Nuclear Structure Experiment II

Lifetime Measurements
Conversion Electron Spectroscopy

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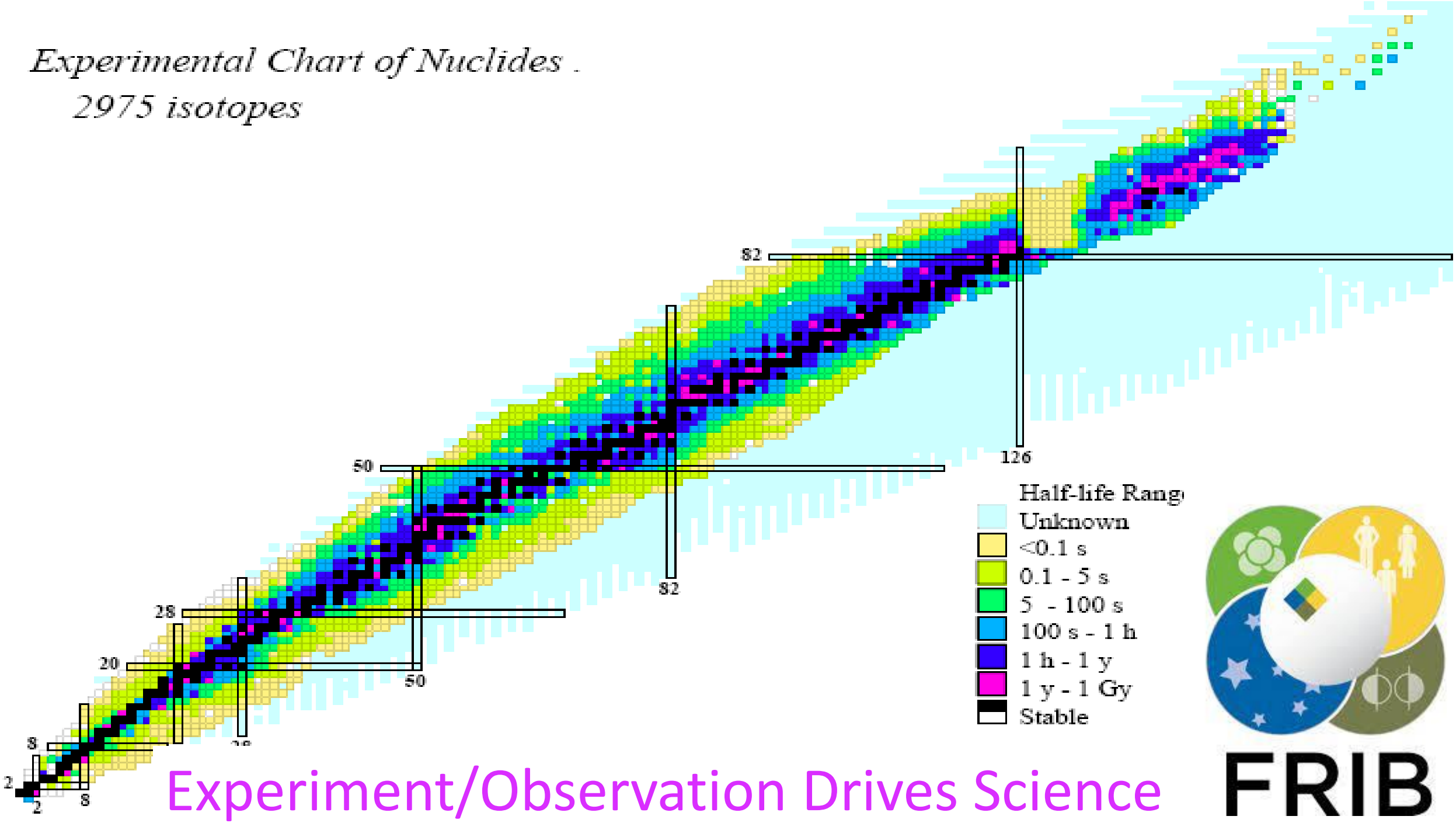
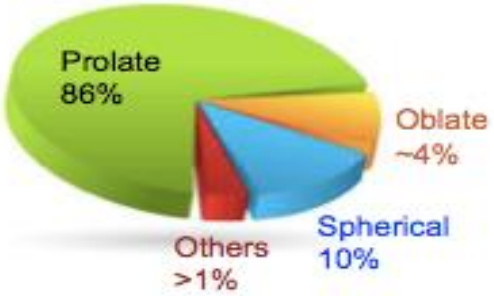


Experiment/Observation Drives Science

FRIB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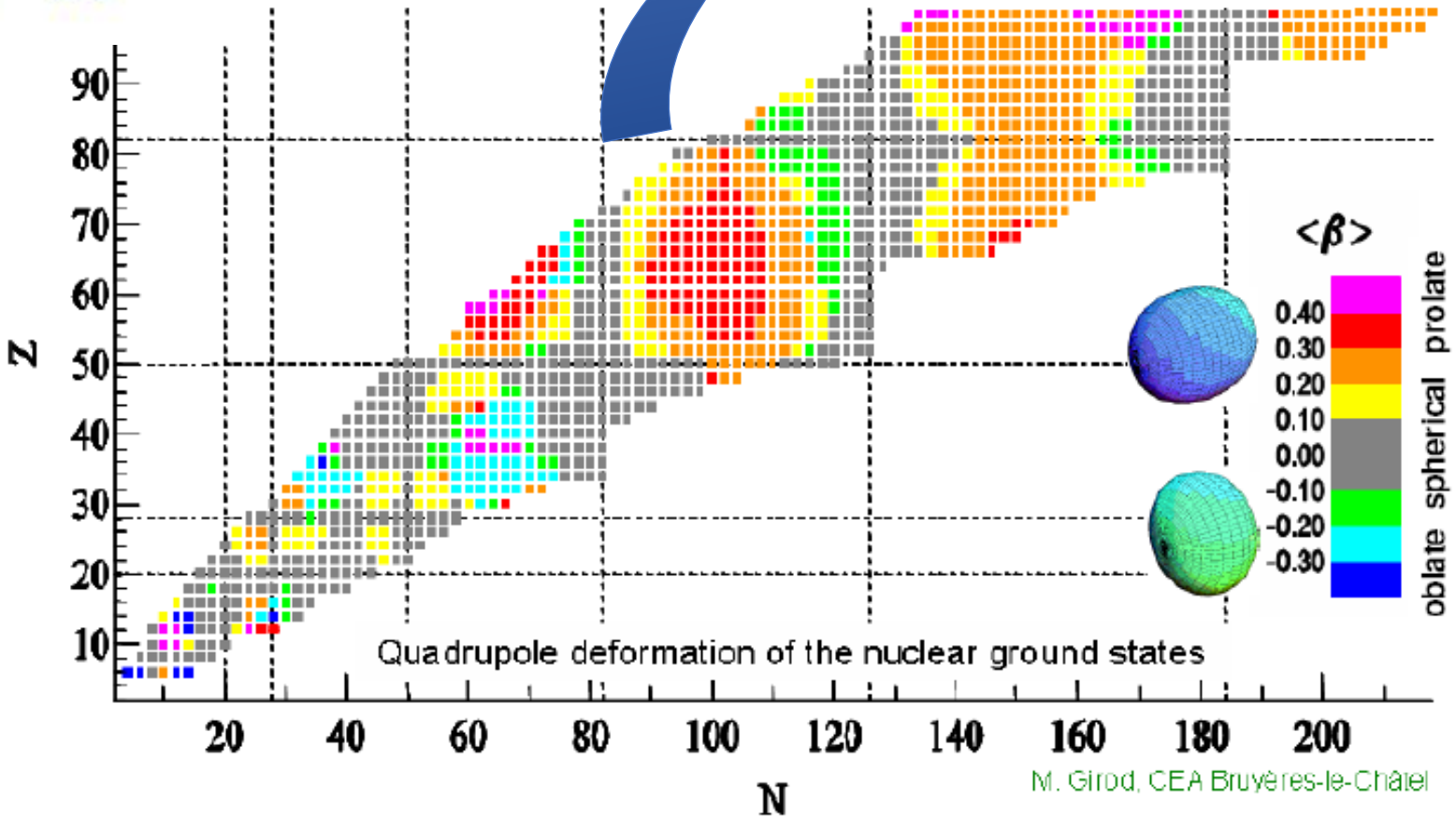
Oblate
~4%
Spherical
10%
Others
>1%


Z
N
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0.40
0.30
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prolate
spherical
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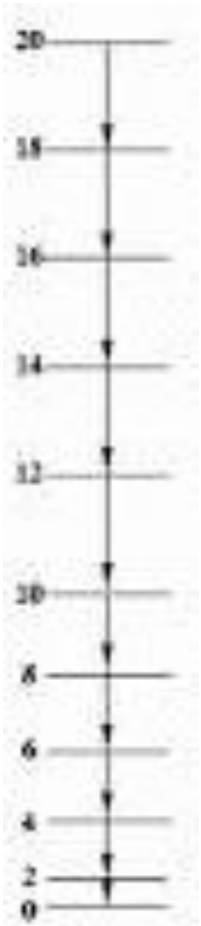
Quadrupole deformation of the nuclear ground states
M. Girod, CEA Bruyères-le-Châtel



Observables for nuclear structure studies:

Energy Levels from gamma-ray spectroscopy: Level energy ratios

Masses of Nuclei from traps: proton and neutron separation energies

Reaction cross sections by spectrometers

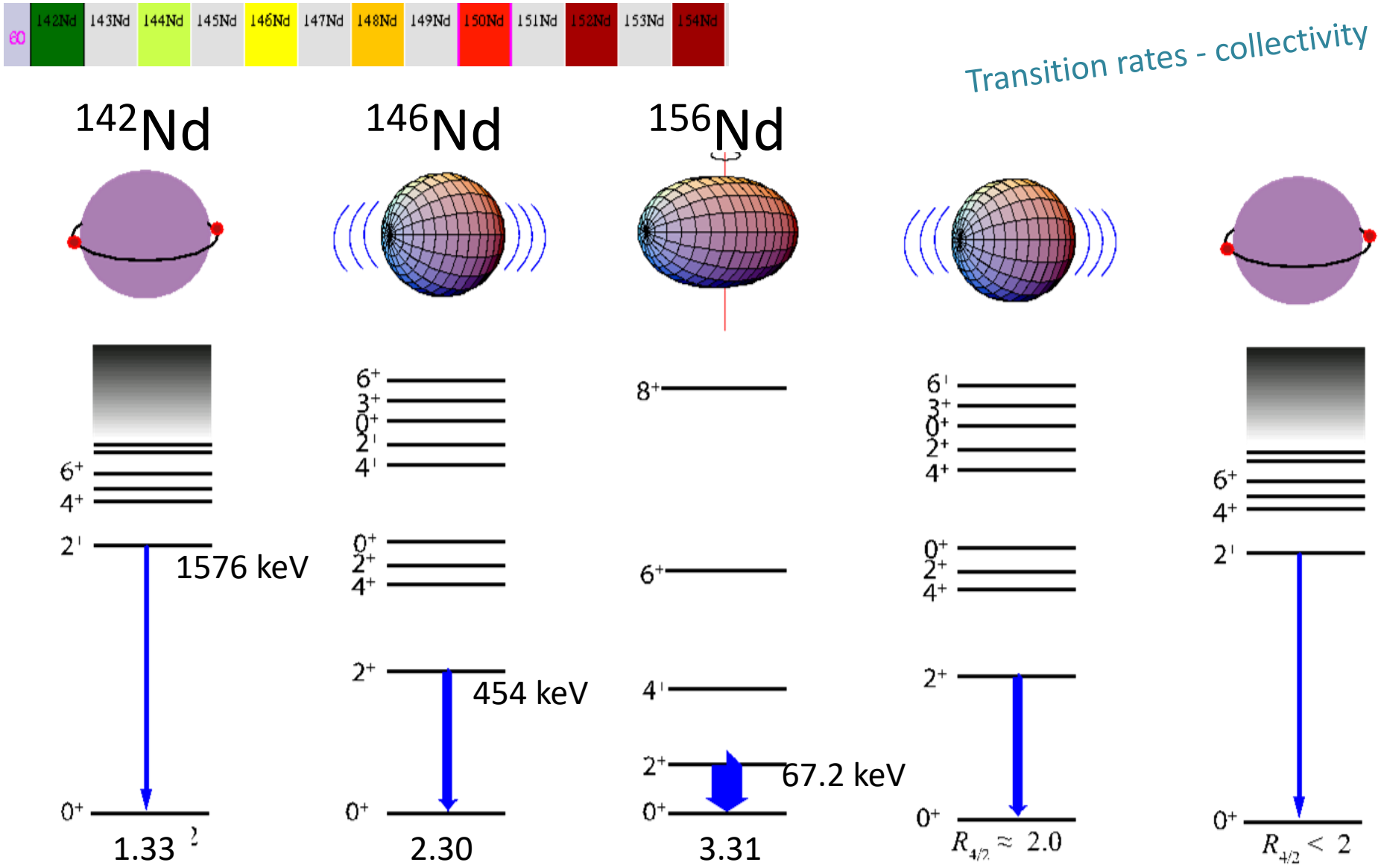
Lifetimes of excited states: Transition Rates

DSAM: Stable Targets

GRID: Stable Targets

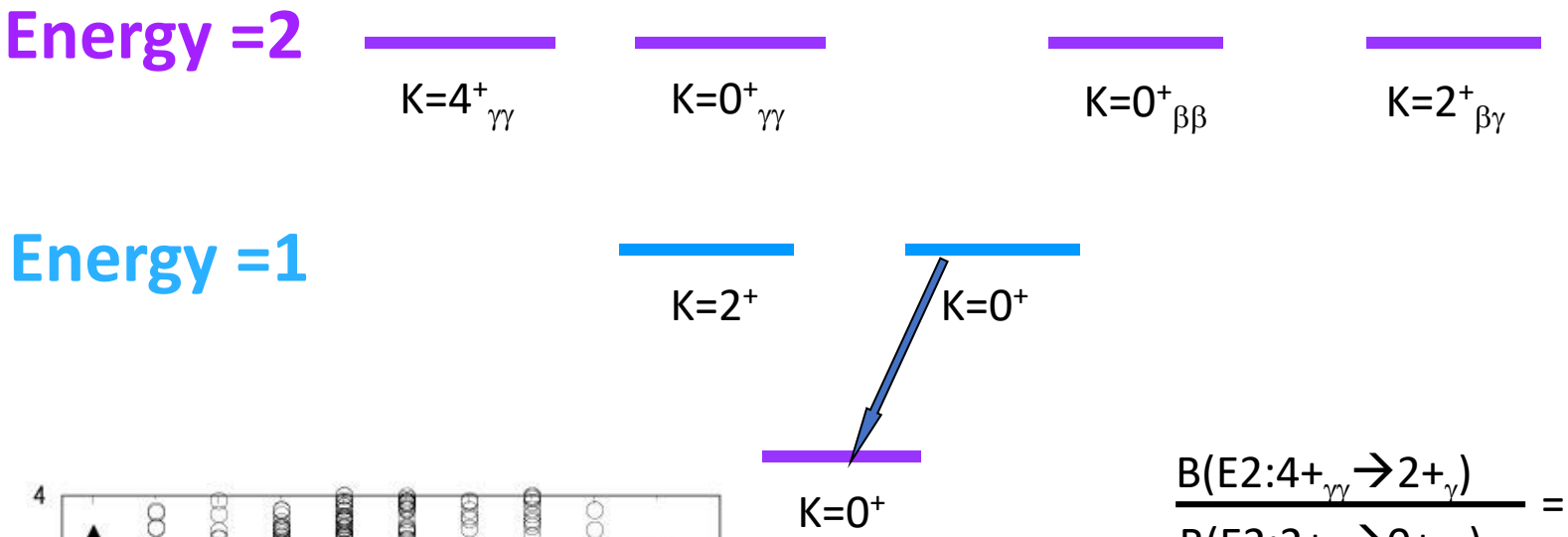
Advanced Time Delay Technique: Exotic Nuclei

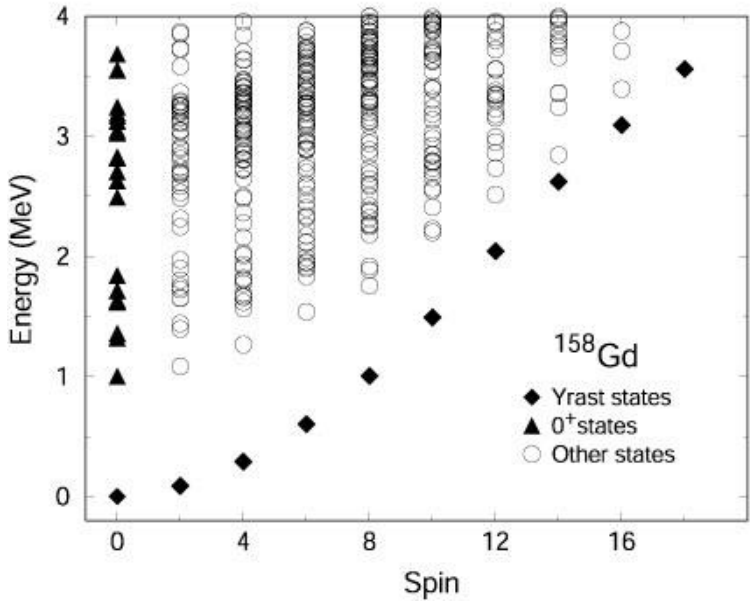
Energy Levels: Evolution of Nuclear Structure



E_{4+}/E_{2+}

Transition Probabilities!





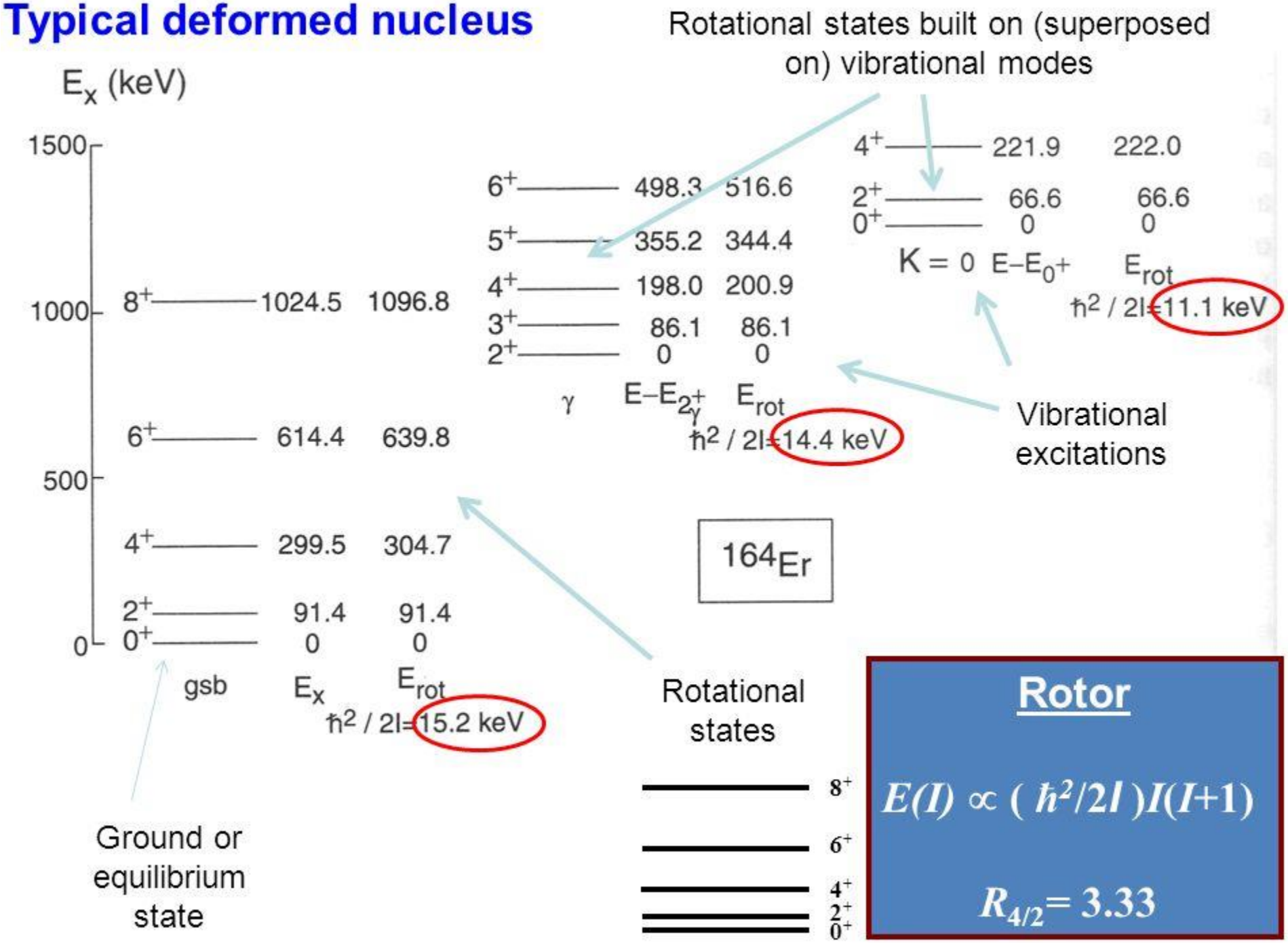
Y.Sun, 2003

$$\frac{B(E2:4+_{\gamma\gamma}\rightarrow 2+_{\gamma})}{B(E2:2+_{\gamma}\rightarrow 0+_{gs})} = 2.78$$

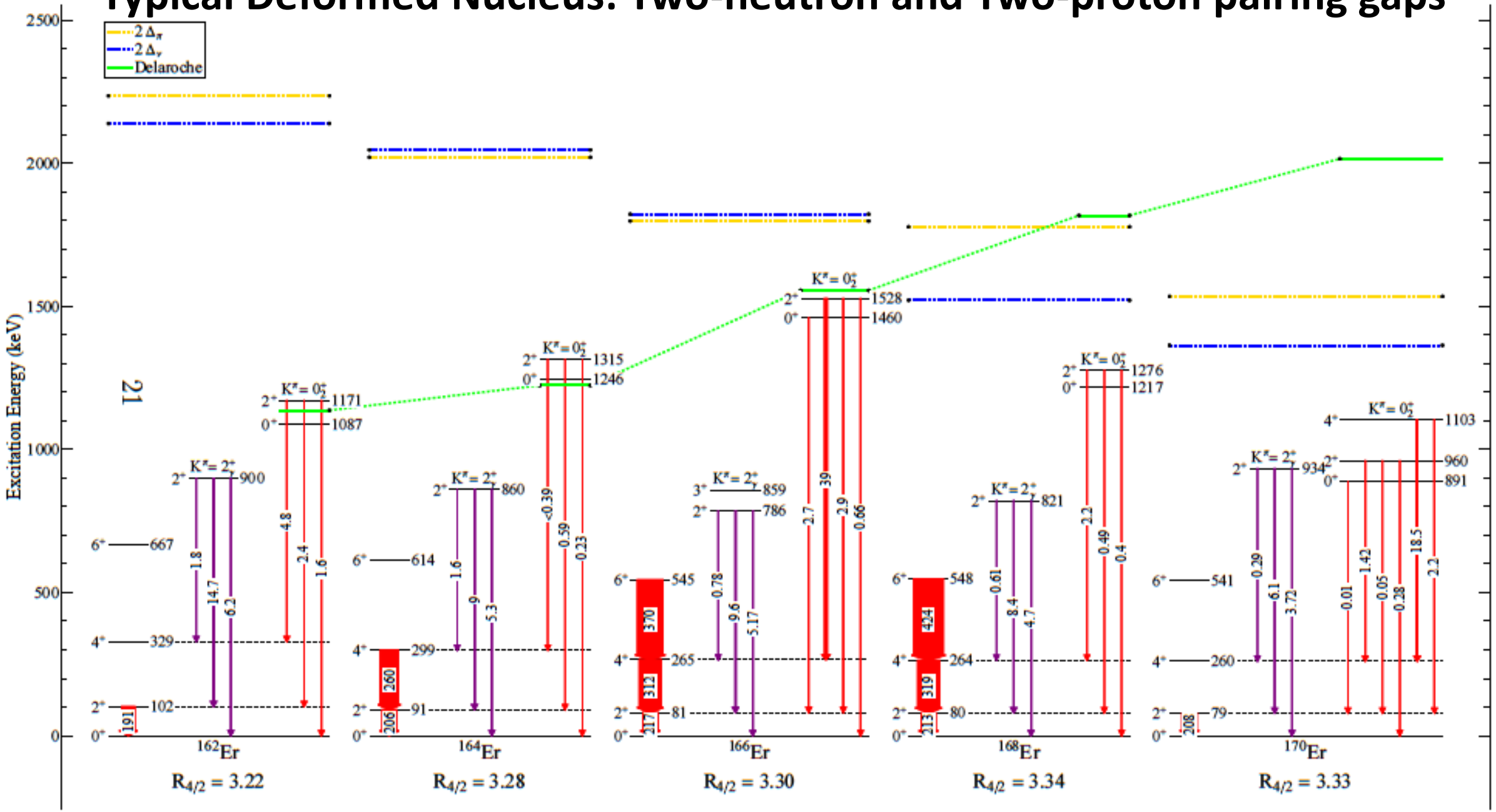
$$\frac{B(E2:0+_{\gamma\gamma}\rightarrow 2+_{\gamma})}{B(E2:2+_{\gamma}\rightarrow 0+_{gs})} = 5.0$$

$$\frac{B(E2:2+_{\beta\beta}\rightarrow 0+_{gs})}{B(E2:2+_{\beta}\rightarrow 0+_{gs})} = 2.0$$

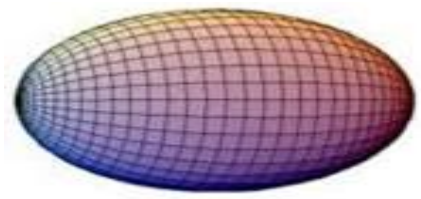
Typical deformed nucleus



Typical Deformed Nucleus: Two-neutron and Two-proton pairing gaps



Lifetime measurements of exotic nuclei



Prolate

Collective Excitations built on the g.s.?

Energies of excitations
Matrix elements
Rx cross sections

….last piece of the puzzle…..**stay tuned!**

$$\lambda_{if} = \frac{2\pi}{\hbar}\left|M_{if}\right|^2 \rho_f$$

Fermi's Golden Rule

Transition probability

Matrix element for the interaction

Density of final states

How is measuring the lifetime of excited nuclear states useful?

Nuclear structure information.
The 'reduced matrix element', B(λL) tells us the overlap between the initial and final nuclear single-particle wavefunctions.

$$T_{fi}(\lambda L) = \frac{8\pi(L+1)}{\hbar L\left((2L+1)!!\right)^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L : J_i \rightarrow J_f)$$

Transition probability (i.e., 1/mean lifetime (τ))

γ-ray energy dependence of transition rate: e.g. E_γ^5 for E2s

$$A \ \ photon \ \ with \ \ \ell \ \ units \ \ of \ \ angular \ \ momentum$$

$$is \ \ called \ \ a \ \ 2^{\ell} - pole \ \ photon.$$

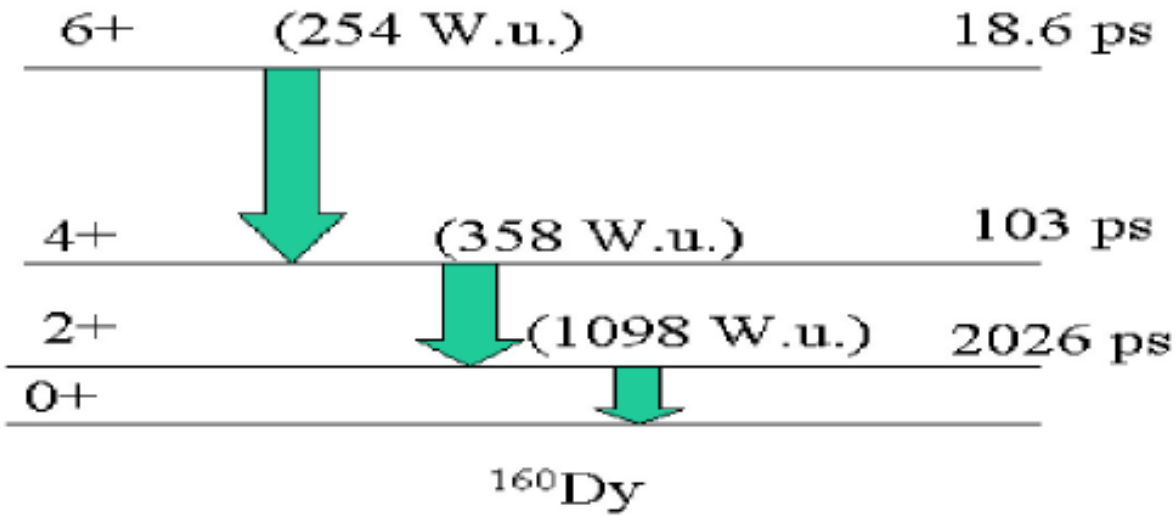
$$\ell = 1 \Rightarrow dipole$$
$$\ell = 2 \Rightarrow quadrupole$$
$$\ell = 3 \Rightarrow octupole$$

Multipolarity is a measure of the angular momentum carried away by the photon.

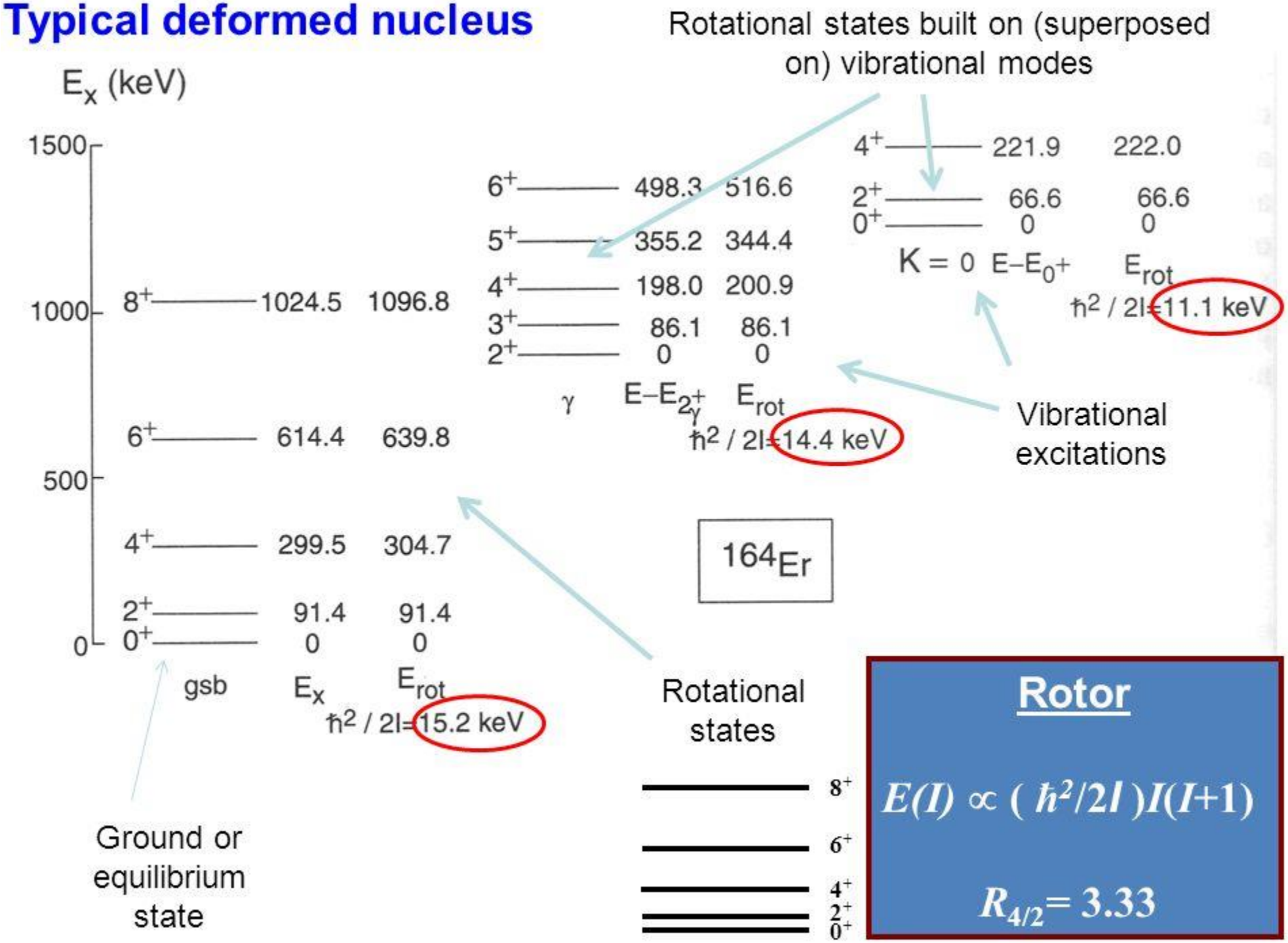
Transitions are classified as **electric** or **magnetic** based on whether the radiation is due to a shift in the charge distribution or a shift in the current distribution.

Weisskopf Estimates: T in seconds; Eγ in keV; A is AMU

Transition Multipolarity	$T_{\frac{1}{2}}$(1 spu) (seconds)
E1	$6.76 \times 10^{-6} E_\gamma^{-3} A^{-\frac{2}{3}}$
E2	$9.52 \times 10^{6} E_\gamma^{-5} A^{-\frac{4}{3}}$
E3	$2.04 \times 10^{19} E_\gamma^{-7} A^{-2}$
E4	$6.50 \times 10^{31} E_\gamma^{-9} A^{-\frac{8}{3}}$
M1	$2.20 \times 10^{-5} E_\gamma^{-3}$
M2	$3.10 \times 10^{7} E_\gamma^{-5} A^{-\frac{2}{3}}$
M3	$6.66 \times 10^{19} E_\gamma^{-7} A^{-\frac{4}{3}}$
M4	$2.12 \times 10^{32} E_\gamma^{-9} A^{-2}$



Typical deformed nucleus



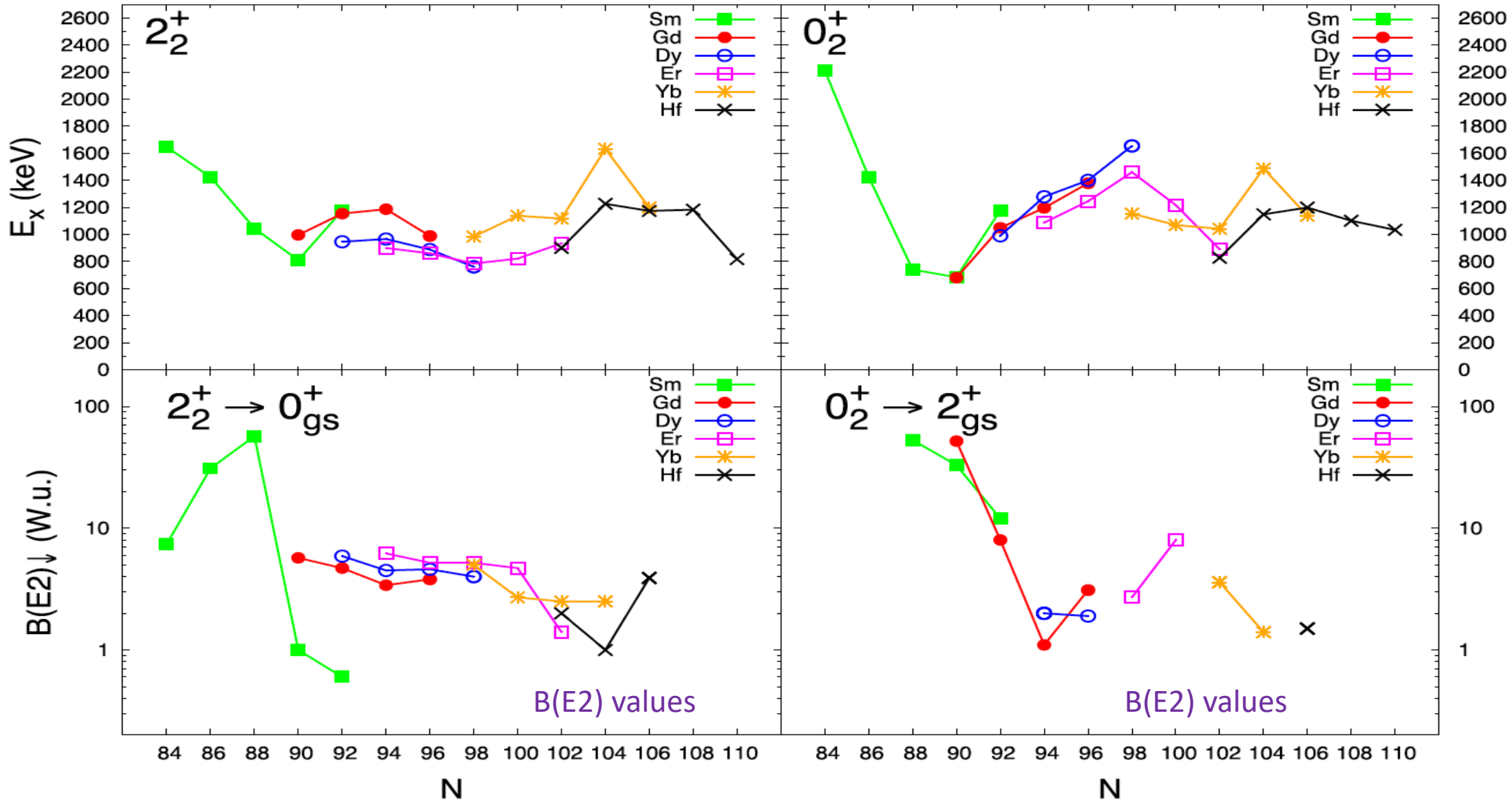
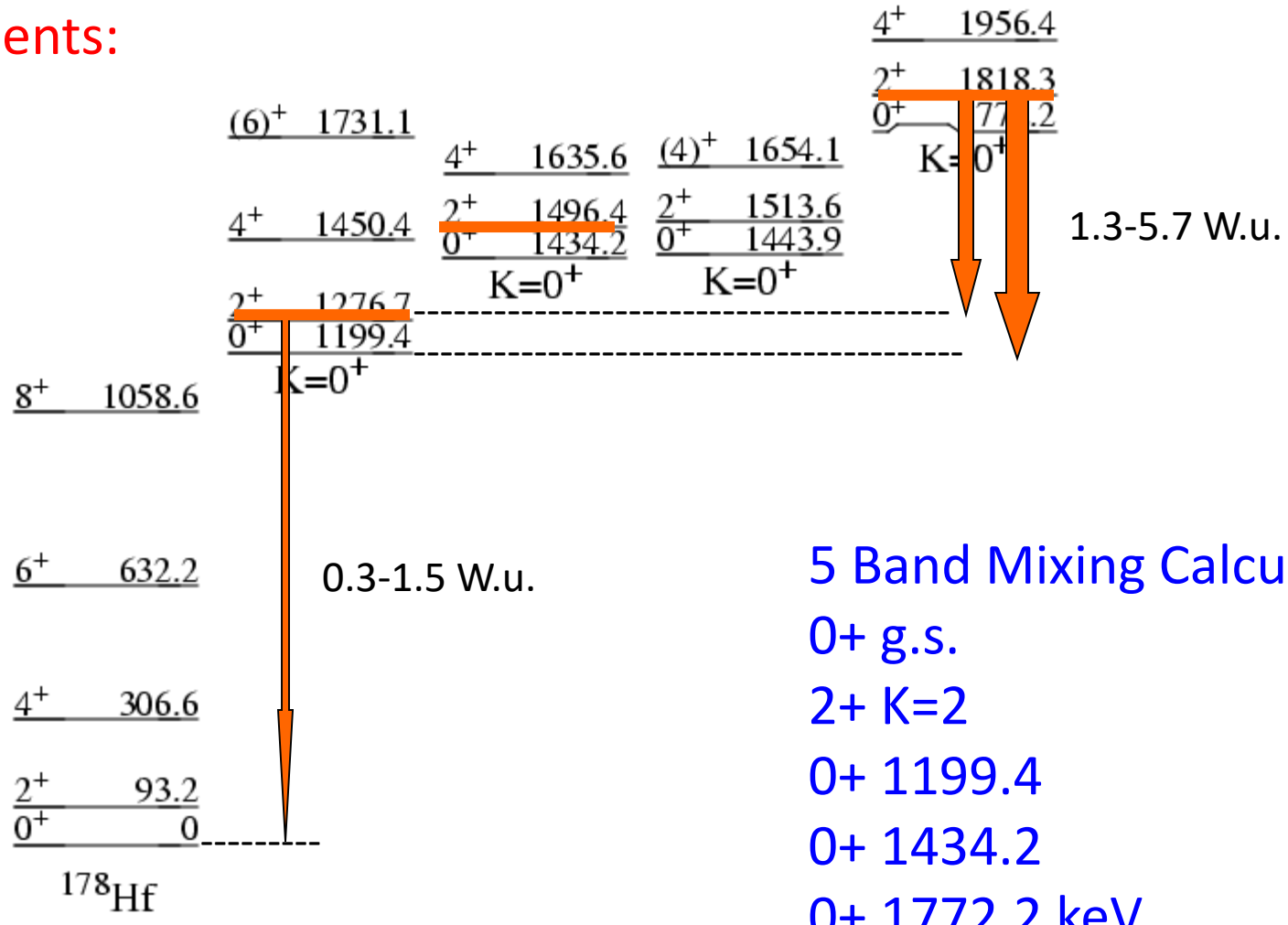


FIG. 1. Systematics of the first excited $K^\pi = 2^+$ "γ" and $K^\pi = 0^+$ bands in several isotopes of Sm, Gd, Dy, Er, Yb, and Hf as a function of neutron number "N" along with the observed $B(E2; 2^+_{K=2^+} \rightarrow 0^+)$ values for the γ bands and the $B(E2; 0^+_2 \rightarrow 2^+_{\text{g.s.}})$ values for the first excited $K^\pi = 0^+$ bands.

GRID Measurements: $E_{1772}/E_{1199} = 1.5$

Lifetime Measurements:



5 Band Mixing Calculation

0+ g.s.

2+ K=2

0+ 1199.4

0+ 1434.2

0+ 1772.2 keV

Aprahamian, Phys. Rev. C65, 031301R (2002)

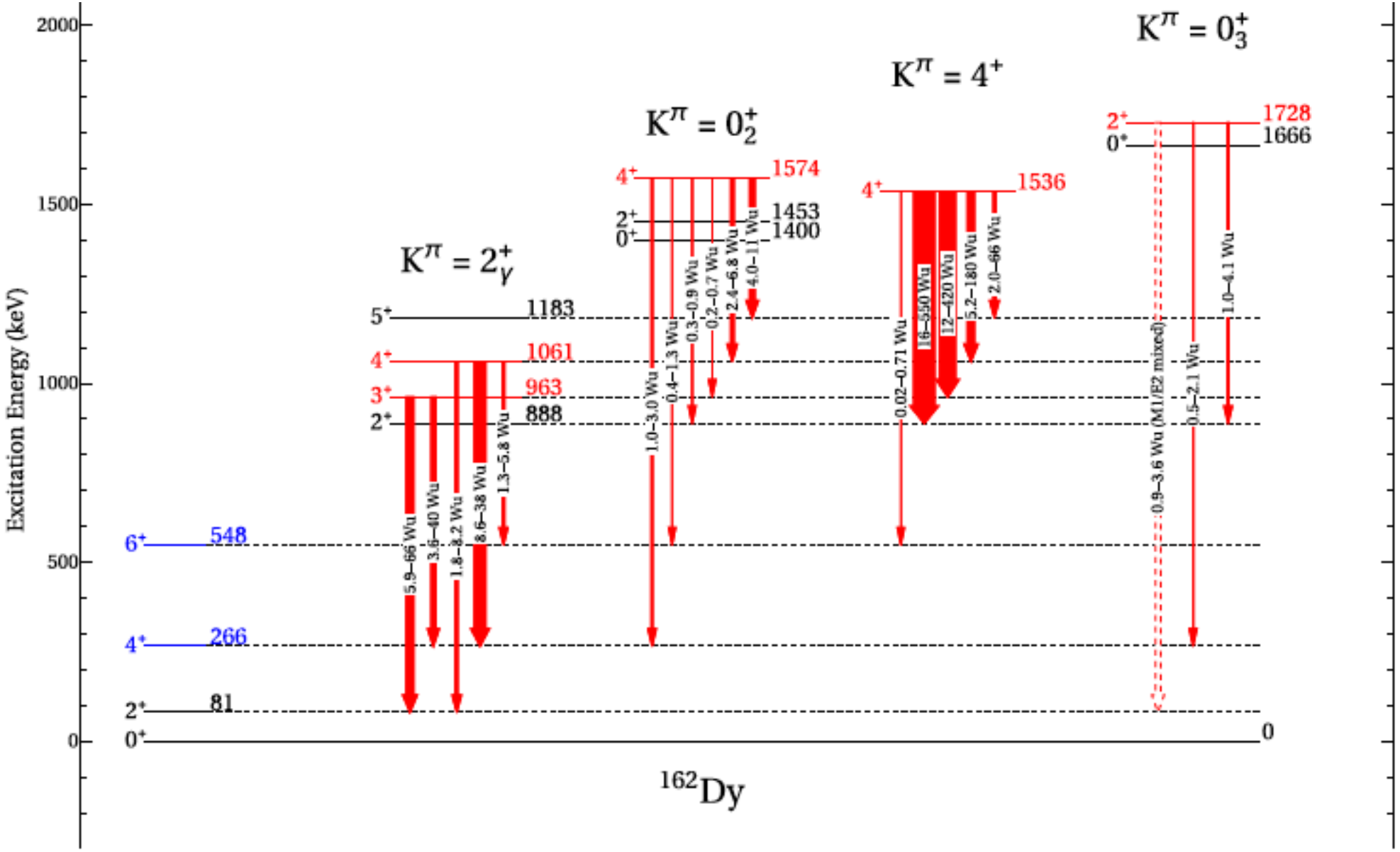
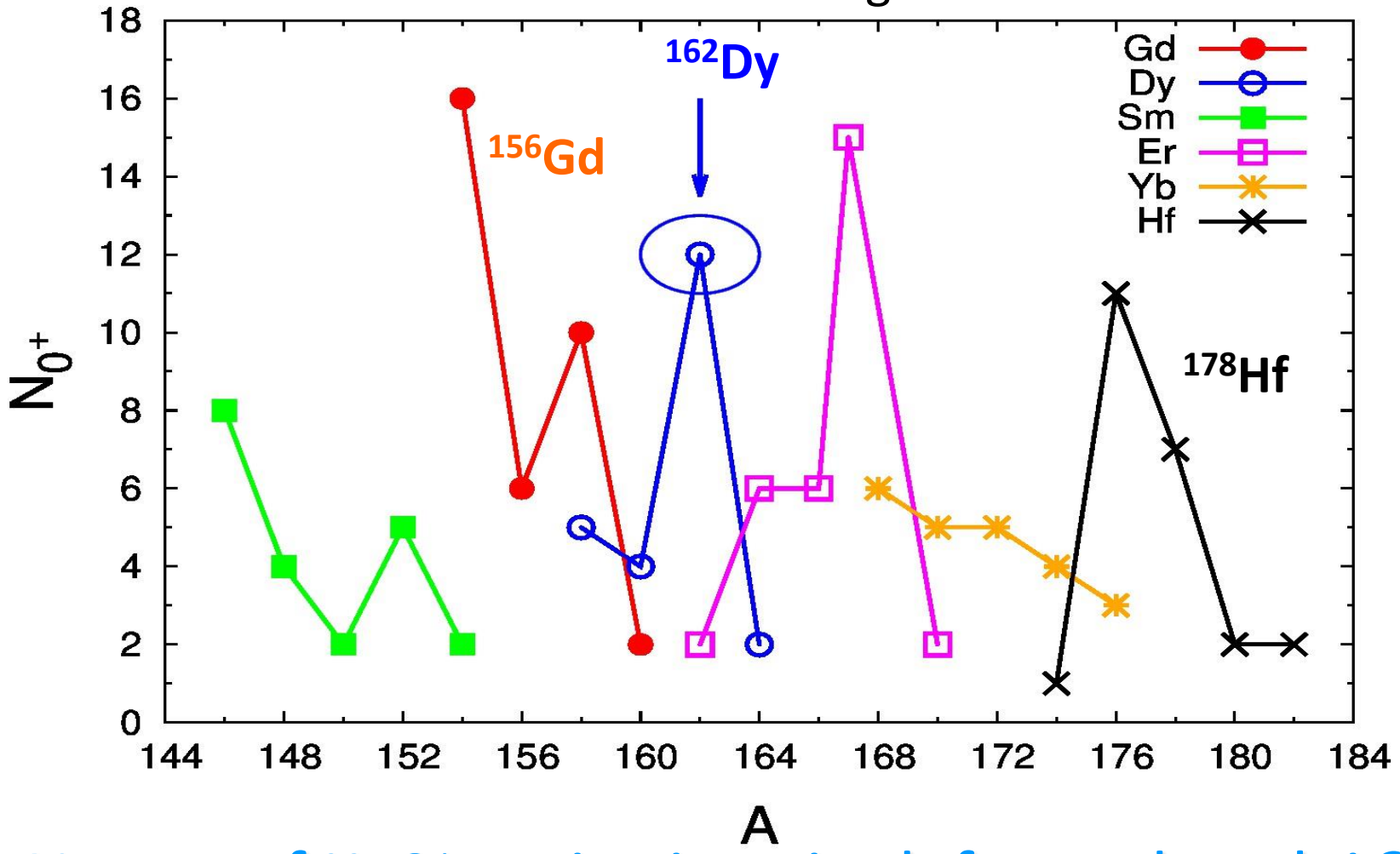


FIG. 3. Partial decay scheme for the positive-parity K^π levels in ^{162}Dy.

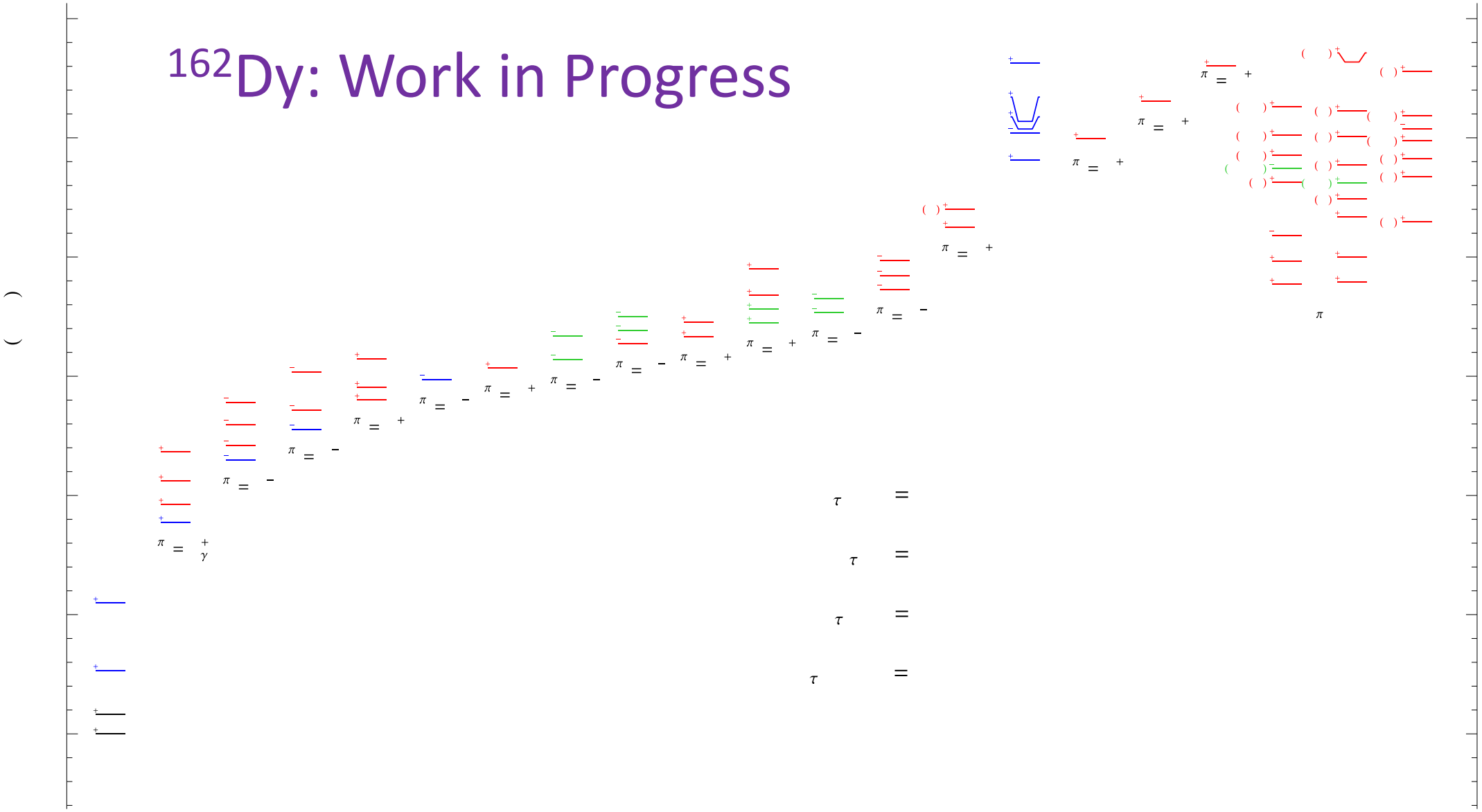
Figure from C. Casarella



Nature of K=0$^+$ excitations in deformed nuclei ?

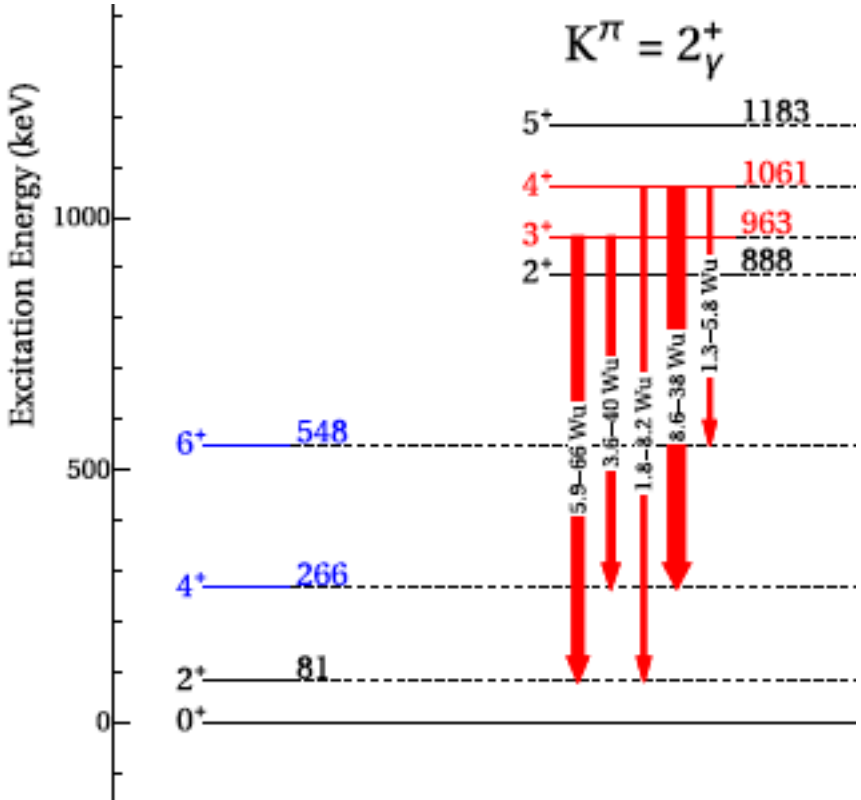
Quasi-particle excitations
Pairing vibrations
Collective excitations

^{162}Dy: Work in Progress



Conversion Electron Spectroscopy

E_{lev} (keV)	E_γ (keV)	K_i^π, J_i^π	K_f^π, J_f^π	τ_{GRID} (ps)	πl	I_γ	$B(E2)$ (W.u.)	$B(E1)$ (mW.u.)	$B(M1)$ (μ_N^2)	Alaga
1060.986	980.335	$2^+, 4^+_\gamma$	$2^+, 0^+_{g.s.}$	0.708–3.17	93% $E2$	67.9(25)	1.8–8.2			1.00
	795.327		$4^+, 0^+_{g.s.}$		90% $E2$	115.0(54)	8.6–38			2.92
	512.464		$6^+, 0^+_{g.s.}$		96.9% $E2$	1.82(7)	1.3–5.8			0.26
	172.835		$2^+, 2^+_\gamma$		$E2$	0.82(3)	116–518			1.00
	98.054		$2^+, 3^+_\gamma$		$M1$	0.09(1)			0.005–0.023	2.22



$$T_{fi}(\lambda L) = \frac{8\pi(L+1)}{\hbar L\left((2L+1)!!\right)^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(\lambda L : J_i \rightarrow J_f)$$

Can have mixed multipolarities for the transitions

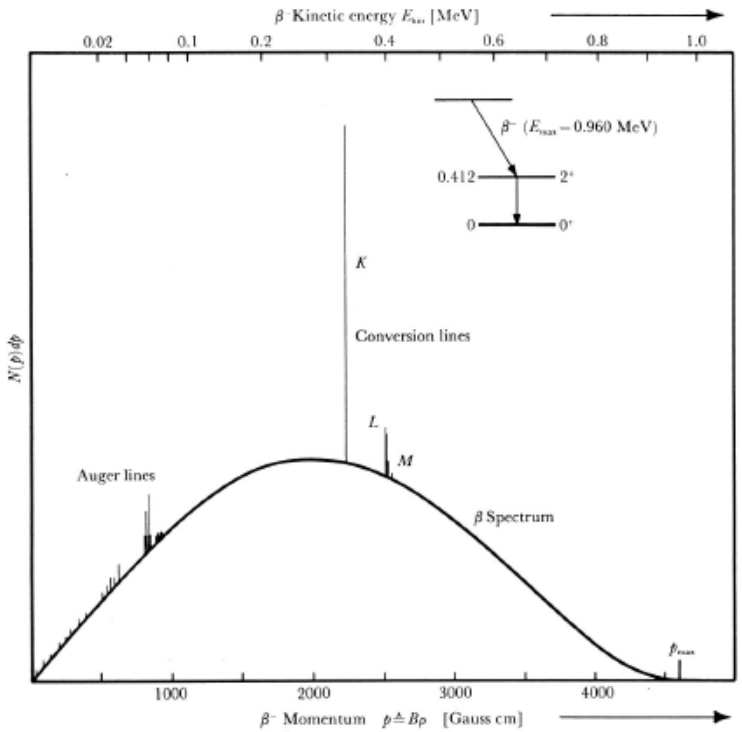
- No gamma ray transitions of type 0➔0.

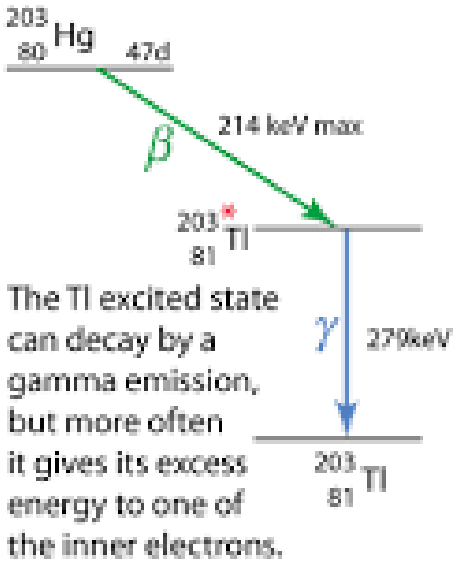
Possible by IC

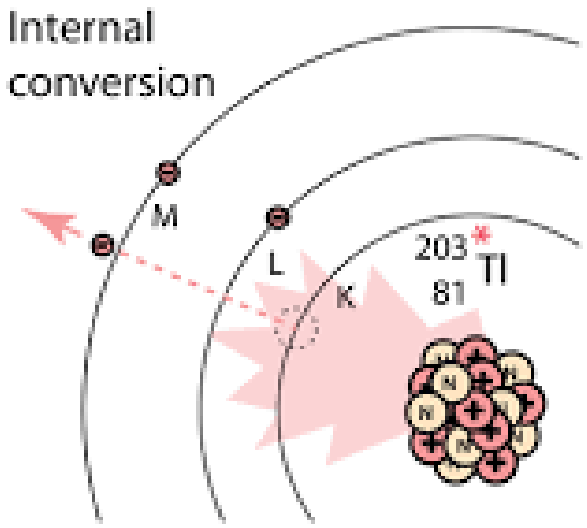
- Can get both electric and magnetic matrix elements contributing to a given decay probability
- Lowest multipolarity is most favored
- Electric matrix elements are generally greater than magnetic matrix elements of the same multipolarity.
- E2 and M1 transition rates are similar

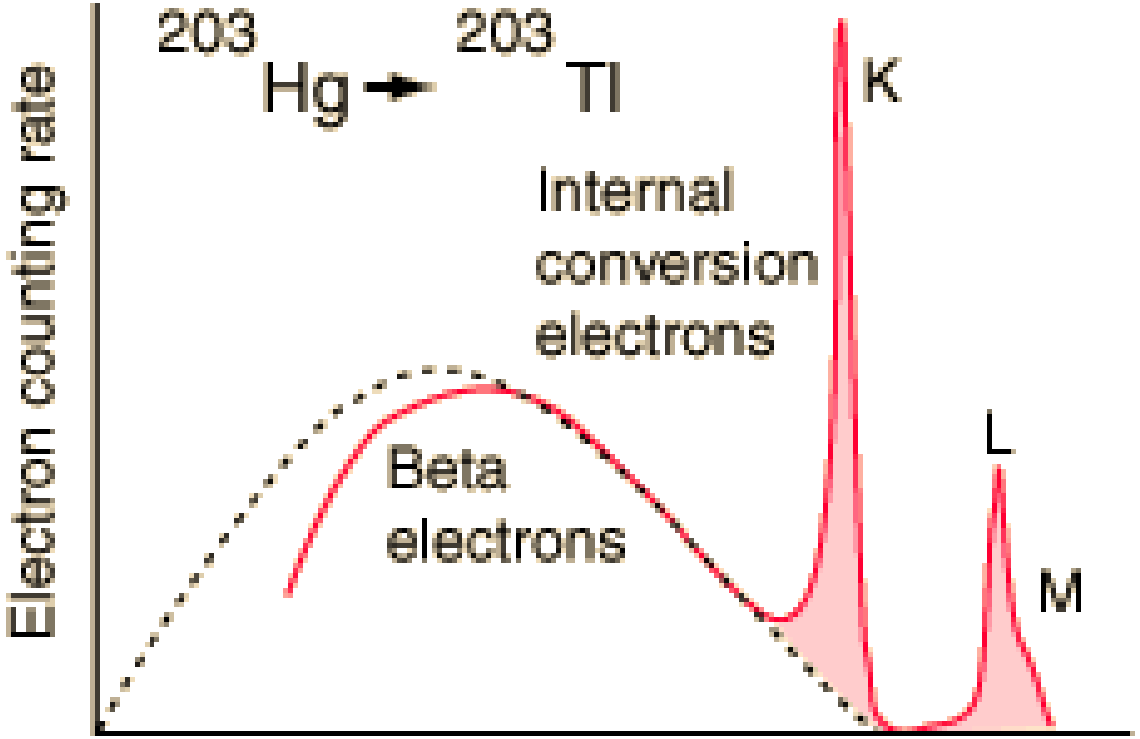
Internal conversion

- $E_{IC}=E_{transition}-E_{electron\ binding\ energy}$









$$\alpha_K = \lambda_K / \lambda_{total}$$

$$\lambda_{total} = \lambda_{gamma} + \lambda_K + \lambda_L + \lambda_M$$

$0^+ \rightarrow 0^+$ transitions…no gamma is emitted by you can see it by Internal conversion

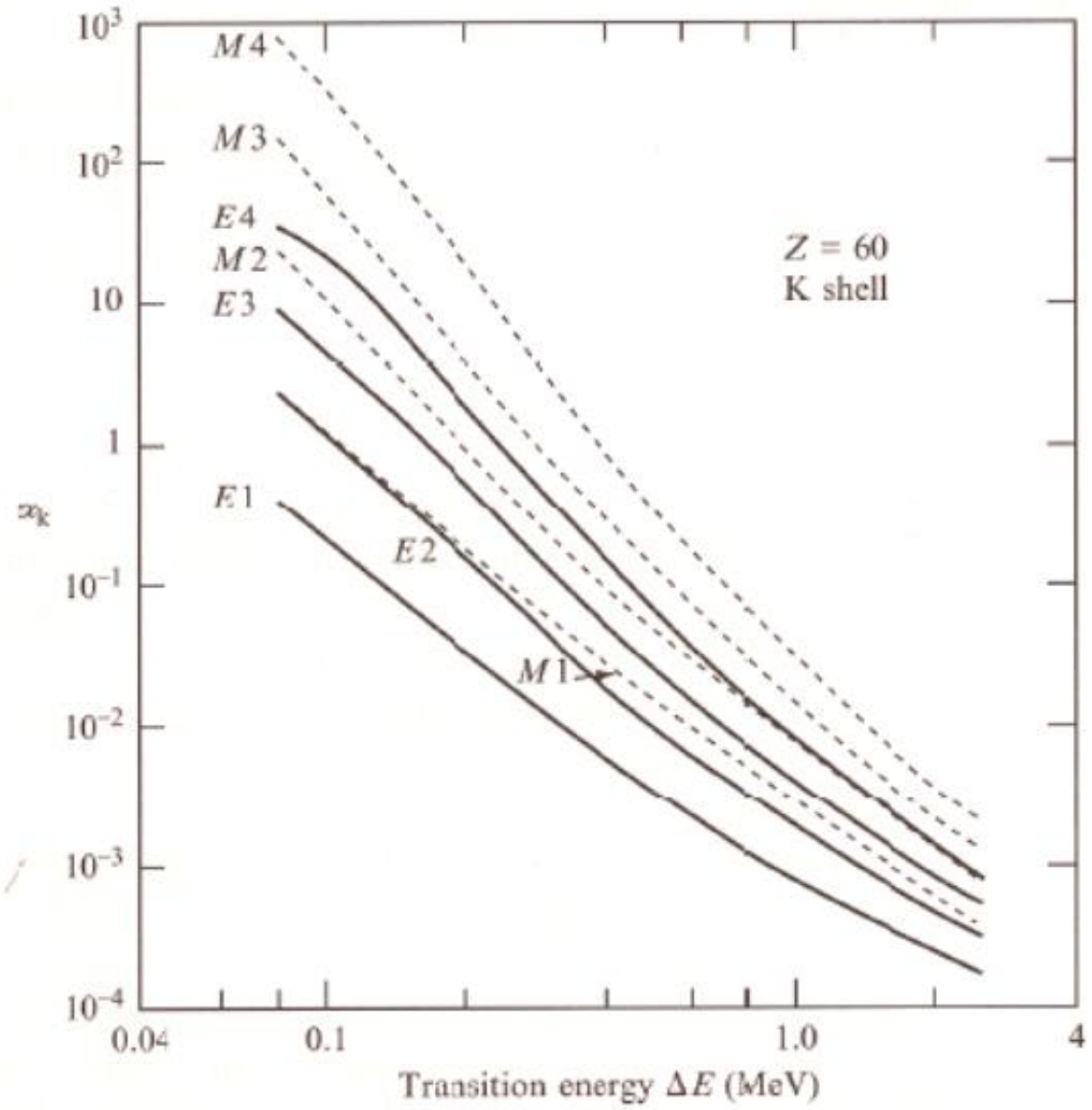


Figure 3.5 The K-electron internal conversion coefficient α_K for various $E\lambda$ and $M\lambda$ transitions for $Z = 60$. From Lederer and Shirley (1978).

IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 43 (2016) 024013 (25pp)
doi:10.1088/0954-3899/43/2/024013

Conversion electron spectroscopy and its role in identifying shape coexisting structures in nuclei via *E*0 transitions

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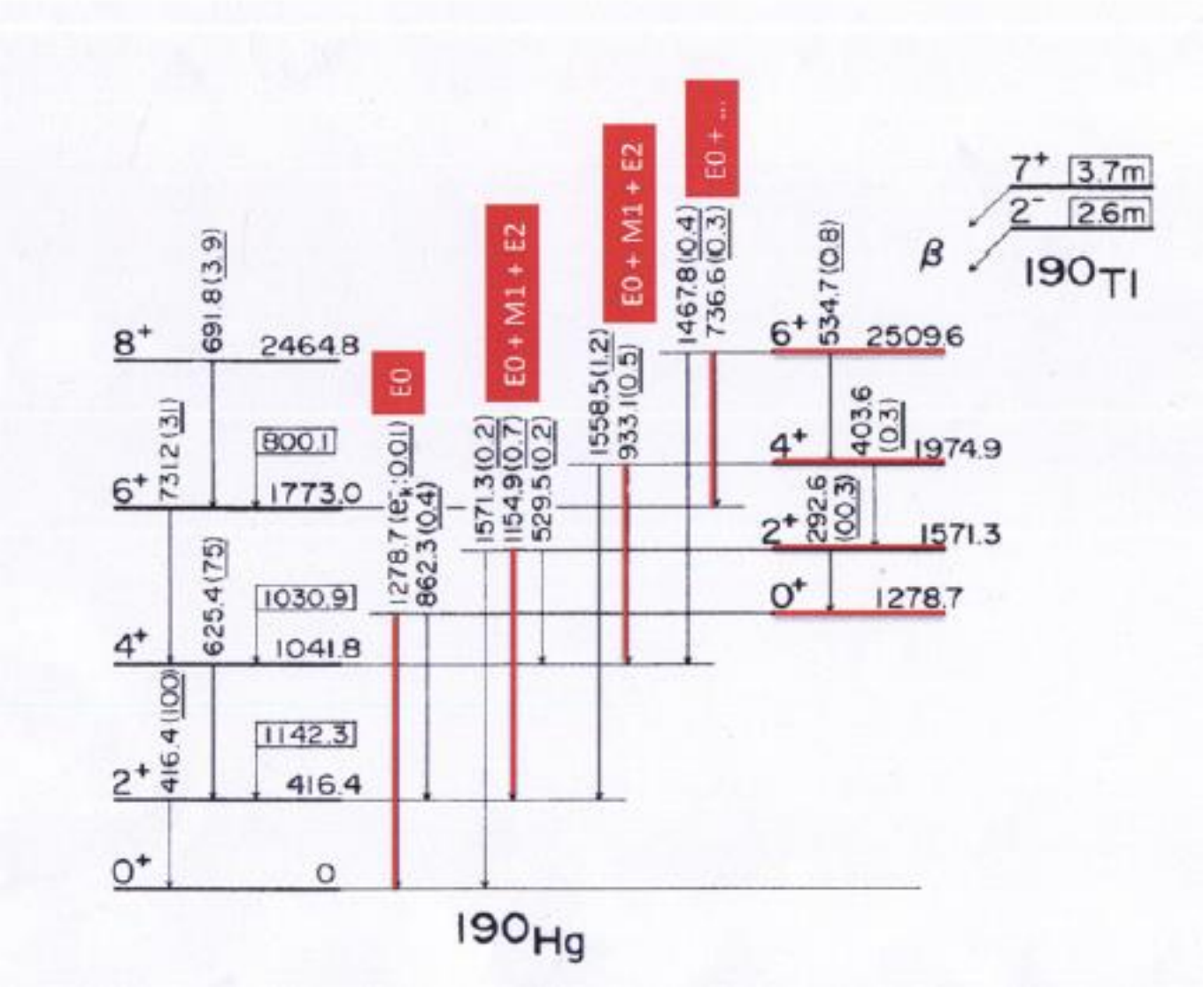


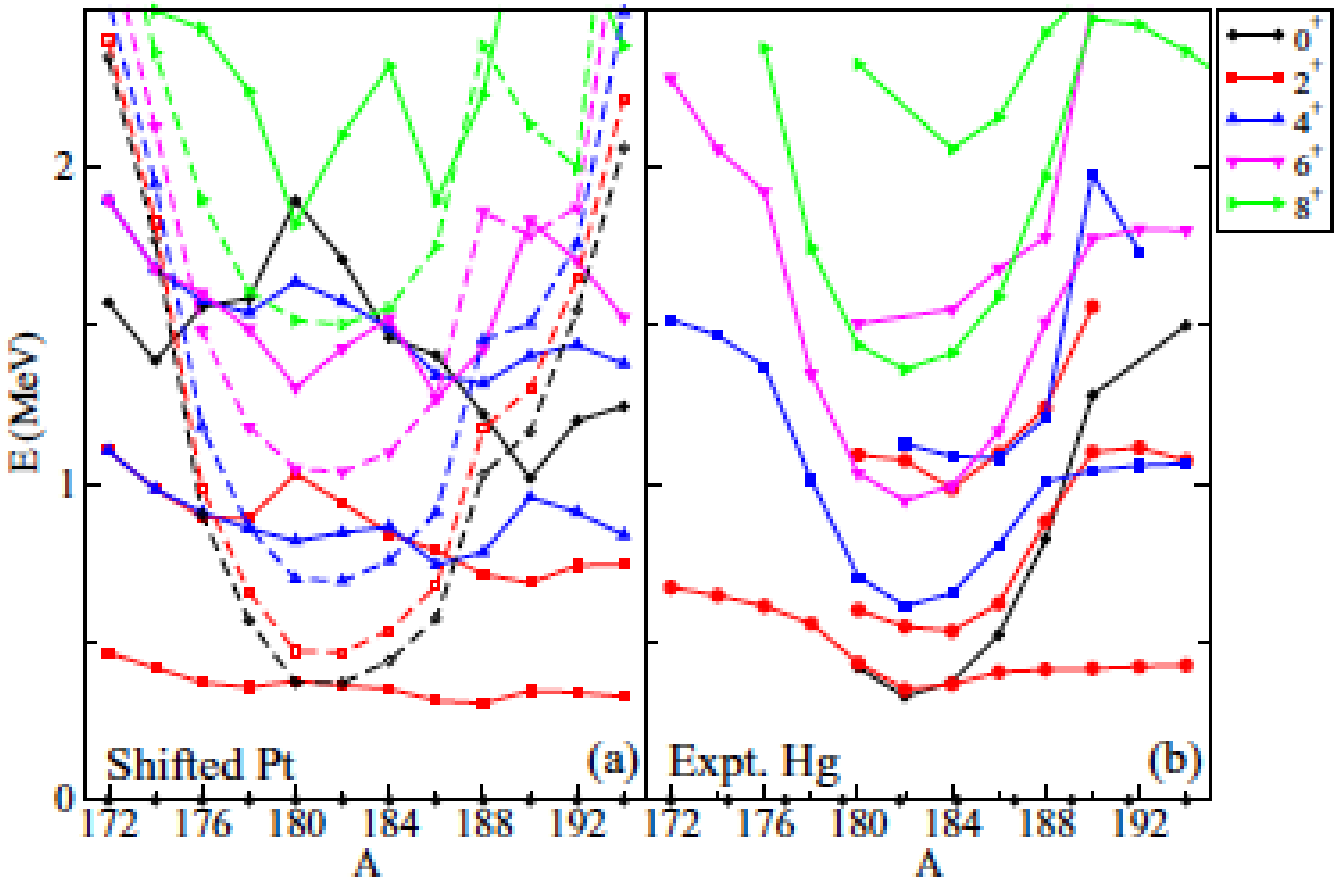
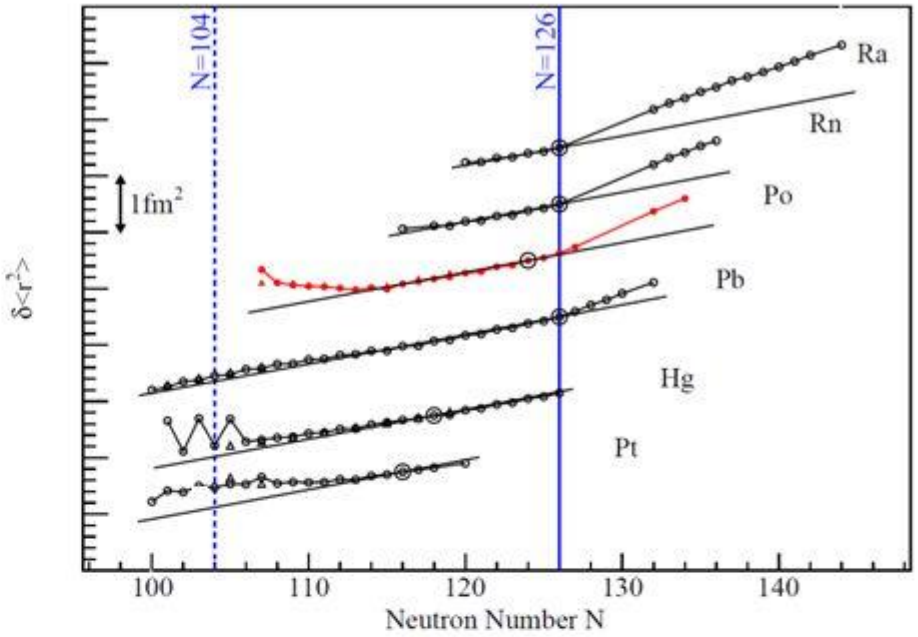


FIG. 2. (Color online) Comparison between the "shifted" theoretical energy spectra for Pt (a) (see text and Fig. 12 in [88]) and the experimental Hg low-lying energy spectra (b).

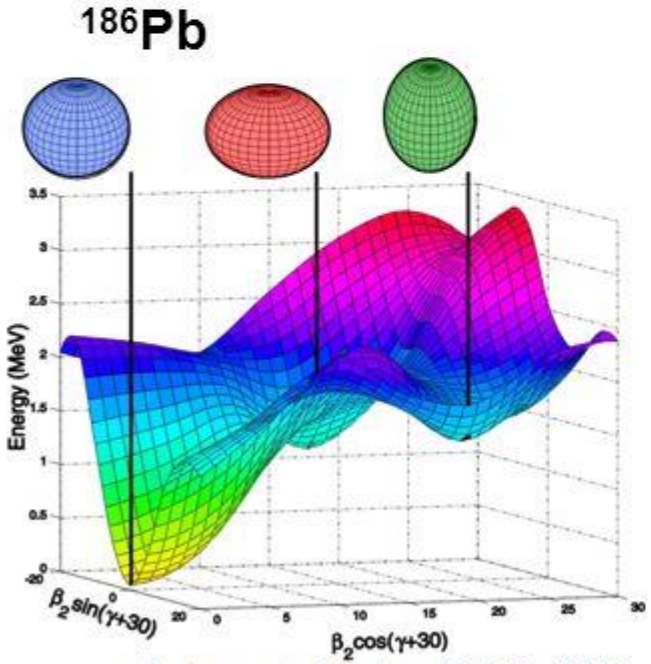
Shape coexistence

- Different types of deformation at low excitation energy
- Interplay between two opposing tendencies
  - Stabilizing effect of closed shells
  - Residual proton-neutron interaction

Heyde and Wood, Review of Modern Physics (2011)



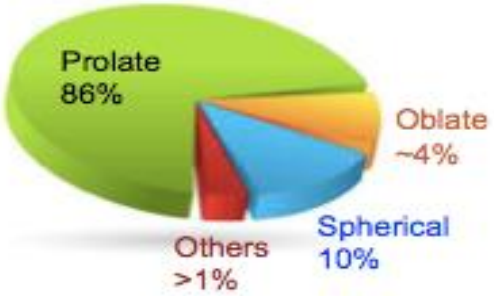
T.E. Cocolios et al, Phys. Rev. Lett. (2011)

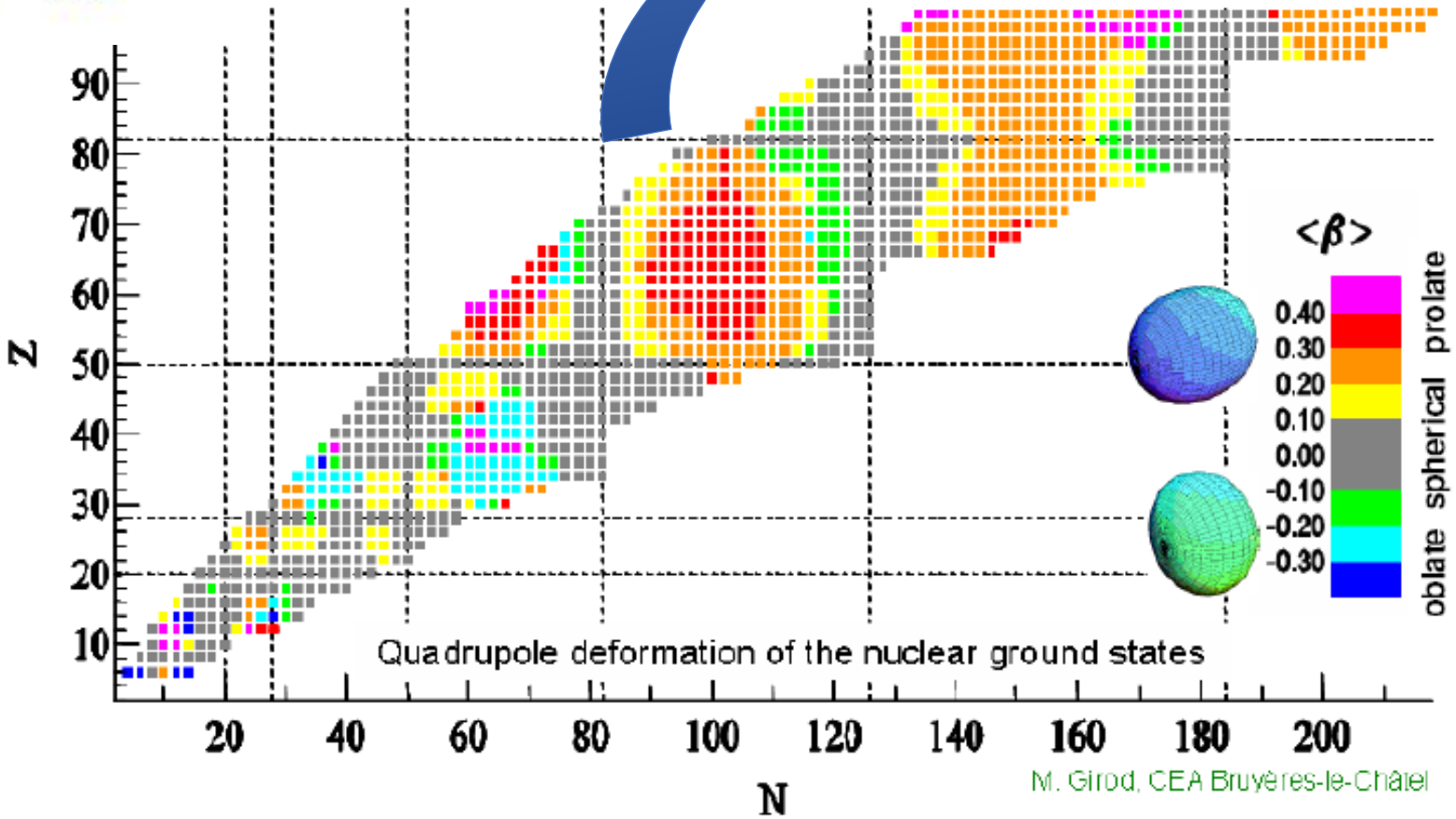


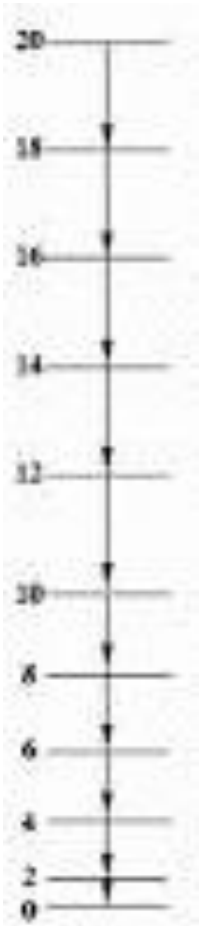
Andreyev et al Nature 405:430 (2000)

- Evidence across the light lead region
- Lack of experimental information
  - Nature of deformation
  - Degree of mixing

- Also appears in other regions of the nuclear chart...
- Campaign to characterise properties of shape coexistence using complementary experimental probes







What is the role of coexistence in the rare-earth region of nuclei?

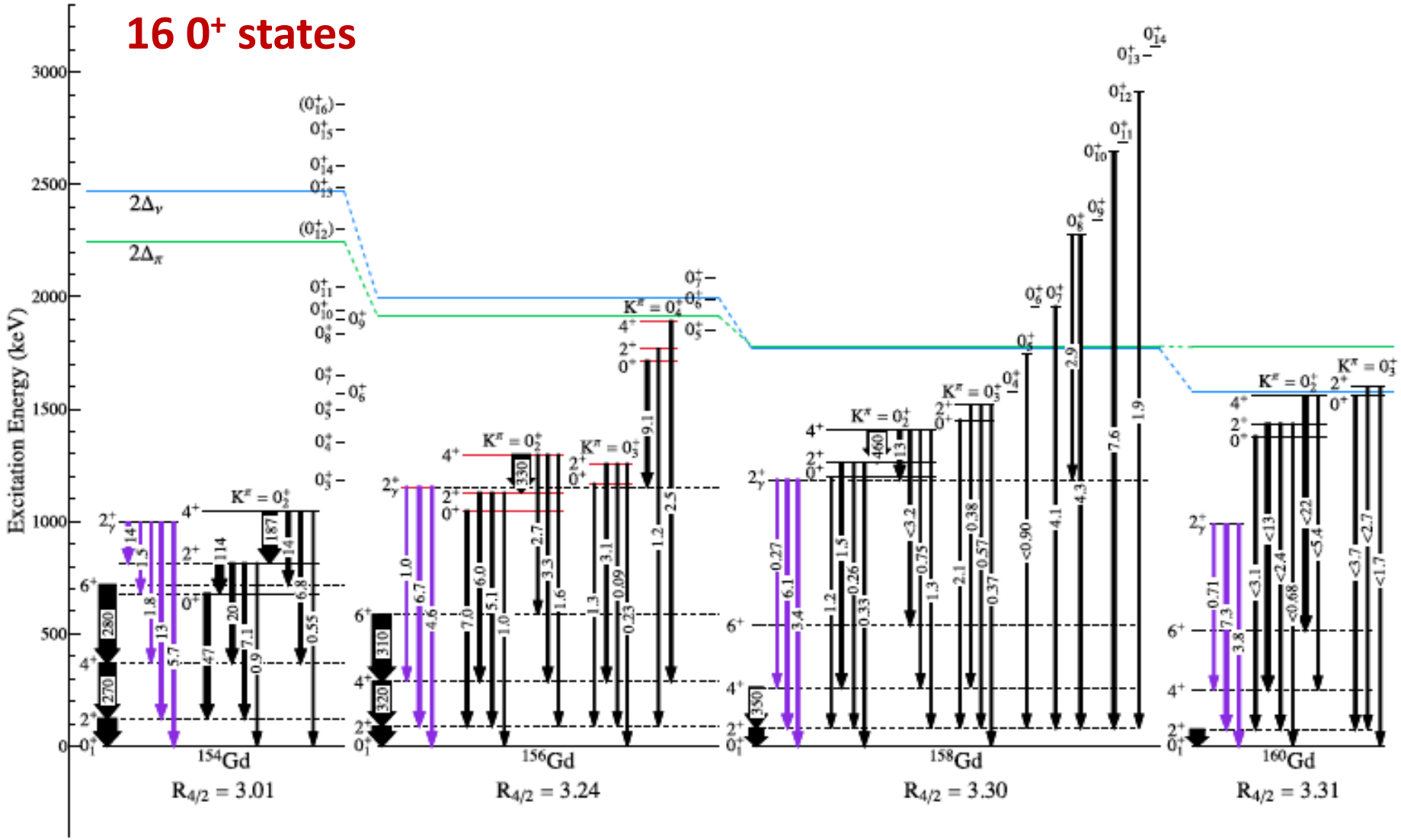
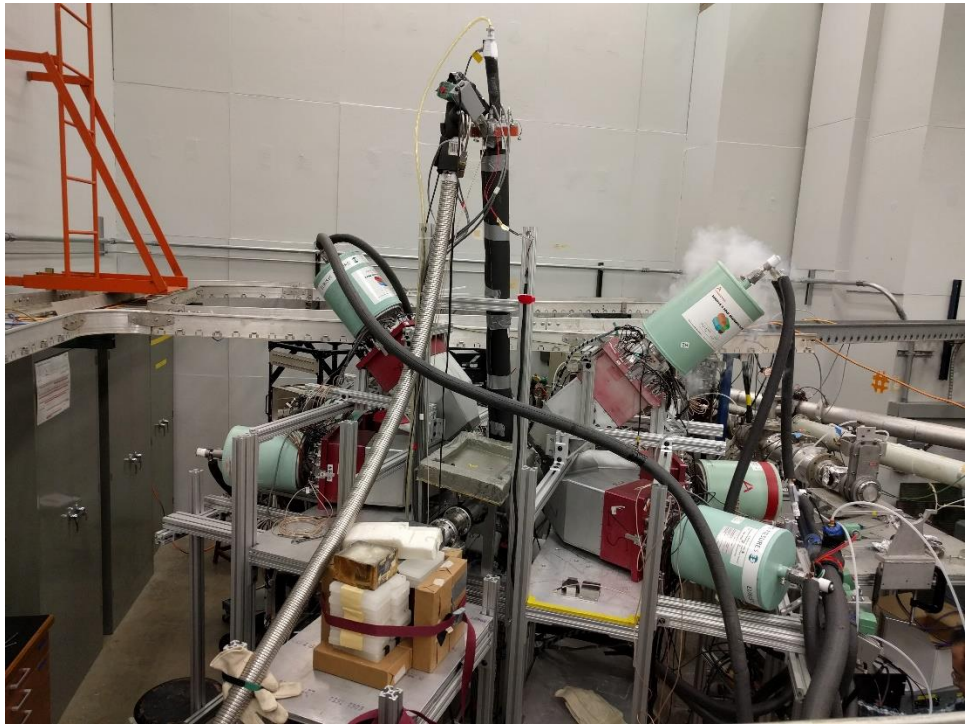


FIG. 6. Partial level schemes for $^{154-160}$Gd showing the lowest $K^{\pi} = 2^{+}$ bands with the known 0^{+} states, transition probabilities, and the two-proton ($\Delta\pi$) and two-neutron ($\Delta\nu$) pairing gaps shown as horizontal lines. The width of the transition lines depopulating the levels of interest are in proportion to the transition probability in W.u.

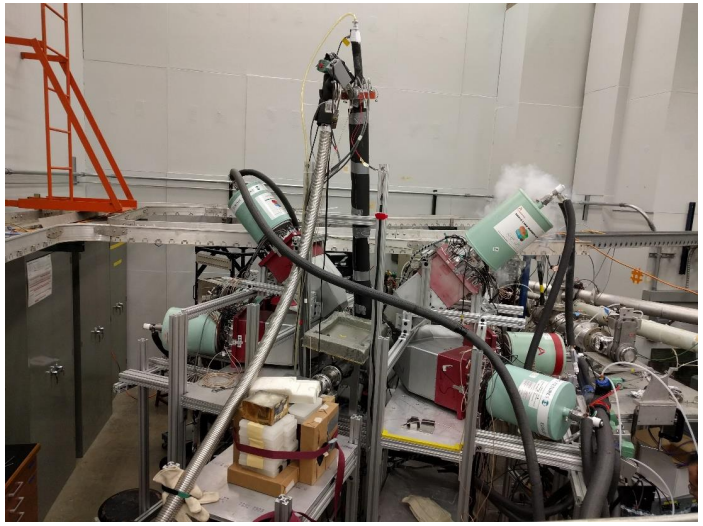
Clovershare was paired with ICEBall (Internal Conversion Electron Ball)

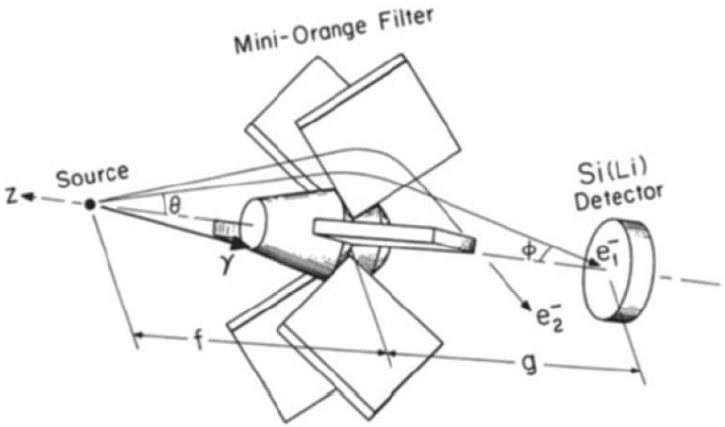
- ICEBall consists of 6 Mini-Orange Spectrometers for detecting conversion electrons
- ^{152}Sm(α,2n) reaction was used
- ^{154}Gd has 16 known 0^+ states. 10 of these were only found in 2006 by Meyer et al.
- The nature of excited 0^+ states is not well understood, E0 transitions are critical for understanding.



U of Wisconsin LaCrosse + ND Nuclear Science Laboratory : NSF MRI 2019

fIreBall consists of 6 Mini-Orange Spectrometers for detecting conversion electrons



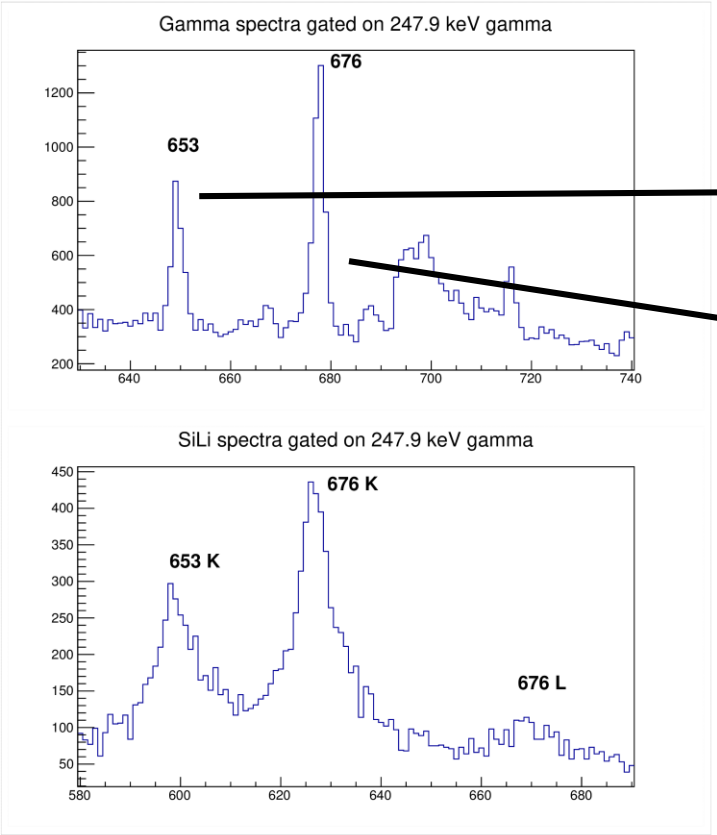


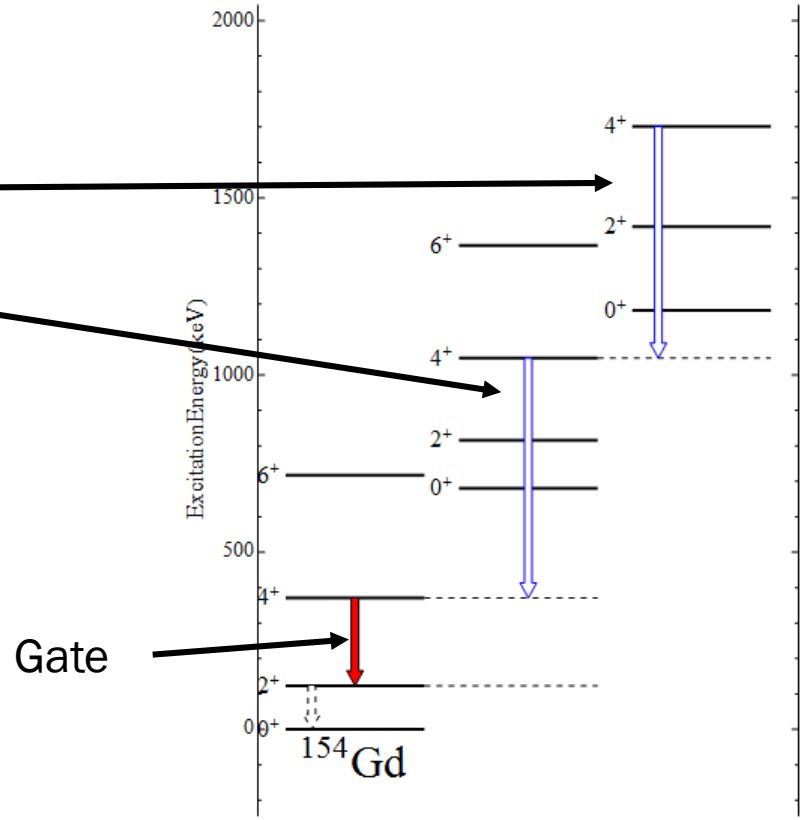
Conversion Electrons in ^{154}Gd and ^{156}Gd

Last piece of the puzzle: E0 Transitions in coincidence with γ-rays

^{154}Gd: Search for E0 Transitions

Proof of populating the first two excited 0^+ bands using 247.9 keV gate

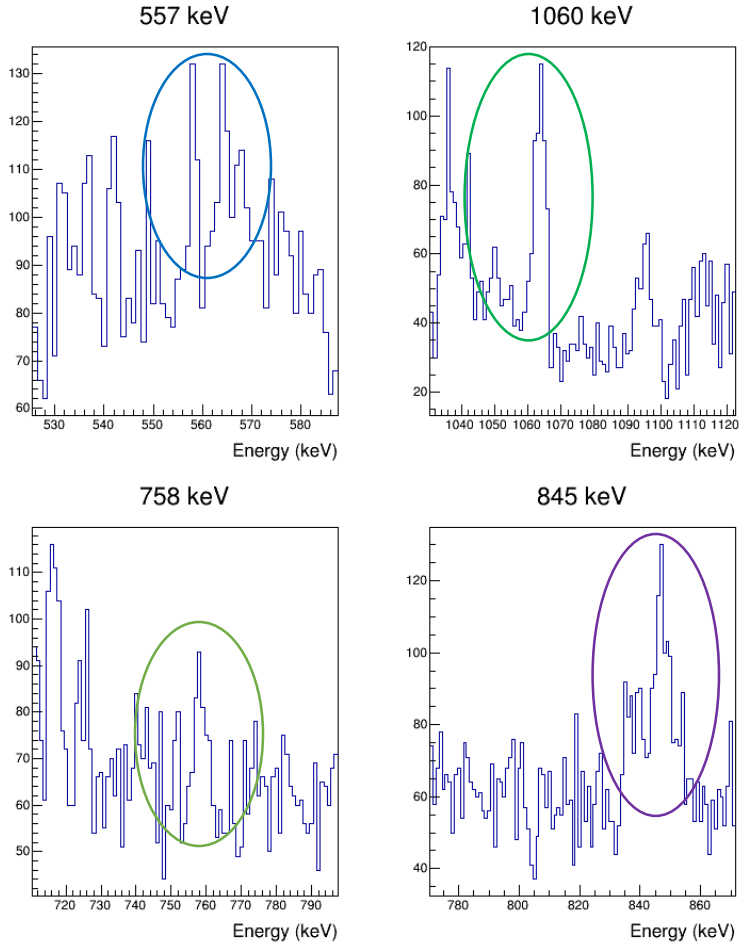




Plots show γ-spectrum with corresponding SiLi spectrum beneath, shifted for the K-electrons to align with the corresponding γ-lines

Search for E0 Transitions in ^{154}Gd

Proof of populating the excited 0^+ bands using 123.1 keV gate



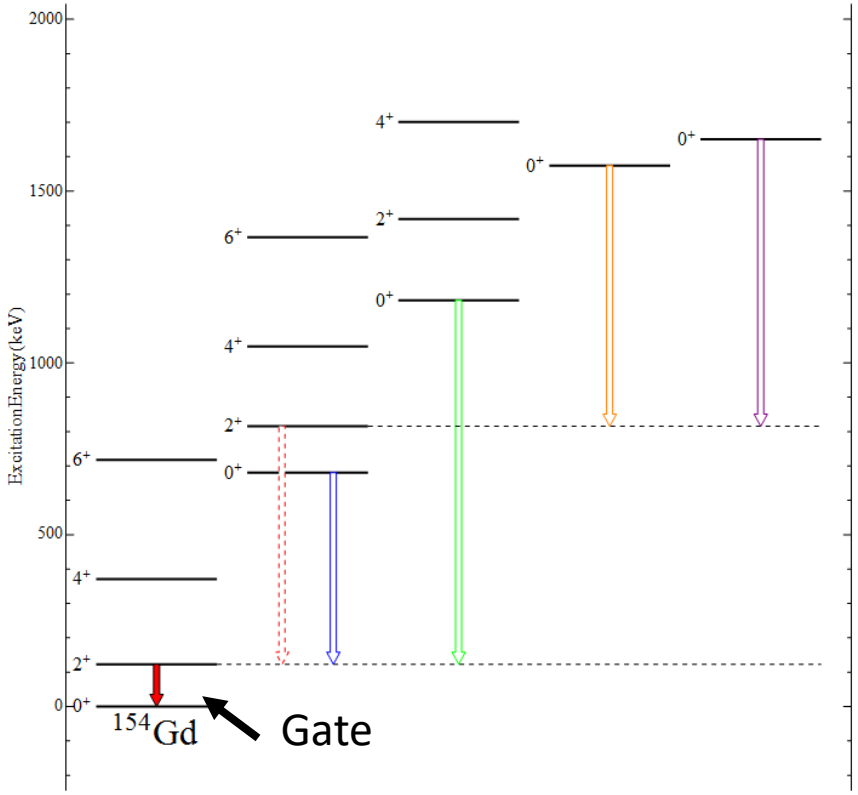


TABLE II: q^2 ($E0/E2$) for $0^+ \rightarrow 0^+$ Transitions

Ei (keV)	Transition	*E*0 (keV)	Transition	*E*2 (keV)	q^2 ($E0/E2$) *K*
1182.091	$0^+ \rightarrow 0^+$ 3 2	501.427	$0^+ \rightarrow 2^+$ 3 *gs*	1059.033	0.0023 (5)
1573.9	$0^+ \rightarrow 0^+$ 6 3	391.85	$0^+ \rightarrow 2^+$ 6 *gs*	1451.7	0.0521 (119)
1573.9	$0^+ \rightarrow 0^+$ 6 2	893.9	$0^+ \rightarrow 2^+$ 6 *gs*	1451.7	0.0168 (77)
1650.3	$0^+ \rightarrow 0^+$ 7 3	468.3	$0^+ \rightarrow 2^+$ 7 *gs*	1527.1	0.2082 (345)
1650.3	$0^+ \rightarrow 0^+$ 7 2	970.3	$0^+ \rightarrow 2^+$ 7 *gs*	1527.1	0.0402 (192)

S. Strauss, to be published

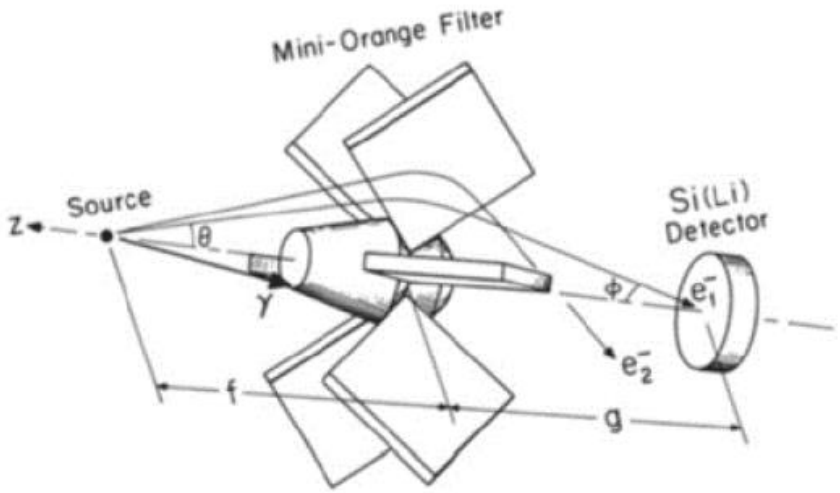


Figure 2: Graphic detailing the mini-orange spectrometer used in ICEBall. The tungsten absorber blocks all direct paths from the source/reaction to the detector while the magnet wings create a field that bends electrons towards the detector.

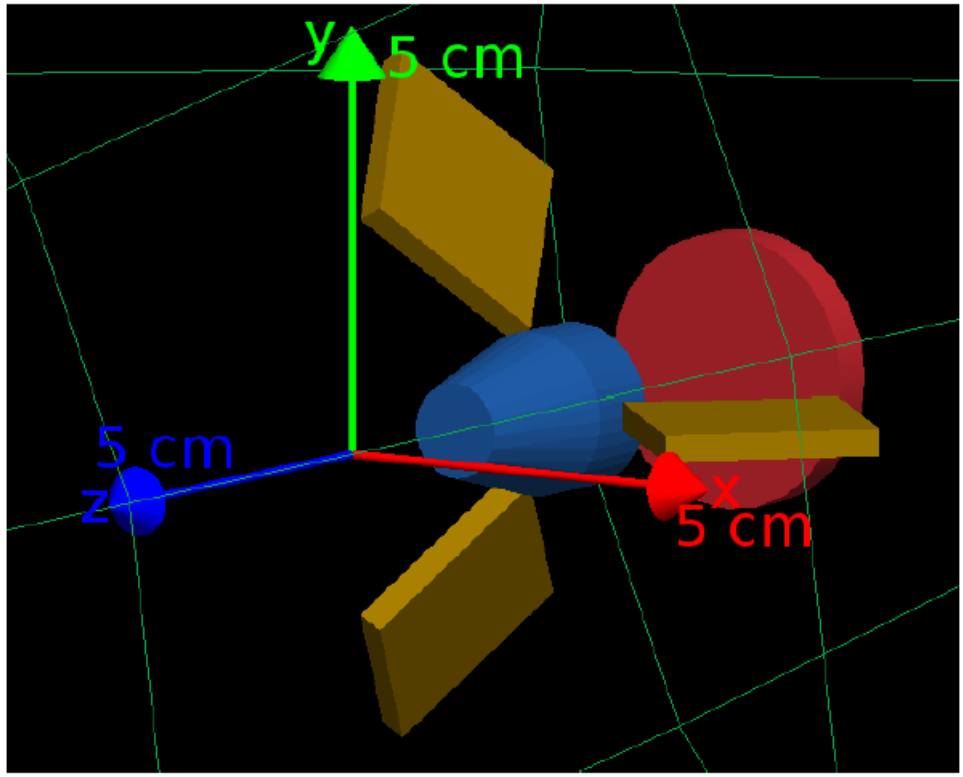


Figure 4: Geant4 simulation setup consisting of one Si(Li) detector with a magnet filter.

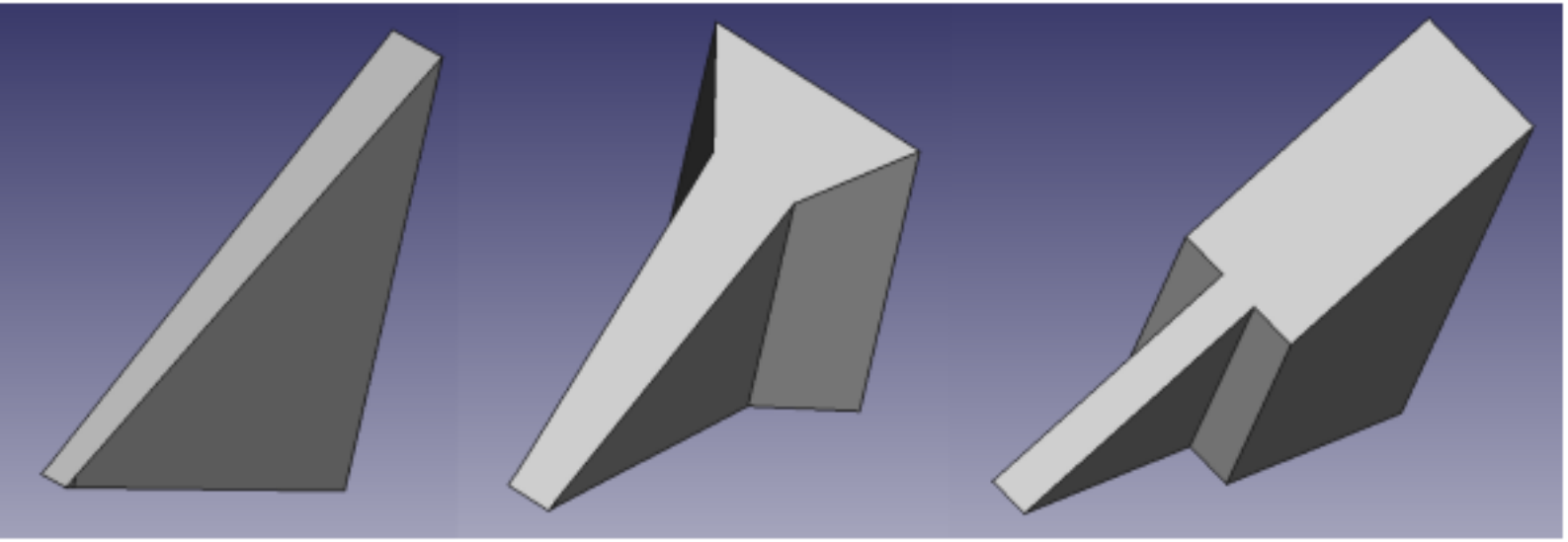


Figure 5: From left to right: Shape 1, Shape 2, and Shape 3

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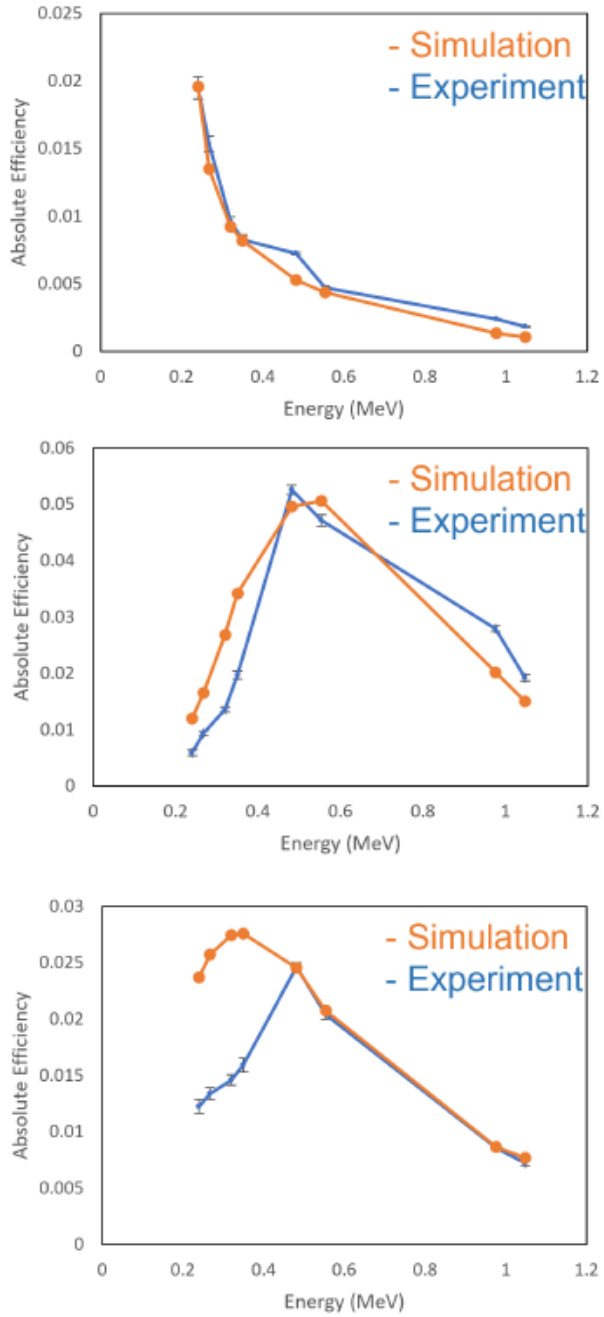
Simulations to improve efficiency



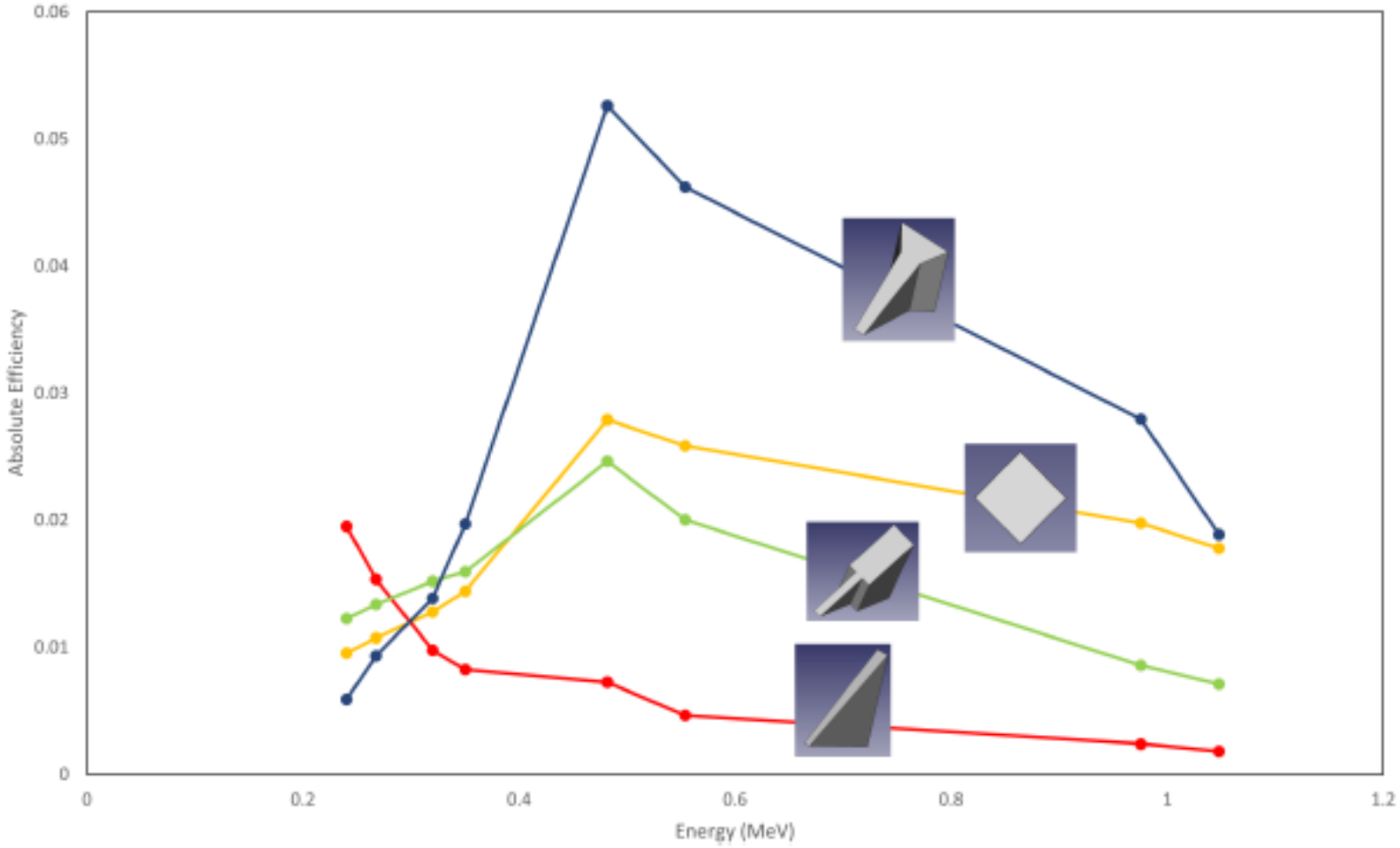


Figure 8: Efficiency curves obtained from experiment for each shape, including the original $SmCo_5$ diamond shape.

Nuclear Structure Experiment II

Two methods to get nuclear structure data!

- Lifetime Measurements
- Conversion Electron Spectroscopy

Are the 0^+ excitations seen in the rare earth region Oscillations built on the ground state or are they Coexisting shapes? Answer soon.....

Thank you!