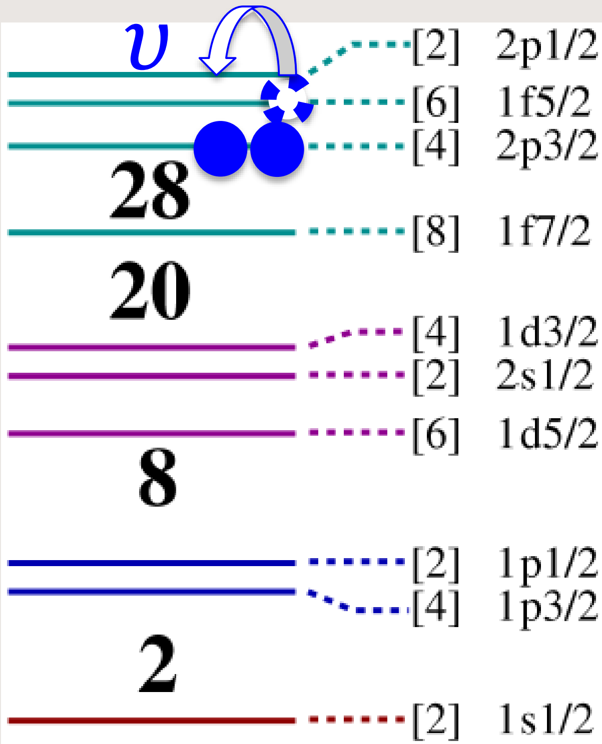
$$\pi(M) = -1^{L+1}$$

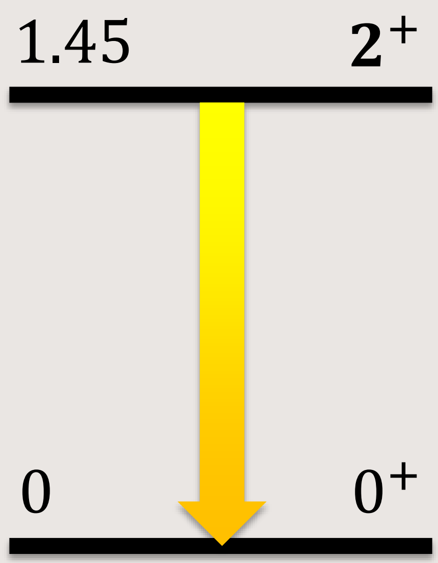
$$E2\ (\text{"}Pure\text{"})$$

$$(\delta = 0)$$

^{58}Ni ("even-even")

- de-excitation





$${}^{58}_{28}Ni_{30}$$

Weisskopf est. (s^{-1})

$$\lambda(\mathrm{E2}) = 7.4 \times 10^7 A^{4/3} E_\gamma{}^5$$

Experiment (s^{-1})

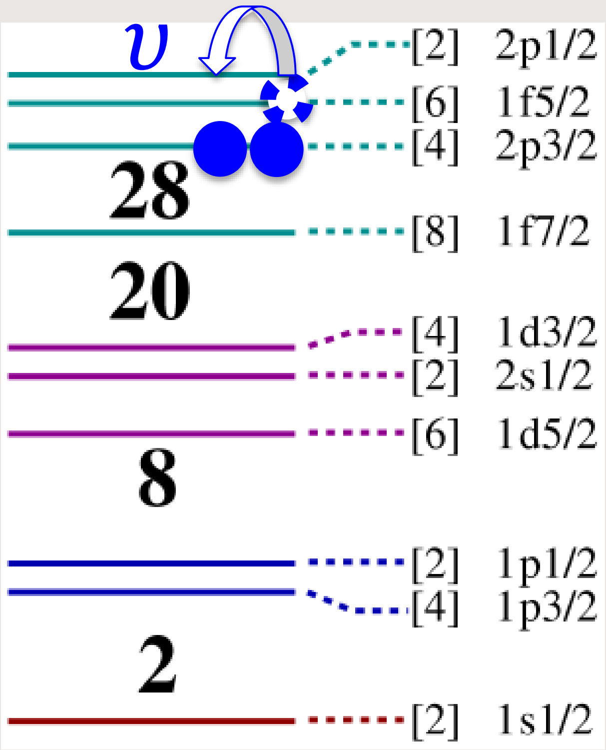
$$\lambda_{exp} = 1.06 \times 10^{12}$$

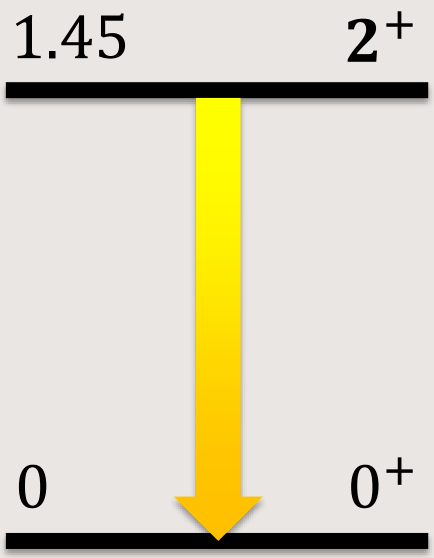
Transition Prob. $(W.u.)$

$$B(E2) = \frac{\lambda_{exp}}{\lambda(E2)} \sim 10$$

^{58}Ni ("even-even")

- de-excitation





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Weisskopf est. (s^{-1})

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Experiment (s^{-1})

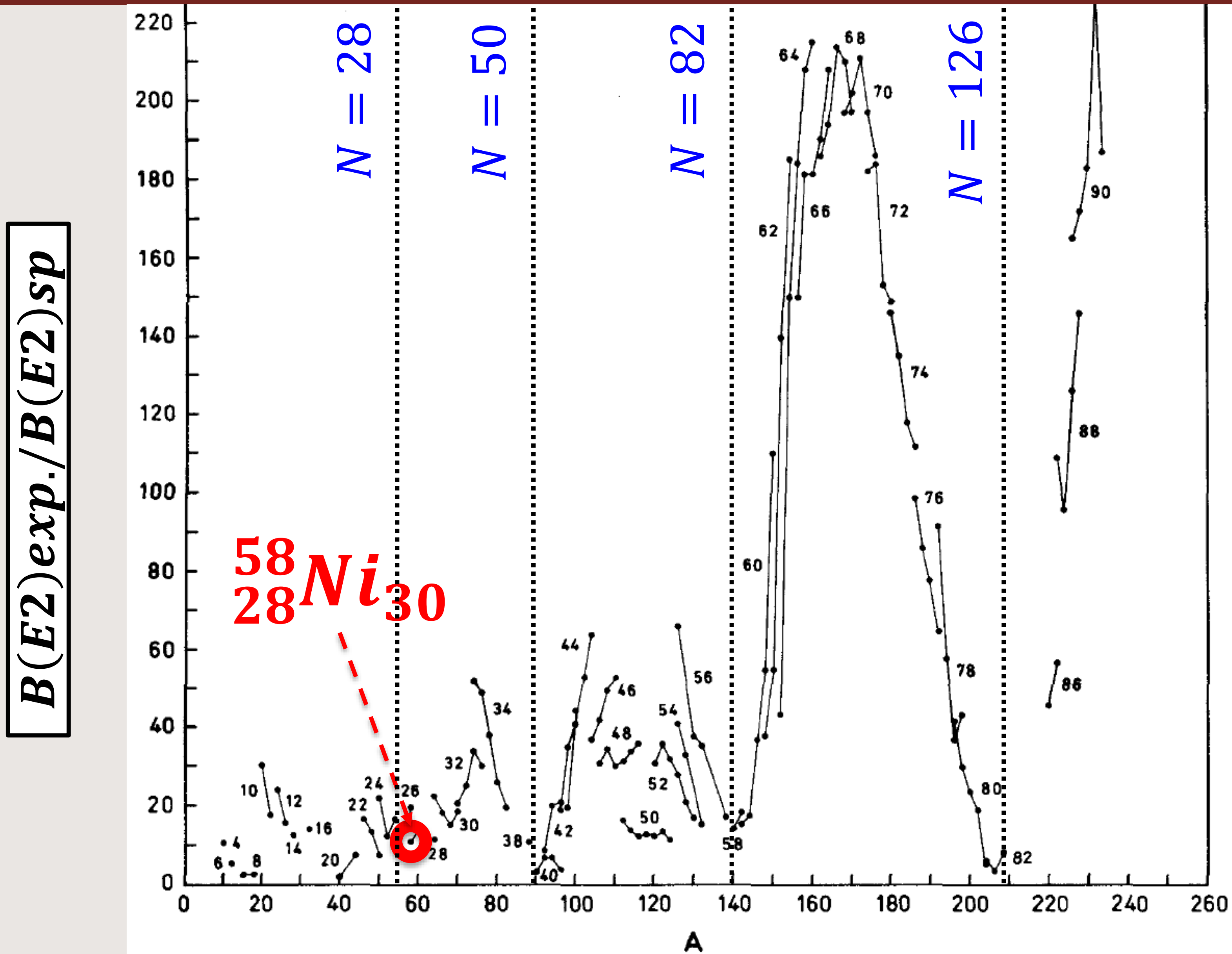
$$\lambda_{exp} = 1.06 \times 10^{12}$$

Transition Prob. $(W.u.)$

$$B(E2) = \frac{\lambda_{exp}}{\lambda(E2)} \sim 10$$

- Something else competes with single-particle motion!

Global B(E2) (even-even)



A. Bohr and B. Mottelson, Nuclear Structure Vol. 2, Ch.4, Pg. 48

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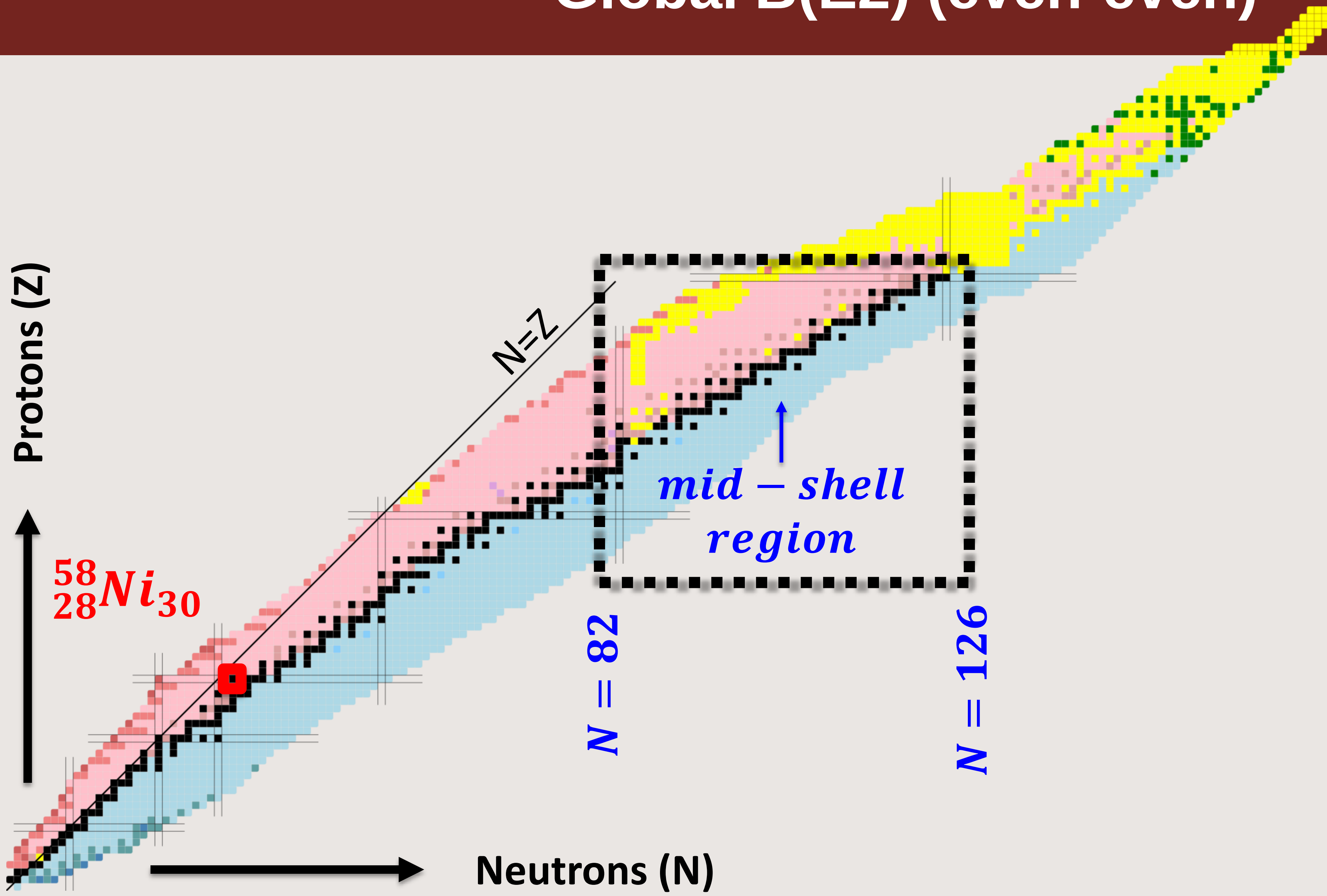
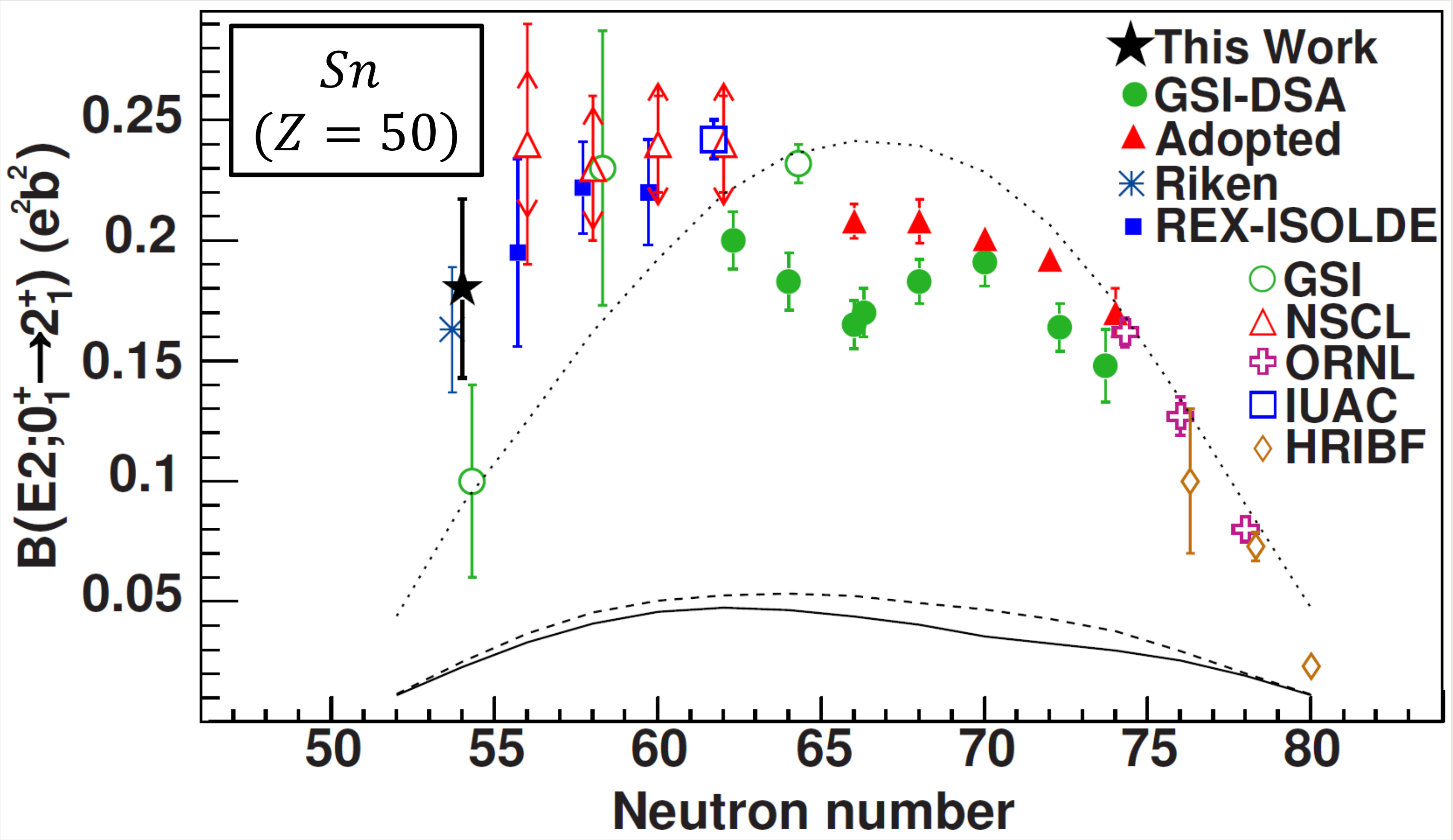
Global B(E2) (even-even)



Mid-shell B(E2)

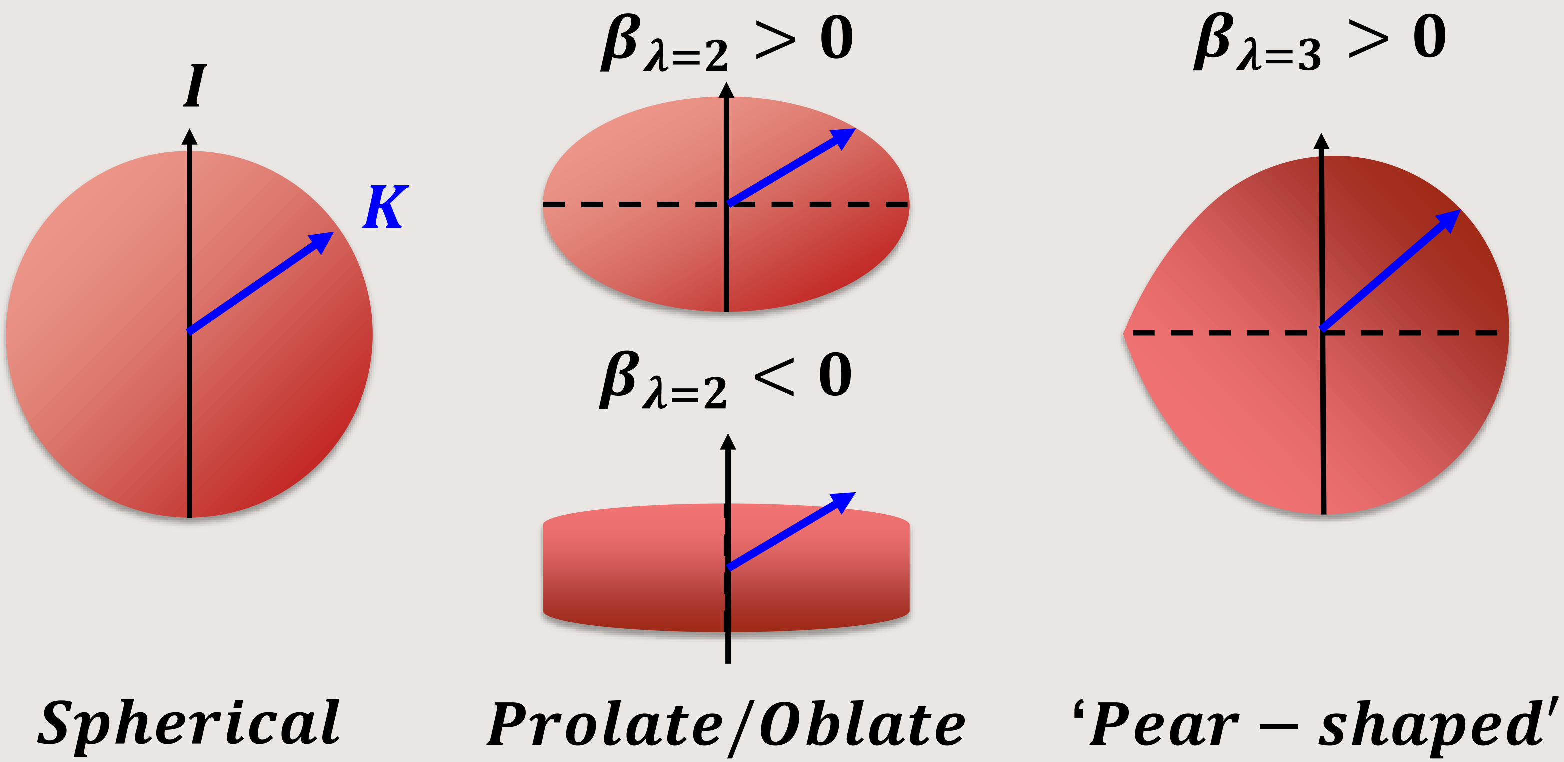
- Calculated versus experimental B(E2) for Sn



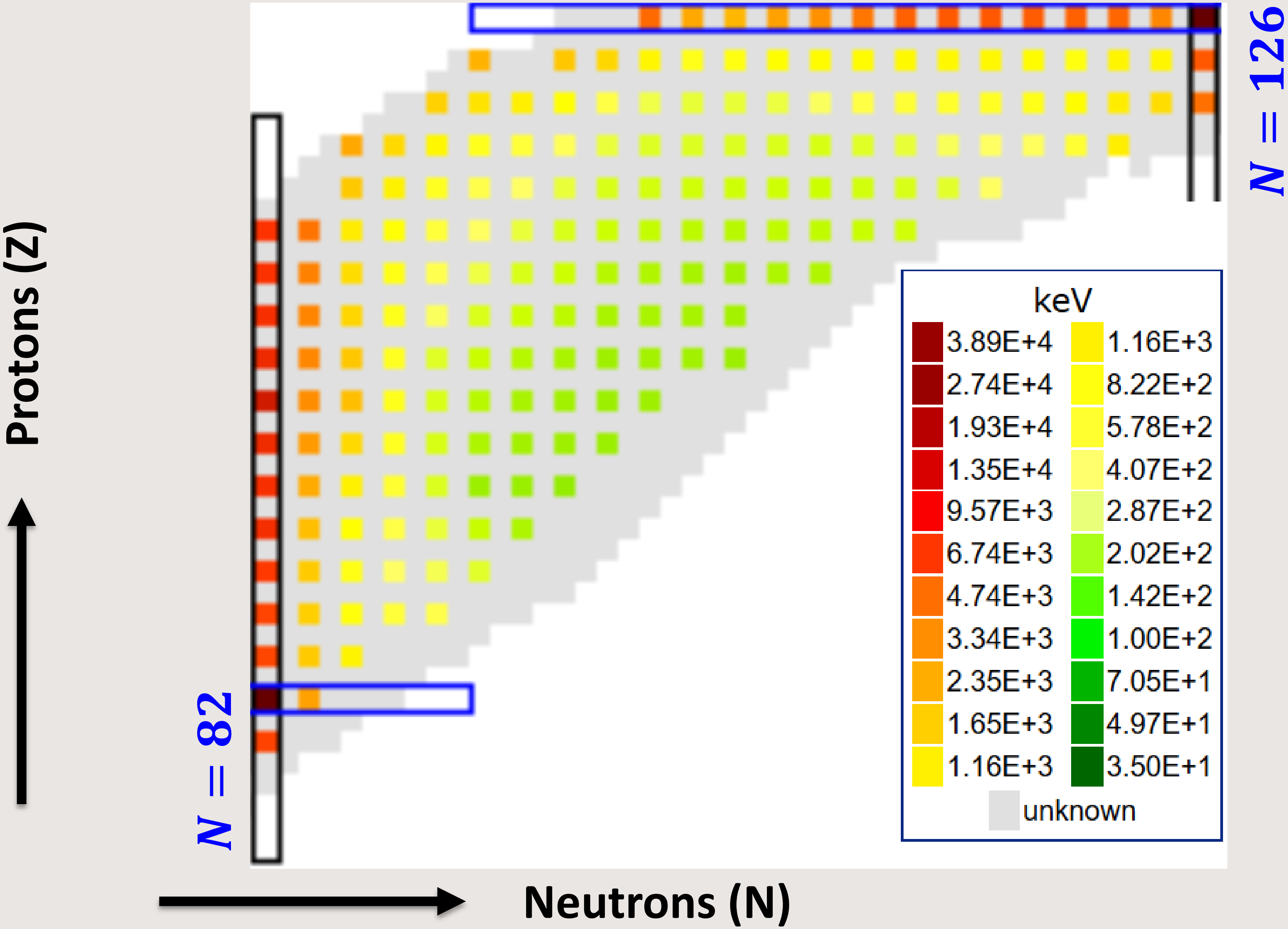
Vincent Bader, PhD. Thesis (2014)
https://groups.nscl.msu.edu/nscl_library/Thesis/index.htm

Deformation in nuclei

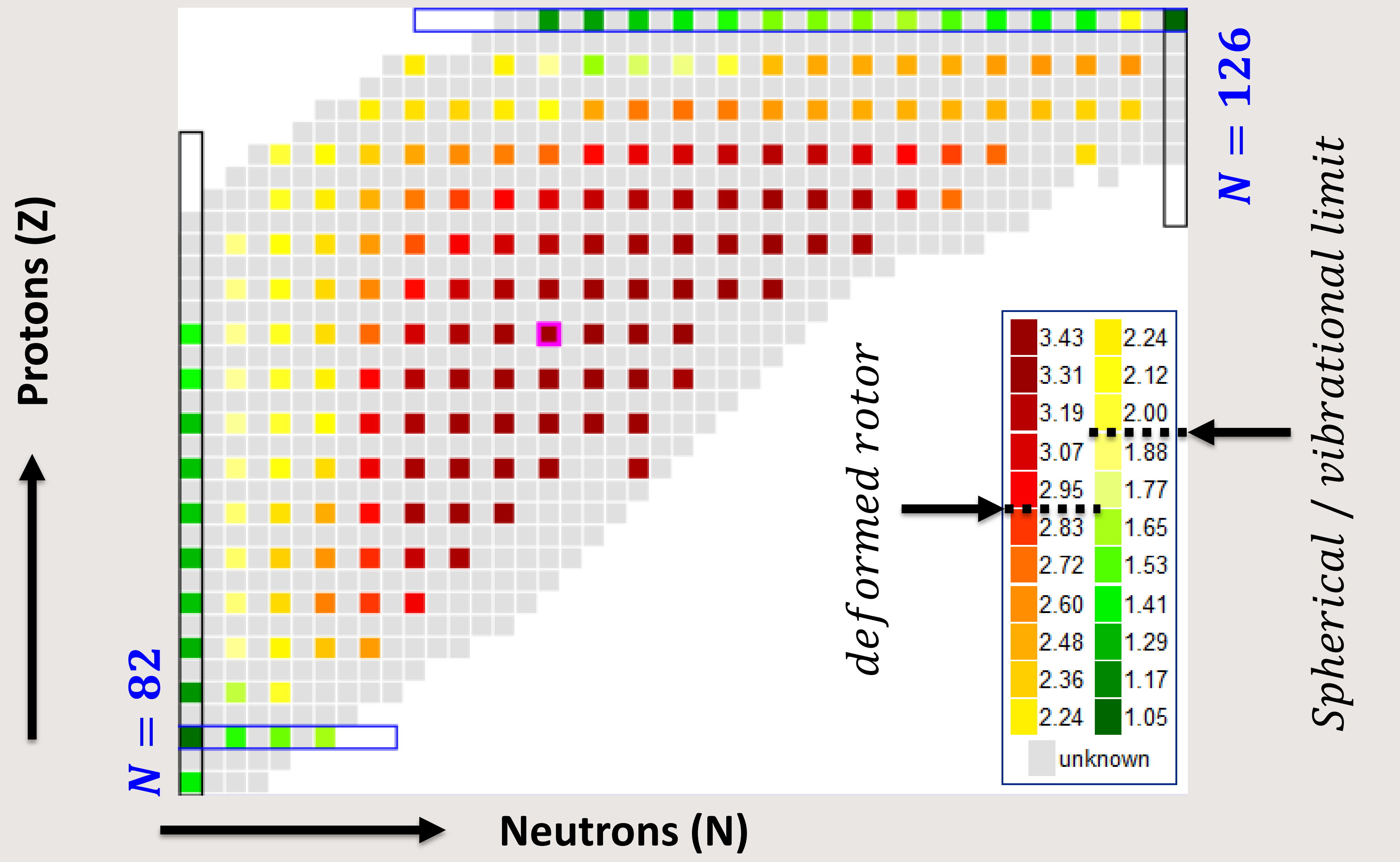
- Deformed nuclear shapes break spherical symmetry and introduce *non-degenerate* states
  - Degeneracy ≡ Equivalency (in energy) of excited states



Global $E_x(2^+)$ (even-even)



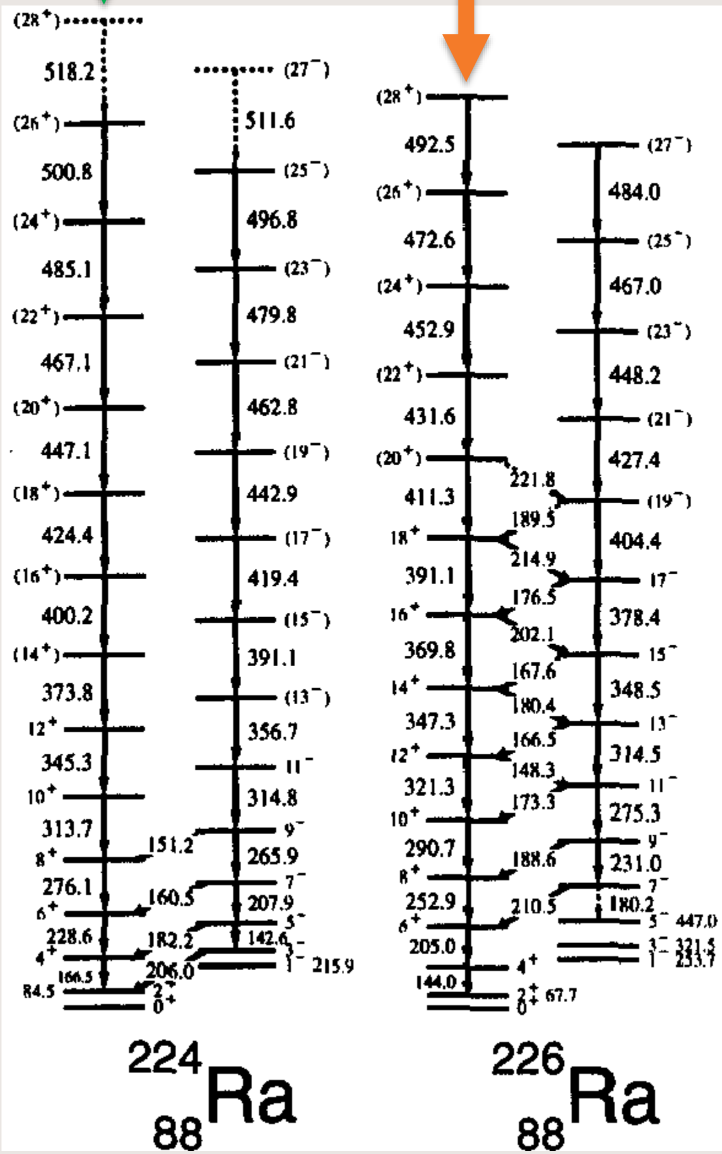
Global $E_x(4^+/2^+)$ (even-even)

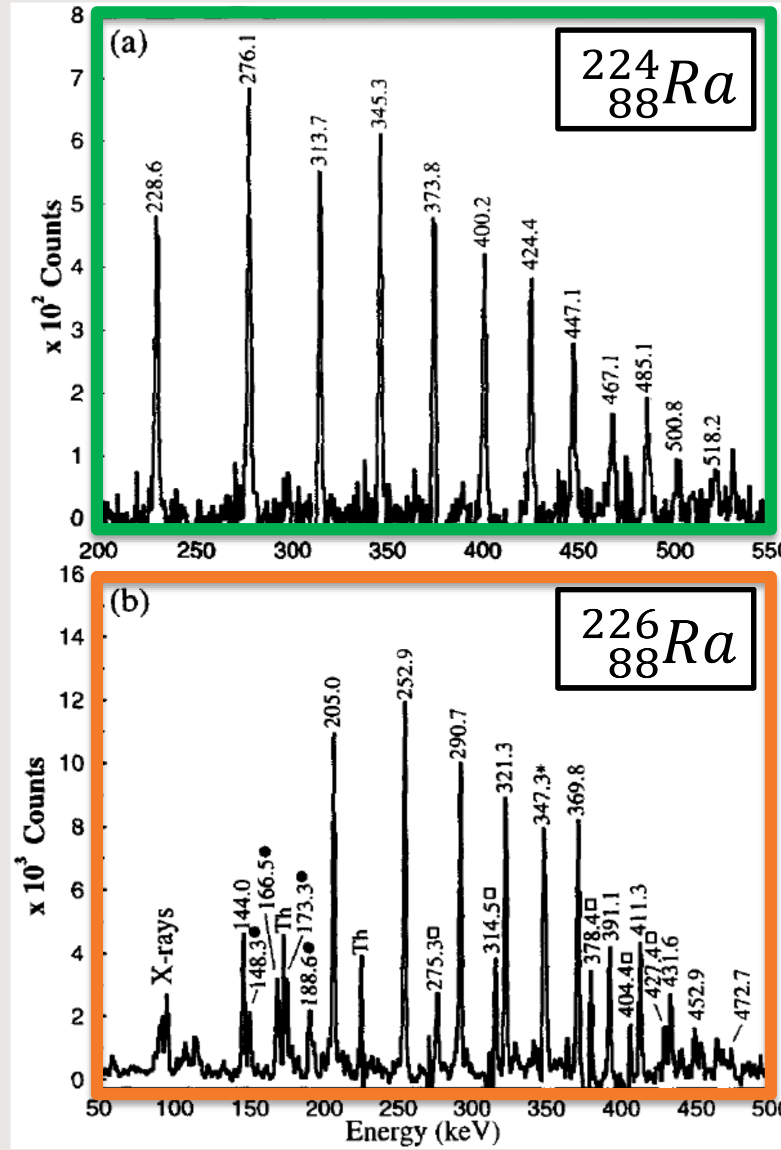


Collective excitations

- Rotations
  - Nucleus behaves as deformed rotor with a distinctive separation of energy eigenvalues ("rotational band")
  - $E_{rot} = \frac{\hbar^2}{2\mathcal{J}} I(I+1),\ \ e.g. \frac{E_{rot}^{4^+}}{E_{rot}^{2^+}} \approx \frac{4(4+1)}{2(2+1)} = \ 3.33$
- Vibrations
  - Transient deformation of equilibrium nuclear shape
- "Giant resonances"
  - Highly collective, high energy, proton-neutron excitations (e.g. Monopole Resonance, Dipole Resonance)

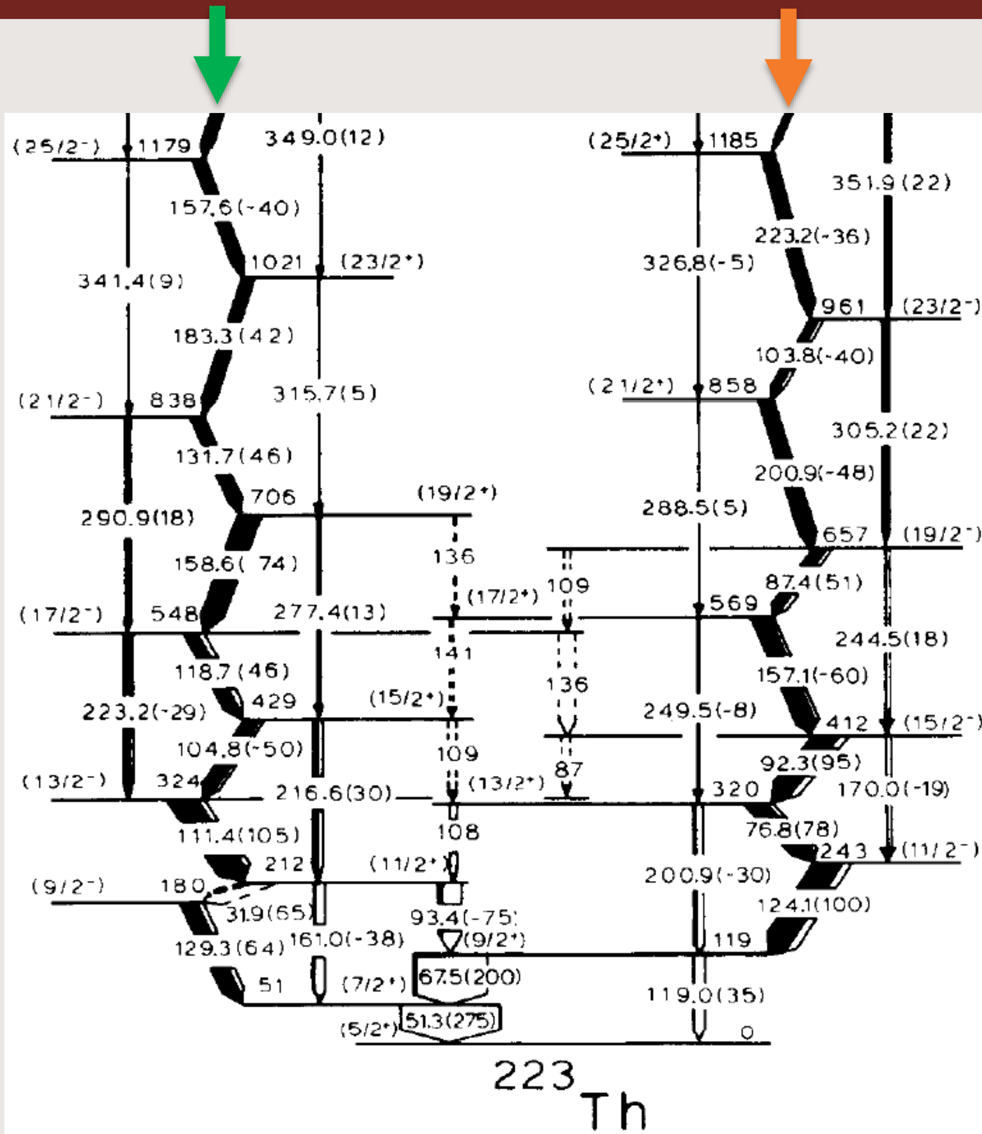
Rotational spectra: radium

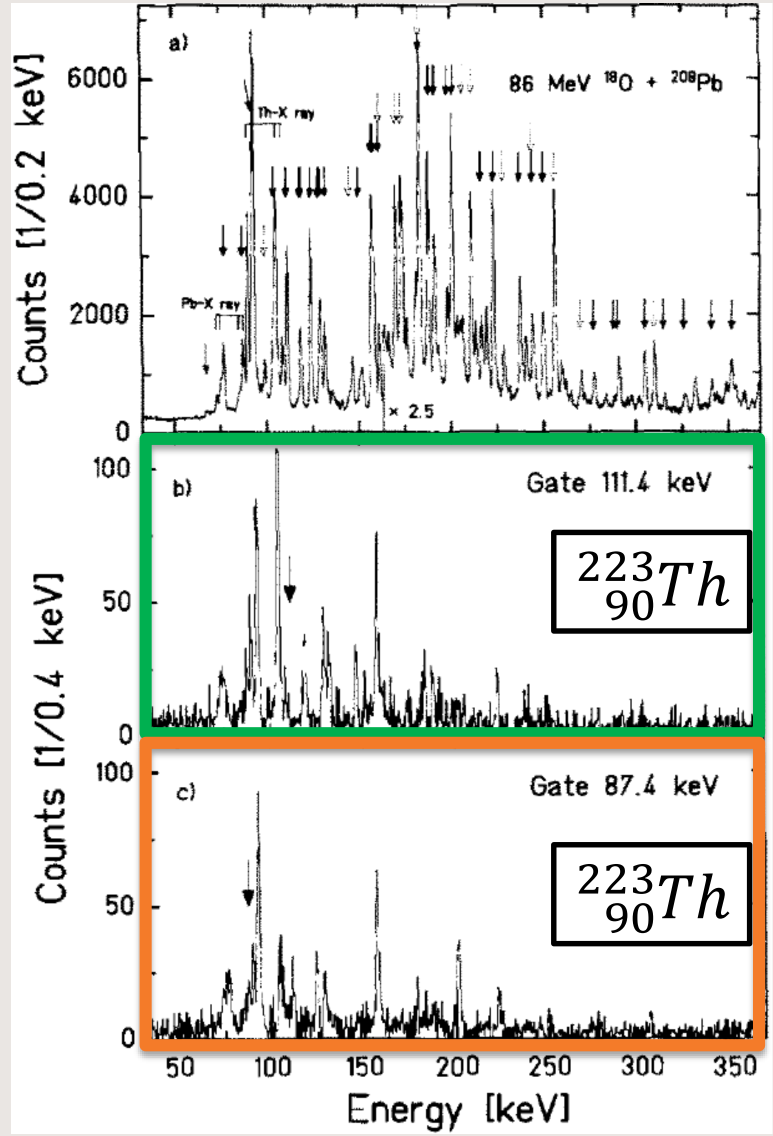




J.F.C. Cocks et al., Nucl. Phys. A 645, 61-91 (1999)

Rotational spectra: thorium





M. Dahlinger et al., Nucl. Phys. A 484, 337-375 (1988)

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Summary

- Both *single-particle* and *collective* excitations compete to determine the properties of excited states
  - Largest collective contributions observed around mid-shell

- Transition probabilities $B(E,M\lambda)$ provide a powerful probe of the collective contribution when compared with theory
  - Simple example near magic N, Z: Weisskopf estimates
  - More complex: Shell Model Calculations

- $B(E,M\lambda)$ values are intimately related to nuclear multipole moments (e.g. $B(E1)$ & dipole moment)

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Thank you!
Merci

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Links

- Comments or suggestions?
  - Email:

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  jhenderson@triumph.ca

- Sign up link to receive course updates:

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