Gamma ray spectroscopy

selected aspects and examples of focusing on in-beam experiments

Marcin Palacz
Heavy Ion Laboratory, University of Warsaw

Gamma ray spectroscopy

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

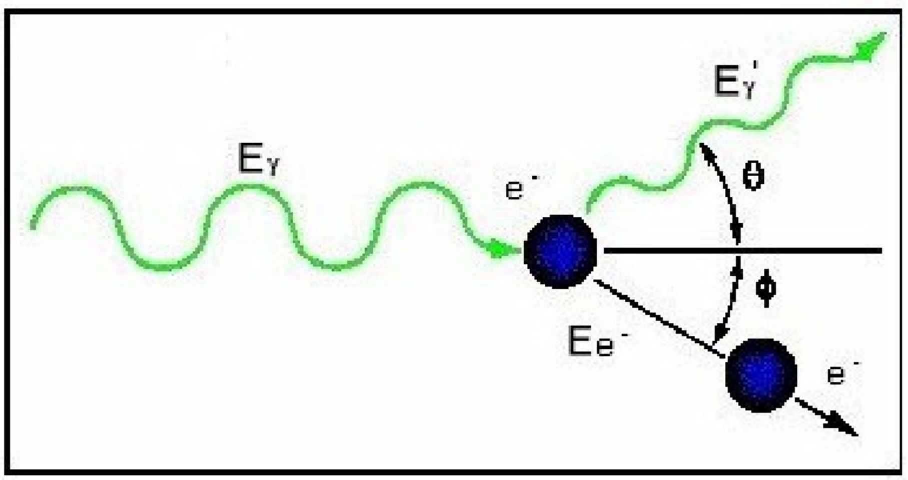
In order to establish properties of excited nuclear states: excitation energy, spin, parity, half-life, magnetic moment, shape (deformation), rotation/oscillation, ...

Interactions of γ 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**



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

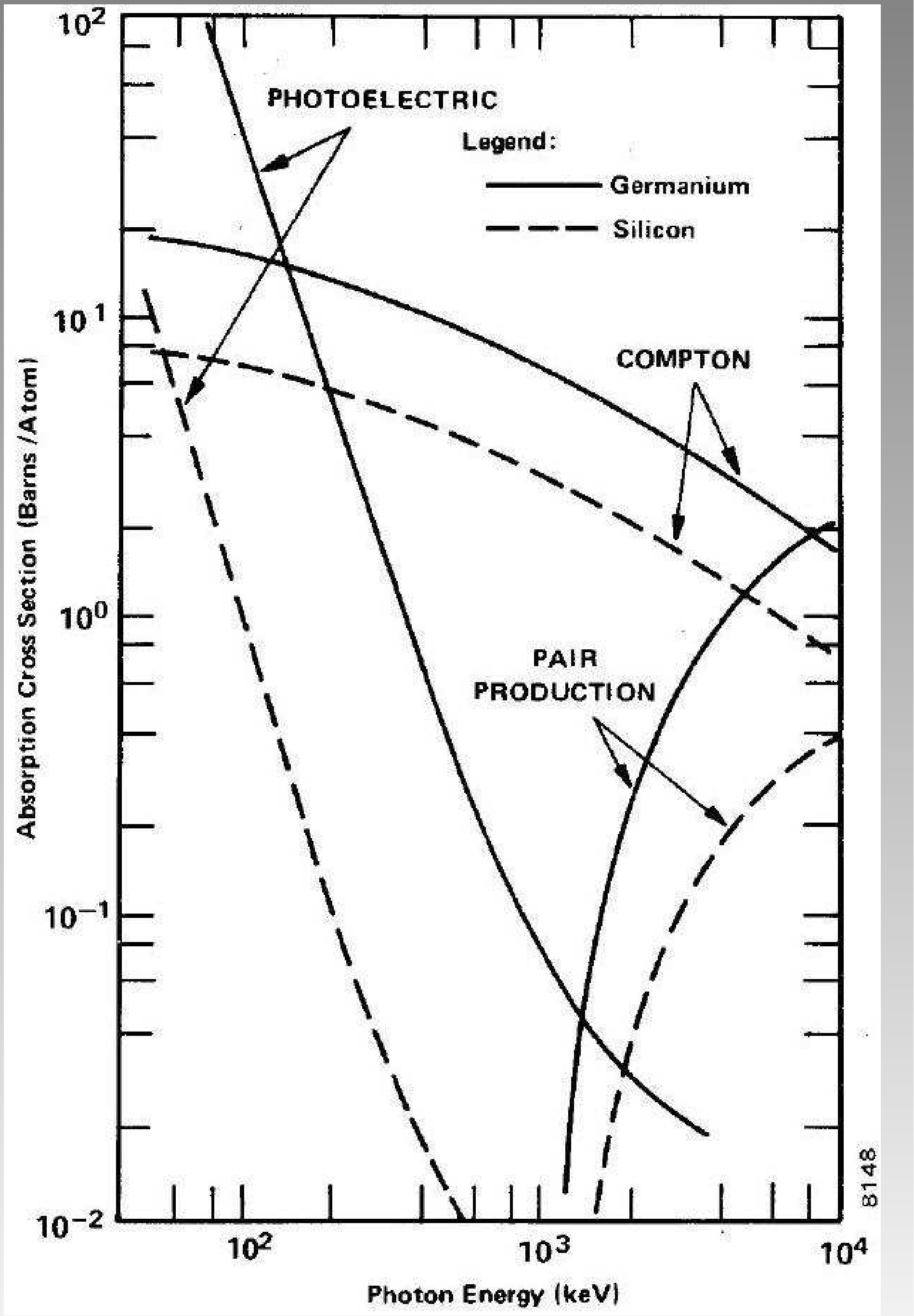
$$max\, E_e = E_\gamma \left(1 - \frac{1}{1 + \frac{2 E_\gamma}{511\, keV}}\right)$$

- **e^+e^- pairs production** (E_γ > 1.02 MeV)
  slowed down e^+ anihilates, giving a colinnear γ-ray pair, 511 keV each

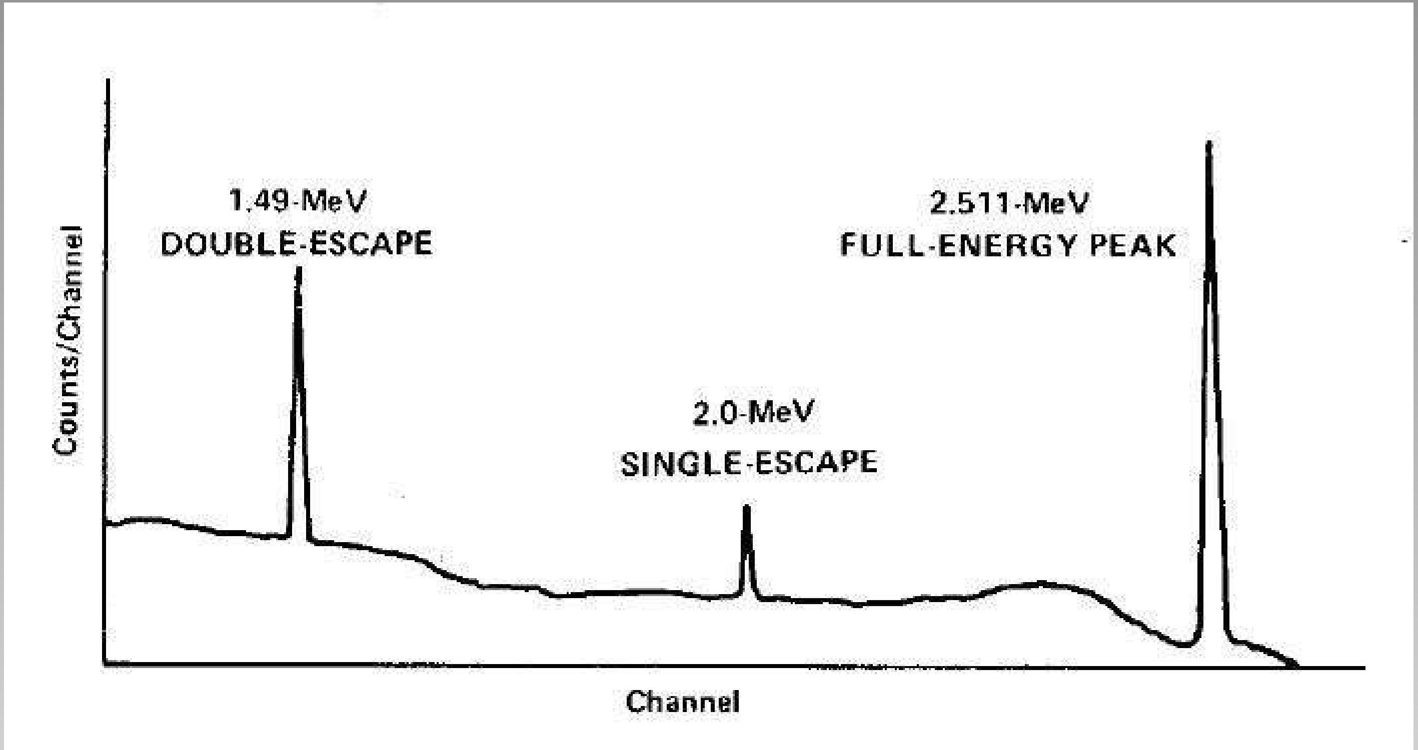
Gamma ray interactions - comparison

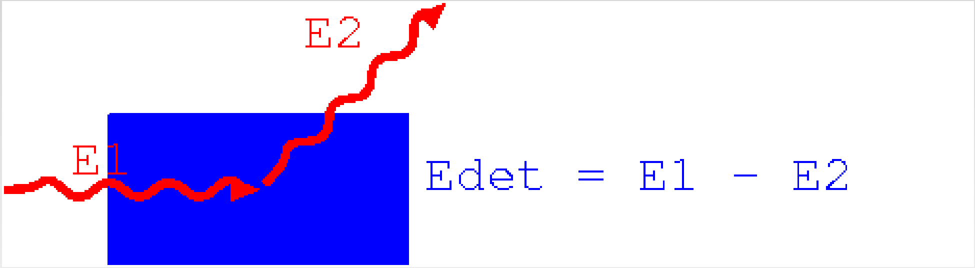
- Bad news:
  Compton scattering dominates for 100-5000 MeV, higher up – pair production.

- 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.



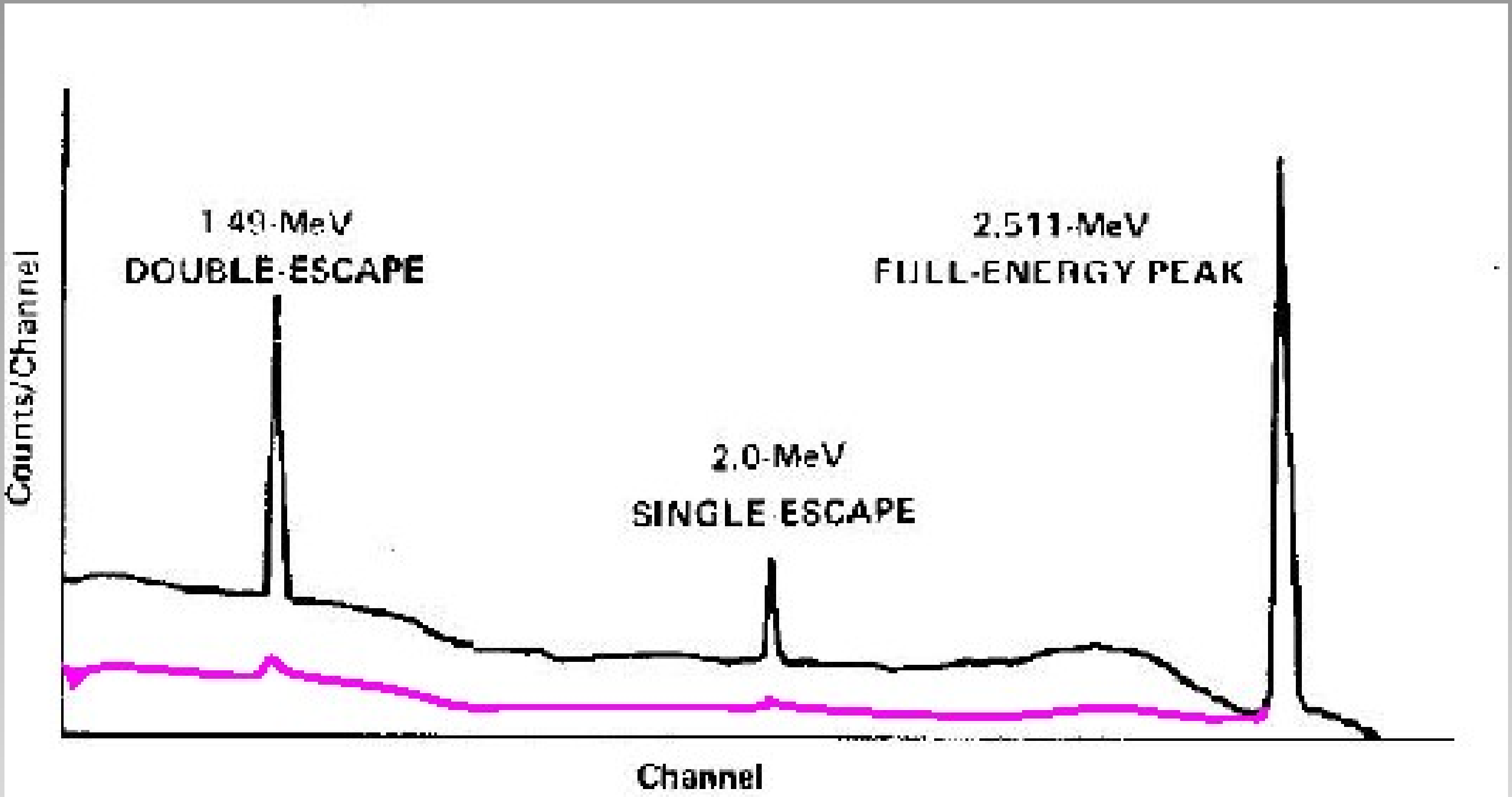
Gamma ray spectrum $E_\gamma = 2.511$ keV

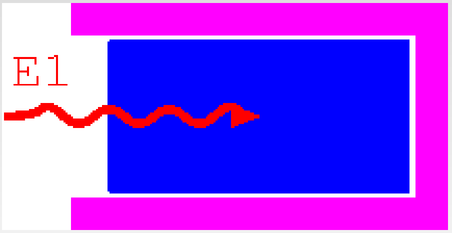




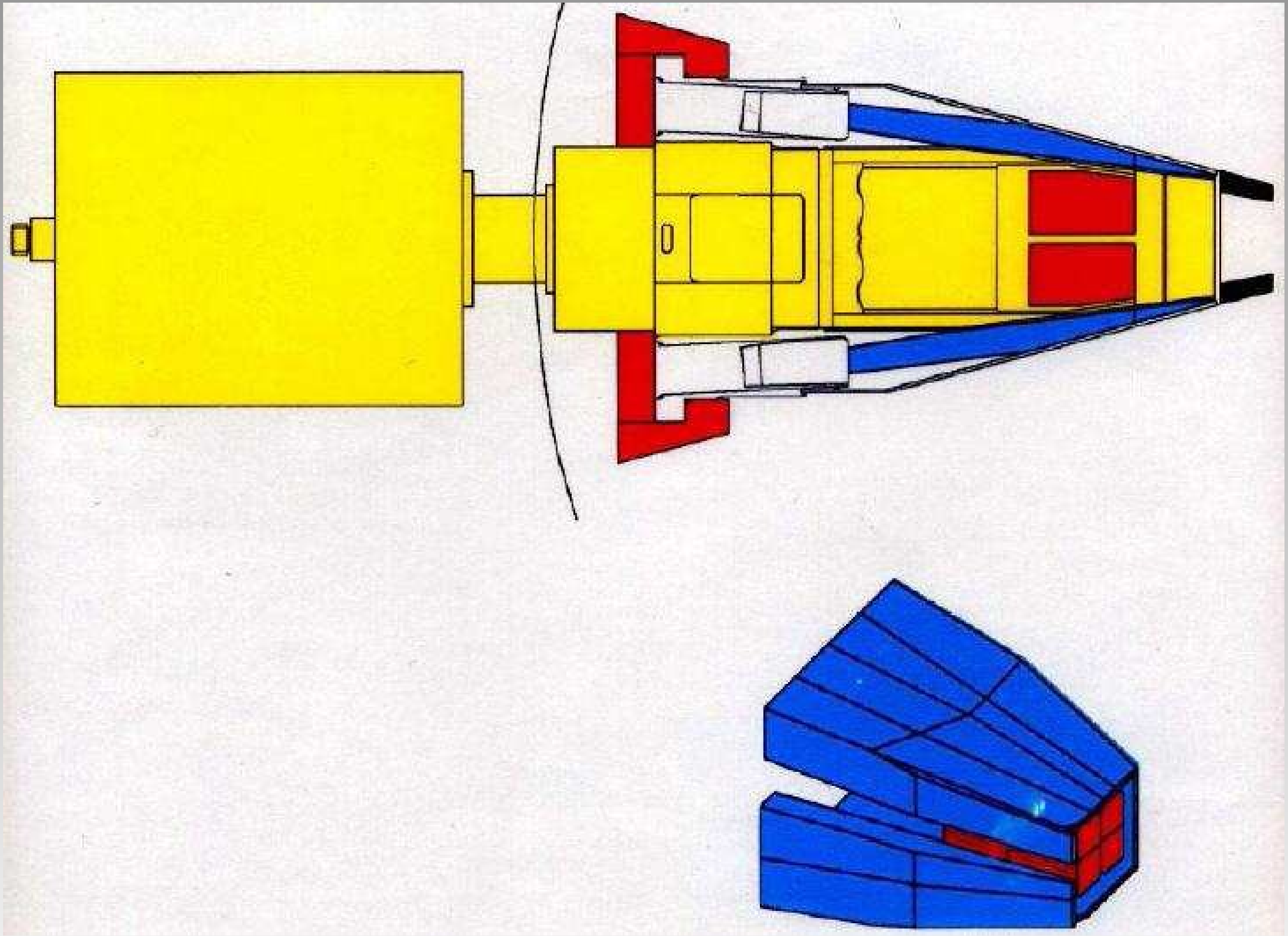
Edet = E1 - E2

Gamma ray spectrum E_γ = 2.511 keV with anti-Compton shield



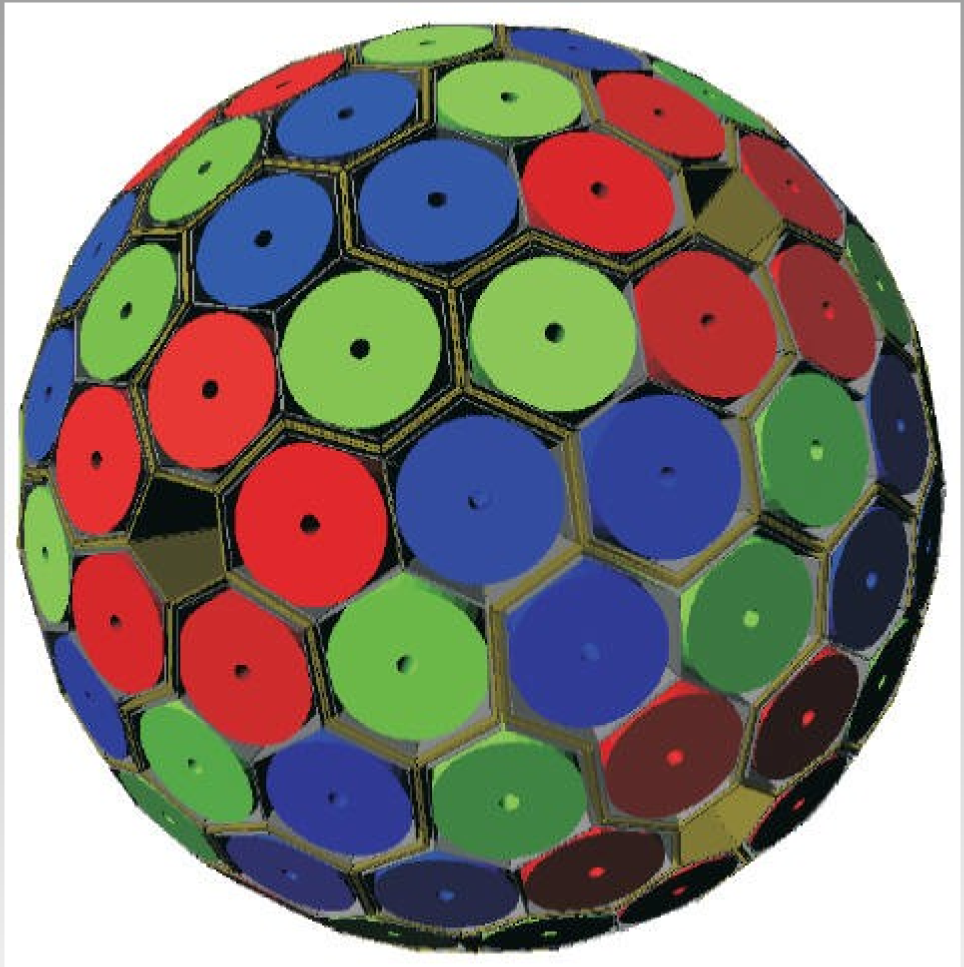


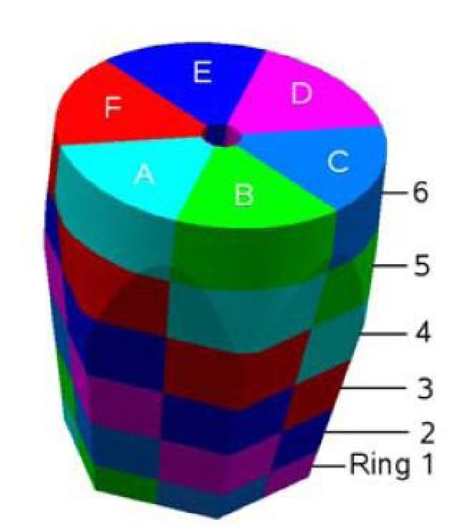
Germanium detector with anti-Compton shield



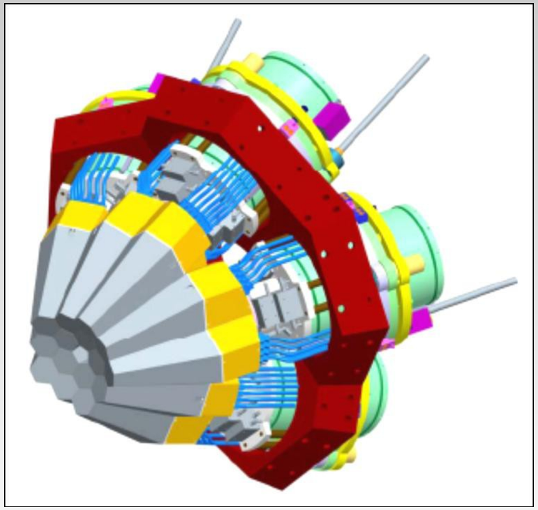
Advanced Gamma Ray Tracking Array

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





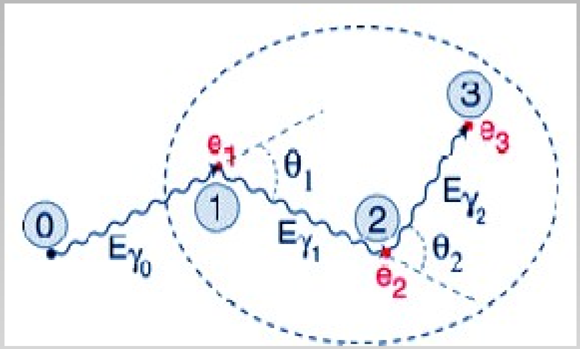
Demonstrator

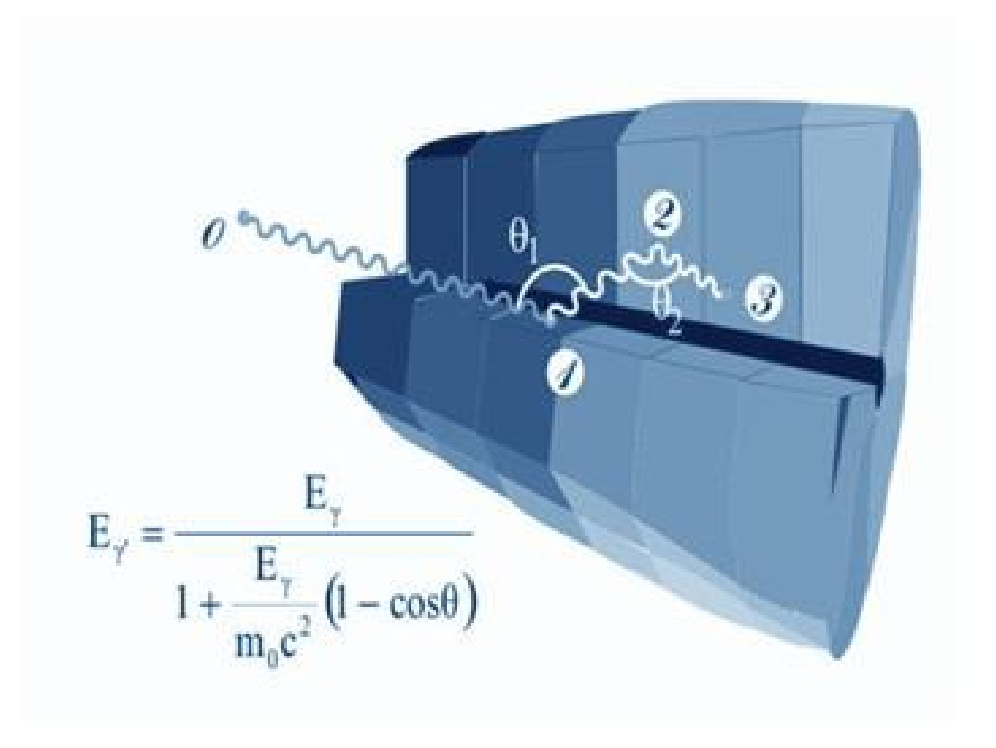


Gamma Ray Tracking Principle

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

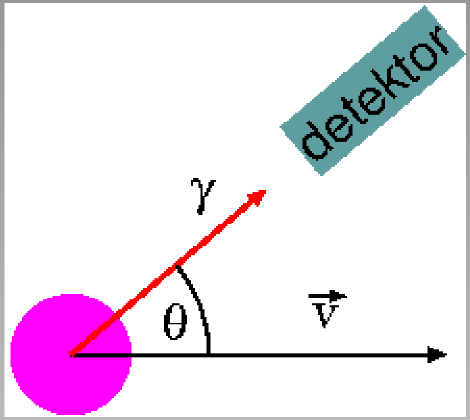




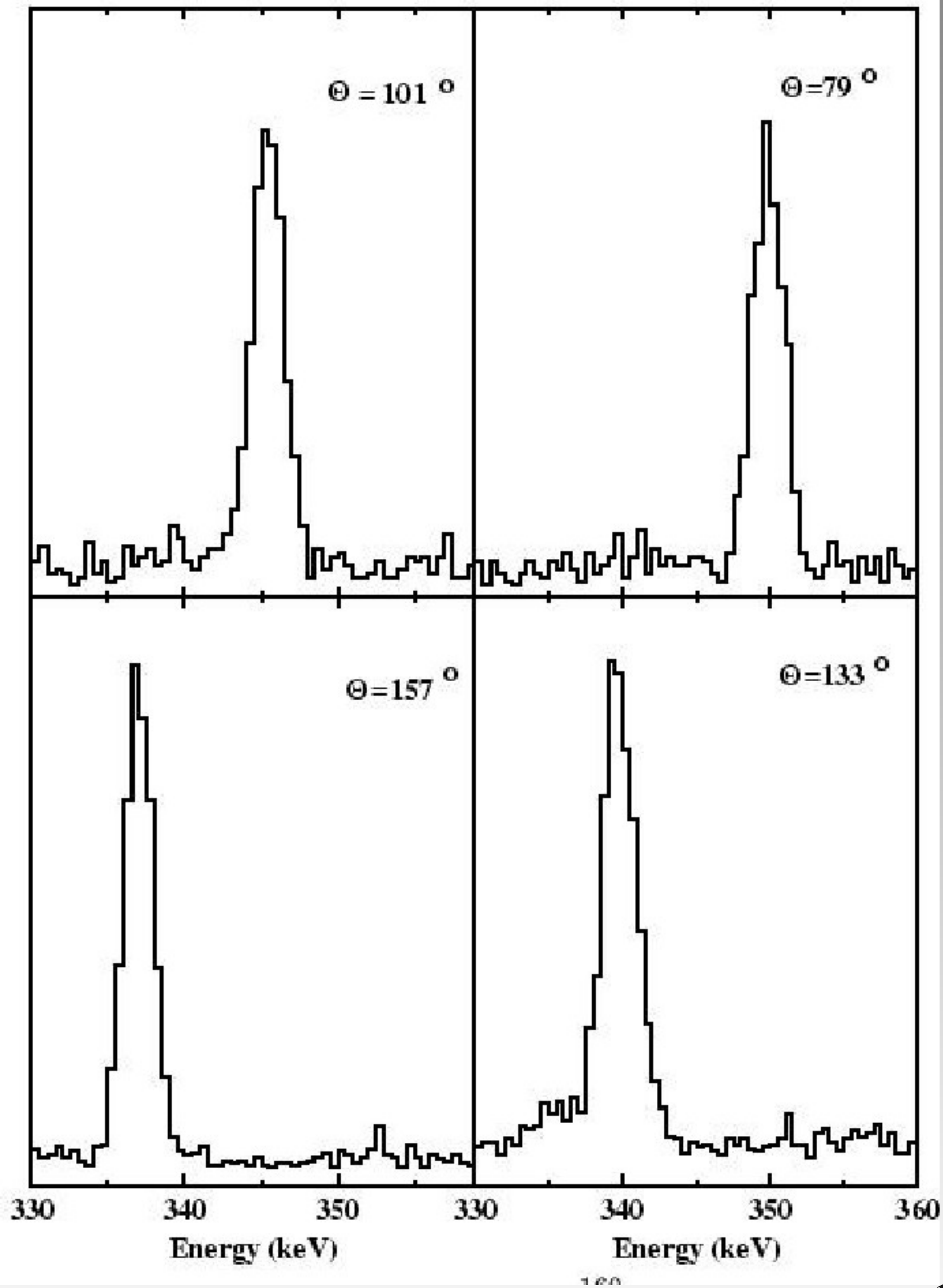
$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$$

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

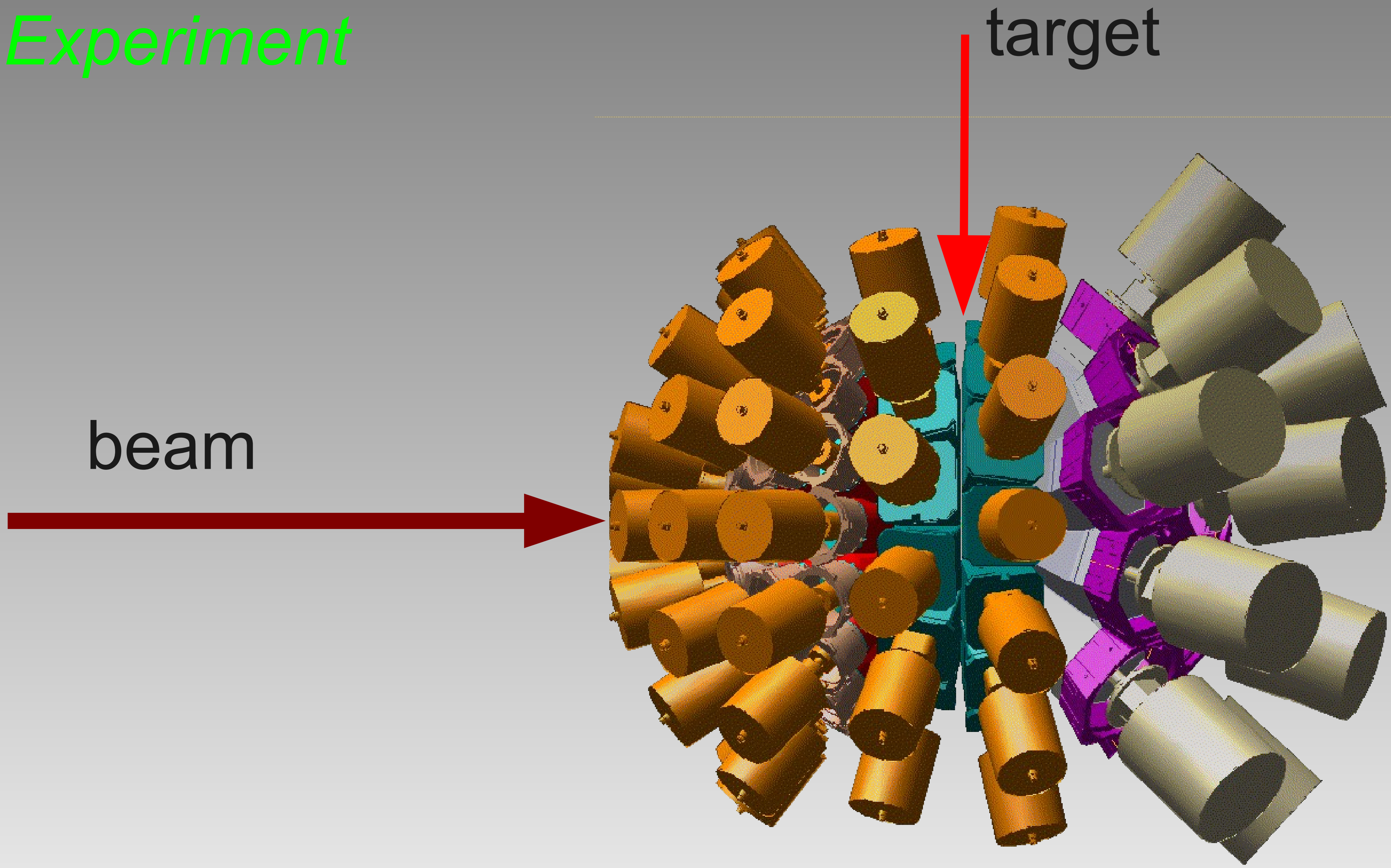
Doppler effect



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

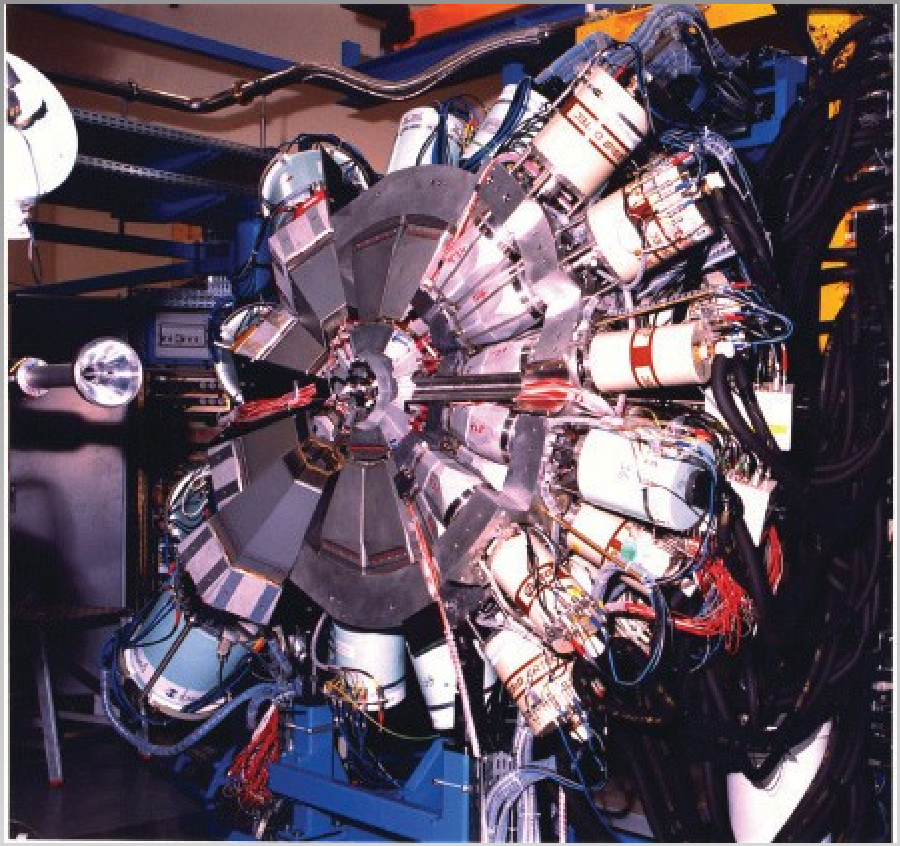


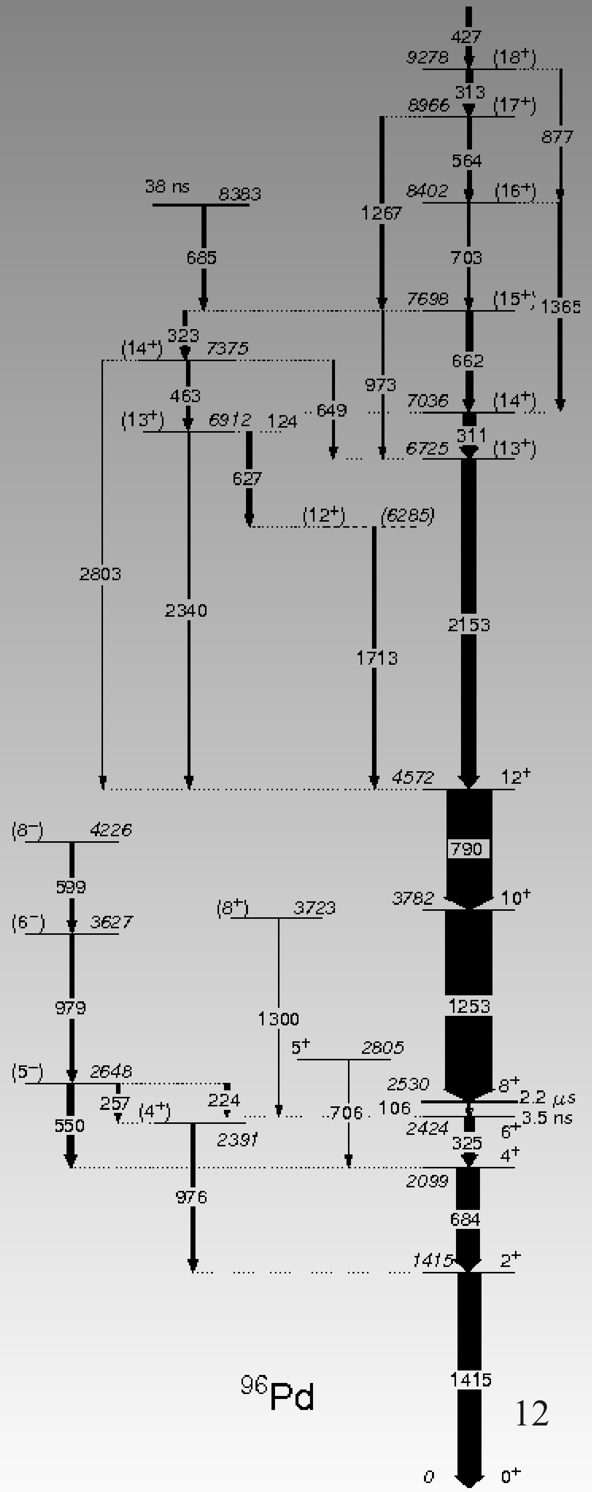
Experiment



For example

^{58}Ni + ^{45}Sc $\rightarrow$ ^{103}In $\rightarrow$ 1p1α2n + ^{96}Pd

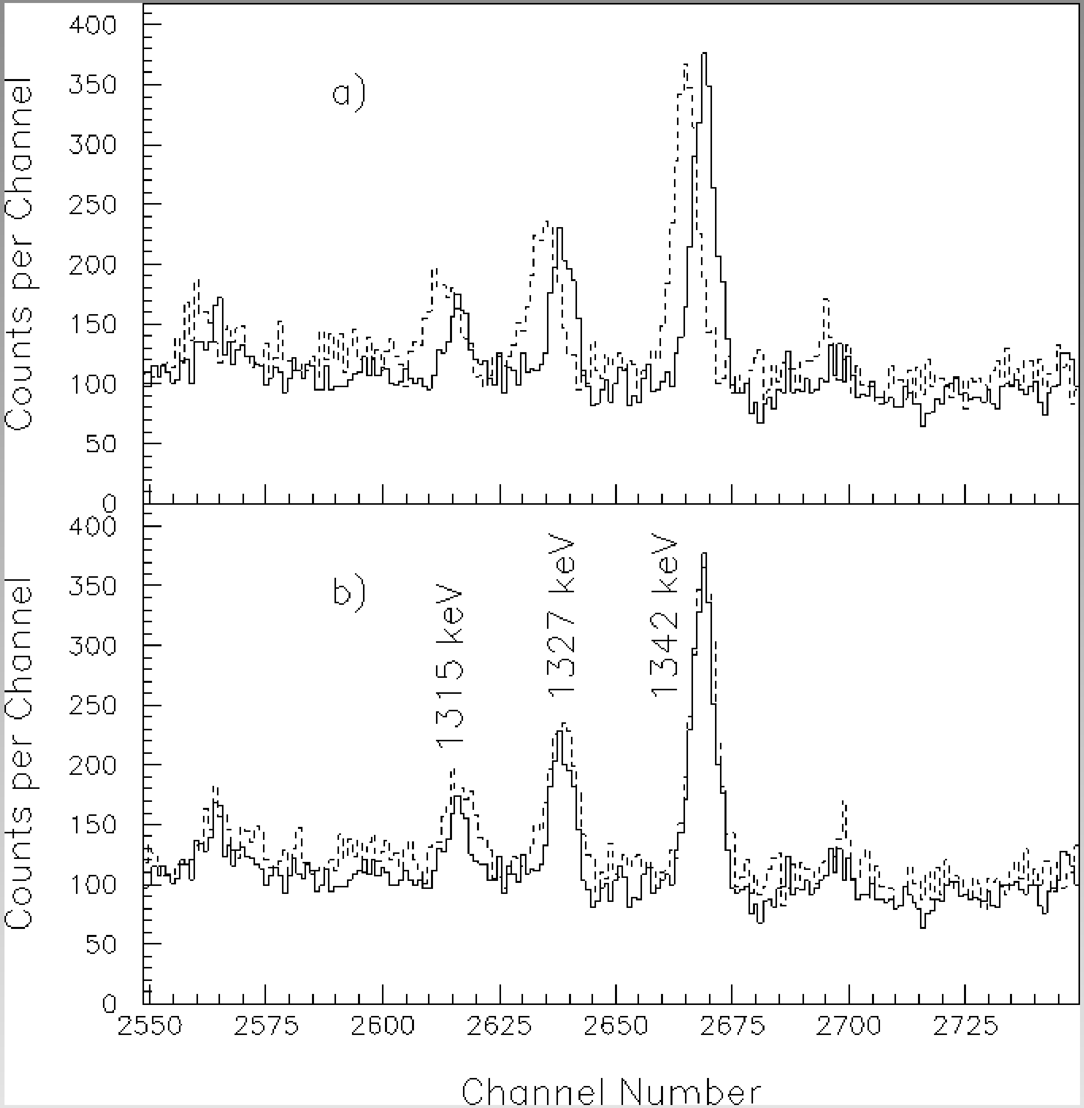




209 Ge detectors,
50 neutron detectors,
charged particle detector
effective data taking time: 310 hours

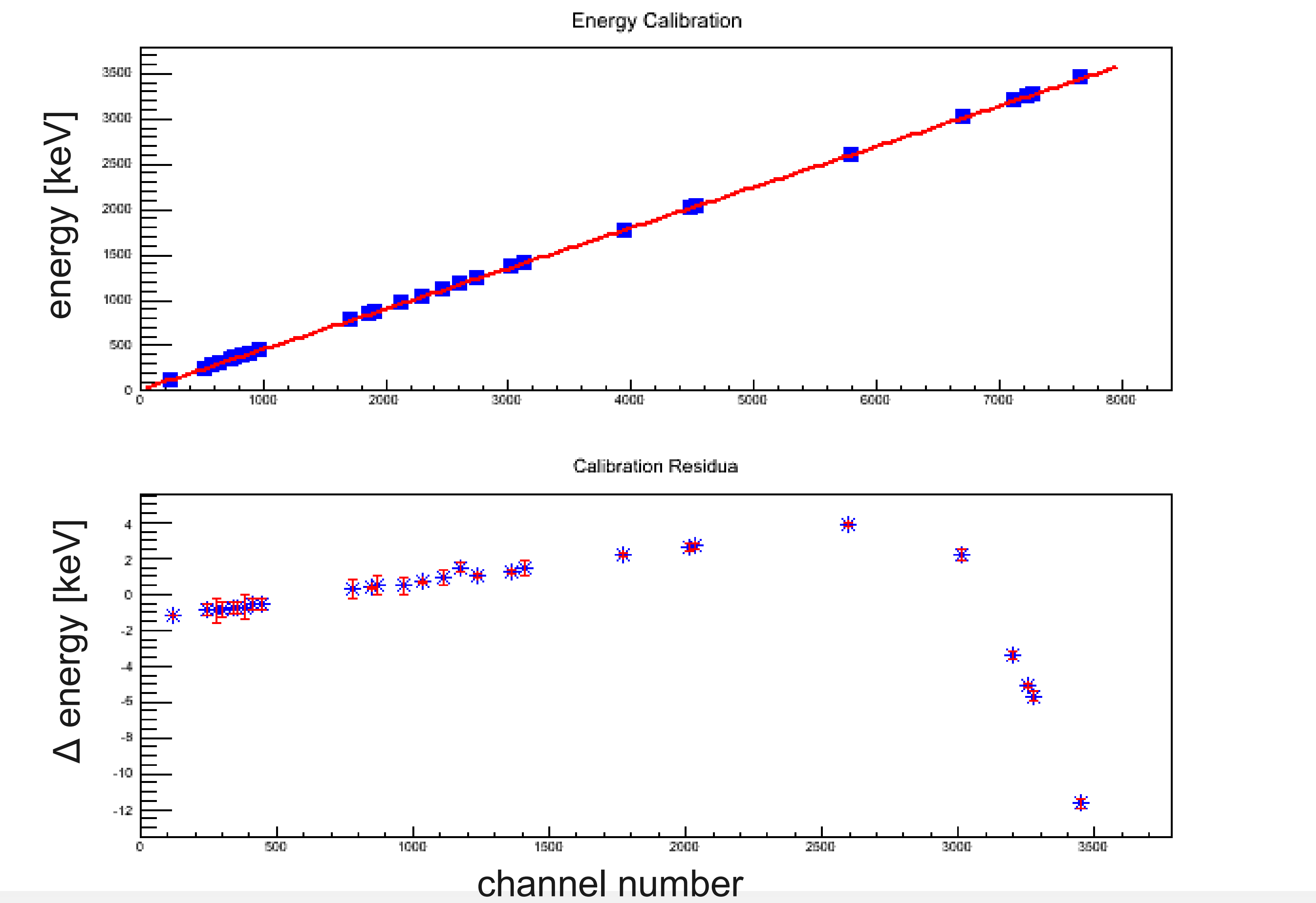
Data processing 1

- Check and correction for instrumental shifts and instabilities
- Data scanned in 2h intervals:
  ~50000 Ge spectra

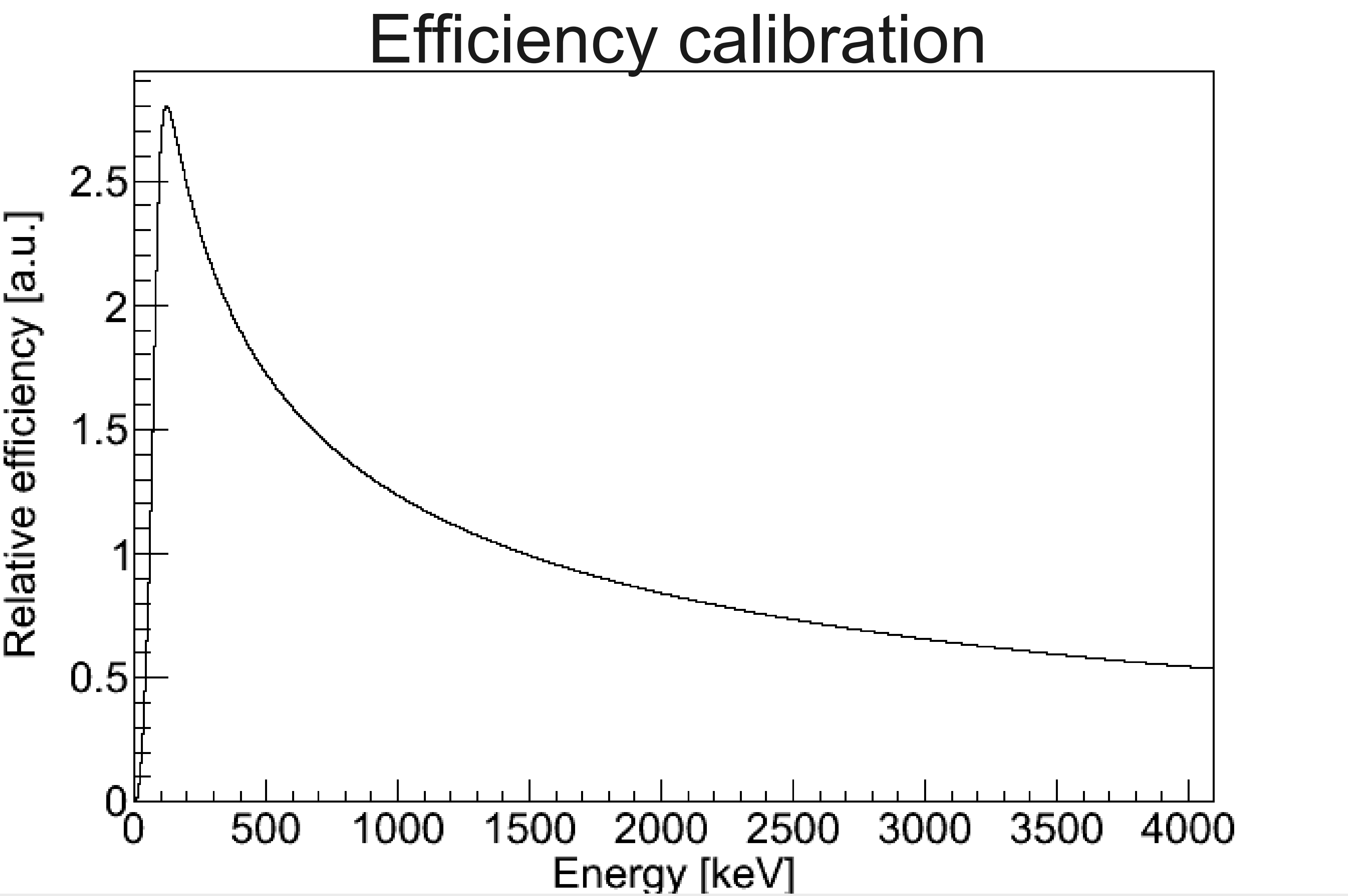


Data processing 2

Energy calibration:
$E = a_0 + a_1 {*} x + \ldots\ldots$



Data processing 3



Data processing 4,5,....

- Checks and corrections of data from ancillary detectors
- Optimizing gates on complementary detectors
- Time calibration
- ....

Data analysis

Aim: to determine properties of excited states

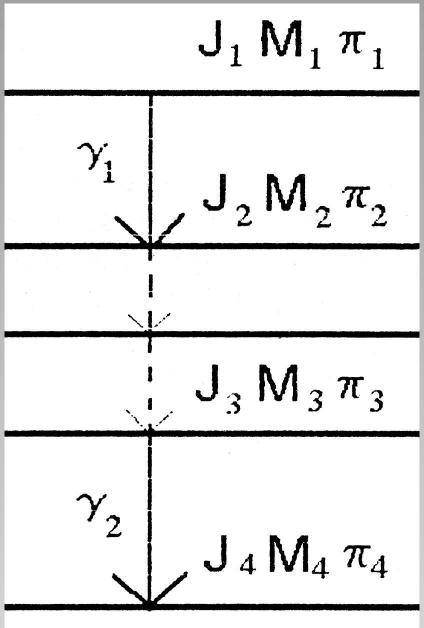
Individual nuclear states have unique spin and parity.
For decay from $(E_i J_i M_i \pi_i)$ to $(E_f J_f M_f \pi_f)$, the electromagnetic radiation must satisfy the following relations:

Energy $E_\gamma = E_i - E_f$

Multipolarity $|J_i - J_f| \le L \le (J_i + J_f)$

M-state $M = M_i - M_f$

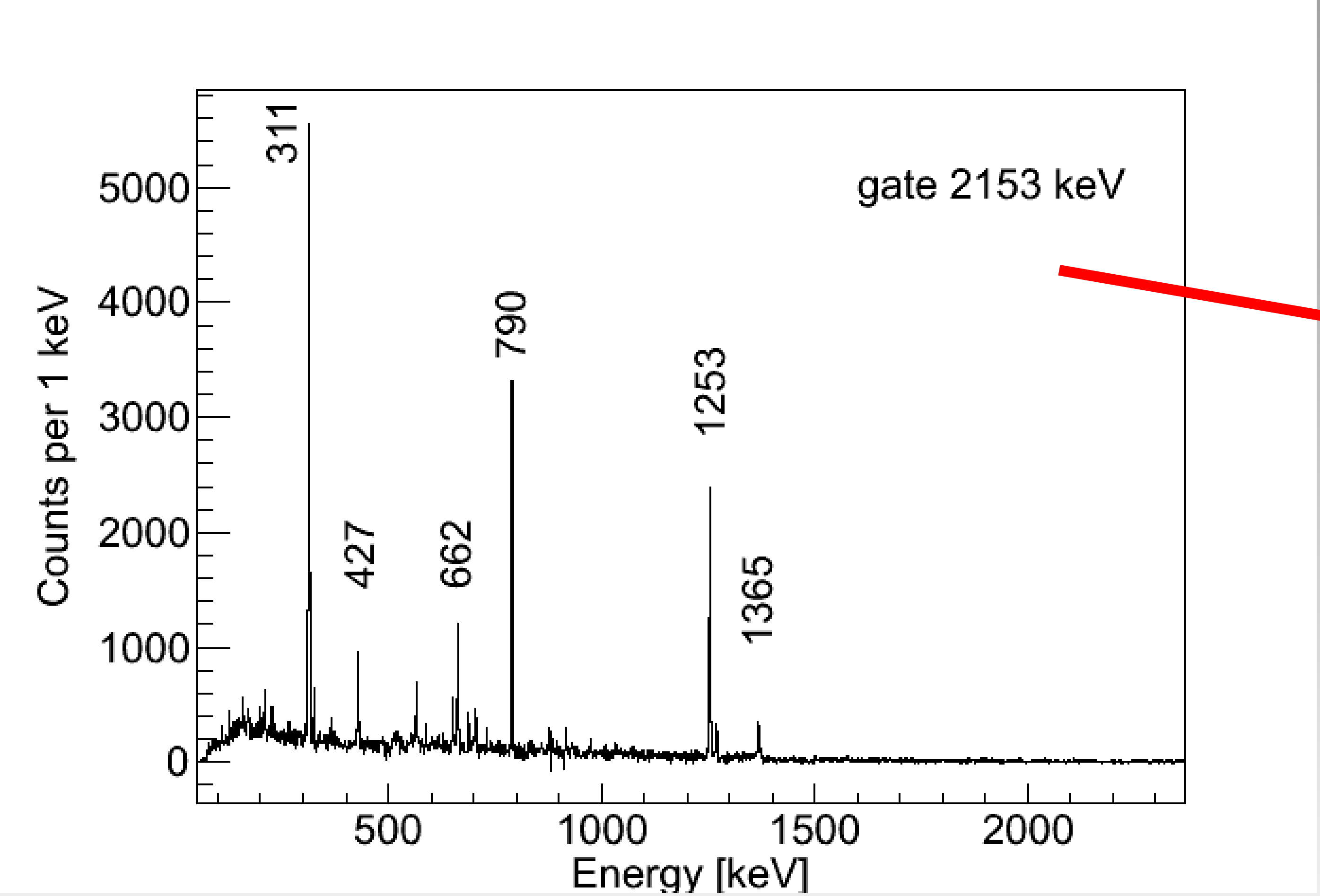
Parity $\pi = \pi_i \pi_f$

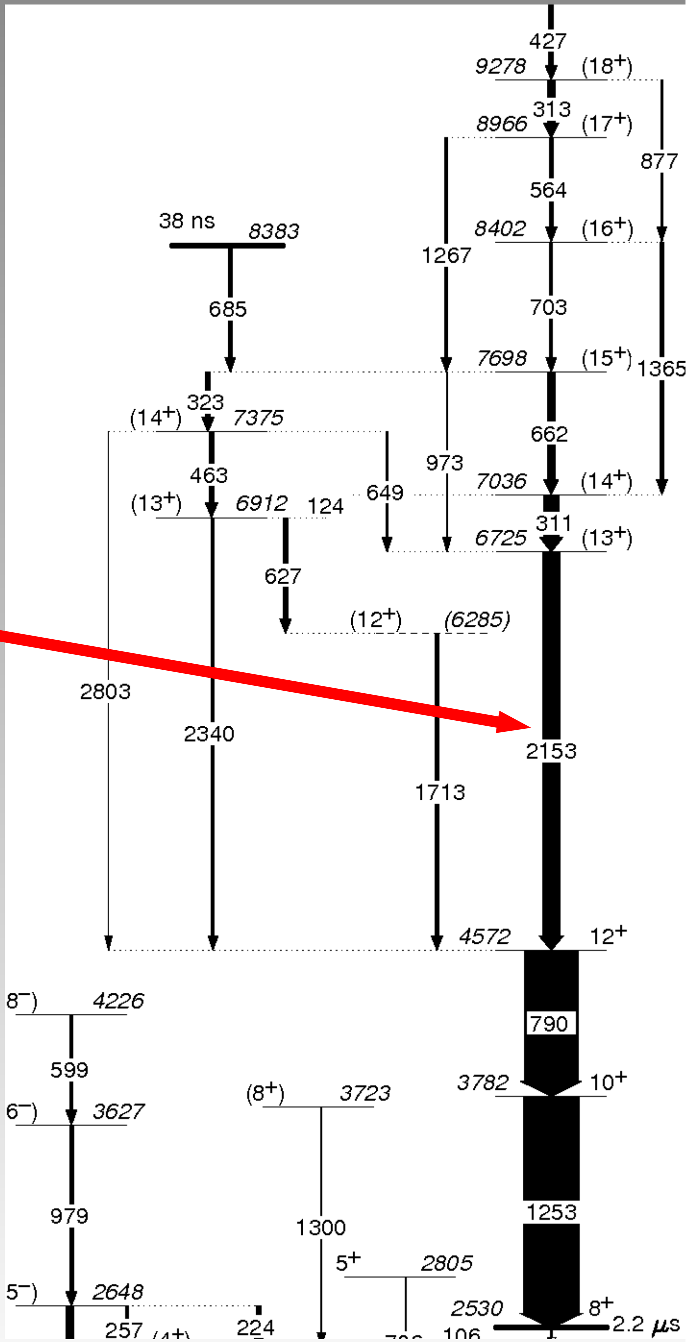


Properties of γ rays → Properties of states

Data analysis – energies of excited states

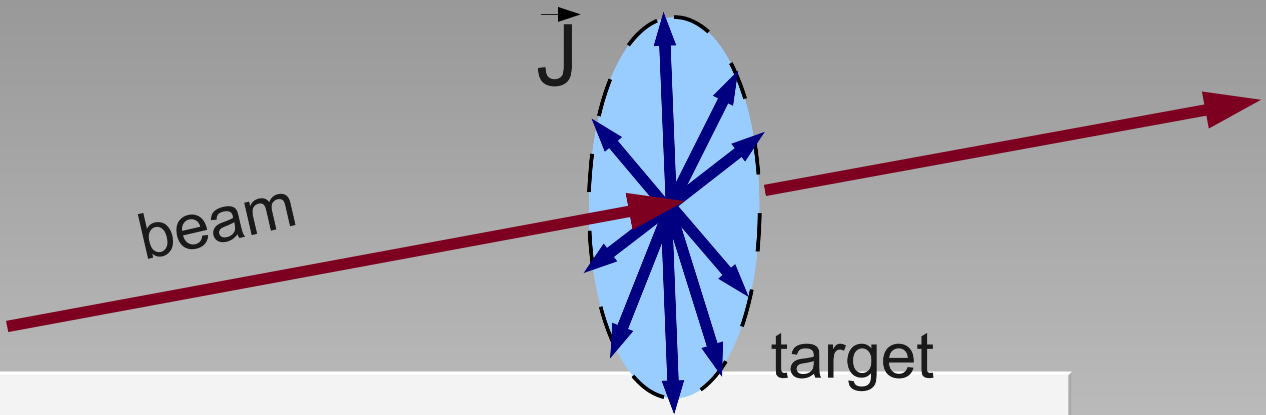
Method: analysis of coincident γ-ray spectra

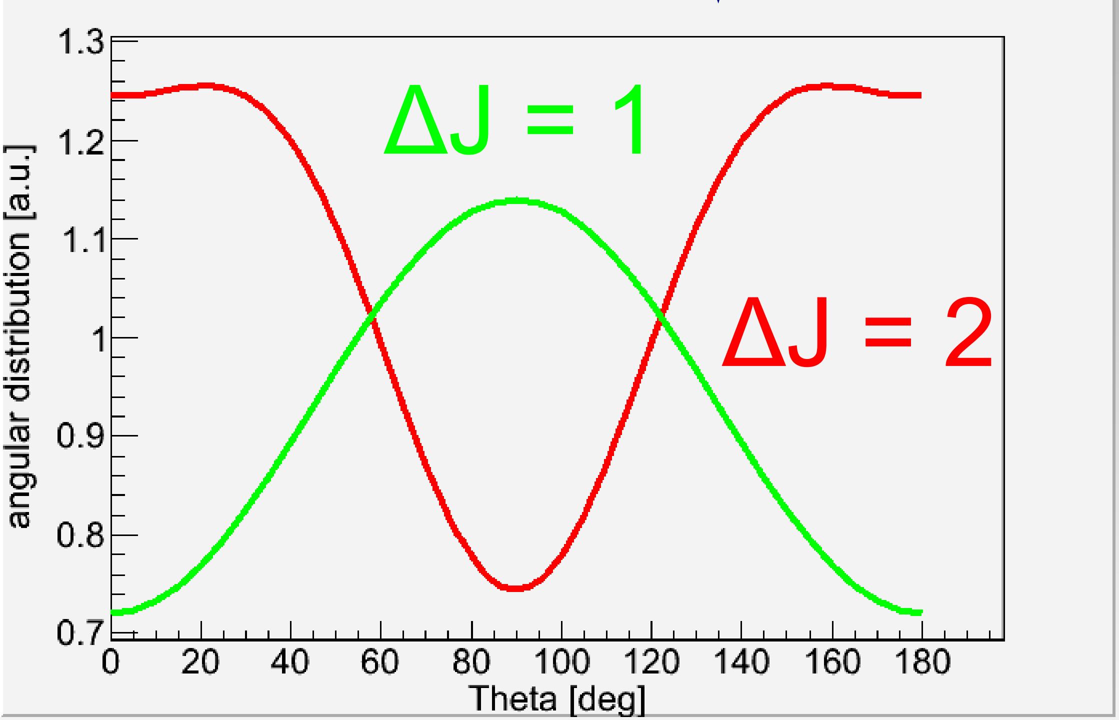


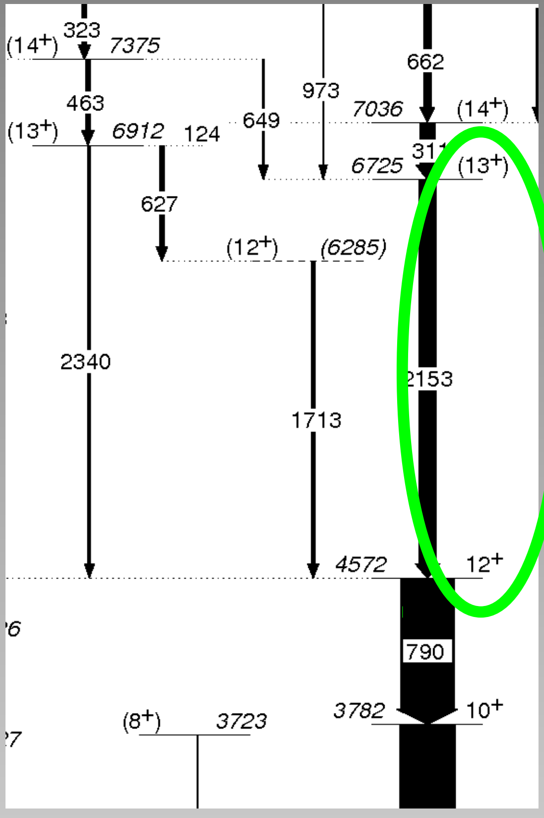


Data analysis – spins

Angular distributions

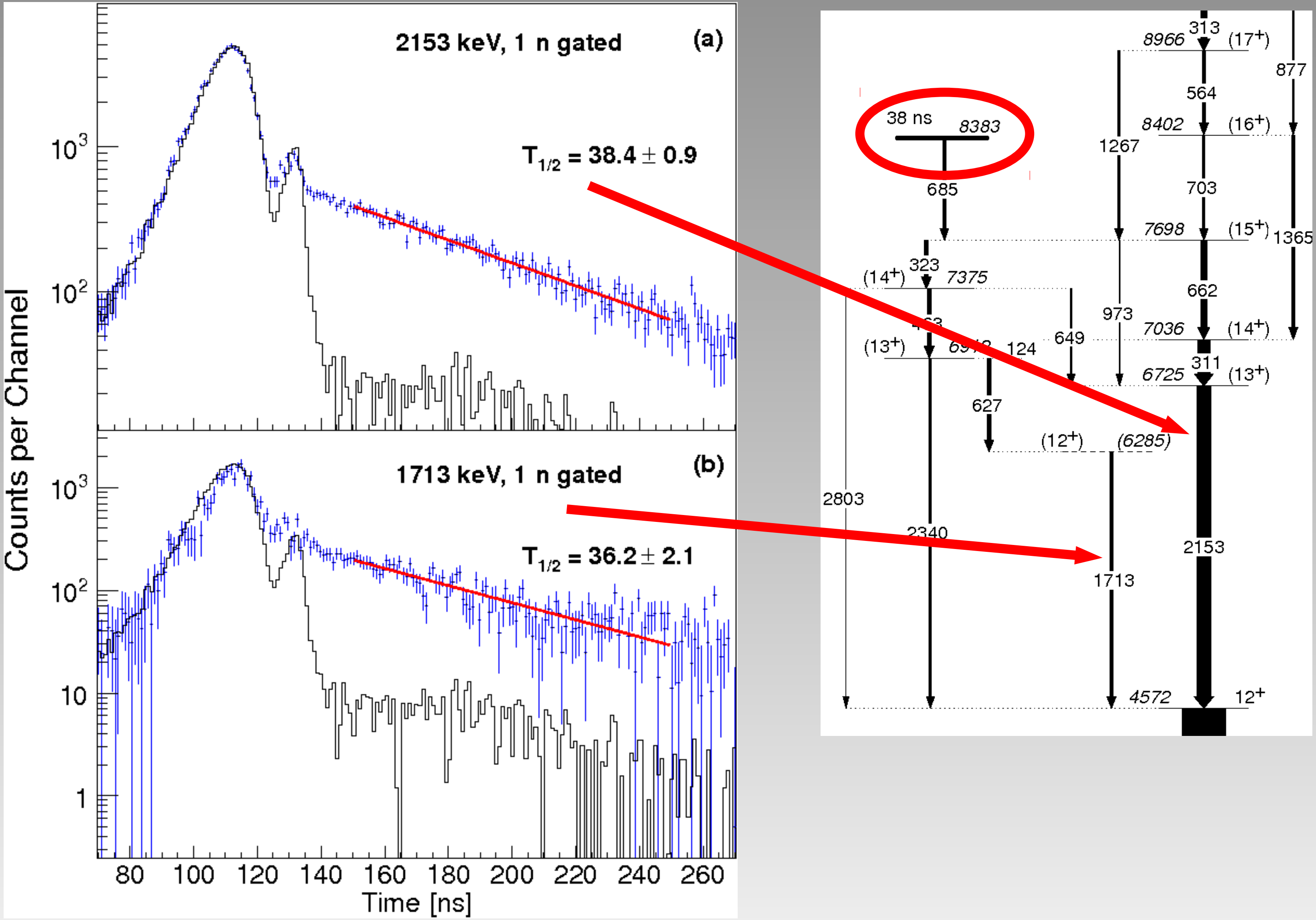




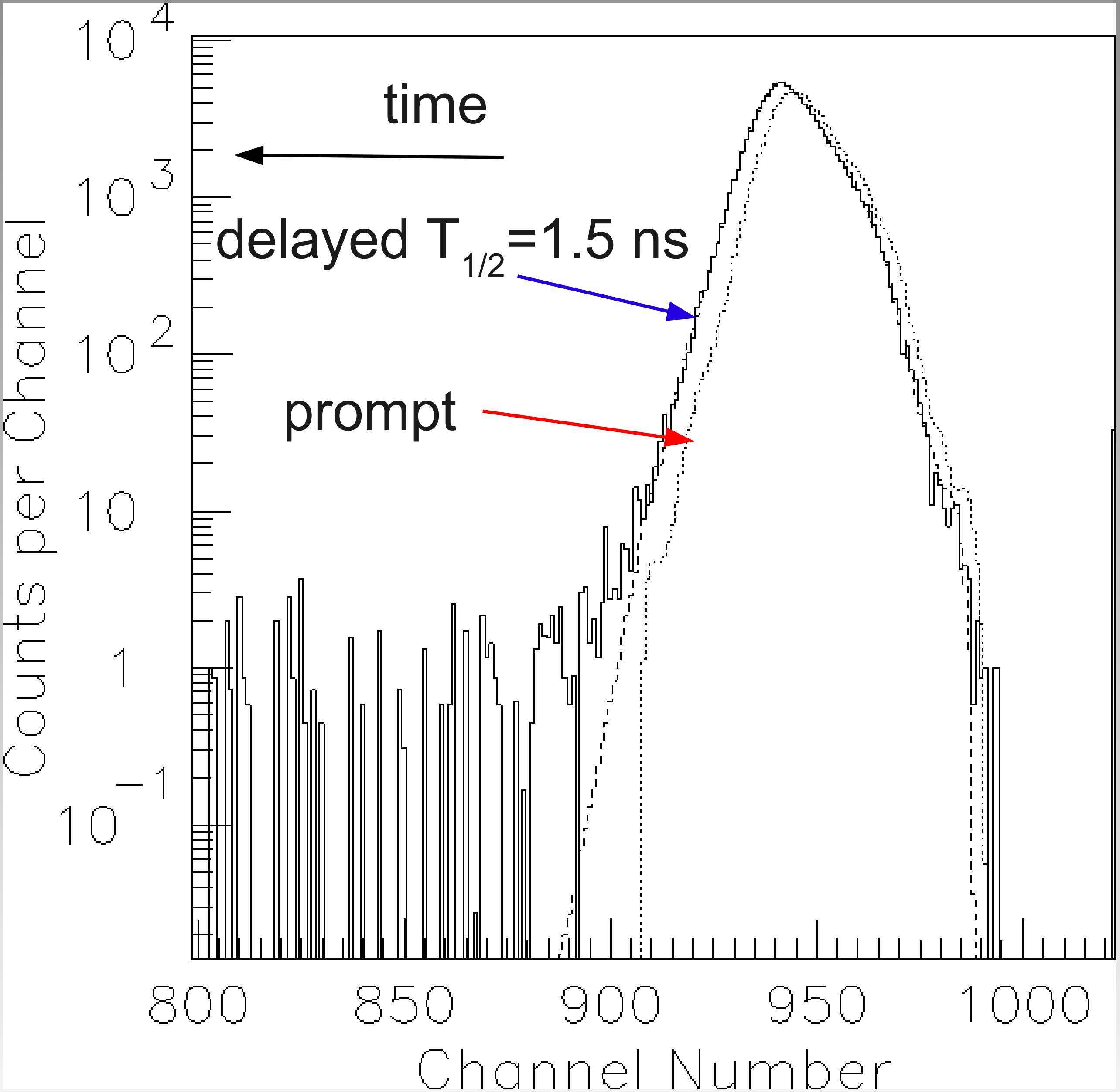


Also:
angular correlations
of coincident γ rays,
polarisation

Data analysis – half-lifes of excited states



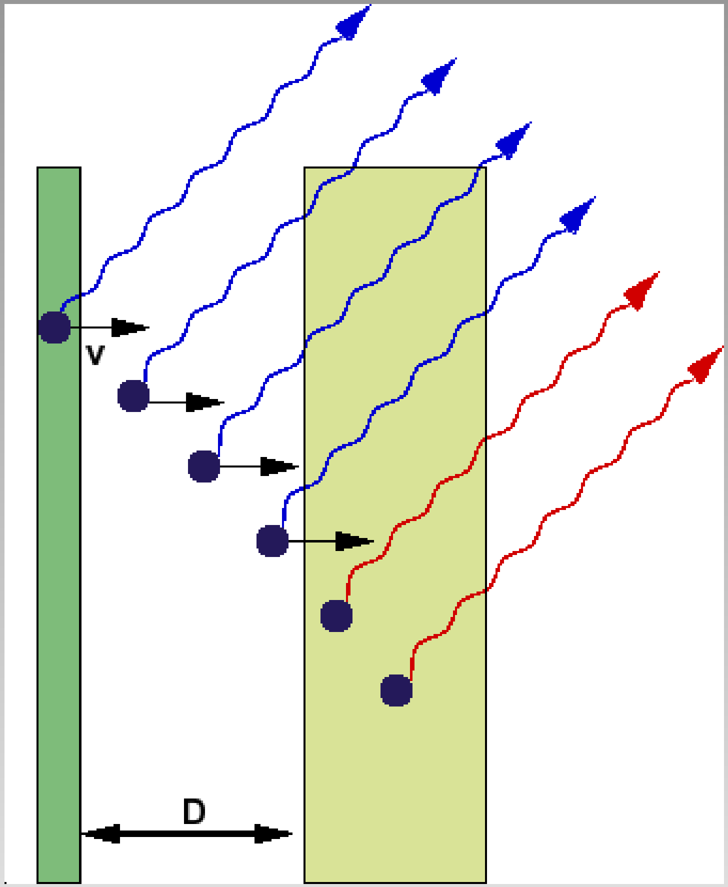
Data analysis – short times

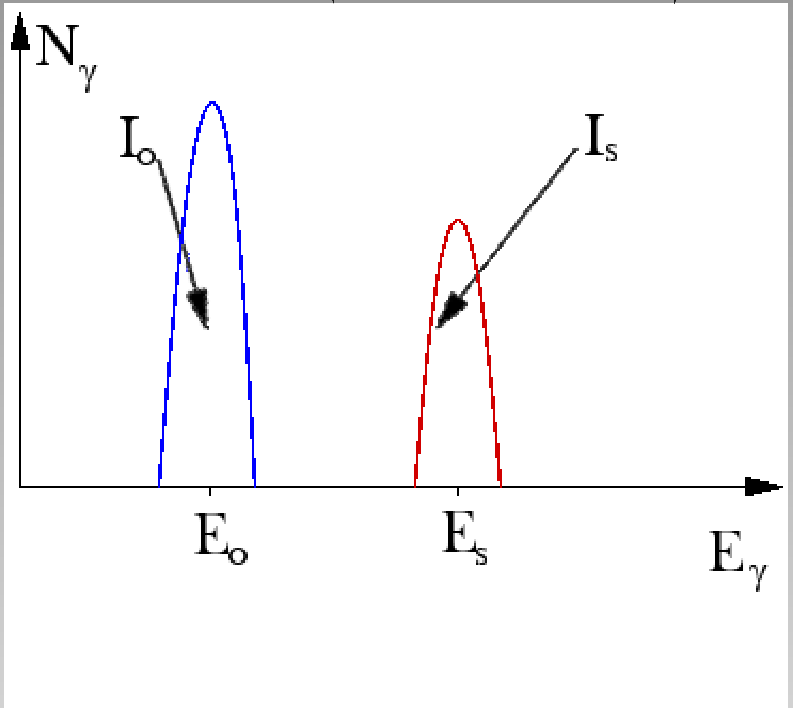


Data analysis – shorter times: RDM

life time range: ~1 ns – 1 ps

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





time of flight: $t_D = \frac{D}{v}$

D = 10 to 500 μm

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

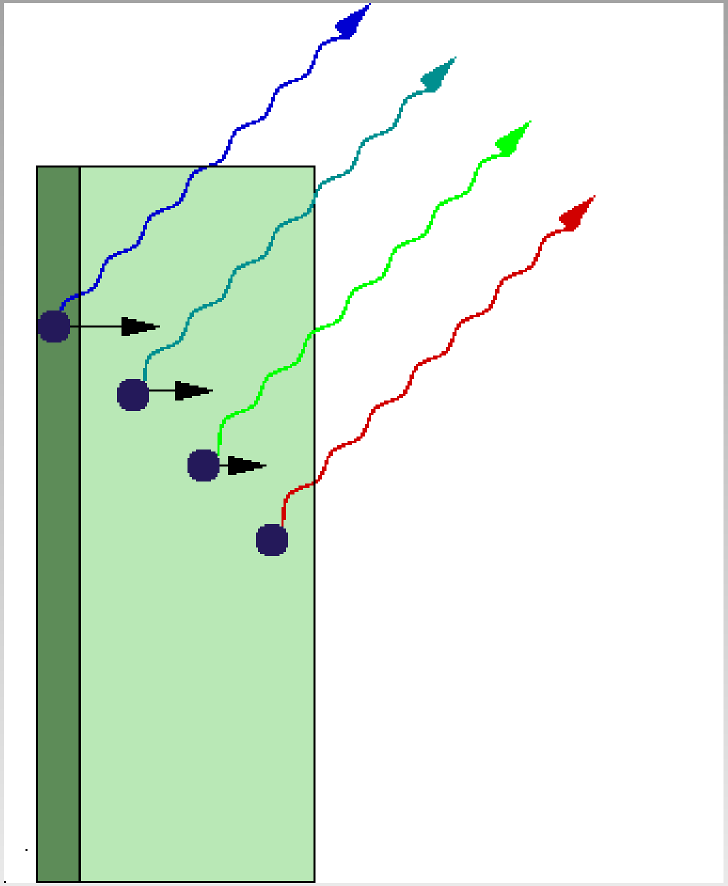
$$\frac{I_o}{I_o+I_s} = \exp\left(-\frac{D}{v\tau}\right) \qquad N_0 = I_0 + I_S$$

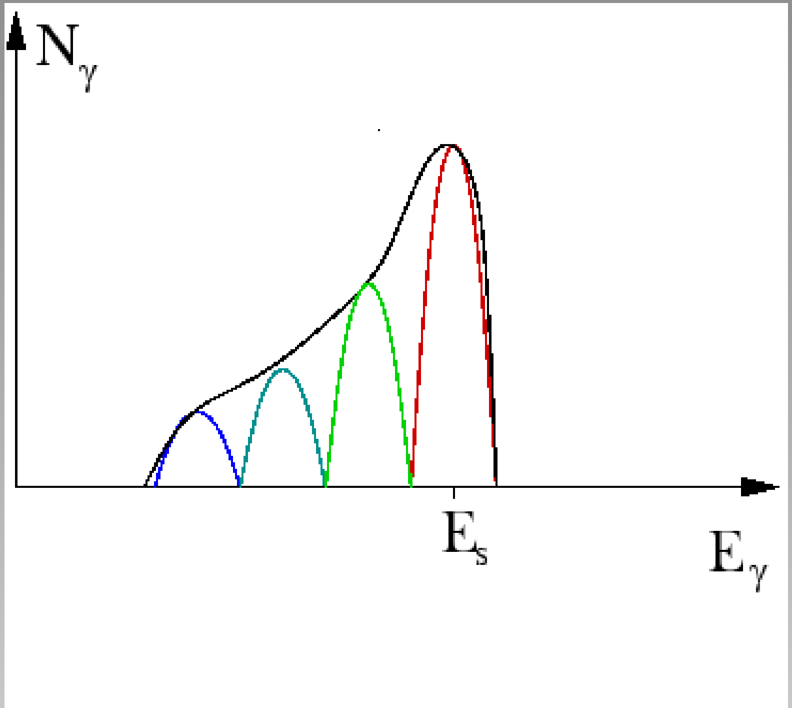
drawings courtesy of M. Zielińska

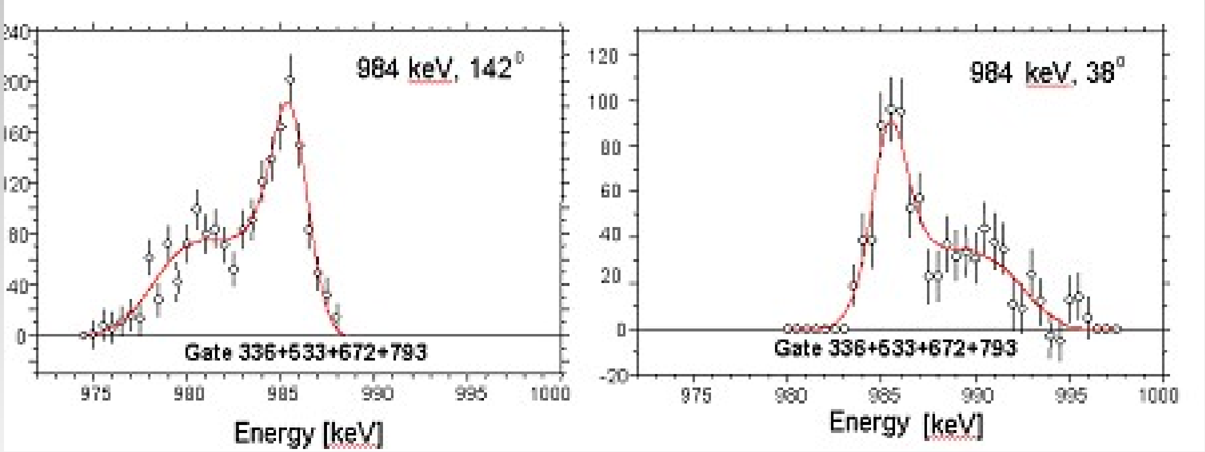
Data analysis – even shorter times DSAM

life time range:

ok. 10^{-11}– 10^{-14} s

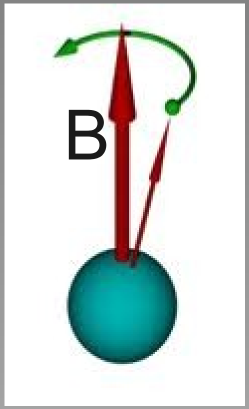






drawings courtesy of M. Zielińska

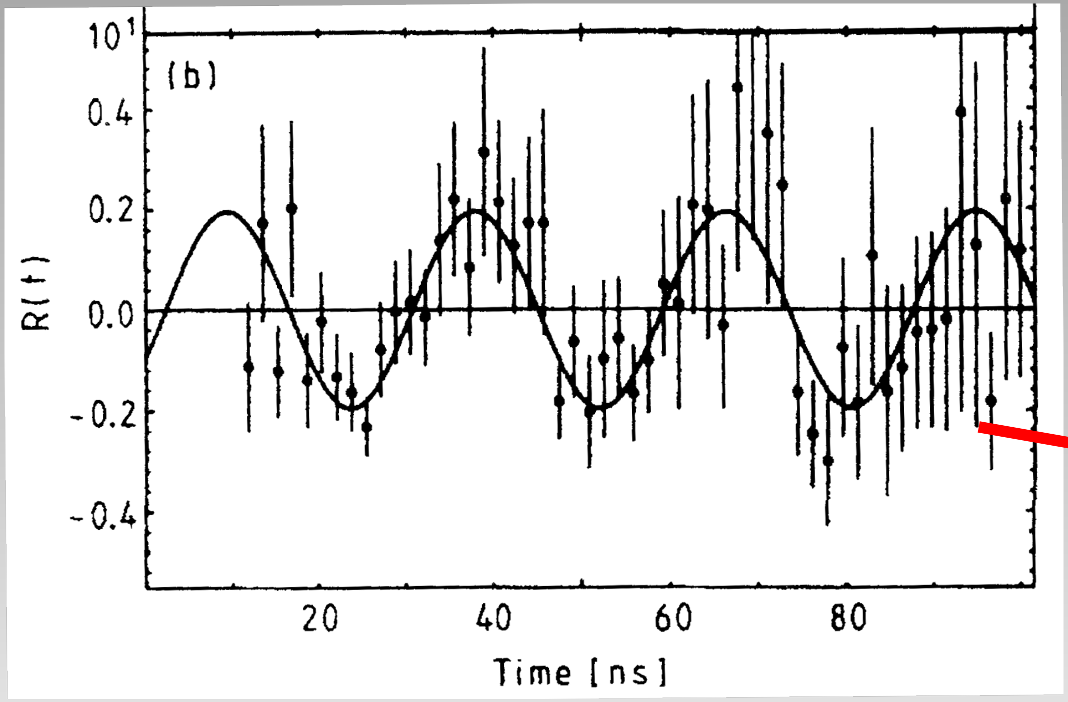
Data analysis – magnetic moments

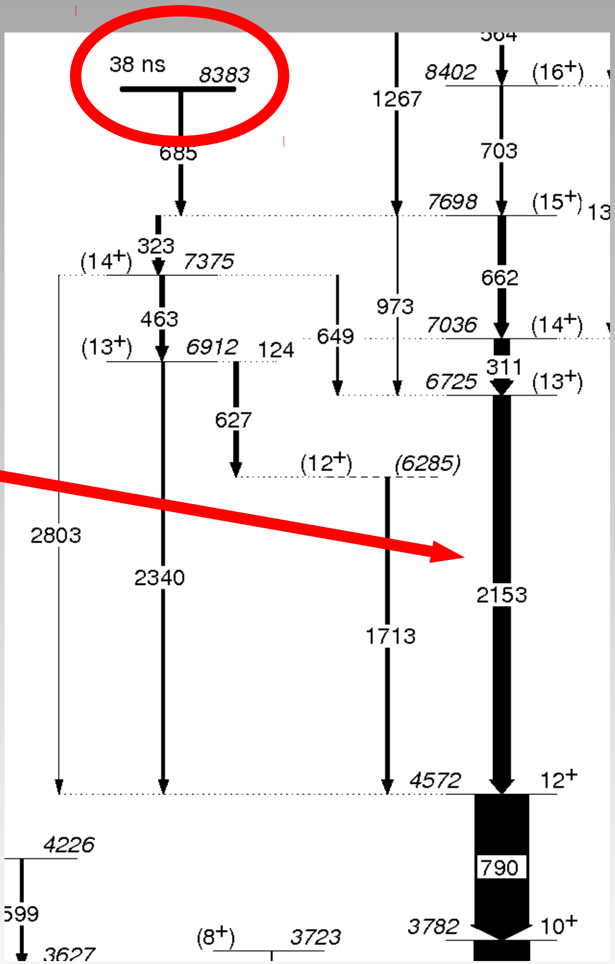


Larmor precession

B - external magnetic field

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





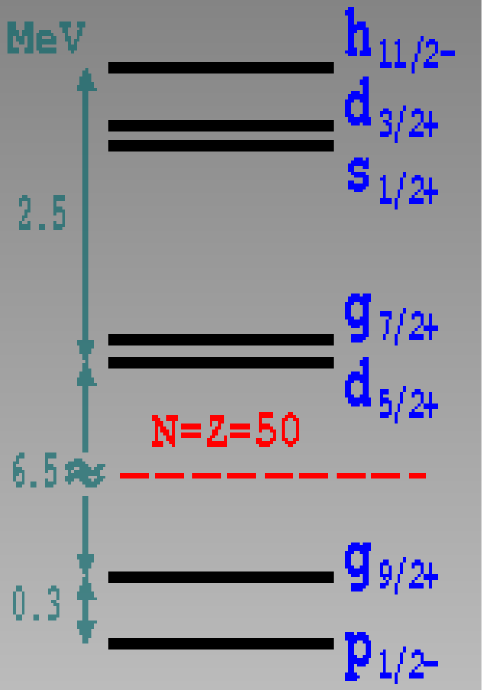
$$R(t)\sim\cos(2t(\theta-\omega_L))$$

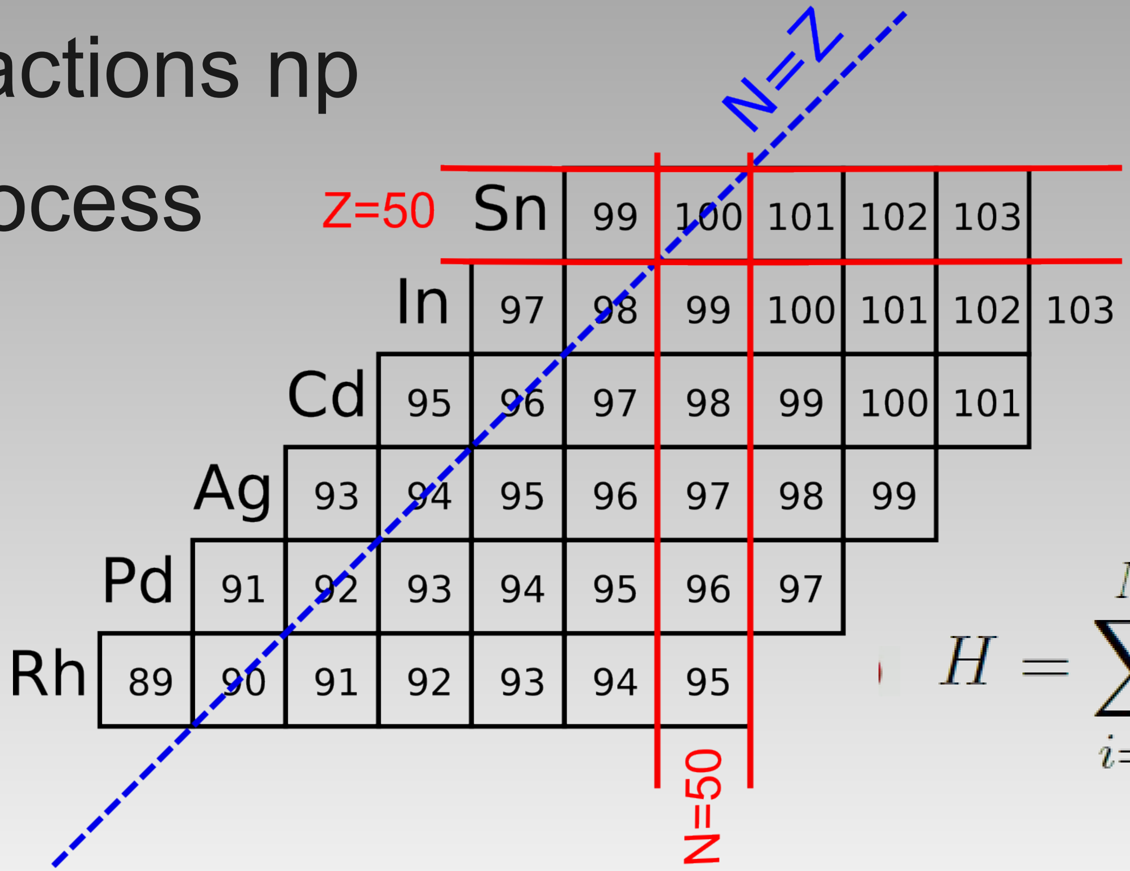
$$\omega_L=\mu_n gB/\hbar$$

g = 0.83(5)

Is this at all interesting ?

- SPE and interactions
- N=50, Z=50 gaps
- Interactions np
- rp-process



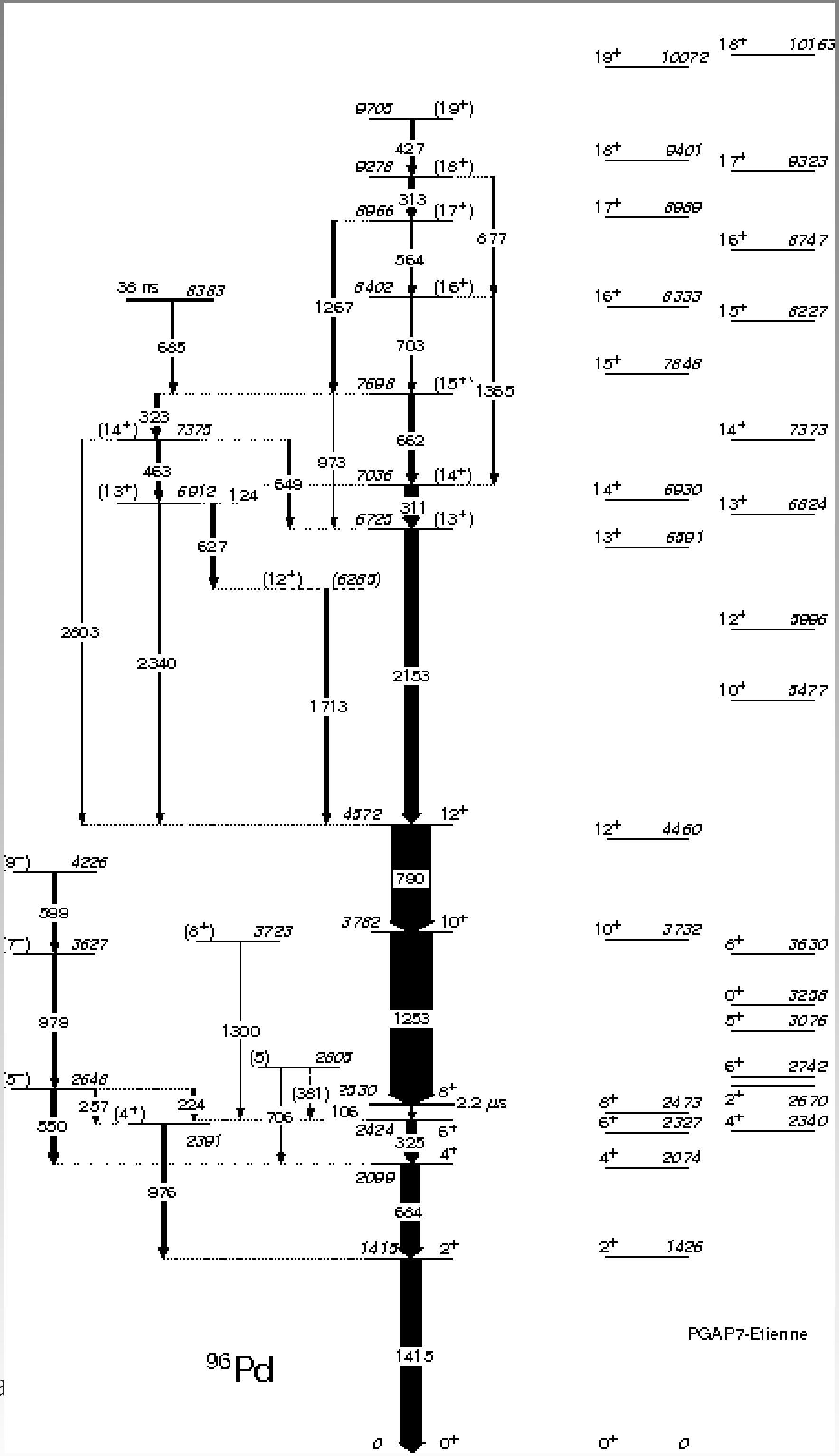


Sn						99	100	101	102	103	
In					97	98	99	100	101	102	103
Cd				95	96	97	98	99	100	101	
Ag			93	94	95	96	97	98	99		
Pd		91	92	93	94	95	96	97			
Rh	89	90	91	92	93	94	95				

$$H = \sum_{i=1}^{M} H_i + \sum_{i<j} H(i,j)$$

OK, but do we really learn anything from ^{96}Pd itself?

- Comparison of the experimental and Shell Model states verifies SPE and interactions,
  in particular size
  of the N=50 gap.
- The negative parity isomeric state cannot be reproduced in this calculations



Summary

- Interactions of γ rays with matter: photo-effect, Compton, e^+e^-
- Compton suppressed Ge γ-ray spectrometers
- Gamma Ray Tracking Array – AGATA
- Doppler effect
- Study of a nucleus in a fusion-evaporation reaction:
    - corrections and calibrations
    - energies of excited states
    - spin/parities
    - life times (including RDM, DSAM)
    - g-factor measurement
- ^{96}Pd, and the region of ^{100}Sn