Gamma ray spectroscopy:

a basic introduction

Magda Zielińska, CEA Saclay, France

Slides 2-13 courtesy of M. Palacz, HIL Warsaw

Gamma ray spectroscopy

Wikipedia: “Gamma ray spectroscopy is the quantitative study of the energy spectra of gamma-ray sources...”

In fact: measurement of γ-ray properties like:

- energy,
- multiplicity,
- coincidences,
- times,
- type (electric/magnetic) and multipolarity,
- perturbation in magnetic field,
- correlation with other reaction or decay products...

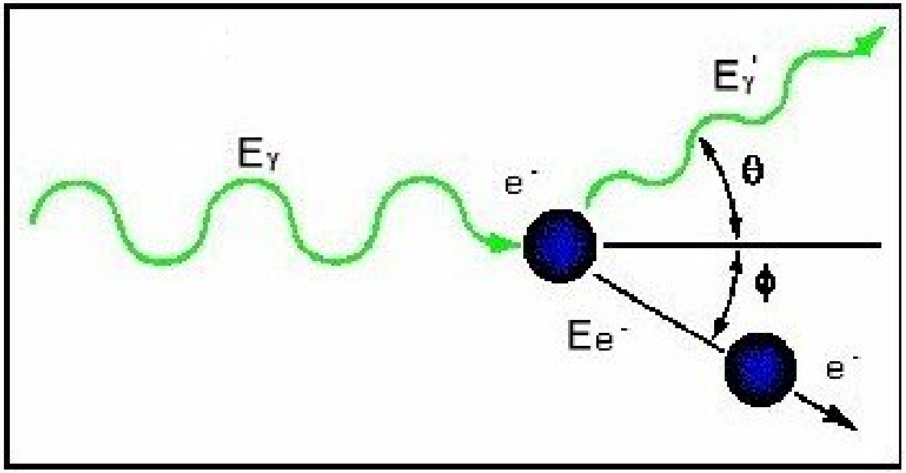
...in order to establish properties of excited nuclear states: excitation energy, spin, parity, half-life, magnetic moment, shape (deformation), rotation/oscillation, ...

Interaction of gamma-rays in matter

- **Photo-electric effect**
  A γ-ray interacts with a bound atomic electron. A photoelectron is emitted, and it is stopped close to the interaction point – full energy deposit in the detector.

  $$E_e = E_\gamma - E_b \qquad \sigma \sim Z^n / E_\gamma^{3.5} \qquad n = 4,5$$

- **Compton scattering**



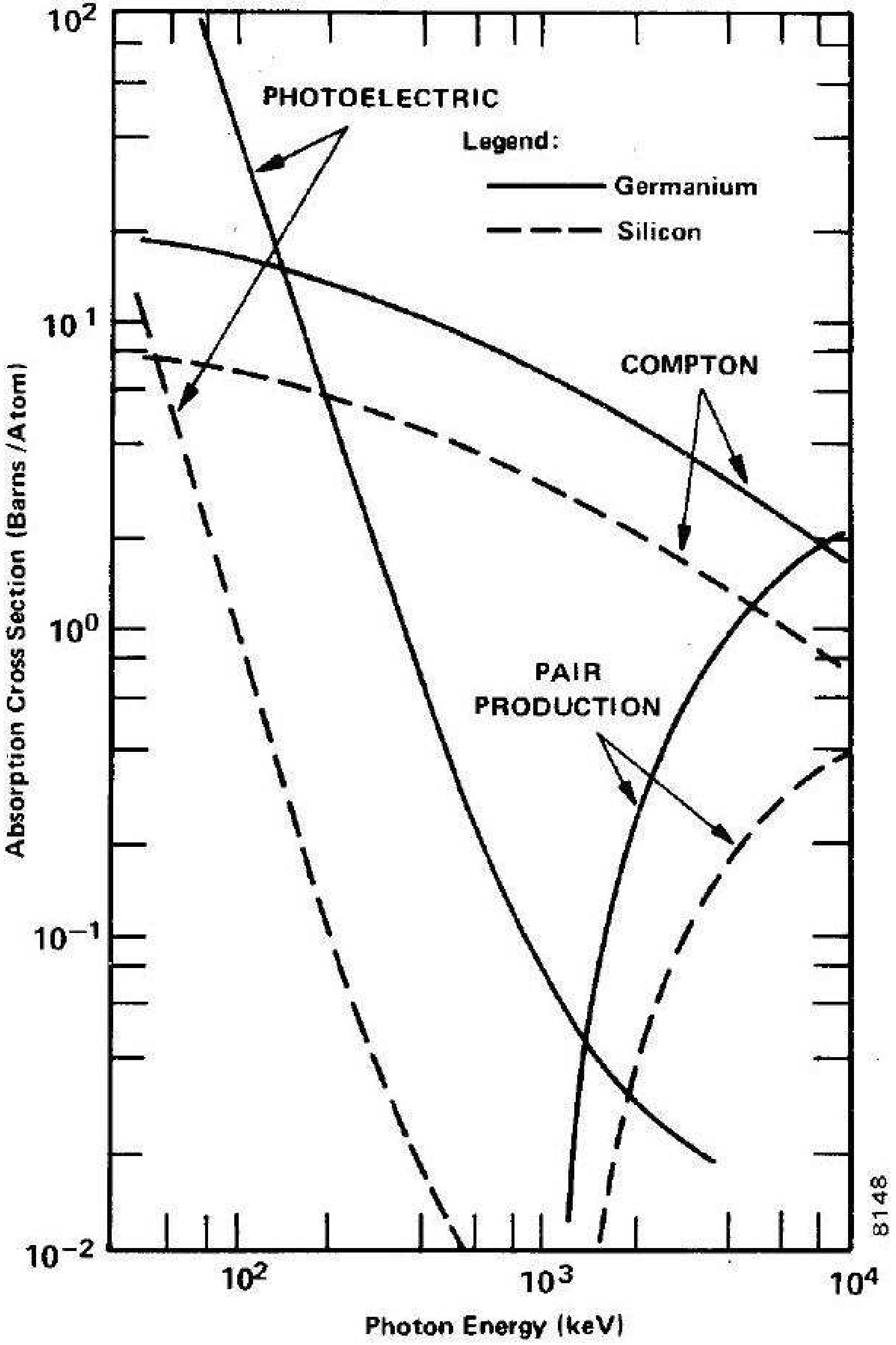
$$E_\gamma' = \frac{E_\gamma}{1 + (1 - \cos(\theta)) \frac{E_\gamma}{m_e c^2}}$$

$$max\, E_e = E_\gamma \left(1 - \frac{1}{1 + \frac{2E_\gamma}{511\, keV}}\right)$$

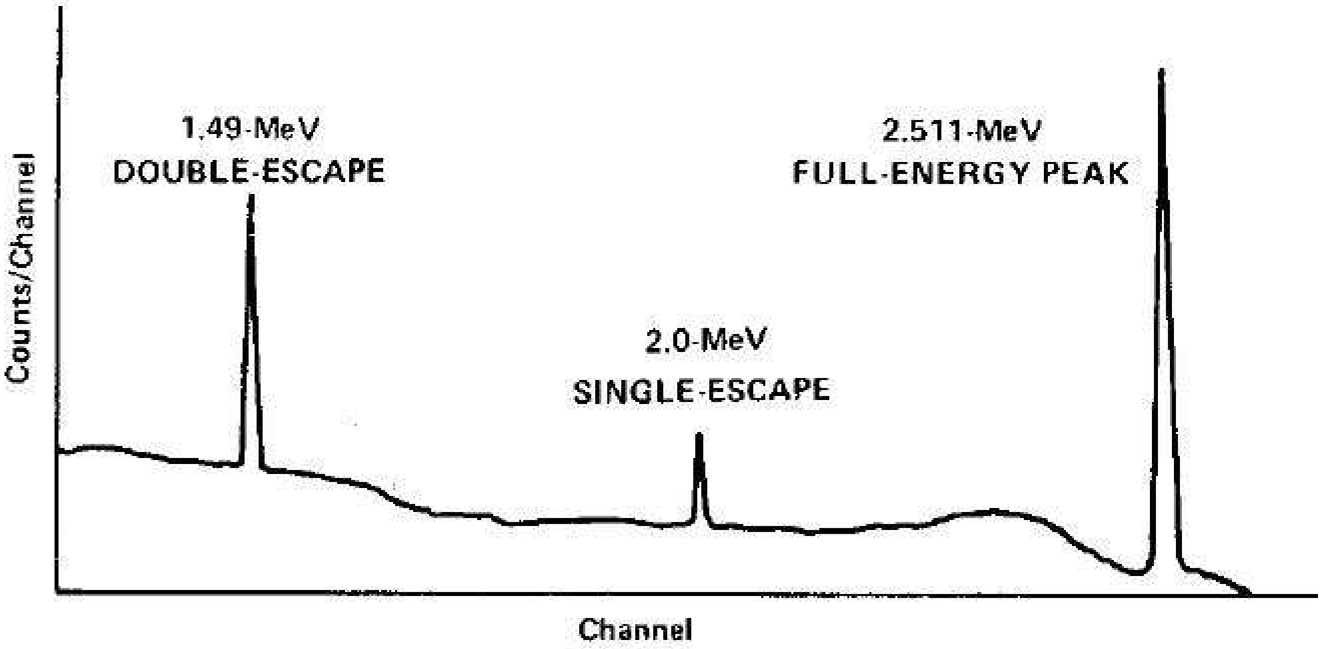
- **e^+e^- pairs production** ($E_\gamma > 1.02$ MeV)
  slowed-down e^+ annihilates, giving a co-linear γ-ray pair, 511 keV each

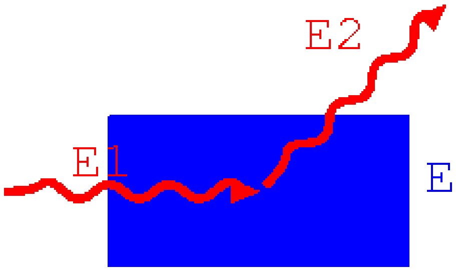
Gamma ray interactions - comparison

- Bad news:
  Compton scattering dominates for 100-5000 keV, higher up – pair production.
- Good and bad news:
  In a large detector volume a γ-ray often interacts a few times. Each time a lower energy γ-ray is created, and finally the photo-effect becomes most probable.
  Probability that a scattered γ-ray escapes is anyway high.



Gamma ray spectrum: $E_\gamma = 2.511$ keV

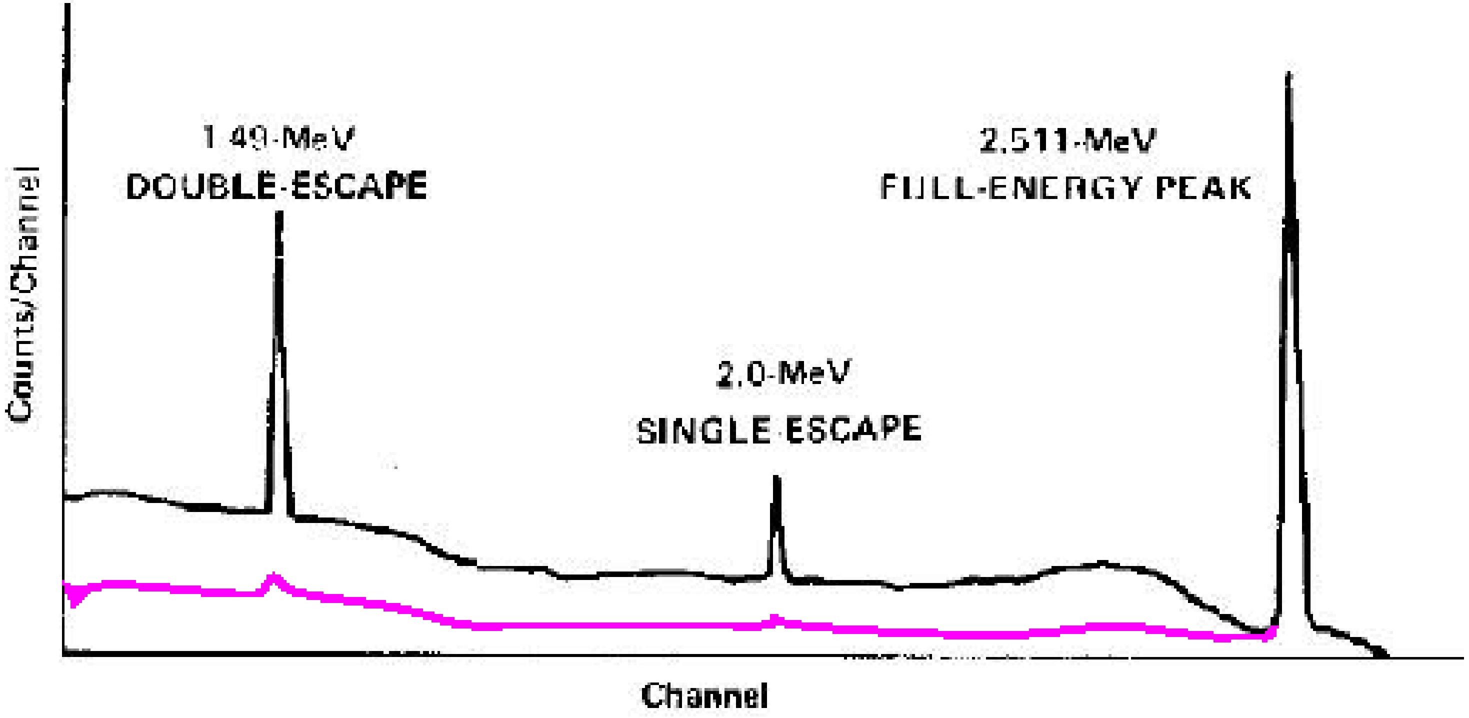


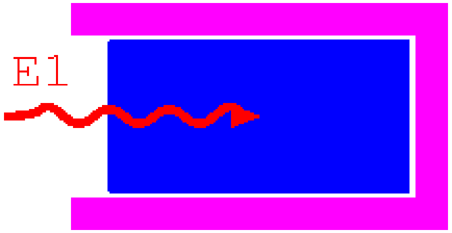


Edet = E1 - E2

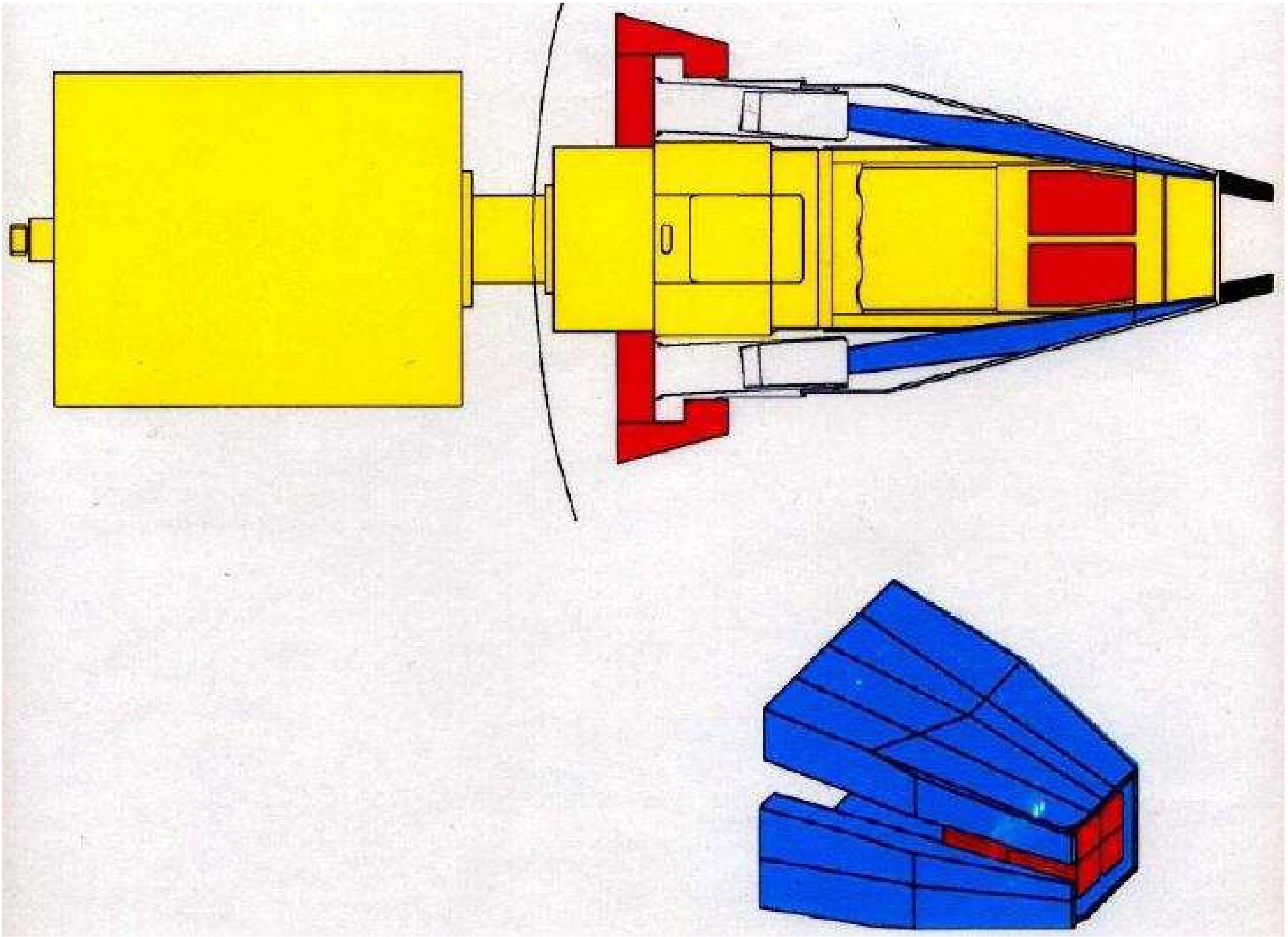
Gamma ray spectrum: E_γ = 2.511 keV

with anti-Compton shield



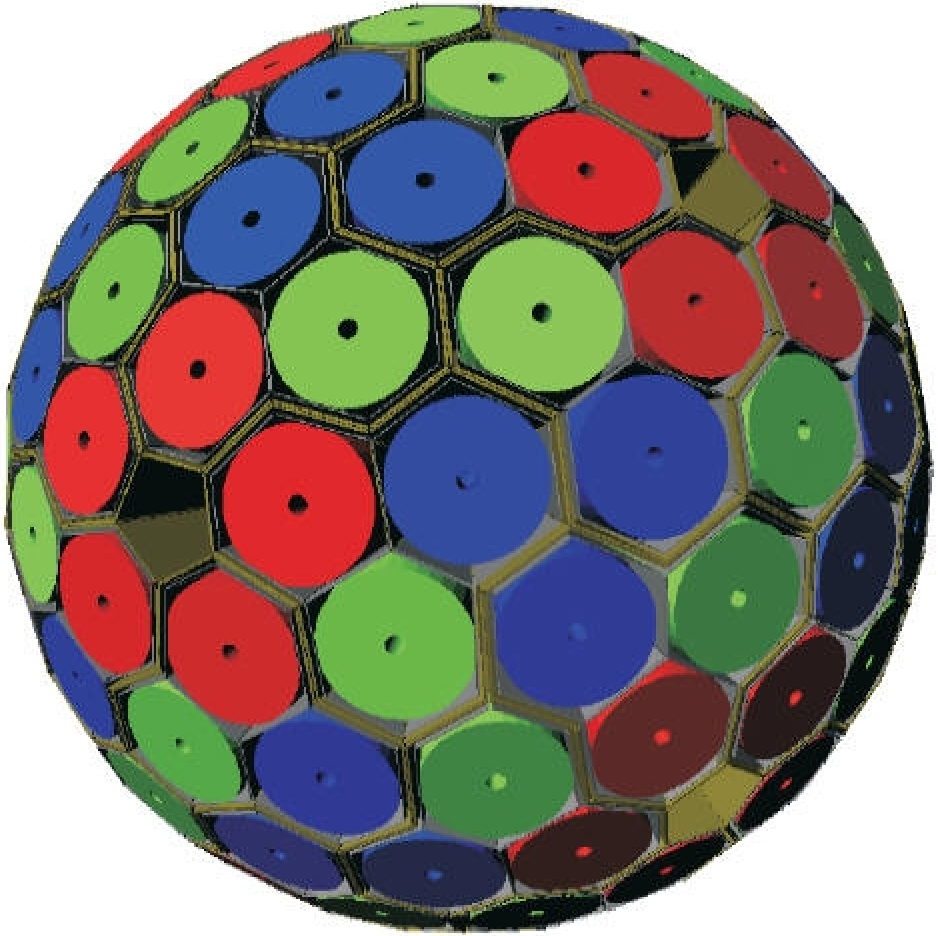


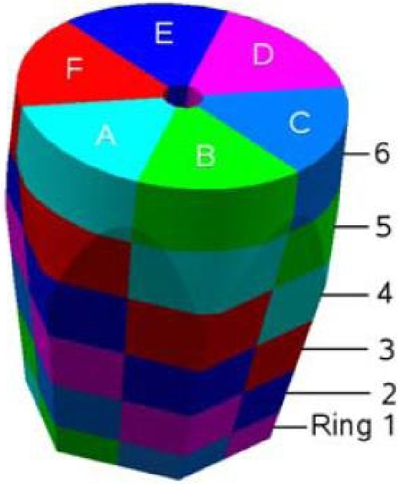
Germanium detector with anti-Compton shield



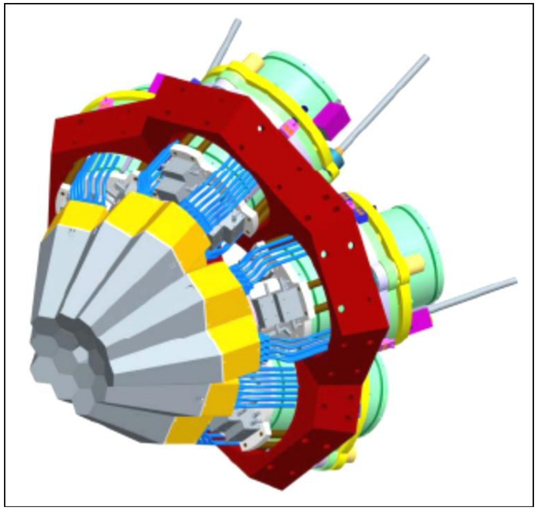
***A**dvanced **Ga**mma Ray **T**racking **A**rray*

A Ge sphere, consisting of
180 x 36 = 3600 segments





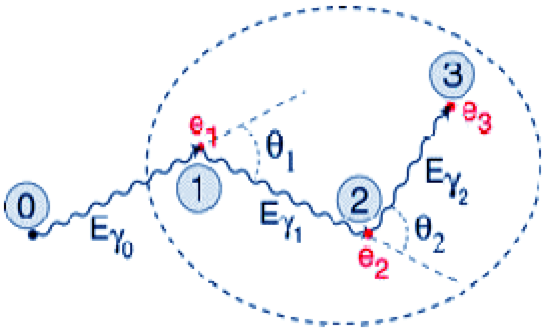
Demonstrator

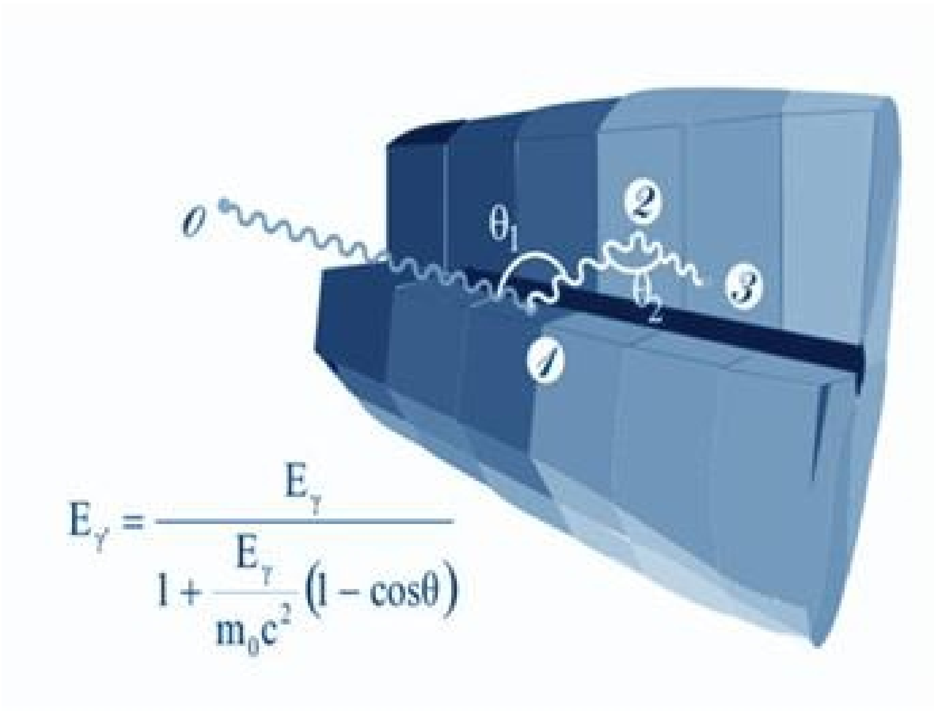


Gamma Ray Tracking Principle

Angle/energy correlation in Compton scattering is used to:

- select interactions (a few out of many) which are due to one γ-ray
- recover full γ-ray energy, and first (second) interaction point

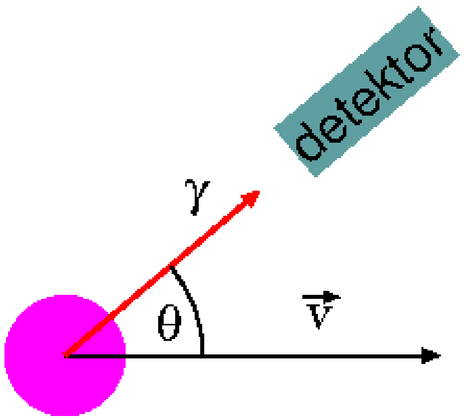




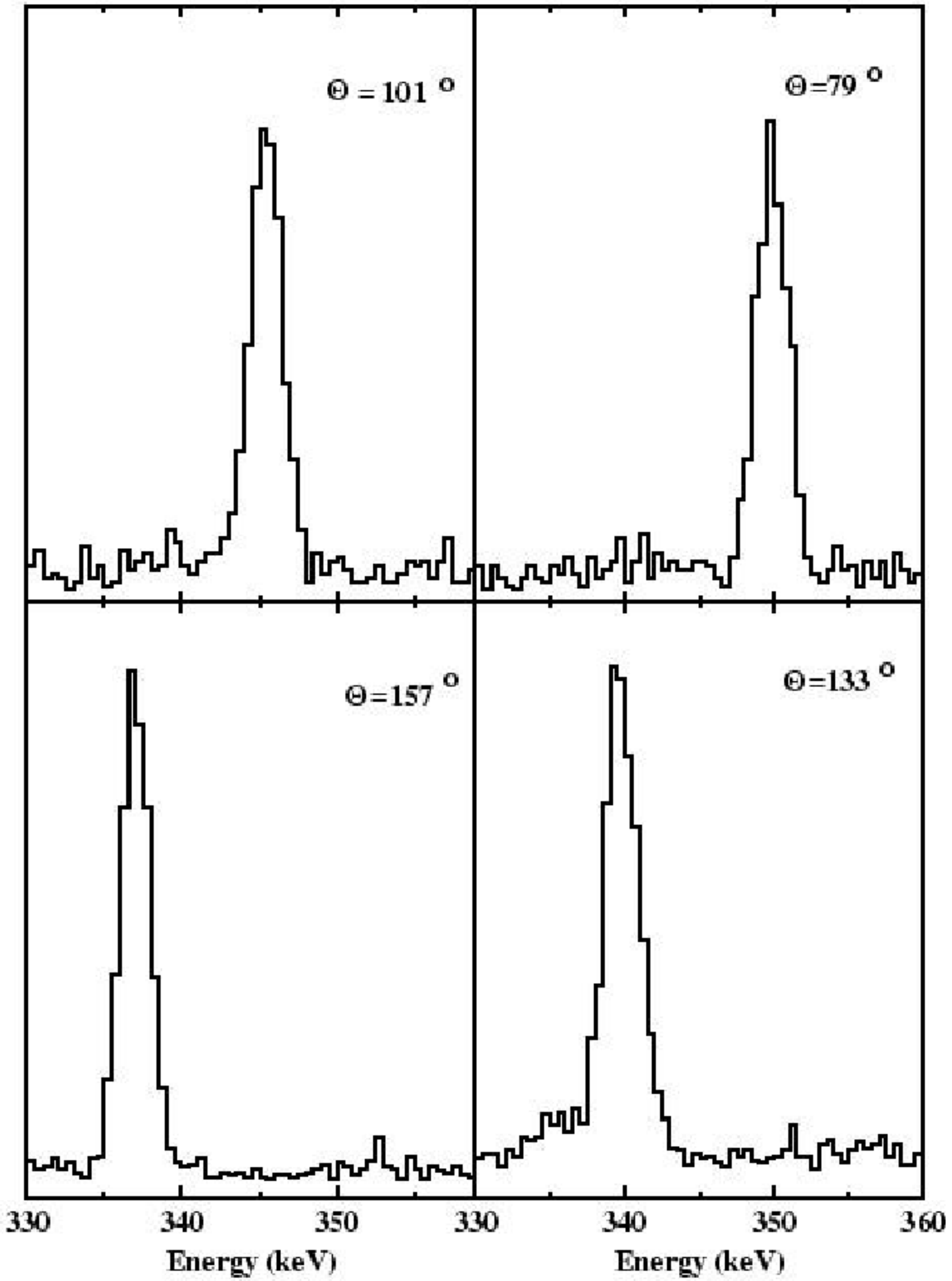
$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0c^2}\left(1-\cos\theta\right)}$$

Segmentation and pulse shape:
x,y,z precision ~ 5 mm

Doppler effect

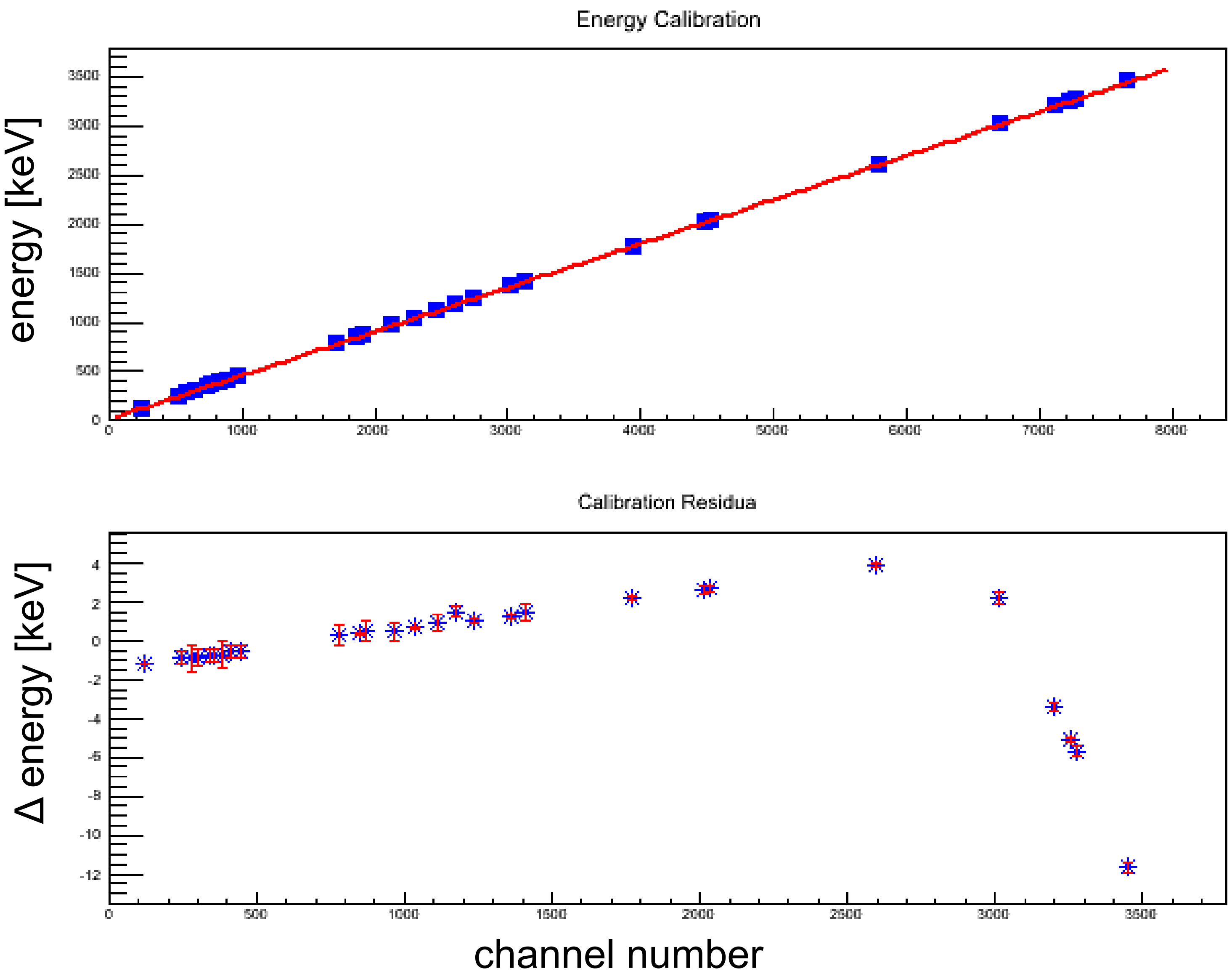


$$E_\gamma' = E_\gamma\left(1 + \frac{v}{c}\cos(\theta)\right)$$



Data analysis

Energy calibration:
$E = a_0 + a_1 * x + ...$

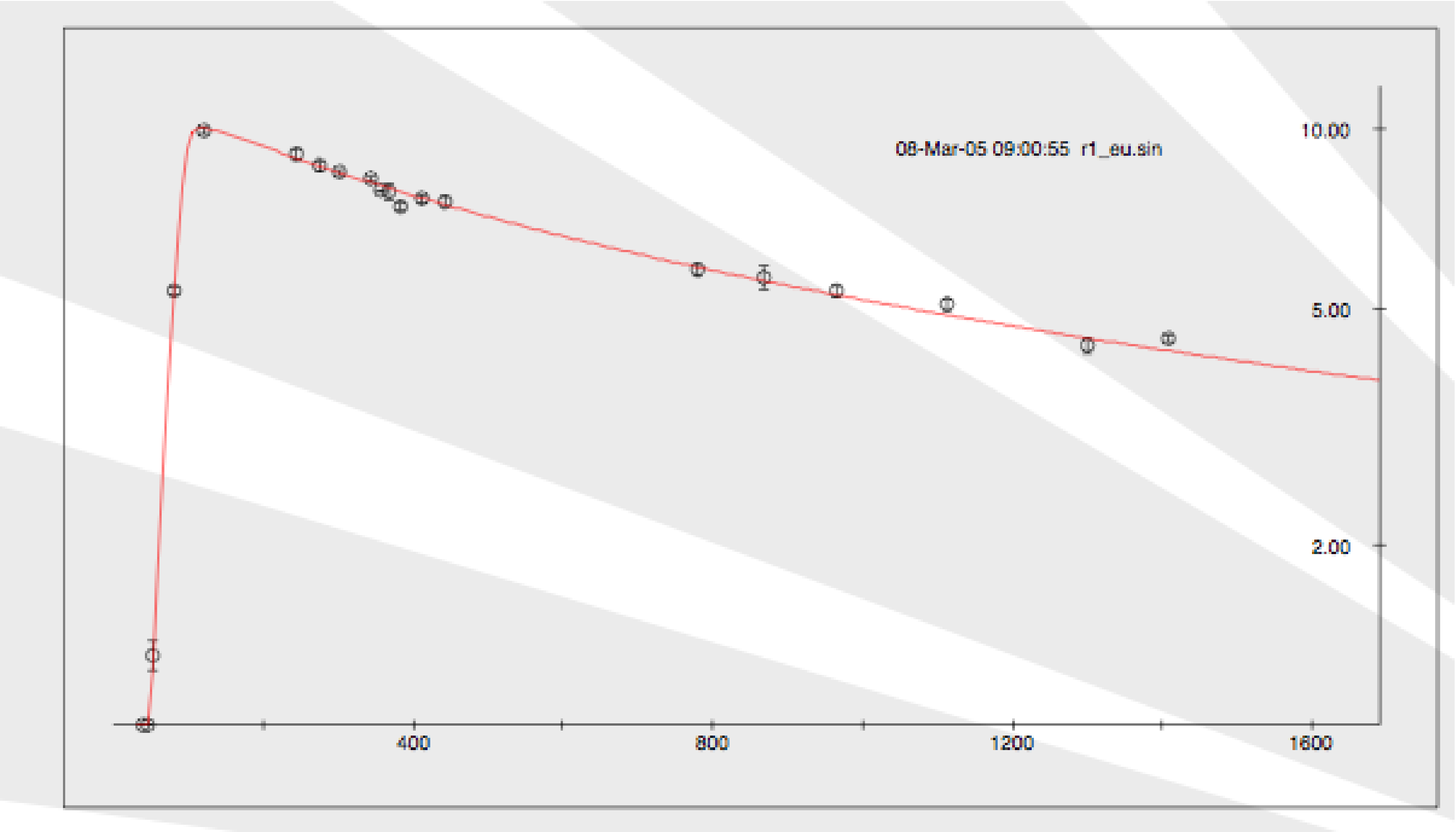


Data analysis

Detector efficiency:

$$\epsilon(E)=\frac{N(E)}{I(E)}=\frac{N(E)}{A*r(E)*t}$$

N(E): number of registered counts
I(E): number of emitted gamma-rays
A: source activity (number of decays per unit time)
r(E): probability of emission of a given gamma ray in a decay (-> Nuclear Data Tables)
t: time of measurement

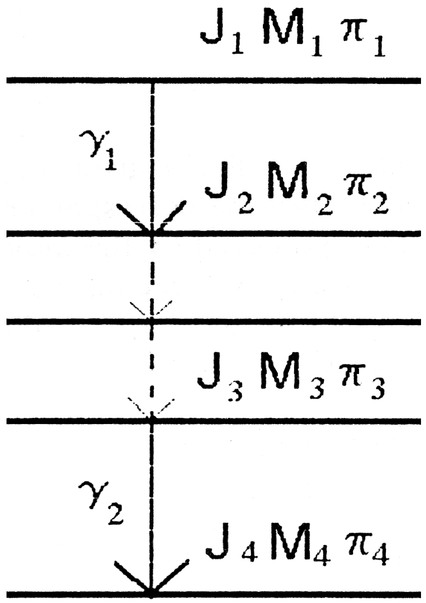


Data analysis

Aim: to determine properties of excited states

Individual nuclear states have unique spin and parity.
For decay from ($E_i J_i M_i \pi_i$) to ($E_f J_f M_f \pi_f$), the electromagnetic radiation must satisfy the following relations:

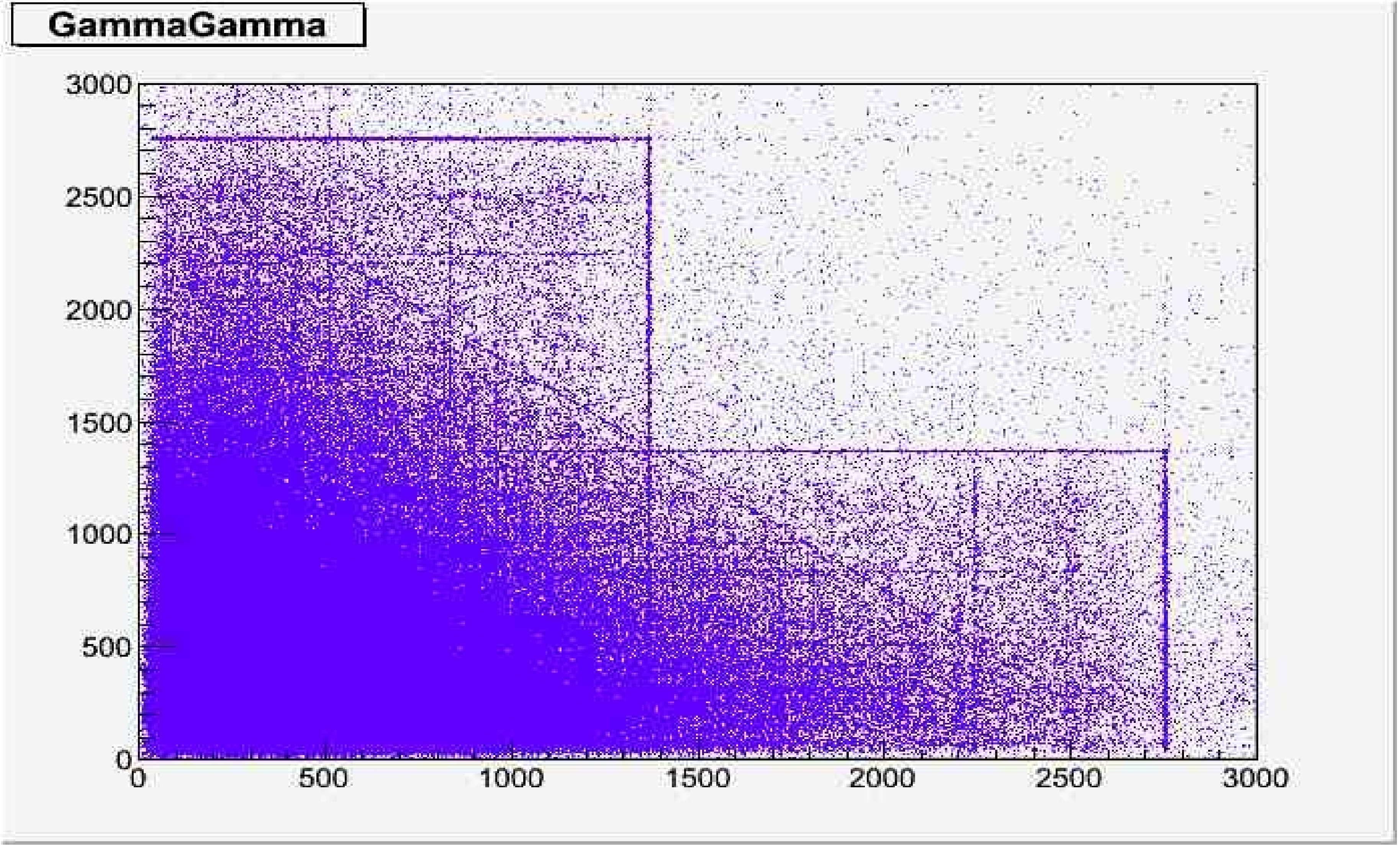
- Energy $E_\gamma = E_i - E_f$
- Multipolarity $|J_i - J_f| \quad L \quad (J_i + J_f)$
- M-state $M = M_i – M_f$
- Parity $\pi = \pi_i \pi_f$



Properties of γ rays → Properties of states

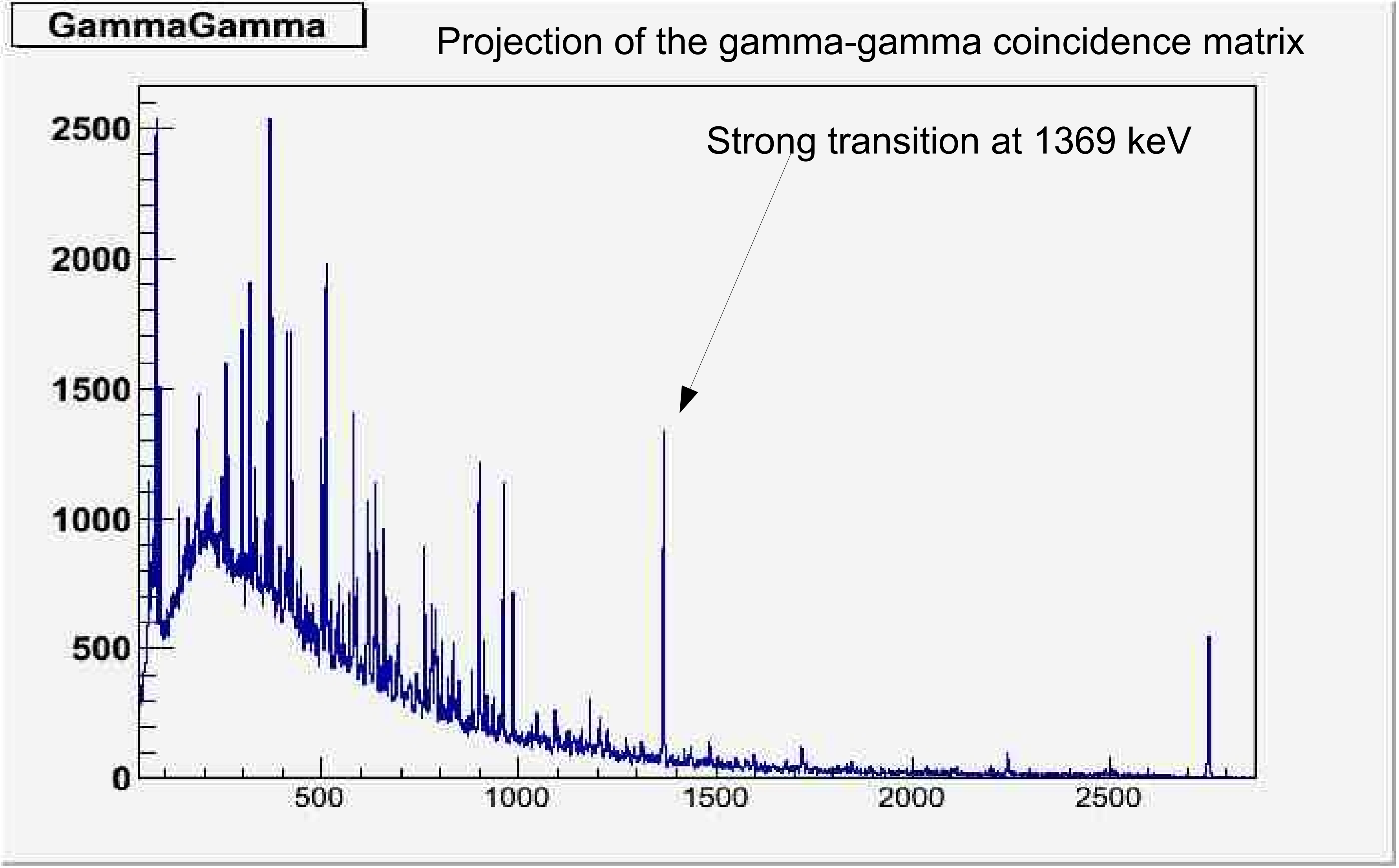
Data analysis – energies of excited states

Method: analysis of coincident γ-ray spectra



Data analysis – energies of excited states

Method: analysis of coincident γ-ray spectra



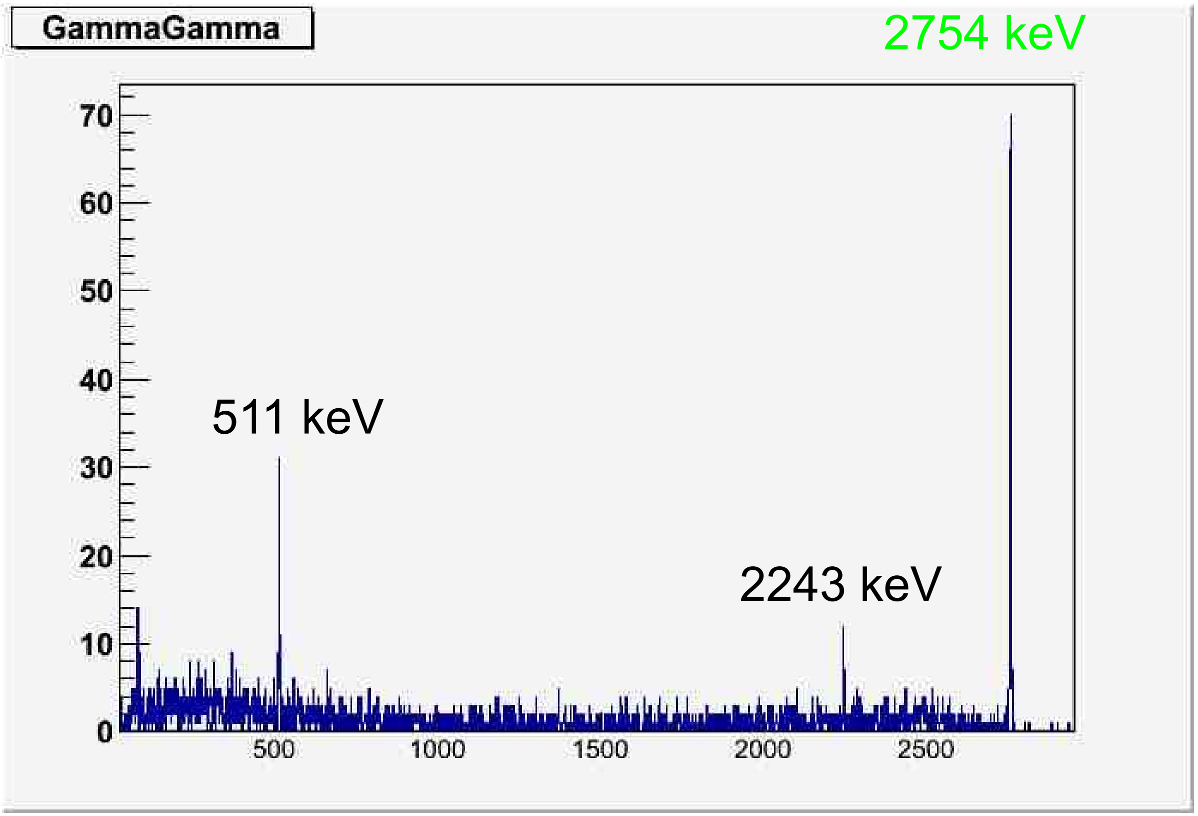
Projection of the gamma-gamma coincidence matrix

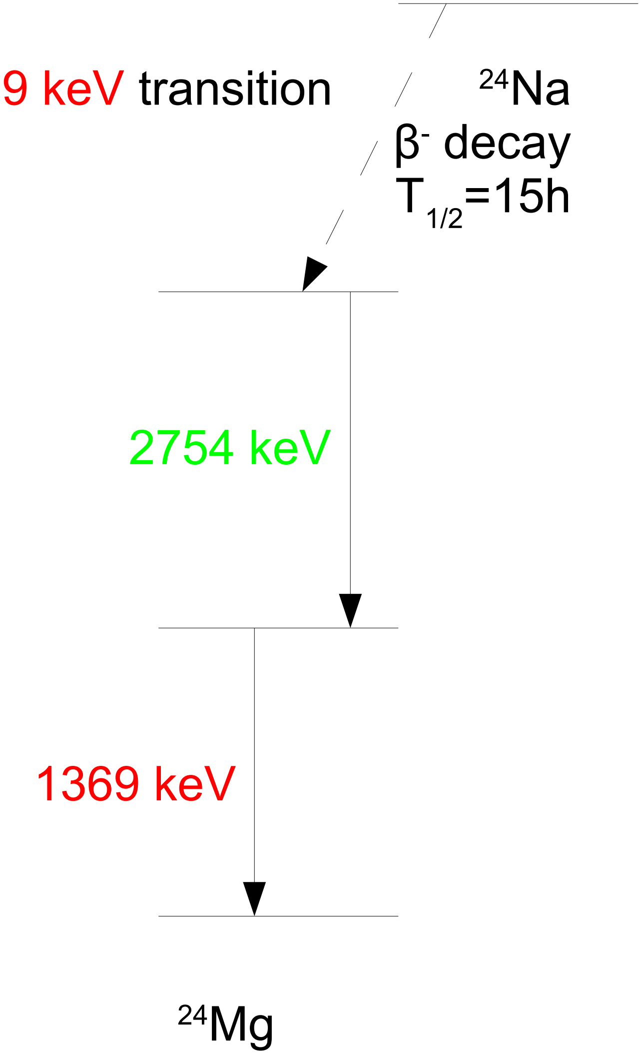
Strong transition at 1369 keV

Data analysis – energies of excited states

Method: analysis of coincident γ-ray spectra

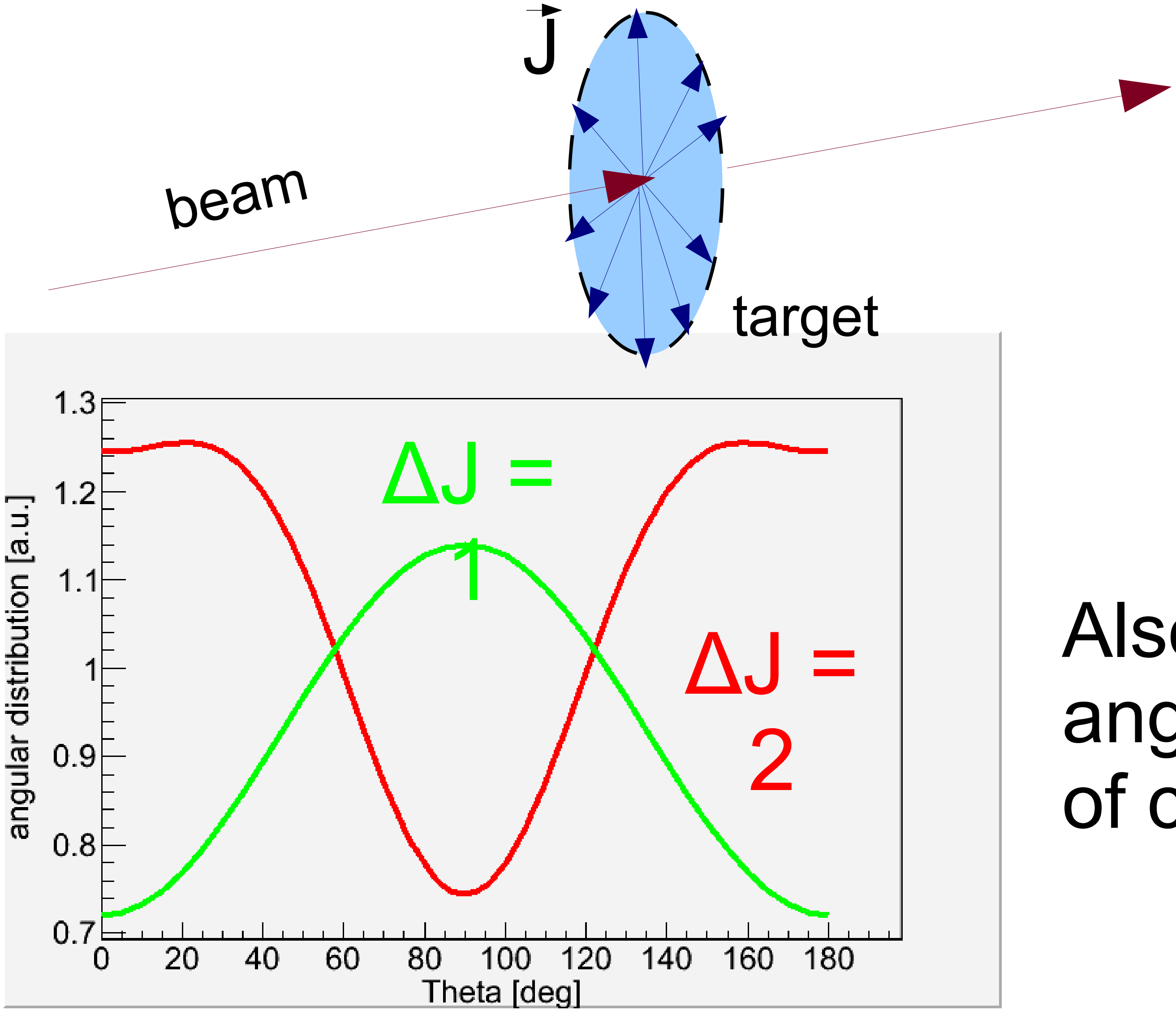
Projection gated on the 1369 keV transition

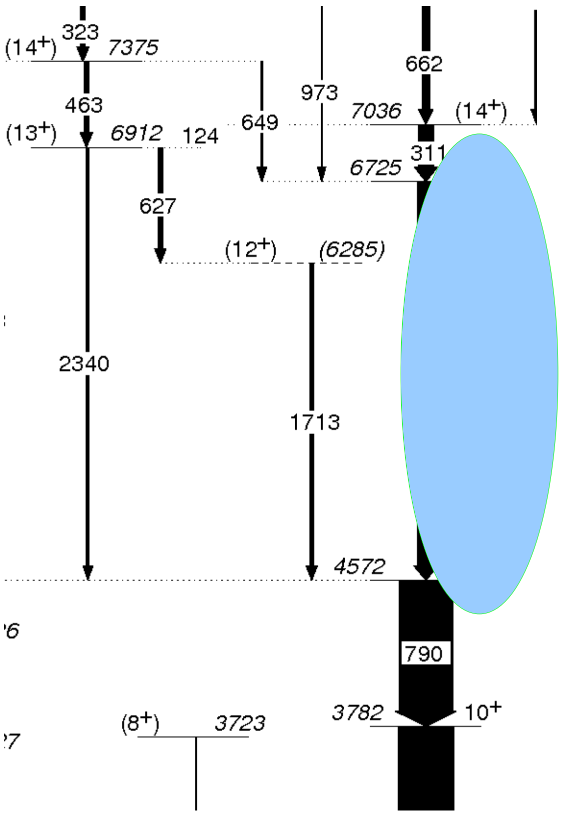




Data analysis – spins

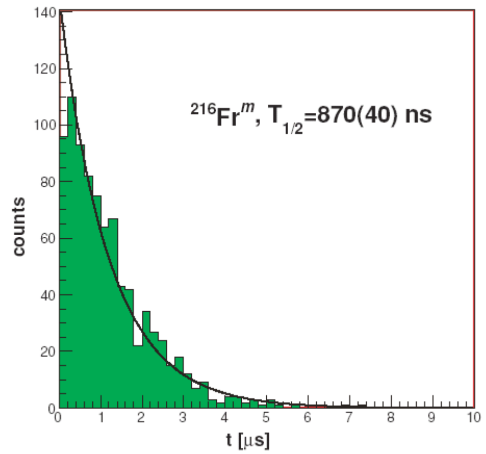
Angular distributions





Also:
angular correlations
of coincident γ rays

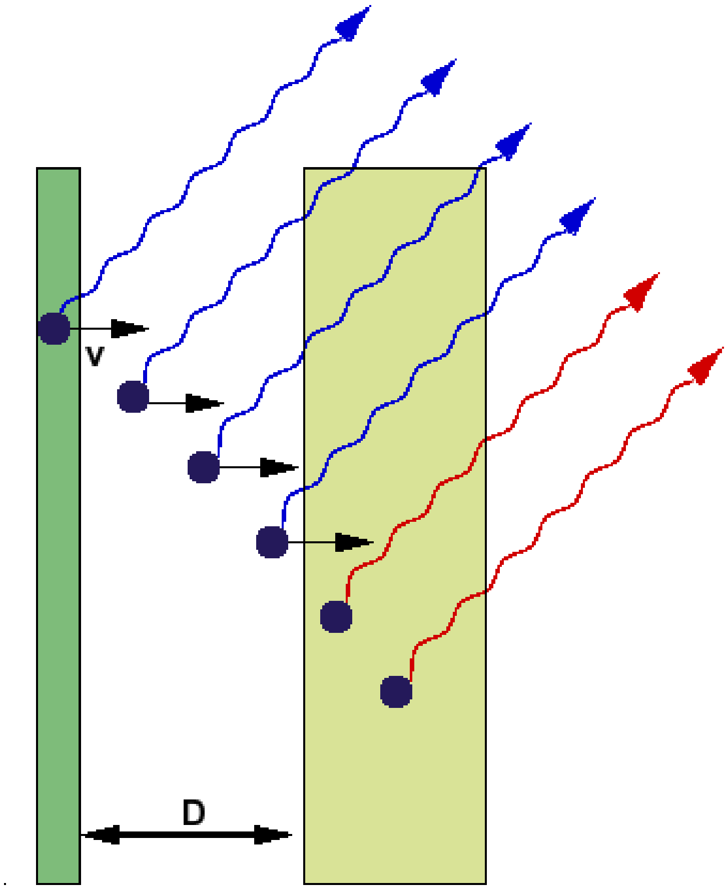
Data analysis - lifetimes of excited states



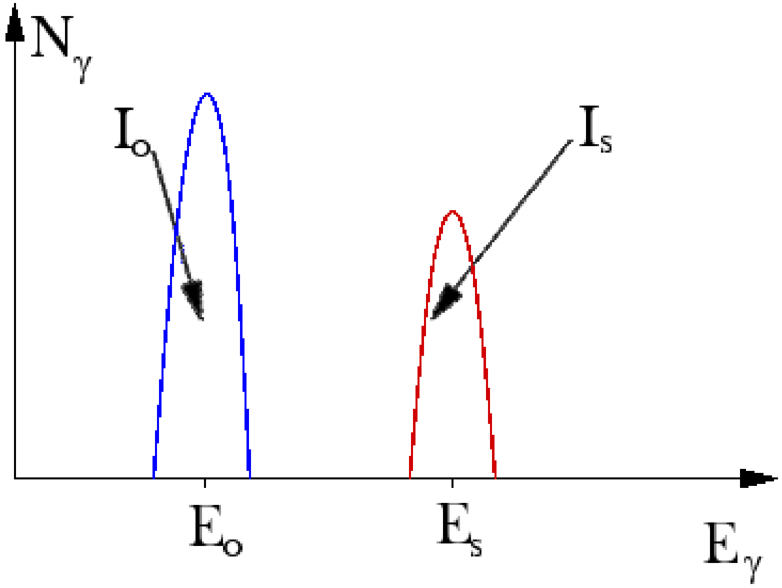
- Direct lifetime measurements
  - Observation of activity decreasing with time (lifetimes longer than 10^{-9}s)
  - Methods making use of the Doppler effect (lifetimes of 10^{-9} - 10^{-14}s)
    - *Recoil Distance Method* (RDM)
    - D*oppler Shift Attenuation Method* (DSAM)
- Coulomb excitation – measurement of transition probabilities (directly related to lifetimes)

Recoil Distance Method

Suitable for lifetmes of $10^{-9} – 10^{-12}$ s



$$E_\gamma = E_0\left(1 + \frac{v}{c}\cos\theta\right)$$



Time of flight between foils (distance D)

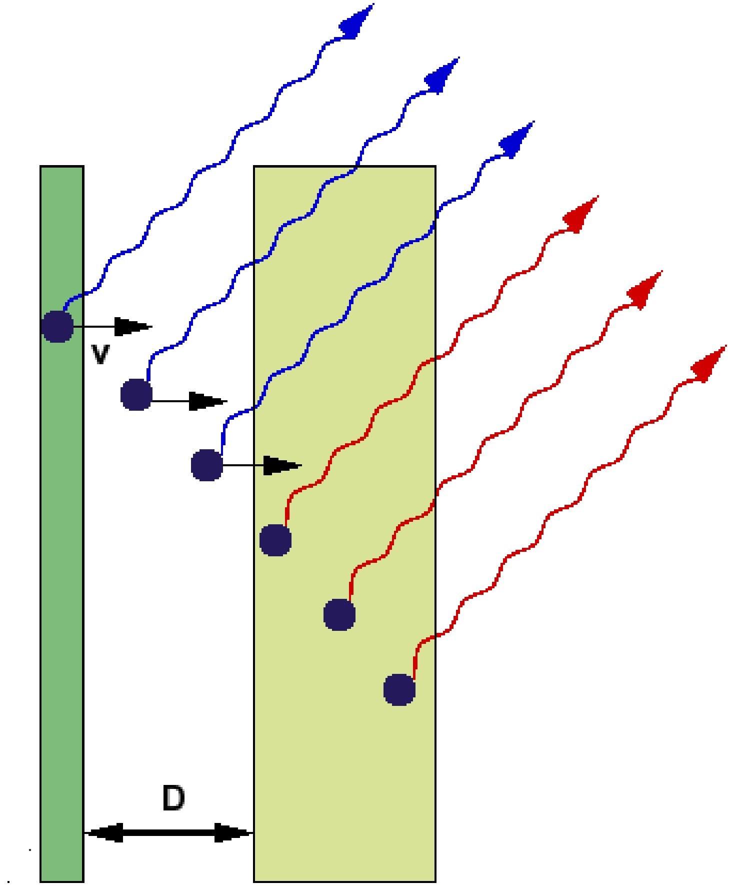
$$t_D = \frac{D}{v}$$

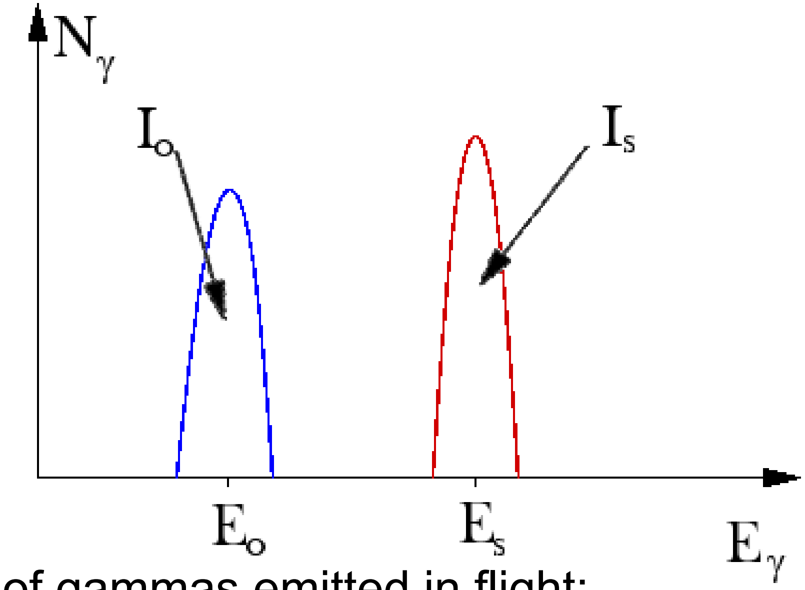
Number of gammas emitted at rest

$$I_s = N_0 \exp\left(-\frac{t_D}{\tau}\right) = N_0 \exp\left(-\frac{D}{v\tau}\right)$$

Recoil Distance Method

For a shorter distance D:





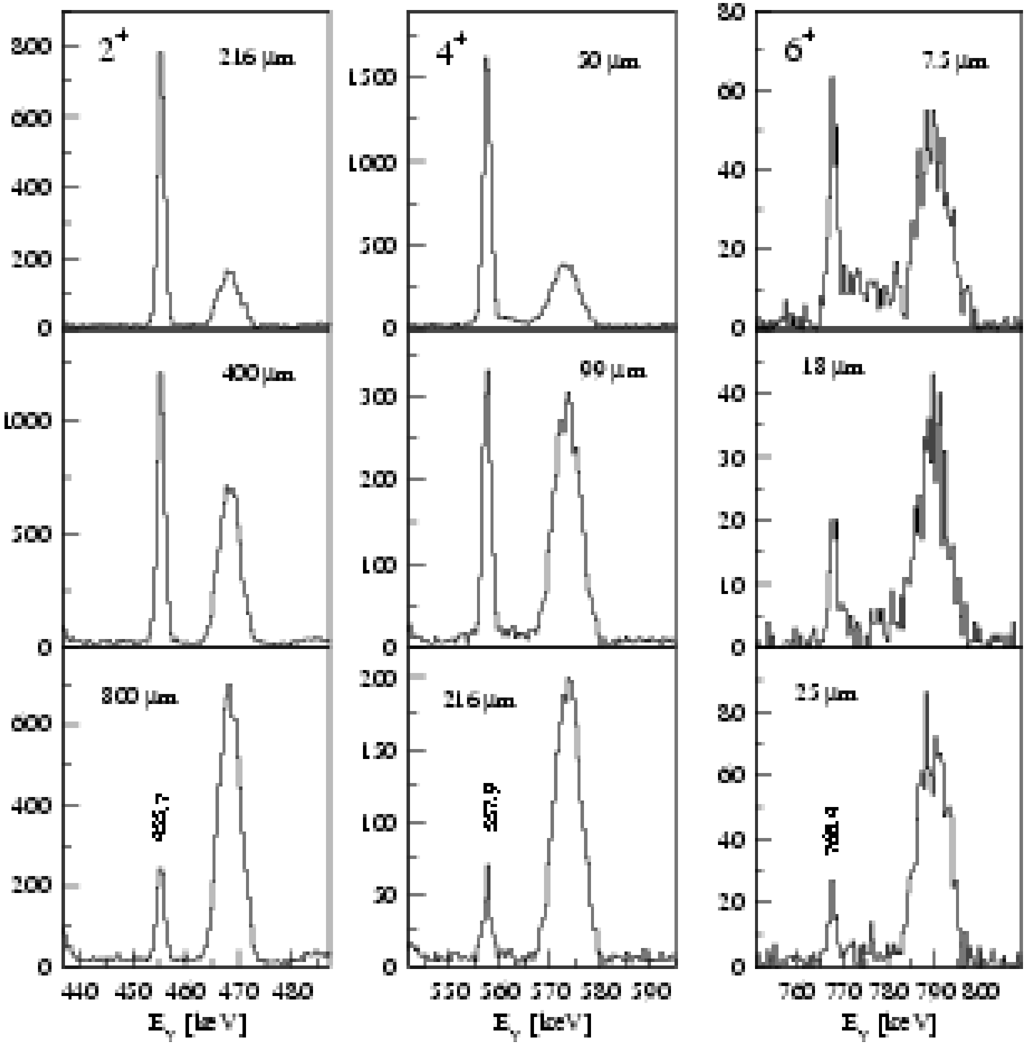
Number of gammas emitted in flight:

$$I_o = N_o - I_s = N_0\left(1 - \exp\left(-\frac{D}{v\tau}\right)\right)$$

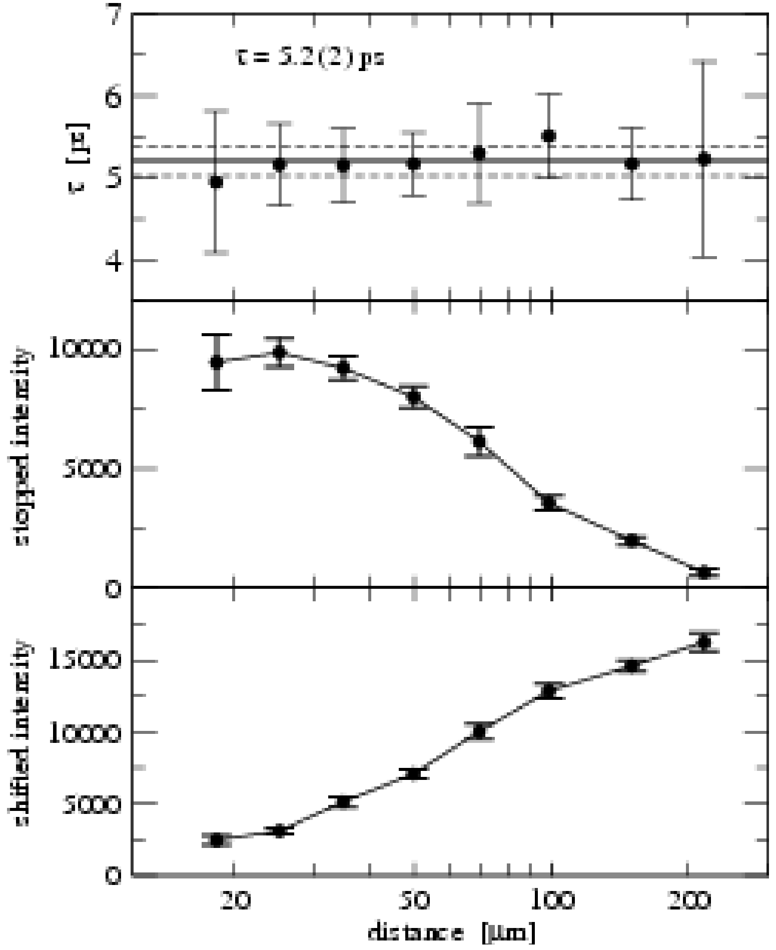
Usually we analyse R(D) defined as:

$$R(D) = \frac{I_o}{I_o + I_s} = \exp\left(-\frac{D}{v\tau}\right)$$

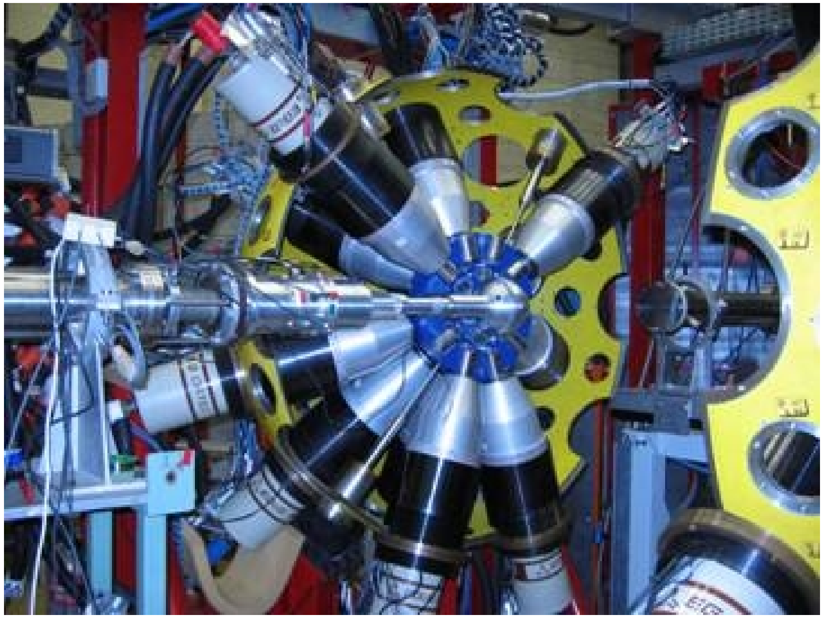
Recoil Distance Method

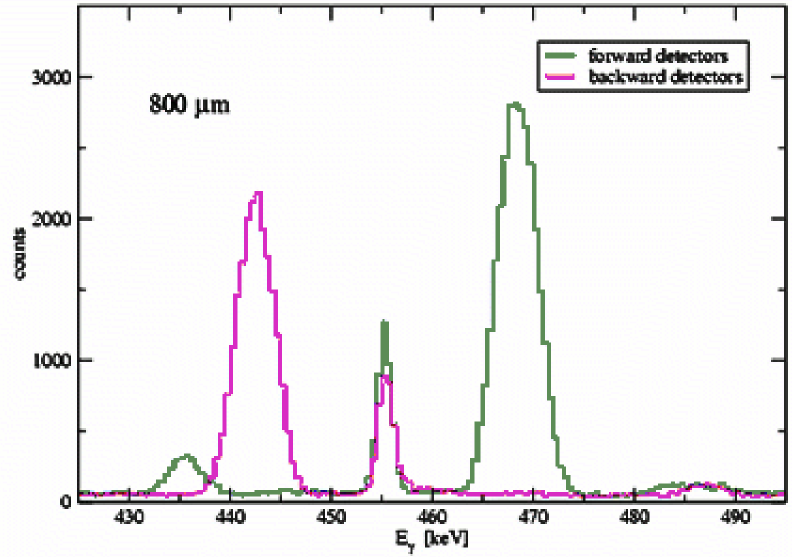


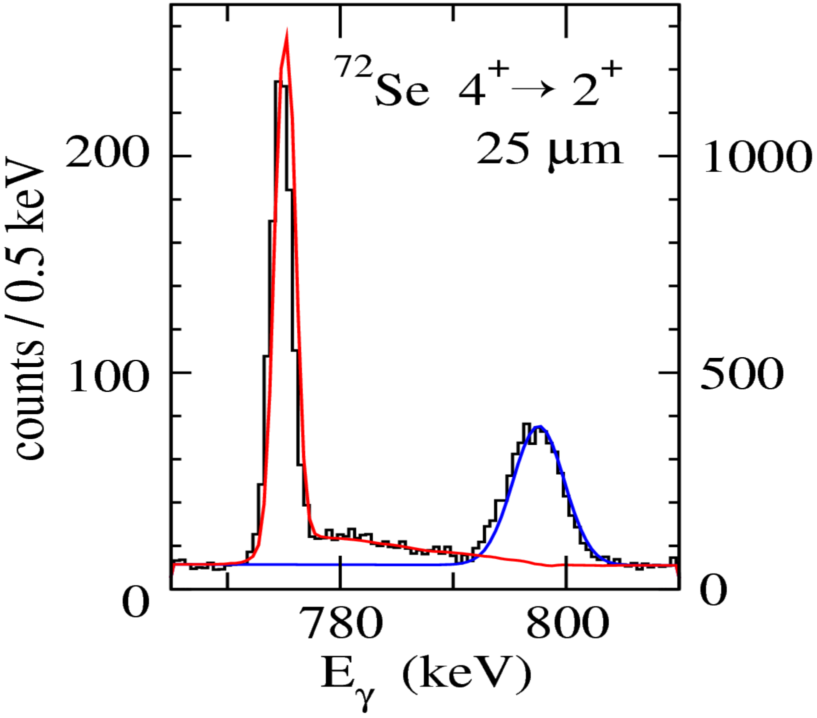
Example: ^{74}Kr , 4^+ , 36°



Plunger

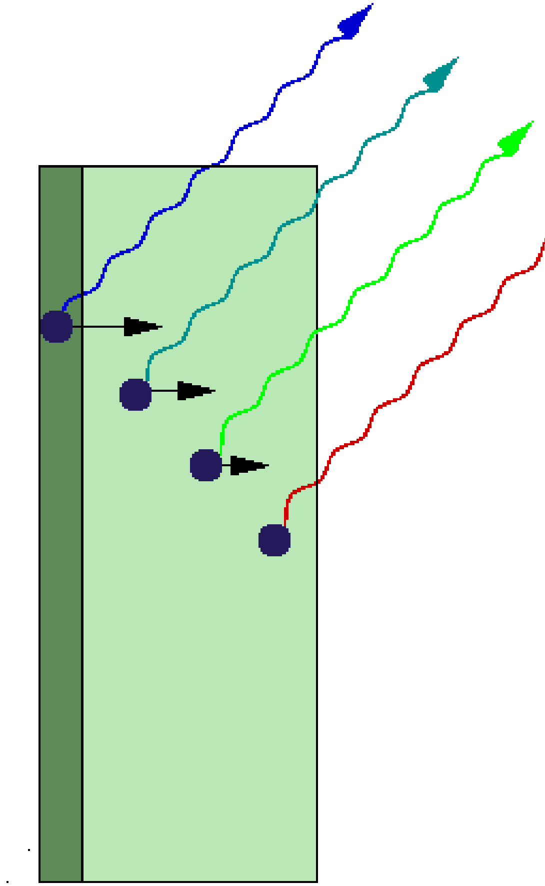


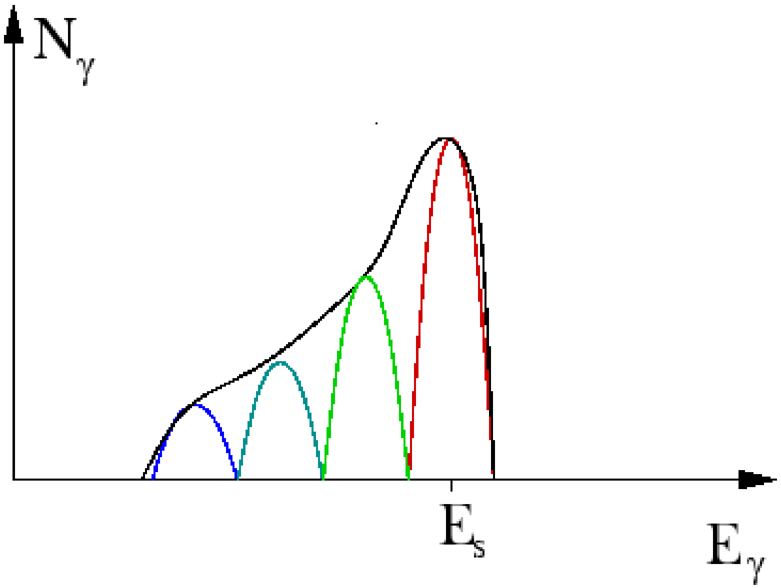

800 μm
forward detectors
backward detectors
counts
3000
2000
1000
0
430
440
450
460
470
480
490
E_γ [keV]

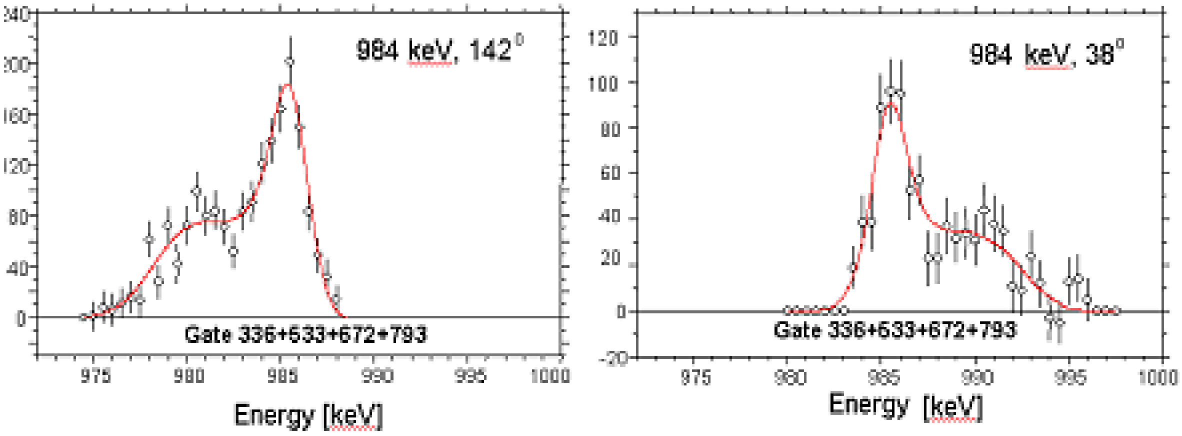

^{72}Se 4$^+$→ 2$^+$
25 μm
counts / 0.5 keV
200
100
0
1000
500
0
780
800
E$_\gamma$ (keV)

Doppler Shift Attenuation Method

Suitable for lifetimes of $10^{-11} – 10^{-14}$ s

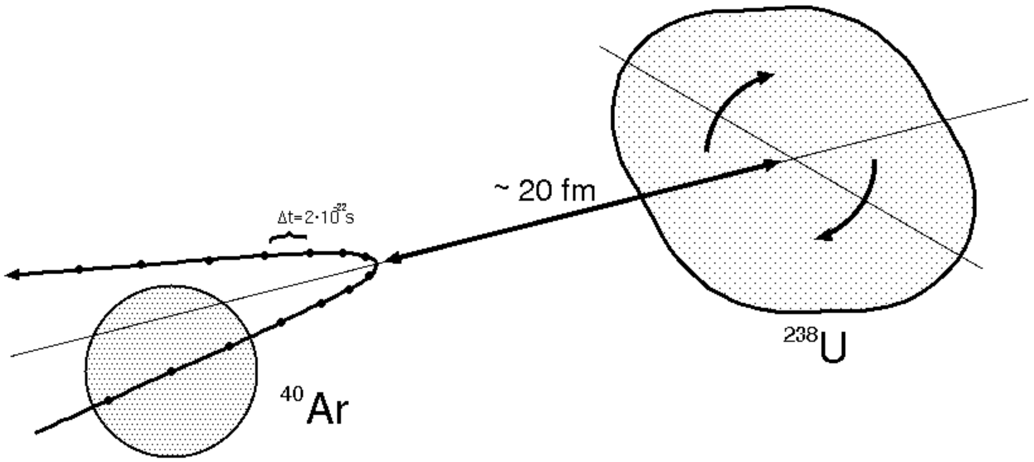




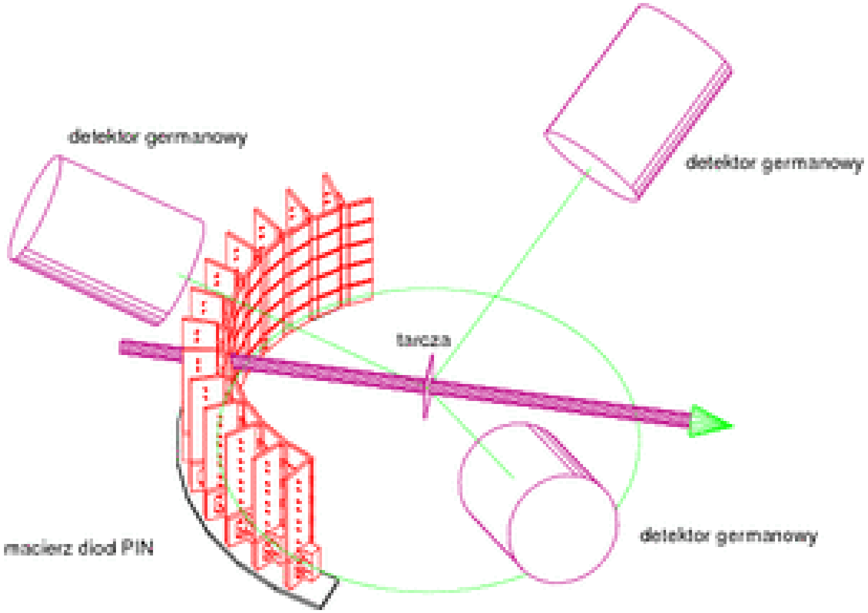


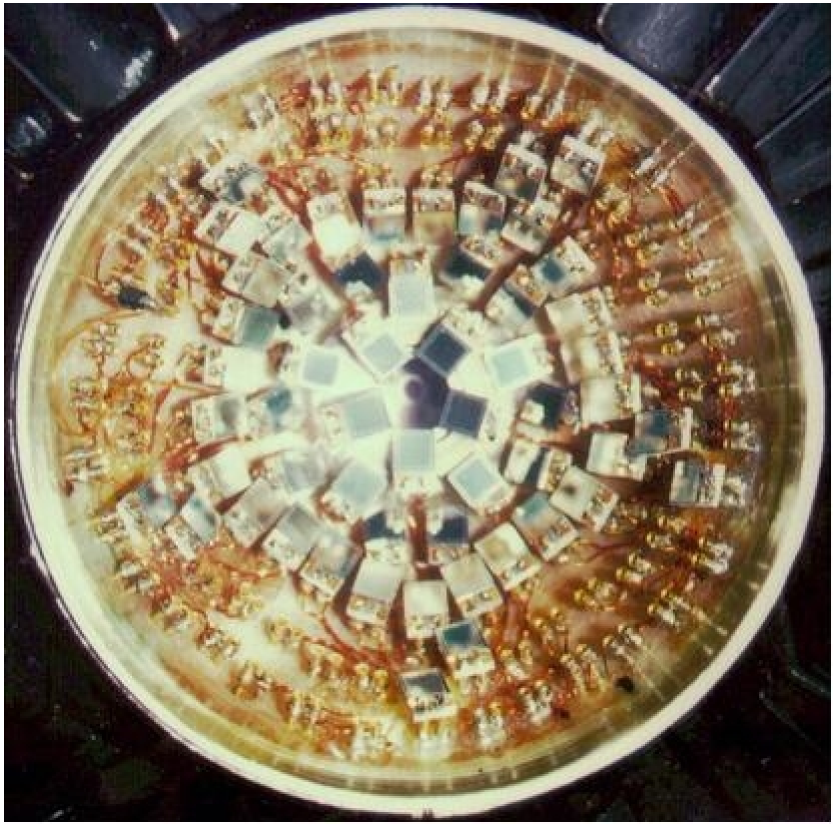
Coulomb excitation

- Beam particle passing near a target nucleus generates a strong electromagnetic field
- It causes excitation of the target nucleus – population of higher-lying states
- Beam energy chosen in such a way that no collisions take place – the nuclei interact without touching each - only electromagnetic interaction possible (and this we know well!)
- Excitation cross-section proportional to reduced transition probability
  → we measure gamma-ray intensities and obtain transitions probabilities between excited states (directly related to their lifetimes)
- Observed excitation depends on scattering angle, beam energy, atomic numbers of collision partners.

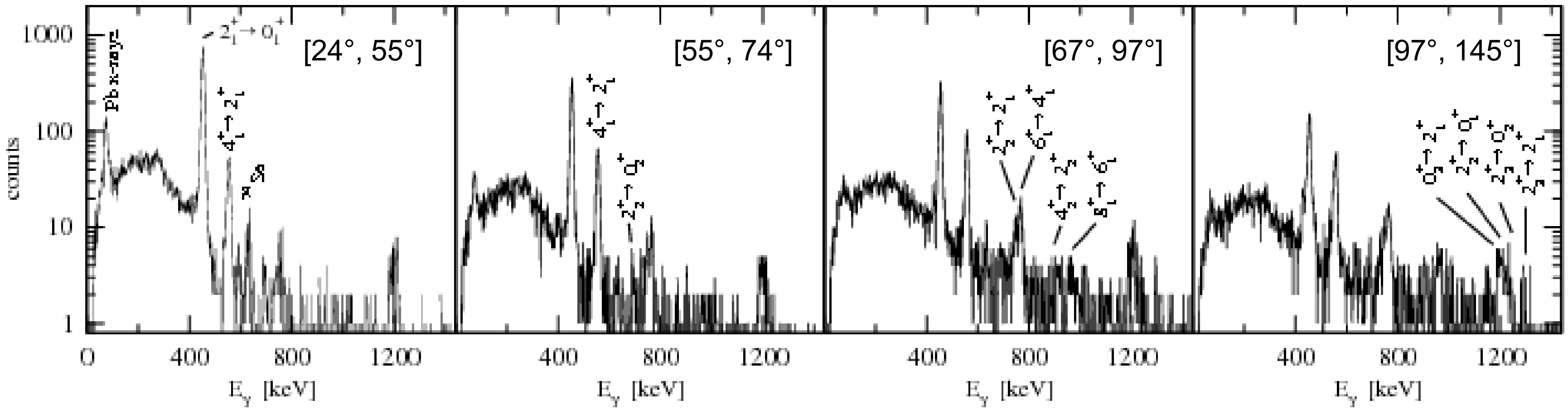


Coulomb excitation

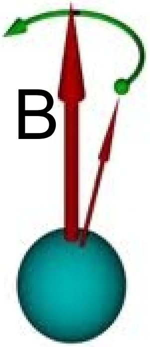




^{74}Kr



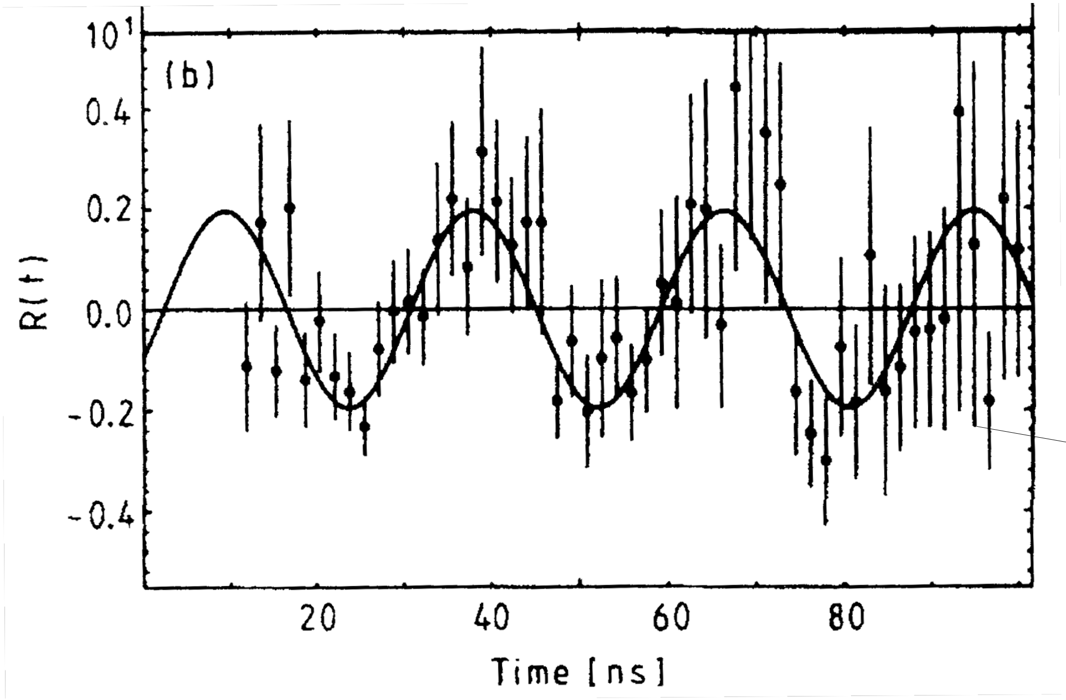
Data analysis – magnetic moments

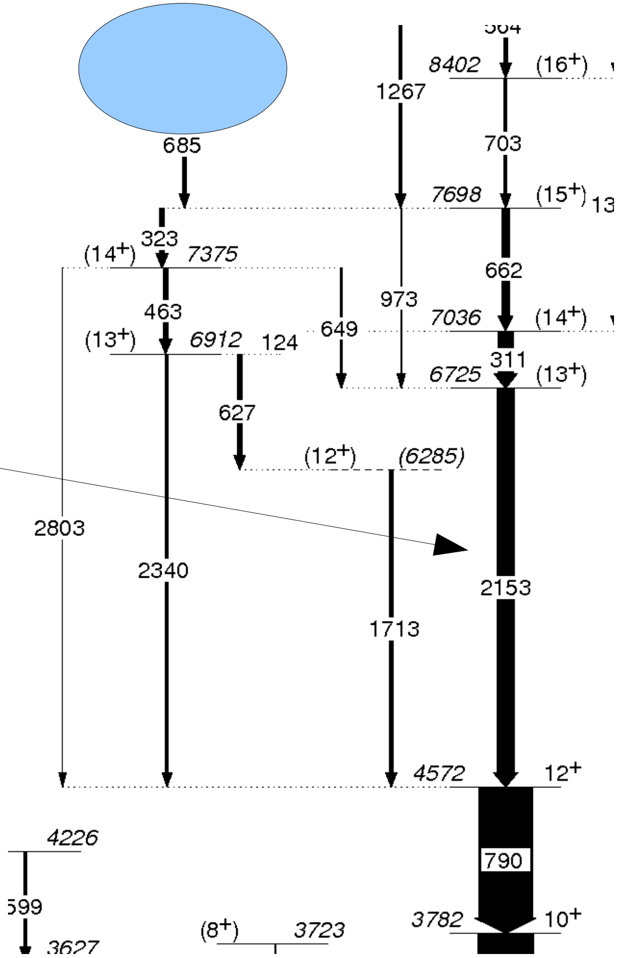


Larmor precession

B - external magnetic field

$$R(t)=\frac{I(t,135^o)-I(t,-135^o)}{I(t,135^o)+I(t,-135^o)}$$





$$R(t)\sim\cos(2t(\theta-\omega_L))$$

$$\omega_L=\mu_n gB/\hbar$$

g = 0.83(5)