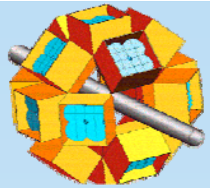


Shape coexistence in exotic nuclei studied by low energy coulomb excitation

Emmanuel Clément

CERN-PH, Geneva

Shapes of exotic nuclei

The **shape** of a nucleus is a **fundamental property** very **sensitive to all types of correlations**

Magnetic dipole and quadrupole moments are reflecting the spatial distribution of the nucleons

➡ **Important benchmarks for nuclear models / theory**

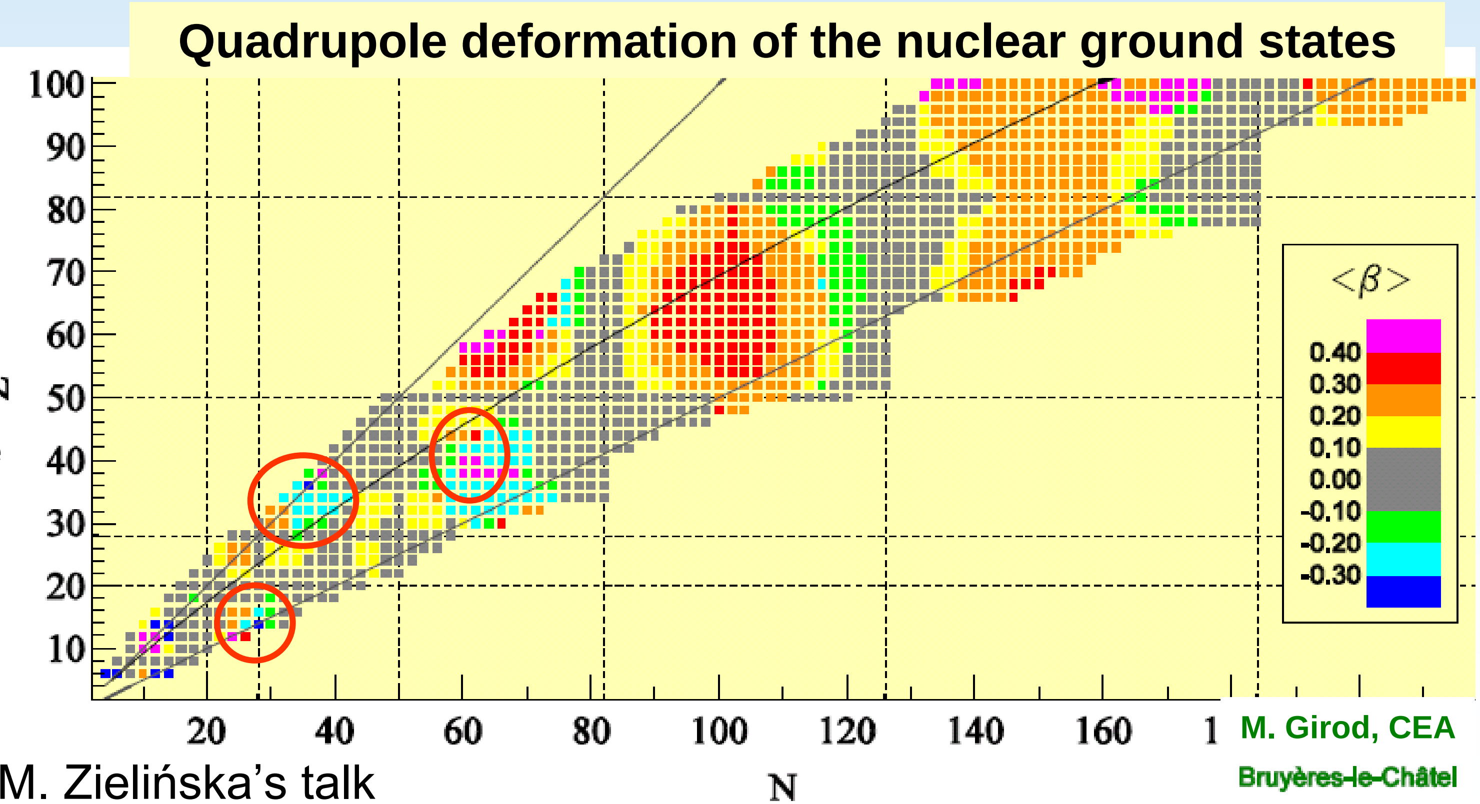
- B(E2) measurement
- Static moment measurement (oblate-prolate)

Prolate-oblate-spherical shape in a small energy range

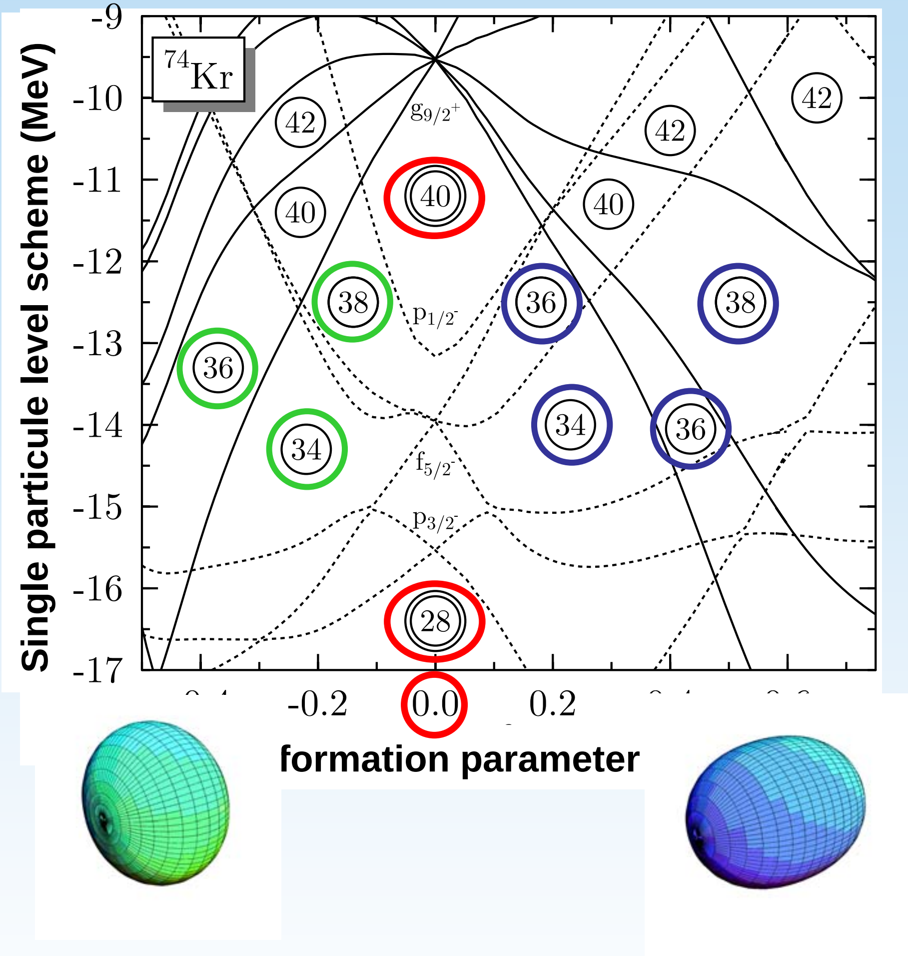
⬇

Shape coexistence

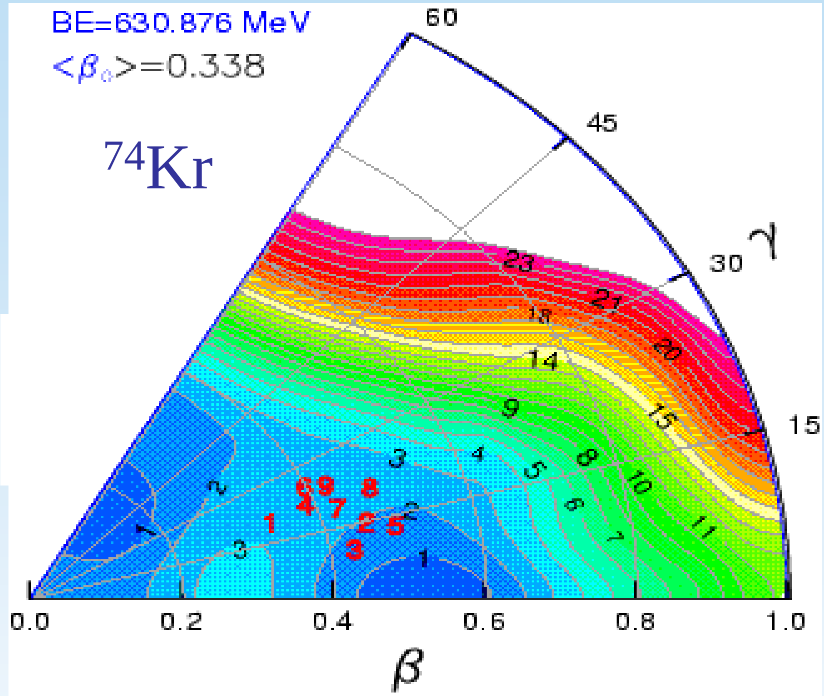
- A=70-80, N=Z
- n-rich Sr&Zr
- n-rich Ar → See M. Zielińska's talk



Shapes coexistence in light Kr isotopes



HFB+Gogny D1S M. Girod *et al.*,
To be published



- Important constraints for modern nuclear structure theories :
  - Predicted values of β_2
  - E (0^+_2), $\rho^2(E0)$, B(E2), Q_0 …
  - Mixing of wave function → GCM

Once upon a time ….

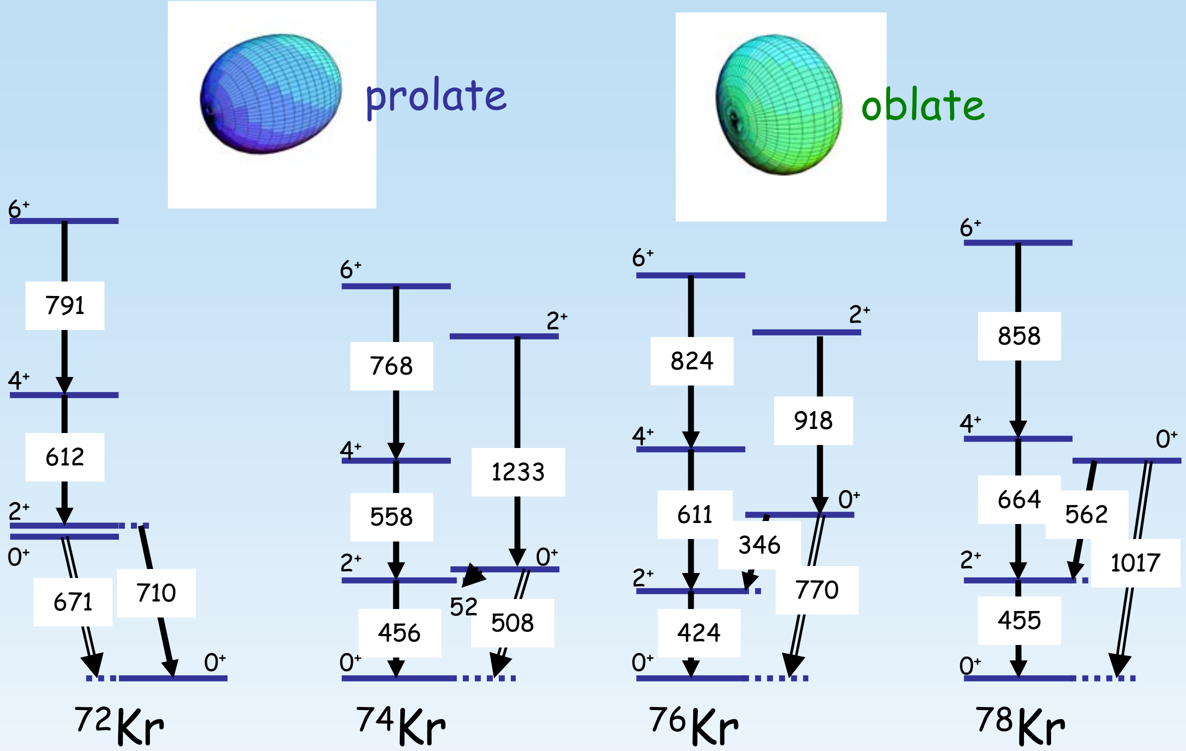
2000 & 2001 Conversion electron spectroscopy : E0 transition

2000 Coulomb excitation of ^{78}Kr

2002 First Coulomb excitation of a radioactive ^{76} Kr beam @ SPIRAL +EXOGAM

2003 Coulomb excitation of a radioactive ^{74}Kr beam @ SPIRAL+EXOGAM

2004 Lifetime measurement of ^{76}Kr and ^{74}Kr @ GASP



Transition strenght : $\rho^2(E_0).10^{-3}$ 72(6) ? 84(18) 79(11) 47(13)

E. Clément *Thèse Université de Paris 11 (2006)*

E. Bouchez *Thèse Université de Strasbourg 1 (2003)*

F. Becker *et al. Nucl. Phys. A **770** (2006)*

Complete measure of reduced transition probability B(E2) and static quadrupole moment

A. Görgen, E. Clément *et al.*
*Eur. Phys. J. A **26**, 153 (2005)*

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

F. Becker *et al.*, Eur. Phys. J. A **4** (1999)

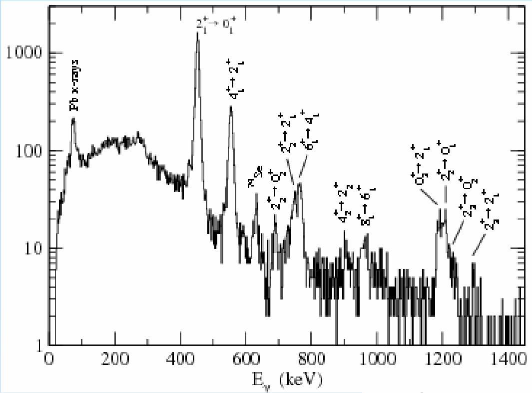
A. Giannatiempo *et al.*, Phys. Rev. C **52** (1995)

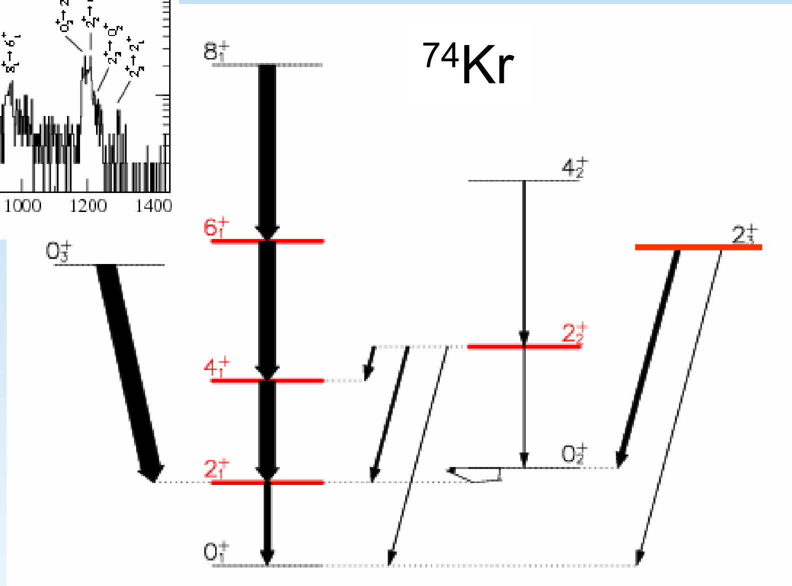
E. Clément, A. Görgen, W. Korten *et al.*
Submitted to Phys. Rev. C

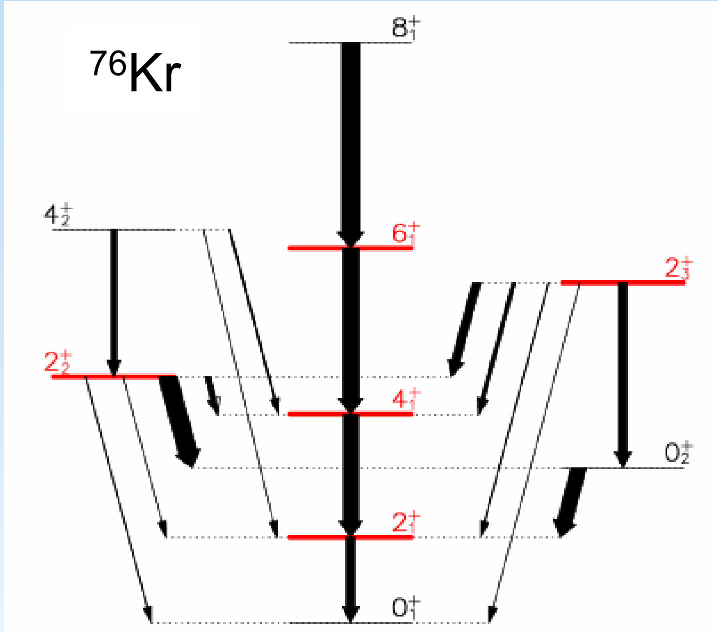
End of 2006 Coherent analysis of all data from ^{76}Kr and ^{74}Kr

In the future Low-energy Coulomb excitation of ^{72}Kr beam development needed

Coulomb excitation analysis with GOSIA







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

In ^{74}Kr and ^{76}Kr, a prolate ground state coexists with an oblate excited configuration

Transition probability : describe the coupling between states

- 5 E2 diagonal matrix element
- 5 E2 diagonal matrix element

First direct experimental proof of the shape coexistence in light Kr isotopes

Spectroscopic quadrupole moment : intrinsic properties of the nucleus

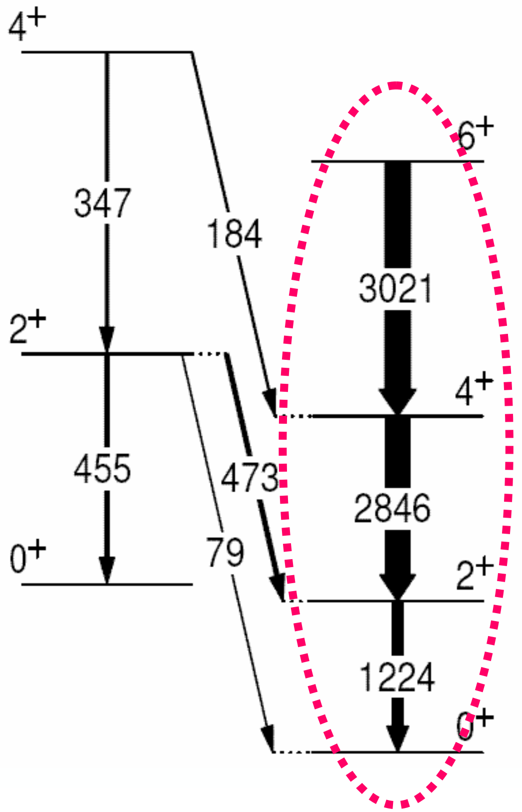
E. Bouchez Thèse SPhN 2003

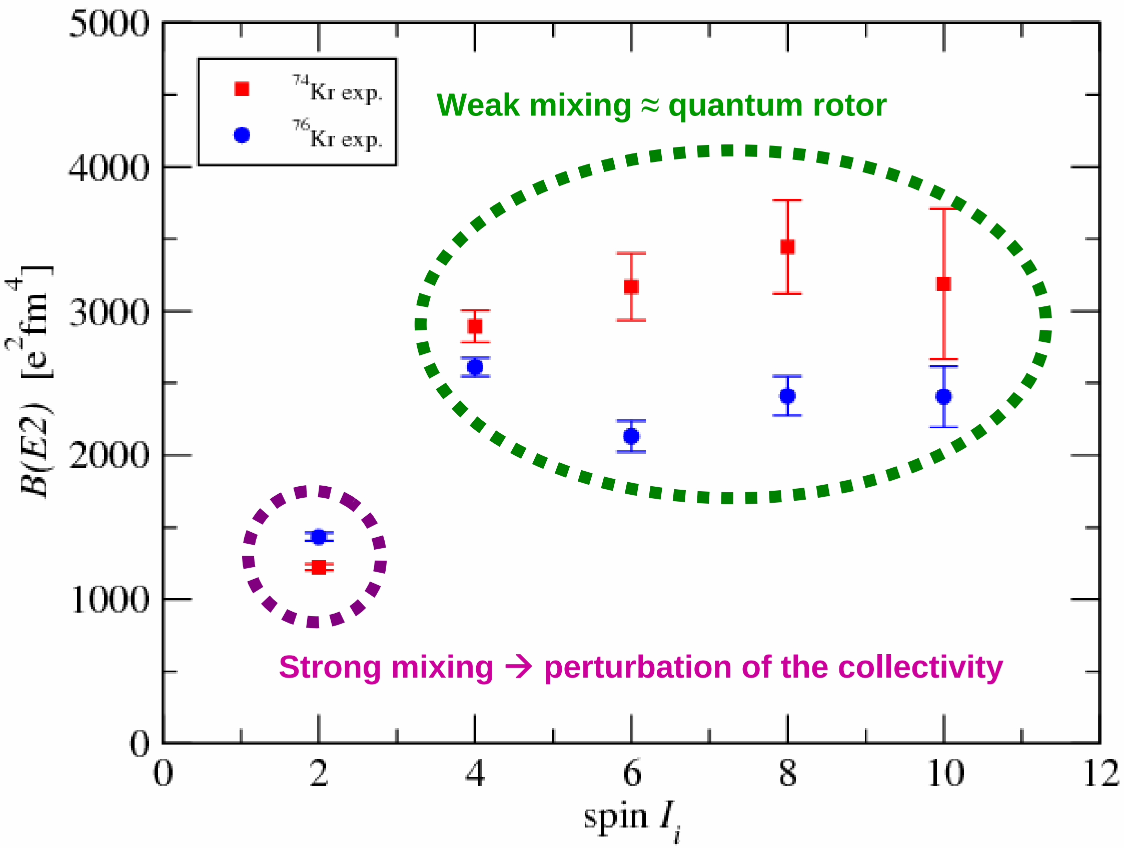
E. Clément Thèse SPhN 2006

E. Clément et al. Submitted to PRC

Configurations mixing (1)

➧ **For the shape-coexisting states, prolate and oblate wave functions are highly mixed**





Configurations mixing (2)

Shape coexistence in a two-state mixing model

$$|I_1\rangle = +\cos\theta_I |I_{\rm pr}\rangle + \sin\theta_I |I_{\rm ob}\rangle$$
$$|I_2\rangle = -\sin\theta_I |I_{\rm pr}\rangle + \cos\theta_I |I_{\rm ob}\rangle$$

Pure states

Perturbed states

Extract mixing and shape parameters from set of experimental matrix elements.

		^{76}Kr	^{74}Kr	^{72}Kr
Energy perturbation of 0^+_2 states E. Bouchez *et al.* Phys. Rev. Lett., ***90*** *(2003)*	$\cos^2\theta_0$	0.73(1)	0.48(1)	0.10(1)
Full set of matrix elements : E. Clément, A. Görgen, W. Korten *el al.* Submitted to PRC	$\cos^2\theta_0$	0.69(4)	0.48(2)	

Model describes mixing of 0^+ states well, but ambiguities remain for higher-lying states. Two-band mixing of prolate and oblate configurations is too simple.

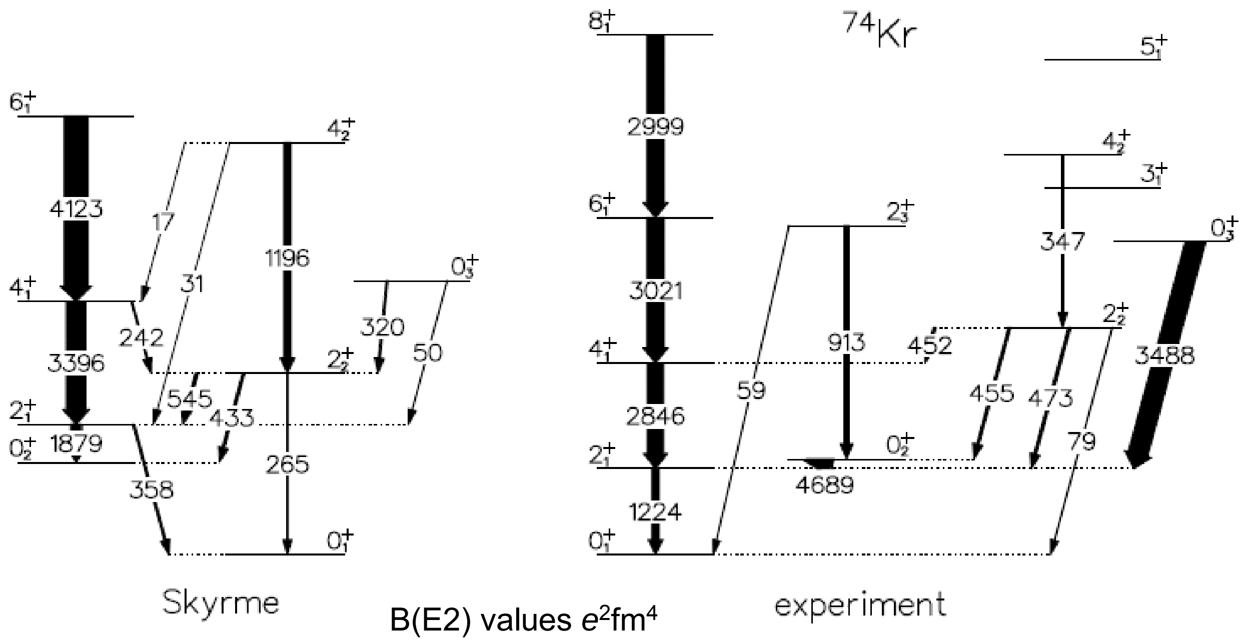
Shape coexistence in mean-field models (2) Skyrme

GCM-HFB (SLy6)
M. Bender, P. Bonche et P.H. Heenen,
Phys. Rev. C 74, 024312 (2006)

HFB+GCM method
Skyrme SLy6 force
density dependent pairing interaction

Restricted to axial symmetry : no K=2 states

- Inversion of oblate and prolate states
- Collectivity of the prolate rotational band is correctly reproduced
- Interband B(E2) are under estimated



Same conclusion for ^{76}Kr

Shape coexistence in mean-field models (3) Gogny

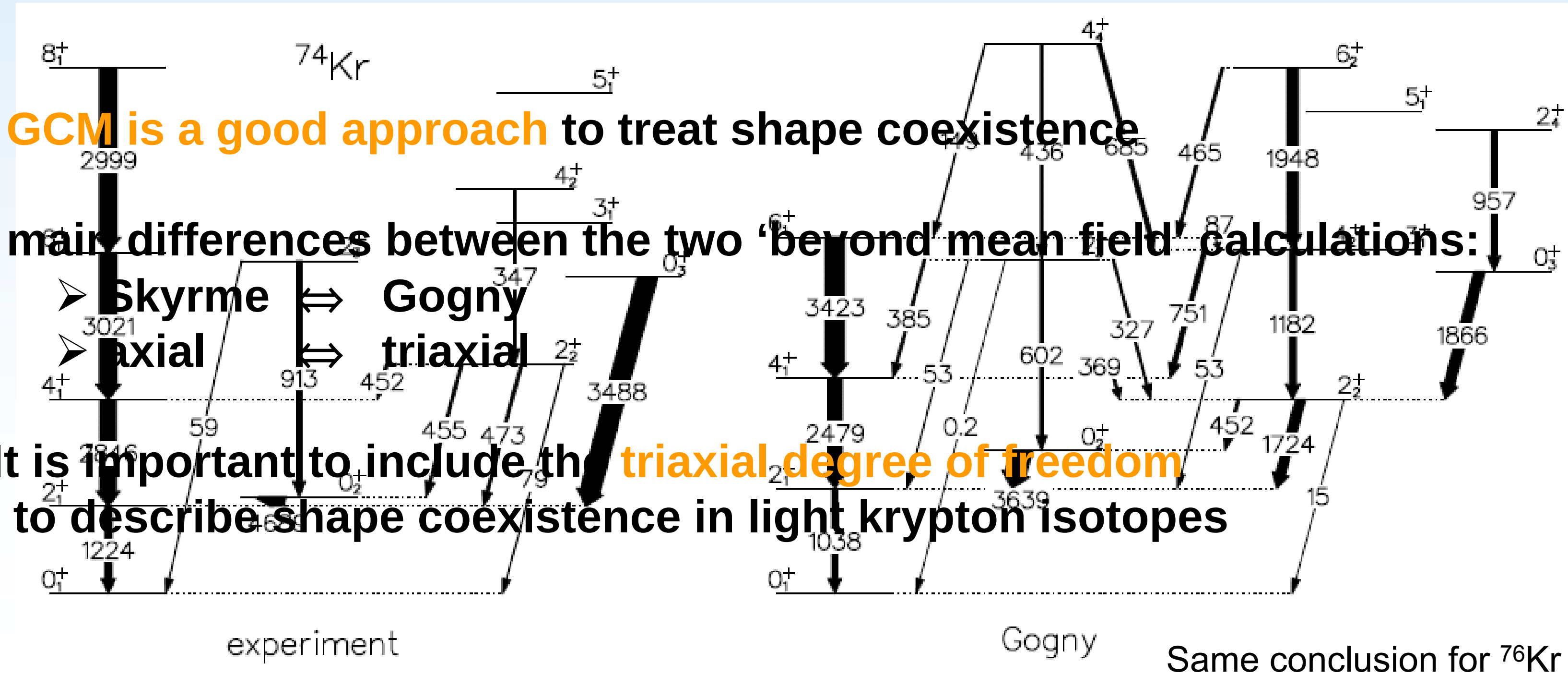
GCM-HFB (Gogny-D1S)
J-P. Delaroche *et al.*
In preparation

HFB+GCM with Gaussian overlap approximation
Gogny D1S force

Axial and triaxial degrees of freedom

The agreement is remarkable for excitation energy and matrix elements

- K=0 prolate rotational ground state band
- K=2 gamma vibrational band
- 2^+_3 oblate rotational state
- Strong mixing of K=0 and K=2 components for 2^+_3 and 2^+_2 states
- Grouping the non-yrast states above 0^+_2 state in band structures is not straightforward



- GCM is a good approach to treat shape coexistence
- main differences between the two 'beyond mean field' calculations:
  - Skyrme ⇔ Gogny
  - axial ⇔ triaxial

- It is important to include the triaxial degree of freedom to describe shape coexistence in light krypton isotopes

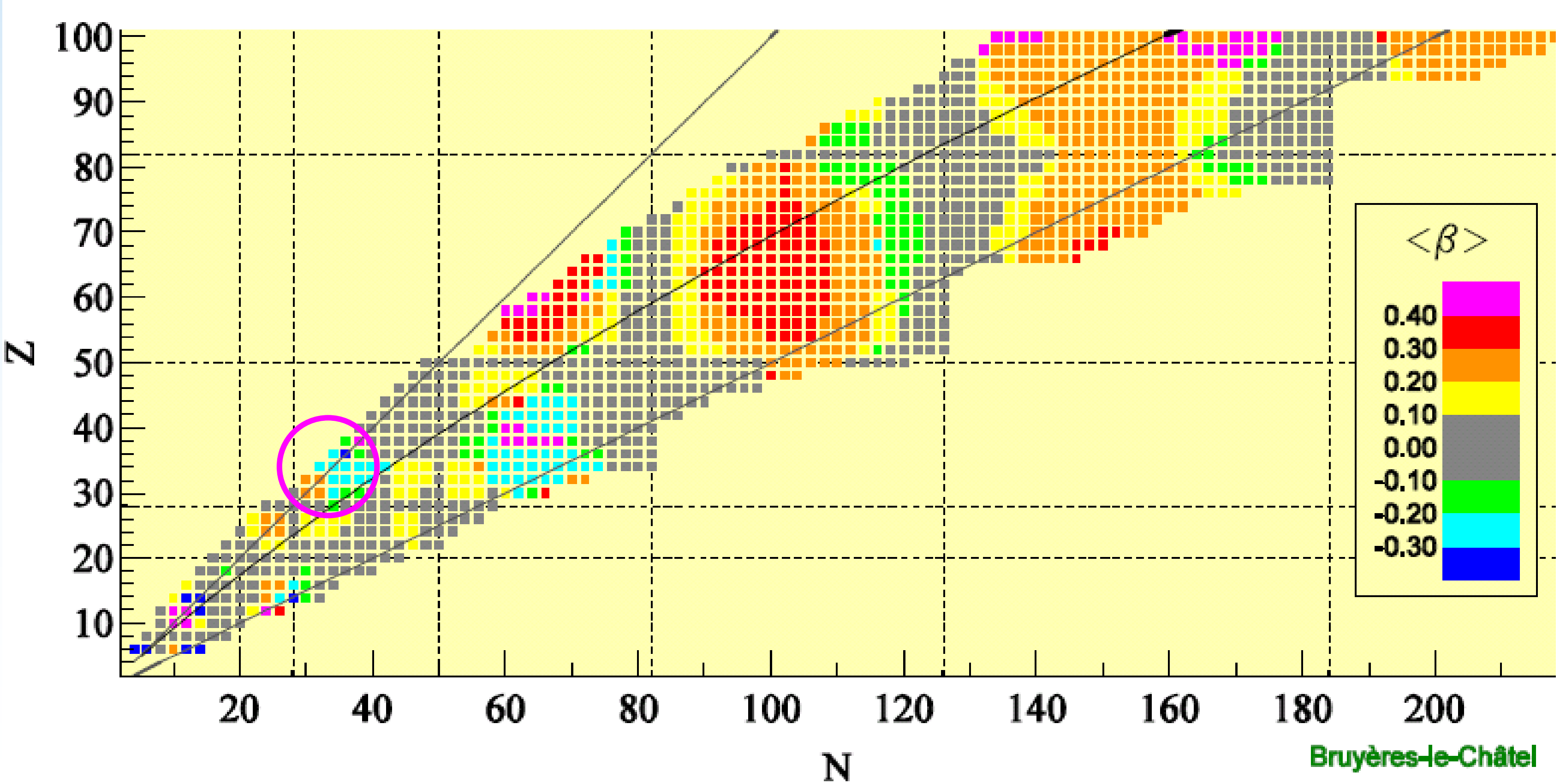
Same conclusion for ^{76}Kr

New area of investigation

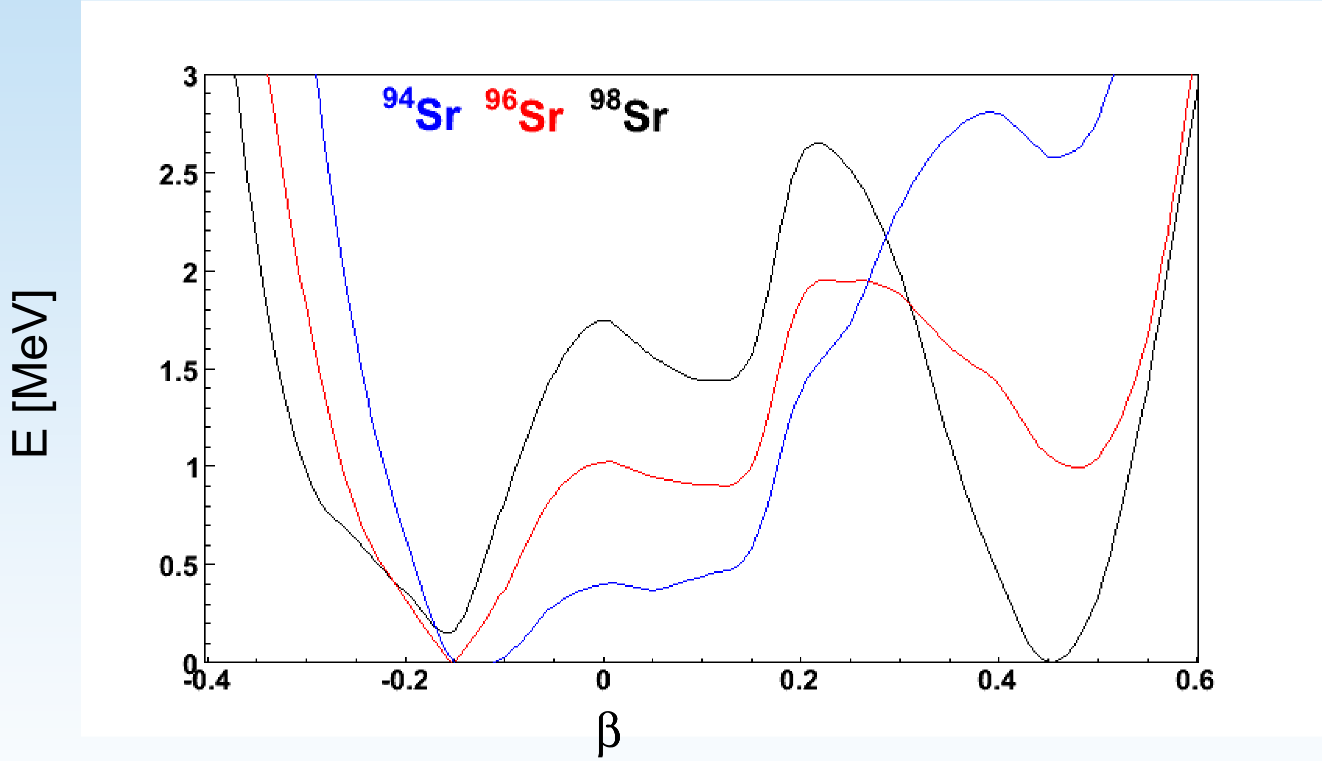
All theoretical calculations predict a sudden onset of quadrupole deformation at the neutron number N=60

Neutron rich Sr & Zr isotopes are accessible by fission of an UC_x target

Coulomb excitation of such nuclei can be performed at REX-ISOLDE



Sr and Zr n-rich isotopes around N=60

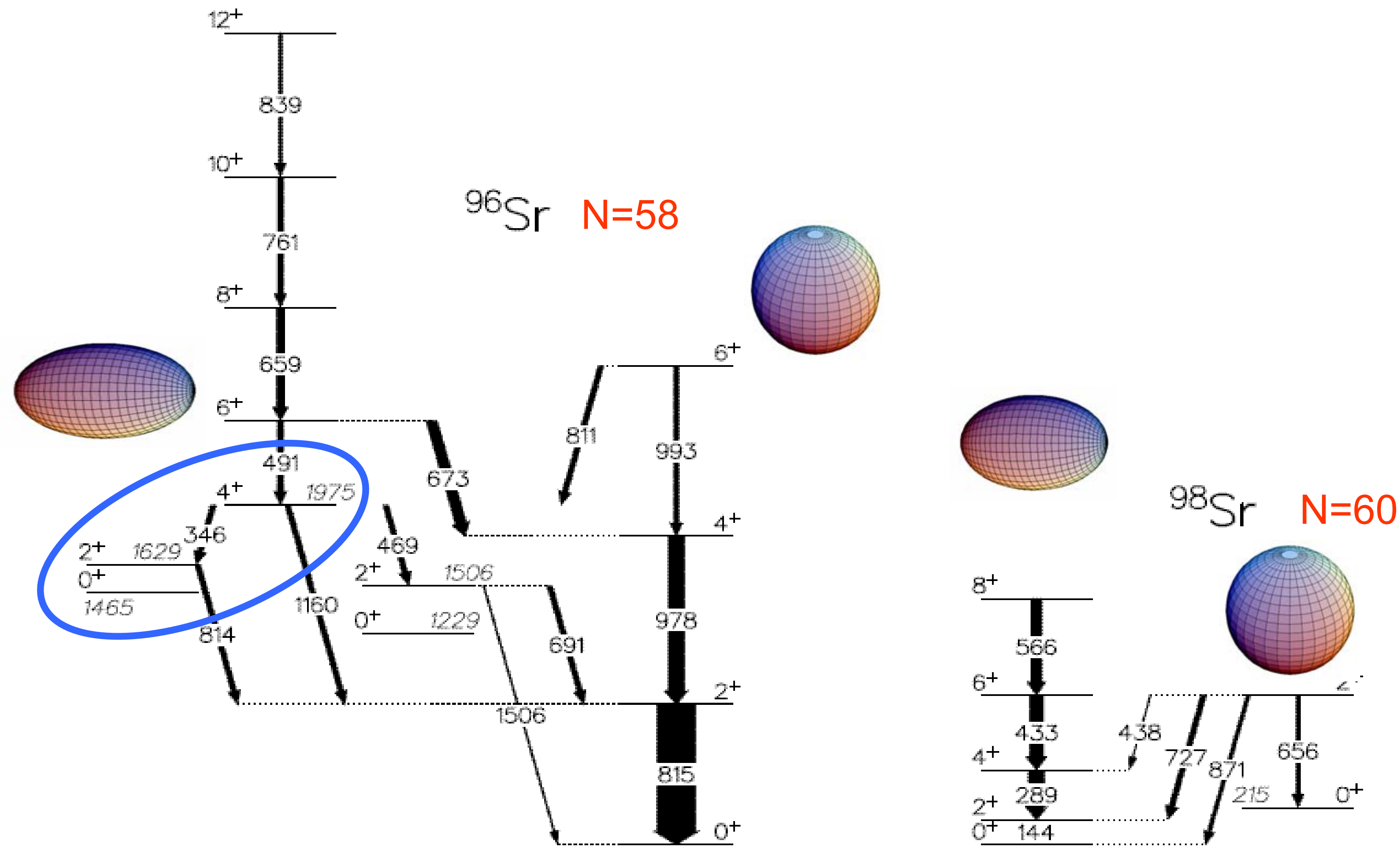


HFB Gogny D1S
M. Girod
CEA Bruyères-le-Châtel

^{96}Sr is a transitional nucleus

- Both deformations should coexist at low energy
  - Shape coexistence between highly deformed and quasi-spherical shapes
  - Electromagnetic matrix elements are stringent test for theory

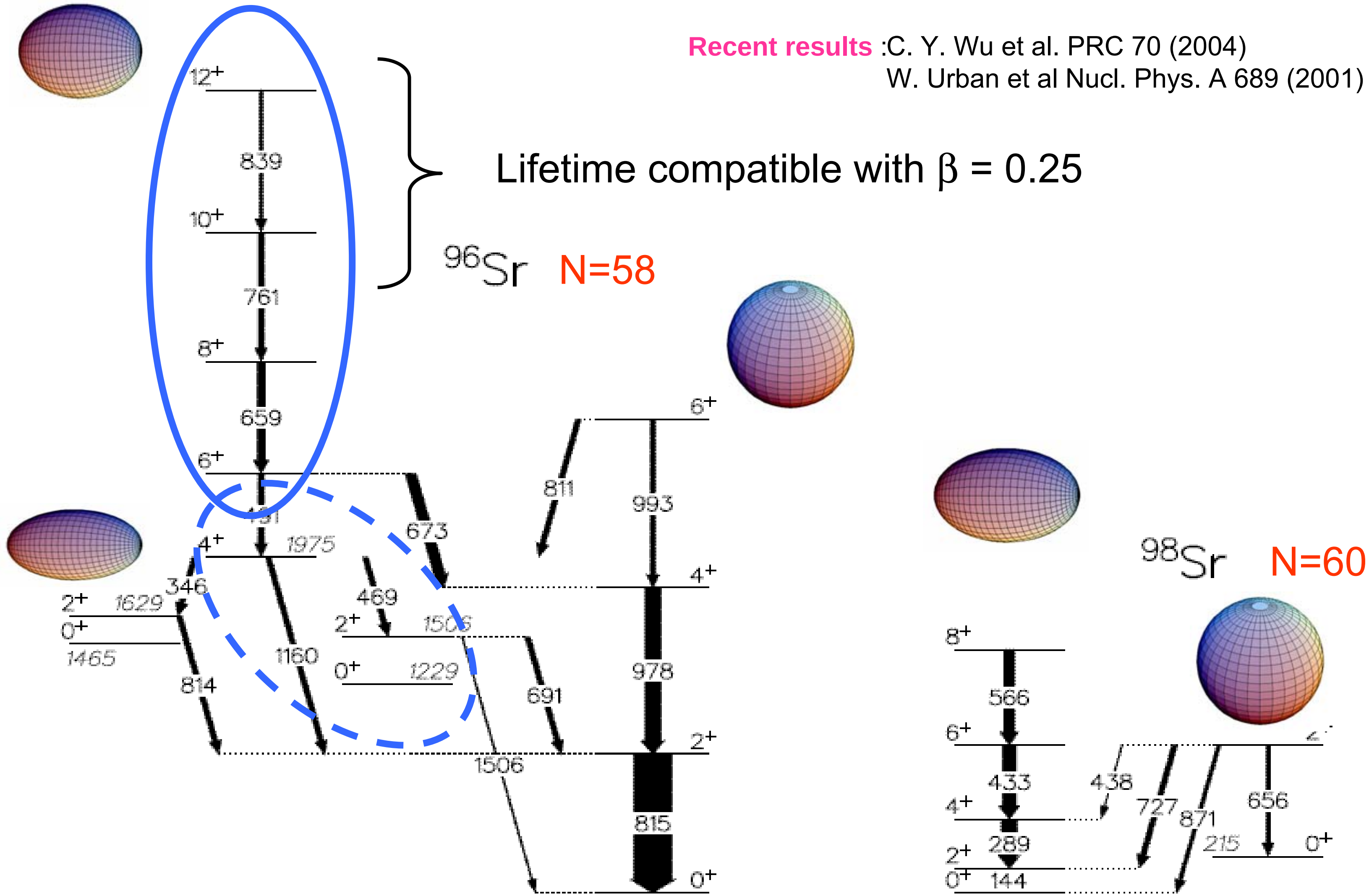
Evidence for shape coexistence in Sr



The highly deformed band $0^+_3 \rightarrow 2^+_3 \rightarrow 4^+_2$ becomes the ground state band in ^{98}Sr

Evidence for shape coexistence in Sr

Recent results :C. Y. Wu et al. PRC 70 (2004)
W. Urban et al Nucl. Phys. A 689 (2001)



The measure of transition strength and intrinsic quadrupole moments is essential to understand the complex shape coexistence in Sr isotopes → Coulomb excitation
Accepted experiment at REX-ISOLDE (IS451)

The onset of deformation around N=58 is maybe more gradual

Conclusion

Coulomb excitation at low energy offers an unique opportunity to understand the complex scenario of shape coexistence in exotic nuclei

Precise comparisons with HFB+GCM calculations are essential to understand the shape coexistence

- **GCM is a good approach to treat shape coexistence.**
- **It is important to include triaxial degree of freedom.**
- **Data from n-rich nuclei will provide more insight into shape coexistence.**

Collaboration

E. Clément,[1] A. Görgen,[1] W. Korten,[1] E. Bouchez,[1] A. Chatillon,[1] Y. Le Coz,[1] Ch. Theisen,[1] J.N. Wilson,[1] M. Zielinska,[5,1] , J.-P. Delaroche[8], M. Girod[8], H. Goutte[8], S. Péru[8], C. Andreoiu,[2] F. Becker,[3] J.M. Casandjian,[4] W. Catford,[9] T. Czosnyka,[5] G. de France,[4] J. Gerl,[3] J. Iwanicki,[5] P. Napiorkowski,[5] G. Sletten,[6] C. Timis[7]

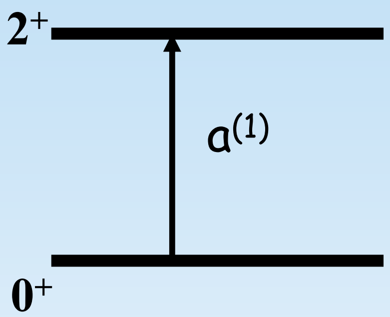
[1]DAPNIA/SPhN, CEA Saclay
[2]Oliver Lodge Laboratory, University of Liverpool
[3]GSI Darmstadt
[4]GANIL
[5]Heavy Ion Laboratory, Warsaw
[6]NBI Copenhagen
[7]University of Surrey
[8]CEA/DIF, DPTA/SPN, CEA Bruyère-le-Châtel

E. Clément[1], A. Görgen[2] , J. Cederkäll[1], P. Delahaye[1], L. Fraile[1], F. Wenander[1], J. Van de Walle[4], D. Voulot[1], C.Dossat[2], W. Korten[2], J. Ljungvall[2], A. Obertelli[2], Ch. Theisen[2], M. Zielinska[2], J. Iwanicki[3], J. Kownacki[3], P. Napiorkowski[3], K. Wrzosek[3], P. Van Duppen[4], T. Cocolios[4], M. Huyse[4], O. Ivanov[4], M. Sawicka [4], I.Stefanescu[4], N. Bree[4], S. Franchoo[5], F. Dayras[6], G. Georgiev[6], A. Ekström[7], M. Guttormsen[8], A.C. Larsen[8], S. Siem[8], N.U.H. Syed[8], P.A. Butler[9], A. Petts[9], D.G. Jenkins[10], V. Bildstein[11], R. Gernhäuser[11], T. Kröll[11], R. Krücken[11], P. Reiter[12], N. Warr[12] ,

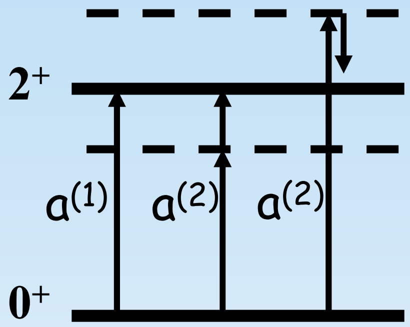
[1]CERN, Geneva, Switzerland
[2]DAPNIA/SPhN, CEA Saclay, France
[3]HIL, Warsaw, Poland
[4]IKS Leuven, Belgium
[5]IPN Orsay, France
[6]CSNSM Orsay, France
[7]Department of Physics, Lund University, Sweden
[8]Department of Physics, University of Oslo, Norway
[9]Oliver Lodge Laboratory, University of Liverpool, UK,
[10]Department of Physics, University of York, UK,
[11]TU München, Germany
[12]IKP Köln, Germany

Coulomb excitation and reorientation effect

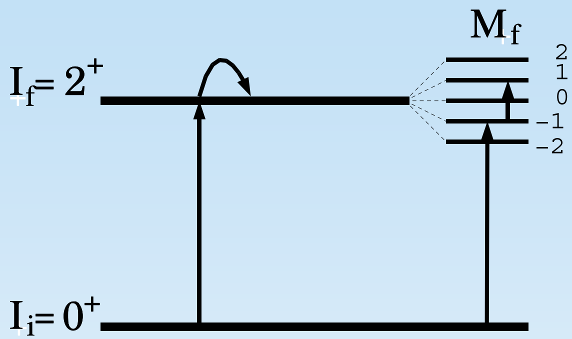
1^er order:



2^nd order:



Reorientation effect



$$\frac{d\sigma}{d\Omega_{i\rightarrow f}} = \frac{d\sigma_{Ruth}}{d\Omega} P_{i\rightarrow f}$$

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

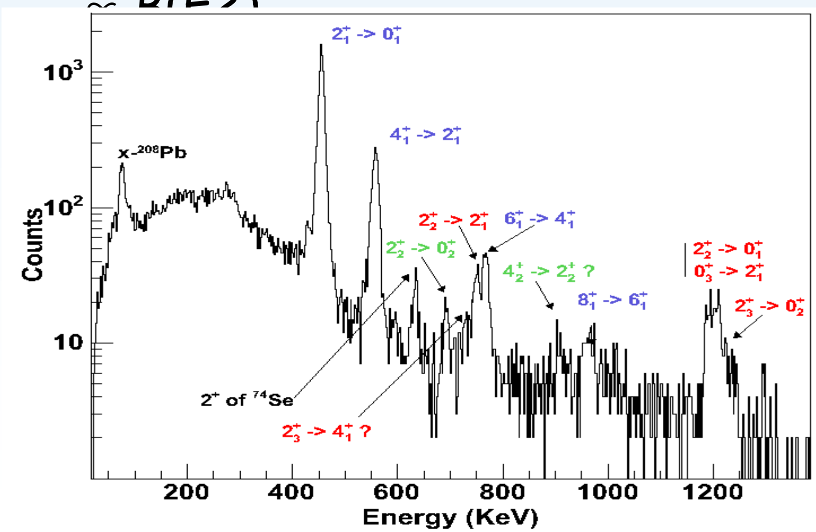
$$a^{(2)} \propto \langle I_f \| \mathcal{M}(E2) \| I_f \rangle \langle I_f \| \mathcal{M}(E2) \| I_i \rangle$$

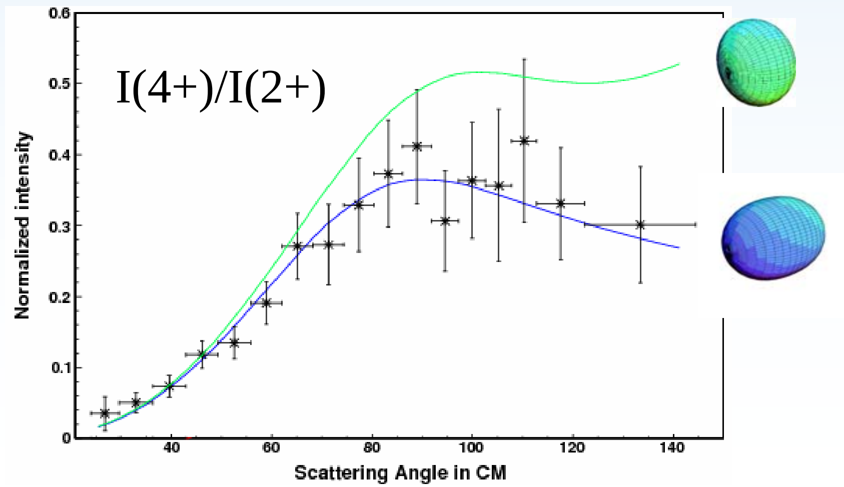
$\rightarrow Q_0$

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

$\propto B(E2)$

Example: differential Coulex cross section from ^{74}Kr SPIRAL experiment: distinguish between prolate and oblate shapes



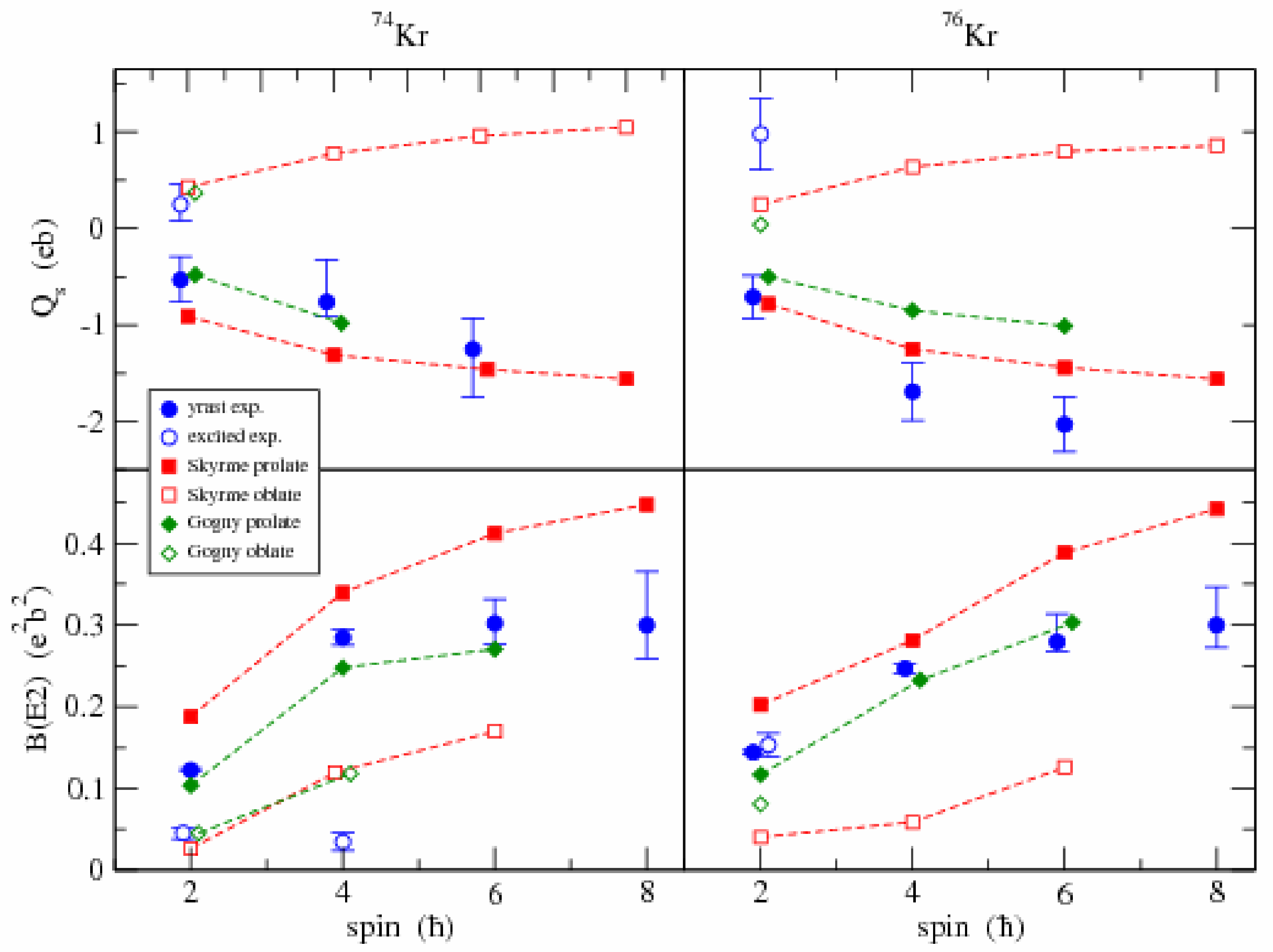


Shape coexistence in mean-field models (1)

- In-band reduced transition probability and spectroscopic quadrupole moments

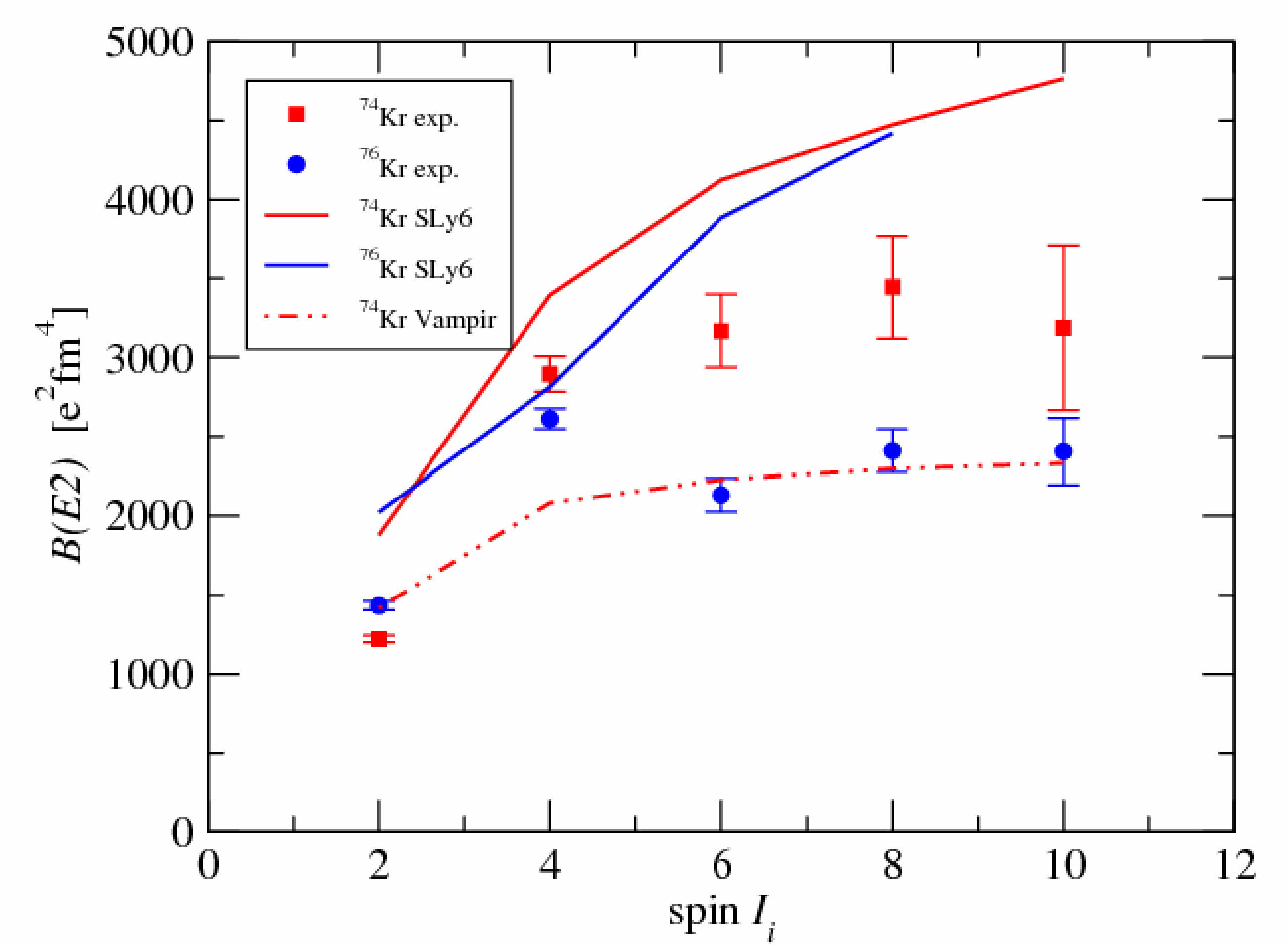
GCM-HFB (SLy6) M. Bender, P. Bonche et P.H. Heenen, Phys. Rev. C 74, 024312 (2006)

GCM-HFB (Gogny-D1S)
E. Clément *et al.*, submitted to PRC
J-P. Delaroche *et al.* In preparation



Vampir calculations

- Reduced transitional probability

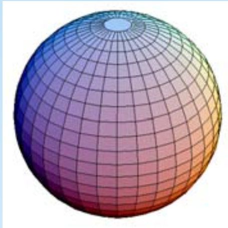


Vampir
A. Petrovici et al.,
Nucl. Phys. A 665, 333 (00)

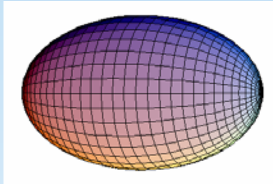
Calculs théoriques:
HFB+BCS-LN+AMPGCM
M. Bender, P. Bonche et P.H. Heenen

Evidence for shape coexistence in Sr and Zr

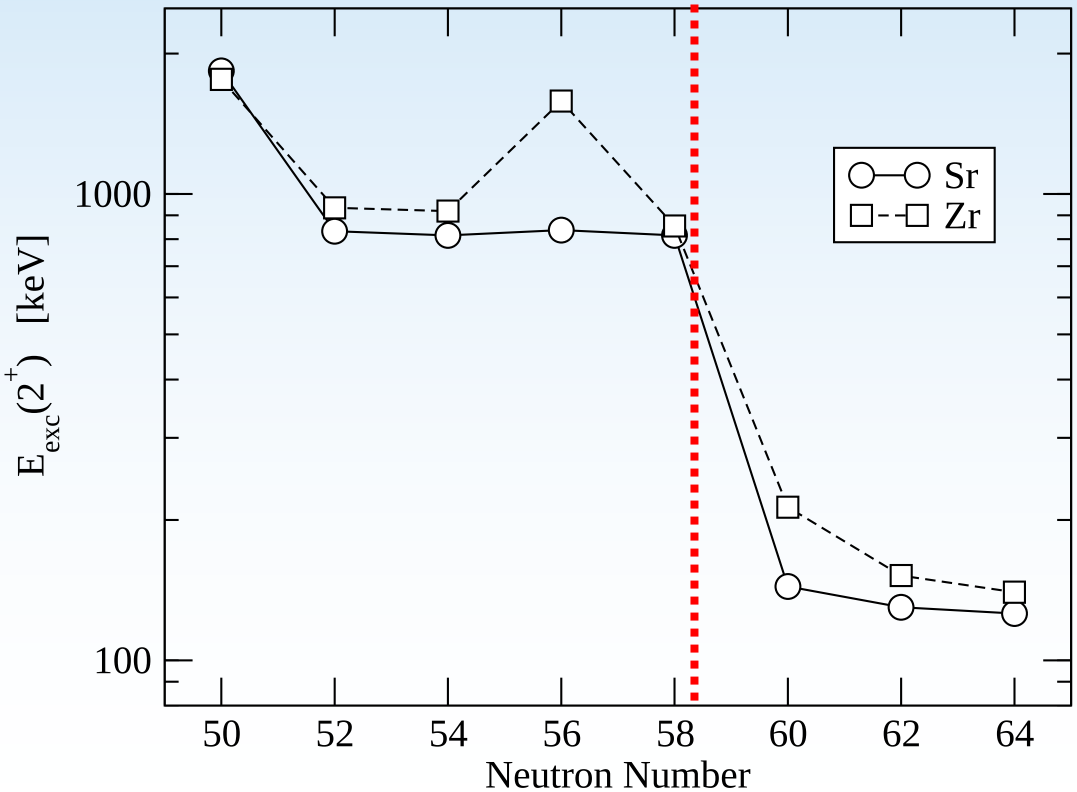
The first evidence is the energy of the 2^+_1 state



N=58



|β| <<1 : Quasi-spherical | **|β| >0 : deformed state**

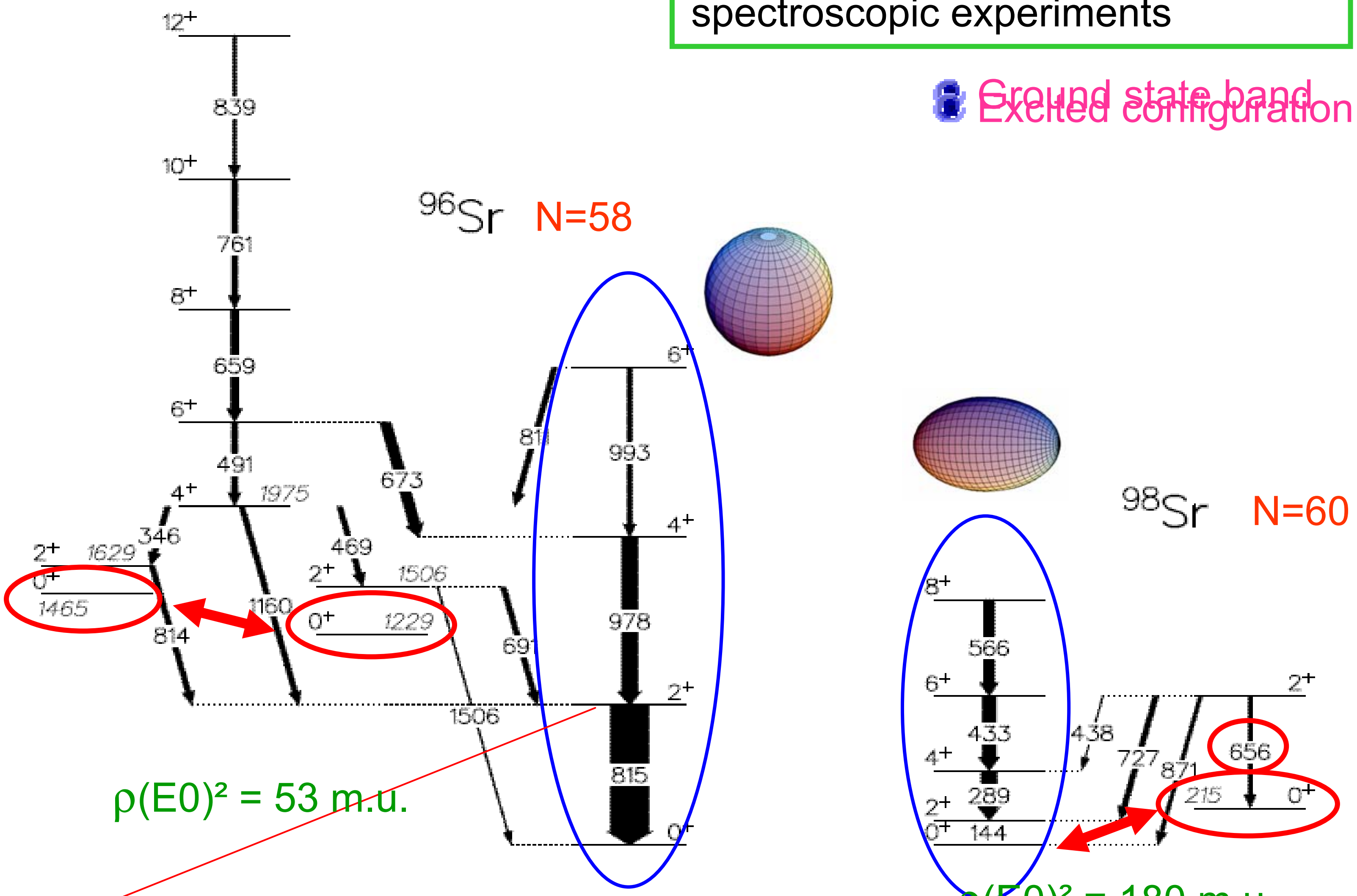


Evidence for shape coexistence in Sr

Level scheme established by spectroscopic experiments

Ground state band

Excited configuration



ρ(E0)² = 53 m.u.

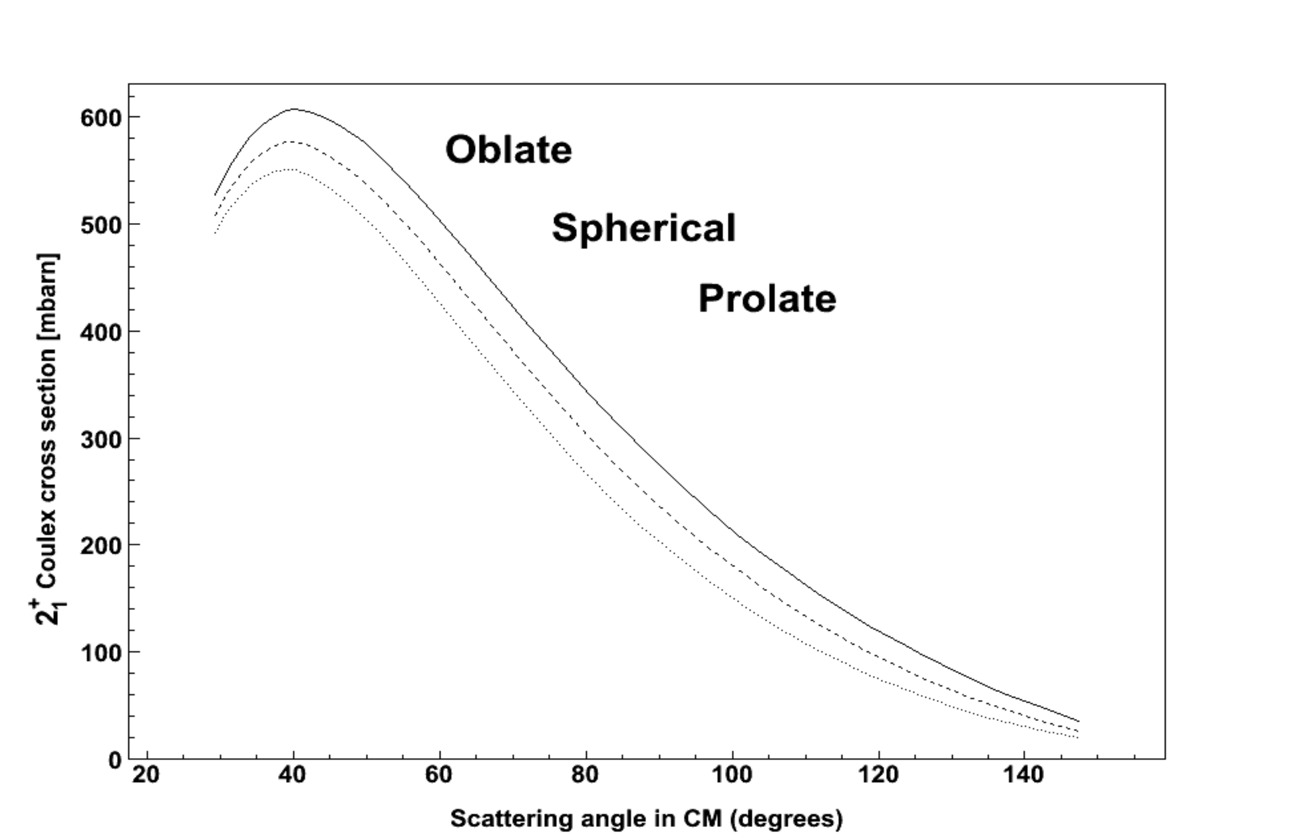
ρ(E0)² = 180 m.u.

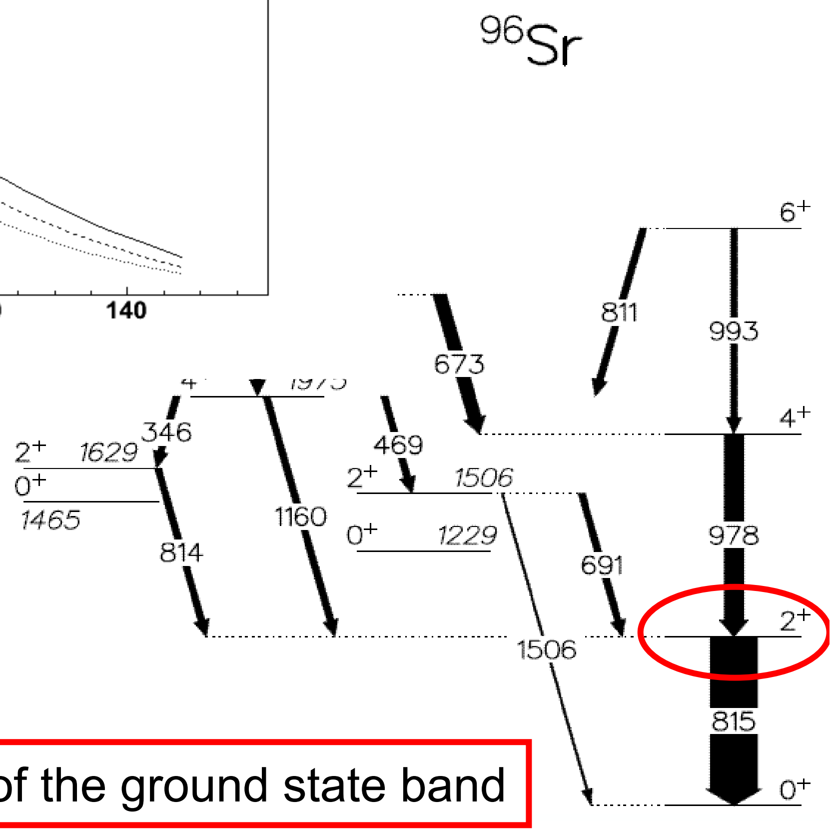
τ = 7(4) ps → Nearly spherical ground state

Highly deformed rotational band β ≈ 0.4

ρ(E0)² is directly linked to deformation and mixing configuration

Coulomb excitation cross section

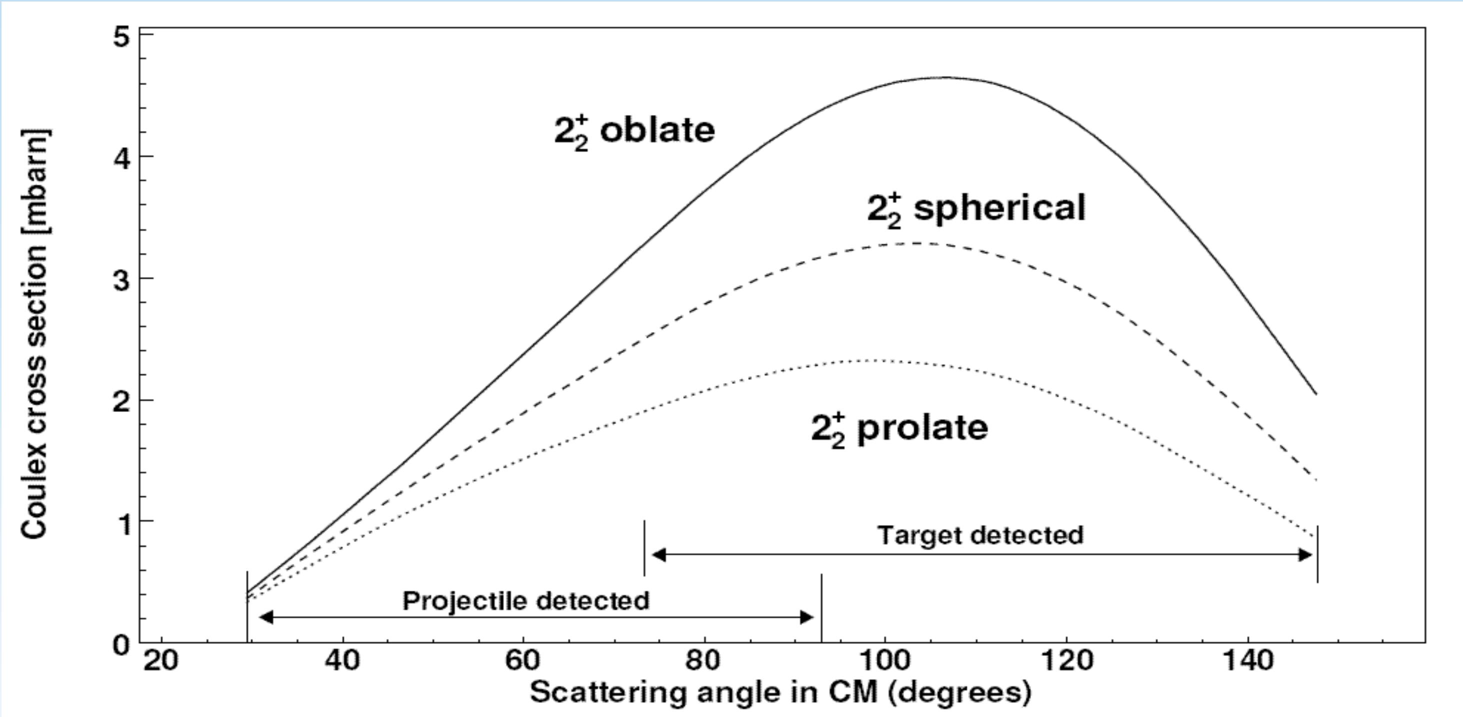


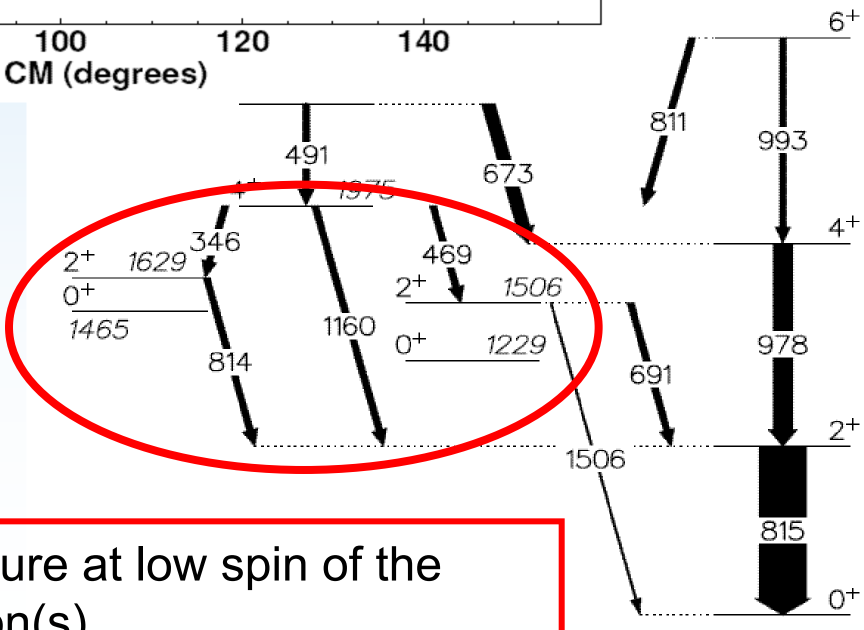


- Improve the B(E2) $0^+_1 \to 2^+_1$: 7(4) ps
- Extract the diagonal matrix element

→ Establish the properties of the ground state band

Coulomb excitation cross section

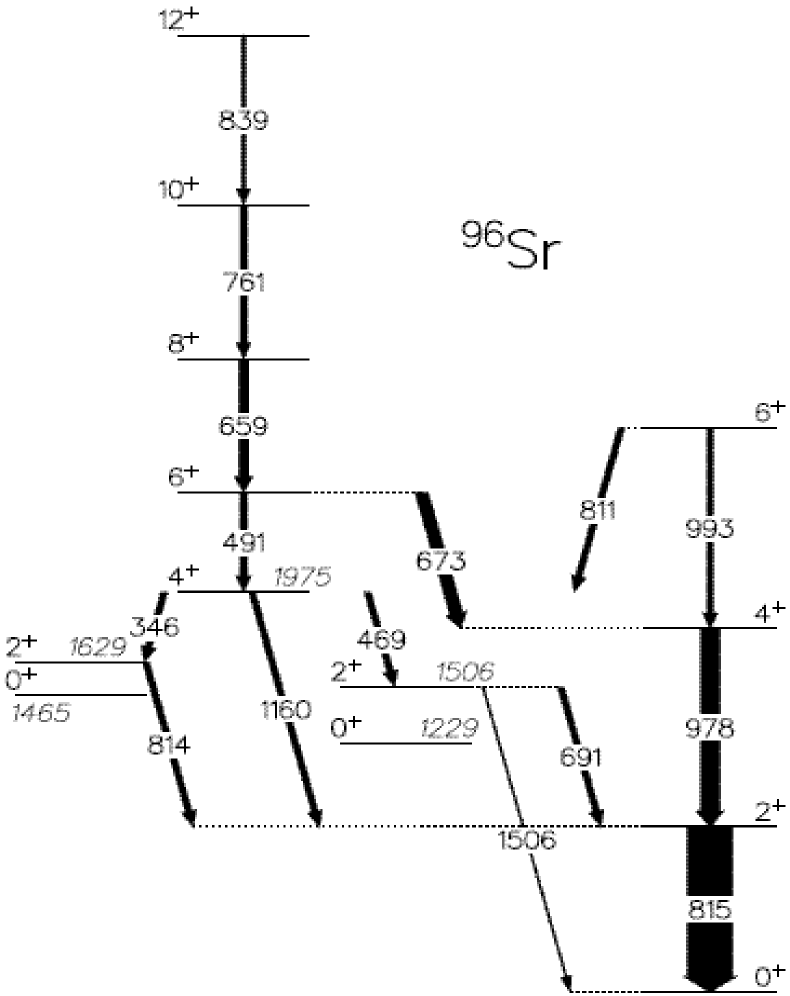




- Establish the set of transitional matrix elements at low spins
- Extract diagonal matrix elements

Understand the structure at low spin of the deformed configuration(s)

Coulomb excitation of ^{96}Sr

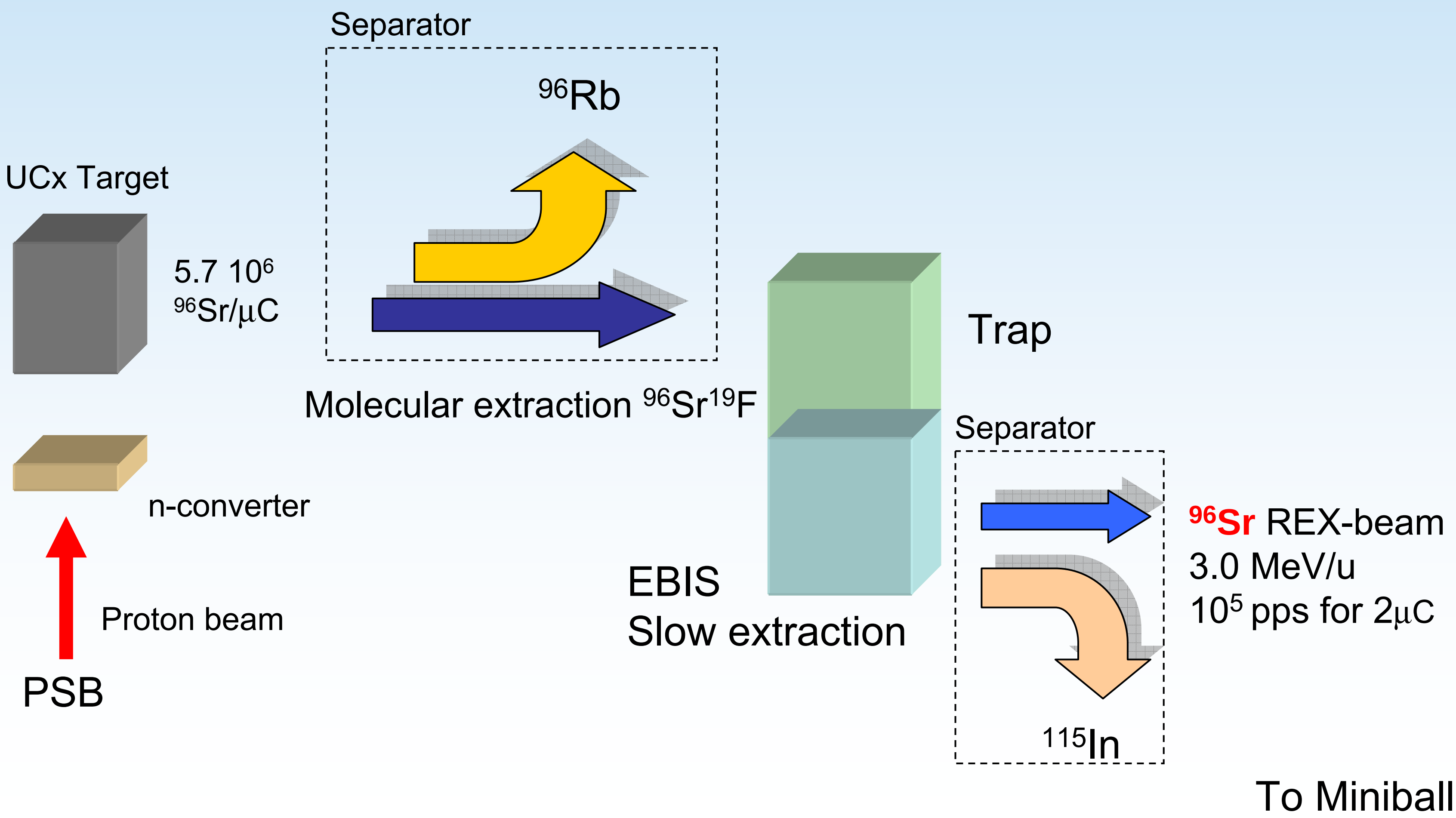


- Improvement of the $B(E2,2^+_1 \rightarrow 0^+_1)$ value
- Measure of the B(E2) related to the $0^+_{2,3}$ and $2^+_{2,3}$ states
- Measure of the diagonal matrix element of the 2^+_1 state
- Measure of the diagonal matrix elements of the 2^+_2 and 2^+_3 states

Experimental details

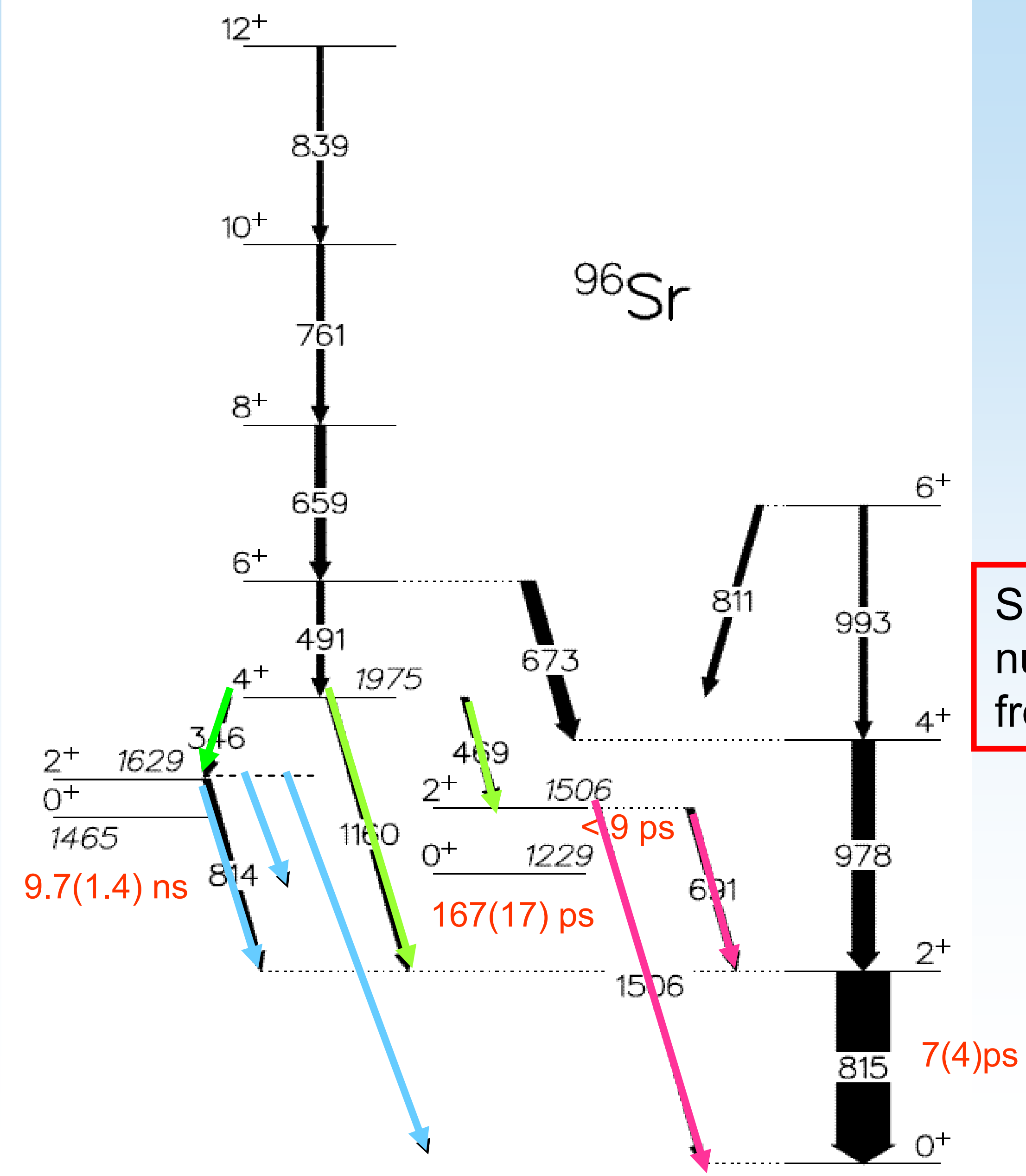
- First Sr beam at REX-ISOLDE
  - Molecular beam has shown the efficiency of this technique in term of purity and intensity…

    see ^{70}Se case *(A. Hurst et al. Isolde workshop and users meeting 2005/2006)*



Coulomb excitation analysis : GOSIA*

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



- Lifetimes
- Branching ratios

Spectroscopic data limit the number of degrees of freedom