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Shapes and shape coexistence at low and high angular momentum

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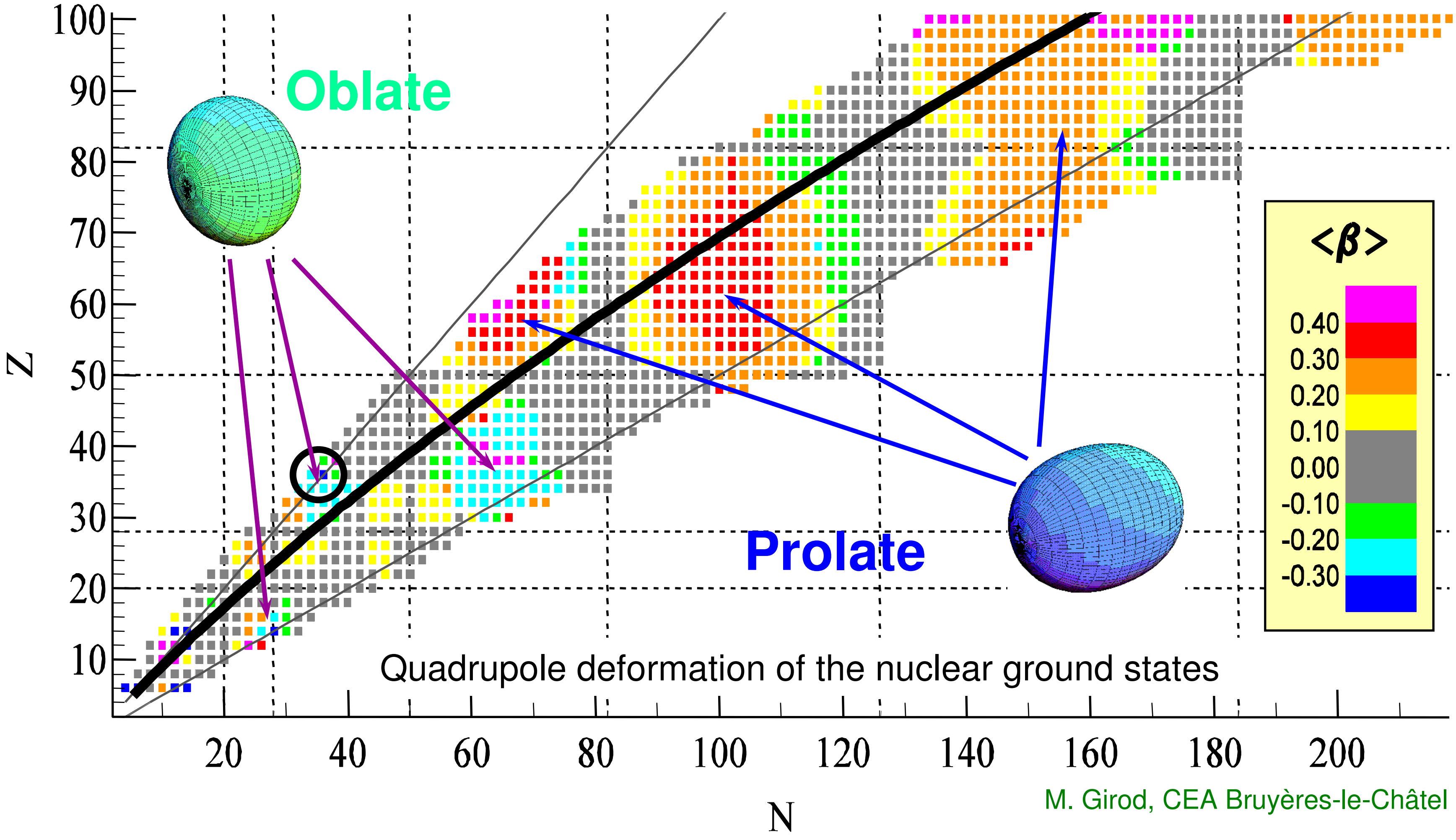
CEA Saclay - DSM / DAPNIA / SPhN

Outline

- Shape coexistence at low spin: light Krypton isotopes
  - Safe projectile Coulomb excitation of SPIRAL beams
  - RDDS lifetime measurement after fusion evaporation
  - Interpretation
- Perspectives: SPIRAL-1 / SPIRAL-2
- New symmetries
- Extreme shapes at very high spins: challenges
  - Very deformed structures in ^{108}Cd
  - Towards hyperdeformation with RIBs ?
- Summary and conclusions

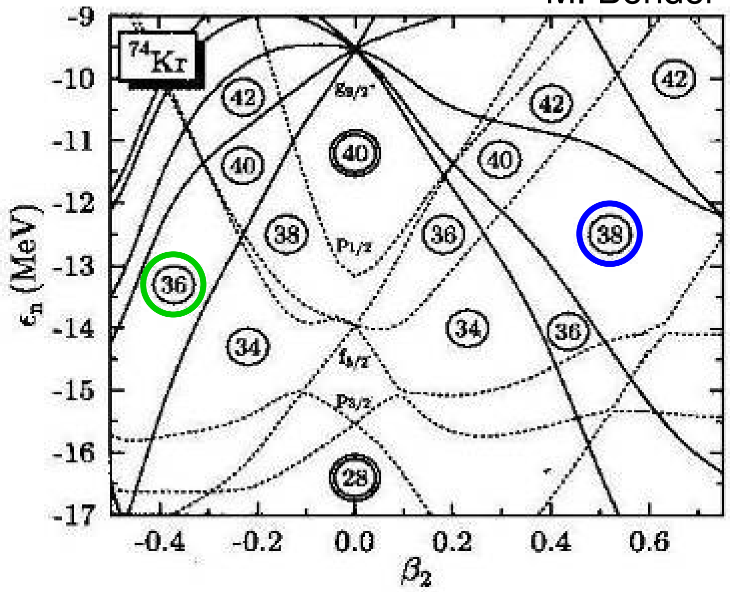
Shapes of atomic nuclei



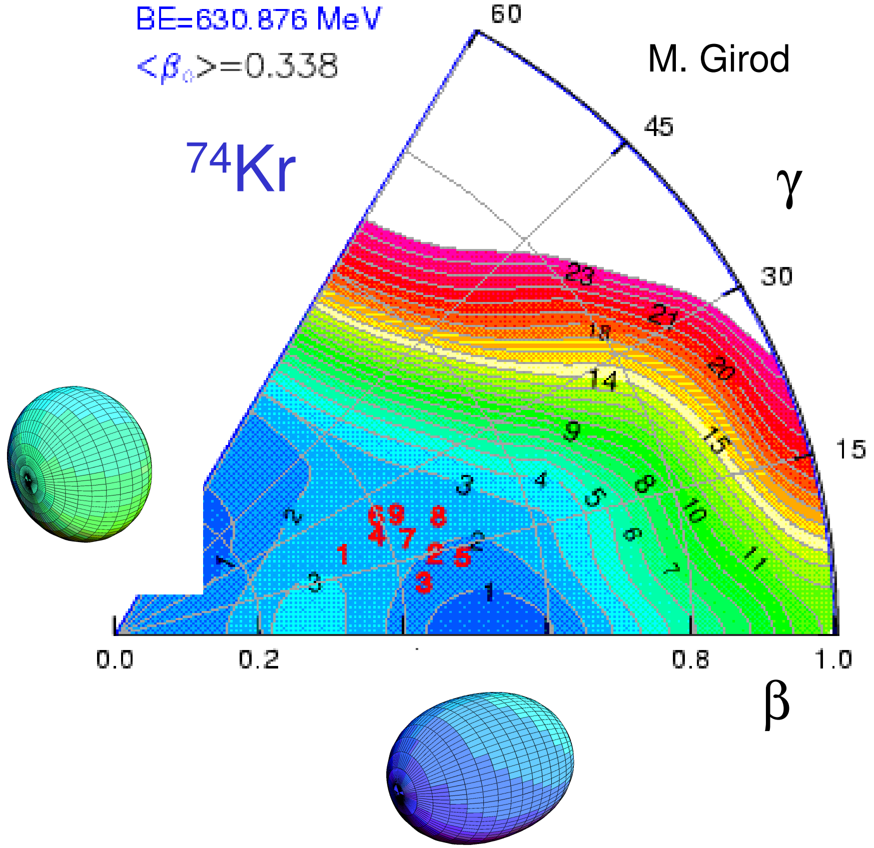
- ➢ oblate ground states predicted for *A~70* near *N=Z*
- ➢ prolate and oblate states within small energy range
  ⇒ shape coexistence

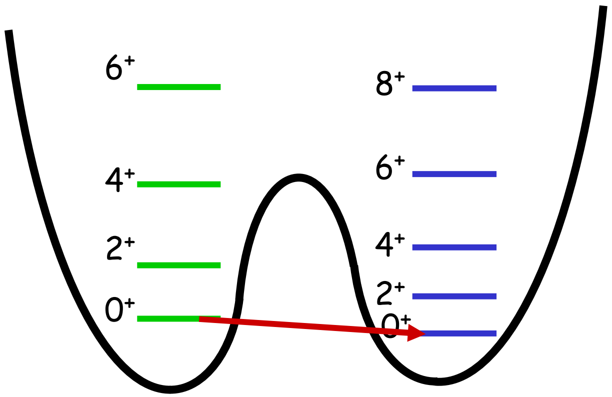
Shape coexistence

M. Bender



oblate prolate



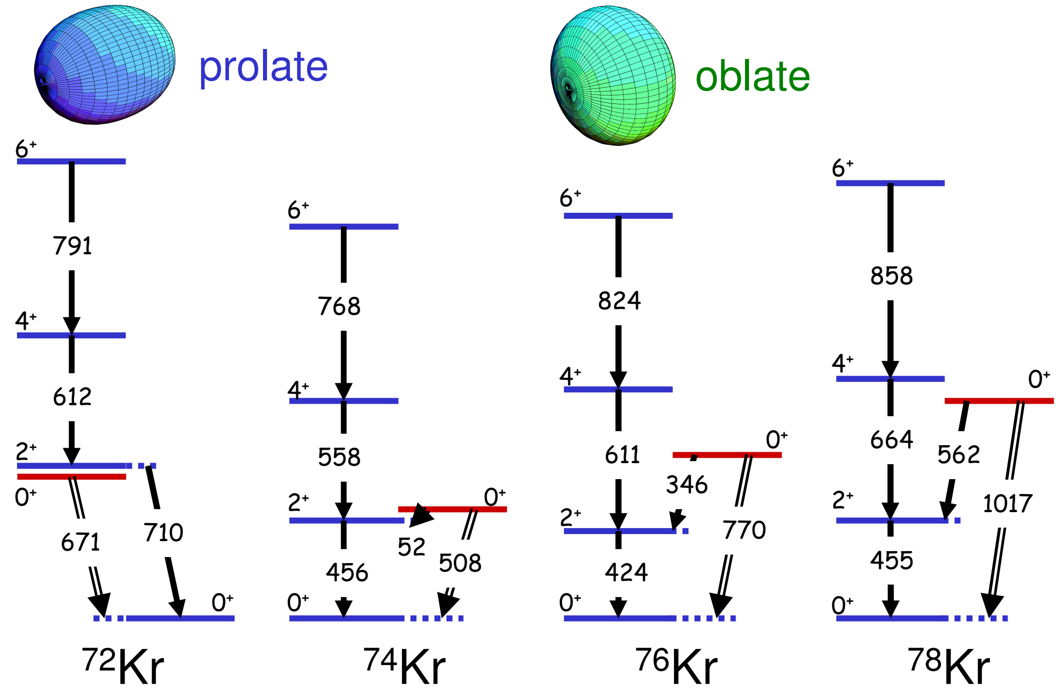


Shape isomer, E0 transition

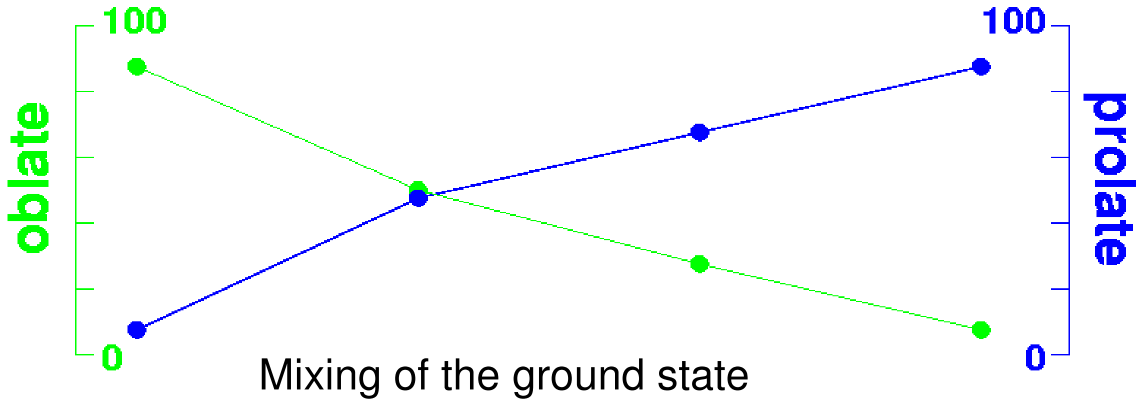
Configuration mixing: $\left|\psi(0_1^+)\right\rangle = a\left|\varphi_{pro}\right\rangle + b\left|\varphi_{obl}\right\rangle$

$$\left|\psi(0_2^+)\right\rangle = a\left|\varphi_{obl}\right\rangle - b\left|\varphi_{pro}\right\rangle$$

Systematics of the light krypton isotopes



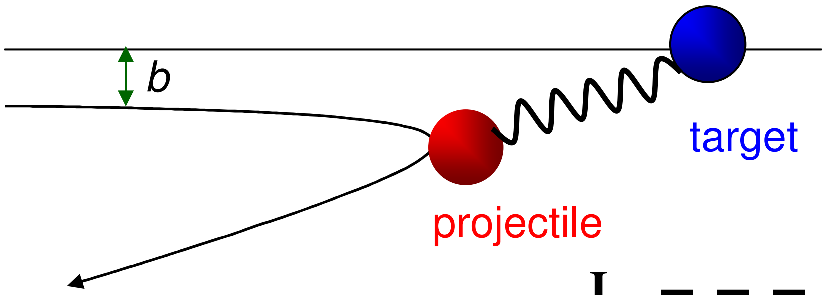
$\rho^2(E0)$ $72 \cdot 10^{-3}$ $85 \cdot 10^{-3}$ $79 \cdot 10^{-3}$ $47 \cdot 10^{-3}$



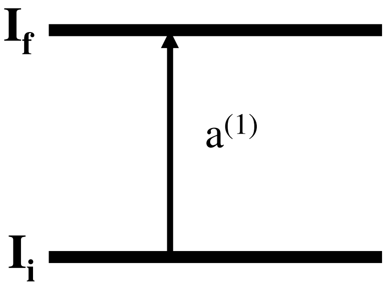
- energy of excited 0^+
- E0 strengths $\rho^2(E0)$
- configuration mixing
- Inversion of ground state shape for ^{72}Kr
- Coulomb excitation to determine the nuclear shapes directly

E. Bouchez et. al.,
Phys. Rev. Lett. 90, 082502 (2003)

Coulomb excitation

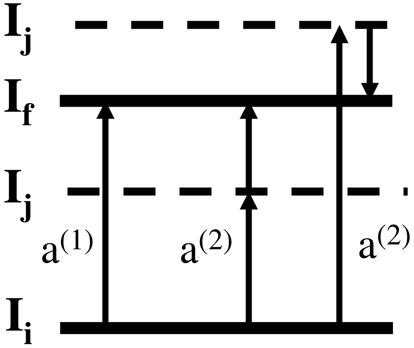


- safe energy: $r_d > 1.25\,(A_T^{\frac{1}{3}} + A_P^{\frac{1}{3}}) + 5\ \text{fm}$
- purely electromagnetic process
- excitatitation cross section is a direct measure of the $E\lambda$ matrix elements.



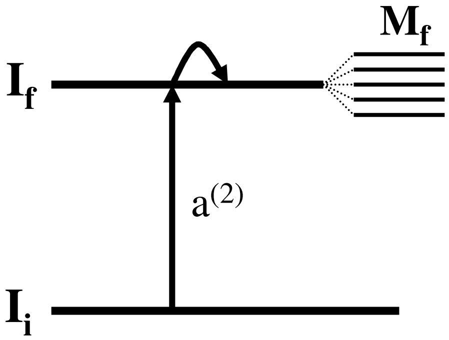
1st order:

$$a^{(1)} \propto \langle I_f \| \mathcal{M}(E2) \| I_i \rangle$$



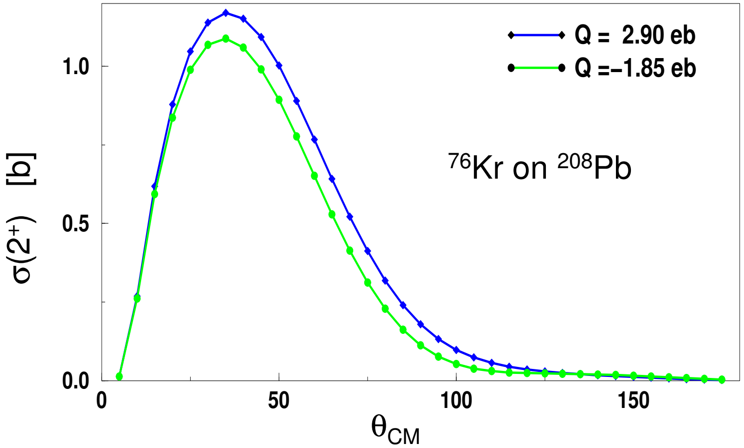
2nd order:

$$a^{(2)} \propto \sum_j \langle I_f \| \mathcal{M}(E2) \| I_j \rangle \langle I_j \| \mathcal{M}(E2) \| I_i \rangle$$



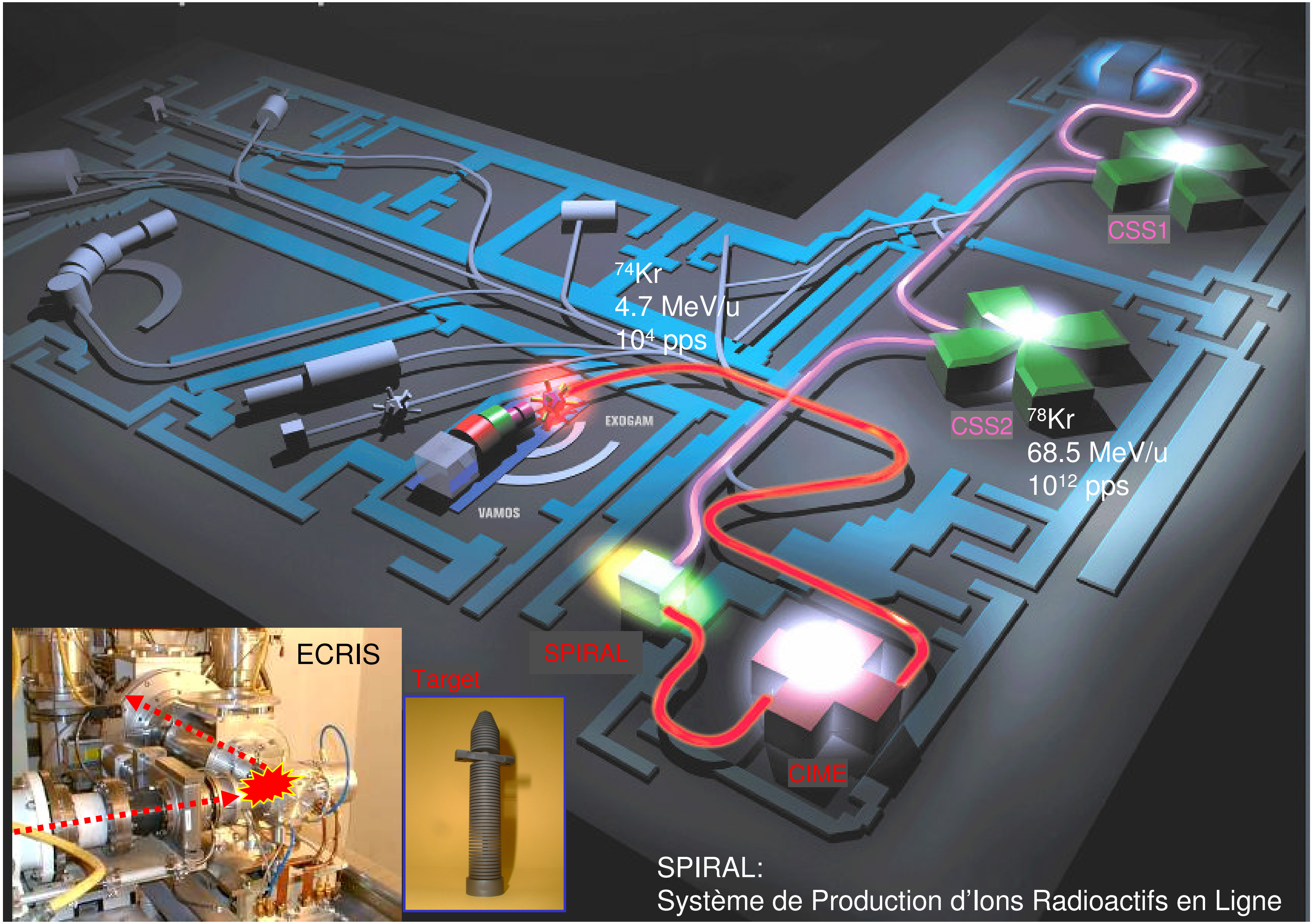
reorientation effect:

$$a^{(2)} \propto \langle I_f \| \mathcal{M}(E2) \| I_f \rangle \langle I_f \| \mathcal{M}(E2) \| I_i \rangle$$

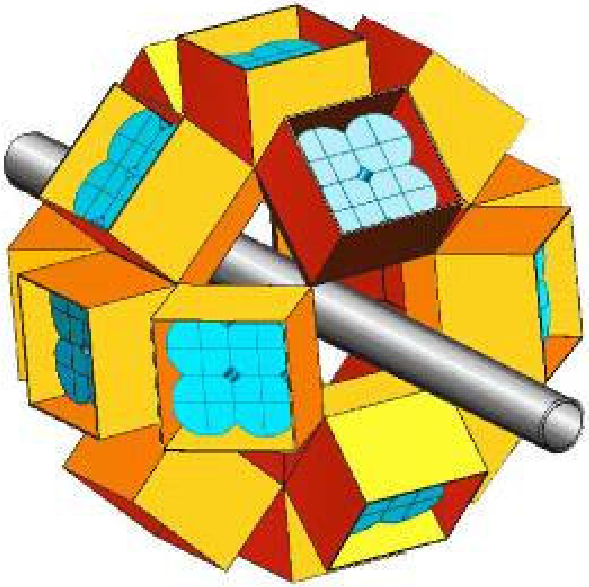


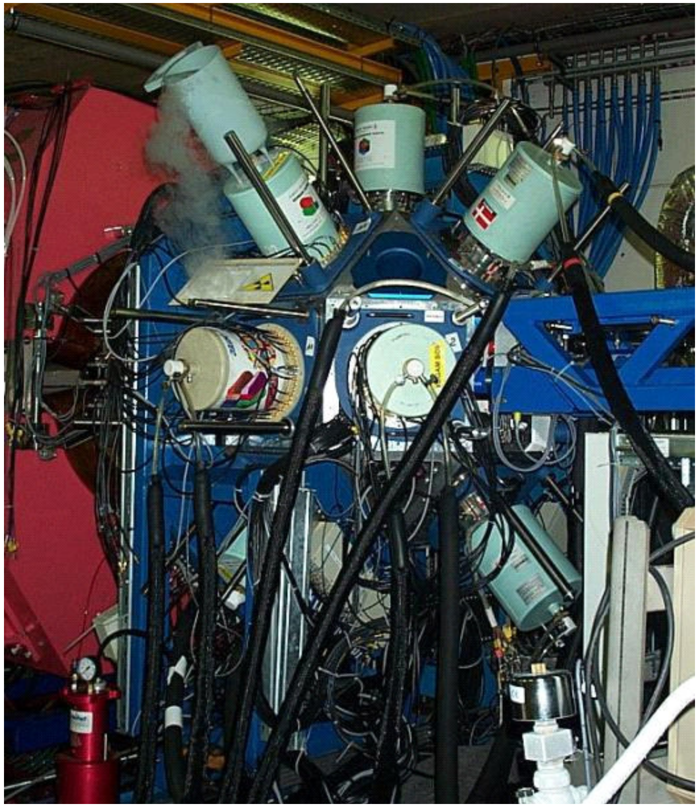
sensitive to diagonal matrix elements
⇒ intrinsic properties of final state:
quadrupole moment including sign

Radioactive beam production: SPIRAL

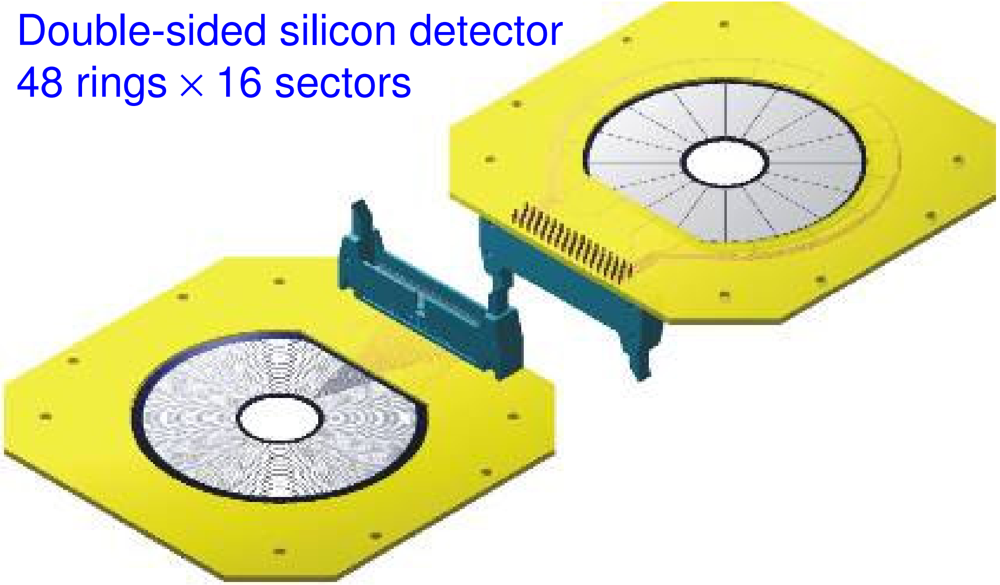


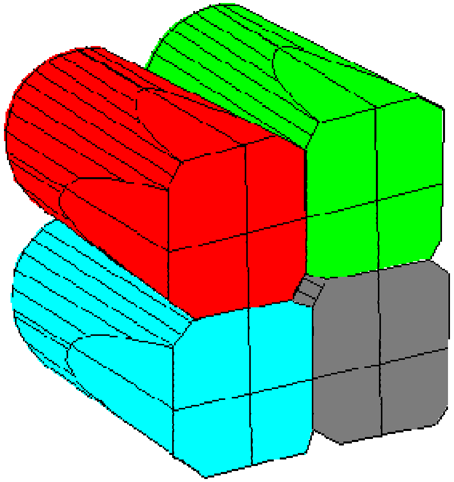
EXOGAM





Double-sided silicon detector
48 rings × 16 sectors

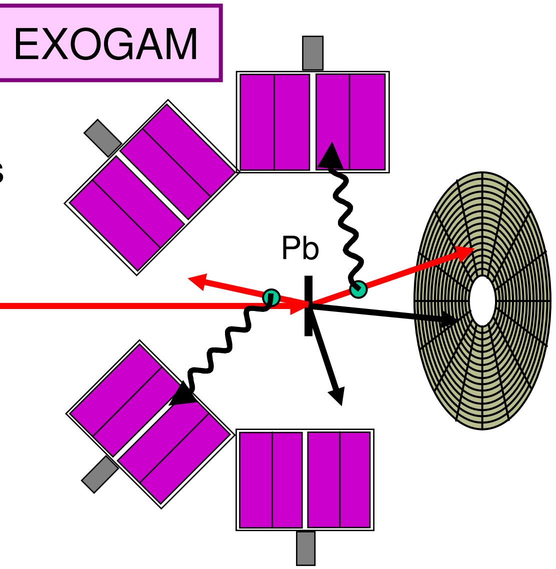


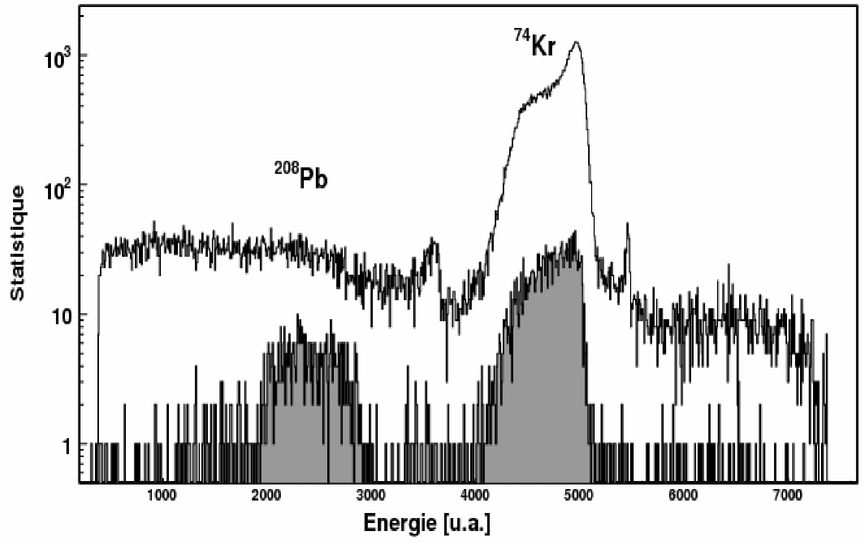


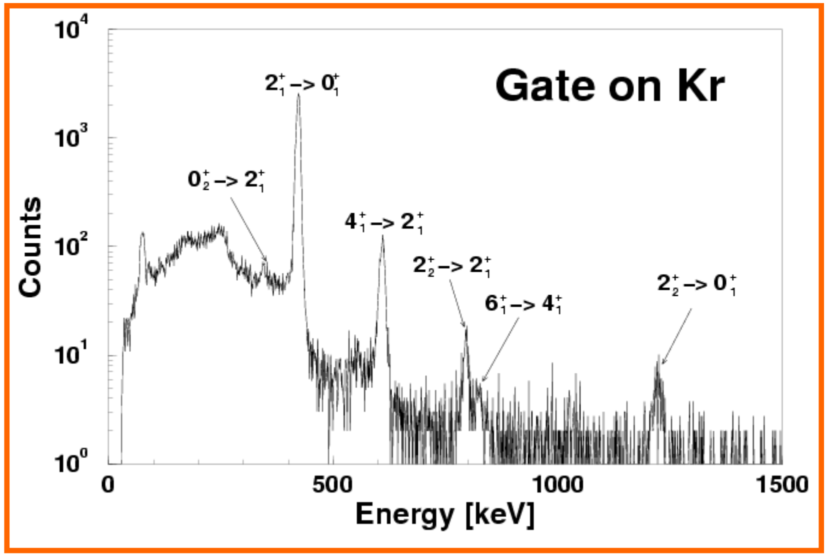
Coulomb excitation of ^{74}Kr and ^{76}Kr

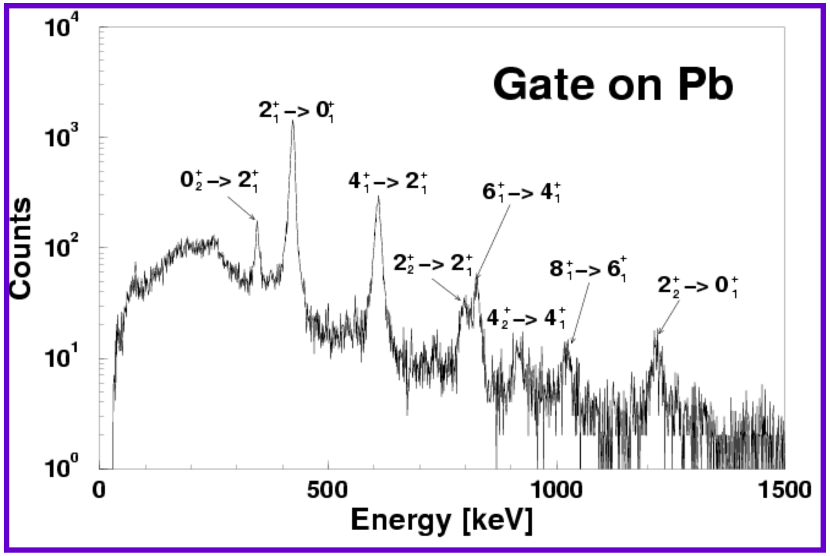
SPIRAL beams
^{76}Kr 5×10^{5} pps
^{74}Kr 10^{4} pps

4.7 MeV/u



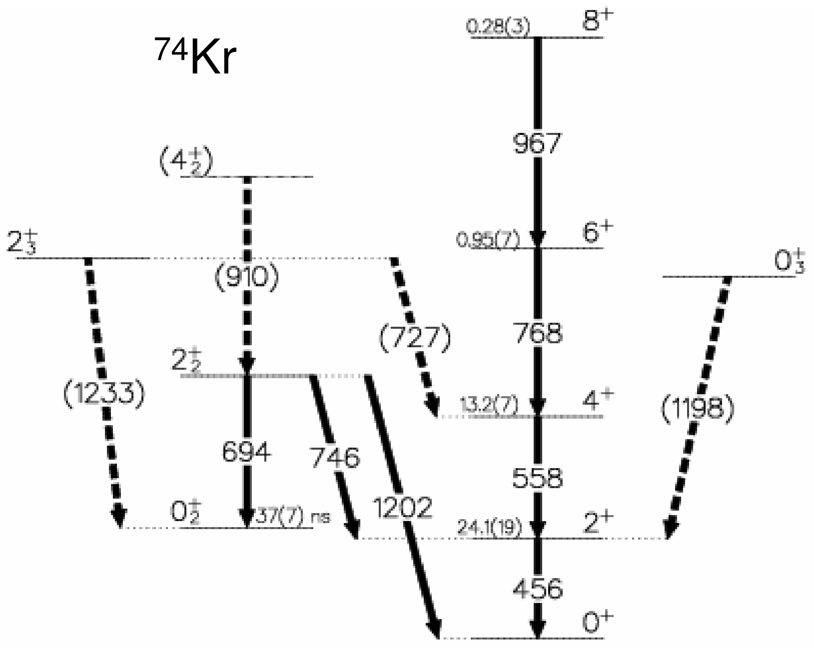






Acta Phys. Pol. B 36, 1281 (2005)

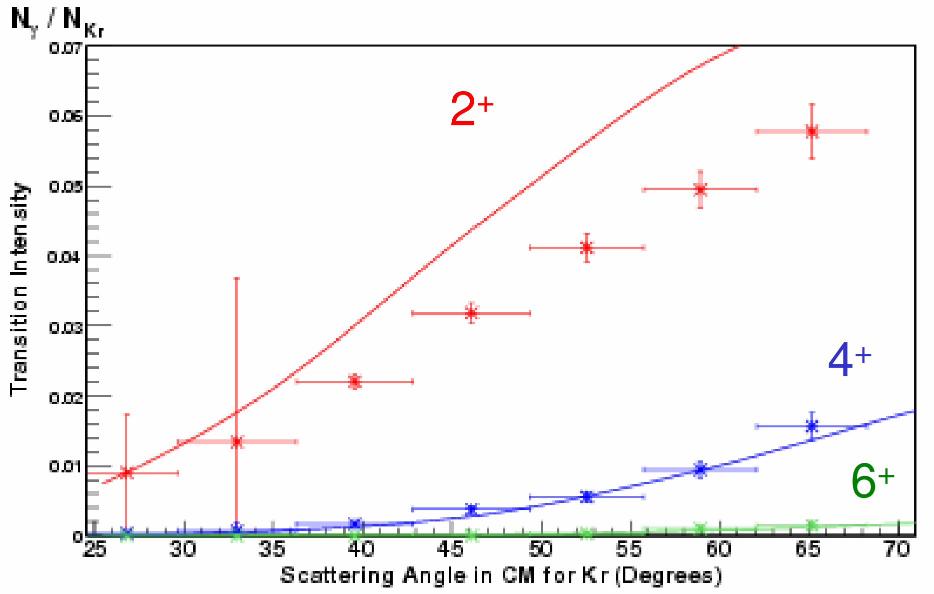
Coulomb excitation analysis : GOSIA*



*D. Cline, C.Y. Wu, T. Czosnyka; Univ. of Rochester

- γ yields as function of scattering angle: differential cross section
- least squares fit of ~ 30 matrix elements (transitional and diagonal)
- experimental spectroscopic data
  - lifetimes
  - branching ratios

- Yields from Coulomb excitation inconsistent with published lifetimes, especially for 4^+ in ^{74}Kr
- New RDM lifetime measurement



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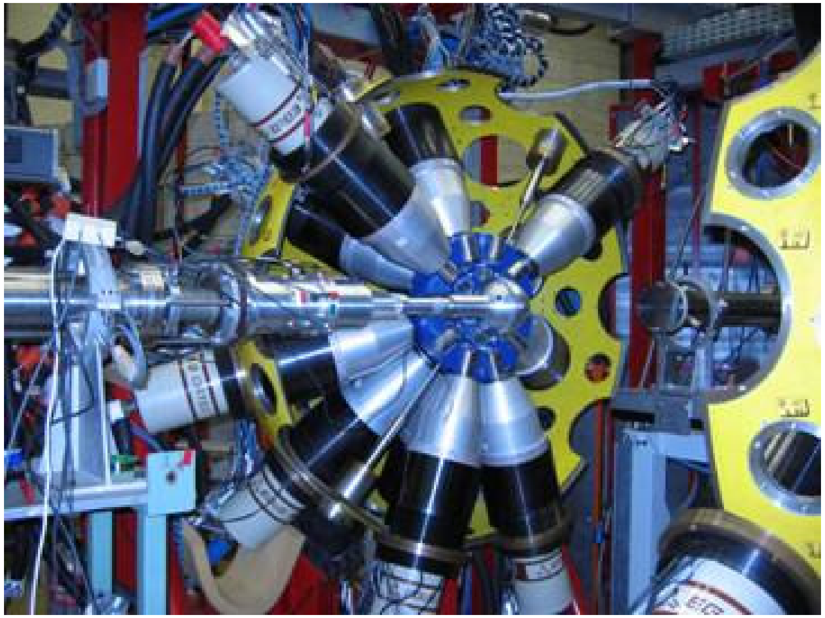
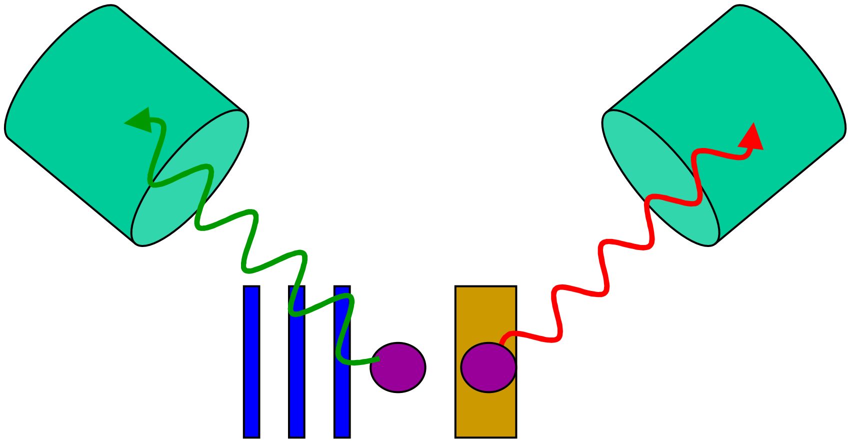
Lifetime measurement with GASP and the Köln Plunger

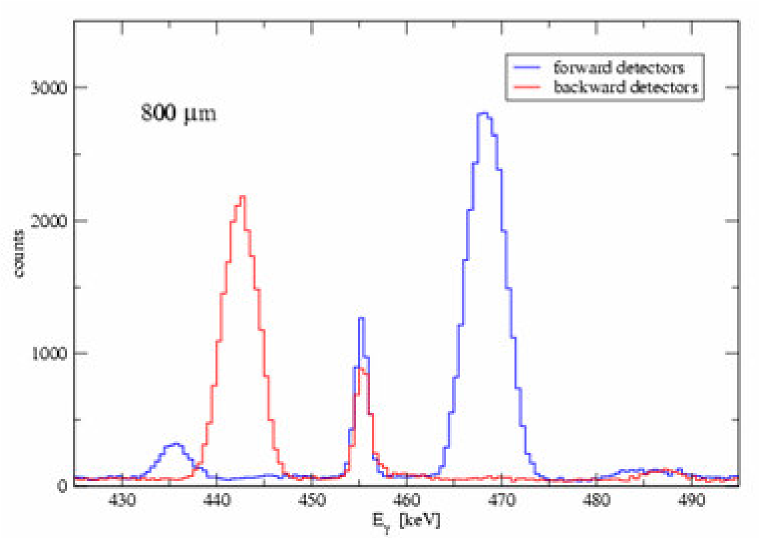


$^{40}Ca(^{40}Ca,a2p)^{74}Kr$

$^{40}Ca(^{40}Ca,4p)^{76}Kr$

124 MeV





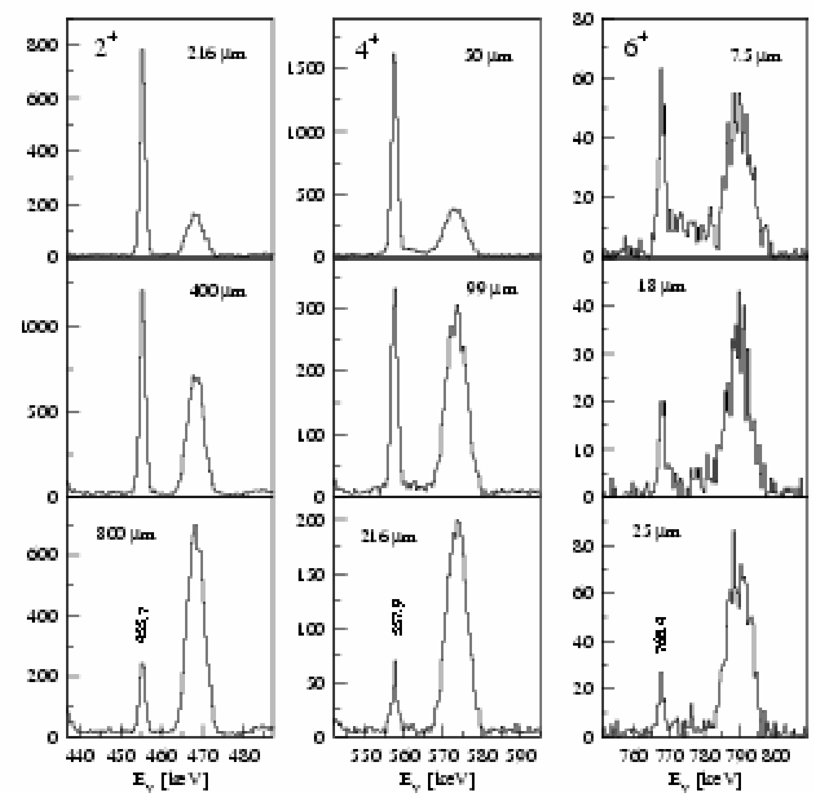
Lifetime results

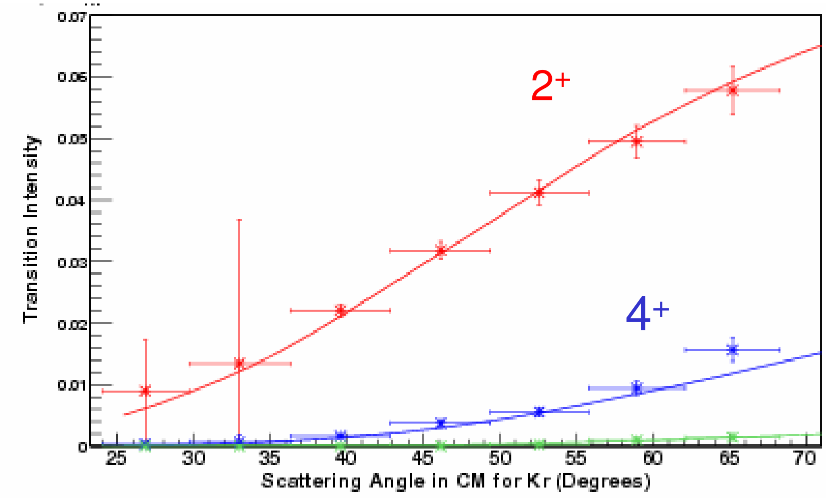
Eur. Phys. J. A 26, 153 (2005)

^{74}Kr	2^+	4^+	^{76}Kr	2^+	4^+	
new	33.8(6)	5.2(2)	new	41.5(8)	3.67(9)	[ps]
	28.8(57)	13.2(7)		35.3(10)	4.8(5)	[ps]
	J. Roth et al., J.Phys.G, L25 (1984)			B. Wörmann et al., NPA 431, 170 (1984)		

^{74}Kr

- forward detectors (36˚)
- gated from above



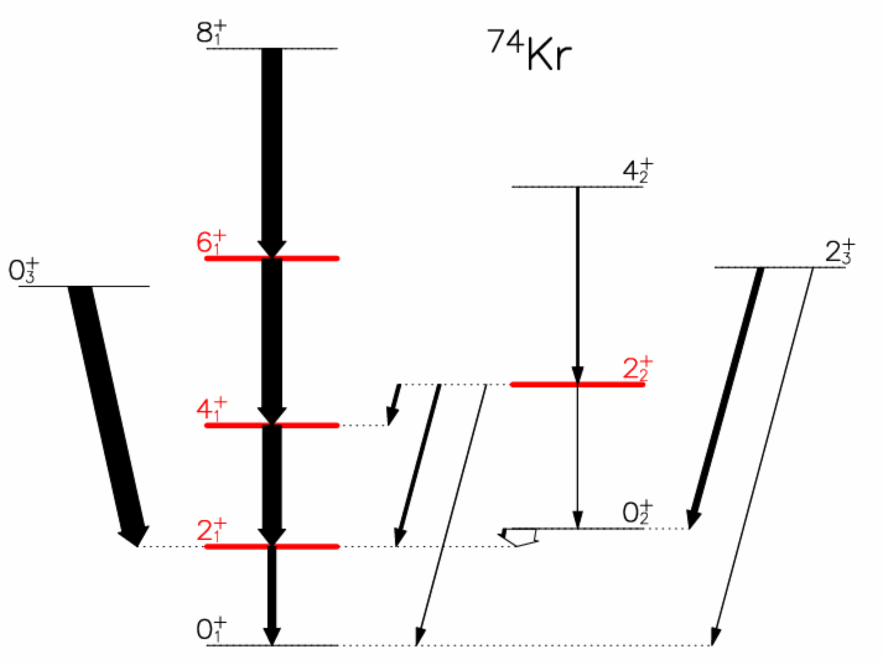


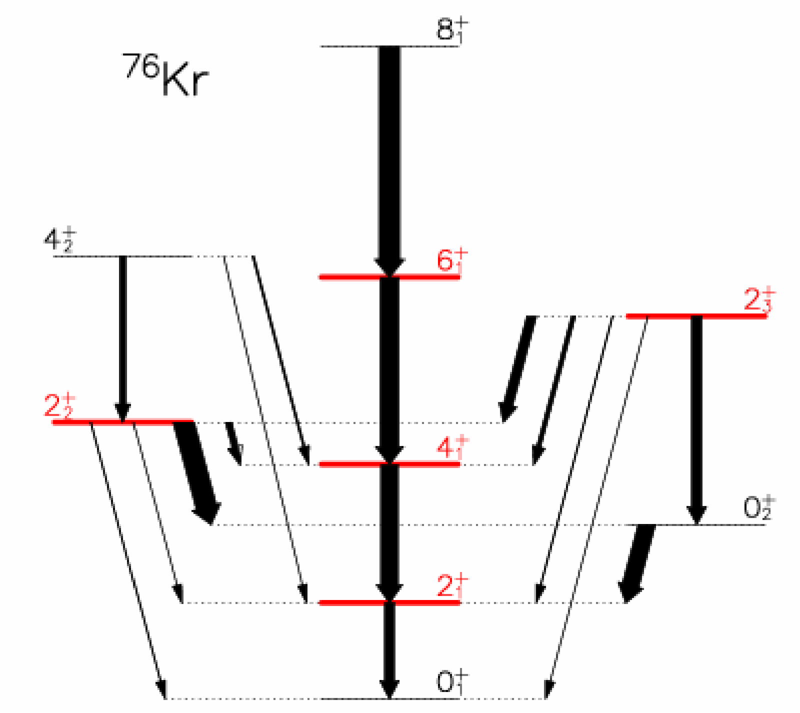
Results consistent with Coulomb excitation.

Lifetimes constrain GOSIA fit.

⇒ enhanced sensitivity for non-yrast transitions and diagonal matrix elements

Result of χ^2 analysis with GOSIA





- 14 transitional E2 matrix elements
- 18 transitional E2 matrix elements

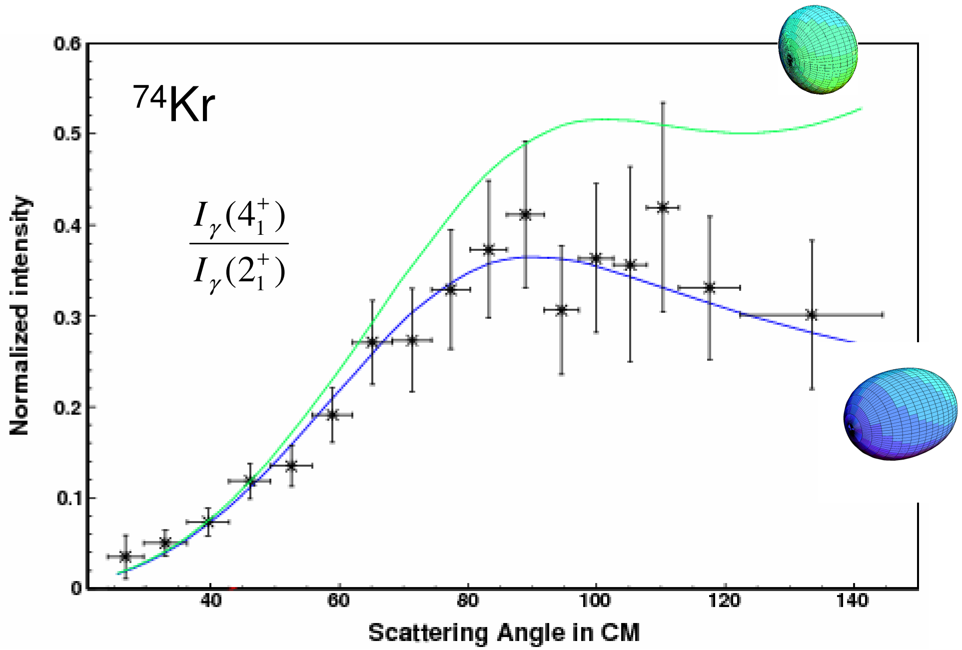
$$B(E2) = \frac{\left|\langle I_f \| \mathrm{M}(E2) \| I_i \rangle\right|^2}{2I_i + 1}$$

- 4 diagonal E2 matrix elements
- 5 diagonal E2 matrix elements

$$eQ_0 = \sqrt{\frac{16\pi}{5}} \frac{1}{\sqrt{2I+1}} \frac{\langle I \| \mathcal{M}(E2) \| I \rangle}{\langle I\,0\,2\,0 | I\,0 \rangle}$$

complete description of collective properties:
important input for "beyond mean field" theories $\Rightarrow$ M. Bender et al.

Sensitivity to quadrupole moments



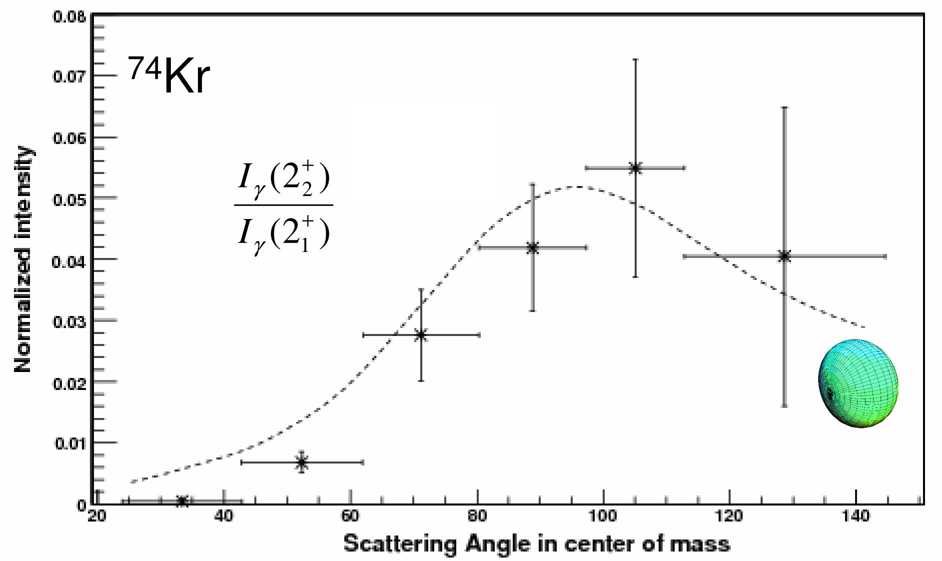
full χ^2 minimization:

$$\langle 2_1^+ \| \mathcal{M}(E2) \| 2_1^+ \rangle = -0.70^{+0.33}_{-0.30}$$

$$\langle 4_1^+ \| \mathcal{M}(E2) \| 4_1^+ \rangle = -1.02^{+0.59}_{-0.21}$$

negative matrix element
(positive quadrupole moment Q_0)

⇒ prolate shape



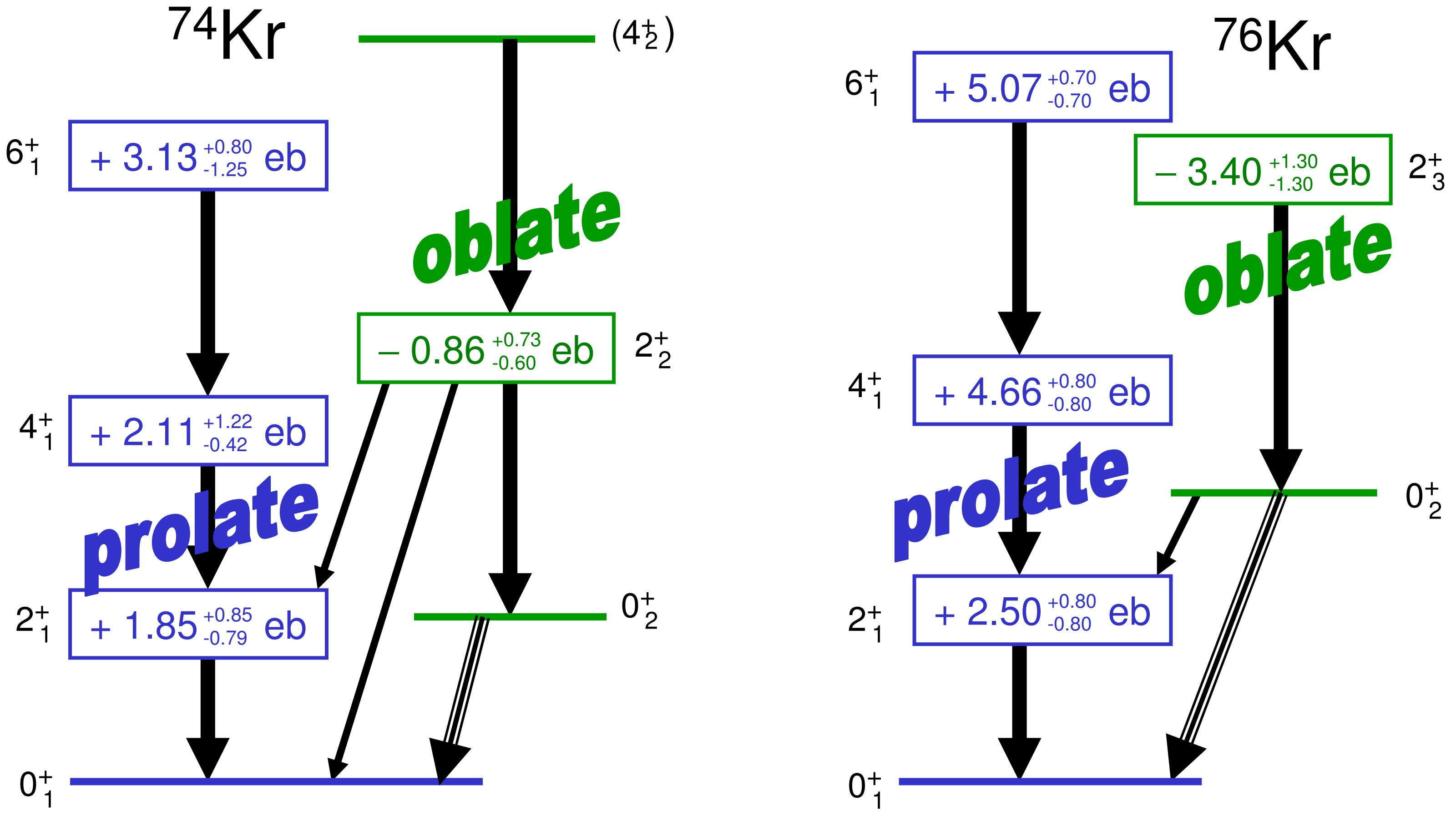
$$\langle 2_2^+ \| \mathcal{M}(E2) \| 2_2^+ \rangle = +0.33^{+0.28}_{-0.23}$$

positive matrix element
(negative quadrupole moment Q_0)

⇒ oblate shape

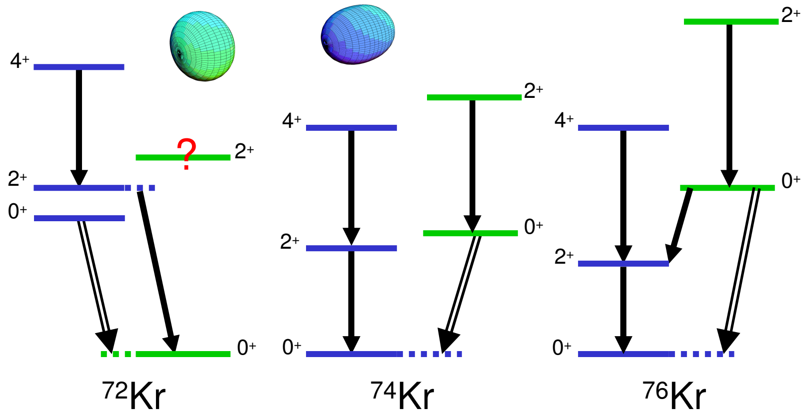
Quadrupole moments Q_0 in ^{74}Kr and ^{76}Kr

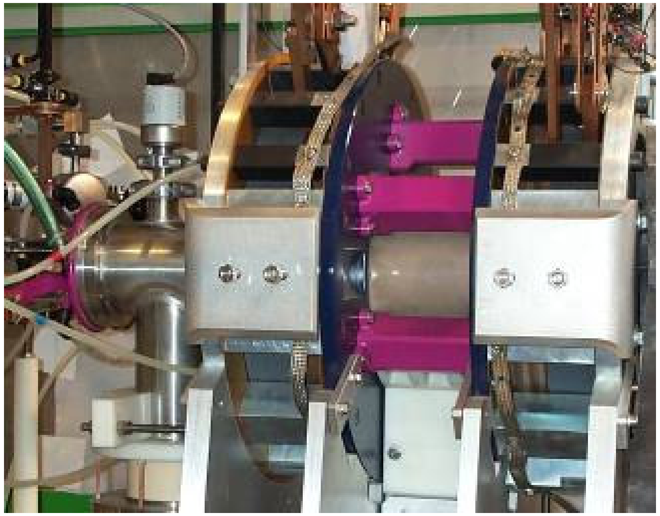
E. Clément et al., to be published



- ➢ direct confirmation of the prolate – oblate shape coexistence
- ➢ first reorientation measurement with radioactive beam

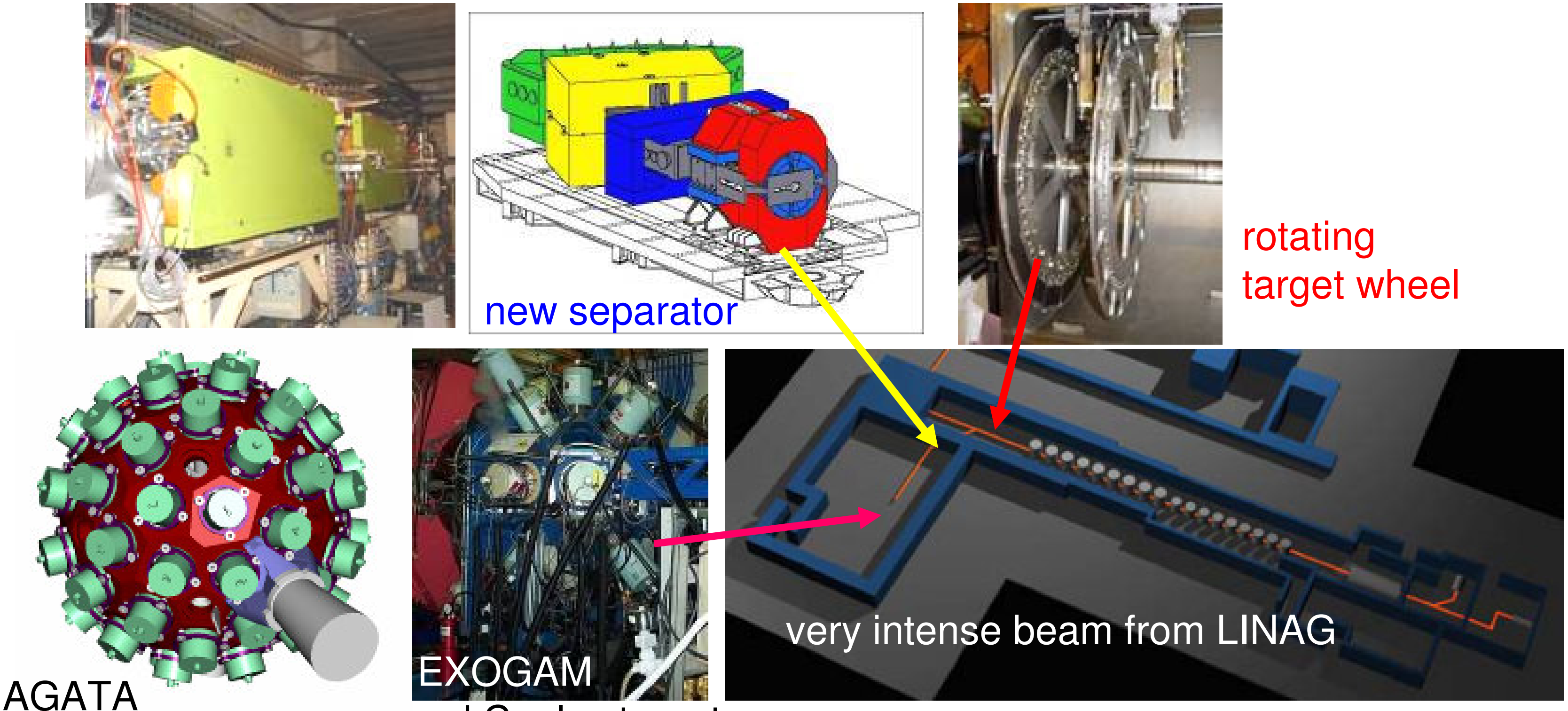
Towards ^{72}Kr





- SPIRAL-1 at present: ~200 pps ^{72}Kr measured before CIME
  ⇒ ~50 pps on target : not feasible
- with 500 pps on target ⇒ precise B(E2) to first and second 2^+ states
- need for more intense primary beams of medium-heavy ions
  benefit for both SPIRAL and fragmentation beams at intermediate energy
  - heavy N≈Z nuclei
  - exotic decays beyond the proton drip line
  - search for isomers and measurement of moments near ^{78}Ni
- GTS source (Grenoble/GANIL) can deliver such intense beams
  example: ~20 eμA ^{78}Kr at 73 A.MeV (3 kW) ⇒ gain ~ factor 10
  ⇒ Letter of Intent

Coulomb excitation after fusion evaporation

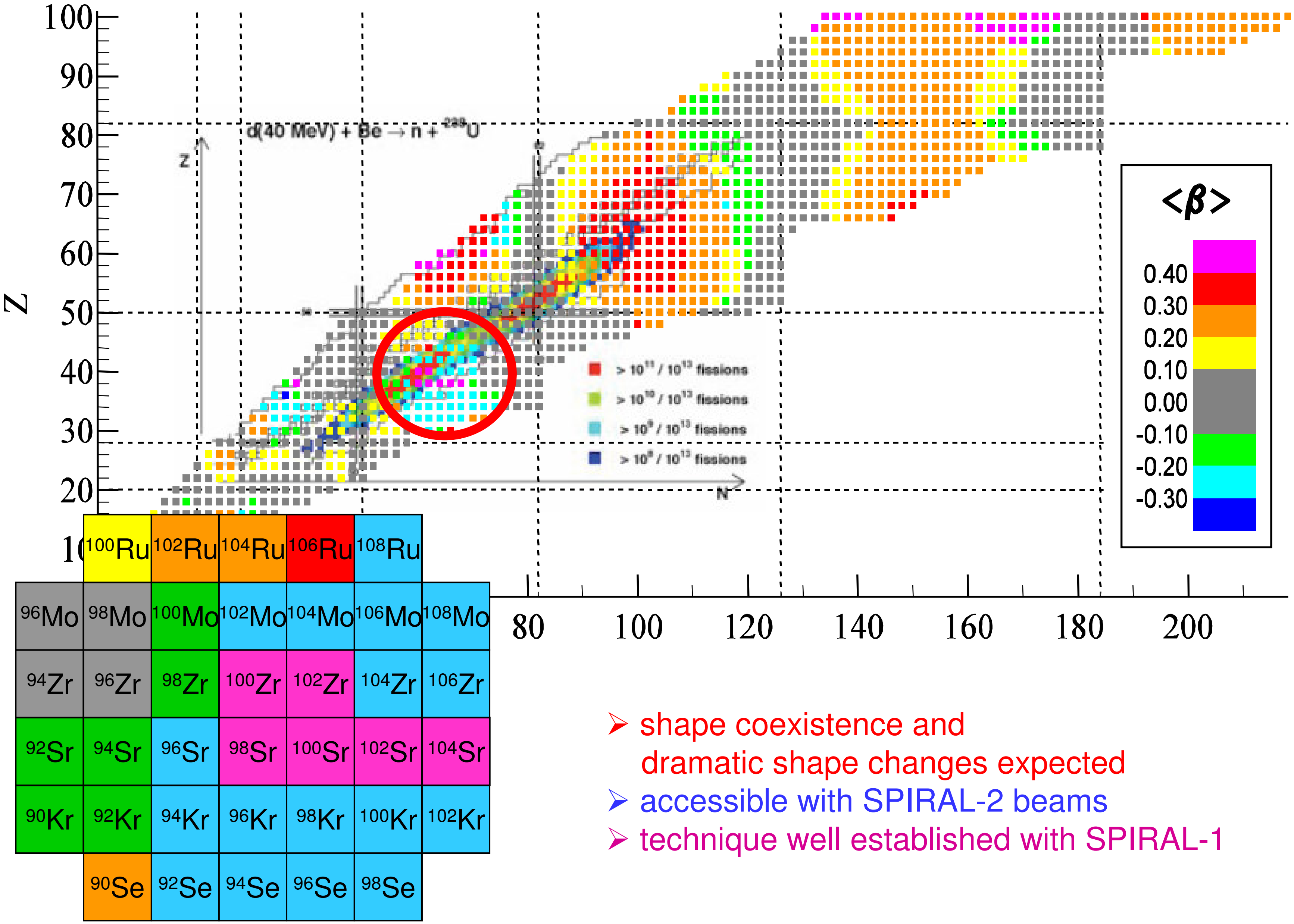


Example: ^{58}Ni+^{12}C → ^{68}Se+2n ($\sigma_{2n} \approx 3$ mb, $\sigma_{tot} \approx 800$ mb)
beam energy: 210 MeV ⇒ recoil energy = 174 MeV = 2.56 A MeV
300 μg/cm^2 target and 100 eμA beam (20+) ⇒ 1.3 ·10^6 ^{68}Se recoils/s
access to non-yrast states – important for shape coexistence

other example:
^{24}Mg(^{58}Ni,2n)^{80}Zr

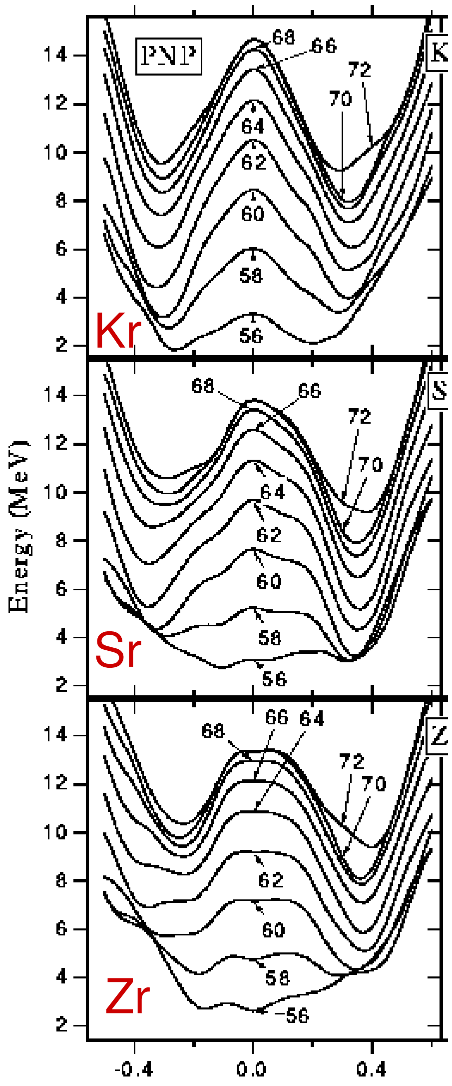
with *A/q=6* and heavier beams:
^{48}Ca(^{208}Pb,2n)^{254}No

Fission fragment beams from SPIRAL-2

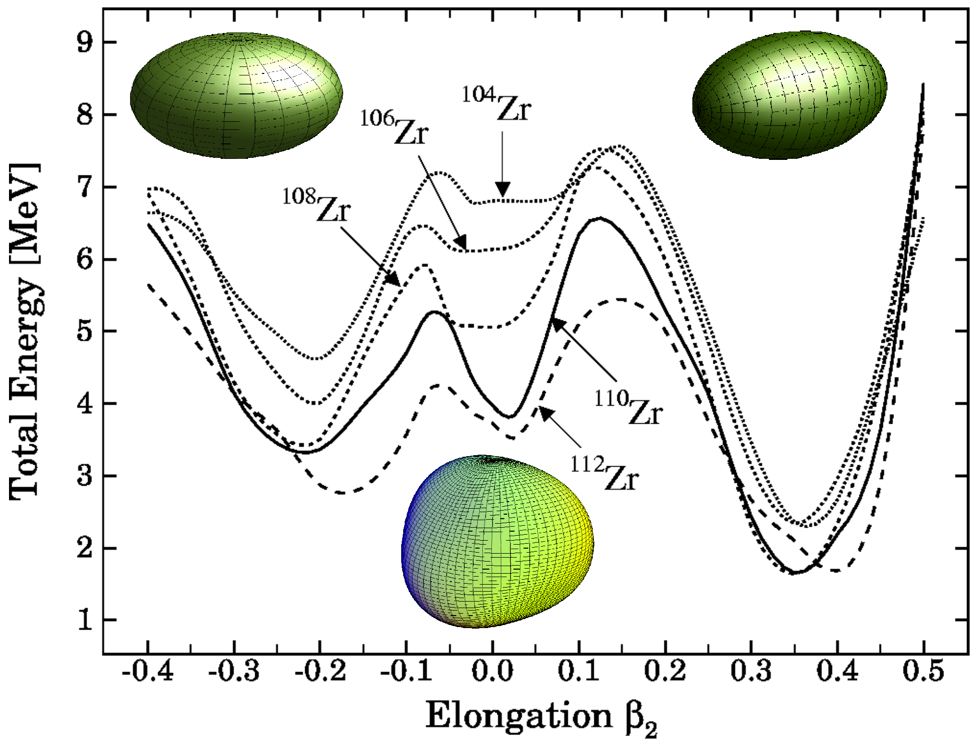


- shape coexistence and dramatic shape changes expected
- accessible with SPIRAL-2 beams
- technique well established with SPIRAL-1

Shape coexistence in neutron-rich fission fragments



J. Skalski et al.,
NPA 617, 282 (1997)

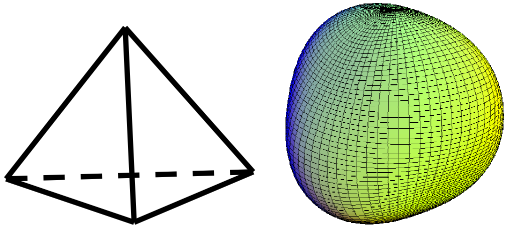


N. Schunck et al., Phys. Rev. C69, 061305(R) (2004)

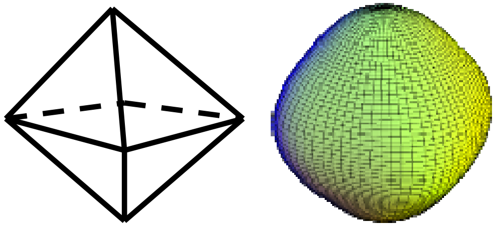
- prolate-oblate shape coexistence around N=60
- new symmetries: tetrahedral shapes

Tetrahedral and octahedral shapes

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

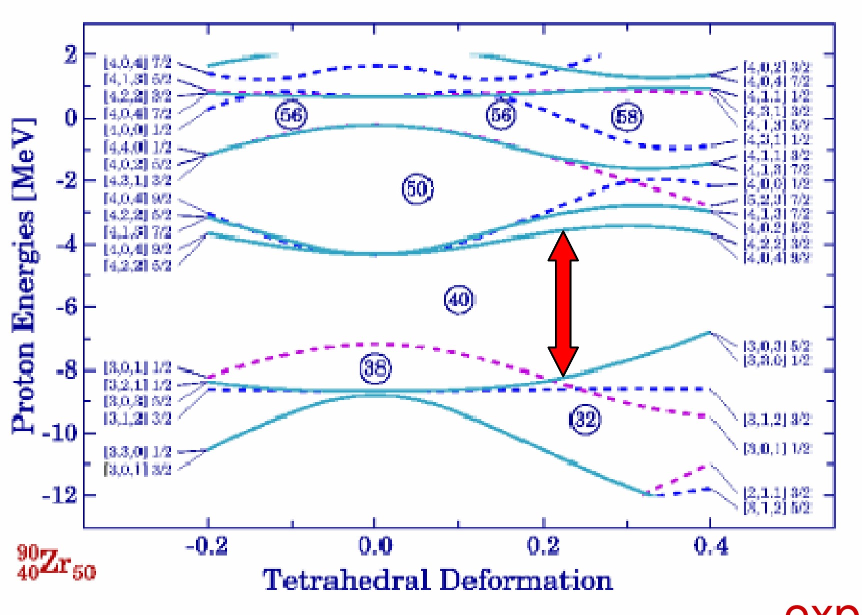


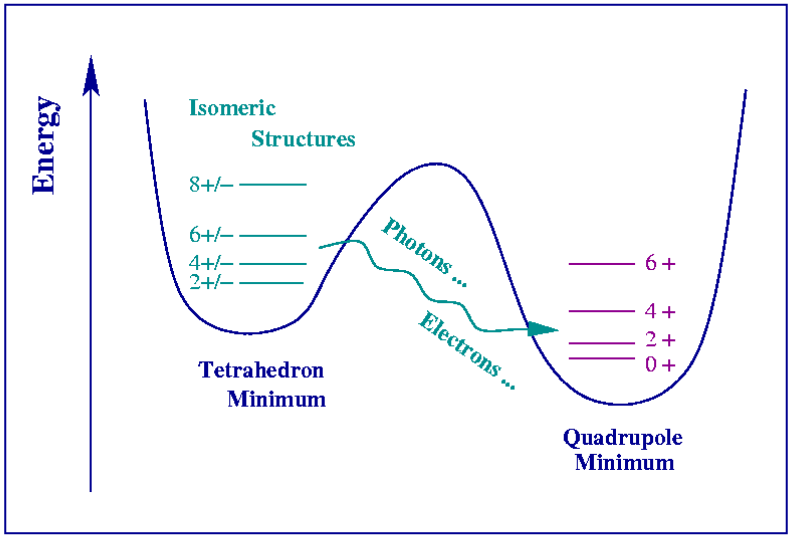
tetrahedral: $\alpha_{32} \neq 0$



octahedral: $\alpha_{40}, \alpha_{44} \neq 0$

symmetry ⇒ degeneracy ⇒ shell gaps ⇒ stability





N. Schunck, J. Dudek

experimental signatures:

- shape isomers
- parity doublets
- static octupole moment Q_3

The superdeformed world

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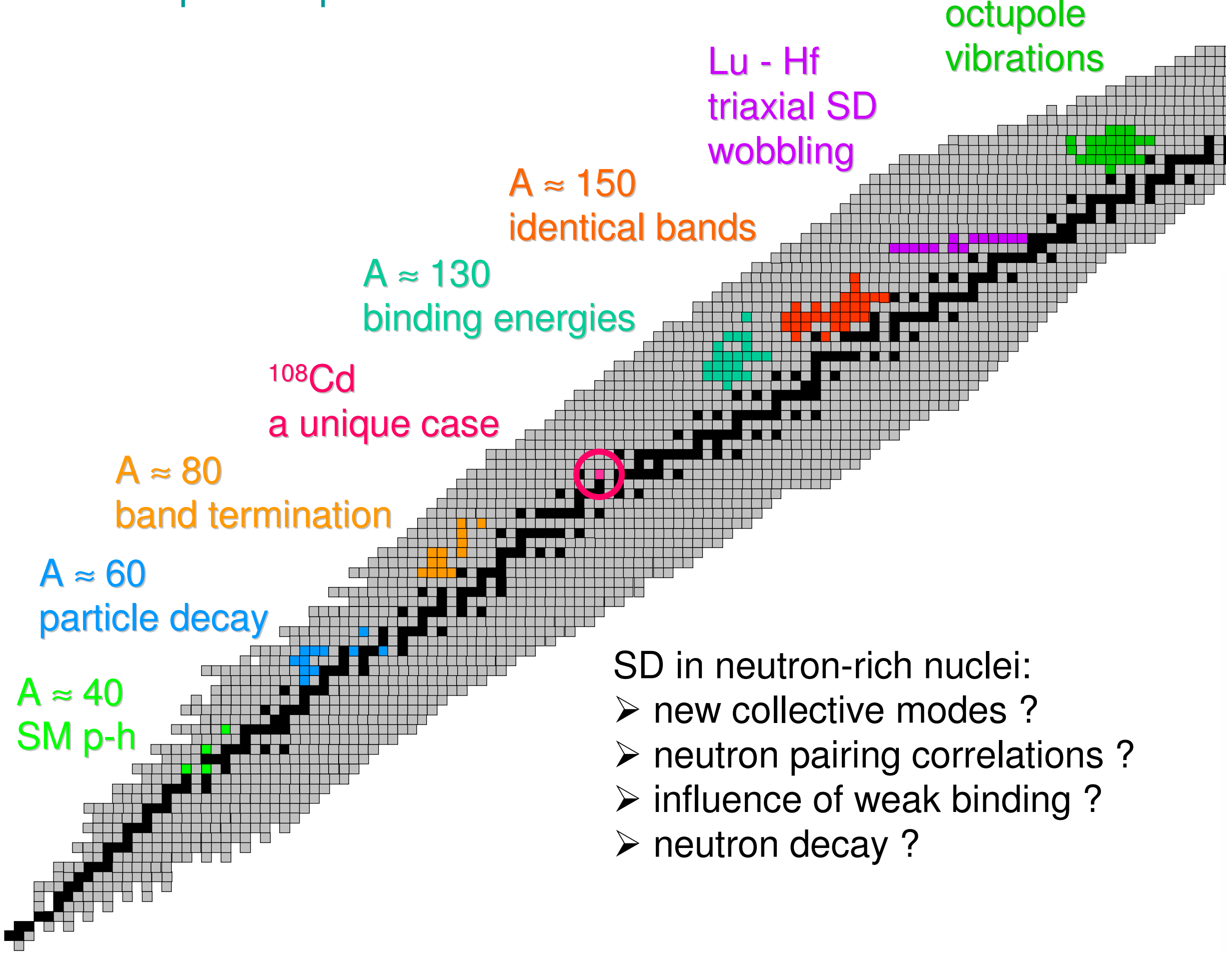
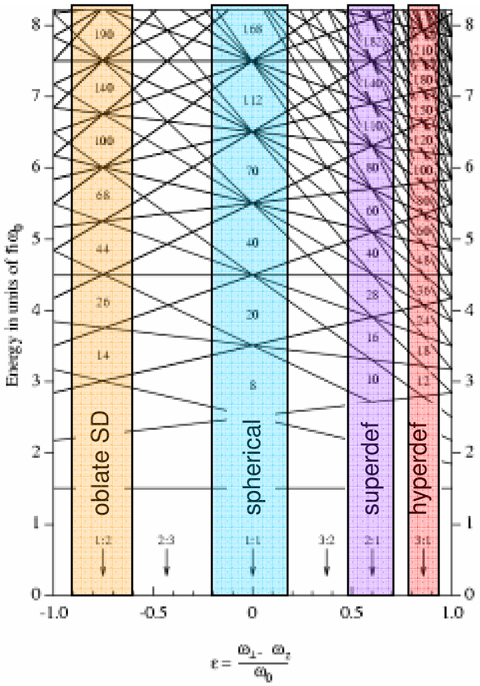
- unique laboratory to study nuclear structure under extreme conditions
- fundamental properties E^*, I, π unknown in most cases
- many phenomena not yet understood
- the closer we look, the more new and unexpected phenomena we find



SD in neutron-rich nuclei:

- new collective modes ?
- neutron pairing correlations ?
- influence of weak binding ?
- neutron decay ?

harmonic oscillator, simple but instructive approach

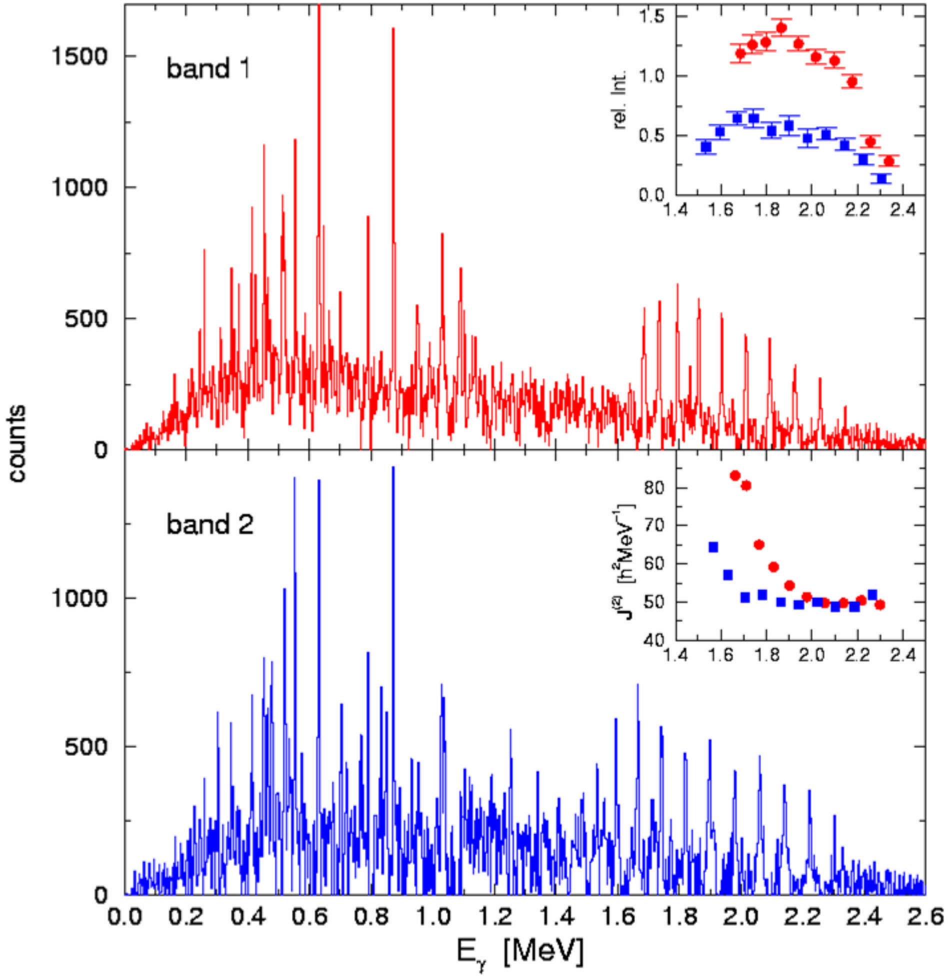


Very deformed structures in ^{108}Cd

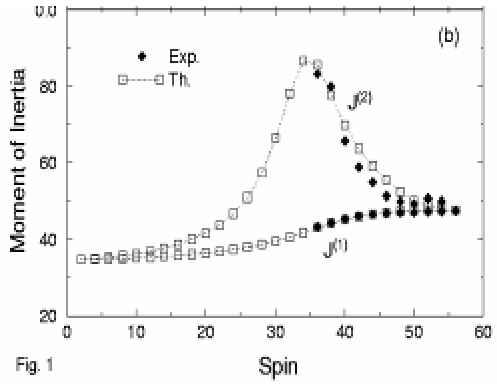
$^{64}Ni(^{48}Ca,4n)^{108}Cd$
Gammasphere @ LBL

R.M. Clark et al., PRL 87, 202502 (2001)
A. Görgen et al., PRC 65, 027302 (2002)

- γ-ray multiplicity
  ⇒ spin range 40-60 ħ
- Doppler shift
  ⇒ lower limit on Q_t, $\beta_2 \geq 0.6$

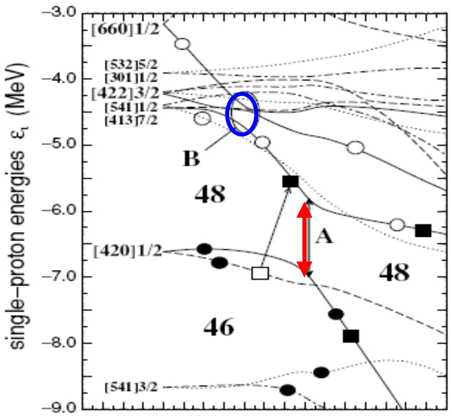


projected shell model



C-T.Lee et al., PRC 65, 041301 (2002)

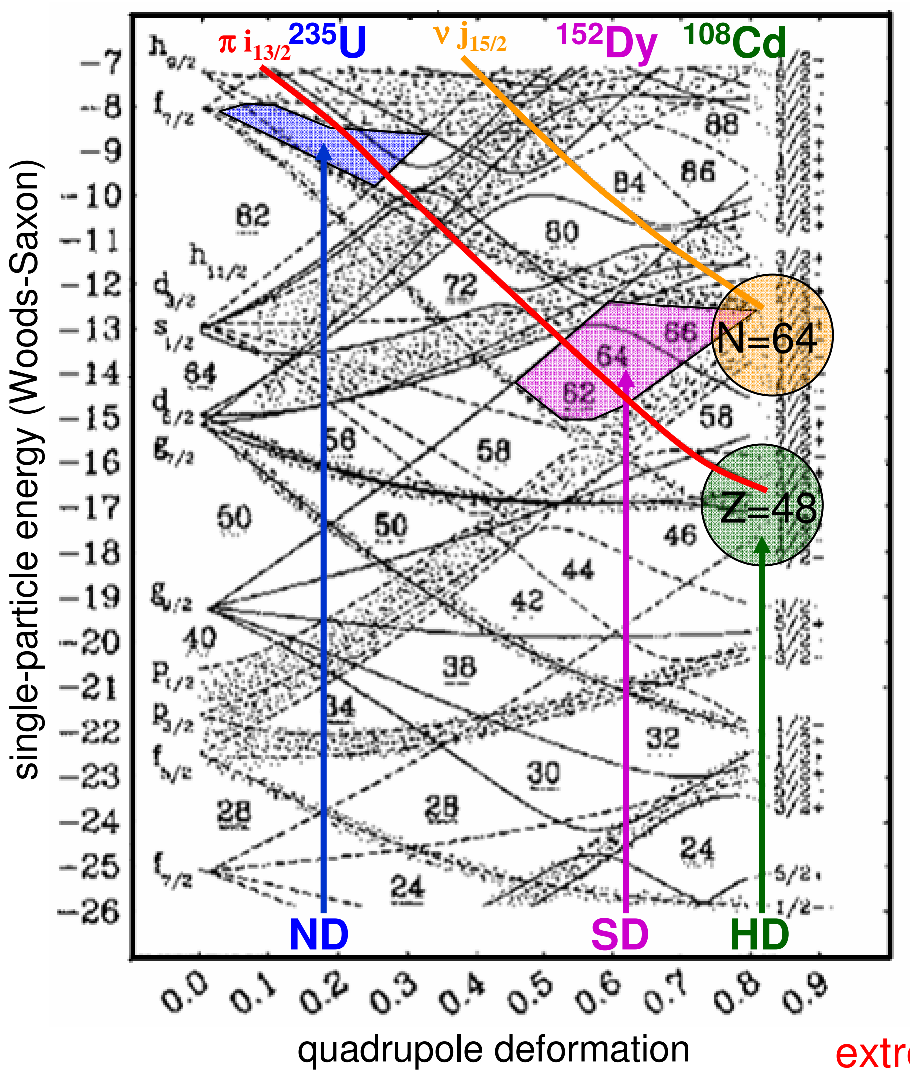
cranked RMF



A.V. Afanasjev, S. Frauendorf,
PRC 72, 031301 (2005)

evidence for occupation of proton $i_{13/2}$ orbital

Intruder orbitals



- one major shell below (N-1)
  ⇒ normal deformed, e.g. ^{235}U
- two major shells below (N-2)
  super-intruder
  ⇒ Superdeformation, e.g. ^{152}Dy
- three major shells below (N-3)
  hyper-intruder occupied in ^{108}Cd
  ⇒ Hyperdeformation ?

Where is the neutron hyper intruder $j_{15/2}$?

- expected to be occupied in ^{112}Cd, ^{114}Cd

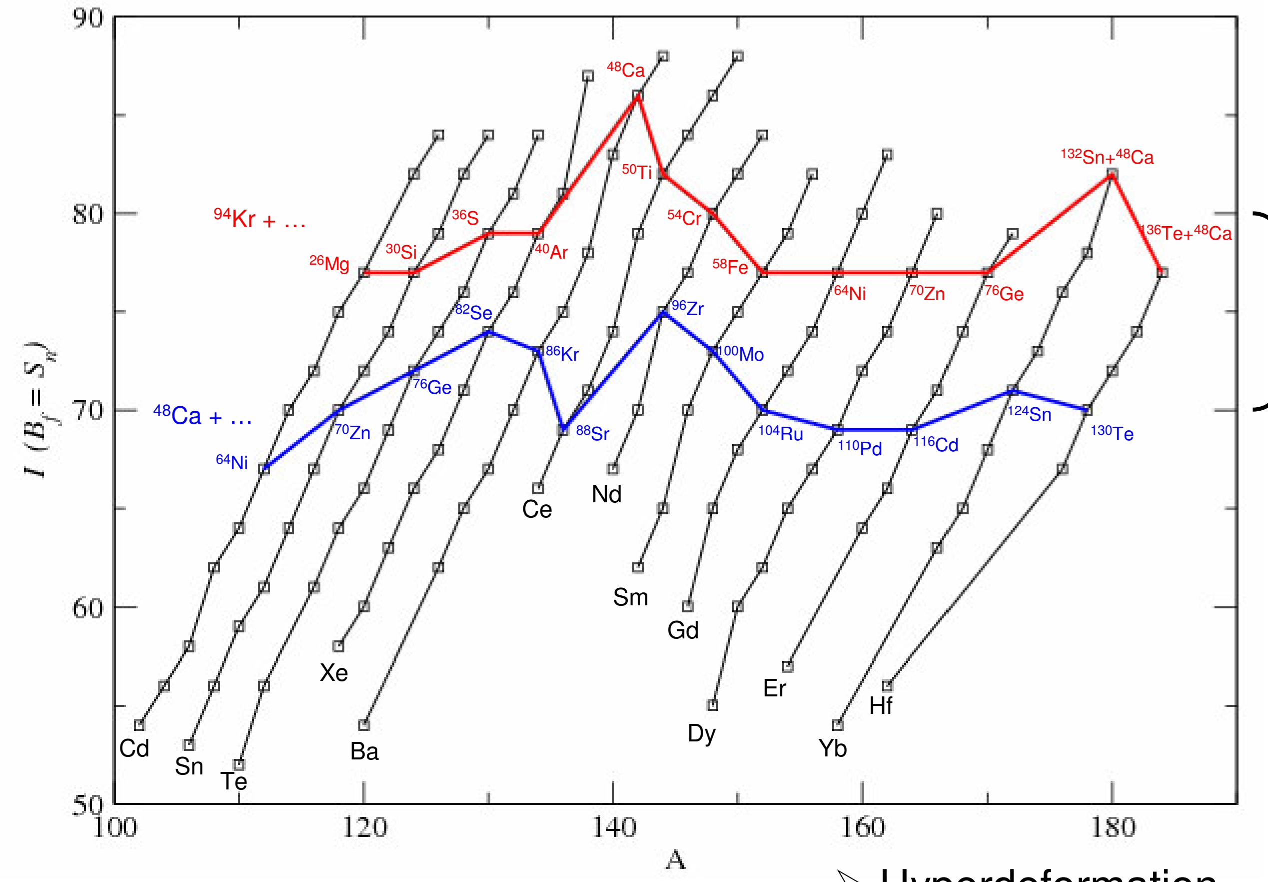
two reasons to go more neutron rich:

- towards doubly-magic hyperdef
- higher angular momentum limit

extreme deformation stabilized by rapid rotation
hints for Jacobi shape transition in ^{108}Cd
D. Ward et al., Phys. Rev. C 66, 024317 (2002)

Angular momentum limit

compound nucleus reached
- in ^{48}Ca induced reaction
- in ^{94}Kr (or ^{132}Sn) induced reaction



new spin regime:
70 - 80 ħ

Examples:

^{48}Ca+ ^{64}Ni → ^{112}Cd*

^{94}Kr+ ^{26}Mg → ^{120}Cd*

^{94}Kr+ ^{48}Ca → ^{142}Ba*

^{132}Sn+ ^{48}Ca → ^{180}Yb*

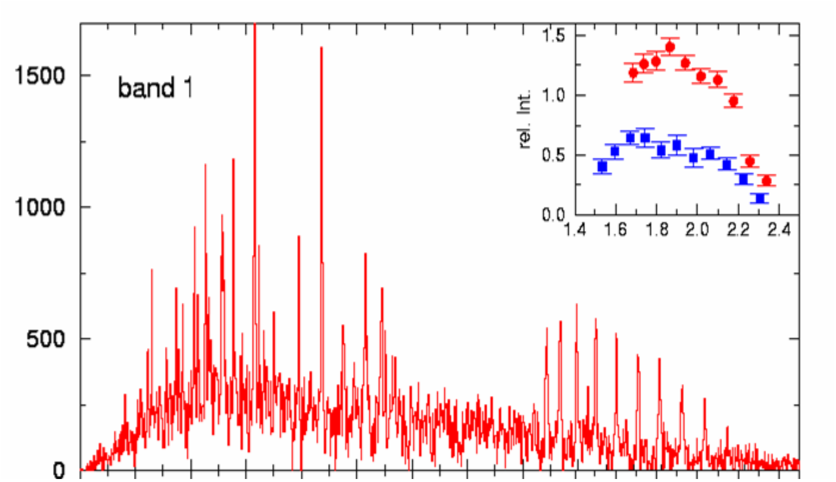
pushing the angular momentum
always led to new physics !

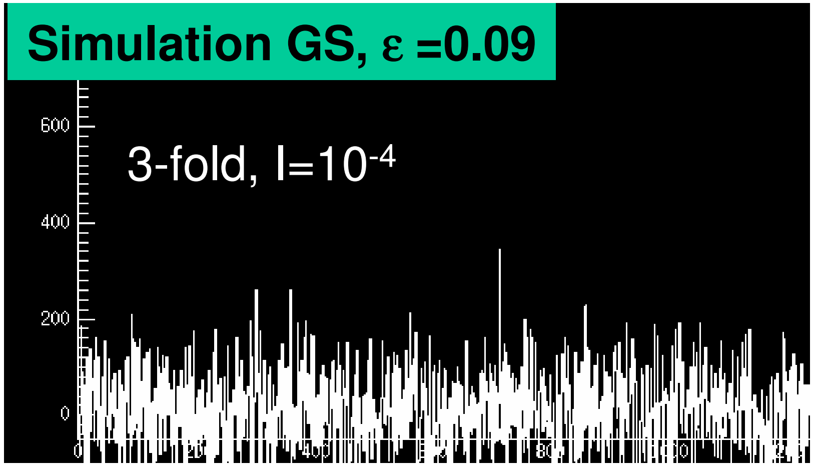
- Hyperdeformation
- Jacobi shape transition
- Band termination
- Collapse of pairing
- …?

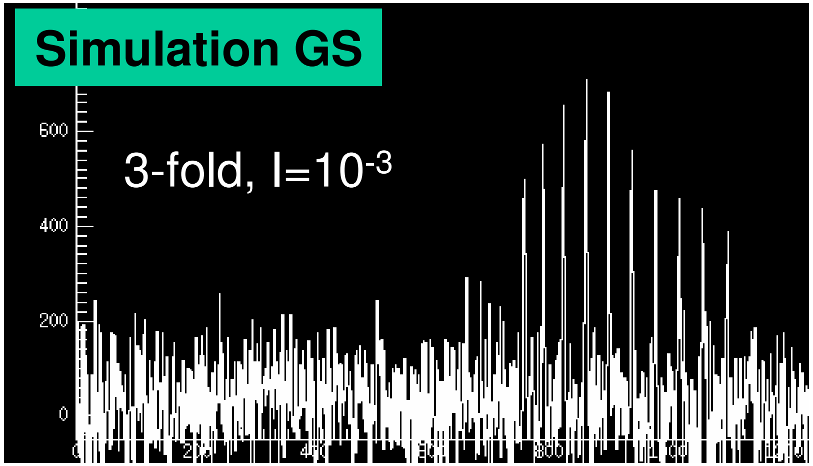
Gamma-ray tracking

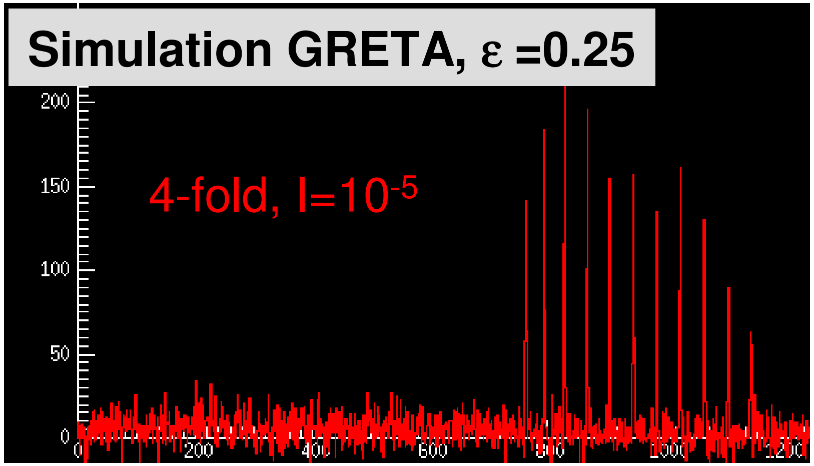
I.-Y. Lee

^{64}Ni (^{48}Ca, 4n) ^{108}Cd, Gammasphere

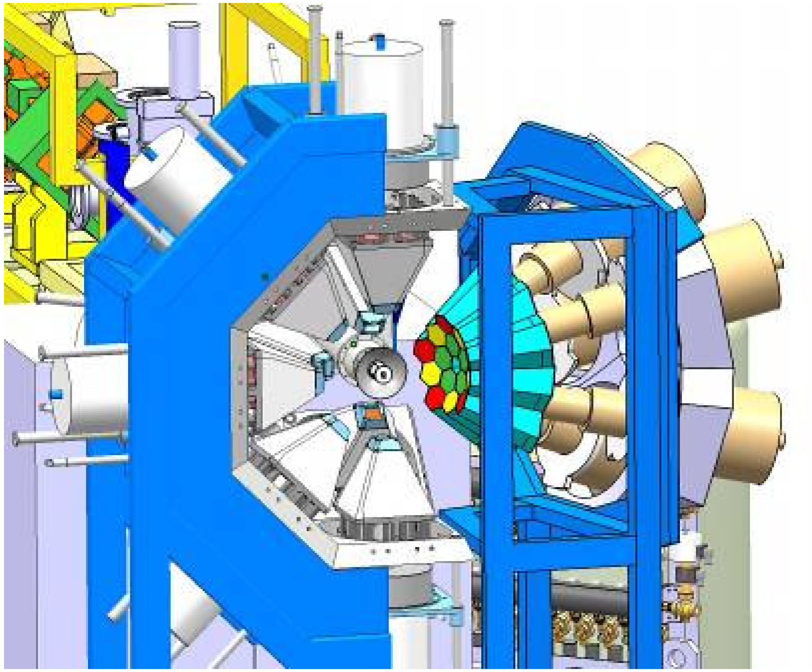








Future of γ-ray spectroscopy at GANIL



AGATA demonstrator @ GANIL
- physics case completed
- technical proposal to be submitted to ASC in June
- campaign starting end 2008 / beginning 2009 ?

SPIRAL-1 developments ?
direct beam line CIME – G1/G2 !

Most SPIRAL-2 experiments will involve γ spectroscopy.
AGATA (in its various stages) and SPIRAL-2
make a very powerful combination.

Working group "Shapes and High Spins" (N. Redon & A.G.)
Letter of Intent: **Your ideas needed !**

Summary and conclusions

- Low-energy projectile Coulomb excitation with RIB
  - direct confirmation of shape coexistence in ^{74,76}Kr
  - first reorientation measurement with RIB
- Plunger lifetime measurement after fusion-evaporation
  - complementary measurement of B(E2) values
  - importance of stable beams
- Perspectives for A≈70 region:
  - intensity upgrade of SPIRAL-1
  - Coulex after fusion-evaporation using LINAG
- Exotic shapes and shape coexistence in fission fragments
  - rich physics case for SPIRAL-2
- Challenges in high-spin physics
  - push the angular momentum limit with SPIRAL-2
  - push the detection limit with AGATA