Shape coexistence in the A $\sim$ 40 region

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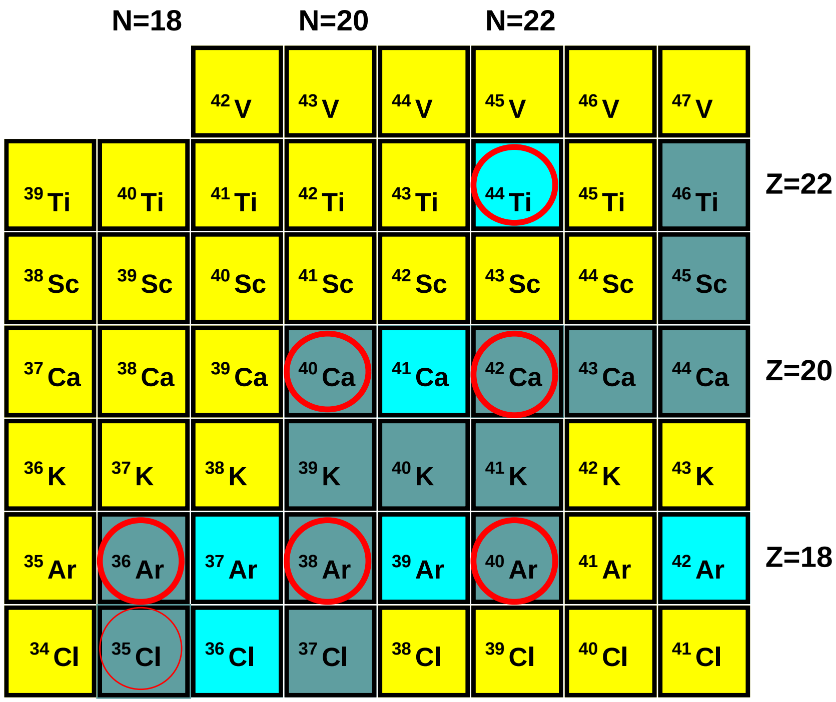
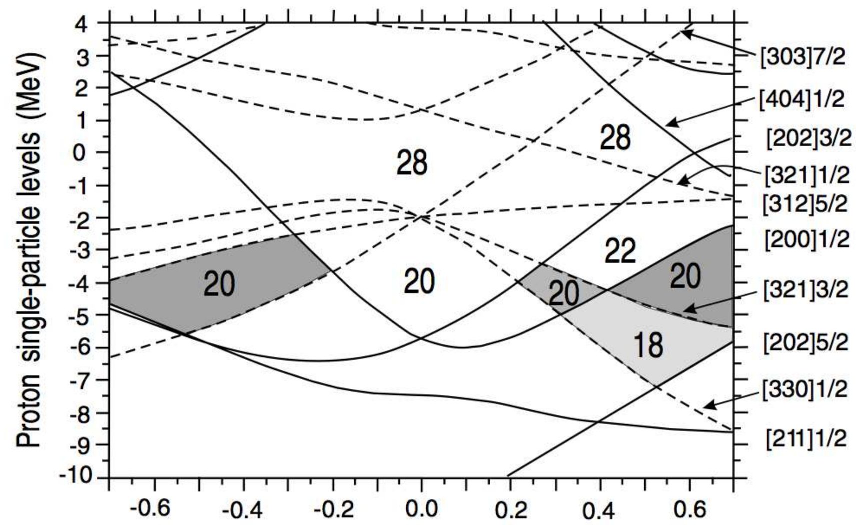
Highly-deformed structures in the A $\sim$ 40 region

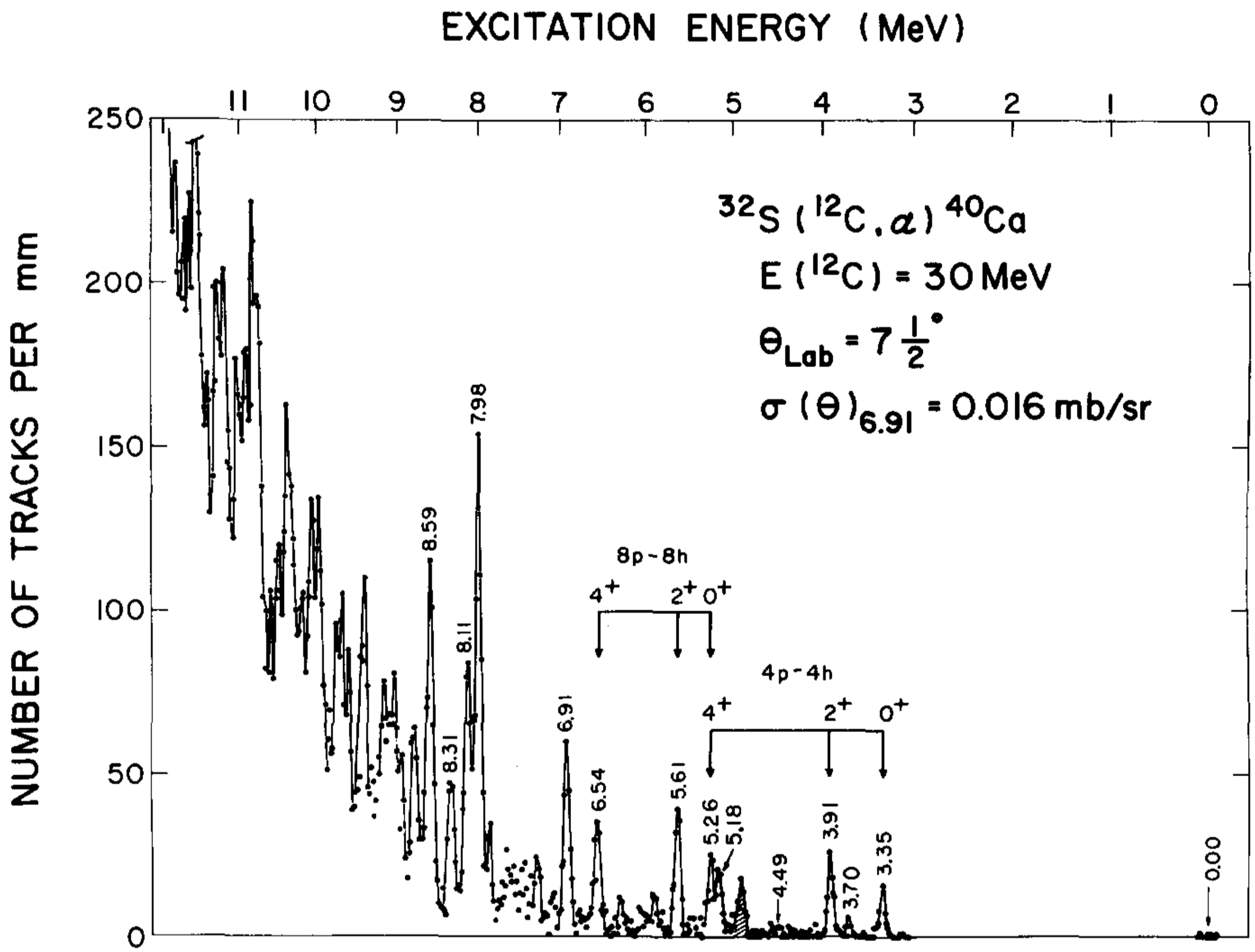


E. Ideguchi et al., PRL 81 (2001) 222501



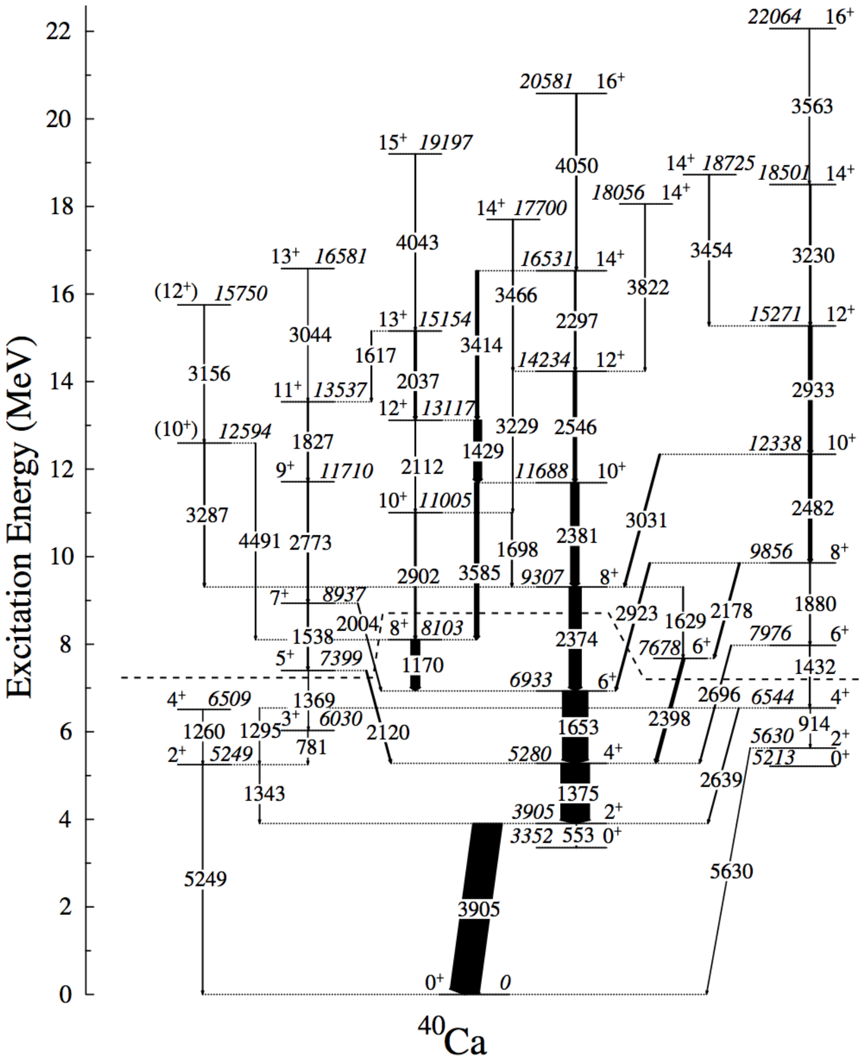
- spherical and highly-deformed magic numbers appear at similar particle numbers – dramatic shape coexistence
- intense transitions linking very deformed structures to ground-state bands – mixing of configurations

Identfication of 4p-4h and 8p-8h structures in ^{40}Ca

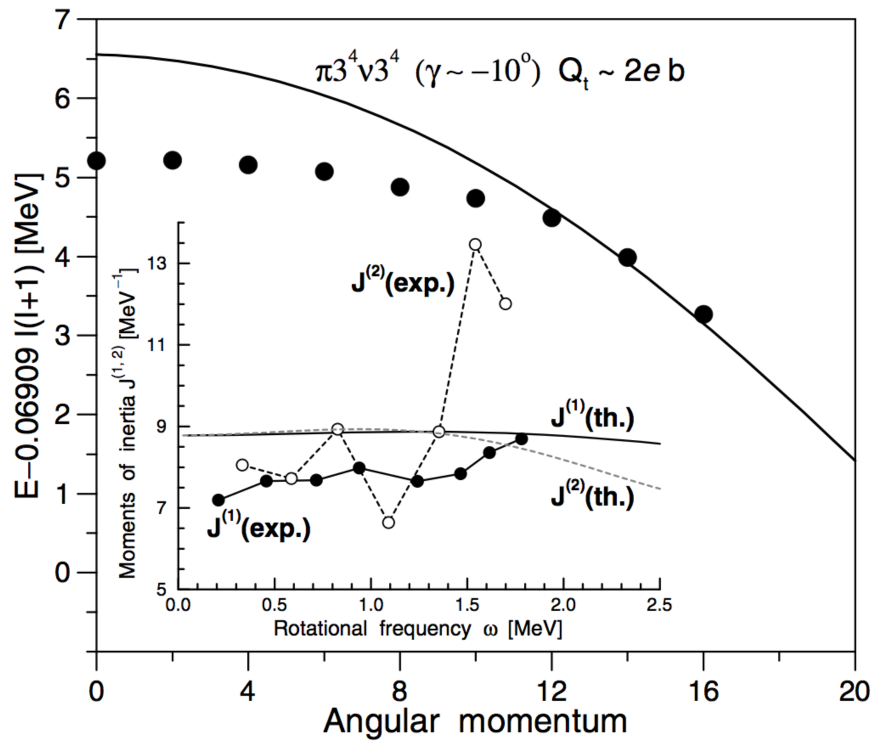


R. Middleton et al, Phys. Lett. 39B (1972) 339

High-spin spectroscopy around ^{40}Ca



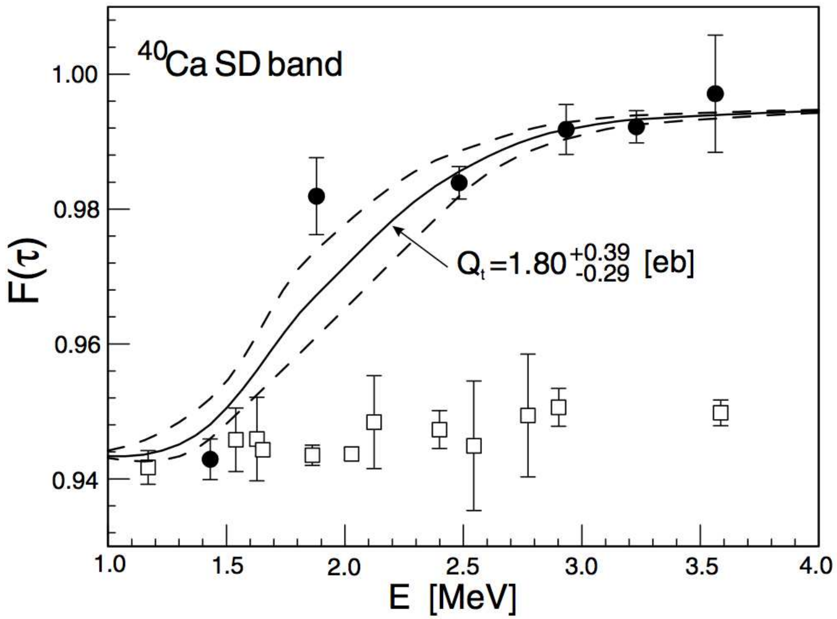
E. Ideguchi et al., PRL 81 (2001) 222501



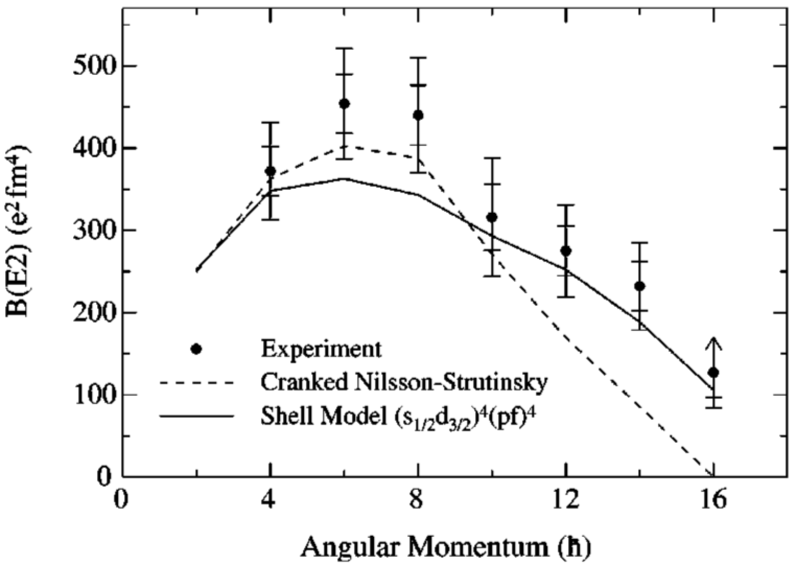
- regular rotational bands built on 0^+ states observed up to spin $14^+ - 16^+$ in ^{40}Ca, ^{38}Ar, ^{36}Ar...

Lifetime measurements in deformed bands

E. Ideguchi et al., PRL 81 (2001) 222501



C. Svensson et al., PRL 85 (2000) 2693



- ^{40}Ca: B(E2; $4^+_{SD} \rightarrow 2^+_{SD}$) = 170 Wu
  - band built on 0^+_2: Q_0 = 0.74 ± 0.14 eb (β = 0.27)

- ^{36}Ar: lifetimes of individual SD states determined, Q_0 not constant in the band:
  $4^+ \rightarrow 2^+$: 114(9) eb (β = 0.46), $6^+ \rightarrow 4^+$: 121(9) eb, $8^+ \rightarrow 6^+$: 116(9) eb,
  $10^+ \rightarrow 8^+$: 97(11) eb, $12^+ \rightarrow 10^+$: 89(9) eb (β = 0.35)

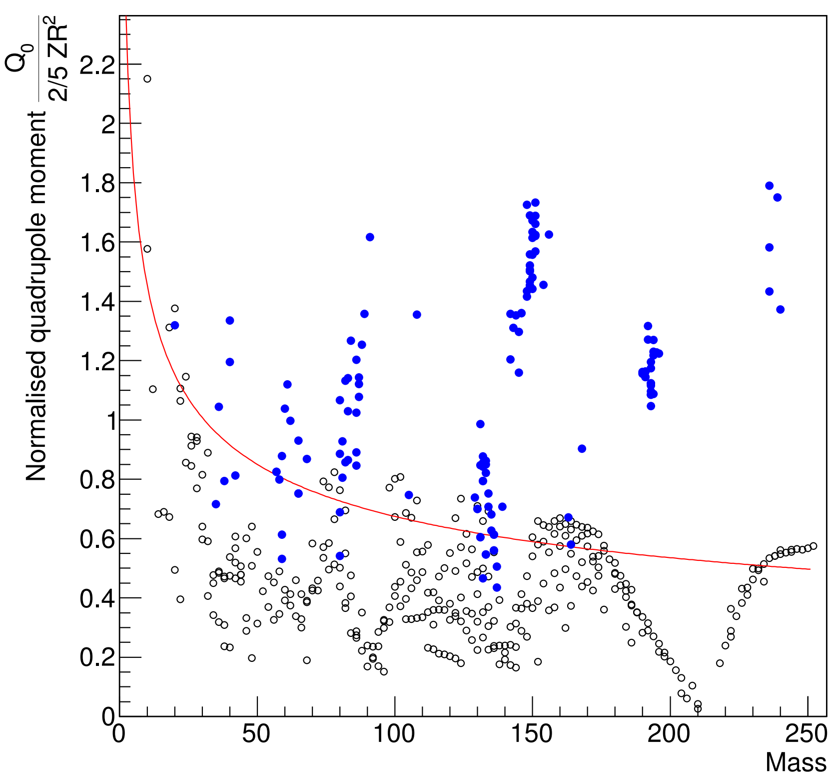
Highly-deformed structures in the A $\sim$ 40 region

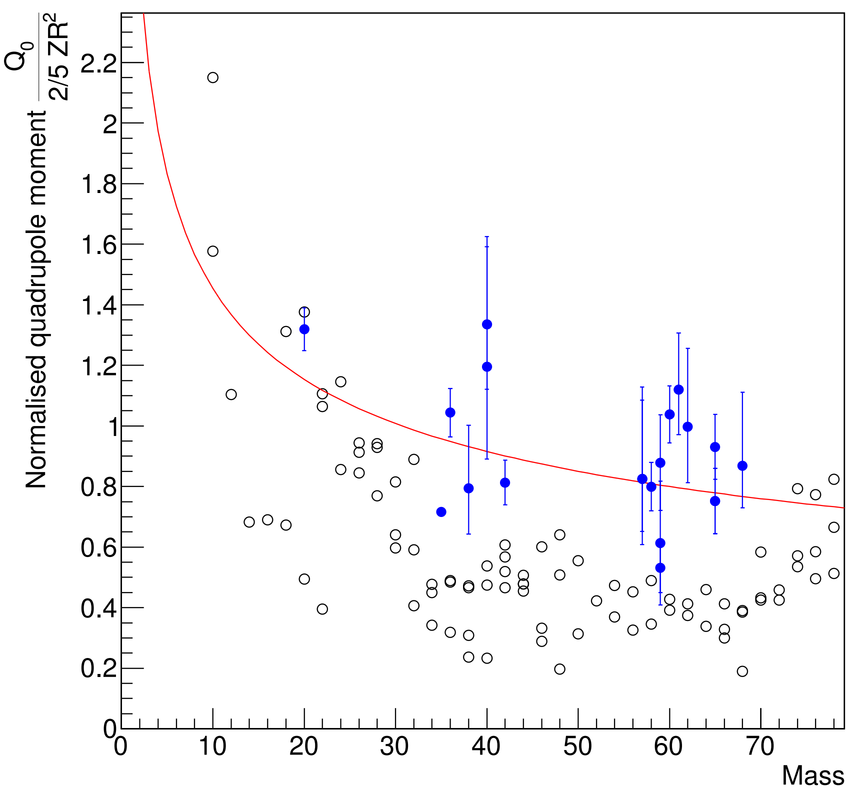
isotope	experimental β_2	configuration	0^+ energy	
^{40}Ca	$0.59^{+0.11}_{-0.07}$	8p-8h	5.2 MeV	E. Ideguchi et al., PRL 81 (2001) 222501
	0.27 ± 0.05	4p-4h	3.4 MeV	
^{36}Ar	0.46 ± 0.03	4p-8h	4.3 MeV	C. Svensson et al., PRL 85 (2000) 2693
^{38}Ar	$(0.42^{+0.11}_{-0.08})$	4p-6h	3.4 MeV	R. Austin, PhD thesis (2004)
	>0.68	4p-6h	4.7 MeV	
^{40}Ar	$0.48^{+0.16}_{-0.10} \pm 0.05$	4p-4h	2.1 MeV	E. Ideguchi et al., PLB 686 (2010) 18
^{44}Ti	not known	8p-4h	3.1 MeV	D. O'Leary et al., PRC 61 (2000) 064314
^{42}Ca	0.43(4) (0^+_2)	6p-4h	1.8 MeV	K. Hadyńska-Klęk, PRL 117 (2016) 062501
	0.45(4) (2^+_2)	6p-4h		

- ^{40}Ca, ^{40}Ar: fit of one Q_0 to the entire band
- ^{36}Ar: individual lifetimes determined, β_2 from those of 4^+, 6^+ and 8^+
- ^{38}Ar: various fit methods tested, results strongly depend on assumptions
- ^{42}Ca: Coulomb excitation

SD bands throughout the nuclear chart

K. Hadyńska-Klęk, PRC submitted



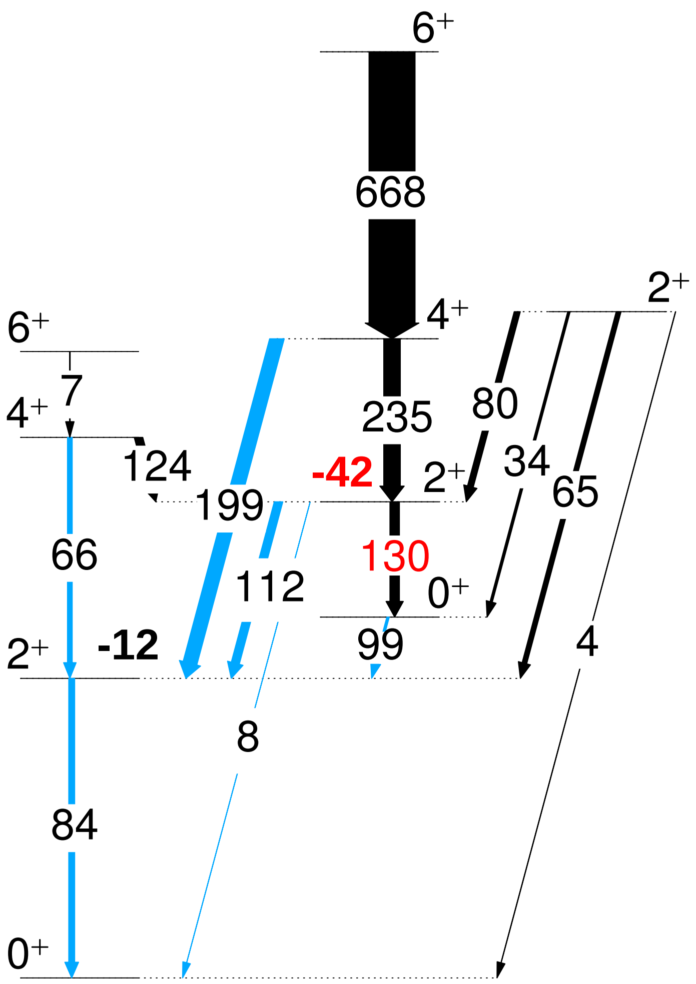


- SD bands in the A∼150, A∼190 and A∼230 regions clearly separated from normal-deformed states
- those for A<150 span a broad range of deformations and are closer to the $A^{-1/3}$ line

Transition probabilities in ^{42}Ca

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

	$\langle I_i \| E2 \| I_f \rangle$ [e·fm^2]	$B(E2\downarrow; I_i^+ \rightarrow I_f^+)$ [W.u.]
$2_1^+ \rightarrow 0_1^+$	$20.5\,^{+0.6}_{-0.6}$	$9.7\,^{+0.6}_{-0.6}$
$4_1^+ \rightarrow 2_1^+$	$24.3\,^{+1.2}_{-1.2}$	$7.6\,^{+0.7}_{-0.7}$
$0_2^+ \rightarrow 2_1^+$	$22.2\,^{+1.1}_{-1.1}$	$57\,^{+6}_{-6}$
$2_2^+ \rightarrow 0_1^+$	$-6.4\,^{+0.3}_{-0.3}$	$1.0\,^{+0.1}_{-0.1}$
$2_2^+ \rightarrow 2_1^+$	$-23.7\,^{+2.3}_{-2.7}$	$12.9\,^{+2.5}_{-2.5}$
$4_2^+ \rightarrow 2_1^+$	$42\,^{+3}_{-4}$	$23\,^{+3}_{-4}$
$2_2^+ \rightarrow 0_2^+$	$26\,^{+5}_{-3}$	$15\,^{+6}_{-4}$
$4_2^+ \rightarrow 2_2^+$	$46\,^{+3}_{-6}$	$27\,^{+4}_{-6}$
	$\langle I_i \| E2 \| I_i \rangle$ [e·fm^2]	Q_{sp} [e·fm^2]
2_1^+	$-16\,^{+9}_{-3}$	$-12\,^{+7}_{-2}$
2_2^+	$-55\,^{+15}_{-15}$	$-42\,^{+12}_{-12}$

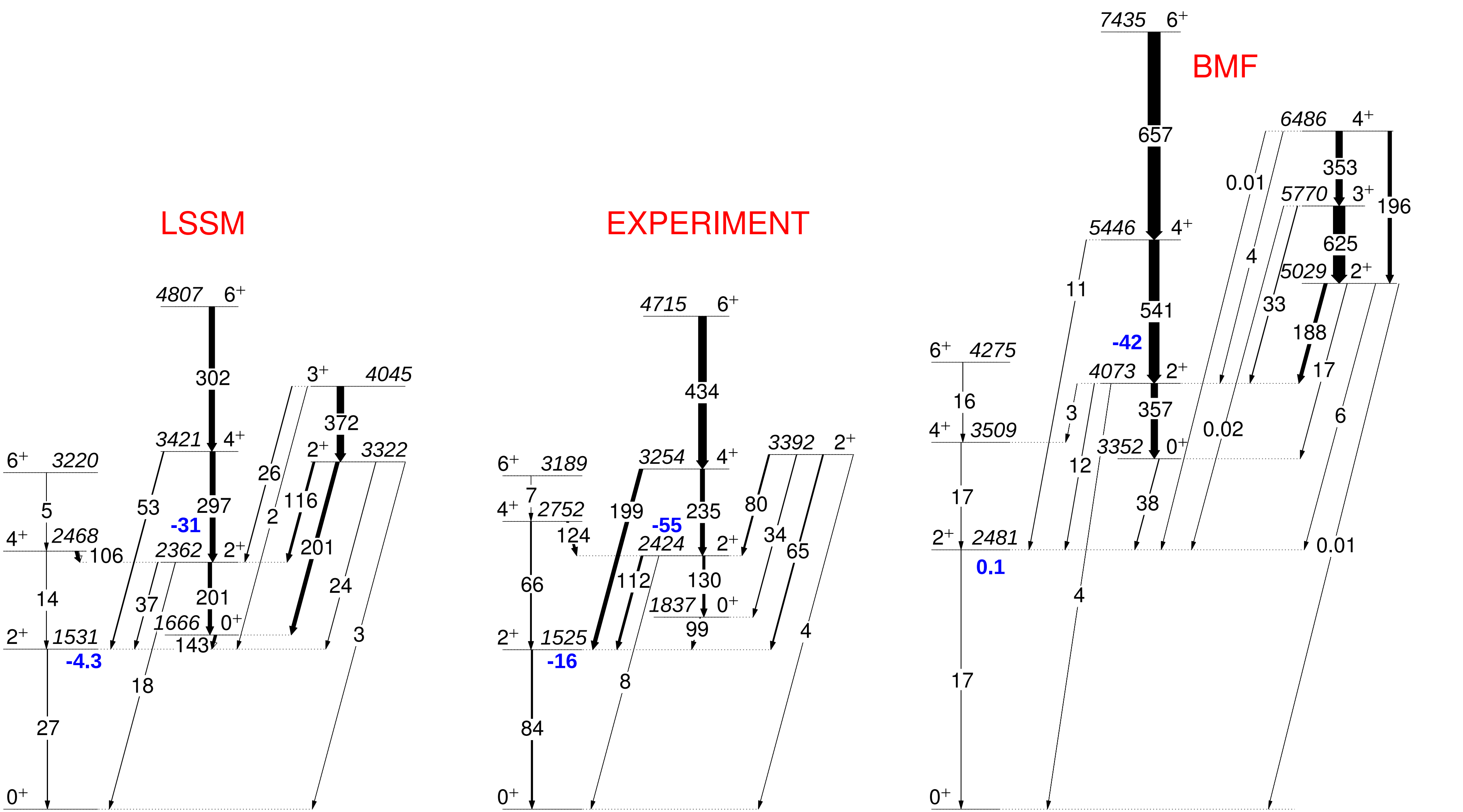


- measured quadrupole moment of 2_2^+ corresponds to $\beta = 0.48(14)$

Comparison with theoretical calculations

K. Hadyńska-Klęk, PRC submitted

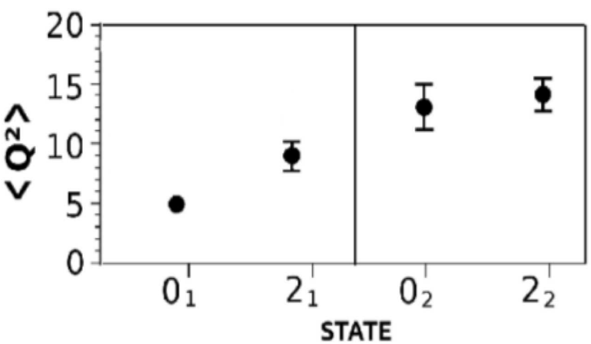
- Large-Scale Shell Model: F.Nowacki, H.Naïdja, B.Bounthong (Strasbourg)
- Beyond Mean Field calculations with Gogny D1S: T. R. Rodriguez (Madrid)

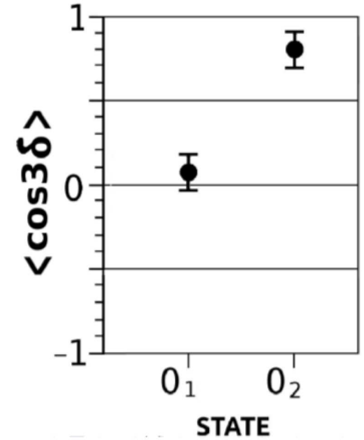


Shape parameters of 0^+ and 2^+ states in ^{42}Ca

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

state	$\langle Q^2 \rangle_{exp}$ [e^{2}fm^4]
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)





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

$$\bar{\gamma} = \arccos \langle \cos(3\delta) \rangle$$

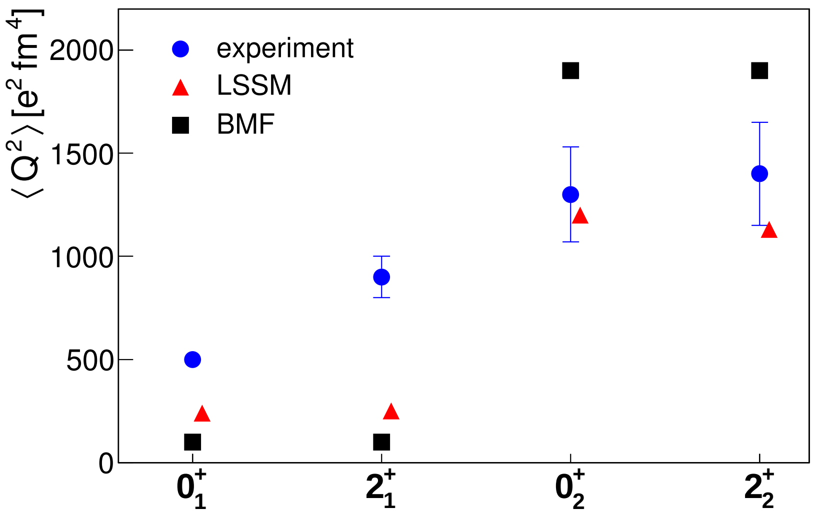
deformation in the side band: $\bar{\beta}$=0.43(4), $\bar{\gamma}$=13(6)°

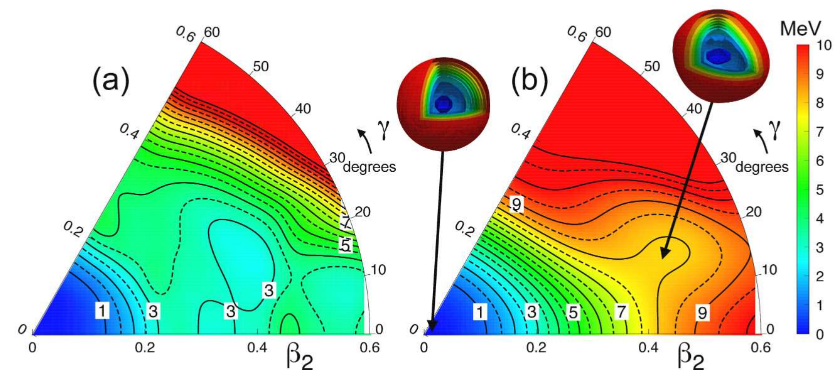
ground-state band: $\bar{\beta}$=0.26(2), $\bar{\gamma}$=29(2)° (?)

are these static deformations, or fluctuations?

softness in β: $\sigma(\mathrm{Q}^2) = \sqrt{\langle \mathrm{Q}^4 \rangle - \langle \mathrm{Q}^2 \rangle^2}$

Comparison with theoretical calculations





- coexistence of two very different structures reproduced by both theories, slightly triaxial SD minimum present in both potential maps
- deformation in the ground-state band increases with spin contrary to theoretical predictions $\rightarrow$ mixing seems to be underestimated by calculations

Configurations of ND and SD structures

^{42}Ca

F.Nowacki, H.Naidja, B.Bounthong
Universiet de Strasbourg, France

state	2p-0h	4p-2h	6p-4h	8p-6h
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
4^+_2	1	15	62	22
6^+_2	1	24	61	14
2^+_3	0	14	59	26
3^+_1	0	4	66	30

^{40}Ca

E.Caurier, J.Menendez, F.Nowacki and A.Poves,
Phys. Rev. C 75, 054317 (2007)

Table V: np-nh structure of the superdeformed band of ^{40}Ca.

J	0p-0h	2p-2h	4p-4h	6p-6h	8p-8h
0	-	-	9	4	87
2	-	-	11	4	85
4	-	-	8	5	87
6	-	-	3	5	91
8	-	-	2	6	91
10	-	-	1	12	87
12	-	-	2	29	69
14	-	-	11	27	63
16	-	-	0	40	60

TABLE IV. Percentage of *n*p-*n*h 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

Shape parameters of 0^+ and 2^+ states in ^{42}Ca

state	$\langle Q^2\rangle_{\text{exp}}$	$\langle Q^2\rangle_{\text{SM}}$	$\sigma(Q^2)_{\text{SM}}$	$\langle Q^2\rangle_{\text{BMF}}$	$\sigma(Q^2)_{\text{BMF}}$
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	$\langle\cos(3\delta)\rangle_{\text{exp}}$	$\langle\cos(3\delta)\rangle_{\text{SM}}$	$\langle\cos(3\delta)\rangle_{\text{BMF}}$
0_1^+	0.06 (10)	0.34	0.34
0_2^+	0.79 (13)	0.67	0.49

$\sigma(Q^2)$ comparable with $\langle Q^2\rangle$ for the ground-state band

$\rightarrow$ fluctuations about a spherical shape

excited band: $\sigma(Q^2)$ few times lower than $\langle Q^2\rangle$

$\rightarrow$ static deformation

Two-states mixing model applied to ^{42}Ca

- we assume that physical states are linear combinations of pure spherical and deformed configurations:

$$|\mathsf{I}_1^+\rangle = +\cos\theta_{\mathsf{I}}\times|\mathsf{I}_p^+\rangle + \sin\theta_{\mathsf{I}}\times|\mathsf{I}_s^+\rangle$$
$$|\mathsf{I}_2^+\rangle = -\sin\theta_{\mathsf{I}}\times|\mathsf{I}_p^+\rangle + \cos\theta_{\mathsf{I}}\times|\mathsf{I}_s^+\rangle$$

	Experiment	SM	BMF
$\cos^2(\theta_0)$	0.88(4)	0.85	0.96
$\cos^2(\theta_2)$	0.39(8)	0.83	0.97

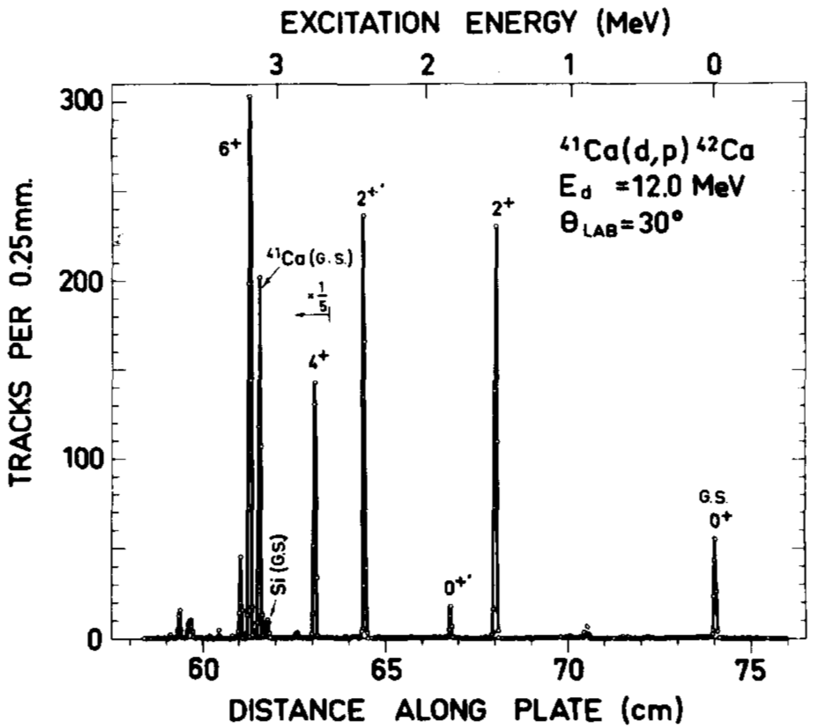
- $\cos^2(\theta_0)$ can be also extracted from E0 transition strength:

$$\rho^2(E0) = \left(\frac{3Z}{4\pi}\right)^2 \cos^2(\theta_0)\sin^2(\theta_0)\cdot\left[\left(\beta_1^2-\beta_2^2\right)+\frac{5\sqrt{5}}{21\sqrt{\pi}}\left(\beta_1^3\cos\gamma_1-\beta_2^3\cos\gamma_2\right)\right]^2$$

- obtained value of 0.84(4) is in perfect agreement with that extracted from E2 matrix elements

- $\cos^2(\theta_2)<0.5$: two-state mixing model cannot be applied to 2^+ states in ^{42}Ca

Population of the deformed structure in one-neutron transfer

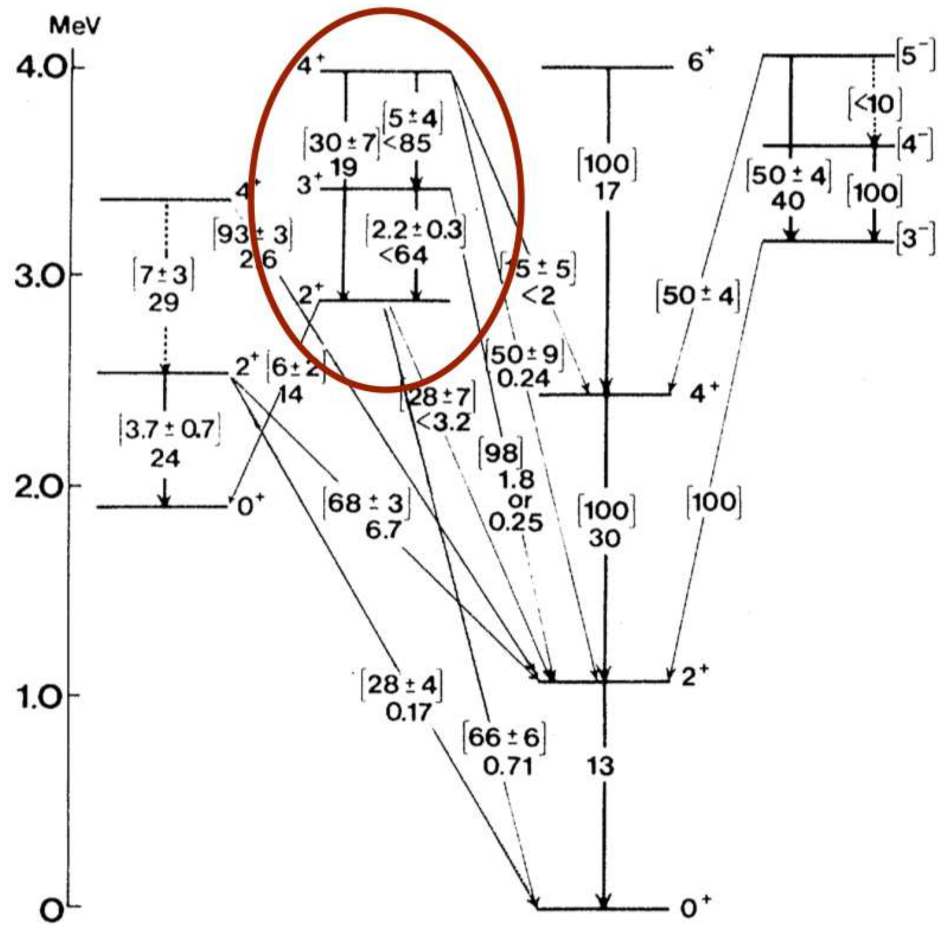


C. Ellegaard et al, Phys. Lett. 40B (1972) 641

- equal population of 2^+_1 and 2^+_2 in (d,p) – configuration mixing
- 4^+_1 populated in one-nucleon transfer – it is not a two-phonon state, so the increase of $\langle Q^2 \rangle$ in the g.s. cannot be interpreted as resulting from the vibrational character of 2^+_1

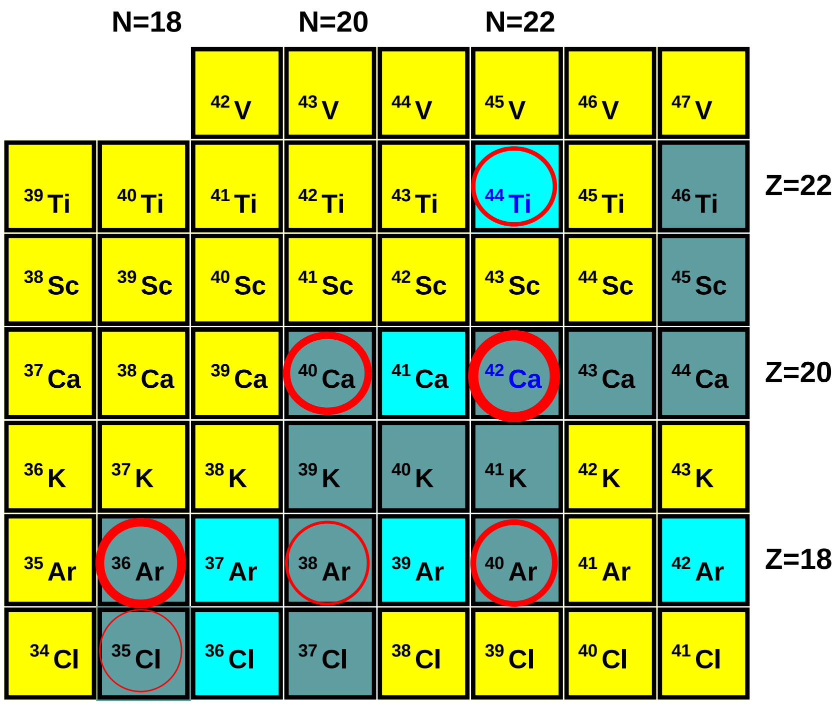
Gamma deformation

J. Simpson et al, PRL 31 (1973) 947



- K=2 band identified in (p,t) and (α, γ) studies of ^{44}Ti
- is there a similar band built on 2_3^+ in ^{42}Ca?

Outlook



- are there similar structures in ^{40,42}Ti and ^{38}Ca?
- what about odd-mass nuclei?
- ^{38}Ar seems not well understood
- role of triaxiality?