Gamma-ray spectroscopy I

Andreas Görgen
DAPNIA/SPhN, CEA Saclay
F-91191 Gif-sur-Yvette
France
agoergen@cea.fr

Lectures presented at the
IoP Nuclear Physics Summer School
September 4 – 17, 2005
Chester, UK

Outline

First lecture
- Properties of γ-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

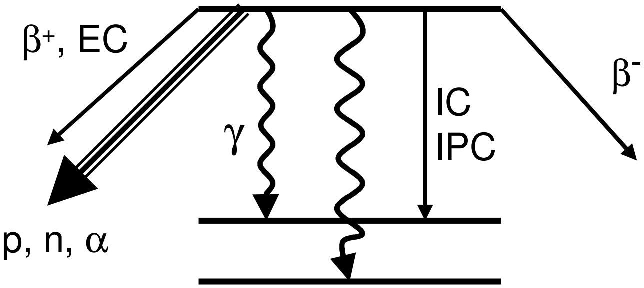
Second lecture
- Angular distribution
- Linear polarization
- Jacobi shape transition
- Charged-particle detectors
- Neutron detectors
- Prompt proton decay
- Recoil-decay tagging
- Rotation and deformation alignment

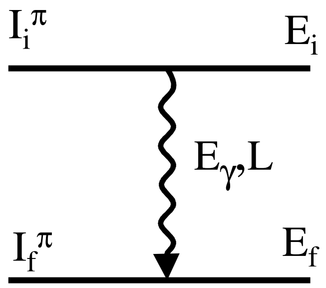
Third lecture
- Spectroscopy of transfermium nuclei
- Conversion-electron spectroscopy
- Quadrupole moments and transition rates
- Recoil-distance method
- Doppler shift attenuation method
- Fractional Doppler shift method
- Magnetic moments
- Perturbed angular distribution
- Magnetic Rotation
- Shears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

Gamma-ray transitions

- decay of excited states
- bound states (below nucleon separation energy or fission barrier)
- decay within the same nucleus





$$E_\gamma = E_i - E_f$$

$$|I_i - I_f| \le L \le I_i + I_f$$

$$\Delta\pi(EL) = (-1)^L$$

$$\Delta\pi(ML) = (-1)^{L+1}$$

What we can learn

- energy
- spin (angular distribution)
- parity (linear polarization)
- lifetime (Doppler-shift methods)
- quadrupole moment (Coulomb excitation)
- magnetic moment (perturbed angular correlation)

multipolarity of γ transitions

ΔI		0*	1	2	3
Δπ	yes	E1 (M2)	E1 (M2)	M2 E3	E3 (M4)
	no	M1 E2	M1 E2	E2 (M3)	M3 E4

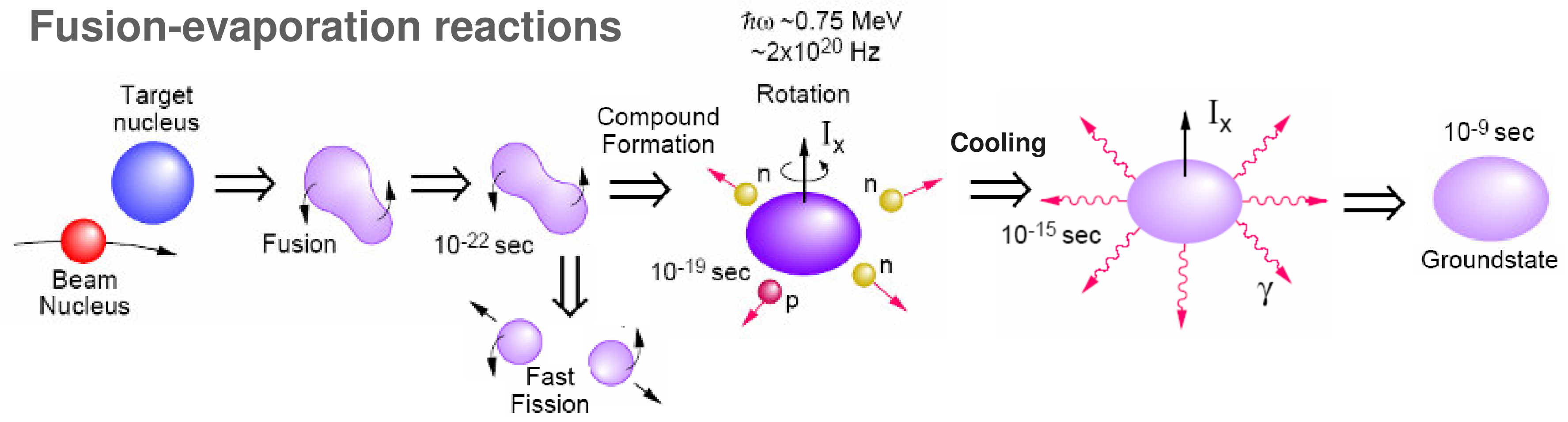
*no 0→0

Reactions

First we have to populate excited states in the nucleus that we want to study:

- radioactive sources
  - produced in reactor or with accelerator
  - populates excited states after α or β decay or fission
- Coulomb excitation
  - electromagnetic excitation of projectile and/or target in collision
  - stable or instable (radioactive beams) nuclei
- fusion-evaporation reactions
  - neutron-deficient nuclei
  - population of high-spin states
- fusion-fission reactions
  - neutron-rich nuclei
- direct reactions
  - nucleon removal or pick-up: (d,p), (p,d), (n,γ), etc.
  - resonances, spectroscopic factors
- deep-inelastic reactions / multi-nucleon transfer
  - moderately exotic nuclei
  - neutron-rich nuclei that are not accessible in fusion-evaporation
- fragmentation
  - exotic nuclei far from stability
  - production of radioactive beams

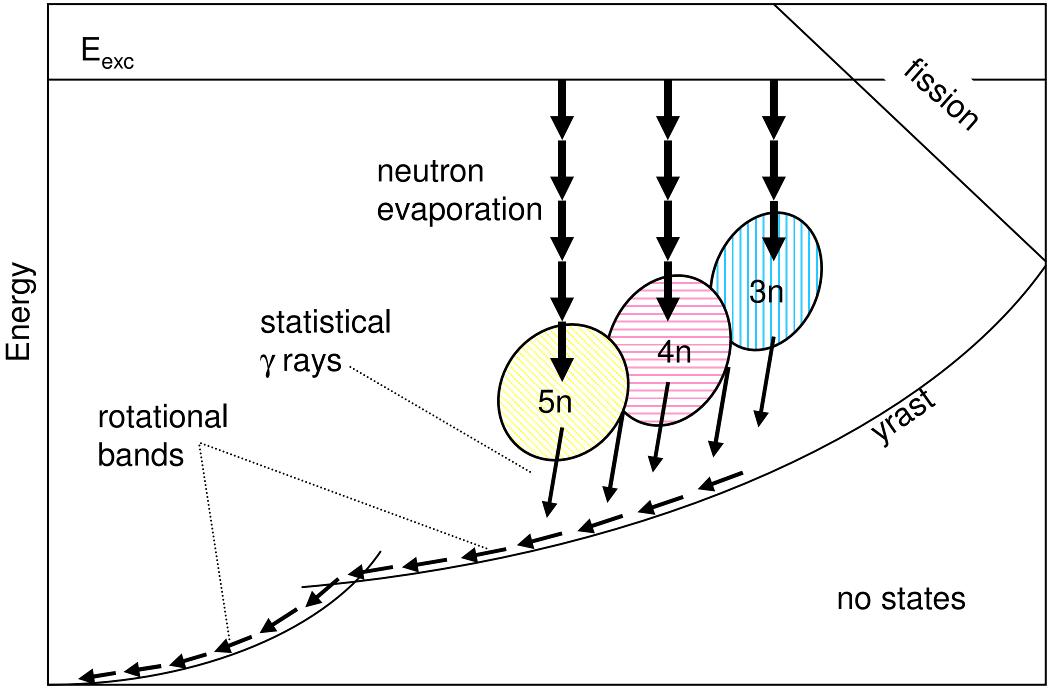
Fusion-evaporation reactions



- large cross sections (~1 barn)
- produces proton-rich nuclei (no Coulomb barrier for neutrons)
- large angular momentum transfer (many γ rays)

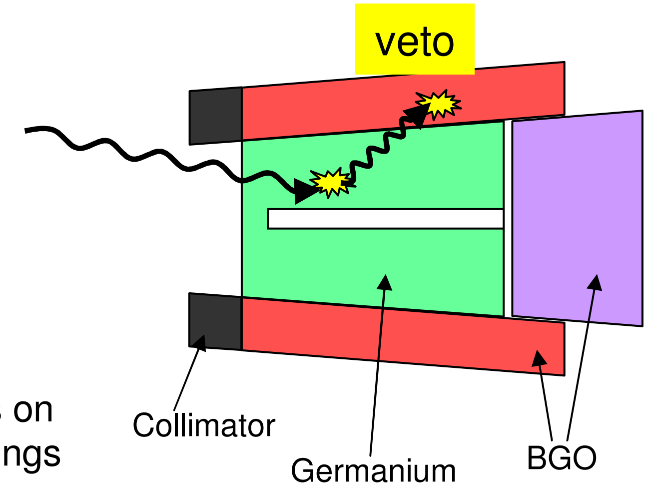
gamma-ray spectrometer with

- high resolution
- large efficiency
- high granularity
- good peak-to-total

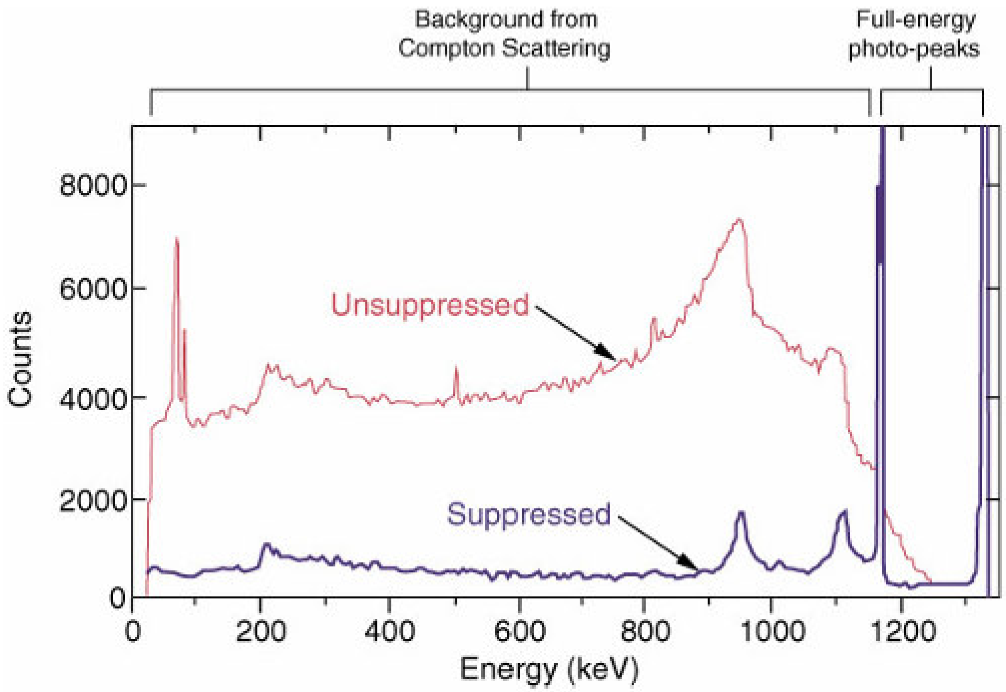


Compton suppressed Germanium detectors

Interaction in Ge crystal
- photo absorption (low energy)
- Compton scattering (intermediate energy)
- pair creation (high energy)

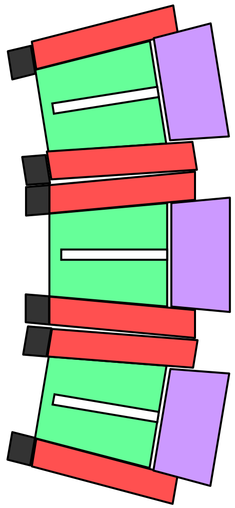


A γ ray of 1 MeV undergoes on average 3 Compton scatterings before photo absorption

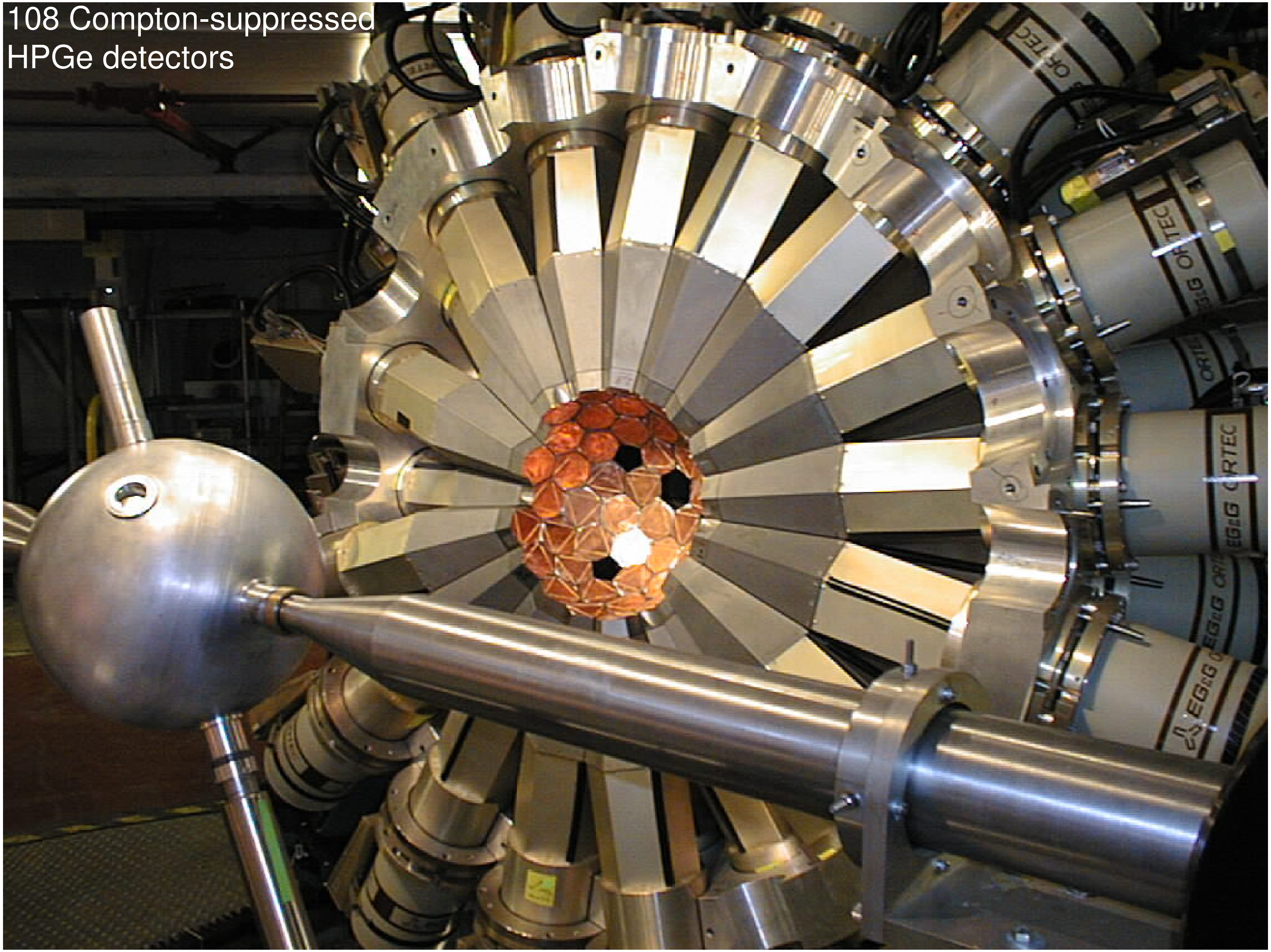


peak-to-total ratio
- unsuppressed P/T ~ 0.15
- suppressed P/T ~ 0.6

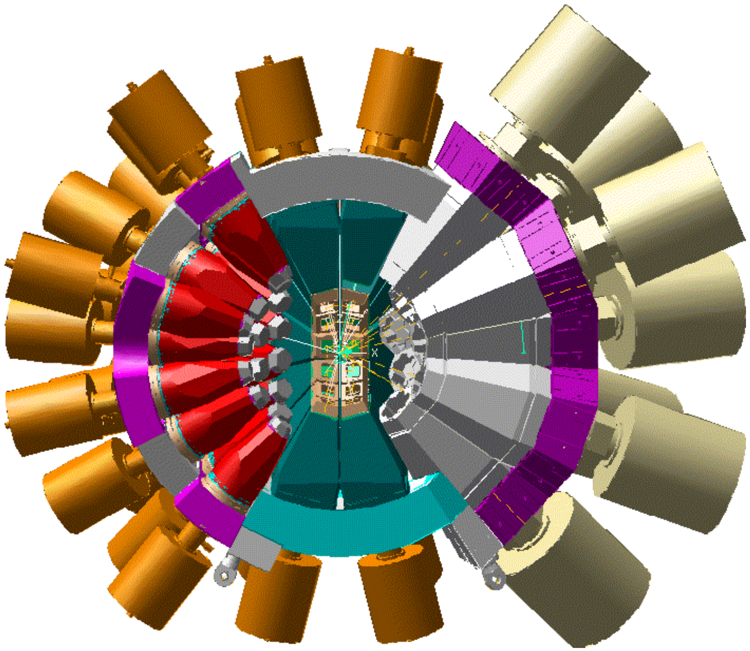
to increase efficiency: use many detectors



Gammasphere (Berkeley/Argonne)



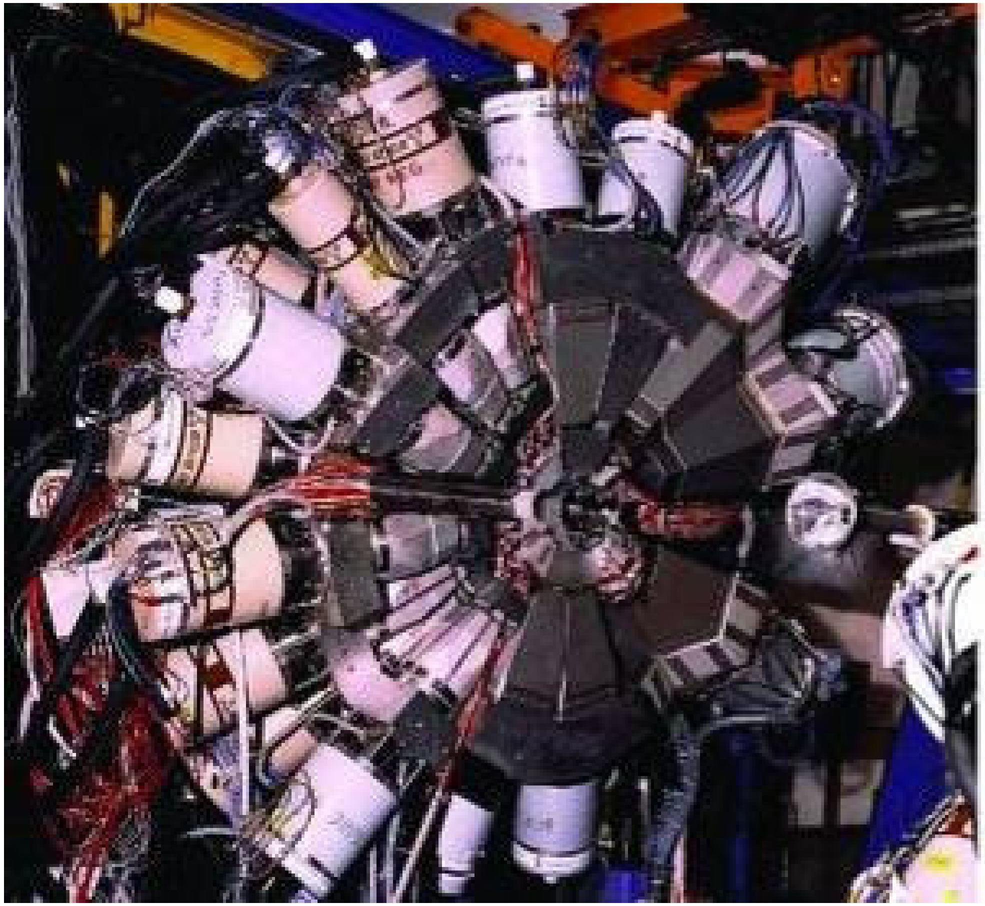
Euroball (Legnaro/Strasbourg)



15 seven-fold
Cluster detectors

30 coaxial
detectors

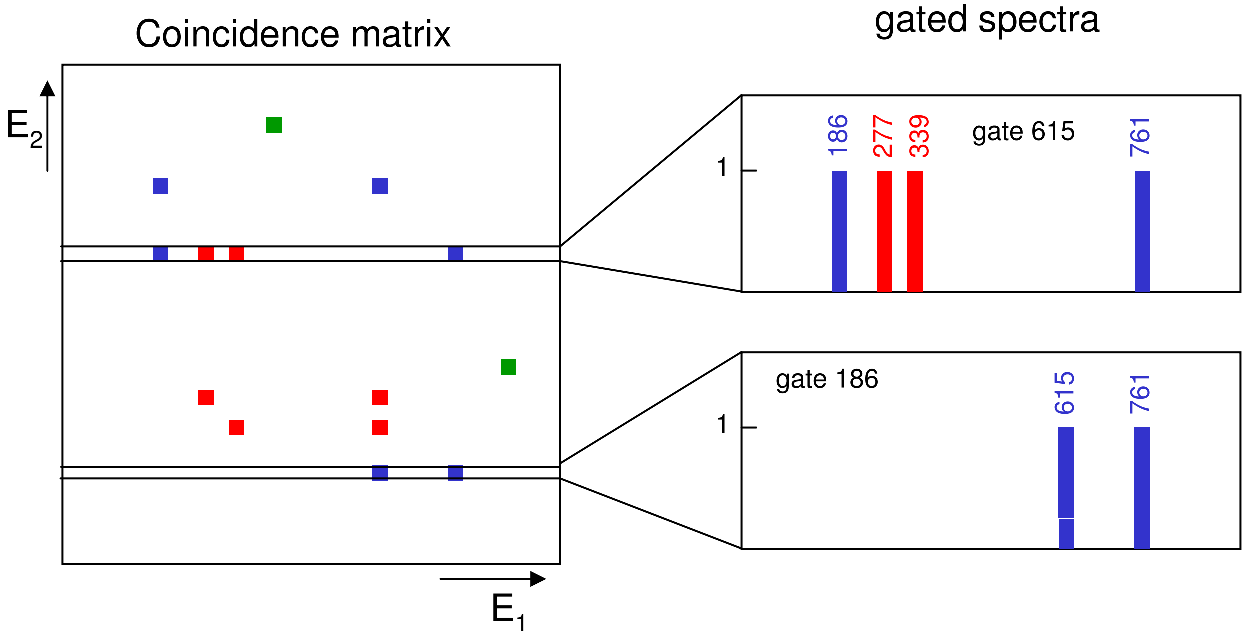
26 four-fold
Clover detectors

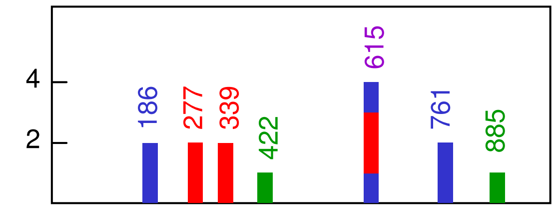


Coincidence technique

```
Event 20583
Det 37   E 422
Det 61   E 885
Event 20584
Det 04   E 277
Det 24   E 615
Det 46   E 339
Event 20585
Det 17   E 761
Det 20   E 186
Det 59   E 615

Event 20586
Det 08   E 615
Det 14   E 120
Det 27   E 802
Det 38   E 571
Det 40   E 222
Det 46   E 419
Det 51   E 350
Det 56   E 588
```

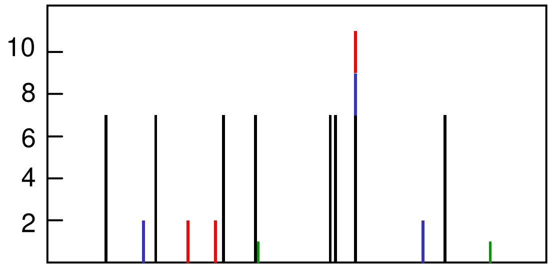


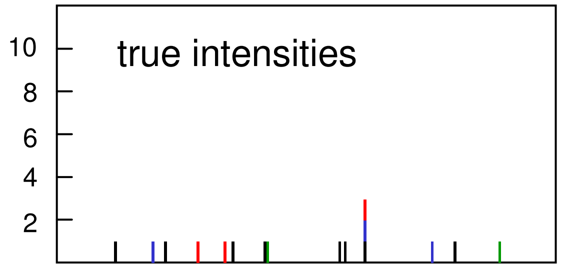


total projection

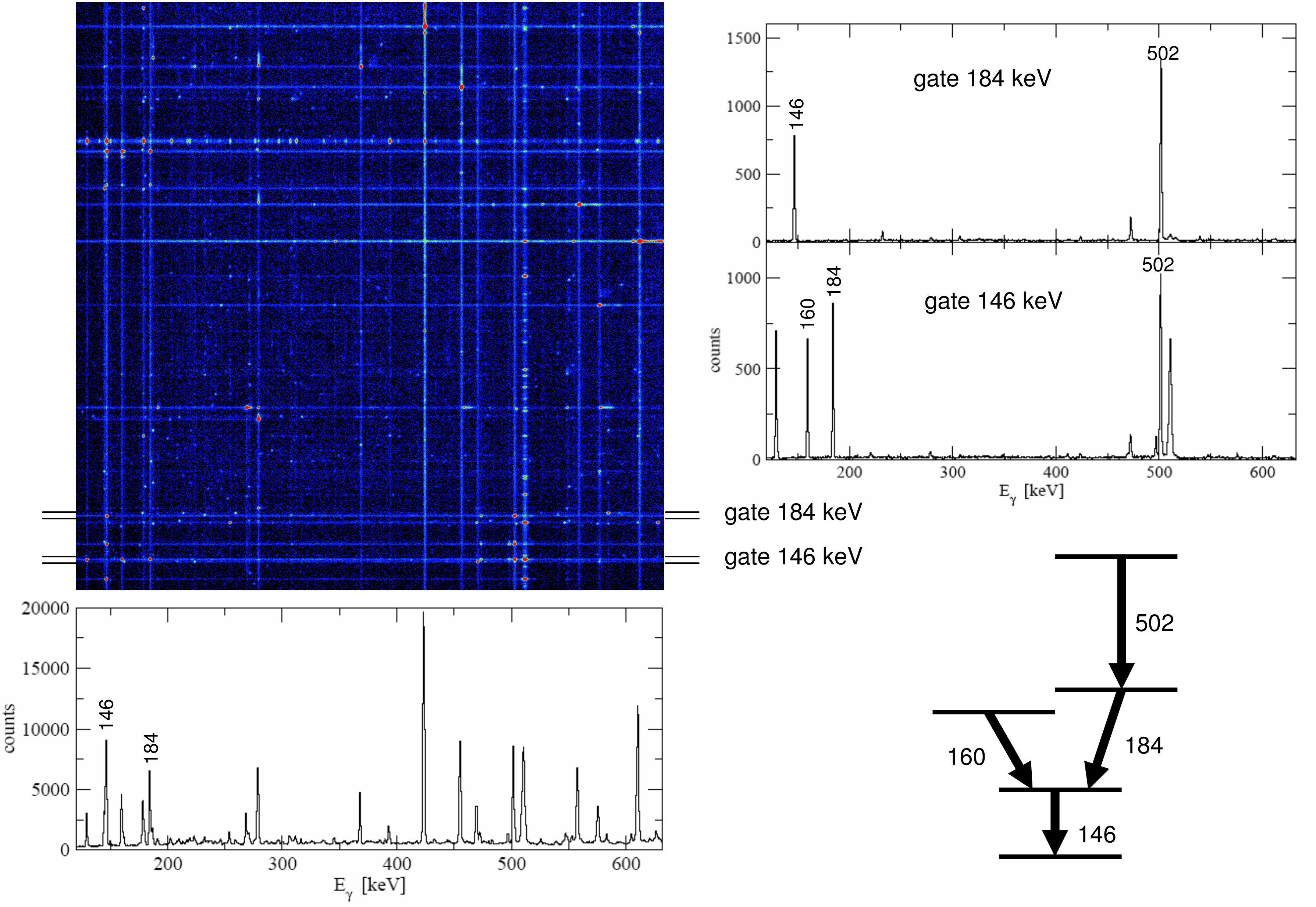
Attention: when n-tuples are broken up and sorted into structures with lower dimension, intensities become incorrect and artefacts may appear!

High-multiplicity events should be analyzed in their native fold.

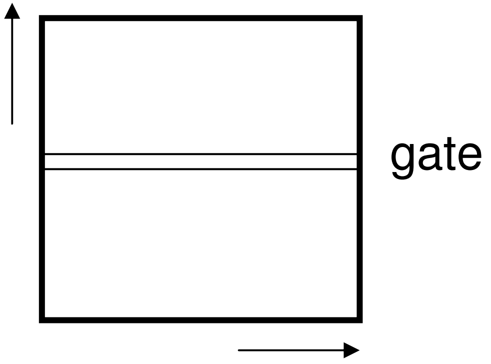


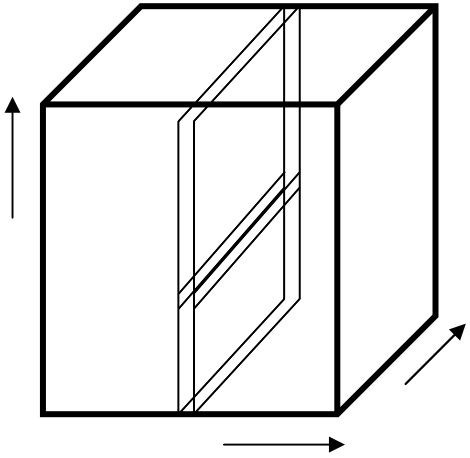


Coincidence technique



Coincidence technique





2D: matrix
gate ⇒ spectrum

3D: cube
1st gate ⇒ matrix
2nd gate ⇒ spectrum

4D: hypercube
1st gate ⇒ cube
2nd gate ⇒ matrix
3rd gate ⇒ spectrum

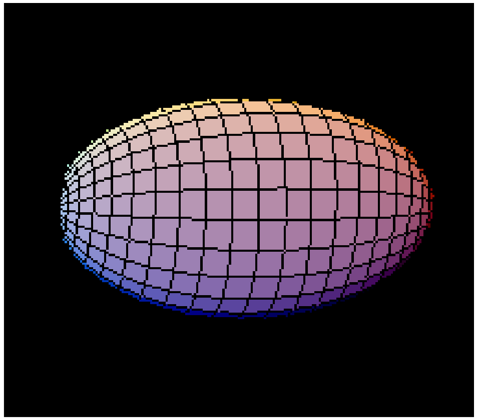
RADWARE
http://radware.phy.ornl.gov

For high-fold data with F>4:
Indexed, energy-ordered data base BLUE
M. Cromaz et al., Nucl. Instr. Meth. A 462, 519 (2001)

general purpose: ROOT
http://root.cern.ch

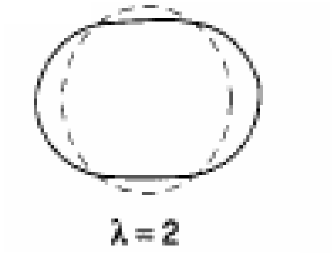
Nuclear deformation

Deformation can be dynamic
e.g. Y_{32} vibration



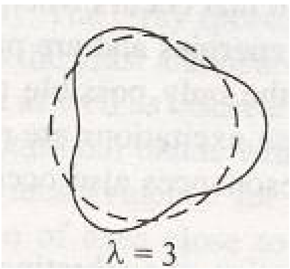
$$R(t) = R_0\left[1 + \sum_{\lambda}\sum_{\mu=-\lambda}^{+\lambda} a_{\lambda\mu}(t)\, Y_{\lambda\mu}(\vartheta,\varphi)\right]$$

quadrupole

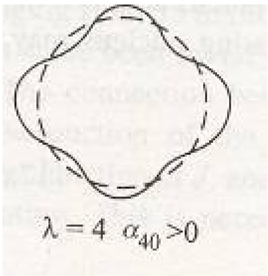


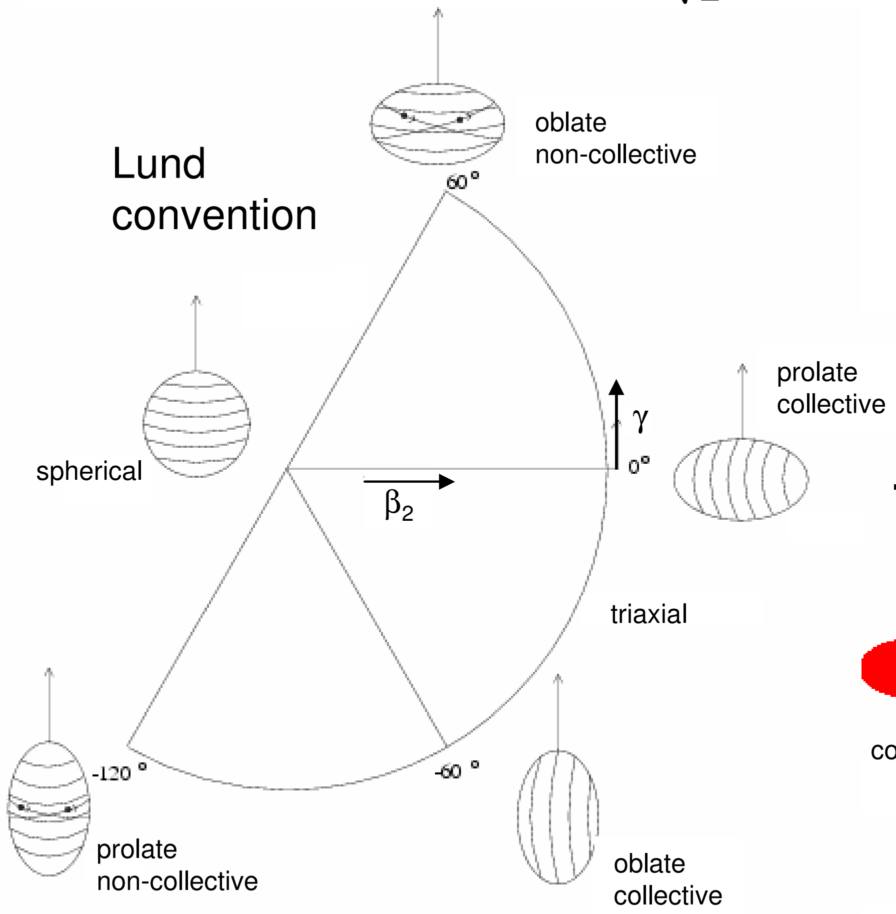
$$a_{20} = \beta\cos\gamma \qquad a_{22} = a_{2\,-2} = \frac{1}{\sqrt{2}}\beta\sin\gamma$$

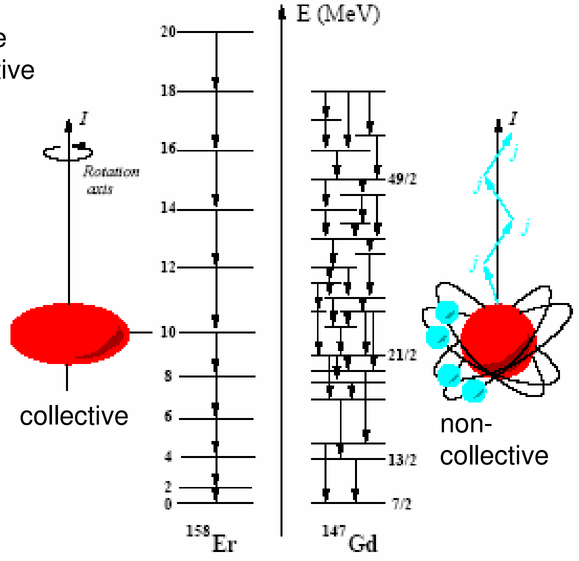
octupole



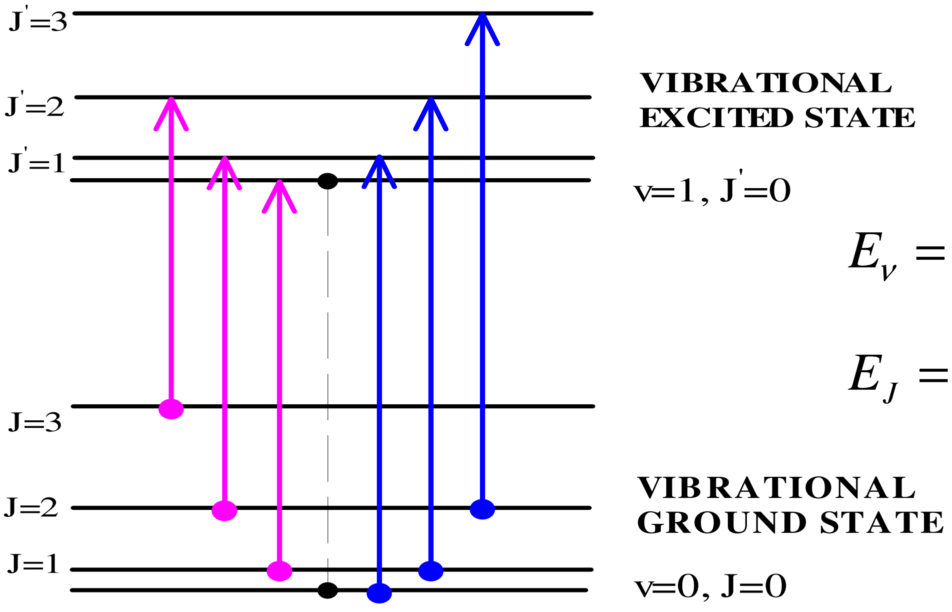
hexadecapole





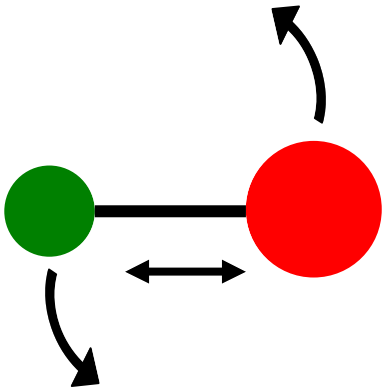


Infrared spectroscopy of a HCl molecule

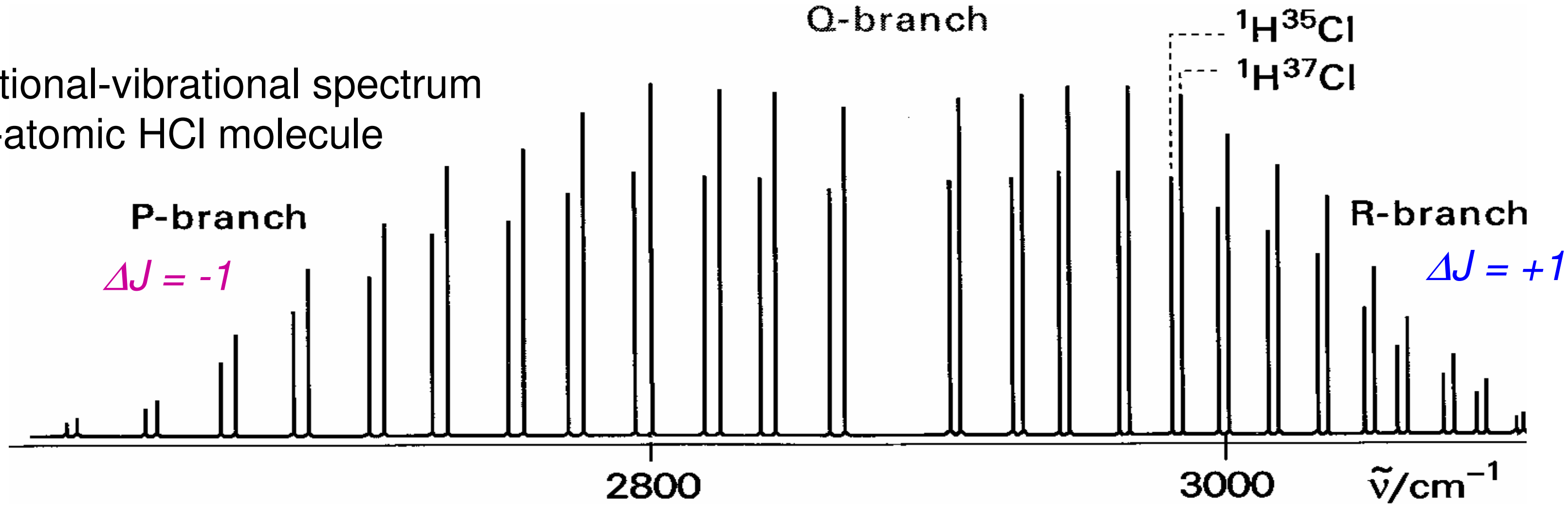


$$E_v = \hbar\omega\,(v + 1/2)$$

$$E_J = \frac{\hbar^2}{2\mathscr{J}} J(J+1)$$



Rotational-vibrational spectrum
of di-atomic HCl molecule



Rotation of deformed nuclei

axial symmetry:
rotational axis ⊥ symmetry axis
for K≠1/2:

$$E(I) = \frac{\hbar^2}{2\mathcal{J}}\left[I(I+1) - K^2\right]$$

kinematic moment of inertia

$$\mathcal{J}^{(1)} = I\left(\frac{\partial E}{\partial I}\right)^{-1} = \frac{I}{\hbar\omega} \approx \frac{\Delta I \langle I \rangle}{E_\gamma}$$

dynamic moment of inertia

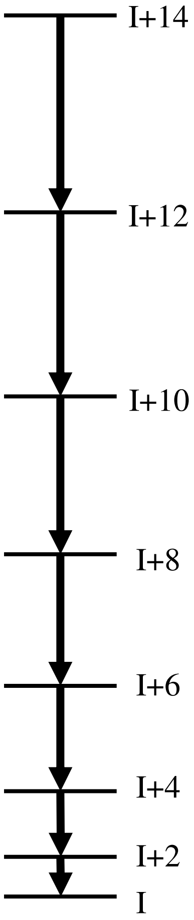
$$\mathcal{J}^{(2)} = \left(\frac{\partial^2 E}{\partial I^2}\right)^{-1} = \frac{\partial I}{\hbar \partial \omega} \approx \frac{(\Delta I)^2}{\Delta E_\gamma}$$

$$\mathcal{J}^{(2)} = \mathcal{J}^{(1)} + \omega \frac{\partial \mathcal{J}^{(1)}}{\partial \omega}$$

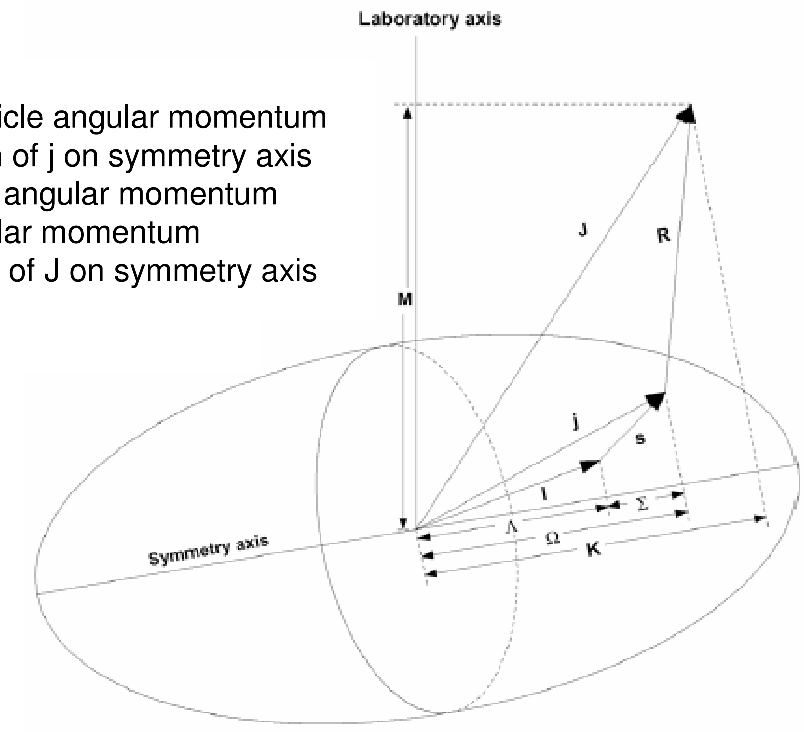
$\mathcal{J}^{(2)}$ measures the variation of $\mathcal{J}^{(1)}$
rigid rotor: $\mathcal{J}^{(2)} = \mathcal{J}^{(1)}$

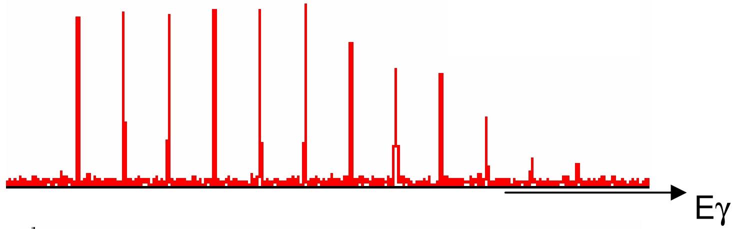
rotational frequency

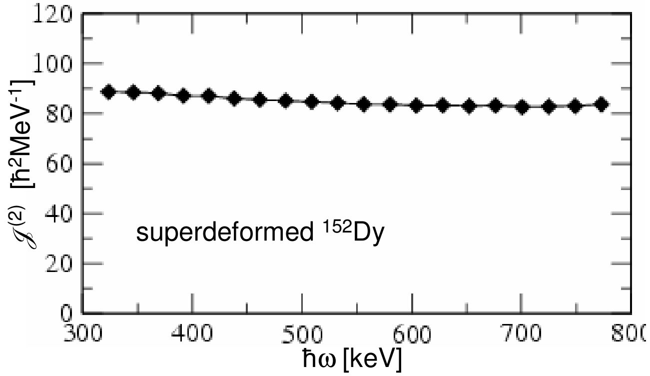
$$\hbar\omega = \frac{\partial E}{\partial I} \approx \frac{E_\gamma}{\Delta I}$$



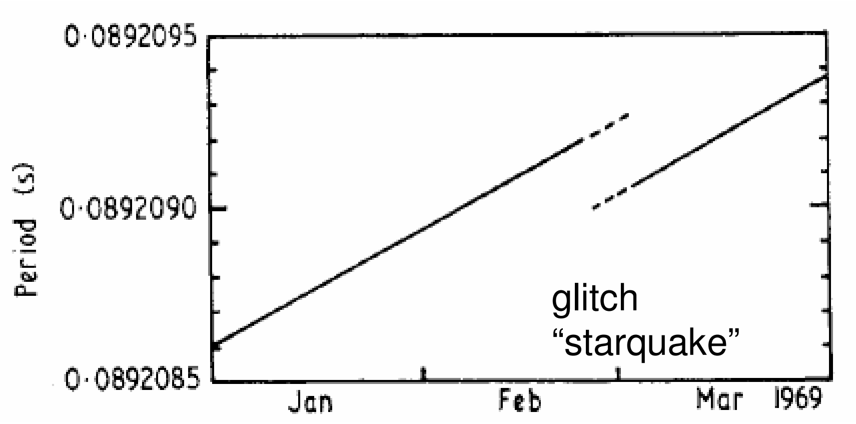
j single-particle angular momentum
Ω projection of j on symmetry axis
R collective angular momentum
J total angular momentum
K projection of J on symmetry axis

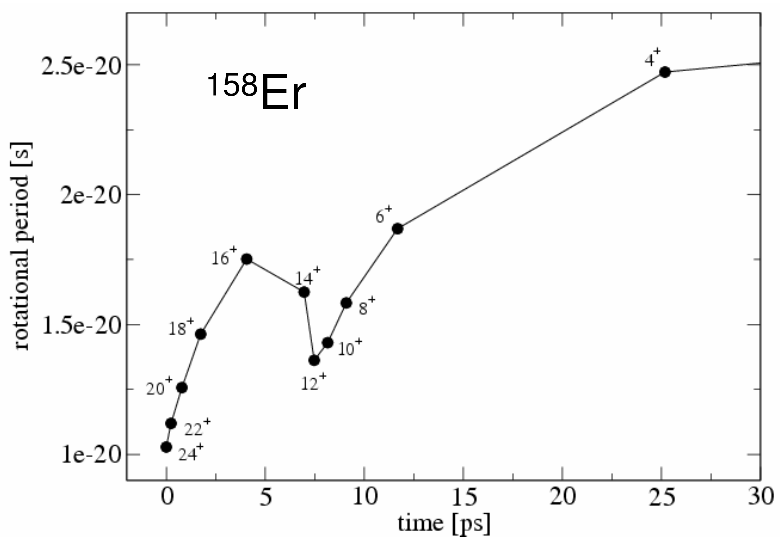


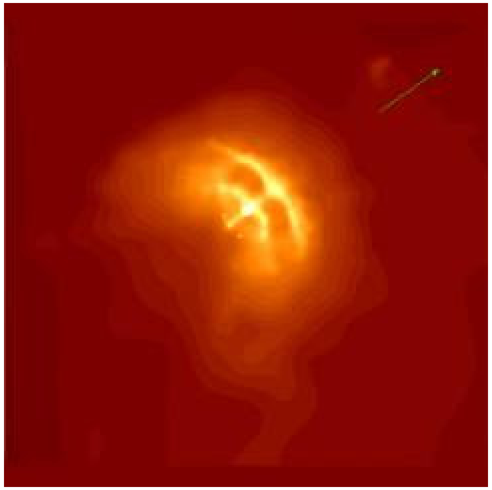




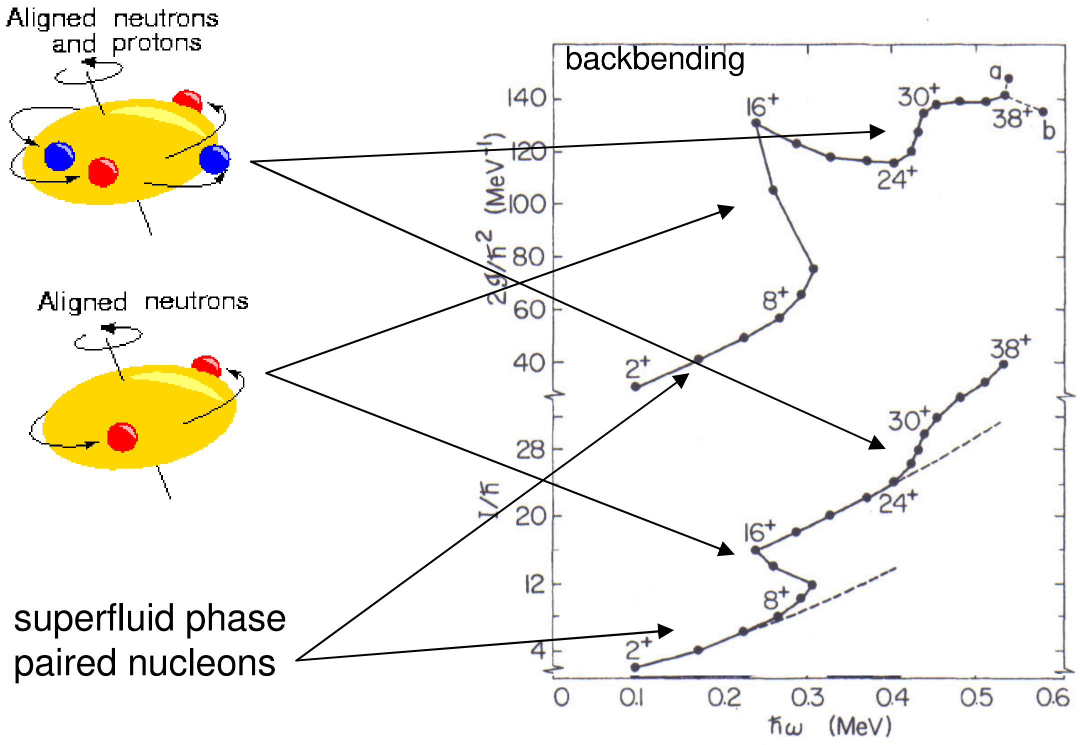
Pair alignment





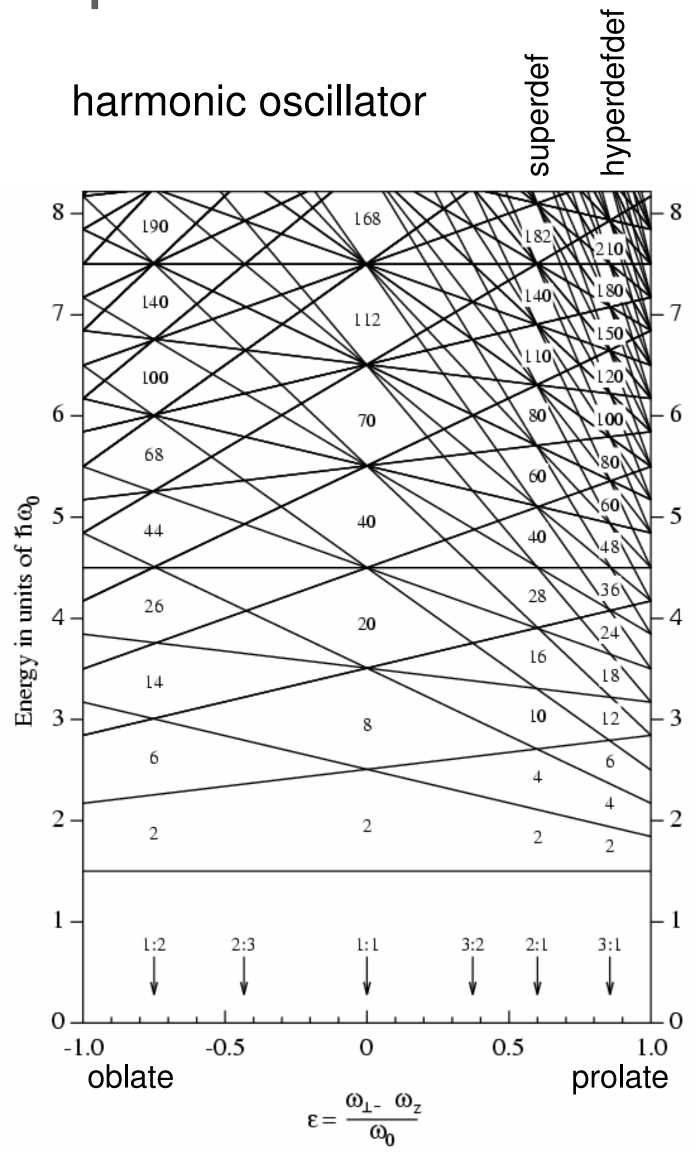


Vela pulsar
rotating neutron star
"light house" effect



Superdeformed nuclei

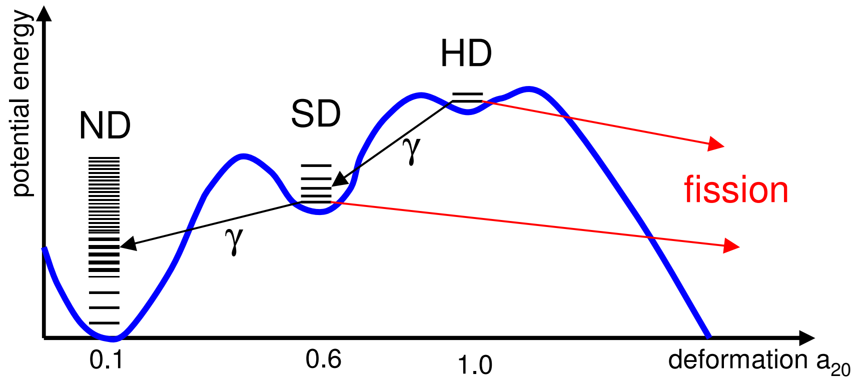
harmonic oscillator

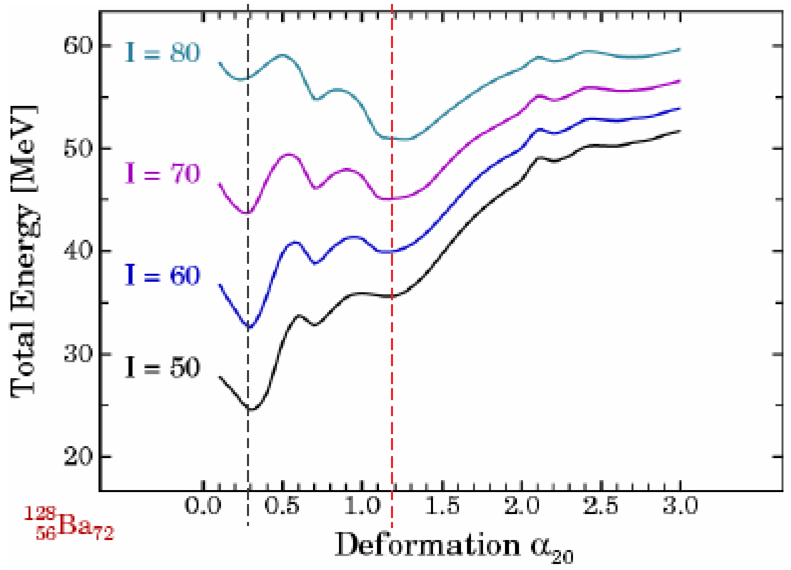


Regions of low level density (shell gaps) stabilize the nucleus at deformed shapes.

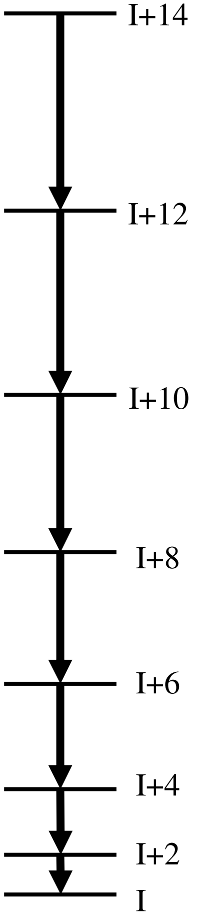
at high spin: interplay between

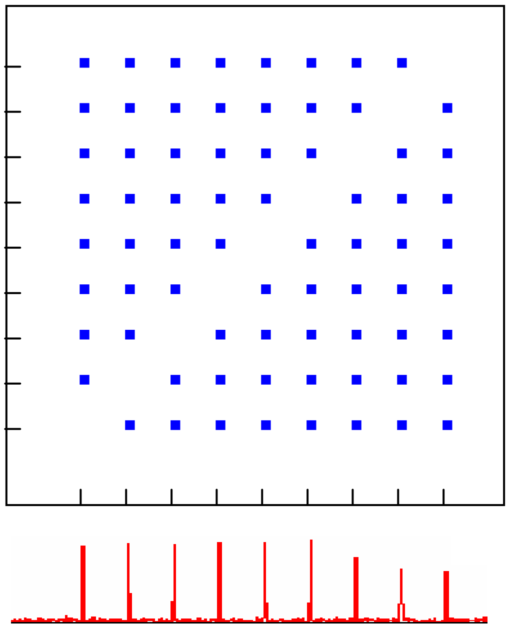
- macroscopic effects: liquid drop
- microscopic effects: shell structure.

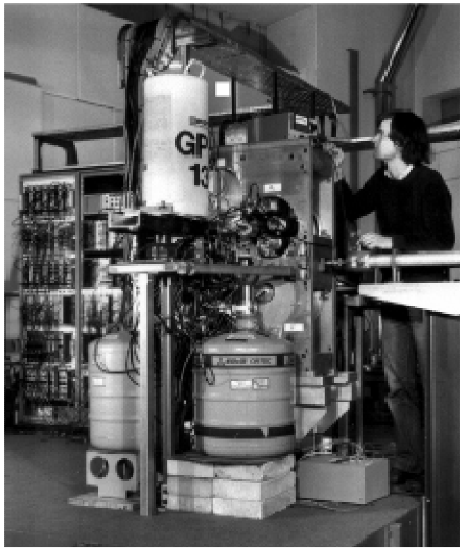




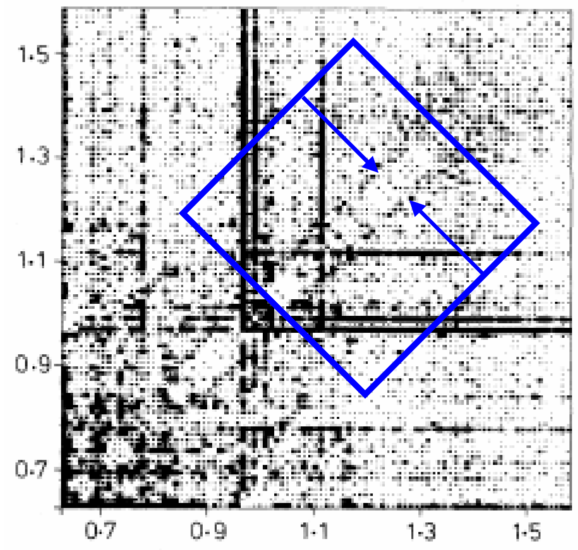
The quest for high-spin superdeformation: ^{152}Dy







TESSA2
6 Compton
suppressed
Ge detectors



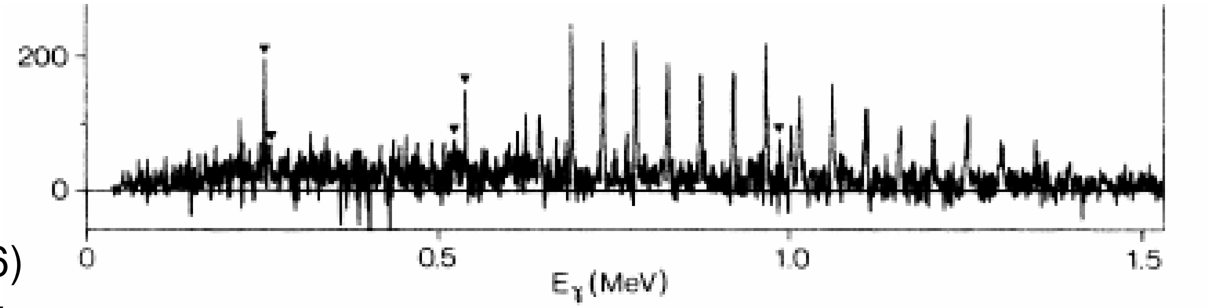
1983, Daresbury Lab
B. Nyakó et al.,
Phys. Rev. Lett. 52, 507 (1984)

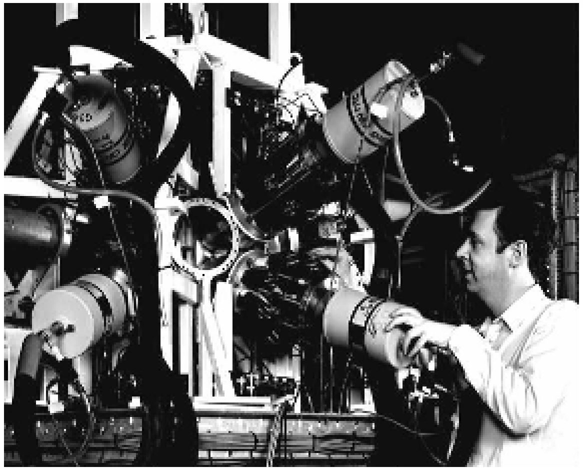
- ridge structure corresponding to energy spacing ΔE = 47 keV
- moment of inertia of the rotational band $\mathcal{J}^{(2)}$ = 85 $\hbar^2$MeV^{-1}
- deformation $\varepsilon > 0.5$

First indication of superdeformation

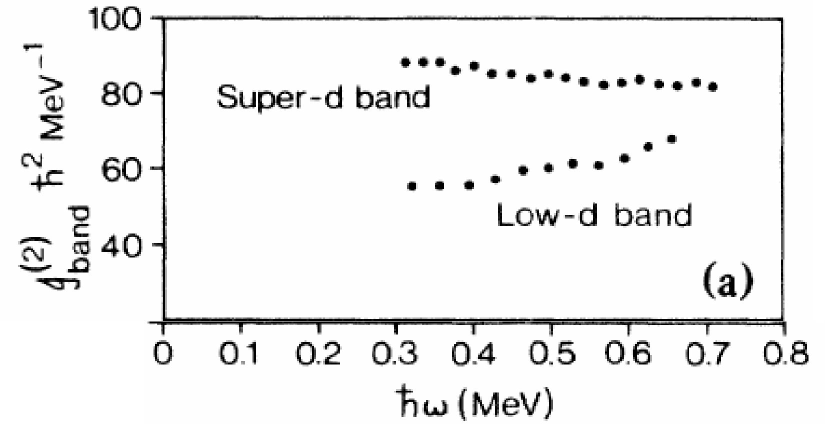
The quest for high-spin superdeformation: ^{152}Dy (2)

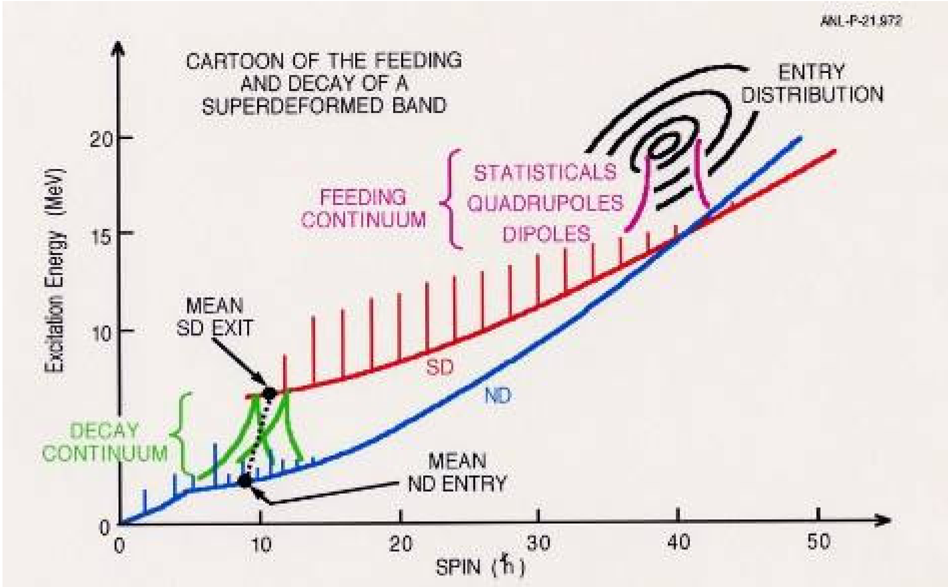
Two years later
Daresbury Lab.
TESSA3 (12 detectors)
P. Twin et al.
Phys. Rev. Lett. 57, 811 (1986)





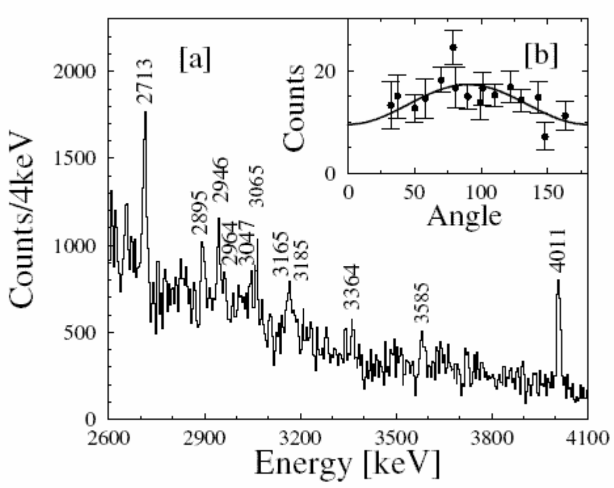
- first discrete superdeformed band
- energy spacing: ΔE = 47 keV

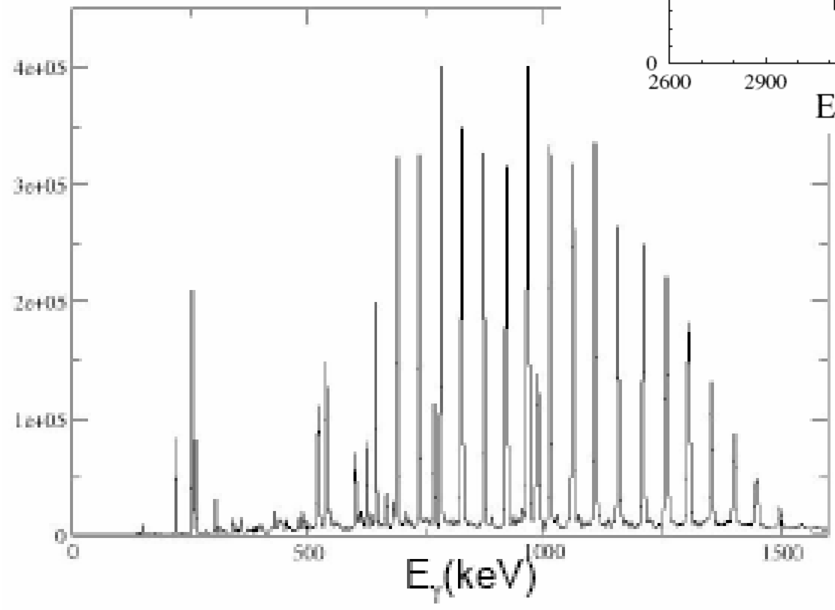


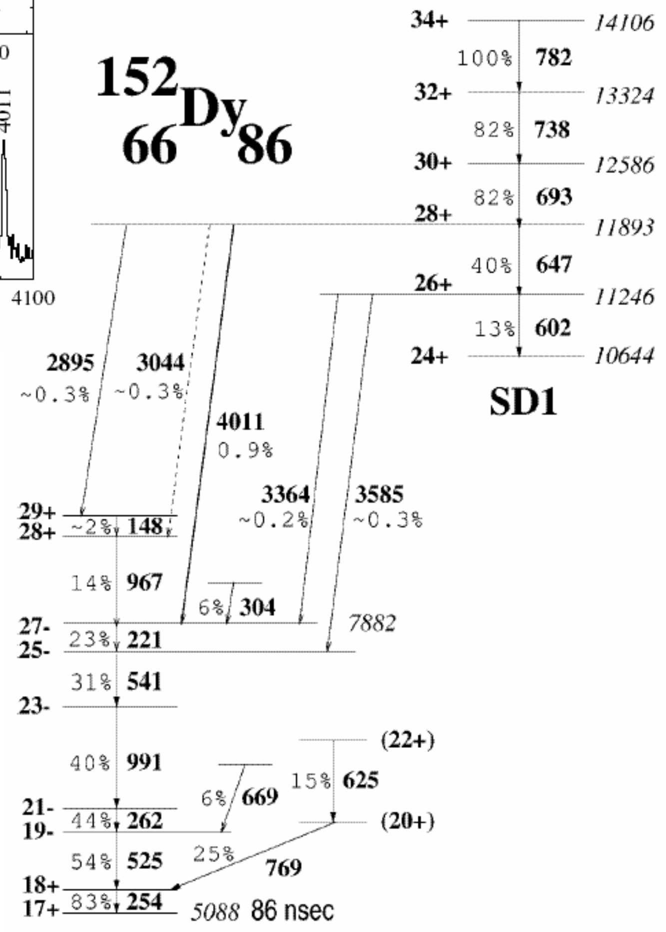


The quest for high-spin superdeformation: ^{152}Dy (3)

20 years later
Argonne National Lab.
Gammasphere
108 Ge detectors





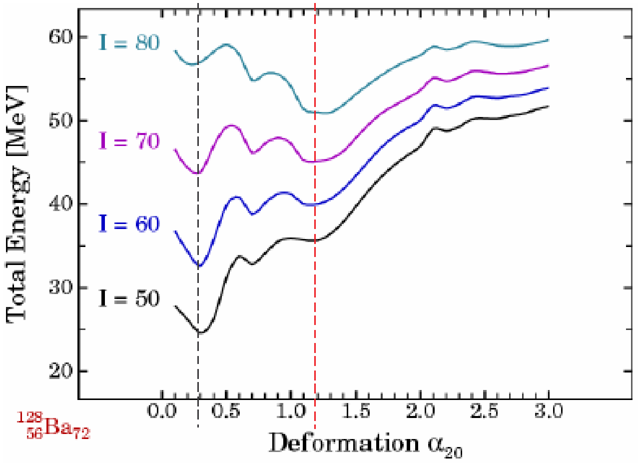


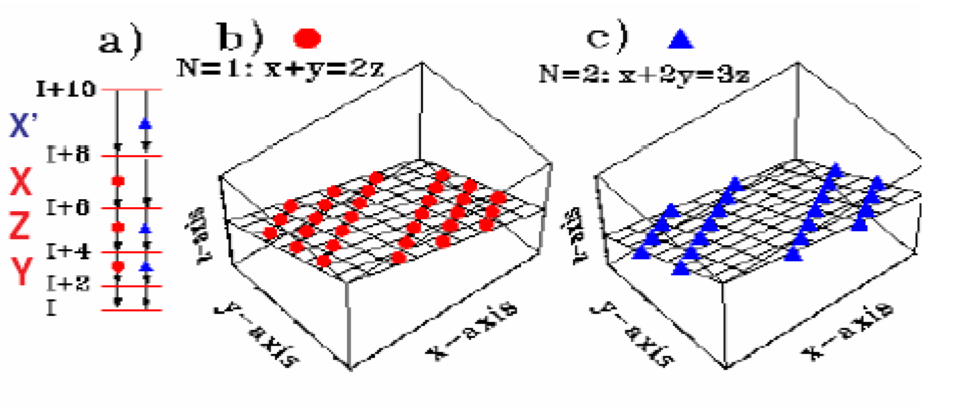
SD band linked
Spins and parity experimentally established.

T. Lauritsen et al.
Phys. Rev. Lett. 88, 042501 (2002)

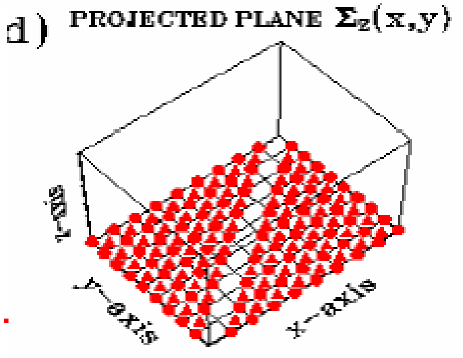
The quest for hyperdeformation

- $^{64}Ni+^{64}Ni$ @ 255, 261 MeV
- 4 weeks beam time (HLHD)
- Euroball IV, Strasbourg
- spins above 70 ħ populated



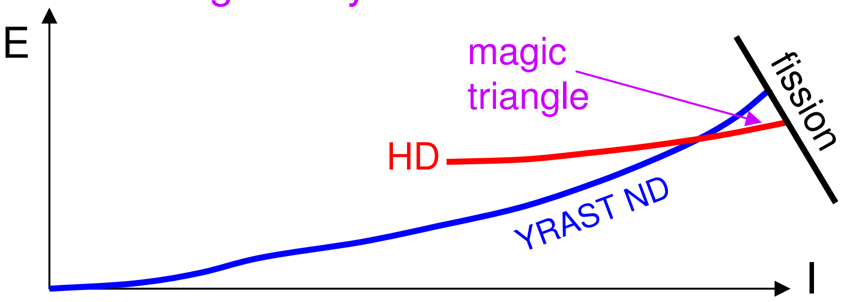


Rotational plane mapping enhances rotational structures

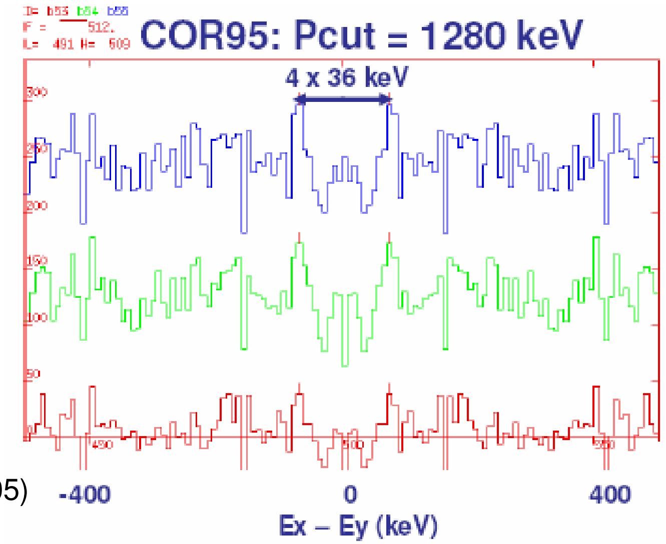


Ridges corresponding to $\mathscr{J}^{(2)}$ = 110 -120 ħ²MeV⁻¹ observed, but no discrete bands.

Some ridges only observed at 261 MeV

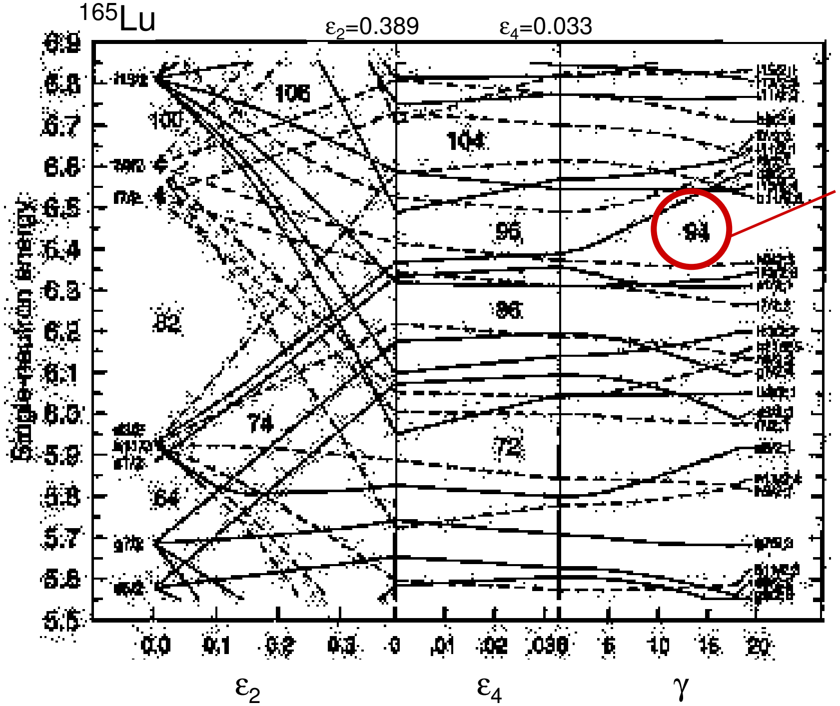


Both shell structure and liquid drop properties important.

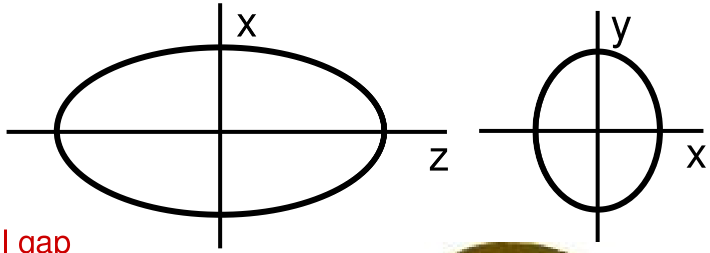


H. Hübel, Acta. Phys. Pol. B 36, 1015 (2005)

Triaxial superdeformation

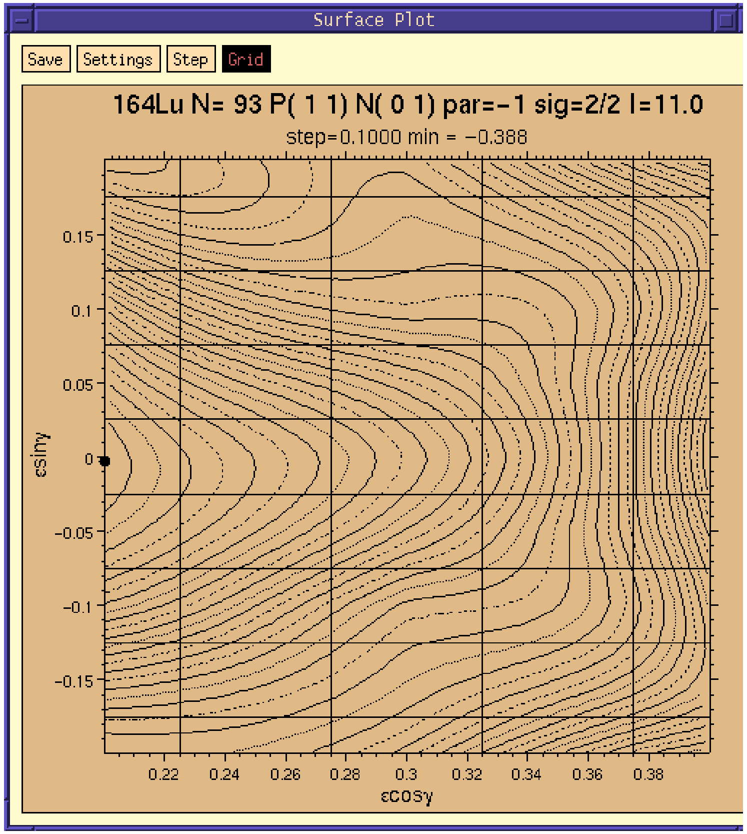


triaxial shell gap

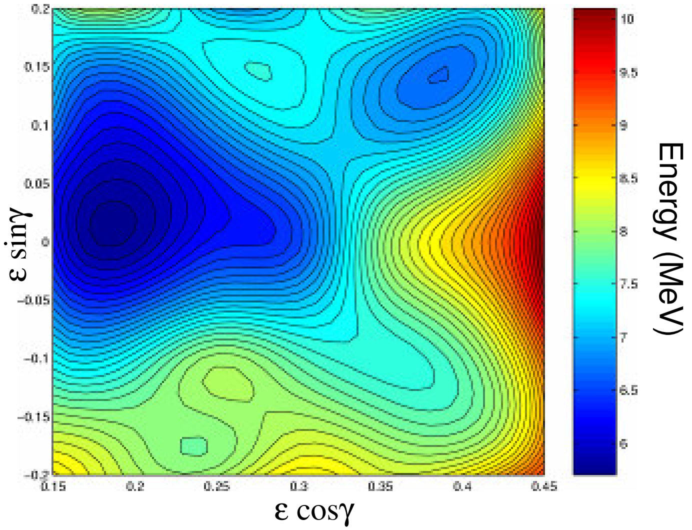


R. Bengtsson, H. Ryde
Eur. Phys. J. A 22, 355 (2004)

ultimate cranker calculation



Potential energy surface for ^{163}Lu at I=57/2



Triaxial nuclei and wobbling

triaxiality: $\mathcal{J}_x > \mathcal{J}_y > \mathcal{J}_z$

high spin: $I \approx I_x >> 1$

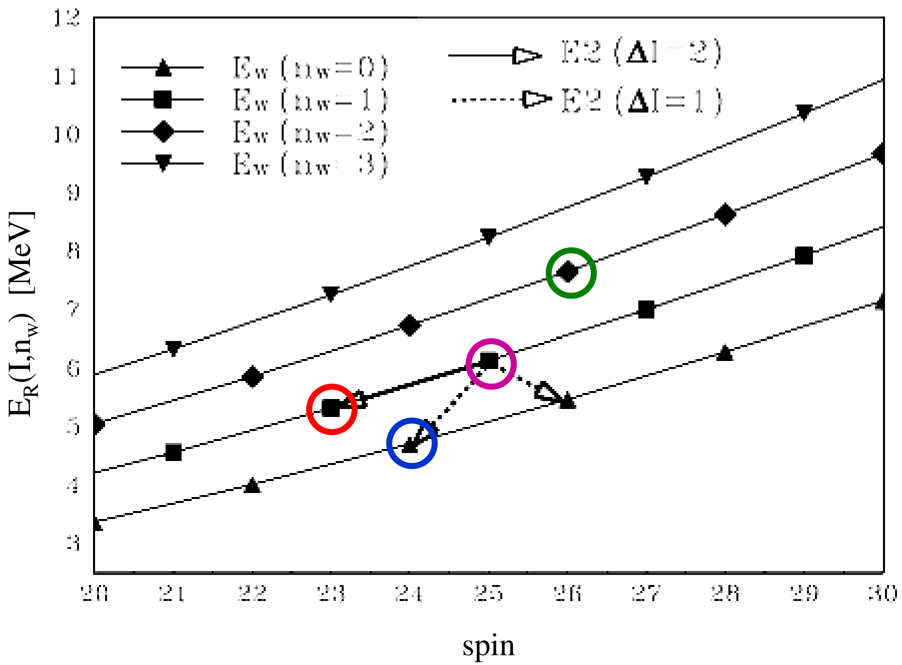
$$E_R(I,n_w) = \underbrace{\frac{I(I+1)}{2\mathcal{J}_x}}_{\text{rotation}} + \underbrace{\hbar\omega_w(n_w + 1/2)}_{\text{phonon}}$$

n_w wobbling phonon number

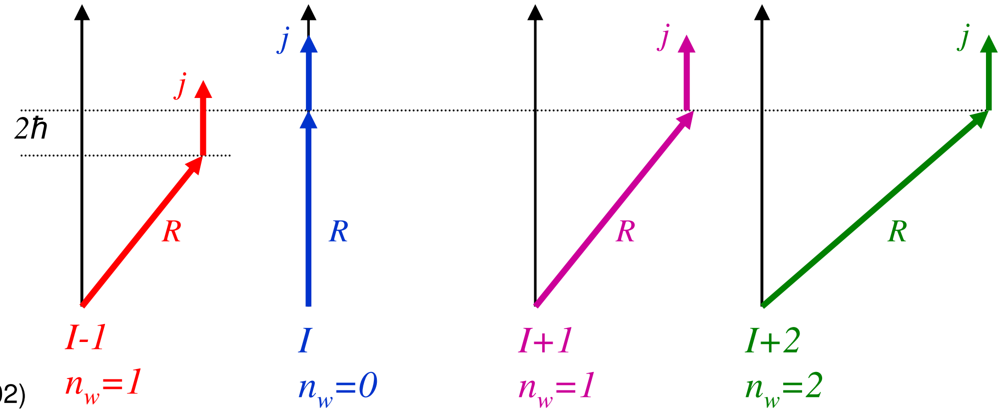
ω_w wobbling frquency

$$\hbar\omega_w = \frac{I}{\mathcal{J}_x}\sqrt{\frac{(\mathcal{J}_x - \mathcal{J}_y)(\mathcal{J}_x - \mathcal{J}_z)}{\mathcal{J}_y \mathcal{J}_z}}$$

Bohr & Mottelson, Vol. 2, p.190 ff



- The wobbling mode is unique to nuclei with stable triaxiality.
- Family of bands with very similar rotational properties.
- Each band characterized by the wobbling phonon number n_w.
- Collective E2 inter-band decay competes with in-band transitions.



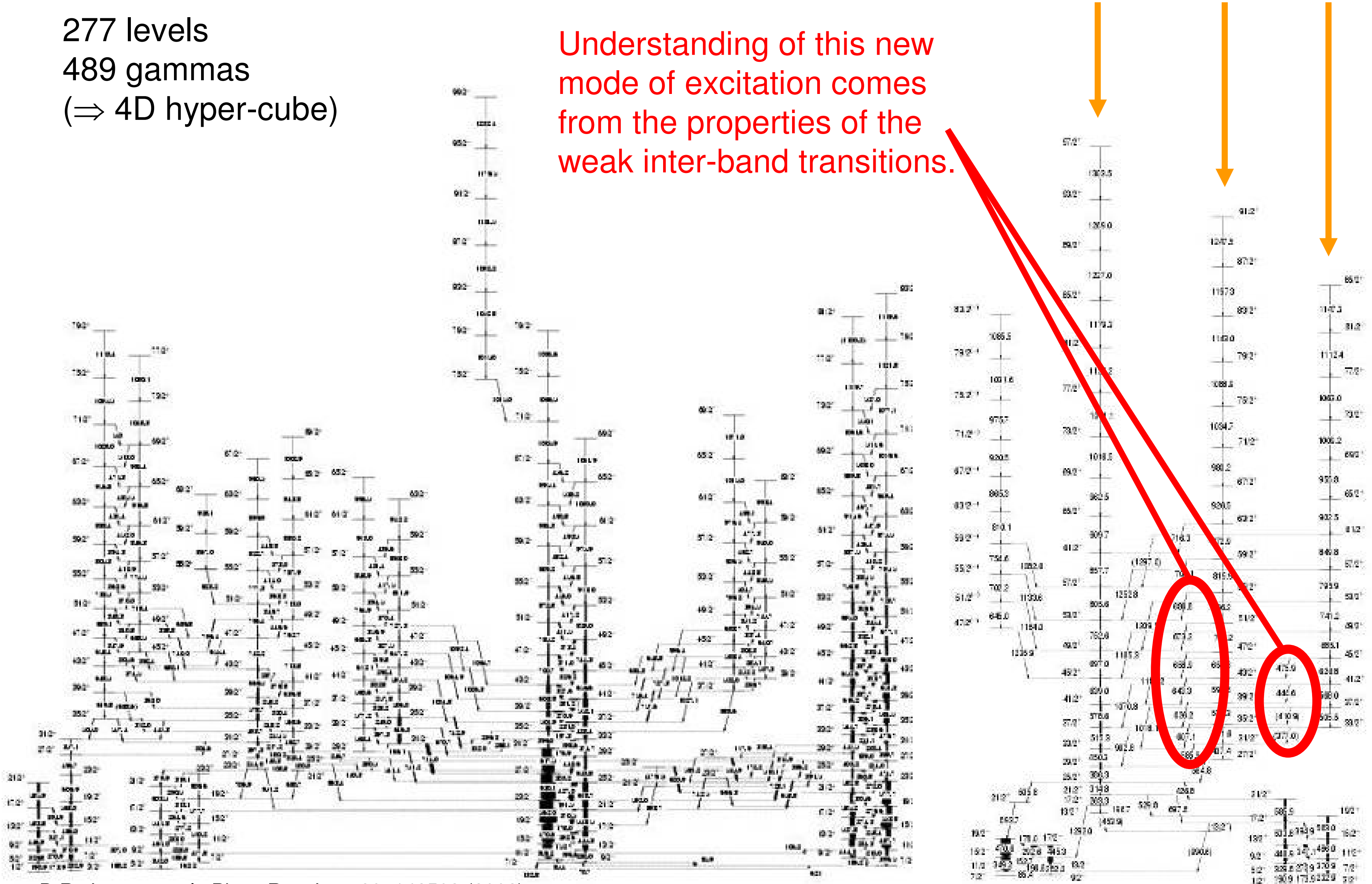
I. Hamamoto, Phys. Rev. C 65, 044305 (2002)

Level scheme of ^{163}Lu

277 levels
489 gammas
(⇒ 4D hyper-cube)

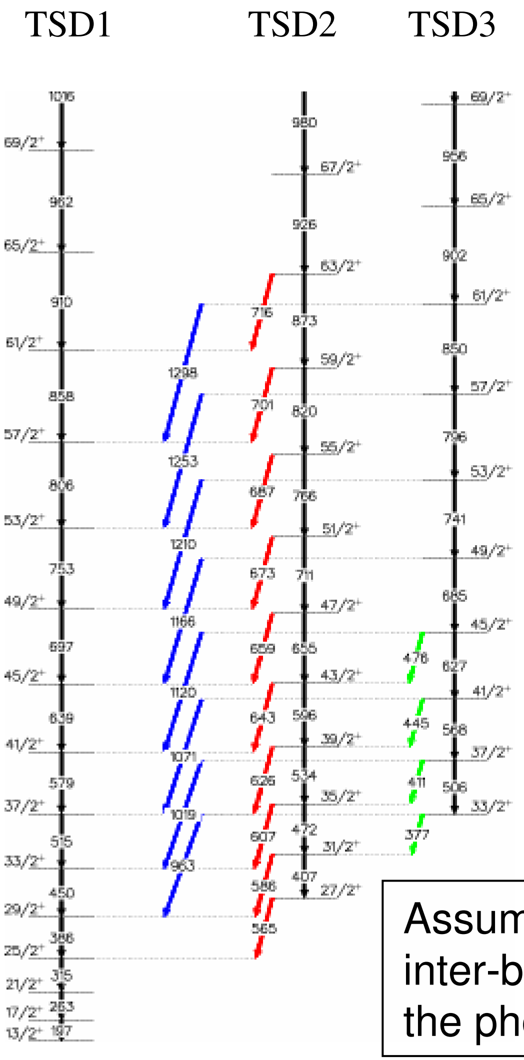
Understanding of this new mode of excitation comes from the properties of the weak inter-band transitions.

triaxial superdeformed wobbling bands

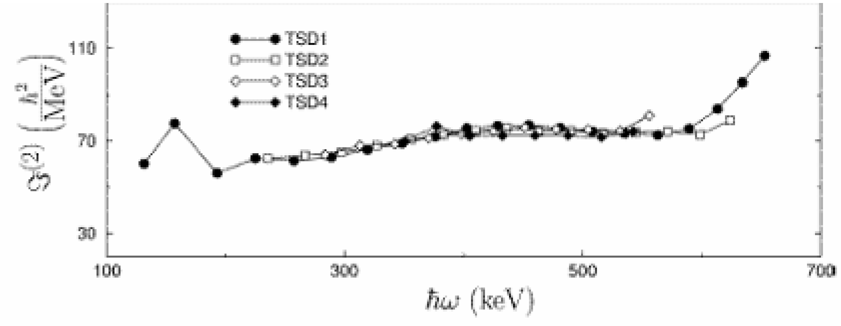


D.R. Jensen et al., Phys. Rev. Lett. 89, 142503 (2002)
Nucl. Phys. A 703, 3 (2002)

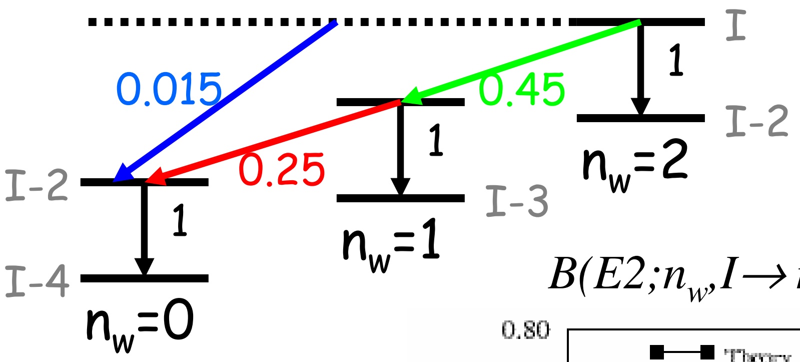
Evidence for the wobbling mode in ^{163}Lu



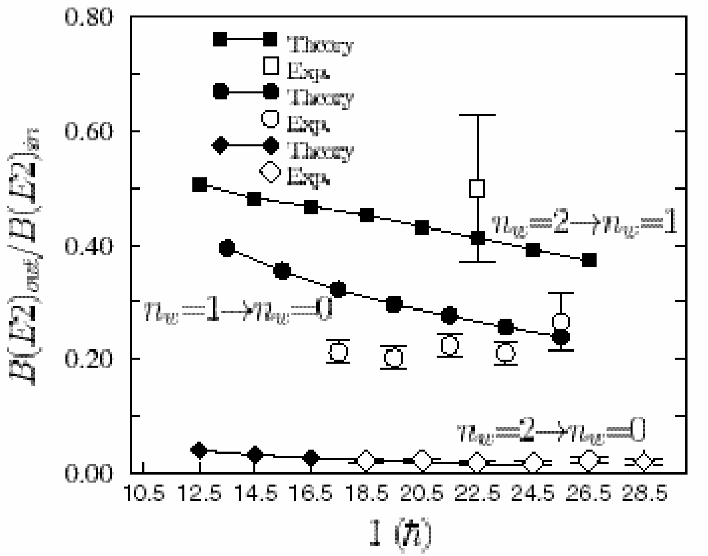
Family of bands with very similar rotational properties.



Part. Rotor calc., B(E2)'s



$B(E2; n_w, I \rightarrow n_w\text{-}1, I\text{-}1) \propto n_w/I$



Assuming E2 character for the inter-band transitions, they follow the phonon rule.

D.R. Jensen et al.,
Phys. Rev. Lett. 89, 142503 (2002)