# Investigation of Low Spin States of $^{154}$Gd Using (p,p′) Reactions

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WNPPC 2017

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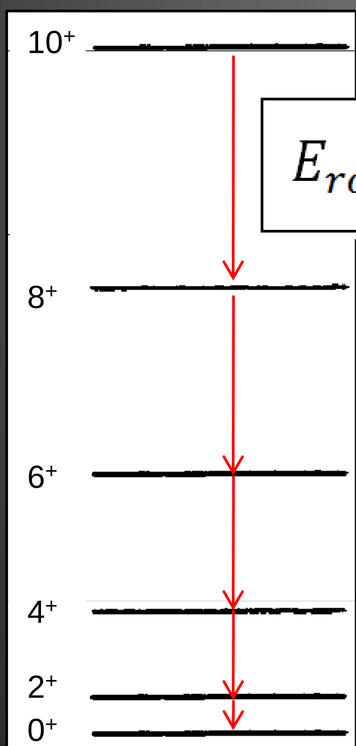
# Collective Model

Rather than focusing on the motion of the valence nucleons, for heavy nuclei located away from closed shells, it is simpler to consider the collective nuclear motion. Rotations and vibrations are the two major types of nuclear motion for this model.

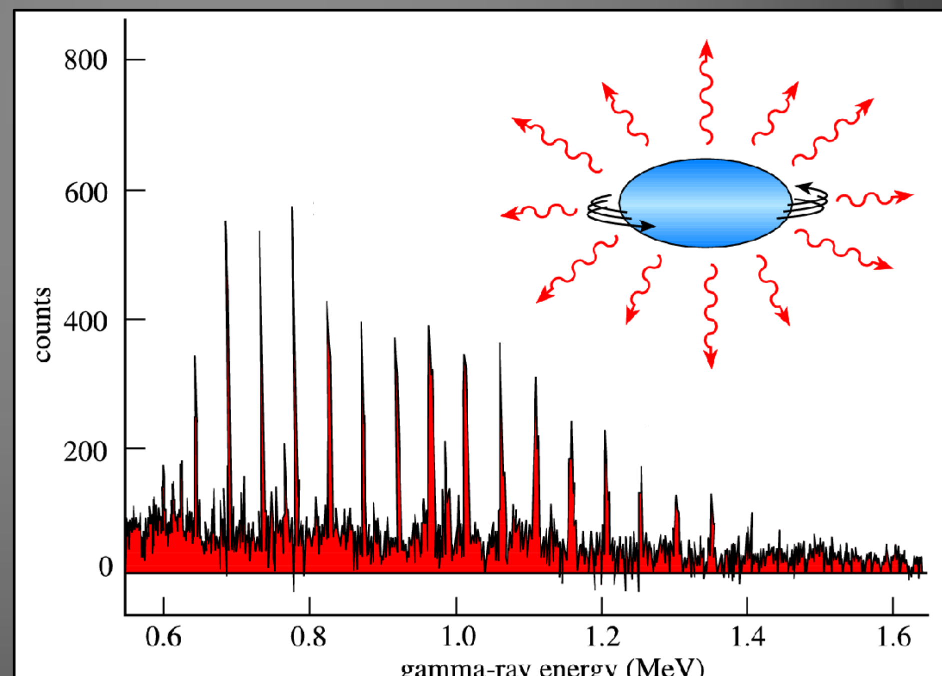
## Rotations

The nuclear excited states generated from a rotating deformed nucleus form a rotational band. Rotational bands exhibit constant difference of γ-ray energies for the intraband transitions.




$$E_{rot} = \frac{J(J+1)\hbar^2}{2\Theta}$$

Example of energy spacing for a rotational band




γ-rays from superdeformed band in $^{152}$Dy.

Bentley *et al*. Gamma ray spectroscopy of super deformed states in the nucleus $^{152}$Dy. (1991)

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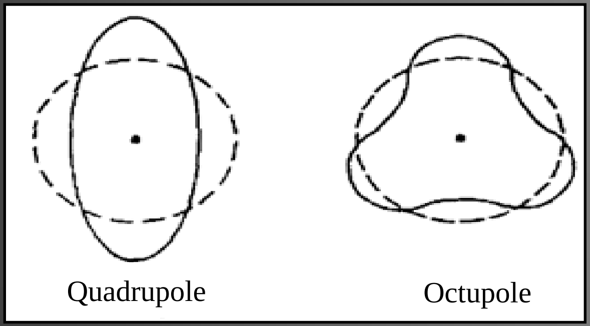
## Vibrations

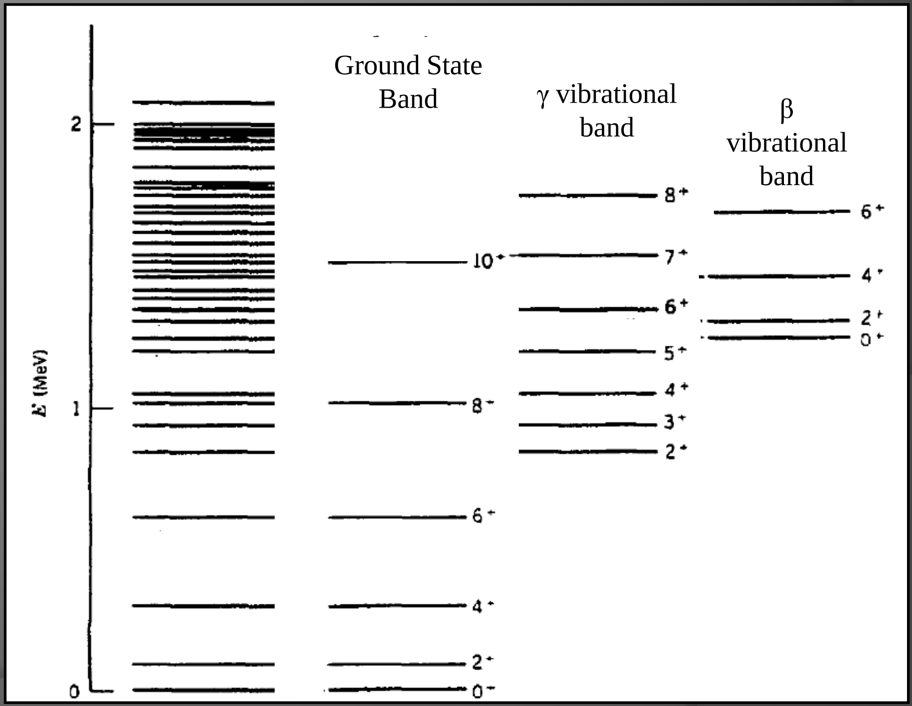
A quantum of vibrational energy is known as a phonon.  Phonons can carry angular momentum and couple together to form excited states.




Rotational bands built on vibrational states in deformed nuclei:

γ vibrational bands: cylindrical symmetry violated.

β vibrational bands: cylindrical symmetry preserved.



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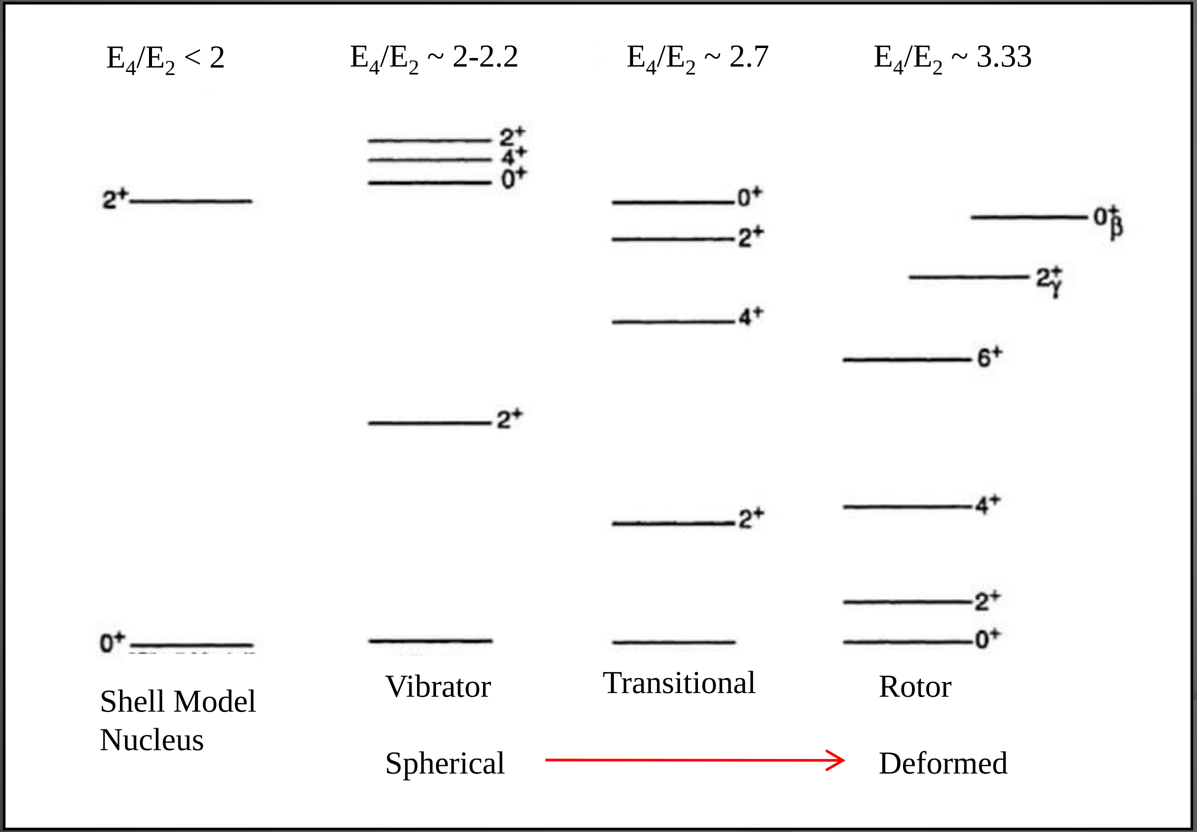


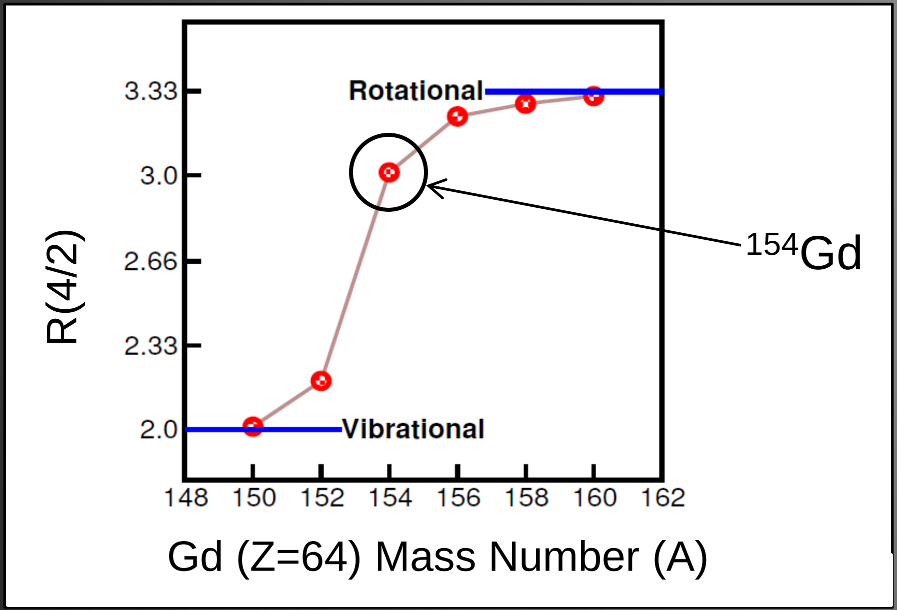

Simplified picture of nuclear band structures

Kenneth S. Krane. Introductory Nuclear Physics. John Wiley and Sons, 1988.

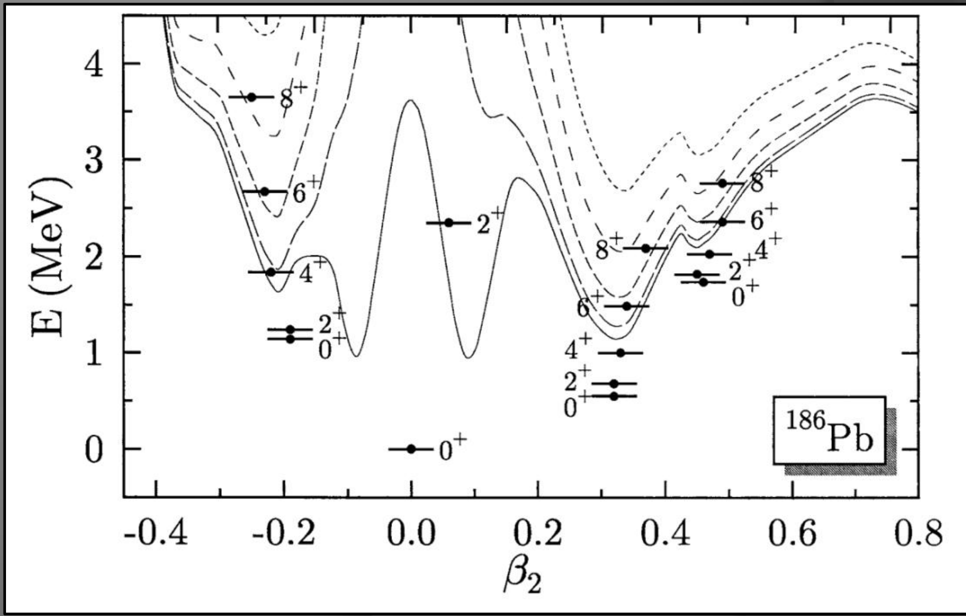
# Motivation

Evidence suggests that several nuclei with N=90, such as $^{154}$Gd and $^{152}$Sm are at a center of a region of rapid shape change from vibrational to rotational character.

One explanation is having coexisting shapes present, where band structures can be associated with different deformations.




T. Ross. *A Study of Gadolinium Isotopes Around N = 90 Utilizing Particle Gamma Coincidences.* (2012).



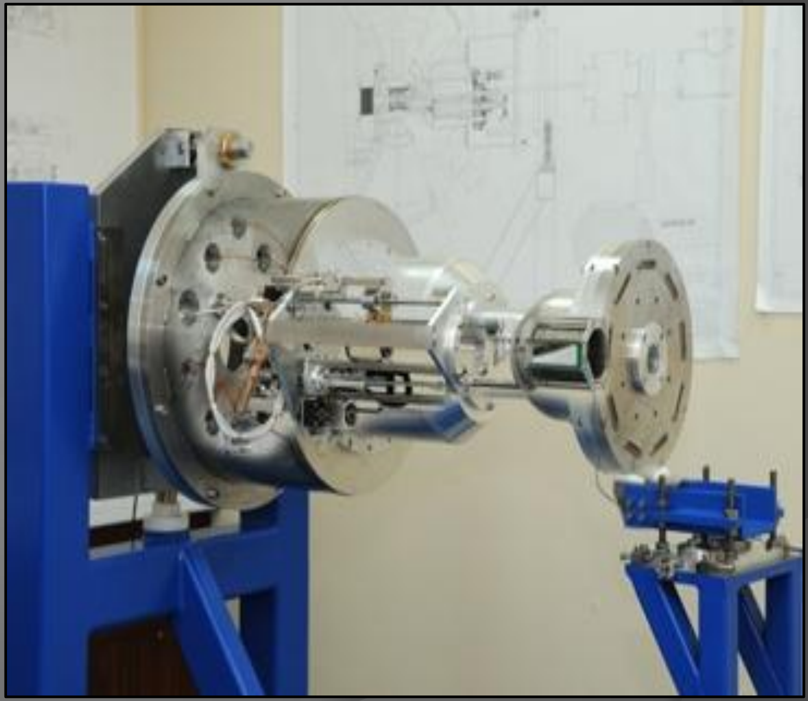

Duguet, T., M. Bender, P. Bonche, and P.-H. Heenen, 2003, Phys. Ltt. B 559, 201.

# Experimental Techniques

Performed at the University of Jyväskylä accelerator laboratory in Finland.

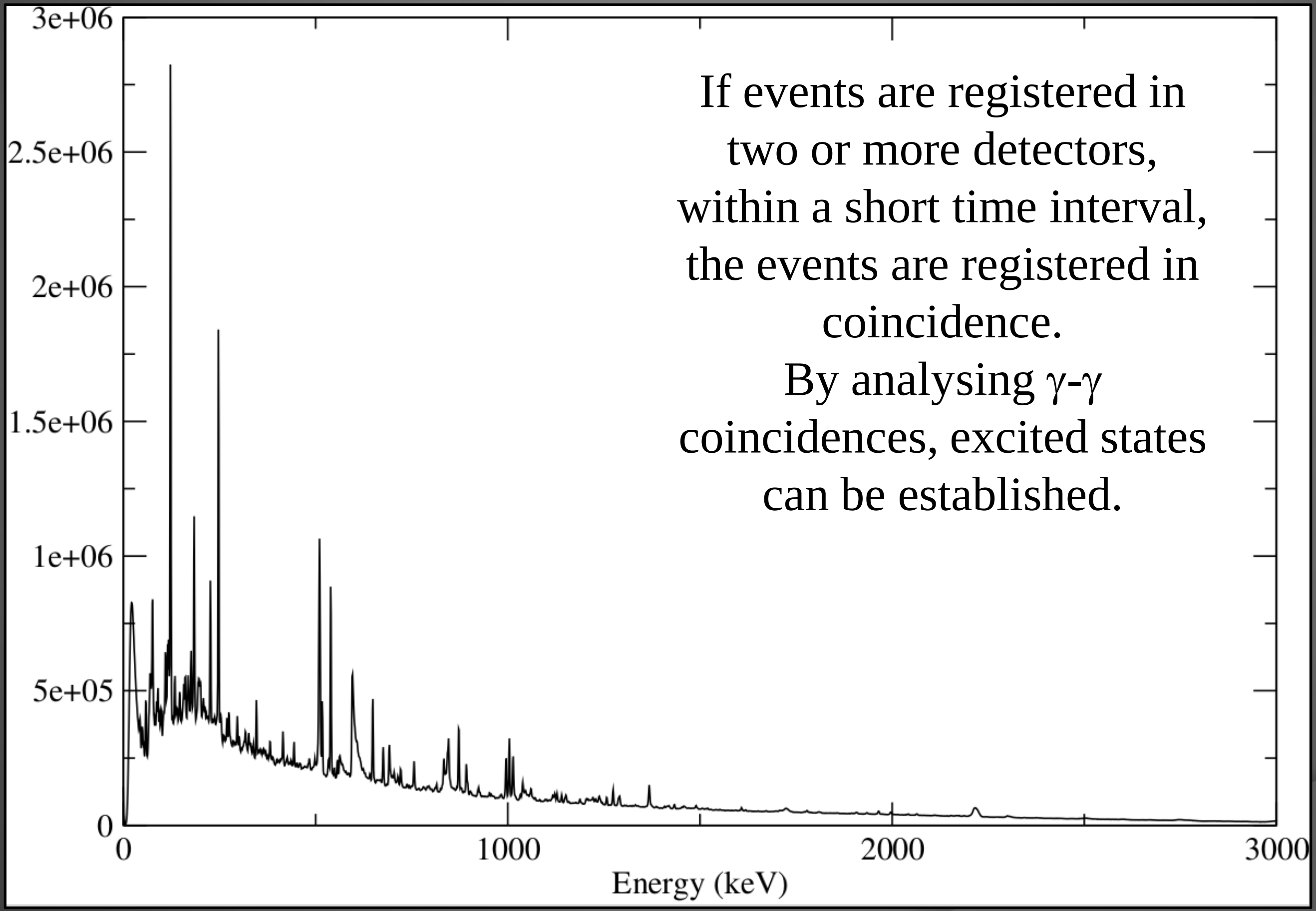
A proton beam of 12 MeV was used to excite a $^{154}Gd$ target, via inelastic proton scattering reactions (p, p') and compound reaction mechanisms.

JUROGAM II: An array of Compton-suppressed High-Purity Germanium (HPGe) detectors used to detect γ radiation from the de-excitation of states.



LISA (Light Ion Spectrometer Array): An array of silicon detectors that helped to distinguish between (p, p’) reactions and (p, xn) reactions by measuring the energies of charged particles.

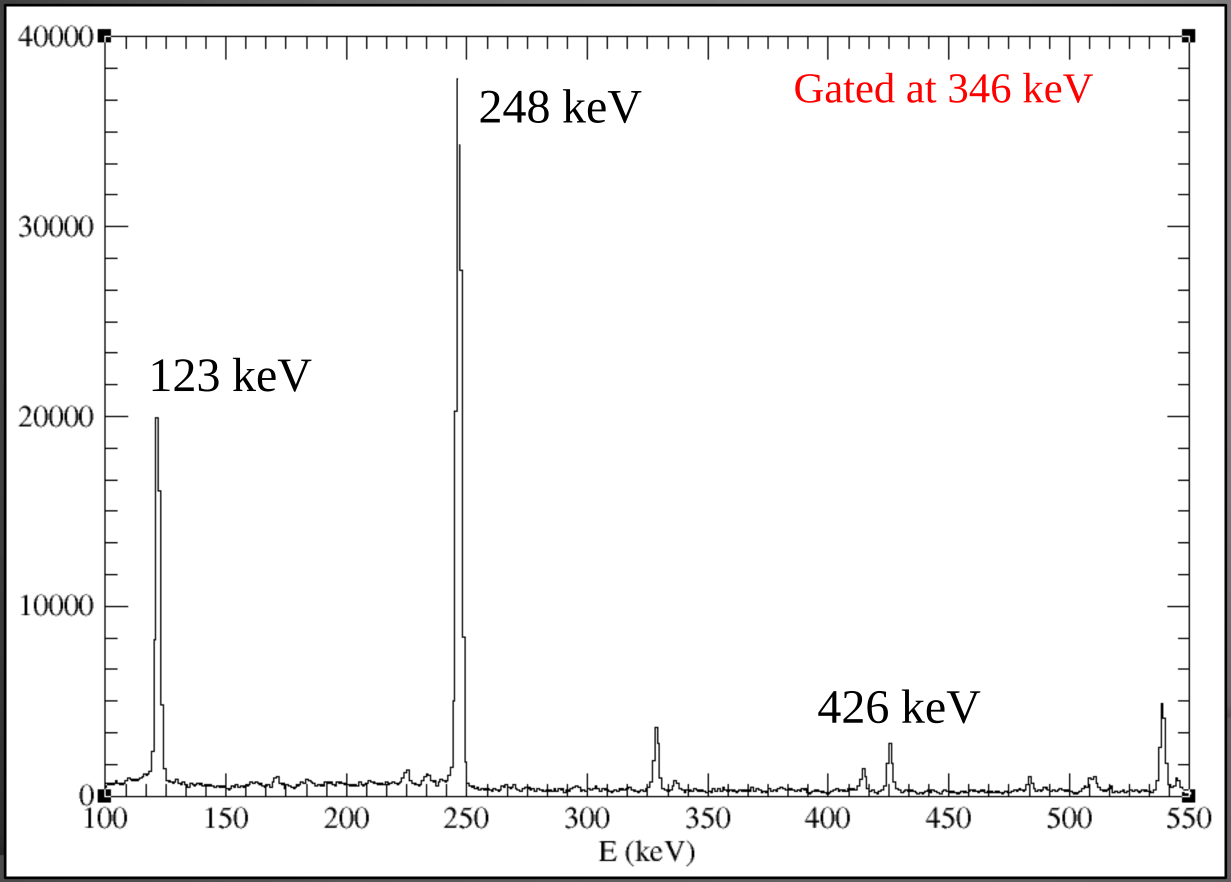
# Looking For γ-γ Coincidences

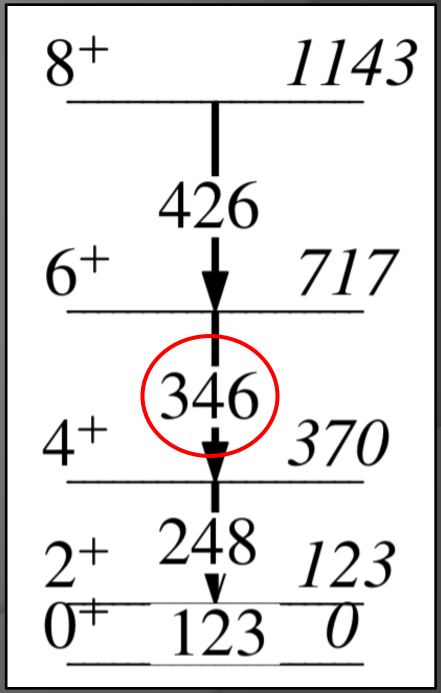



Projection of γ-γ Coincidence Matrix

# Yrast Band

Collective rotational band. Demonstrates approximate maximum angular momentum transfer in reaction to be ~ 8ħ.



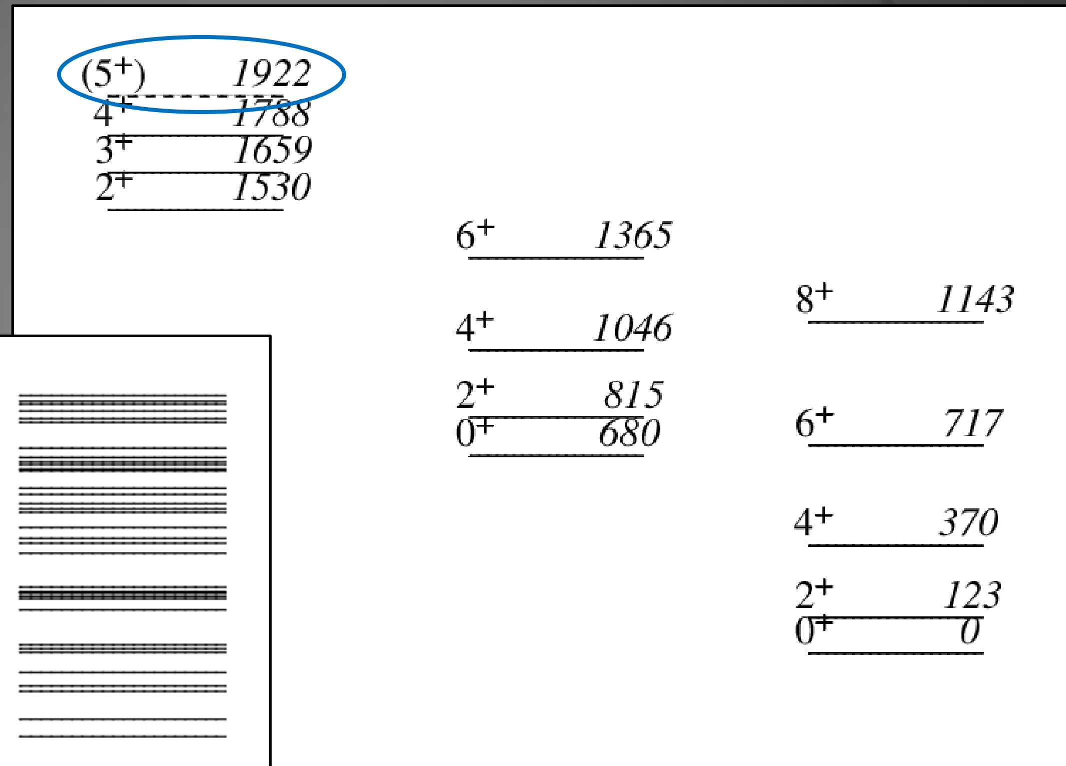



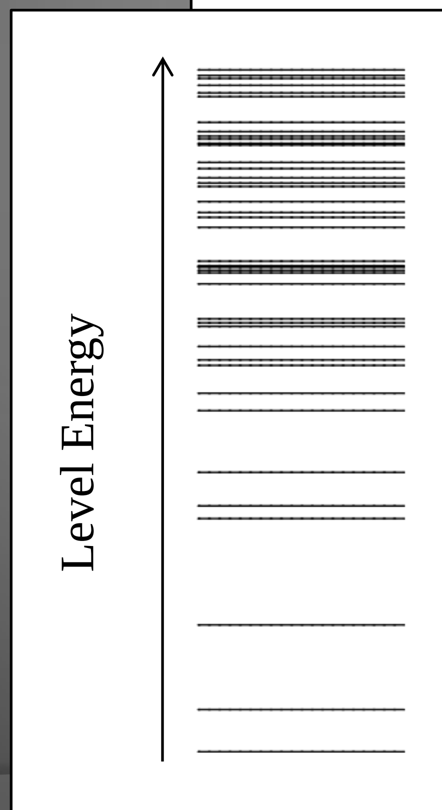
# Establishing New Levels

Approximately 80 levels and 300 gammas have been established.

New level proposed at 1922 keV  for excited $2^+$ band.

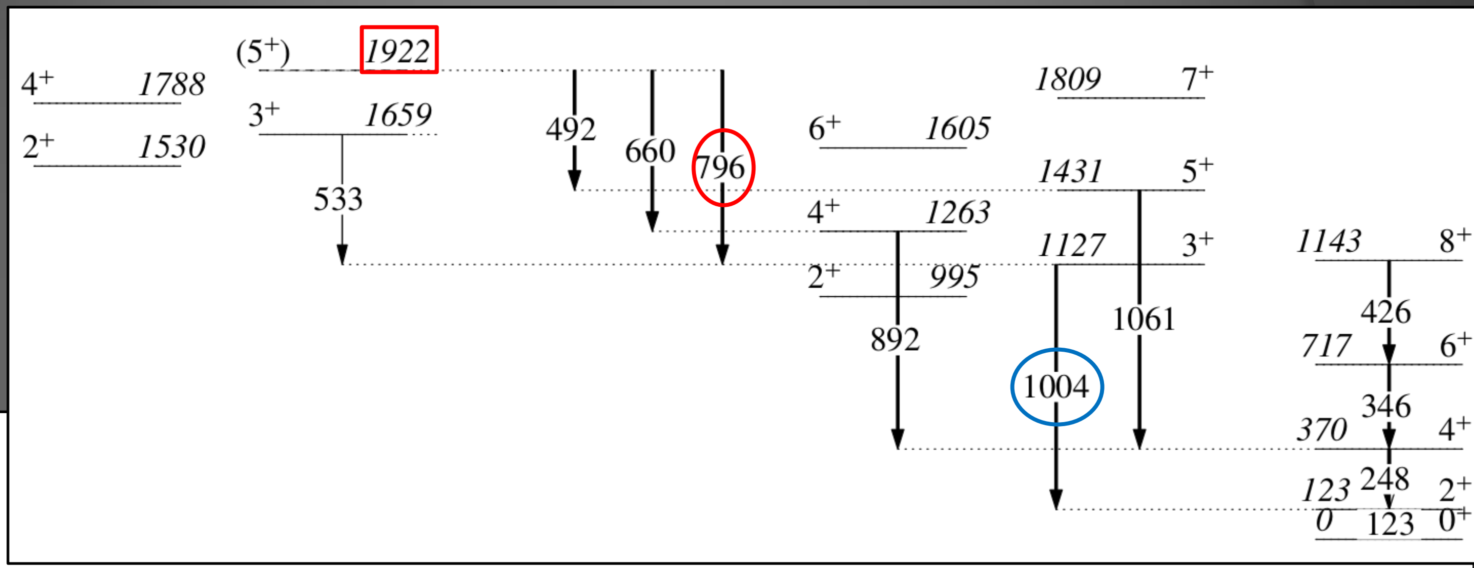
Level density increases with increasing energy.

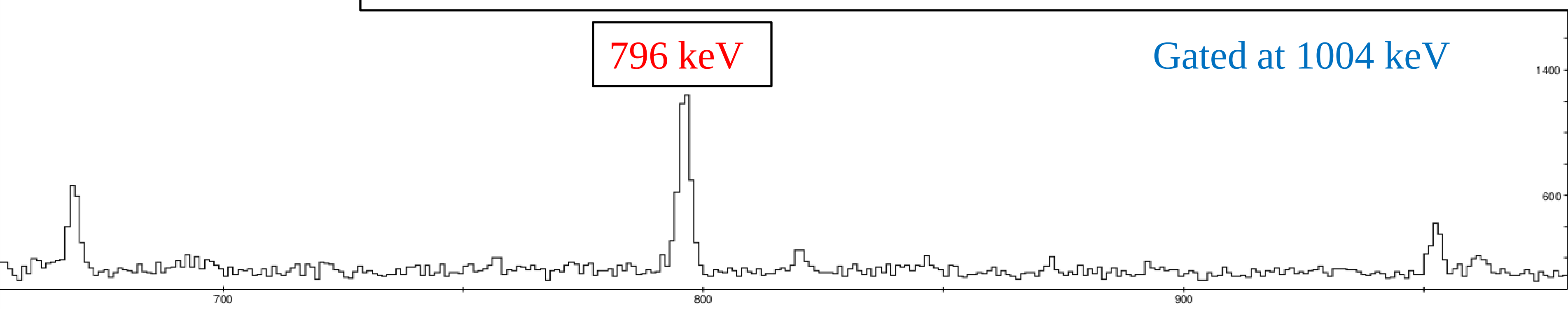


# Second $K^{\pi}=2^{+}$ Band

Second γ vibrational band.
New level proposed at 1922 keV.



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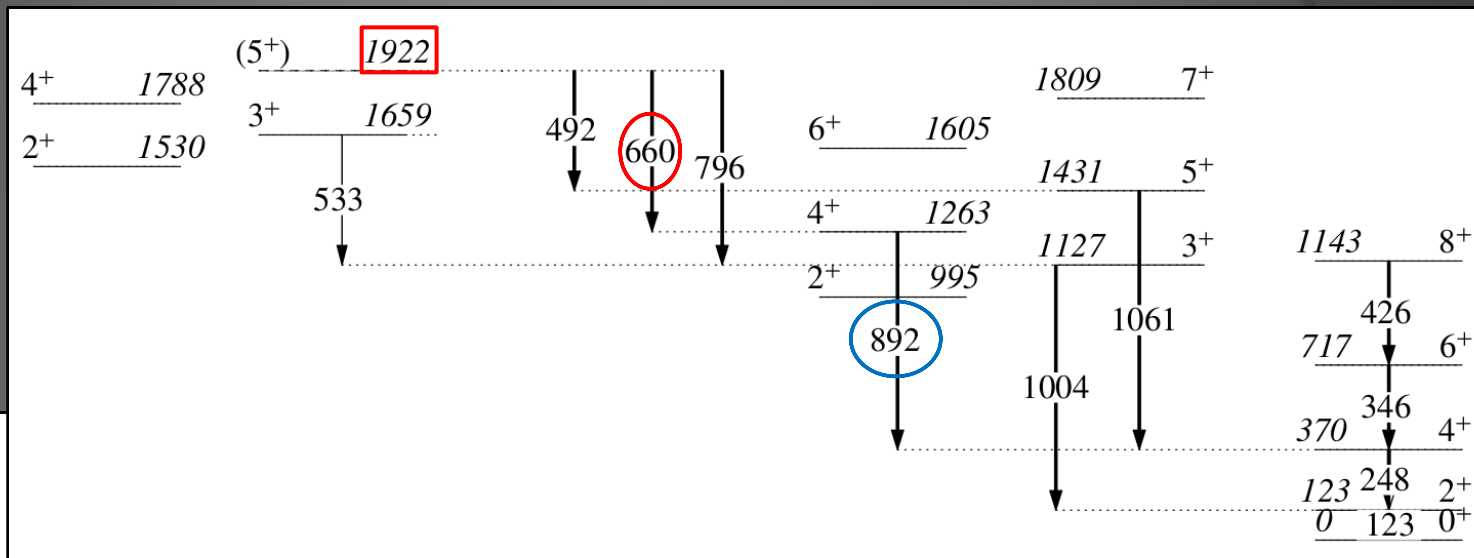


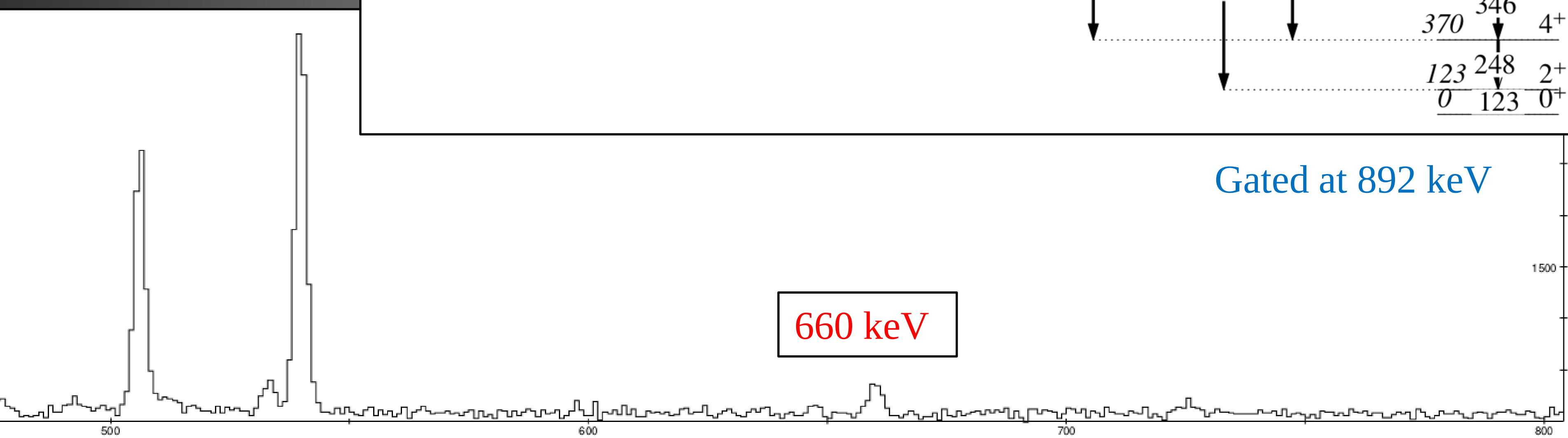

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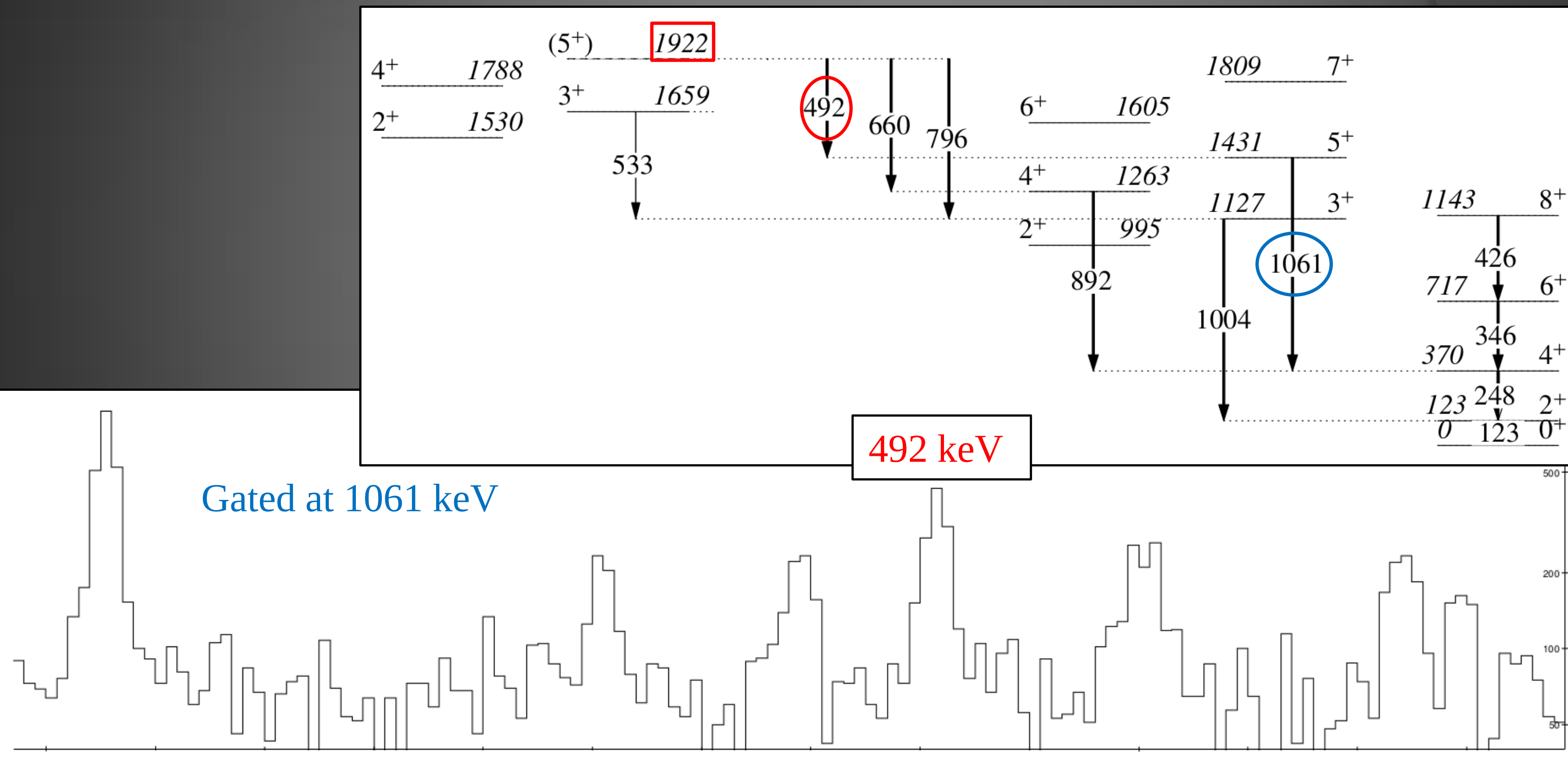


# Branching Ratios

Branching ratios can be helpful when investigating nuclear structure through the calculations of relative B(E2) values.

Two methods to calculate branching ratios.

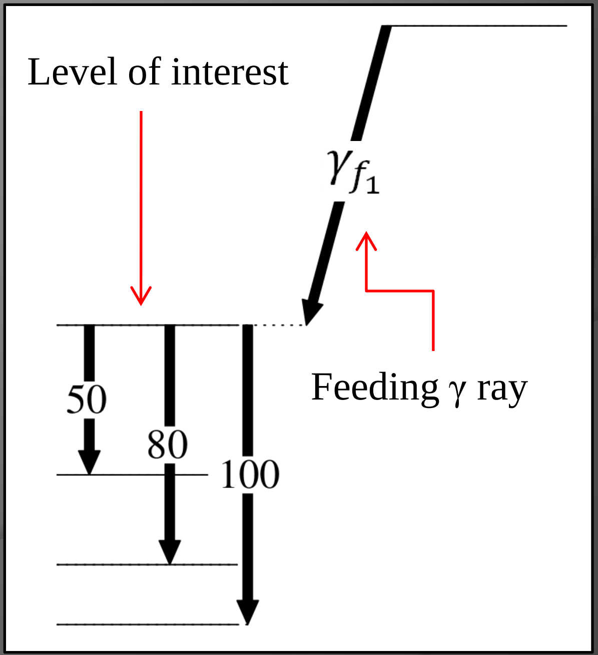
## Method 1: Above

Gate on a strong γ ray feeding the level of interest.

Peak areas of coincident γ ray are converted to intensities, taking into account efficiency corrections.

Branching ratios can then be calculated:

$$BR_{\gamma_i} = \frac{I_{\gamma_i}}{\sum_{k=1}^{n} I_{\gamma_k}}$$



# Branching Ratios

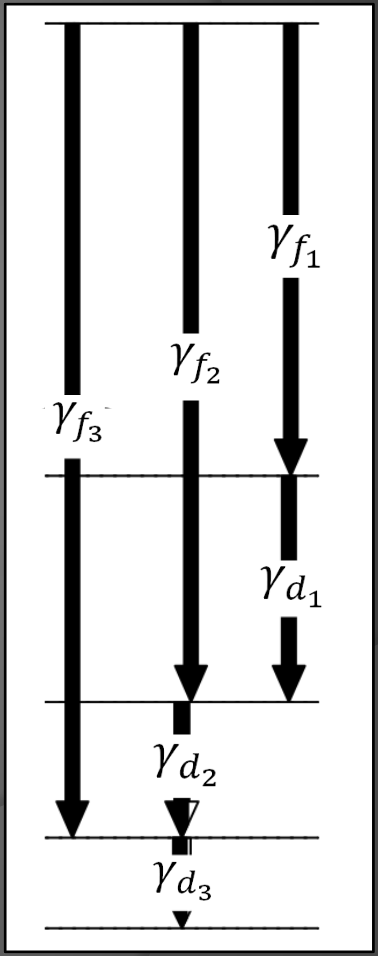
Second method to calculate branching ratios.

Method 2: Below

$$I_{\gamma_f} \simeq \frac{I'_f}{A\epsilon_{\gamma_d} B_{\gamma_d}}$$

$$BR_{\gamma_i} = \frac{I_{\gamma_i}}{\sum_{k=1}^{n} I_{\gamma_k}}$$

Note how the normalization constant (*A*) would cancel in the above equation.



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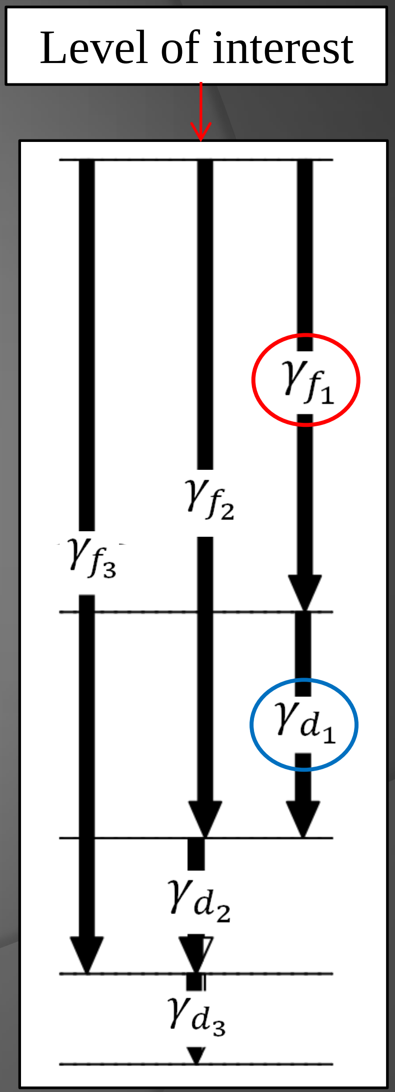
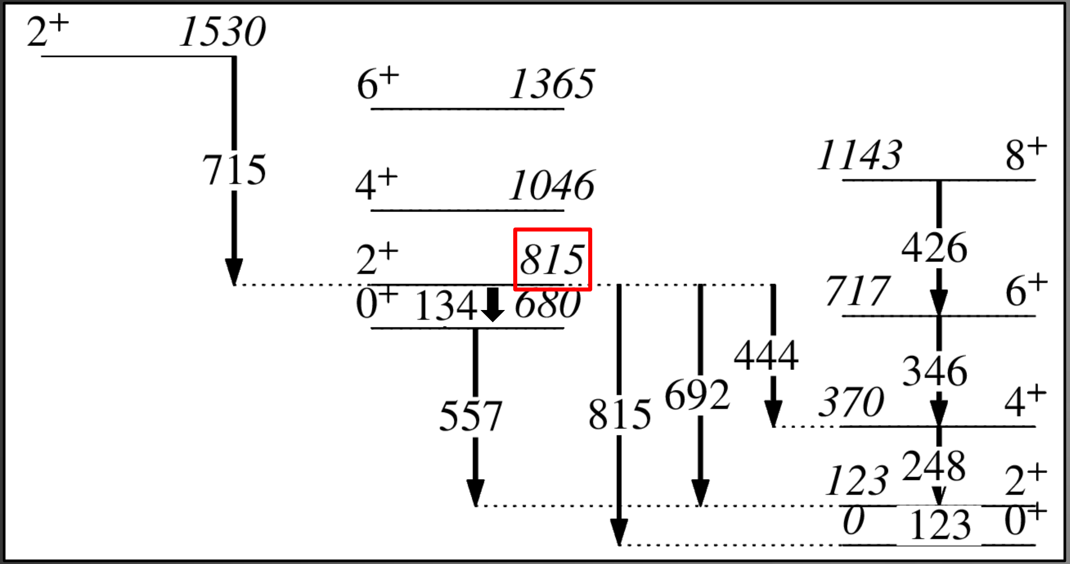


# Branching Ratios

Comparing the two methods. Focus on level at 815 keV.



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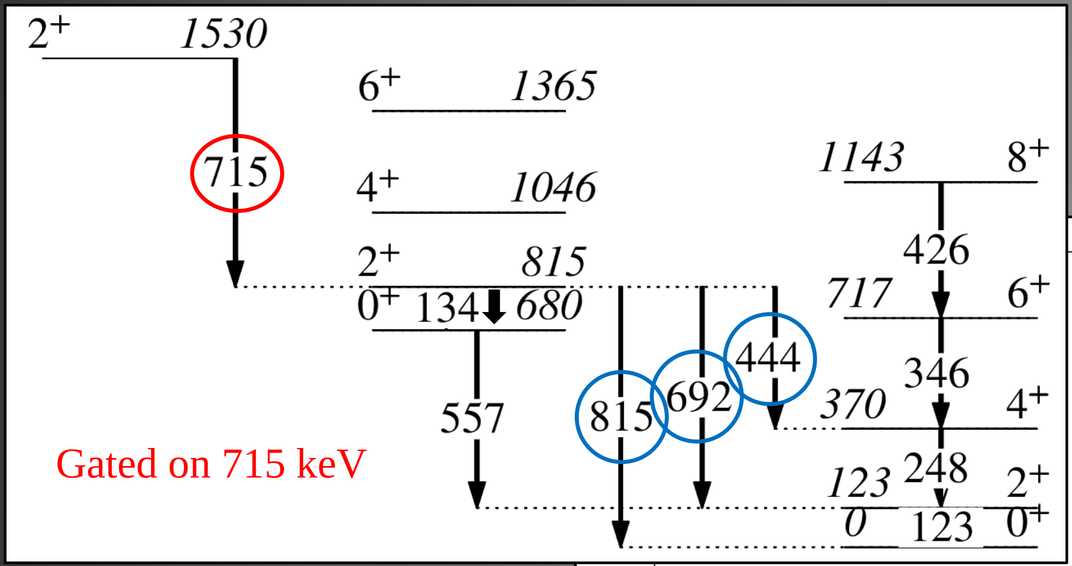


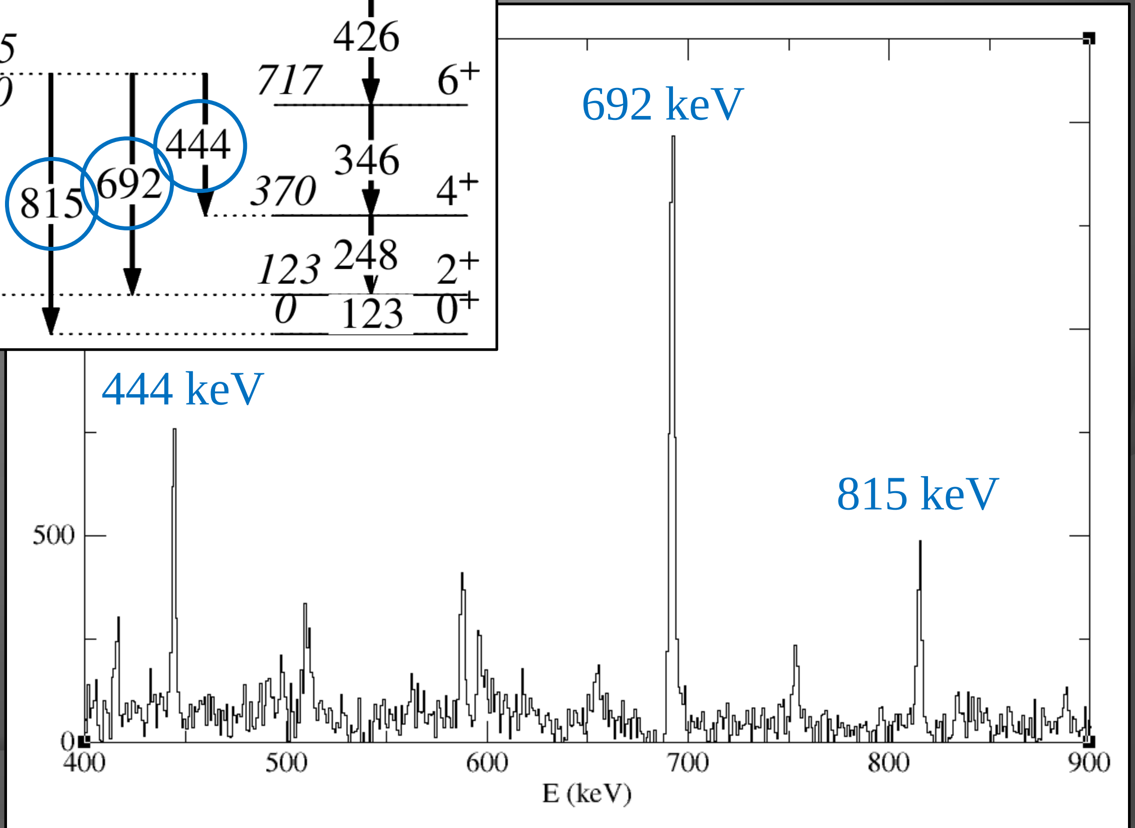

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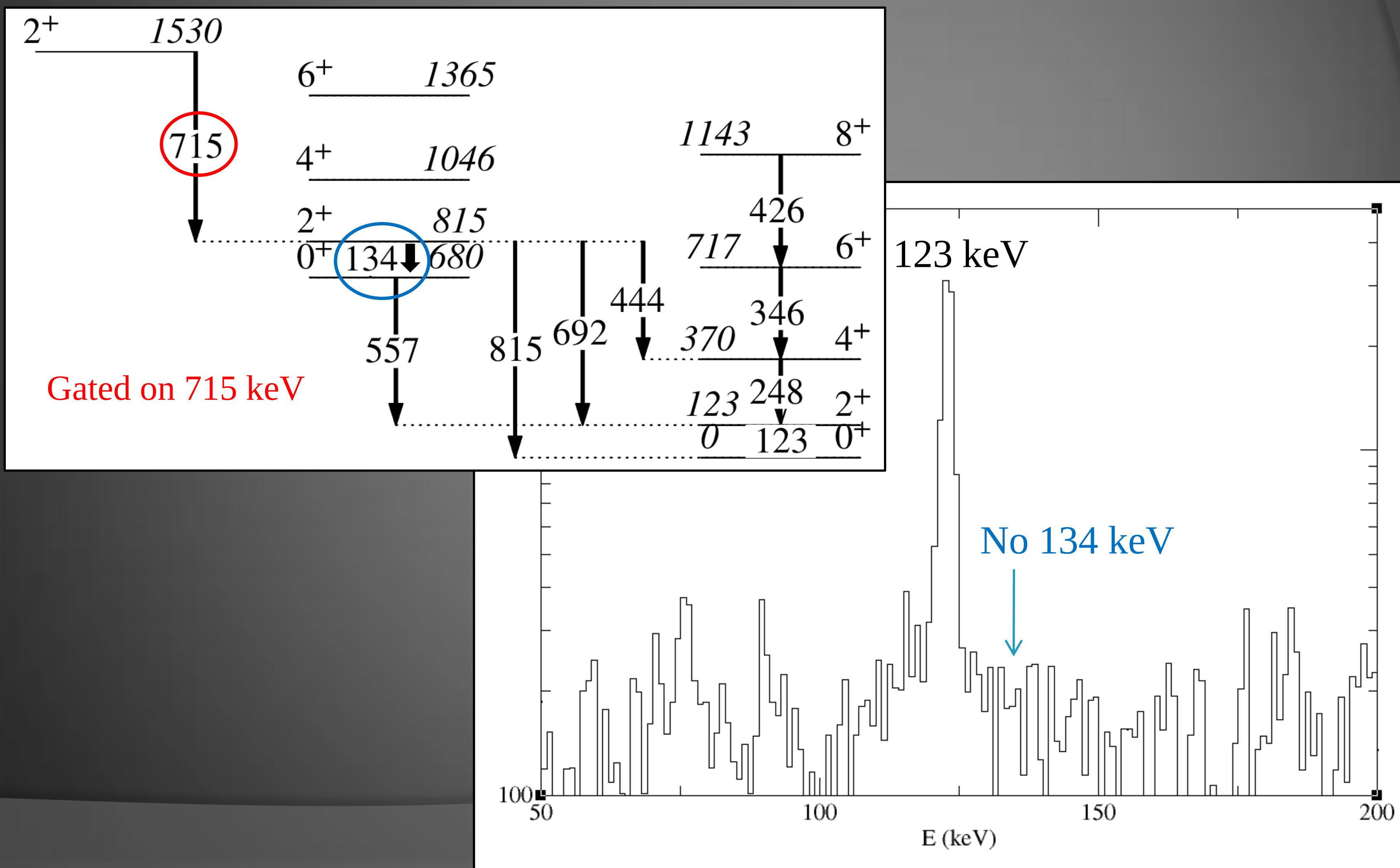

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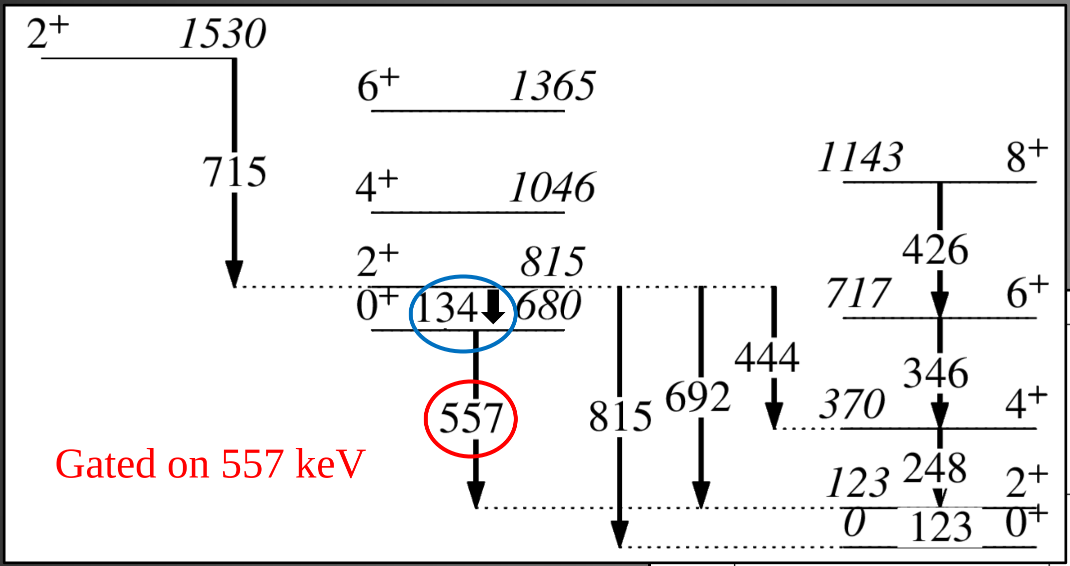


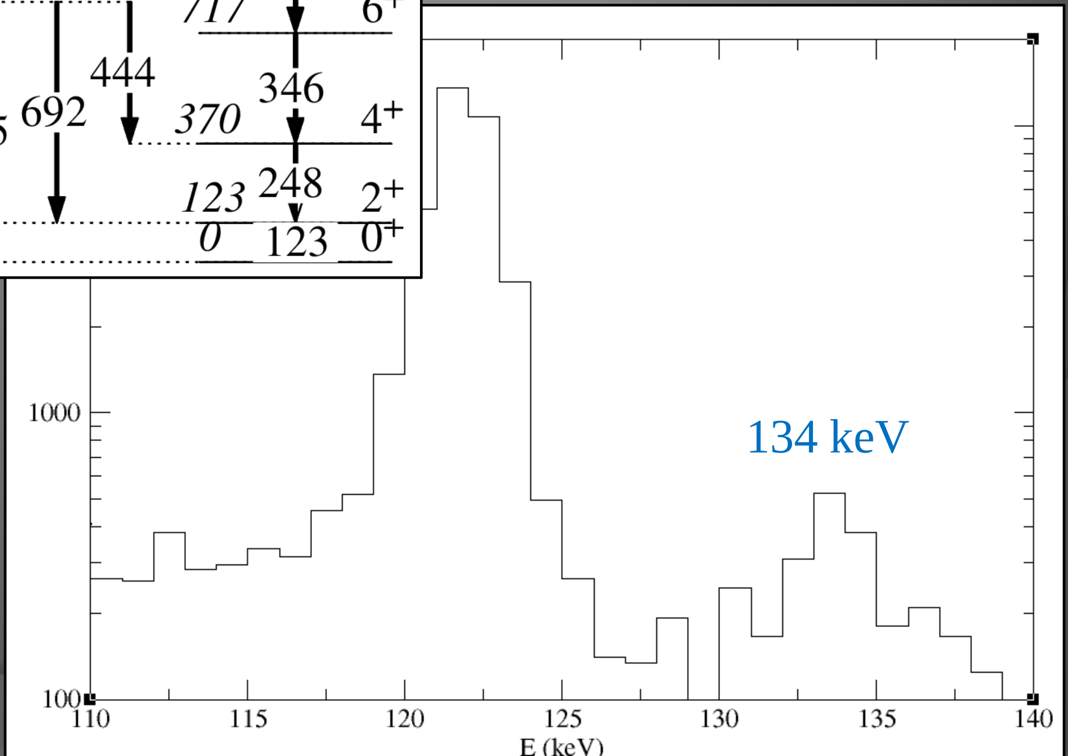

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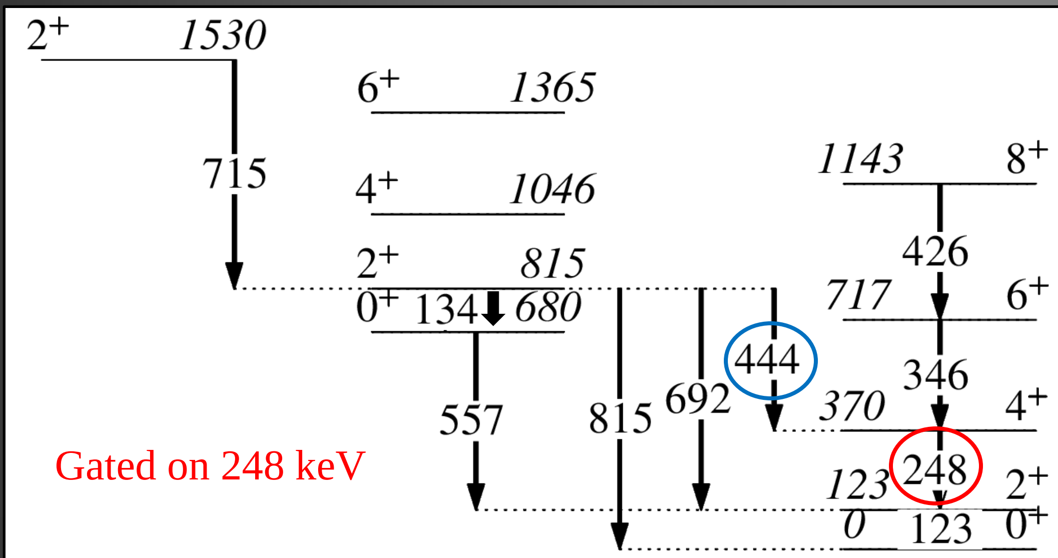


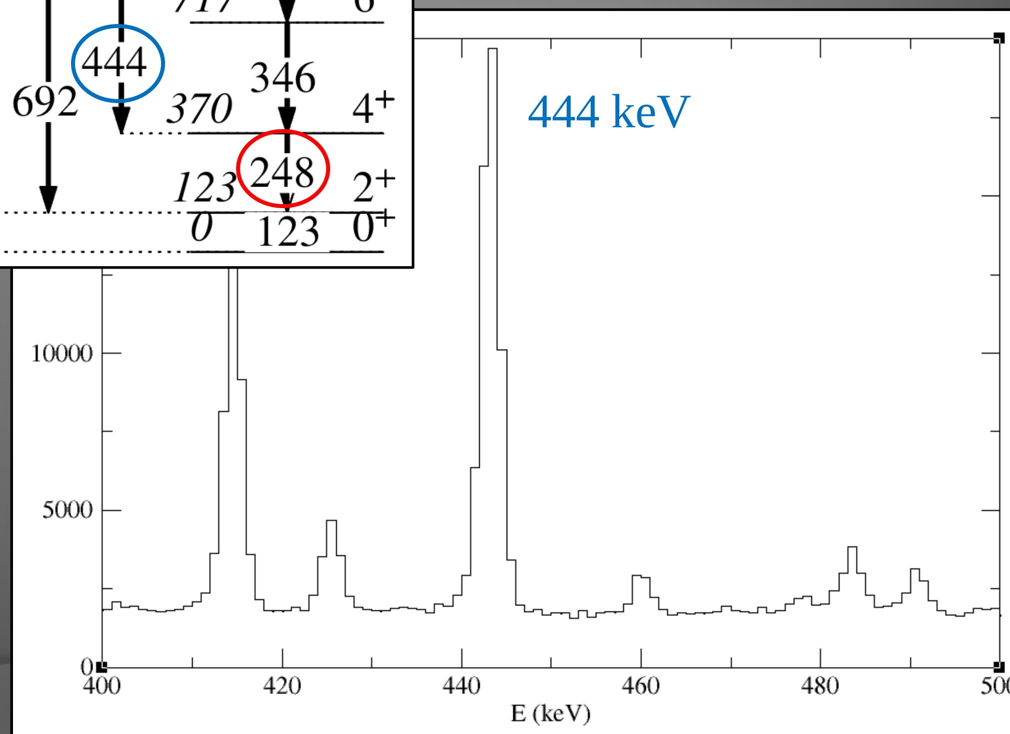

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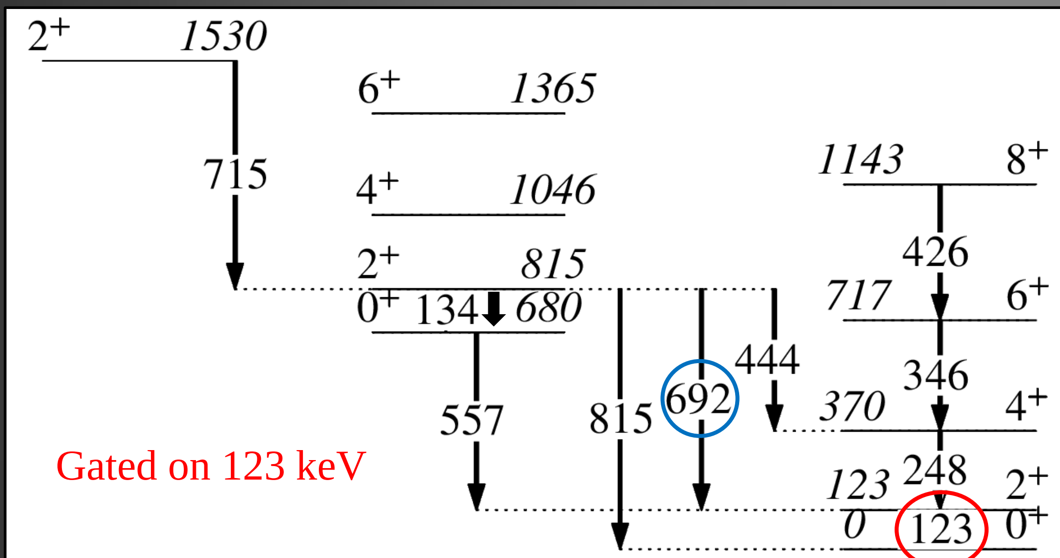


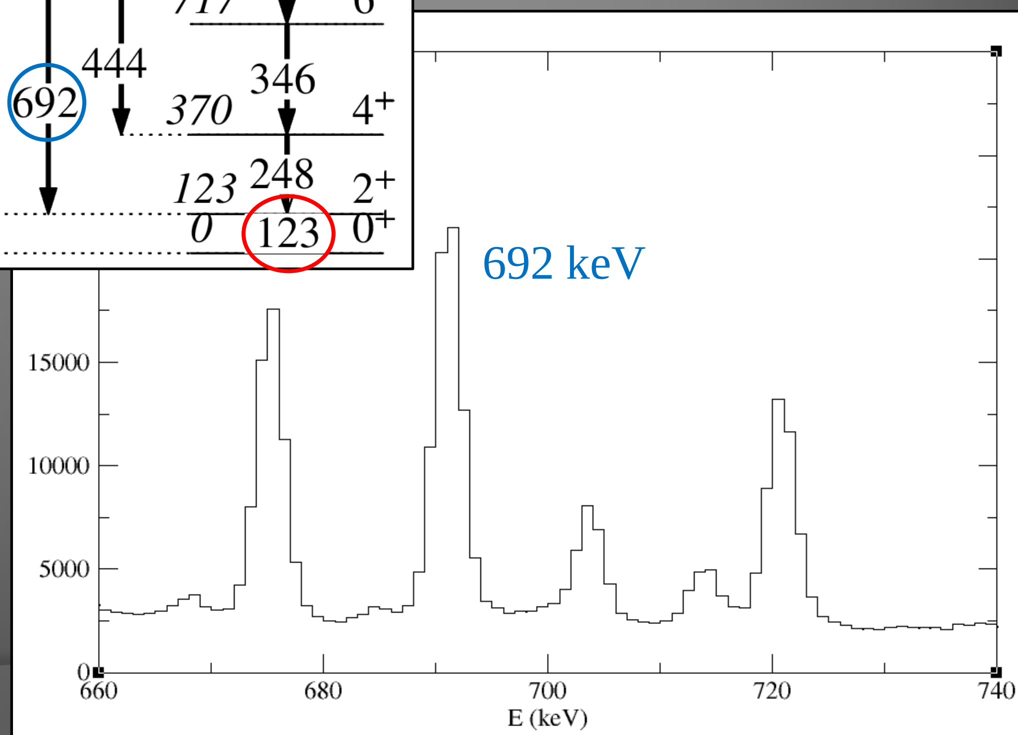

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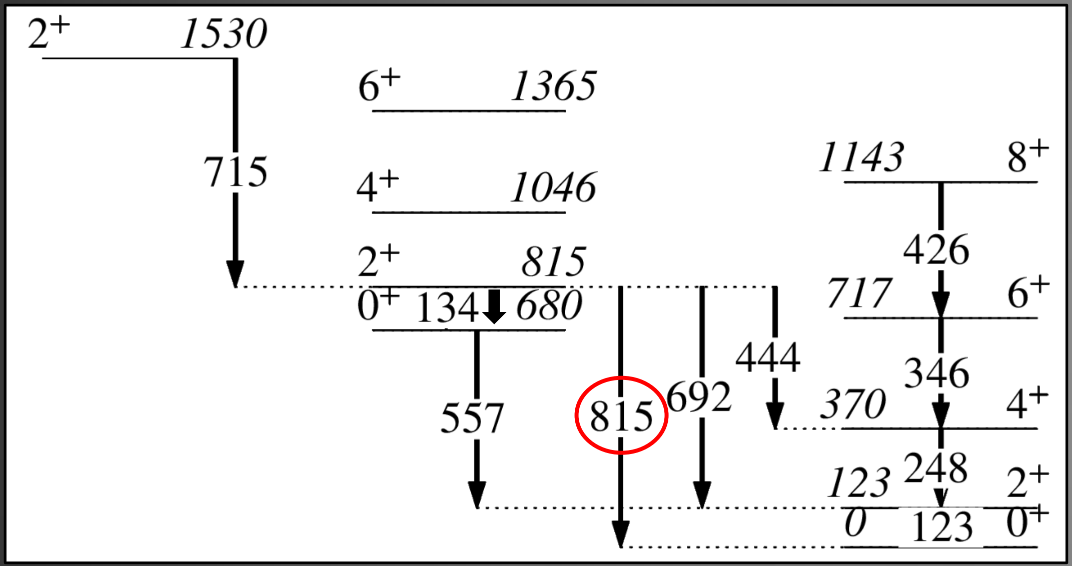
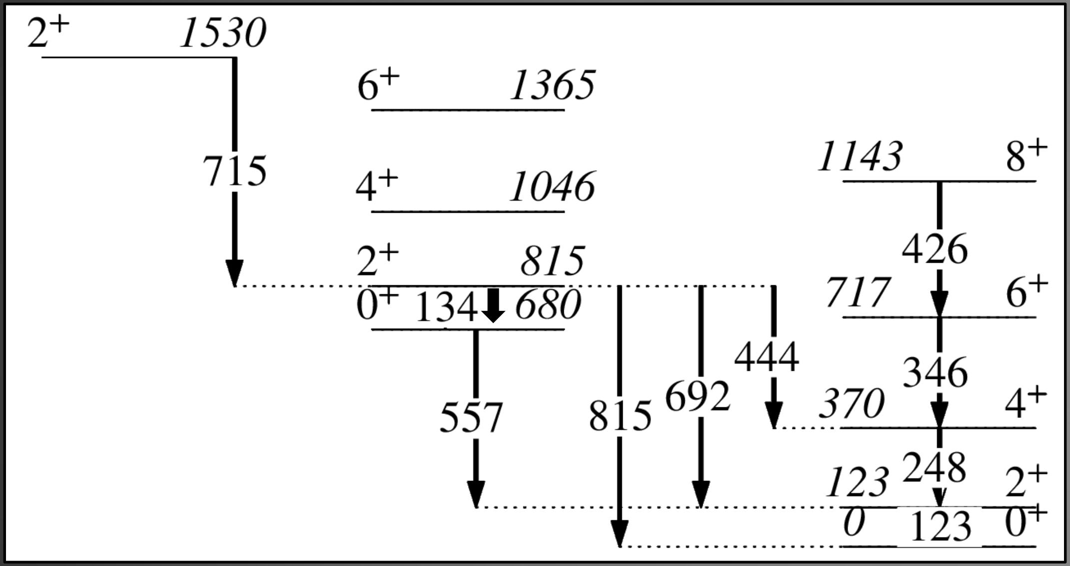



For below method, ground state transitions can be calculated via:

$$I_{\gamma_{gs}} = I_{\gamma_{gs(singles)}} \frac{I_{\gamma'_{(coincidence)}}}{I_{\gamma'_{(singles)}}}$$

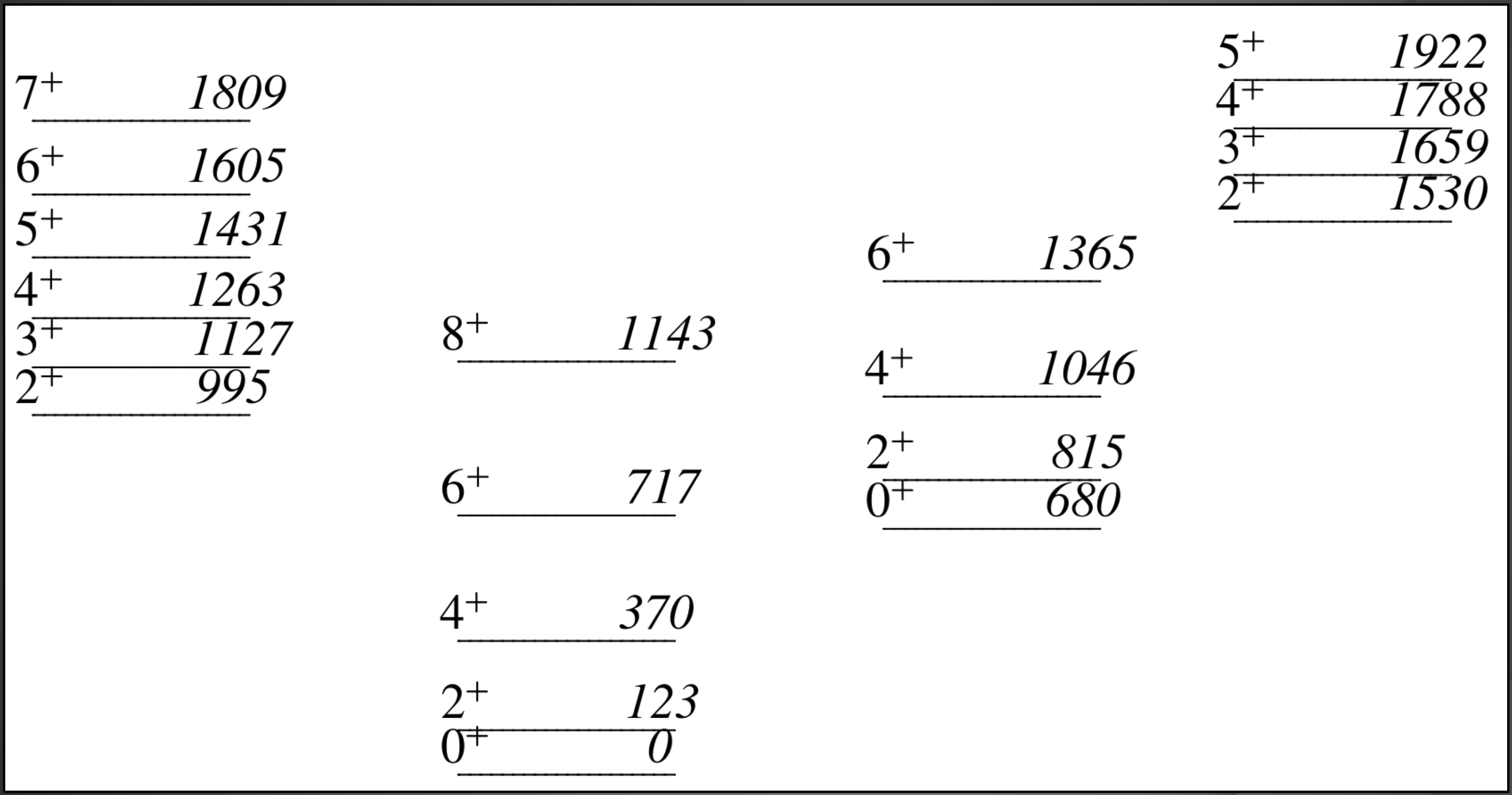
# Branching Ratios

Comparing the two methods. Focus on level at 815 keV.



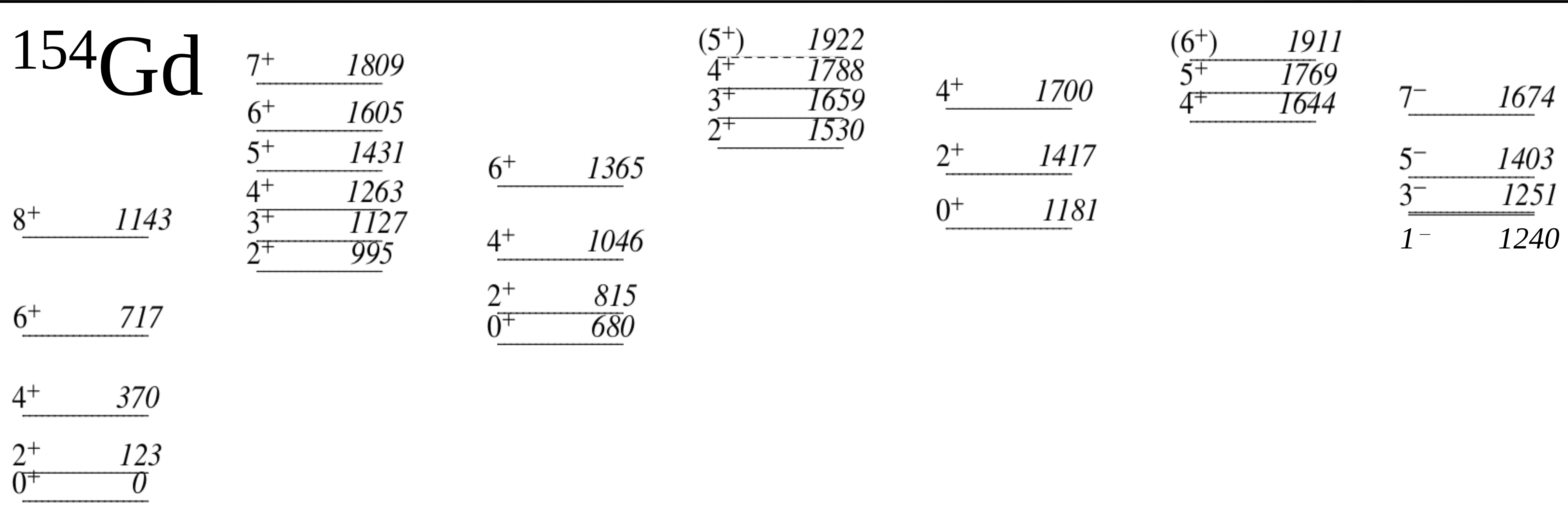

| Gamma (keV) | BR Above | BR Below |
|---|---|---|
| 134 | n/a | 0.003 ± 0.0003 |
| 444 | 0.17 ± 0.04 | 0.17 ± 0.01 |
| 692 | 0.64 ± 0.06 | 0.64 ± 0.02 |
| 815 | 0.19 ± 0.03 | 0.17 ± 0.01 |

# Indications of Shape Coexistence

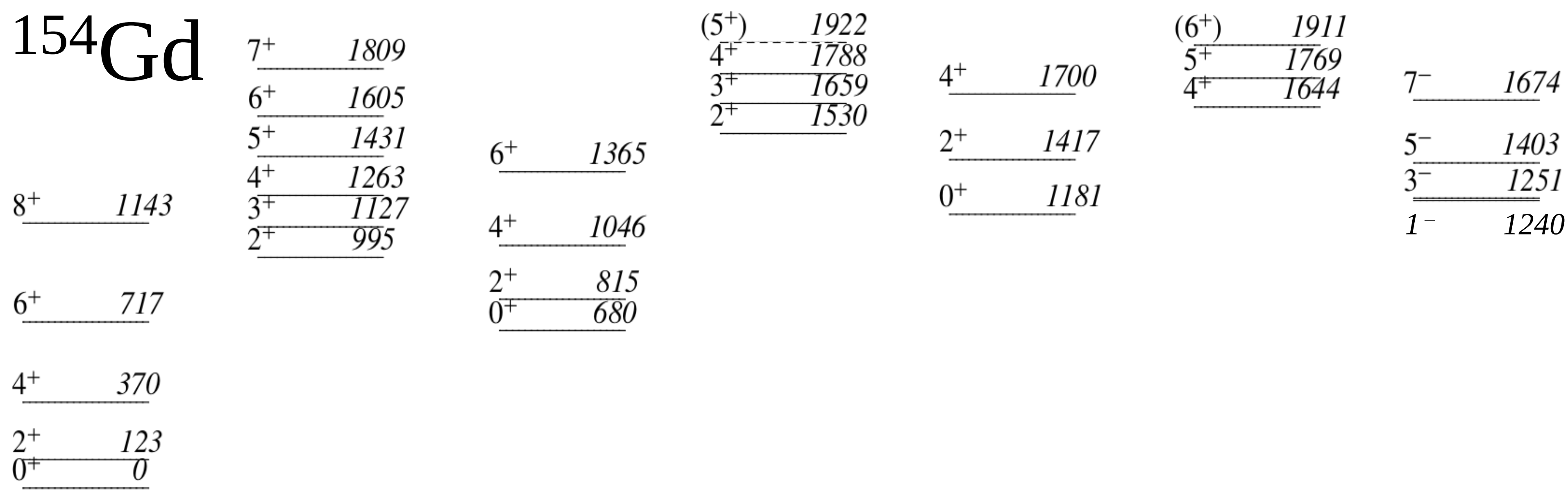


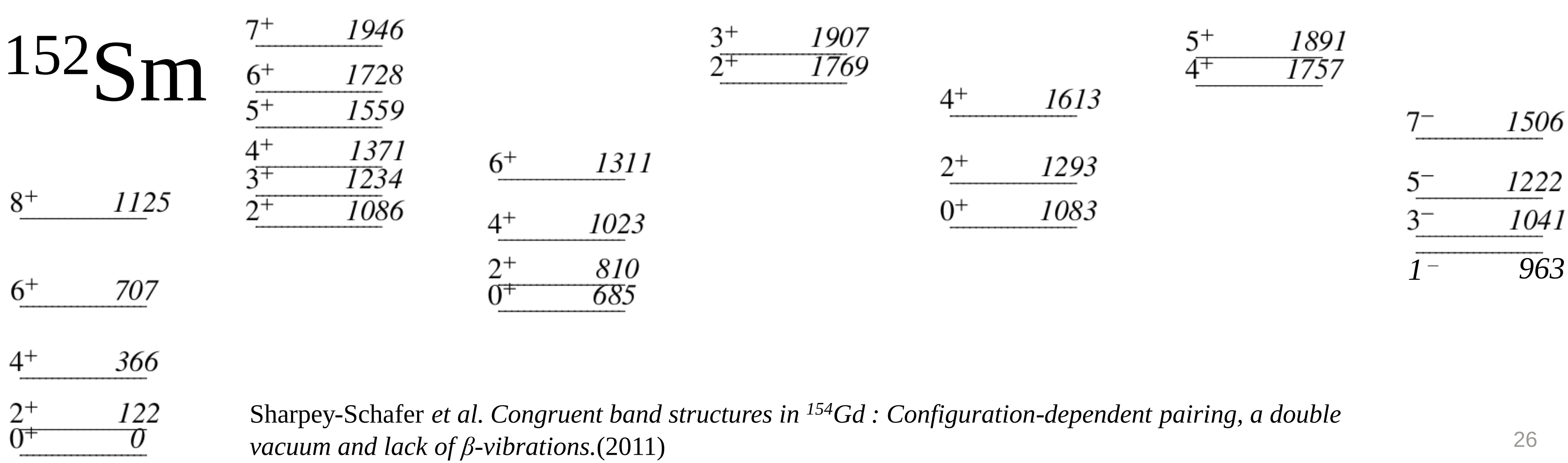

Similarities between ground state and low lying first excited $0^+$ band might imply strong mixing between the two bands.

# Comparisons with $^{152}$Sm



# Comparisons with $^{152}$Sm




Sharpey-Schafer *et al. Congruent band structures in $^{154}$Gd : Configuration-dependent pairing, a double vacuum and lack of β-vibrations.*(2011)

# Conclusion

In conclusion approximately 80 levels and 300 gammas have been established.
Out of which there are 20 new levels and 40 new transitions.

Branching ratios using above and below techniques have been calculated to later aide in placement of levels into bands.

This is one of many studies required in order to fully understand the nuclear structure in the N=90 region.

# Acknowledgments

University of Guelph, Guelph, ON, Canada

*B. Hadinia, P. E. Garrett, L. Bianco, V. Bildstein, A. Diaz-Varela, B. Jigmeddorj, A. T. Laffoley, A.D. MacLean, A.J. Radich, E. T. Rand, C. E. Svensson, J. Wong*

University of Jyväskylä, Jyväskylä, Finland

*K. Auranen,  T. Grahn, P. T. Greenlees, A. Herzan, U. Jakobsson, R. Julin, S. Juutinen, J. Konki, M. Leion, J. Pakarinen, P. Peura, P. Rahkila, P. Ruotsalainen, M. Sandzelius, J. Saren, C. Scholey, J. Sorri, S. Stolze, J. Uusitalo*

Daresbury Laboratory, Warrington, United Kingdom

*M. Labiche*

University of Liverpool, Liverpool, United Kingdom

*D. O'Donnell, R. D. Page, E. S. Parr, J. Revill*

Work supported by the Canada Foundation for Innovation, the Natural Sciences and Engineering Research Council of Canada, the National Research Council of Canada and the Canadian Research Chairs program. In addition, this work was supported by the Academy of Finland under the Finnish Center of Excellence Programme and the UK Science and Technologies Facilities Council. The authors would like to thank the GAMMAPOOL European Spectroscopy Resource for the loan of germanium detectors for JUROGAM II.

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Science & Technology Facilities Council
Daresbury Laboratory

University of Liverpool

NSERC CRSNG

Canada Foundation for Innovation
Fondation canadienne pour l'innovation

# Branching Ratios

Two methods to calculate branching ratios.

Method 2: Below

Can determine a branching ratio when a strong feeding $\gamma$ ray is absent.

Should yield identical results as gating from above when statistics are available.

$$N_{fd} = AI_{\gamma_f}\epsilon_{\gamma_f}B_{\gamma_d}\epsilon_{\gamma_d}\epsilon_{fd}\eta(\theta_{fd})$$

$N_{fd}$: Number of counts in a coincidence peak between the draining and feeding $\gamma$ rays
$A$: Normalisation constant
$I_{\gamma_f}$: Intensity of the "feeding" $\gamma$ ray from level of interest
$\epsilon_{\gamma_f}/\epsilon_{\gamma_d}$: Singles photopeak efficiencies
$B_{\gamma_d}$: Branching ratio of the "draining" $\gamma$ ray
$\epsilon_{fd}$: Coincidence efficiency
$\eta(\theta_{fd})$: Angular correlation attenuation factor

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Can be neglected since large time coincidence gates were made. Assumption verified by gating from above to check calculated branching ratios.

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Can be neglected due to symmetry of JUROGAM II spectrometer, which generally results in a very small effect on γ ray intensities.

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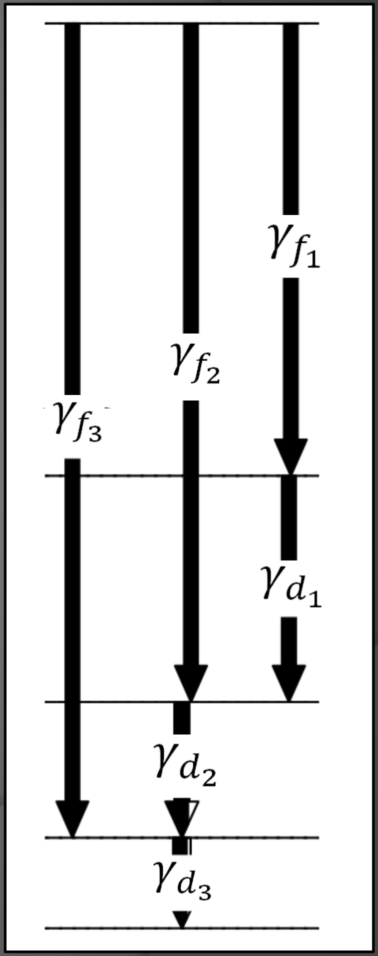
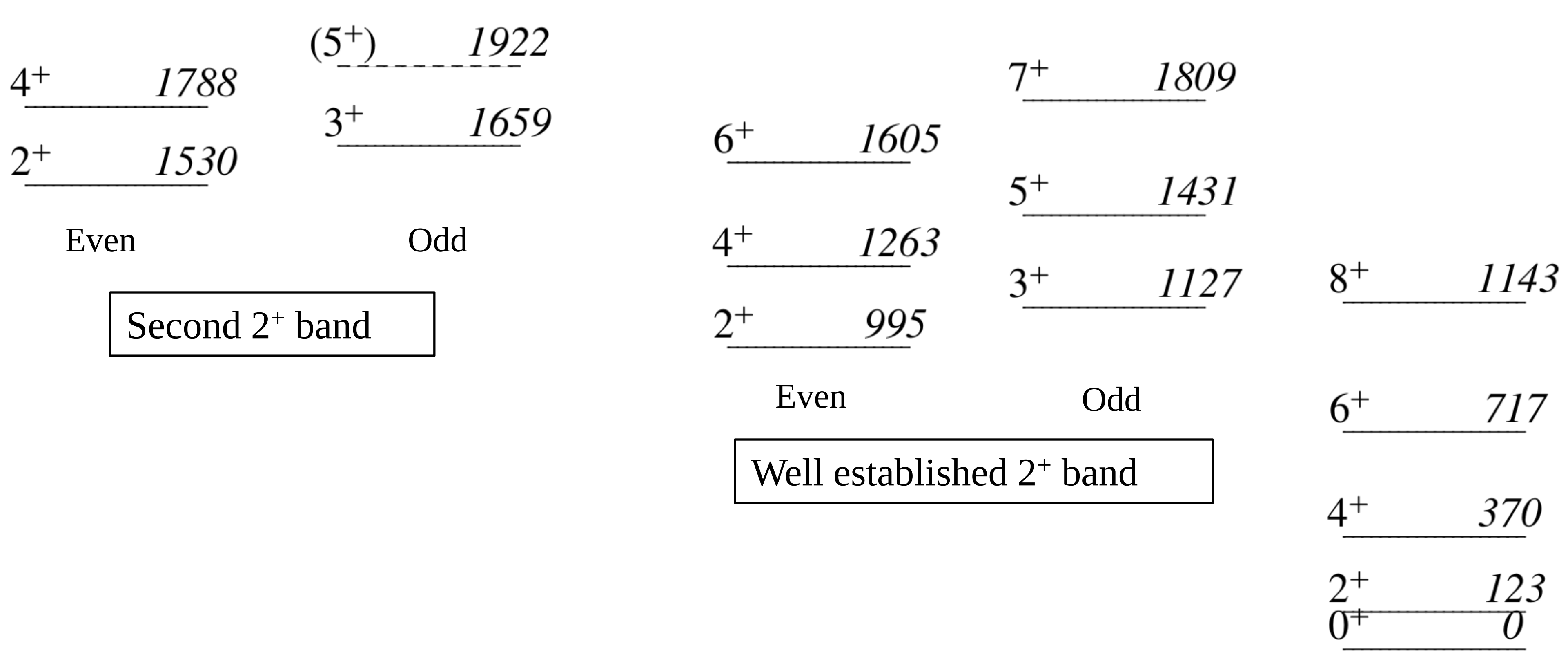


# Second $K^{\pi}=2^{+}$ Band

Second γ vibrational band.
New level proposed at 1922 keV.

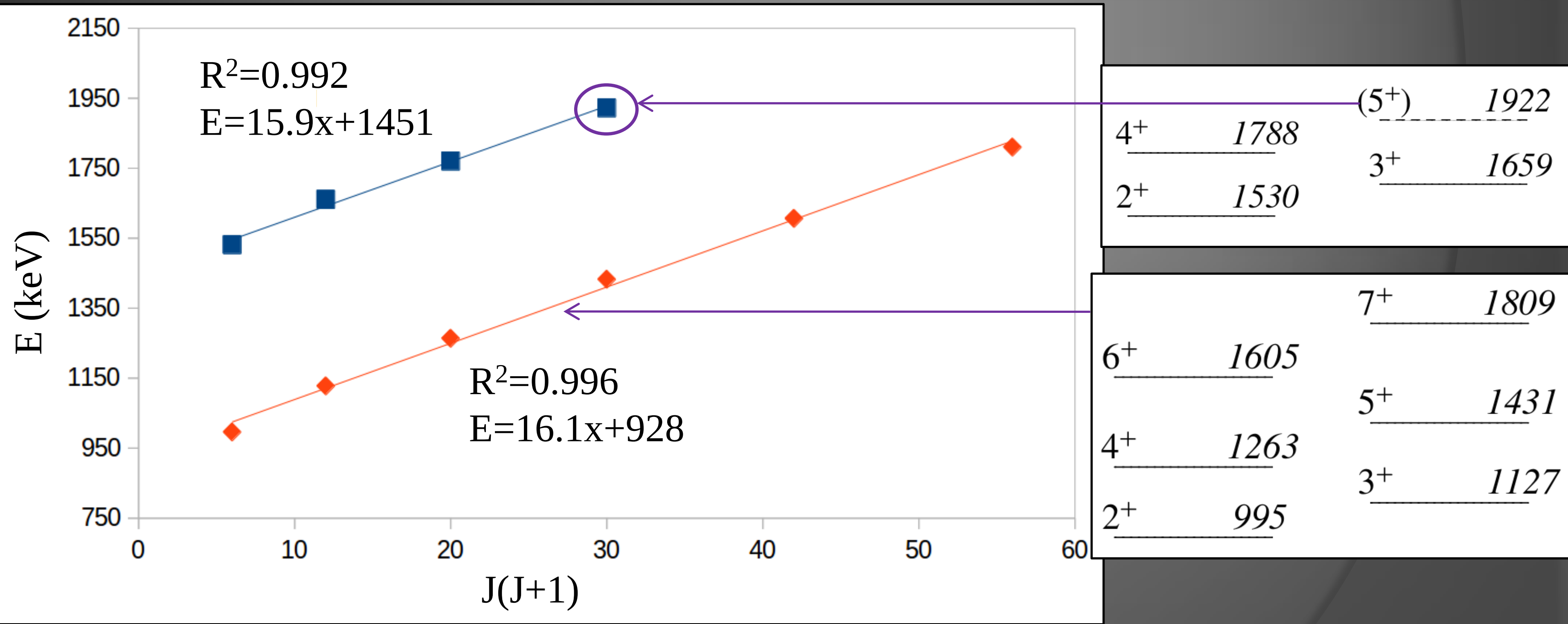


# Second $K^{\pi}=2^{+}$ Band

Second γ vibrational band.
New level proposed at 1922 keV.

$$E_{rot} = \frac{J(J+1)\hbar^2}{2\Theta}$$

Similar $R^2$ values and moments of inertia.
Therefore good preliminary guess for $5^+$ state for second γ vibrational band.



# Relative B(E2) Calculations

The transition strengths for an electric quadrupole can provide information on the collective properties of a transition.

$$B(E2) = \frac{9.527 \times 10^6 BR}{E_\gamma^5 A^{4/3} \ln(2) \tau (1+\alpha)} \frac{\delta^2}{1+\delta^2} [W.u.]$$

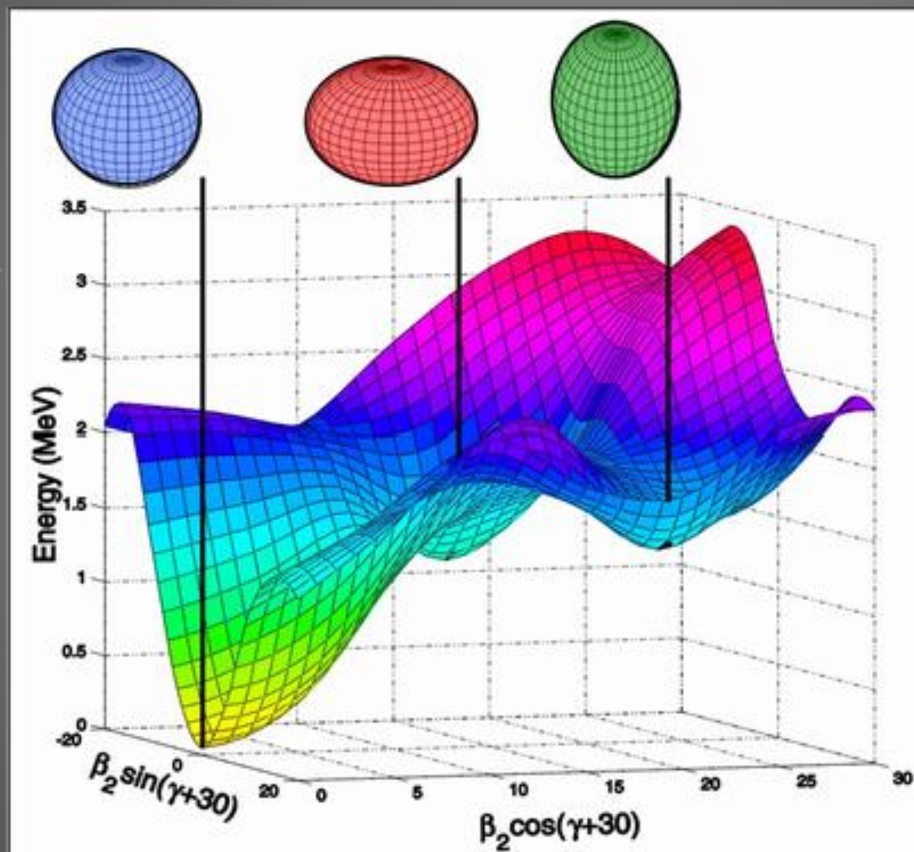
However since the lifetime for all the energy levels are not all known, a relative transition strength can be calculated. This can help us identify whether excited states are members of a certain band.

$$B(E2)_i = B(E2)_{strongest} \left(\frac{BR_i}{BR_{strongest}}\right) \left(\frac{E^5_{\gamma,strongest}}{E^5_{\gamma,i}}\right) \left(\frac{1+\alpha_{strongest}}{1+\alpha_i}\right)$$

However the internal conversion coefficient would be neglected in cases where it is much less than 1.

# Shape Coexistence

Nuclei have the ability to minimize their energy by adopting different deformed nuclear shapes.




Competing minima close together.

Coexisting collective structures and coexisting shapes are present in nuclei.

A. N. Andreyev *et al.* *A Triplet of Differently Shaped Spin-Zero States in the Atomic Nucleus $^{186}$Pb.* (2000)

1

# Phase Transitions vs Shape Coexistence

Shape coexistence: Two distinct Hilbert Spaces, where the calculations required can be done separately for the different, coexisting structures. These can then mix but are considered largely independent.

Phase Transition: Only one Hilbert space, with no separation possible. If you were to take the limit of the corresponding states, on one end you would get rotational states, and on the other you would get vibrational states.