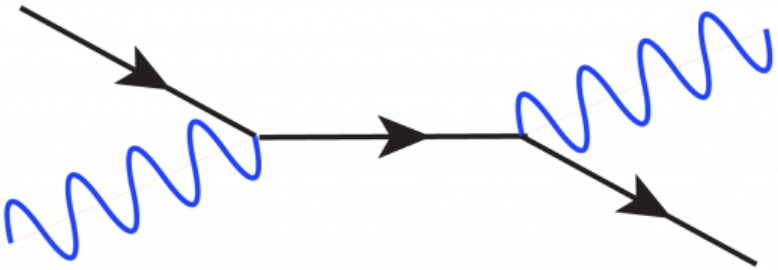
In-beam γ-ray spectroscopy using RIB
Selected Recent Results



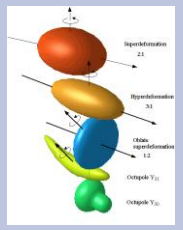
EURORIB-15

Radioactive beams from in-flight and ISOL facilities

- γ-ray detectors coupled to charged particle detectors
- Coulomb Excitation and Transfer reaction as experimental method
- Excitation energy, spectroscopic factor, B(Eλ) and electromagnetic moment

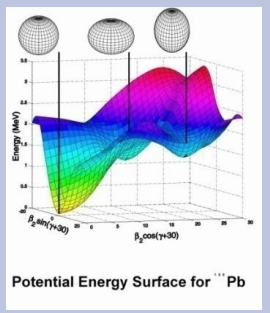
In the last 7 years :
23 papers from safe coulex with RIB
1 Nature
9 Phys. Rev. Lett.
12 Phys. Rev. C
1 Phys. Lett. B.

^{17}C N=20 collapse
^{43}S, ^{46}Ar N=28 collapse
Shape coexistence in Sr/Rb



^{220}Rn and ^{224}Ra

^{208}Pb

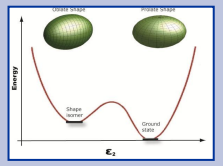


Shape coexistence and exotic shapes

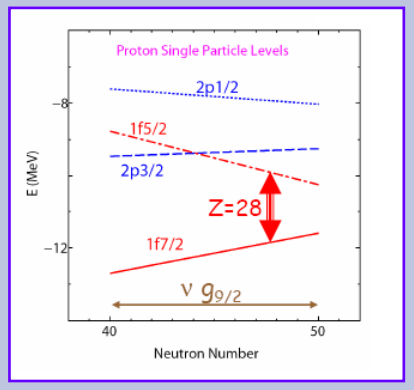
B(E2) in Sn, In and Cd

^{100}Sn

^{132}Sn



$^{68-78}$Ni



Toward N=50 :
- Zn spectroscopy
- $pf_{5/2}$ migration,
- sp and collectives states in Cu

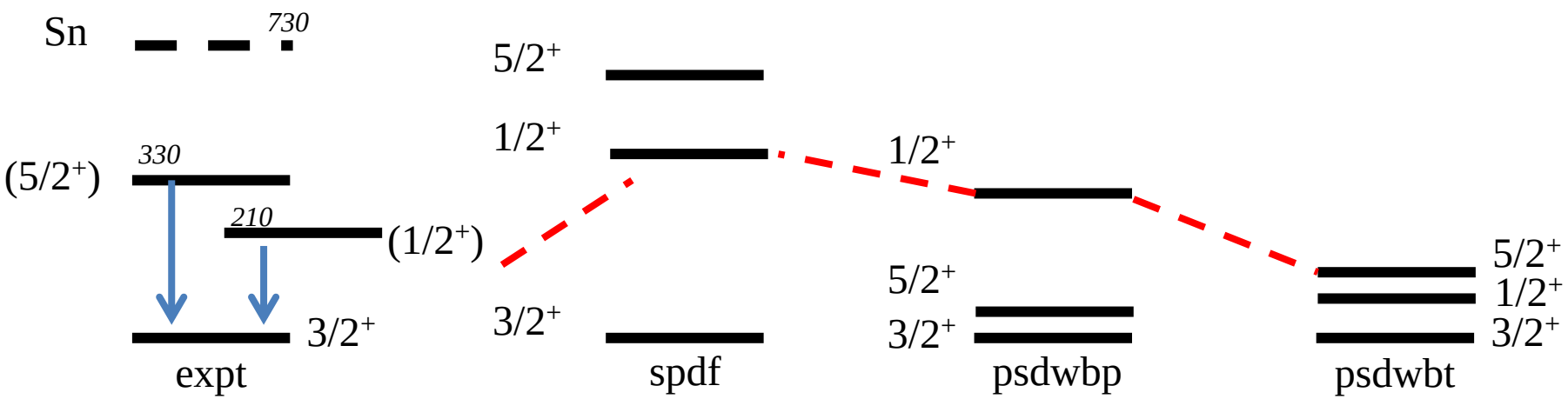
$^{40-48}$Ca

- N=20 and N=28 shell erosion; island of inversion
- Enhancement of N=16

N=20 erosion and ehancement of N=16

Spectroscopic information from transfer reaction and Coulex at SPIRAL1 and Rex-Isolde

Extend the knowledge to the n-rich C → ^{17}C spectroscopy

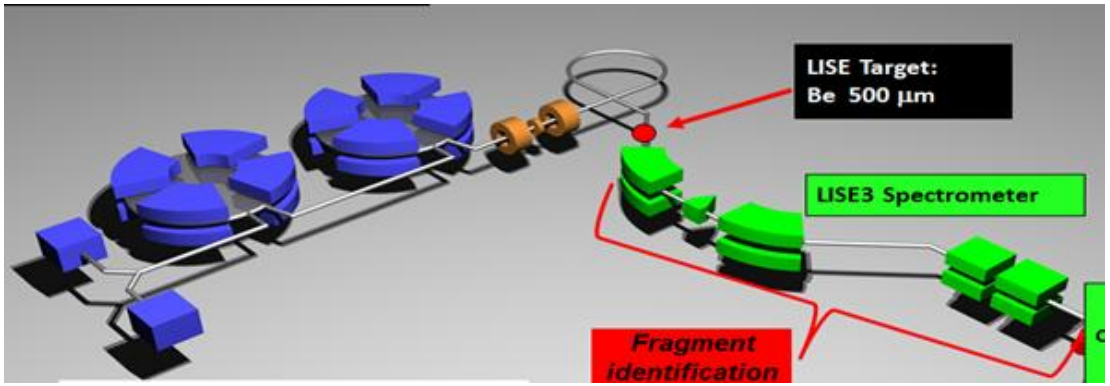


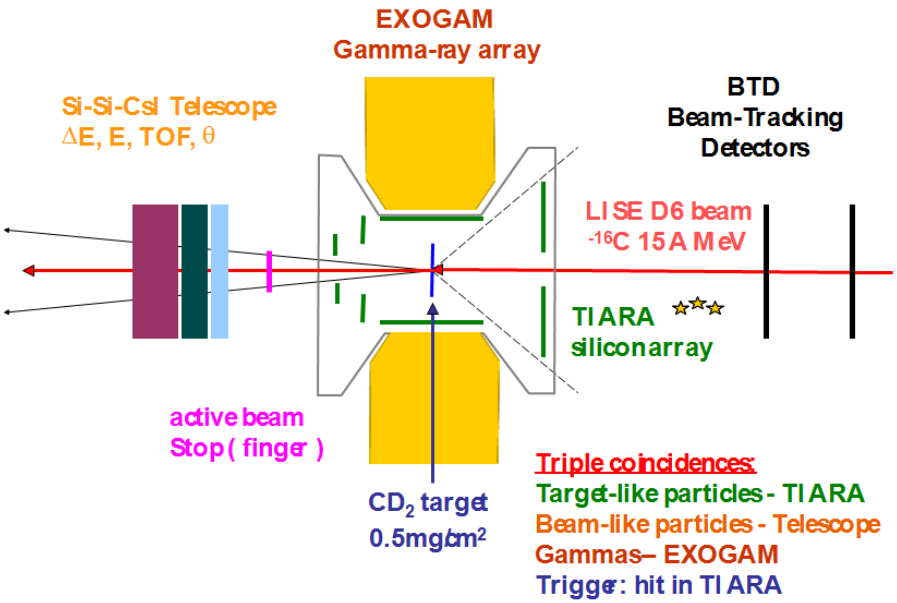
<u>Objectives :</u>

- ❖Spin assignement of the 3 bound states
- ❖Spectroscopic factor of the GS to constraint its micropscopical configuration
- ❖Locate the $3/2^+$ unbound state → $0d_{3/2}$ as constraint for SM calculations

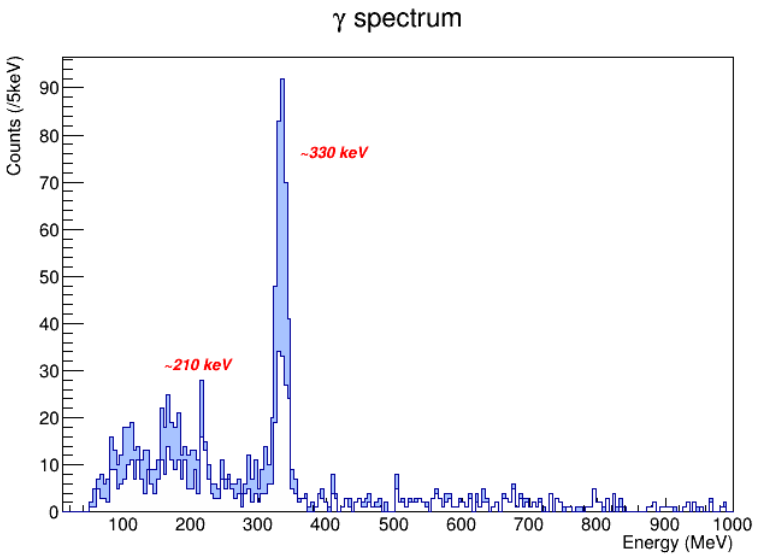
^{18}O beam at 65MeV/A

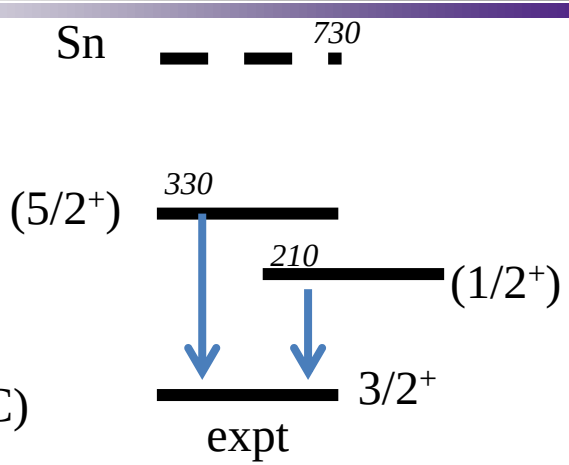
^{16}C secondary beam at 15MeV/A ~4.10^4pps



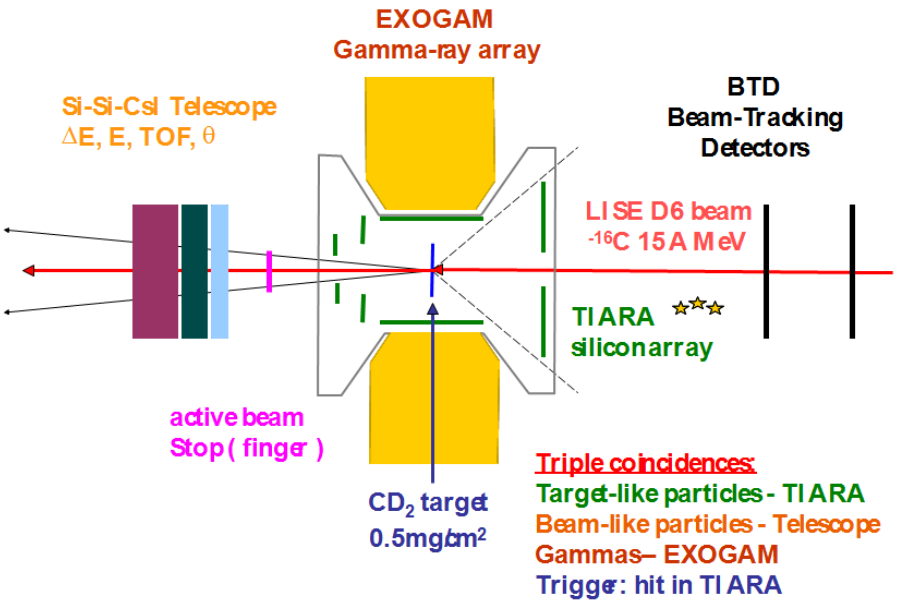


Experimental setup



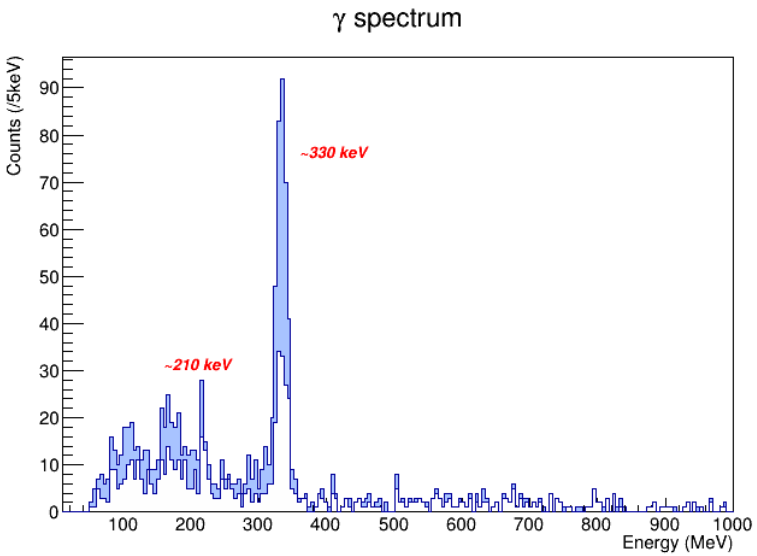


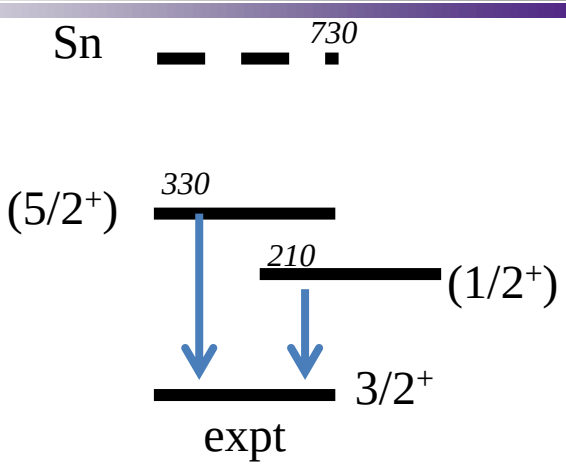
X. Pereira-López (USC/LPC)

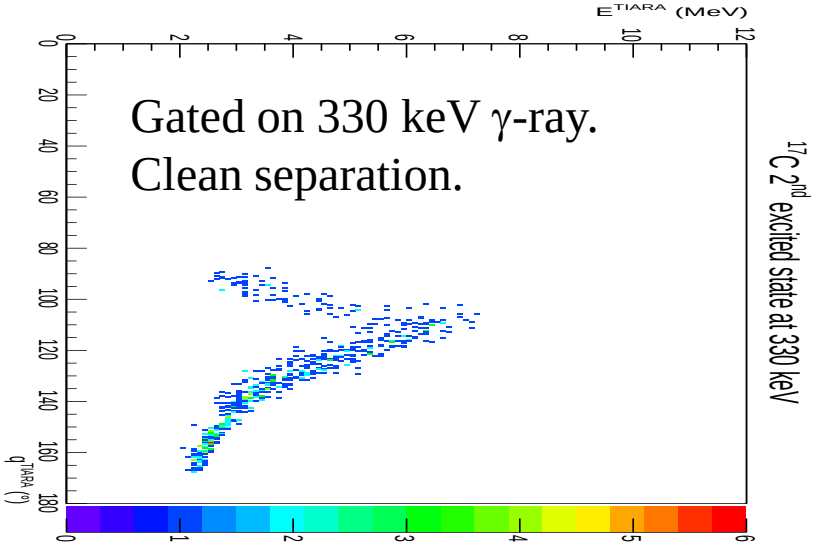


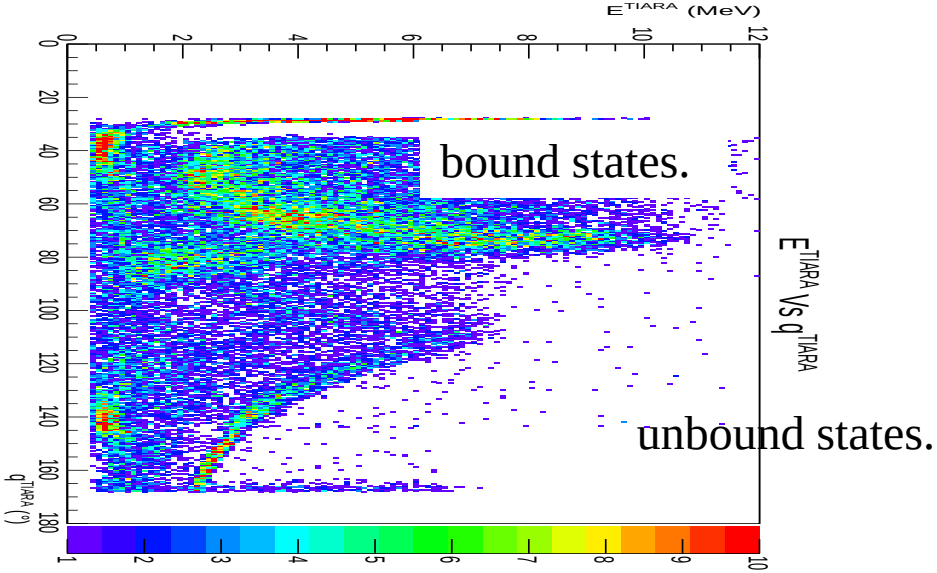
- γ-rays to separate states ~100 keV appart that could not be separated in TIARA

- The 210 keV transition corresponds to an s-state which population decreases in the barrel.



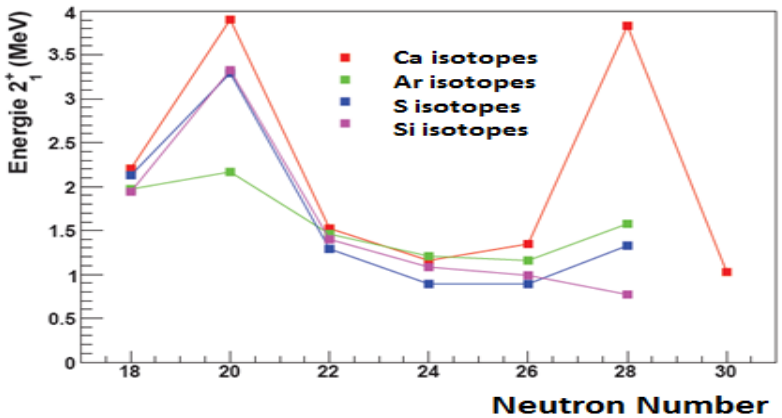


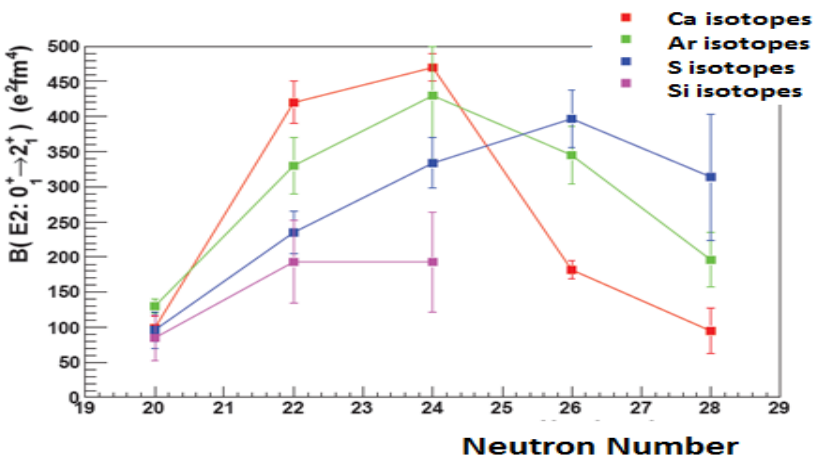




Energy angle correlations.

The N=28 Shell erosion





^{46}Ar

$$B(E2;0^+ \rightarrow 2^+_1) = 196(39)e^2fm^4$$

H. Scheit et al., Phys.Rev.Lett **77** (1996)

$$B(E2;0^+ \rightarrow 2^+_1) = 218(39)e^2fm^4$$

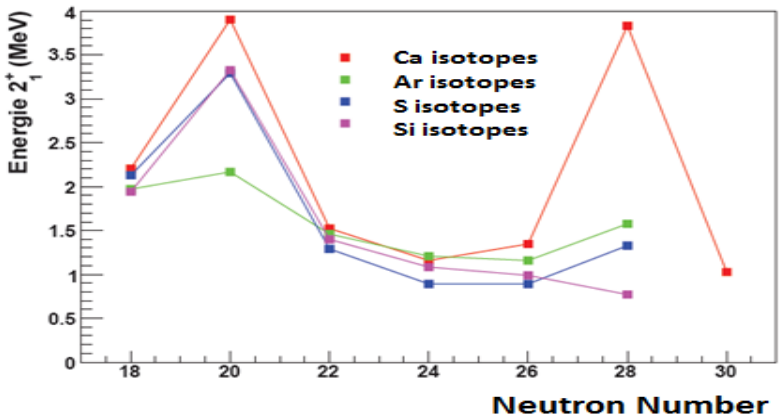
A. Gade et al., Phys. Rev. C 74 (2006)

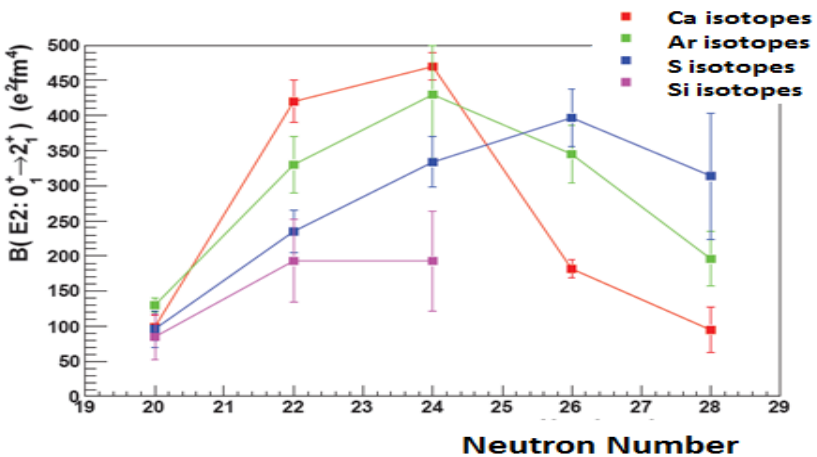
Lifetime measurement

Isotope	E_γ (keV)	$J^\pi_i \rightarrow J^\pi_f$	τ (ps)	$B(E2)$ (e^2fm^4)
^{44}Ar	1158	$2^+ \rightarrow 0^+$	5.9(2.0)	67^{+44}_{-17}
	1588	$4^+ \rightarrow 2^+$	$3.9^{+3.6}_{-2.9}$	21^{+60}_{-10}
	693	$6^+ \rightarrow 4^+$	>40	<128
^{46}Ar	1552	$2^+ \rightarrow 0^+$	$0.8^{+0.3}_{-0.4}$	114^{+67}_{-32}

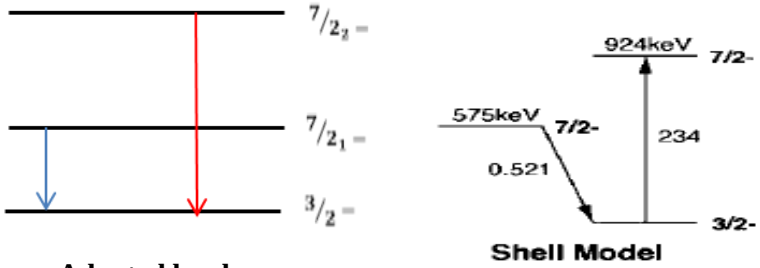
D. Mengoni et al., Phys.Rev.C 82 (2010)

The N=28 Shell erosion





^{43}S

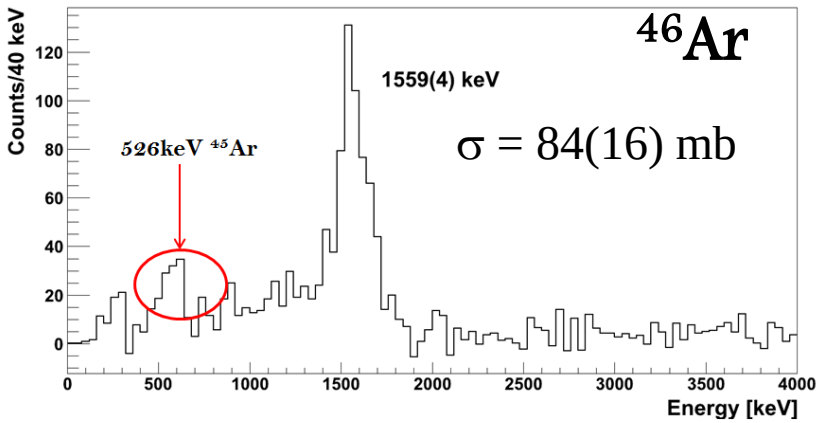


Adopted level scheme for ^{43}S

L.Gaudefroy et al, Phys.Rev.Lett 102(2009)

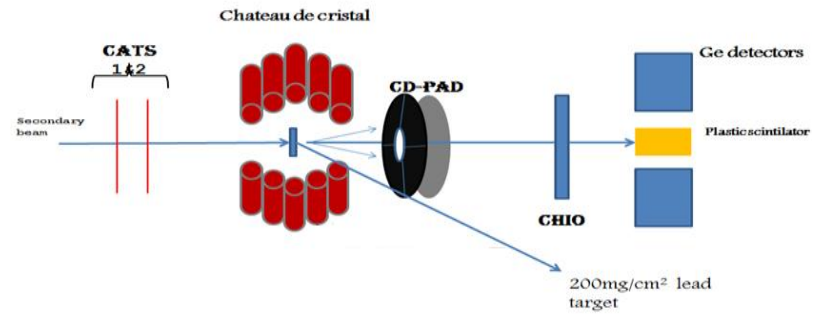
Nucleus	E/A (MeV)	E_γ (keV)	$B(E2\uparrow)$ (e^2 fm^4)
^{35}Al	43.8	1006 (19)	142 (52)
^{37}Si	45.1	1437 (27)	101 (45)
^{39}P	46.3	976 (17)	97 (30)
^{41}S	47.4	449 (8)	167 (65)
		904 (16)	232 (56)
^{43}S	42.0	≈940	175 (69)
^{45}Cl	43.0	929 (17)	87 (24)

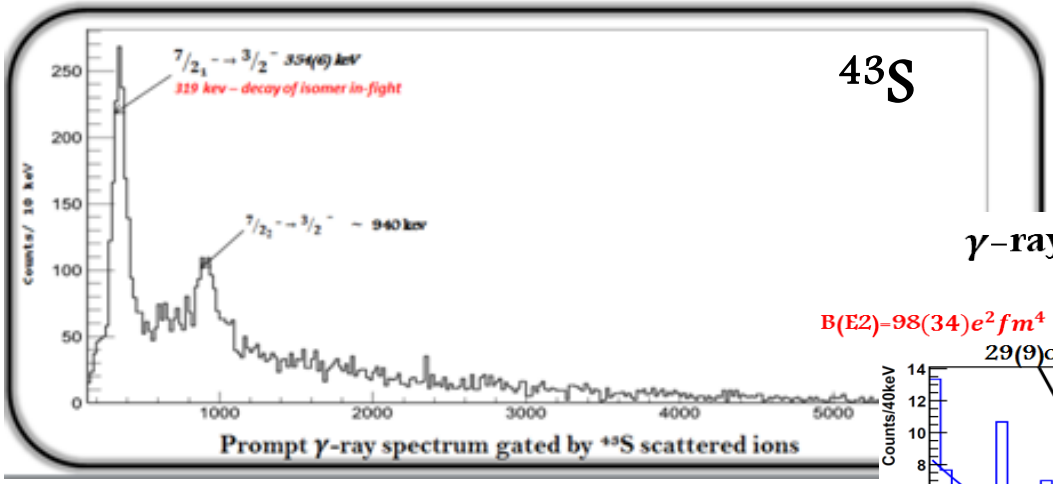
R.Ibbotson et al. Phys.Rev.C 59(1999)



Prompt gamma-ray spectra gated by ^{46}Ar scattered ions conditioned on the safe angle up to 3.25^0

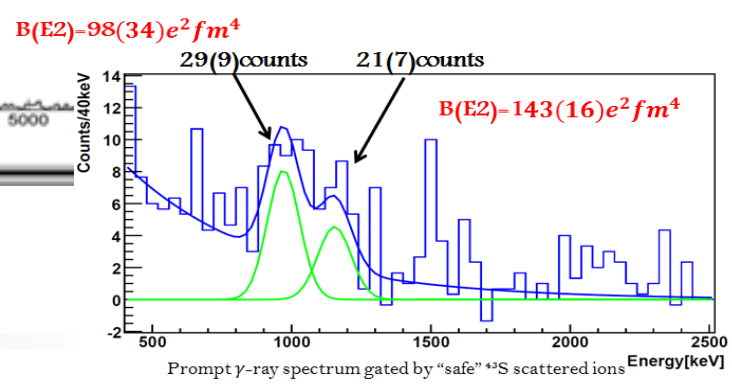
B(E2) = 269(31) e^2fm^4

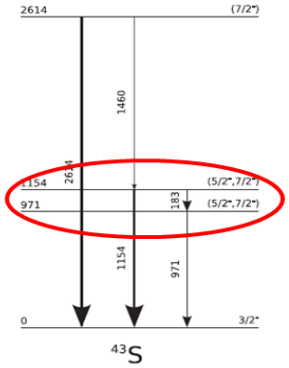




S. Calinescu IFIN-HH

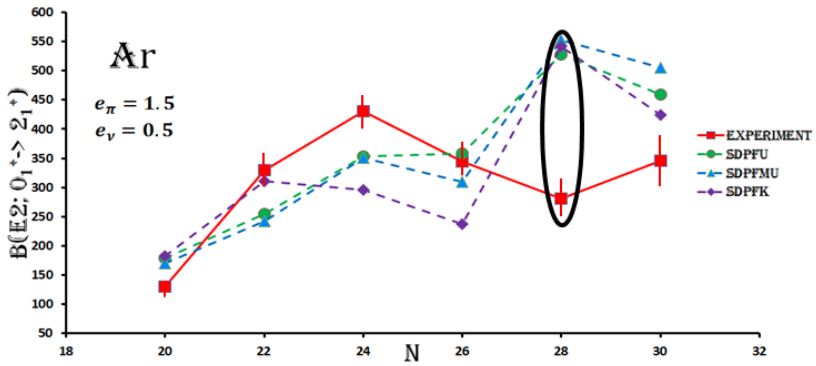
γ-ray spectrum of ^{43}S : the assumption of two states





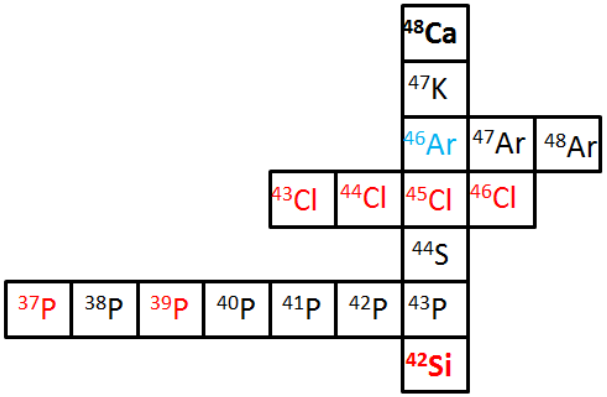
L.A. Riley et al., Phys.Rev.C 80(2009)

Shell model predictions for the Ar isotopic chain



Predicted level schemes for ^{46}Ar using NuShellX code by A.Brown

- All three interactions manage to reproduce the energy of the 2^+ state
- Global agreement between the experimental B(E2) values and the theoretical predictions, except for ^{46}Ar!!!



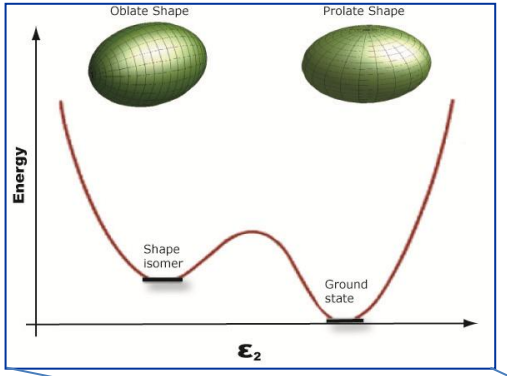
In ^{46}Ar, the B(E2,$0^+ \rightarrow 2^+$) = 269(31)e²fm⁴ is in agreement with previous Coulex excitations measurements. Further supports the semi-magic character of ^{46}Ar and confirms the puzzling deviation to SM calculations

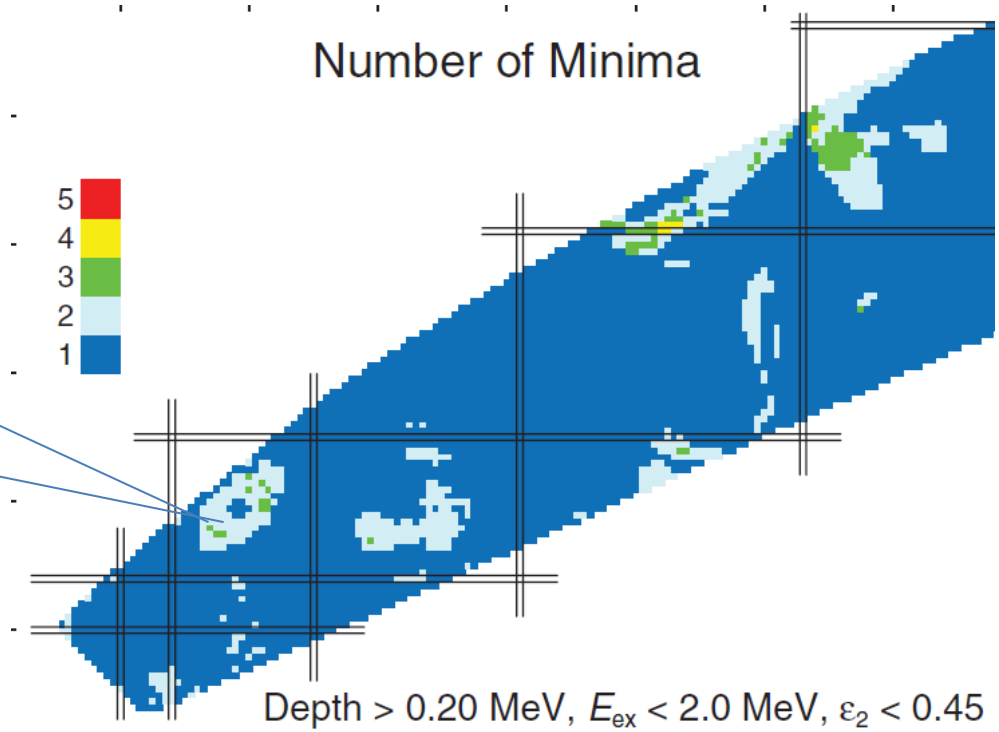
In ^{43}S the 971 keV and 1154 keV states have corresponding B(E2) of 98(34)e²fm⁴ and 143(16)e²fm⁴

Further investigation by safe Coulex from the on-going SPIRAL1-upgrade ^{41}S, $^{37\text{-}39}$P, $^{43\text{-}45}$Cl

Shapes

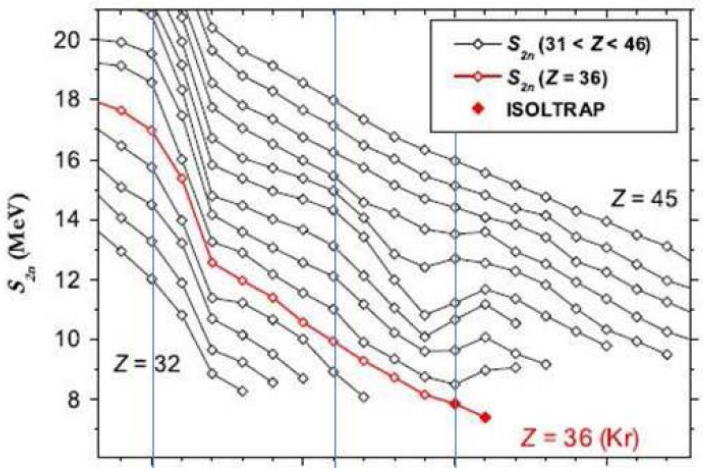
1) Shape coexistence and shape change
2) Octupole correlations *L. P. Gaffney et al, Nature **497**, 199 (2013)*



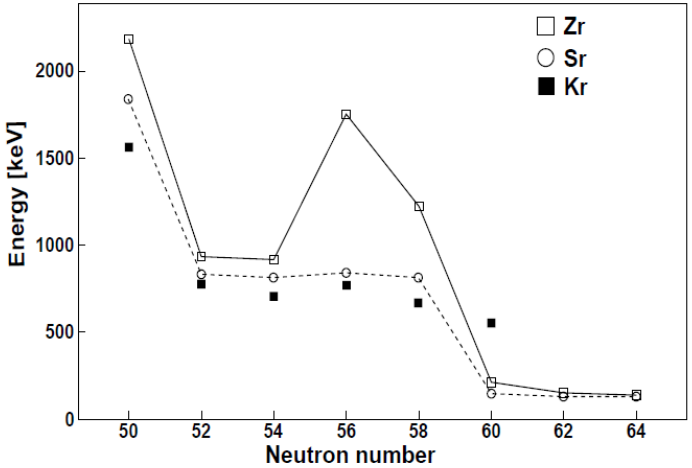


P. Möller et al Phys. Rev. Lett 103, 212501 (2009)

Shape Transition at N=60



S. Naimi et al., Phys. Rev. Lett. 105, 032502 (2010).

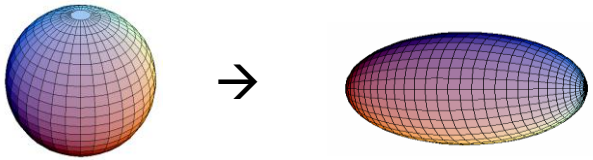


M. Albers et al., Phys. Rev. Lett. 108, 062701 (2012)

- The n-rich nuclei between Z=37 and Z=42 present at N=60 one of the most impressive deformation change in the nuclear chart

Point to a specific π–ν combinaison

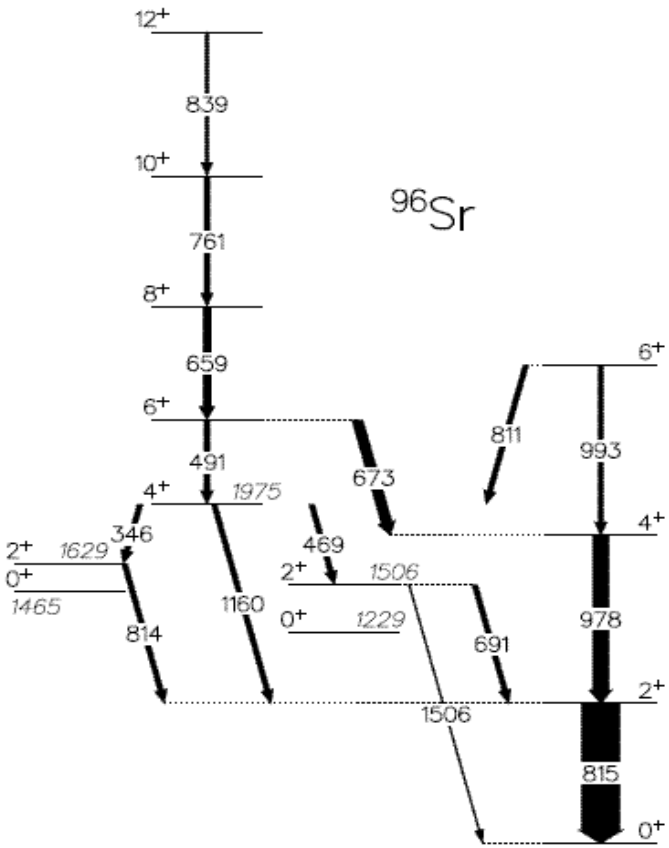
+ 2ν



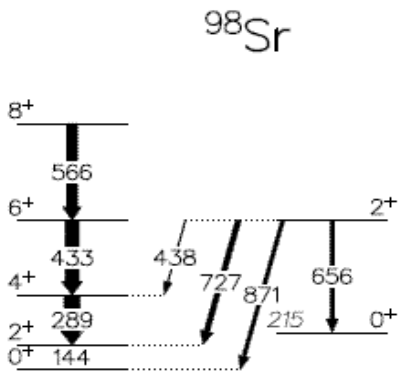
Shape coexistence

- B(E2)'s connecting states to probe the collectivity and the mixing of configurations
- Q_o to determine the deformation

Coulomb excitation of RIB



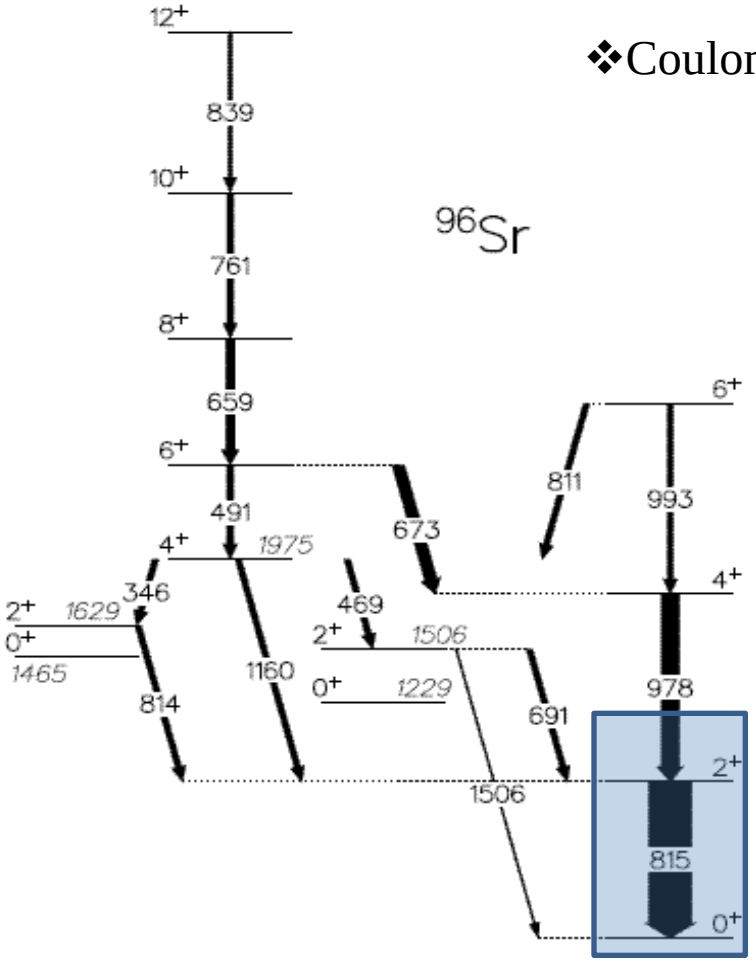
N=58

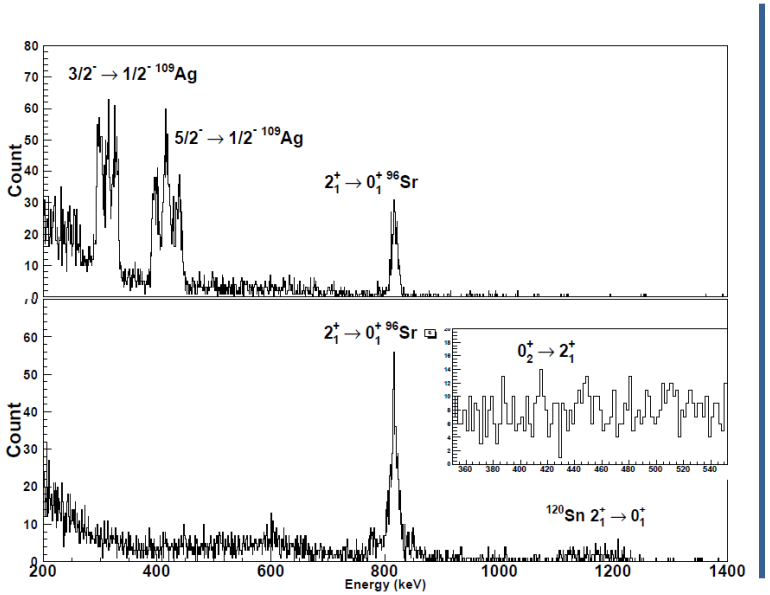


N=60

Coulomb excitation results

❖Coulomb excitation of ^{96}Sr at 2.8 MeV/A –REX-ISOLDE

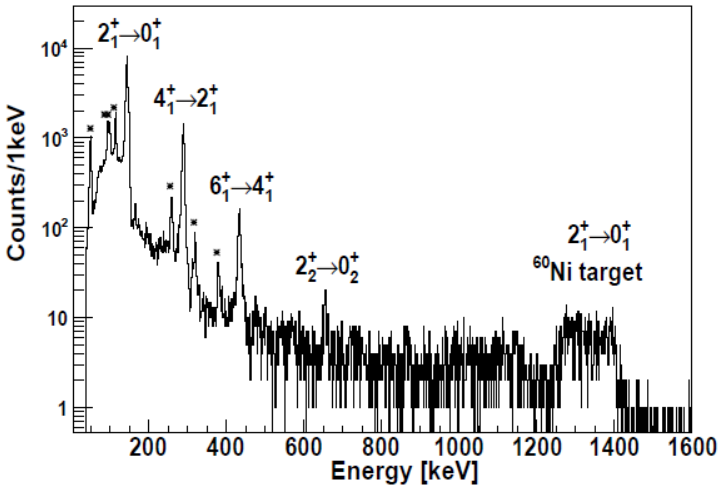


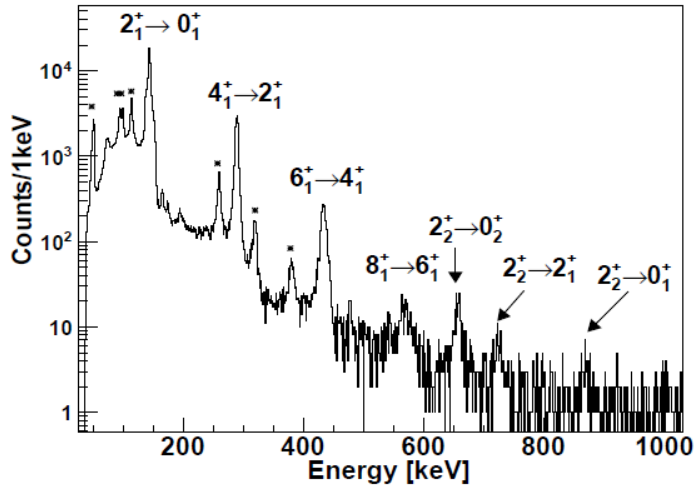


E. Clément et al , in preparation

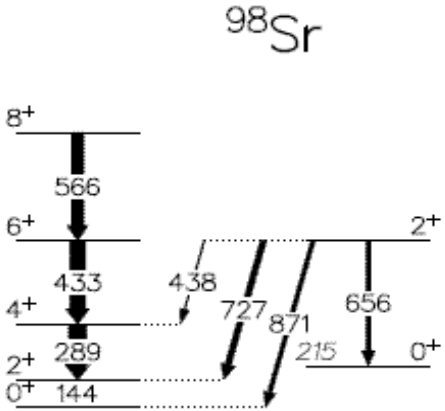
E. Clément et al. EPJ Web of Conferences **62**, 01003 (2013)

Coulomb excitation results





- ❖Coulomb excitation of ^{98}Sr at 2.8 MeV/A
- ❖Ground state and non-yrast states populated

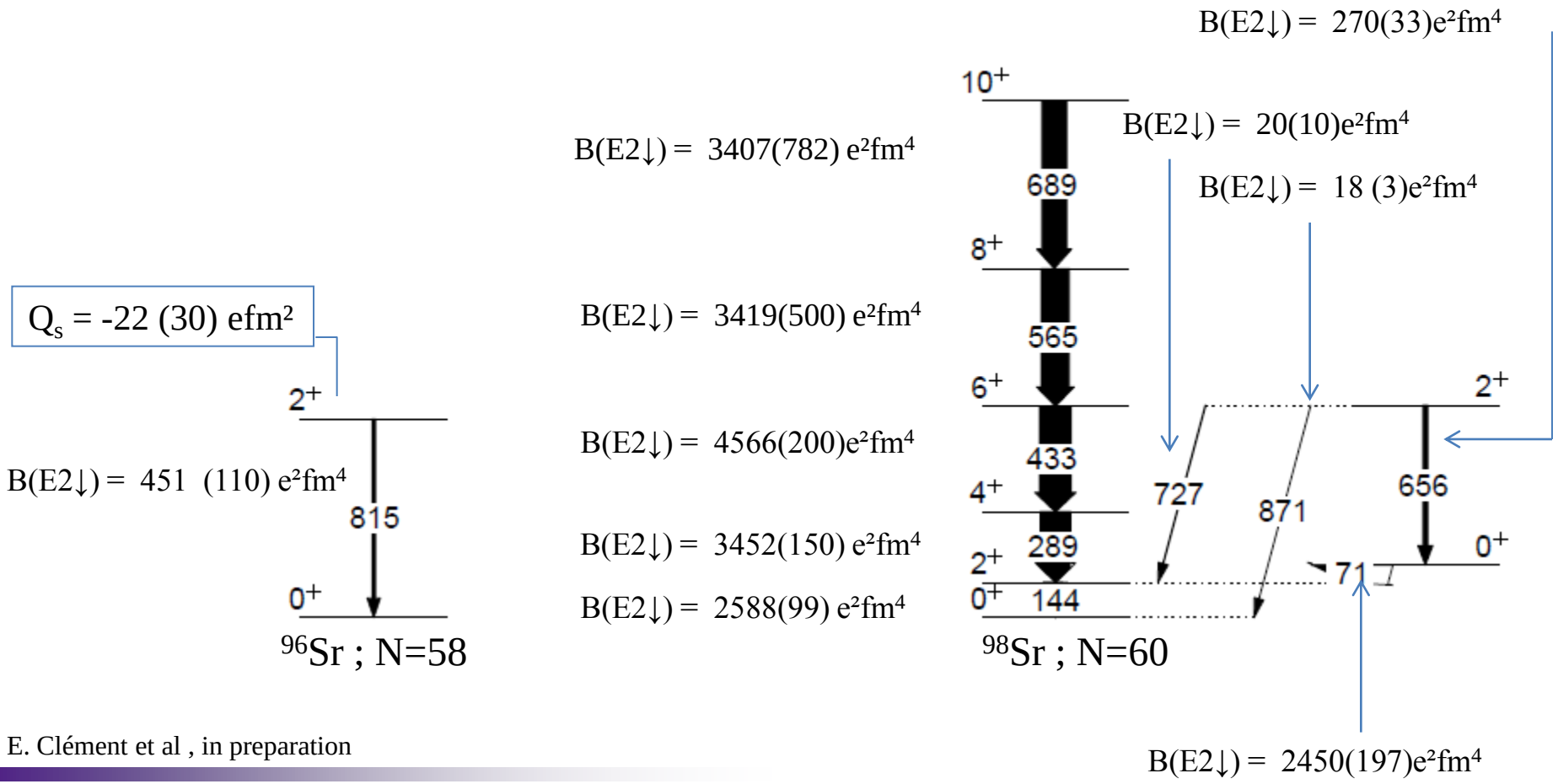


E. Clément et al , in preparation

E. Clément et al. EPJ Web of Conferences **62**, 01003 (2013)

- ^{96}Sr :The Electric spectroscopic Q_0 is small as its B(E2) is rather large

  → Vibrator character
  → Weak quadrupole deformation

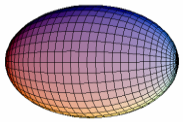


E. Clément et al , in preparation

- ^{96}Sr :The Electric spectroscopic Q_0 is small as its B(E2) is rather large

  → Vibrator character
  → Weak quadrupole deformation

- ^{98}Sr
  → The ground state band is a rotor
  → Excited configuration similar to ^{96}Sr

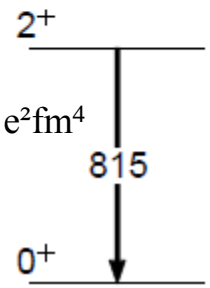


$\beta \sim 0.4$

$|\beta| < 0.1$

Q_s = -22 (30) efm²

B(E2↓) = 451 (110) e²fm⁴



^{96}Sr ; N=58

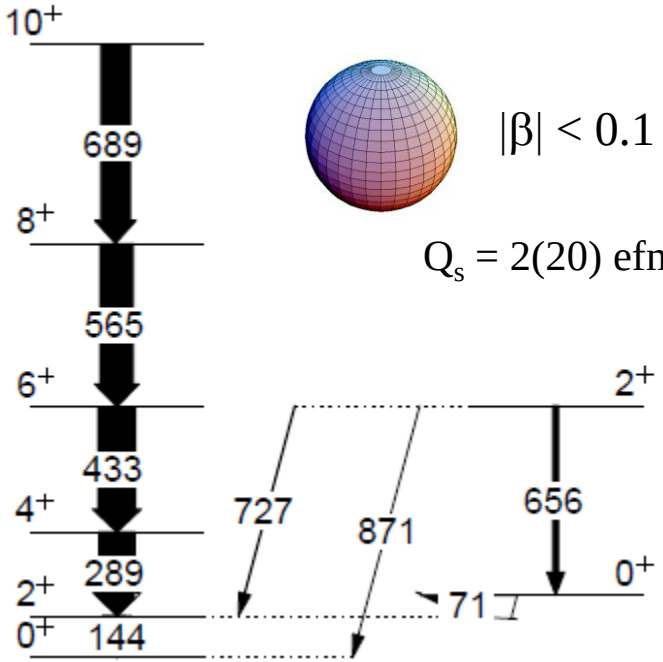
Q_s = -95(100) efm²

Q_s = -121(13) efm²

Q_s = -187 (8) efm²

Q_s = -52 (14) efm²

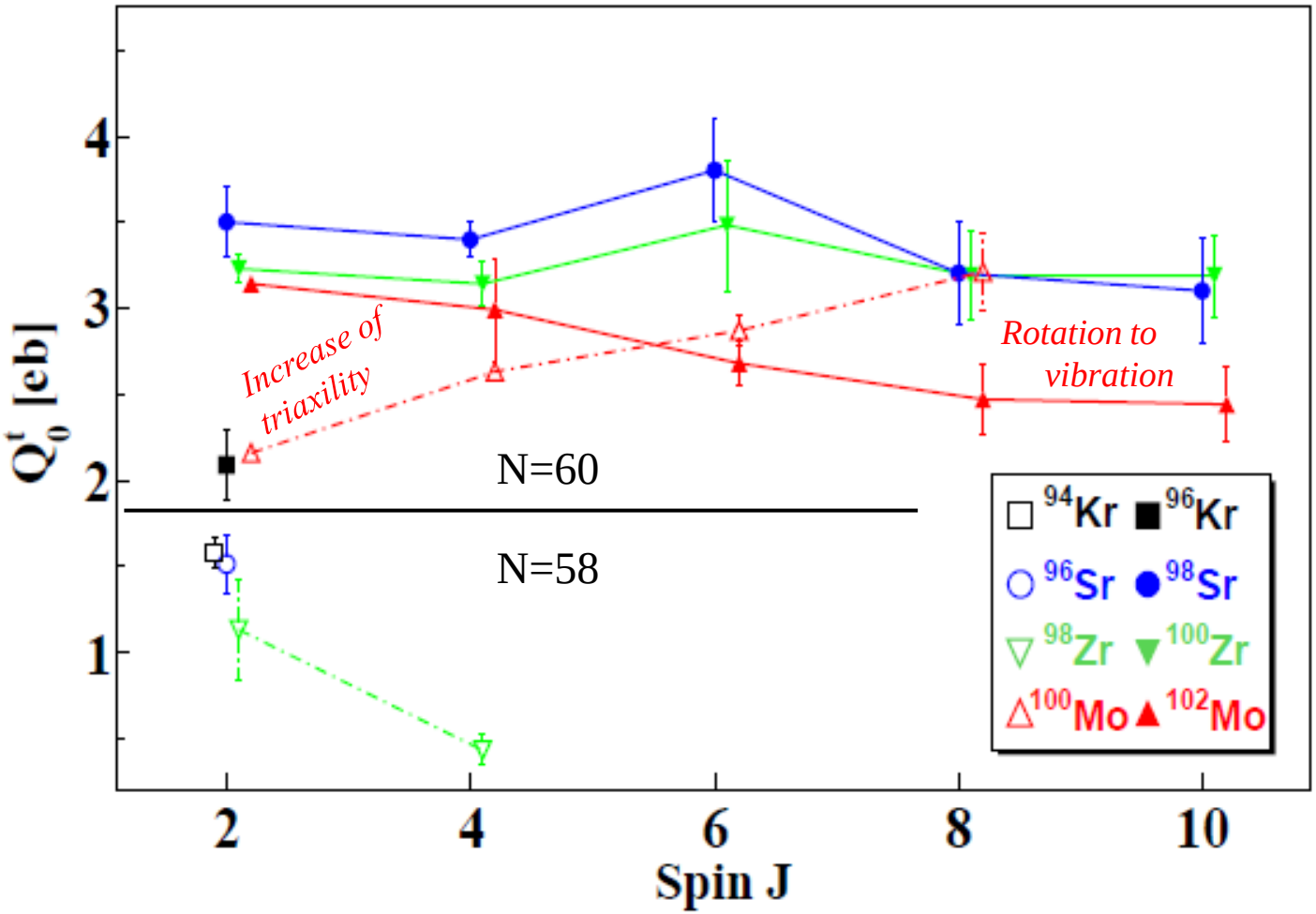
Q_s = 2(20) efm²



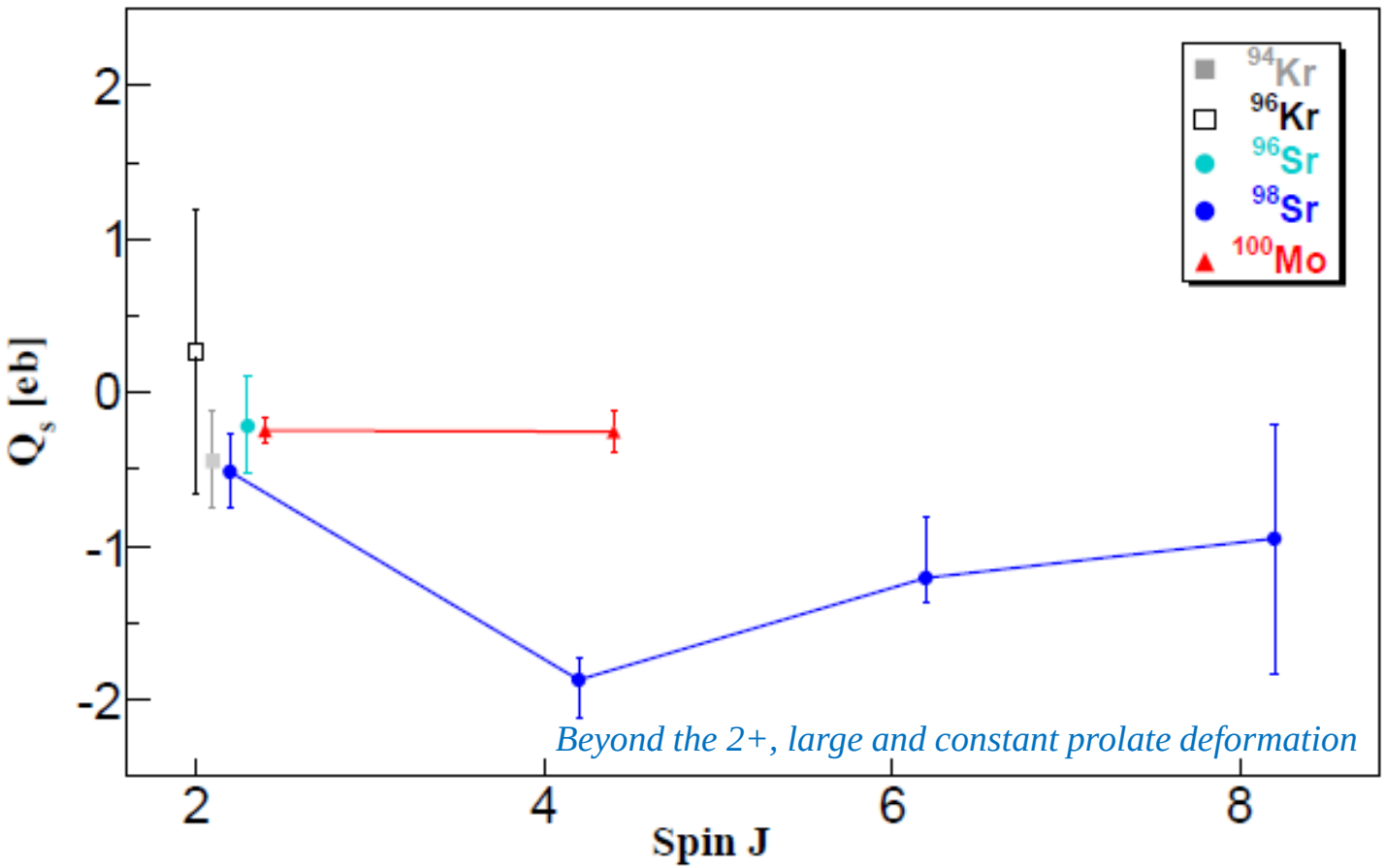
^{98}Sr ; N=60

E. Clément et al , in preparation

Systematic of Transitional Quadrupole moment around N=60



E. Clément et al , in preparation



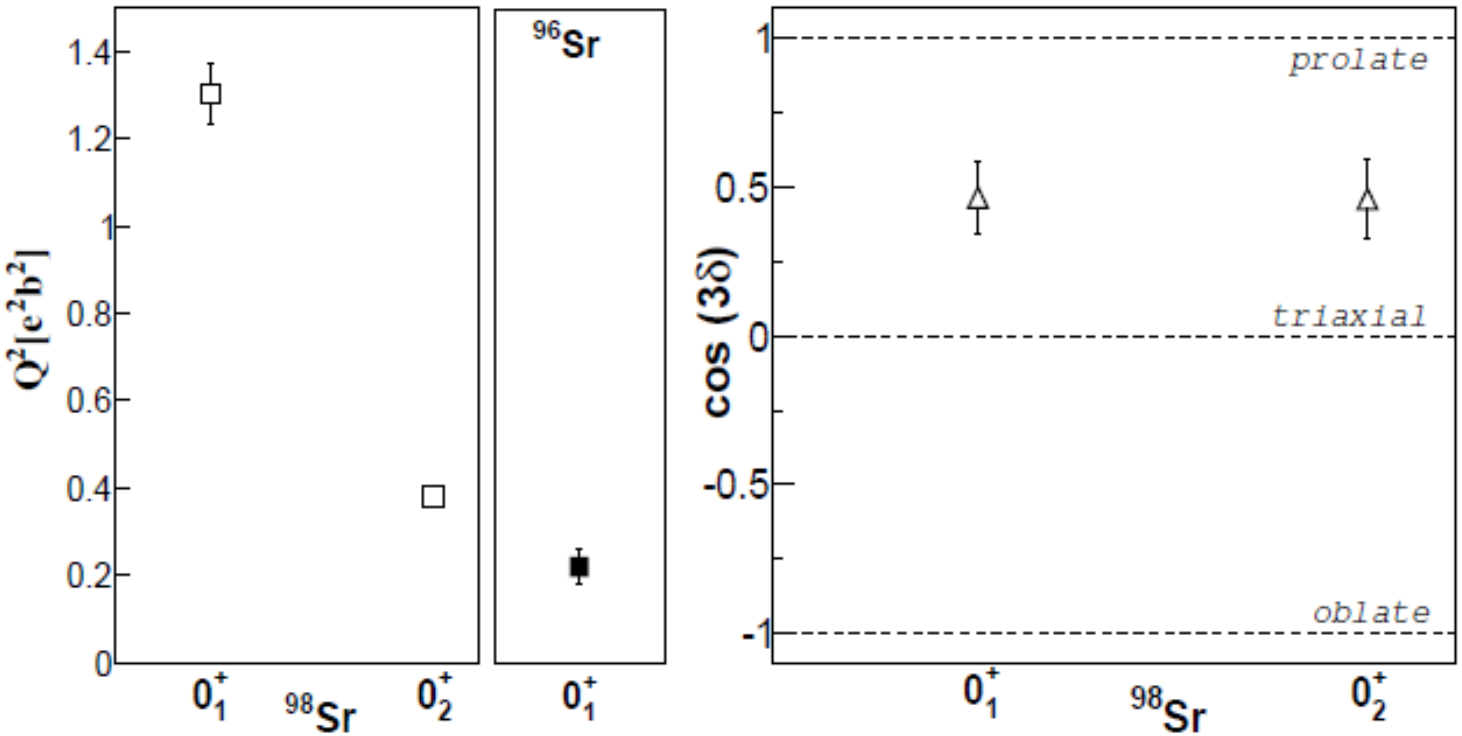
K. Wrzosek-Lipska et al. Phys. Rev. C 86, 064305 (2012).

M. Albers et al., Phys. Rev. Lett. 108, 062701 (2012)

E. Clément et al , in preparation

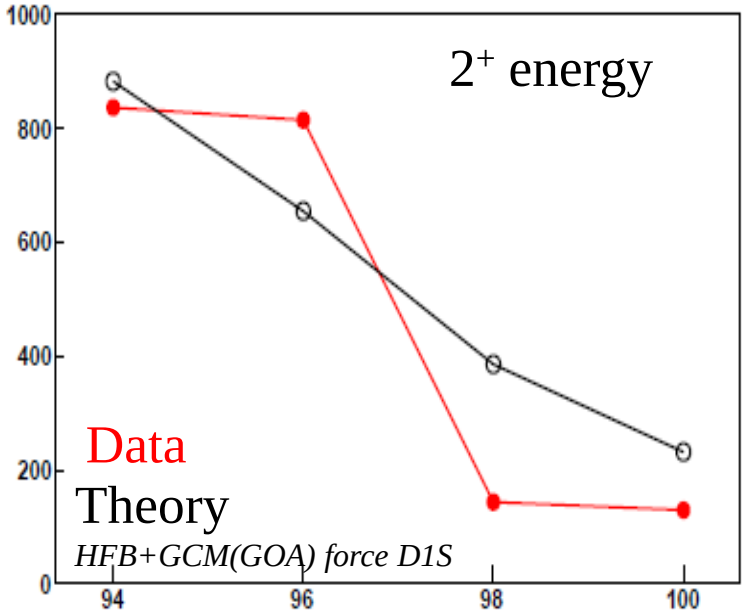
- Deformation of the 0^+ states analyzed with the Quadrupole Sum Rules formalism

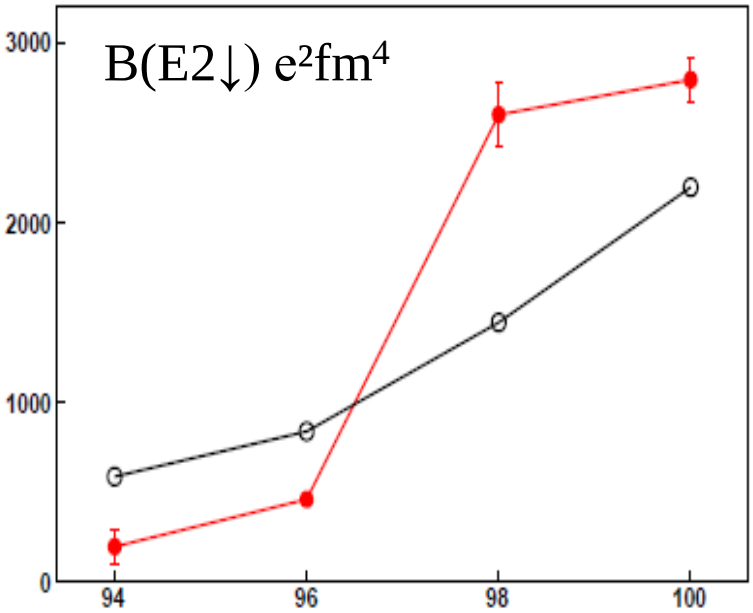
- Sums of quadrupole E2 matrix elements give $Q^2 \sim |\beta_2|$ and $\cos(3\delta) \sim \gamma$



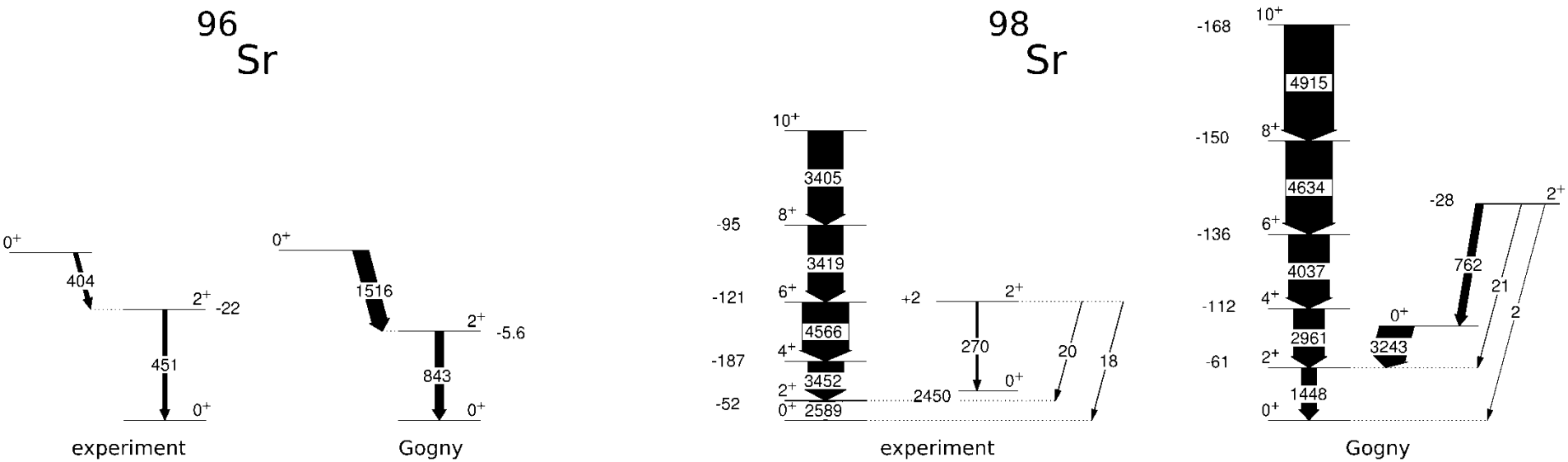
E. Clément et al , in preparation

Comparison with theory :





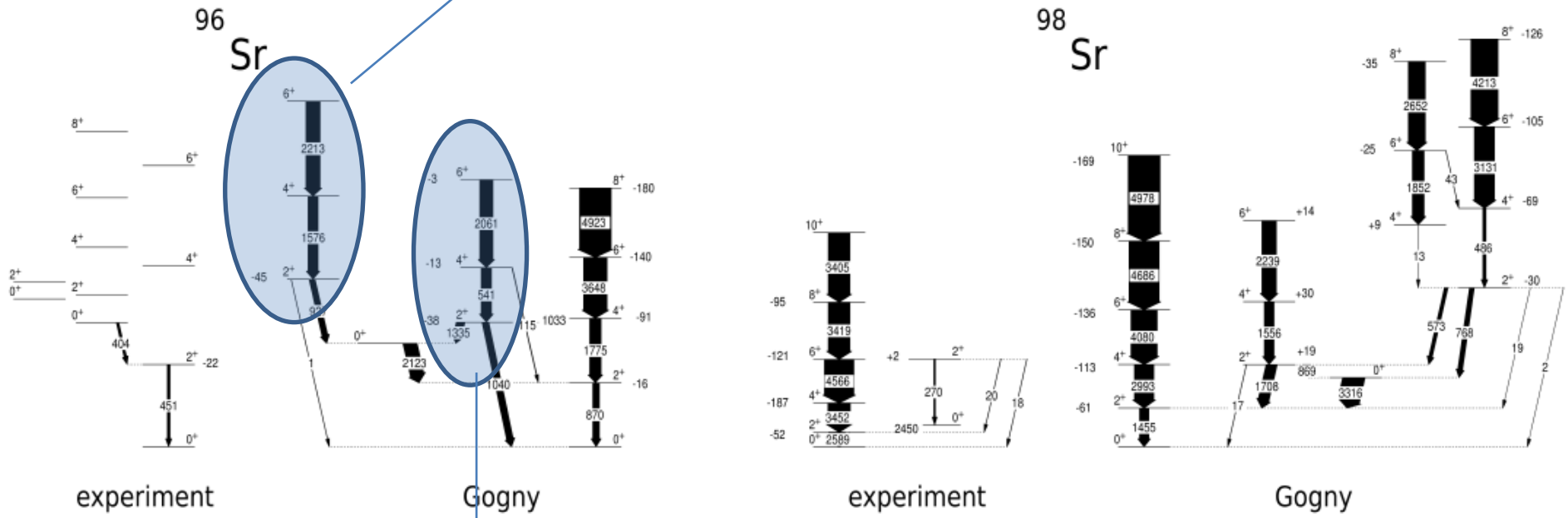
Comparison with theory :



E. Clement and CEA-Bruyère-Le-Chatel in preparation

Comparison with theory :

More deformed with a larger contribution of K=0.

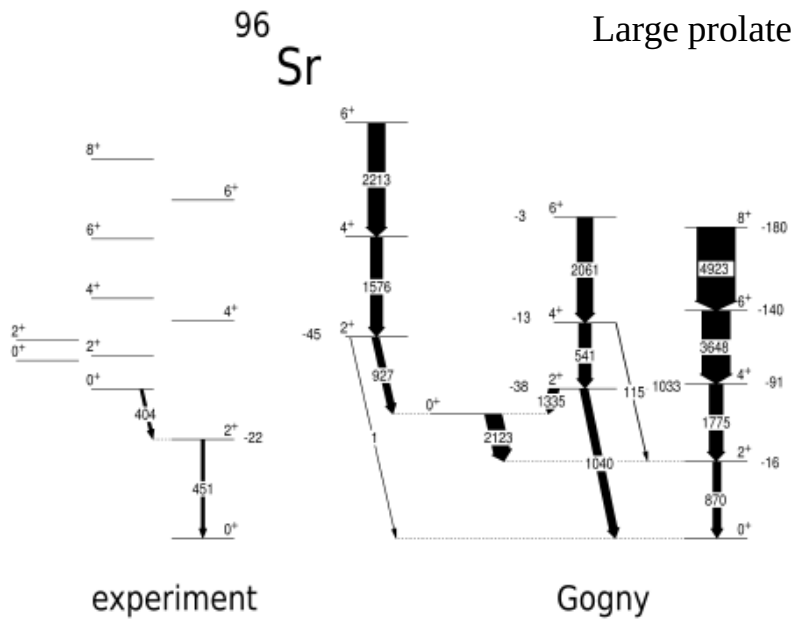


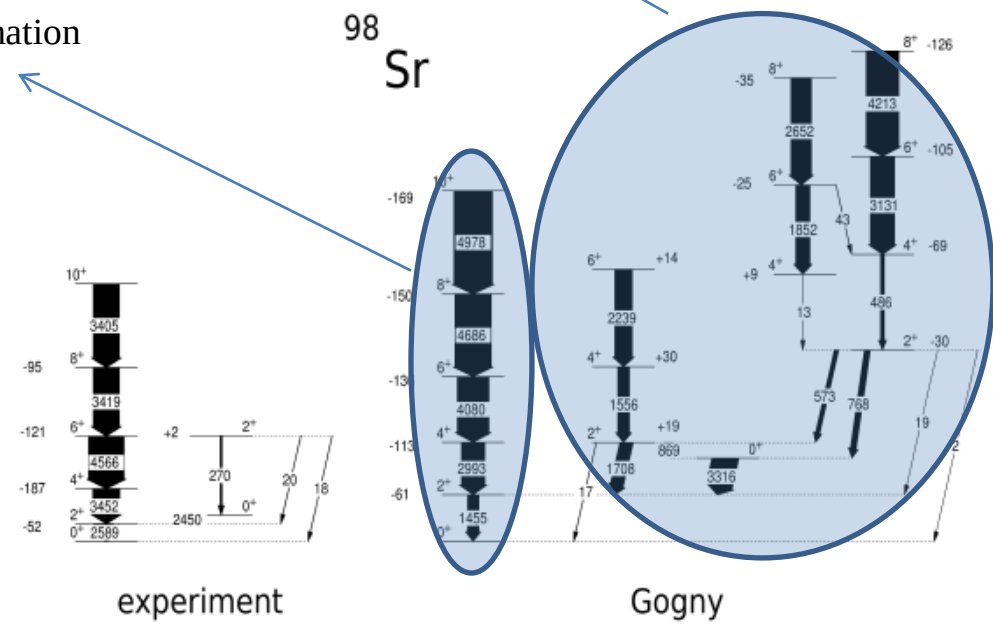
Large B(E2) values and small Qs.
Contribution of the triaxial degree of freedom
K=0 component below 50%

E. Clement and CEA-Bruyère-Le-Chatel in preparation

Similarly to the Kr case, a clear classification of the states and the assignment of non-yrast bands is difficult, due to γ softness and K=0 and K =2 mixing.

Large prolate deformation





- The first theoretical excited band, predicted to be mainly of K=2 character
- Probably calculated too low in excitation energy since it is not observed experimentally.
- Large calculated $B(E2,2^+_2 \rightarrow 2^+_1)$ value and the relative proximity of the three 2^+ states suggest a very complex mixing between bands in the calculation.

E. Clement and CEA-Bruyère-Le-Chatel in preparation

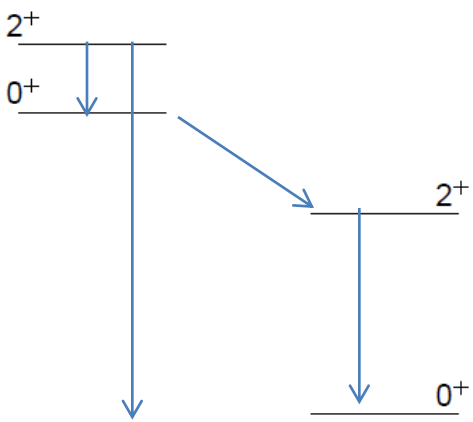
Shape coexistence in a two-state mixing model

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

Pure states

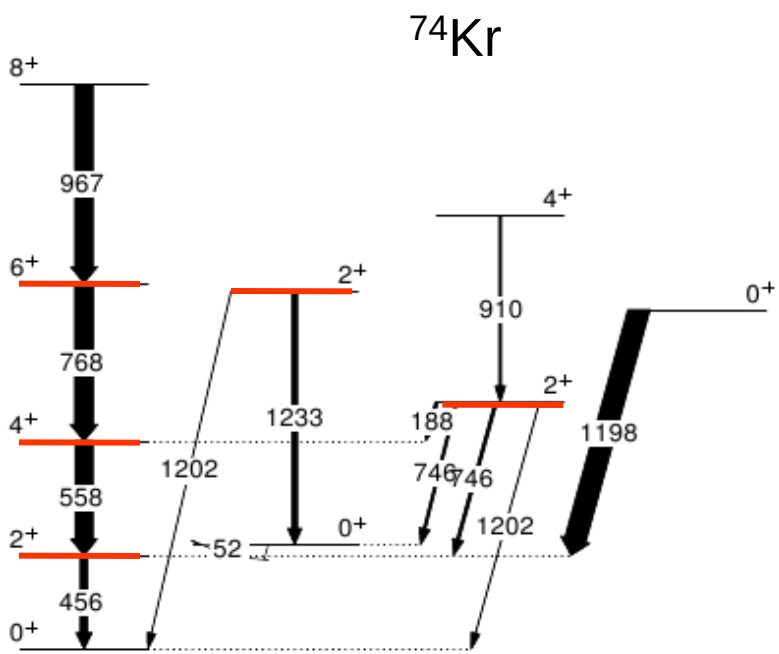
Perturbed states

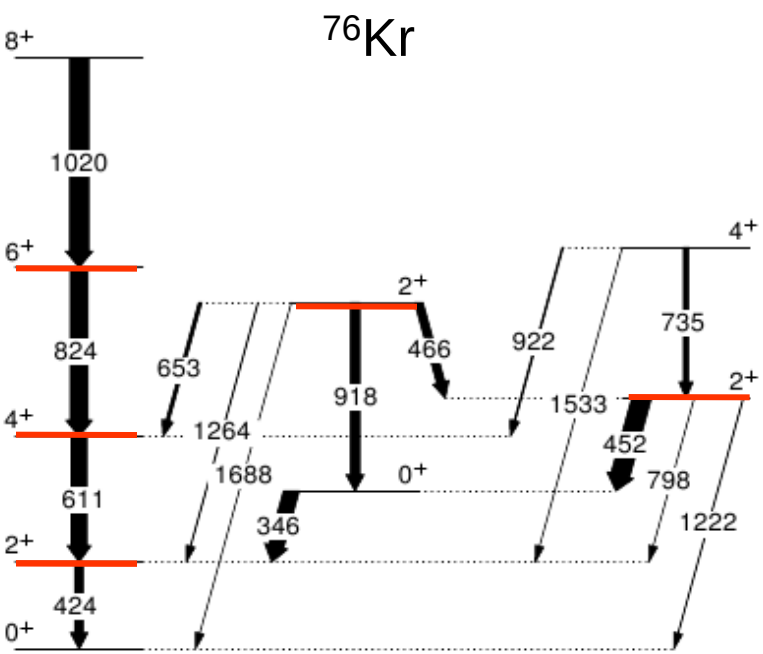
Extract mixing and shape parameters from set of experimental matrix elements.



$$\tan\theta_0 = A \pm \sqrt{A^2+1}, \qquad A = \frac{M_{11}^2 + M_{21}^2 - M_{12}^2 - M_{22}^2}{2(M_{11}M_{12} + M_{21}M_{22})}$$

$$\tan\theta_2 = \frac{M_{11}\tan\theta_0 + M_{12}}{M_{21}\tan\theta_0 + M_{22}},$$





E. Clément et al. Phys. Rev. C 75, 054313 (2007)

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

Shape coexistence in a two-state mixing model

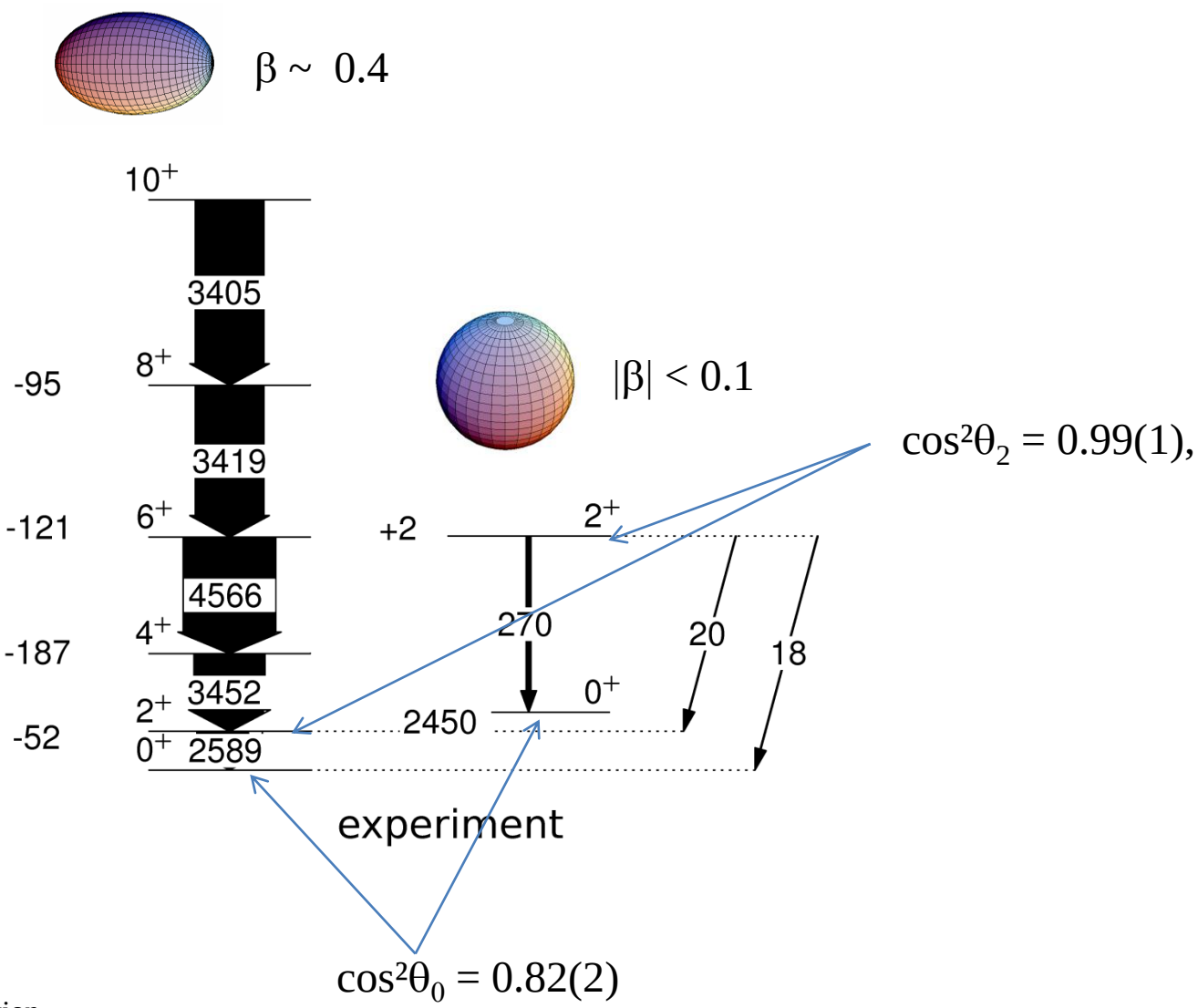
$$|I_1\rangle = +\cos\theta_I|I_{pr}\rangle + \sin\theta_I|I_{ob}\rangle$$
$$|I_2\rangle = -\sin\theta_I|I_{pr}\rangle + \cos\theta_I|I_{ob}\rangle$$

Pure states

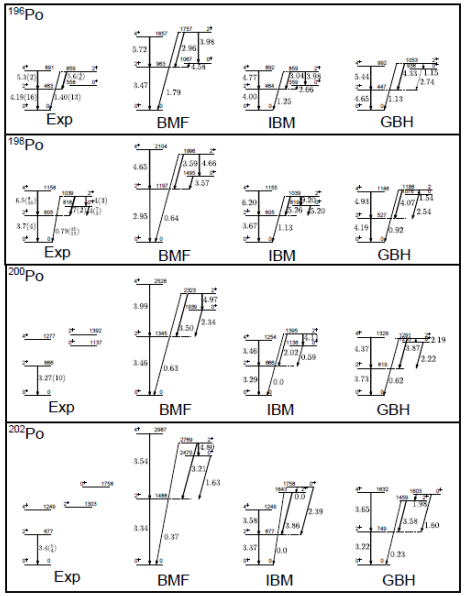
Perturbed states

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 et al. Phys. Rev. C 75, 054313 (2007)	0.69(4)	0.48(2)	*
Excited Vampir approach: A. Petrovici et al., Nucl. Phys. A 665, 333 (00)	*	0.6	0.5

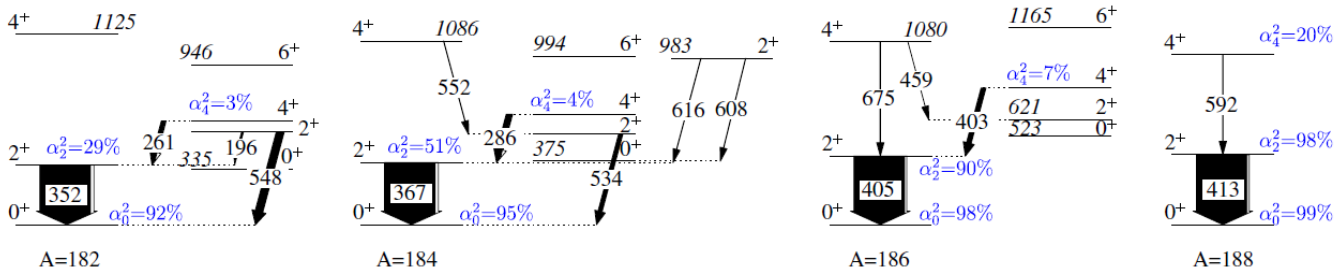


E. Clément et al , in preparation



Isotope	α^2_{0+}	α^2_{2+}
^{194}Po	12 %	29 %
^{196}Po	85 %	50 %
^{198}Po	94 %	69 %
^{200}Po	97 %	92 %
^{202}Po	99 %	88 %

N. Kesteloot et al submitted to PRC



N. Bree et al, PRL 112, 162701 (2014)

- Over long isotopic chains, the two level mixing model shows that intrinsic configurations remain and the measured values are the results of the mixing amplitude

- True for Kr, Po and Hg so far →Sr, Zr, Pb ?

Conclusion

- In-beam γ-ray spectroscopy with RIB provides fundamental information in the study of the nuclear structure far from stability

- Post-accelerated RIB at the suitable energies allow high quality spectroscopic measurement

<u>Where to look :</u>

At N=28 and N=20 new post-accelerated RIB for Transfer and Coulex data

RIB in the 3rd island of invertion : post accelerated beam of Co, Fe in the vicinity of N=40

Large isotopic chain for the shape coexistence , triple shape coexistence in the Pb, Sr/Zr chain