Shape transitions and coexistence

GDR Resanet /GT2/ October 2018

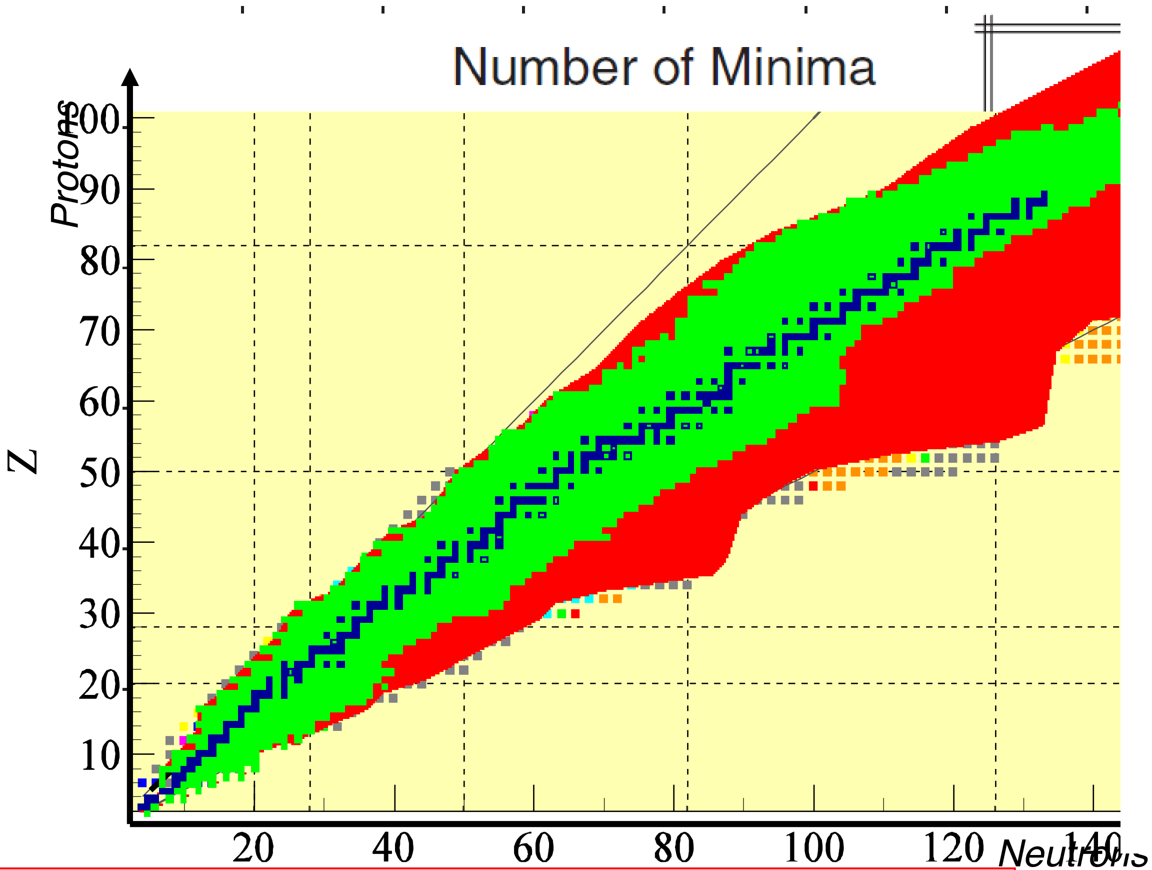
Shape coexistence is a spectacular and universal phenomena

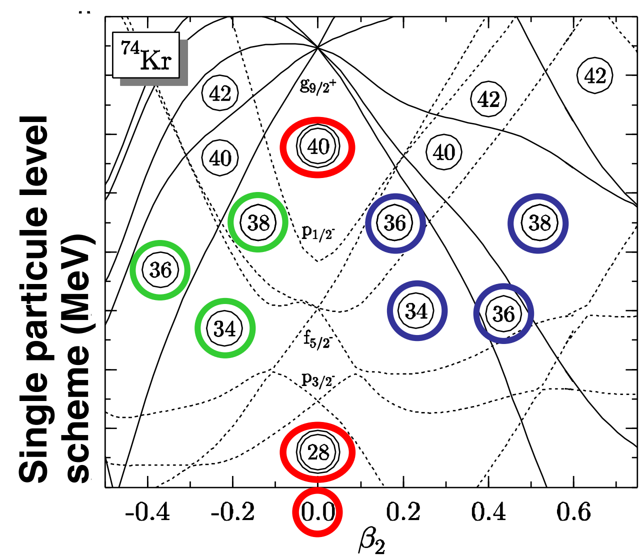
It reflects the competition between the spherical shape stabilizing the nucleus and its natural tendencies to deform

- Competition between spherical gap and residual energy which minimize the energy of the deformed configuration
- Two different microscopical configurations with different shape coexist at low excitation energy (<2 MeV) in the same nucleus

The excitation energy of the corresponding configuration is similar, separated by a barrier keeping the mixing between the wave functions weak allowing the states to keep their nature

Shape coexistence ; Universal phenomena





Bruyères-le-Châtel

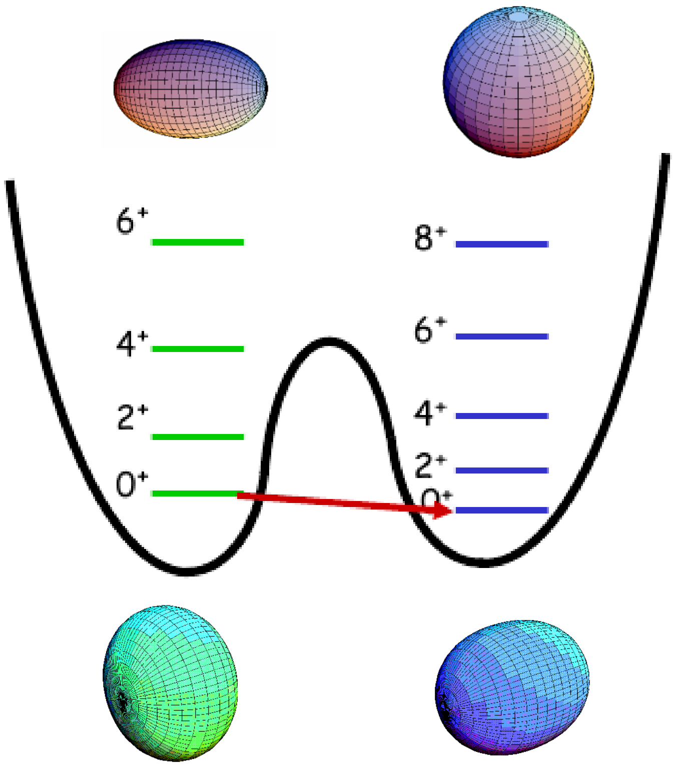
M. Girod, CEA Bruyères-le-Châtel

- *The last decade shown us that this exoctic phenomena is not rare.*
- *From isolated case to « island of occurrence »*
- *Balance between the tendency to stabilize nuclei in a spherical shape and the general deformation-driving tendency*

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

Kris Heyde and John L. Wood Rev. Mod. Phys. ***83****, 1467 (2011)*

Experimental evidences

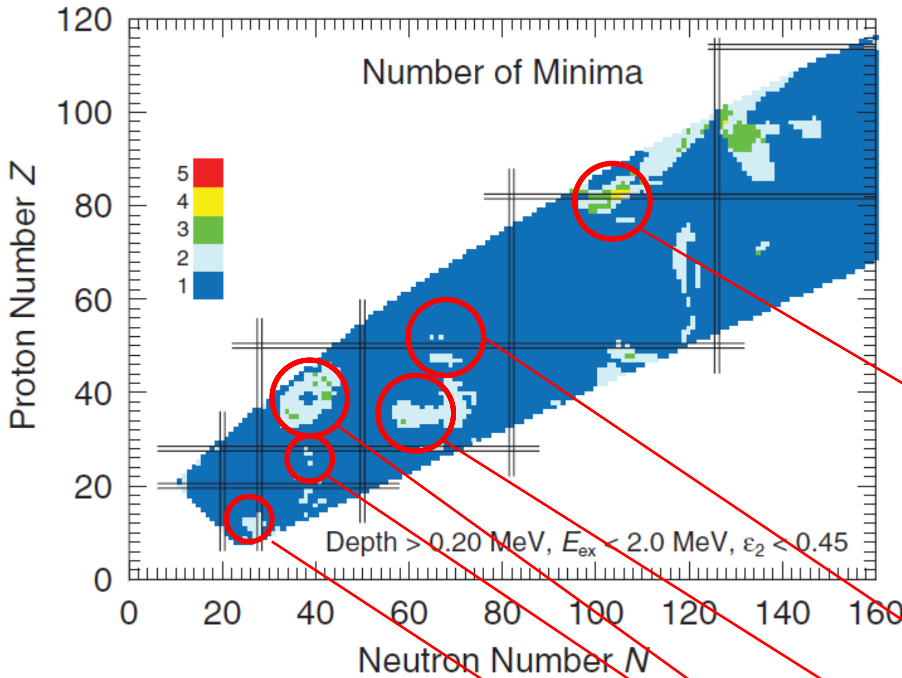


- Shape isomers
- Level scheme (band structure)
- Transition probabilities
- Quadrupole moment : Q_s
- Charge Radius

ISOL facilities with post-accelerated RIB (>10^3 pps) and advanced technic in beam manipulation and laser technic have revolutionized the field

Which mechanism is the origin of shape coexistence ?

Microscopical effect ⟺ Symmetries in the mean field



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

Intensively discussed and experimentally investigated since decades

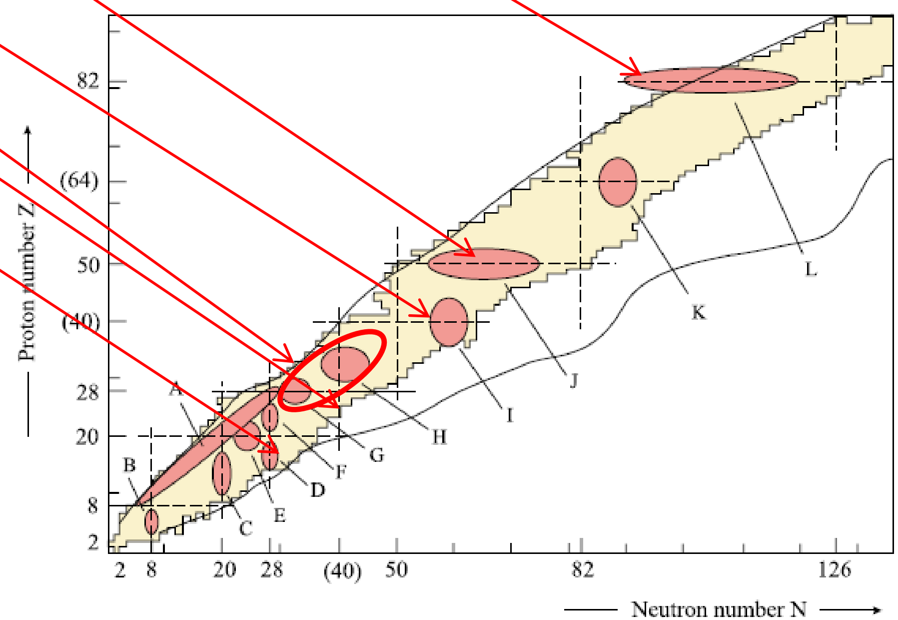
Shape coexistence occurs close to (π) shell or sub-shell closure closed by high j-orbitals

π–ν correlation energy

Shape coexistence at low energy in « doubly magic »
^{42}Ca : K. Hadynska-Klek et al, PRL 117, 062501 (2016)

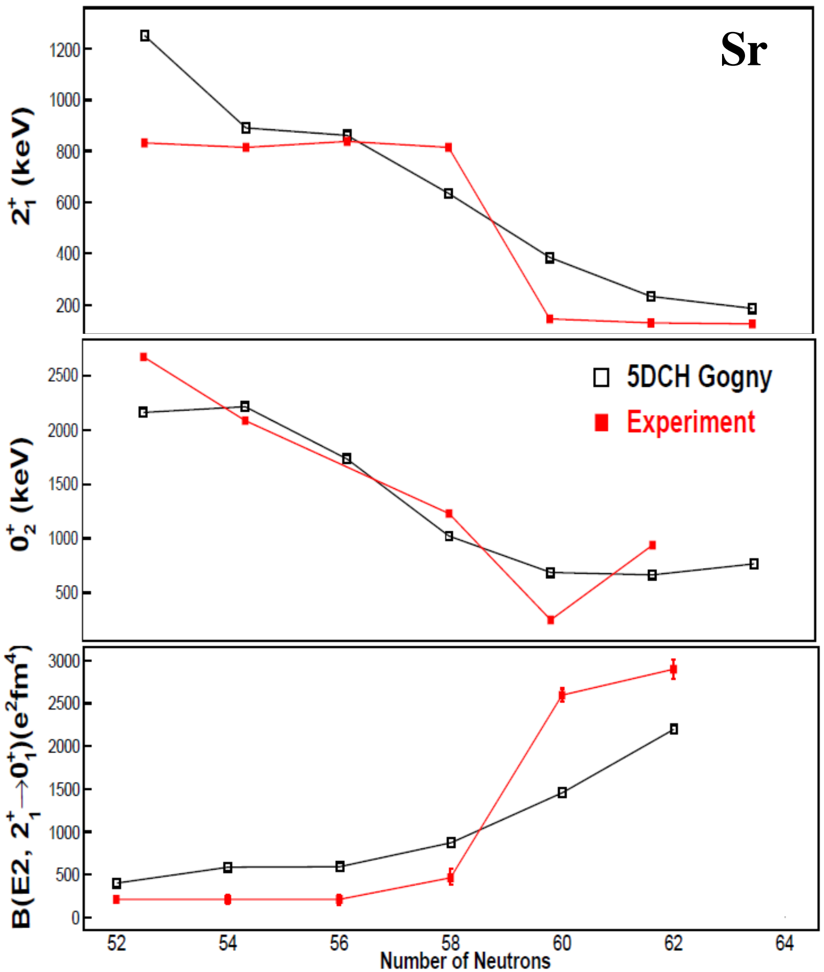
The ^{56,78}Ni region doesn't appears here

^{80}Ge : A. Gottardo et al. PRL. 116, 182501 (2016)
^{56}Ni : J. Zhang, et al. PRC 49, 562 (1994)



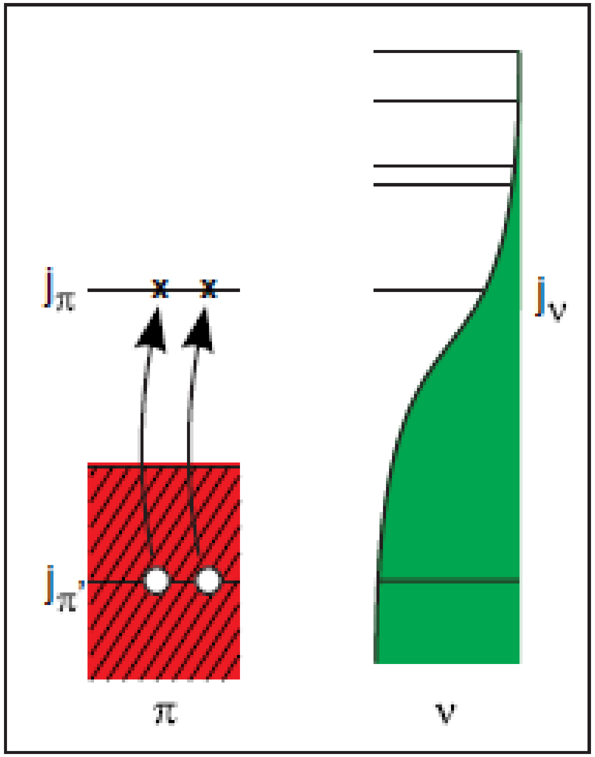
Kris Heyde and John L. Wood
Rev. Mod. Phys. **83**, 1467 (2011)

J. P. Delaroche *et al*., *Phys. Rev. C 81, 014303 (2010)*.



Unified view ?

Kris Heyde and John L. Wood Rev. Mod. Phys. 83, 1467 (2011)



$$E_{\text{intr}}(0^+) = 2(\varepsilon_{j_\pi} - \varepsilon_{j'_\pi}) - \Delta E_{\text{pair}} + \Delta E_M + \Delta E_Q,$$

Pairing energy

Monopole correction

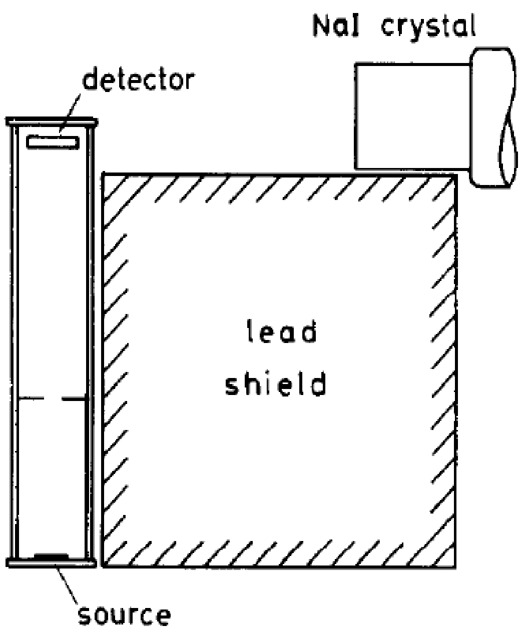
p-n quadrupole binding energy

p-n residual energy

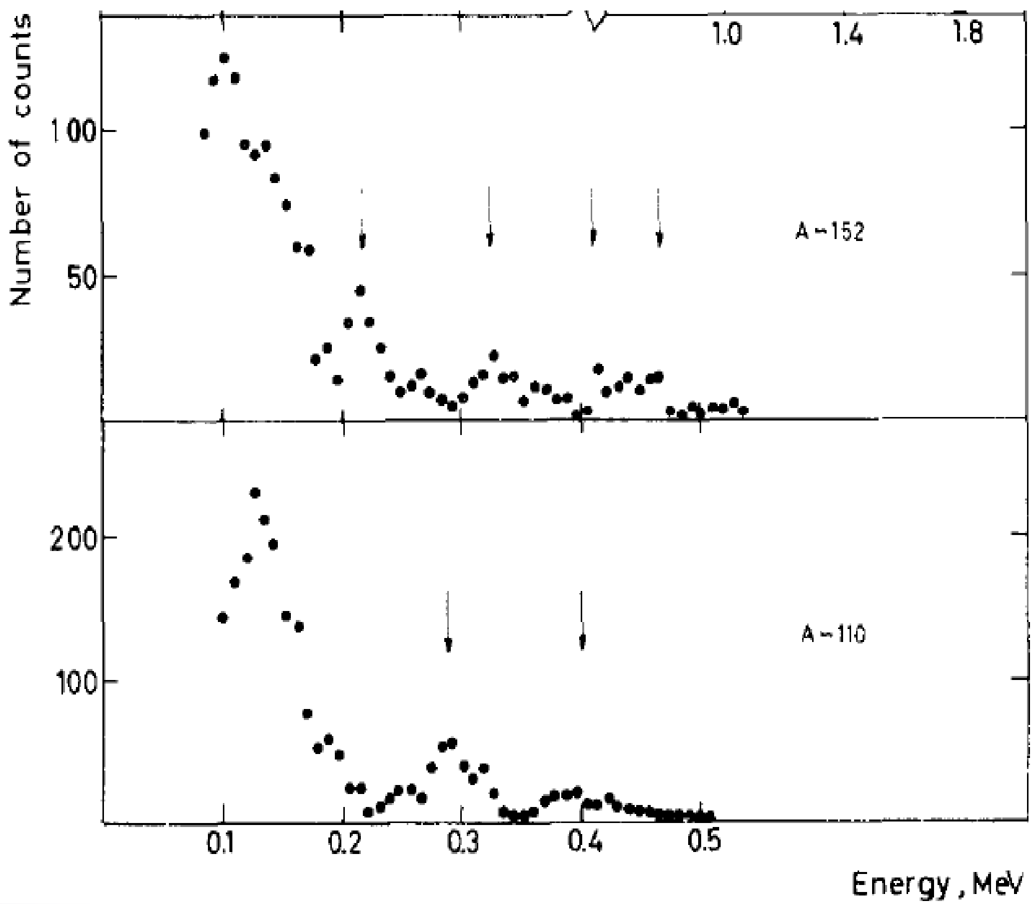
In an unified view, the appearance of shape coexistence at low energy is a competition between energy gap and a residual interaction that lower the energy of such configuration

What did we achieve today : The exemple of the shape coexistence and transition at A=100

It has been established in the 60's that elements with A~ 110 Z ~ 40 belong to a new island of stable deformation similar to the rare earth region



S. A. E. Johansson, Nucl. Phys. **64** (1965) 147

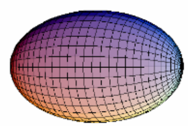


Shape coexistence at A= 100

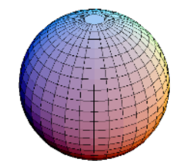
The 2^+_1 in ^{96}Sr is weakly deformed

The ground state band in ^{98}Sr has a large prolate deformation and the 2^+_2 is similar to the ground state in ^{96}Sr

- Shape coexistence in ^{98}Sr
- Shape inversion at N=60



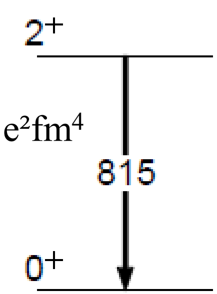
$\beta >$ 0.4



$|\beta| <$ 0.2

$\boxed{Q_s = -22\ (31)\ \text{efm}^2}$

$B(E2\downarrow) =$ 450 (110) e^2fm^4



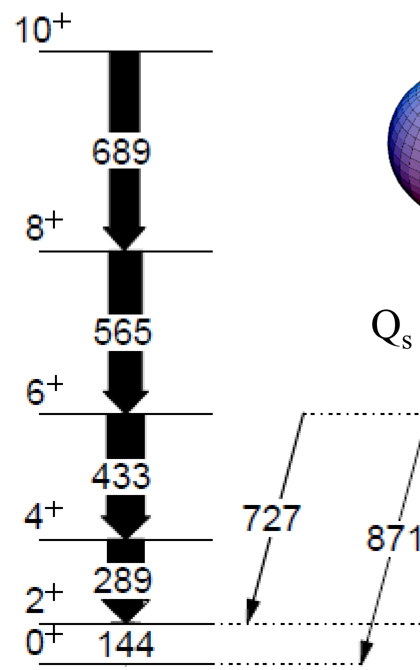
^{96}Sr ; N=58

Q_s = -90(80) efm²

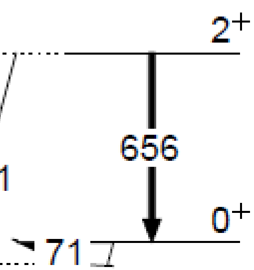
Q_s = -130(23) efm²

Q_s = -213 (16) efm²

Q_s = -48 (25) efm²



Q_s = +3(24) efm²



$\rho^2(E0)$ = 53 mu

^{98}Sr ; N=60

E. C., et al, Phys.Rev.Lett. 116, 022701 (2016)

E. C., et al, Phys.Rev.C 94, 054326 (2016)

Shape coexistence at A= 100

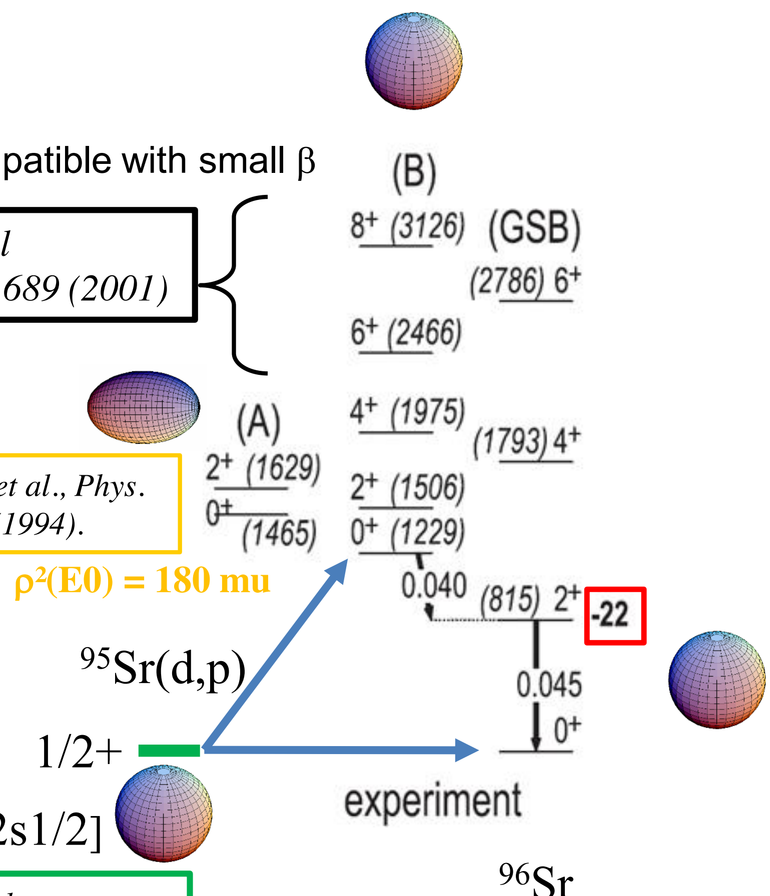
Multi-messager :

Systematics with Coulex, Transfer, E0 and Laser spectroscopy

Lifetime compatible with small β

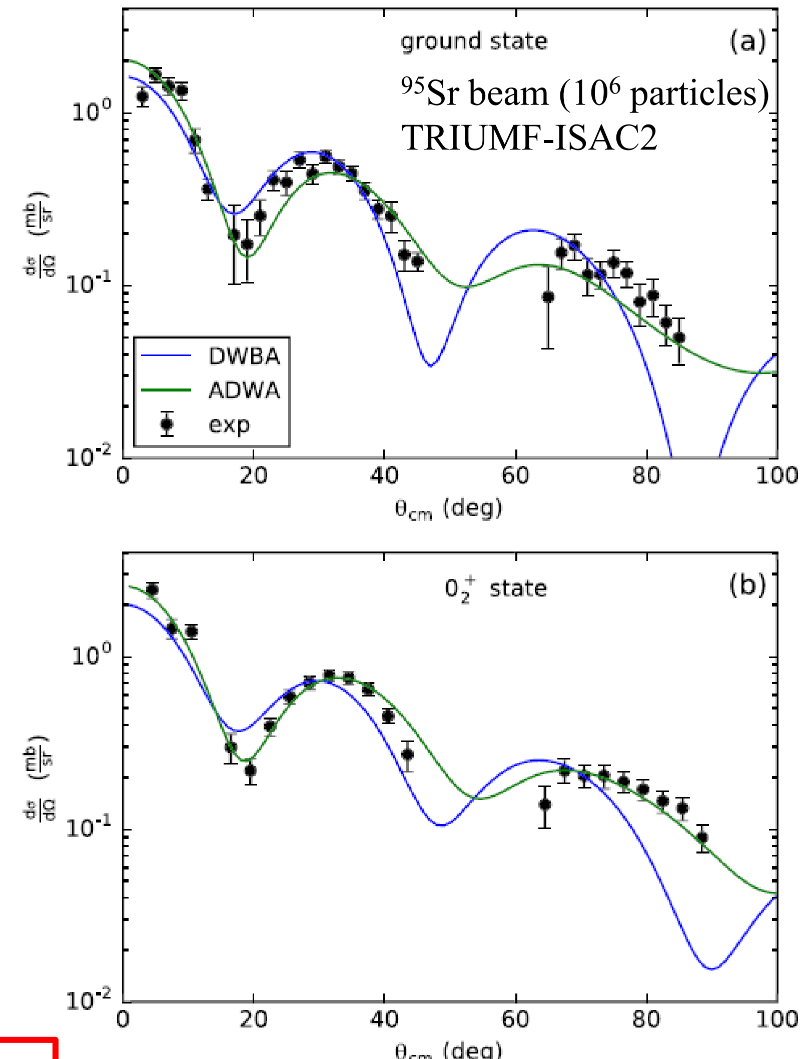
W. Urban et al
Nucl. Phys. A 689 (2001)

G. Lhersonneau et al., Phys. Rev. C 49, 1379 (1994).



F. Buchinger et al., Phys. Rev. C 41, 2883 (1990)

E. C., et al, Phys.Rev.Lett. 116, 022701 (2016)



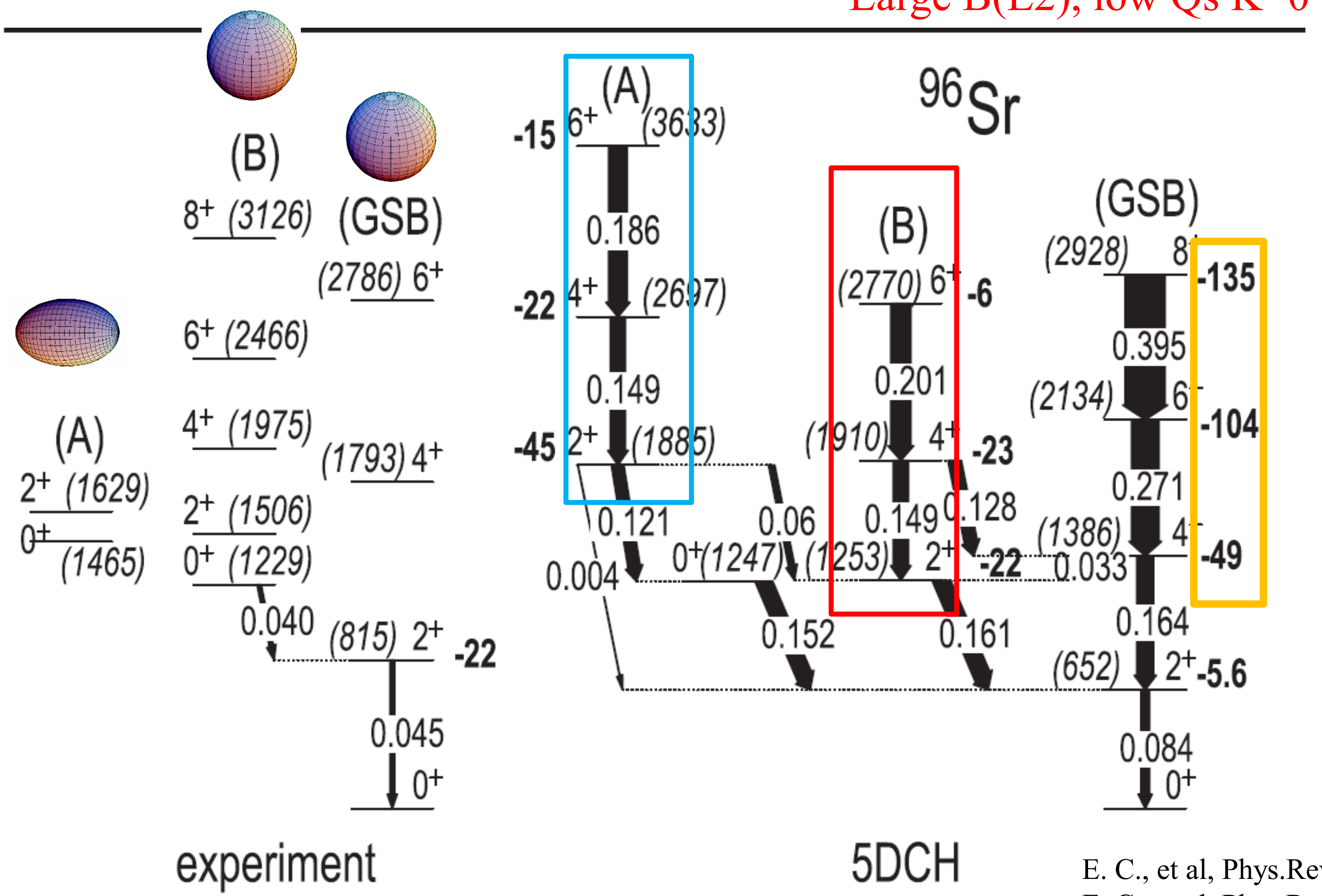
S.Cruz et al, Physics Letters B 786 (2018) 94–99

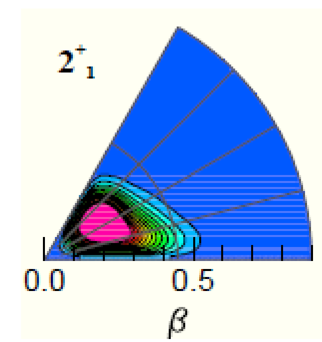
Shape coexistence at A= 100

From a theoretical point of view

Large B(E2), higher Qs K=0 ~70%

Large B(E2), low Qs K=0 < 50%



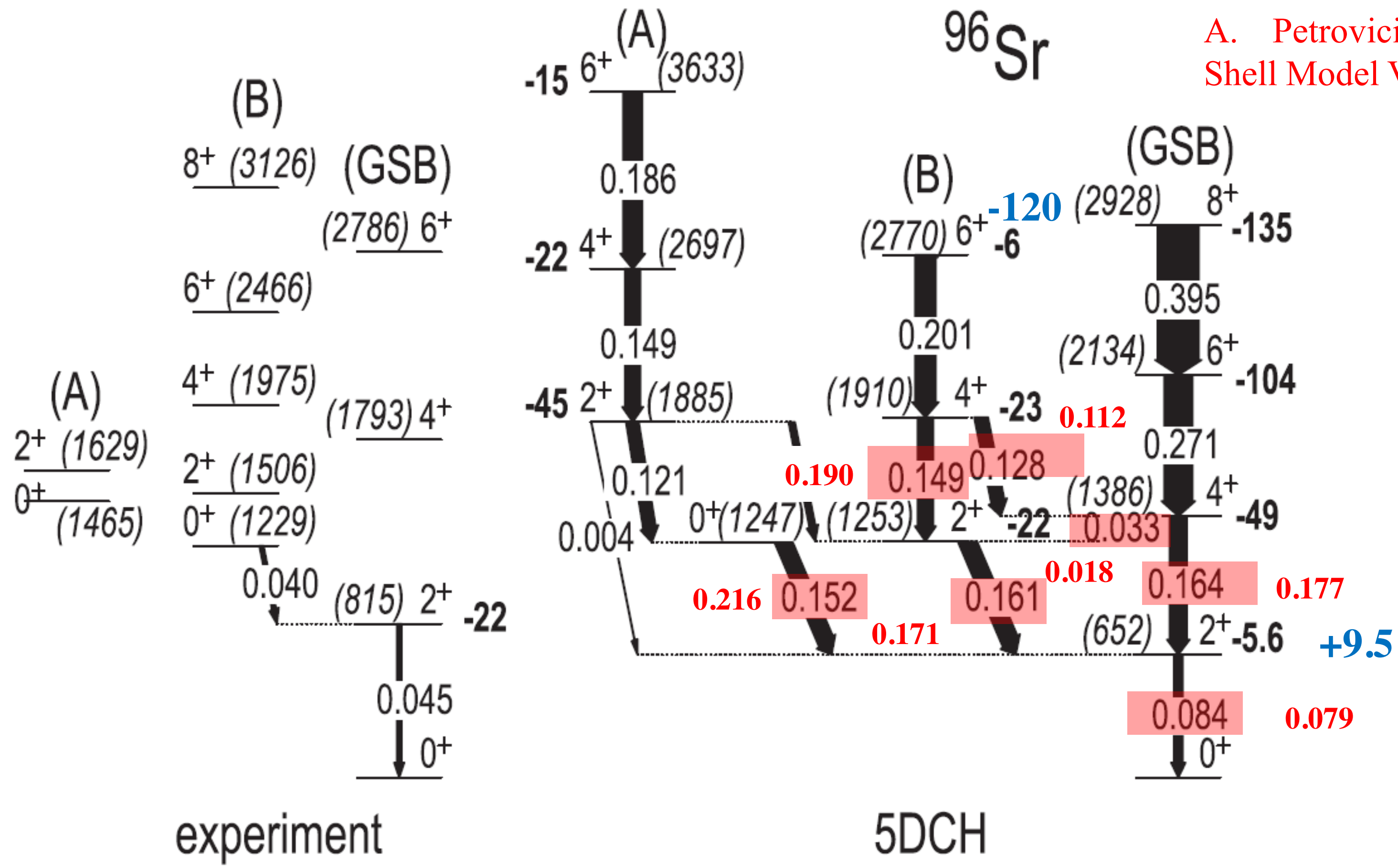


(30% K=2)

E. C., et al, Phys.Rev.Lett. 116, 022701 (2016)
E. C., et al, Phys.Rev.C 94, 054326 (2016)
S.Cruz et al, Physics Letters B 786 (2018) 94–99

Shape coexistence at A= 100

From a theoretical point of view

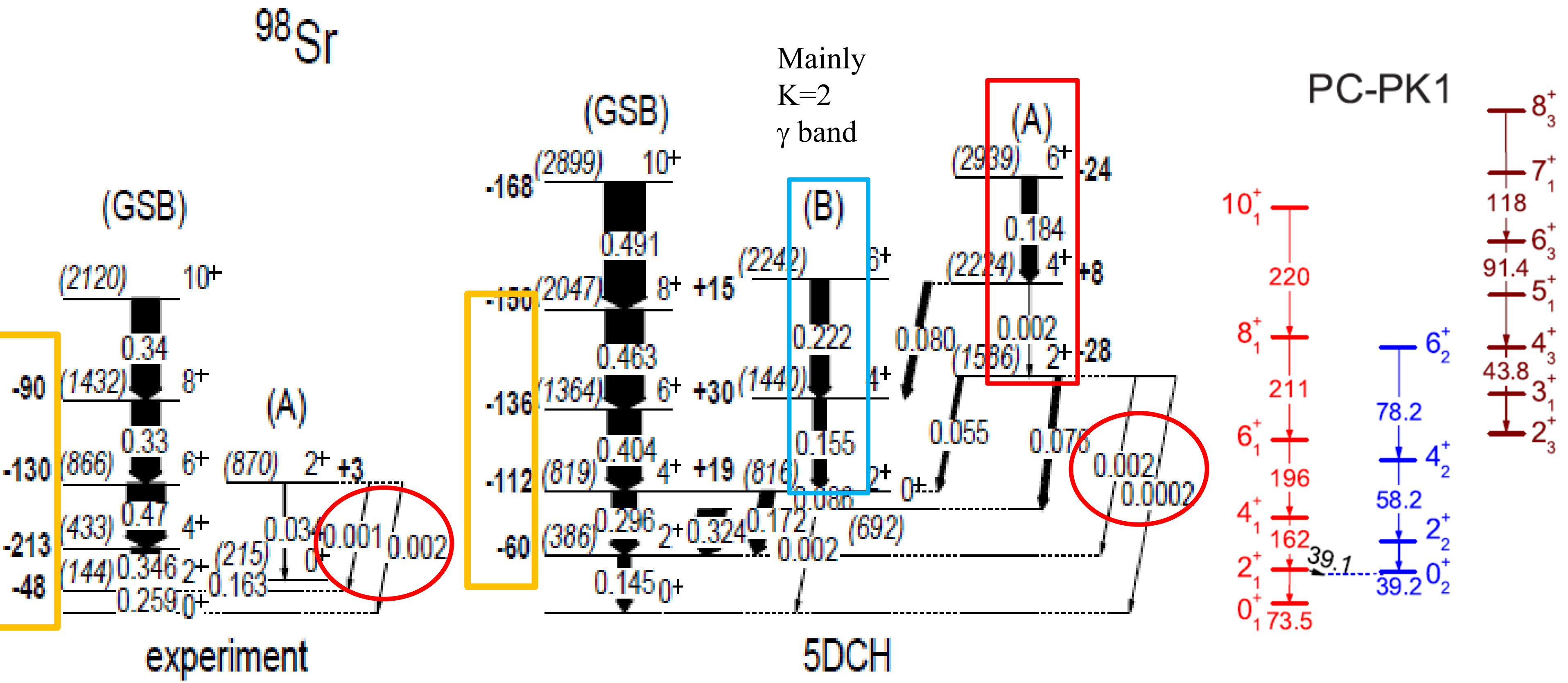


A. Petrovici PRC 85, 034337 (2012)
Shell Model VAMPIR

E. C., et al, Phys.Rev.Lett. 116, 022701 (2016)
E. C., et al, Phys.Rev.C 94, 054326 (2016)

Shape coexistence at A= 100

From a theoretical point of view



J. Xiang et al . Phys. Rev. C 93, 054324 (2016)

E. C., et al, Phys.Rev.Lett. 116, 022701 (2016)

E. C., et al, Phys.Rev.C 94, 054326 (2016)

Shape coexistence at A= 100

From a theoretical point of view

E0 transition

^{96}Sr

I_1^π	I_2^π	experiment	5DCH (Gogny)	Excited VAMPIR
		B($E2$, $I_1 \rightarrow I_2$) (W.u.)		
2_1^+	0_1^+	$17.3^{+4.0}_{-3.2}$	32	30
4_1^+	2_1^+		63	68
0_2^+	2_1^+	15.3(16) [10]	58	83
0_3^+	2_1^+	0.028(11) [11]		
2_2^+	2_1^+	> 8.9 [10]	62	65
4_1^+	2_2^+		13	7
4_2^+	2_2^+		57	73
4_2^+	4_1^+		49	47
		$\rho^2(E0)$ (10^{-3})		
0_2^+	0_1^+		106	66
0_3^+	0_1^+		22	
0_3^+	0_2^+	185(50)[13]	95	9

^{98}Sr

I_1^π	I_2^π	experiment	5DCH (Gogny)	5DCH (PC-PK1)
		B($E2$, $I_1 \rightarrow I_2$) (W.u.)		
2_1^+	0_1^+	96 (3)	54	73.5
4_1^+	2_1^+	129^{+8}_{-7}	110	162
6_1^+	4_1^+	175^{+17}_{-14}	150	196
8_1^+	6_1^+	123^{+19}_{-14}	173	211
2_2^+	0_2^+	13 (2)	28	39.2
0_2^+	2_1^+	61 (5)	120	195^{a}
2_2^+	0_1^+	0.77 (13)	0.07	
2_2^+	2_1^+	$0.61^{+0.22}_{-0.30}$	0.78	
2_2^+	4_1^+	4^{+4}_{-2}	19.4	
		$\rho^2(E0)$ (10^{-3})		
0_2^+	0_1^+	53(5)[21]	179	117
0_3^+	0_1^+		40	
0_3^+	0_2^+		75	

Theory

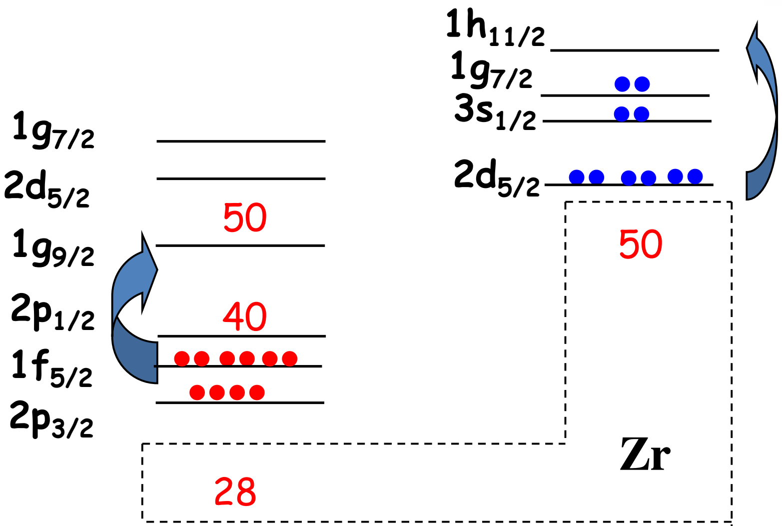
	0_1^+	0_2^+		2_1^+	2_2^+		4_1^+	4_2^+		6_1^+	6_2^+		8_1^+	8_2^+
^{96}Sr, $\rho^2(E0)$ (10^{-3})														
0_2^+	106	-	2_2^+	28	-	4_2^+	83	-	6_2^+	82	-	8_2^+	60	-
0_3^+	22	95	2_3^+	117	65	4_3^+	113	43	6_3^+	89	32	8_3^+	44	44
^{98}Sr, $\rho^2(E0)$ (10^{-3})														
0_2^+	179	-	2_2^+	81	-	4_2^+	43	-	6_2^+	27	-	8_2^+	20	-
0_3^+	40	75	2_3^+	120	1	4_3^+	0	16	6_3^+	0	27	8_3^+	2	32

Discrepencies are huge !!

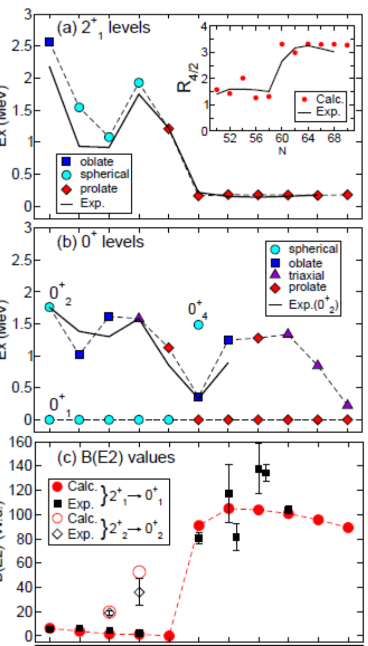
E. C. et al, Phys.Rev.C 94, 054326 (2016)

Shape coexistence at A= 100

From a theoretical point of view



	0^+_1		2^+_1		0^+_2		2^+_2	
	π	ν	π	ν	π	ν	π	ν
$2f_{7/2}$	-	0.09	-	0.06	-	0.12	-	0.08
$3p_{3/2}$	-	0.01	-	0.01	-	0.01	-	0.01
$1h_{11/2}$	-	0.68	-	0.40	-	2.04	-	1.96
$1g_{7/2}$	0.14	0.09	0.11	0.06	0.15	1.38	0.15	1.37
$2d_{3/2}$	0.06	0.10	0.04	0.16	0.05	0.71	0.05	0.73
$3s_{1/2}$	0.01	0.20	0.01	1.11	0.03	0.41	0.03	0.38
$2d_{5/2}$	0.08	5.04	0.07	4.38	0.22	1.69	0.21	1.84
$1g_{9/2}$	0.51	9.79	0.42	9.81	3.49	9.64	3.40	9.63
$2p_{1/2}$	1.85	-	1.87	-	0.80	-	0.88	-
$2p_{3/2}$	3.59	-	3.69	-	2.54	-	2.60	-
$1f_{5/2}$	5.76	-	5.79	-	4.72	-	4.68	-



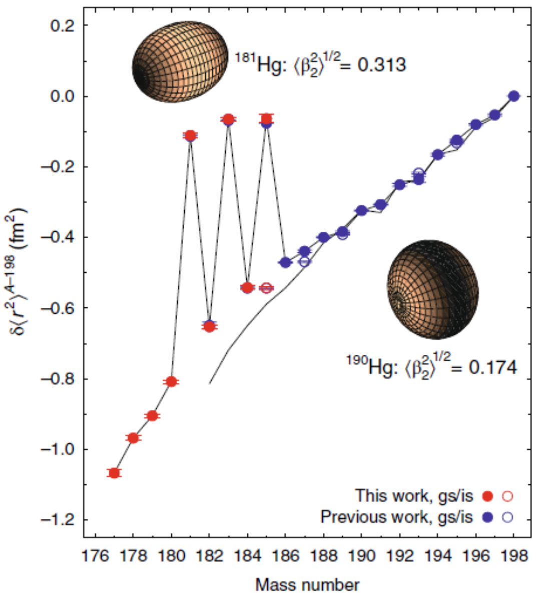
The spherical 2^+_1 is a simple neutron excitation

The $0^+_2/2^+_2$ deformed configuration is a $(2p\text{-}2h/4p\text{-}4h)\pi_{pf} \rightarrow g_{9/2}$ excitation coupled to ν in the intruder $h_{11/2}$, $g_{7/2}$ from the $d_{5/2}$

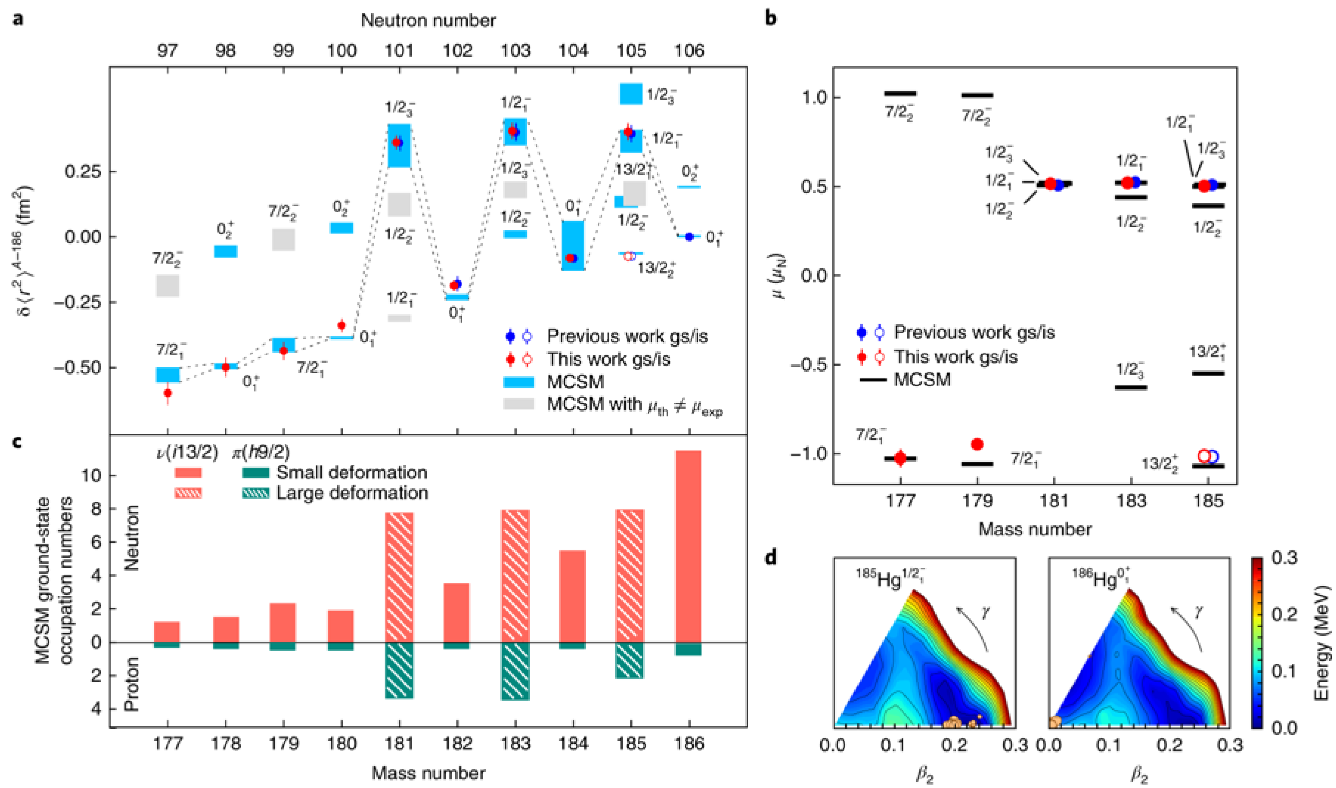
T. Togashi et al, Phys.Rev.Lett. 117, 172502 (2016)
C. Kremer et al, Phys.Rev.Lett. 117, 172503 (2016)

(It is an island of inversion …)

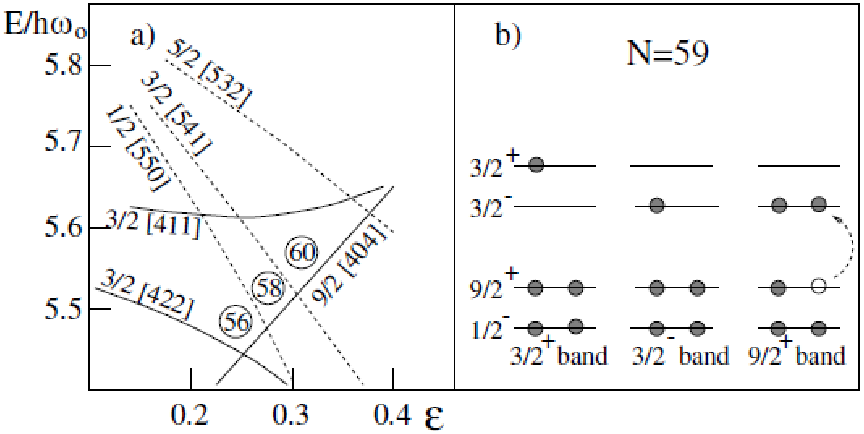
Shape coexistence at Z = 82



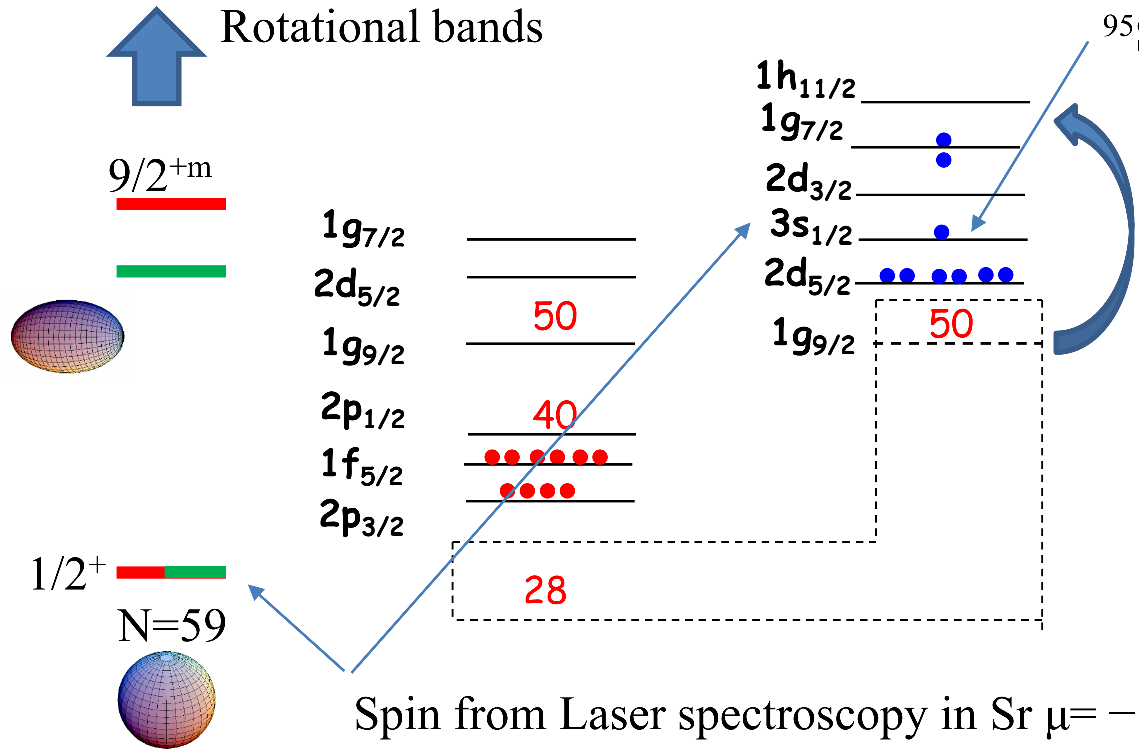
B. A. Marsh, et al. Nature Physics October 2018



The full story includes also α-decay, E0 and coulex



W. Urban et al, Eur. Phys. J. A 22, 241{252 (2004)



$^{95}Sr_{57}(d,p) \rightarrow 0^{+m}_{2}$

$9/2^{+m}$ shape isomer

« It is a neutron state »

Spin from Laser spectroscopy in Sr μ= − 0.4983(9)

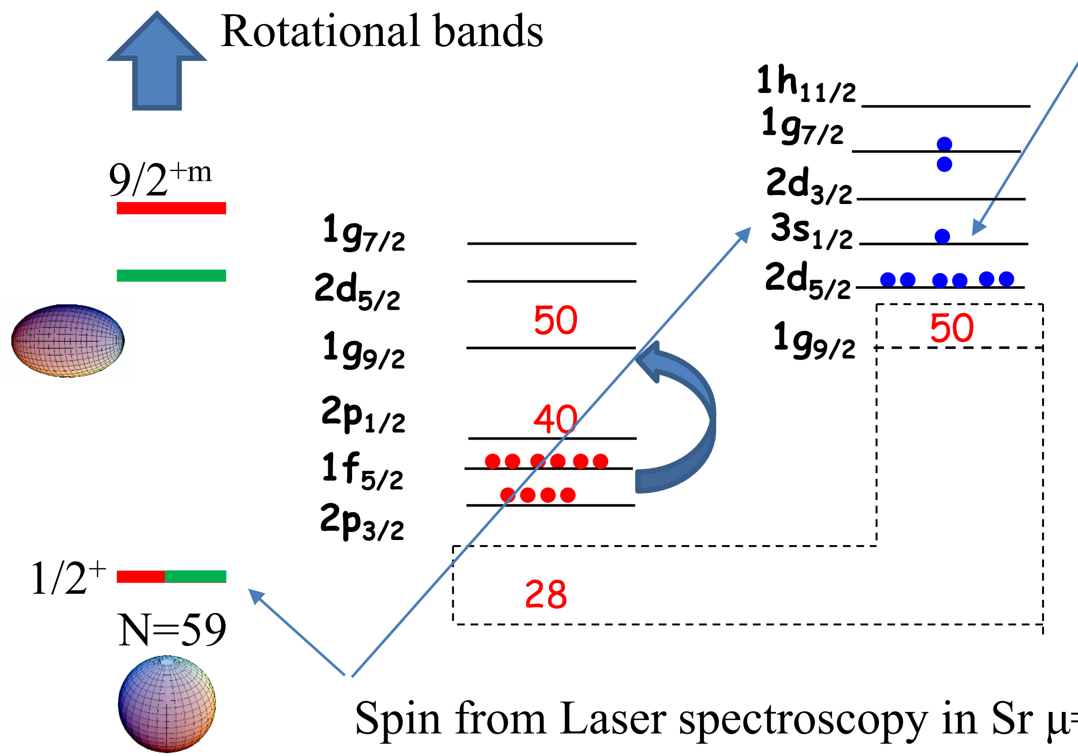
	0_1^+		2_1^+		0_2^+		2_2^+	
	π	ν	π	ν	π	ν	π	ν
$2f_{7/2}$	-	0.09	-	0.06	-	0.12	-	0.08
$3p_{3/2}$	-	0.01	-	0.01	-	0.01	-	0.01
$1h_{11/2}$	-	0.68	-	0.40	-	2.04	-	1.96
$1g_{7/2}$	0.14	0.09	0.11	0.06	0.15	1.38	0.15	1.37
$2d_{3/2}$	0.06	0.10	0.04	0.16	0.05	0.71	0.05	0.73
$3s_{1/2}$	0.01	0.20	0.01	1.11	0.03	0.41	0.03	0.38
$2d_{5/2}$	0.08	5.04	0.07	4.38	0.22	1.69	0.21	1.84
$1g_{9/2}$	0.51	9.79	0.42	9.81	3.49	9.64	3.40	9.63
$2p_{1/2}$	1.85	-	1.87	-	0.80	-	0.88	-
$2p_{3/2}$	3.59	-	3.69	-	2.54	-	2.60	-
$1f_{5/2}$	5.76	-	5.79	-	4.72	-	4.68	-

laboratoire commun CEA/DSM CNRS/IN2P3

T. Togashi et al, Phys.Rev.Lett. 117, 172502 (2016)
C. Kremer et al, Phys.Rev.Lett. 117, 172503 (2016)

$\nu g_{9/2}$ occupancy un-changed

$\pi g^{+1}_{9/2}$ excitation



$^{95}Sr_{57}(d,p) \rightarrow 0^{+m}_2$

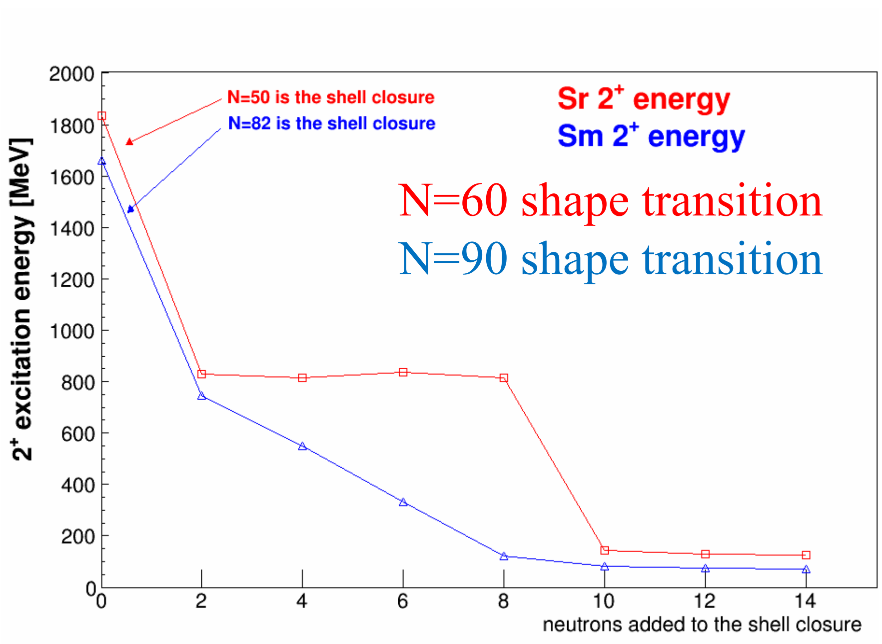
$9/2^{+m}$ shape isomer

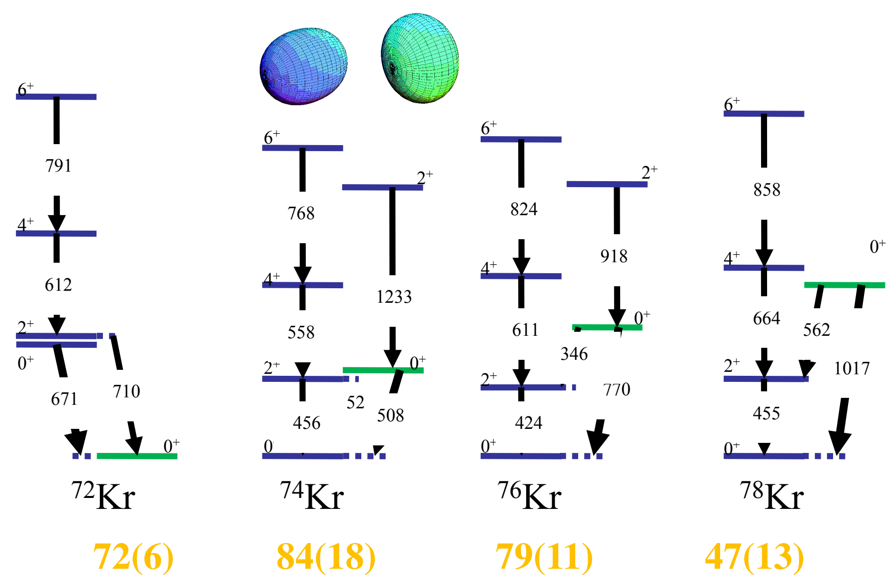
« It is a neutron state »

« It is a proton state » ?

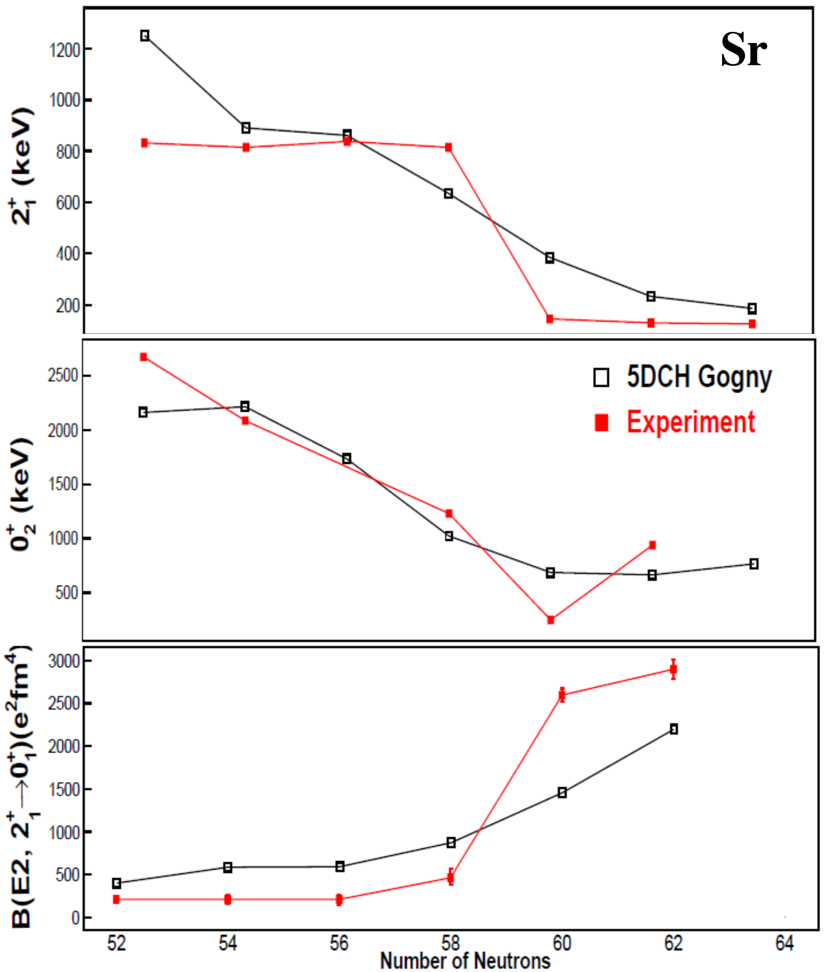
Possible ?

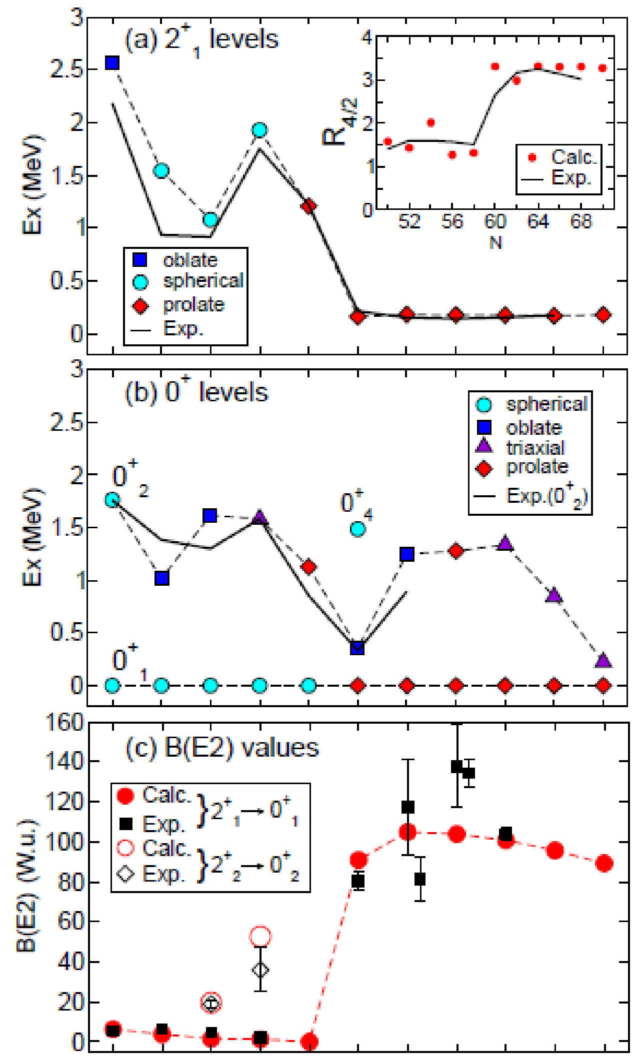
Shape transitions
Many cases ….





J. P. Delaroche *et al.*, *Phys. Rev. C 81, 014303 (2010).*





T. Togashi et al, Phys.Rev.Lett. 117, 172502 (2016)
C. Kremer et al, Phys.Rev.Lett. 117, 172503 (2016)

Conclusion

Shape coexistence is a spectacular and universal phenomena
It reflects the competition between the spherical shape stabilizing the nucleus and its natural tendencies to deform

Today it is more about shell effect and p-n interaction than “shapes”

Shape coexistence and shell evolution near the ground are the same subject

The A=100 and the n-deficient Hg/Pb are exceptional cases in term of experimental and theoretical effort

Shape coexistence at N=20, 28, 40, 50, N=Z have not been discussed.
Need for more experimental data to understand the whole story.

The experimental effort has been boosted by the **ISOL facilities** (Laser, Coulex, Transfer)

The MCSMC shed a new light on the phenomena