# Gamma-ray spectroscopy II

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# Outline

First lecture

- Properties of $\gamma$-ray transitions
- Fusion-evaporation reactions
- Germanium detector arrays
- Coincidence technique
- Nuclear deformations
- Rotation of deformed nuclei
- Pair alignment
- Superdeformed nuclei
- Hyperdeformed nuclei
- Triaxiality and wobbling

Second lecture

- Angular distribution
- Linear polarization
- Jacobi shape transition
- Charged-particle detectors
- Neutron detectors
- Prompt proton decay
- Recoil-decay tagging
- Rotation and deformation alignment

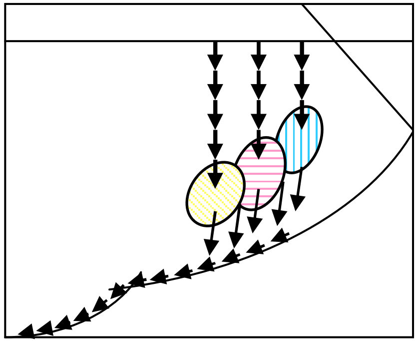
Third lecture

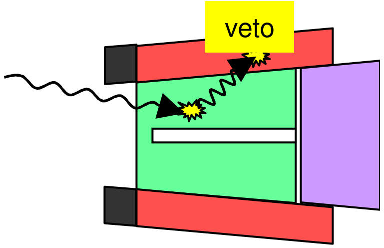
- Spectroscopy of transfermium nuclei
- Conversion-electron spectroscopy
- Quadrupole moments and transition rates
- Recoil-distance method
- Doppler shift attenuation method
- Fractional Doppler shift method
- Magnetic moments
- Perturbed angular distribution
- Magnetic Rotation
- Shears Effect

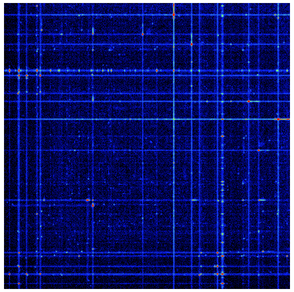
Fourth lecture

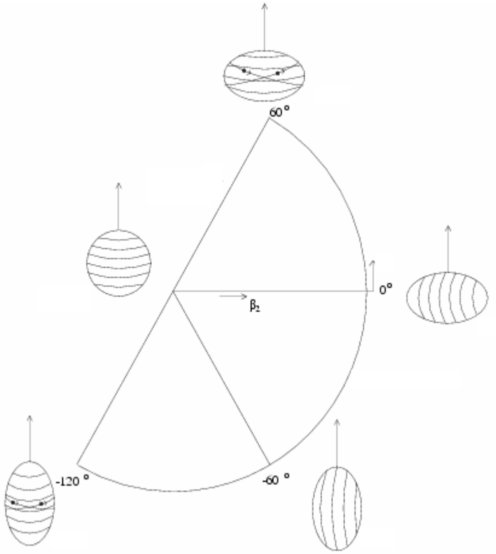
- Fast fragmentation beams
- Isomer spectroscopy after fragmentation
- E0 transitions
- Shape coexistence
- Two-level mixing
- Coulomb excitation
- Reorientation effect
- ISOL technique
- Low-energy Coulomb excitation of $^{74}$Kr
- Relativistic Coulomb excitation of $^{58}$Cr
- Gamma-ray tracking
- AGATA

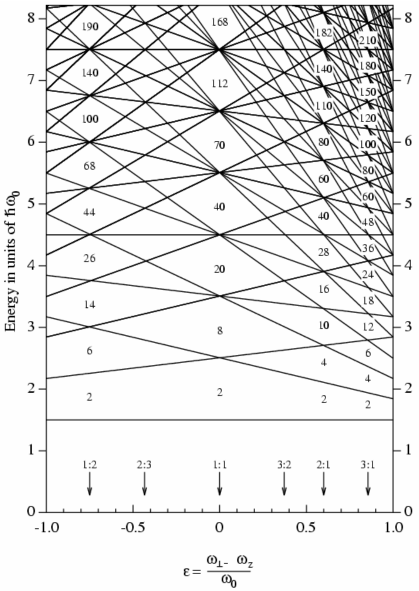
# Summary (I)

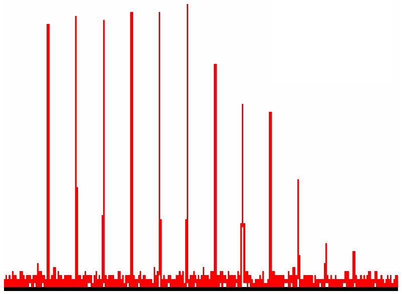


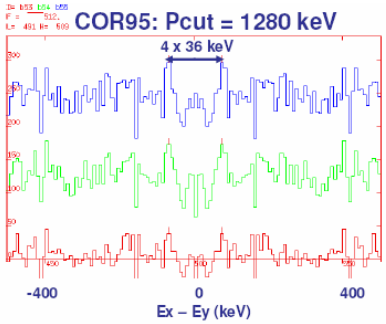

veto

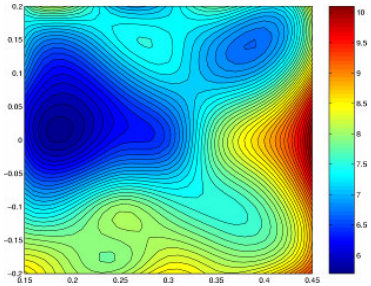


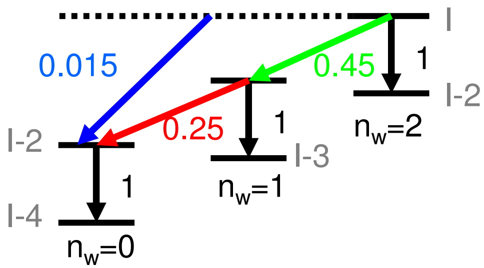

60°
0°
-120°
-60°

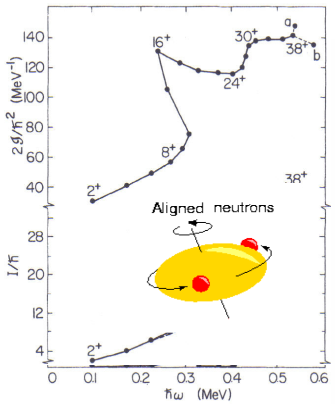

Energy in units of ħω₀
ε = (ω⊥ - ωz)/ω₀
1:2
2:3
1:1
3:2
2:1
3:1

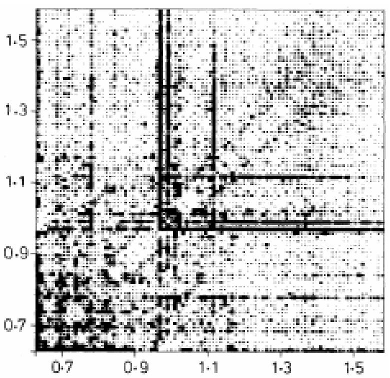


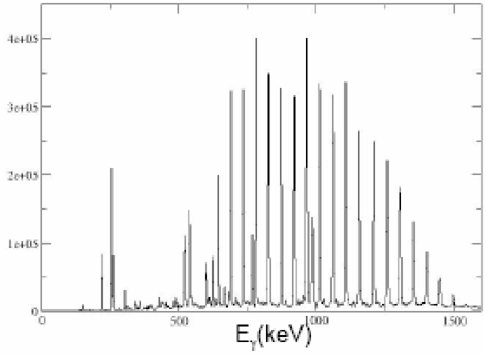

COR95: Pcut = 1280 keV
4 x 36 keV
-400
0
400
Ex – Ey (keV)

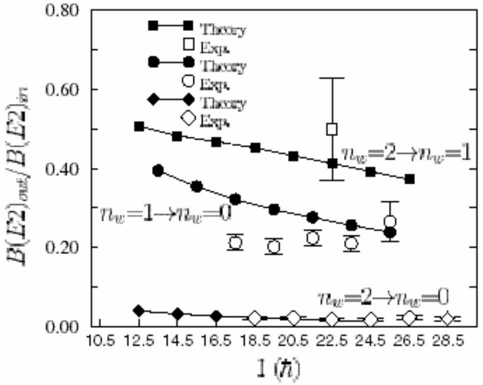



I
0.015
0.45
1
I-2
0.25
1
I-2
I-3
1
I-4
nw=2
nw=1
nw=0

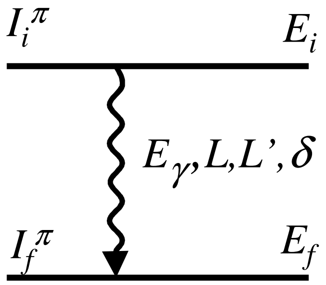

2ℐ/ħ² (MeV⁻¹)
I/ħ
ħω (MeV)
Aligned neutrons



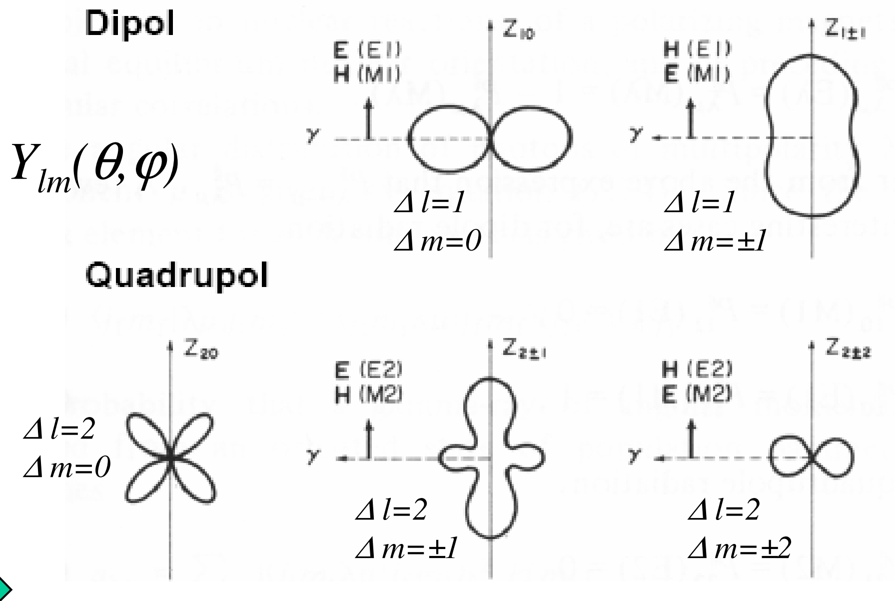

Eγ(keV)


B(E2)out/B(E2)in
I (ħ)
Theory
Exp.
nw=2→nw=1
nw=1→nw=0
nw=2→nw=0

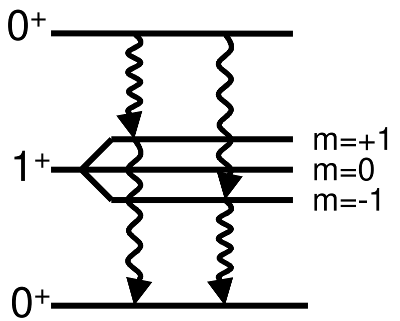
# Angular correlation

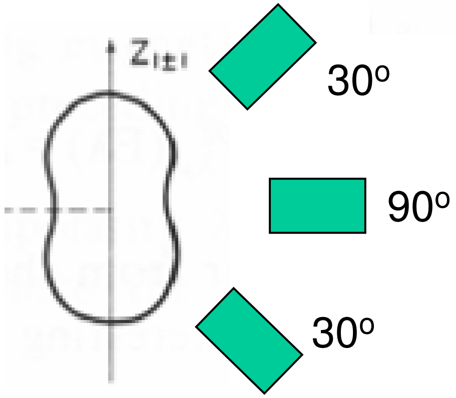


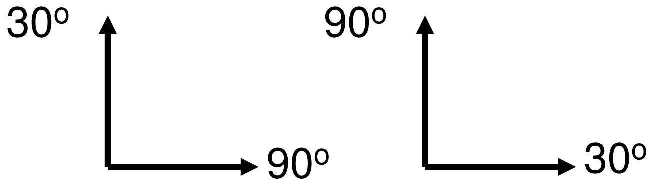

$$W(\vartheta) = 1 + \sum_k A_k P_k(\cos\vartheta)$$




simple example:




Directional correlation from oriented states

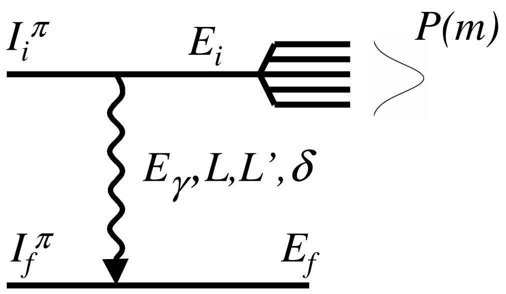
$$R_{DCO} = \frac{I(\gamma_1,\theta_1;\gamma_2,\theta_2)}{I(\gamma_1,\theta_2;\gamma_2,\theta_1)}$$

Most transitions following fusion-evaporation reactions have stretched dipole or quadrupole character.

⇒ compare experimental $R_{DCO}$ with values for dipole-dipole, dipole-quadrupole, quadrupole-quadrupole cascades

⇒ often sufficient for spin assignments

# Angular distribution




Alignment of angular momentum after fusion-evaporation reaction:

$$P(m) = \frac{\exp\left(\frac{-m^2}{2\sigma^2}\right)}{\sum_{m'=-I}^{+I} \exp\left(\frac{-m'^2}{2\sigma^2}\right)}$$

$$W(\vartheta) = 1 + \sum_k A_k P_k(\cos\vartheta)$$

The coefficients $A_k$ depend on

- the multipolarity L
- the mixing parameter δ
- the population width σ

$$A_k(L, L', I_f, I_i) = \rho_k(I_i) \frac{1}{1+\delta^2}\left[F_k(L, L, I_f, I_i) + 2\delta F_k(L, L', I_f, I_i) + 2\delta^2 F_k(L', L', I_f, I_i)\right]$$

$$\rho_k(I_i) = \sqrt{2I_i + 1} \sum_{m=-I}^{+I} (-1)^{I_i - m} \langle I_i\, m\, I_i - m | k\, 0\rangle\, P(m)$$

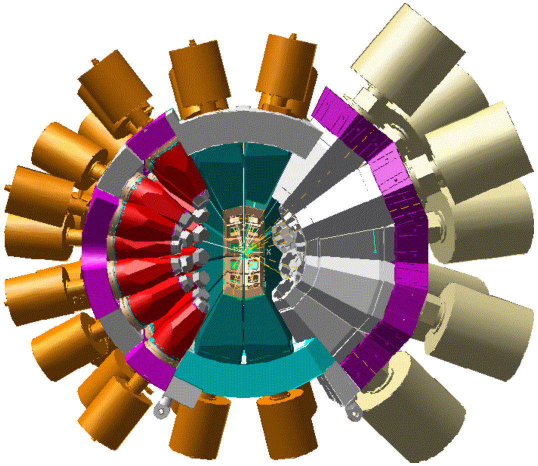
Ferentz-Rosenzweig coefficients

$$F_k(L, L', I_f, I_i) = (-1)^{I_f + I_i - 1} \sqrt{(2L+1)(2L'+1)(2I_i+1)(2k+1)} \begin{pmatrix} L & L' & k \\ 1 & -1 & 0 \end{pmatrix} \begin{Bmatrix} L & L' & k \\ I_i & I_i & I_f \end{Bmatrix}$$

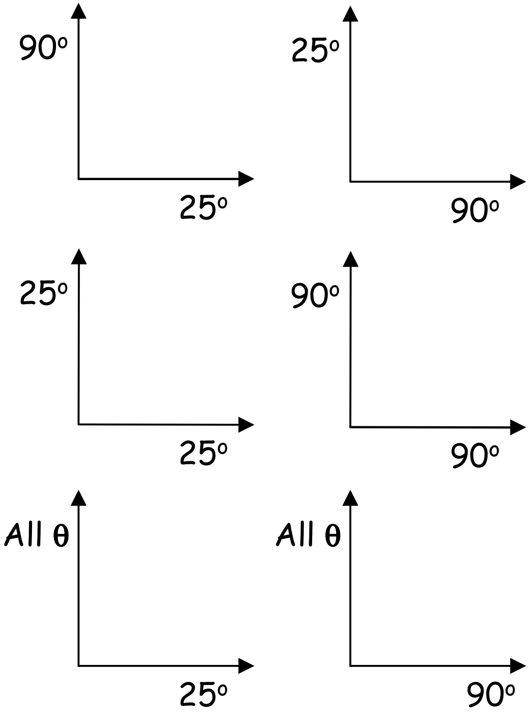
Clebsch-Gordan Racah

σ/*I* is approximately constant (for a given reaction).
Normalize to transition with known multipolarity, e.g. $2^+ \rightarrow 0^+$

# Example: Angular distribution with EUROBALL



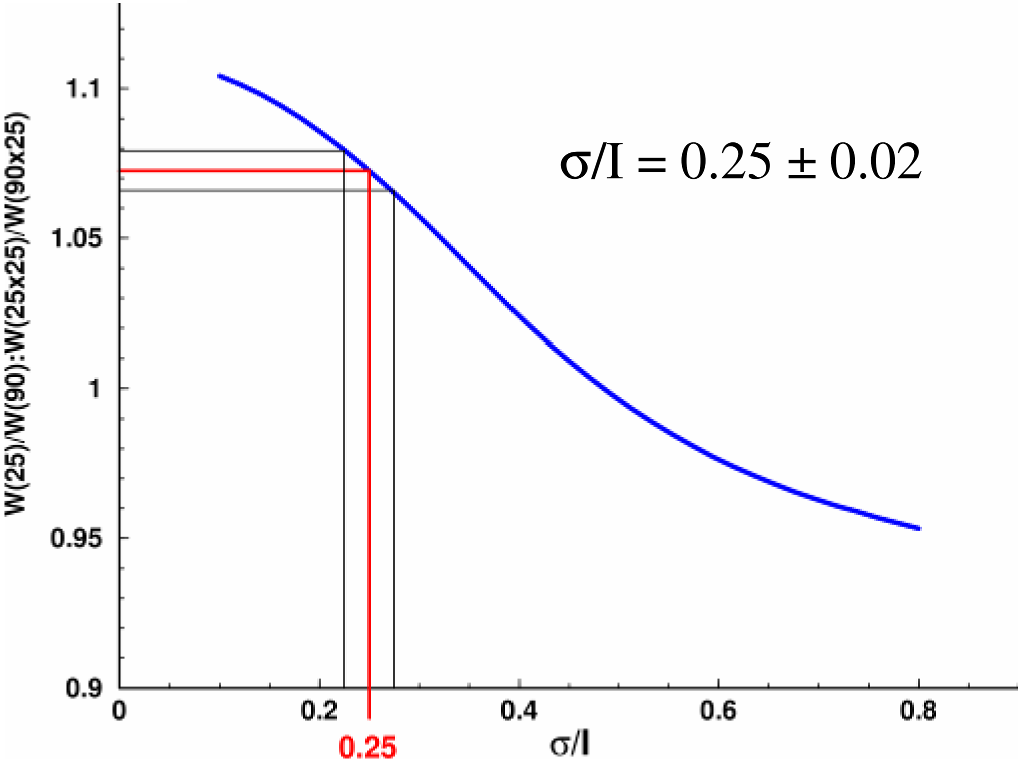
25° angle: ring1 + ring2 (tapered)
ring 7 (clusters)
90° angle: ring4 + ring5 (clovers)



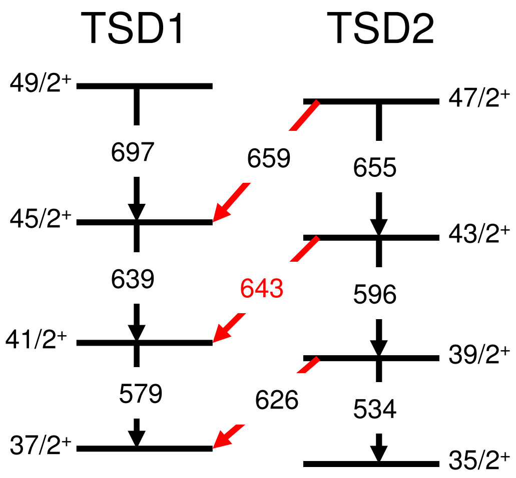

$$\frac{\frac{W(25)}{W(90)}}{\frac{W(25\times 25)}{W(90\times 25)}}$$

$^{139}La(^{29}Si,5n)^{163}Lu$ with $E_{beam}$= 153 MeV

Average of 8 stretched E2 transitions in TSD1 and TSD2

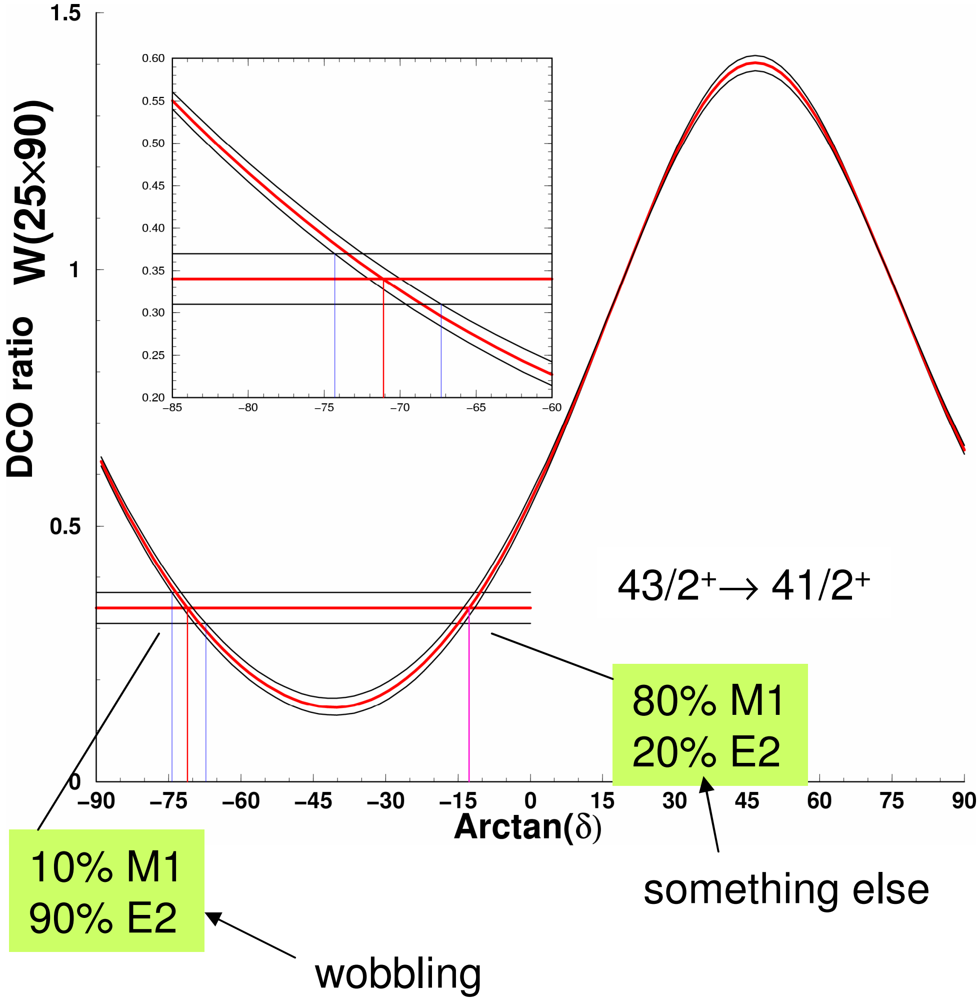


# Measuring the mixing parameter δ



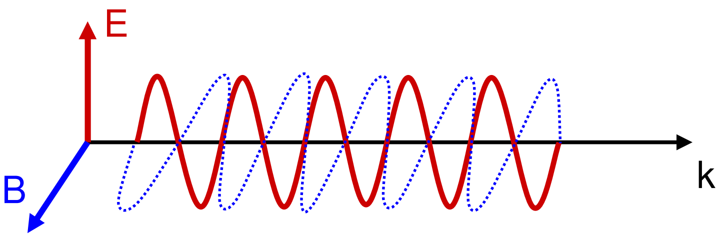

We know σ/I and have assigned $I^{\pi}$
For wobbling bands, we expect
$\Delta I$=1 E2 inter-band transitions.
⇒ L=1, L'=2, large δ

Two possible solutions

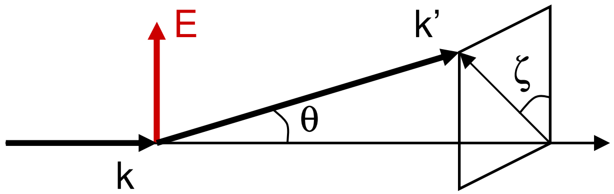



Angular distribution cannot distinguish between the two.
⇒ measure the linear polarization to establish electric or magnetic character.

# Linear polarization




linear polarization: fixed direction of electric field vector E

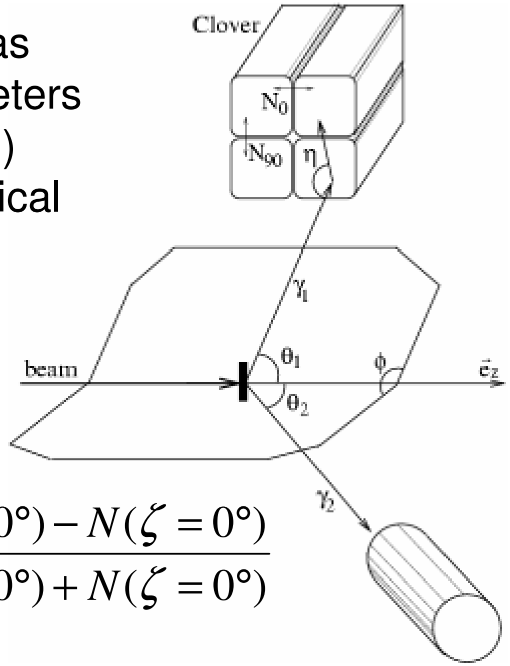



Compton scattering is sensitive to linear polarization: Klein-Nishina formula

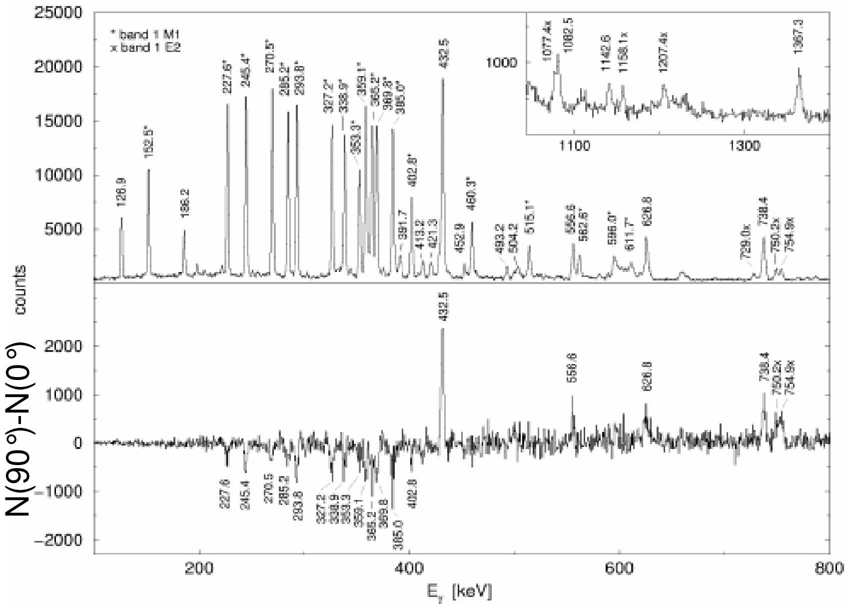
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\frac{\omega'^2}{\omega^2}\left(\frac{\omega'}{\omega} + \frac{\omega}{\omega'} - 2\sin^2\theta\cos^2\zeta\right)$$

Effect is largest at θ=90°

Clover detectors as Compton polarimeters (at 90° in Euroball) horizontal vs. vertical scattering

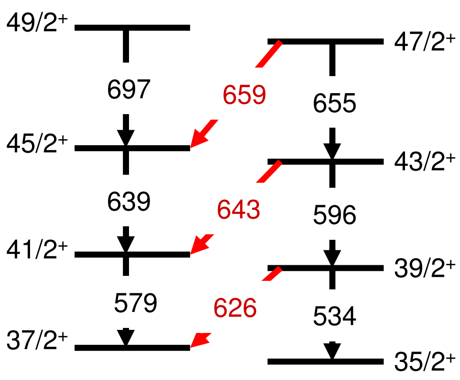



$$P = \frac{A}{Q} = \frac{1}{Q}\frac{N(\zeta = 90°) - N(\zeta = 0°)}{N(\zeta = 90°) + N(\zeta = 0°)}$$

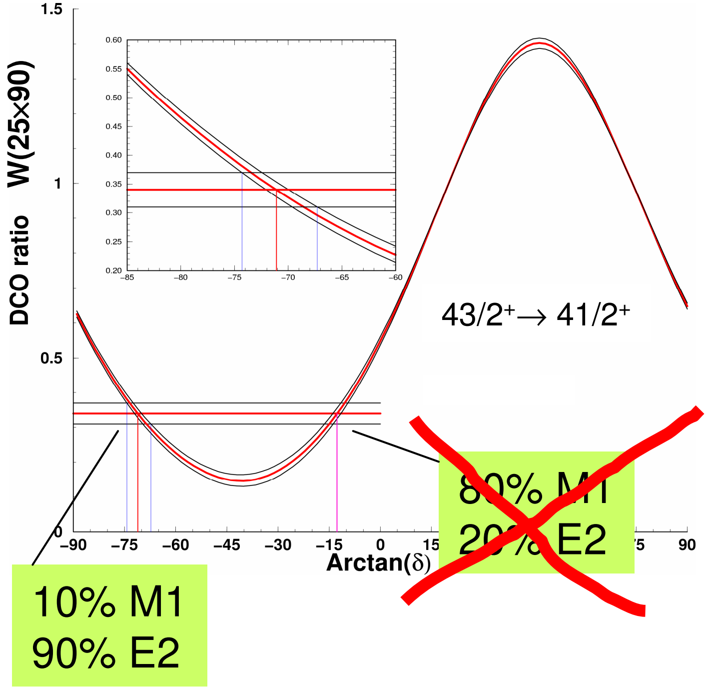



electric transitions appear positive, magnetic transitions negative

# Polarization measurement in $^{163}$Lu




| | Eγ | $A = \frac{N(90°) - N(0°)}{N(90°) + N(0°)}$ | |
|---|---|---|---|
| E2 | 579 | **0.10 ± 0.03** | positive |
| | 697 | **0.13 ± 0.03** | |
| | 386 | **0.06 ± 0.05** | |
| | 534 | **0.05 ± 0.04** | |
| M1 | 349 | **-0.11 ± 0.05** | negative |
| inter-band | 607 | **0.05 ± 0.05** | positive ⇒ electric |
| | 626 | **0.12 ± 0.05** | |
| | 643 | **0.11 ± 0.05** | |
| | 659 | **0.17 ± 0.09** | |
| | 673 | **0.18 ± 0.09** | |




Confirmation of the wobbling mode in $^{163}$Lu through combined angular distribution and linear polarization measurement.

S.W. Ødegård et al., Phys. Rev. Lett. 86, 5866 (2001)

# MacLaurin shapes

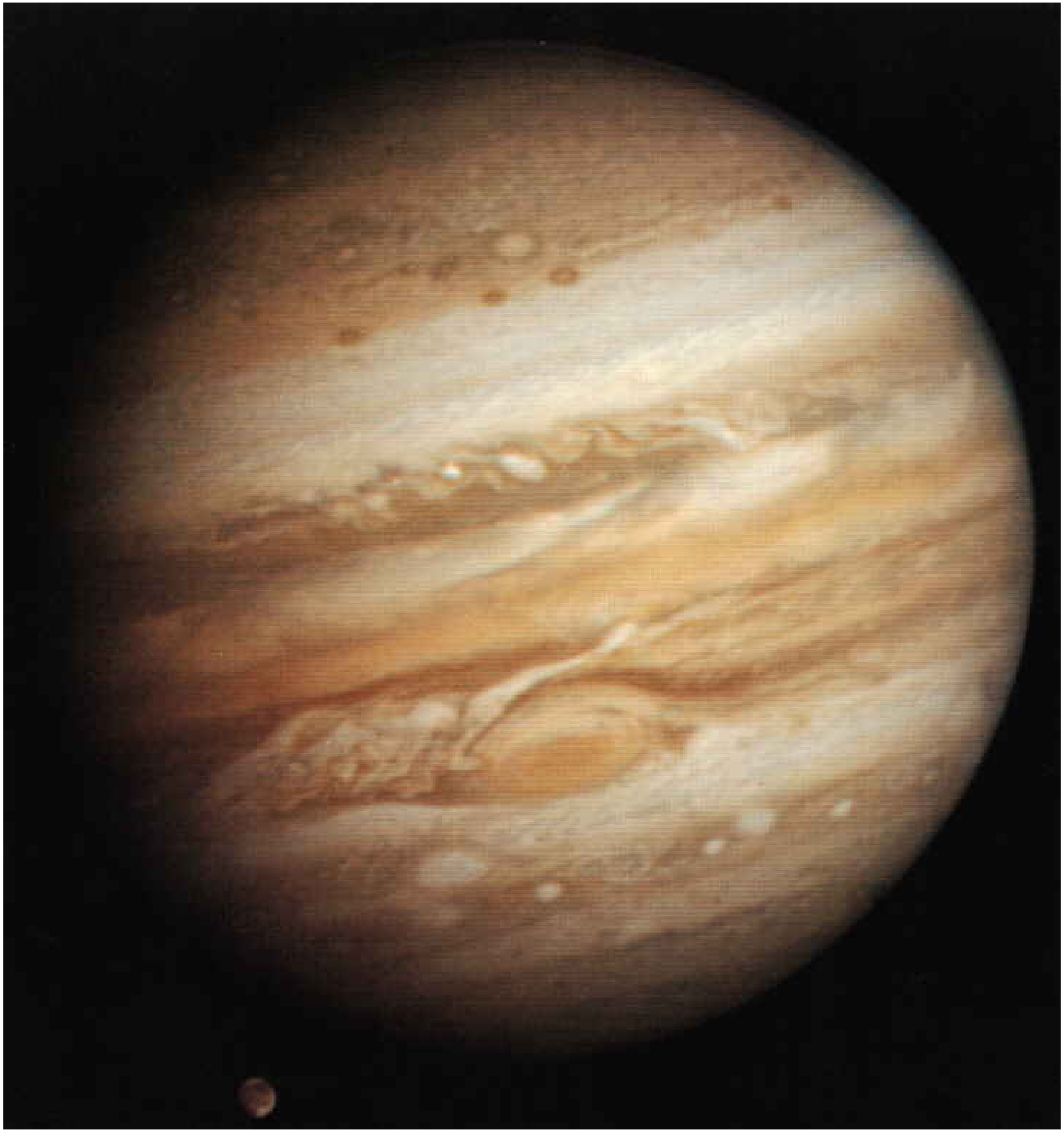
What happens if we spin a liquid drop ?

It becomes oblate !

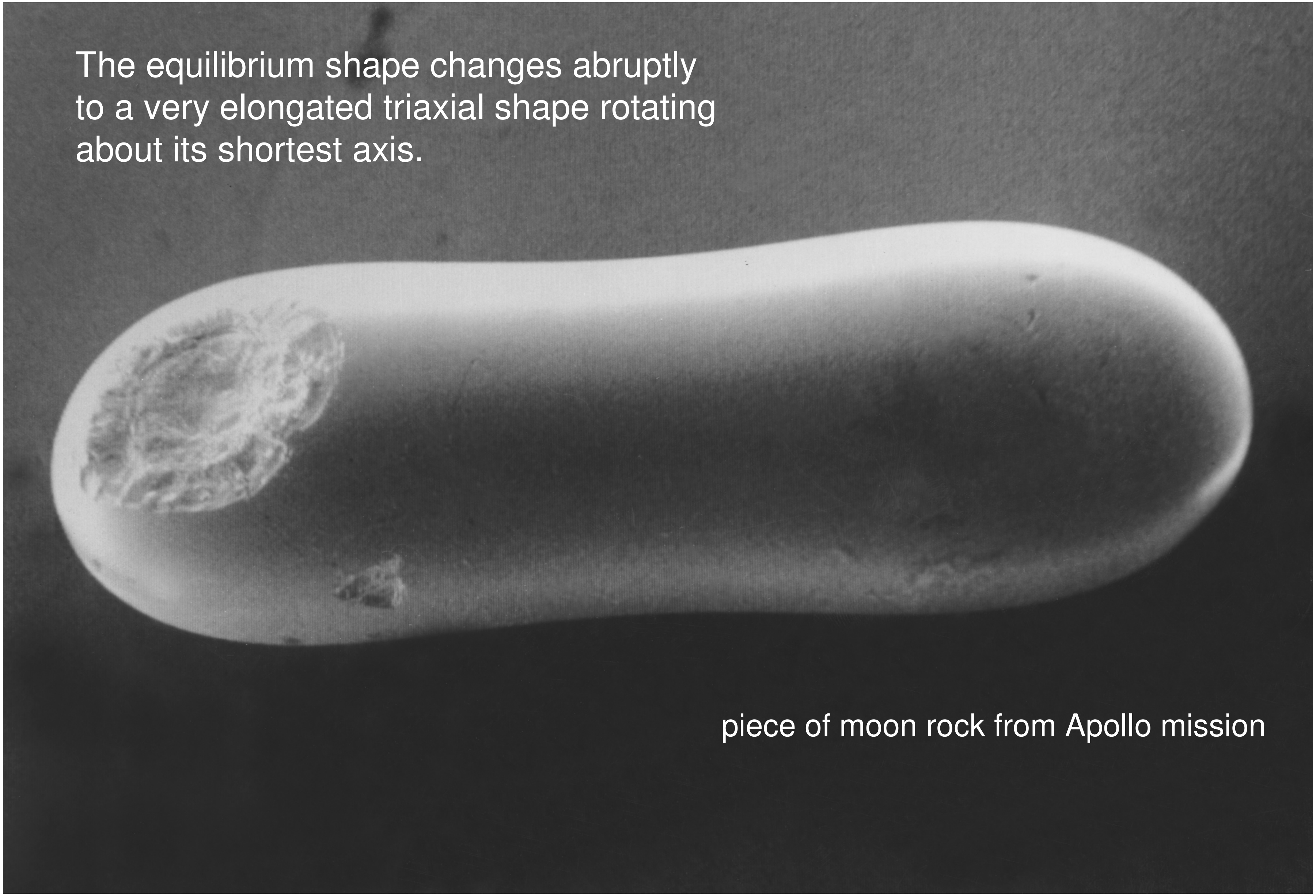
Jupiter:
- T = 9 h 50 min
- polar / equatorial axis ~ 15/16

MacLaurin shape after C. MacLaurin (1698-1746)

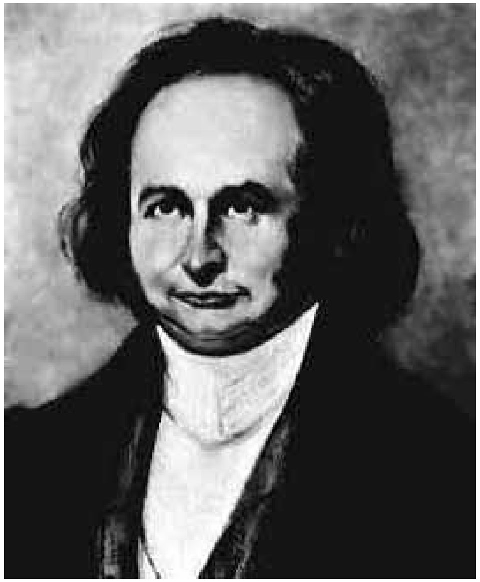
But what if we spin really fast ?



# Jacobi shapes



## The Jacobi shape transition in nuclei



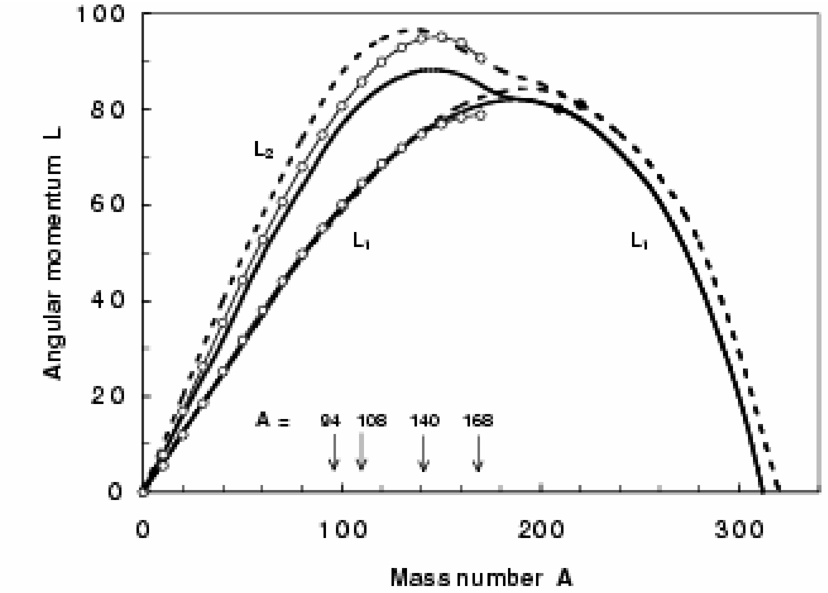
Carl Gustav Jacob Jacobi (1804 - 1851) discovered transition from oblate to triaxial shapes in the context of rotating, idealized, incompressible gravitating masses in 1834.

In 1961 Beringer and Knox suggested a similar transition in the case of atomic nuclei, idealized as incompressible, uniformly charged, liquid drops endowed with surface tension.

Liquid drop calculation

Jacobi transition for $L > L_1$
Fission barrier vanishes for $L > L_2$

W.D. Myers and W.J. Swiatecki
Acta Phys. Pol. B 32, 1033 (2001)



## What is the signature of a Jacobi transition in nuclei ?

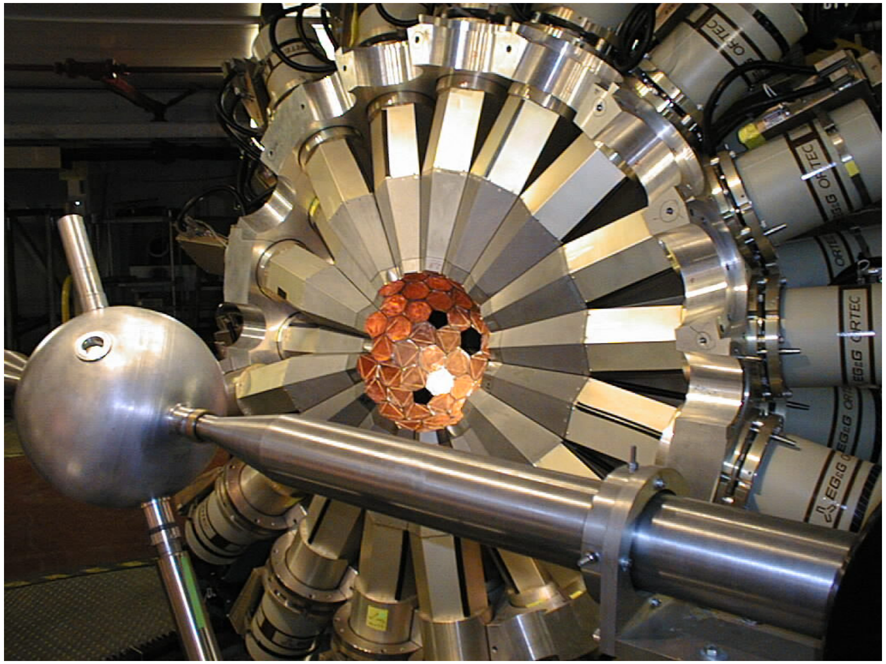
- sharp decrease of frequency with increasing angular momentum (giant backbend of the moment of inertia)
- frequency of collective rotation is related to the E2 γ-ray energy: $\hbar\omega = \frac{1}{2} E_\gamma$
- many rotational bands at high spin quasi-continuous transitions
- measure the energy of the quasi-continuous 'E2 bump' as a function of angular momentum
- series of experiments with Gammasphere

$^{48}$Ca + $^{50}$Ti @ 200 MeV
$^{48}$Ca + $^{64}$Ni @ 207 MeV
$^{48}$Ca + $^{96}$Zr @ 207 MeV
$^{48}$Ca + $^{124}$Sn @ 215 MeV

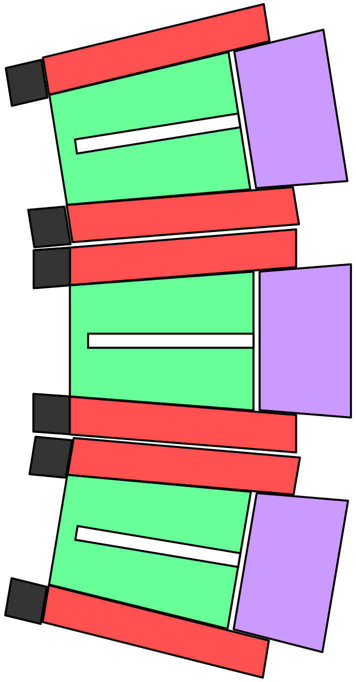
as neutron rich as possible:
⇒ higher fission barrier

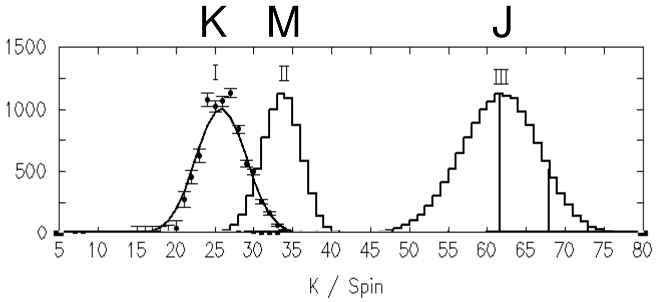
dapnia SPhN cea saclay

# Measuring angular momentum with Gammasphere



108 Compton-suppressed
HPGe detectors



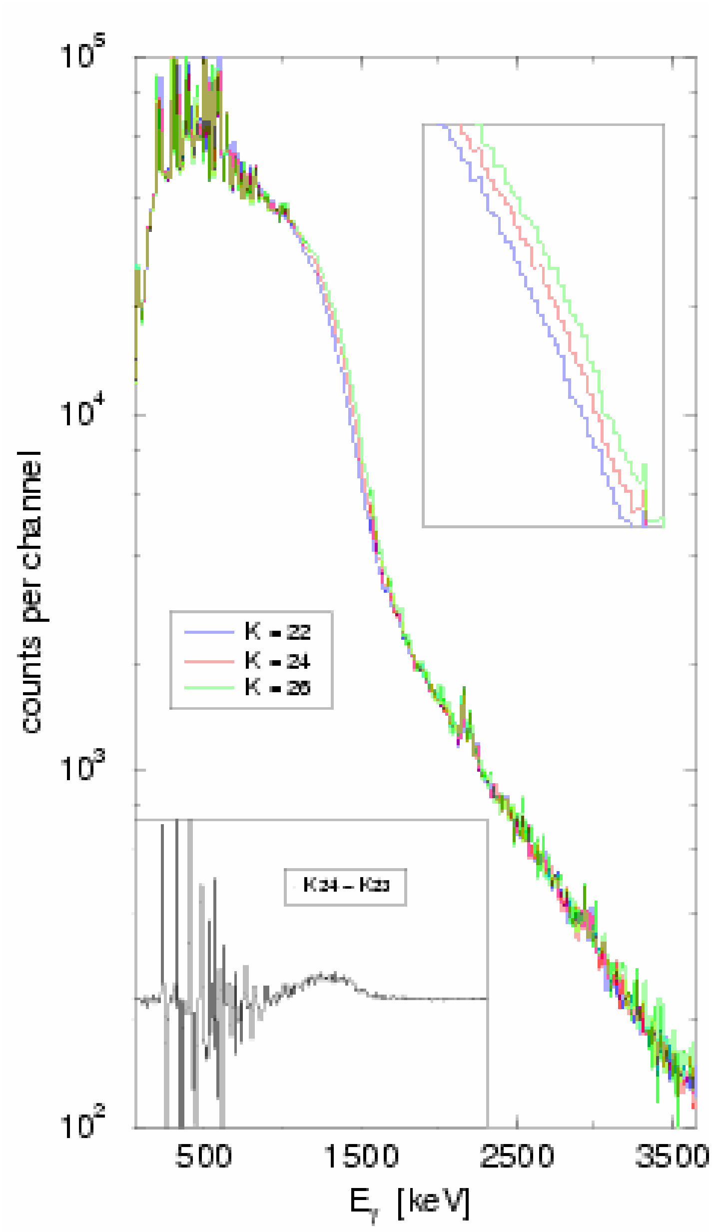



108 Ge detectors
6 x 108 = 648 BGO detectors

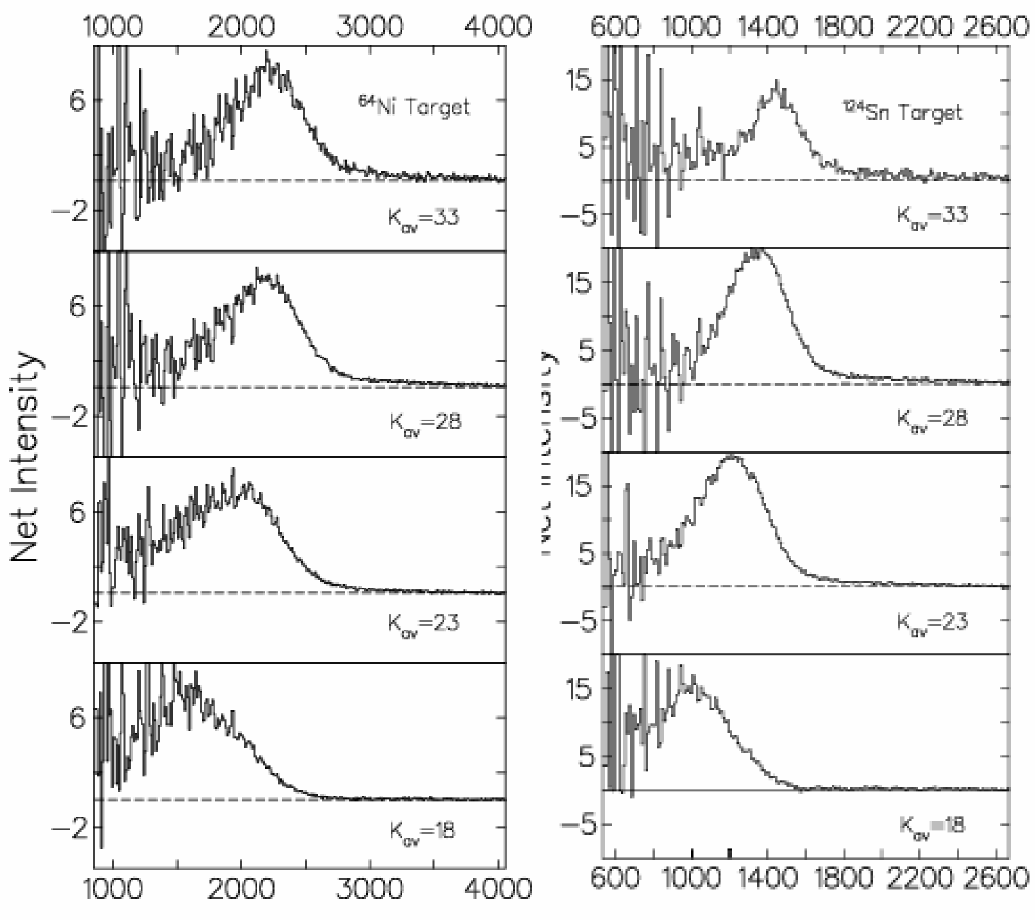
increase in false veto signals
reduced Ge efficiency
but very high granularity

K = number of hits = fold
M = $\gamma$ rays emitted = multiplicity (from response function)
J = initial angular momentum (from angular distribution)

# The E2 bump

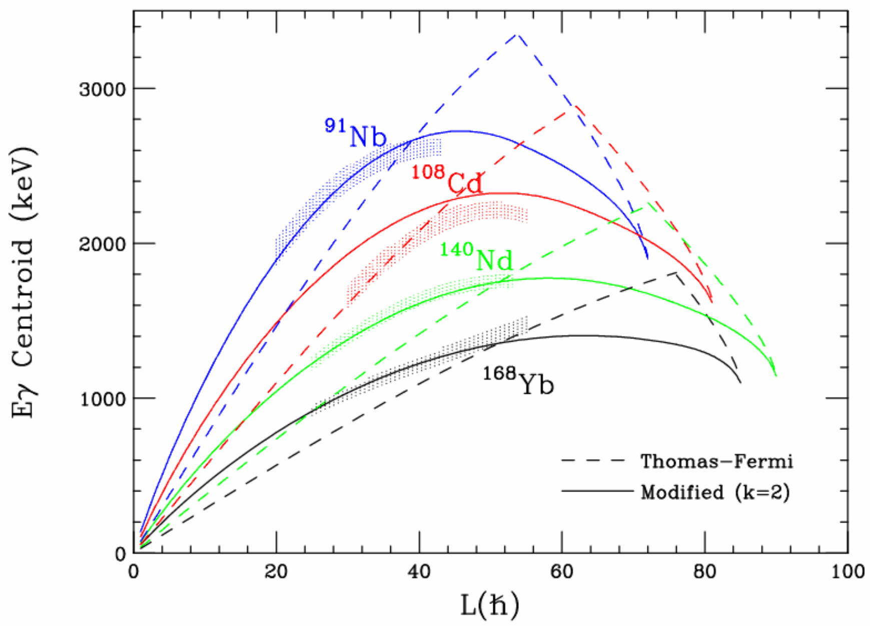


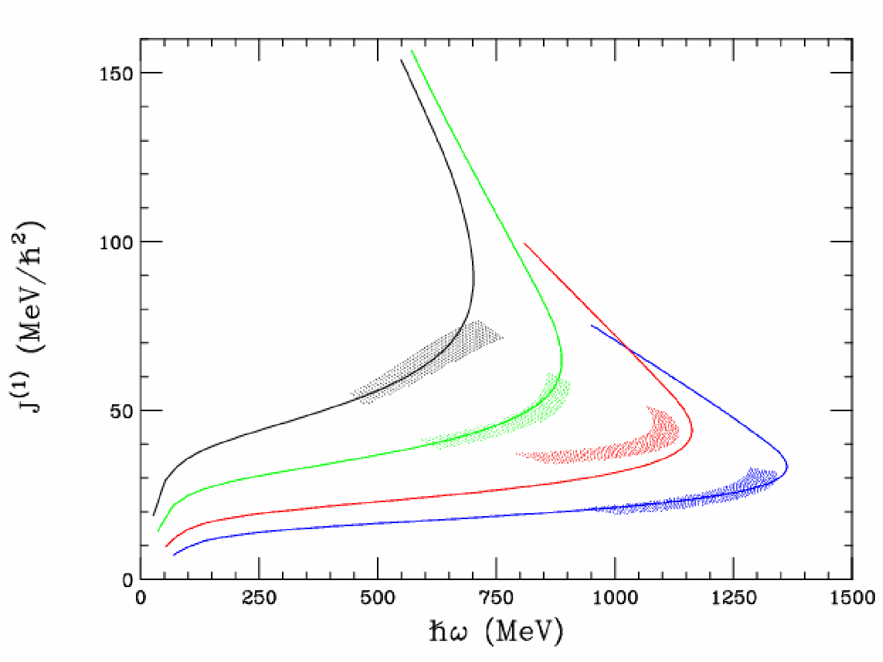

Incremental spectra:
Multiplicity ($K_{av}$-1) gated spectrum
subtracted from ($K_{av}$+1) spectrum




K measures the angular momentum
E2 bump measures rotational frequency

# Comparison to liquid drop calculations




D. Ward et al., Phys. Rev. C 66, 024317 (2002)

two modifications:

- lower effective moment of inertia at low spin due to pairing
- no collective rotation about axially symmetric (MacLaurin) shapes in nuclei, instead, collective rotations are associated with (mostly) prolate shapes
  → no sharp transition caused by breaking of axial symmetry, but smooth transition

# Charged-particle evaporation

## $^{40}Ca + ^{40}Ca$ @ 167 MeV

The nucleus of interest is often only weakly populated compared to a large background of other nuclei.

neutrons are deeply bound, charged-particle evaporation favored despite Coulomb barrier

Additional sensitivity from:

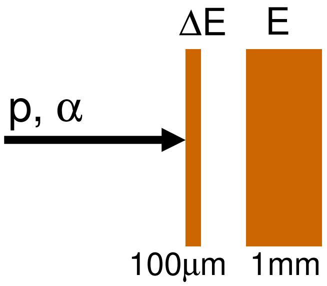
- charged-particle detectors
- neutron detectors
- recoil detectors
- tagging techniques

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $^{78}$Zr 2n | $^{79}$Zr 1n | $^{80}$Zr |
| | | | | | $^{76}$Y p3n | $^{77}$Y p2n 0.18 | $^{78}$Y pn | $^{79}$Y 1p |
| | | | | | $^{75}$Sr αn | $^{76}$Sr 2p2n 4.06 | $^{77}$Sr 2pn 2.95 | $^{78}$Sr 2p |
| | | | $^{72}$Rb αp3n | $^{73}$Rb αp2n 0.01 | $^{74}$Rb αpn 2.49 | $^{75}$Rb αp 5.35 | $^{76}$Rb 3pn 101 | $^{77}$Rb 3p 2.31 |
| | | $^{70}$Kr 2α2n | $^{71}$Kr 2αn 0.18 | $^{72}$Kr 2α 0.37 | $^{73}$Kr α2pn 52 | $^{74}$Kr α2p 20.3 | $^{75}$Kr 4pn 132 | $^{76}$Kr 4p 74.2 |
| | | $^{69}$Br 2αp2n | $^{70}$Br 2αpn 6.82 | $^{71}$Br 2αp 11.4 | $^{72}$Br α3pn 38.2 | $^{73}$Br α3p 128 | $^{74}$Br 5pn 3.23 | $^{75}$Br 5p 68.2 |
| | $^{67}$Se 3αn | $^{68}$Se 3α 5.07 | $^{69}$Se 2α2pn 1.57 | $^{70}$Se 2α2p 94 | $^{71}$Se α4pn 0.46 | $^{72}$Se α4p 102 | $^{73}$Se 6pn | $^{74}$Se 6p 1.57 |
| | $^{66}$As 3αpn | $^{67}$As 3αp 15 | $^{68}$As 2α3pn | $^{69}$As 2α3p 35.6 | $^{70}$As α5pn | $^{71}$As α5p 2.03 | $^{72}$As 7pn | $^{73}$As 7p |
| $^{64}$Ge 4α 1.48 | $^{65}$Ge 3α2pn | $^{66}$Ge 3α2p 8.3 | $^{67}$Ge 2α4pn | $^{68}$Ge 2α4p 0.37 | $^{69}$Ge α6pn | | | |

cross sections in mb

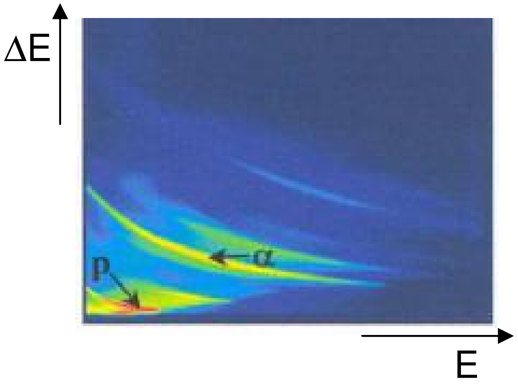
# Charged particle detection

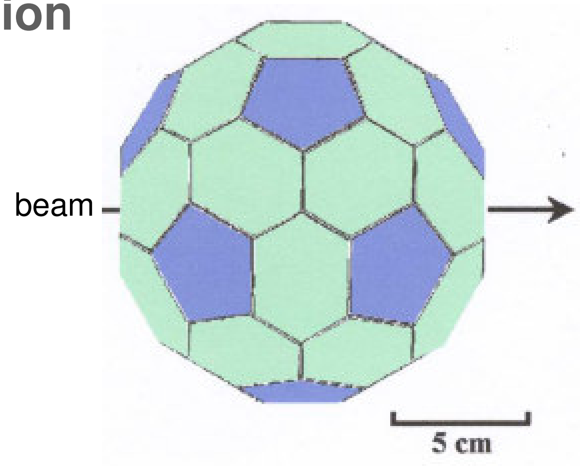
Si telescope




stopping power

$$\frac{dE}{dx} \propto \frac{mZ^2}{E}$$

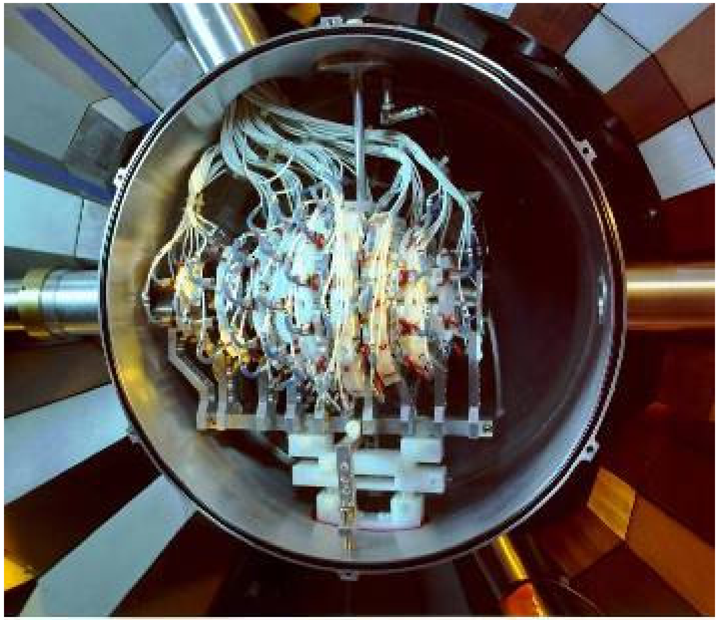


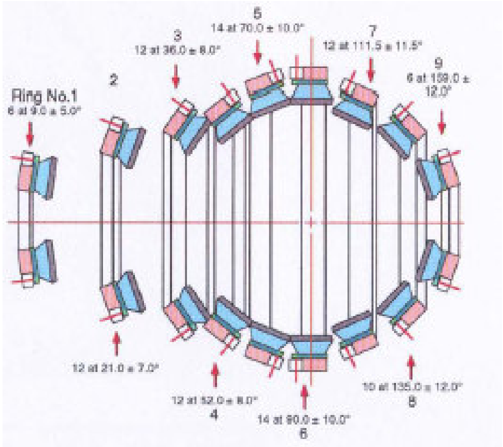




Italian Silicon Sphere ISIS
Laboratori Nazionali di Legnaro

30 hexagons
12 pentagons

used with GASP and Euroball



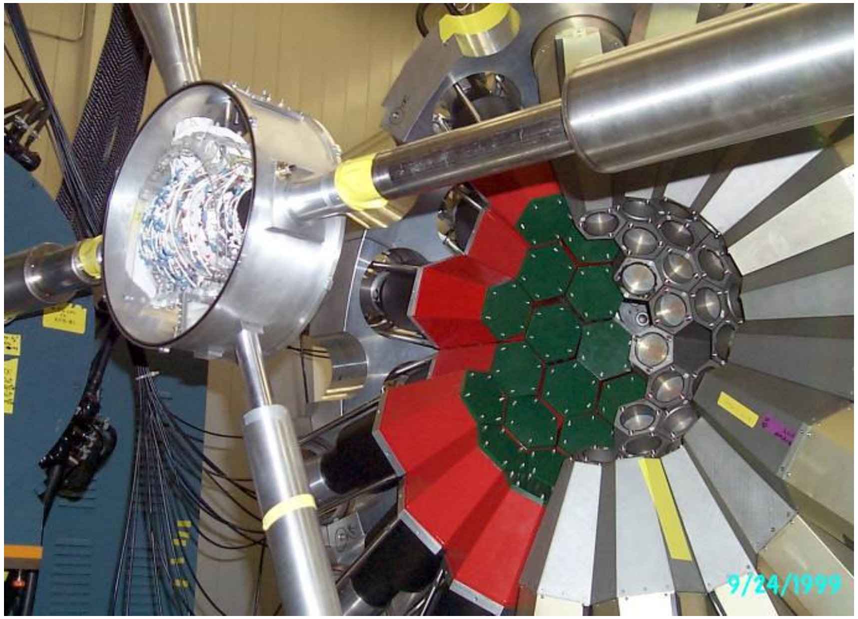



95 CsI(Tl) Scintillators in 9 rings

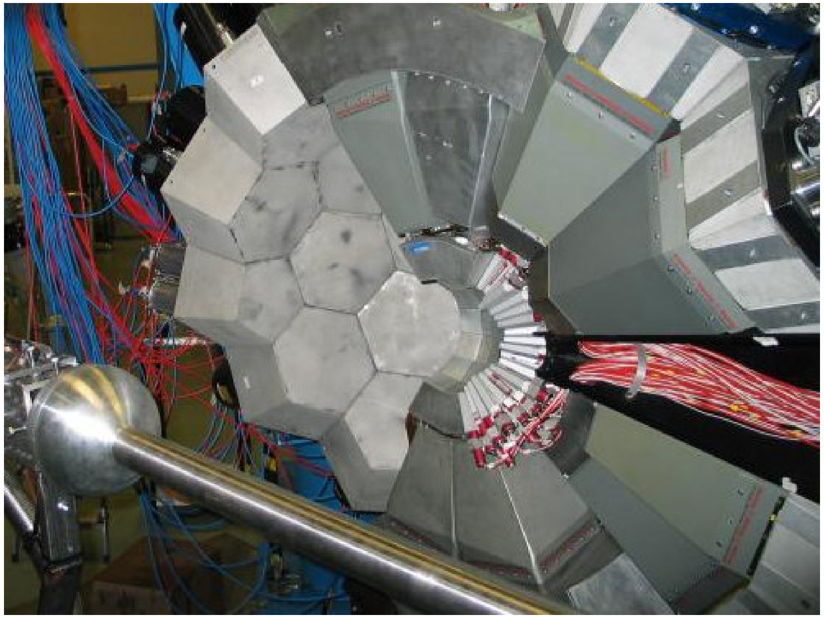
used with Gammasphere

Microball,
Washington University St. Louis

# Neutron detection

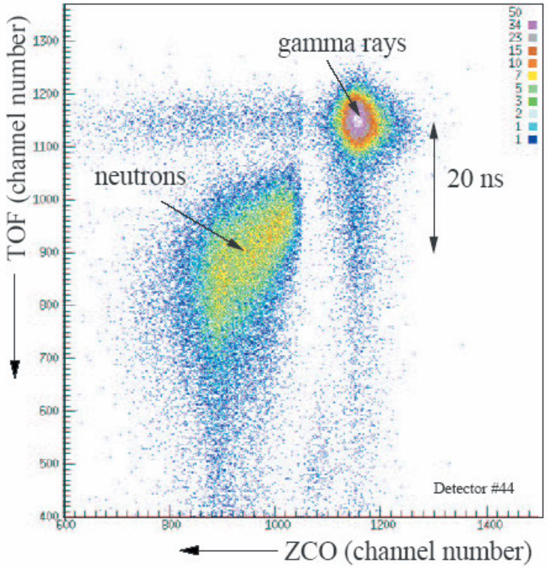



Gammasphere with Microball and Neutron shell (Washington University, St. Louis)

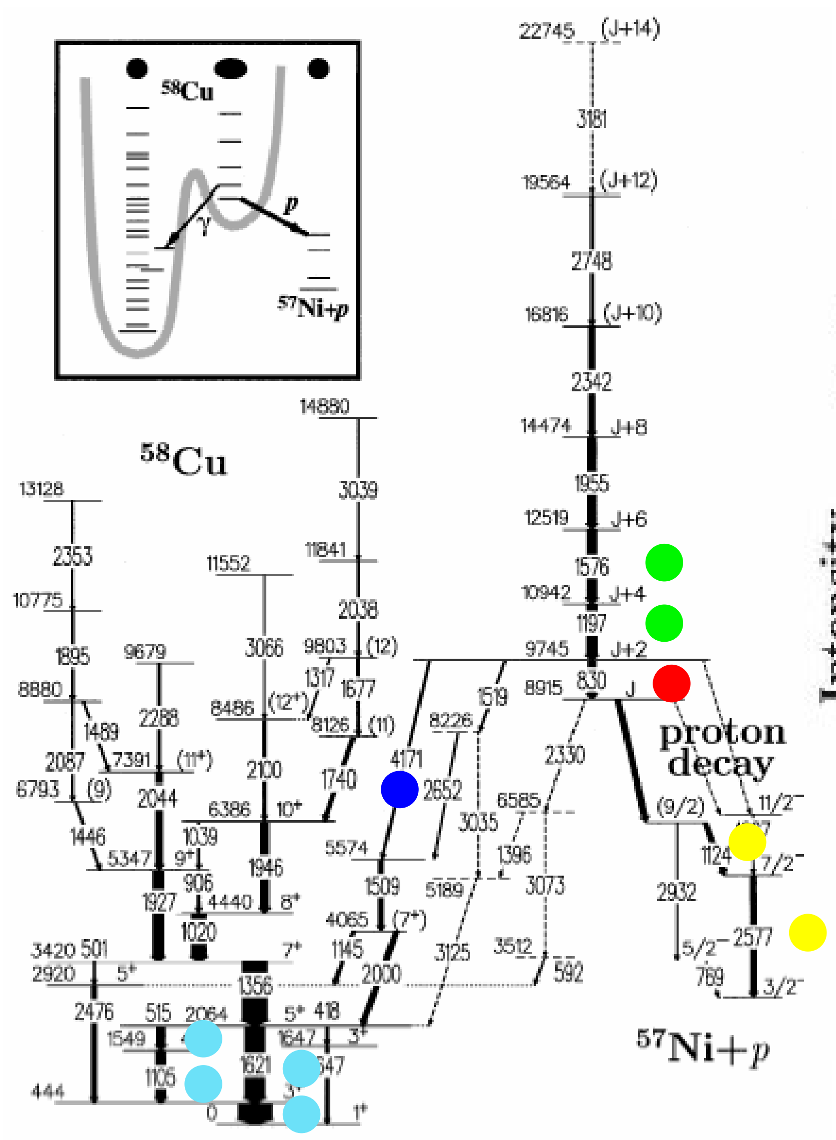


Euroball with Neutron wall (Uppsala University)

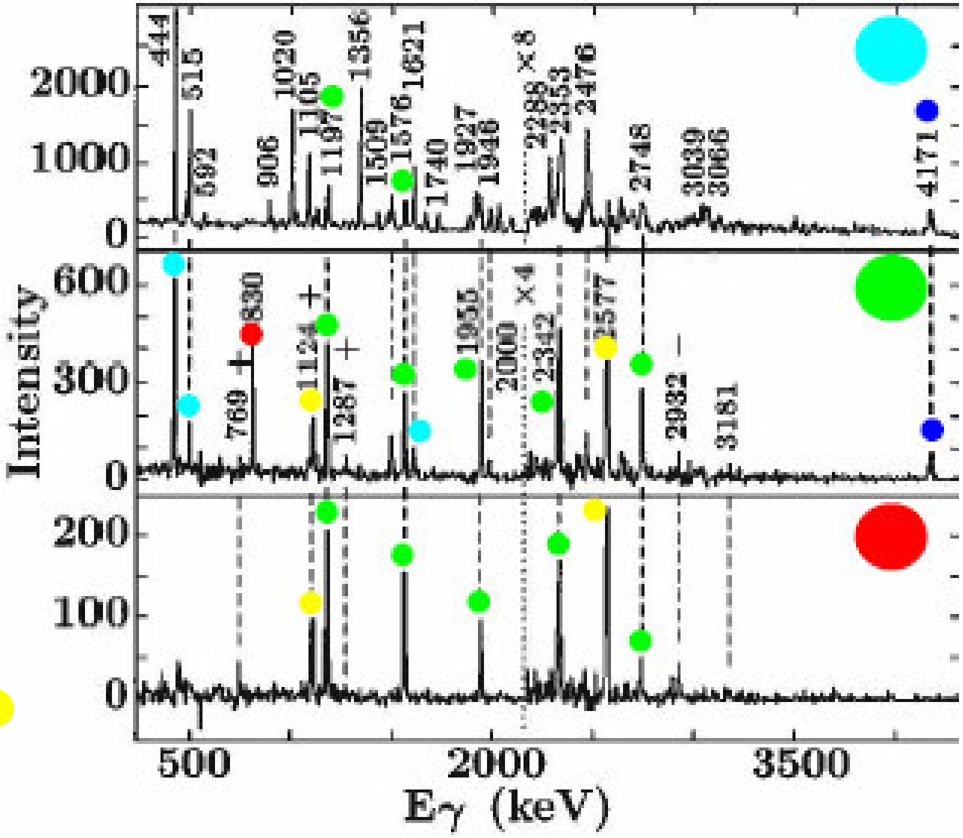
- can be used to select or veto neutron evaporation
- most powerful together with charged-particle detection
- used to study nuclei near N=Z line
  - isospin symmetry
  - proton-neutron pairing
  - shape coexistence
  - astrophysical rapid-proton capture process
- neutrons are separated from γ rays by time of flight and pulse shapes (zero-crossing time)
- difficult to distinguish two-neutron hit from scattering



# Prompt proton decay in $^{58}$Cu

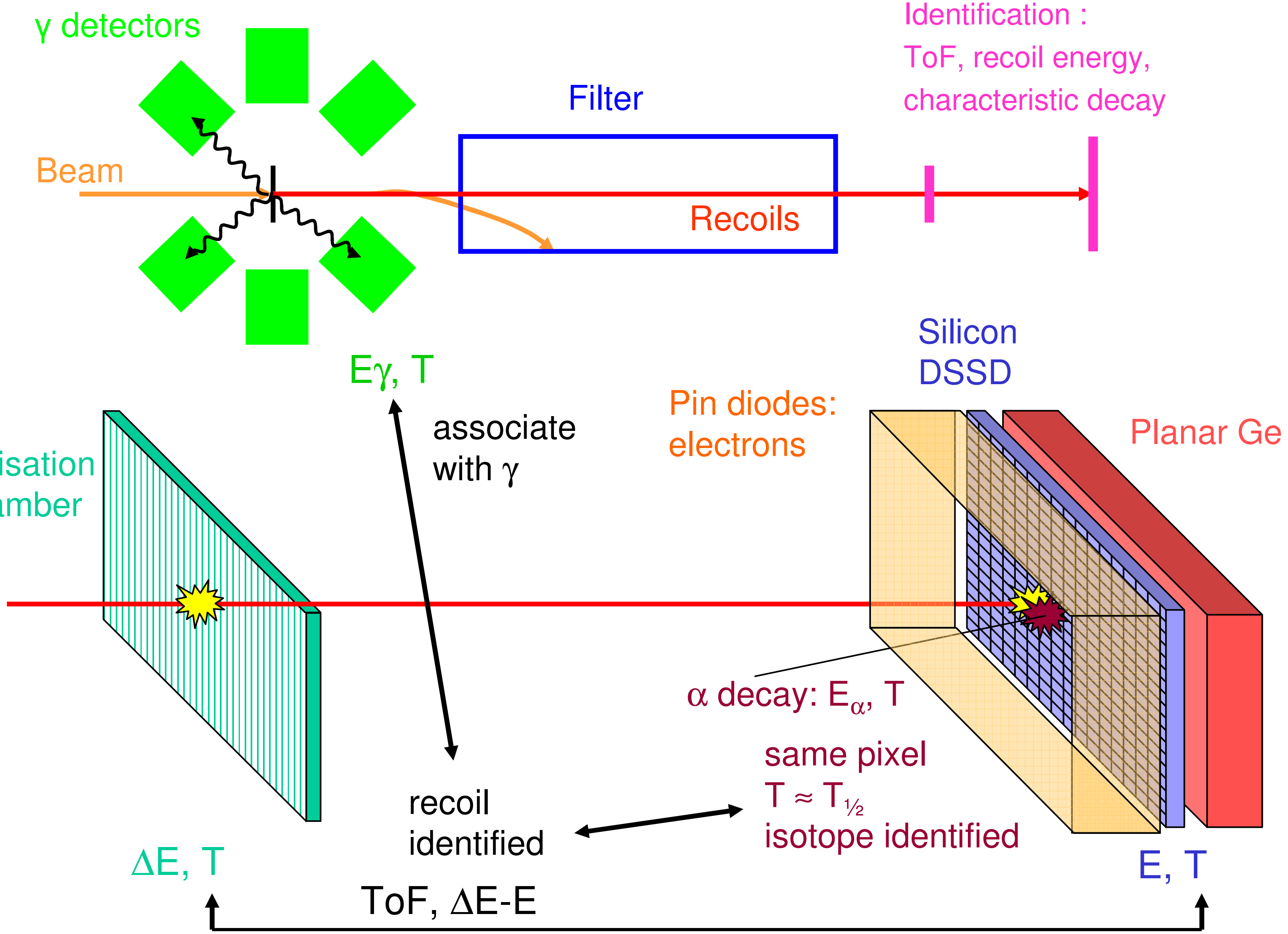



- $^{28}$Si($^{36}$Ar,$\alpha pn$)$^{58}$Cu
- gate on 1α + 1p +1n
- $\sigma_{rel}$ = 0.3 %
- Gammasphere, Microball, Neutron Shell

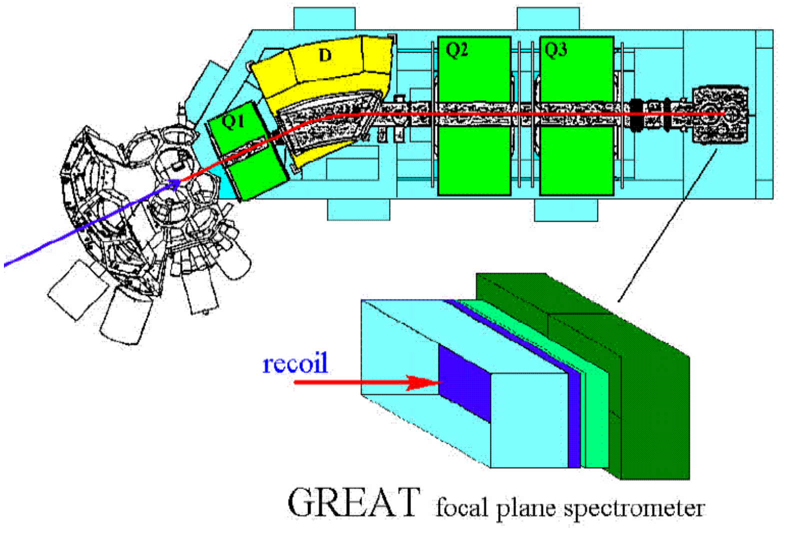



D. Rudolph et al., Phys. Rev. Lett. 80, 3018 (1998)
Eur. Phys. J. A 14, 137 (2002)

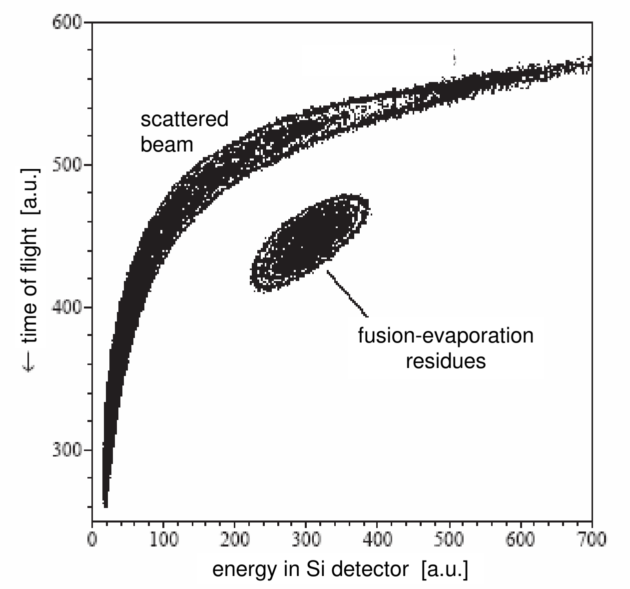
# Recoil decay tagging

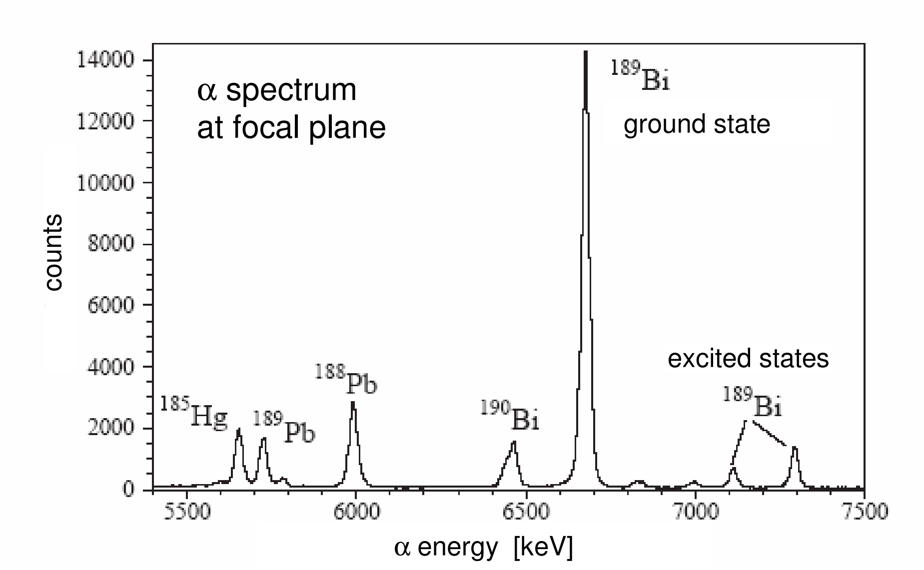


# JUROGAM – RITU – GREAT at Jyväskylä

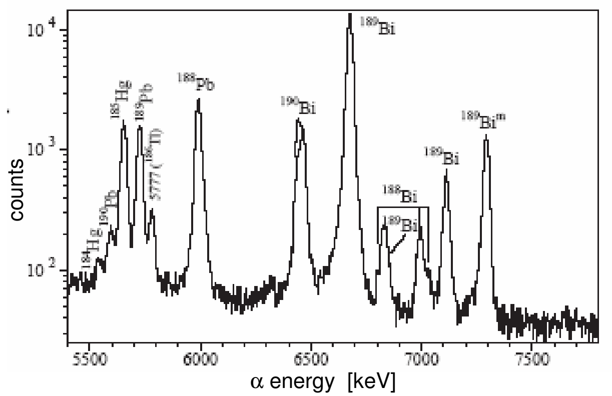


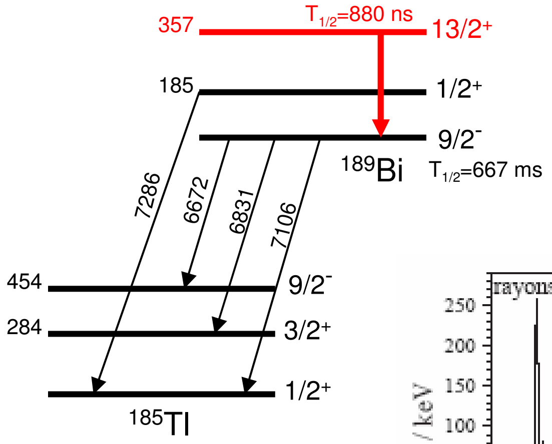

$^{109}Ag(^{83}Kr,3n)^{189}Bi$ ; 12μb

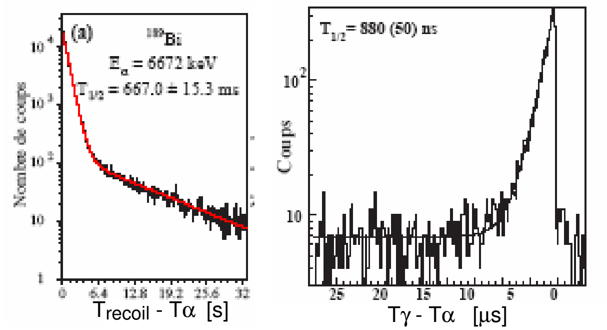


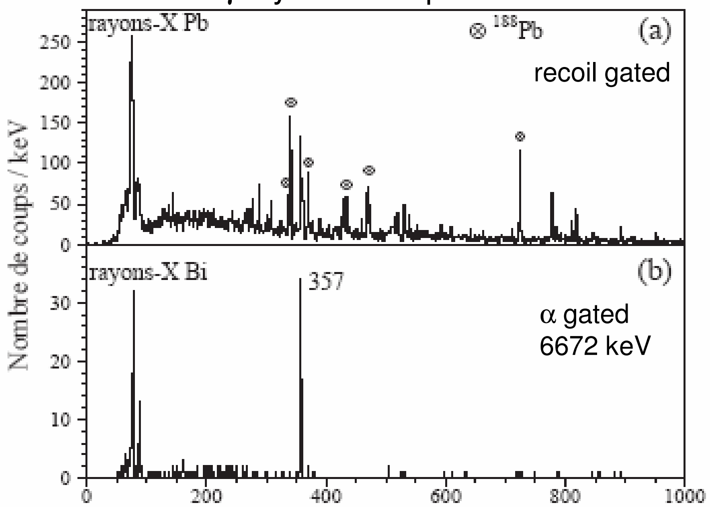
# Recoil-decay tagging: $^{189}$Bi spectra



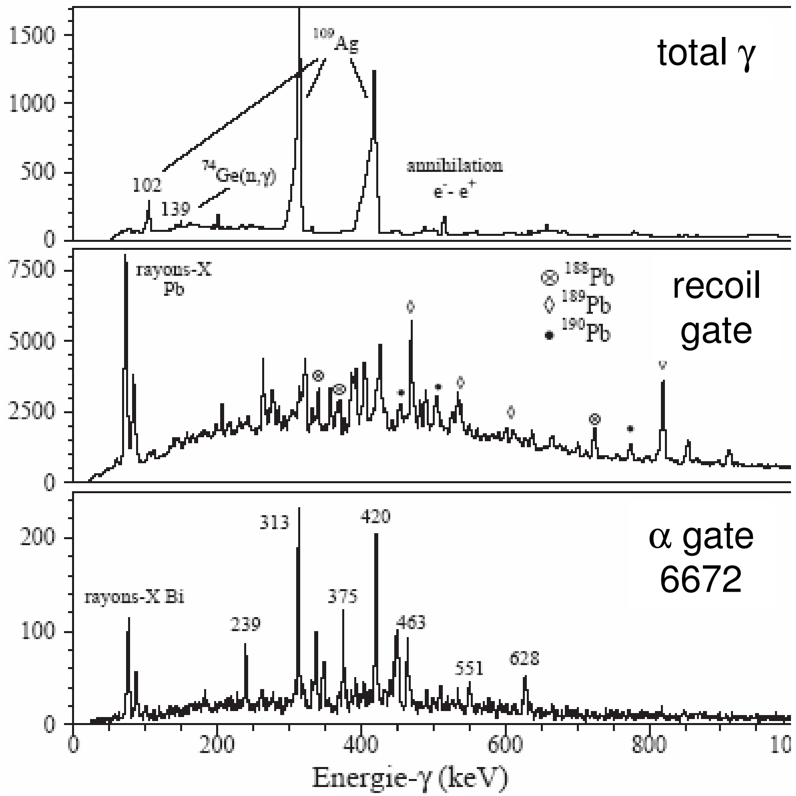




γ rays at focal plane



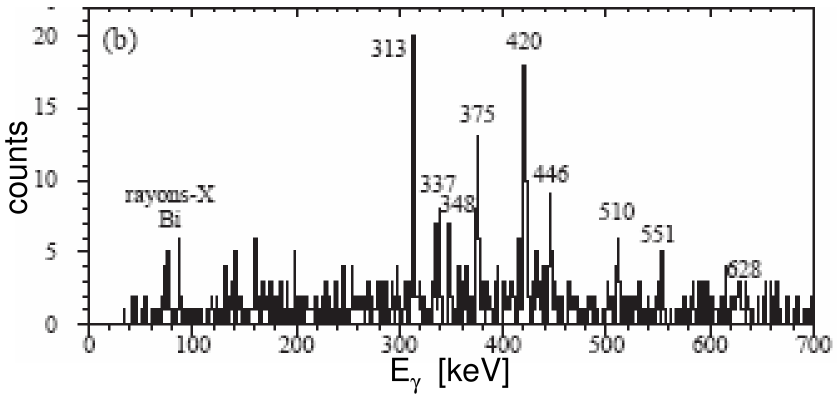

prompt γ rays at target



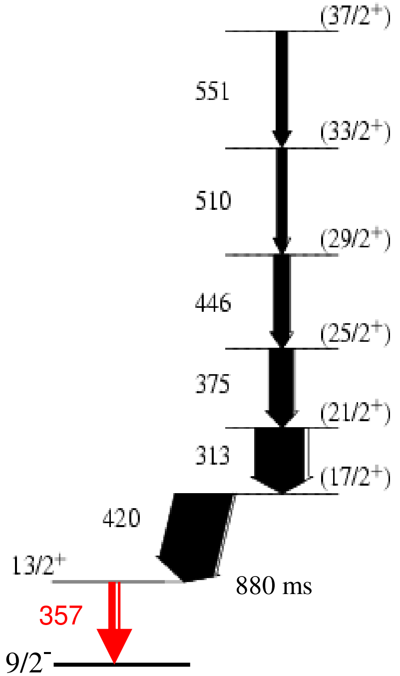

α and γ tagging:

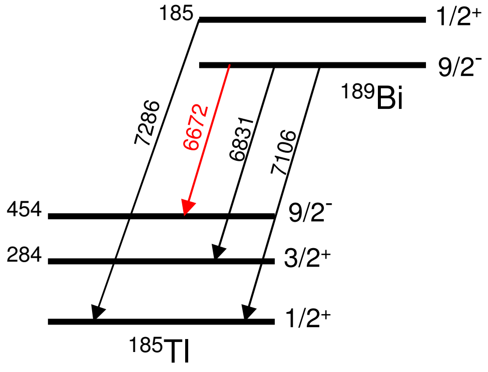
α gate: 6672 keV; γ gate: 357 keV

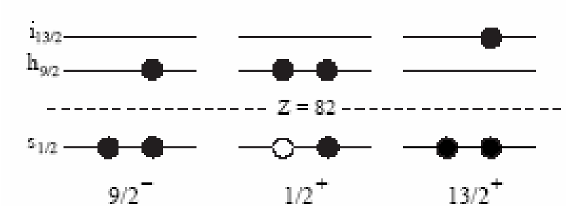
A. Hürstel et al.,
Eur. Phys. J. A 15, 329 (2002)



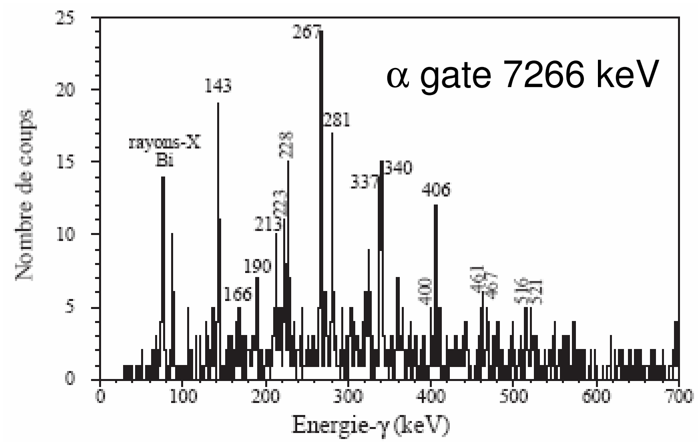
# $^{189}$Bi level schemes

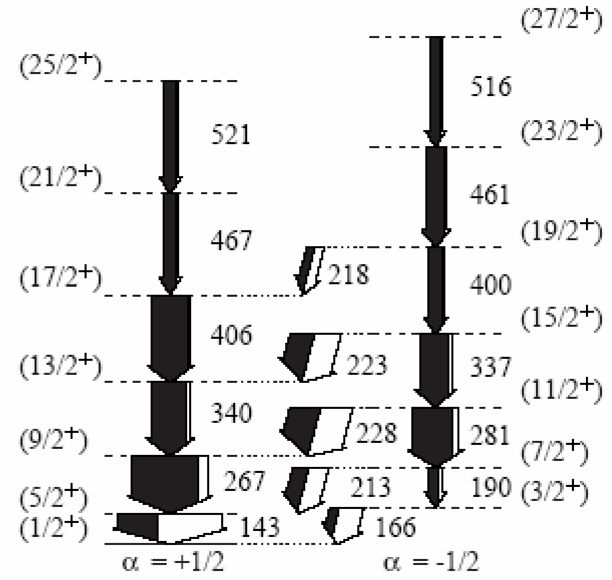


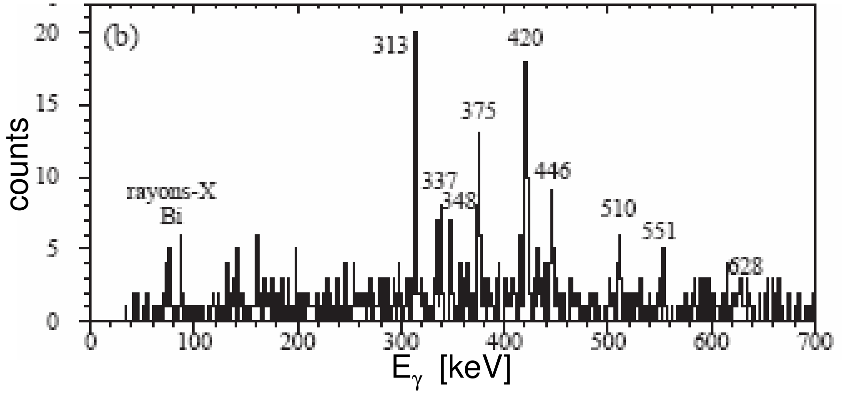




A. Hürstel et al.,
Eur. Phys. J. A 21, 365 (2004)



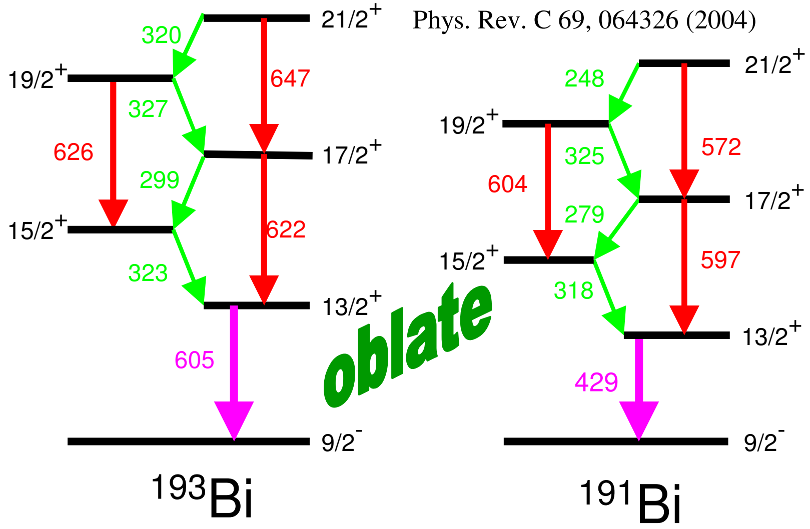

α and γ tagging:
α gate: 6672 keV; γ gate: 357 keV



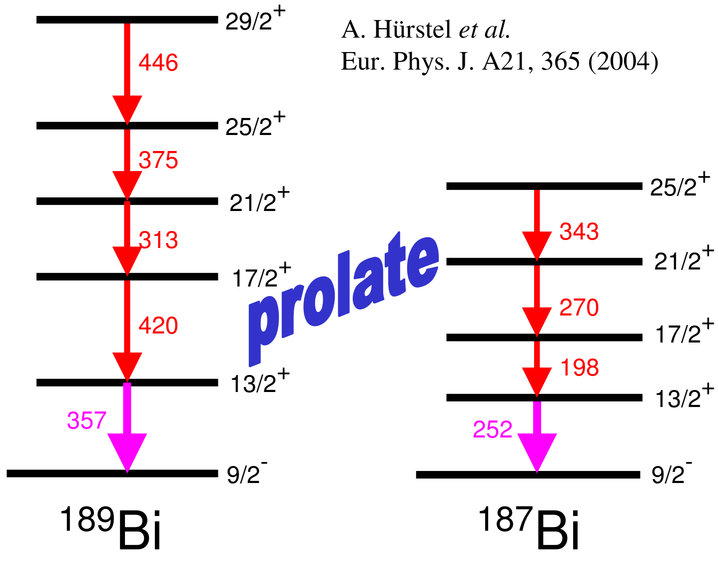
# Systematics of the neutron-deficient Bi isotopes

M1
E2
M2

P. Nieminen *et al*
Phys. Rev. C 69, 064326 (2004)

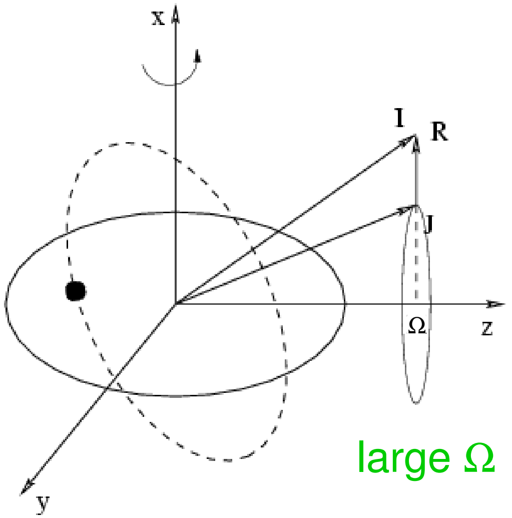



A. Hürstel *et al.*
Eur. Phys. J. A21, 365 (2004)

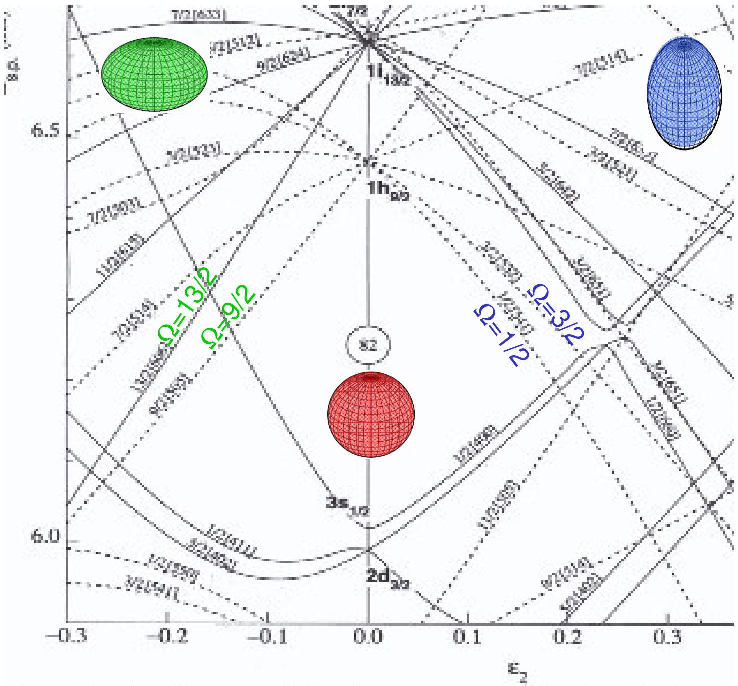


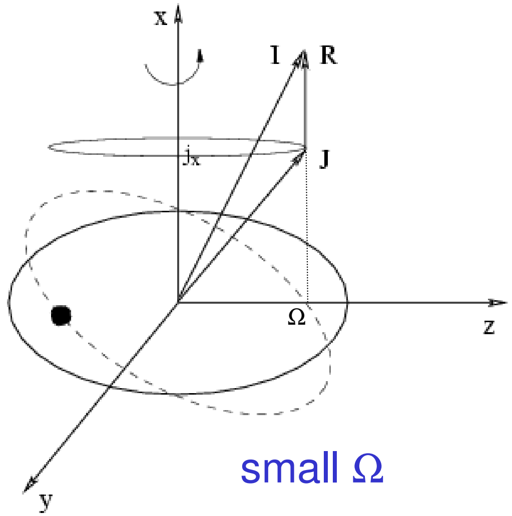

strongly coupled bands
➔ deformation aligned

decoupled bands
➔ rotation aligned




large Ω




small Ω