Studies of super-deformed states in atomic nuclei using the Coulomb excitation method

Kasia Hadyńska-Klęk

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SSNET Workshop, Orsay, France
07.11 – 11.11.2016

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→ The story of ^{42}Ca
→ COULEX results
→ Theory
→ Definition of **superdefomation?**

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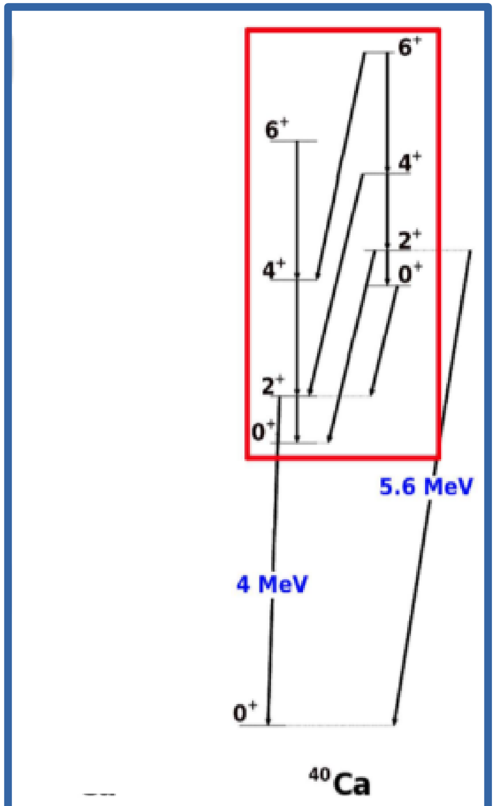
Motivation – SD in ^{42}Ca?

→ **Superdeformed band in ^{40}Ca** (DSAM, ANL)

$B(E2; 4^+ \rightarrow 2^+) = 170$ Wu
$Q_t=1.80(+10.39,-0.29)$ eb → $\beta_2=0.59(+0.11,-0.07)$

(E. Ideguchi et al., PRL 87, 222501 (2001), C.J. Chiara et al., PRC 67, 041303R (2003))



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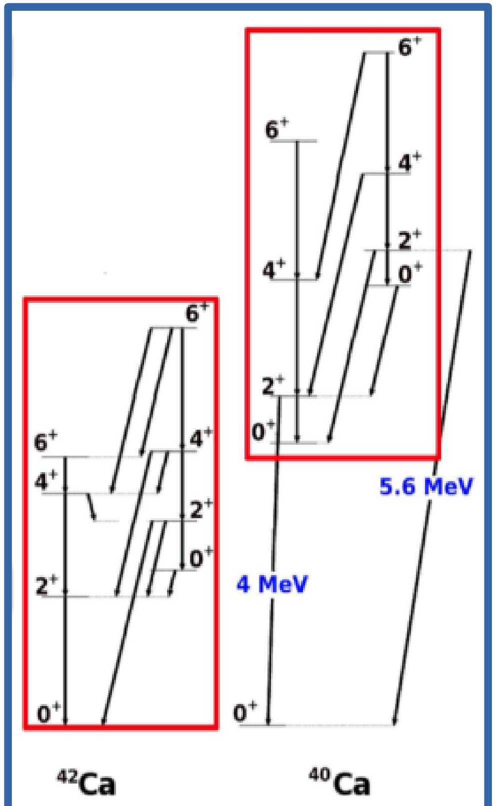

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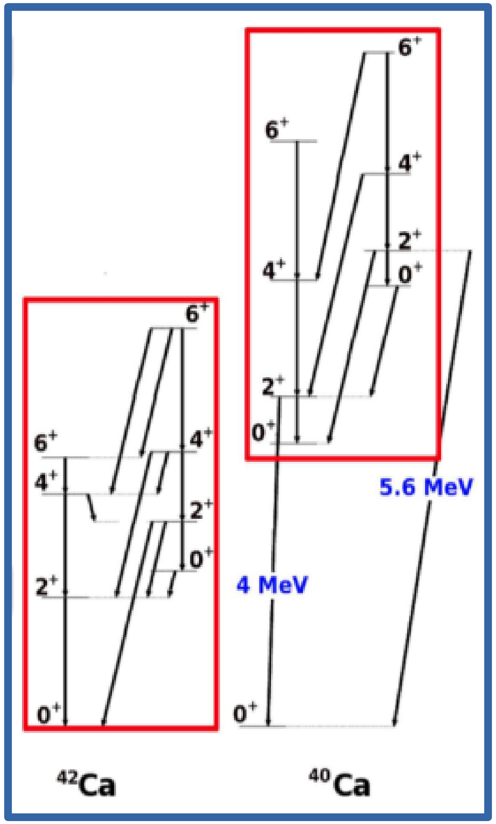


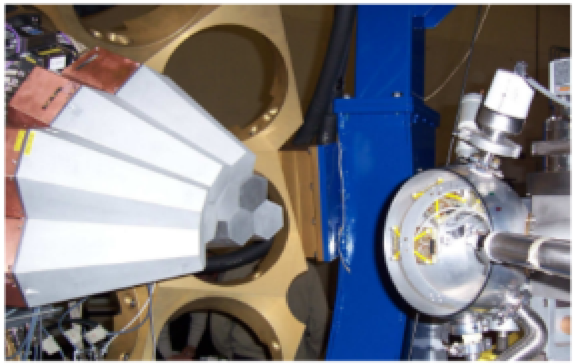
→ **Superdeformed bands in A~40 mass region:**
^{36}Ar, ^{38}Ar, ^{40}Ar, ^{44}Ti

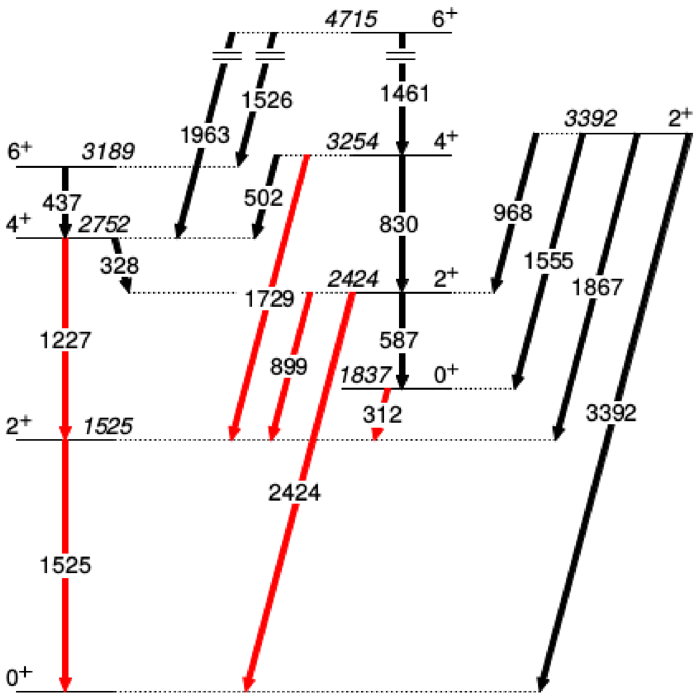
(in all cases β_2 between 0.4-0.6)

C.E.Svensson et al., PRL 85 (2000) 2693
D.Rudolph et al., PRC 65 (2002) 034305
E.Ideguchi et al., PLB 686 (2010) 18
D.C.O'Leary et al., PRC 61 (2000) 064314

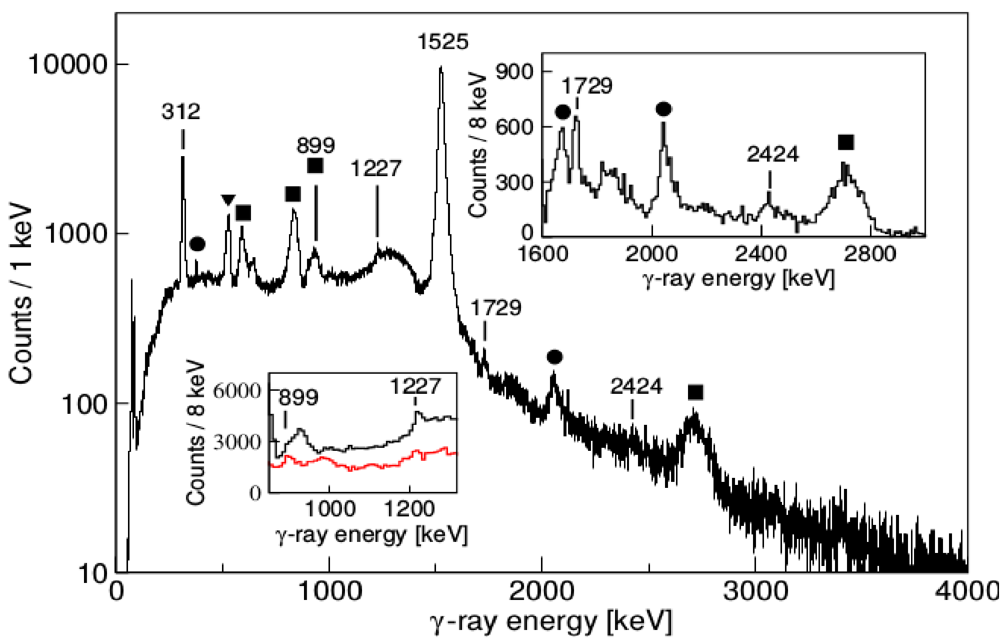
Coulomb excitation of ^{42}Ca

- INFN LNL
- Beam: ^{42}Ca, 170 MeV
- Targets:
  - ^{208}Pb, 1 mg/cm^2
  - ^{197}Au, 1 mg/cm^2
- AGATA: 3 triple clusters, 143.8 mm from the target
- DANTE: 3 MCP detectors, 100-144^o

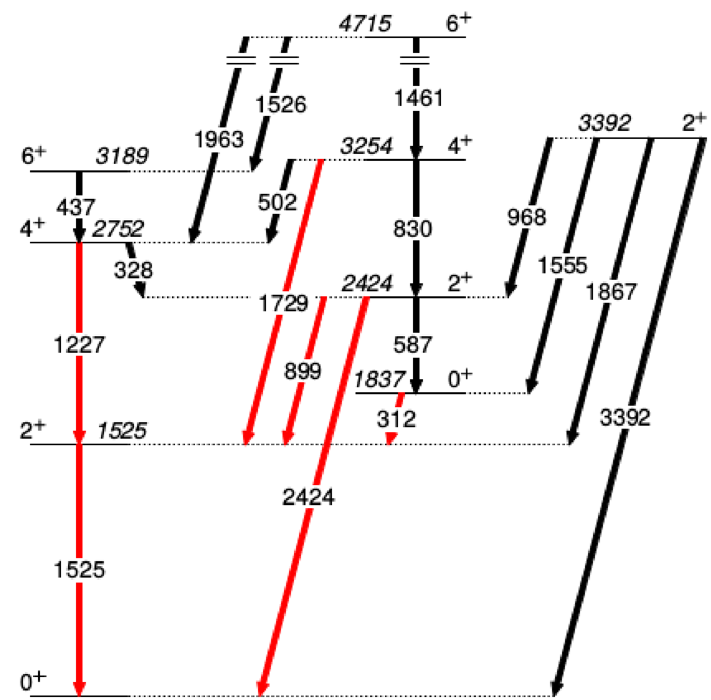




Results – spectrum of ^{42}Ca



■ Pb (208, 207, 206, 204)
▼ 511 keV
● ^{43}Ca



Results – transition probabilities

$I_i^+ \rightarrow I_f^+$	$\langle I_i \| E2 \| I_f \rangle$ [e fm^2] Present	$B(E2\downarrow; I_i^+ \rightarrow I_f^+)$ [W.u.] Present	$B(E2\downarrow; I_i^+ \rightarrow I_f^+)$ [W.u.] Previous
$2_1^+ \rightarrow 0_1^+$	$20.5^{+0.6}_{-0.6}$	$9.7^{+0.6}_{-0.6}$	9.3 ± 1 [36]
			11 ± 2 [28]
			9 ± 3 [27]
			8.5 ± 1.9 [45]
$4_1^+ \rightarrow 2_1^+$	$24.3^{+1.2}_{-1.2}$	$7.6^{+0.7}_{-0.7}$	50 ± 15 [28]
			11 ± 3 [27]
			10^{+10}_{-8} [45]
$6_1^+ \rightarrow 4_1^+$	$9.3^{+0.2}_{-0.2}$	$0.77^{+0.03}_{-0.03}$	0.7 ± 0.3 [27]
$0_2^+ \rightarrow 2_1^+$	$22.2^{+1.1}_{-1.1}$	57^{+6}_{-6}	64 ± 4 [27]
			100 ± 6 [28]
			55 ± 1 [42]
			64 ± 4 [45]
$2_2^+ \rightarrow 0_1^+$	$-6.4^{+0.3}_{-0.3}$	$1.0^{+0.1}_{-0.1}$	2.2 ± 0.6 [28]
			1.5 ± 0.5 [27]
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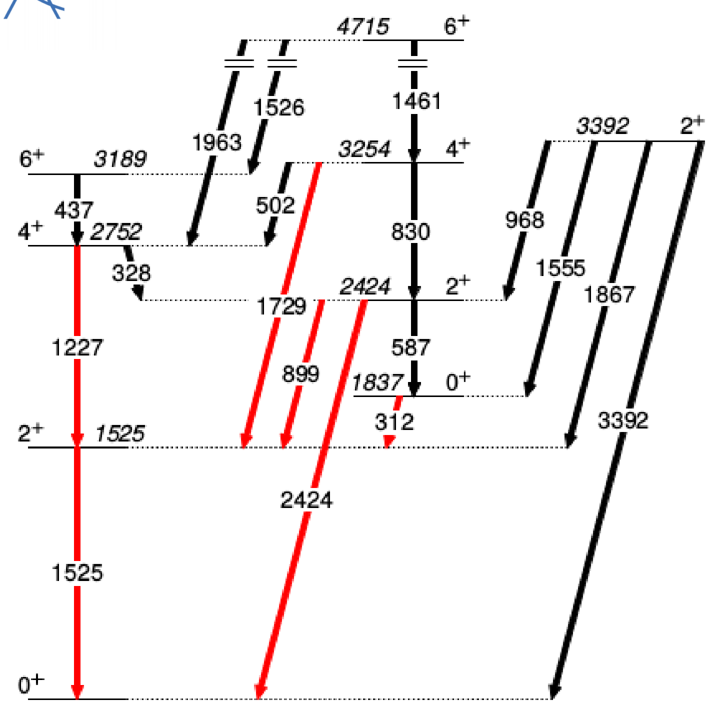
$2_2^+ \rightarrow 2_1^+$	$-23.7^{+2.3}_{-2.7}$	$12.9^{+2.5}_{-2.5}$	17 ± 11 [28]
			19^{+22}_{-14} [27]
			14^{+35}_{-9} [45]
$4_2^+ \rightarrow 2_1^+$	42^{+3}_{-4}	23^{+3}_{-4}	30 ± 11 [28]
			16 ± 5 [27]
			12^{+7}_{-4} [45]
$2_2^+ \rightarrow 0_2^+$	26^{+5}_{-3}	15^{+6}_{-4}	< 61 [27]
			< 46 [45]
$4_2^+ \rightarrow 2_2^+$	46^{+3}_{-6}	27^{+4}_{-6}	60 ± 30 [27]
			60 ± 20 [28]
			40^{+40}_{-30} [45]

	$\langle I_i \| E2 \| I_f \rangle$ [e fm^2]	Q_{sp} [e fm^2]	
$2_1^+ \rightarrow 2_1^+$	-16^{+9}_{-3}	-12^{+7}_{-2}	-19 ± 8 [36]
$2_2^+ \rightarrow 2_2^+$	-55^{+15}_{-15}	-42^{+12}_{-12}	



K. Hadyńska-Kłęk *et al.*, PRL 117, 062501 (2016)

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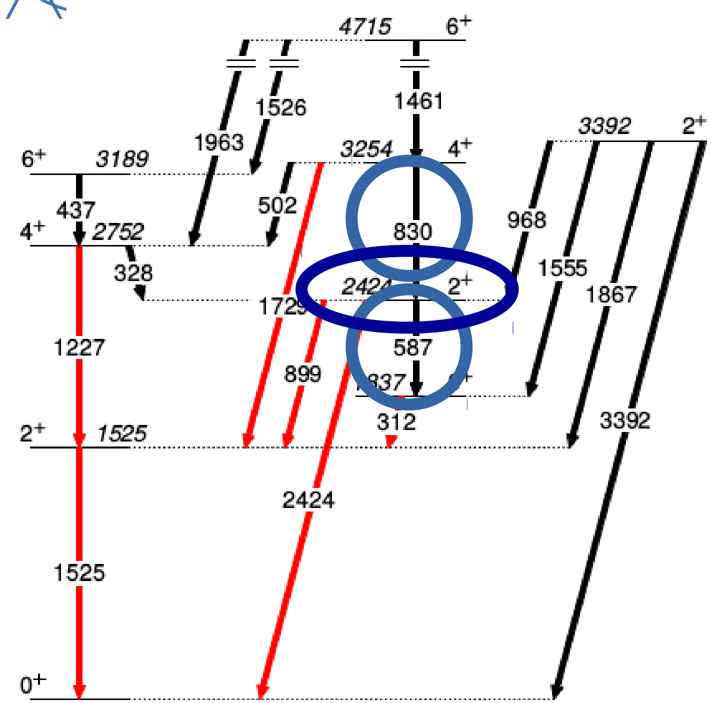


K. Hadyńska-Klęk *et al.*, PRL 117, 062501 (2016)

Discussion:
Quadrupole Shape Invariants

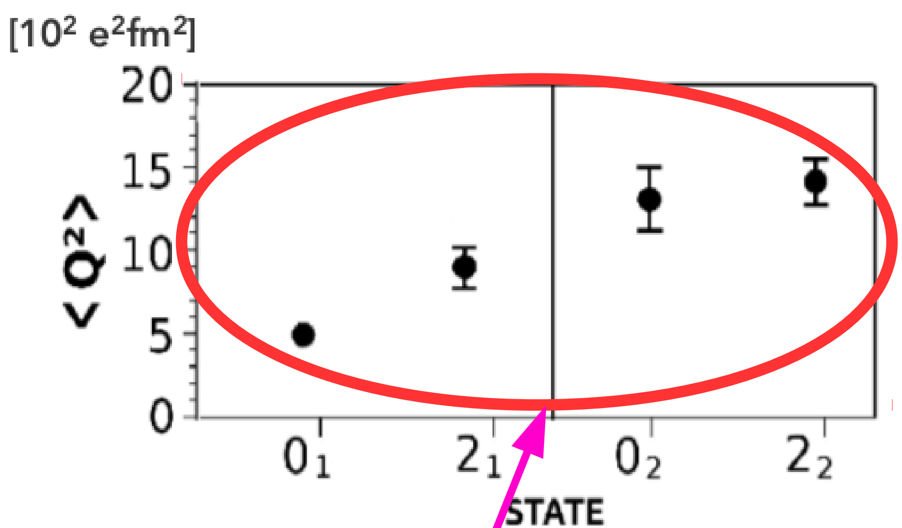
$$\frac{1}{\sqrt{5}}\langle Q^2\rangle = \frac{1}{\sqrt{2I_i+1}}\sum_t \langle i\|E2\|t\rangle\langle t\|E2\|f\rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_f & I_t\end{Bmatrix}$$

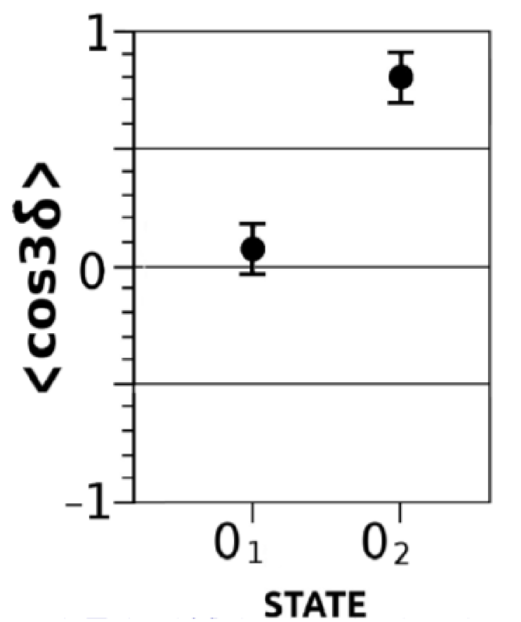
$$\langle Q^3\cos(3\delta)\rangle = \mp\frac{\sqrt{35}}{\sqrt{2}}\frac{1}{\sqrt{2I_i+1}}\sum_{tu}\langle s\|E2\|u\rangle\langle u\|E2\|t\rangle\langle t\|E2\|s\rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_s & I_t & I_u\end{Bmatrix}$$

K. Kumar, PRL 28, 249 (1972)

state	$\langle Q^2\rangle_{exp}$
0_1^+	500 (20)
2_1^+	900 (100)
0_2^+	1300 (230)
2_2^+	1400 (250)

state	$\langle\cos(3\delta)\rangle_{exp}$
0_1^+	0.06 (10)
0_2^+	0.79 (13)





Increasing deformation in GSB and stable in the side band

Discussion:
Quadrupole Shape Invariants

cos(3δ)~0.8 – slightly triaxial - prolate 0_2

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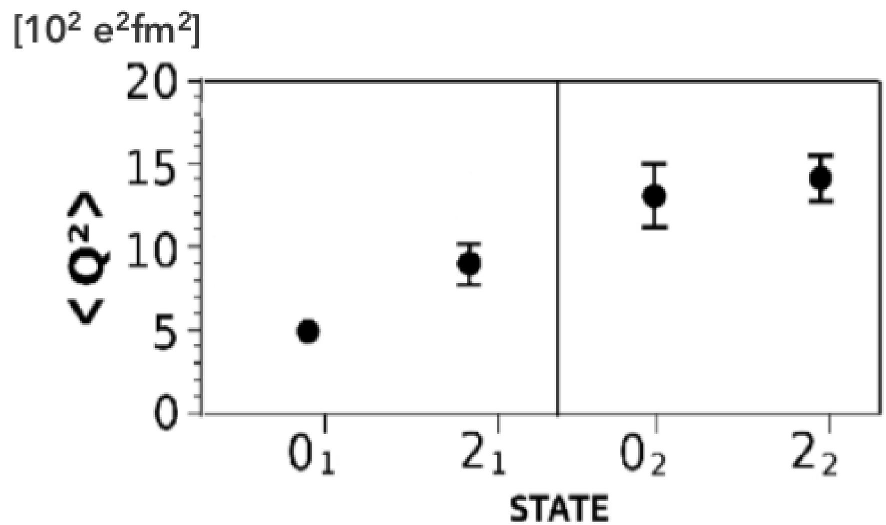

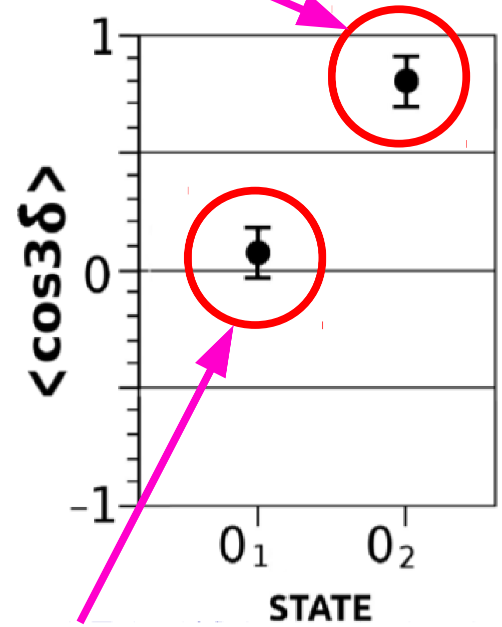

cos(3δ)~0 – triaxial GS

Discussion: Quadrupole Shape Invariants

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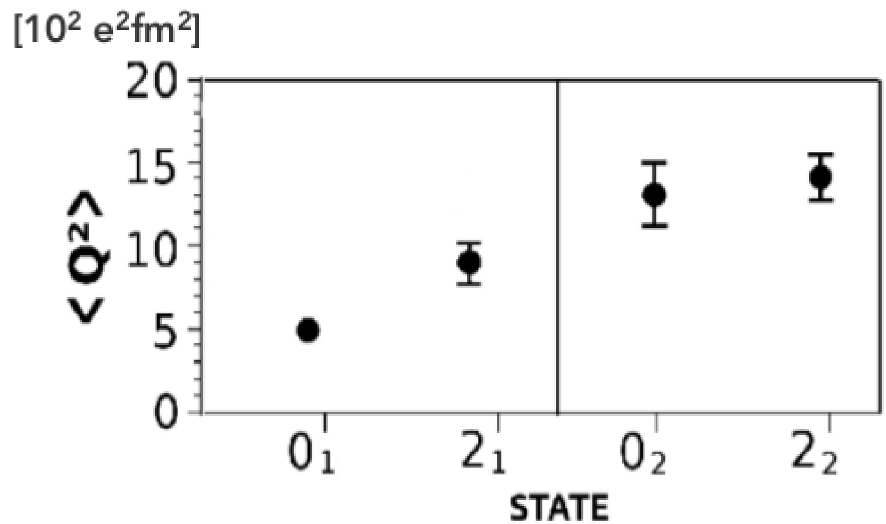

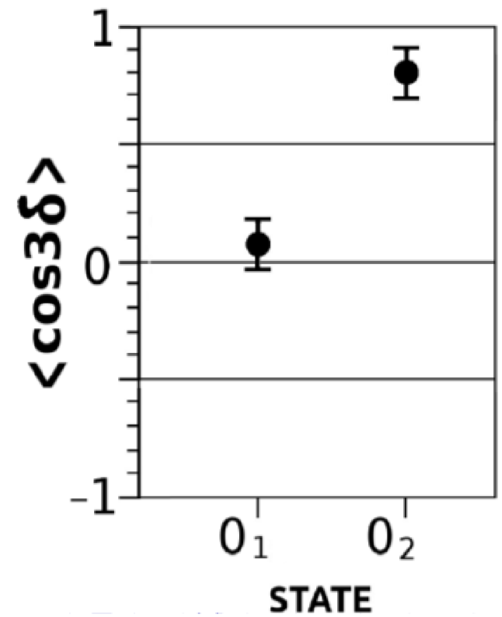

0_1 β=0.26(2) and γ=29(2)°
0_2 β=0.43(2) and γ=13(6)°

$$\beta = \sqrt{\langle \beta^2 \rangle} = \sqrt{\frac{\langle Q^2 \rangle}{q_0^2}},$$

$$\gamma = \arccos\langle \cos(3\delta) \rangle,$$

J. Srebrny and D. Cline, Int. J. Mod. Phys. E20, 422 (2011)

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Quadrupole Shape Invariants

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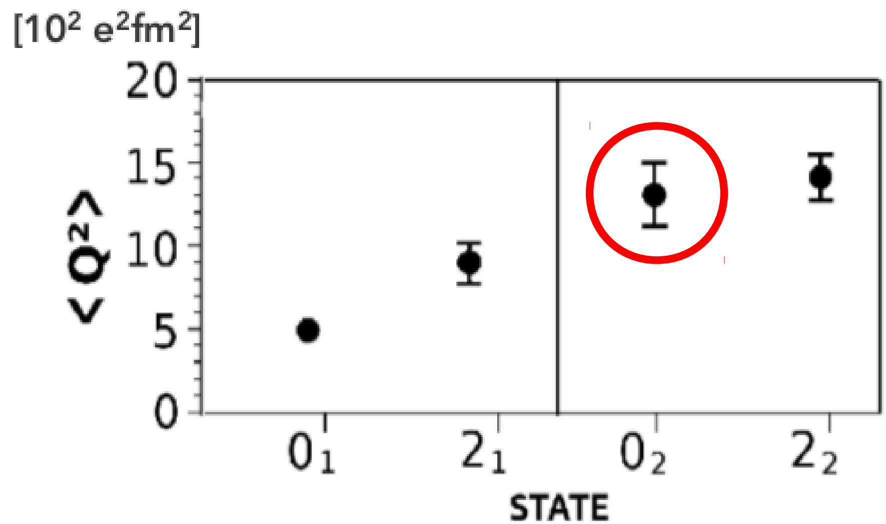

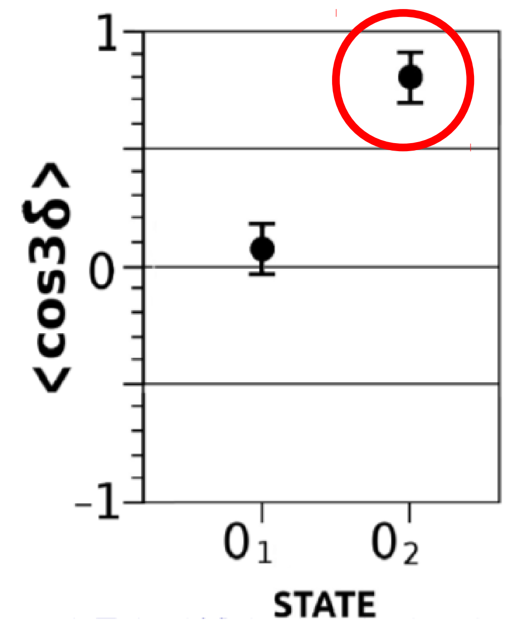

0_2 β=0.43(2) and γ=13(6)°

SUPERDEFORMED
slightly triaxial
SIDE BAND

Discussion: Quadrupole Shape Invariants

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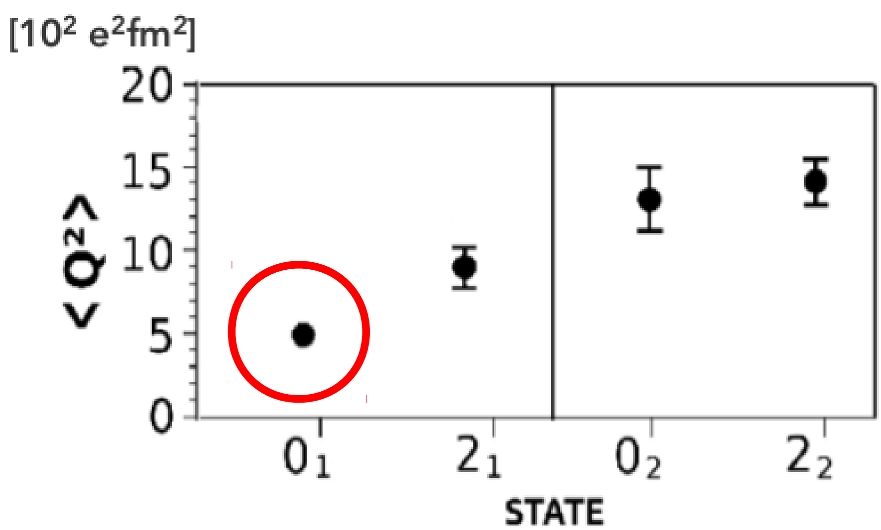

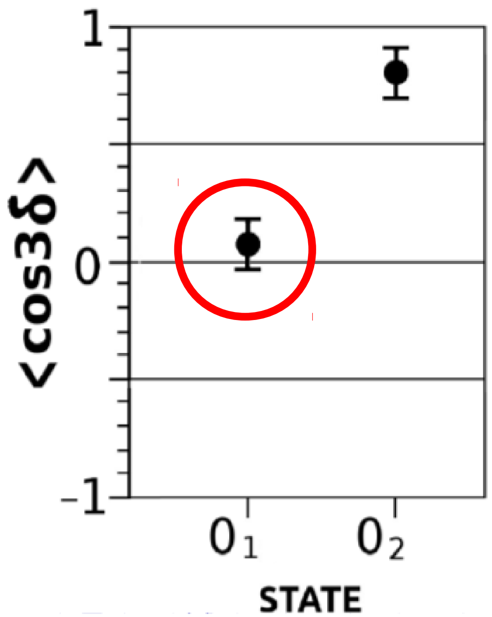

0_1 β=0.26(2) and γ=29(2)°

Non-zero triaxial deformation of the ground state?

Discussion:
Shape parameters

Why non-zero deformation of the ground state?

→ **fluctuations** about the spherical shape
→ maximum triaxiality - effect of averaging over **<u>all possible quadrupole shapes</u>**
→ **the dispersion of Q^2 , $\sigma(Q^2)$, should be comparable to Q^2 value**

$$\sigma(Q^2) = \sqrt{\langle Q^4 \rangle - \langle Q^2 \rangle^2}$$

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Insufficient experimental data
Theoretical predictions and the full set of ME from:

Large Scale Shell Model	Beyond Mean Field
F.Nowacki, H.Naïdja, B.Bounthong Université de Strasbourg, France	T. R. Rodríguez Universidad Autónoma de Madrid, Spain

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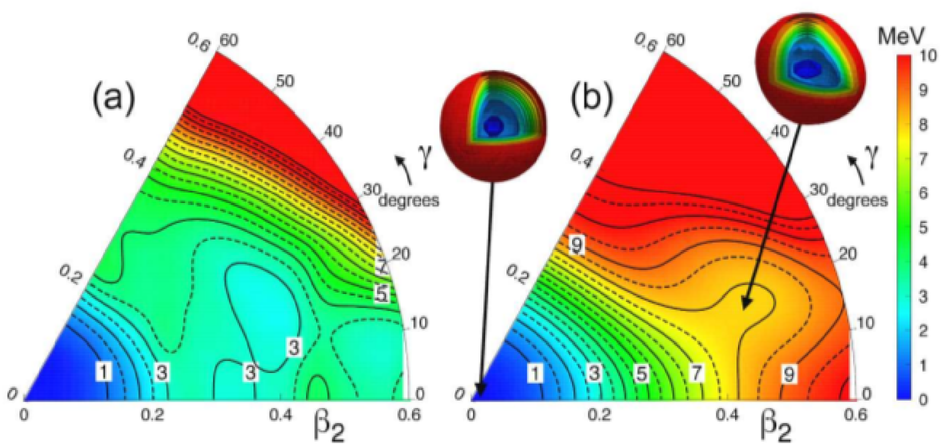
Insufficient experimental data
Theoretical predictions and the full set of ME from the SM and BMF calculations



Both approaches predict:

0_1 - SPHERICAL
0_2 - TRIAXIAL/PROLATE

Discussion:
Shape parameters

We use the theoretical predictions and the full set of ME from the calculations:
- Large Scale Shell Model (F.Nowacki, H.Naïdja, B.Bounthong - Strasbourg)
- Beyond Mean Field (T. R. Rodríguez - Madrid)

state	$\langle Q^2 \rangle_{exp}$	$\langle Q^2 \rangle_{SM}$	$\sigma(Q^2)_{SM}$	$\langle Q^2 \rangle_{BMF}$	$\sigma(Q^2)_{BMF}$
0_1^+	500 (20)	240	470	100	250
2_1^+	900 (100)	250	490	100	310
0_2^+	1300 (230)	1200	500	1900	520
2_2^+	1400 (250)	1130	500	1900	300

state	$\langle \cos(3\delta) \rangle_{exp}$	$\langle \cos(3\delta) \rangle_{SM}$	$\langle \cos(3\delta) \rangle_{BMF}$
0_1^+	0.06 (10)	0.34	0.34
0_2^+	0.79 (13)	0.67	0.49

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Shape parameters

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0_1 - SPHERICAL with large fluctuations around minimum

0_2- SUPERDEFORMED, SLIGHTLY TRIAXIAL/PROLATE shape

What does it mean SUPERDEFORMED?

→ a quantitative definition of superdeformation does not seem to exist
→ authors use various subjective criteria, rarely clearly defined

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→ deformation corresponding to axes ratio between **3:2:1 and 2:1:1** → corresponding β parameter: 0.4-0.6: A~130 mass region, e.g. ^{152}Dy, and some in the A~40 region:

β_2=0.46±0.03 (^{36}Ar),
β_2=0.48± 0.05 (^{40}Ar)

P. Nolan and P. Twin, Annu. Rev. Nucl. Part. Sci. 38, 533 (1988)
R.V.F. Janssens, T.L. Khoo, Annu. Rev. Nucl. Part. Sci. 41, 321 (1991)
C.E. Svensson, et al., Phys. Rev. Lett. 85, 2693 (2000)
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→ normal deformation: 1.3:1:1 (β ~ 0.3)

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$\beta_2=0.46\pm0.03$ (^{36}Ar),
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→ the deformation parameters determined from quadrupole invariants in ^{42}Ca:
$\boldsymbol{\beta_2=0.43(2)}$ for $\boldsymbol{0_2}$ and $\boldsymbol{\beta_2=0.45(2)}$ for $\boldsymbol{2_2}$ state

What does it mean SUPERDEFORMED?

Shell configuration in A~40 region

→ complex particle-hole configuration

^{40}Ca: 8p-8h, $\beta_2 \simeq 0.6$

TABLE IV. Percentage of np-nh components and energy of the first three 0^+ states (GS, ND, and SD) of ^{40}Ca.

	0p-0h	2p-2h	4p-4h	6p-6h	8p-8h	E(th)	E(exp)
0^+_{GS}	65	29	5	–	–	0	0
0^+_{ND}	1	1	64	25	9	3.49	3.35
0^+_{SD}	–	–	9	4	87	4.80	5.21

^{42}Ca, β_2=0.43(2) (0_2) and β_2=0.45(2) (2_2)

J_i^pi	2p0h	4p2h	6p4h	8p6h
0_1⁺	40%	40%	17%	3%
2_1⁺	45%	36%	16%	3%
4_1⁺	55%	35%	9%	1%
6_1+	55%	35%	9%	1%
0_2⁺	10%	18%	**49%**	23%
2_2+	12%	13%	**50%**	24%
2_3+	0%	14%	**59%**	26%
3_1+	0%	4%	**66%**	30%
4_2+	1%	15%	**62%**	22%
6_2+	1%	24%	**61%**	14%

4p-4h: ^{36,40}Ar, β_2=0.46 and β_2=0.48

3p-3h: ^{35}Cl: $\beta_2 \simeq 0.37$

Summary and outlook

- the properties of low-lying states in ^{42}Ca were studied using low-energy Coulomb excitation – 0^+, 2^+ and 4^+ states observed in both bands
- the quadrupole deformation parameters of the $0^+$and 2^+ states in GSB and SDB in ^{42}Ca were determined from the measured reduced matrix elements
- the results were compared with SM and BMF calculations
- the non-zero deformation of the ground state has been attributed to the fluctuations around the spherical shape
- a large static deformation of β=0.43(2) and β=0.45(2), for $0_2^+$and 2_2^+ was observed, proving the **superdeformed** character of the side band
- the cos(3δ) parameter measured for 0_2 brings the first experimental evidence for **non-axial** character of SD bands in the A∼40 mass region
- COULEX of SD bands in other A∼40 nuclei: ^{40}Ca, $^{36\text{-}40}$Ar, ^{44}Ti – projects in preparation/ongoing

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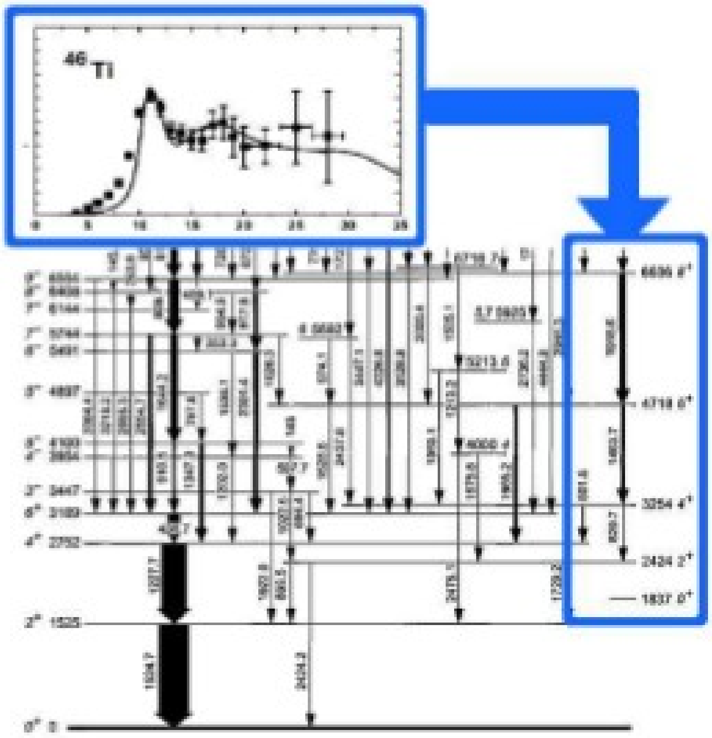
Superdeformed and Triaxial States in ^{42}Ca

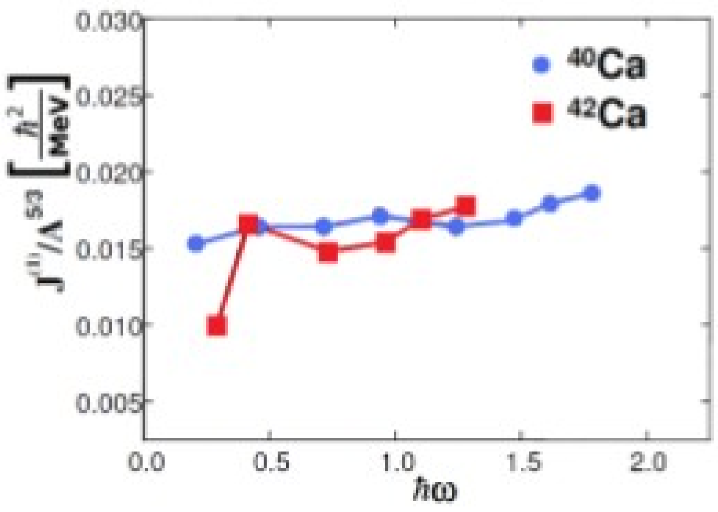
K. Hadyńska-Klęk,[1,2,3,4] P. J. Napiorkowski,[1] M. Zielińska,[5,1] J. Srebrny,[1] A. Maj,[6] F. Azaiez,[7] J. J. Valiente Dobón,[4] M. Kicińska-Habior,[2] F. Nowacki,[8] H. Naïdja,[8,9,10] B. Bounthong,[8] T. R. Rodríguez,[11] G. de Angelis,[4] T. Abraham,[1] G. Anil Kumar,[6] D. Bazzacco,[12,13] M. Bellato,[12] D. Bortolato,[12] P. Bednarczyk,[6] G. Benzoni,[14] L. Berti,[4] B. Birkenbach,[15] B. Bruyneel,[15] S. Brambilla,[14] F. Camera,[14,16] J. Chavas,[5] B. Cederwall,[17] L. Charles,[8] M. Ciemała,[6] P. Cocconi,[4] P. Coleman-Smith,[18] A. Colombo,[12] A. Corsi,[14,16] F. C. L. Crespi,[14,16] D. M. Cullen,[19] A. Czermak,[6] P. Désesquelles,[20,21] D. T. Doherty,[5,22] B. Dulny,[6] J. Eberth,[15] E. Farnea,[12,13] B. Fornal,[6] S. Franchoo,[7] A. Gadea,[23] A. Giaz,[14,16] A. Gottardo,[4] X. Grave,[7] J. Grębosz,[6] A. Görgen,[3] M. Gulmini,[4] T. Habermann,[9] H. Hess,[15] R. Isocrate,[12,13] J. Iwanicki,[1] G. Jaworski,[1] D. S. Judson,[24] A. Jungclaus,[25] N. Karkour,[21] M. Kmiecik,[6] D. Karpiński,[2] M. Kisieliński,[1] N. Kondratyev,[26] A. Korichi,[21] M. Komorowska,[1,2] M. Kowalczyk,[1] W. Korten,[5] M. Krzysiek,[6] G. Lehaut,[27] S. Leoni,[14,16] J. Ljungvall,[21] A. Lopez-Martens,[21] S. Lunardi,[12,13] G. Maron,[4] K. Mazurek,[6] R. Menegazzo,[12,13] D. Mengoni,[12] E. Merchán,[9,28] W. Męczyński,[6] C. Michelagnoli,[12,13] J. Mierzejewski,[1] B. Million,[14] S. Myalski,[6] D. R. Napoli,[4] R. Nicolini,[14] M. Niikura,[7] A. Obertelli,[5] S. F. Özmen,[1] M. Palacz,[1] L. Próchniak,[1] A. Pullia,[14,16] B. Quintana,[29] G. Rampazzo,[4] F. Recchia,[12,13] N. Redon,[27] P. Reiter,[15] D. Rosso,[4] K. Rusek,[1] E. Sahin,[4] M.-D. Salsac,[5] P.-A. Söderström,[30] I. Stefan,[7] O. Stézowski,[27] J. Styczeń,[6] Ch. Theisen,[5] N. Toniolo,[4] C. A. Ur,[12,13] V. Vandone,[14,16] R. Wadsworth,[22] B. Wasilewska,[6] A. Wiens,[15] J. L. Wood,[31] K. Wrzosek-Lipska,[1] and M. Zieliński[6]

Motivation – SD in ^{42}Ca?

Low energy branch of ^{46}Ti Giant Dipole Resonance decay feeding the states in the side band in ^{42}Ca (M.Kmiecik *et al.*, Acta Phys. Pol. **B36**, 1169(2005))

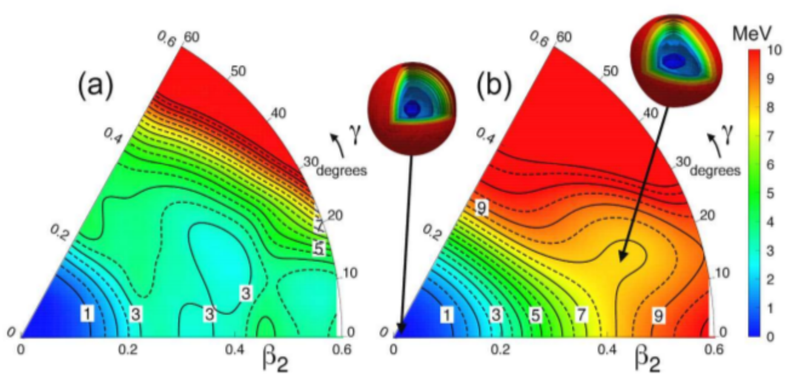


Moments of inertia of states in the side band in ^{42}Ca look very similar to states in SD-band in ^{40}Ca, (A.Maj *et al.* Key Topics in Nuclear Structure, page 417, (2005), M.Lach *et al.* EPJ A 16, 3, 309-311 (2003))



Theory

Large Scale Shell Model	Beyond Mean Field
F.Nowacki, H.Naïdja, B.Bounthong Université de Strasbourg, France	T. R. Rodríguez Universidad Autónoma de Madrid, Spain
ANTOINE code	RVAMPIRE code
6 particle-hole excitations from $s_{1/2}$ and $d_{3/2}$ orbitals to pf orbitals	T.R.Rodríguez and J.L.Egido, Phys. Rev. C 81, 064323 (2010)
Effective charges: 1.5e (protons) and 0.5e (neutrons)	HFB, Gogny D1S interaction to define the energy density functional
Same method as the one used for SD in ^{40}Ca: E.Caurier, J.Menendez, F.Nowacki and A.Poves, Phys. Rev. C 75, 054317 (2007)	→ Particle number and angular momentum symmetry restoration → Quadrupole (axial and non-axial) shape mixing within generator coordinate method

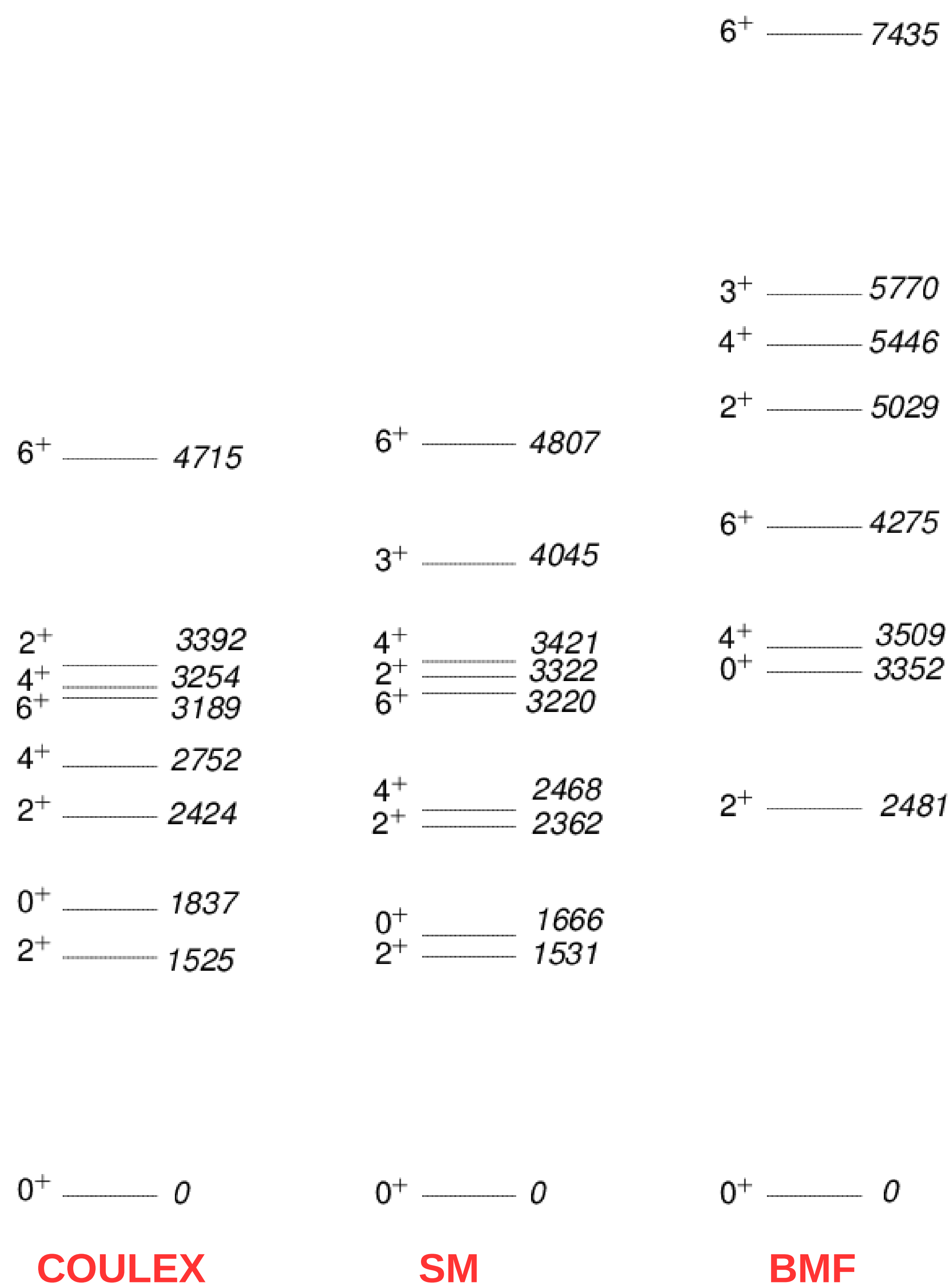


Both approaches predict:

0_1 - SPHERICAL

0_2 - TRIAXIAL/PROLATE

$I_i^+ \to I_f^+$	$\langle I_i \| E2 \| I_f \rangle$ [e fm^2] Present	SM	BMF	$B(E2\downarrow; I_i^+ \to I_f^+)$ [W.u.] Present	Previous
$2_1^+ \to 0_1^+$	$20.5^{+0.6}_{-0.6}$	11.5	9.14	$9.7^{+0.6}_{-0.6}$	9.3 ± 1 [36]
					11 ± 2 [28]
					9 ± 3 [27]
					8.5 ± 1.9 [45]
$4_1^+ \to 2_1^+$	$24.3^{+1.2}_{-1.2}$	11.3	12.2	$7.6^{+0.7}_{-0.7}$	50 ± 15 [28]
					11 ± 3 [27]
					10^{+10}_{-8} [45]
$6_1^+ \to 4_1^+$	$9.3^{+0.2}_{-0.2}$	8.2	14.3	$0.77^{+0.03}_{-0.03}$	0.7 ± 0.3 [27]
$0_2^+ \to 2_1^+$	$22.2^{+1.1}_{-1.1}$	11.9	6.1	57^{+6}_{-6}	64 ± 4 [27]
					100 ± 6 [28]
					55 ± 1 [42]
					64 ± 4 [45]
$2_2^+ \to 0_1^+$	$-6.4^{+0.3}_{-0.3}$	9.4	4.4	$1.0^{+0.1}_{-0.1}$	2.2 ± 0.6 [28]
					1.5 ± 0.5 [27]
					1.2 ± 0.3 [45]
$2_2^+ \to 2_1^+$	$-23.7^{+2.3}_{-2.7}$	-13.6	-7.7	$12.9^{+2.5}_{-2.5}$	17 ± 11 [28]
					19^{+22}_{-14} [27]
					14^{+35}_{-9} [45]
$4_2^+ \to 2_1^+$	42^{+3}_{-4}	21.9	10.1	23^{+3}_{-4}	30 ± 11 [28]
					16 ± 5 [27]
					12^{+7}_{-4} [45]
$2_2^+ \to 0_2^+$	26^{+5}_{-3}	32	42	15^{+6}_{-4}	< 61 [27]
					< 46 [45]
$4_2^+ \to 2_2^+$	46^{+3}_{-6}	52	70	27^{+4}_{-6}	60 ± 30 [27]
					60 ± 20 [28]
					40^{+40}_{-30} [45]
	$\langle I_i \| E2 \| I_f \rangle$ [e fm^2]			Q_{sp} [e fm^2]	
$2_1^+ \to 2_1^+$	-16^{+9}_{-3}	-4.3	0.1	-12^{+7}_{-2}	-19 ± 8 [36]
$2_2^+ \to 2_2^+$	-55^{+15}_{-15}	-31	-42	-42^{+12}_{-12}	



What does it mean SUPERDEFORMED?

Shell configuration in A~40 region

→ complex particle-hole configuration

^{40}Ca: 8p-8h, $\beta_2 \simeq 0.6$

TABLE IV. Percentage of np-nh components and energy of the first three 0^+ states (GS, ND, and SD) of ^{40}Ca.

	0p-0h	2p-2h	4p-4h	6p-6h	8p-8h	E(th)	E(exp)
0^+_{GS}	65	29	5	–	–	0	0
0^+_{ND}	1	1	64	25	9	3.49	3.35
0^+_{SD}	–	–	9	4	87	4.80	5.21

^{42}Ca, β_2=0.43(2) (0_2) and β_2=0.45(2) (2_2)

J_i^pi	2p0h	4p2h	6p4h	8p6h
0_1⁺	40%	40%	17%	3%
2_1⁺	45%	36%	16%	3%
4_1⁺	55%	35%	9%	1%
6_1+	55%	35%	9%	1%
0_2⁺	10%	18%	**49%**	23%
2_2+	12%	13%	**50%**	24%
2_3+	0%	14%	**59%**	26%
3_1+	0%	4%	**66%**	30%
4_2+	1%	15%	**62%**	22%
6_2+	1%	24%	**61%**	14%

4p-4h: $^{36,40}Ar$, β_2=0.46 and β_2=0.48

3p-3h: ^{35}Cl: $\beta_2 \simeq 0.37$

Conclusion:

a quantitative definition of superdeformation does not seem to exist