Nuclear Structure from Gamma-Ray Spectroscopy

2019 Postgraduate Lectures

Lecture 10: Experimental Techniques

Why Study Gamma Rays?

- The strong force constrains the distribution and motion of the nucleons within the nucleus
- Nuclear charges and currents generate time-varying EM potentials and fields – these reflect the underlying structure
- Gamma rays arise from EM interactions and allow a probe of structure without large perturbations of the nucleus
- The EM interaction is well understood

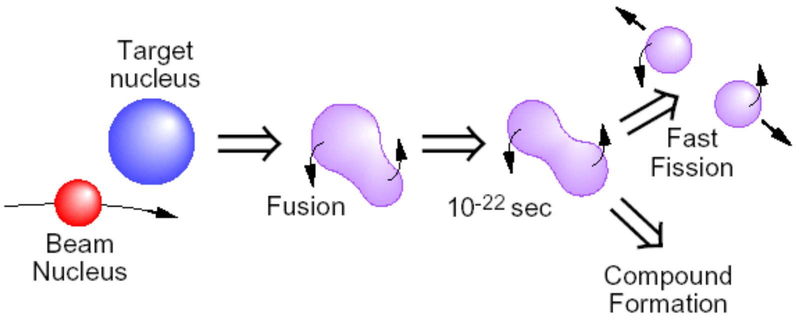
Gamma Ray Spectroscopy

- Gamma rays provide a superb probe for nuclear structure
  - relatively easy to detect with good efficiency and resolution
  - emitted by almost all low-lying states
  - penetrating enough to get out to detectors
  - no model dependence in the interaction (EM is well understood)

Spectroscopic Techniques

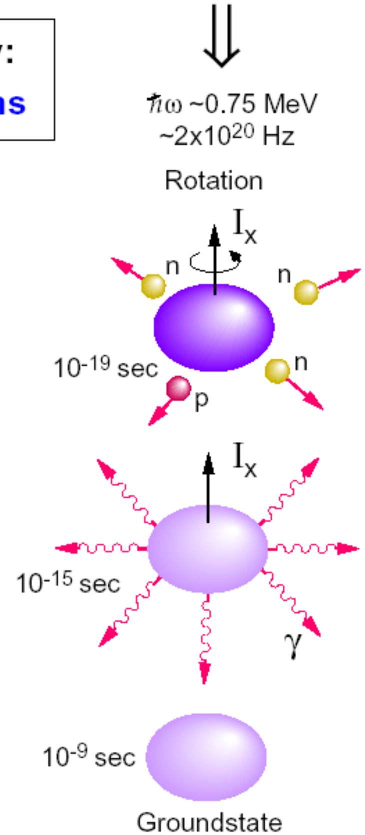
- Energies, coincidence relationships
  - level structure
- Angular correlations, linear polarisation
  - spin and parity
- Doppler shift, lineshape analysis
  - lifetime, quadrupole moment
- Branching ratios, multipole mixing ratios
  - wavefunctions, transition matrix elements

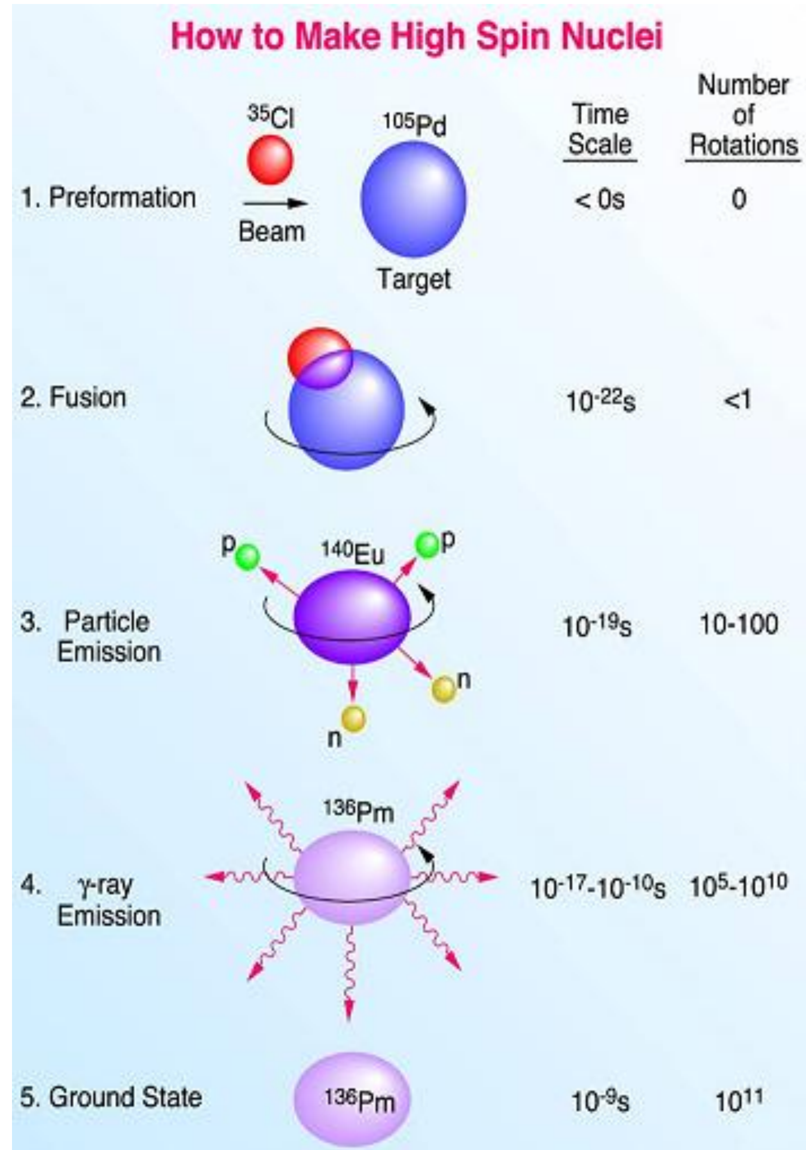
Fusion Evaporation Reactions



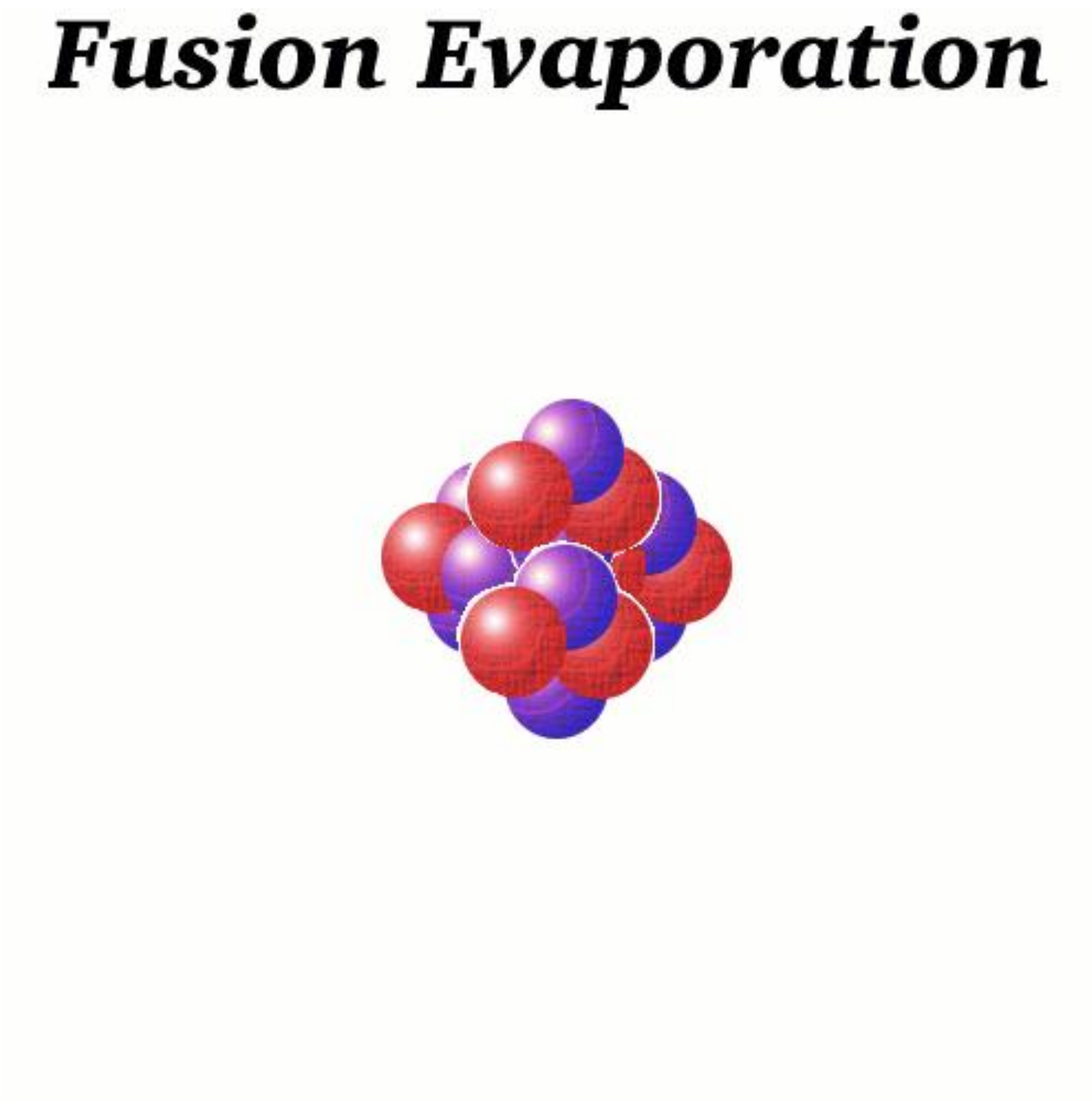
In-Beam Gamma Spectroscopy:
Fusion-Evaporation Reactions

- Large cross section; ~1 barn
- Ideal for populating states with very high angular momentum (as high as ~70 ħ)
- Large gamma-ray multiplicity
  - → need high-granularity high-efficiency high-resolution gamma detector array
- No Coulomb barrier for neutrons
  - → tends towards proton-rich nuclei, hard to make neutron-rich





Nuclear Reaction



David Campbell
Florida State
University

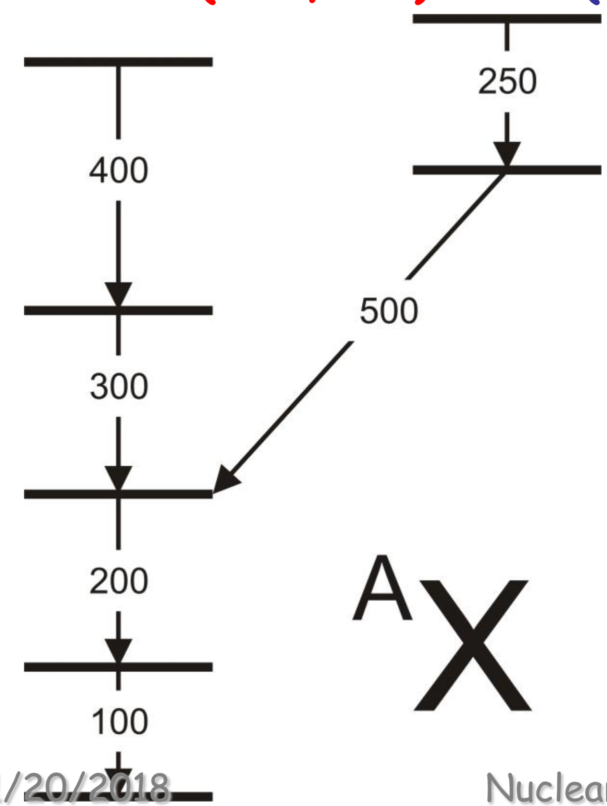
Generating spectra from high-fold coincidence data.

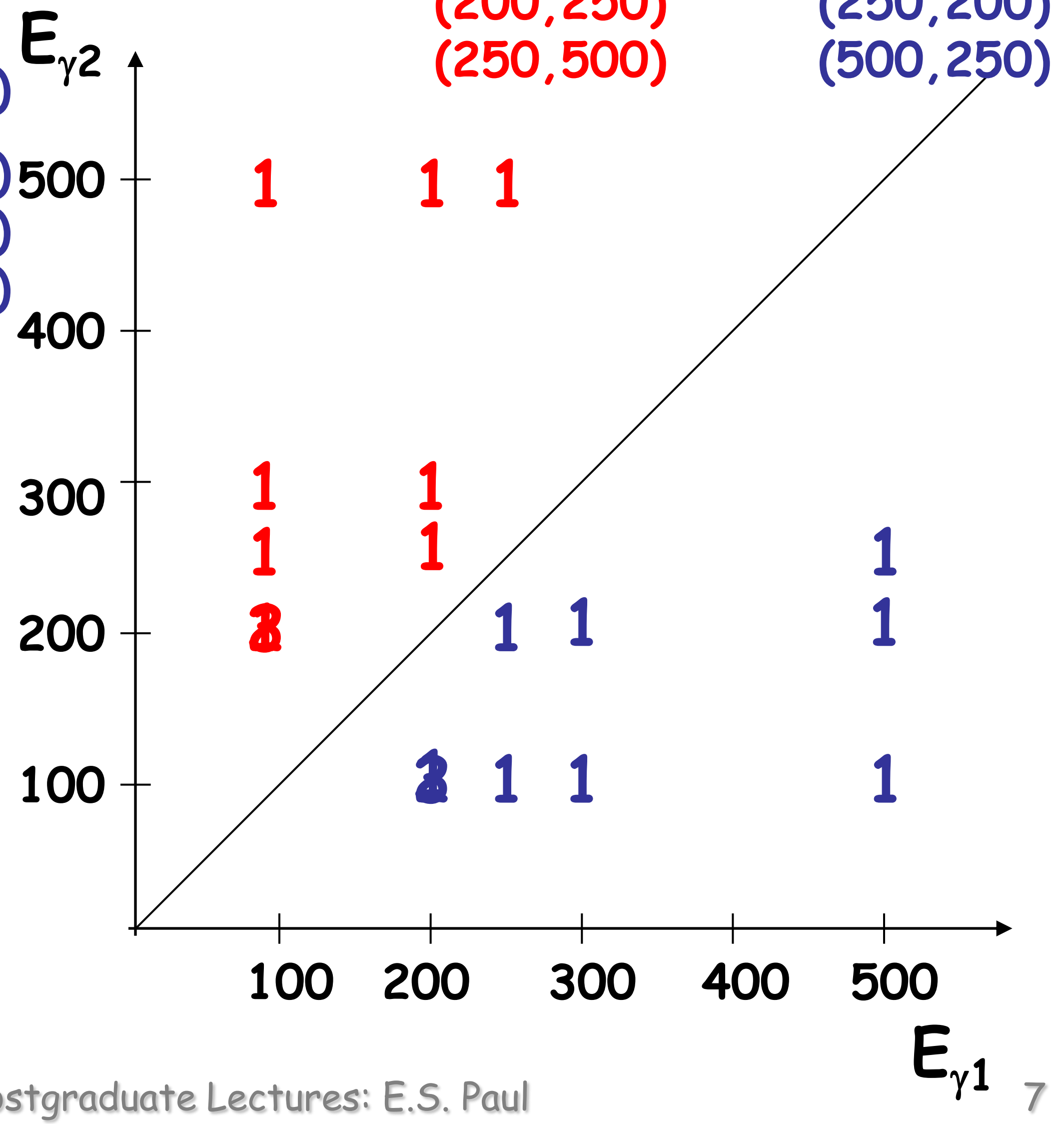
Raw Event 1: 100, 200.
Raw Event 2: 100, 200, 300.
Raw Event 3: 100, 200, 500, 250.

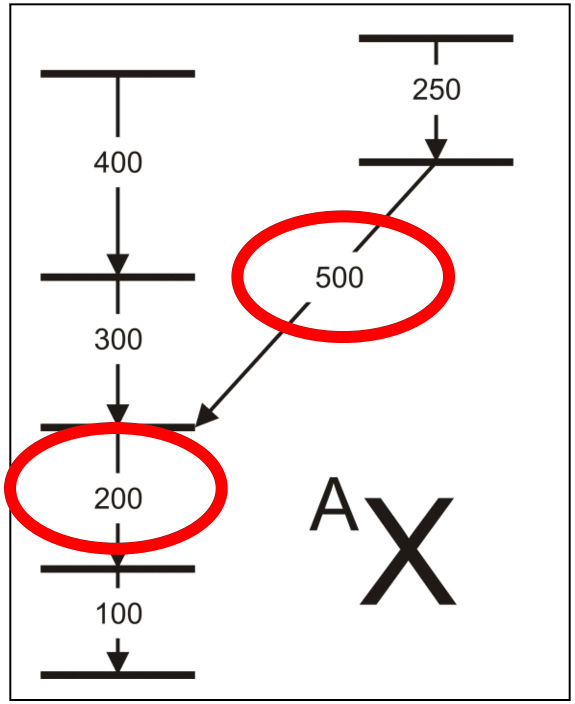
Event 1 (100, 200) (200,100)

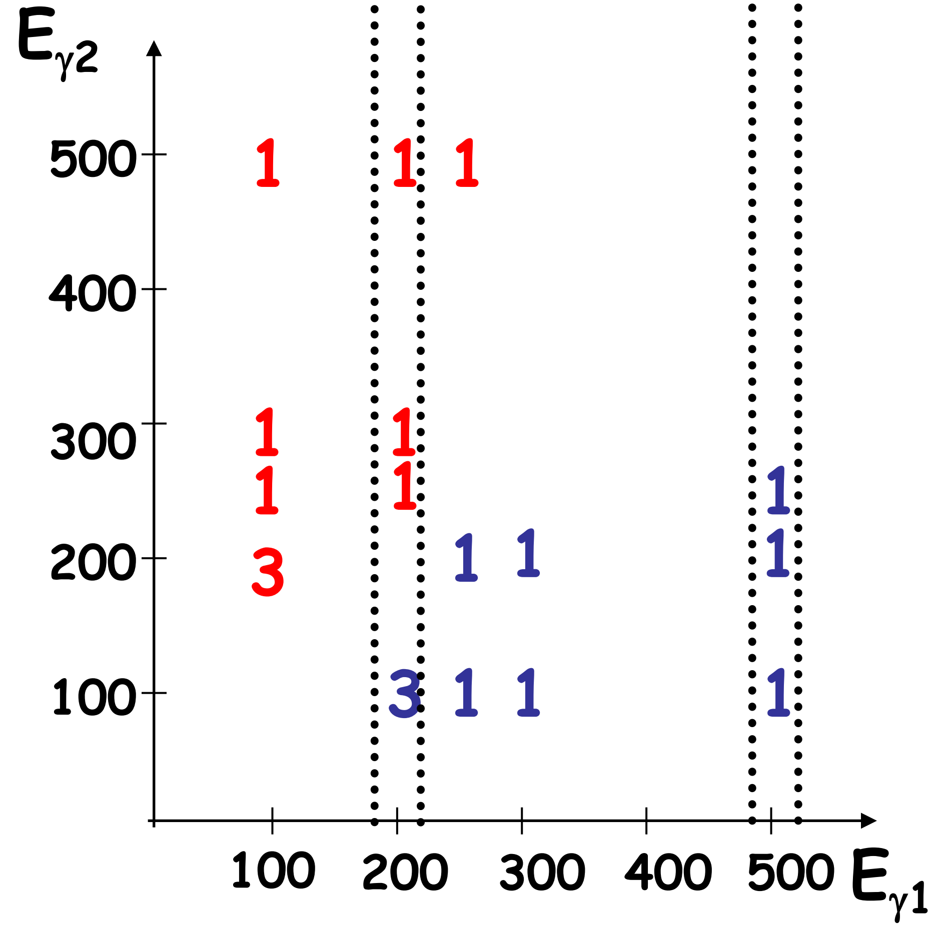
Event 2 (100,200) (200,100)
(100,300) (300,100)
(200,300) (300,200)

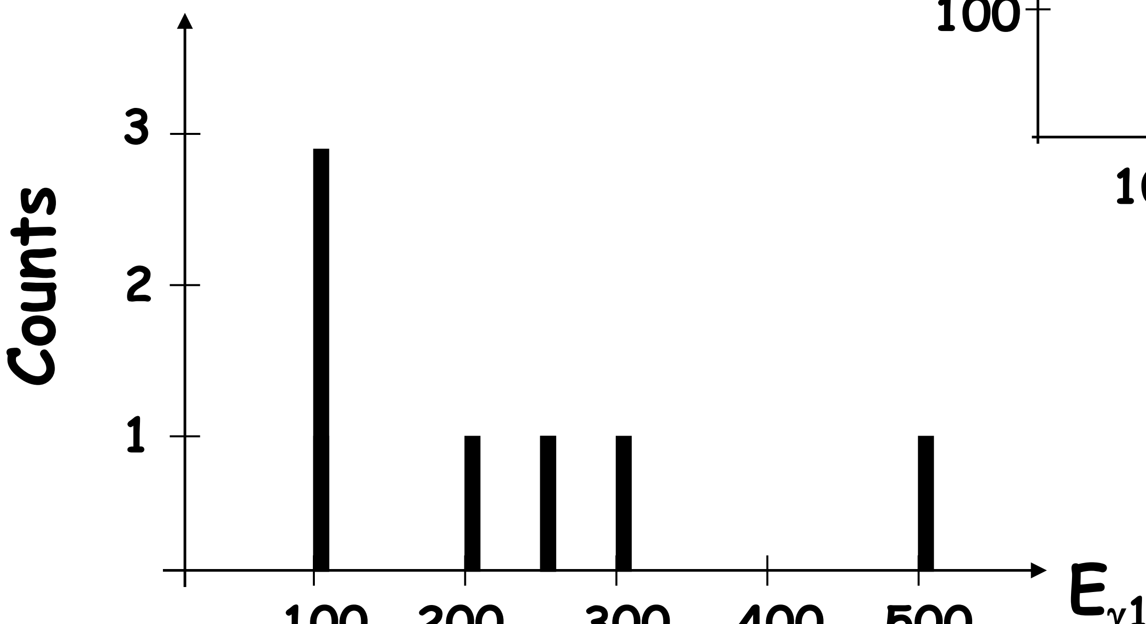
Event 3 (100,200) (200,100)
(100,500) (500,100)
(100,250) (250,100)
(200,500) (500,200)
(200,250) (250,200)
(250,500) (500,250)





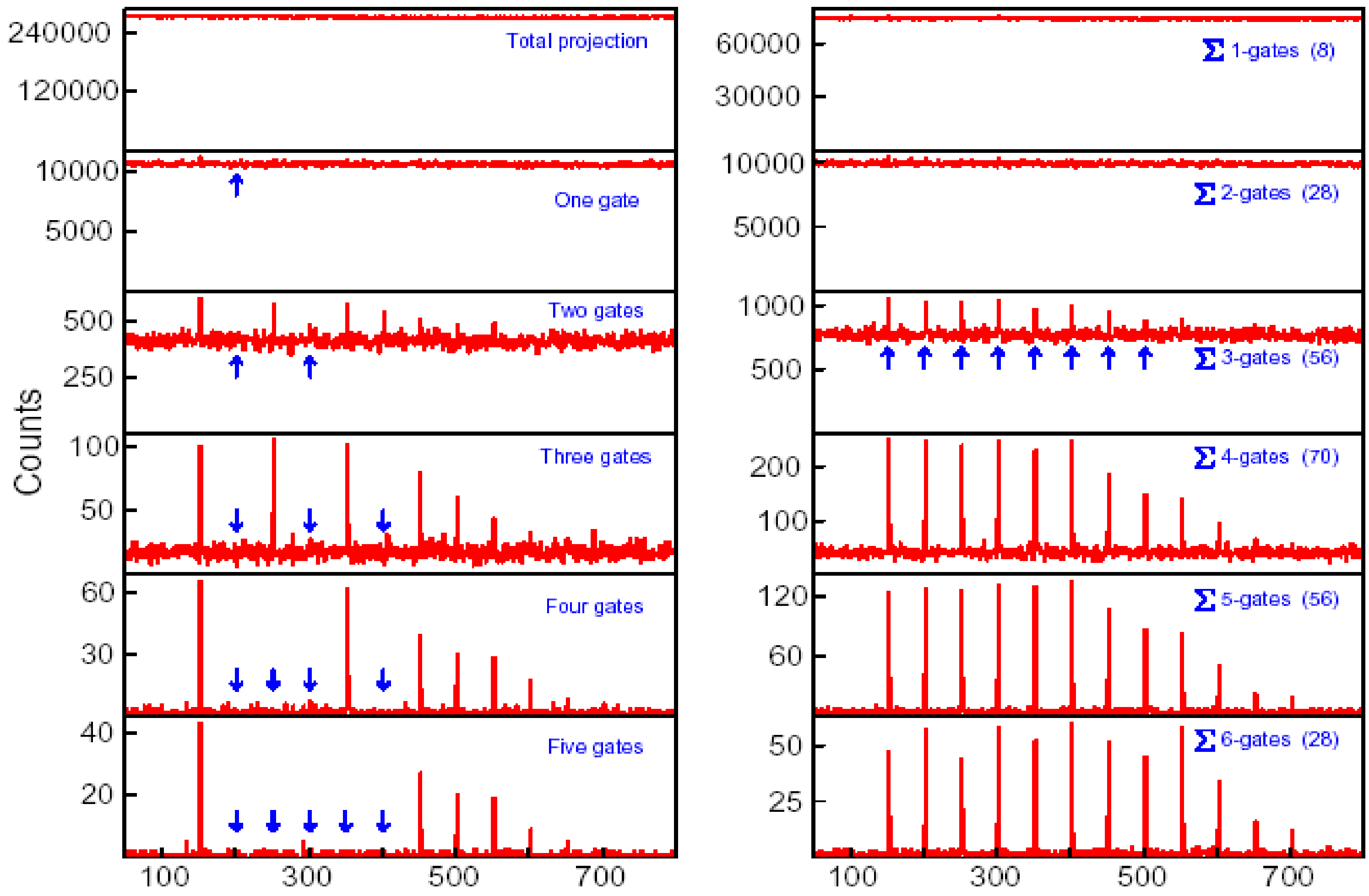

250
400
500
300
200
100
AX


Eγ2
500
400
300
200
100
100 200 300 400 500
Eγ1

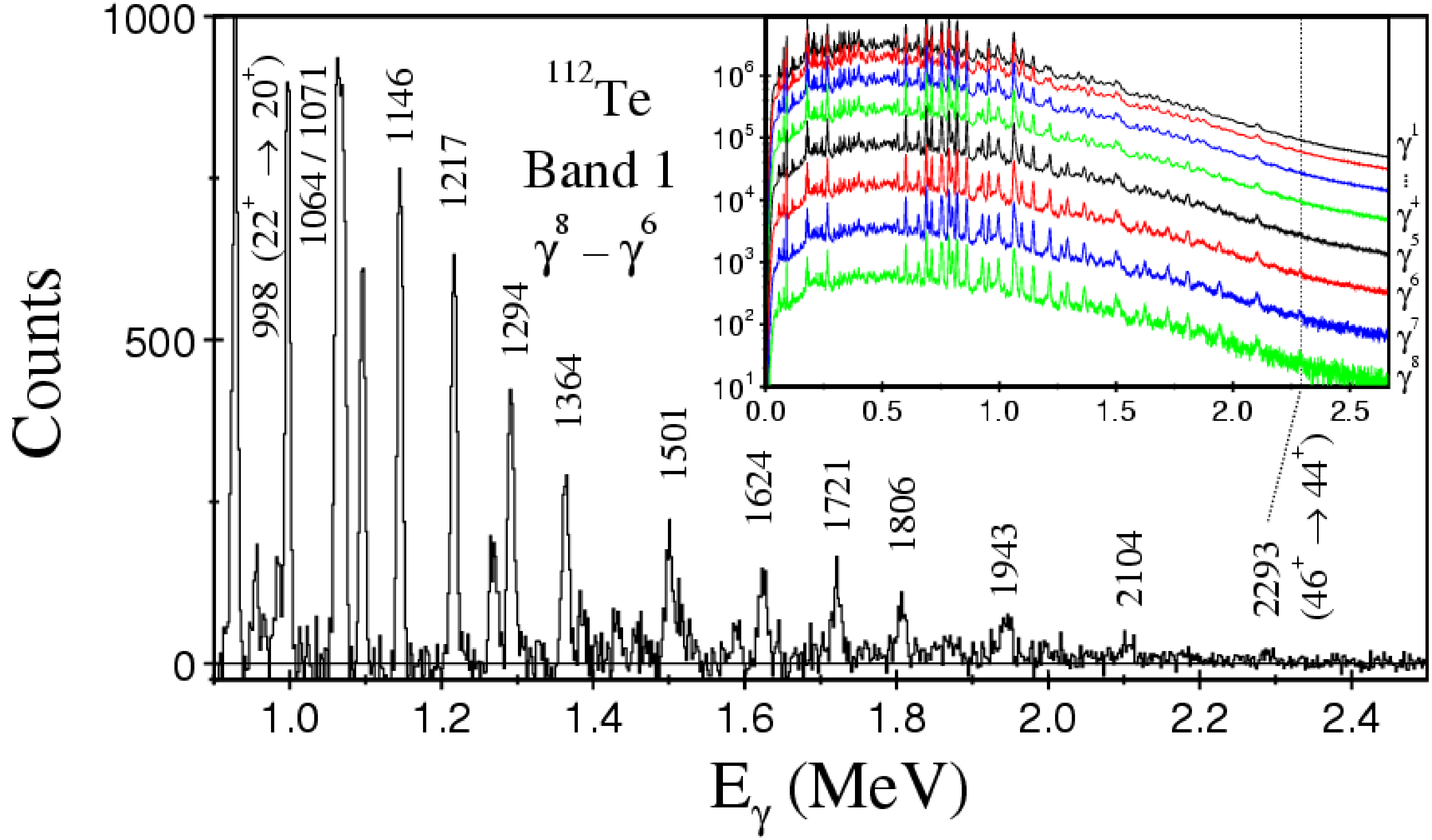

Counts
3
2
1
100 200 300 400 500
Eγ1

Coincidence Gates

Improving Peak-to-Background - gated spectra



High-Fold Spectra



- High-fold coincidence spectra from Gammasphere

Angular Distributions

- Following a heavy-ion fusion-evaporation reaction the nuclear spin is aligned in a plane perpendicular to the beam axis

$$\underline{\ell} = \underline{r} \times \underline{p}$$

- This provides a reference quantisation axis against which gamma-ray angular distributions $I_\gamma(\theta)$ can be measured

- The angular distributions depend on the multipolarity of the emitted gamma ray, i.e they are different for dipole and quadrupole transitions.

Angular Distribution Function

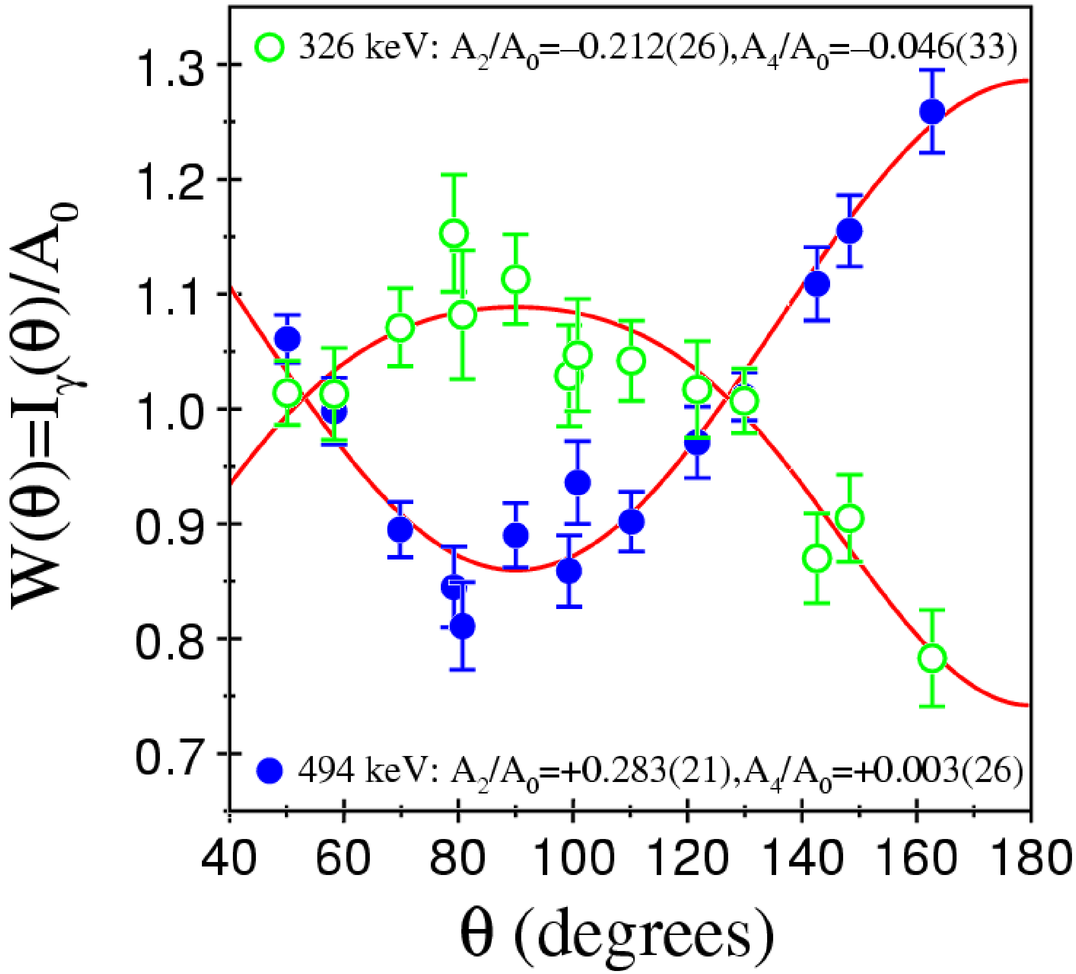
- The general form for the angular distribution function of radiation emitted following a heavy-ion fusion-evaporation reaction is:

$$W(\theta) = A_0 \,[\, 1 + Q_2\{A_2/A_0\}P_2(\cos\theta) + Q_4\{A_4/A_0\}P_4(\cos\theta) \,]$$

  where Q_k are geometrical attenuation coefficients which account for the finite size of the detectors and $P_k(\cos\theta)$ are Legendre polynomials. Here θ is defined relative to the beam axis

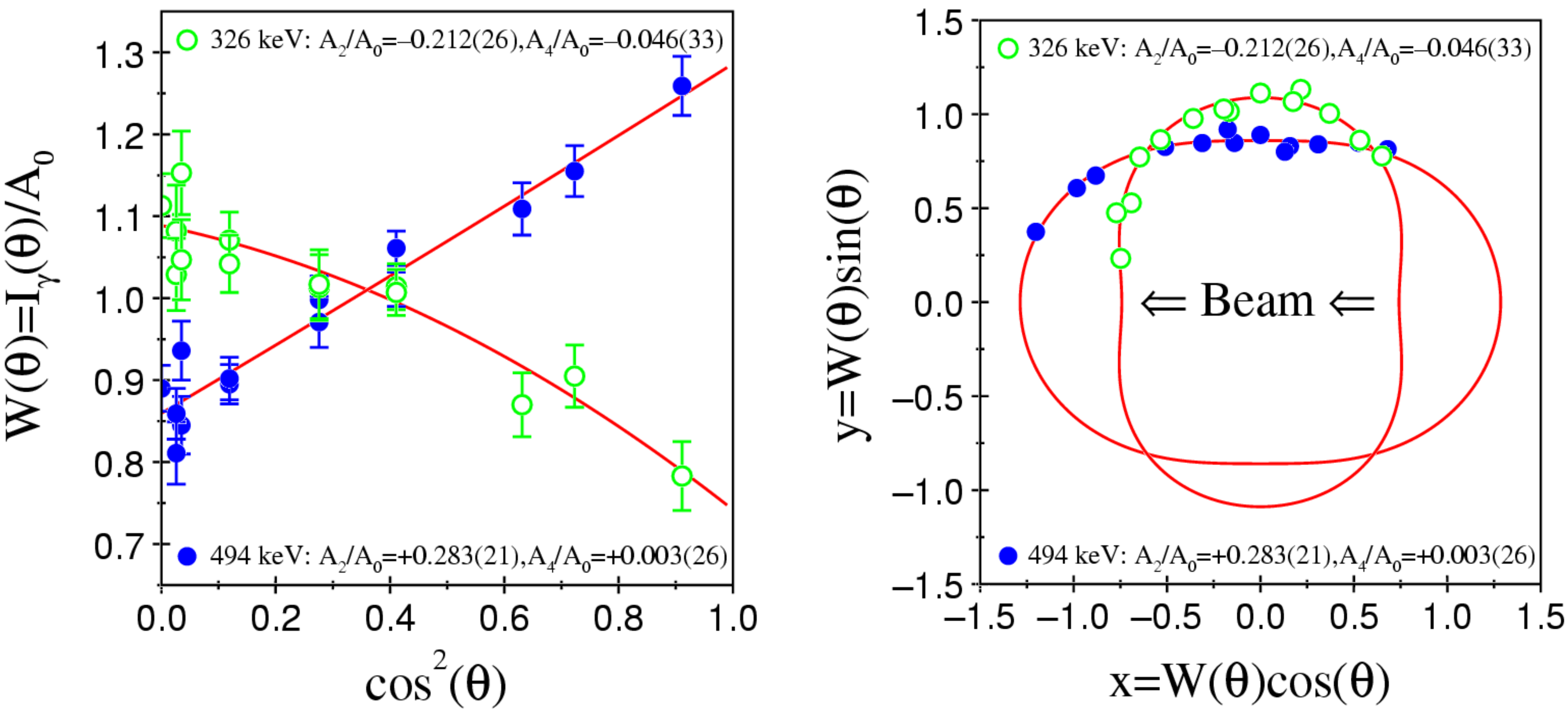
- The measured A_k/A_0 coefficients are compared to theory for different types of radiation

Angular Distributions in ^{109}Te



- Typically A_4/A_0 is close to zero
- And A_2/A_0 ~ +0.3 for a pure quadrupole (ΔI = 2) transition
- Or A_2/A_0 ~ -0.3 for a pure dipole (ΔI = 1) transition

Angular Distributions in ^{109}Te



Note: for $A_4/A_0 = 0$, $W(\theta)$ is linear in $\cos^2\theta$

Theoretical A_k/A_0 Values

- If the two lowest multipoles of the radiation are L and L' = $L+1$, the A_k/A_0 coefficients may be written as:

$$A_k/A_0 = a_k B_k(J_i)\,[1/(1+\delta^2)]$$

$$\times\,[\,F_k(J_f\,L\,L\,J_i) + 2\delta\,F_k(J_f\,L\,L'\,J_i) + \delta^2\,F_k(J_f\,L'\,L'\,J_i)\,]$$

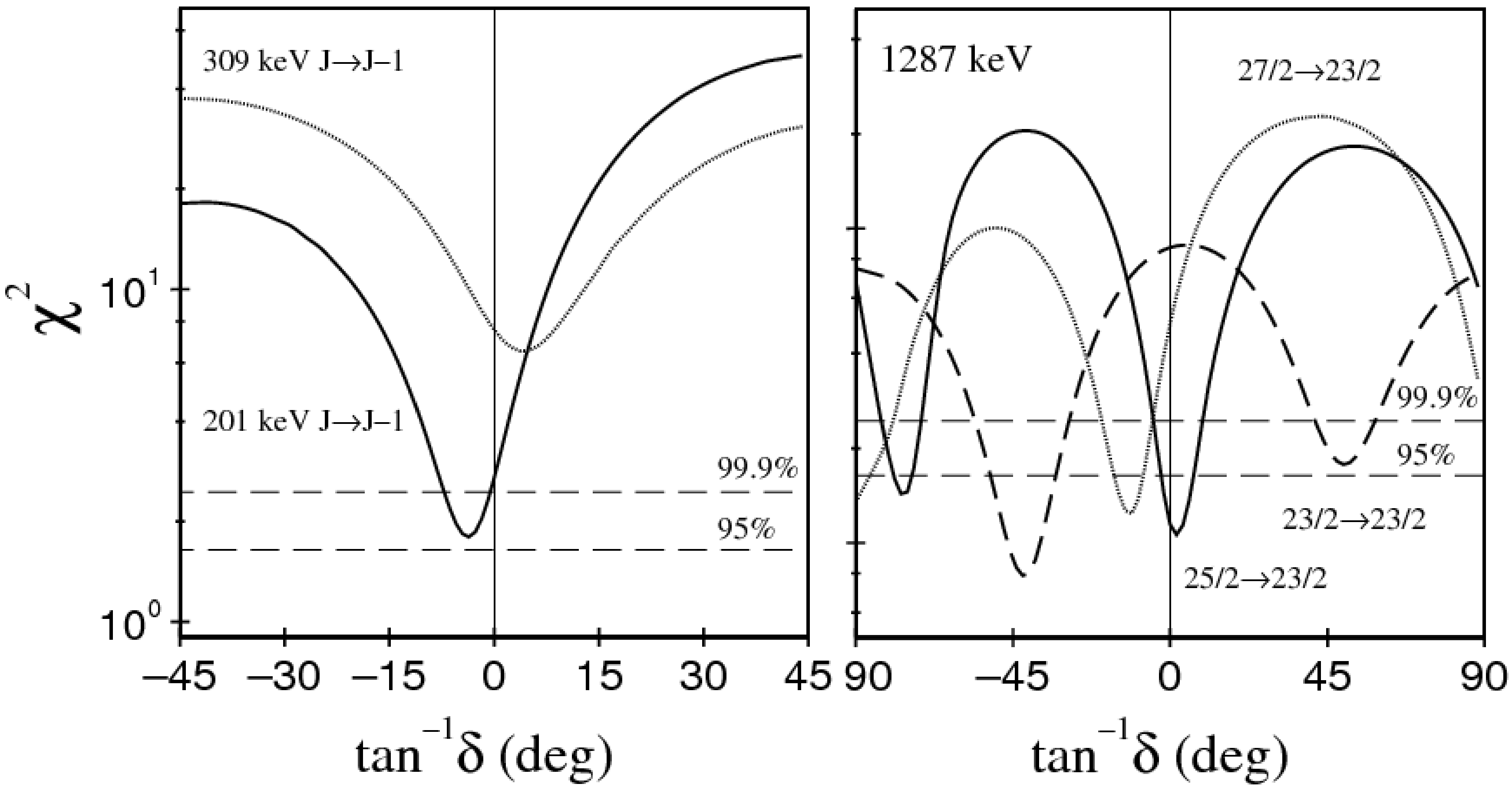
where a_k are attenuation coefficients, $B_k(J_i)$ are statistical tensors for complete alignment, and δ is the multipole mixing ratio:

$$\delta = \langle J_f||L'||J_i\rangle \,/\, \langle J_f||L||J_i\rangle$$

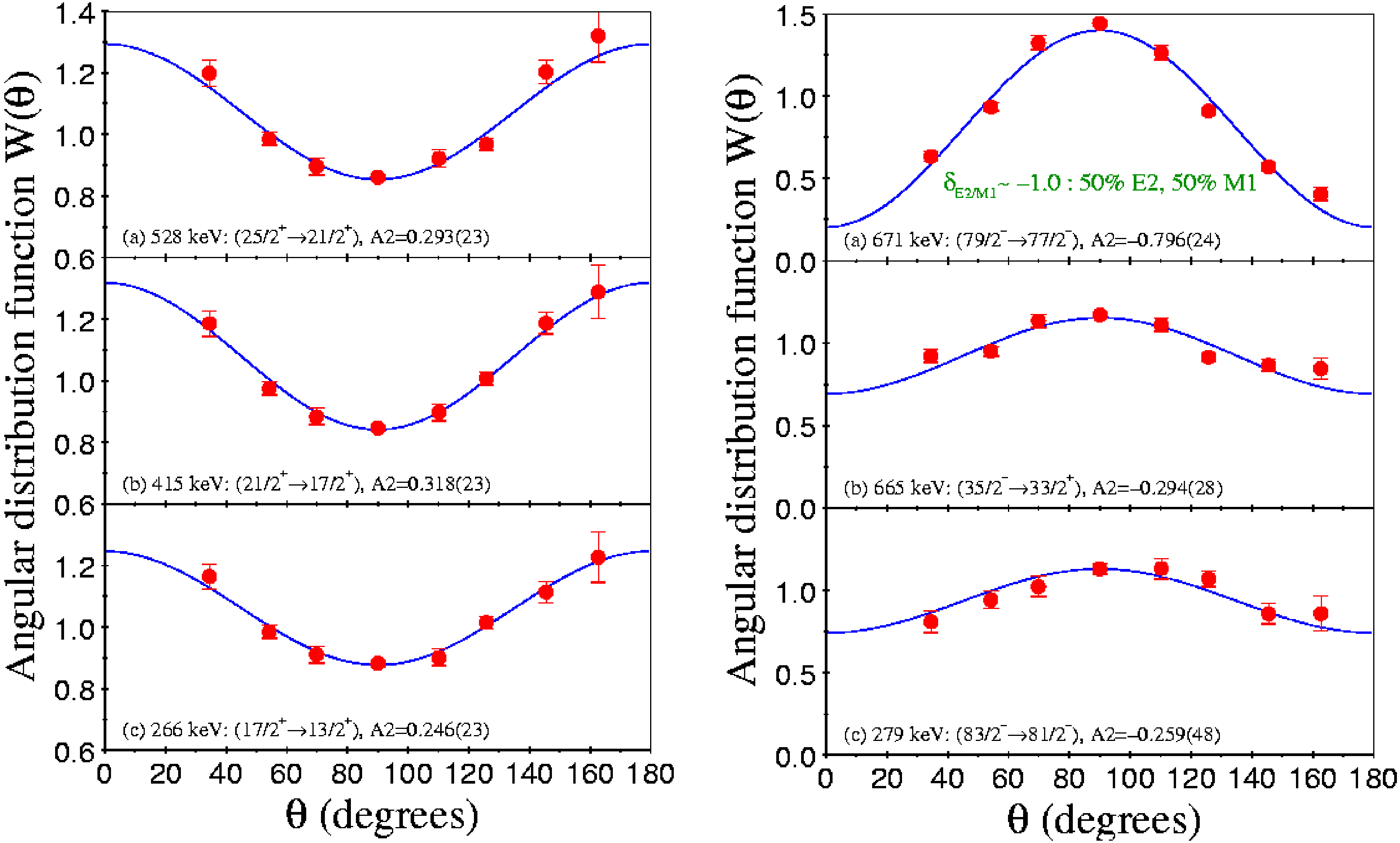
Multipole Mixing Ratio

- Because of the relative multipole transition probabilities, we only need to consider M1/E2 mixing
- For a $\Delta I = 1$ transition, M1 radiation accounts for $1 / [1+\delta^2]$ (typically 95%) of the intensity, while E2 radiation accounts for $\delta^2 / [1+\delta^2]$ (typically 5%) of the intensity
- The mixing ratio, a ratio of reduced matrix elements, can be positive or negative and perturbs the angular distribution

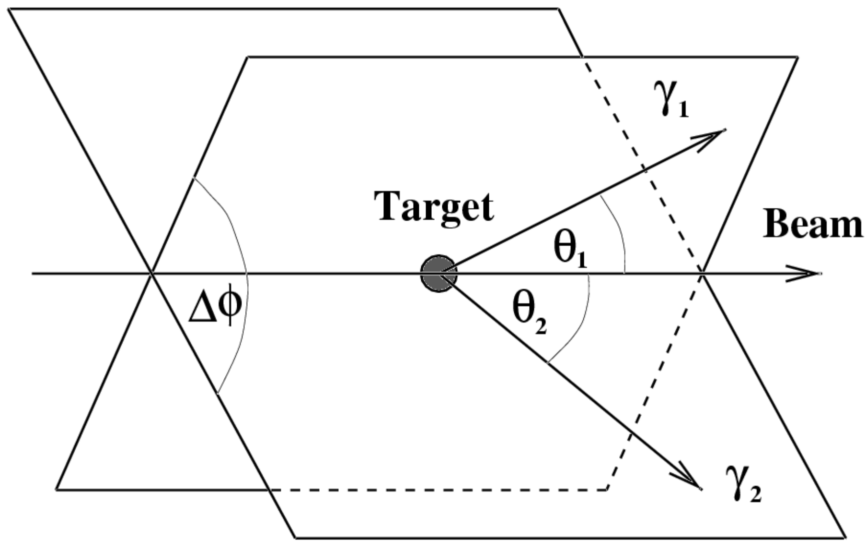
Multipole Mixing Ratios



Angular Distributions in ^{157}Er



Angular Correlations



Two γ rays are emitted at angles θ_1 and θ_2 with respect to the beam direction.
$\Delta\varphi = \varphi_1 - \varphi_2$ is the angle between the planes defined by the beam and outgoing γ rays

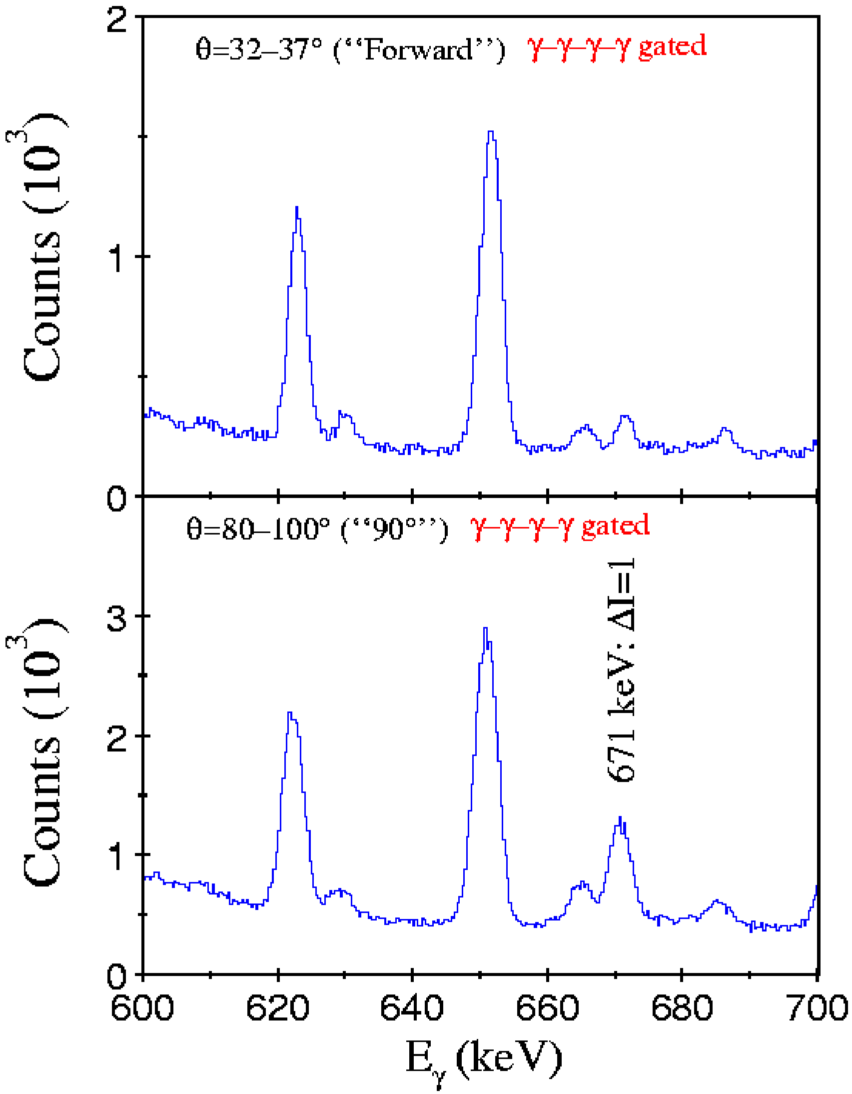
- The probability (i.e. intensity) for this specific configuration is described by:

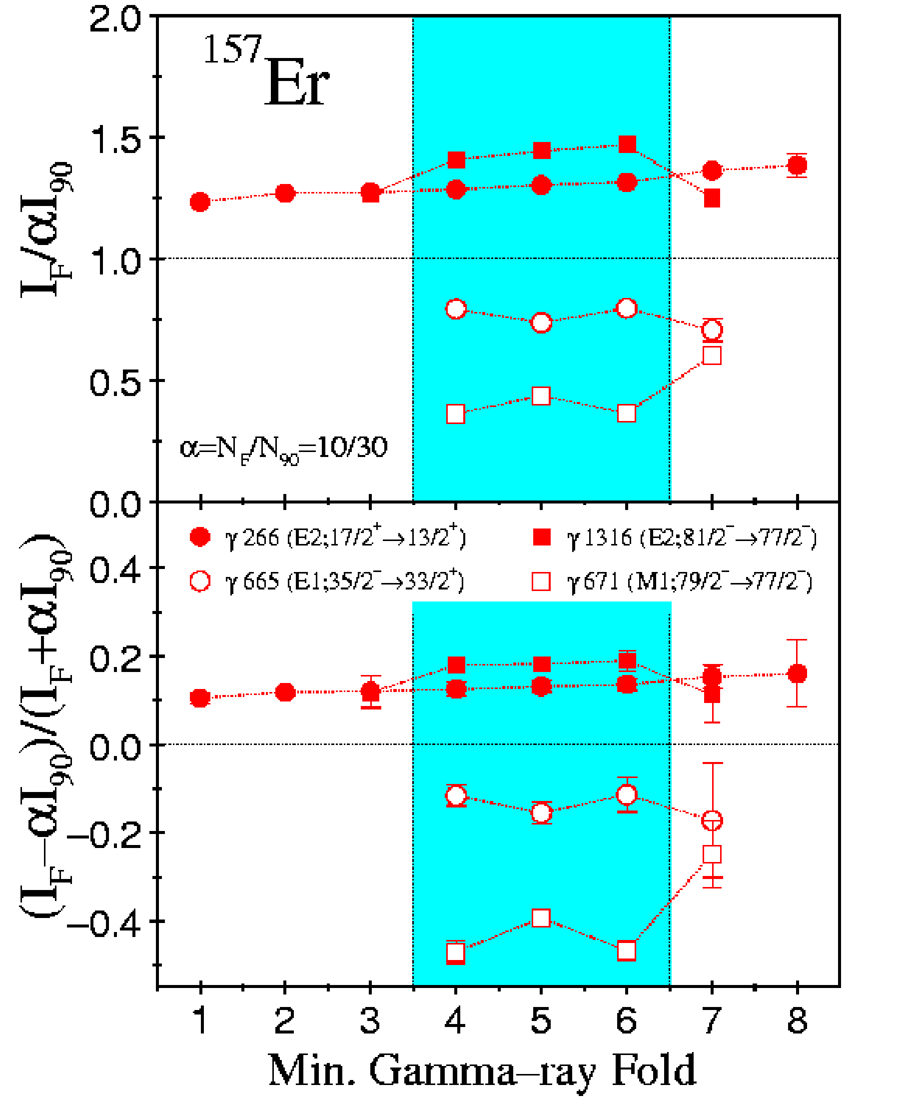
$$W(\theta_1,\theta_2,\Delta\varphi)$$

- A "DCO" ratio is defined as:

$$R_{DCO} = \frac{W(\theta_1,\theta_2,\Delta\varphi)}{W(\theta_2,\theta_1,\Delta\varphi)}$$

Angular Correlation Ratios: ^{157}Er





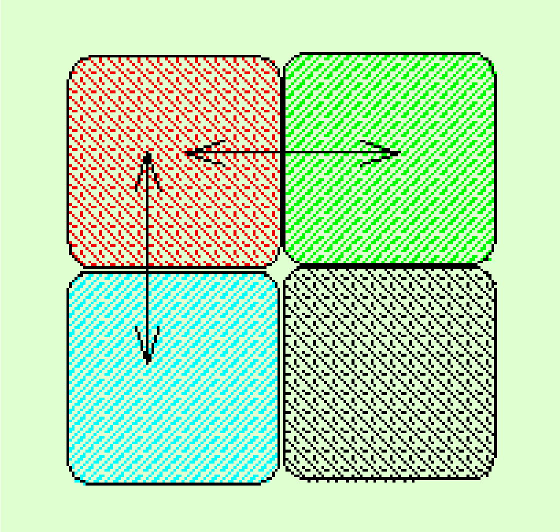
Linear Polarisations

- Compton scattering can be used to measure the gamma ray linear polarisation – the direction of the electric vector with respect to the beam-detector plane

- The linear polarisation distinguishes between magnetic (M) and electric (E) character of radiation of the same multipolarity

- The scattering cross section is larger in the direction perpendicular to the electric field vector of the radiation

Clover Detector



- The Compton scattering between the elements of a clover detector can be used to determine experimental linear polarisations
- The vertical and horizontal addback intensities are measured

Experimental Asymmetry

- The experimental asymmetry is defined as:

$$A = \{ N_{\perp} - N_{\parallel} \} / \{ N_{\perp} + N_{\parallel} \}$$

where $N_{\perp}$ and $N_{\parallel}$ are the intensities of scattered photons perpendicular and parallel to the reaction plane

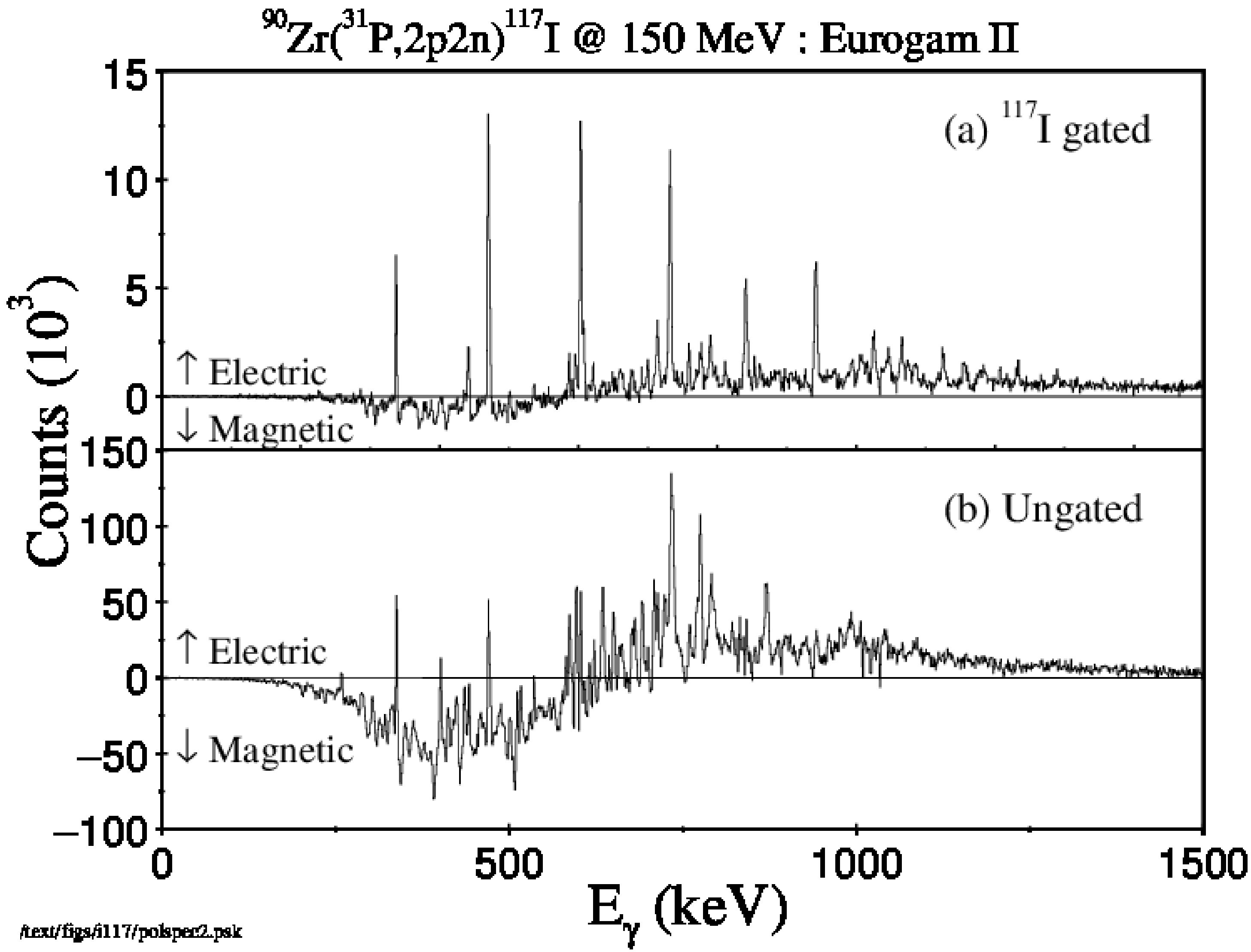
- The experimental linear polarisation is then:

$$P = A / Q$$

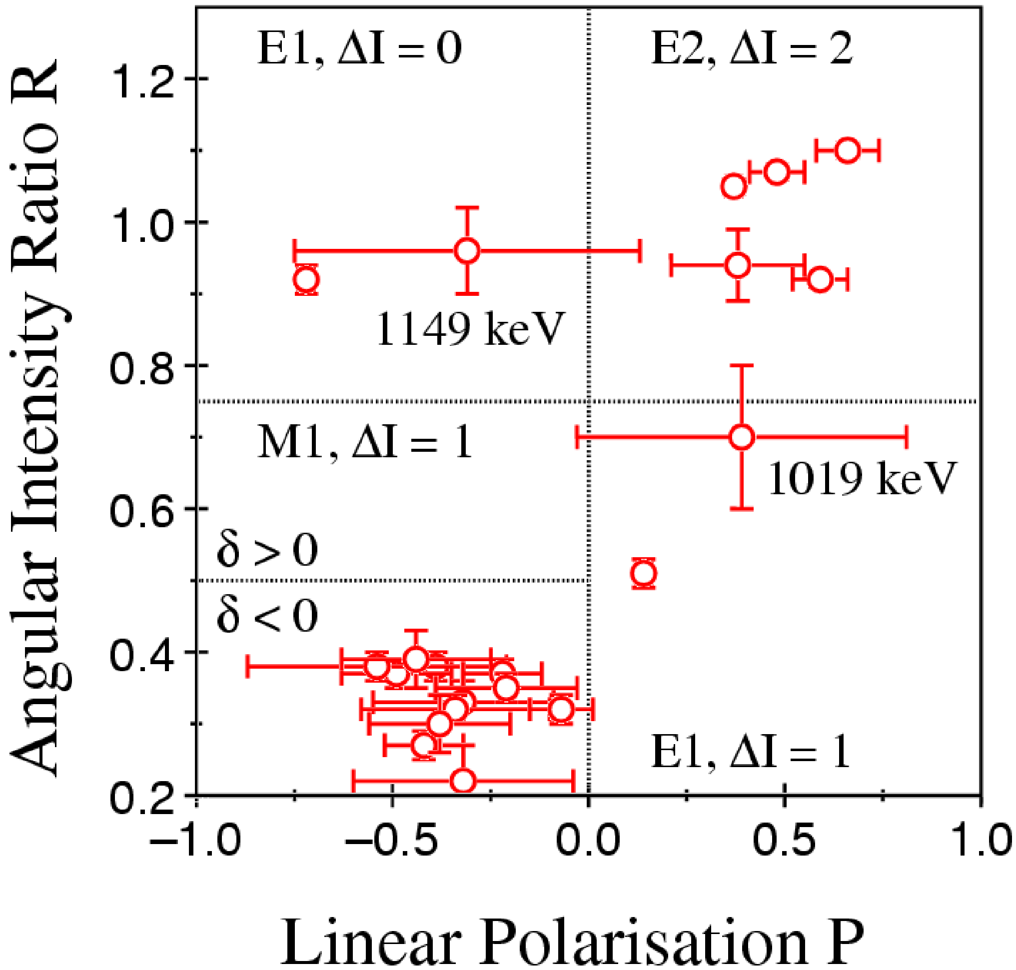
where Q is the polarisation sensitivity of the detector (a function of gamma ray energy)

- For a stretched E2: $P > 0$ For a stretched M1: $P < 0$

Polarisation Spectra



Spins and Parities



- Combining linear polarisation and angular correlation measurements uniquely defines the multipolarity of gamma rays
- Data from Eurogam

Flash Animations

- Cube Gating
- Level Scheme Building
- Level Scheme Formation

- Compton Suppression
- Compton Suppression 2
- Clover Addback

David Campbell (Florida State University)