The Abdus Salam International Centre for Theoretical Physics

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Joint ICTP-IAEA Workshop on Nuclear Structure Decay Data: Theory and Evaluation

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Experimental Nuclear Physics II

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Kolkata
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IAEA.org International Atomic Energy Agency

The Abdus Salam International Centre for Theoretical Physics

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VECC

Gopal Mukherjee

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Road Map for Gamma ray spectroscopy

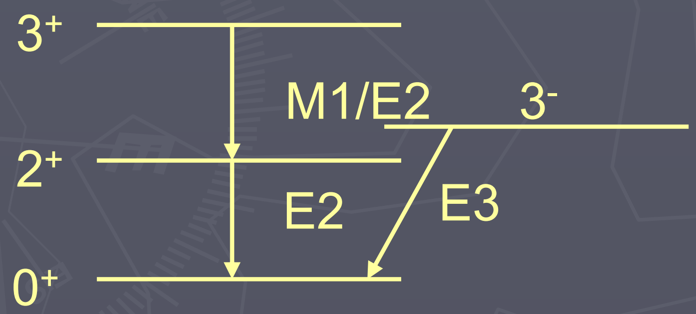
- **Production of Nuclei at High Angular Momentum**
  - o **Nuclear Reaction: Fusion, inelastic transfer, fission**
- **Detection of Gamma Rays**
  - o **Gamma-ray detector array: GDA, INGA, Gammasphere**
- **Building up a level scheme**
  - o **Correlation between γ-rays, intensity, J^{π} Lifetimes ($T_{1/2}$) …**
- **Interpretation of the level scheme**
  - o **Theory, systematic …**

Road Map for Gamma ray spectroscopy

- **Production of Nuclei at High Angular Momentum**
  - **Nuclear Reaction: Fusion, inelastic transfer, fission**

- **Detection of Gamma Rays**
  - **Gamma-ray detector array: GDA, INGA, Gammasphere**

- **Building up a level scheme**
  - **E_γ, Correlation between gamma rays, I_γ, J^π, Lifetimes ($T_{1/2}$) ...**

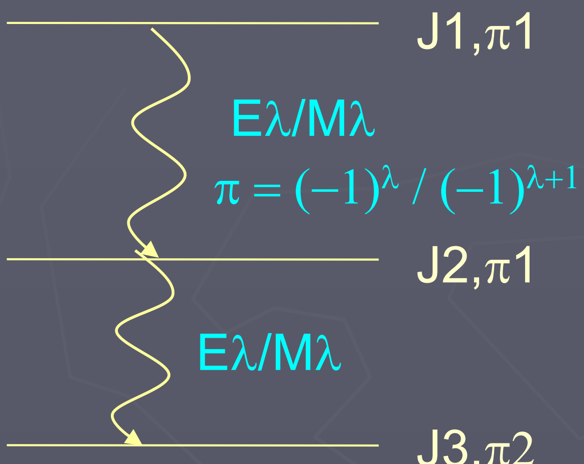


Spin & parity of a state

Type and Multipolarity of γ-ray

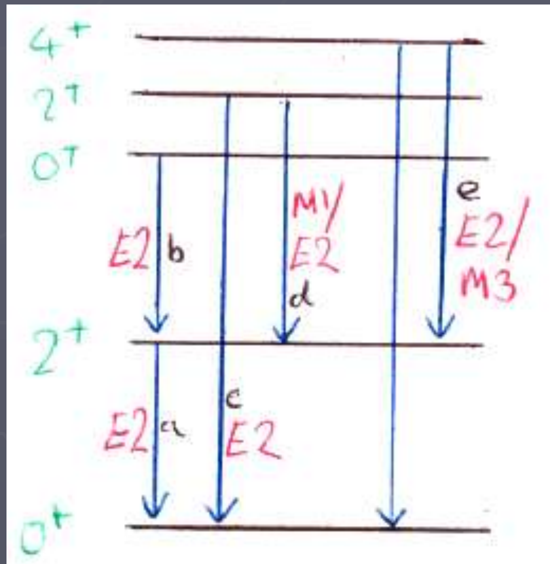
ICC, γ-ray Angular distribution / DCO ratio and Polarization measurement

Determination of Spin of a Nuclear State



Angular Momentum Rule

$|J1 - J2| < \lambda < J1+J2$



Parity Rules

EL	Parity Change	Example, $I_i^{\pi_i} \rightarrow I_f^{\pi_f}$.
$E1$	Yes	$1^- \rightarrow 0^+$
$E2$	No	$2^+ \rightarrow 0^+$
$E3$	Yes	$3^- \rightarrow 0^+$
$E4$	No	$4^+ \rightarrow 0^+$

ML	Parity Change	Example, $I_i^{\pi_i} \rightarrow I_f^{\pi_f}$.
$M1$	No	$1^+ \rightarrow 0^+$
$M2$	Yes	$2^- \rightarrow 0^+$
$M3$	No	$3^+ \rightarrow 0^+$
$M4$	Yes	$4^- \rightarrow 0^+$

Strength of multipole transitions: E1 > M1/E2 > M2/E3 >…

So, if we know the type (E/M) and multipolarity (λ) of the transition, then the spin and parity (J^{π}) of an excited state can be determined if J^{π} of a state is known.

Deduction of Transition Multipolarity

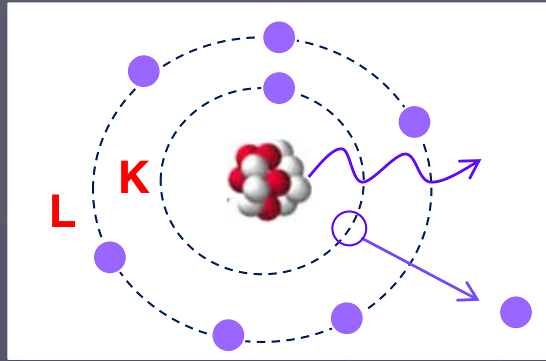
Basic techniques

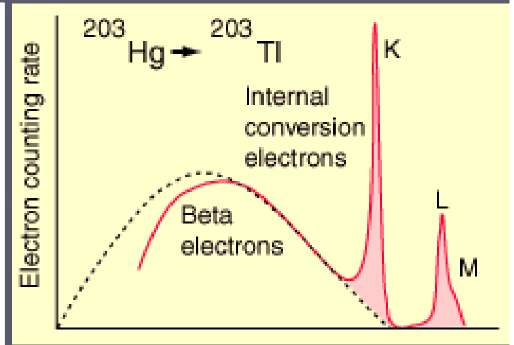
- Internal conversion electrons
- Angular distributions
- Angular correlations (DCO ratios)
- Gamma-ray polarization

Internal conversion electrons

α → Internal conversion coefficient

$$\alpha^{tot} = \frac{I_{ce}}{I_\gamma} = \alpha_K + \alpha_L + \alpha_M + \ldots$$

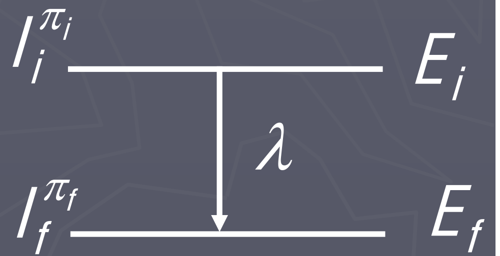




Intensity ratio

∞	E0
1	Low energy isomers
10^{-1} <	50< Z
10^{-2} - 10^{-3}	30<Z < 50
10^{-4} - 10^{-5}	Z < 30

$$E_\gamma = E_i - E_f$$
$$E_i^{ce} = E_\gamma - B_i, i = K, L, \ldots$$



$$\alpha_K(E\lambda) \propto Z^3 \left(\frac{\lambda}{\lambda+1}\right)\left(\frac{2m_e c^2}{E}\right)^{L+5/2}$$

Important for heavy nuclei, where inner electron shells are closer to the nucleus

Important for low-energy transitions

ICC from total intensity balances –example 1

Works well for γ–rays with energies below about 250 keV

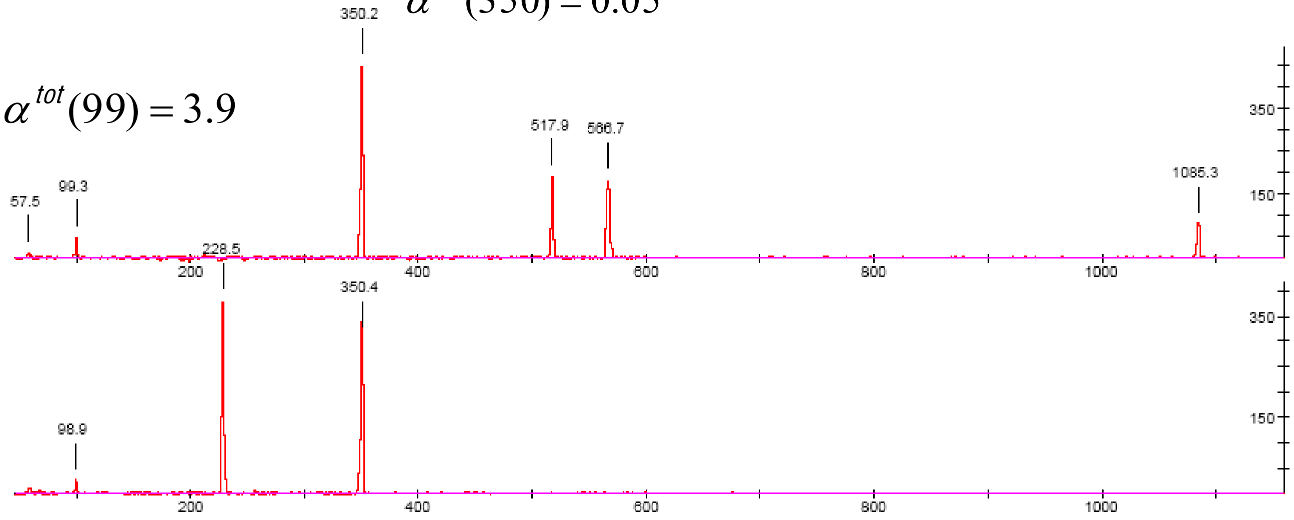
In out-of-beam (or decay) coincidence data

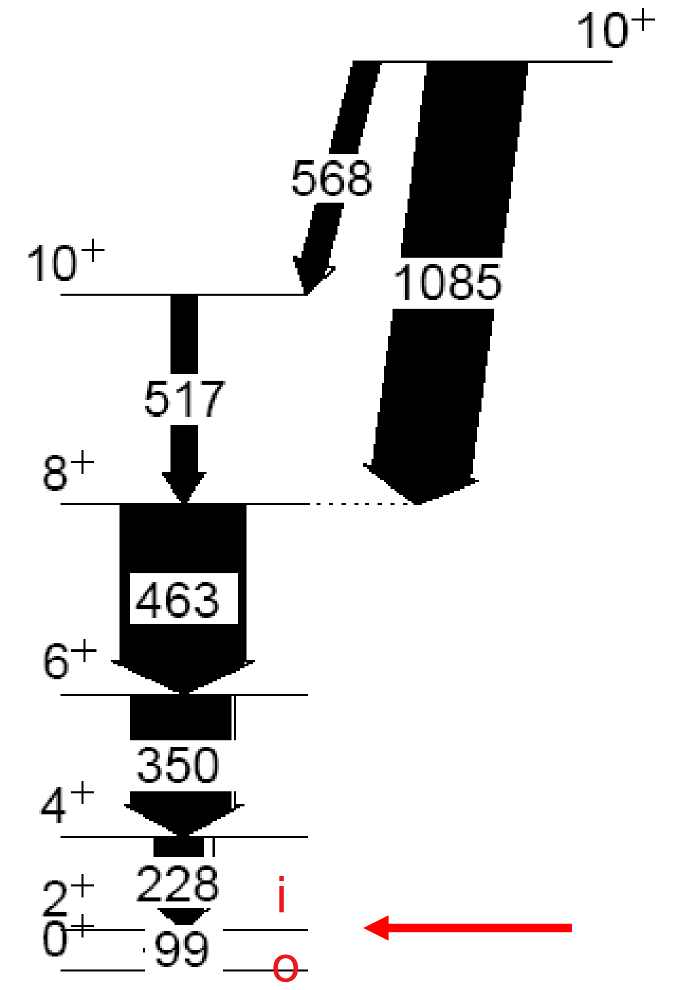
$$I_{\gamma_i}^{tot} = I_{\gamma_i} \times (1+\alpha_i^{tot}) \equiv I_{\gamma_o}^{tot} = I_{\gamma_o} \times (1+\alpha_o^{tot})$$

$$\alpha_o^{tot} \equiv (I_{\gamma_i}\varepsilon_o / I_{\gamma_o}\varepsilon_i) \times (1+\alpha_i^{tot}) - 1$$

$\alpha^{tot}(350) = 0.05$

$\alpha^{tot}(99) = 3.9$





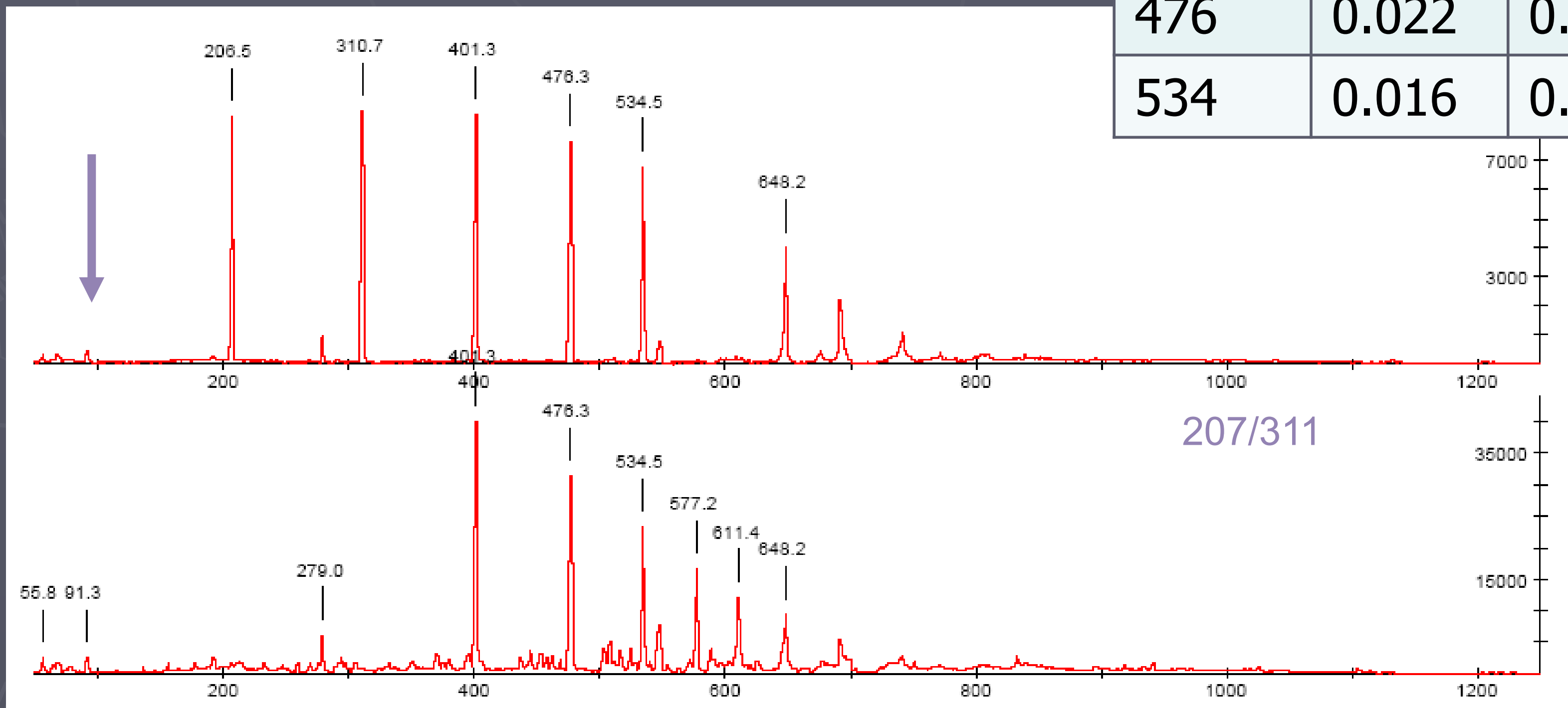
ICC from total intensity balances –example 2

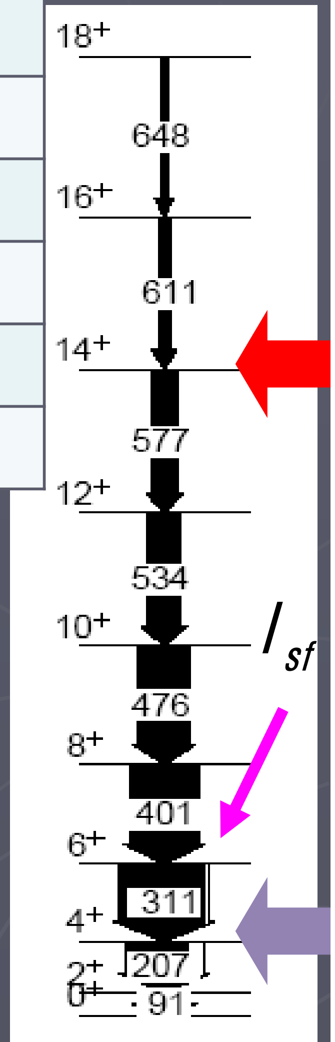
In-beam: only when gating from “above”

$$I_{\gamma_i}^{tot} = I_{\gamma_i} \times (1+\alpha_i^{tot}) \equiv I_{\gamma_o}^{tot} = I_{\gamma_o} \times (1+\alpha_o^{tot})$$

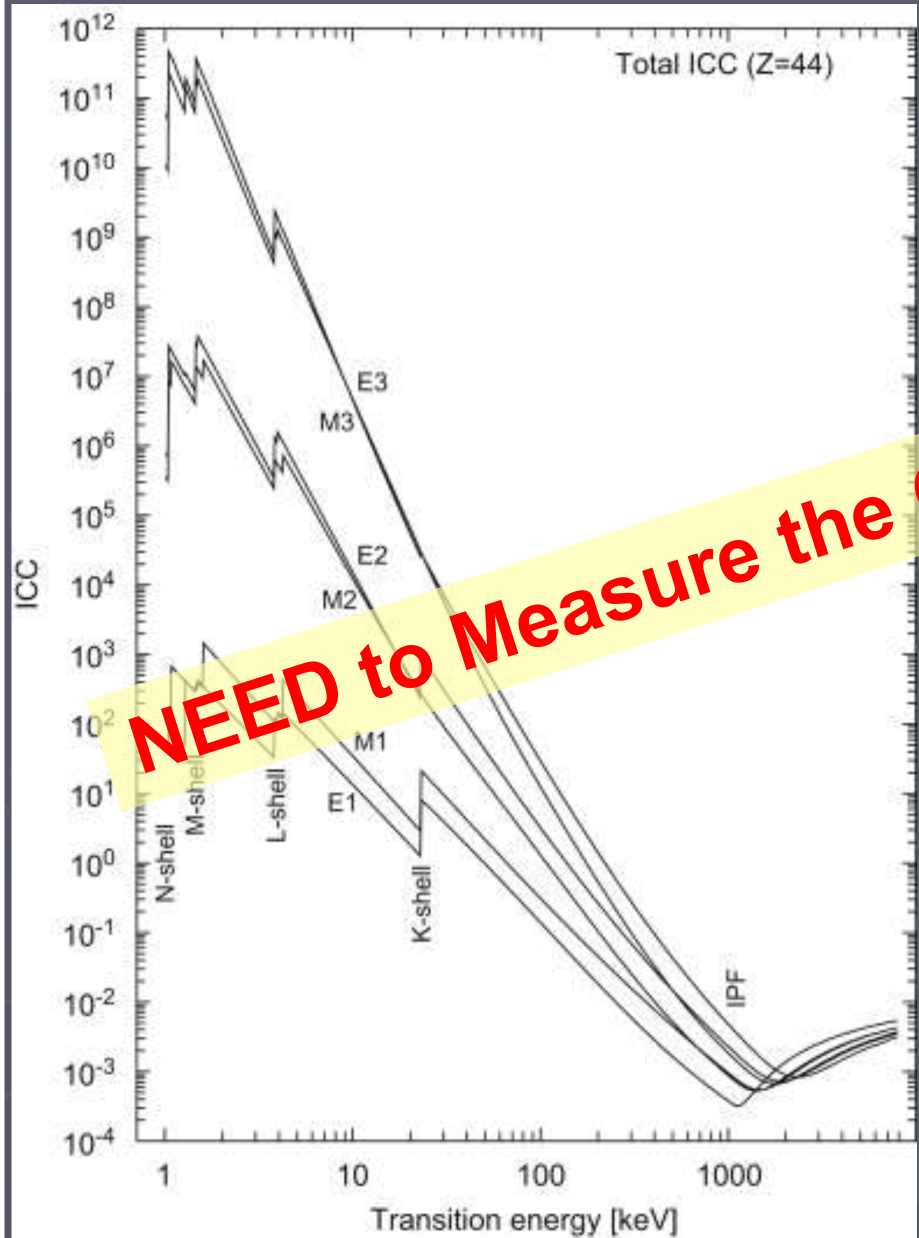
$$I_{\gamma_i}^{tot} = I_{\gamma_o}^{tot} + I_{sf}$$

E_γ	α_{tot}	Rel. Eff
91	5.12	0.10
207	0.256	0.12
311	0.071	0.11
401	0.035	0.105
476	0.022	0.097
534	0.016	0.091





^{174}Hf



NEED to Measure the Conversion electrons

BrIccS v2.3 (9-Dec-2011)

Z=82 (Pb, Lead)

γ-energy: 100 keV

Mixing Ratio δ: 1.00

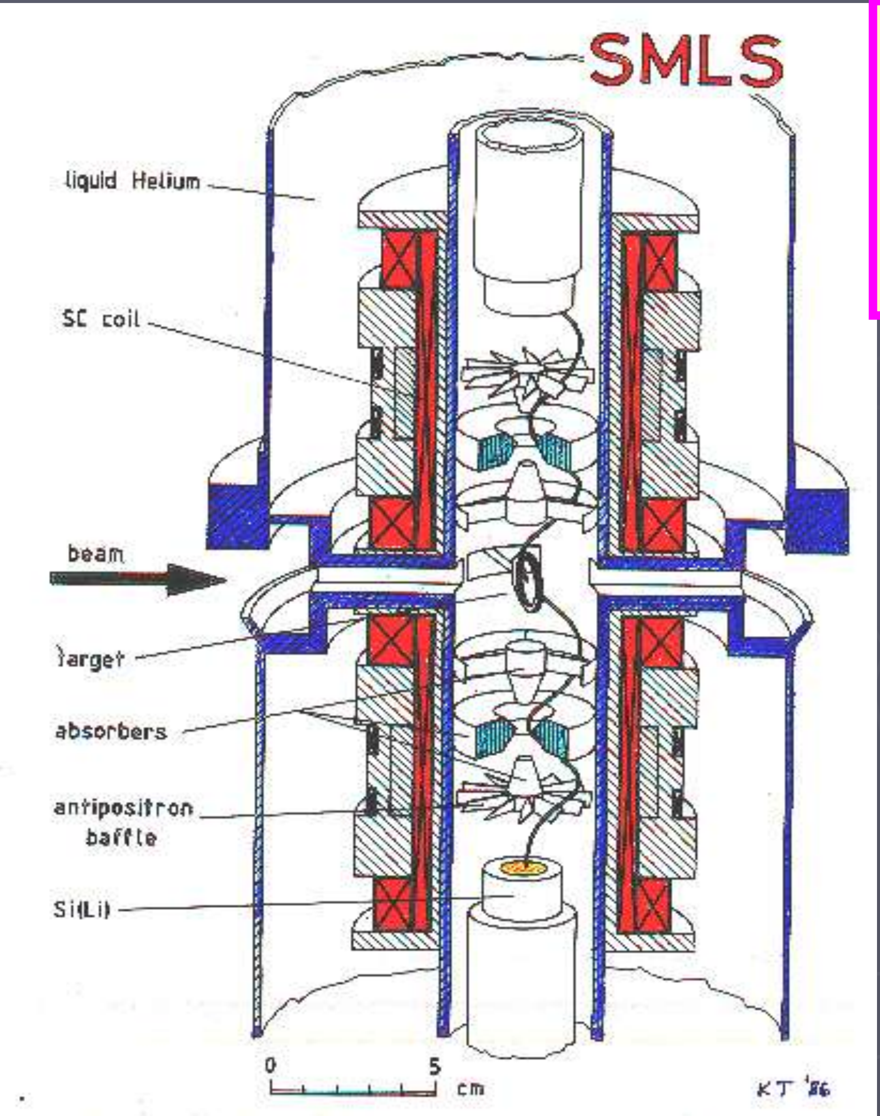
Data Sets: BrIccFO

Shell	E(ce)	M1	E2
Tot		9.353E+00	6.324E+00
K	12.00	7.615E+00	5.194E-01
L-tot	85.37	1.330E+00	4.322E+00
K/L		5.727E+00	1.202E-01
M-tot	96.56	3.118E-01	1.142E+00
L/M		4.264E+00	3.785E+00

$Z = 72$, $E_\gamma = 91$ keV

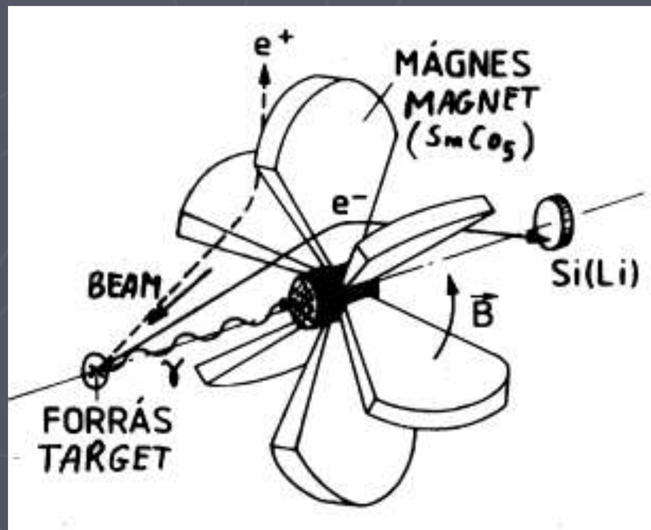
Shell	E(ce)	M2	E3
Tot		5.250E+01	1.258E+02
K	25.65	3.653E+01	2.429E+00
L-tot	80.70	1.216E+01	9.223E+01
K/L		3.004E+00	2.634E-02
M-tot	88.74	2.987E+00	2.467E+01
L/M		4.071E+00	3.739E+00

Basic electron transporters



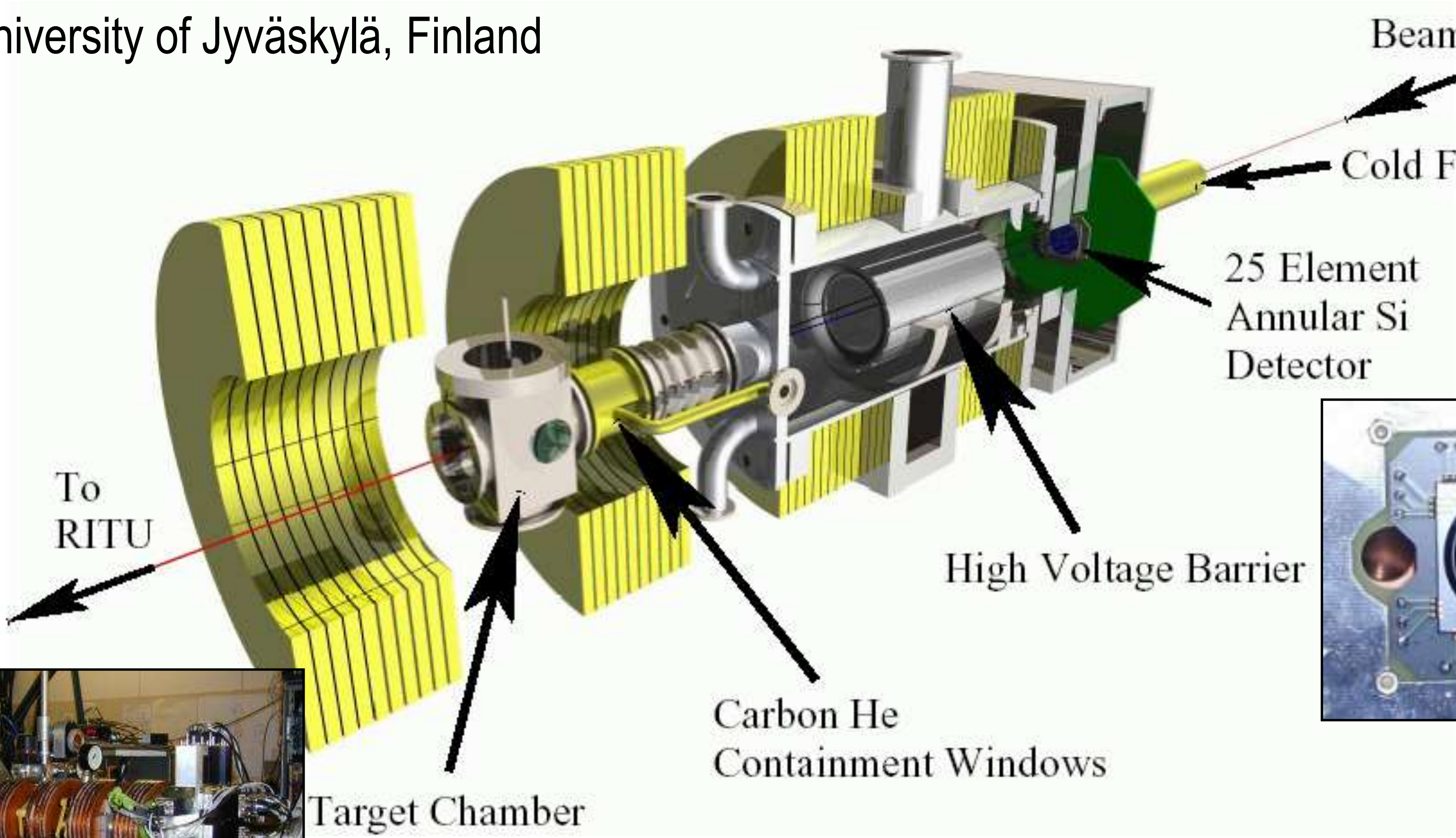
Superconducting solenoid
- ❑ Broad-range mode – 100 keV up to a few MeV
- ❑ Lens mode – finite transmitted momentum bandwidth (Δp/p~15-25%) – high peak-to-total ratio

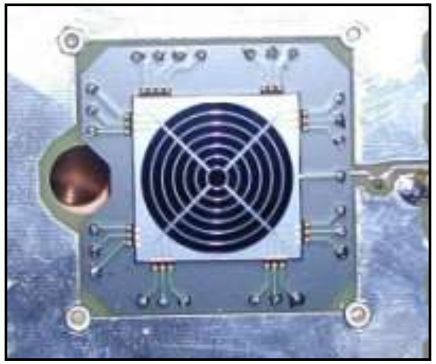
Mini-orange (looks like a peeled orange)
- ❑ transmission > 20%
- ❑ small size and portability, but poorer quality

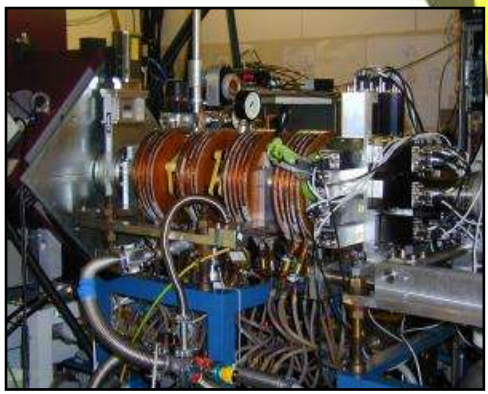


The SACRED Electron Spectrometer

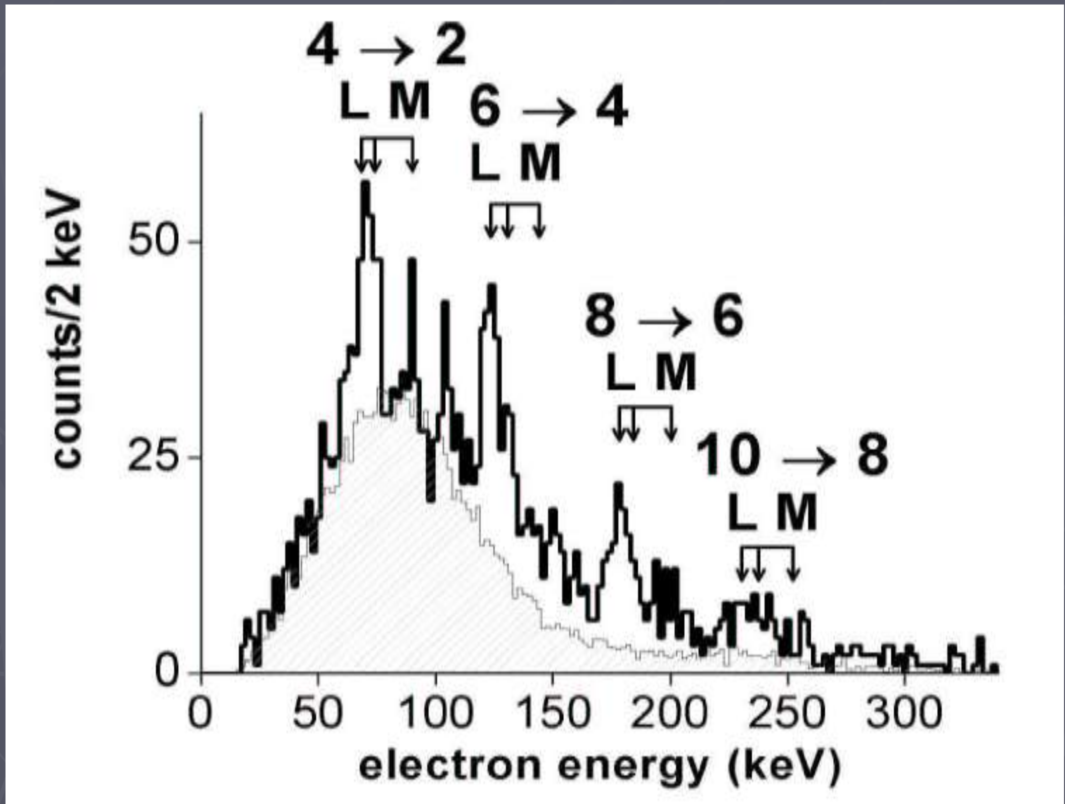
University of Jyväskylä, Finland

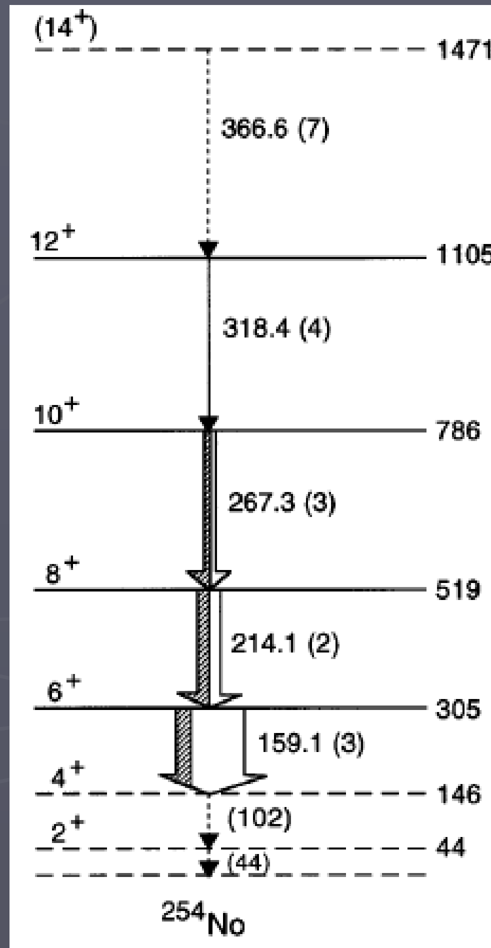






Recoil-gated CE spectrum from $^{208}Pb(^{48}Ca,2n)^{254}No$

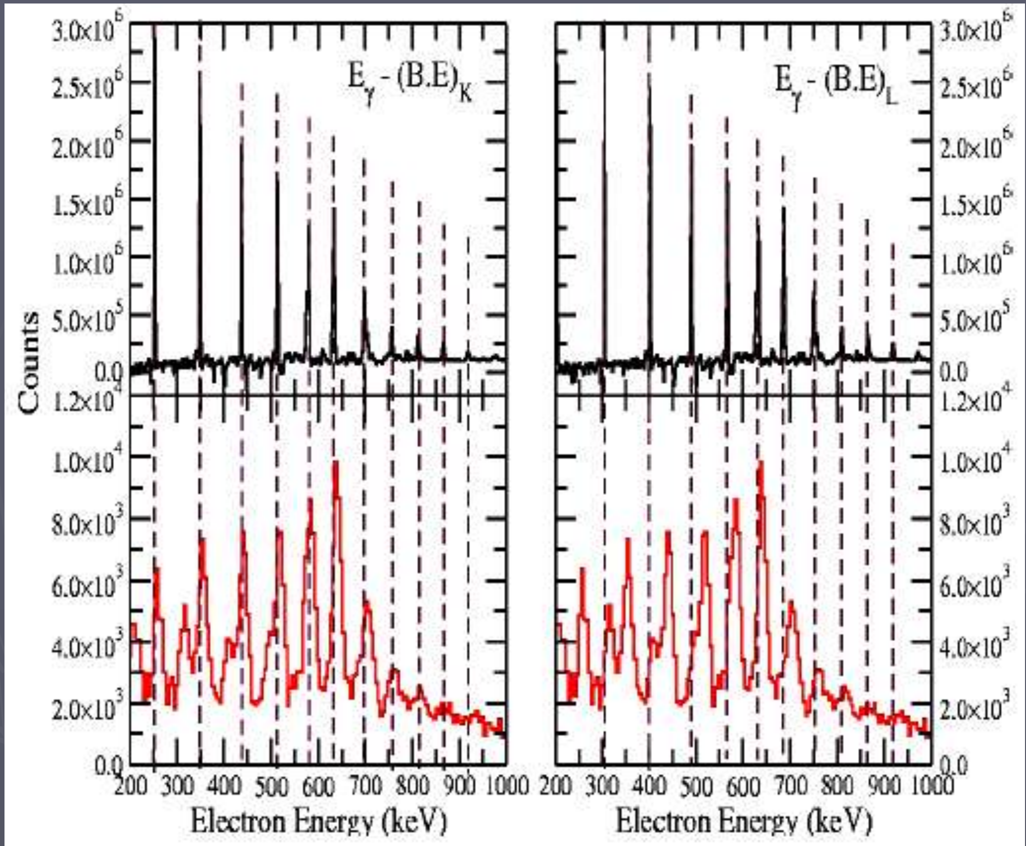




P.A. Butler et al.,PRL 89 (2002) 202501

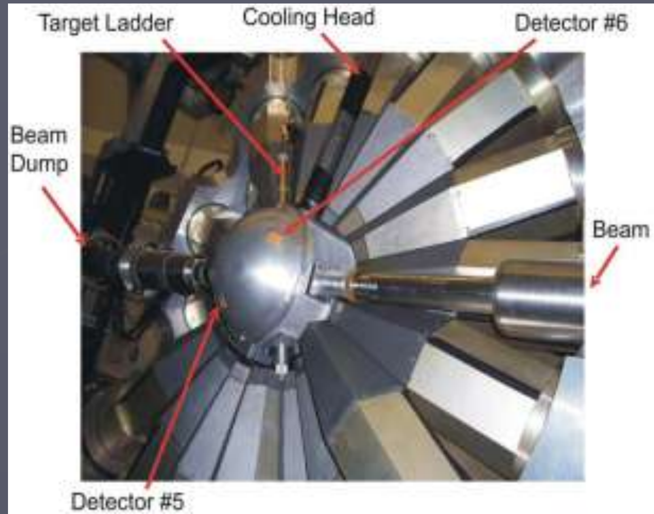
Example of experimentally determined conversion coefficient

$^{48}Ca + ^{123}Sb \rightarrow ^{167}Lu + 4n$ at 203 MeV

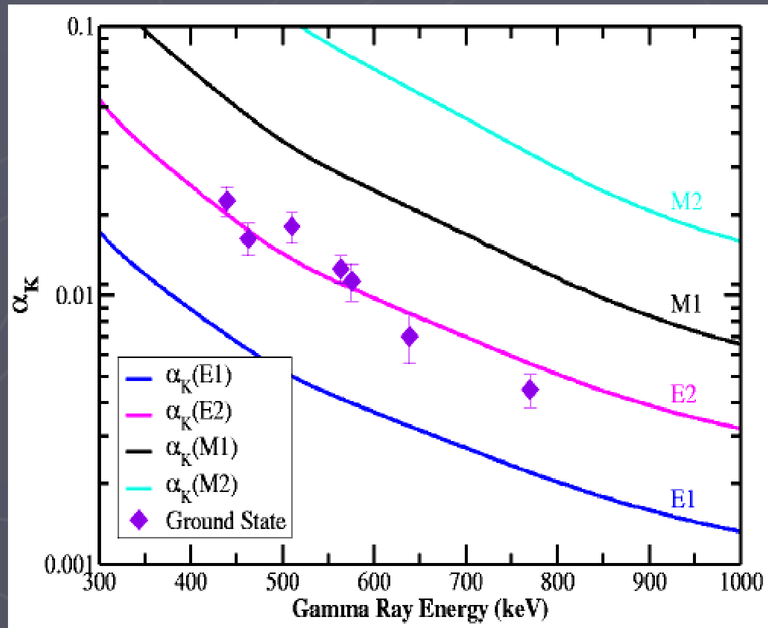


$$\alpha_K = \frac{N_{e_K} \times \epsilon_\gamma}{N_\gamma \times \epsilon_{e_K}} \times c$$

The constant c is determined from the calculated α_K value of a known (E2) transition.



^{167}Lu: Gammasphere with ICE Ball (Mini Orange Spectrometer)



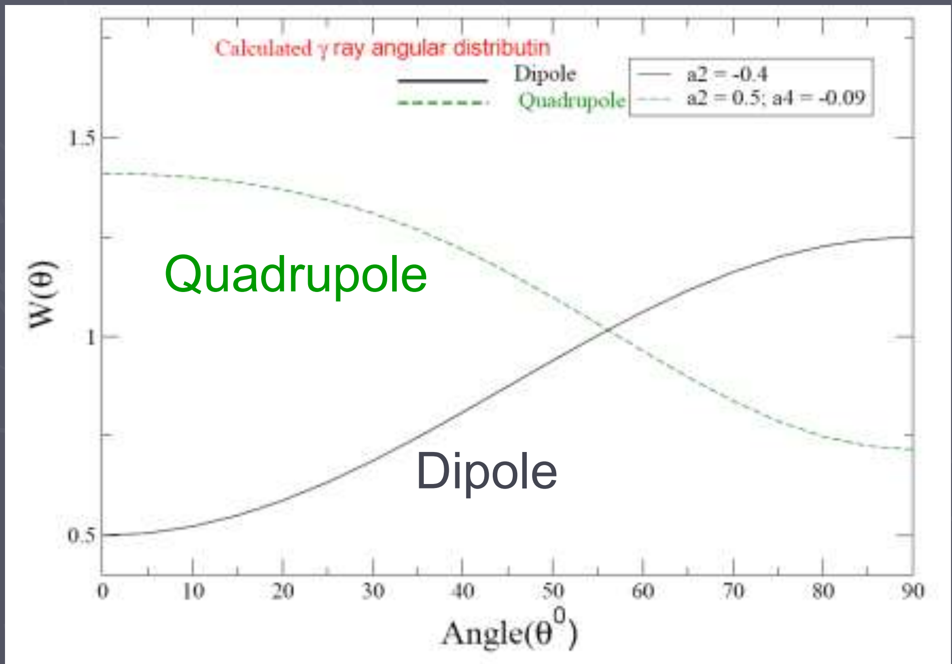
G. Gurdal: Ph.D Thesis (2002)

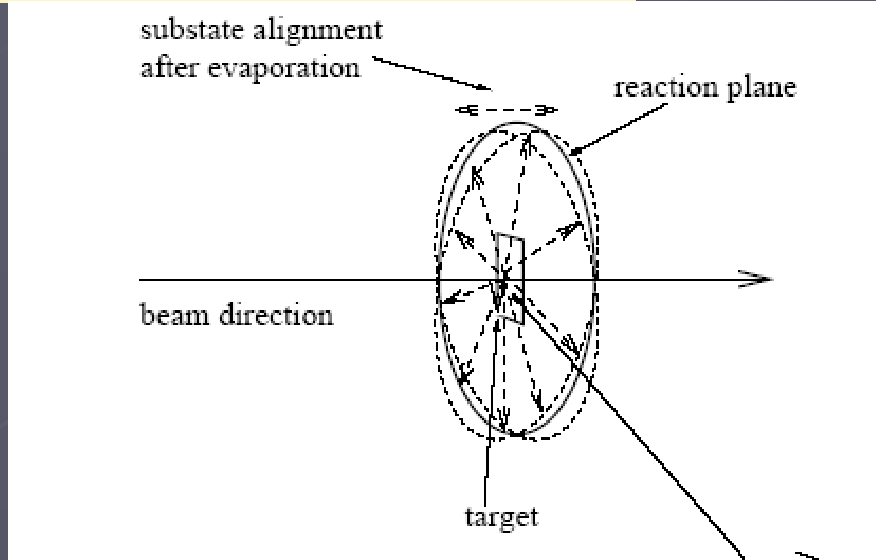
Angular Distributions

The gamma-rays emitted from nuclear reactions exhibit angular distributions:

Angular-distribution

$$W(\theta) = 1 + a_2P_2(\cos\theta) + a_4P_4(\cos\theta)$$



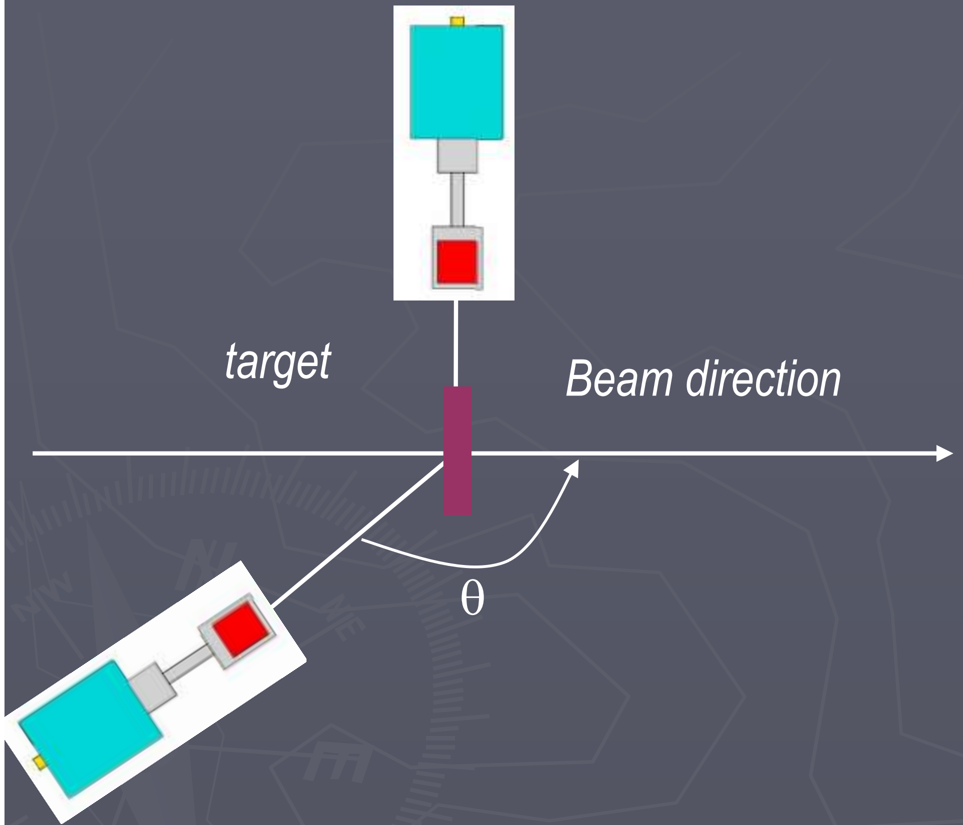


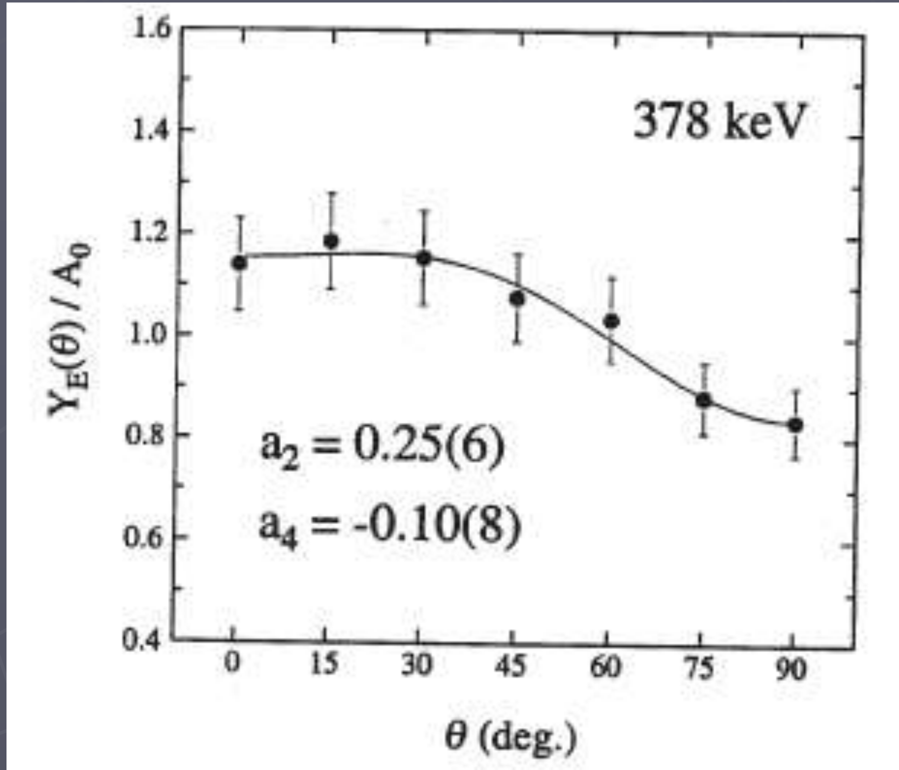
The orientation of the nucleus will be slightly attenuated by the emission of evaporated particles (n,p,α) and γ–rays.

$$P_m(J) = \frac{\exp(-m^2/2\sigma^2)}{\sum_{m=-J}^{J}\exp(-m^2/2\sigma^2)}$$

Angular Distributions: Experiment

Measure: the γ-ray yield as a function of θ





- ❑ using a single detector – “singles” mode – contaminants
- ❑ using a large gamma-ray array – “coincidence” mode - you must be careful!

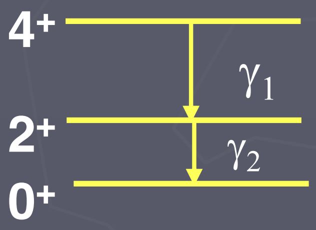
ANUGULAR DISTRIBUTION FOR PURE MULTIPOLES

Angular distribution coeffs for pure multipoles in high spin limit for ideal initial M-distribution P(M) =1 for M=0 or ± ½

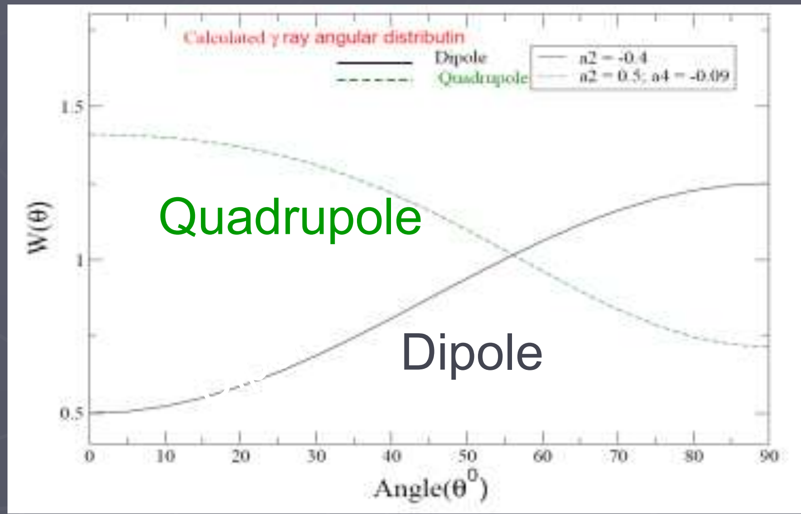
ΔJ	L	a_2	a_4
0	1	0.500	0
0	2	-0.357	-.542
1	1	-0.250	0
1	2	-0.179	0.429
2	2	0.357	-0.107

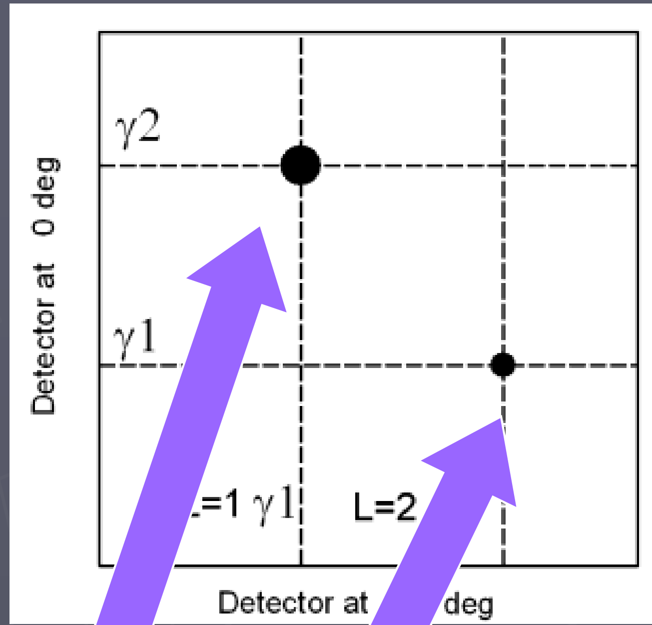
Directional Correlation from Oriented Nuclei (DCO Ratio)

For low intensity transitions, singles measurements are contaminated.



Suppose multi-polarity of γ_2 is known





Use coincidences between two detectors, one near 90° and the other near 0° w.r.t beam direction

$$DCO = W(\gamma_1,\theta_1; \gamma_2,\theta_2)/W(\gamma_1,\theta_2; \gamma_2,\theta_1)$$

$$R_{DCO} = \frac{I^{\gamma}_1 \text{ at } \theta=\theta_1 \text{ gated by } \gamma_2 \text{ at } \theta=\theta_2}{I^{\gamma}_1 \text{ at } \theta=\theta_2 \text{ gated by } \gamma_2 \text{ at } \theta=\theta_1}$$

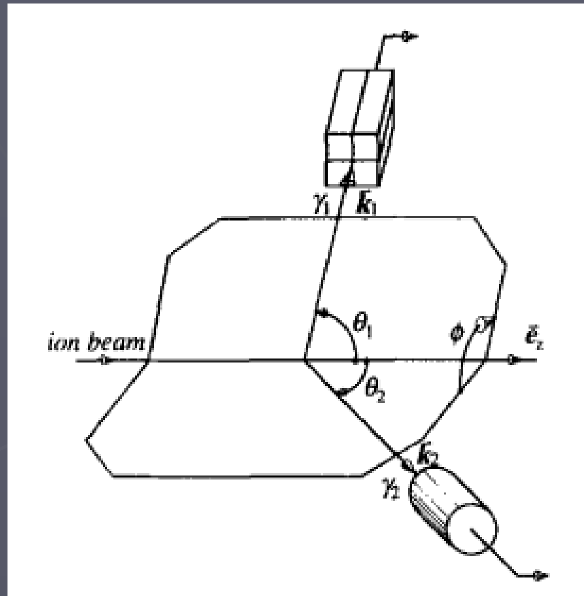
$R_{DCO} = 1$ for same λ of γ_1 & γ_2

$R_{DCO} = 0.5$ or 2.0 for different λ of γ_1 & γ_2

POLARIZATION MEASUREMENTS

To measure the parity from the type (E/M) of γ-ray transition

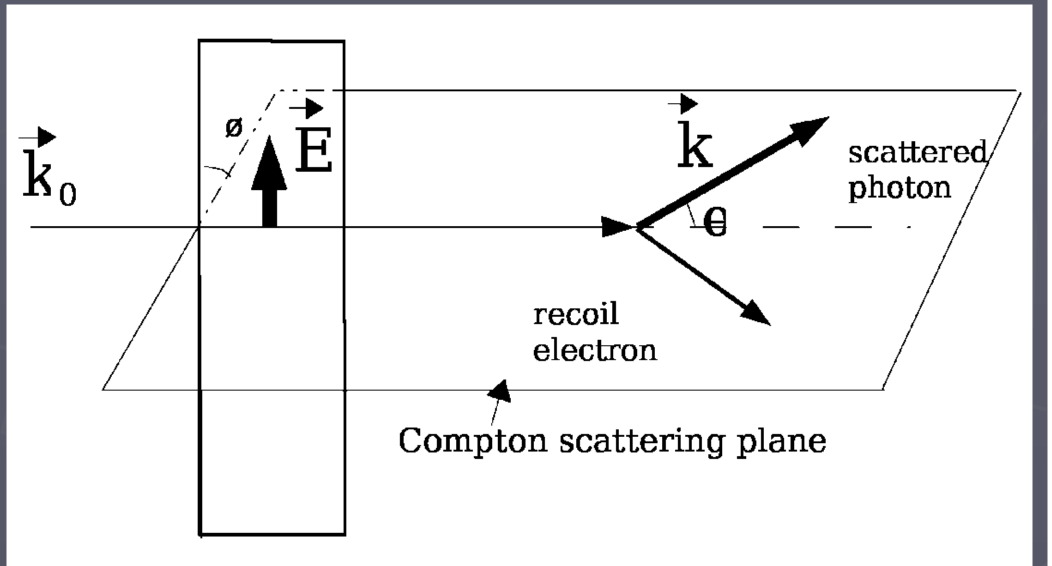
- Angular distribution for both E1 and M1 similar; maximum at 90°
- Can be distinguished by polarization measurement
- Stretched E1 transition has polarization vector in-plane
- stretched M1 transition has polarization vector perpendicular to plane
- Maximum polarization at $\theta = 90°$
- Can be studied in
  (i) singles
  (ii) in coincidence with another detector (PDCO)
  (iii) measuring polarization of both detectors (PPCO)



References:
RMP31(1959)711
NIM163(1979)377
NIMA362(1995)556
NIMA378(1996)516
NIMA430(1999)260

Measurement of Polarization

- Compton Scattering is sensitive to the polarization direction
- Vertically polarized photons would be preferentially scattered in the horizontal plane

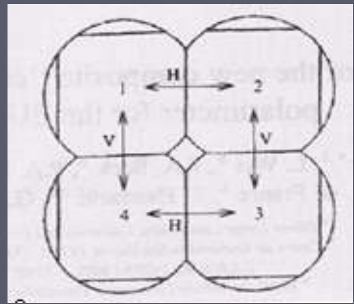


- Klein-Nishina formula

$$d\sigma_\phi = (r_0^2 / 2)(k^2/k_o^2)[(k_o / k) + (k / k_o) - 2 \sin^2\theta \cos^2\phi] d\Omega$$

  - Maximum sensitivity at θ ~ 90°

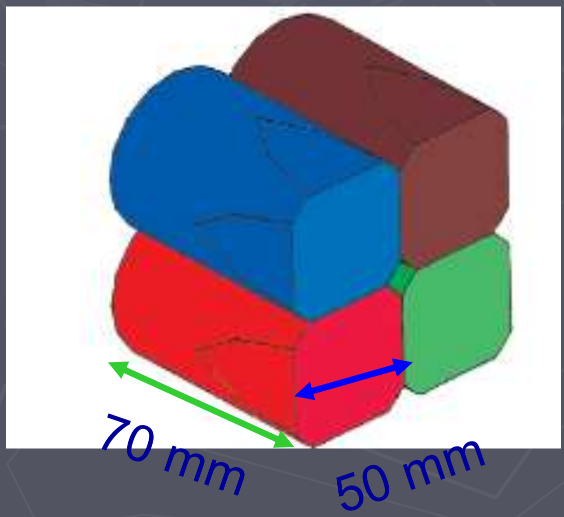
Clover Germanium detectors are best suited for Polarization Measurement



$$A(E_\gamma) = \frac{a(E\gamma)N_\perp - N_{||}}{a(E\gamma)N_\perp + N_{||}}$$

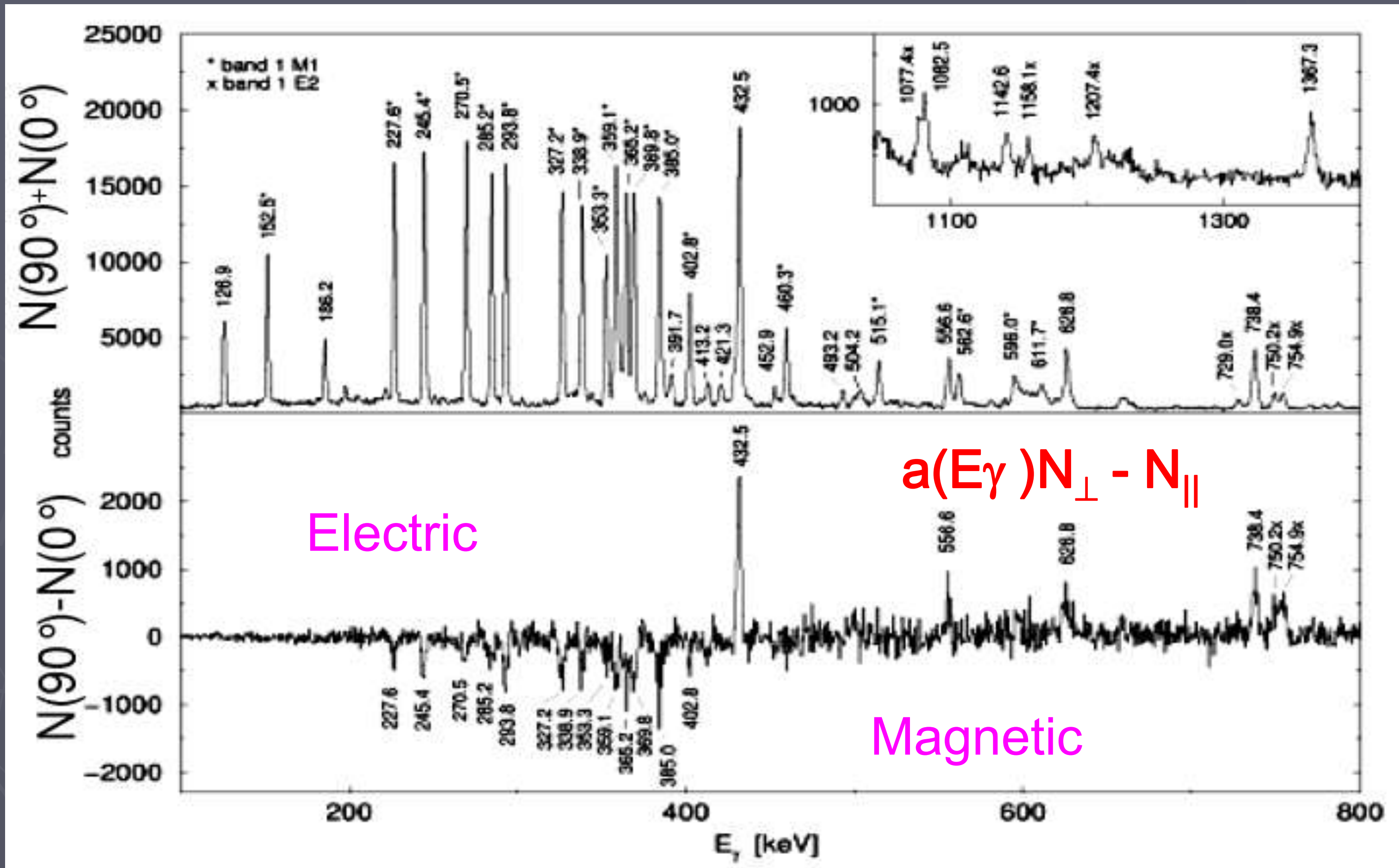
Correction factor $$a(E\gamma) = \frac{N_{||}(\text{Source})}{N_\perp(\text{Source})}$$

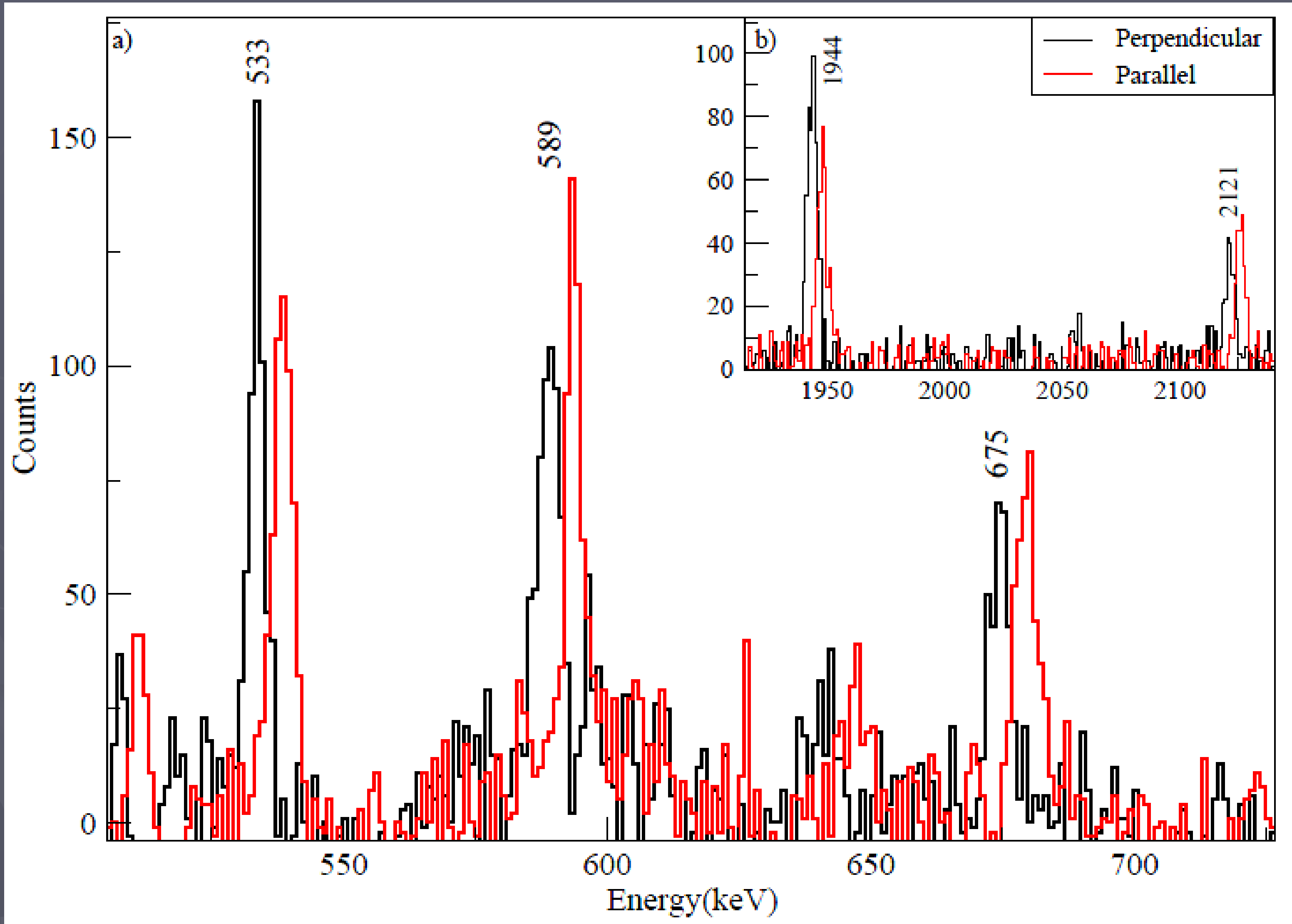
$N_\perp$ and $N_{||}$ are perpendicular and parallel counts with respect to the reaction plane, respectively.



$A(E_\gamma)$ = Positive ➔ Electric type
= Negative ➔ Magnetic type

Measurement of Polarization





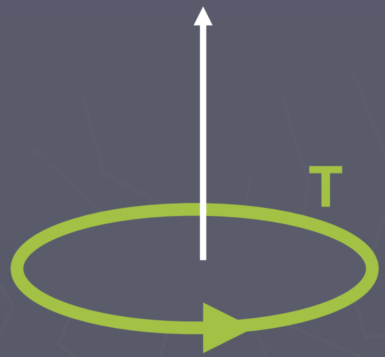
a)
533
589
675
Counts
150
100
50
0
550
600
650
700
Energy(keV)
b)
1944
2121
100
80
60
40
20
0
1950
2000
2050
2100
Perpendicular
Parallel

g-Factor

- Current loop produces a magnetic dipole moment $\mu = iA/c$
- Moving charge loop has a moment

$$\mu = (e/T)^* \pi r^2/c = evr/2c = (e/2mc)\, \ell\hbar$$

- There is a similar equation for the internal charges in a proton due to its intrinsic spin
- Total magnetic moment contribution due to protons in a nucleus $\mu = g_l \ell + g_s s$
- Neutrons can only contribute due to the spin



Nuclear Magneton

$$\mu_N = \frac{e\hbar}{2 M_p c}$$

We have $g_l = \mu_N$ $g_s = 5.5857\ \mu_N$ for proton

$g_l = 0$ $g_s = -3.8256\ \mu_N$ for neutron

$$g_I = g_R I + \frac{K^2}{I+1}\left[g_K - g_R\right]$$

$$g_K = \sum_{\Omega_i} \Omega_i \; g_{\Omega_i}$$

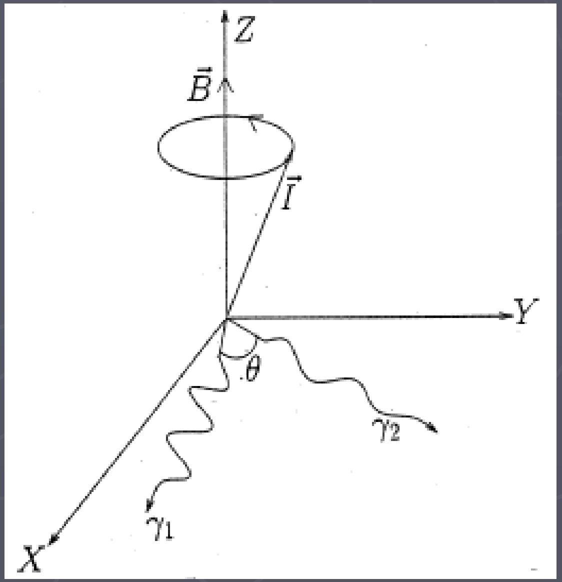
[$Nn_Z\ \Lambda\Omega$]

Measurement of g-factor

A nucleus with magnetic moment μ will precess in an external magnetic field B with the Larmor frequency ω_L

$$\omega_L = -\frac{\mu B}{\hbar I} = -g\frac{\mu_N B}{\hbar}$$

In fusion reaction, the nuclear spin is preferentially oriented perpendicular to the beam direction, leading to an anisotropy in angular distribution



$$W(\theta) = A_0\left\{1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)\right\}$$

The effect of precession of the spin in the external field is to rotate the angular distribution in time t by an angle $\Delta\theta = \omega_L t$

Level with mean life time τ will rotate by $\omega_L \tau$

Larmor Frequency

- Larmor frequency in an external magnetic field $\omega_L = g\mu_N B/\hbar$
- Corresponds to a time period $T=\pi/\omega$ = 60 ns(g/B)

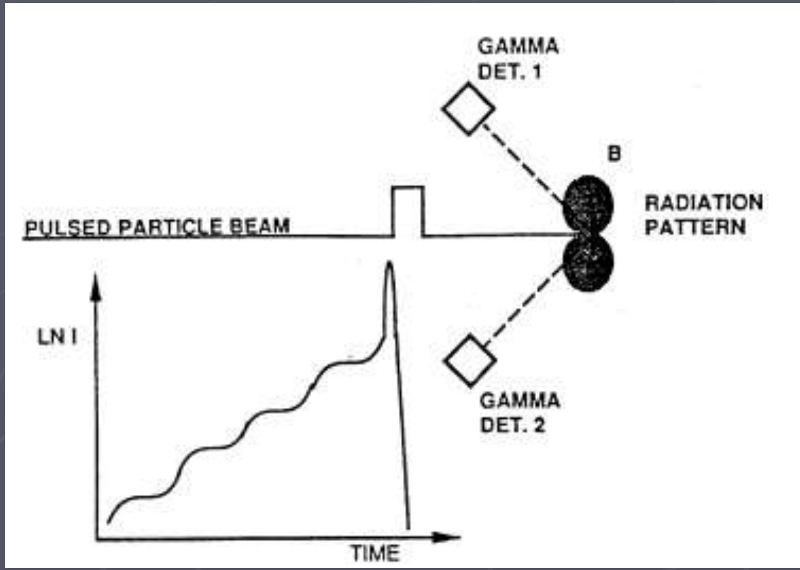
  g in Nuclear Magneton, B in Tesla

- External magnetic field varies over wide range
  - 1-2 Tesla $\rightarrow$ iron-core electromagnet
  - 5-12 Tesla $\rightarrow$ superconducting solenoid
  - 10-100 Tesla $\rightarrow$ static field in ferromagnet
  - 10^3-10^4 Tesla $\rightarrow$ transient magnetic field for fast moving ions in a magnetized material
- Depending on the lifetime τ different types of field employed

TDPAD Technique

- Stop the recoiling nuclei in a diamagnetic cubic lattice
- Apply external magnetic field ~ Tesla perp. To beam dir.
- Decay curve of the isomer by delayed coincidence or pulsed beam
- Put detectors at ±θ in the reaction plane

- Compare the ratio of counts in +θ and -θ detectors
- Decay curve in the presence of external field



$$I(\theta, t, B) = I_o \exp\left(-\frac{t}{\tau}\right) W(\theta, t, B)$$

$$W(\theta, t, B) = \sum_k A_k P_k\left(\cos\{\theta - \omega_L t\}\right)$$

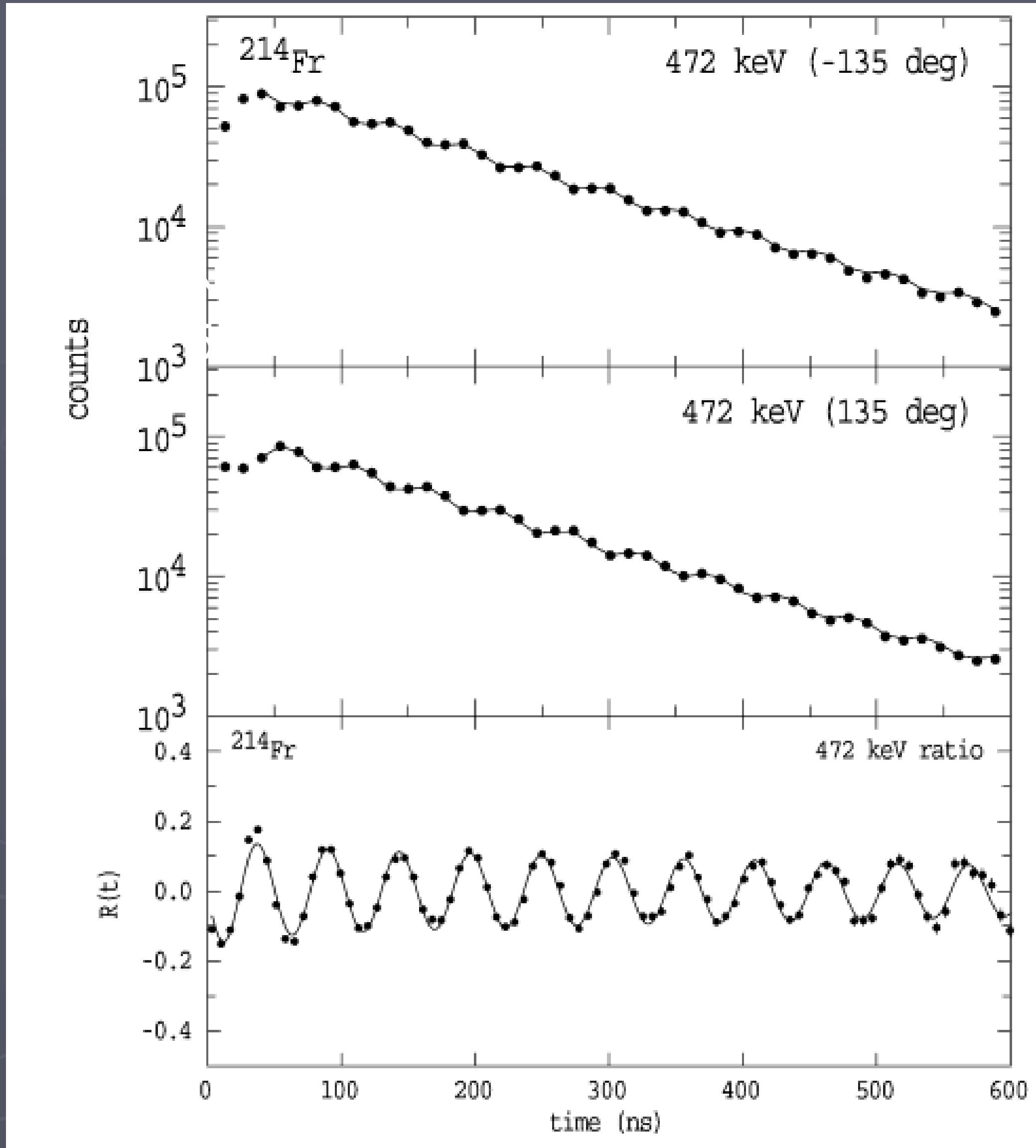
TDPAD measurement in ^{214}Fr

- produced in ^{208}Pb(^{11}B,5n)
- γ–γ delayed coincidence with 1068 keV line of ^{214}Fr
- Mean life for 11^{+} isomer τ =148 ns
- External field 2.4 T
- Plotted ratio R(t)

$$R = \frac{I(+\theta)-I(-\theta)}{I(+\theta)+I(-\theta)}$$

- R ~ ¾ a_2 $\sin(2\omega_L t)\sin(2\theta)$
- Maximum sensitivity at θ=45°

g = 0.511



End of Lecture-2