Nuclear structure at the highest spins

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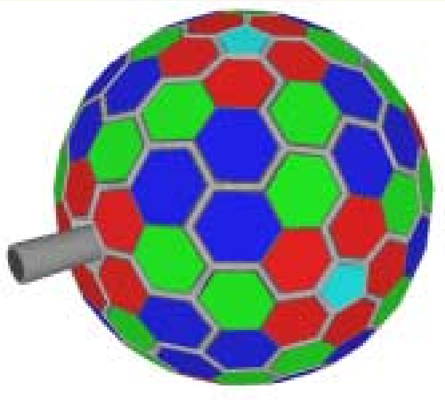
Key Questions

- What is the maximum angular momentum a nucleus can sustain?
- What exotic shapes can be stabilized and how do collective shapes evolve?
- What are the new symmetries, shapes, and excitation modes at the limits of angular momentum?
- How is the shell structure changed – where are the new closed shells and which new high-j orbitals appear?
- How is the rotational behavior affected by the quenching of pairing and by the finiteness of the nuclear system?



Outline

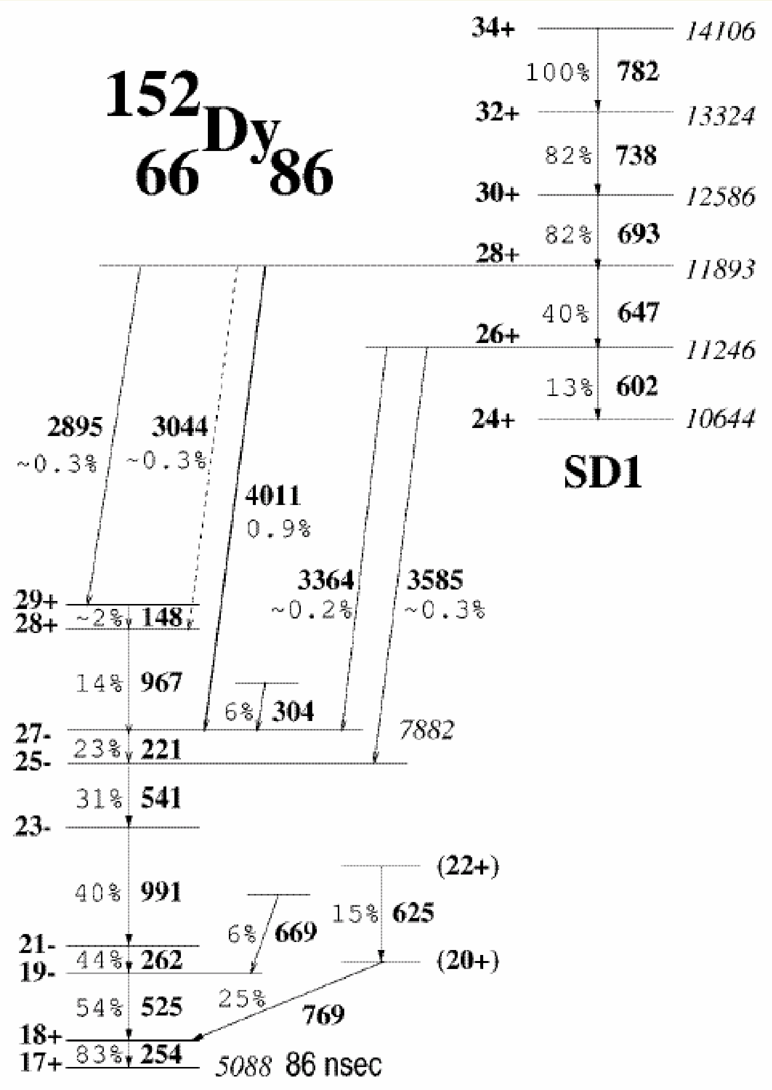
Recent results and current efforts:

- What have we achieved?
- How have we achieved it?
- How can we improve?
- Where are the limits today?

Future opportunities:

- Gamma-ray tracking array (AGATA)
- radioactive beams (EURISOL)

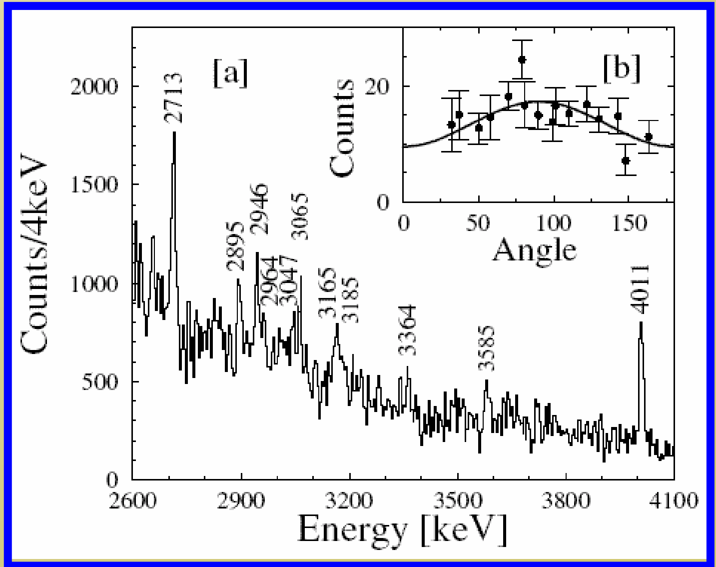
Superdeformation



T. Lauritsen et al., PRL 88, 042501 (2002)
PRL 89, 282501 (2002)

- We know more than 200 SD bands
- For most of them, we are still missing crucial experimental information:
  - excitation energy
  - spin, parity
  - lifetimes
  - decay and feeding properties
  - …

Two weeks of beam time needed to pull out links (and 16 years of trying…)
ε_{ph} @ 4 MeV : Gammasphere: ~2%, AGATA ~20%



resolving power

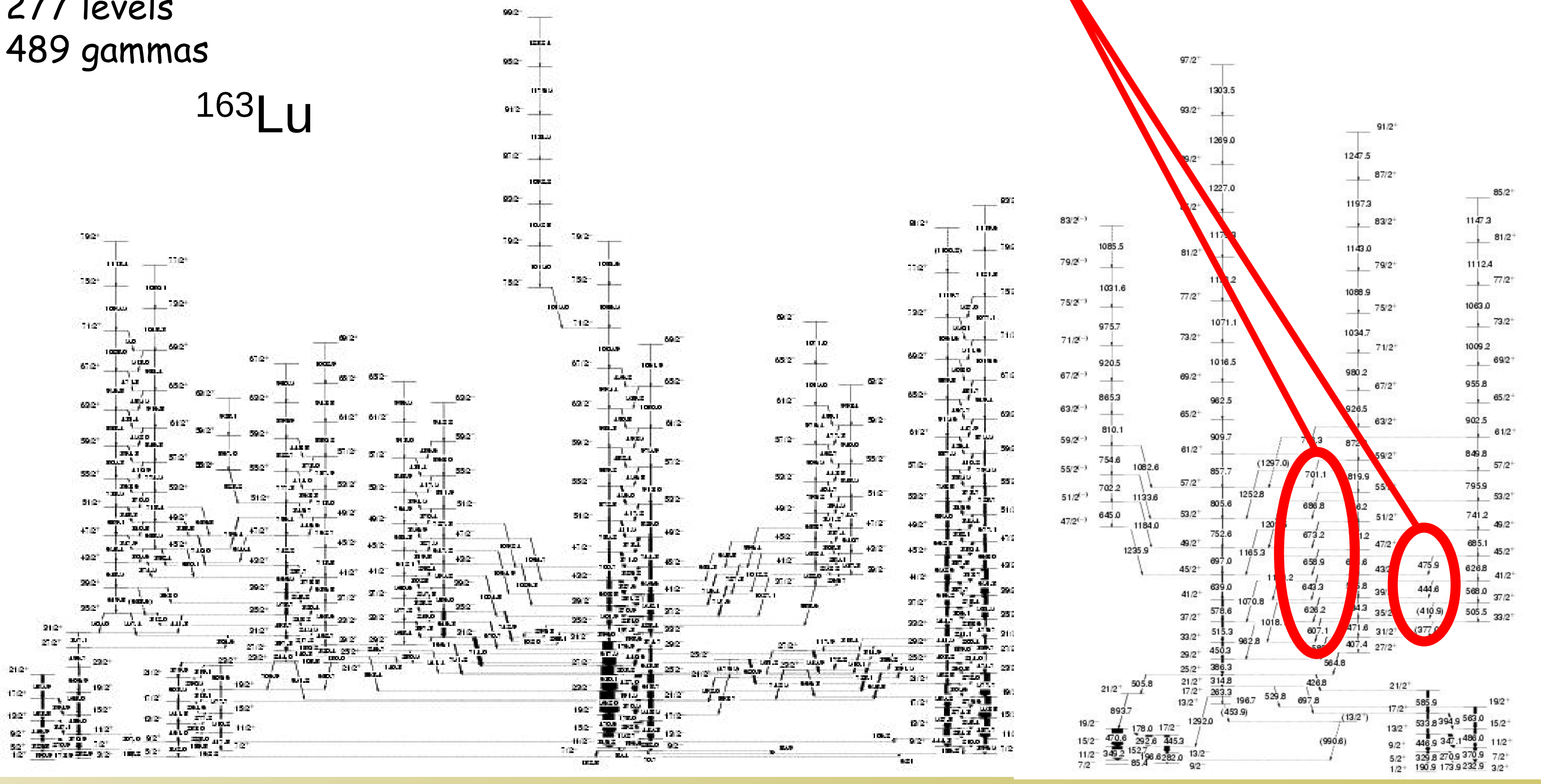
coincidence efficiency

Evidence for the wobbling mode from the properties of very weak interband transitions

277 levels

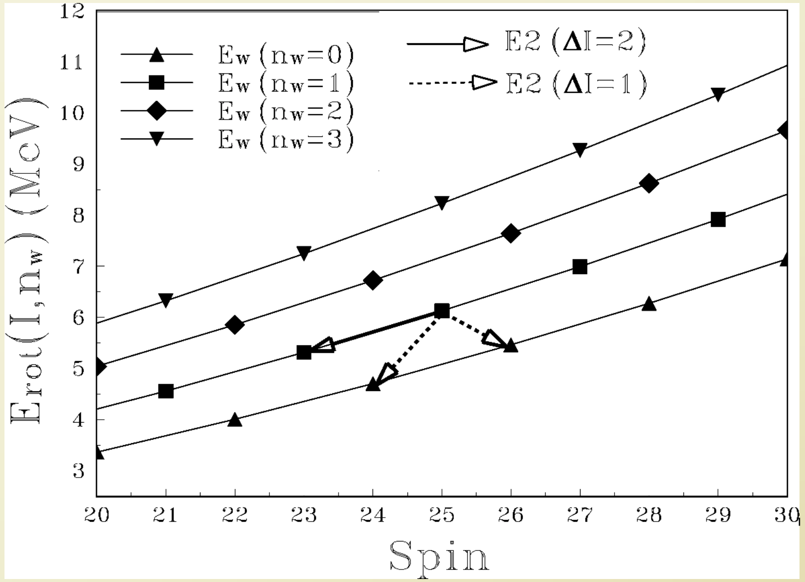
489 gammas

^{163}Lu



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

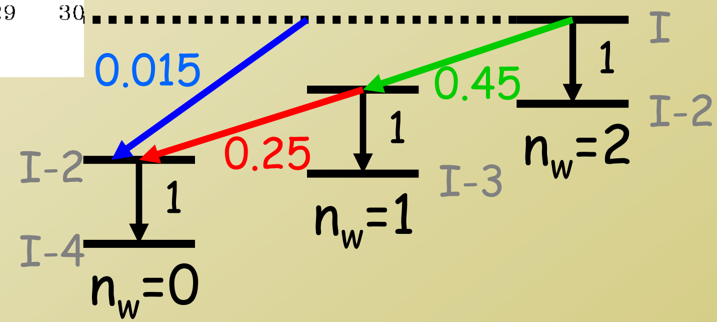
Wobbling of a triaxial nucleus

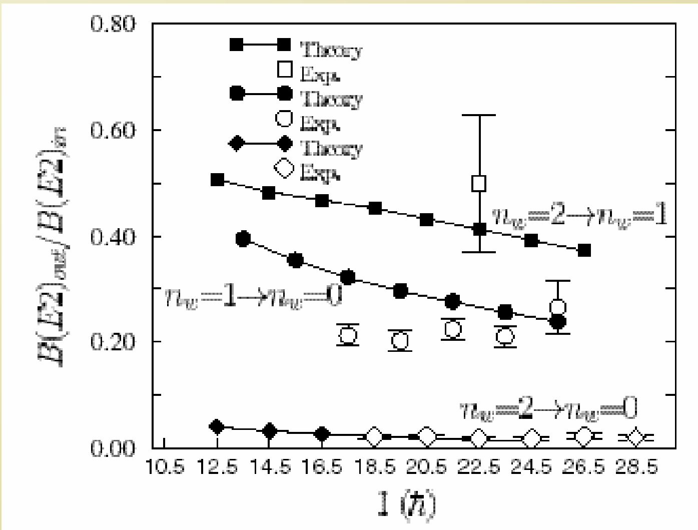


- unique to triaxial nuclei
- family of bands with same intrinsic structure
- characterized by wobbling phonon n_w
- characteristic interband transitions (ΔI=1, E2)

$$E_R(I, n_w) = \frac{I(I+1)}{2J_x} + \hbar\omega_w (n_w + 1/2)$$

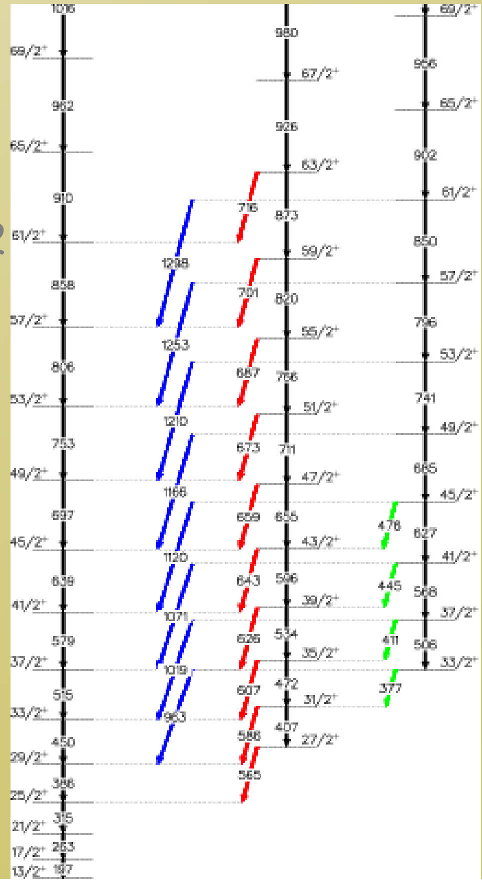
Part. Rotor calc., B(E2)'s





- ✓ Efficiency
- ✓ Resolution
- ✓ Selectivity
- ✓ Polarization sensitivity

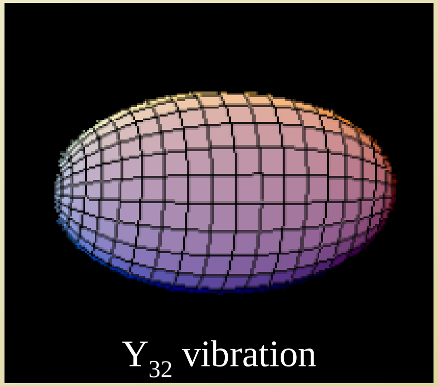
of EUROBALL

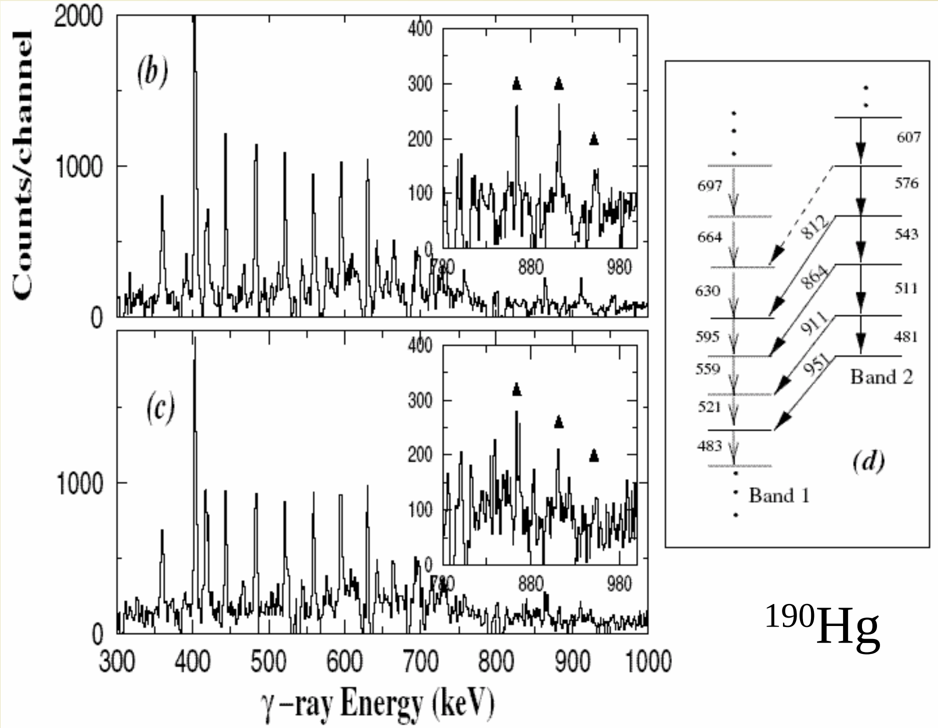


Octupole vibrations of superdeformed nuclei

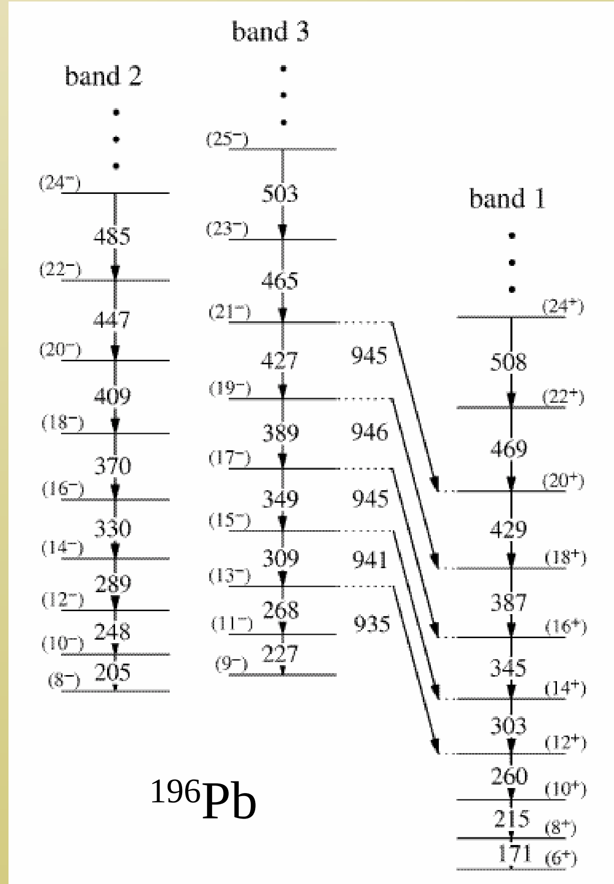
Strong E1 inter-band transitions
competing with fast E2 SD transitions

Evidence from linear polarization measurement
with EUROBALL Clover detectors





A. Korichi et al., Phys. Rev. Lett. 86, 2746 (2001)

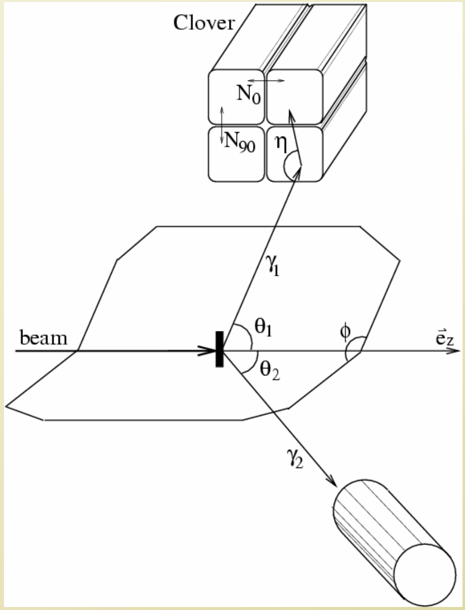


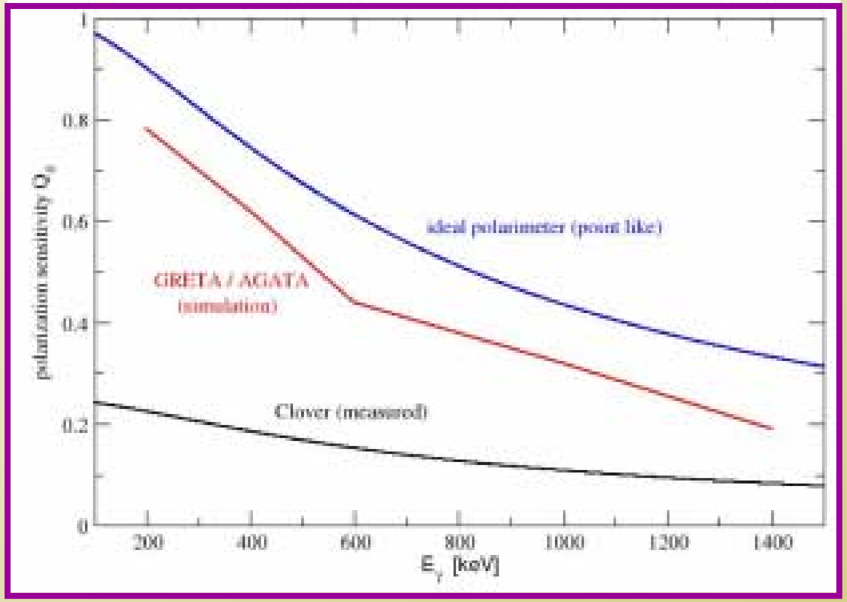
D. Roßbach et al., Phys. Lett. B 513, 9 (2001)

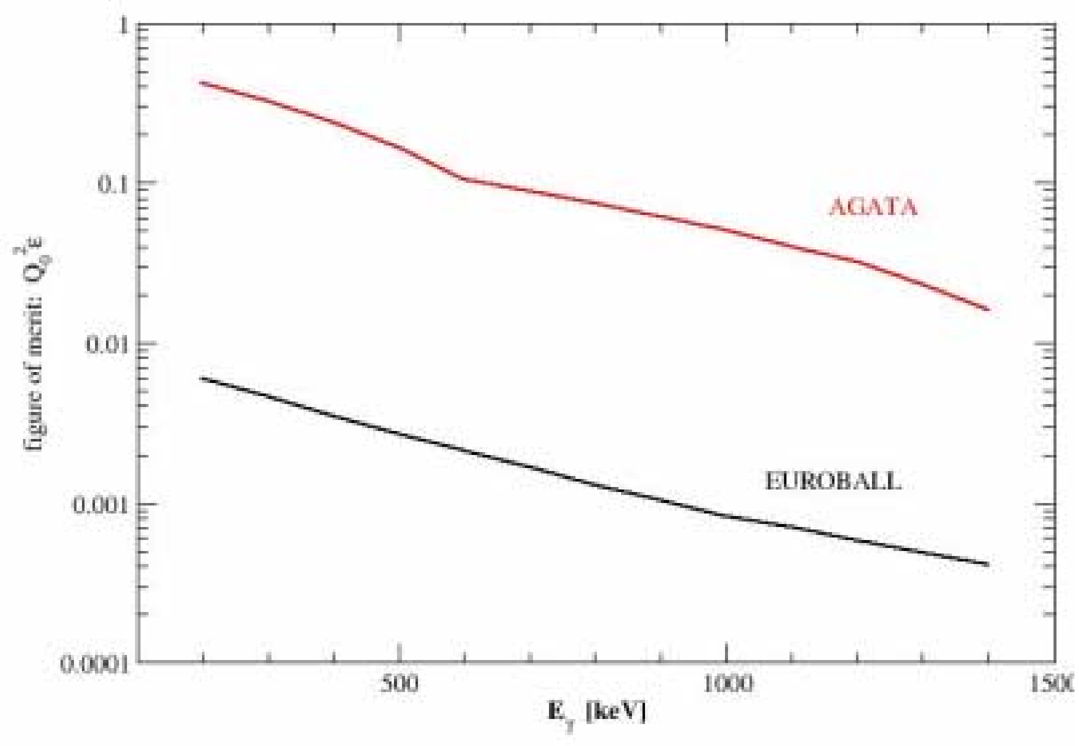
AGATA as Compton polarimeter

Two requirements:

- Polarization sensitivity Q_0:
  precise measurement of scattering angle
- efficiency ε



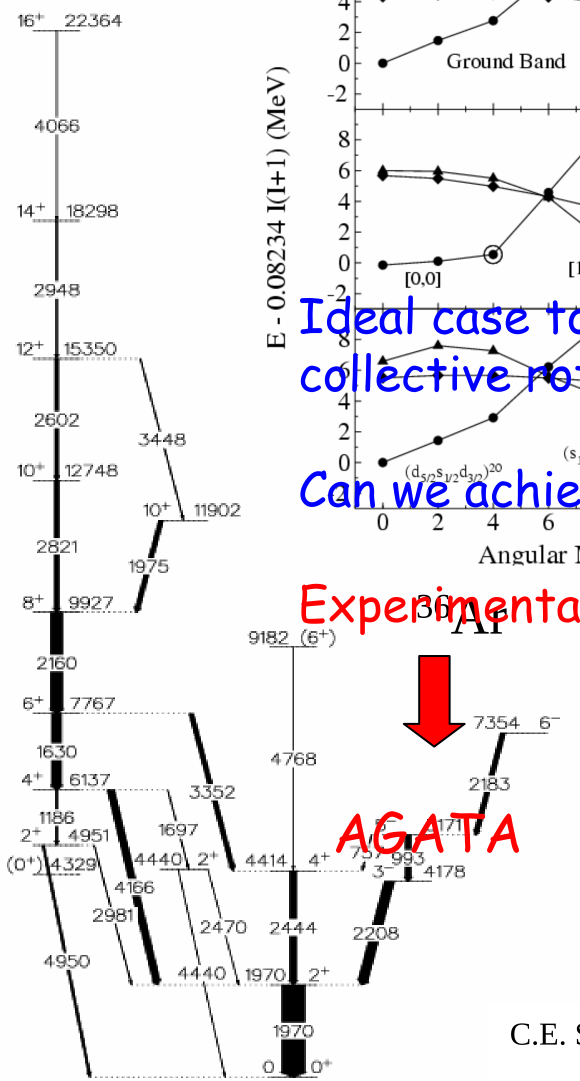


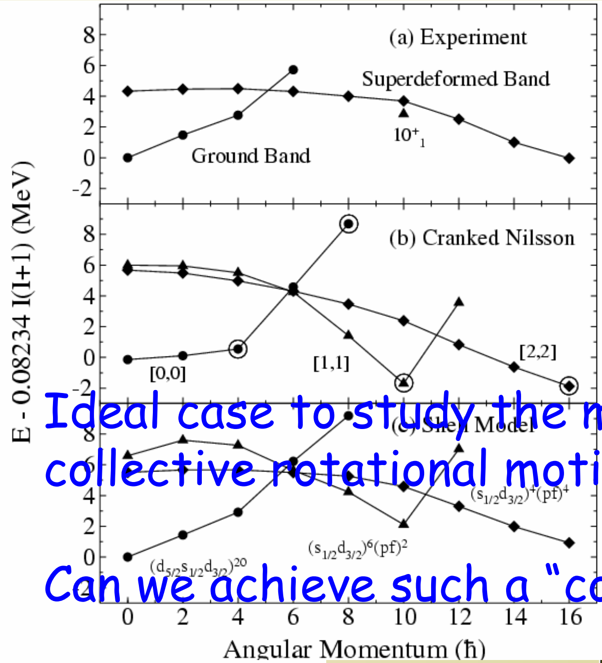


- ✓ multipole character of weak transitions
- ✓ precise measurement of mixing ratio δ

SD band in ^{36}Ar

- New region of superdeformation
- full experimental information: excitation energy, spin, parity, lifetimes
- Valence space small enough for full SM compare SM with CNS
- Spin fully exhausted: observed up to non-collective terminating state 16$^+$ smooth band termination in SD



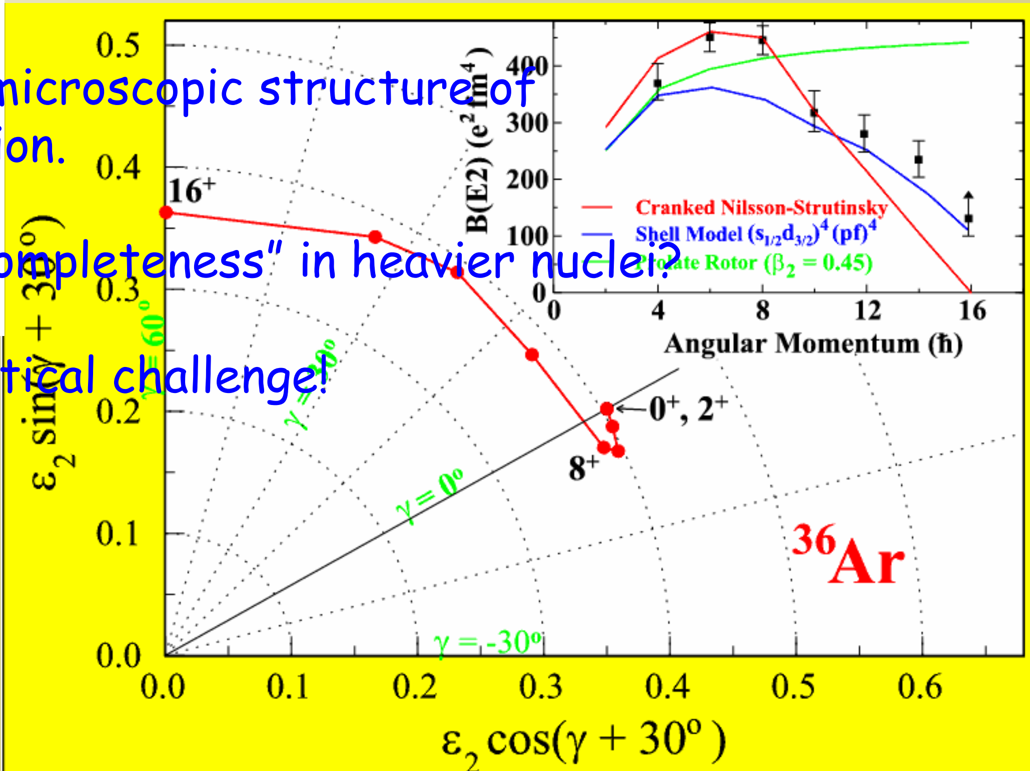


Ideal case to study the microscopic structure of collective rotational motion.

Can we achieve such a "completeness" in heavier nuclei?

Experimental and theoretical challenge!

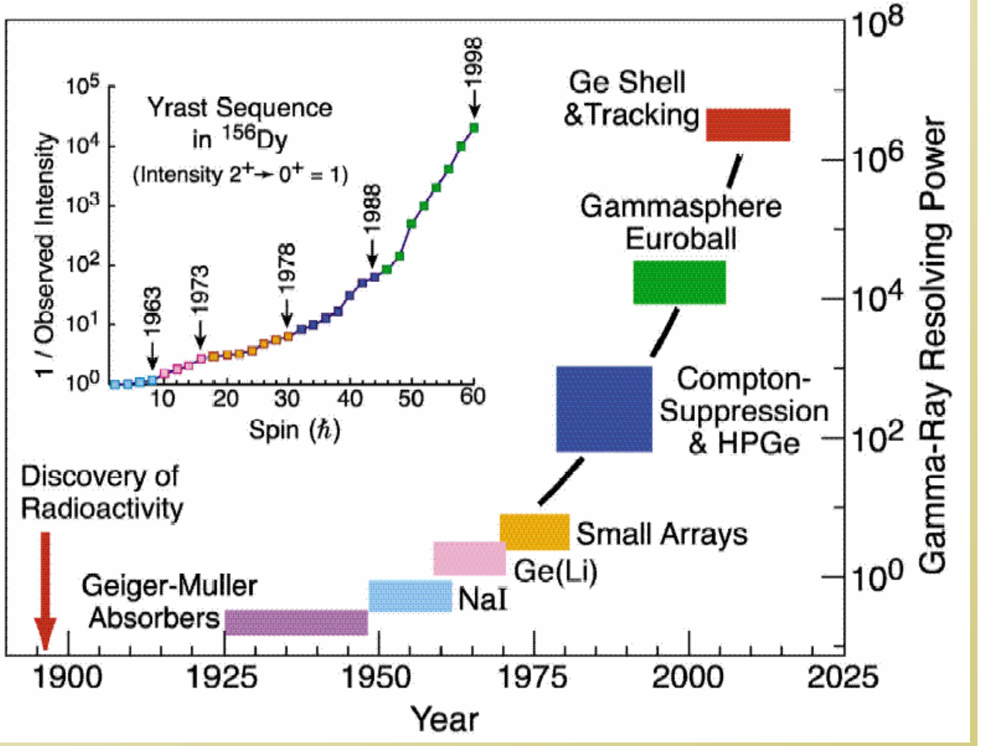
AGATA



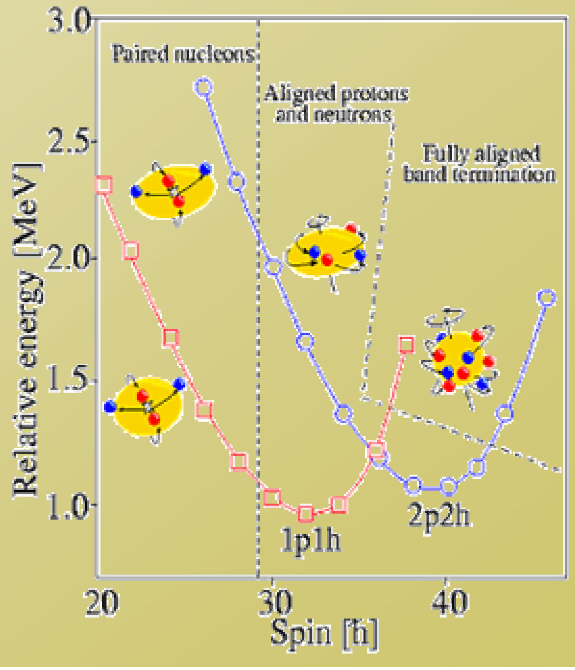
C.E. Svensson et al., Phys. Rev. Lett. 85, 2693 (2000)
Phys. Rev. C 63, 061301 (2001)

AGATA allows "complete" spectroscopic studies of discrete states up to the highest spins.

How does pairing evolve with angular momentum?
Study quenching and collapse of nuclear superfluidity at high spin.
Is there T=0 proton-neutron pairing?
(in heavy N=Z nuclei)



Study transition from collective rotation to non-collective states:
Smoothly terminating bands allow identification of detailed microscopic structure and relate collective and single-particle properties.
(c.f. contribution Eddie Paul)
What structures feed terminating states?



What about macroscopic (liquid drop) effects at very high spin?

Jacobi shape transition

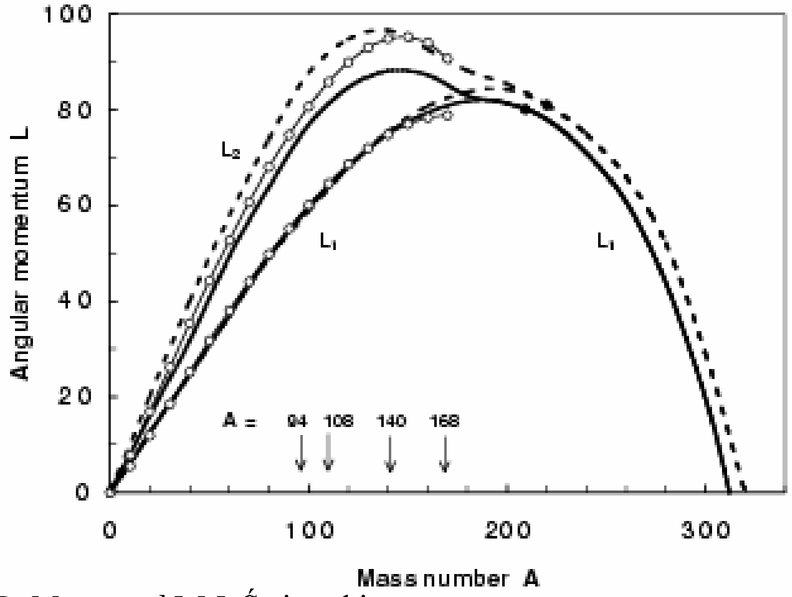
Superdeformed nuclei

- elongation due to shell effects
- observed down to relatively low spin
- in isolated mass regions

Jacobi shapes

- elongation due to centrifugal force
- appear only at very high spin
- over wide range of nuclei

Thomas-Fermi model

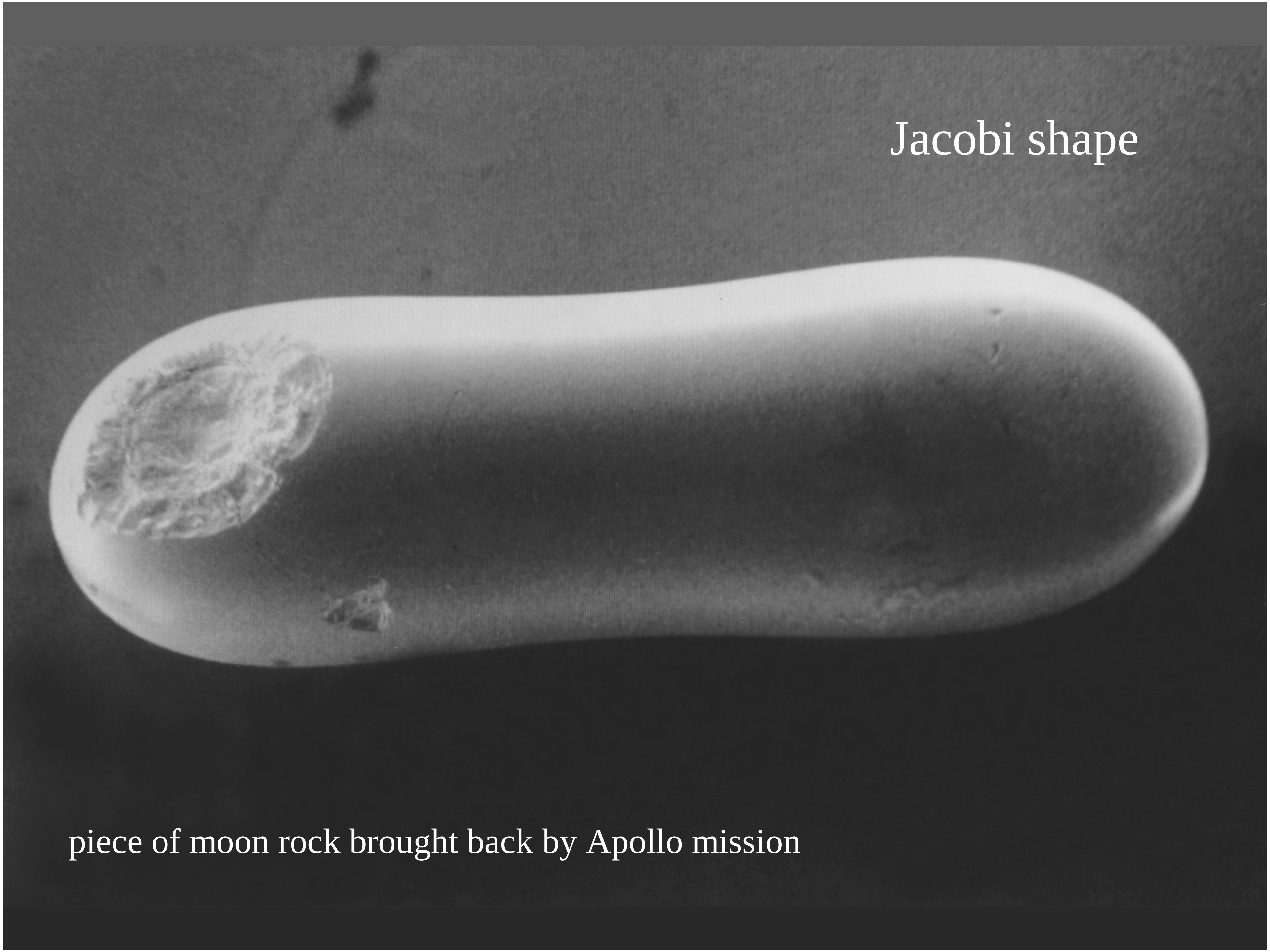


W.D. Myers and W.J. Świątecki,
Acta Phys. Pol. B 32, 1033 (2001)

MacLaurin shape

polar/equatorial axis ~ 15/16

Jacobi shape



piece of moon rock brought back by Apollo mission

What is the signature of a Jacobi shape 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: $\hbar\omega = E_\gamma/2$

- many rotational bands at high spin quasi-continuous transitions

- measure the energy of the quasi-continuous 'E2 bump' as a function of angular momentum

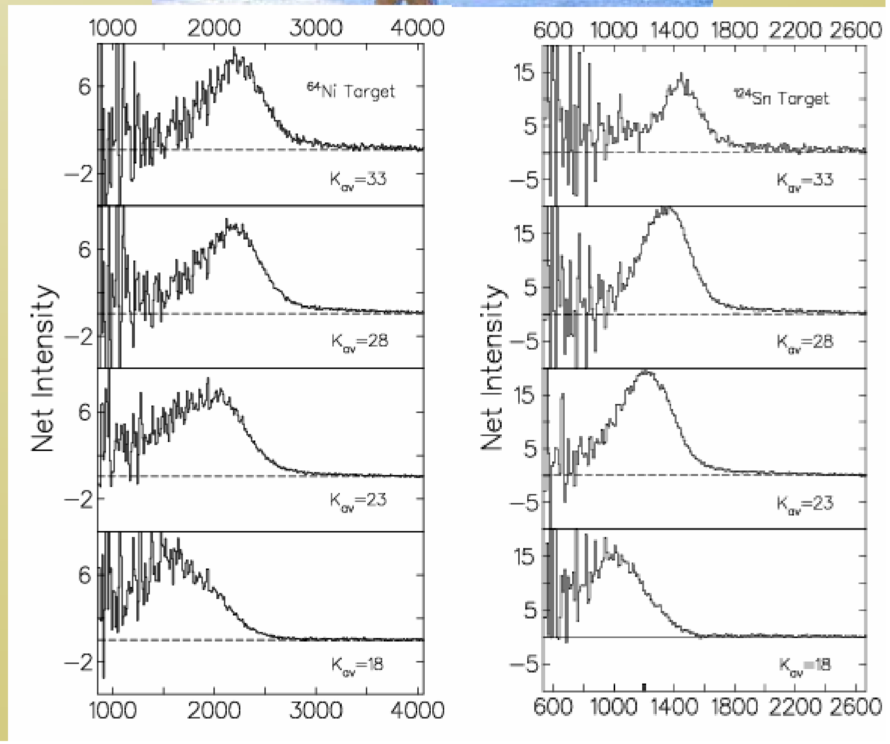
- experiments with Gammasphere and 8π

  $^{48}Ca + ^{50}Ti$

  $^{48}Ca + ^{64}Ni$

  $^{48}Ca + ^{96}Zr$

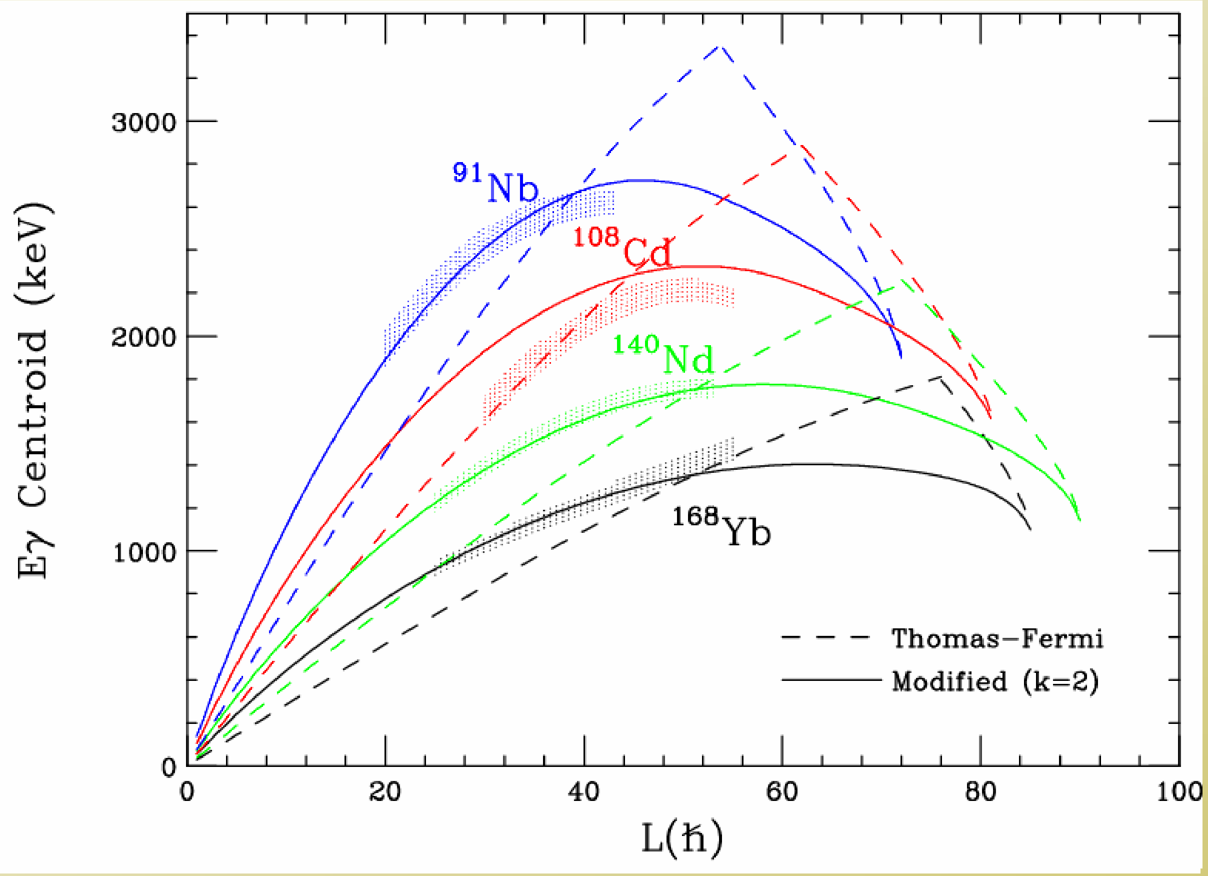
  $^{48}Ca + ^{124}Sn$



Results

Thomas-Fermi model:
two modifications

- pairing at low spin
- smooth transition



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

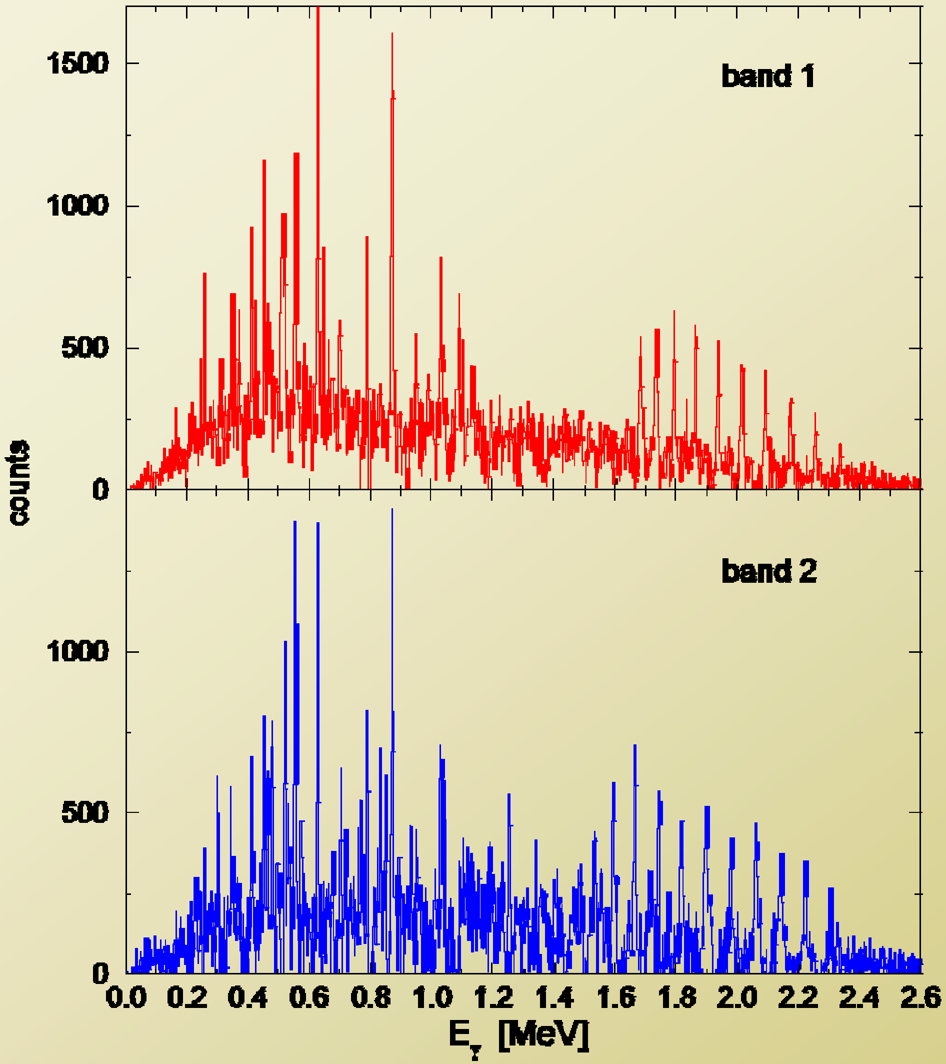
Observations:

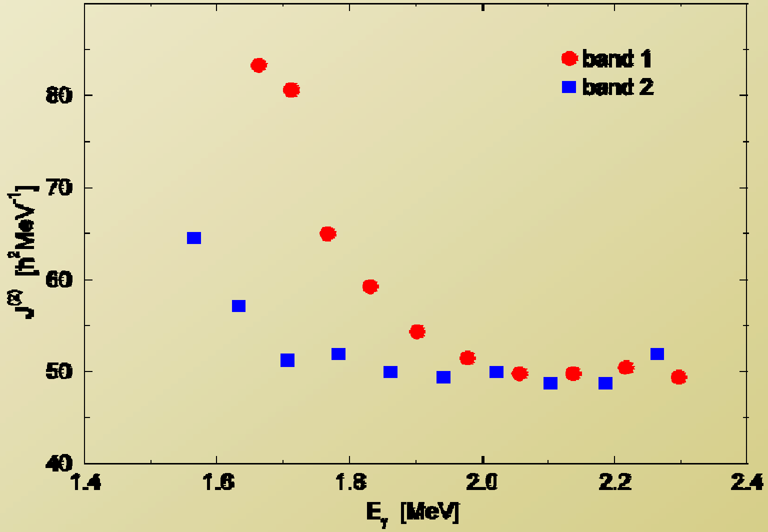
- 3 out of 4 cases show flattening
- no sign of sudden transition (as expected)
- good agreement with modified Thomas-Fermi model
- firs hint for Jacobi transition in nuclei – without being a strict proof

How can we improve with AGATA ?

- Granularity: accurate measurement of gamma-ray multiplicity
  no problems with double hits in detectors
- Count rate capability: no pile-up problems
- Efficiency: we don't run out of steam where it gets interesting

Very extended shapes in ^{108}Cd



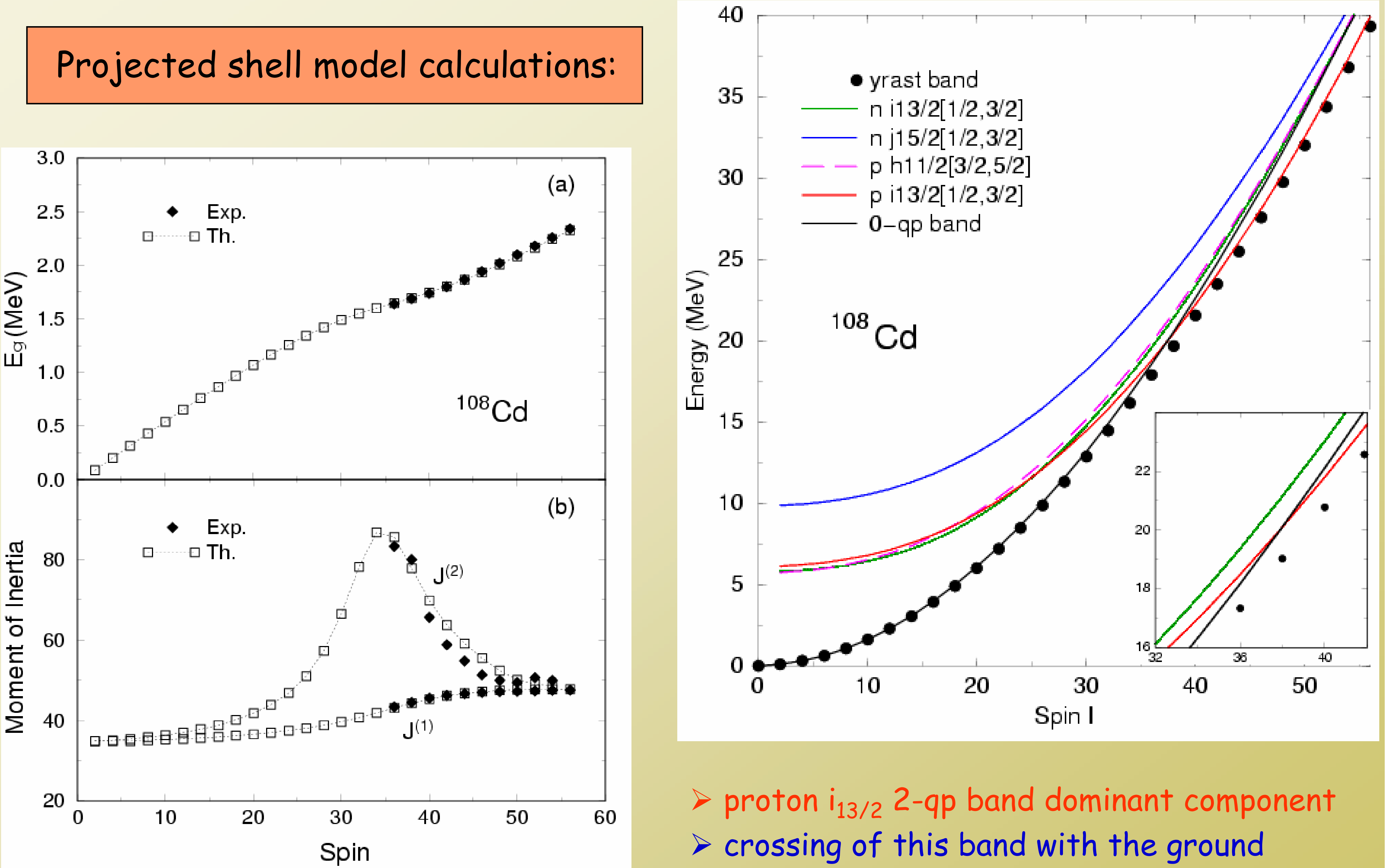


- large moment of inertia $\Im^{(2)}$
- steep rise of $\Im^{(2)}$ at low frequencies

  band crossing ?
- spin: 40 – 60 ħ ($\Im^{(1)} = \Im^{(2)}$; multiplicity)
- fractional Doppler shifts: c/a > 1.8
- cranked Strutinsky: c/a ~ 2.3

R.M. Clark et al., Phys. Rev. Lett. 87, 202502 (2001)
A. Görgen et al. Phys. Rev. C 65, 027302 (2002)

Projected shell model calculations:

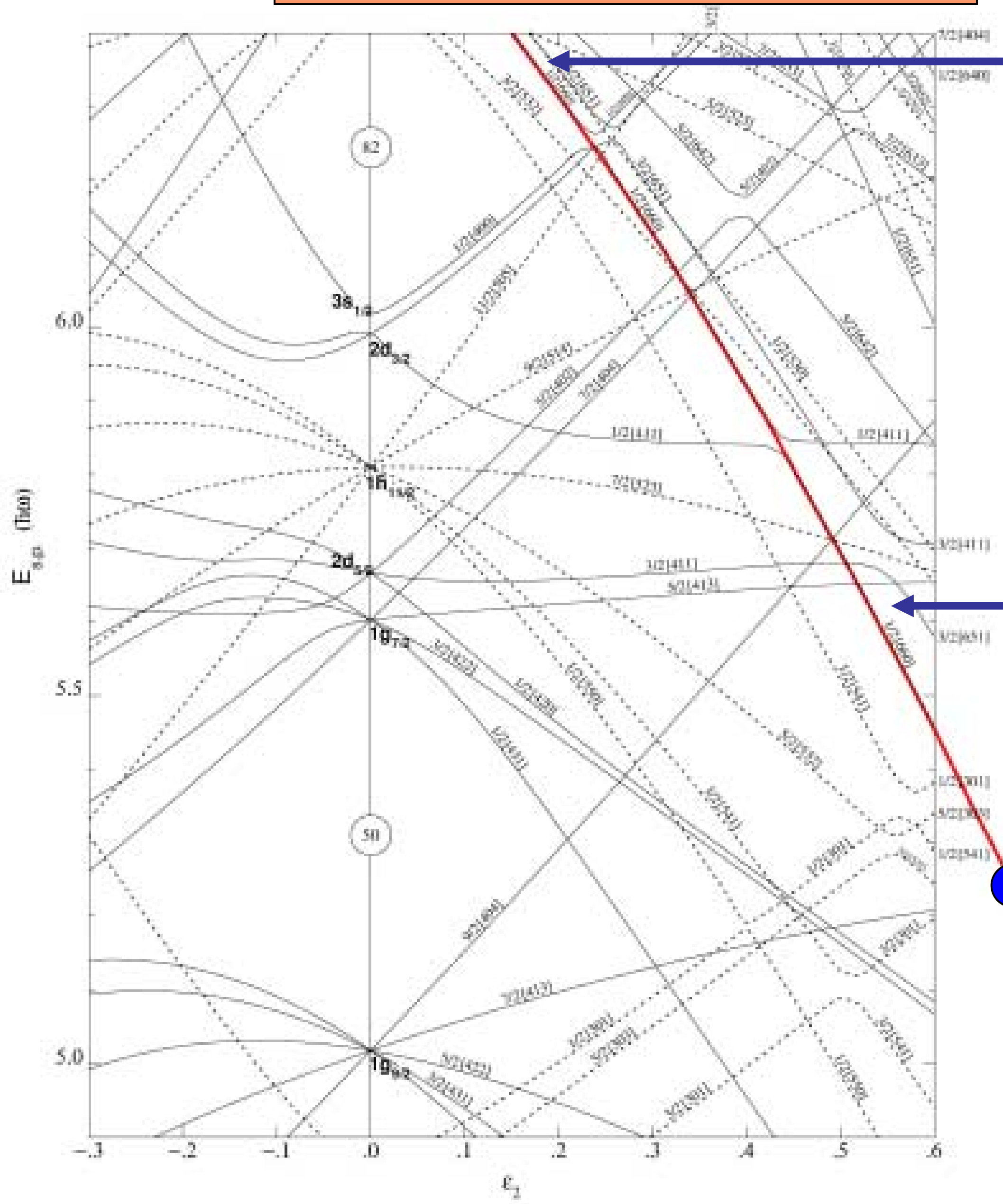


$\Rightarrow$ spin range of band: 36-56 $\hbar$

- proton $i_{13/2}$ 2-qp band dominant component
- crossing of this band with the ground band explains steep rise in $\mathfrak{I}^{(2)}$

C.T. Lee et al., Phys. Rev. C 65, 041301(R) (2002)
A. Görgen et al., AIP Conf. Proc. 656, 17 (Berkeley 2002)

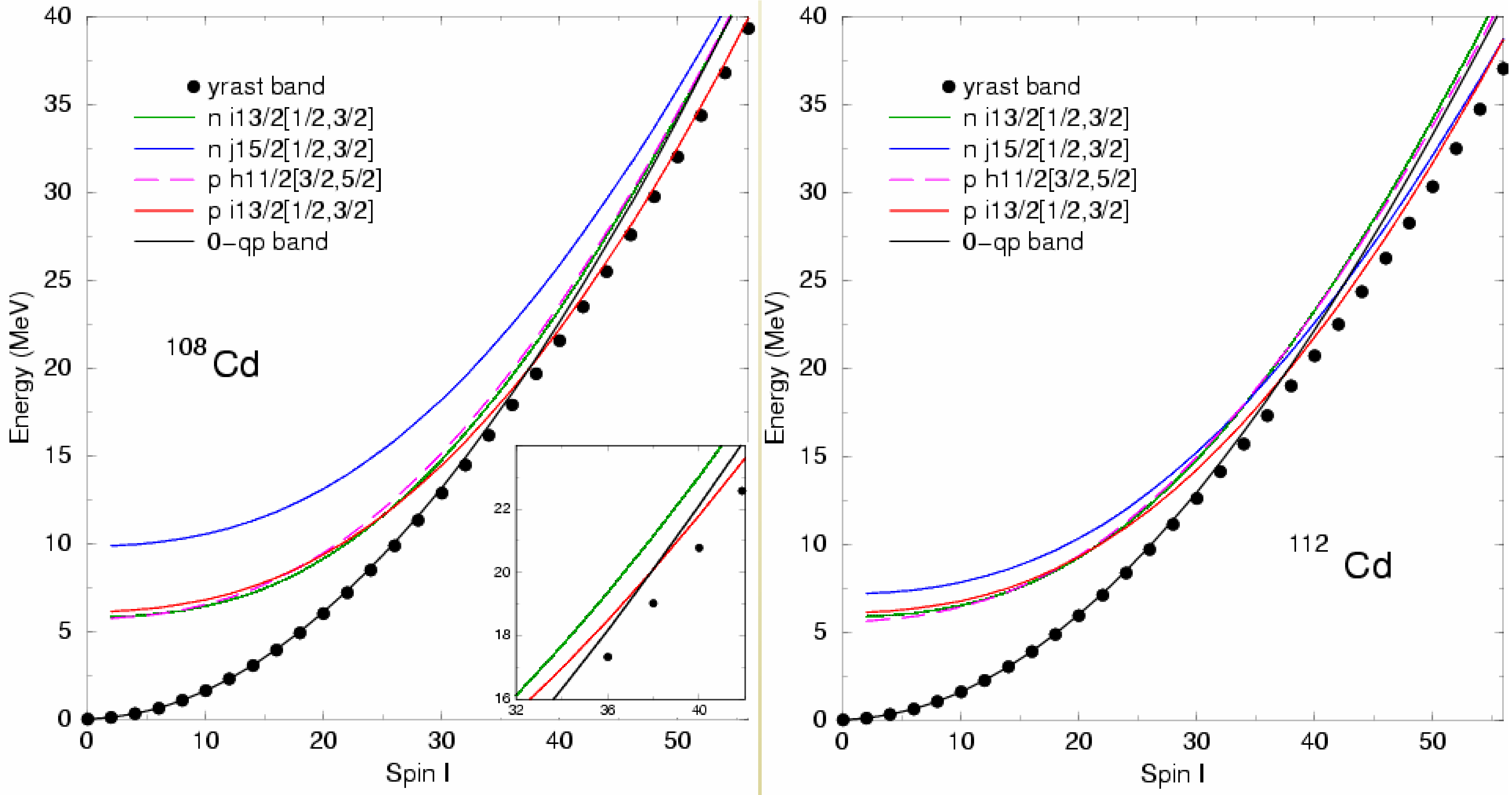
Role of the proton $i_{13/2}$ orbital



^{235}U
normal intruder
from one shell above

^{152}Dy
super intruder
from two shells above

^{108}Cd
hyper intruder
from three shells above



Where is the $j_{15/2}$ neutron hyperintruder orbital?

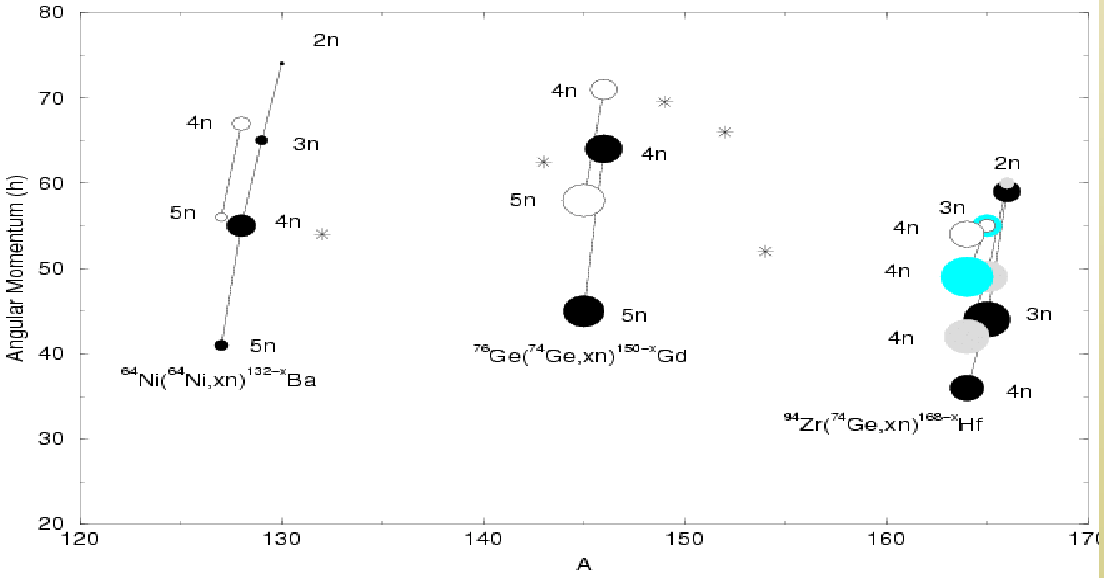
In ^{112}Cd, only four neutrons away, the $\nu j_{15/2}$ becomes important !

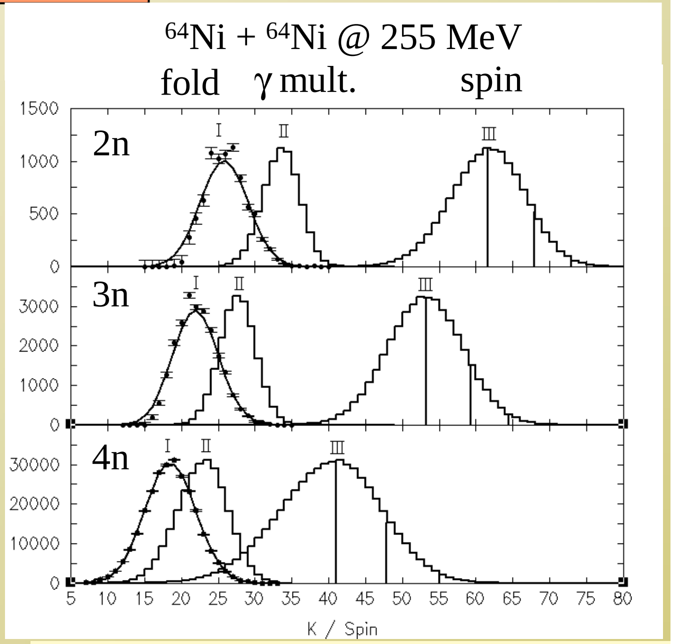
Problem: reaction that brings in enough angular momentum.

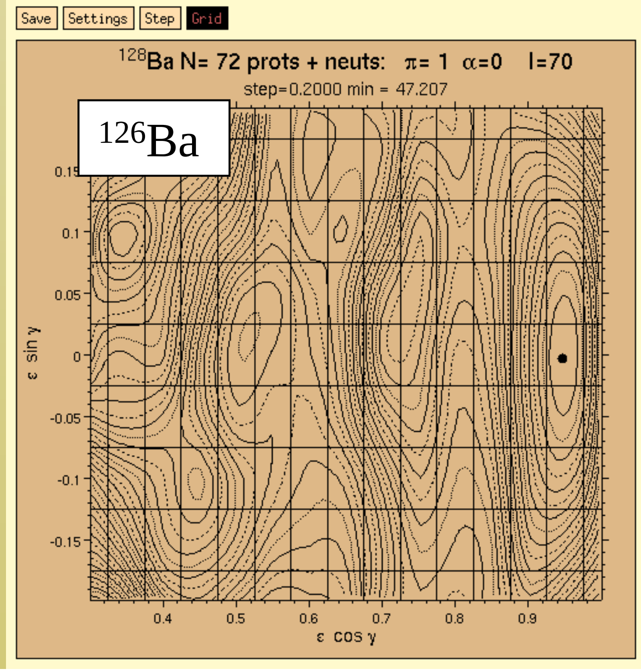
Fusion-evaporation reactions to populate the highest spins

Five years ago: Berkeley/Bonn/Copenhagen collaboration:

- Shell structure at ε_2=1.0 is very hard to predict.
- Hyperdef can only be populated at ultra-high spin.
- Let's find the best reactions for the highest spins first.
- Systematic study of various reactions with the 8π spectrometer.







conclusions:

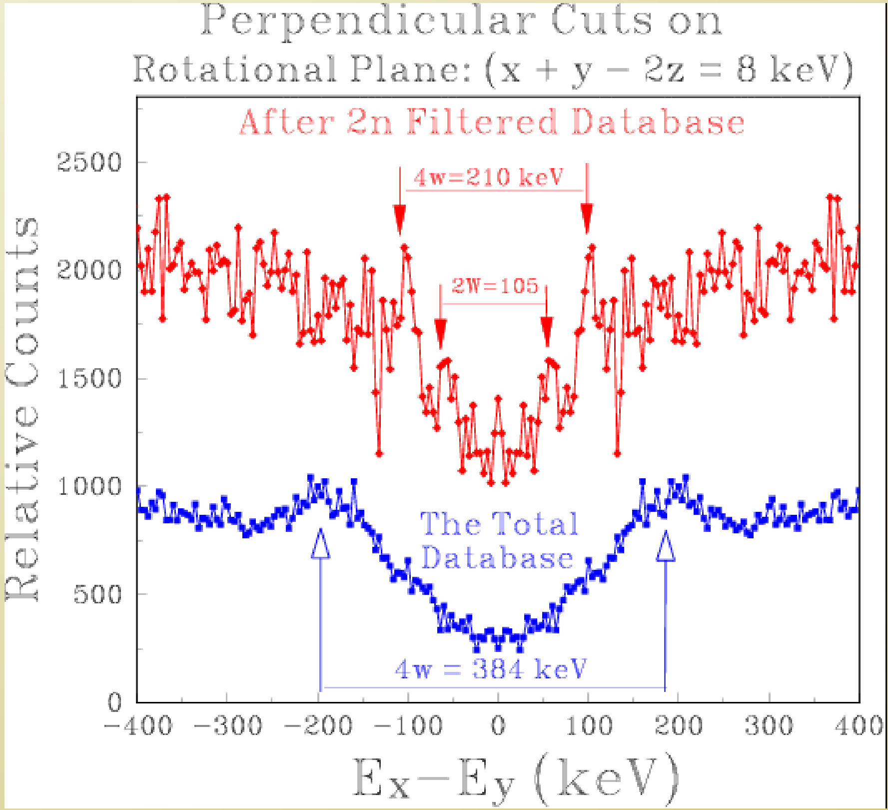
- mass around A=130
- as neutron rich as possible
- cold symmetric reactions
- near-magic projectile and target
- preferably 2n channel

J. Domscheit et al., NPA 689, 655 (2001)

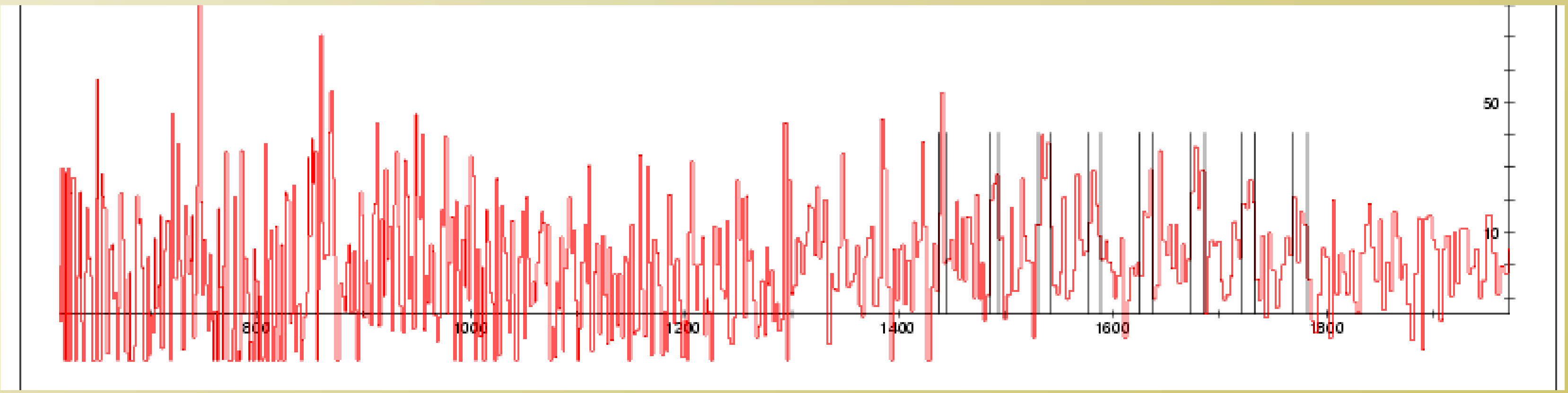
$^{64}Ni + {}^{64}Ni$ @ 261 MeV Gammasphere

Analysis of ridge structures:

- data "filtered" to enhance 2n channel
- rotational plane: $|E_x + E_y - 2E_z| < \delta$
- matrix E_x+E_y vs. E_x-E_y
- perpendicular cut at $(E_x+E_y)/2 = 1440 \pm 142$ keV
- ridge structure with $\Delta E = 52$ keV
- only seen in 2n channel, not in total data set



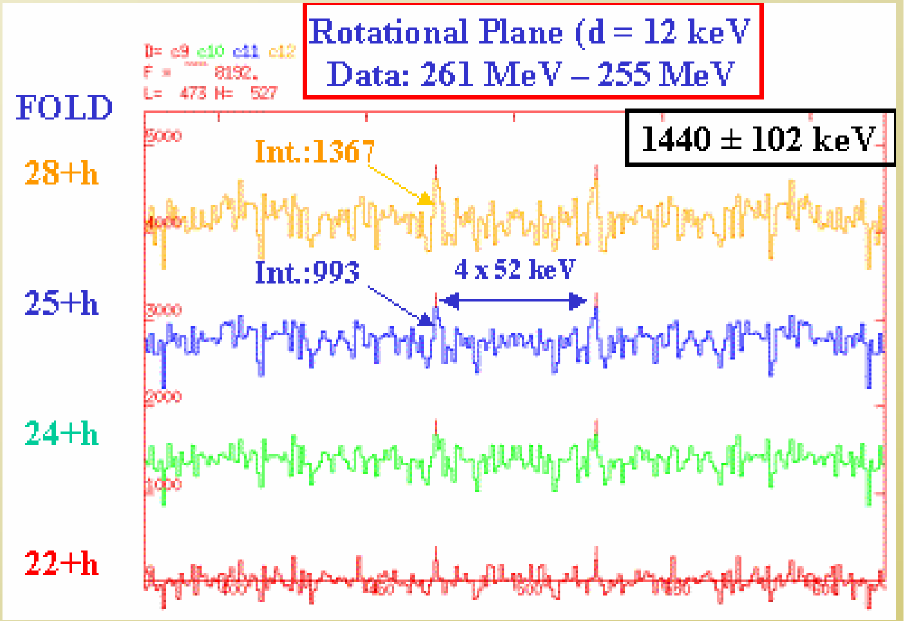
Systematic search for discrete bands
(using various algorithms)
spectrum with highest "score": $\Delta E = 48$ keV



The HLHD (hyper-long hyper-def) experiment

huge data set: 39×10^9 events at 255 MeV
36×10^9 events at 261 MeV
Euroball IV + Inner Ball + Diamant
analysis still in progress
no convincing discrete band (yet)
ΔE = 52 keV ridge structure confirmed at 261 MeV
but not confirmed at 255 MeV

Only a small window of
spin and excitation energy

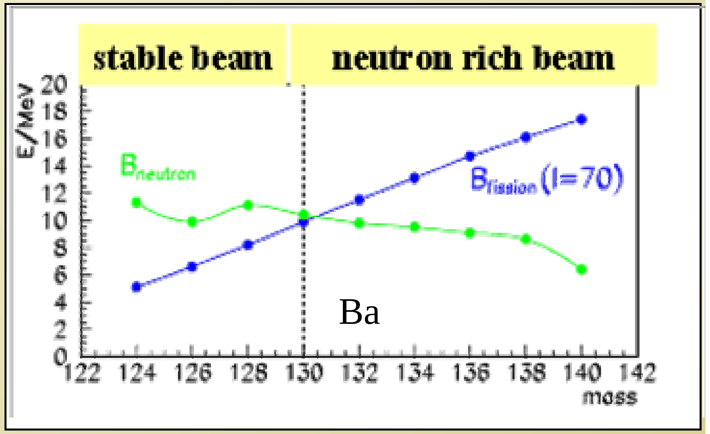


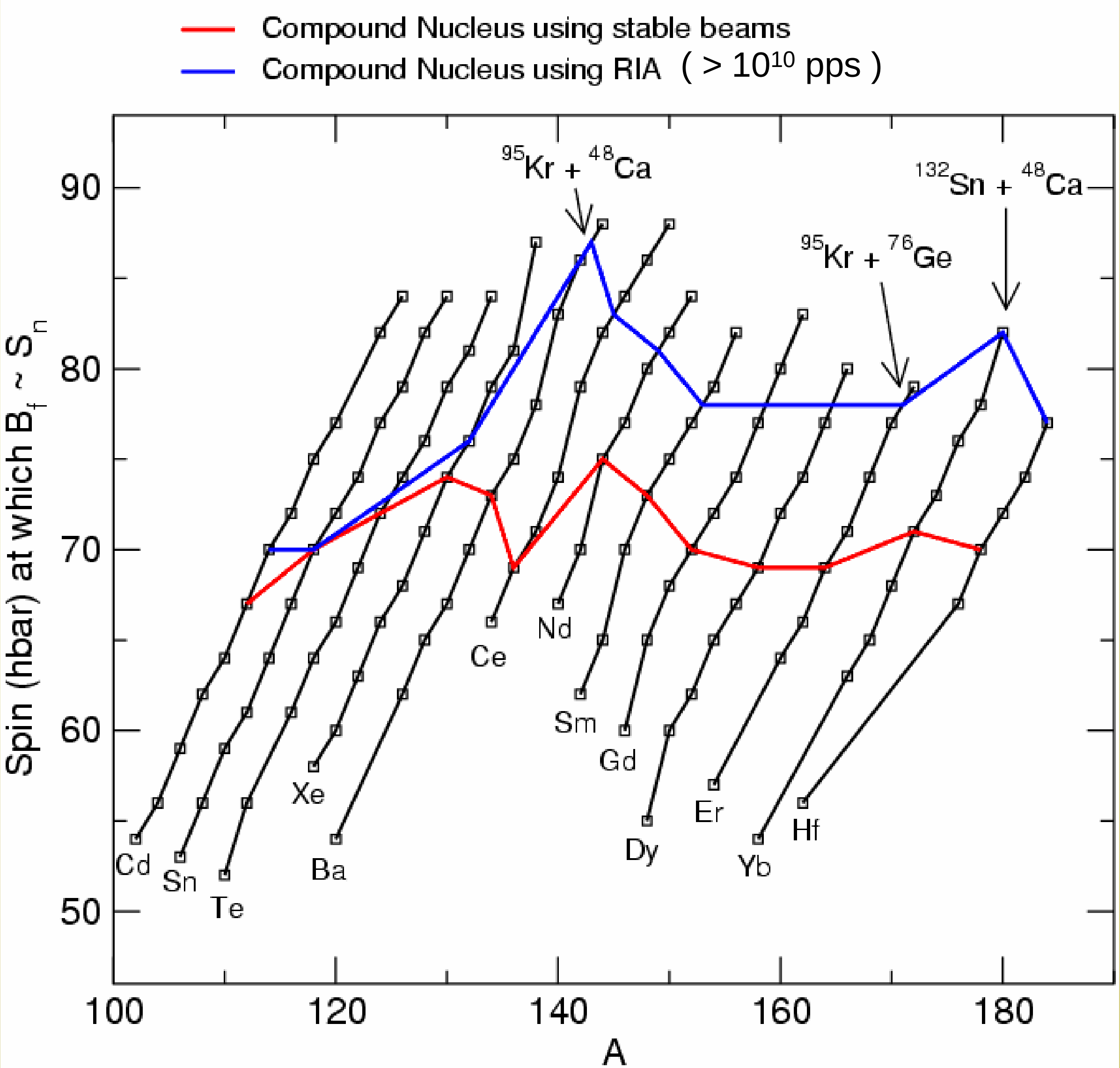
Statistical significance of ridge: 4.5 σ
Fluctuation analysis: number of paths $N_p \geq 10$
Ridge intensity: ~ 5×10^{-5} of 2n channel
~ 10^{-6} of total fusion
$\Rightarrow$ Intensity of an individual band: ~ 10^{-7}
(worst case)

Resolving power of
AGATA is needed !

Two crucial steps ahead towards hyperdef:

- ➢ resolving power ⇒ AGATA
- ➢ open the spin window ⇒ neutron rich beams

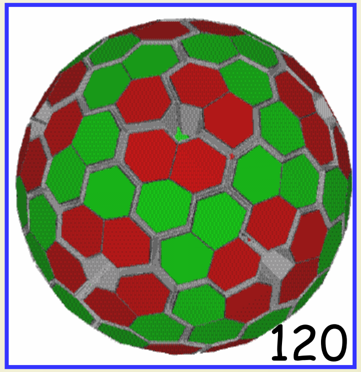




RIA/EURISOL
pushes the spin limit 10 ħ

lots of room for new physics

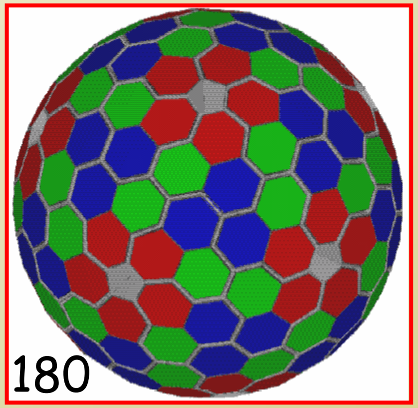
AGATA configuration



For $M\gamma$=30 and Δx=5mm:

ε_{ph} = 0.19

ε_{ph} = 0.24

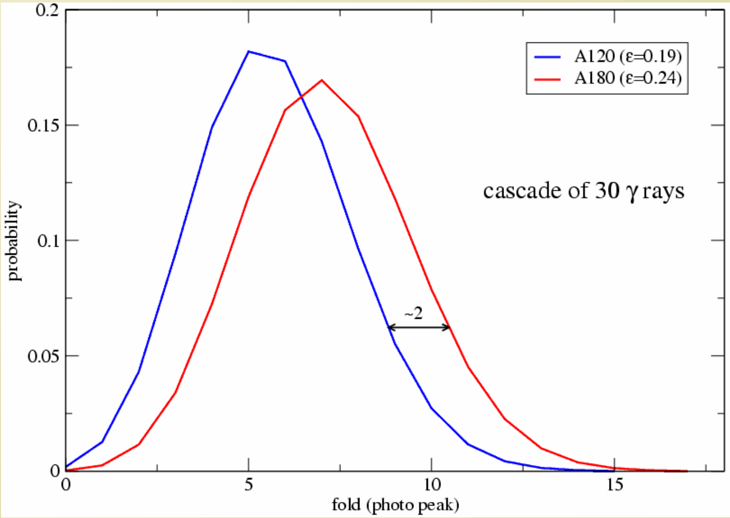


Resolving power:

$$RP = \exp\left[\frac{\ln(N_0/N)}{(1-\ln\epsilon_a/\ln R)}\right]$$

$$\frac{RP(A180)}{RP(A120)} = 2.5$$

Coincidences: sextuples ⇔ octuples



The loss of performance when reducing AGATA to 120 detectors is severe for high-spin physics !

conclusions

- The nucleus at high angular momentum is a unique laboratory to study the nuclear many-body problem.
- The interesting new stuff is always found at the limits.
- AGATA will push these limits considerably.
- The availability of exotic radioactive beams offers rich new opportunities in many fields of nuclear physics and also at high spin.