A search for

thermodynamical signatures of phase transitions in the nuclear continuum

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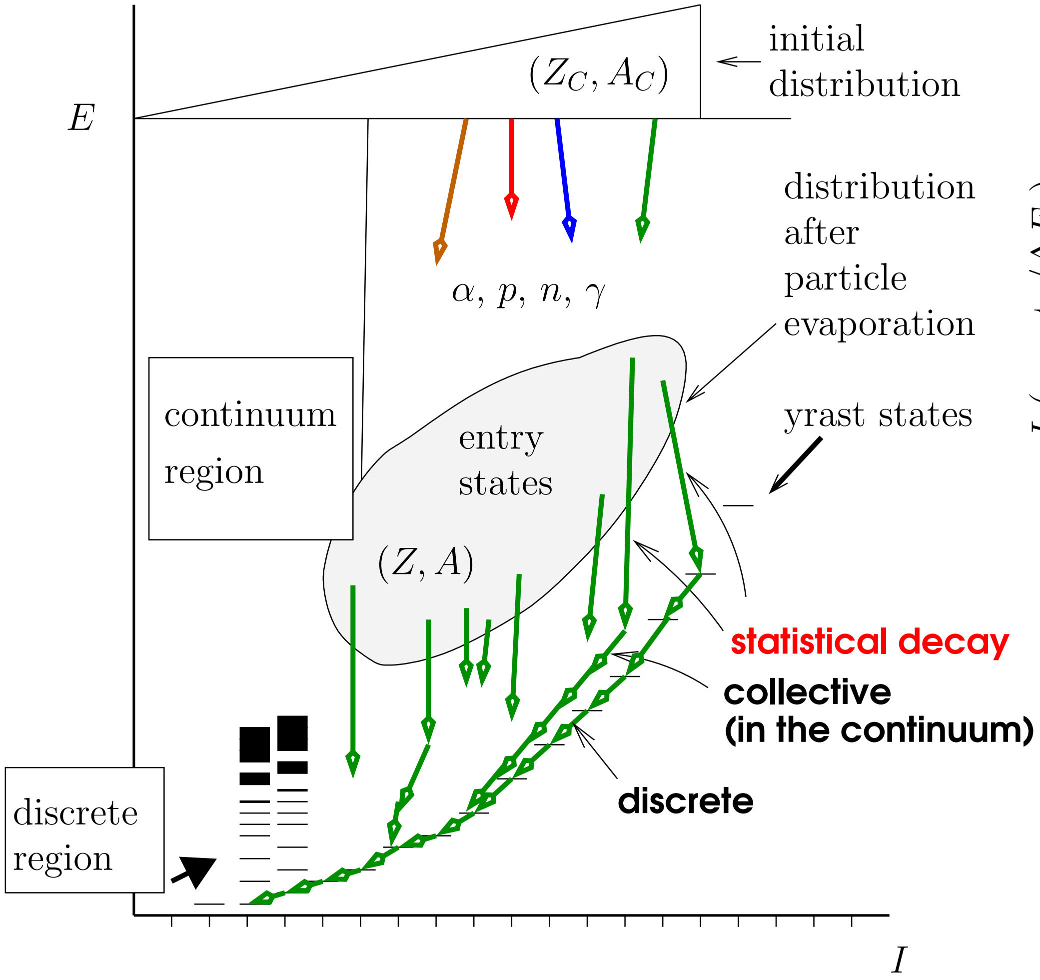
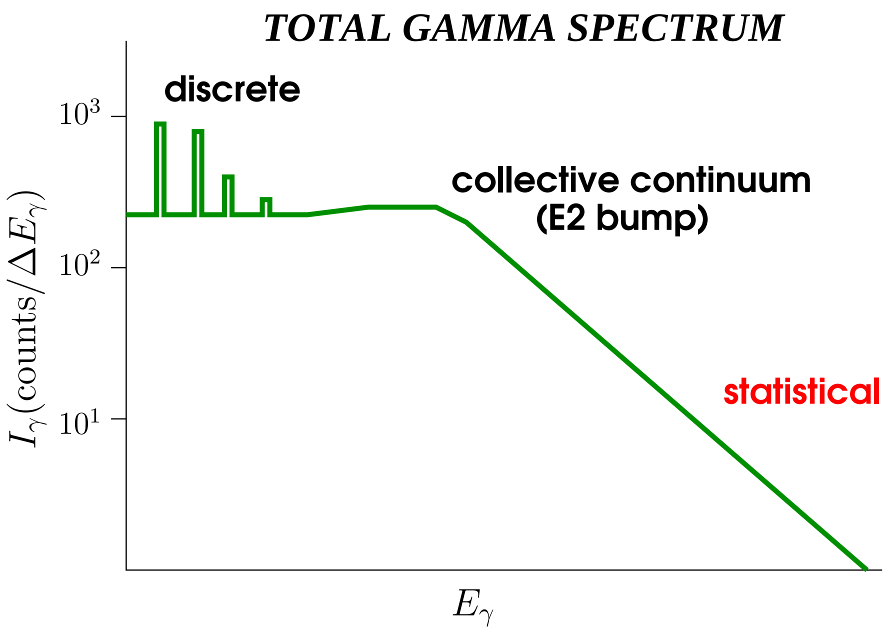
Fusion-evaporation reaction

Our picture of the gamma decay:



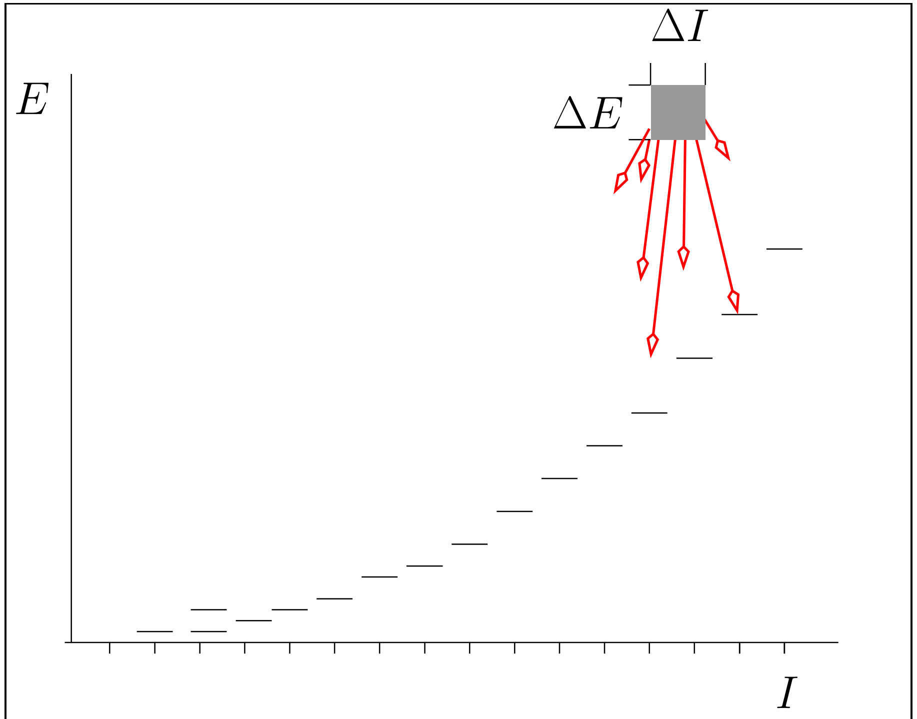
gamma spectroscopy:

... what we see:

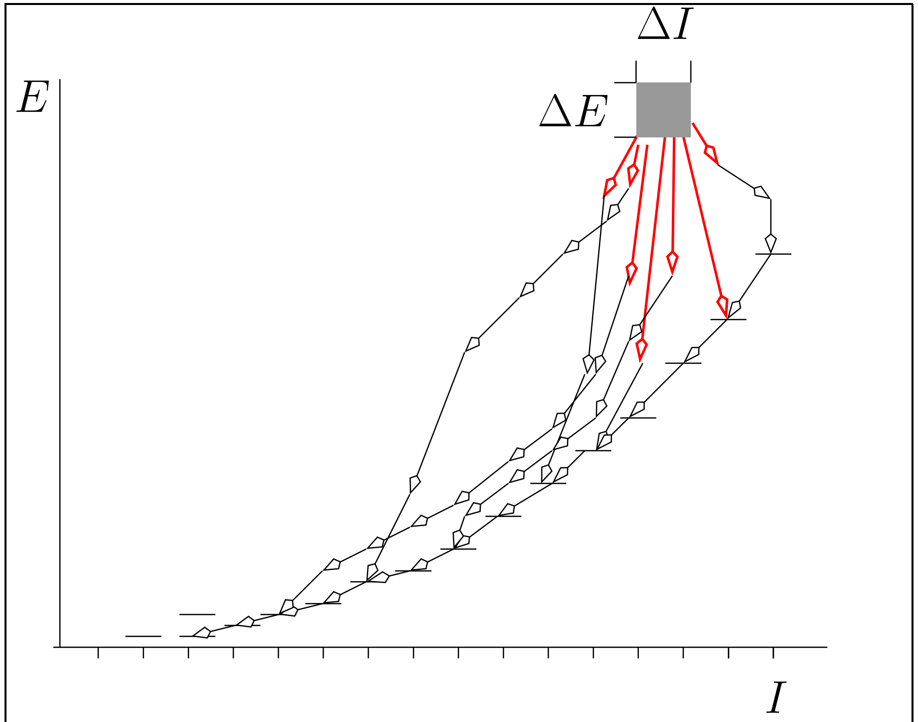


→ Our topic: the statistical part...

Continuum spectroscopy



The goal of continuum γ-spectroscopy: observing **only** radiation emitted by a well defined region $\longrightarrow$ primary radiation.



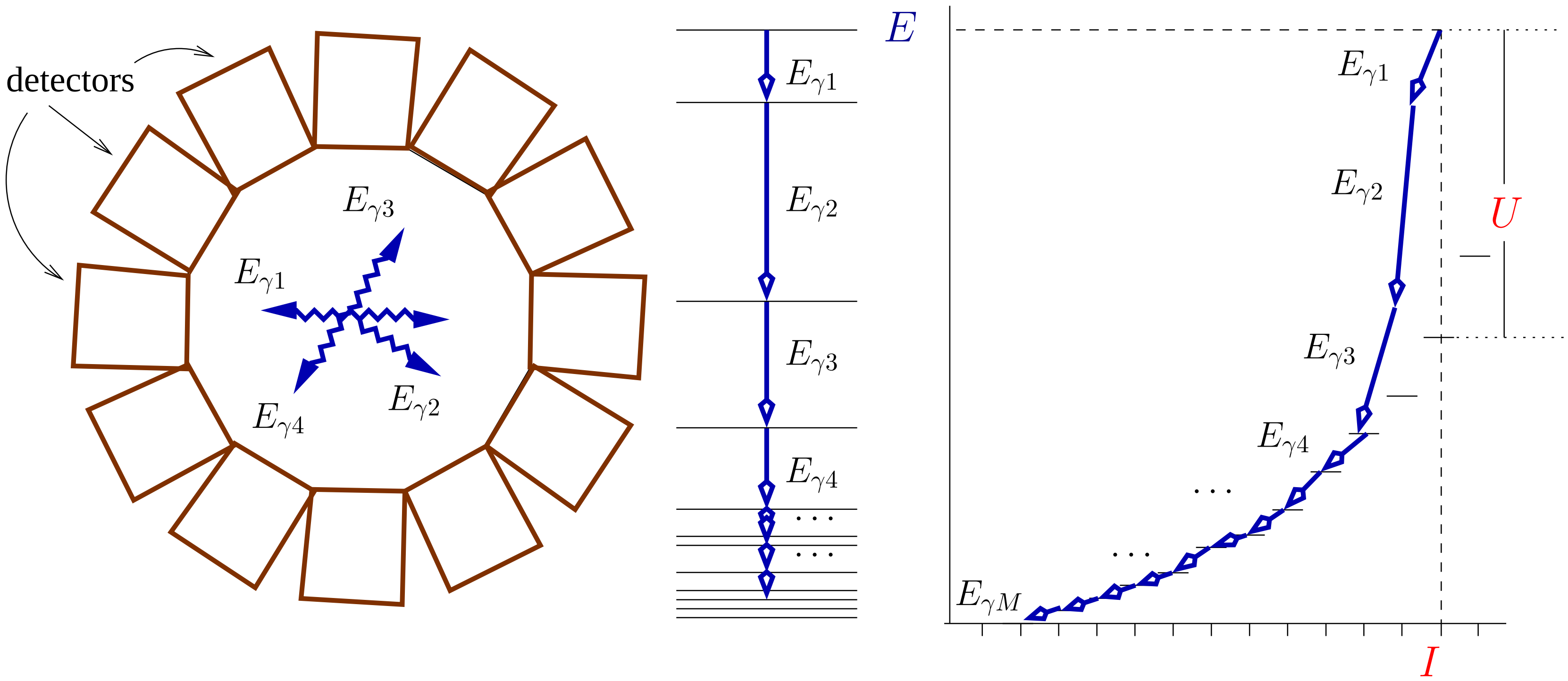
However, any detector system will observe the **full cascades** down to the ground state.

Proposal:

1. Define $\Delta E, \Delta I$ boxes at high excitation and spin: The H-k technique.
2. Obtain an approximation to the primary radiation from that box: Energy Ordered Spectra.

The H-k technique

Let's suppose: (i) 100% efficiency, (ii) high segmentation, (iii) 4π coverage.



M = multiplicity

$$\boldsymbol{E} = \sum_{i}^{M} E_{\gamma i}$$

$$M = M_{yrast} + M_{QC\,E2} + M_{stat}$$

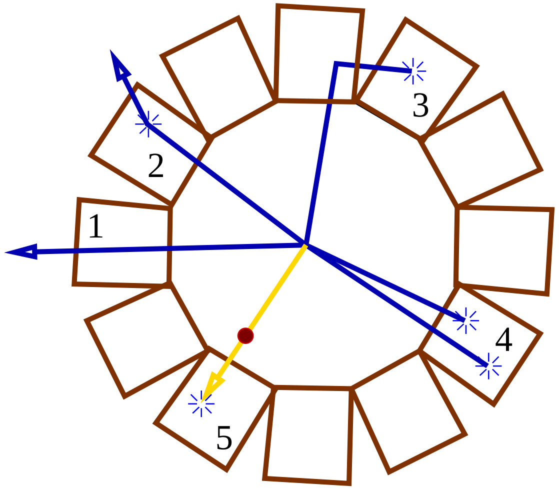
$$\boldsymbol{I} = \sum \langle M_{yrast} \rangle \cdot \Delta I_{yrast} + \langle M_{QC\,E2} \rangle \cdot \Delta I_{QC\,E2} + \langle M_{stat} \rangle \cdot \Delta I_{stat}$$

$\Delta I_{yrast} = 2$ (rotational nuclei); $\Delta I_{QC\,E2} = 2$; $\Delta I_{stat} \approx 0.5$

$\langle M_{yrast} \rangle$, $\langle M_{QC\,E2} \rangle$, $\langle M_{stat} \rangle$ depend on the reaction

$$U = E - E_{yrast}(I)$$

The H-k technique: non-perfect detection system



1. Some rays may escape the spectrometer.
2. Incomplete detection.
3. Detector-detector scattering.
4. pile-up.
5. Other sources: n and high energy p.

Effect: Neither E nor M is correct.

$$M \longrightarrow k = \text{ number of detectors that fired}$$

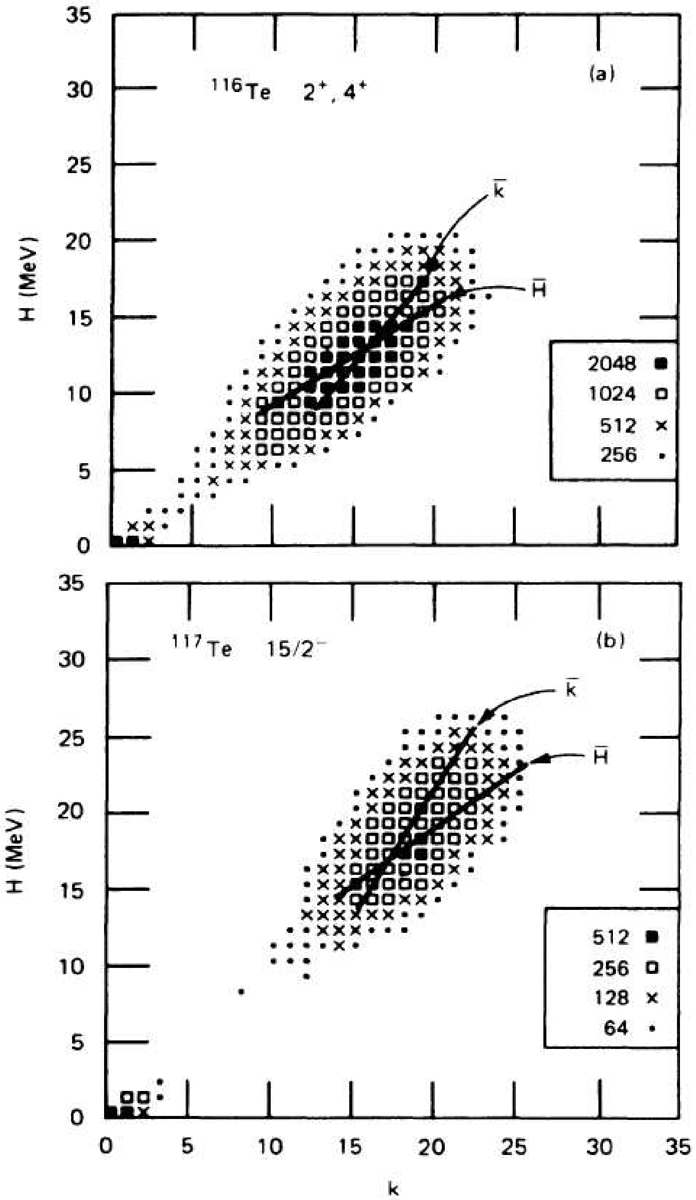
$$\{E_{\gamma 1}, E_{\gamma 2}, \ldots\} \longrightarrow \{h_1,\ h_2,\ \ldots, h_k\} \text{ : pulse heights in the detectors}$$

$$E \longrightarrow H = \sum_{i=1}^{k} h_i = \text{ Total pulse height}$$

Correction:

$$(M, E) \Leftarrow \text{Response Function} \Leftarrow (k, H)$$

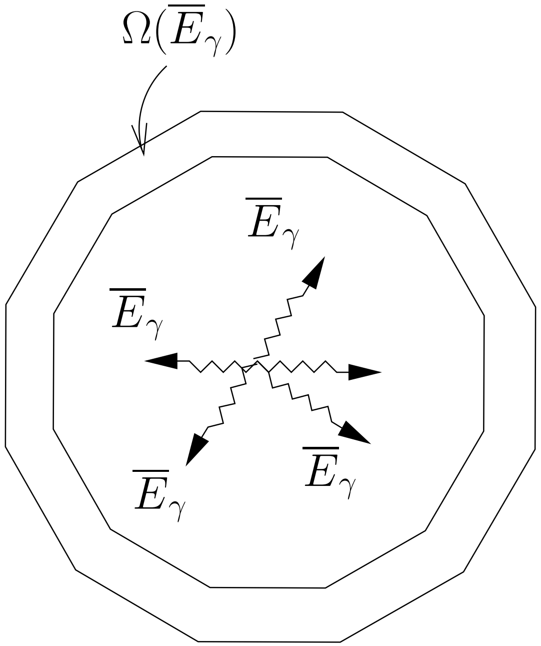
[Jääskeläinen et al., 1983], *Nucl. Instr. Meth.* **204**, 385. "*The Spinspectrometer: design, instrumentation and* **response characteristics of a 4π γ-ray multidetector system.**

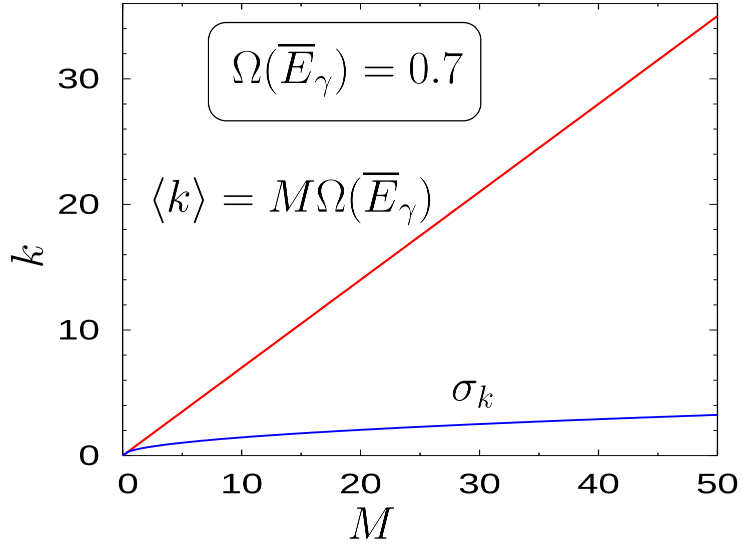


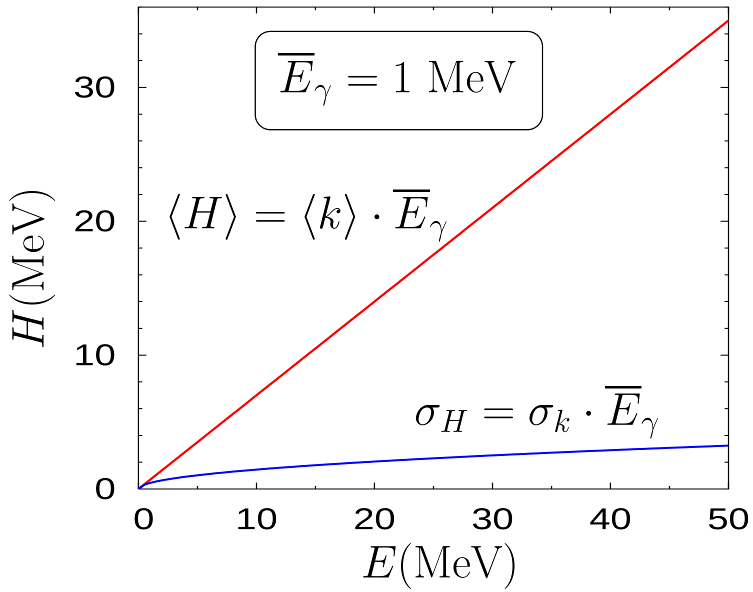
- Ref:[Lee et al., 1987] *Phys. Rev.* C **35**, 605.
- Reaction: ^{70}Zn(^{50}Ti,xn)^{116,117}Te. $E_{lab} = 170$ MeV.
- Lab: Tandem at Oak Ridge National Lab.
- Detection:
  - Spin Spectrometer: 70 NaI
  - 2 Large volumen Ge (efficency 25%)
- Entry state distribution in the $H - k$ plane obtained by gating on the
  (a) $2^+ \to 0^+$ of ^{116}Te.
  (b) $15/2^- \to 11/2^-$ of ^{117}Te.

The easiest detection model:

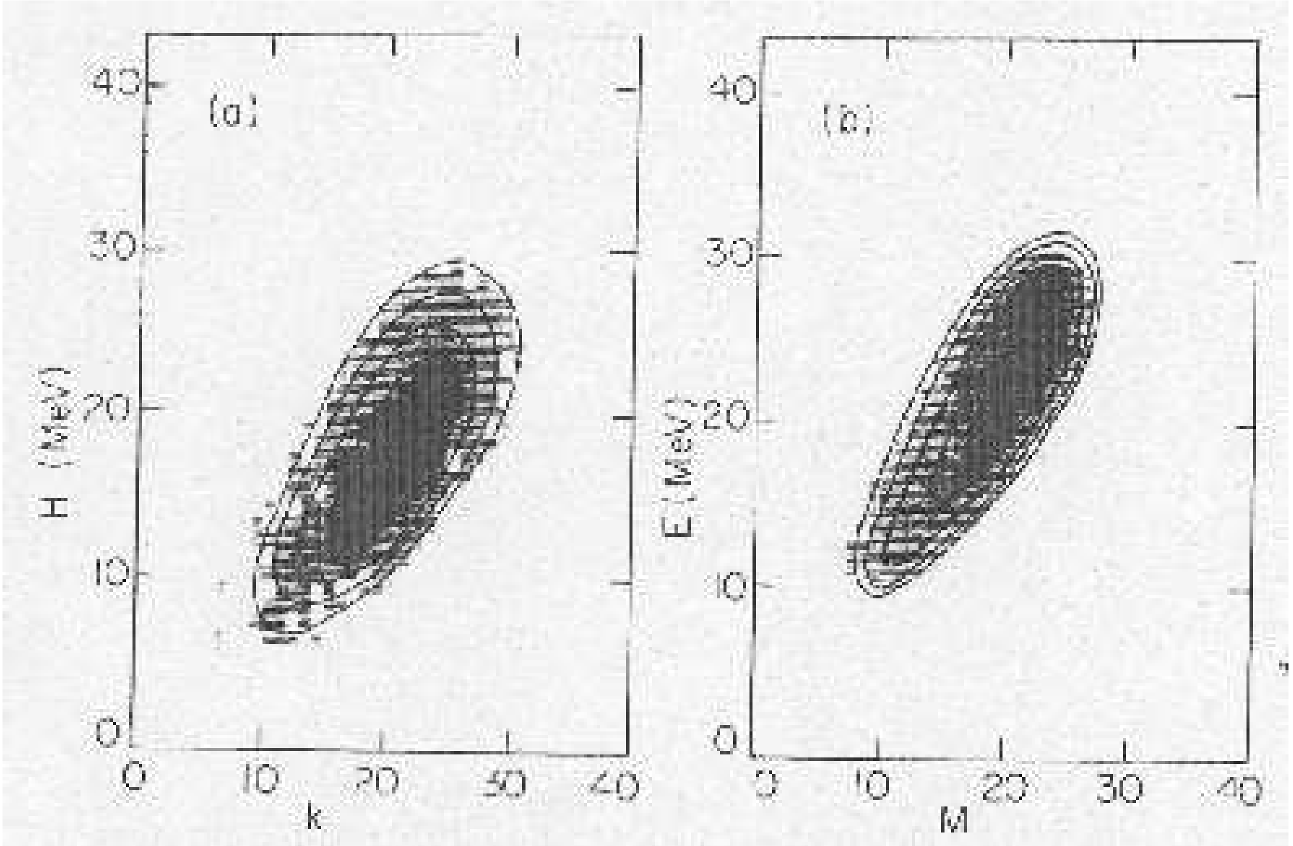
- M incident gamma rays.
- Each with energy $\overline{E}_\gamma$
- Detection efficiency $\Omega(\overline{E}_\gamma)$ for the entire spectrometer.
$$\overline{E}_\gamma = \frac{E}{M}$$
- Ignore the division into N detectors.
- Probability $\longrightarrow$ Binomial distribution





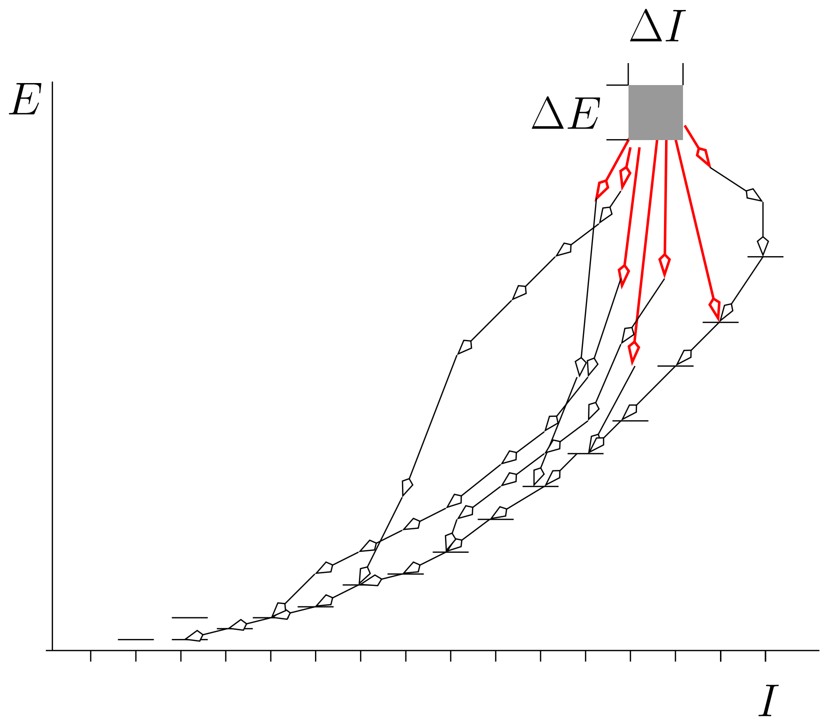


Experimental $H - k \rightarrow E - M$



- Reference: [Jääskeläinen et al., 1983] *Nucl. Instr. Meth.* **204**, 385.
- Reaction: ^{146}Nd(^{20}Ne,$6n$)^{160}Yb, $E_{lab} = 136$ MeV.
- Entry population in the (a) $k - H$ plane; $\longrightarrow$ (b) Reduction to the $M - E$ plane.

Conclusion: $[\Delta E, \Delta I]$ boxes at defined (E, I) values are experimentally possible.



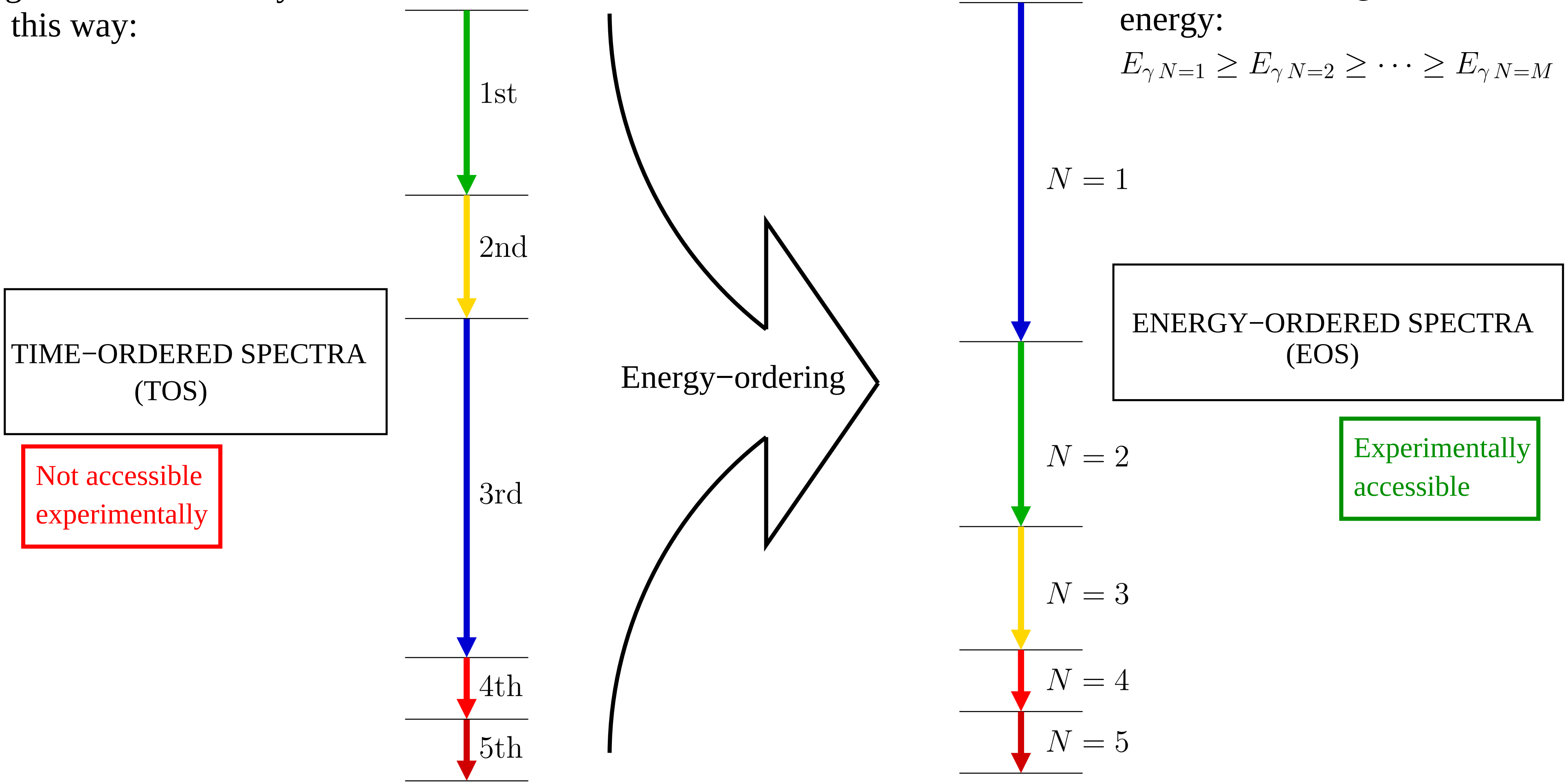
Next problem: **primary radiation**

Ordered spectra

The time sequence of a gamma cascade may look this way:

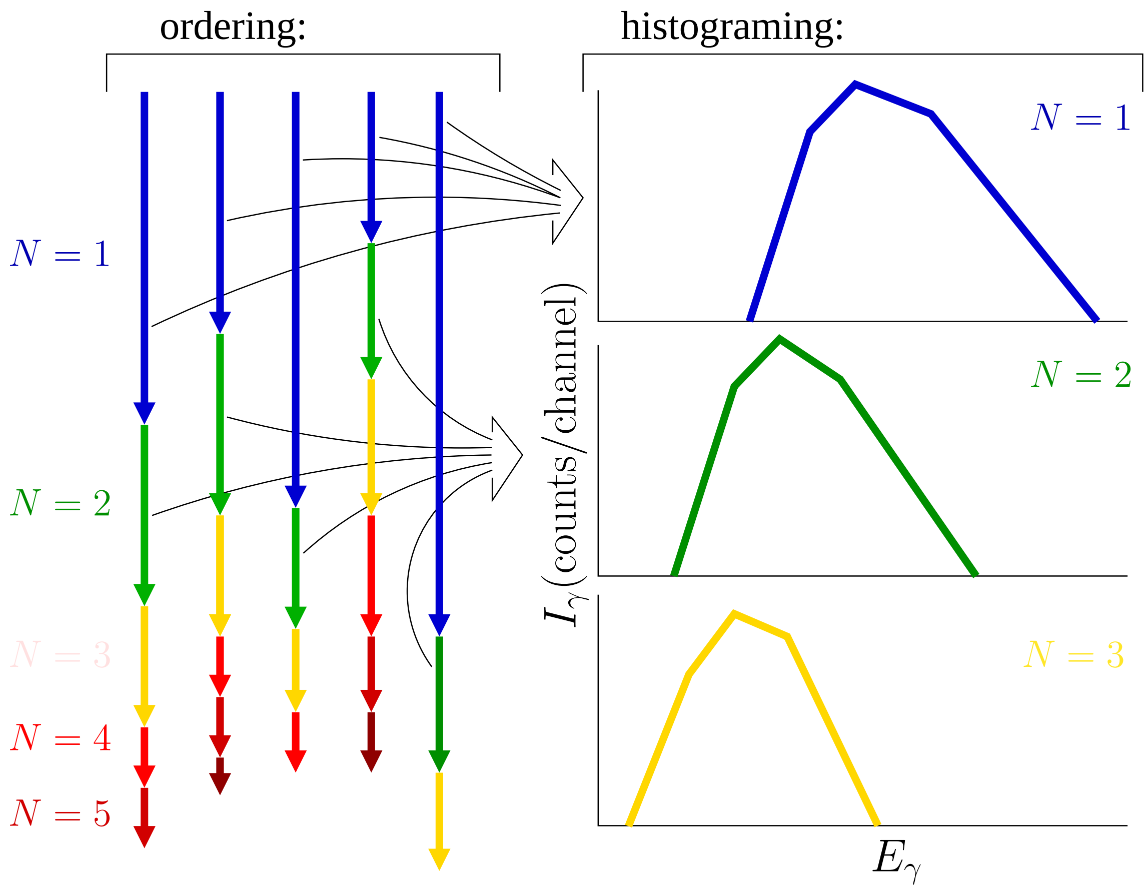
The gamma rays can be ordered according to their energy:

$$E_{\gamma\, N=1} \geq E_{\gamma\, N=2} \geq \cdots \geq E_{\gamma\, N=M}$$

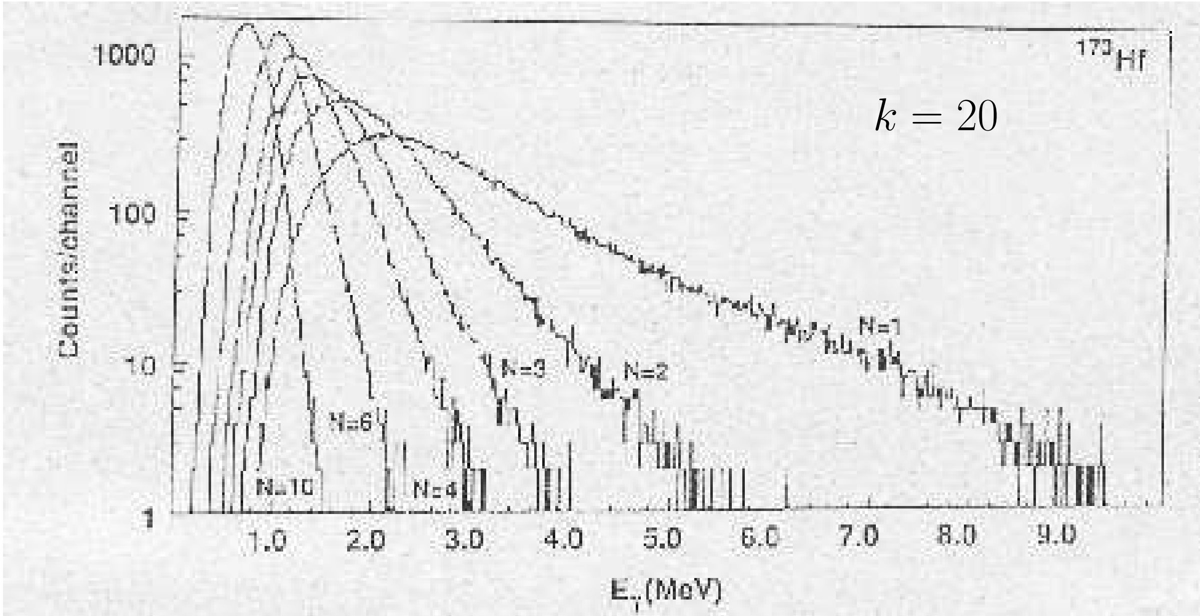


Reference: [Baktash et al., 1990] *Nucl. Phys.* **A520**, 555c.

Constructing Energy-ordered spectra



Experimental Energy-Ordered Spectra



Reaction: ^{130}Te(^{44}Ca,4n)^{170}Hf. $E_{lab} = 196$ MeV

Set-up: SpinSpectrometer (52 NaI) + 18 CS-Ge

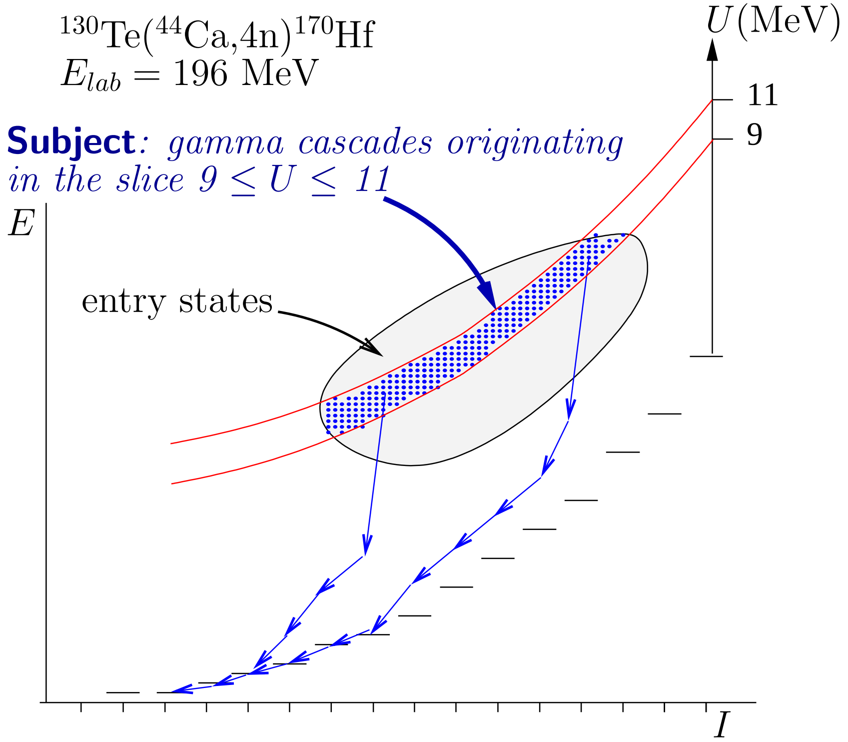
(Remember: GASP I = 80 BGO + 40 Ge)

Target: 1 mg/cm^2.

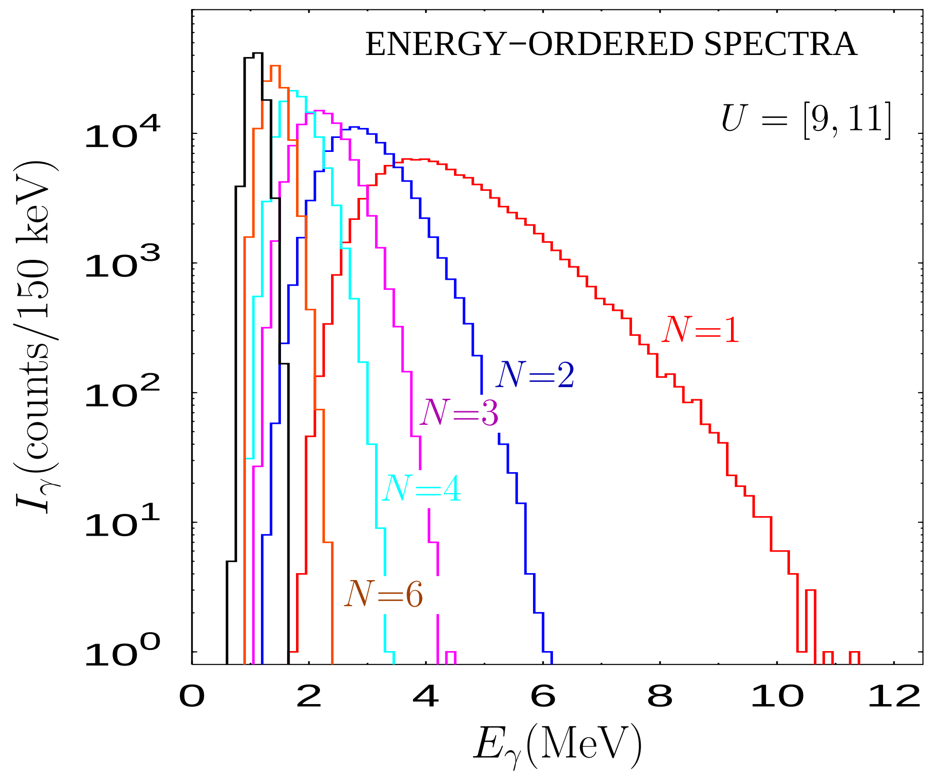
[Baktash et al., 1990] *Nucl. Phys.* **A520**, 555c.

Simulated Energy-Ordered Spectra

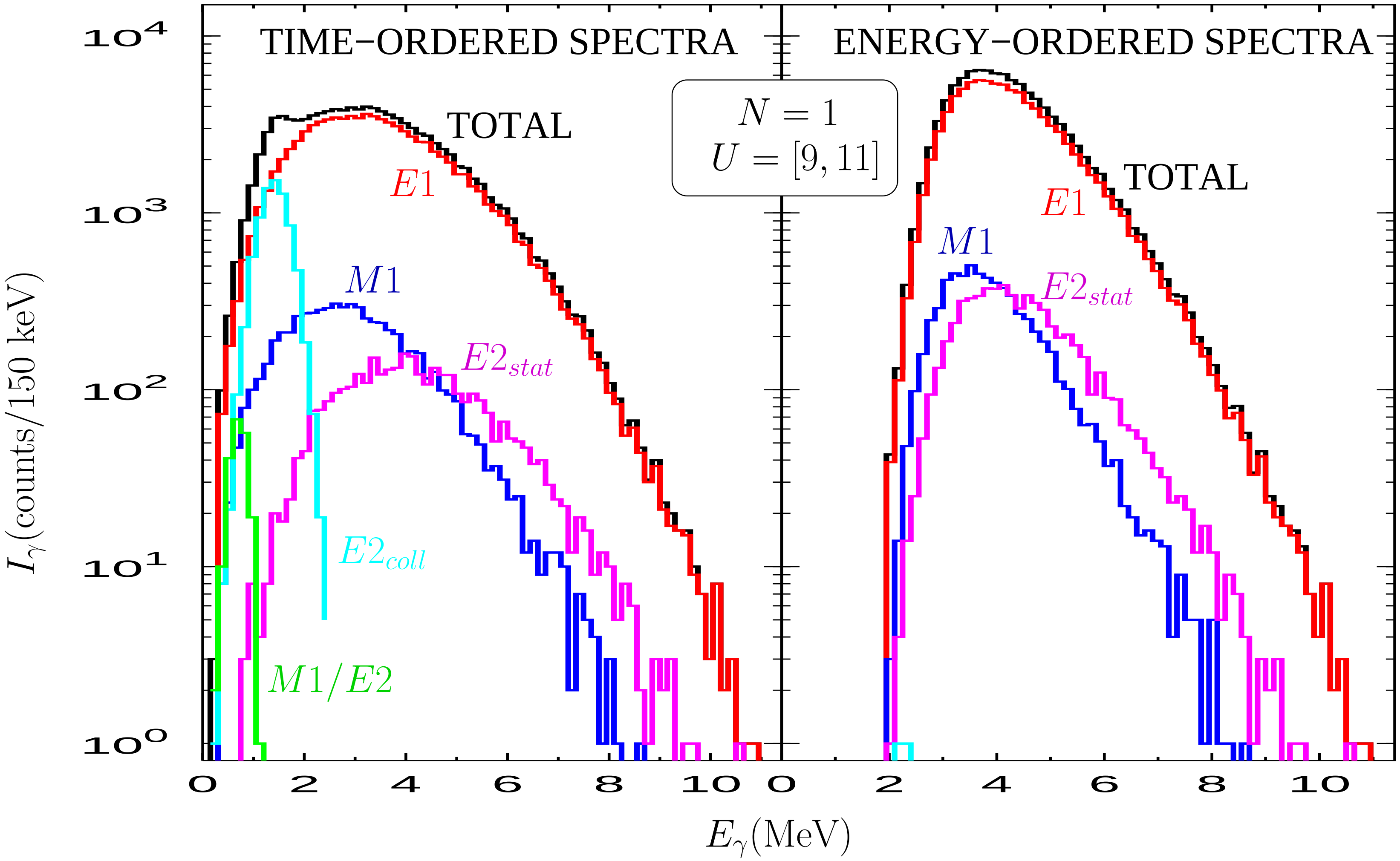
Based on the Monte Carlo code GAMBLE.
[Leander, 1987]*Comp. Phys. Comm.* **47** 311.



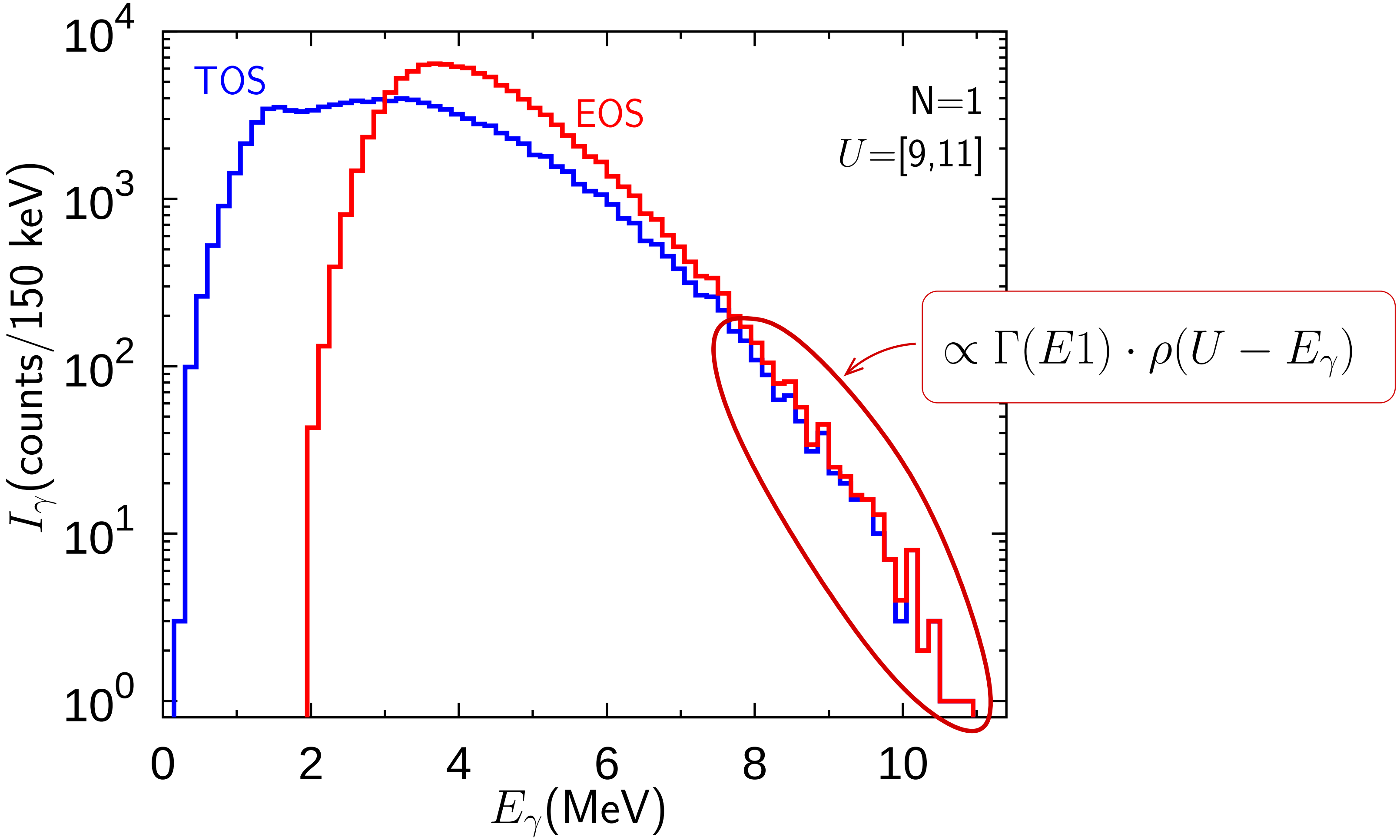
Input Parameters
Statistical Decay
Level density: Fermi Gas. $a = 20$ MeV^{-1}
Gamma strengths: M1, E2 : single-particle E1: GDR (from systematics)
Collective Decay
$\mathcal{J}$, Q_0, Γ_{rot}, i (s.p. alignment) Typical values for $A \approx 160$
Yrast line: Experimental + RLDM



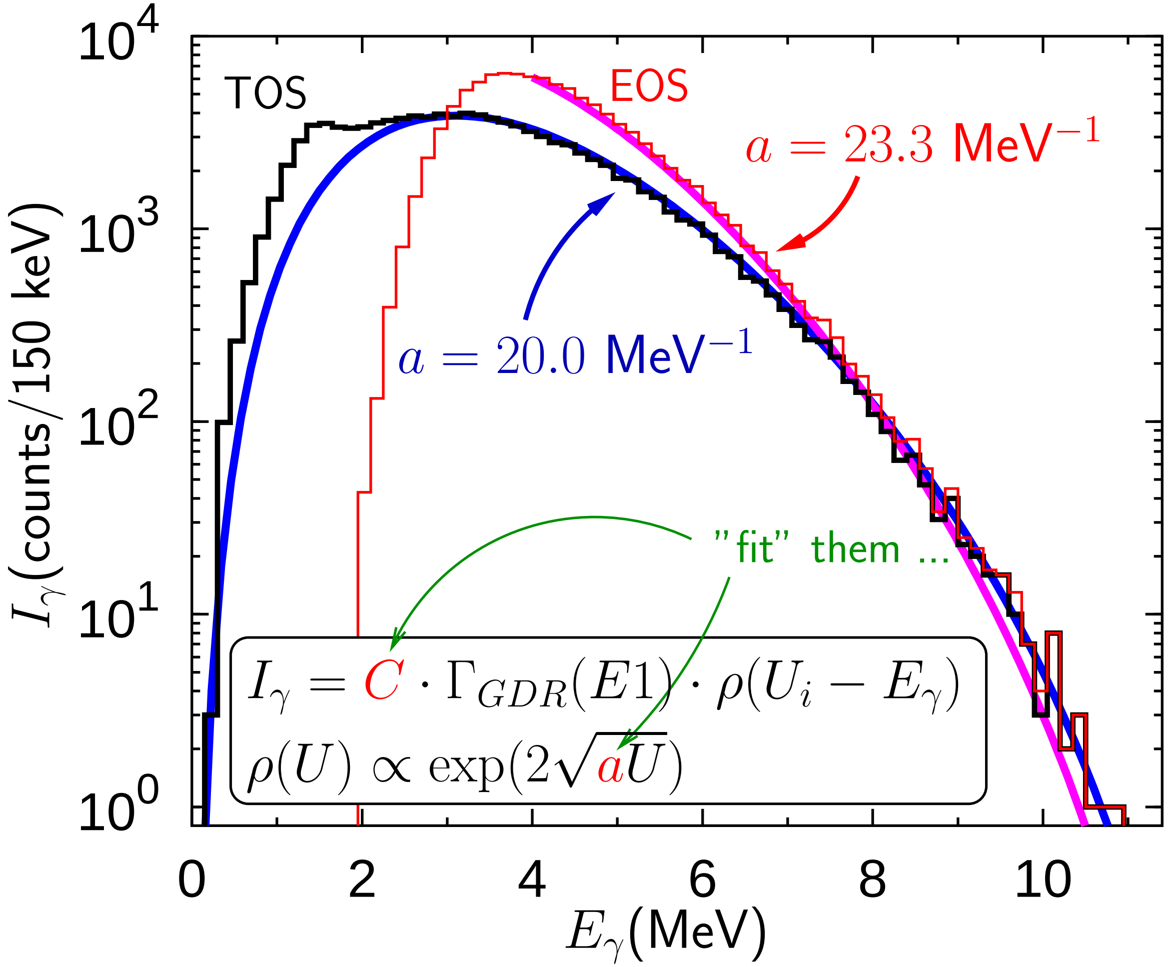
Spectral decomposition of Ordered Spectra



Conclusion: EOS are mainly composed by E1 radiation.



Conclusion: EOS = TOS at high transition energies



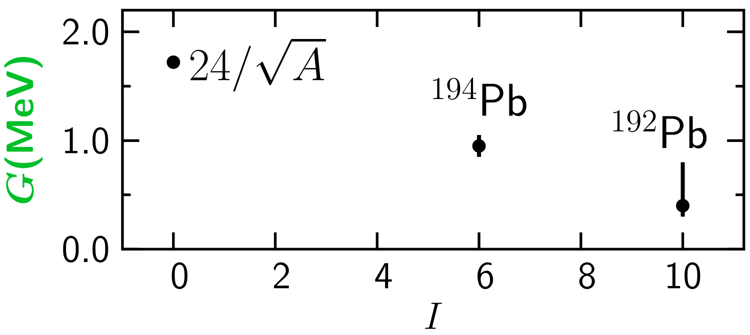
Conclusion: $\boldsymbol{a}$ ... measurable at high spin.

[Cristancho, 1995] Heavy Ions Physics **2**, 299.

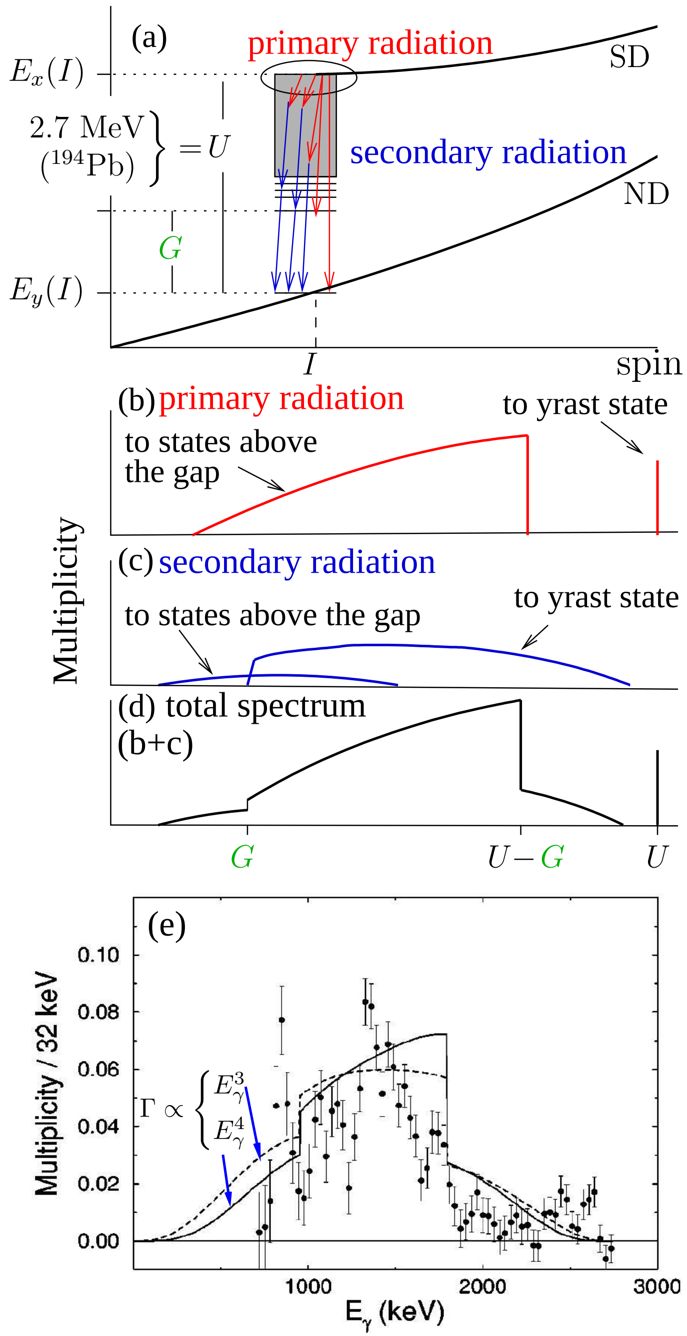
Experiment 1: Dependence of pairing on spin

[McNabb et al., 2000] *Phys. Rev.* C **61**, 31304(R).

- **Purpose: Quasicontinuous decay of superdeformed bands.**
- Detection: GAMMASPHERE.
- Reactions: ^{173,174}Yb(^{23,25}Mg,5n)^{192,194}Pb.
- Data analysis: Fit the total gamma spectrum with
  - $\rho_{CT}(U) = \exp(U/T) = \exp[(U - \boldsymbol{G})/T]$,
  - $\Gamma(E_\gamma) \propto \begin{cases} E_\gamma^4 \\ E_\gamma^3 \end{cases}$.
- Result:



Conclusion: Pairing decreases with spin.

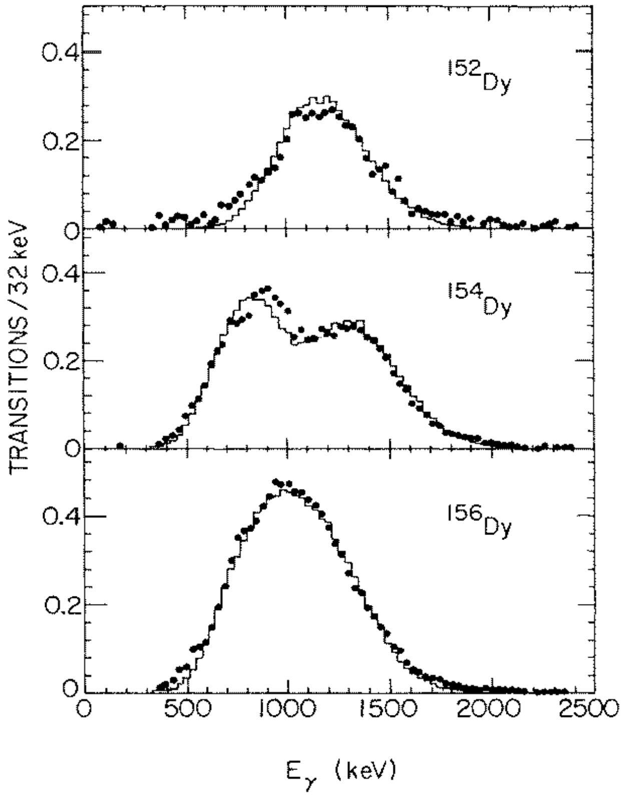


Experiment(s) 2: Phase shape transitions in ^{154}Dy

Quasi-continuum E2 spectra in ^{152,154,156}Dy

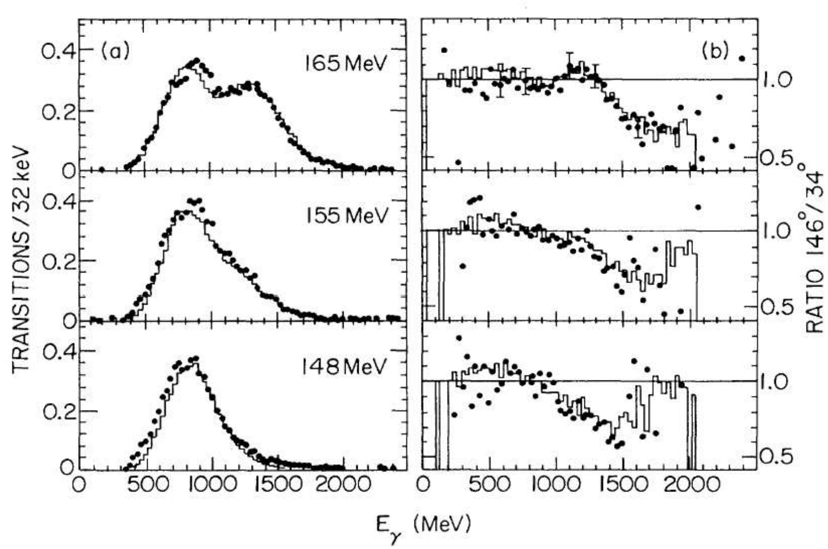
[Holzmann et al., 1989] *Phys. Rev. Lett.* **62**, 520.

$$E_\gamma = \frac{\hbar^2}{2\mathcal{J}}(2I-1)$$



- "Same" reaction: ^{120,122,124}Sn(^{36}S,4n)^{154,156}Dy.
- Average entry points lie at very similar (I_{entry}, E_{entry}) values.
- Only ^{154}Dy shows two maxima.

Quasi-continuum E2 spectra in ^{154}Dy



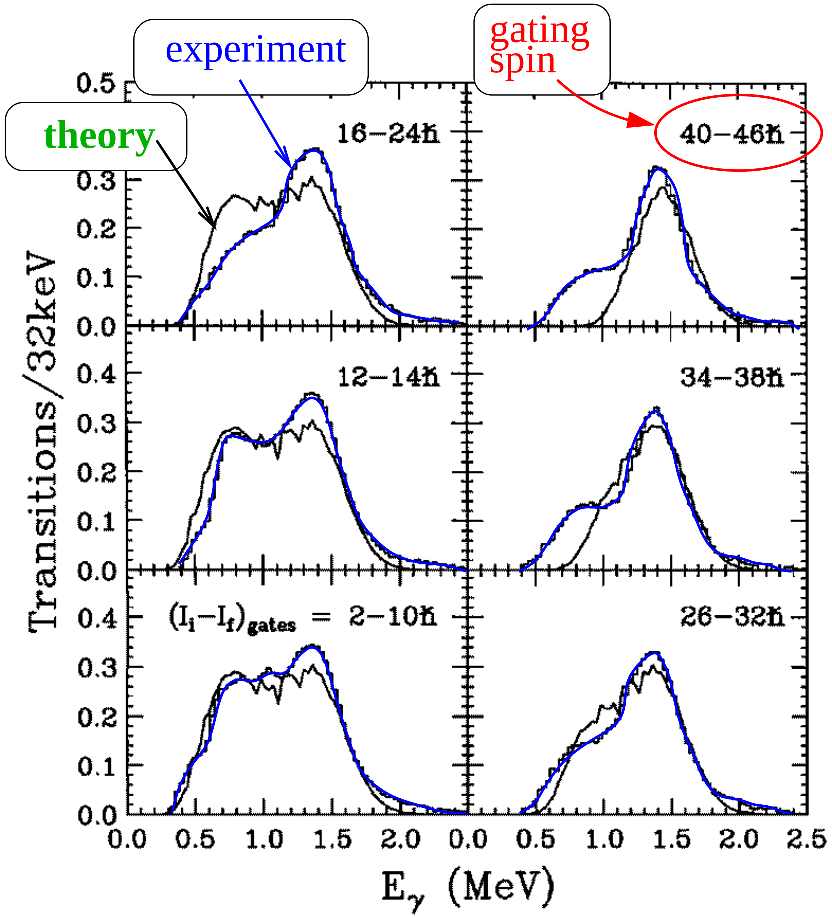
- Average multiplicity and energy both increase with beam energy.
- Lower peak remains constant: $\langle E_\gamma \rangle \approx 0.8$ MeV does not change.

Conclusion: Transitions associated to the upper peak precede the ones that build up the lower peak.

Spin-gated E2 quasicontinuum spectra

[Ma et al., 2000] *Phys. Rev. Lett.* **84**, 5967.

Detection: Gammasphere early-inplementation (36 CS-Ge).

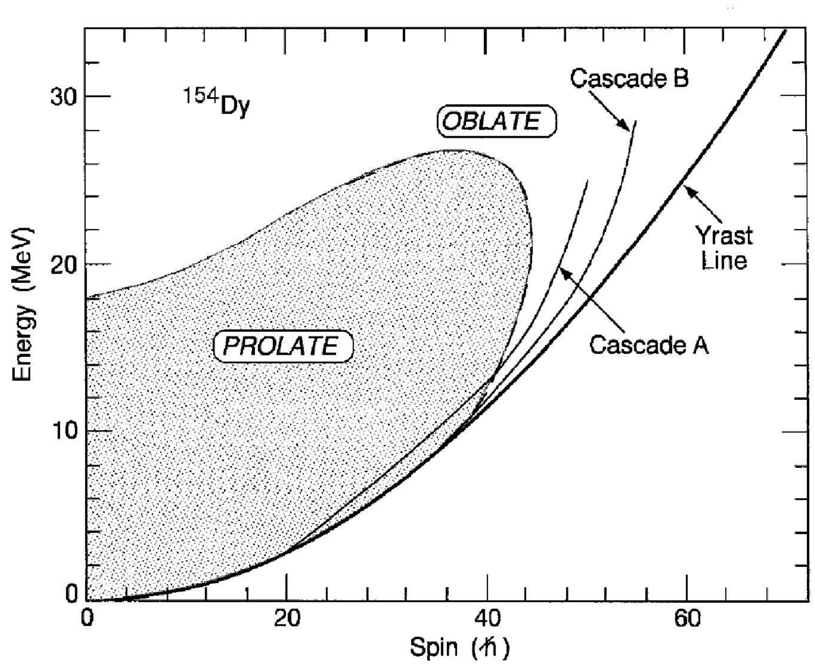


$$E_\gamma = \frac{\hbar^2}{2\mathcal{J}}(2I-1) \longrightarrow \begin{cases} \text{lower spins: large } \mathcal{J} \\ \text{higher spins: smaller } \mathcal{J} \end{cases}$$

Conclusion: shape transition

Theory: Finite Temperature Hartree-Fock-Bogoljubov

[Martin and Egido, 1995] *Phys. Rev.* C **51**, 3084.



Conclusion: temperature-induced shape transitions !!

Some considerations:

- "Shape transition" is a thermodynamical concept...
- ... Could we see thermodynamical signatures of phase shape transition in ^{154}Dy?...
- Look at thermodynamical properties $\longrightarrow$ level densities $\longrightarrow$ relationship $U \leftrightarrow T$: $\boldsymbol{a}$

Proposal

1. Take GASP I
2. 80 BGO for continuum studies: work out...
   (a) $(H-k) \longrightarrow (E-M)$ response function: [Jääskeläinen et al., 1983].
   (b) Experiment $\longrightarrow$ ^{154}Dy.
   (c) Define $[\Delta U, \Delta I]$ boxes. Obtain EOS from boxes in different spin-energy regions. Obtain $\boldsymbol{a}$ for each box.
   (d) What else can you do with EOS?... gamma strengths? What about other orders, say $N = 2, 3, \ldots-$EOS? What does "Order Statistics" say?
3. 40 CS-Ge: reproduce (or improve) the procedure by [Ma et al., 2000] to study E2 quasicontinuum.
4. Cross-check results from 2. and 3.

References

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[McNabb et al., 2000] McNabb, D. P., Cizewski, J. A., Khoo, T. L., Lauritsen, T., Hauschild, K., Ding, K. Y., Fotiades, N., Younes, W., Archer, D. E., Bauer, R. W., Becker, J. A., Bernstein, L. A., Clark, R. M., Deleplanque, M. A., Diamond, R. M., Fallon, P., Lee, I. Y., Machiavelli, A. O., MacLeod, R. W., aned A. Lopez-Martens, F. S. S., and Kelly, W. H. (2000). Quasicontinuous decay spectra of superdeformed bands in ^{192,194}Pb and energy gaps in level density at moderate angular momenta. *Phys. Rev. C*, 61:031304(R).