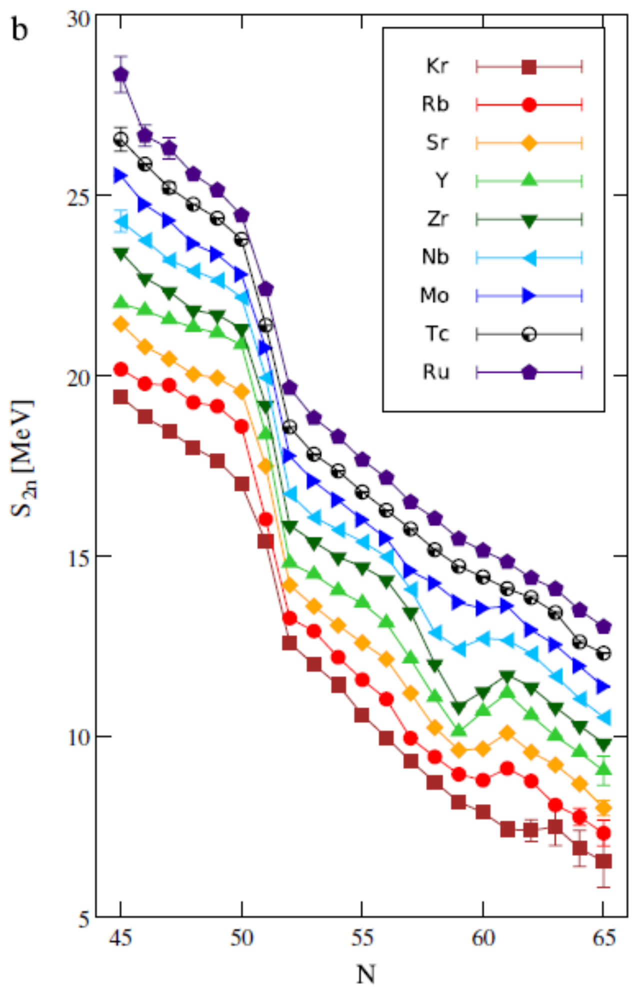
Spectroscopic Quadrupole Moment in ^{96,98}Sr : Shape coexistence at N=60

E.Clément-GANIL
IS451 Collaboration

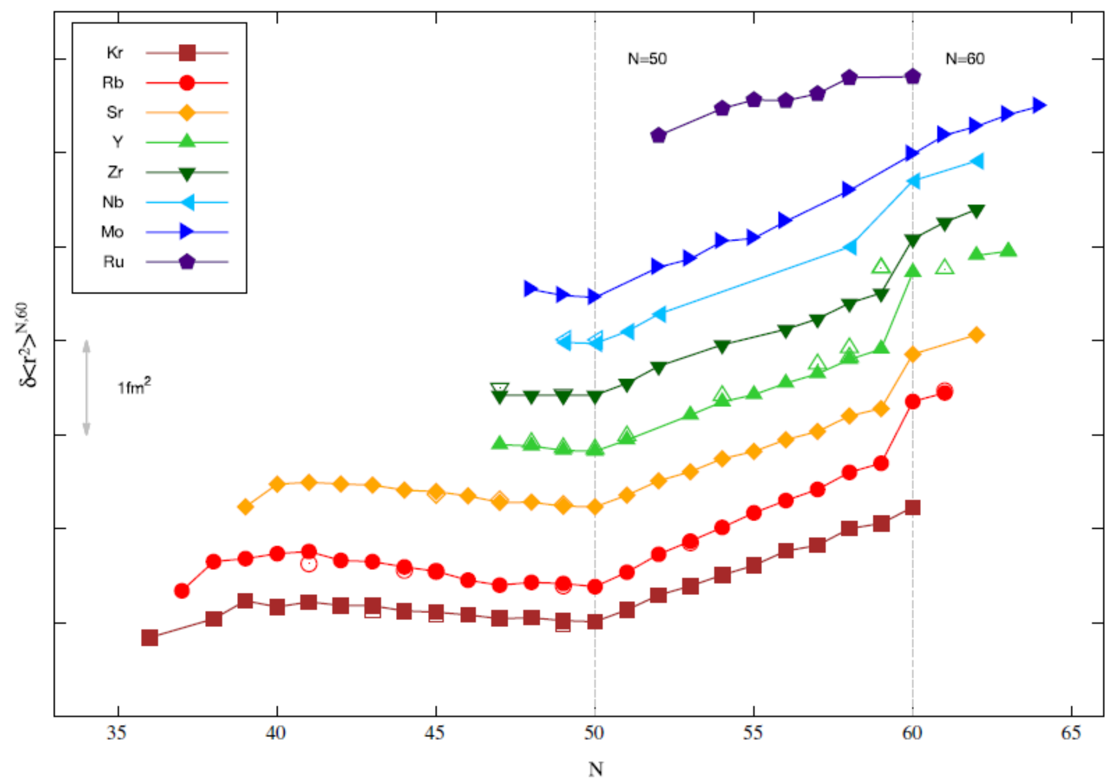
Shape Transition at N=60

P. Campbell, I.D. Moore, M.R. Pearson
Progress in Particle and Nuclear Physics 86 (2016) 127–180



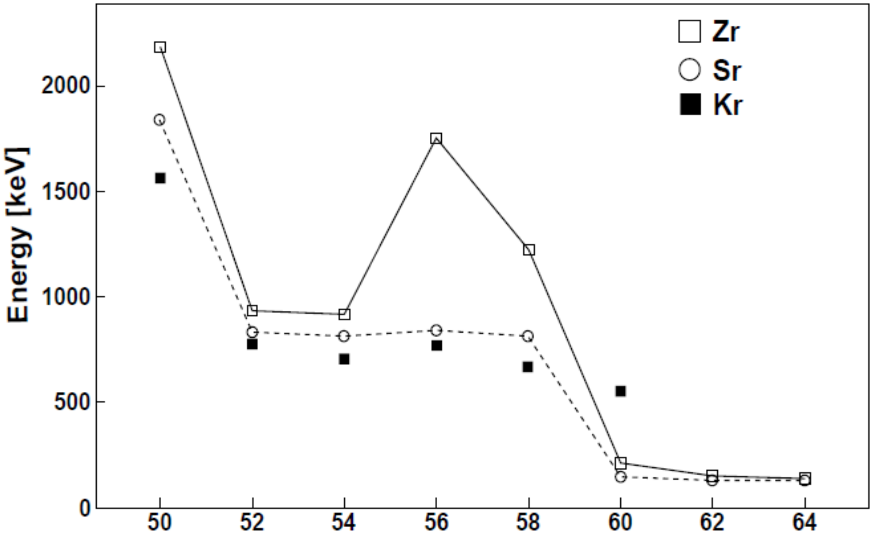
- ❑ The n-rich nuclei between Z=37 and Z=41 present at N=60 one of the most impressive deformation change in the nuclear chart
- ❑ Localized within the Z degree of freedom
  - → Point to a specific π−ν interaction

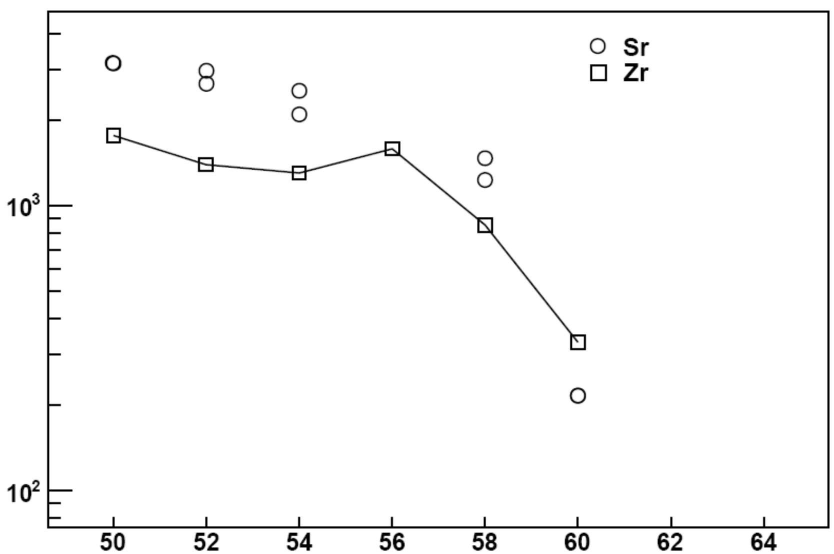
162 P. Campbell et al. / Progress in Particle and Nuclear Physics 86 (2016) 127–180



Shape Transition at N=60

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



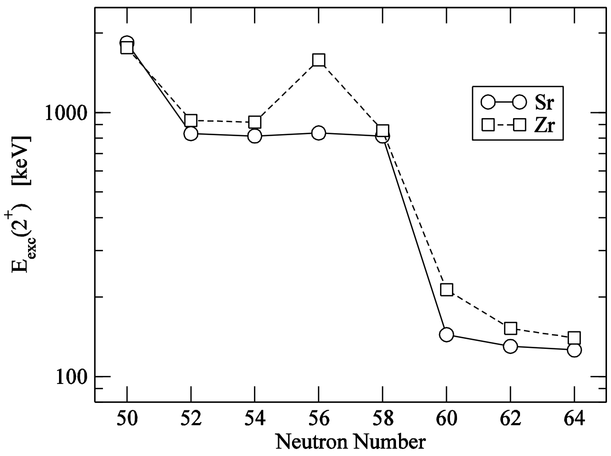


❖First spectroscopy (GS and 2^+_1) indicated a shape change from β ~0.1 to β~0.4

❖0^+_2 states are indication of shape coexistence
→ Shape inversion ?

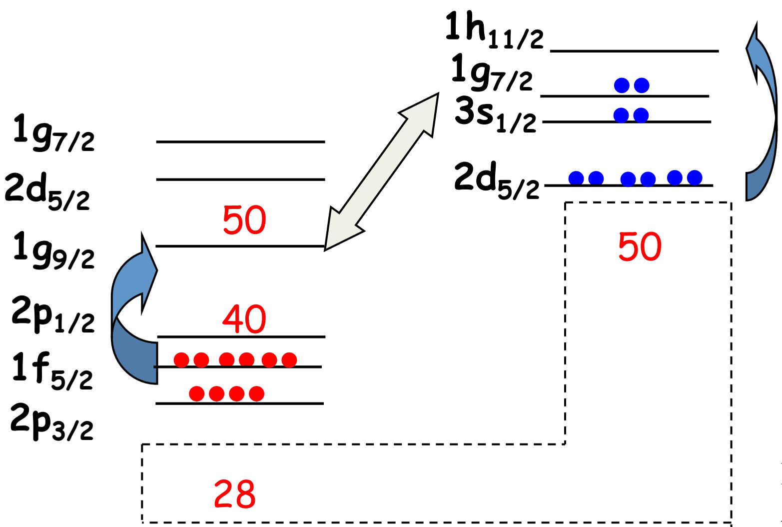
❖Kr isotopes behave differently : smooth 2^+ change, delayed S_{2n} increase, no low lying 0^+_2

Shape Transition at N=60



The sharp transition and magnitude of the deformation remain still a challenge for theories (> 100 theoretical papers since the 70's)

✓HFB + the generator coordinate method (GCM)
✓the macroscopic-microscopic method
✓the shell model
✓the Monte Carlo shell model
✓the interacting boson model (IBM) approximation
✓the VAMPIR model
✓covariant density functional (DF) theory (PC-PK1).



❑ 0^+_2 state created by (2p-2h/4p-4h) excitation across Z=40

❑ Beyond N=60, $g_{7/2}$ and $h_{11/2}$ are populated, the $\pi-\nu$ interaction and the participates to the lowering 0^+_2 state and to the high collectivity of 2^+_1 state.

❑ In BMF calculations, two minima appear in the PES

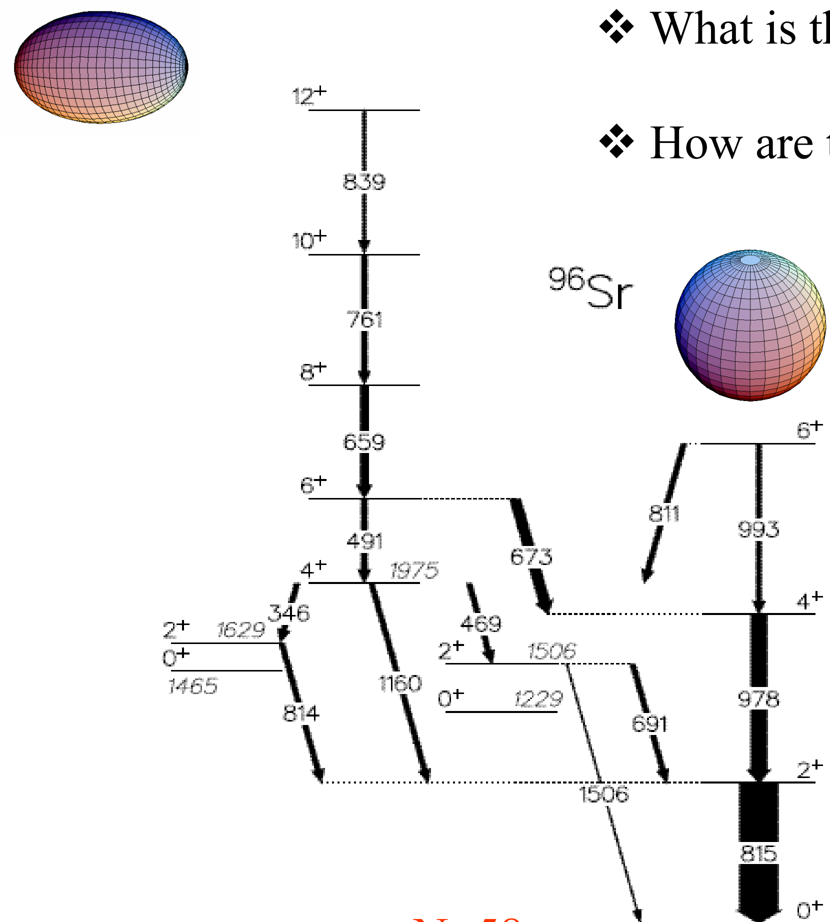
Mainly GS and level scheme are known and limit the comparison with theoretical models

K. Sieja et al PRC 79, 064310 (2009)
A. Petrovici PRC 85, 034337 (2012)
T. Togashi et al, arXiv:1606.09056v1; T. Togashi et al, Accepted PRL (2016)
C. Kremer et al, arXiv:1606.09057v1 (2016)

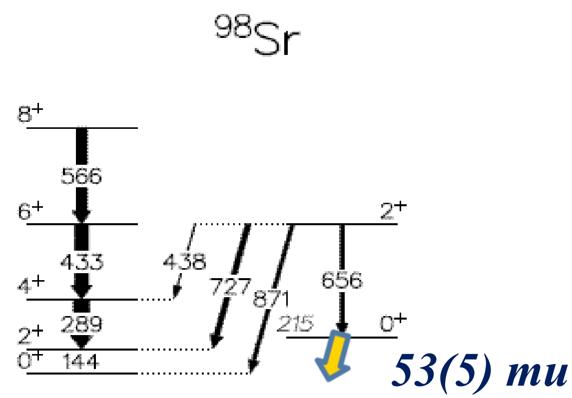
Shape Transition at N=60

- ❖ What is the shape of the corresponding 2^+ states ?
- ❖ How are the different configurations connected ?

→ Coulomb excitation of RIB



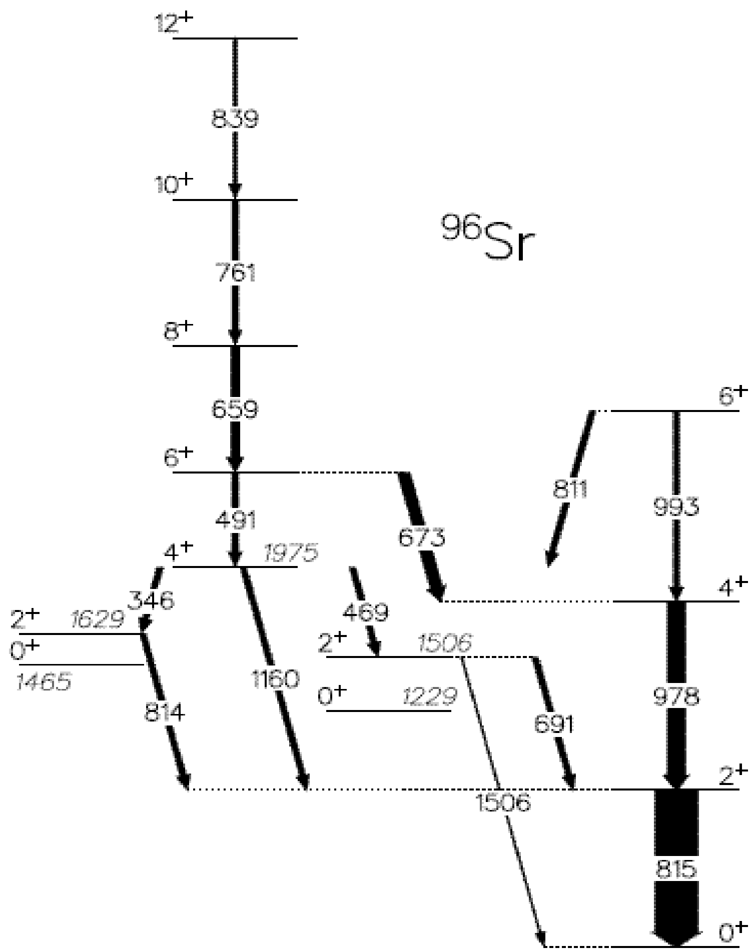
N=58

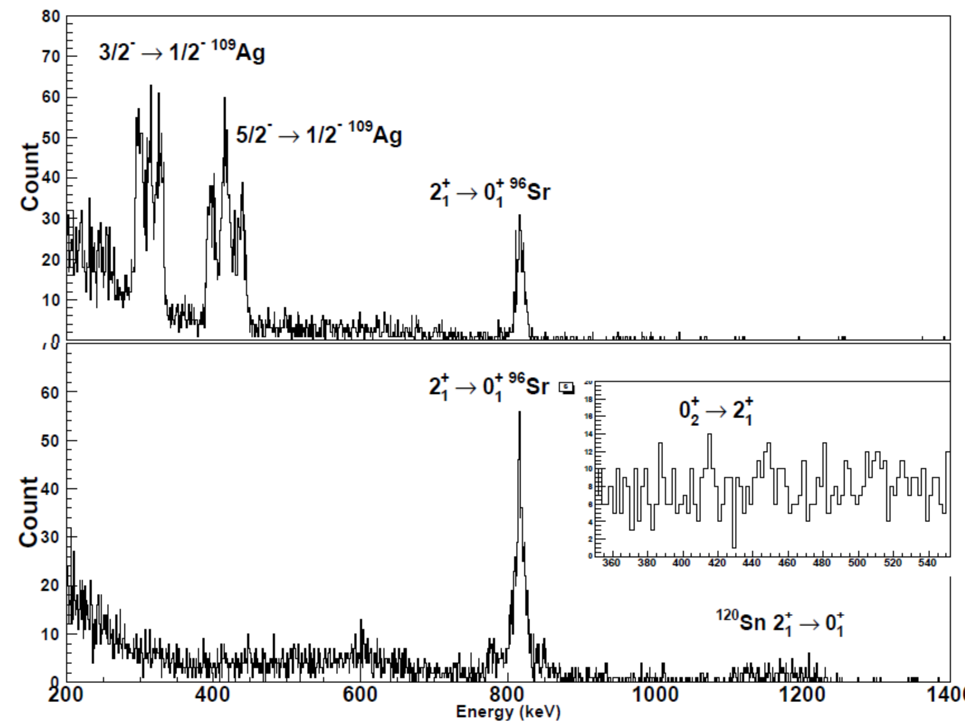


N=60

Safe Coulomb excitation of ^{96,98}Sr beams at REX-ISOLDE using the MINIBALL array at CERN

^{96}Sr $T_{1/2}$ =1.07 sec. 7000 pps at 275 MeV
^{98}Sr $T_{1/2}$ =0.65 sec. 60000 pps at 276 MeV





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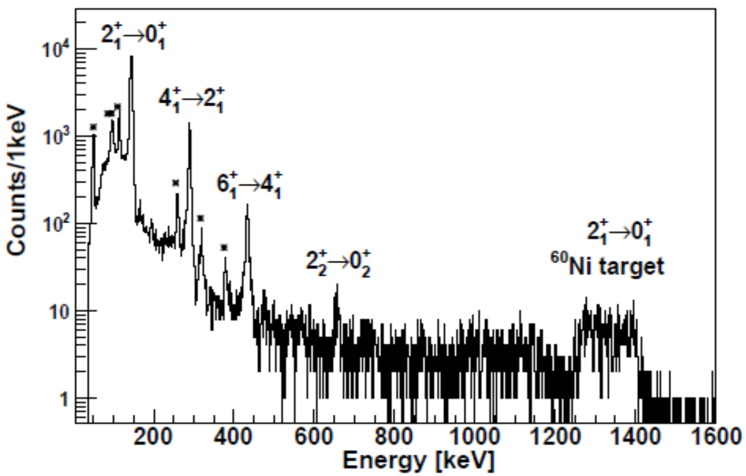

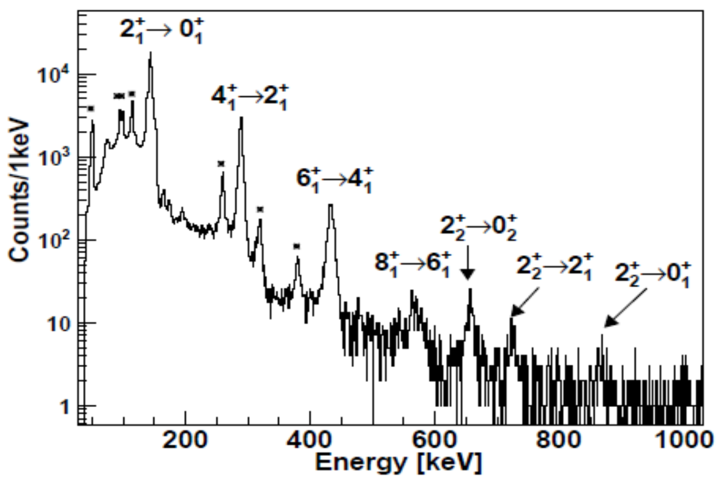

^{96}Sr $T_{1/2}$ =1.07 sec. 7000 pps at 275 MeV
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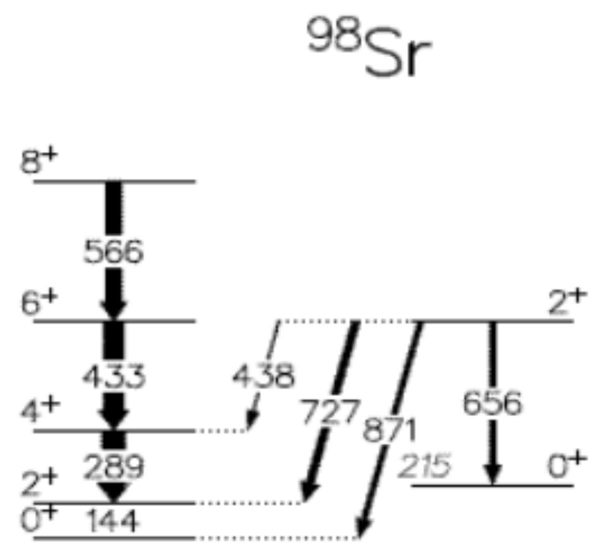
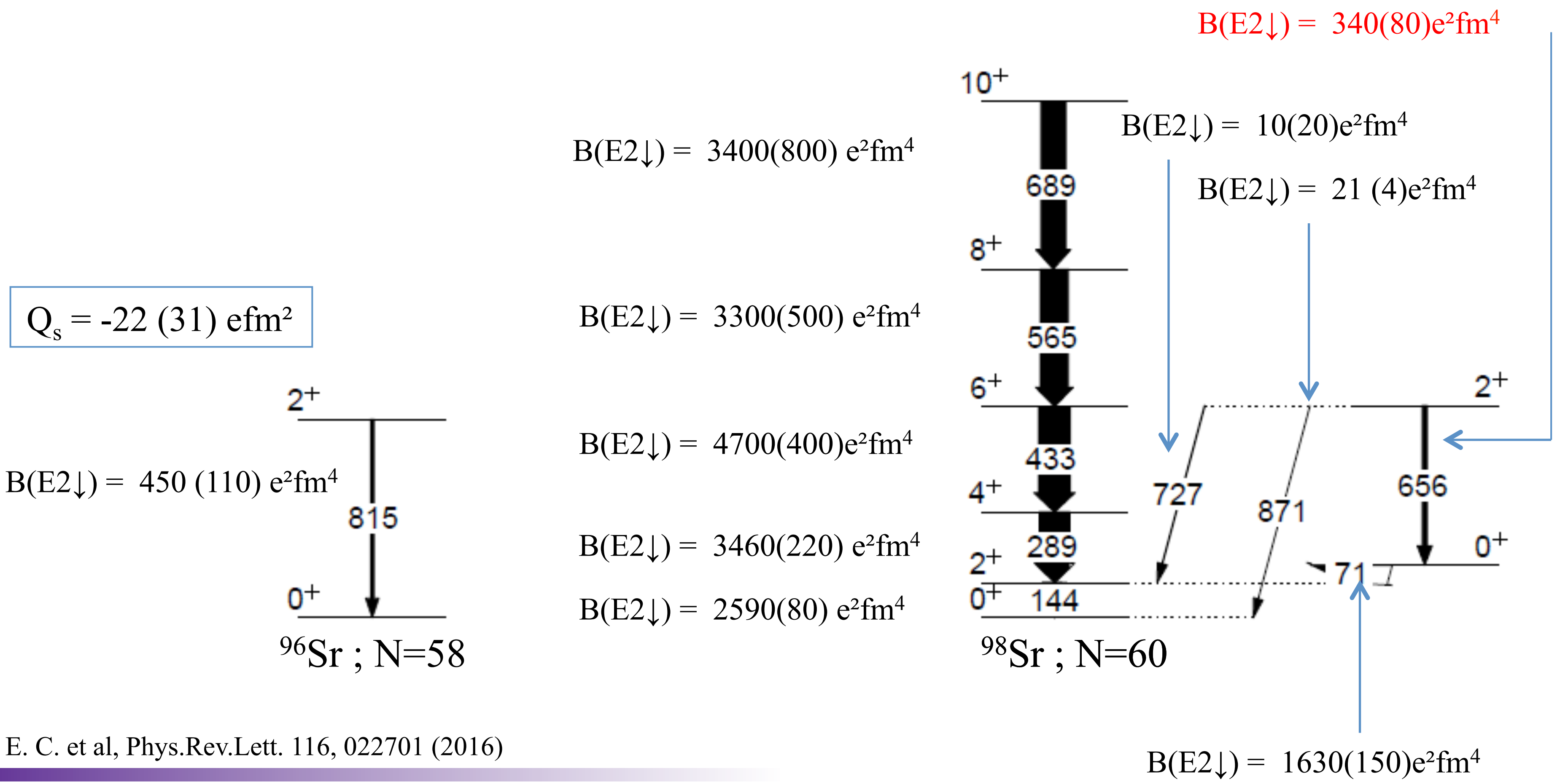
The Coulomb excitation cross section is analyzed using the least-squares fitting code GOSIA
T. Czosnyka, D. Cline, and C. Y. Wu, Bull. Am. Phys. Soc. **28,** 745 (1983).



Shape Coexistence in $^{96,98}Sr$

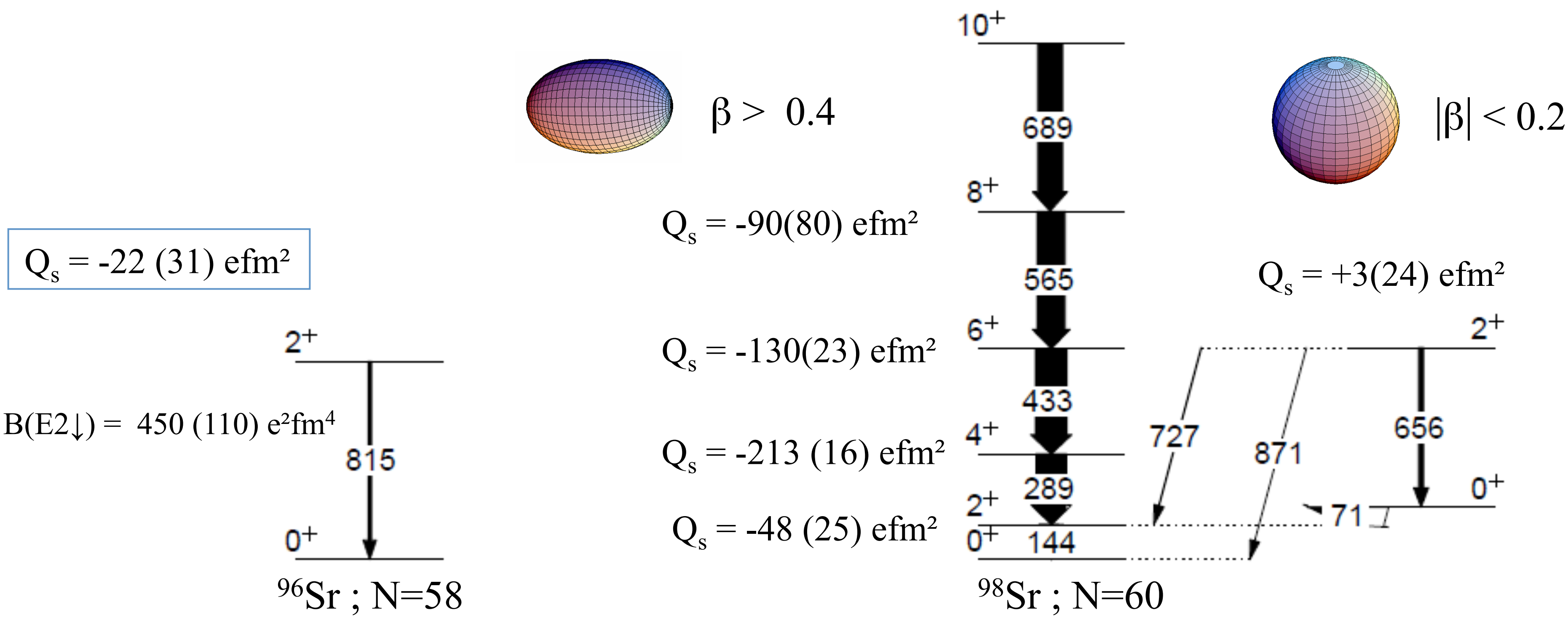


E. C. et al, Phys.Rev.Lett. 116, 022701 (2016)

Shape Coexistence in ^{96,98}Sr

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

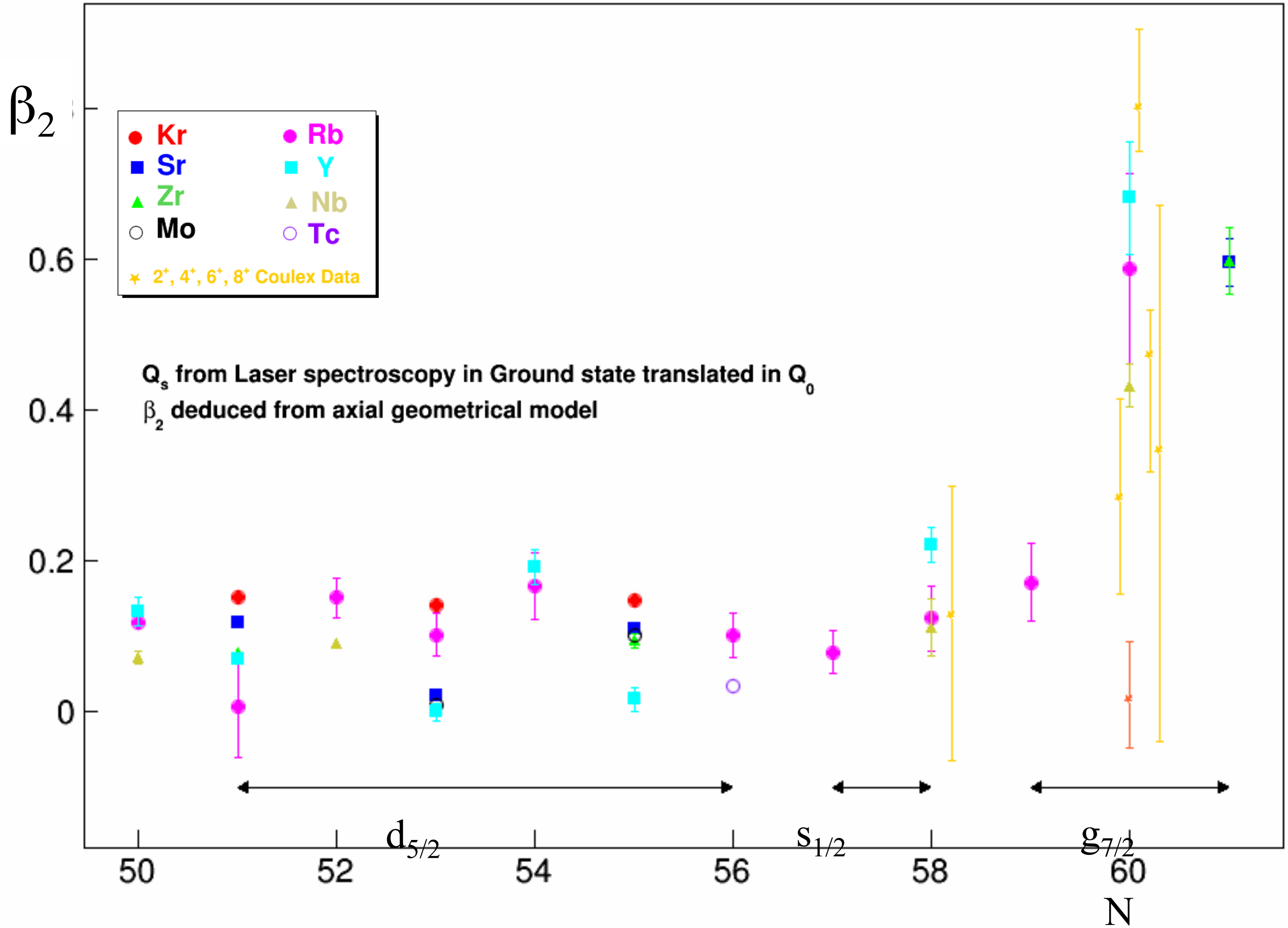
Shape coexistence in ^{98}Sr
Shape inversion at N=60



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

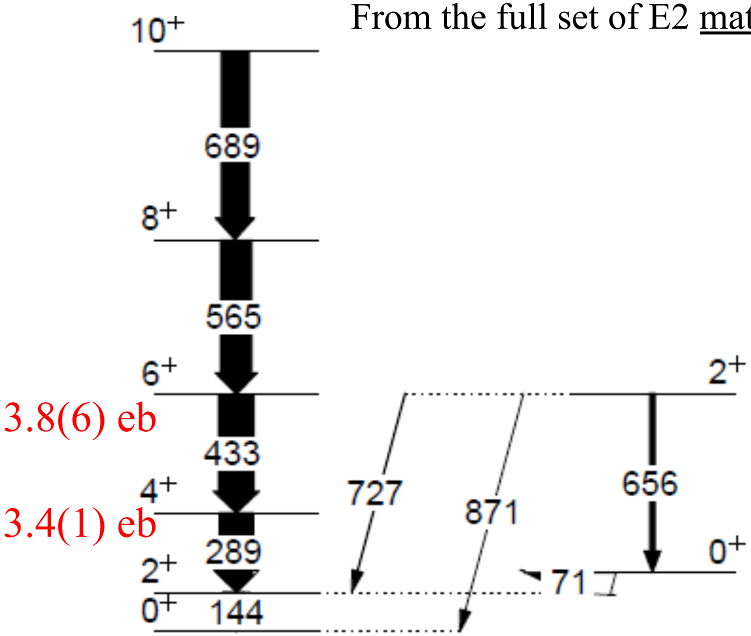
Shape Coexistence at N=60

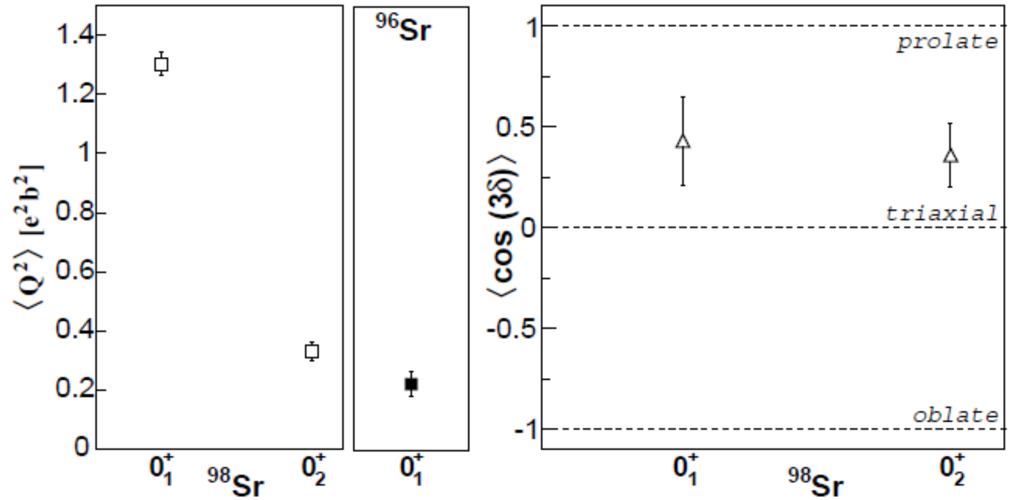
Comparison between Ground and Excited state Quadrupole moments



Shape Coexistence in ^{96,98}Sr

From the full set of E2 matrix elements, 0^+ states deformation can be probed using the QSR formalism





Shape coexistence in a two-state mixing model

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

Perturbed states

Pure states

$\cos^2\theta_0$	0.87(1)		
$\cos^2\theta_2$	0.99(1)		Un-perturbated
Q_0^{pr}	+3.85(6) eb		
Q_0^{sph}	-0.5(3) eb		
$\langle 2_p^+\|E2\|2_p^+\rangle$	-1.45(2) eb	$-0.63\ ^{+0.32}_{-0.28}$	exp
$\langle 2_s^+\|E2\|2_s^+\rangle$	+0.18(10) eb	$+0.04\ ^{+0.32}_{-0.20}$	exp

The sharp transition is related to the very weak mixing between competing configurations in contrast to the N~Z cases in Kr and Hg isotopes

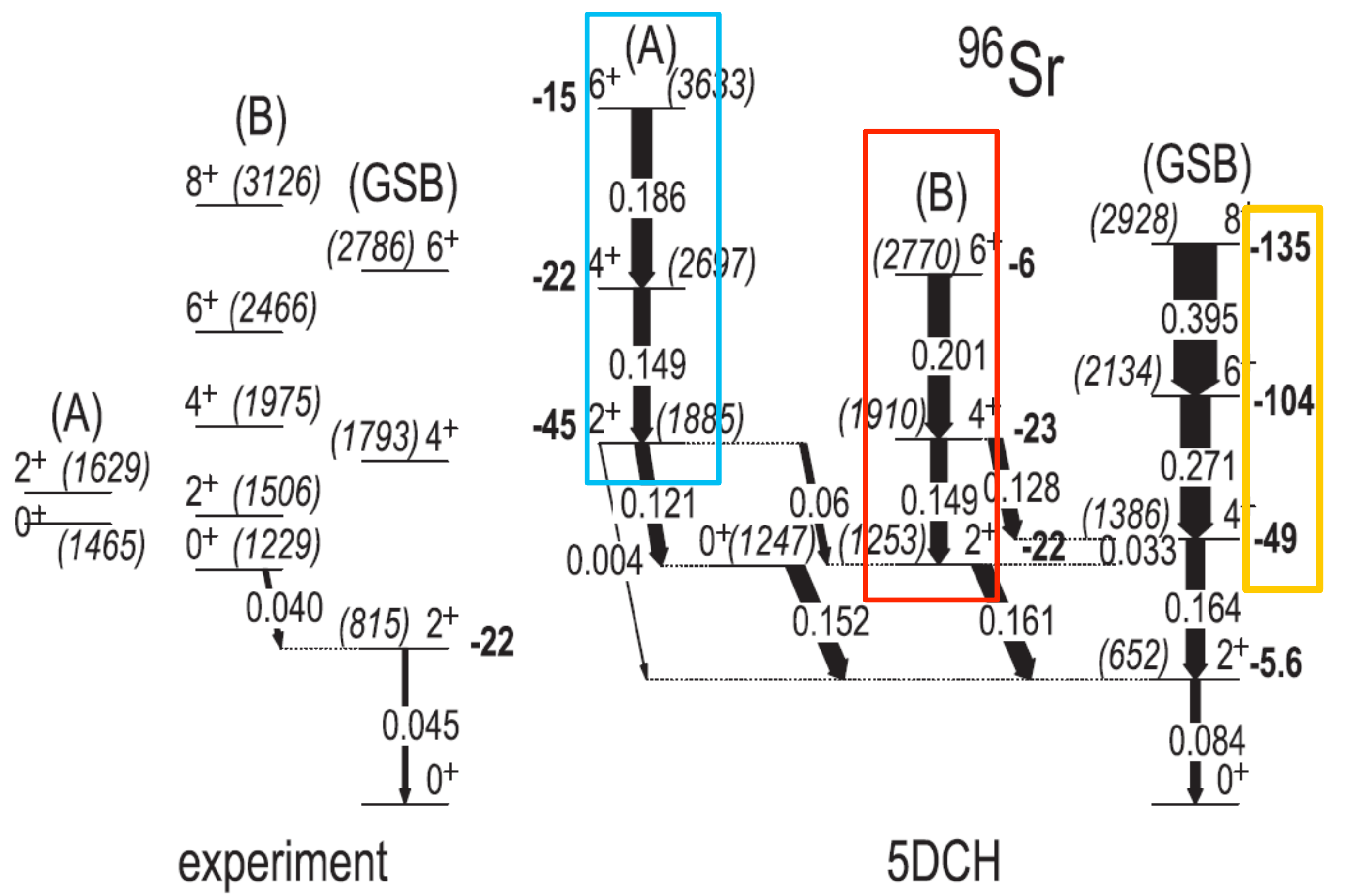
E. C. et al, Phys.Rev.Lett. 116, 022701 (2016)
E.C . et al, Submitted to PRC

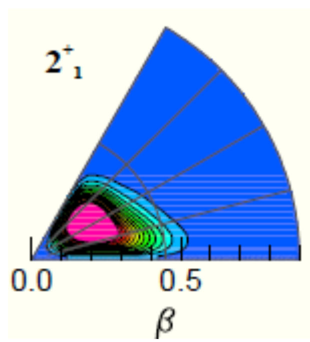
Collectivity around N=60

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.Clément

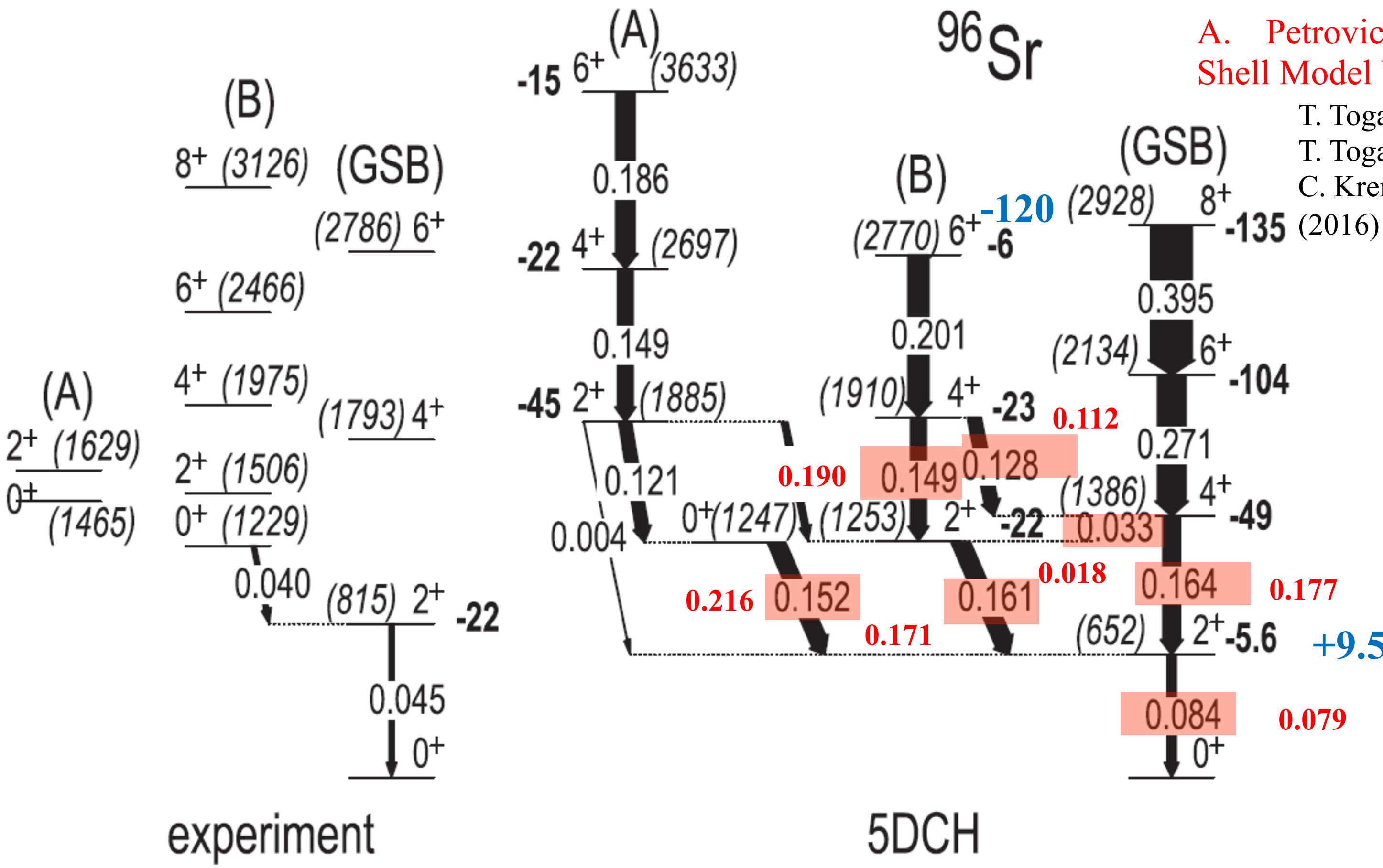
E. C. et al, Phys.Rev.Lett. 116, 022701 (2016)

Collectivity around N=60

From a theoretical point of view

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

T. Togashi et al, arXiv:1606.09056v1;
T. Togashi et al, Accepted PRL (2016)
C. Kremer et al, arXiv:1606.09057v1 (2016)



E. C. et al, Phys.Rev.Lett. 116, 022701 (2016)
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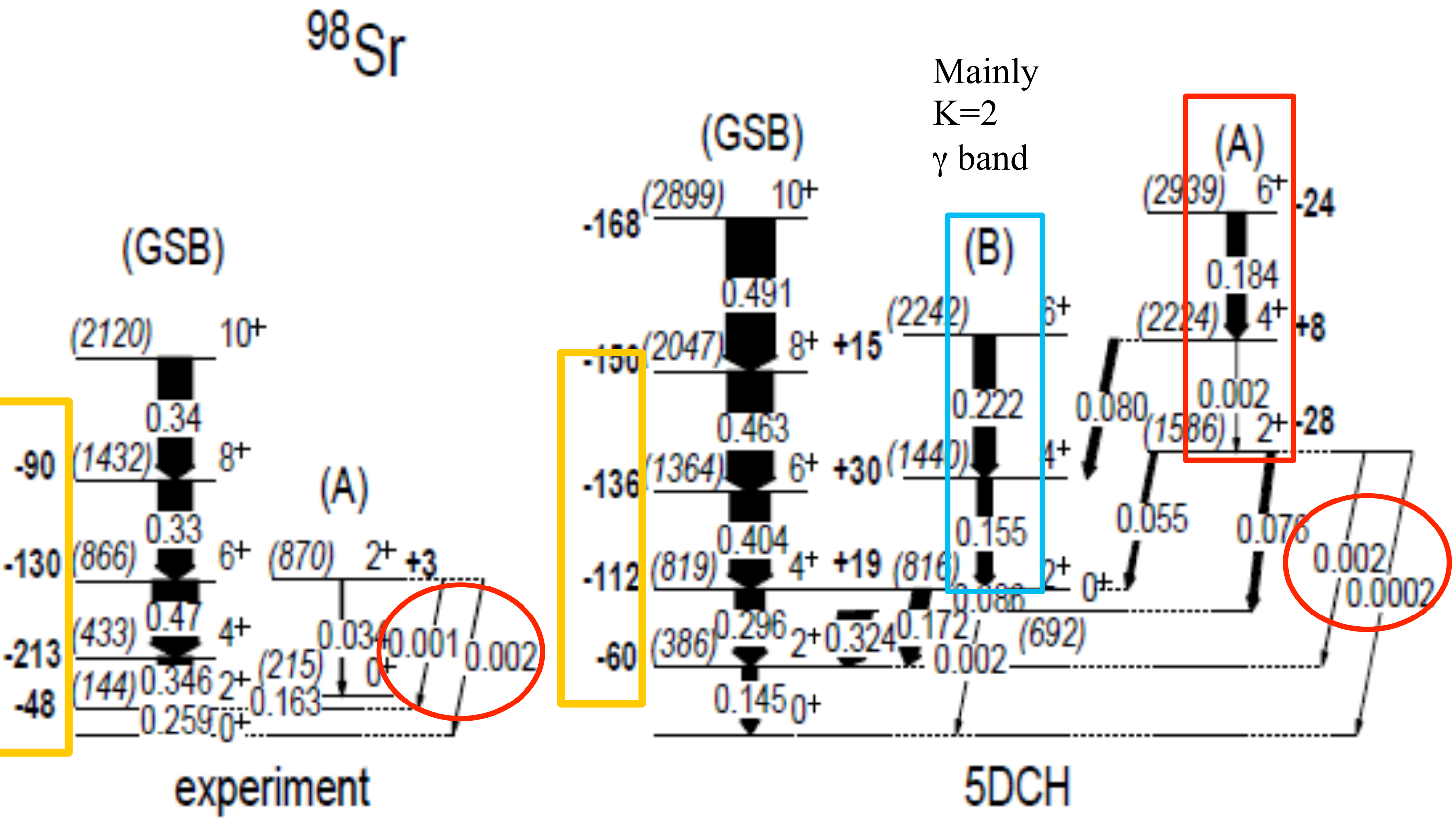
Collectivity around N=60

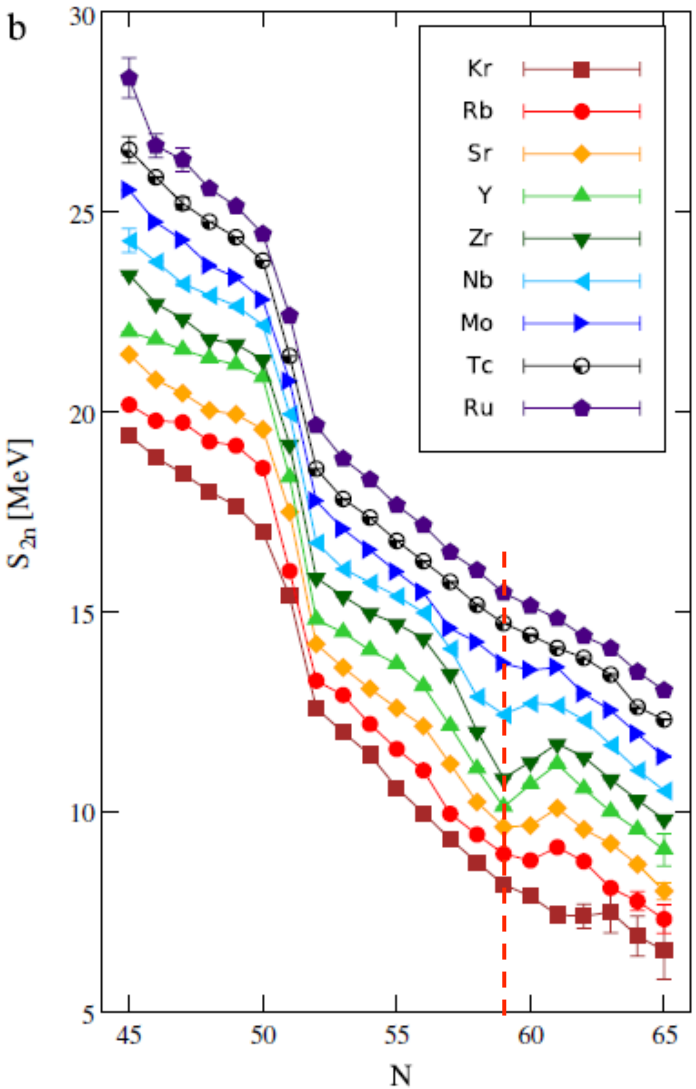
From a theoretical point of view



T. Togashi et al, arXiv:1606.09056v1;
T. Togashi et al, Accepted PRL (2016)
C. Kremer et al, arXiv:1606.09057v1 (2016)

J. Xiang et al . Phys. Rev. C 93, 054324 (2016)
E. Clément, et PRL. 116, 022701 (2016)

Conclusions



- We investigated the collectivity and the deformation in ^{96,98}Sr at the shape transition using RIB and the Coulomb excitation technique at REX-ISOLDE, CERN

- First levels in ^{98}Rb

- E2 matrix elements have been extracted and establish shape coexistence between small and large prolate deformations that do not mix and give rise to a sharp transition at N=60 where triaxiality plays a role

- *HFB+GCM Gogny force D1S* calculations reproduce the trend
- Large set of E0 transition strengths calculated

- Shell Model calculations (VAMPIR) show a nice agreement with BMF for B(E2) between low lying states

- The MCSM calculations are very promising

→Why Kr behave differently ?

Fission runs at AGATA@GANIL (spectroscopy, $T_{1/2}$)

→ See J. Dudouet's talk on Thursday 16:35

ISOL facilities beams

→Confusing predictions for ^{96}Sr beyond the 2^+_1 ?

→ Pseudo and quasi –SU(3) approach is valid in this case, similarly to an island of inversion

PRL 116, 022701 (2016) PHYSICAL REVIEW LETTERS week ending 15 JANUARY 2016

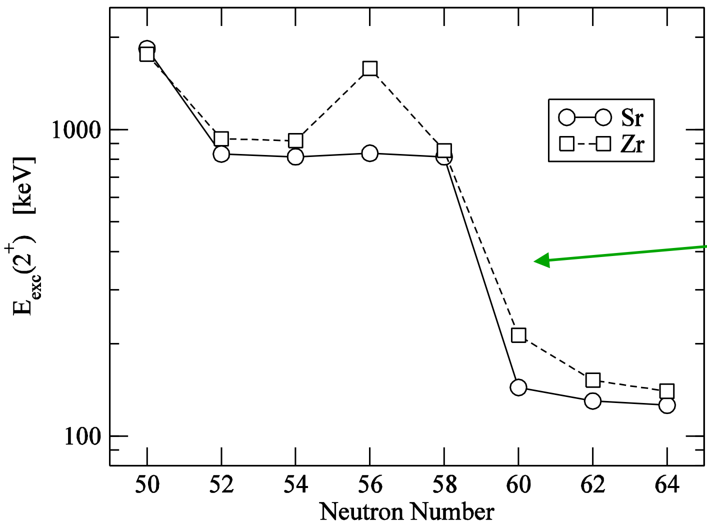
Spectroscopic Quadrupole Moments in ^{96,98}Sr: Evidence for Shape Coexistence in Neutron-Rich Strontium Isotopes at $N = 60$

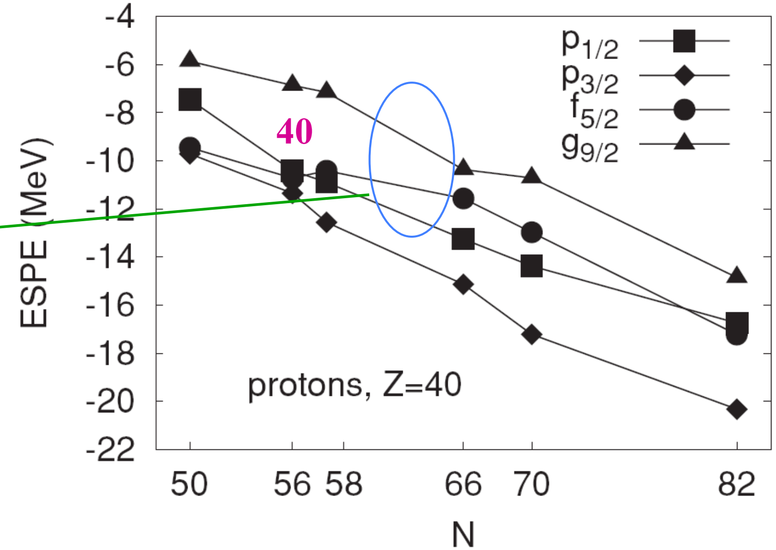
E. Clément,[1,2,*] M. Zielińska,[3,4] A. Görgen,[5] W. Korten,[3] S. Péru,[6] J. Libert,[6] H. Goutte,[3] S. Hilaire,[6] B. Bastin,[1] C. Bauer,[7] A. Blazhev,[8] N. Bree,[9] B. Bruyneel,[8] P. A. Butler,[10] J. Butterworth,[11] P. Delahaye,[1,2] A. Dijon,[1] D. T. Doherty,[3] A. Ekström,[12] C. Fitzpatrick,[13] C. Fransen,[8] G. Georgiev,[14] R. Gernhäuser,[15] H. Hess,[8] J. Iwanicki,[4] D. G. Jenkins,[11] A. C. Larsen,[5] J. Ljungvall,[14] R. Lutter,[15] P. Marley,[11] K. Moschner,[8] P. J. Napiorkowski,[4] J. Pakarinen,[2] A. Petts,[10] P. Reiter,[8] T. Renstrøm,[5] M. Seidlitz,[8] B. Siebeck,[8] S. Siem,[5] C. Sotty,[14] J. Srebrny,[4] I. Stefanescu,[9] G. M. Tveten,[5,2] J. Van de Walle,[2] M. Vermeulen,[11] D. Voulot,[2] N. Warr,[8] F. Wenander,[2] A. Wiens,[8] H. De Witte,[9] and K. Wrzosek-Lipska[4]

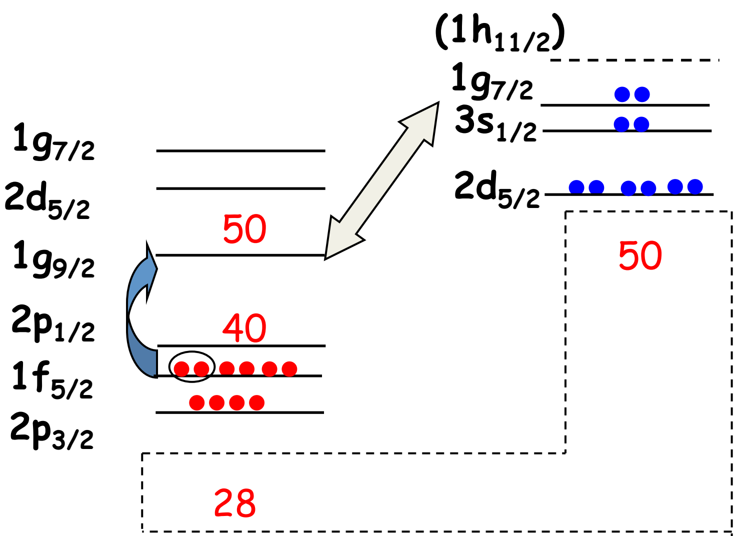
Shape Transition at N=60

50 years later, where are we ?

laboratoire commun CEA/DSM CNRS/IN2P3







- ❑ 0^+_2 state created by 2p-2h excitation across Z=40
- ❑ Beyond N=60, $g_{7/2}$ is populated, the $\pi-\nu$ interaction participates to the lowering 0^+_2 state and to the high collectivity of 2^+_1 state.
- ❑ In BMF calculations, two minima appear in the PES

K. Sieja et al PRC 79, 064310 (2009)
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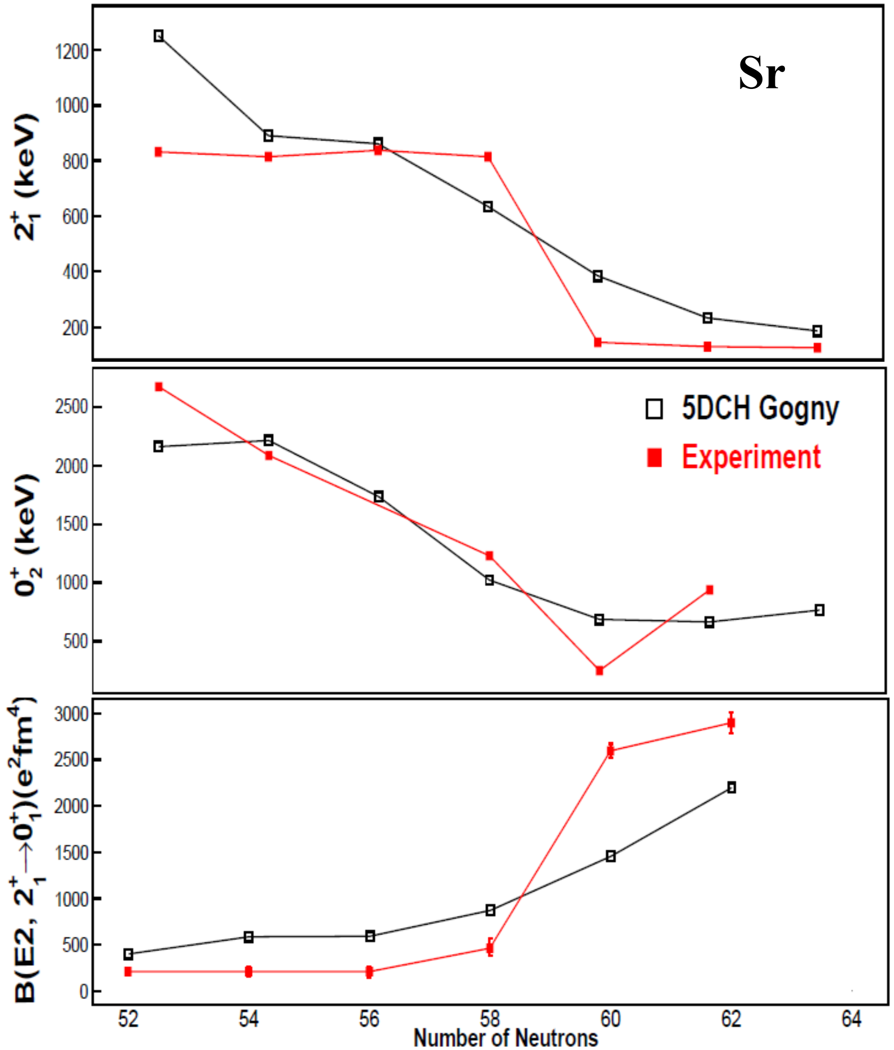
Collectivity around N=60

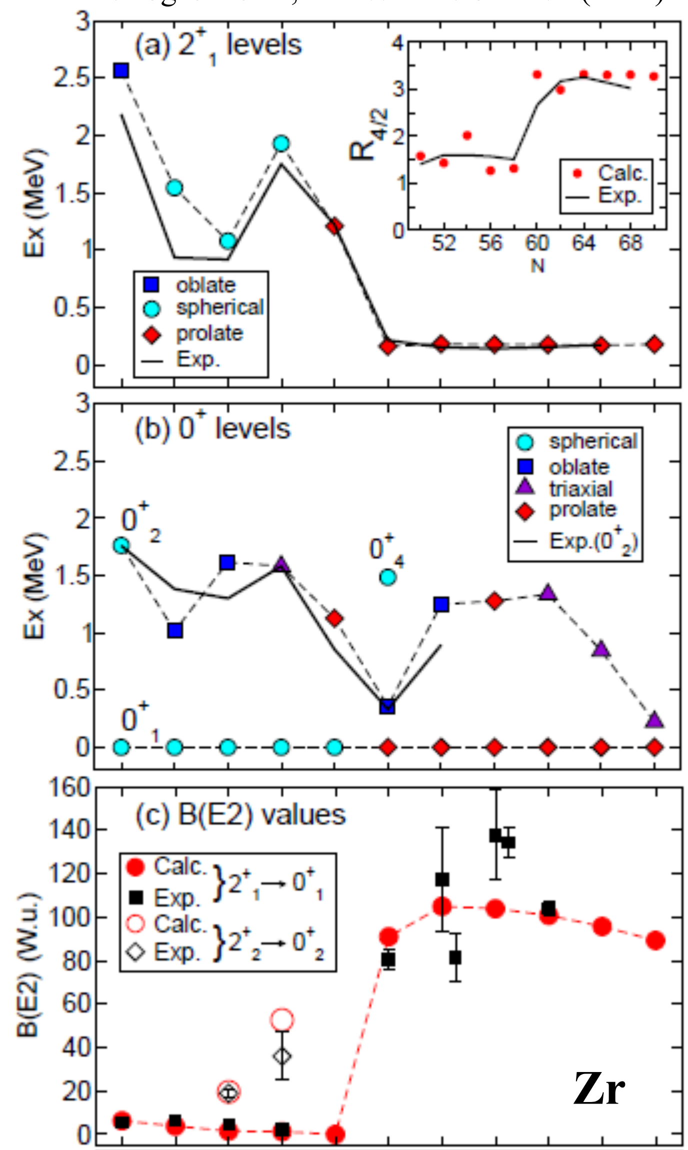
From a theoretical point of view

laboratoire commun CEA/DSM CNRS/IN2P3

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



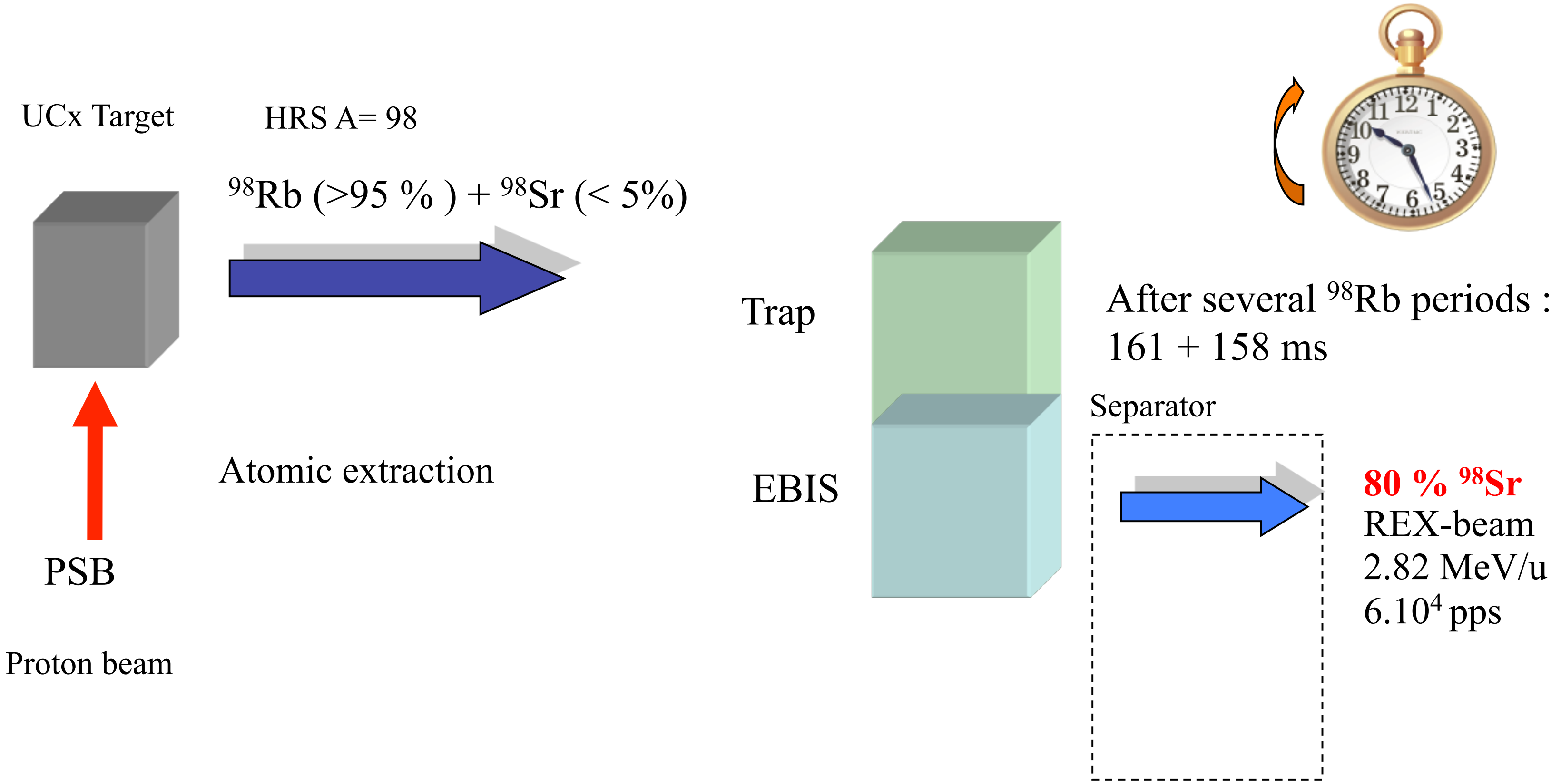
T. Togashi et al, arXiv:1606.09056v1 (2016)

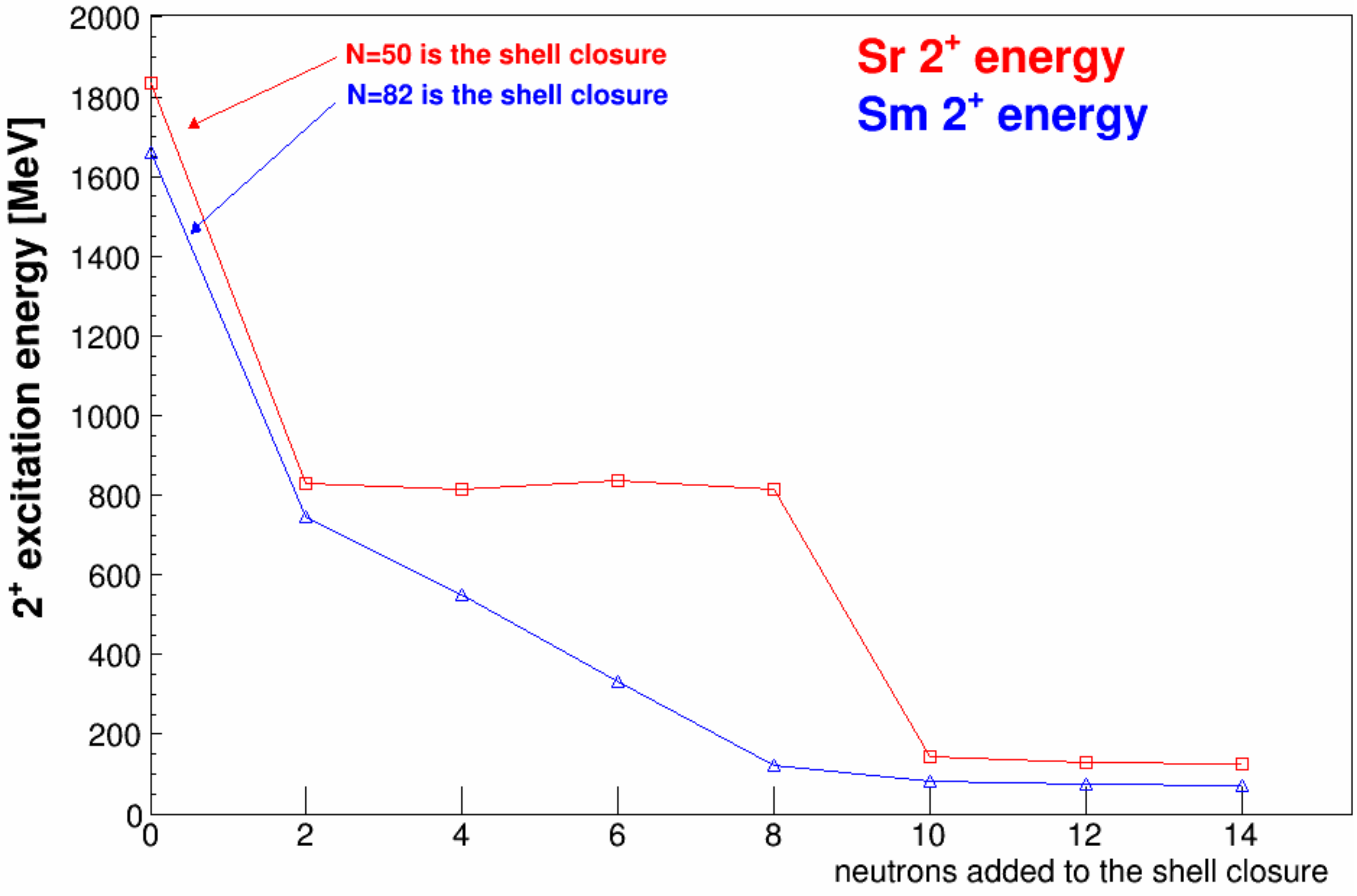


- Post-accelerated radioactive $^{96,98}Sr$ beam at REX-ISOLDE (2.8 MeV/A) ^{96}Sr $T_{1/2}$ = 1s, ^{98}Sr $T_{1/2}$ = 0.6 s
- Safe Coulomb excitation
- B(E2)'s and Q_0 extracted from the Coulomb excitation cross section

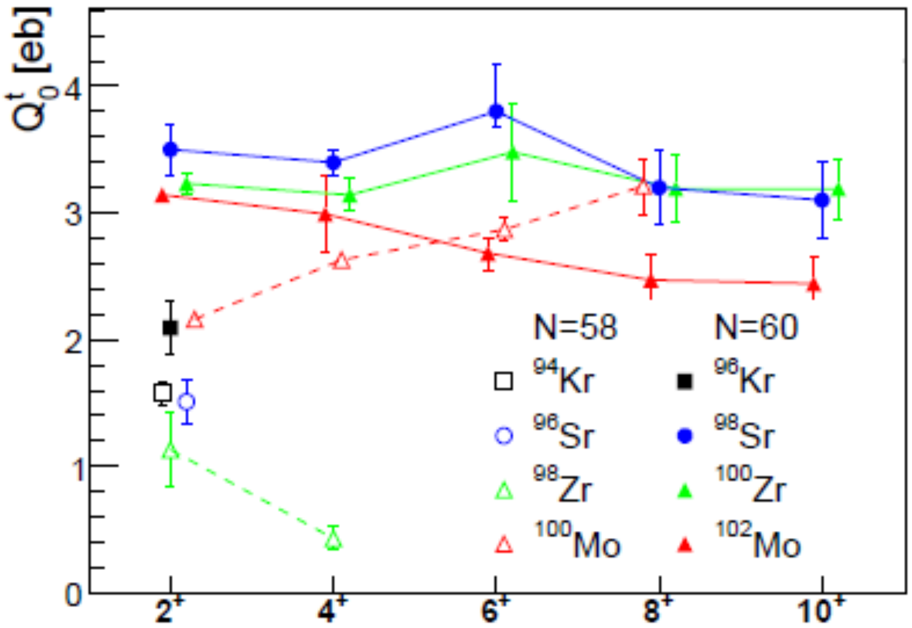
ıre $^{96}Sr^{23+}$ REX-
ım
ȝ7 MeV/u
to 0.5 ~10^4 pps

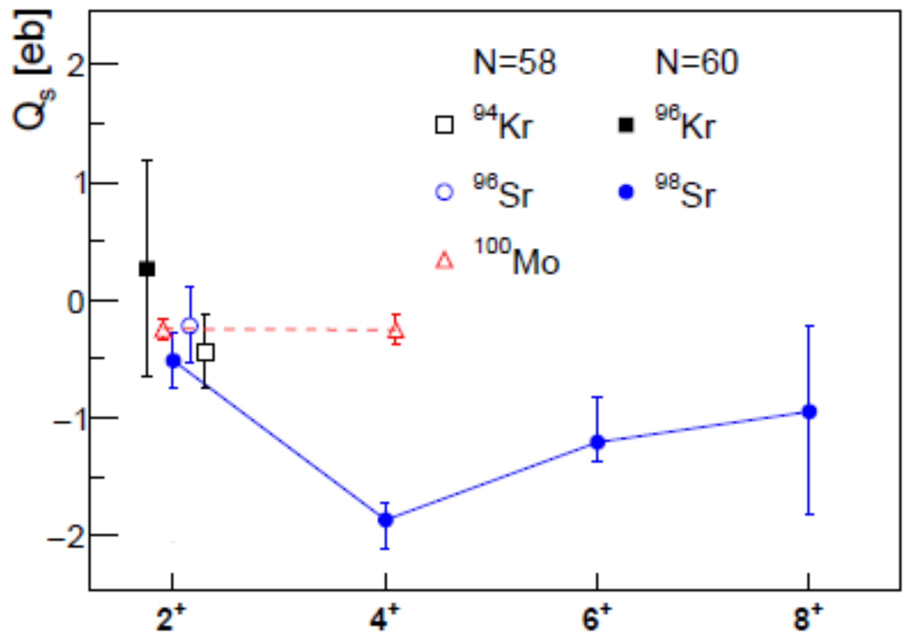
- Post-accelerated radioactive $^{96,98}Sr$ beam at REX-ISOLDE (2.8 MeV/A)
- Safe Coulomb excitation
- B(E2)'s and Q_0 extracted from the Coulomb excitation cross section




N=50 is the shell closure
N=82 is the shell closure
Sr 2+ energy
Sm 2+ energy
2+ excitation energy [MeV]
neutrons added to the shell closure
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
14

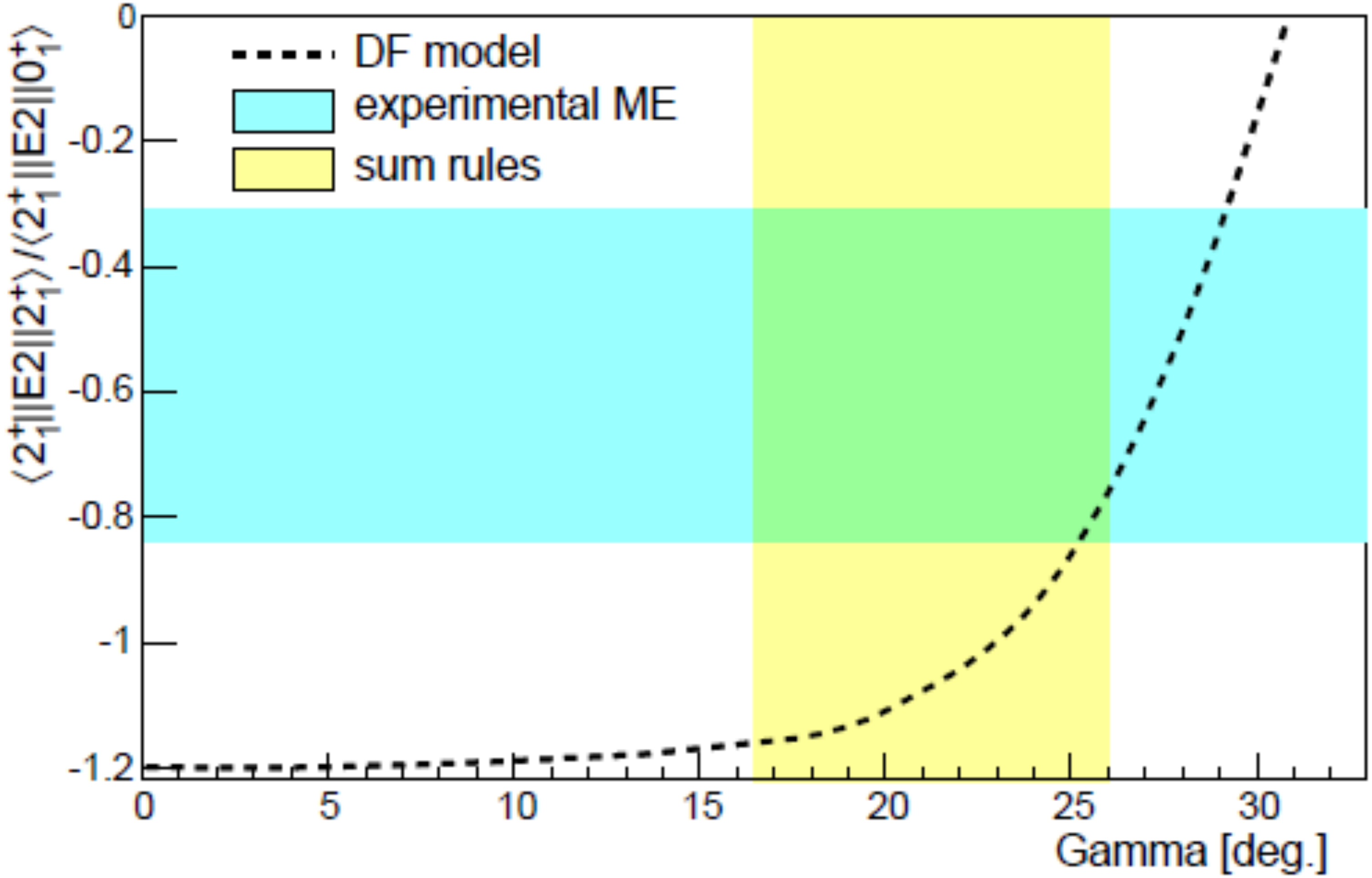
Collectivity around N=60





E. Clément, M. Zielinska et al, Phys.Rev.C in prep.

Davydov-Filippov model



Experimental results 3/3

laboratoire commun CEA/DSM GANIL spiral2 CNRS/IN2P3

Inputs:
*Level scheme
*Experimental setup
*$I\gamma\ (\theta_{cm})$
*known τ,BR,$\delta(E\lambda/M\lambda)$, g

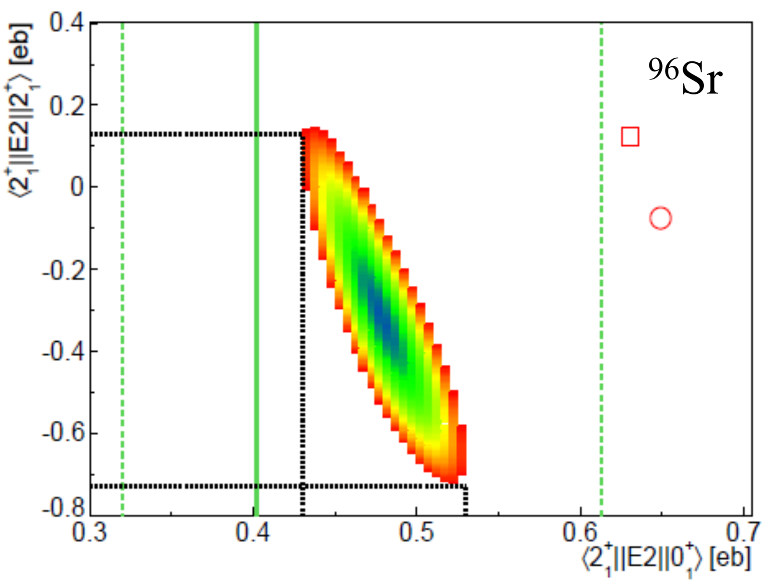
Electromagnetic Matrix Elements

Coulomb excitation cross section

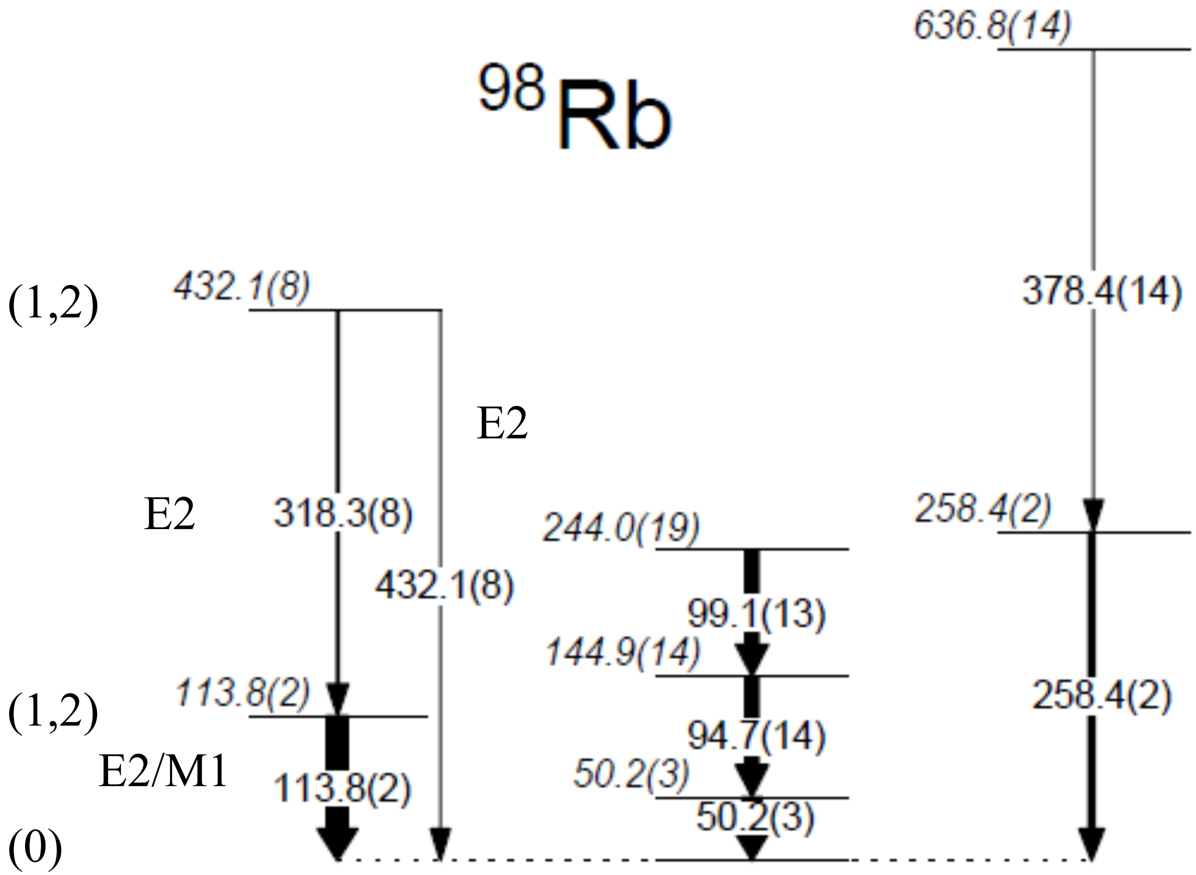
χ^2 minimization

Calculated decay intensities
vs
Observed decay

Complete set of Elect. Matrix Elements



M. Zielinska et al Eur. Phys. J. A (2016) 52: 99



98Rb
636.8(14)
378.4(14)
(1,2)
432.1(8)
E2
E2
318.3(8)
432.1(8)
244.0(19)
258.4(2)
99.1(13)
144.9(14)
258.4(2)
(1,2)
113.8(2)
E2/M1
113.8(2)
94.7(14)
50.2(3)
50.2(3)
(0)

^{96}Sr

I_1^π	I_2^π	B($E2$, $I_1 \rightarrow I_2$) (W.u.) experiment	5DCH (Gogny)	Excited VAMPIR
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	B($E2$, $I_1 \rightarrow I_2$) (W.u.) experiment	5DCH (Gogny)	5DCH (PC-PK1)
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	

^{96}Sr, $\rho^2(E0)$ (10^{-3})

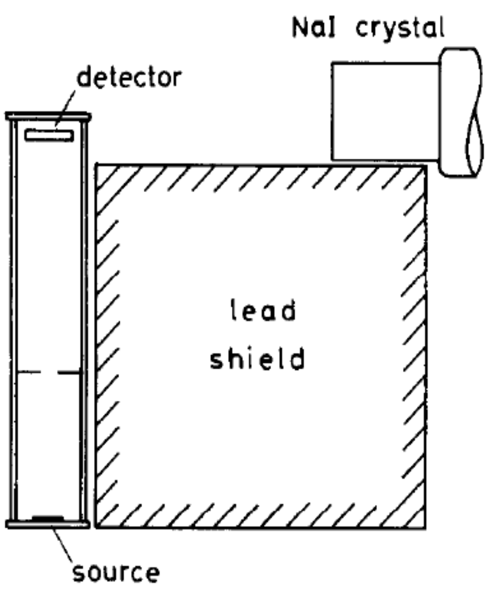
	0_1^+	0_2^+		2_1^+	2_2^+		4_1^+	4_2^+		6_1^+	6_2^+		8_1^+	8_2^+
0_2^+	106	-	2_2^+	28	-	4_2^+	83	-	6_2^+	82	-	8_2^+	60	-
0_3^+	22	95	2_3^+	117	65	4_3^+	113	43	6_3^+	89	32	8_3^+	44	44

^{98}Sr, $\rho^2(E0)$ (10^{-3})

	0_1^+	0_2^+		2_1^+	2_2^+		4_1^+	4_2^+		6_1^+	6_2^+		8_1^+	8_2^+
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

Shape Transition at N=60

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



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