Giant Dipole Resonance – tool for hot nuclei studies

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International Workshop on Acceleration and Applications of Heavy Ions, Warszawa, 27.02 – 12.03.2011

- The properties of Giant Dipole Resonances
- GDR as a tool for excited nuclei studies
- The results of the measurements:
  - GDR width as a function of spin and temperature of nucleus
  - The exotic shapes investigation
  - Isospin mixing
- Perspectives

Giant Nuclear Resonances

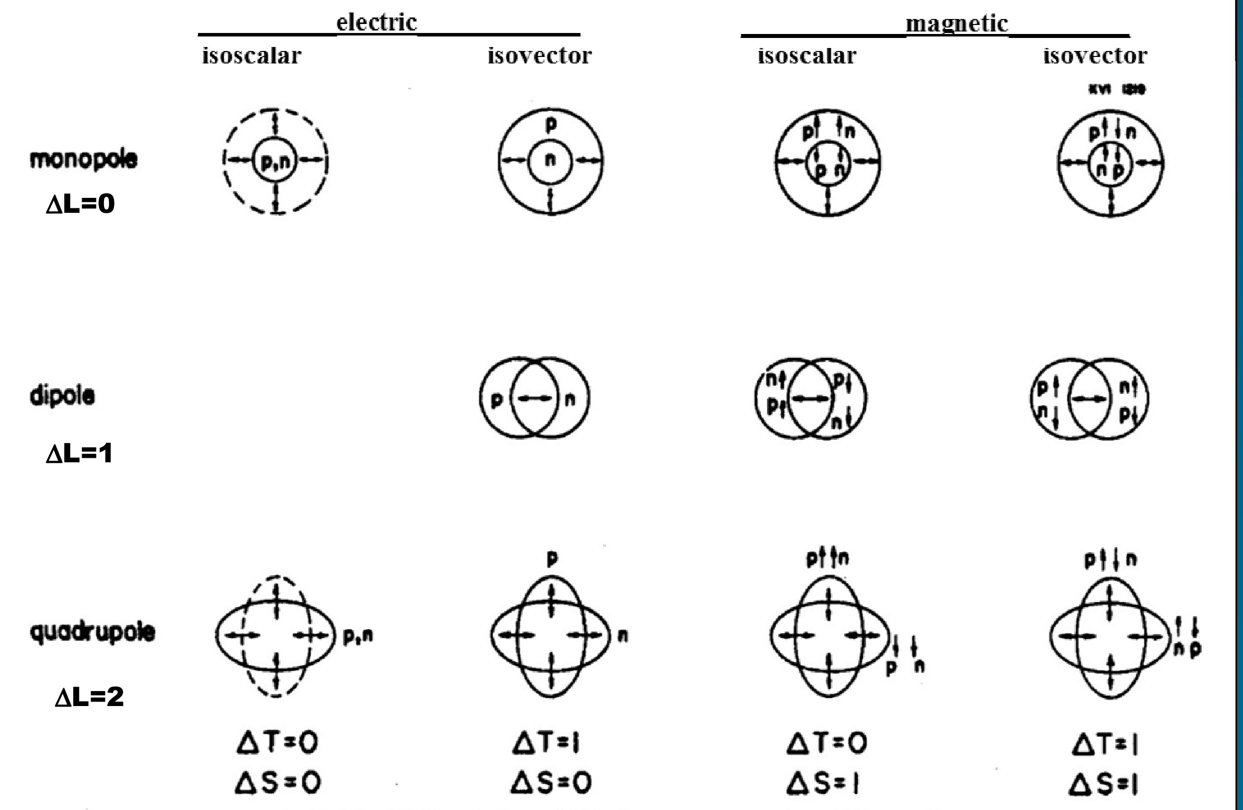
- Collective excitations of atomic nuclei consisting in oscillations of nucleons.

- Called giant resonances (giant vibrations) because of large cross sections, close to maximum allowed for all nucleons participating in excitation

- At the microscopic level giant resonances can be described in terms of correlated particle-hole excitations

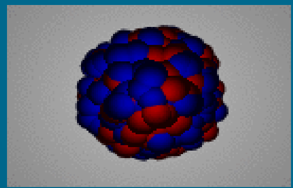
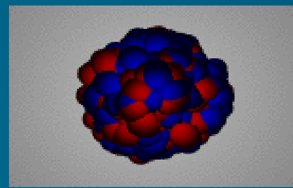
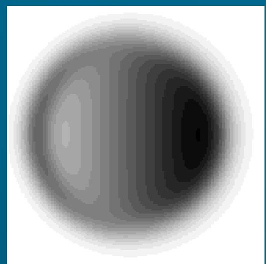
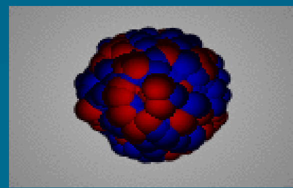
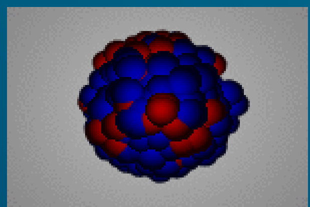
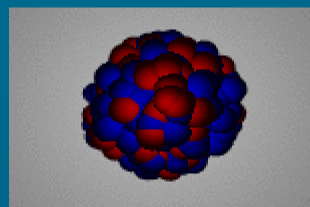
Giant Nuclear Resonances

Usually classified in terms of three characteristic quantum numbers:
L, *S*, and *T*, where *L* - the orbital angular momentum,
S - the (intrinsic) spin,
T - the isospin carried by the resonance oscillation.



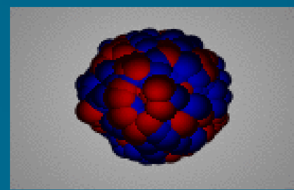
Macroscopic diagrams of the giant resonances

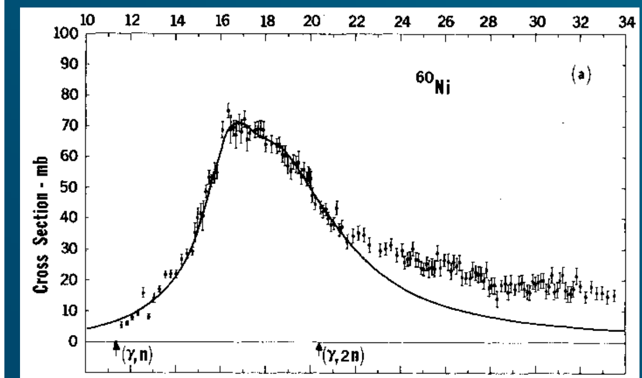
Electric Giant Resonances

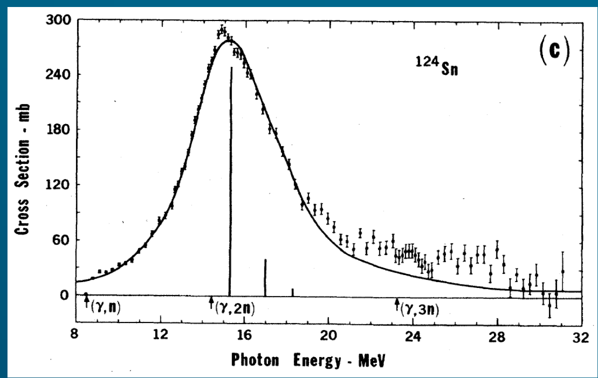
	Isoscalar		Isovector	
Monopole		1977		1983
Dipole		1996		1948
Quadrupole		1971		1980

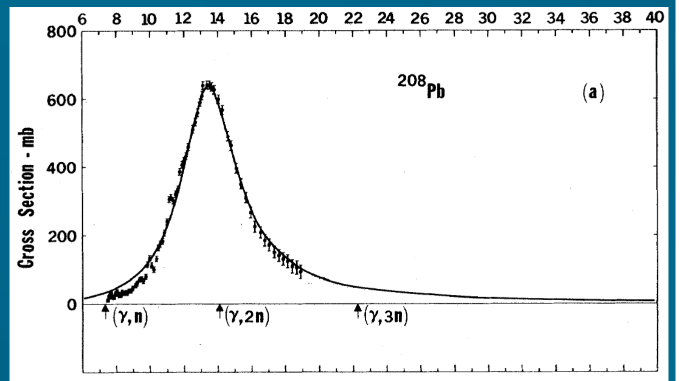
Giant Dipole Resonance

- The giant electric dipole isovector resonance – giant dipole resonance (GDR) is the oldest and best known of the nuclear giant resonances.
- Observed for the first time in 1947 and 1948 by Baldwin and Klaiber in (γ,fission) and (γ,n) reactions
- Measured using photoabsorbtion reactions for different nuclei from ^{3}He to ^{238}U (Berman and Fultz 1975)

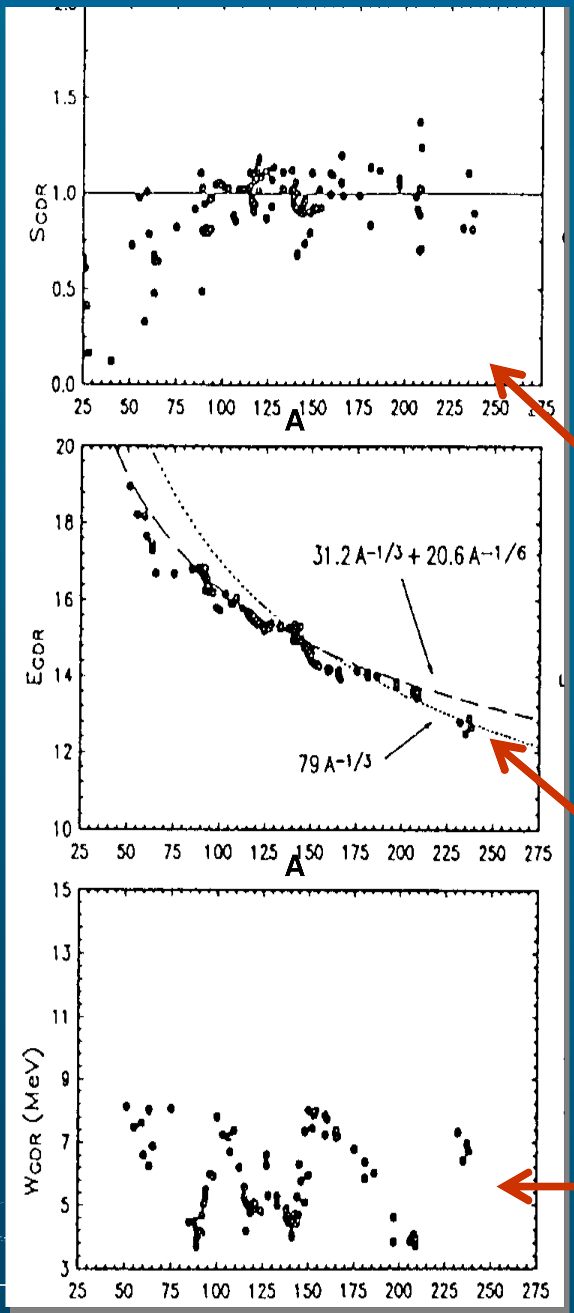




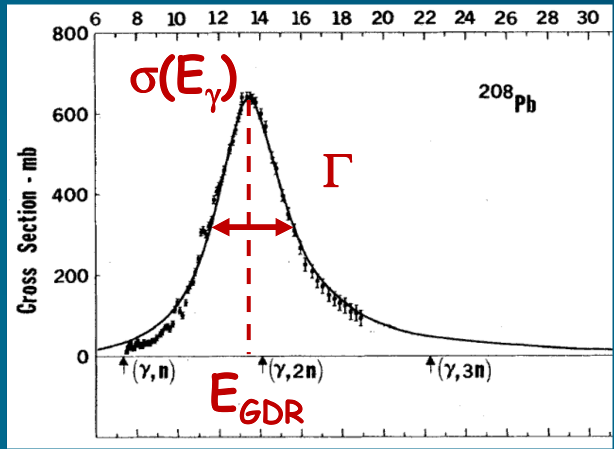




Ground state GDR



Photoabsorbtion cross section – GDR strength function:



$$\sigma(E_\gamma) = \frac{\sigma_0 \Gamma^2_{GDR} E^2_\gamma}{(E^2_\gamma - E^2_{GDR})^2 + \Gamma^2_{GDR} E^2_\gamma}$$

- **Strength σ_0=1 (S_{GDR})**
  (maximum corresponding to 100% of nucleons participating in oscillations
  calculated from Energy Weighted Sum Rule – giant vibration, large collectivity)

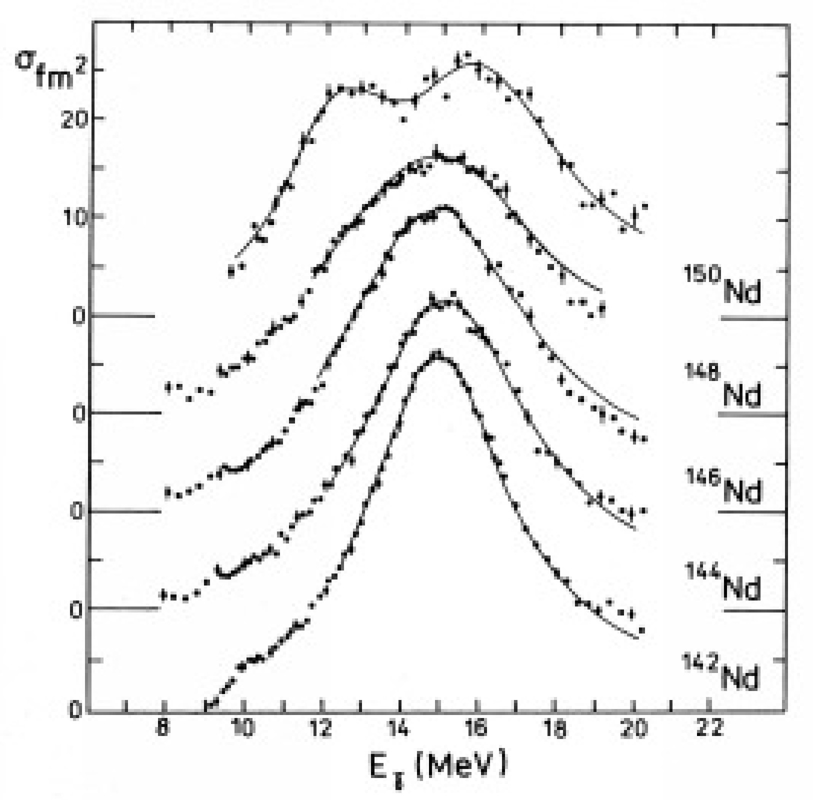
- **Energy – centroid (E_{GDR}):**

$$E_{GDR} = 31.2 A^{-1/3} + 20.6 A^{-1/6} \; [MeV]$$

  energy of oscillations ~ 1/R

- **Width (Γ_{GDR})**
  Γ ~ -1/t

GDR lineshape – deformed nucleus



superposition
of two Lorentzian function

$$\sigma(E_\gamma) = \sigma_1(E_\gamma) + \sigma_2(E_\gamma),$$

$$\sigma_k(E_\gamma) = \frac{\sigma_0 \Gamma_k^2 E_\gamma^2}{(E_\gamma^2 - E_k^2)^2 + \Gamma_k^2 E_\gamma^2}$$

Hill-Wheeler parameterization

$$E_k = E_{GDR}\frac{R}{R_k} = E_{GDR}\exp\left[-\sqrt{\frac{5}{4\pi}}\beta\cos(\gamma + \frac{2\pi k}{3})\right],$$

$$E_{GDR} \approx 79A^{-\frac{1}{3}}$$

quadrupole deformation parameter β

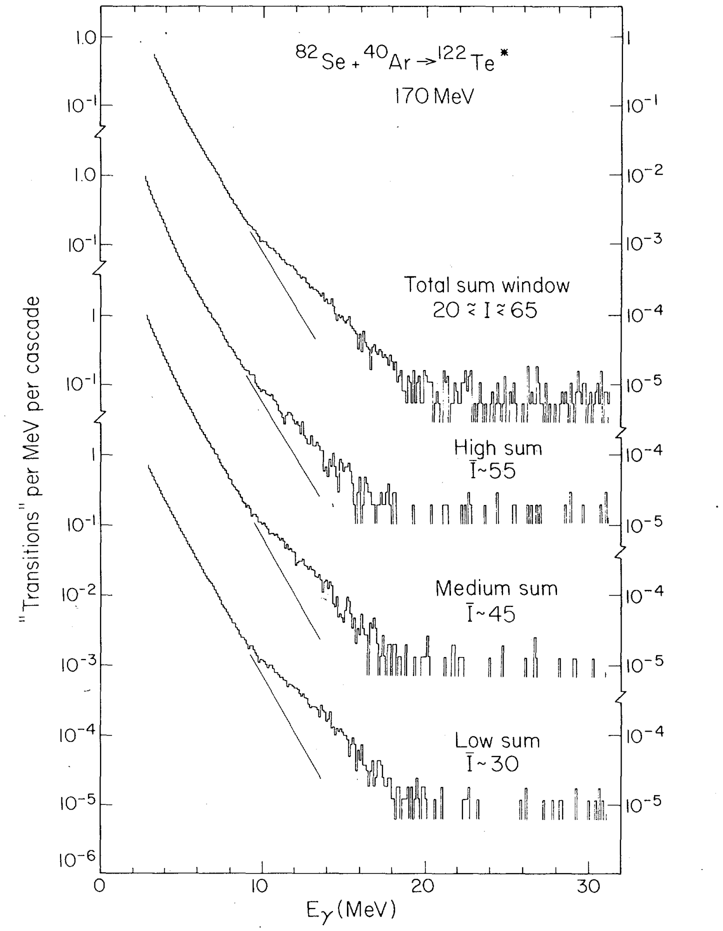
$$\beta = \sqrt{\frac{4\pi}{5}}\frac{\frac{E_2}{E_1} - 1}{0.5\frac{E_2}{E_1} + 0.87}$$

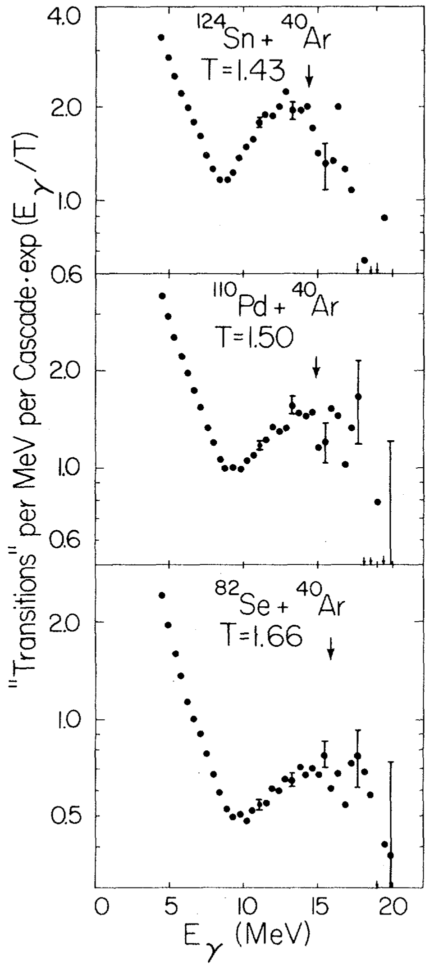
GDR in excited nuclei

GDR can be built on excited state of nucleus - Brink hypothesis, 1955

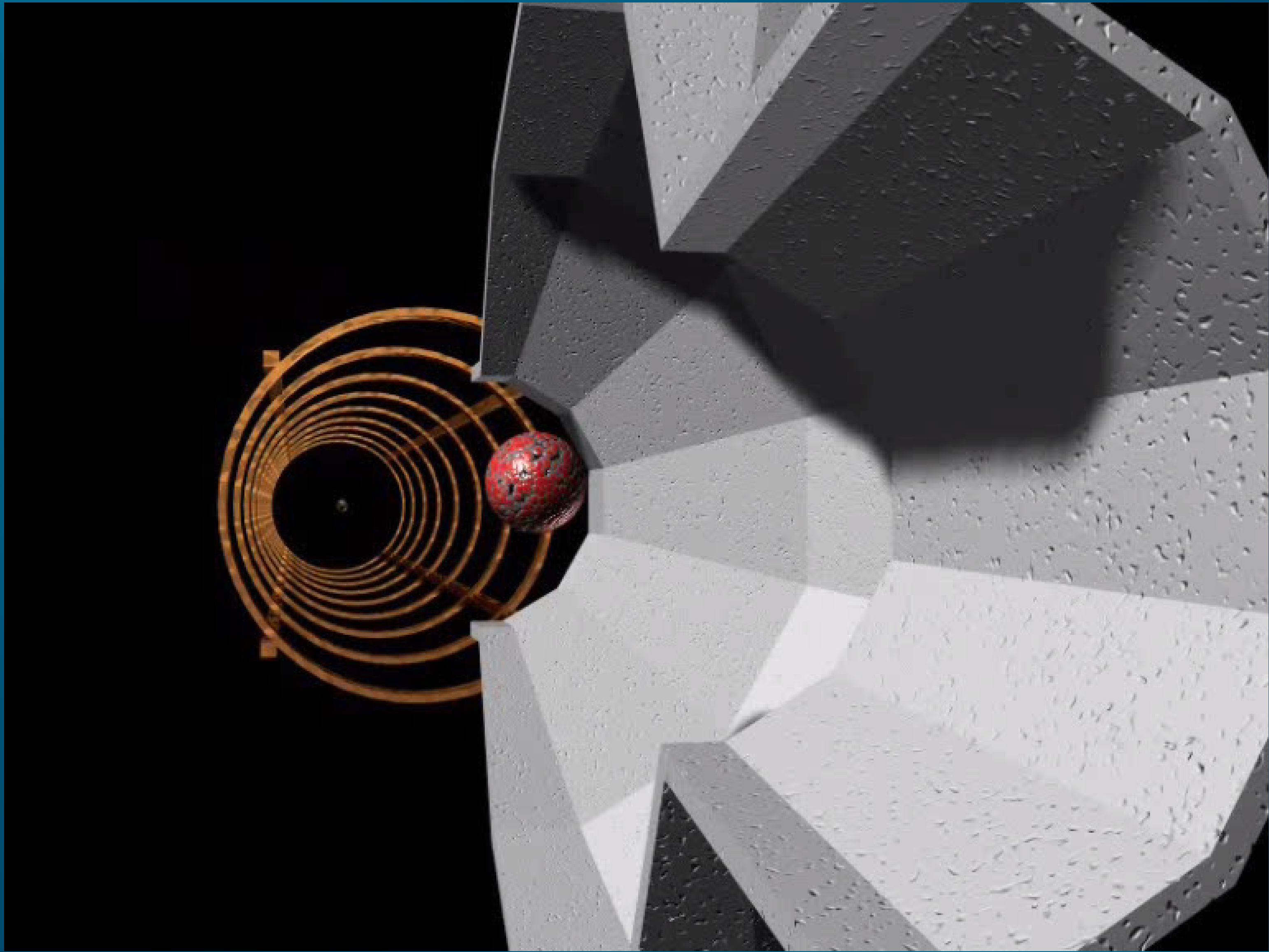
Observation of Giant Dipole Resonances Built on States of High Energy and Spin

J. O. Newton,[(a)] B. Herskind,[(b)] R. M. Diamond, E. L. Dines,[(c)] J. E. Draper,[(c)]
K. H. Lindenberger,[(d)] C. Schück,[(e)] S. Shih,[(f)] and F. S. Stephens
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 2 March 1981)



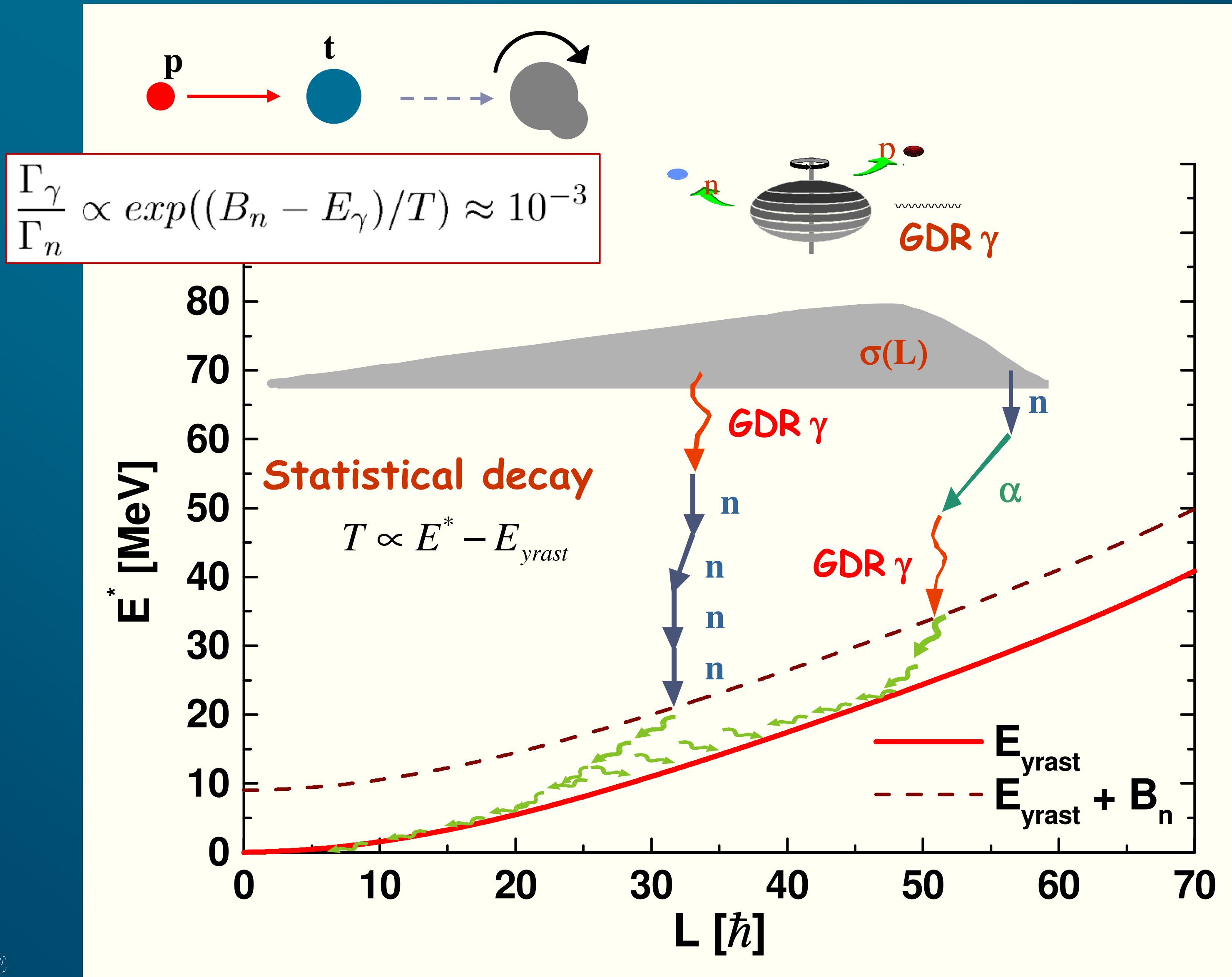


Fusion – evaporation reaction.

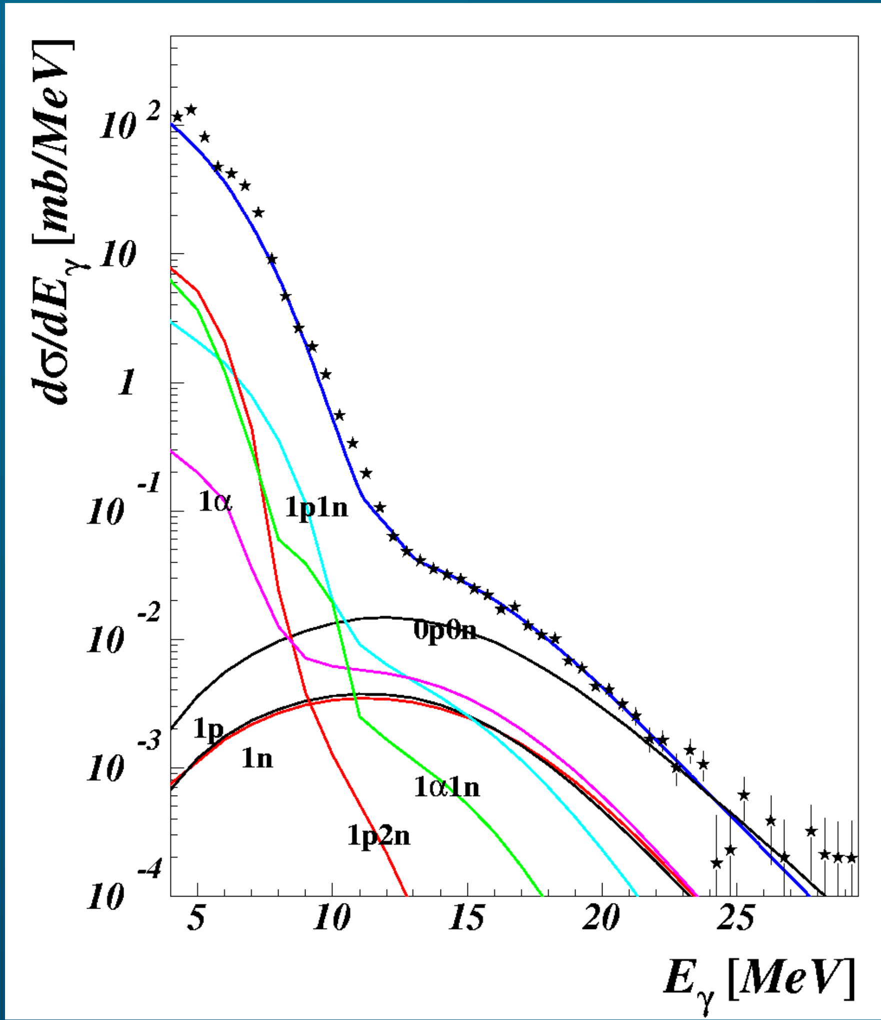


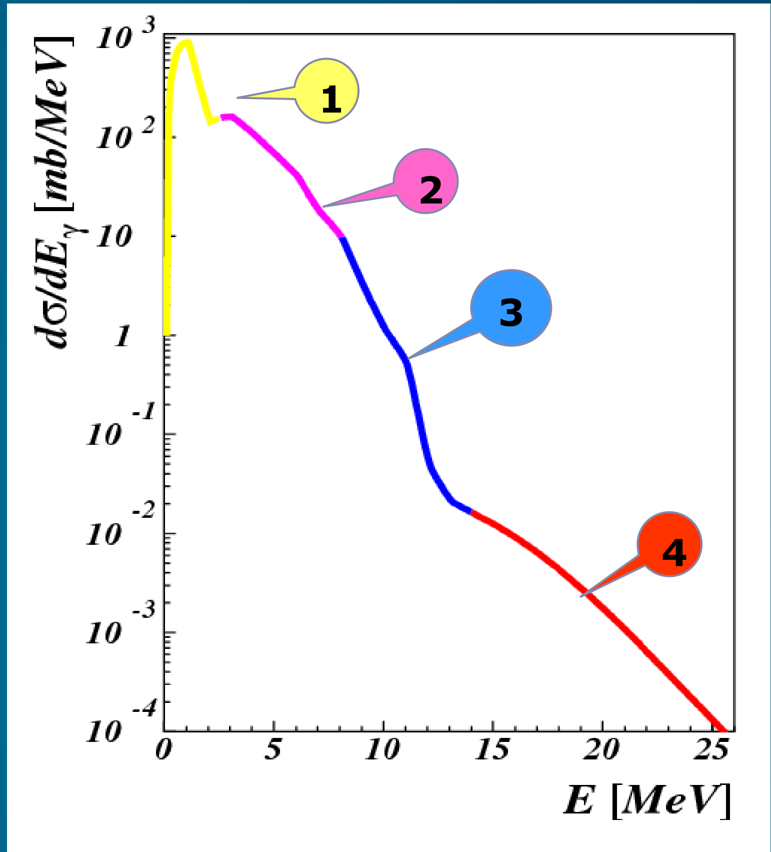
Excerpt from the © Jerzy Grebosz movie „Mysterious World of Atomic Nuclei"

Decay of compound nucleus



Energy spectrum of emitted γ rays

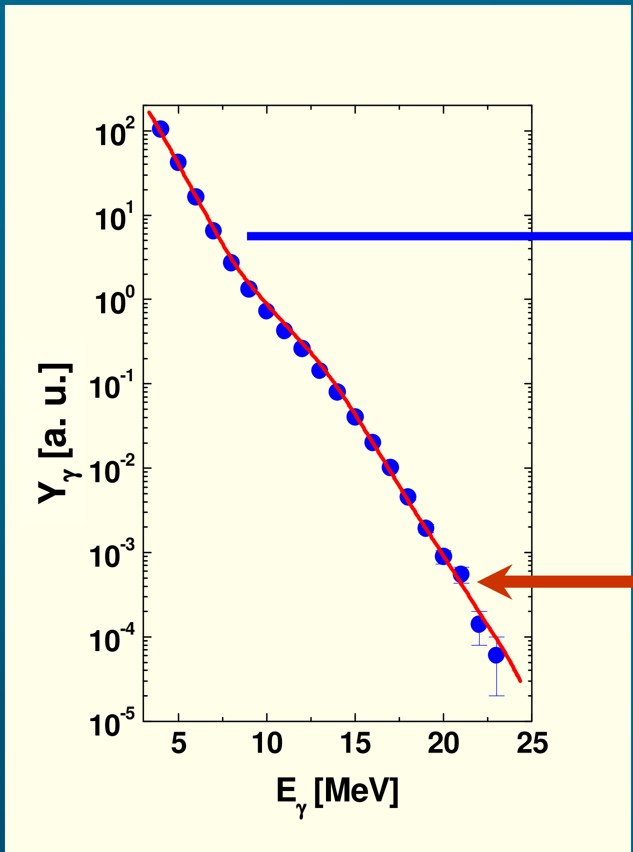




Continous spectrum

Extraction of GDR parameters

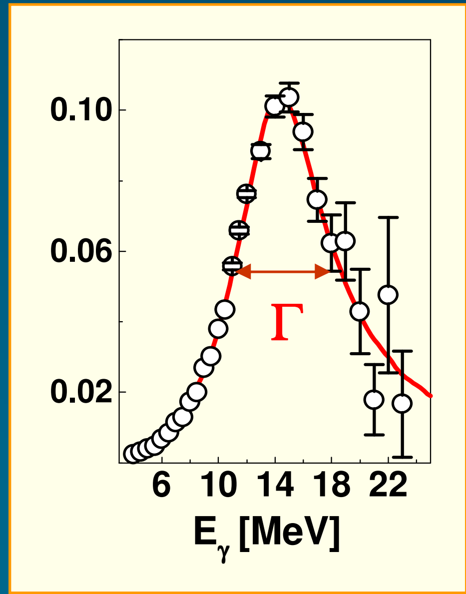
$$\sigma(E_\gamma) = \frac{S\Gamma E_\gamma^2}{(E_\gamma^2 - E_{GDR}^2) + \Gamma^2 E_\gamma^2}$$



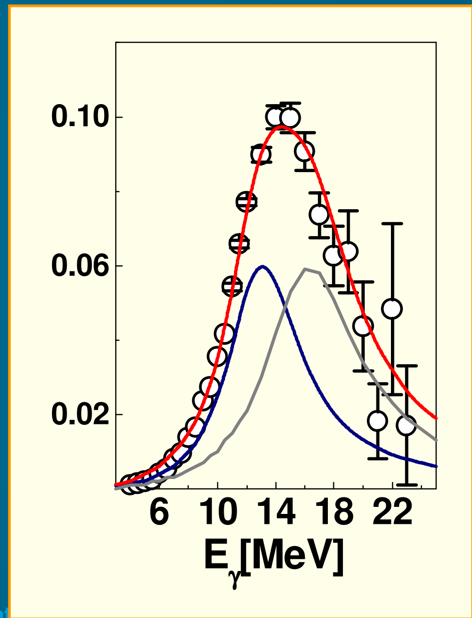
CASCADE

detector's response function

χ^2 - minimization



$$\sigma(E_\gamma) = \frac{S_1\Gamma_1 E_\gamma^2}{(E_\gamma^2 - E_{GDR1}^2) + \Gamma_1^2 E_\gamma^2} + \frac{S_2\Gamma_2 E_\gamma^2}{(E_\gamma^2 - E_{GDR2}^2) + \Gamma_2^2 E_\gamma^2}$$



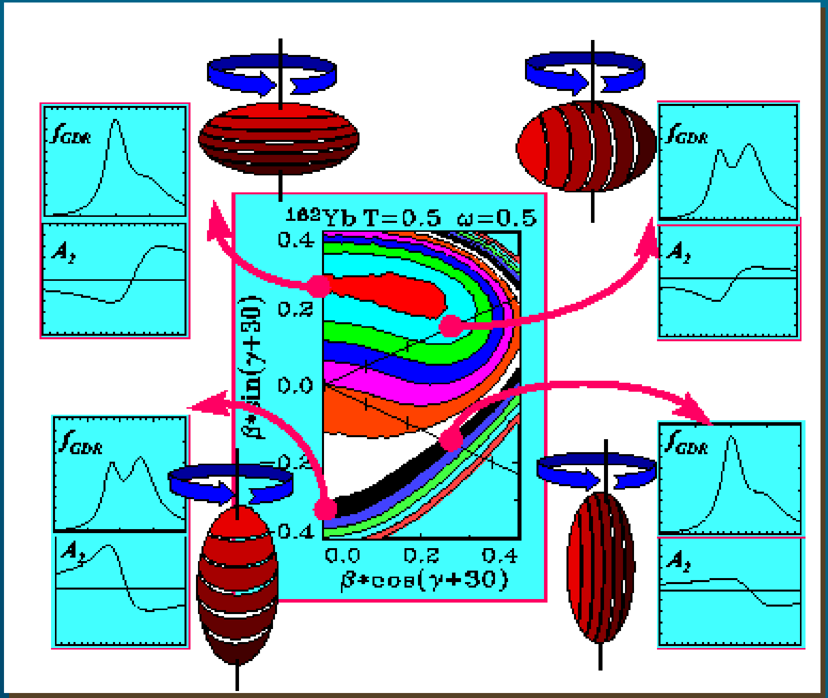
deformation parameter of nucleus

$$\beta \approx 1.06 \frac{E_2 - E_1}{E_{GDR}}$$

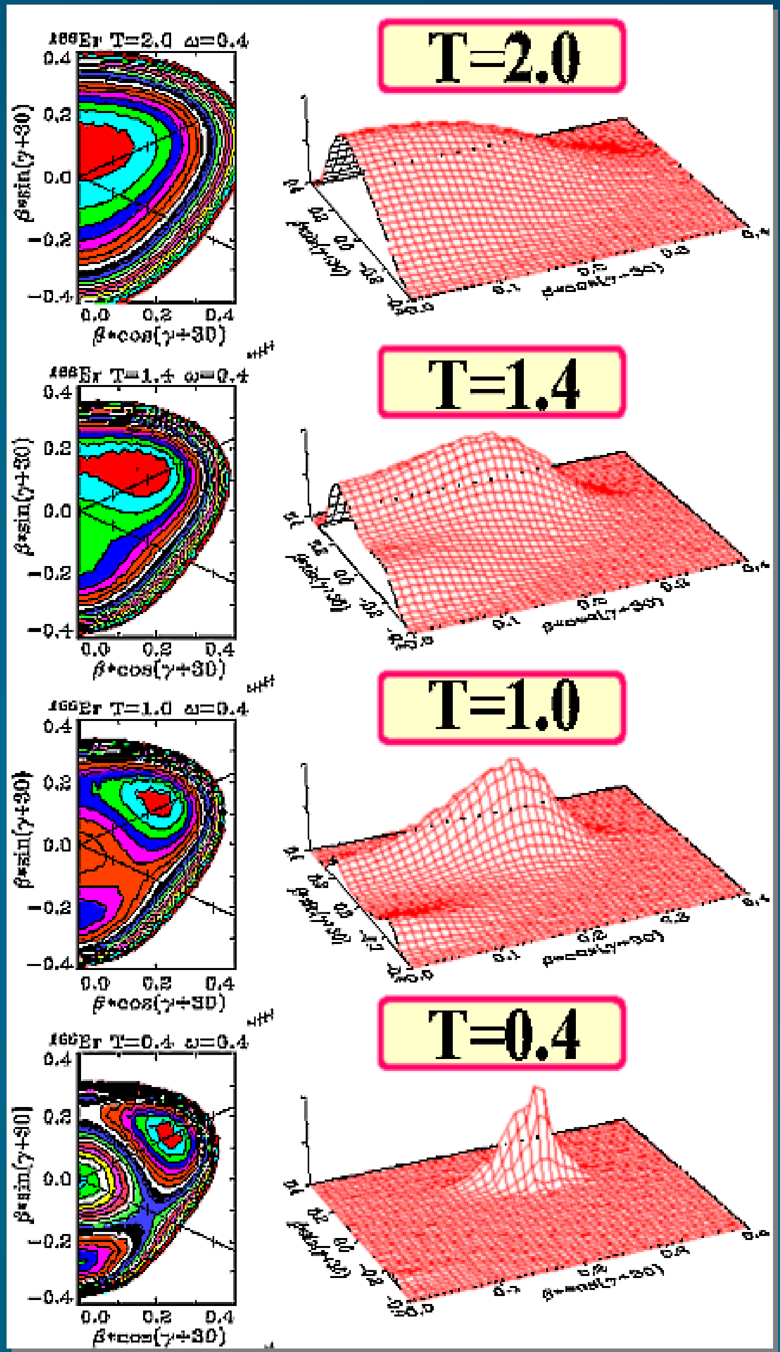
Thermal shape fluctuations

probability of existing a nucleus
at given shape (described by β and γ)

$$P(T,\varpi;\beta,\gamma) \propto \exp\left[-\frac{F(T,\varpi;\beta,\gamma)}{T}\right]$$

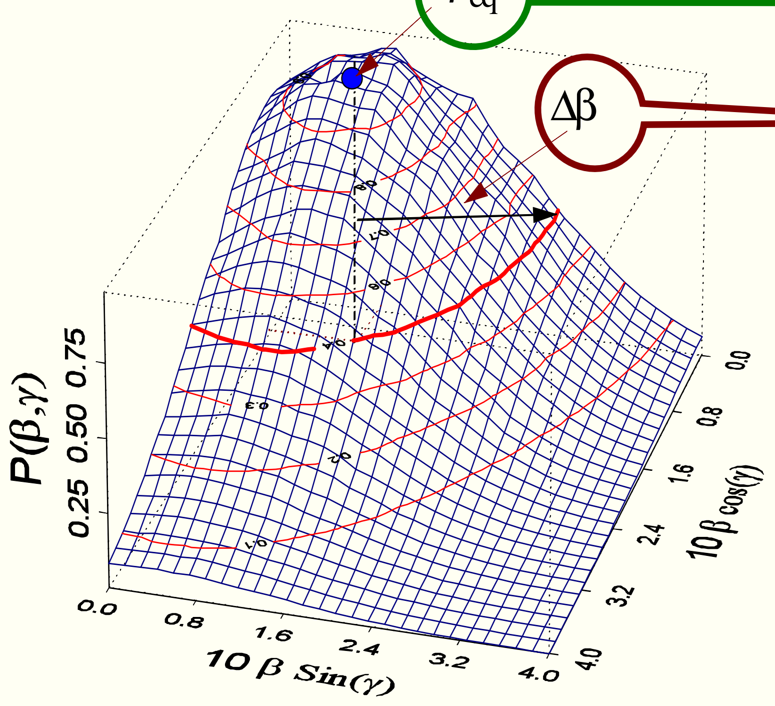


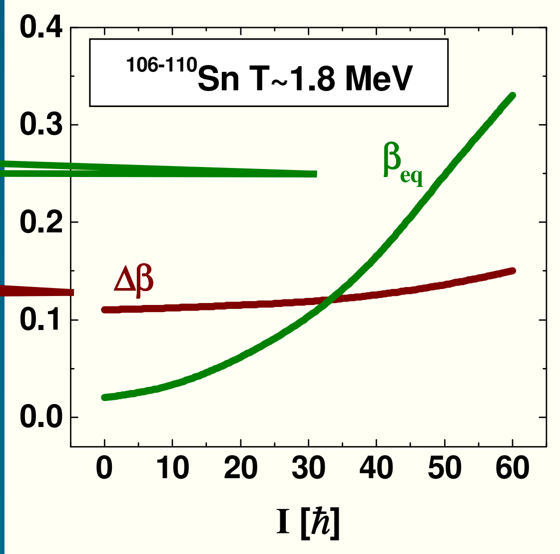
Shapes ensemble



Thermal shape fluctuations

$$P(\beta,\gamma) \propto e^{\frac{-F(\beta,\gamma)}{T}}$$





β_{eq} ~ I
$\Delta\beta$ ~ T

β equilibrium
(the most probable)

GDR strength function (average – measured):

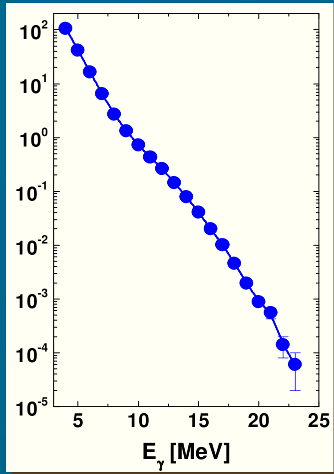
$$f_{GDR}^{av}(T,I) = \iint f_{GDR}(\beta,\gamma,\omega) e^{-F(T,I;\beta,\gamma)/T(I;\beta,\gamma)} \beta^4 \left|\sin(3\gamma)\right| d\beta d\gamma$$

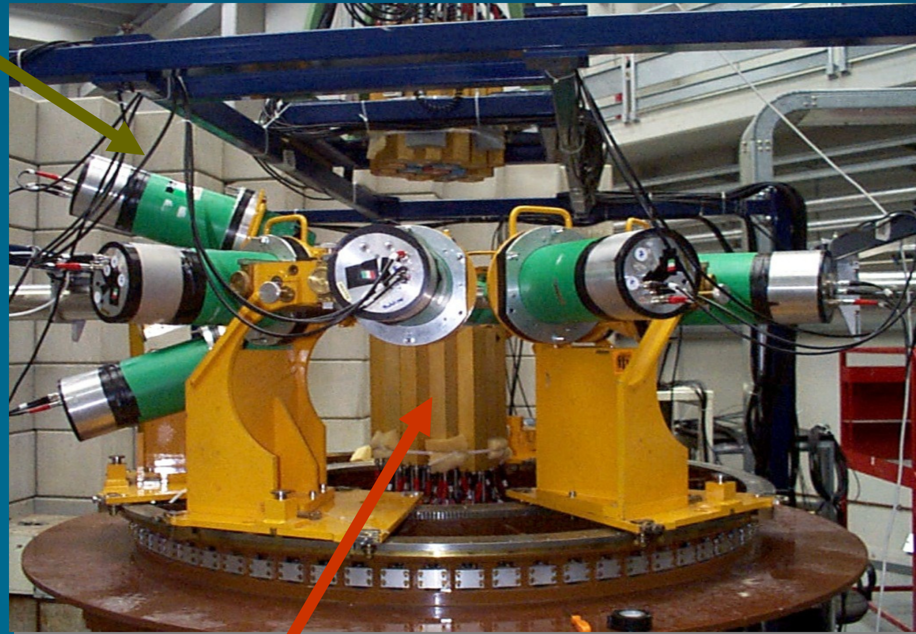
HECTOR (High Energy gamma-ray deteCTOR) array:

(Copenhagen)-Milano-Kraków collaboration since 1989

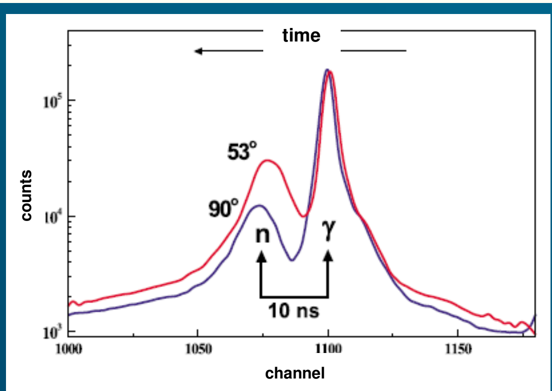
HECTOR - 8 large BaF_2 detectors

high energy
γ-ray spectra





neutron discrimination using time of flight

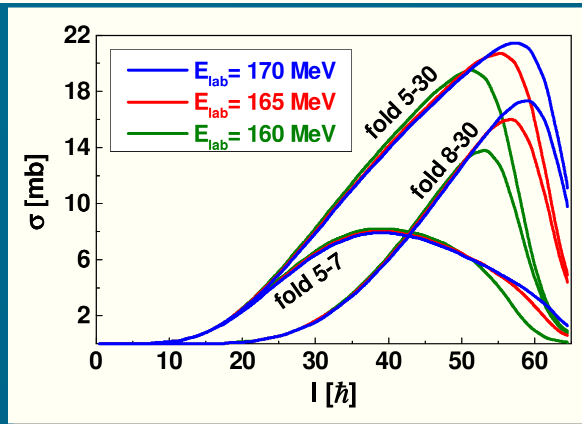


HELENA multiplicity filter (38 small BaF_2)

sum energy

fold (measured multiplicity)

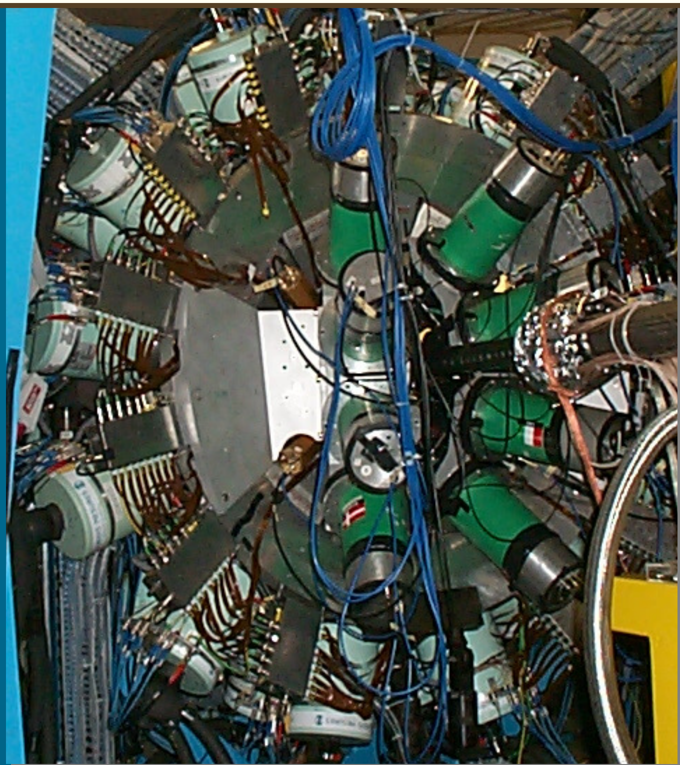
spin distributions



Measurements

- HECTOR – GDR
- EUROBALL, NORDBALL, PEX – discrete transitions
- multiplicity filter (spin) HELENA
- light charged particles (EUCLIDES, GARFIELD)

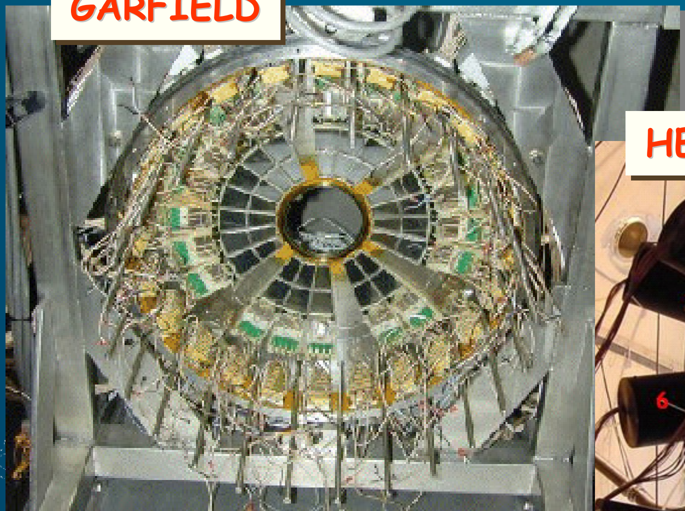
EB IV + HECTOR + EUCLIDES exp.



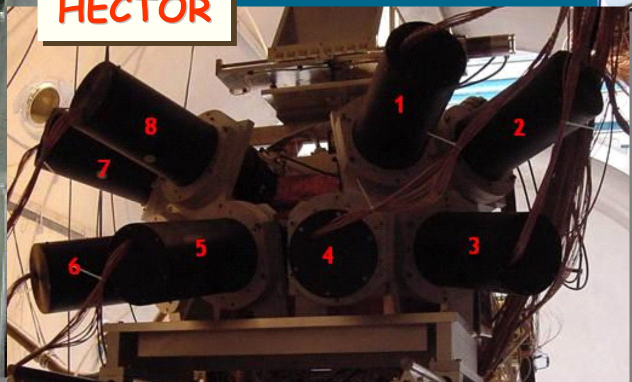
HECTOR + NORDBALL

HECTOR + PEX

GARFIELD



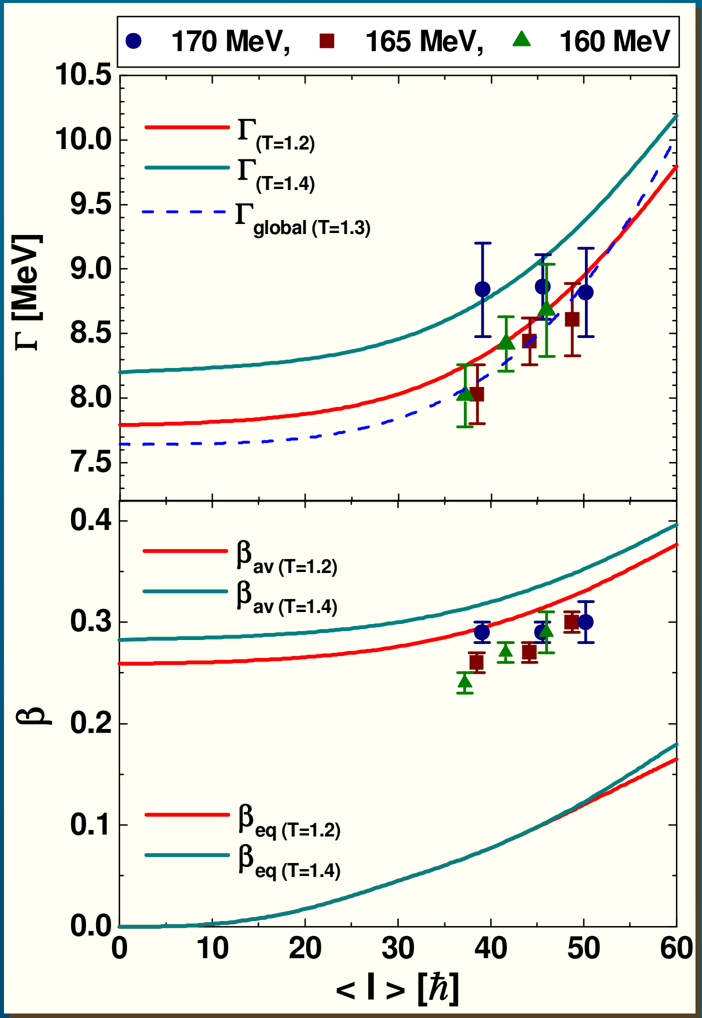
HECTOR



The dependence of the GDR width on angular momentum

GDR width Γ and deformation parameter β for ^{147}Eu

M. Kmiecik et al. Nucl. Phys. A674 (2000) 29



$$\beta_{av} = Z^{-1}\int \frac{D[\alpha]}{I^{\frac{3}{2}}}\beta e^{-\frac{F}{T}}, \quad Z = \int \frac{D[\alpha]}{I^{\frac{3}{2}}} e^{-\frac{F}{T}}$$

$$\Delta\beta = \sqrt{\langle \beta^2 \rangle - \beta_{av}^2}$$

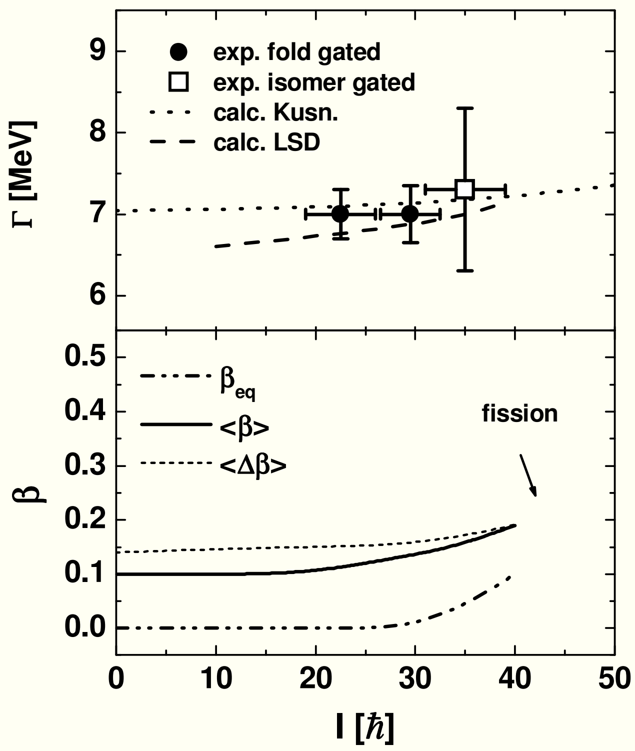
$for\ \Delta\beta > \beta_{eq} \quad \beta_{av}\ slightly \uparrow for\ I \uparrow$

$for\ \beta_{eq} > \Delta\beta \quad \beta_{av} \uparrow strongly\ with\ I \uparrow$

The GDR width increases due to deformation increase and thermal shape fluctuations

Isomer gated GDR

M. Kmiecik et al. PR C70, 064317 (2005)

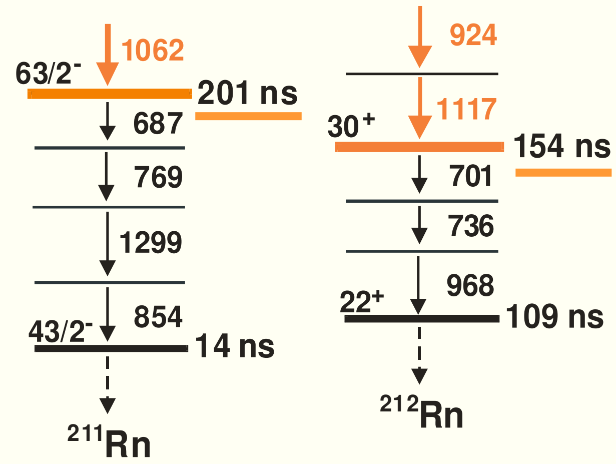


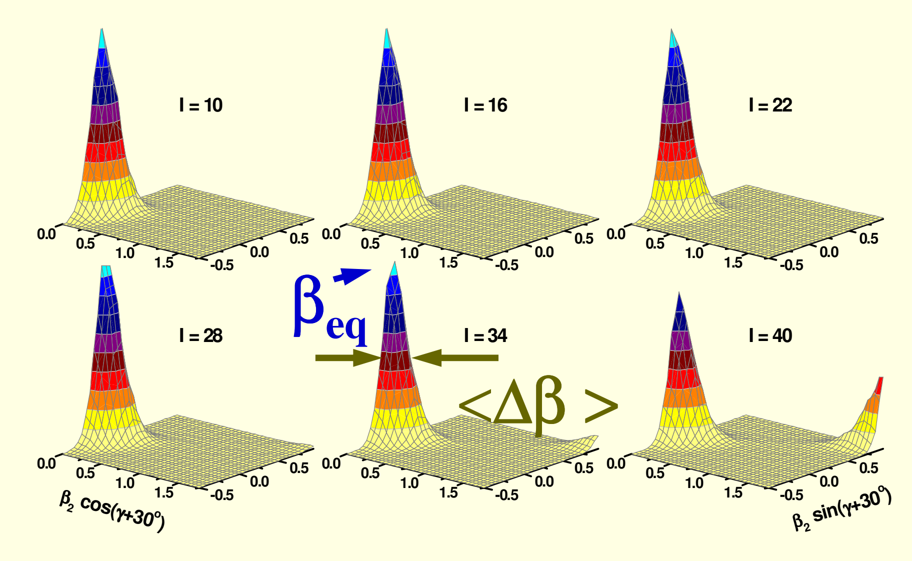
no significant increase of GDR width observed

96 MeV $^{18}O + ^{198}Pt \rightarrow ^{216}Rn^*$

$E^*=56$MeV, $L_{max}=39\hbar$

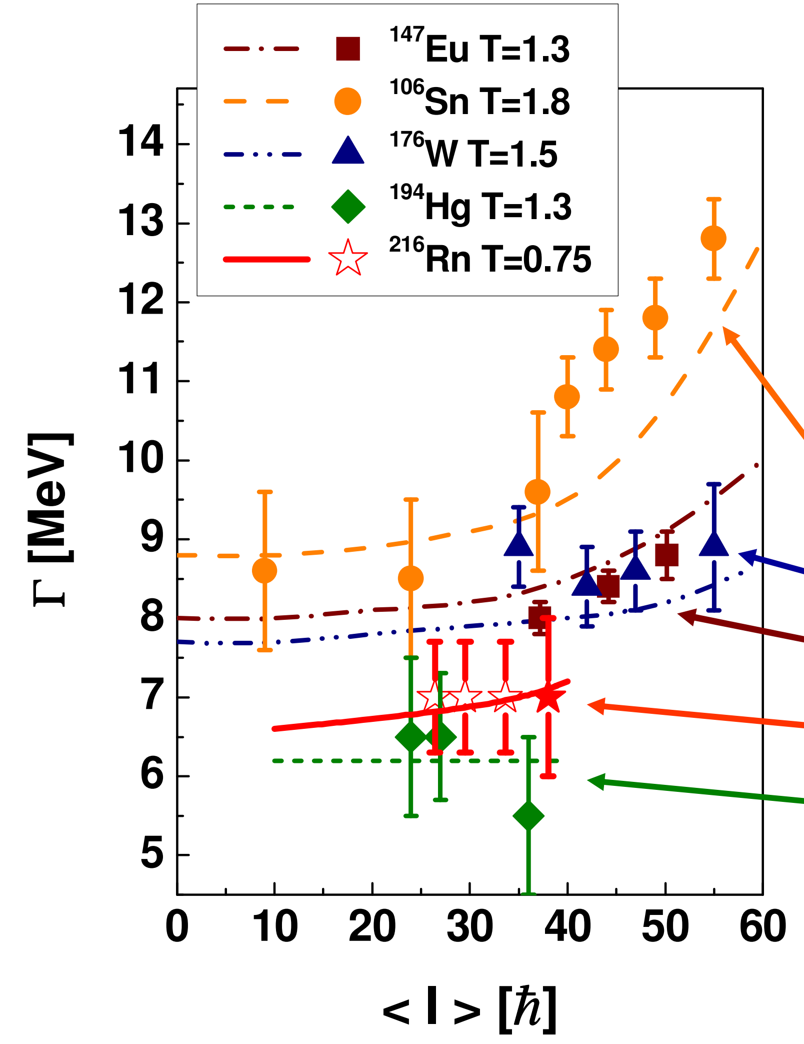
gating on isomers – choosing nuclei at highest spins surviving fission





small deformation up to the fission limit

The GDR width at finite temperature



$$I = \Im \cdot \varpi$$

$$\Im \propto A^{5/3}$$

larger deformation increase
(at the same spin)
for nuclei of smaller mass

effect of rotational frequency

M.Mattiuzzi et al. Nucl. Phys. A612 (1997) 262

M. Kmiecik et al. Nucl. Phys. A674 (2000) 29

M. Kmiecik et al., Phys. Rev. C70, 064317 (2005)

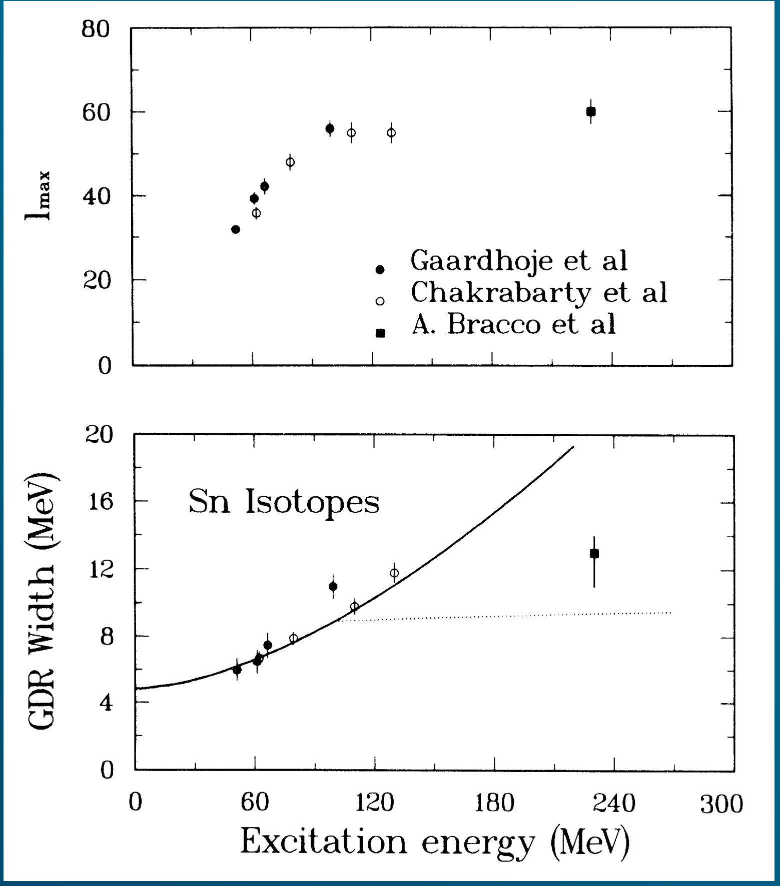
F. Camera et al. Phys. Rev. C60 (1999) 014306

The GDR width Γ behaviour as a function of nuclei temperature

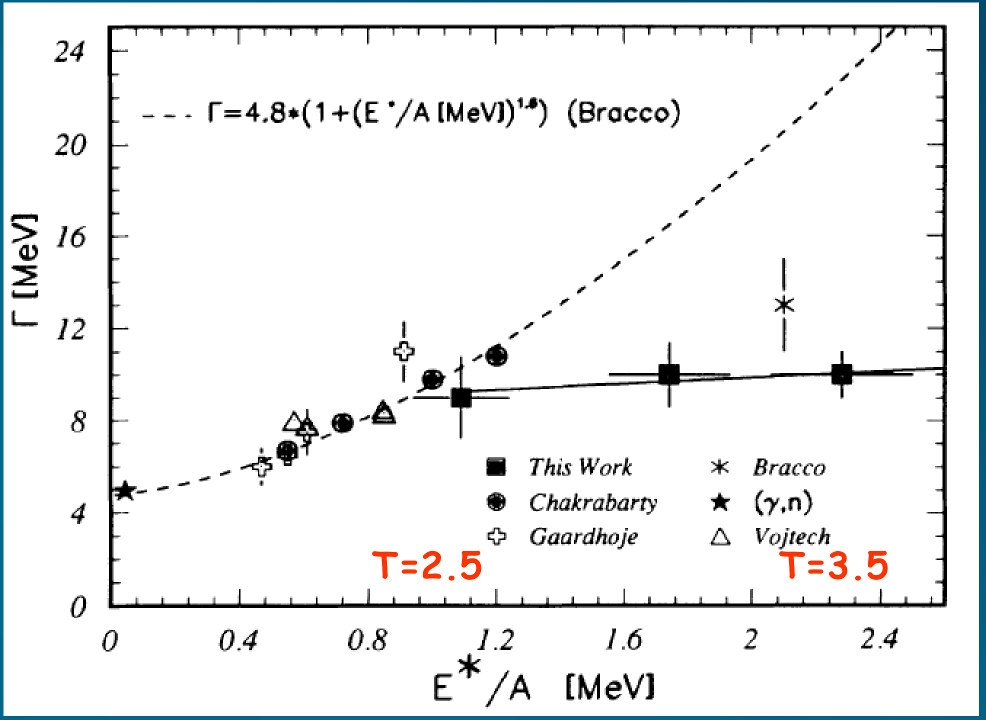
The temperature evolution of GDR width

Γ_{GDR} saturation?

A. Bracco et al., PRL 62 (1989) 2080



G. Enders et al., PRL 69 (1992) 249



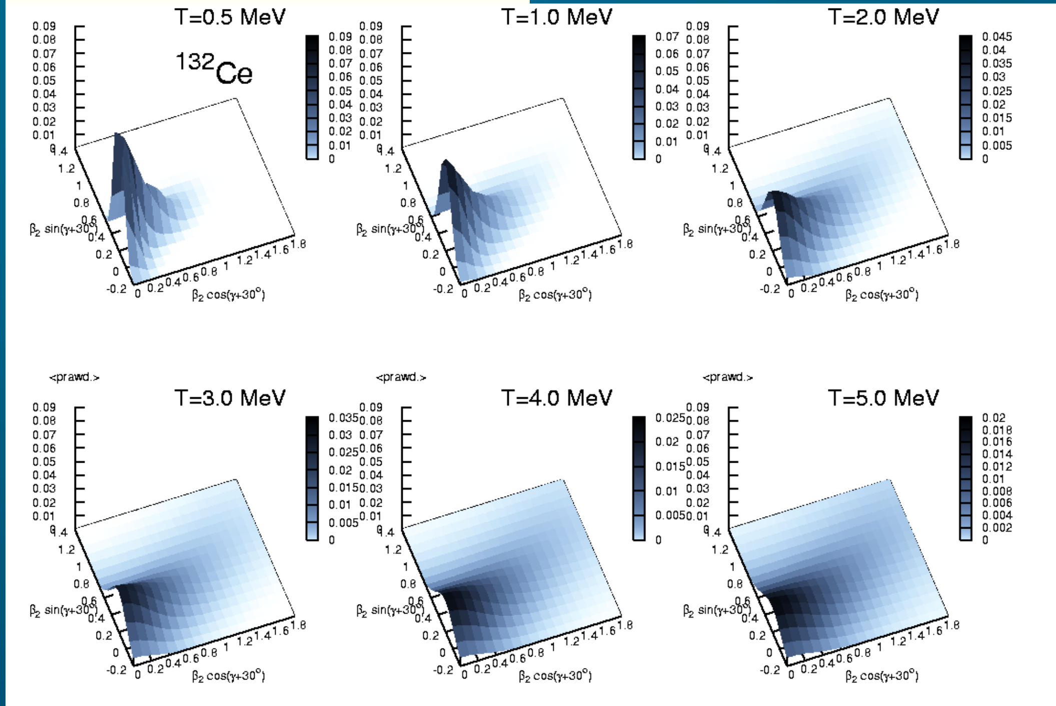
Possible explanations:

- saturation of the transferred angular momentum
- preequilibrium emission

P.M.Kelly et al. PRL82 (1999) 3404

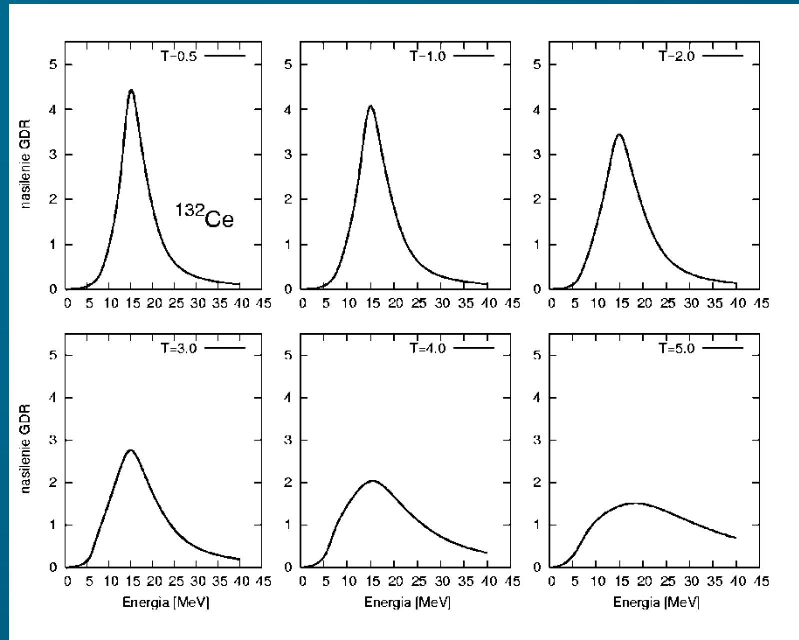
The temperature evolution of GDR width

Calculations for ^{132}Ce



Shape probability distribution

Effective GDR width increases with T

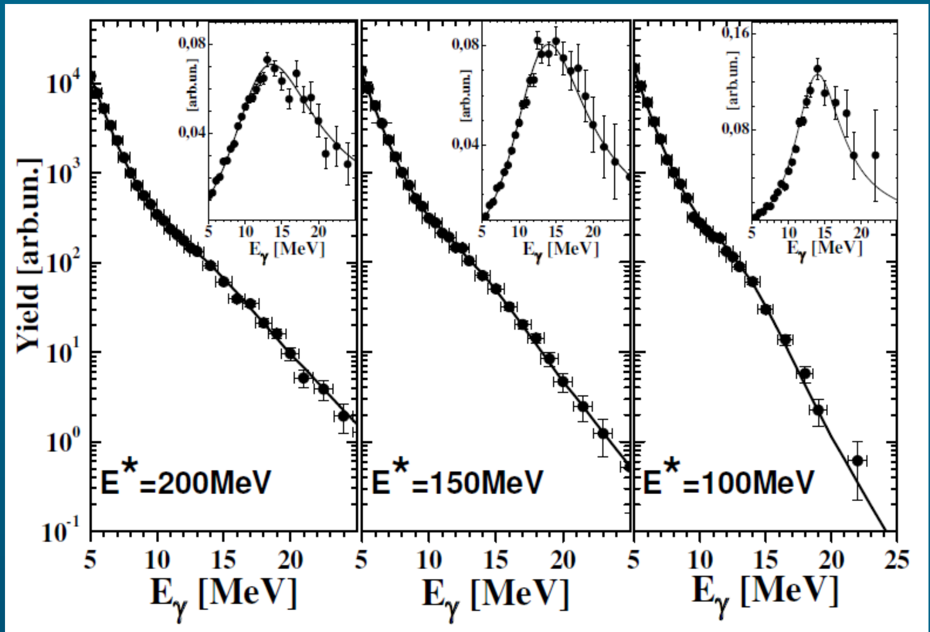


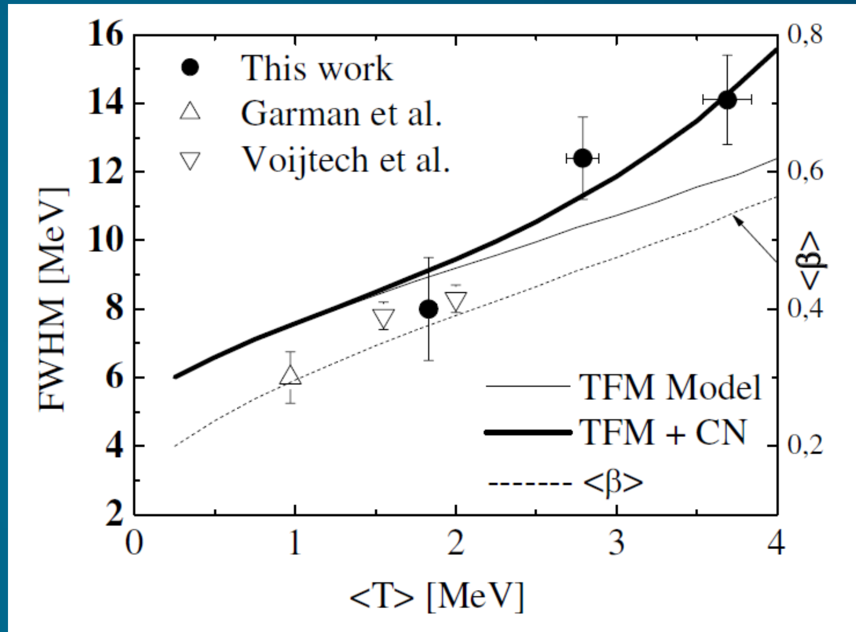
The GARFIELD+HECTOR experiment

(γ rays and charged particles measured)

^{132}Ce

O. Wieland et al., Phys. Rev. Lett. 97, 012501 (2006)





The GDR width increases with temperature (up to 4 MeV).

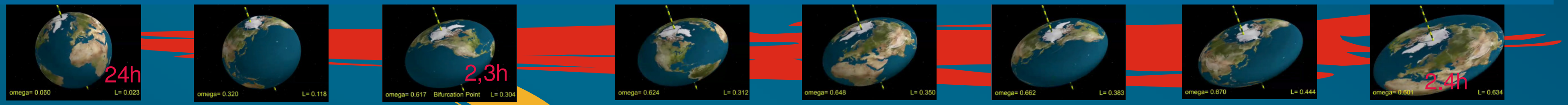
The results are in agreement with calculations based on thermal shape fluctuation model including compound nucleus life time.

Jacobi shape transition

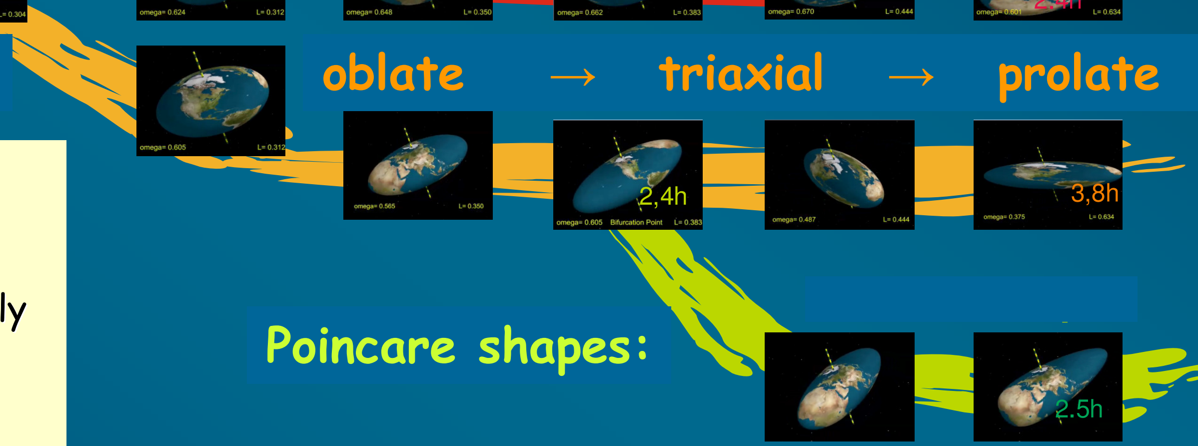
Theoretical shapes of rotating gravitating body

Colin MacLaurin (1742) showed that, as the angular momentum increases, the spherical body (Earth) will become more flat (oblate). It changes it's shape to an ellipsoid with two equal long axes, rotating around the short axis.

McLaurin shapes: spherical → oblate → more flat oblate



Jacobi shapes: oblate → triaxial → prolate



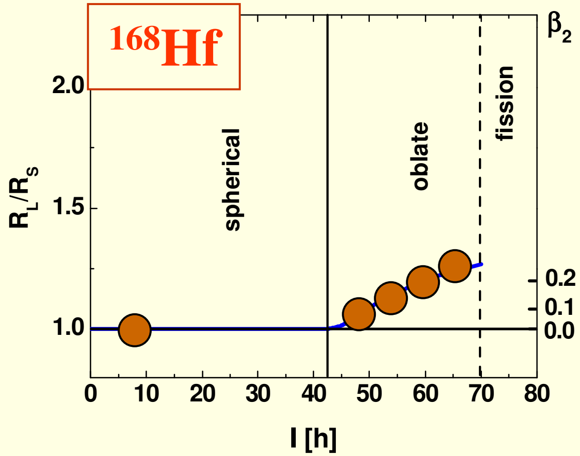
Carl Gustav Jacob Jacobi in 1834 calculated that at certain angular velocity the rotating body (gravitating *mass rotating synchronously)* may change abruptly the shape from MacLaurins oblate shape to triaxial and then more elongated. (Jacobi bifurcation).

Poincare shapes:

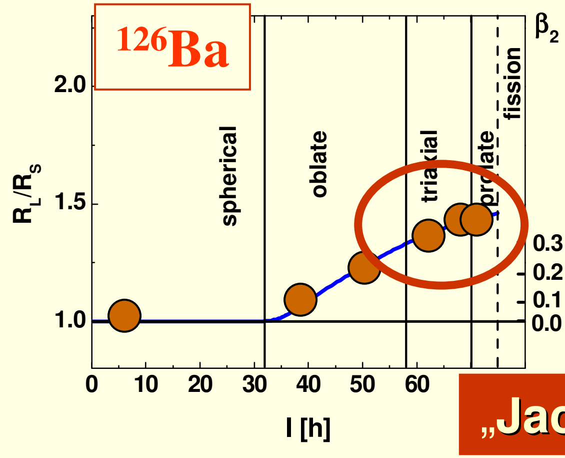
triaxial → pear shape

Henri Poincare (1885) described new shapes that could be obtained by rotating mass at the Jacobi path at given angular velocity. The body having Jacobi elongated triaxial shape can change it at multiple bifurcation point a pear shape

Evolution of the shape of hot nucleus as a function of spin

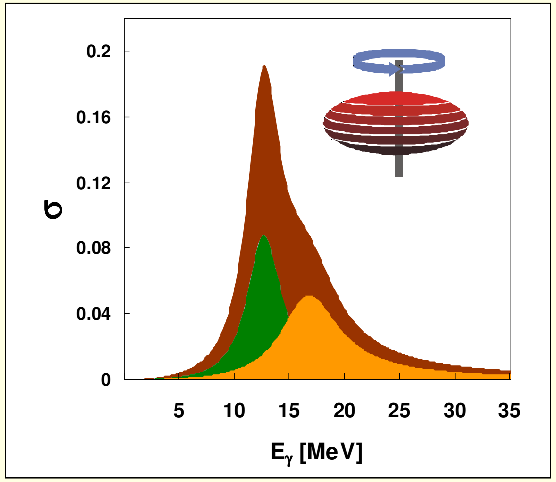


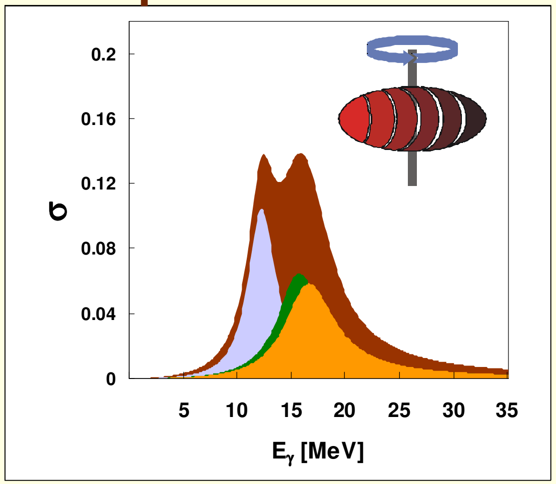
"Oblate"→fission



„Jacobi shapes"

„Oblate" →3-axial→ →"prolate"→fission

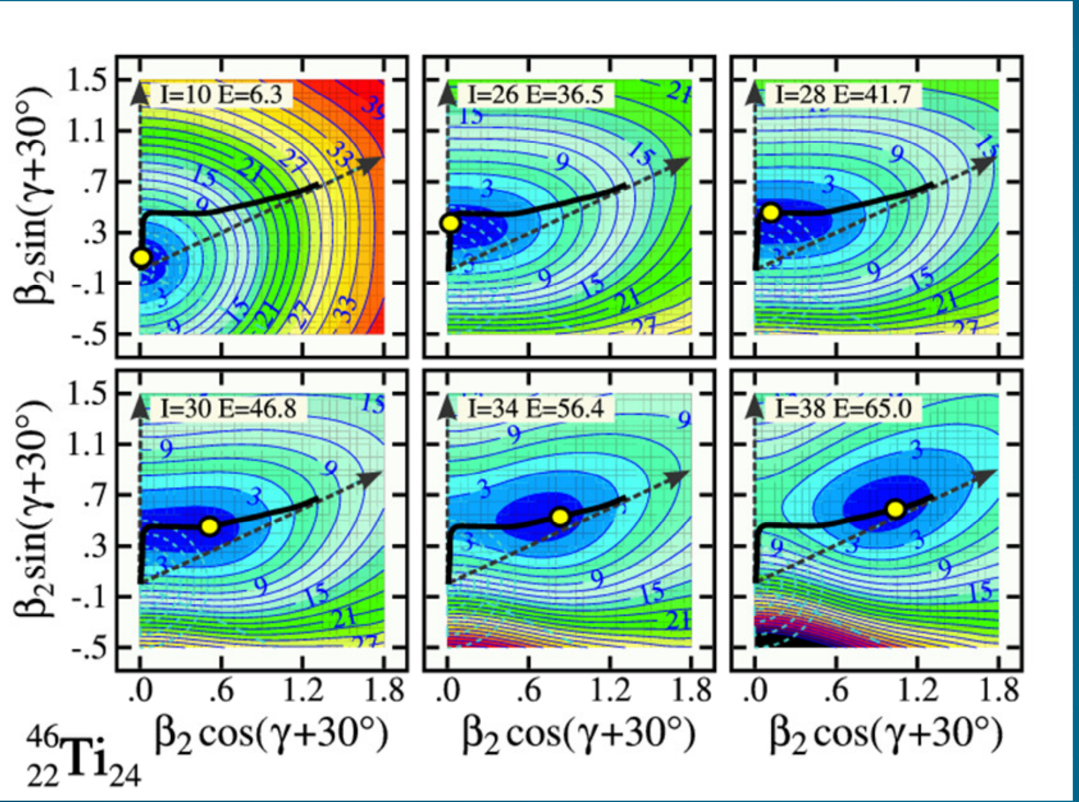




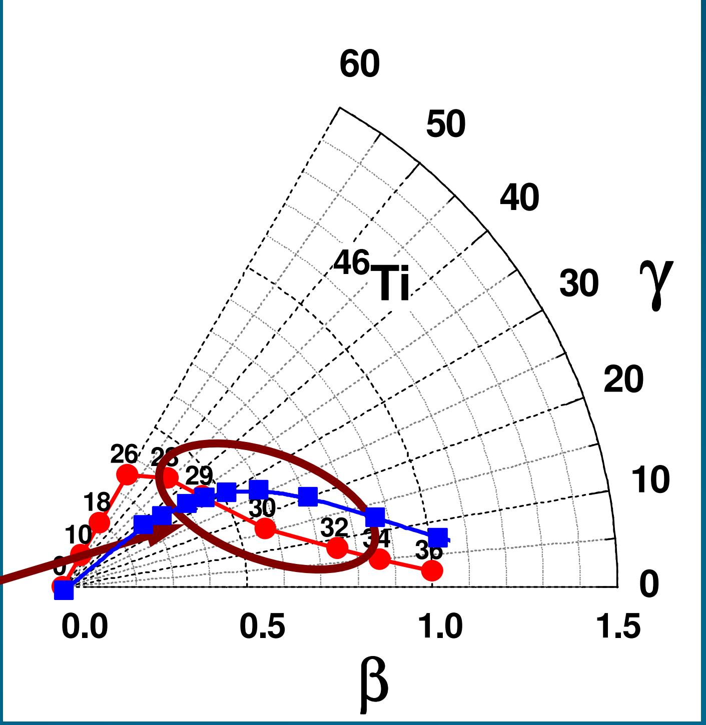
Jacobi shape transition - theoretical predictions

potential energy calculated
with LSD (Lublin-Strasbourg Drop) model:

Dudek & Pomorski Phys. Rev. C67 (2003) 044316



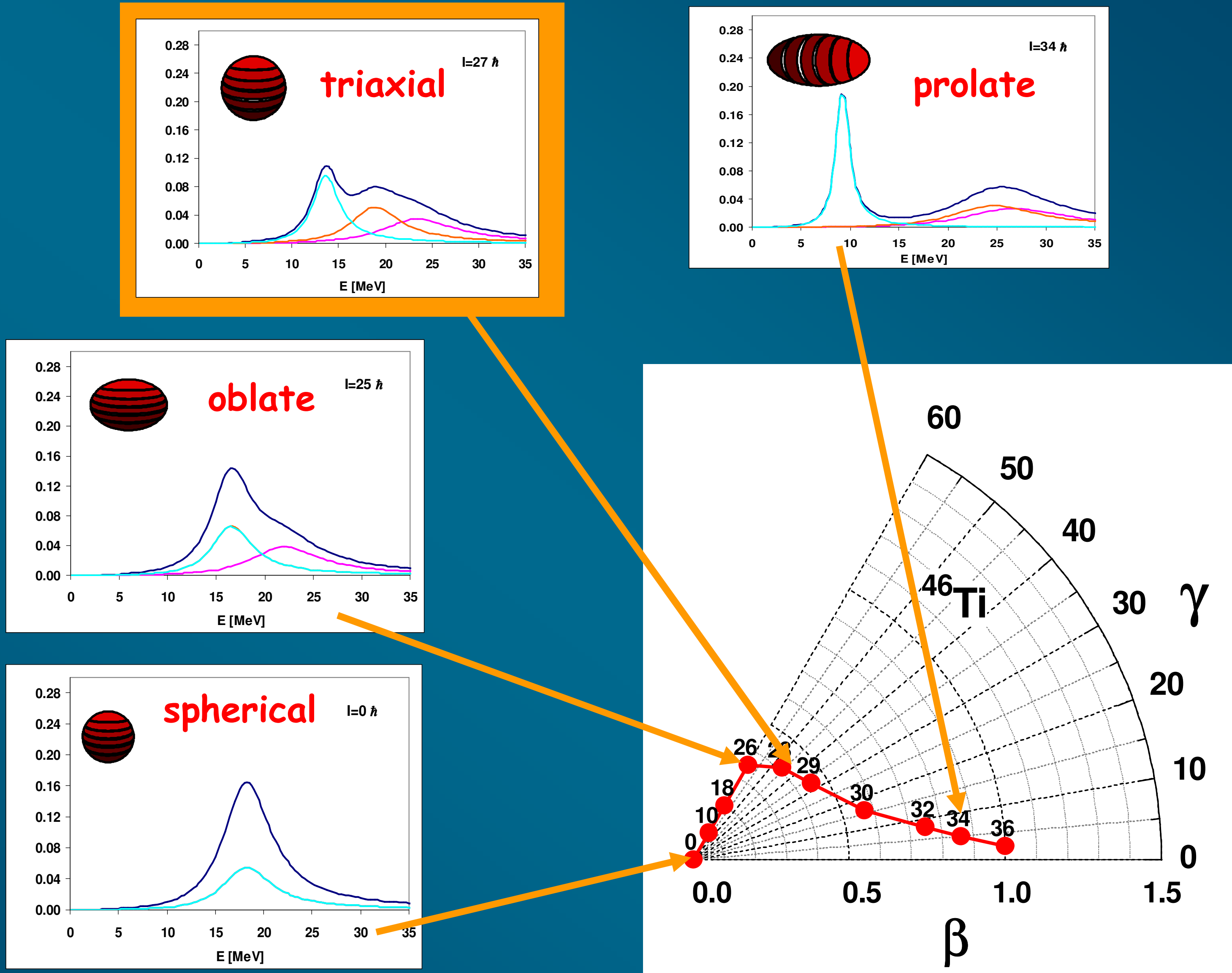
equilibrium shape evolution



Jacobi shape transition

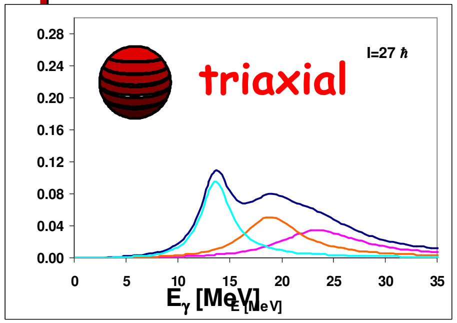
average shape

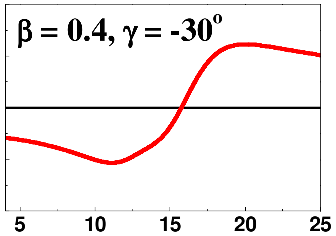
Jacobi shape transition – GDR strength function



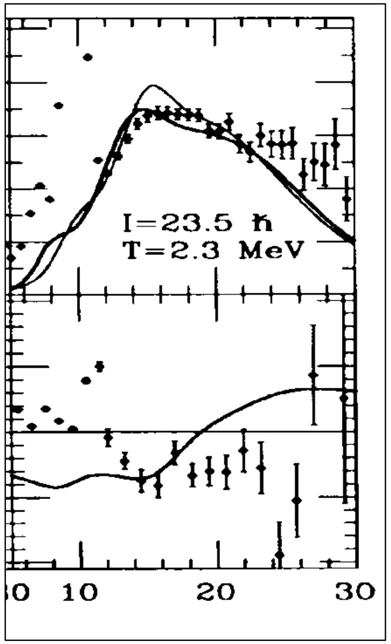
First signatures of Jacobi shape transition

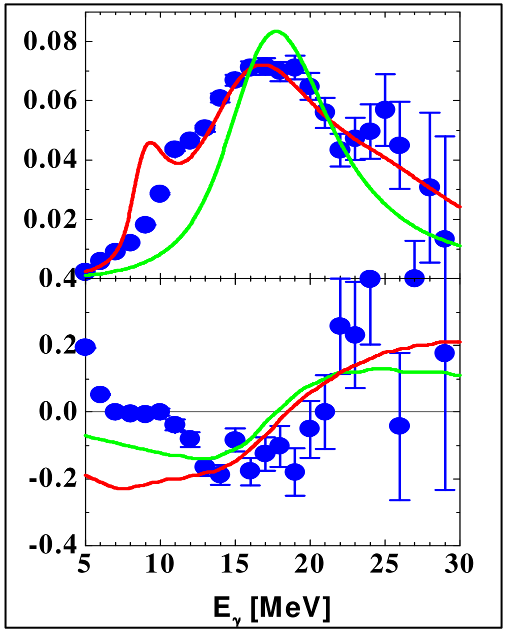
predictions





- **M. Kicińska-Habior et al., Phys. Lett. B308 (1993) 225:** *Seattle exp.* - Possible signature of the Jacobi shape transition for ^{45}Sc in the inclusive GDR spectrum



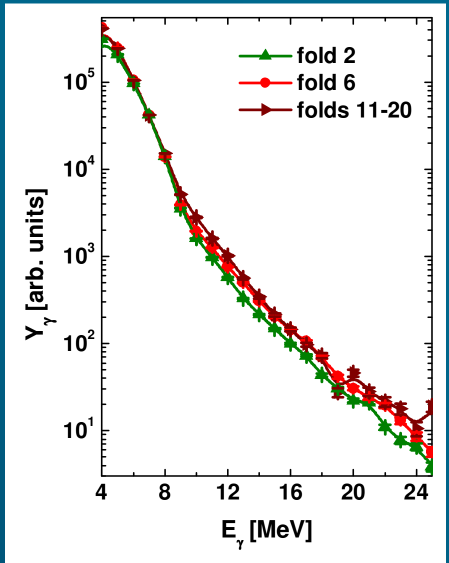


- **A. Maj et al, Nucl. Phys. A687 (2001) 192:** *NBI exp.* – Possible signatures of the Jacobi shape transition for ^{46}Ti in the multiplicity gated GDR spectra and angular distributions

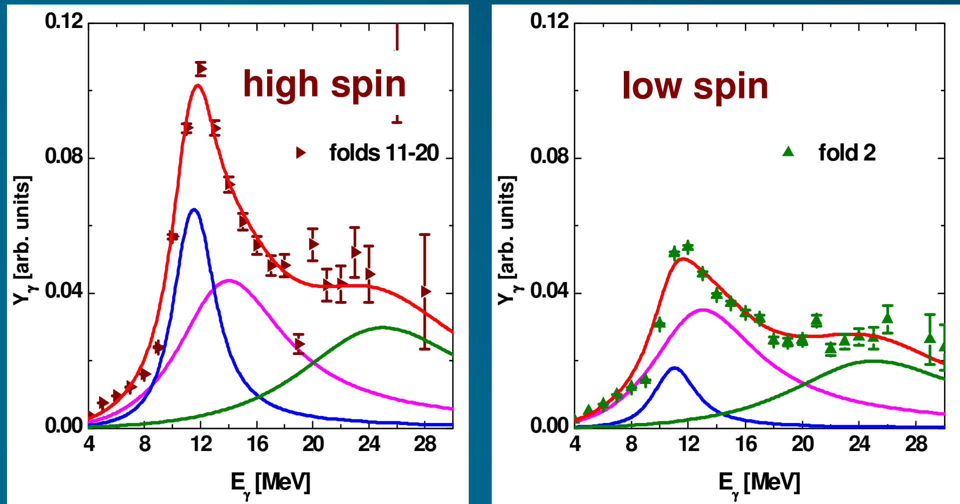
HECTOR+EUROBALL experiment

105 MeV ^{18}O + $^{28}Si \Rightarrow {}^{46}Ti^*$
$L_{max} \approx 35\,\hbar$
$E^* = 85$ MeV

A. Maj et al., Nucl. Phys. A731 (2004) 319c.

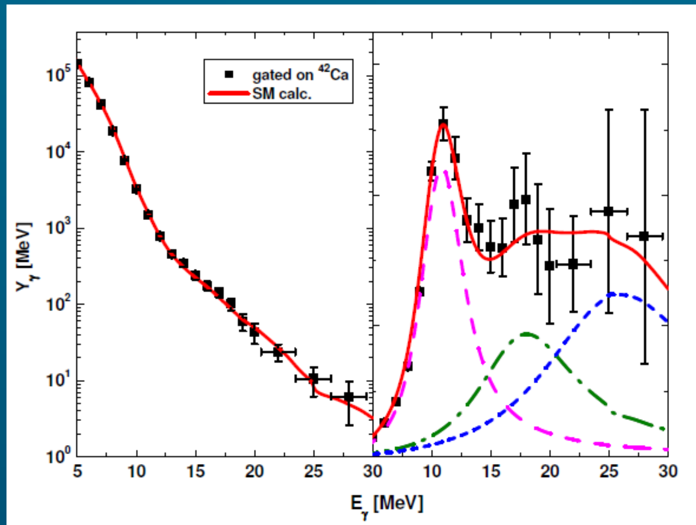


multiplicity gated

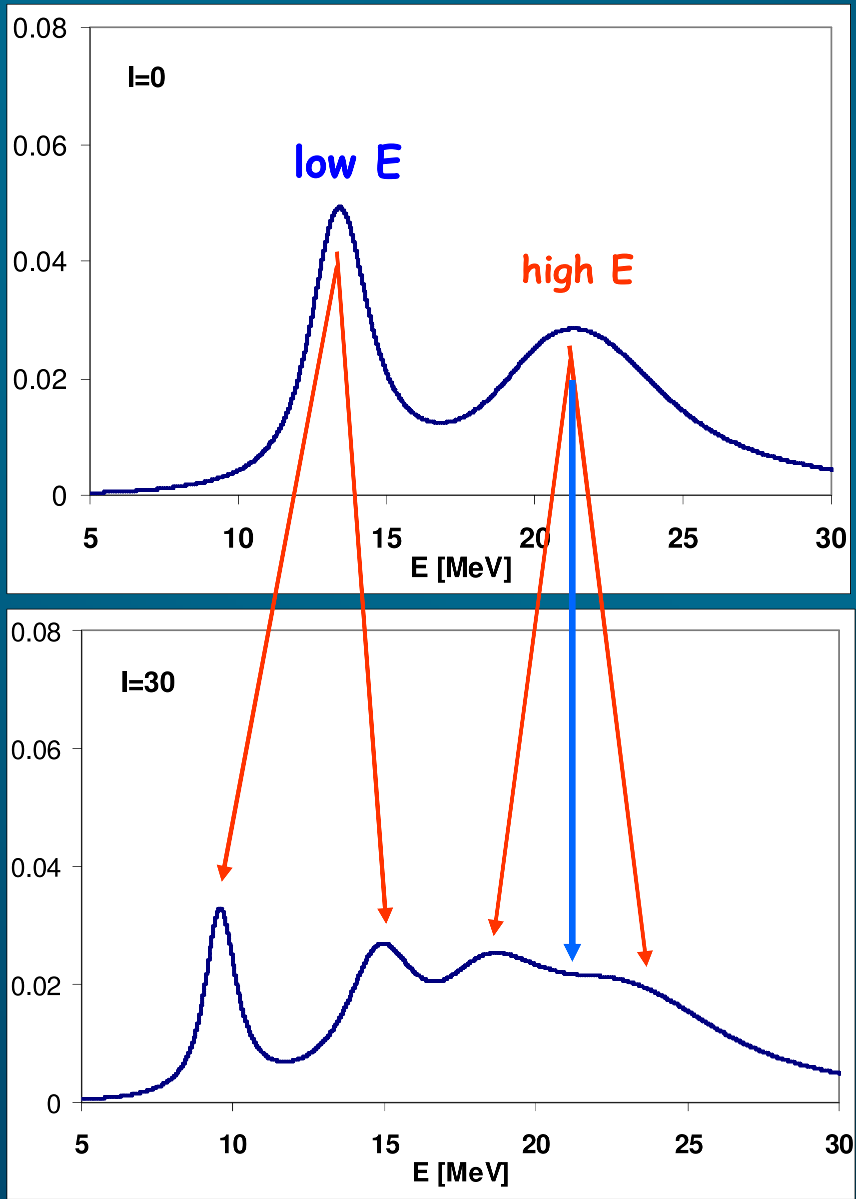


low energy component increasing with spin

gated with
γ transitions
in ^{42}Ca residuum



Coriolis splitting of the GDR components



prolate
β=0.5

ω=0

ω=2.8

(I=30 for A=46)

K. Neergård, Phys. Lett. 110B (1982) 7

$$\Omega_{2,3}^{2} = \frac{\omega_2^2 + \omega_3^2}{2} + \omega^2 \pm \sqrt{\Delta}$$

$$\Delta = \frac{1}{4}\left(\omega_2^2 - \omega_3^2\right)^2 + 2\omega^2\left(\omega_2^2 + \omega_3^2\right)$$

J.J. Gaardhøje, A. Maj et al., Acta. Phys. Pol. B24 (1993) 139; T. Døssing, private communication

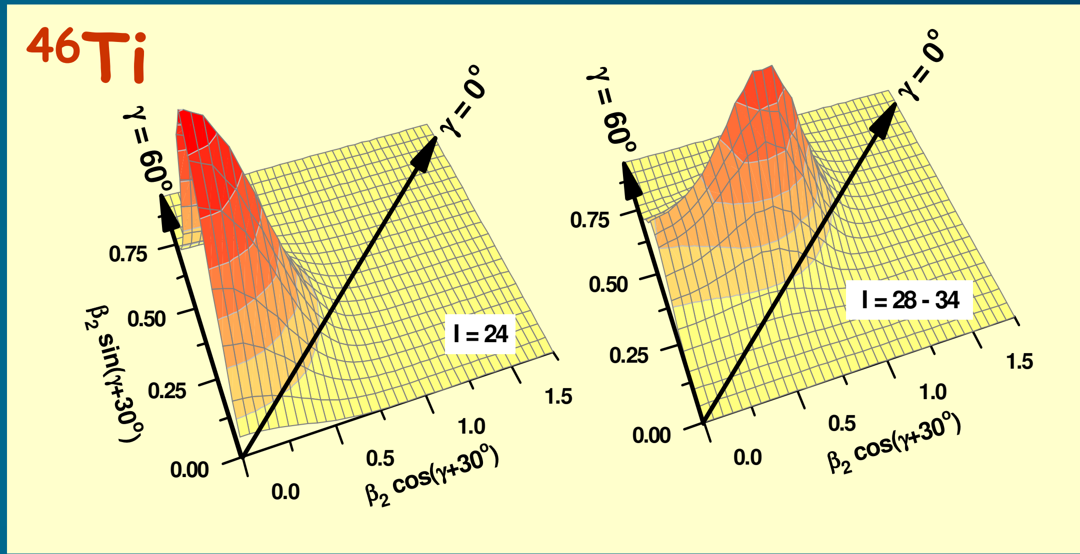
Frequency

$\omega = 0$	$\omega > 0$
ω_1	ω_1
ω_2	$\Omega_2 + \omega$
	$\Omega_2 - \omega$
ω_3	$\Omega_3 + \omega$
	$\Omega_3 - \omega$

LSD calculations

thermal shape
fluctuations +
Coriolis splitting

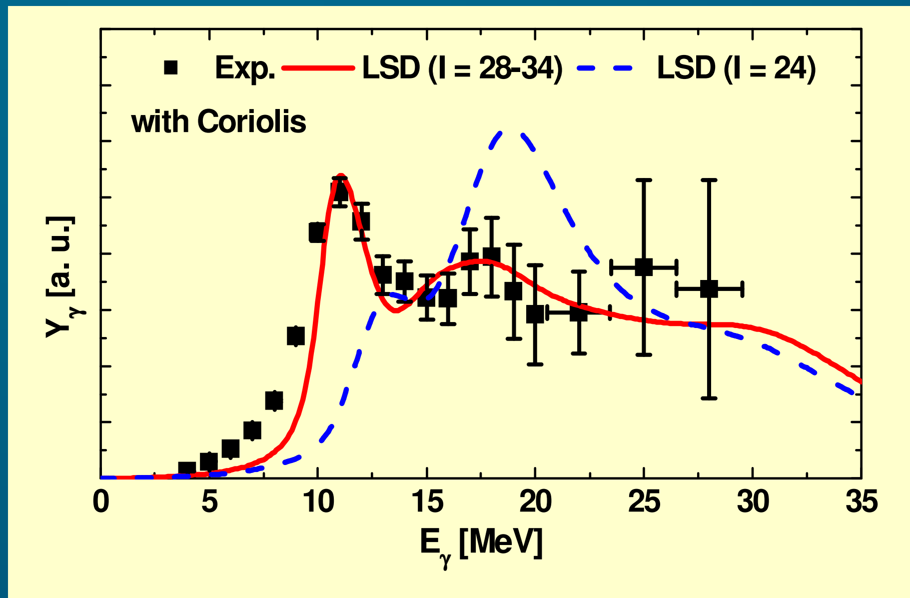
$P(\beta,\gamma) \propto \exp(-F(b,g)/T)$



$$f^{av}_{GDR}(T,I) = \iint f_{GDR}(\beta,\gamma,\omega)e^{-F(T,I;\beta,\gamma)/T(I;\beta,\gamma)}\beta^4 \left|\sin(3\gamma)\right| d\beta d\gamma$$

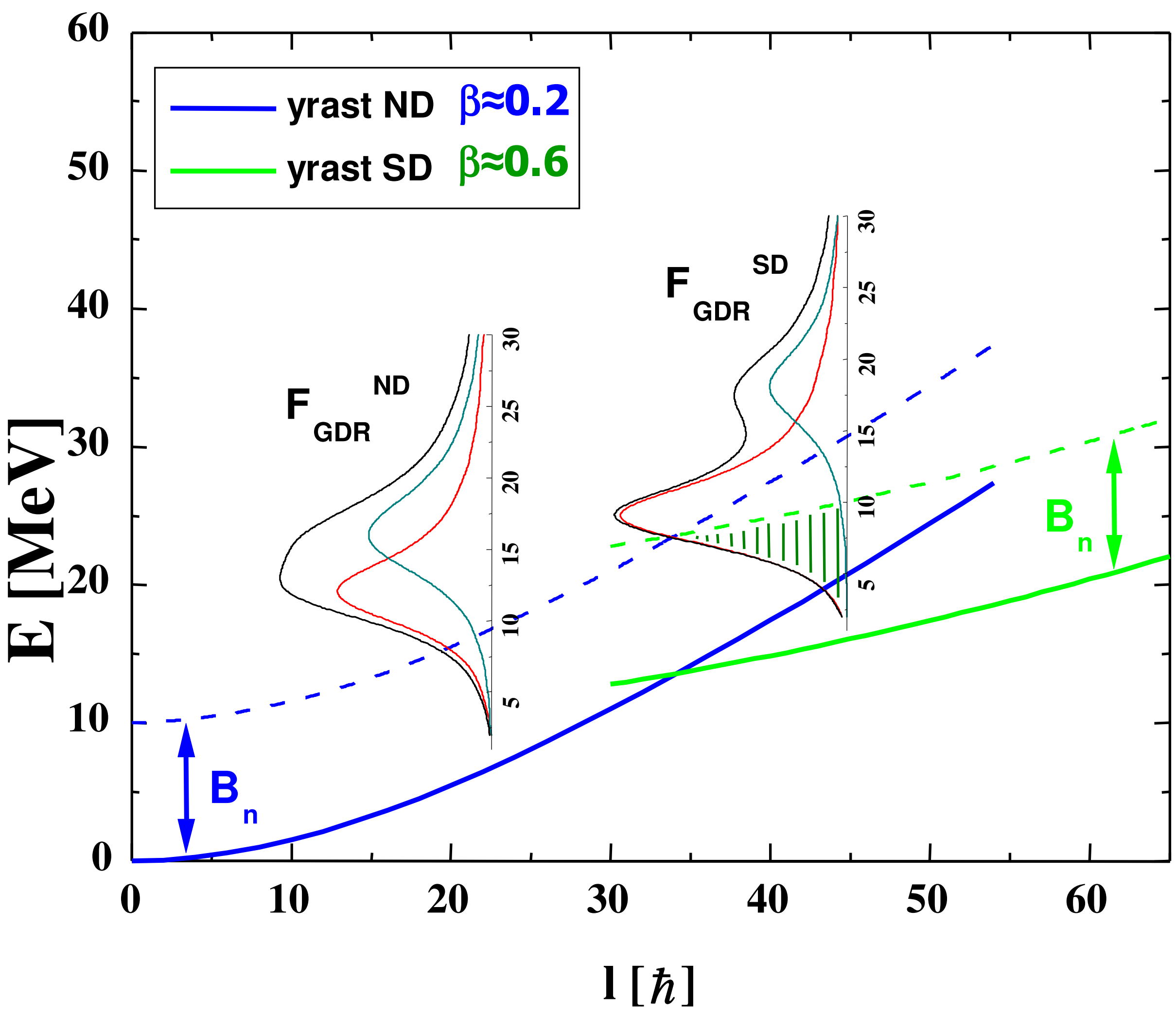
Jacobi shape transition and indicated for the first time Coriolis effect

A. Maj et al., Nucl. Phys. A731, 319c (2004)



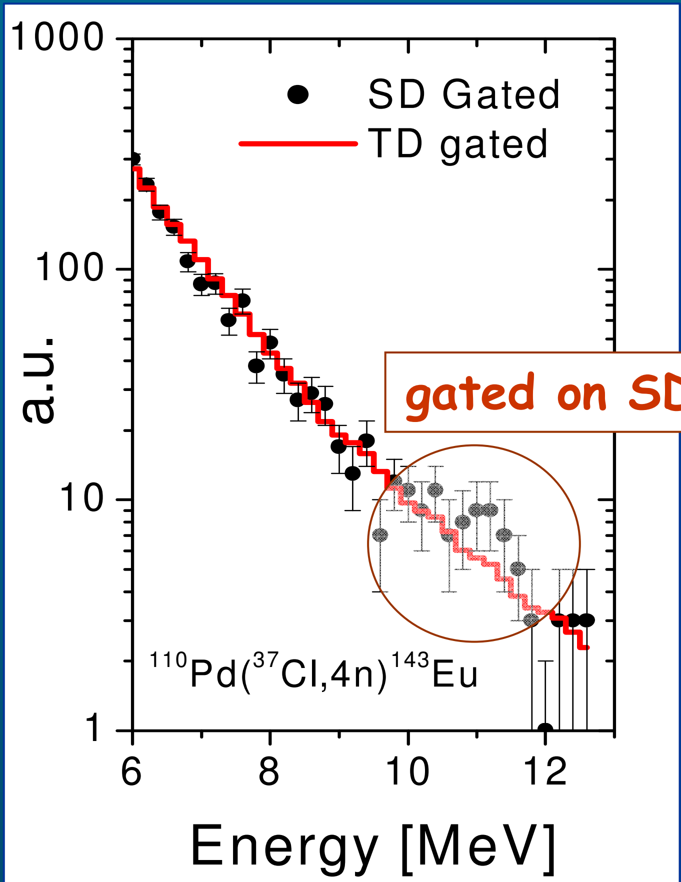
GDR built on superdeformed nucleus

GDR built on superdeformed nucleus - predictions



GDR built on superdeformed nucleus - indications

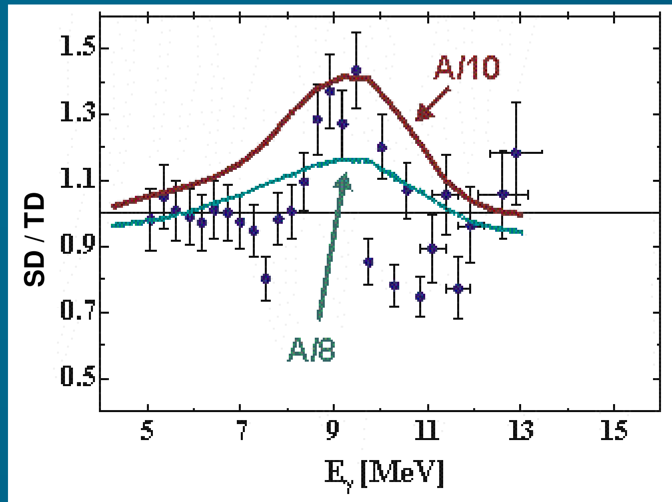
^{37}Cl(165 MeV) on ^{110}Pd ⇒ ^{147}Eu*



^{143}Eu

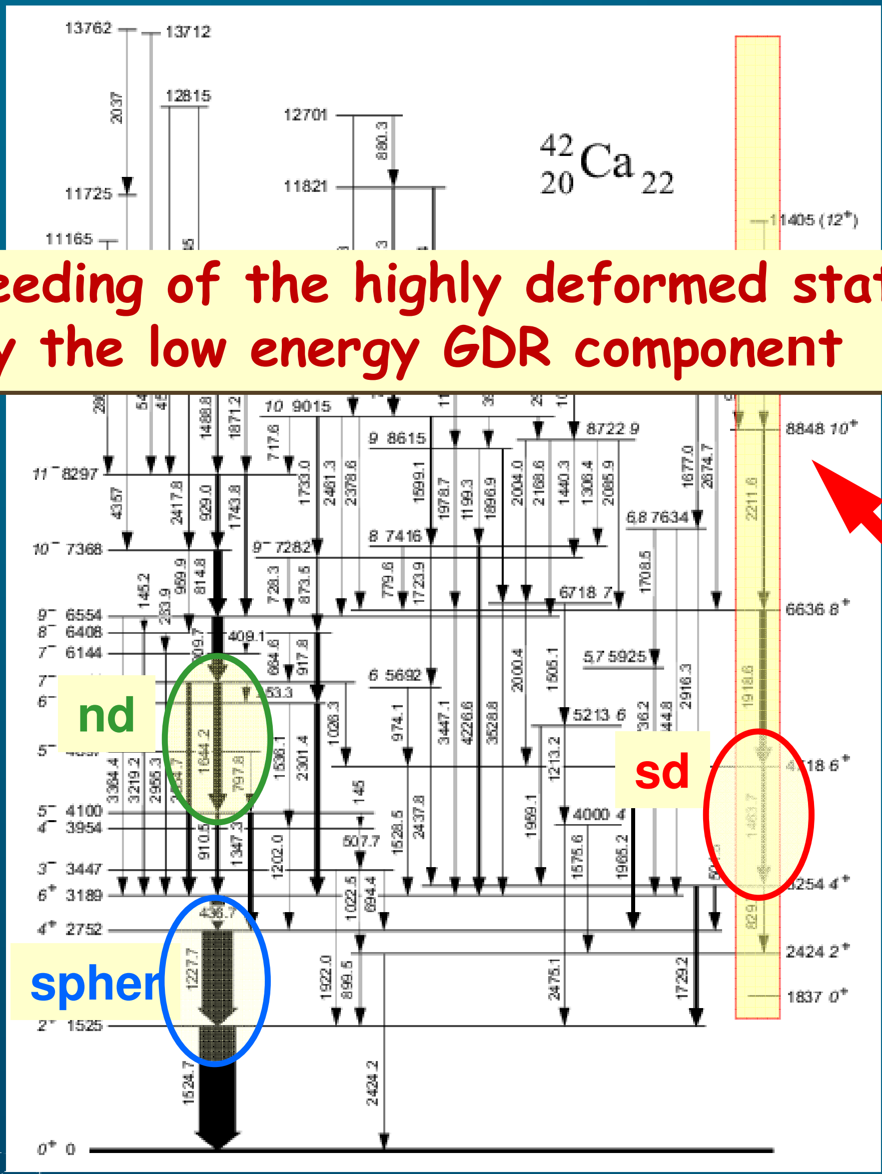
gated on SD band

F. Camera et al., Acta Phys. Pol. B32 (2001) 807

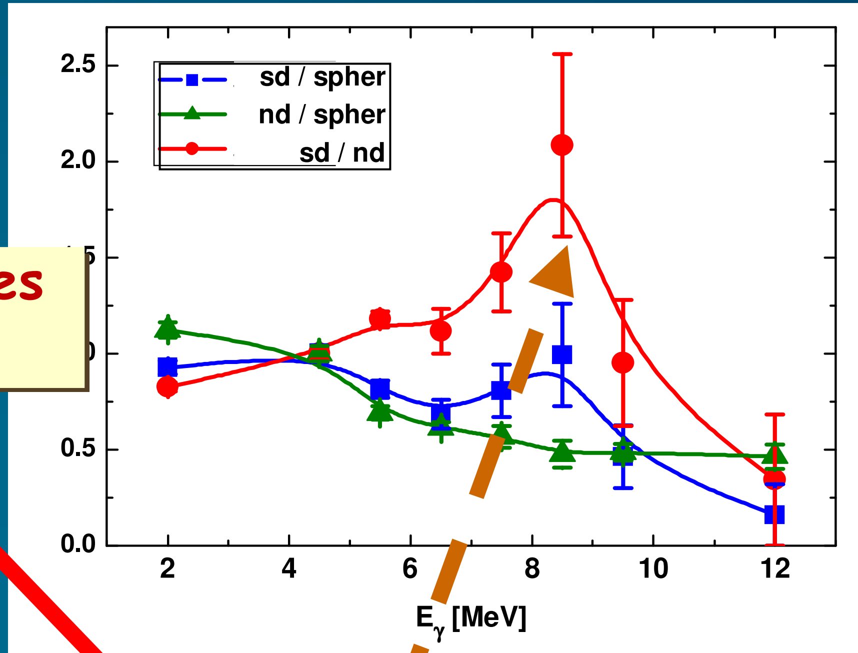


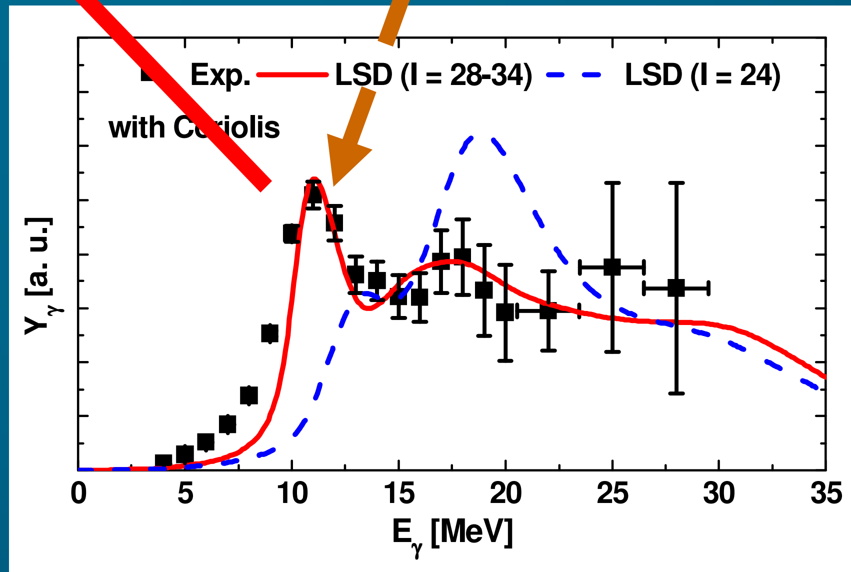
Feeding of highly deformed states by GDR - ^{42}Ca case

feeding of the highly deformed states by the low energy GDR component



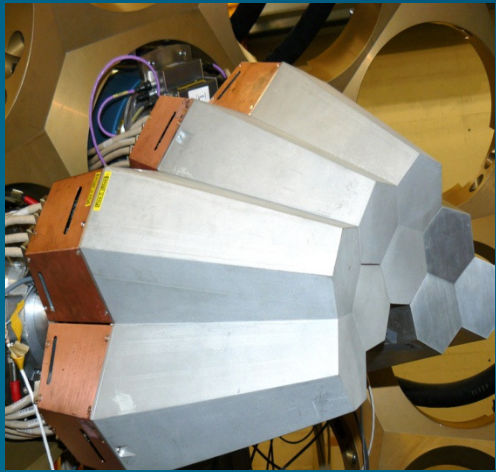
M. Kmiecik et al., Acta Phys. Pol. B36 (2005) 1169





Search for highly deformed states in ^{42}Ca using Coulomb excitation – AGATA Demonstrator experiment

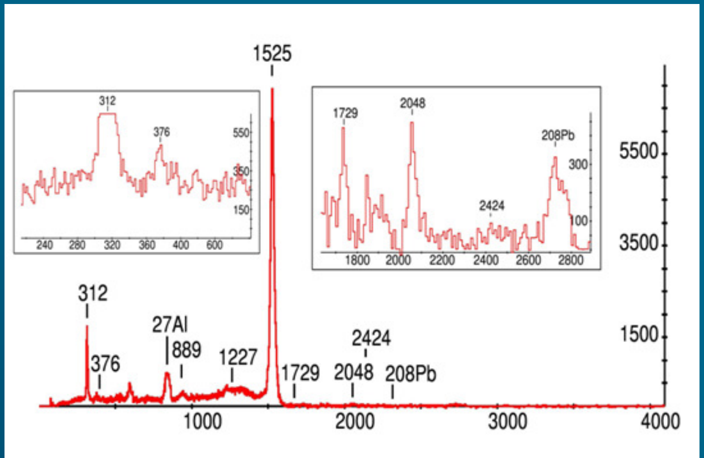
Experiment proposed by Adam Maj (IFJ PAN Krakow),
Paweł Napiorkowski (HIL Wrasaw)
and Faical Azaiez (IPNO Orsay)



goal:
investigate the deformation of nucleus
at states from the highly deformed band

reaction:
Coulomb excitation ^{42}Ca on ^{208}Pb target

measured:
•γ rays
•back-scatered projectiles

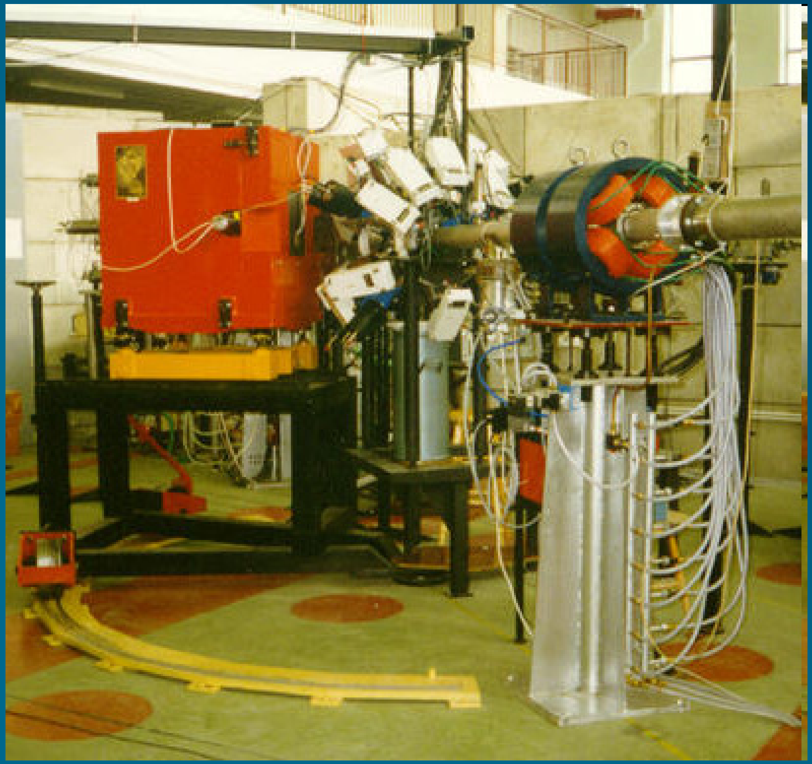


Isospin mixing studies in Heavy Ion Laboratory in Warsaw

GDR studies in Warszawa

- **JANOSIK set-up**
  - 25 cm x 29 cm NaI(Tl) detector for high-energy γ-ray measurement
    with shield (plastic + ^{6}LiH + lead) to reduce cosmic background
  - Si-Ball – p and α detection

M. Kicińska-Habior et al., Acta Phys. Pol. B27 (1996)547,
Acta Phys. Pol. B28 (1997)219



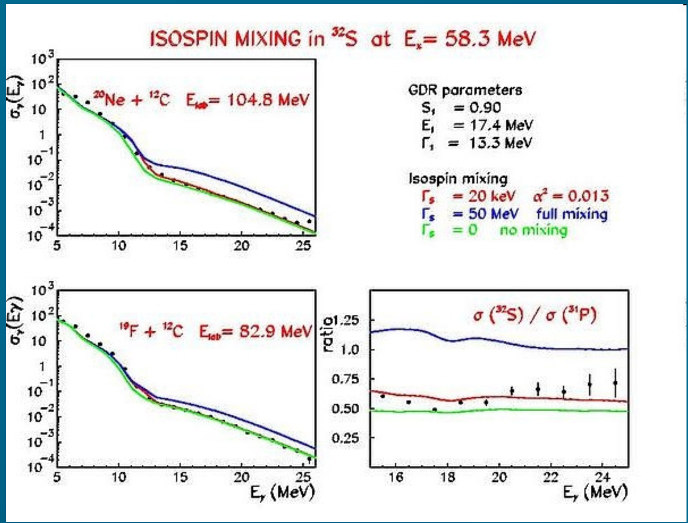
- **Isospin mixing investigations**

GDR measured for two neighbouring
N=Z and N≠Z nuclei at similar excitation energies

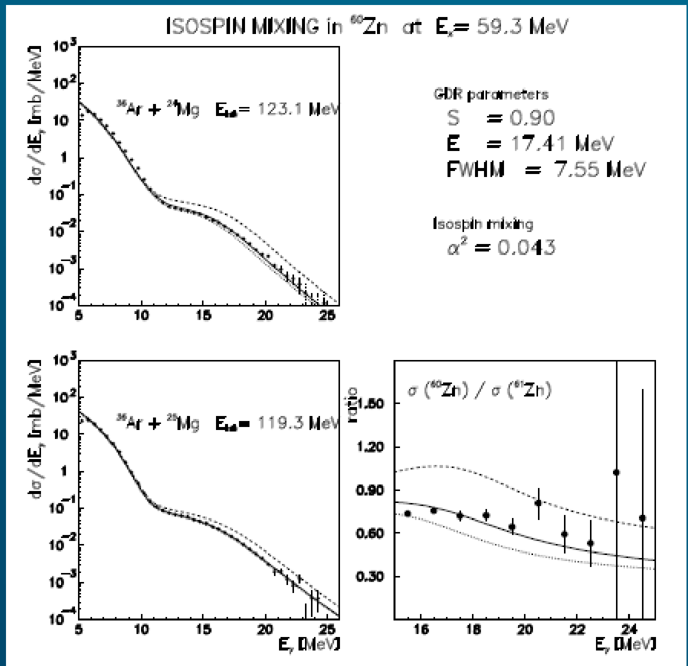
N≠Z – GDR parameters extracted
– statistical model Cascade
N=Z – α^2 (isospin mixing probabilty) obtained

M. Kicińska-Habior et al., Acta Phys. Pol. B36 (2005) 1133

Isospin mixing

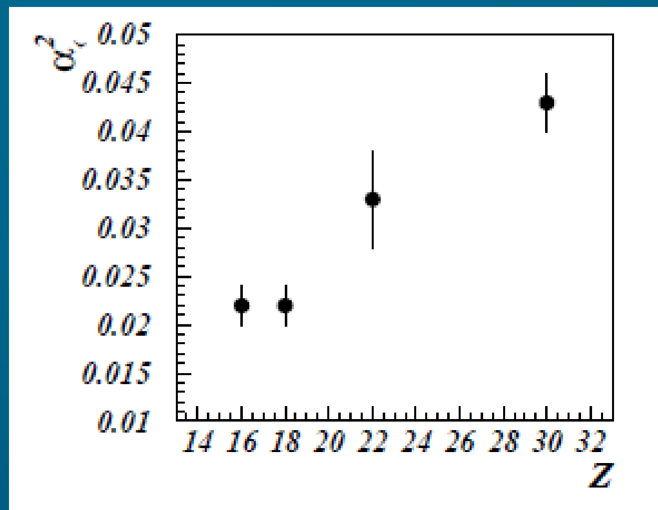


M. Kicińska-Habior et al., Nucl. Phys. A731c (2004) 138

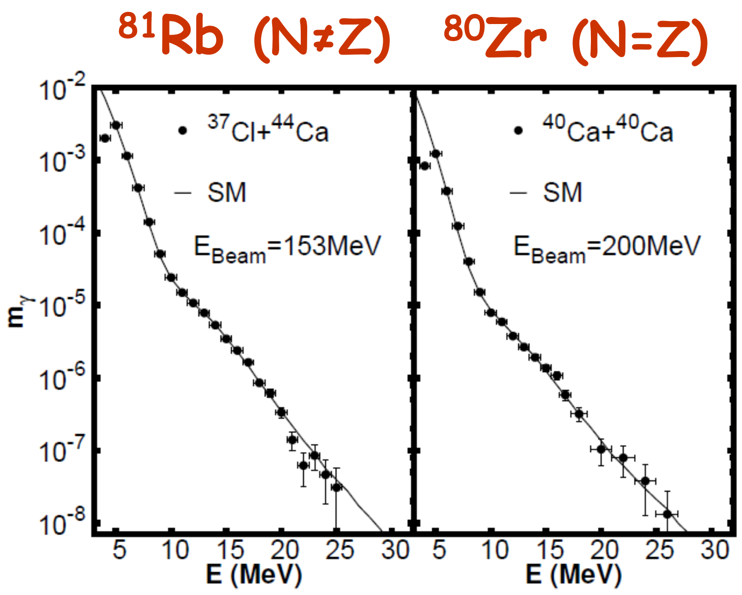


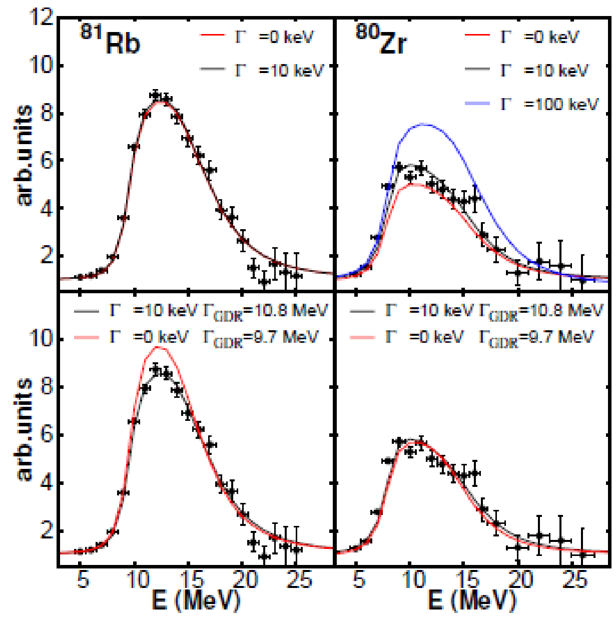
E. Wójcik et al., Acta Phys. Pol. B37 (2006) 207

E. Wójcik et al., Acta Phys. Pol. B38 (2007) 1469

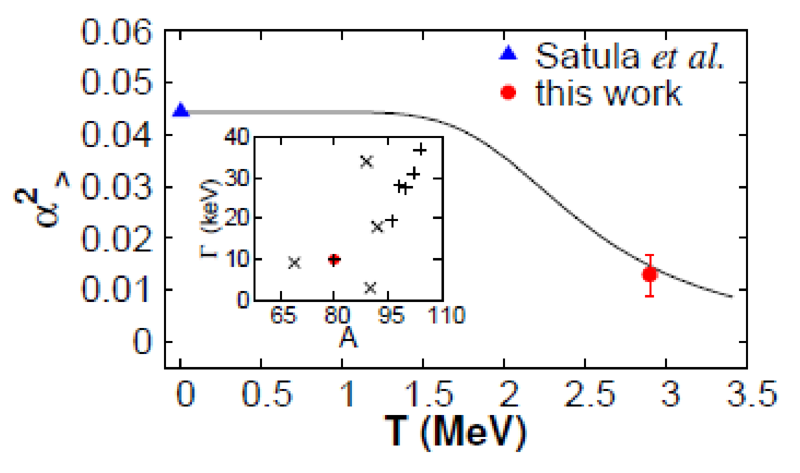


Isospin mixing studied by HECTOR collaboration



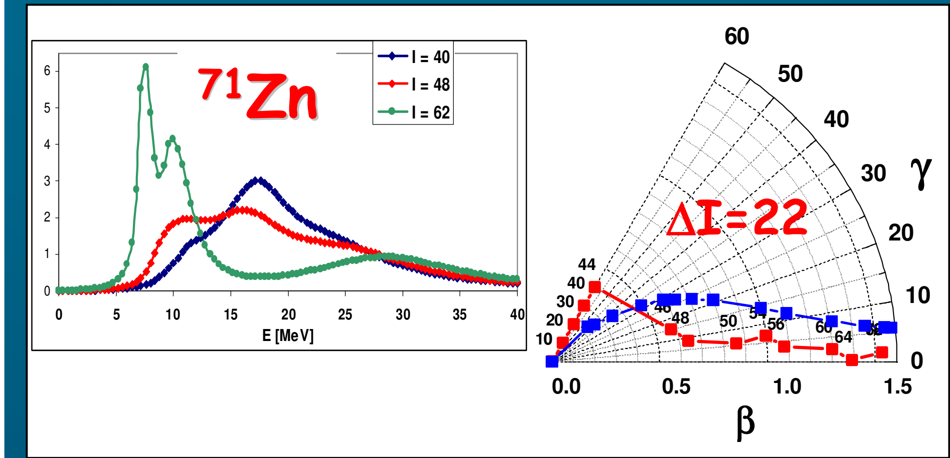


A. Corsi et al., to be published

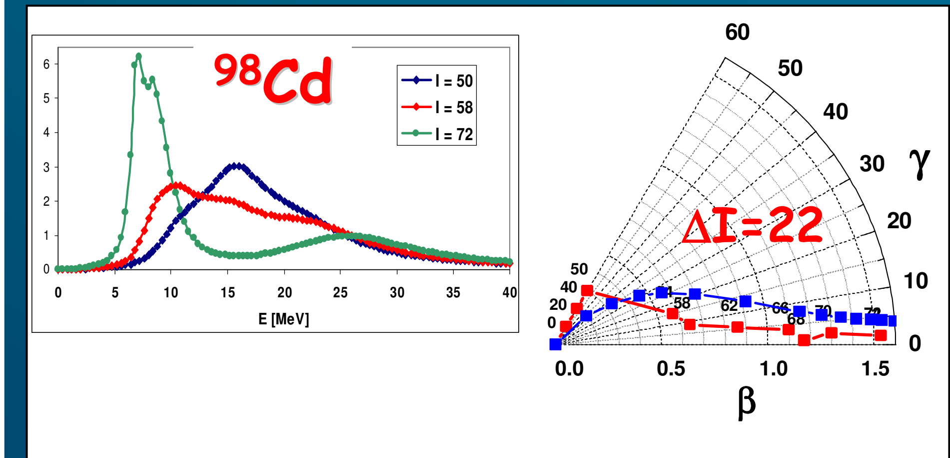


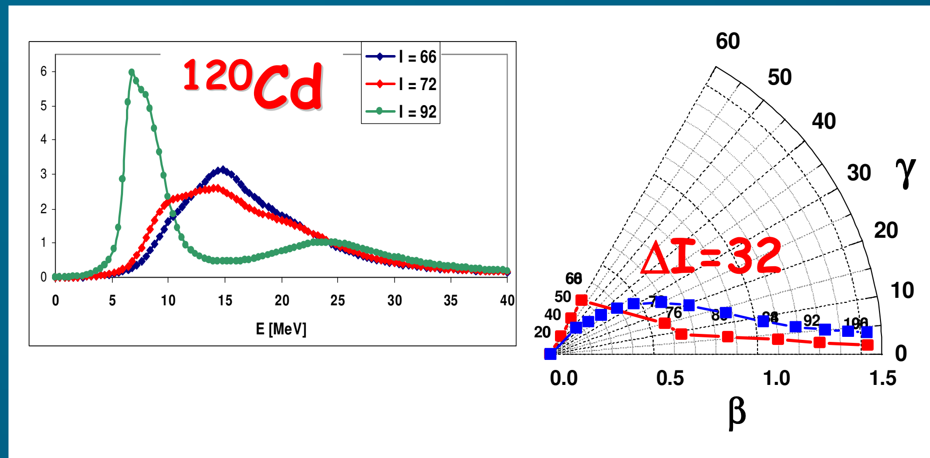
Perspectives

Theoretical predictions for Jacobi shape transition - examples



- wide spin window for Jacobi shapes
- large spins



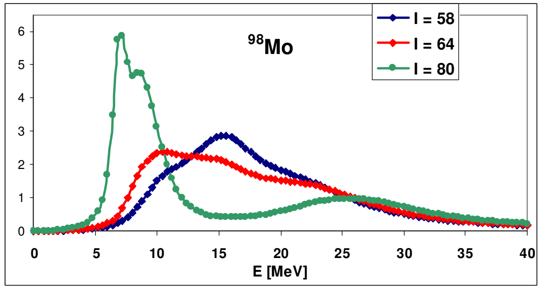


Future experiments

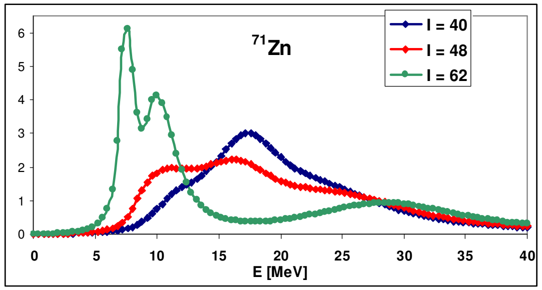
- Possible with high intensity radioactive beams that will be available at new facilities (e.g. SPIRAL2)

$^{68}_{28}$Ni + $^{30}_{14}$Si → $^{98}_{42}$Mo;
10^8 pps
E_b = 500MeV, I_{max} = 85 ħ, E* = 150 MeV

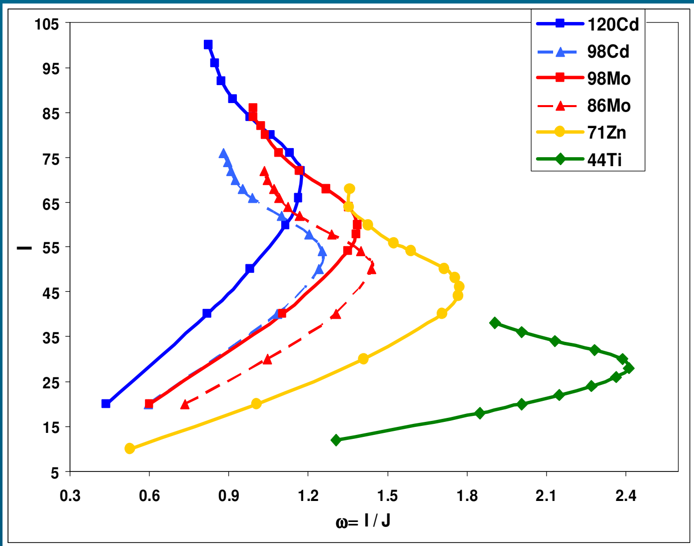
$^{58}_{28}$Ni + $^{28}_{14}$Si → $^{86}_{42}$Mo;
stable
E_b = 400MeV, I_{max} = 68 ħ, E* = 110 MeV



$^{23}_{10}$Ne + $^{48}_{20}$Ca → $^{71}_{30}$Zn;
10^6 pps
E_b = 220MeV, I_{max} = 70 ħ, E* = 160 MeV

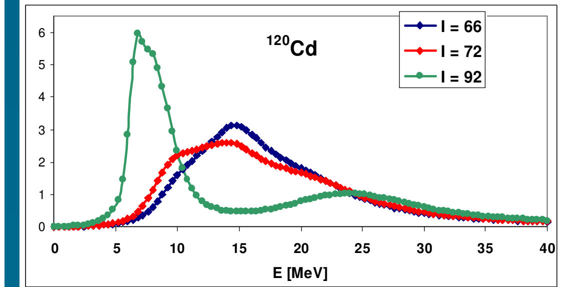


Summary of the experimental programme for GANIL

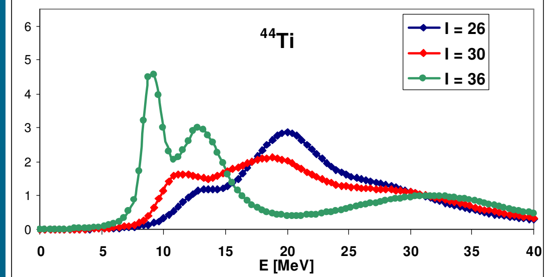


$^{94}_{36}$Kr + $^{26}_{12}$Mg → $^{120}_{48}$Cd;
10^{10} pps
E_b = 900MeV, I_{max} = 100 ħ, E* = 190 MeV

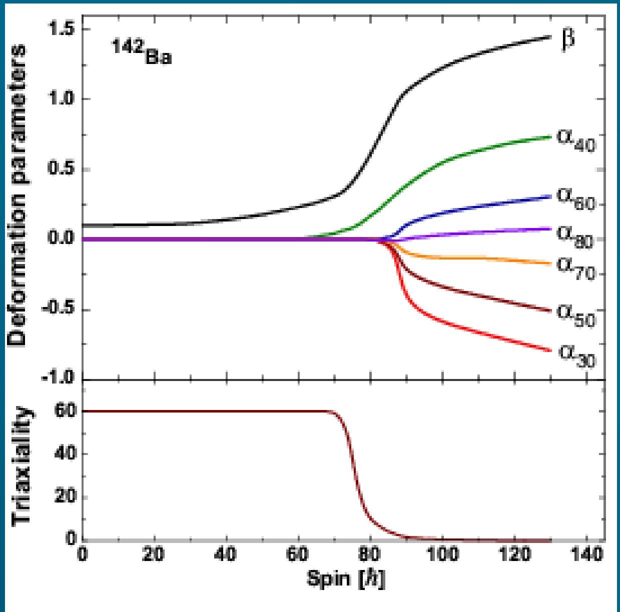
$^{40}_{20}$Ca + $^{58}_{28}$Ni → $^{98}_{48}$Cd;
stable
E_b = 250MeV, I_{max} = 78 ħ, E* = 120 MeV



$^{12}_{6}$C + $^{32}_{16}$S → $^{44}_{22}$Ti
stable
E_b = 170MeV, I_{max} = 38 ħ, E* = 130 MeV



Poincare shapes investigations



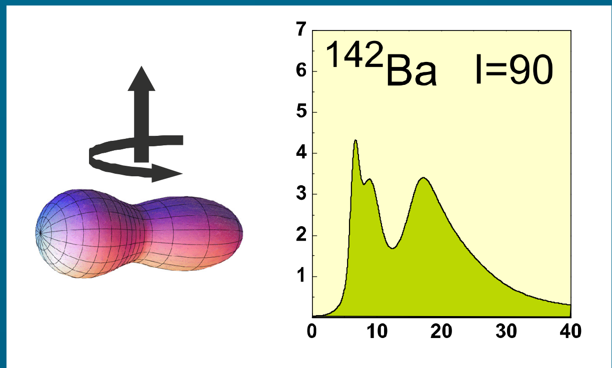
Poincare shapes predicted for the first time

New calculations based on the LSD model, allowing odd-rank deformation parameters (α_{30}, α_{50}, α_{70}) be free:

K. Mazurek, J. Dudek et al., Acta Phys. Pol. (2011) in print

A.Maj, K. Mazurek, J. Dudek, M. Kmiecik, D. Rouvel "Shape evolution at high spins and temperatures: nuclear Jacobi and Poincare transition", J. Mod. Phys. E19 (2010) 53

to be observed in the GDR strength function

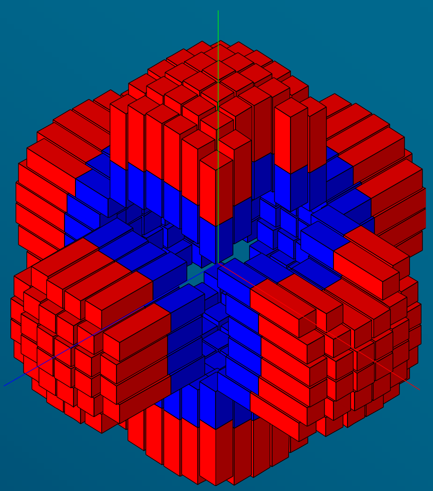


At GANIL –SPIRAL2 (later stage: Phase2-Day2)

$^{94}Kr + ^{48}Ca \rightarrow ^{142}Ba$

New very efficient high-energy γ-ray detector

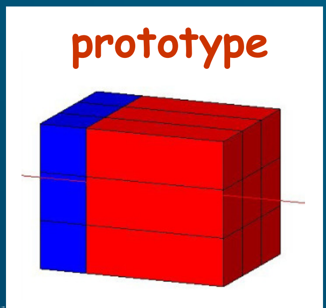
PHOTON ARRAY FOR STUDIES WITH RADIOACTIVE ION AND STABLE BEAMS



PARIS desing concepts:

- high efficiency detector consisting of phoswich detectors for medium resolution spectroscopy and calorimetry of γ rays in large energy range

Phoswich detector will consit of new **$LaBr_3$(Ce)** 5 x 5 cm crystals and conventional crystals **NaI**.
The first stage will be the prototype made of 9 phoswich detectors.



PARIS will be used as a high and low-energy photon deterctor, multiplicity filter of high resolution and sum-energy detector (calorimeter),

It will be mechanically compatible with other detectors: e. g. AGATA, GASPARD

Summary

- The GDR strength functions (lineshape) measurements deliver information on properties of nucleus (at ground and exited state)
  - At given temperature the shape of the nucleus is described by the shape distribution
  - The deformation of nucleus increases with spin due to increase of angular momentum and it is larger for higher rotational frequency
  - The thermal shape fluctuations are important in describing shapes of nuclei as a function of temperature
  - At high temperatures the CN life time has to be taken into account
  - The GDR can be built on superdeformed structure, and low energy component feeds the highly deformed states.
  - The GDR spectra measurements provide information about isospin mixing coefficient
- Perspectives for future investigations concern Jacobi and Poincare shape transitions at new facilities with radioactive beams
- The new, very efficient detector PARIS is developed

Thanks to

Kraków: Adam Maj, Kasia Mazurek, Michał Ciemała, Mirek Zięmbliński …….

Milano: Angela Bracco, Franco Camera, Oliver Wieland, Silvia Leoni,
Anna Corsi, ……….

Warszawa: Marta Kicińska-Habior

………..