Coulex of SD band in ^{40}Ca

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Super-deformation in ^{40}Ca

VOLUME 87, NUMBER 22 PHYSICAL REVIEW LETTERS 26 NOVEMBER 2001

Superdeformation in the Doubly Magic Nucleus $^{40}_{20}\mathrm{Ca}_{20}$

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A rotational band with seven γ-ray transitions between states with spin $2\hbar$ and $16\hbar$ has been observed in the doubly magic, self-conjugate nucleus $^{40}_{20}\mathrm{Ca}_{20}$. The measured transition quadrupole moment of $1.80^{+0.39}_{-0.29}e$b indicates a superdeformed shape with a deformation $\beta_2 = 0.59^{+0.11}_{-0.07}$. The features of this band are explained by cranked relativistic mean field calculations to arise from an 8-particle 8-hole excitation.

DOI: 10.1103/PhysRevLett.87.222501 PACS numbers: 21.10.Tg, 21.10.Re, 23.20.Lv, 27.40.+z

Studies of superdeformed (SD) rotational bands in nuclei have been the focus of major experimental and theo-

ments for some of the low-spin states in ^{40}Ca have been reported [6], and discussed [7] as multiparticle-multihole

Super-deformation in ^{40}Ca

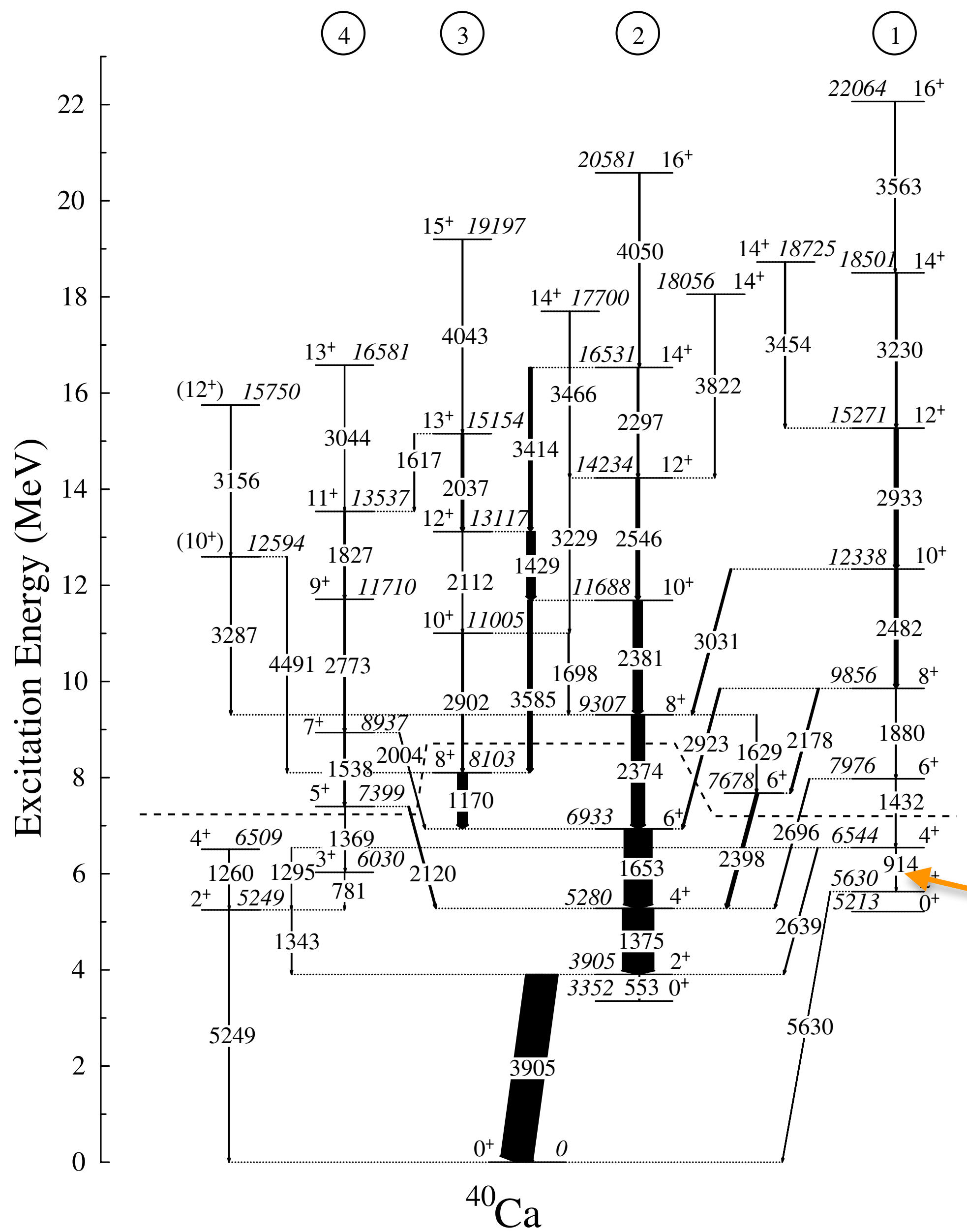

FIG. 1. Partial level scheme of ^{40}Ca; the energy labels are given in keV, and the widths of the arrows are proportional to the relative intensities of the γ rays. Only the levels below the dashed line were known prior to this work.

222501-2

Band ②: ND

Q_t=0.74(±0.14)eb

β_2=0.27(±0.04)

Band ①: SD

Q_t=1.80(+10.39,-0.29) eb

β_2=0.59(+0.11,-0.07)

B(E2; 4$^+$-2$^+$)=170 [W.u.]

Historical Super-deformation in ^{152}Dy

VOLUME 57, NUMBER 7 PHYSICAL REVIEW LETTERS 18 AUGUST 1986

Observation of a Discrete-Line Superdeformed Band up to $60\hbar$ in ^{152}Dy

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M. A. Bentley, H. W. Cranmer-Gordon, P. D. Forsyth, D. Howe, A. R. Mokhtar, J. D. Morrison, and J. F. Sharpey-Schafer
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and

G. Sletten
Niels Bohr Institute, Risø, Roskilde, DK-2100 Copenhagen, Denmark
(Received 5 May 1986)

A rotational band of nineteen transitions with a moment of inertia $\mathcal{J}^{(2)}_{\text{band}}$ of $84\hbar^2$ MeV^{-1} has been observed in ^{152}Dy. The band feeds into the oblate yrast states between 19^- and 25^- and it is proposed that the lowest member of the band has a spin of 22^+ and thus the band extends up to $60\hbar$. It is identified as the yrast superdeformed band and its intensity accounts for the whole of the ridge structure seen previously in continuum E_γ-E_γ correlations.

PACS numbers: 21.10.Re, 23.20.Lv, 27.70.+q

The nucleus ^{152}Dy has been extensively studied and three different structures have been identified. The low-spin yrast levels have a pseudovibrational structure[1] which develops into a low-deformation ($\beta \approx 0.15$) prolate rotational band[2] extending up to $40\hbar$. This band, in the spin region between $8\hbar$ and $38\hbar$, lies between 0.5 and 1.5 MeV above the yrast states which have a weak oblate structure formed by particles in equatorial orbits.[3–5] At higher spins the γ-ray continuum is dominated by a collective $E2$ bump.[6] Part of this bump has been shown to arise from superdeformed ($\beta \approx 0.6$) bands from the existence of ridges with a inertia $\mathcal{J}^{(2)} = (85 \pm 2)\hbar^2$ MeV^{-1} in

used in TESSA2[10] with twelve escape-suppressed germanium detectors.[11] The states in ^{152}Dy were populated by the reaction ^{108}Pd(^{48}Ca, $4n$) at 205 MeV with a target consisting of two 500-μg-cm^{-2} self-supporting foils isotopically enriched at 95% in ^{108}Pd. A 15-mg-cm^{-2} gold catcher foil was positioned 5 cm downstream of the targets such that it was outside the focus of the germanium detectors but within the full detection efficiency of the BGO ball. A total of over 150 million double (Ge-Ge) coincidences were recorded together with the sum energy and number of hits (fold) in the BGO ball. The time difference between the BGO ball and the second coincidence germanium

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A rotational band of nineteen transitions with a moment of inertia $\mathcal{J}^{(2)}_{\text{band}}$ of 8
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together with the sum
(fold) in the BGO ball.
the BGO ball and the

Super-deformation

nuclear shape far from the sphere
ratio of semi major axis to semi minor axises:
2:1:1 (β_2=0.6)

Normal deformation:

1.3:1:1 (β_2=0.3)

Hiper-deformation:

3:1:1 (β_2=1.3)

Super-deformation w ^{40}Ca
Shell Model Theory

PHYSICAL REVIEW C **75**, 054317 (2007)

Coexistence of spherical states with deformed and superdeformed bands in doubly magic ^{40}Ca: A shell-model challenge

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[1]*IReS, Bât27, IN2P3-CNRS/Université Louis Pasteur BP 28, F-67037 Strasbourg Cedex 2, France*
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(Received 15 February 2007; published 14 May 2007)

Large-scale shell-model calculations, with dimensions reaching 10^9, are carried out to describe the recently observed deformed (ND) and superdeformed (SD) bands based on the first and second excited 0^+ states of ^{40}Ca at 3.35 and 5.21 MeV, respectively. A valence space comprising two major oscillator shells, *sd* and *pf*, can accommodate most of the relevant degrees of freedom of this problem. The ND band is dominated by configurations with four particles promoted to the *pf* shell (4p-4h in short). The SD band by 8p-8h configurations. The ground state of ^{40}Ca is strongly correlated, but the closed shell still amounts to 65%. The energies of the bands are very well reproduced by the calculations. The out-band transitions connecting the SD band with other states are very small and depend on the details of the mixing among the different np-nh configurations; in spite of that, the calculation describes them reasonably. For the in-band transition probabilities along the SD band, we predict a fairly constant transition quadrupole moment $Q_0(t) \sim 170\, e\ \mathrm{fm}^2$ up to $J = 10$ that decreases toward the higher spins. We submit also that the $J = 8$ states of the deformed and superdeformed bands are maximally mixed.

DOI: 10.1103/PhysRevC.75.054317 PACS number(s): 21.60.Cs, 23.20.Lv, 27.40.+z

Super-deformation w ^{40}Ca Theory

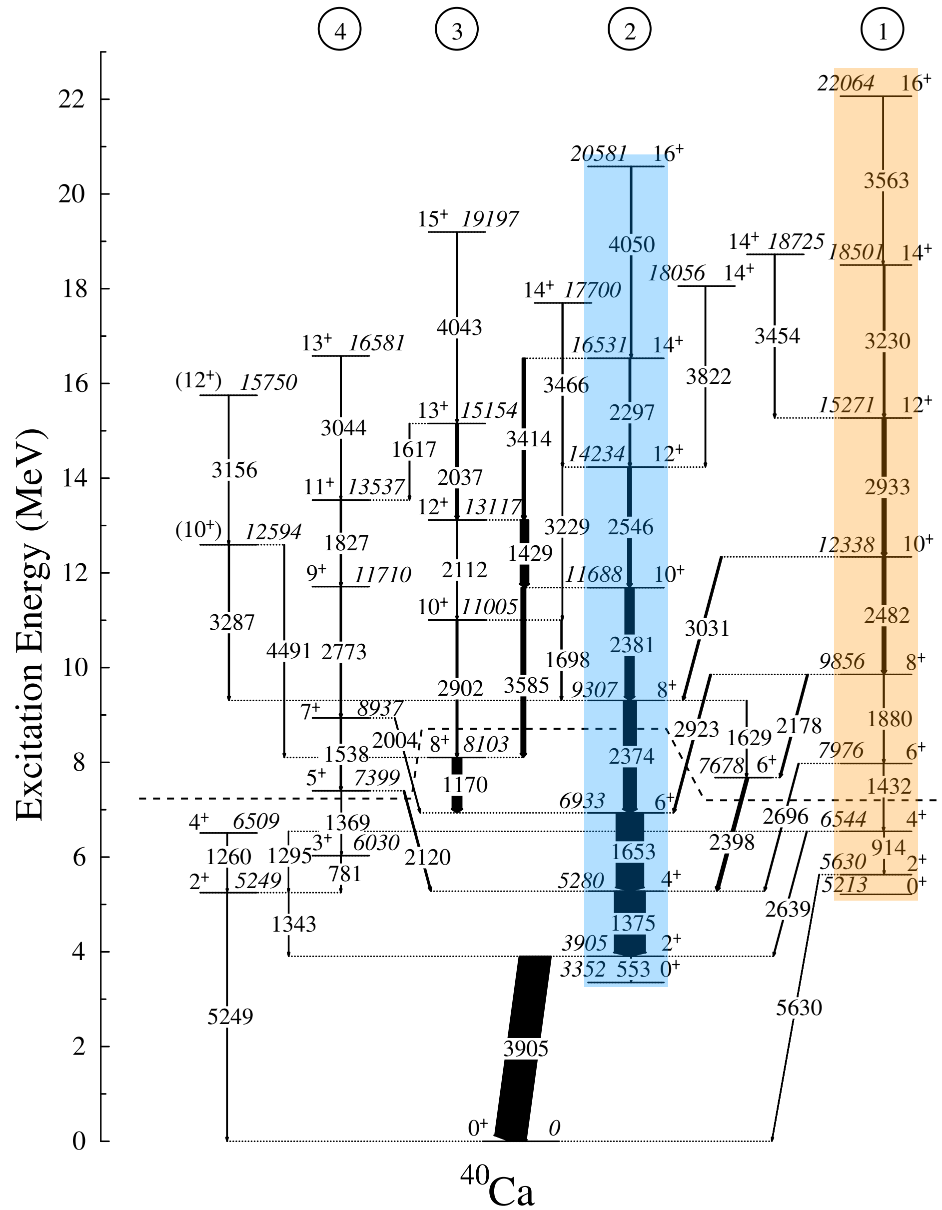
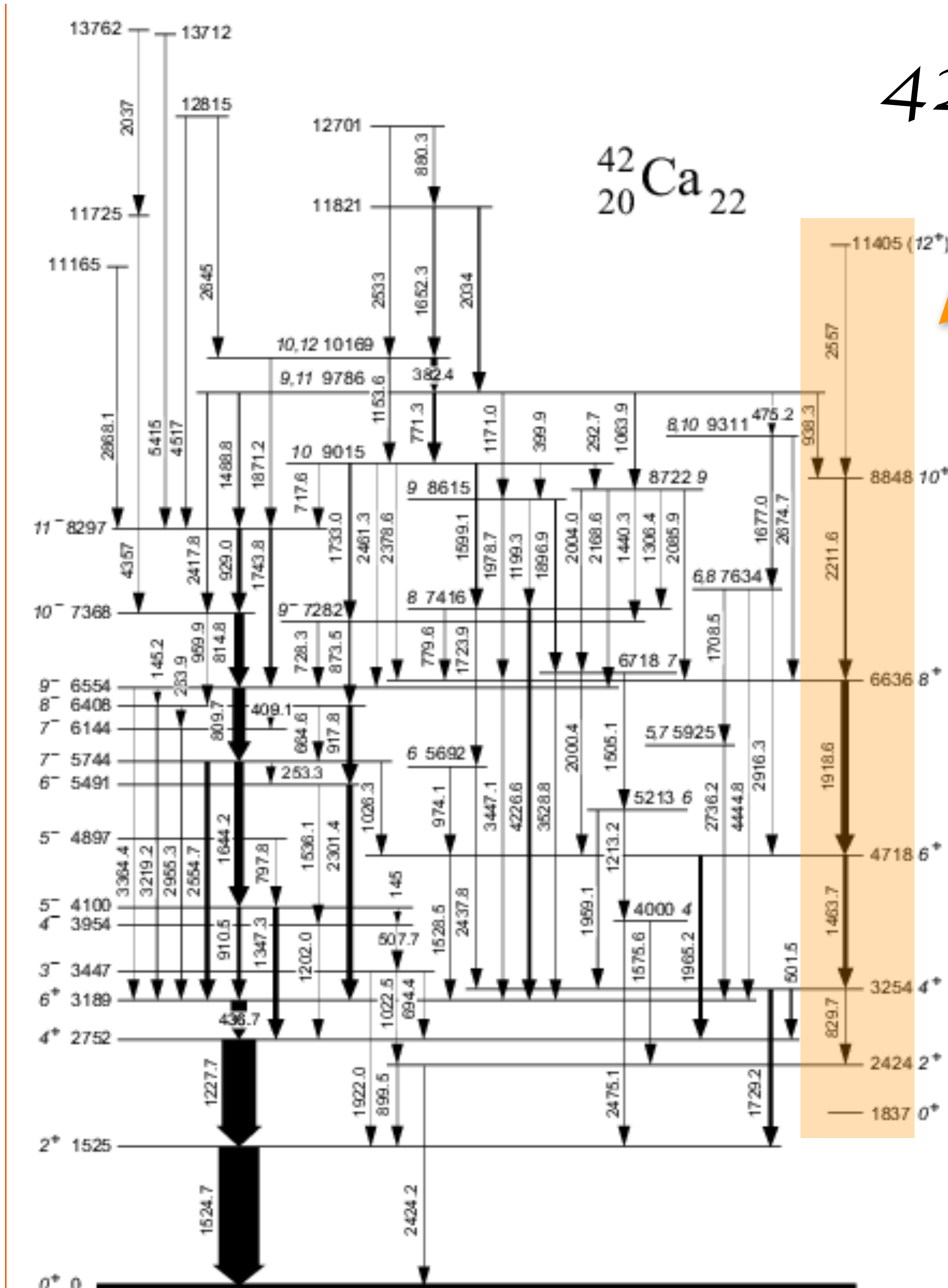


FIG. 1. Partial level scheme of ^{40}Ca; the energy labels are given in keV, and the widths of the arrows are proportional to the relative intensities of the γ rays. Only the levels below the dashed line were known prior to this work.

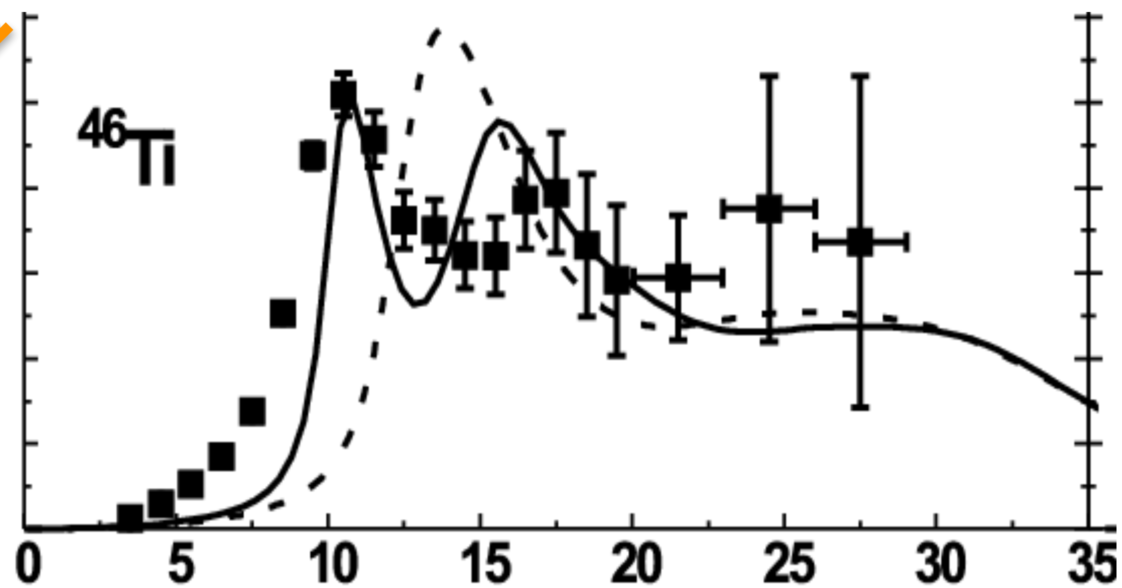
TABLE IV. Percentage of np-nh components and energy of the first three 0^+ states (GS, ND, and SD) of ^{40}Ca.

	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

In Search of Super-deformation
^{42}Ca's Way



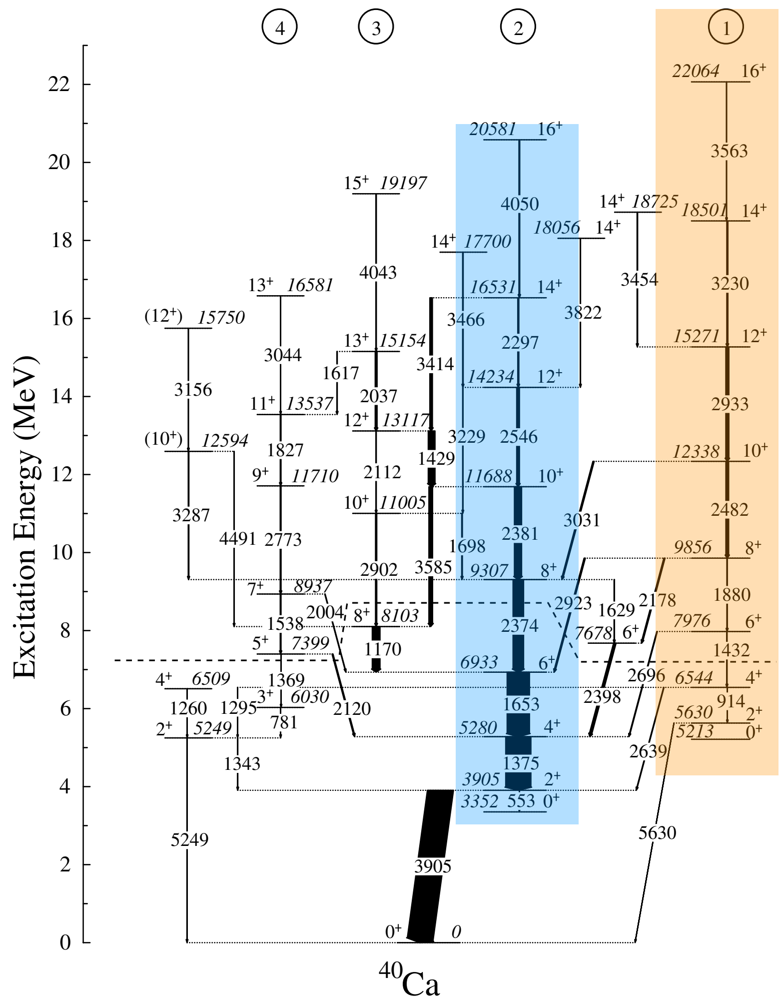
M. Lach et al., Eur Phys J. A12, 381 (2001) EB+RFD exp.



GDR decay in ^{46}Ti populate band w ^{42}Ca (HECTOR + EB IV)

M. Kmiecik et al.,
Acta Phys. Pol. B36, 1169 (2005).

^{40}Ca vs ^{42}Ca



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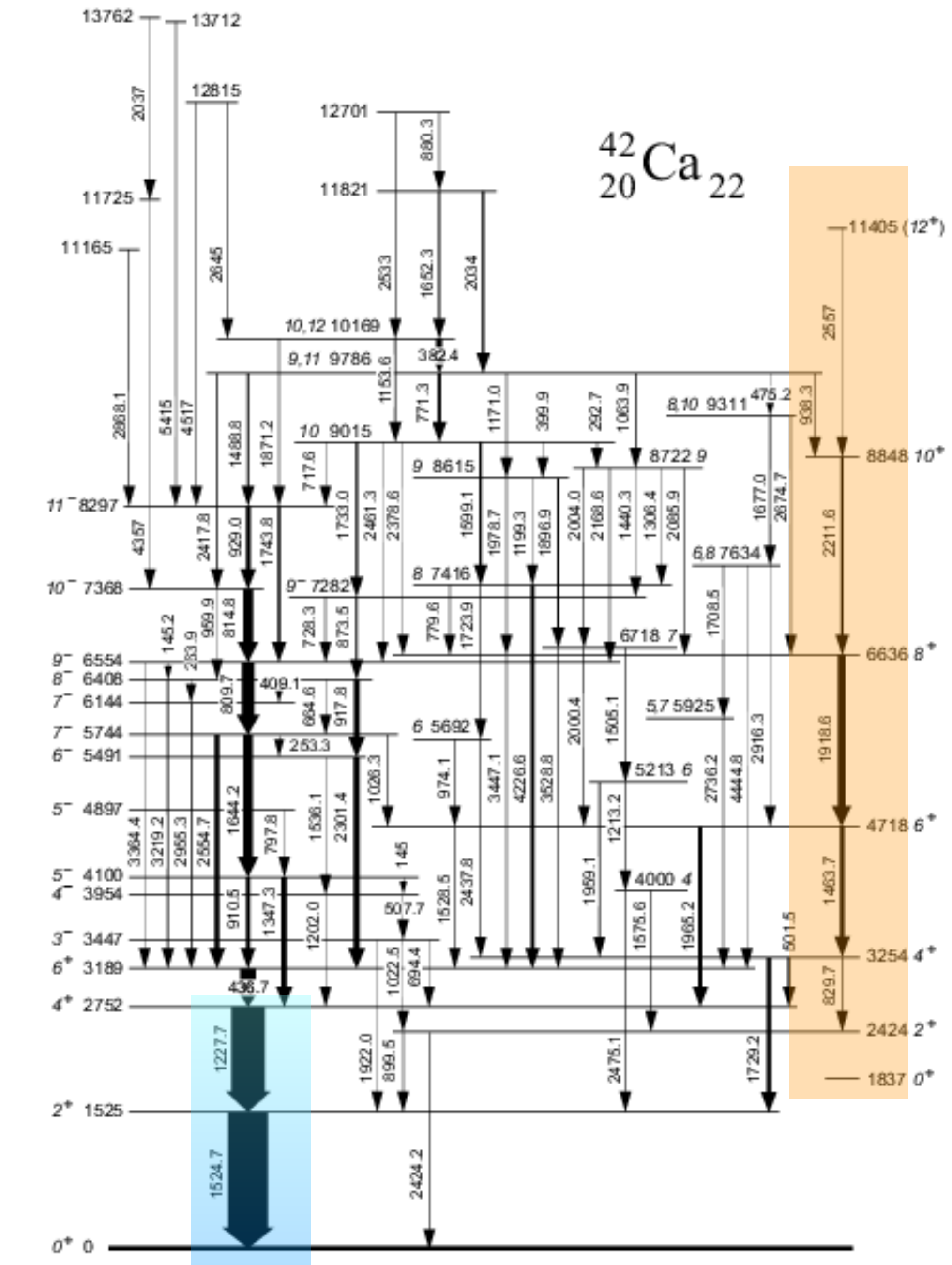


^{40}Ca vs ^{42}Ca

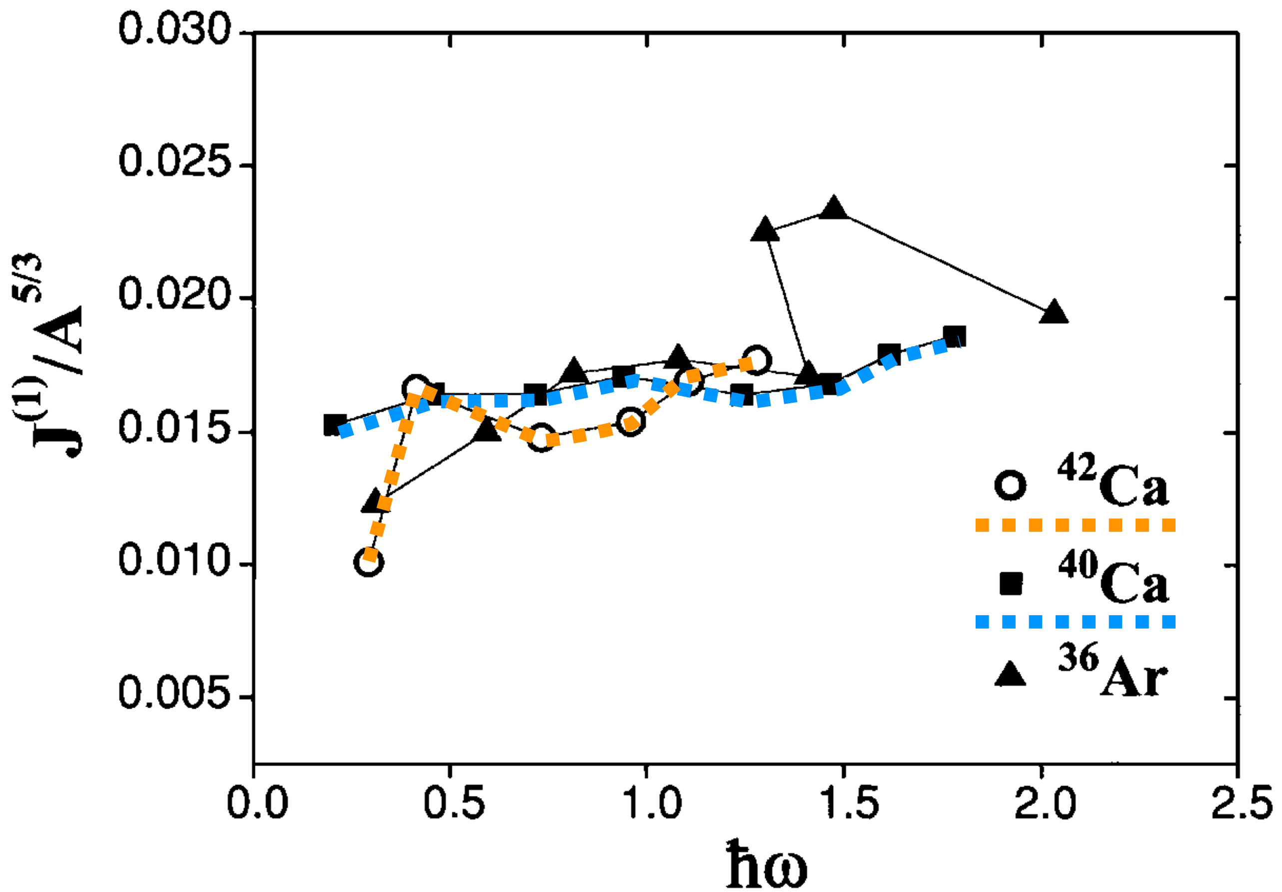
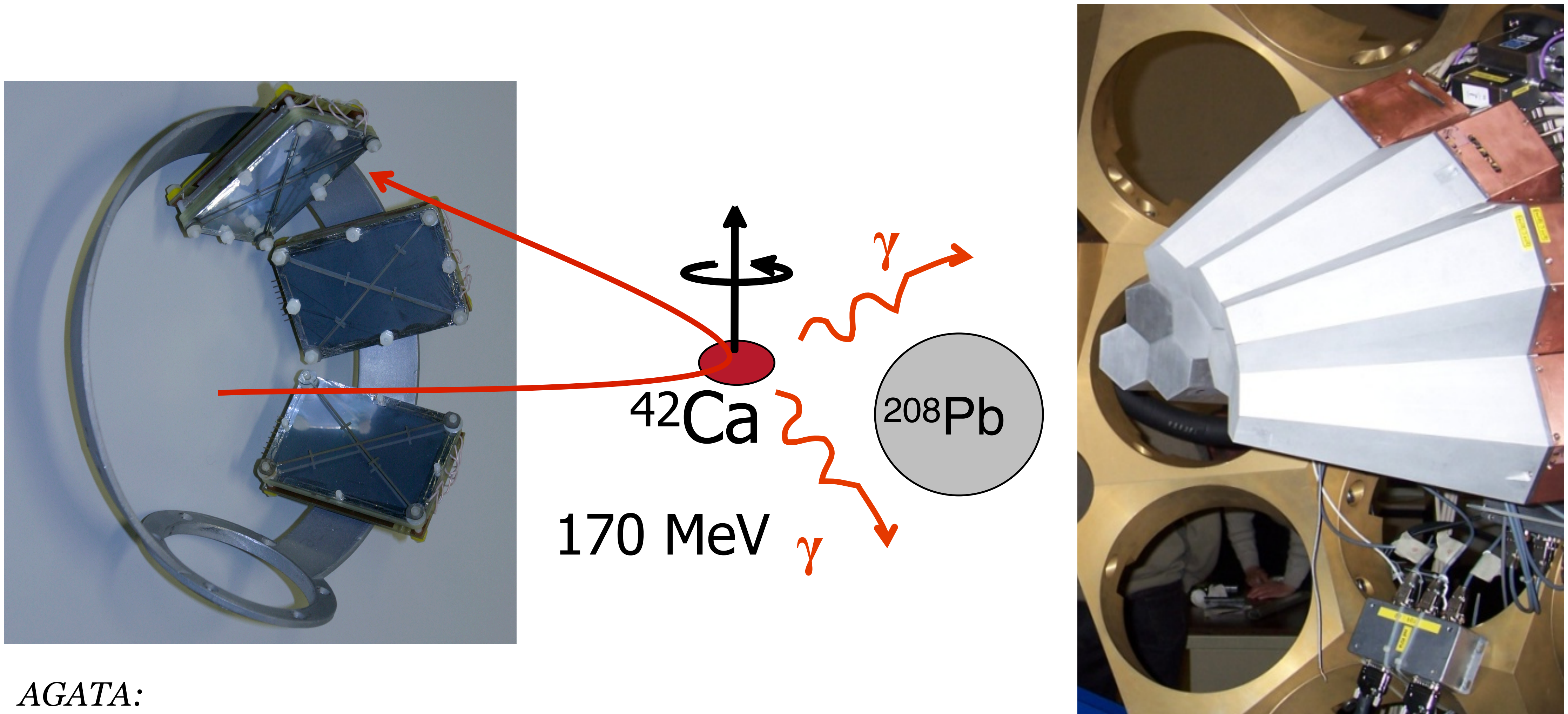


Fig. 4. The kinematic $J^{(1)}$ moments of inertia, scaled by $A^{5/3}$, as a function of rotational frequency for non-yrast positive-parity states in ^{42}Ca and for superdeformed bands in ^{40}Ca [8] and ^{36}Ar [7].

M. Lach et al., Eur Phys J. A12, 381 (2001) EB+RFD exp.

Coulomb excitation of ^{42}Ca @ LNL

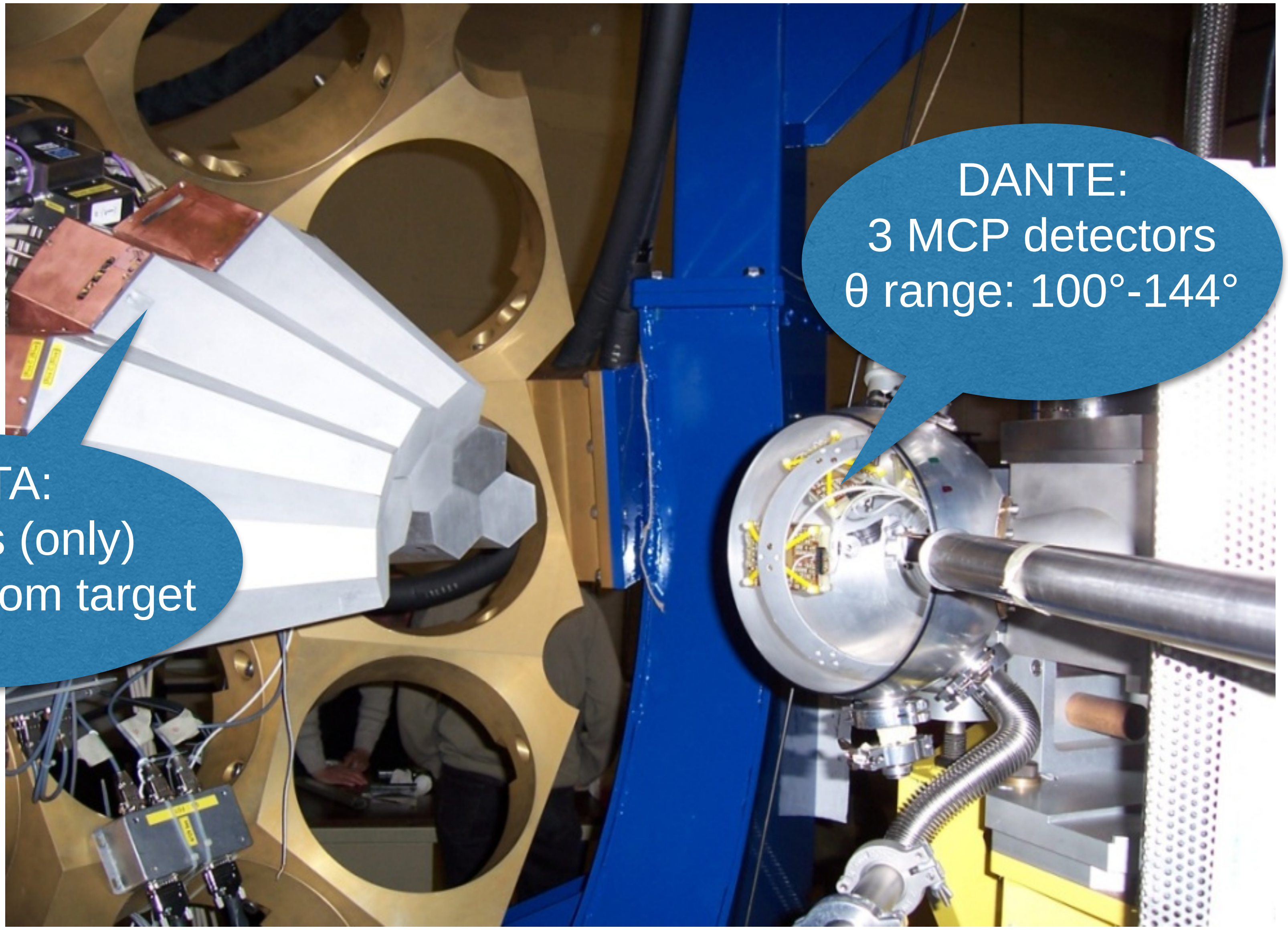


AGATA:
S. Akkoyun et al., Nucl. Instrum. Methods Phys. Res., Sect. A 668, 26 (2012).

DANTE:
A. Gadea et al., Nucl. Instrum. Methods A 654, 88 (2011).
J. J. Valiente-Dobón et al., Acta Phys. Pol. B37, 225 (2006).

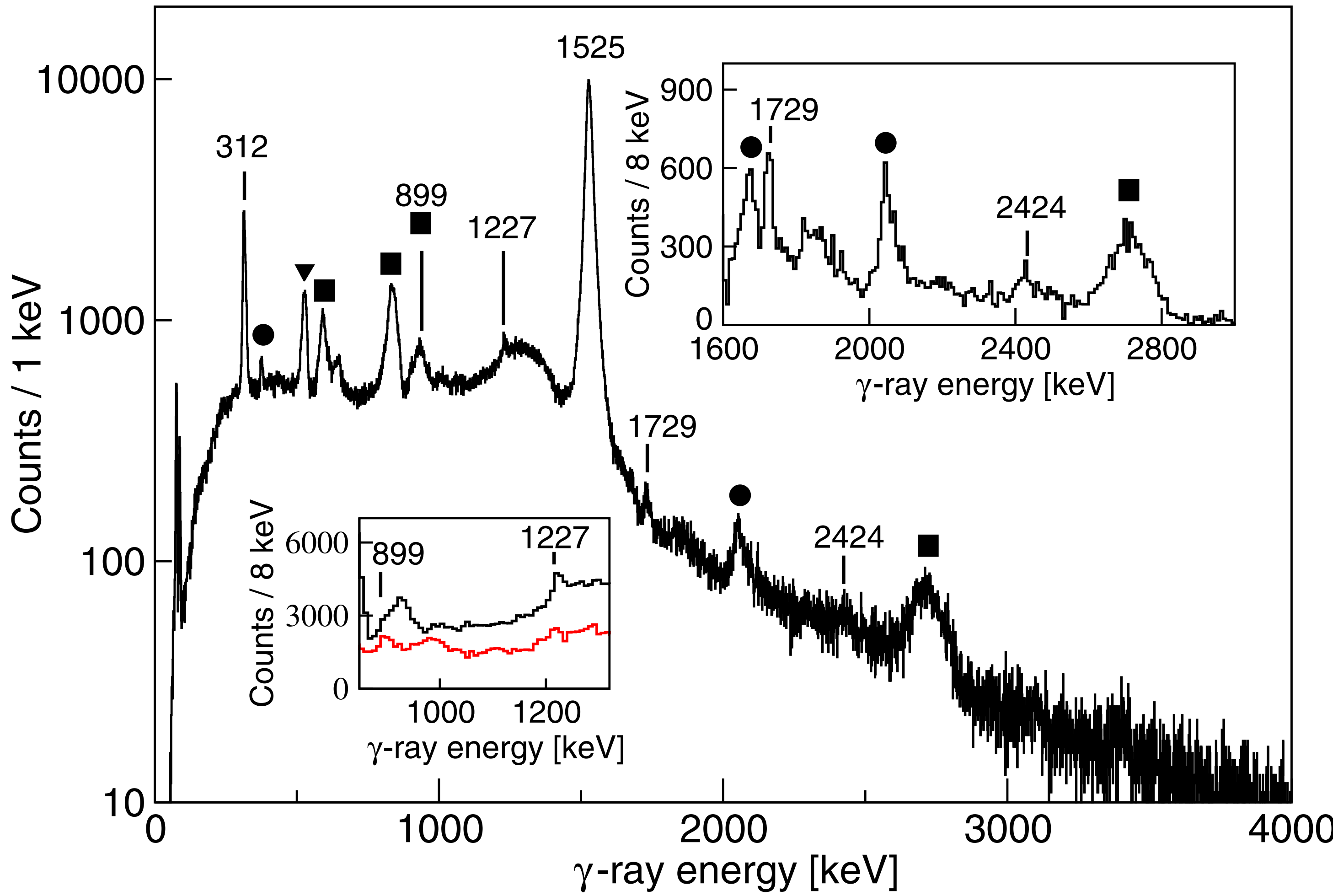
^{42}Ca COULEX @ LNL

- Experiment :
  February 2010
- Beam:
  ^{42}Ca, 170 MeV
- targets:
  ^{208}Pb, 1 mg/cm^2
  ^{197}Au, 1 mg/cm^2
- 70% Coulomb barrier
- p–γ coincidence rate
  150÷250 Hz

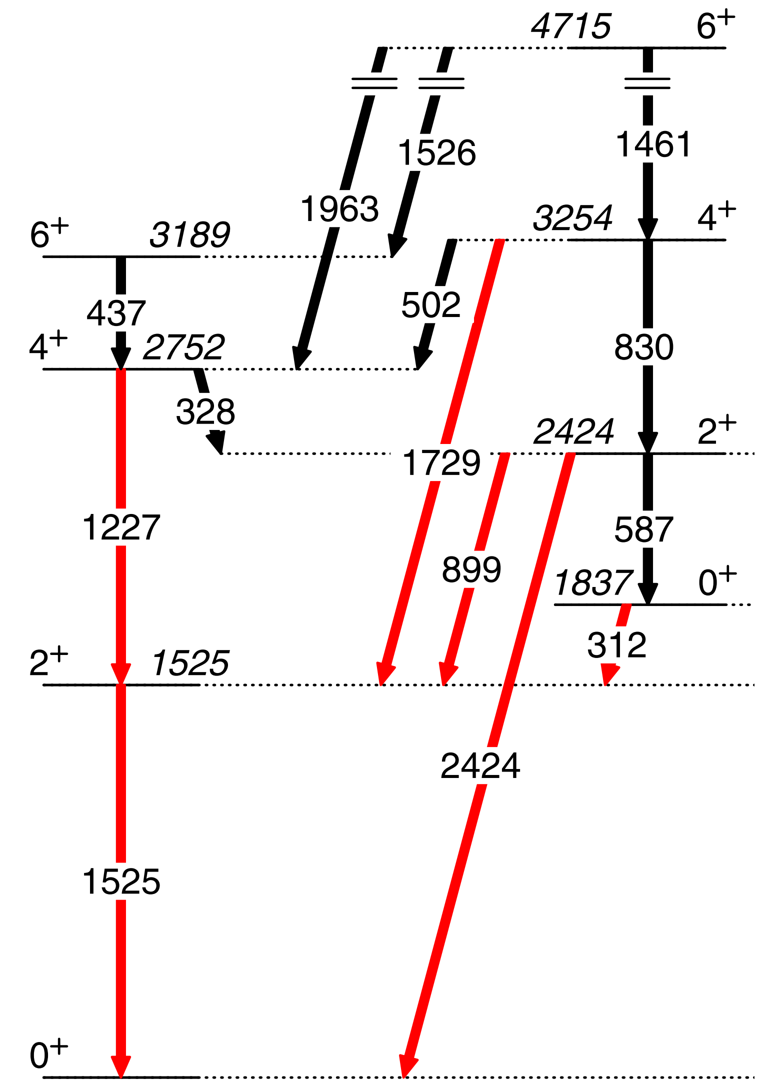


The first use of AGATA to measure unknown

Results from LNL



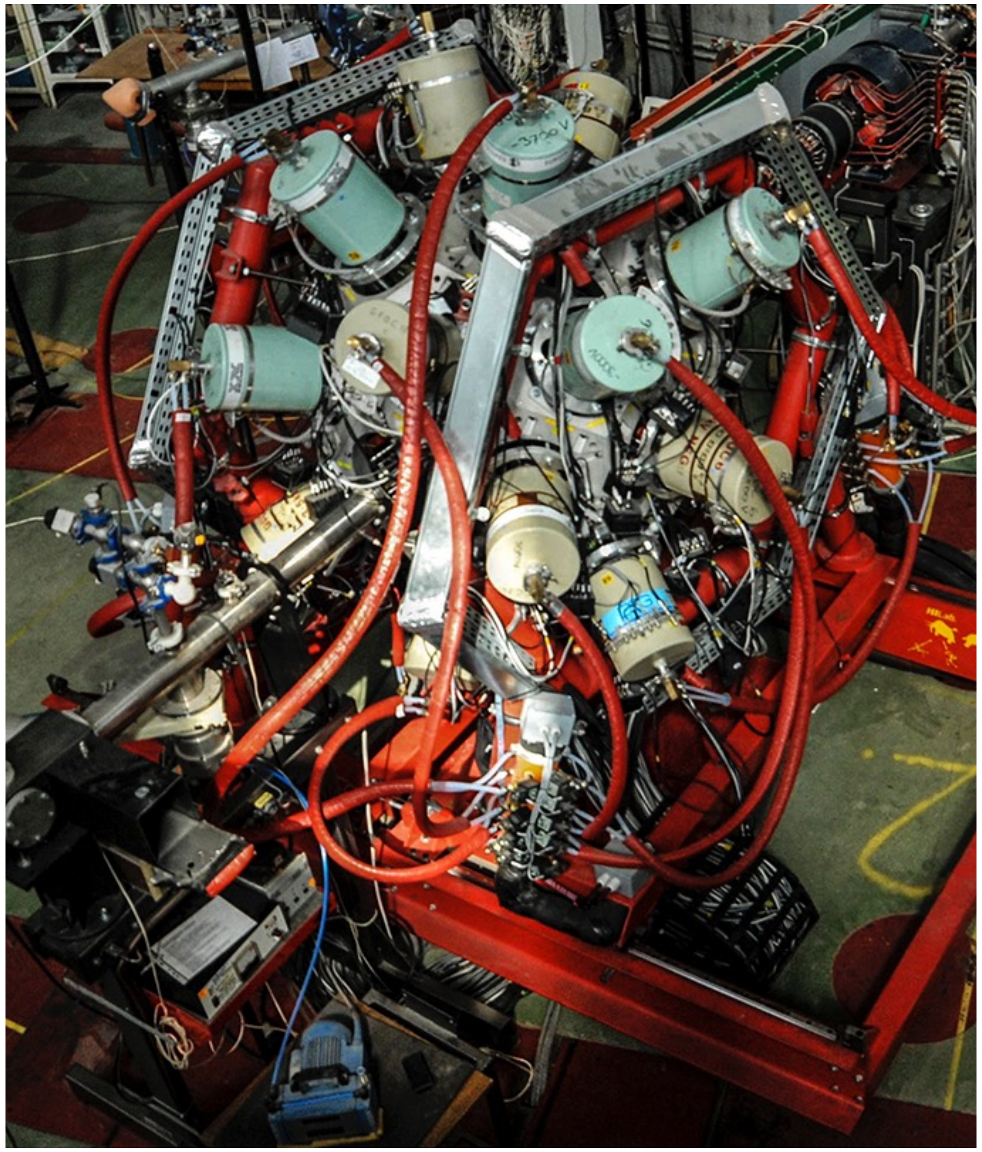
■ Pb (208, 207, 206, 204)
▼ 511 keV
● ^{43}Ca



^{42}**Ca**

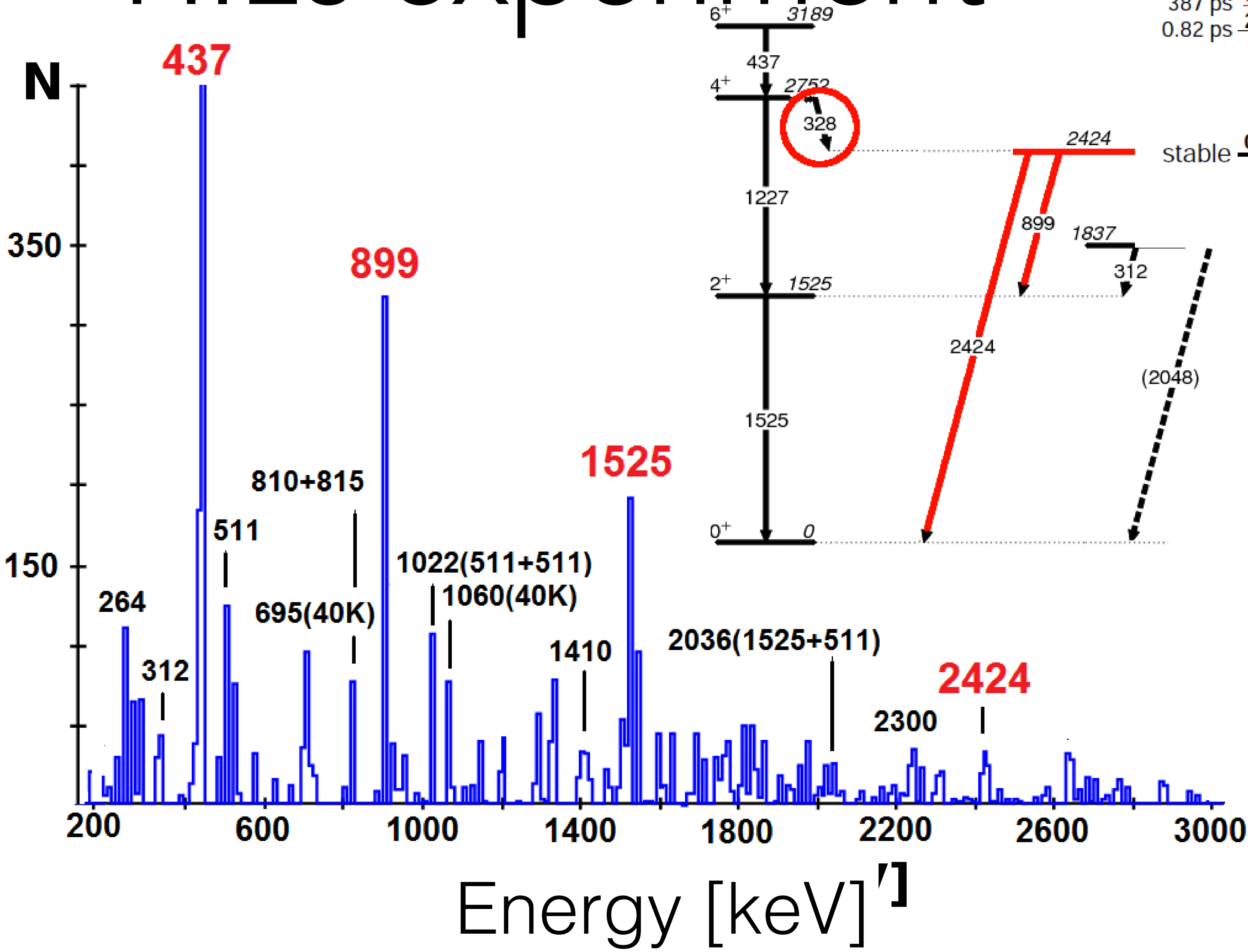
Experiment @ HIL

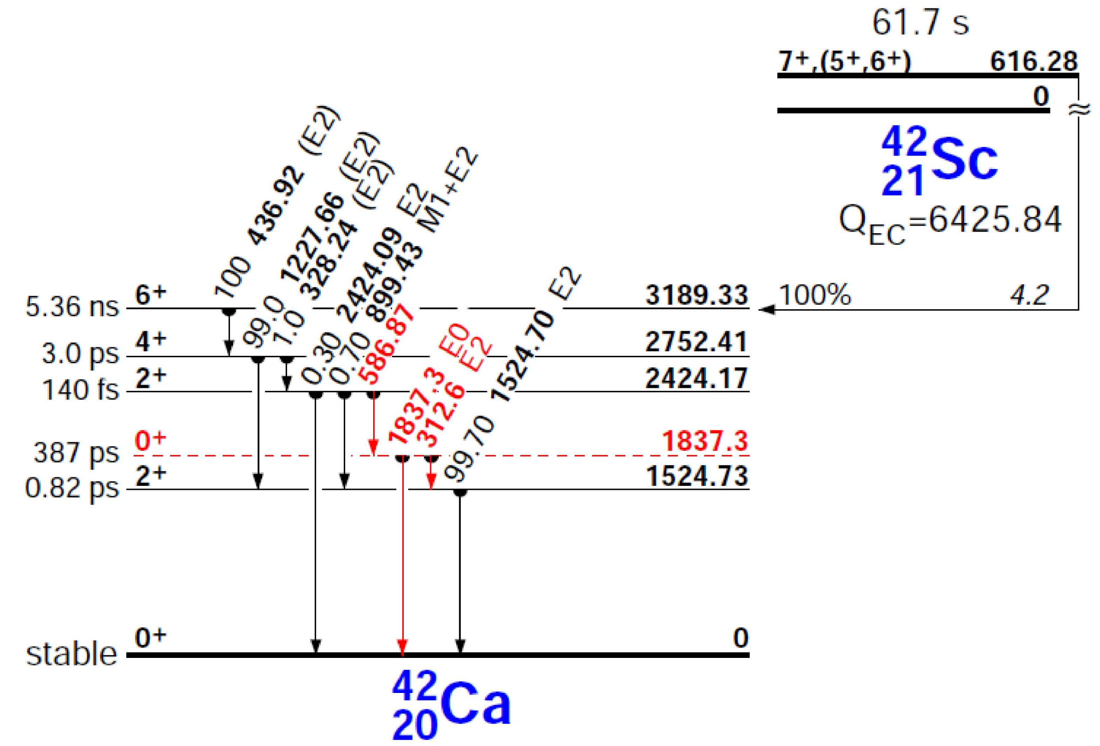
- Experiment: October, 2011
- Beam: ^{32}S, 76 MeV
- Target: ^{12}C, 4 mg/cm^2
- Reaction: $^{12}C(^{32}S,2p)^{42}Ca$
  110 mb (COMPA & PACE)
- EAGLE-II:
  15 HPGe Euroball Phase I od
  GAMMAPOOL



J. Mierzejewski et al., Nucl. Instrum. Methods A 659, 84 (2011).

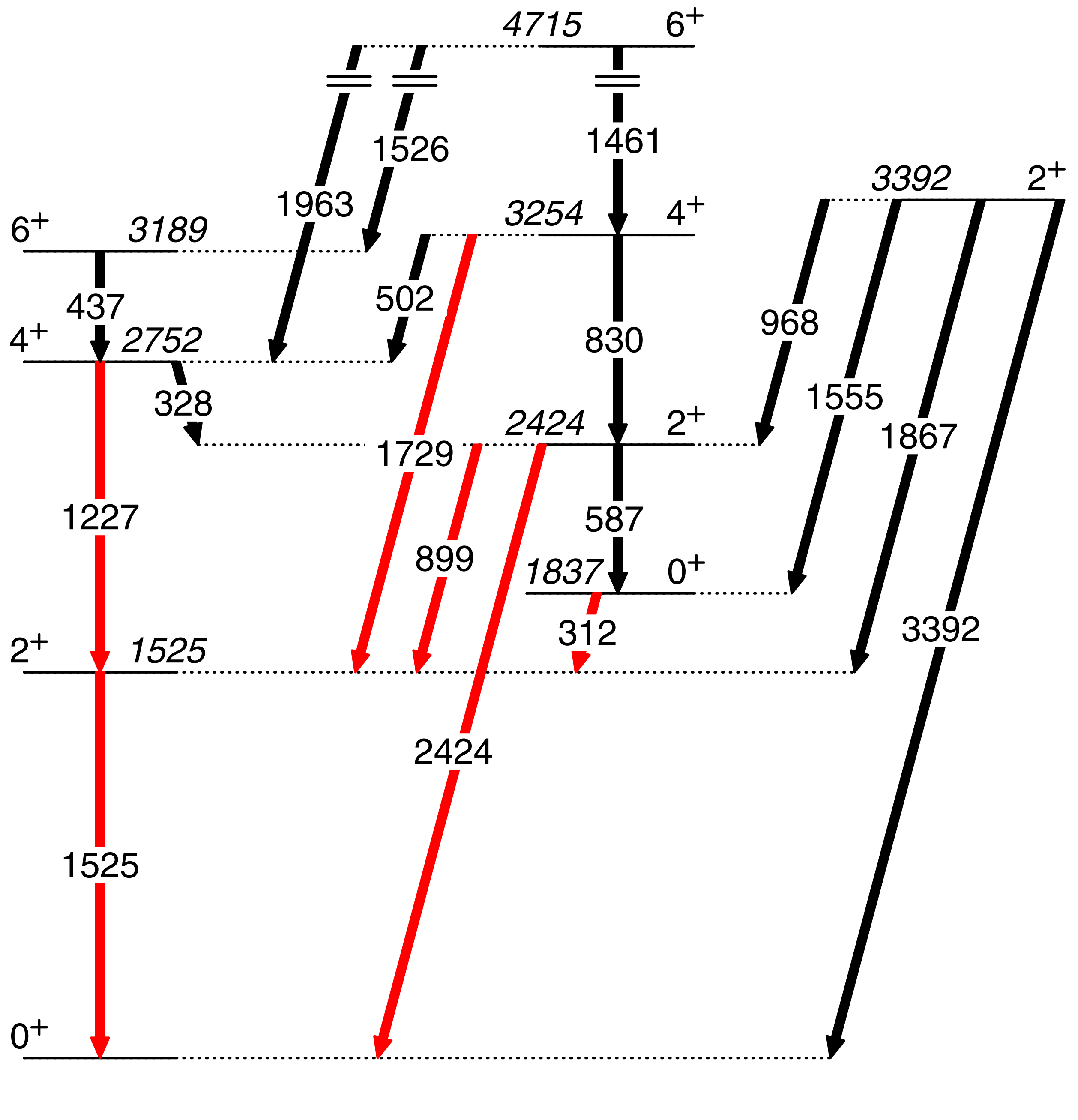
Result from HIL's experiment





Off-beam Coincidence spectrum gated on 328 keV line

Electromagnetic structure of ^{42}Ca



^{42}Ca

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

Deformation of ^{42}Ca

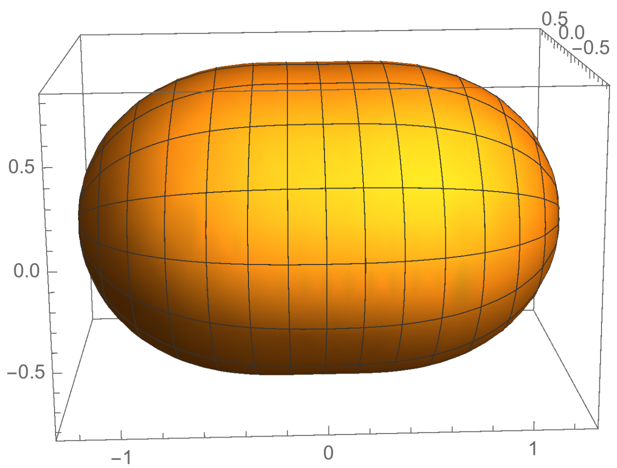
$$\frac{1}{\sqrt{5}}\langle Q^2\rangle = \langle i\,|[E2\times E2]_0|\,i\rangle =$$

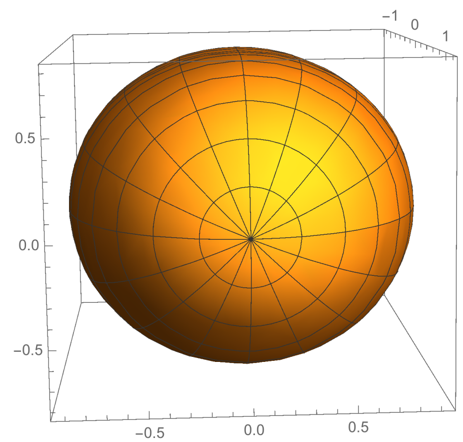
$$= \frac{1}{\sqrt{(2I_i+1)}}\sum_t \langle i\|\mathrm{E2}\|t\rangle\langle t\|\mathrm{E2}\|i\rangle \begin{Bmatrix} 2 & 2 & 0 \\ I_i & I_i & I_t \end{Bmatrix}$$

$$\sqrt{\frac{2}{35}}\langle Q^3 cos3\delta\rangle = \langle i\,|[[E2\times E2]_2\times E2]_0|\,i\rangle =$$

$$= \frac{\mp 1}{(2I_i+1)}\sum_{t,u} \langle i\|\mathrm{E2}\|u\rangle\langle u\|\mathrm{E2}\|t\rangle\langle t\|\mathrm{E2}\|i\rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{Bmatrix}$$

Non-energy weighted quadrupole sum rules
K. Kumar, Phys. Rev. Lett. 28, 249 (1972).



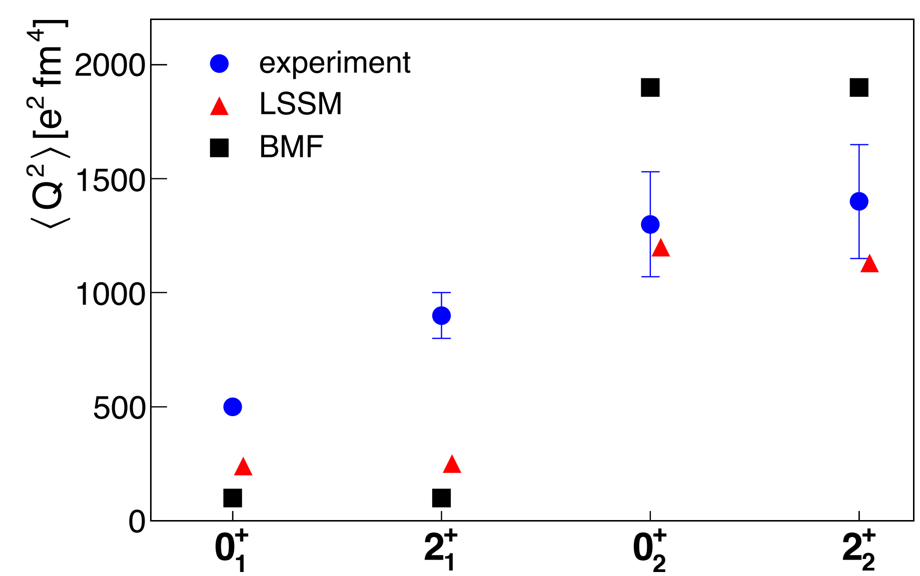


<Q^2>[e^{2}fm^4]

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

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

for 0_2^+
β_2=0.43(2)
γ=13(-6,+5)°

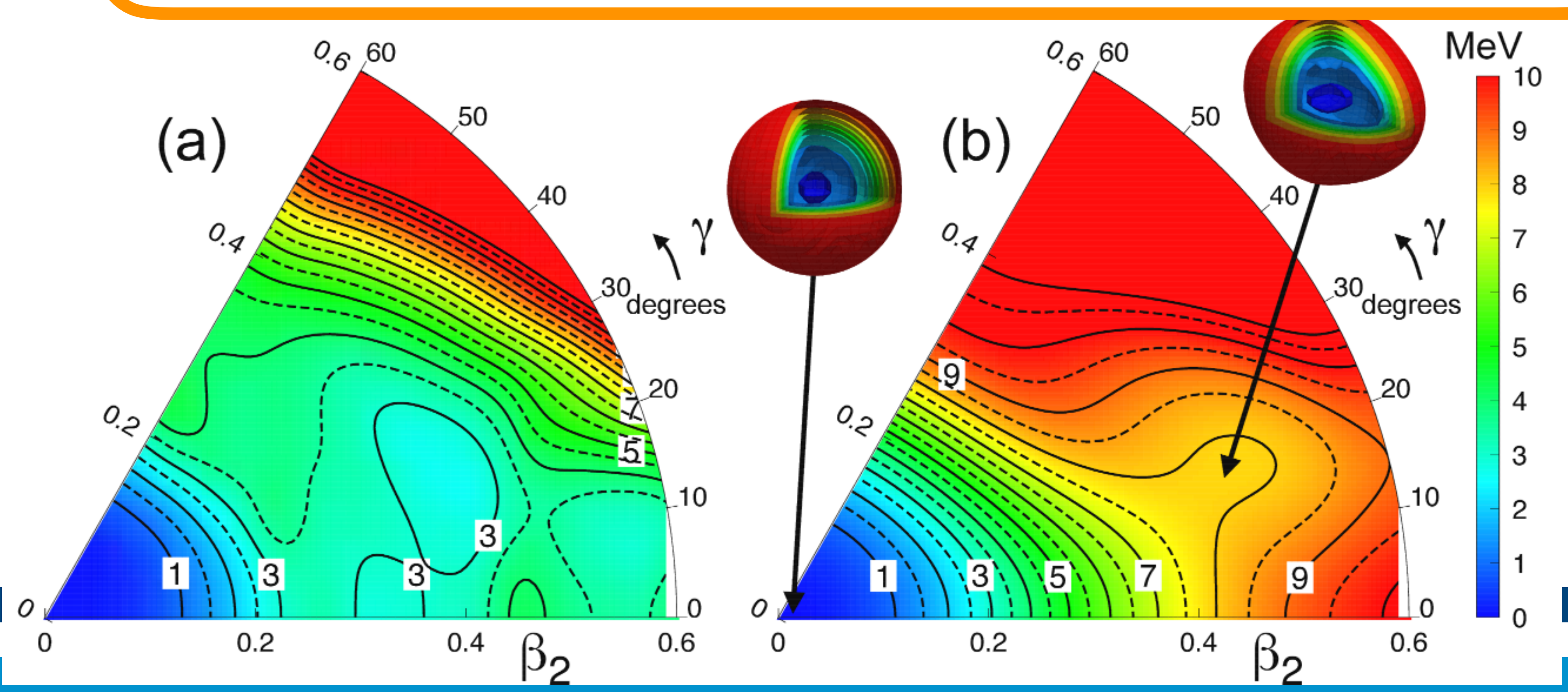


Deformation of ^{42}Ca

$\langle Q^2 \rangle [e^2 fm^4]$

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

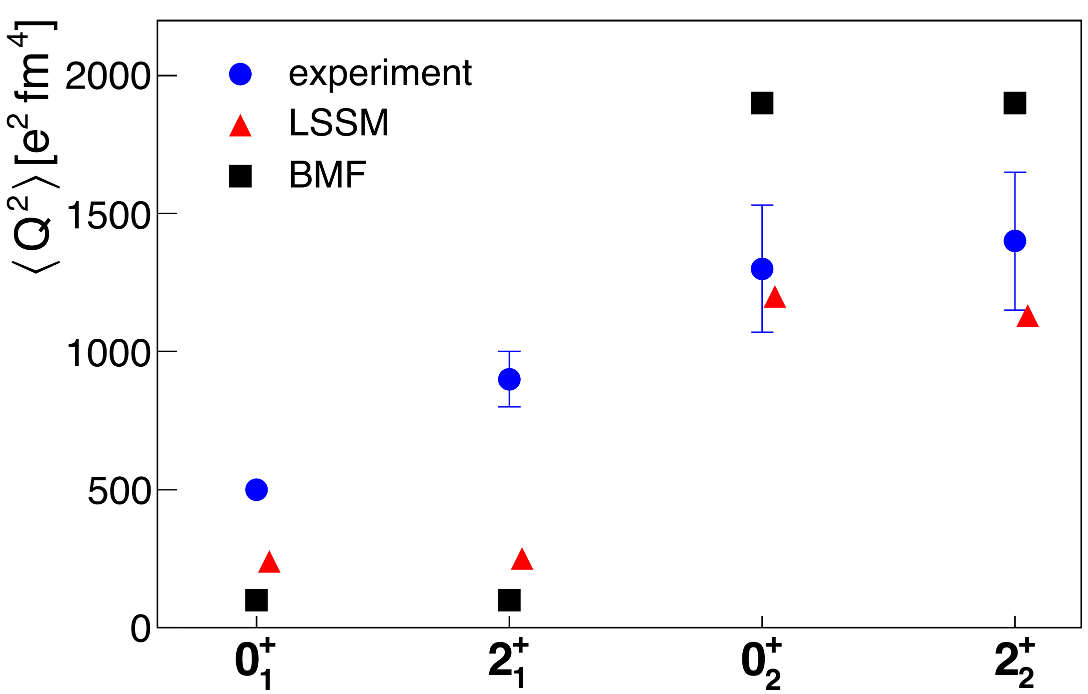
SM



BMF

Why SUPER-DEFORMATION in ^{42}Ca

- Significant deviation from a spherical shape
  - for A≈40 region we consider $\beta_2 \gtrsim 0.4$
- Complex configuration of the super-deformed state.
  - multi-quasi-particle excitation (6p-4h)
- Collective-like band build on the super-deformed state.



Superdeformed and Triaxial States in ^{42}Ca

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PRL **117,** 062501 (2016) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2016

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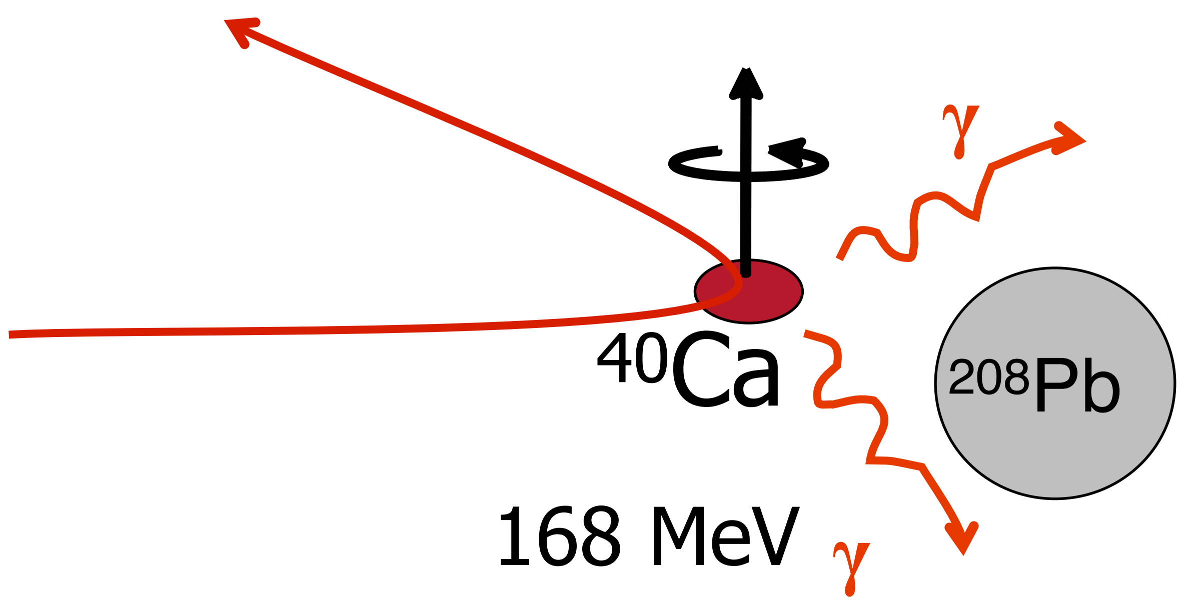
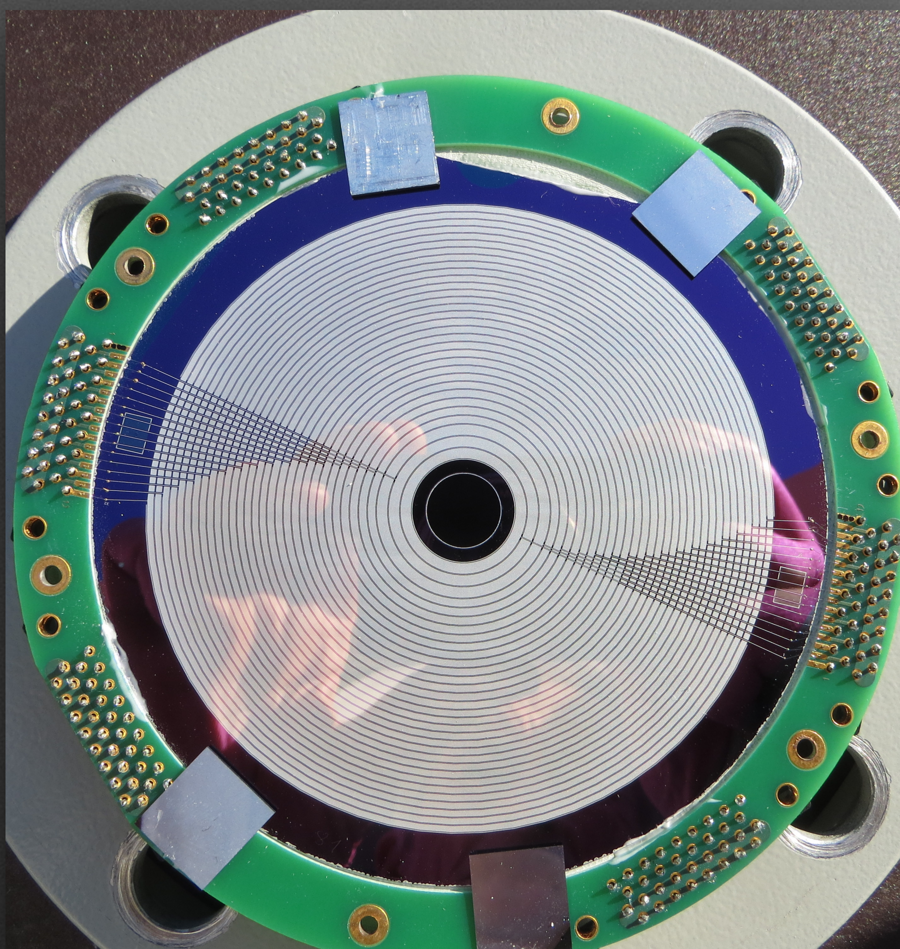
NEW!

PRC paper accepted!

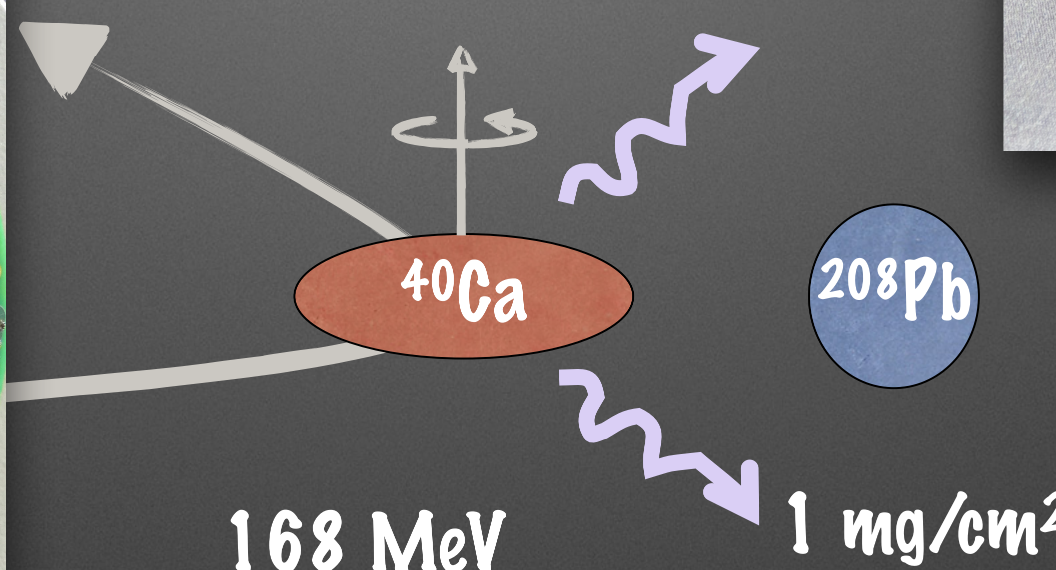
Project
^{40}Ca COULEX



Experiment



DSSSD LuSiA CD



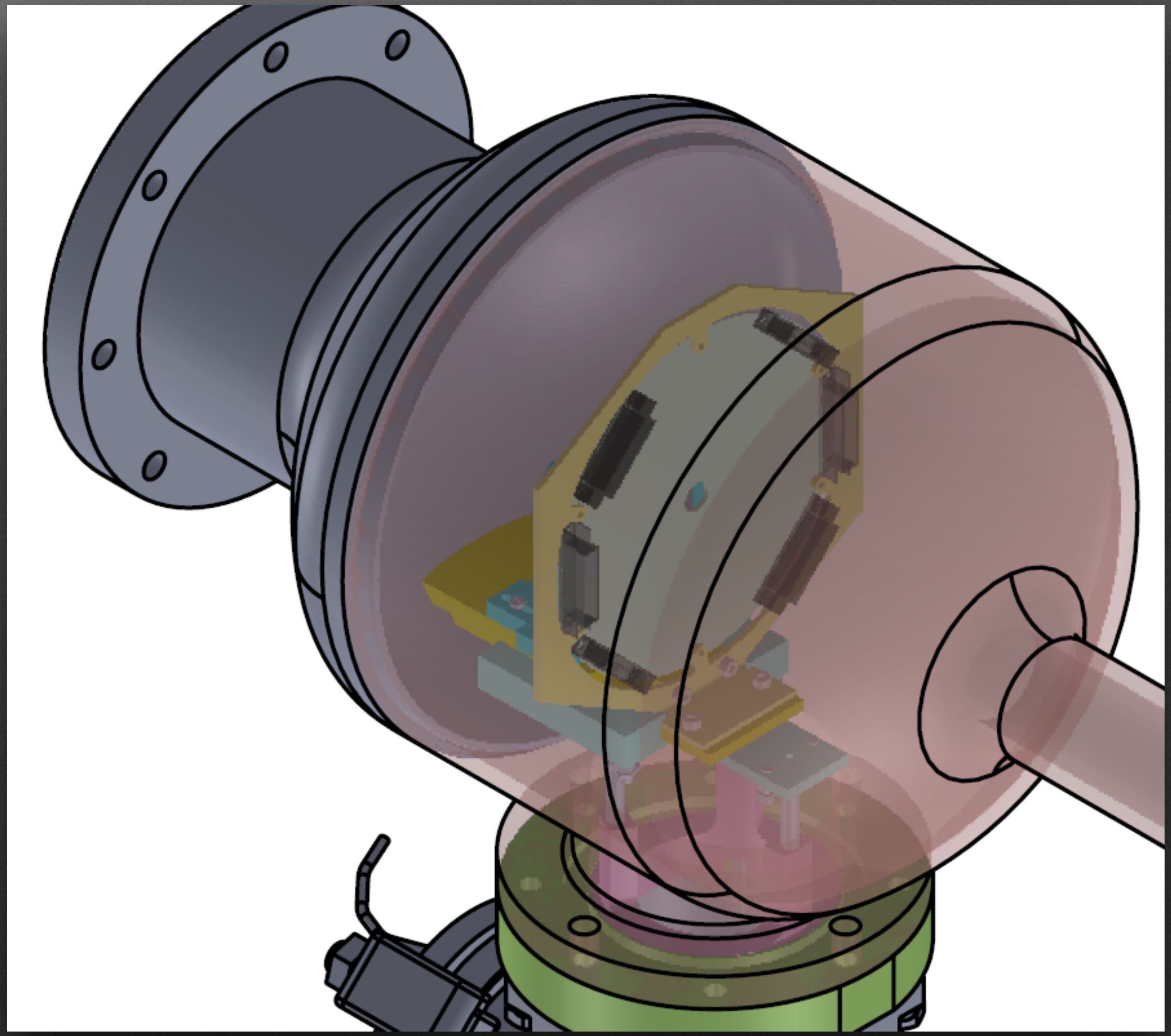
PARIS:
A. Maj et al., Acta Phys. Pol. B 40, 565 (2009)
LuSIA:
M.Komorowska et al., Acta Phys. Pol. B 47, 923 (2016)

Experimental setup: Paris

- 2 PARIS clusters placed 15 cm from target
- Efficiency (by Ciemała & Labiche)
  - 4% for 4MeV
  - 3.5% for 6MeV
  - 6% for 1MeV

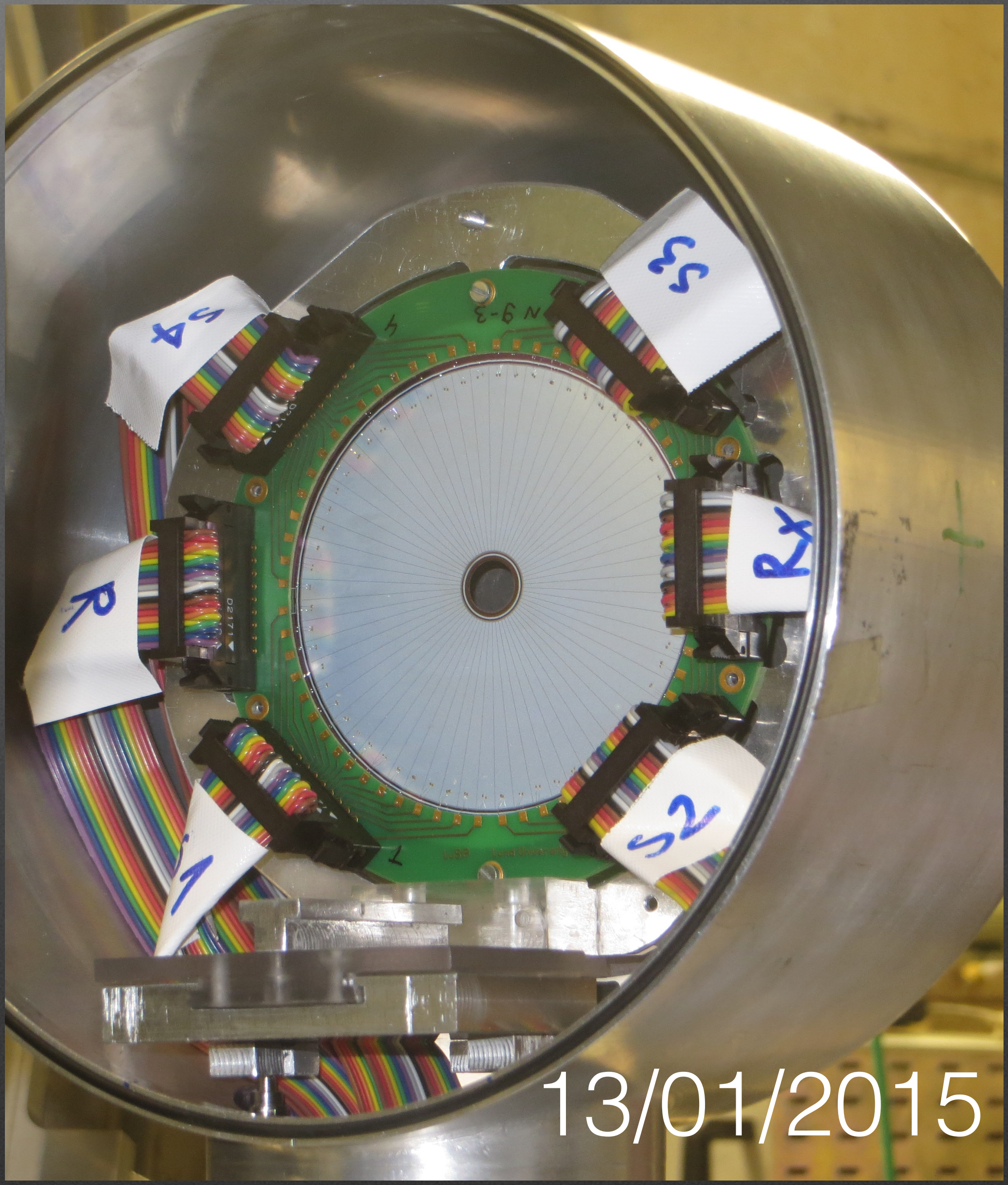
Experimental Setup: LuSiA CD detector

- New CD detector for a scattered HI for IPNO
- DSSSD from CEA Saclay installed for MINORCA campaign
- ϑ_{LAB} range: 120-169 deg
- 32 rings ($\Delta\vartheta_{LAB}$ =1.54 deg)
- 64 sectors in ($\Delta\varphi_{LAB}$=5.625 deg)



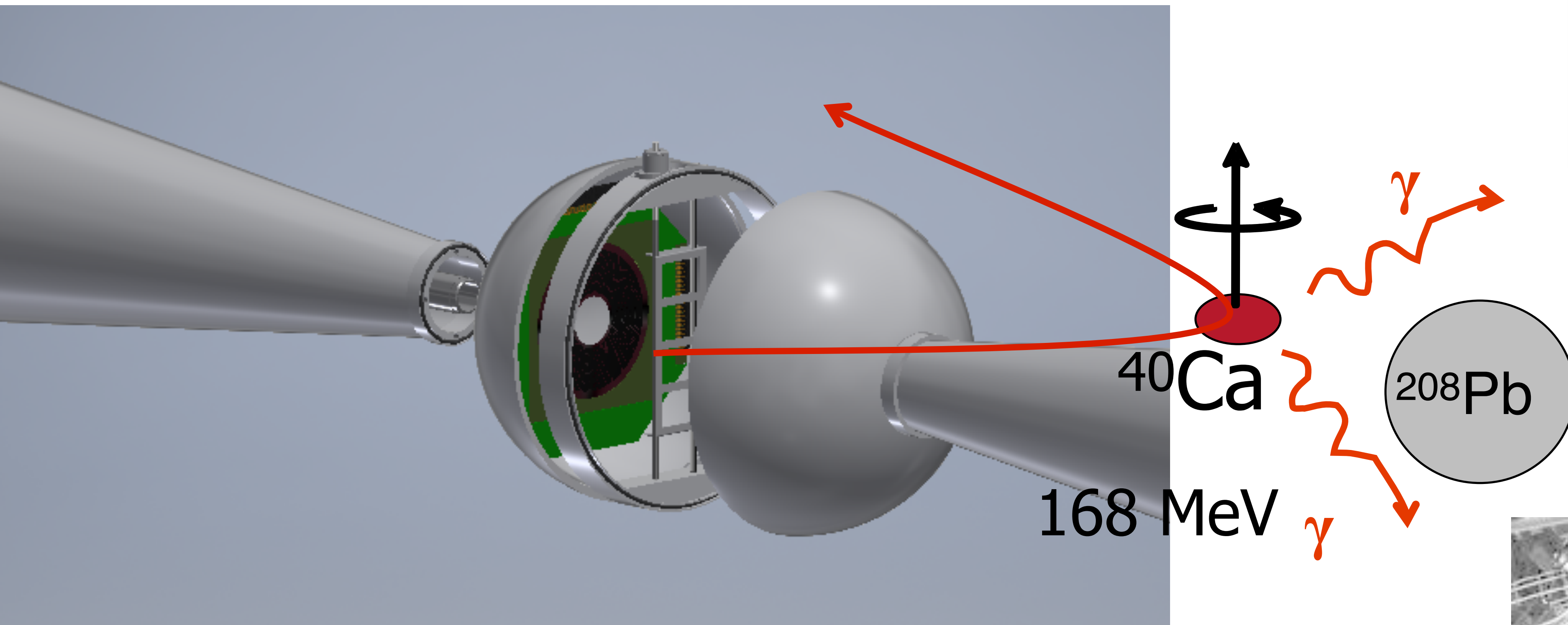
Experimental Setup: CD detector

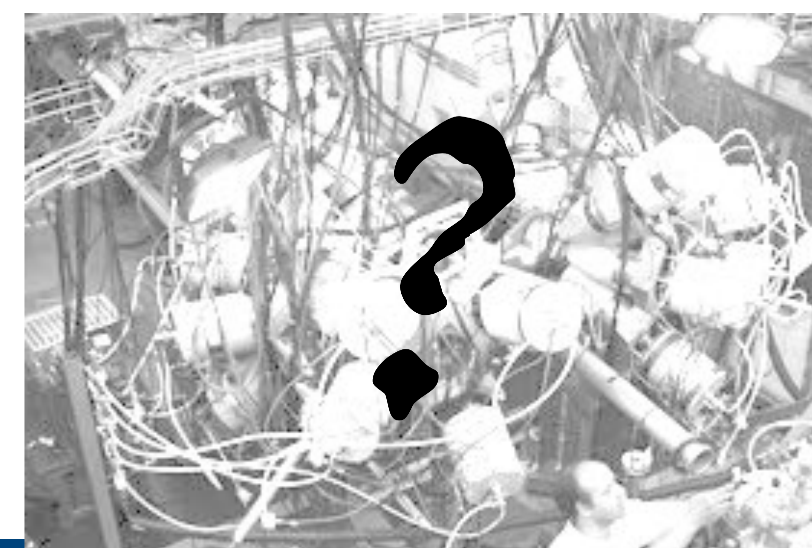
- New CD detector for a scattered HI for IPNO
- DSSSD from CEA Saclay installed for MINORCA campaign
- ϑ_{LAB} range: 120-169 deg
- 32 rings ($\Delta\vartheta_{LAB}$ =1.54 deg)
- 64 sectors in ($\Delta\varphi_{LAB}$=5.625 deg)
- Successful experiments in January 2015: COULEX of ^{74}Se and ^{146}Nd, ^{148}Sm



Project
^{40}Ca COULEX

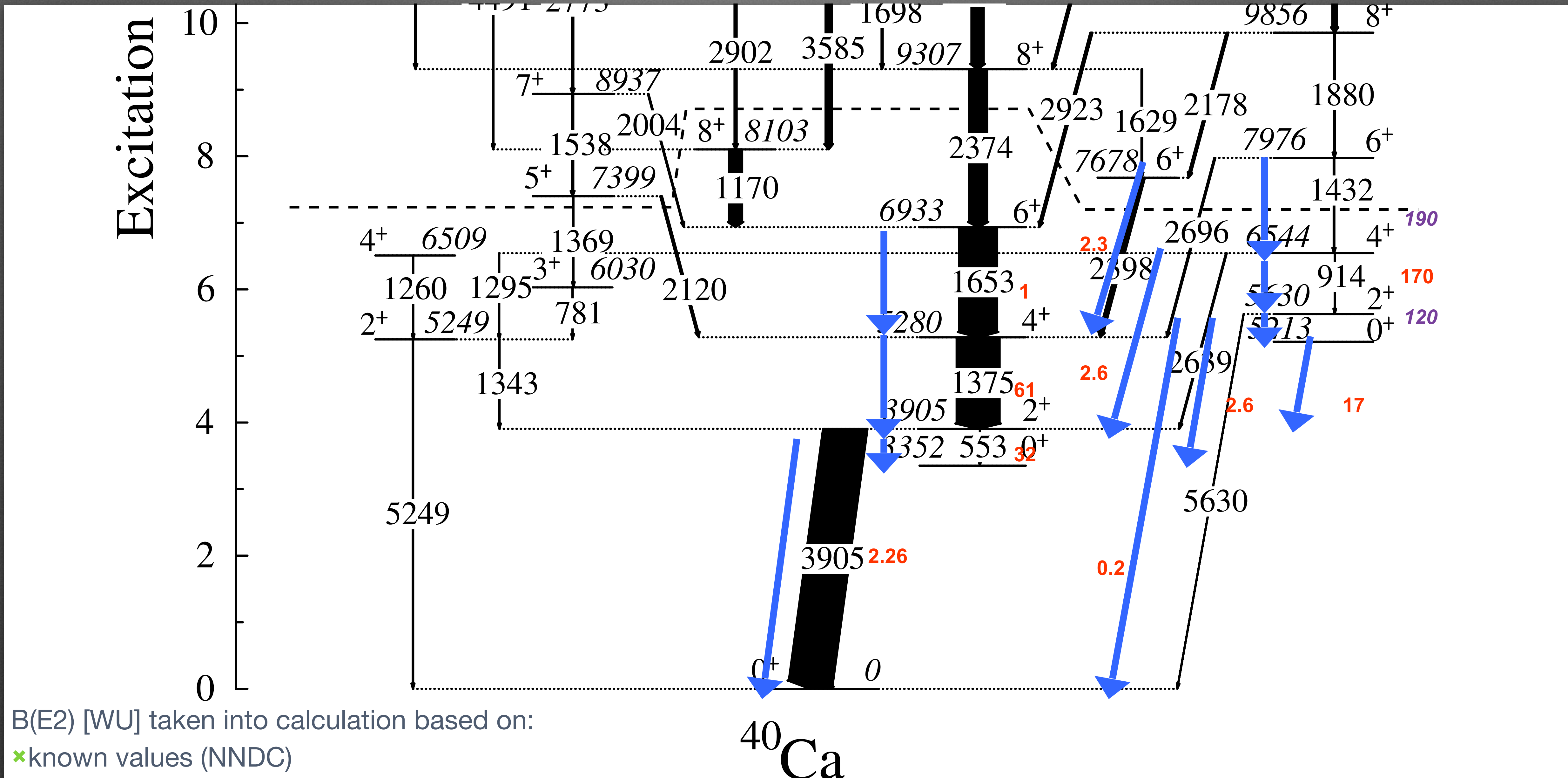
PARIS





NewBall

PARIS:
A. Maj et al., Acta Phys. Pol. B 40, 565 (2009)



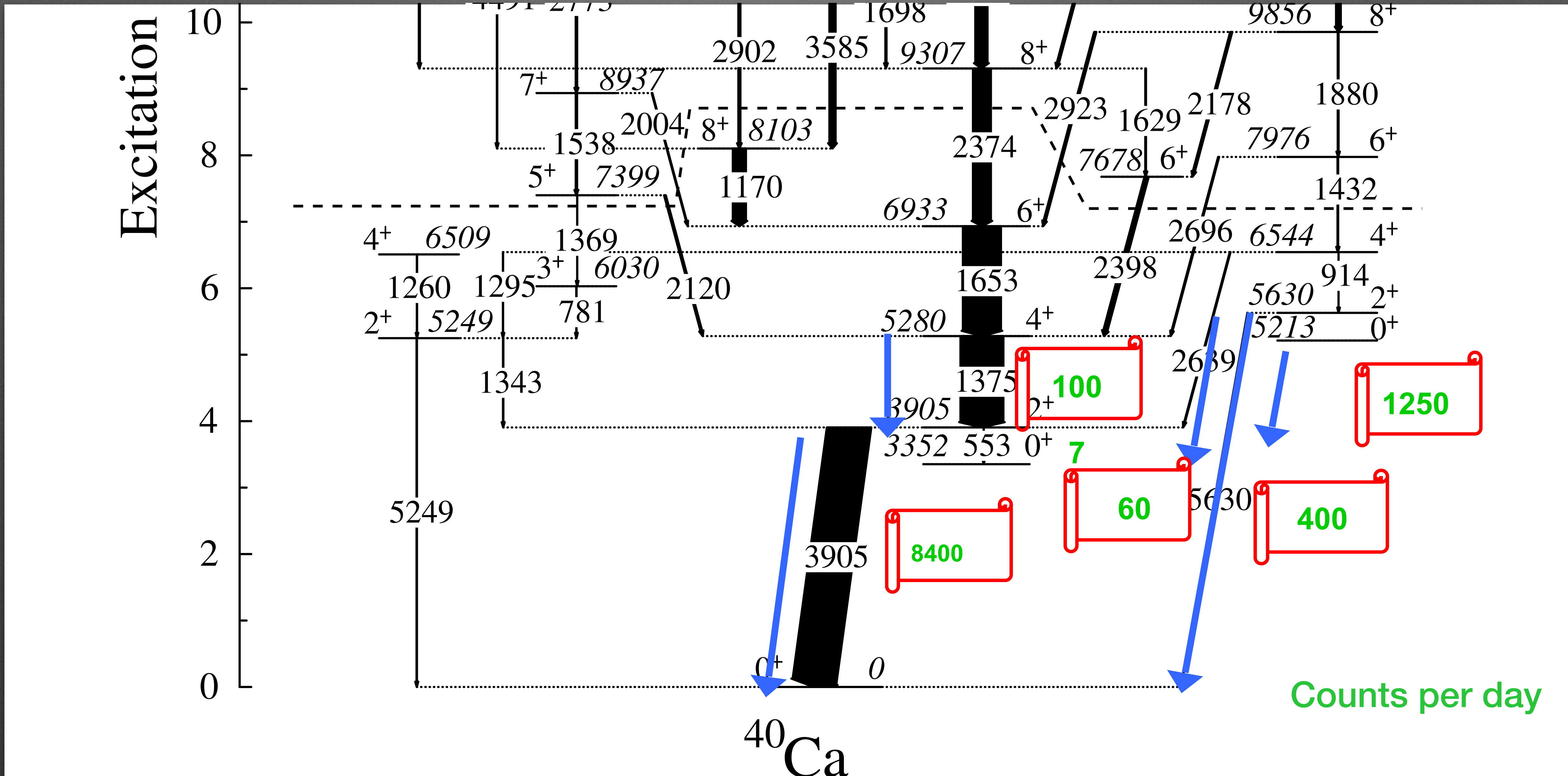
B(E2) [WU] taken into calculation based on:

- known values (NNDC)
- *rigid rotor model*

Part of a level scheme from E. Ideguchi *et al.* Phys.Rev.Lett. 87 (2001) 222501

Simulation of ^{40}Ca Coulex

GOSIA: T. Czosnyka et al. Am. Phys. Soc. 28, 745 (1983)



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Summary

- EXPERIMENTAL GOAL:

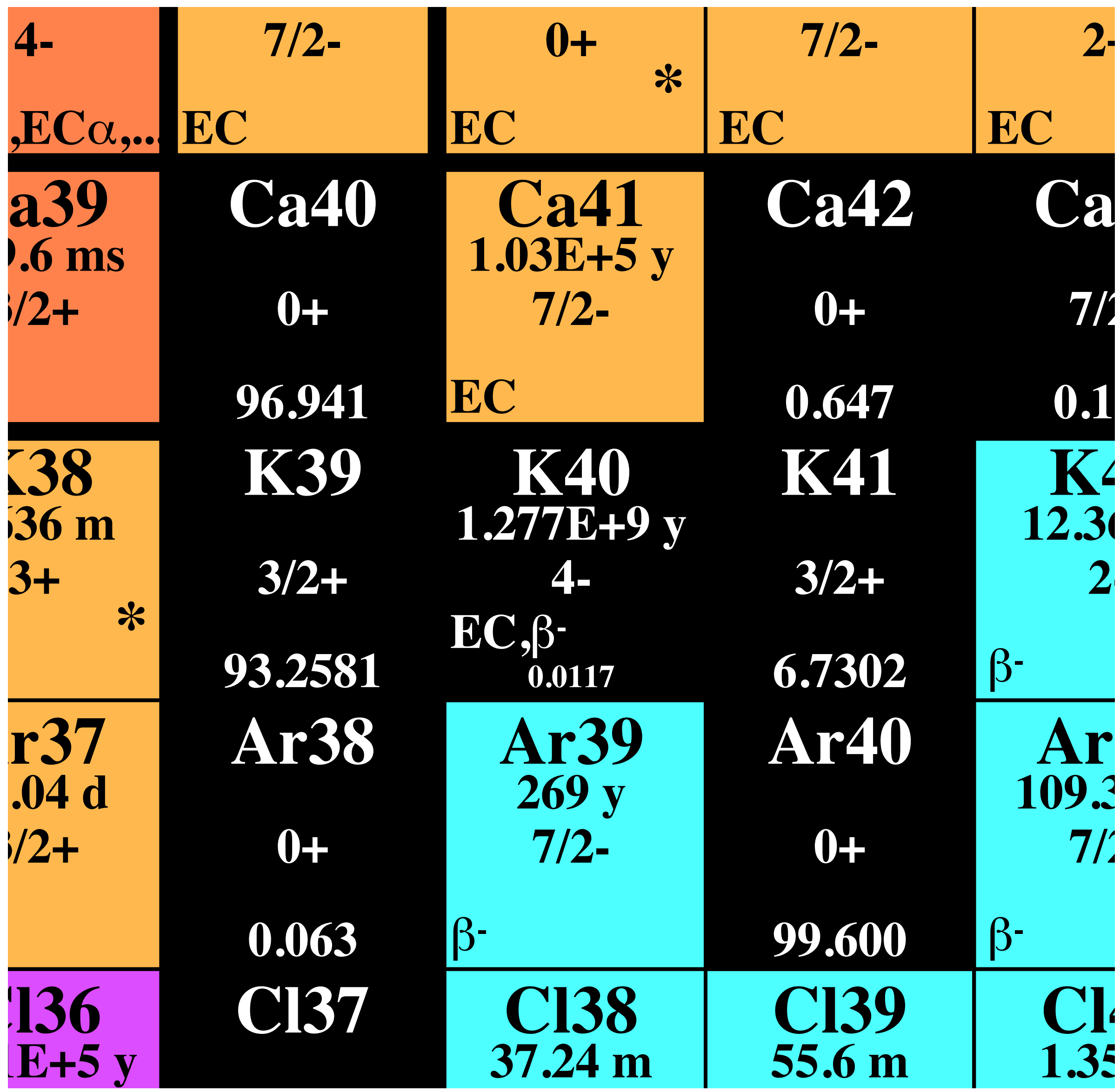
To determine deformation of SD 0^+ bandhed in ^{40}Ca

- BEAM REQUEST:

18 UT of ^{40}Ca beam 12nAe, 168MeV

In order to achieve the accuracy better the 5 % in the weakest line of the 2sd decay we request 5 days of in-beam data taking (15 shifts) and 1 day (3 shifts) for the particle detector setup.

Super-deformation study in the vicinity of A=40



PARIS@ALTO 2018?

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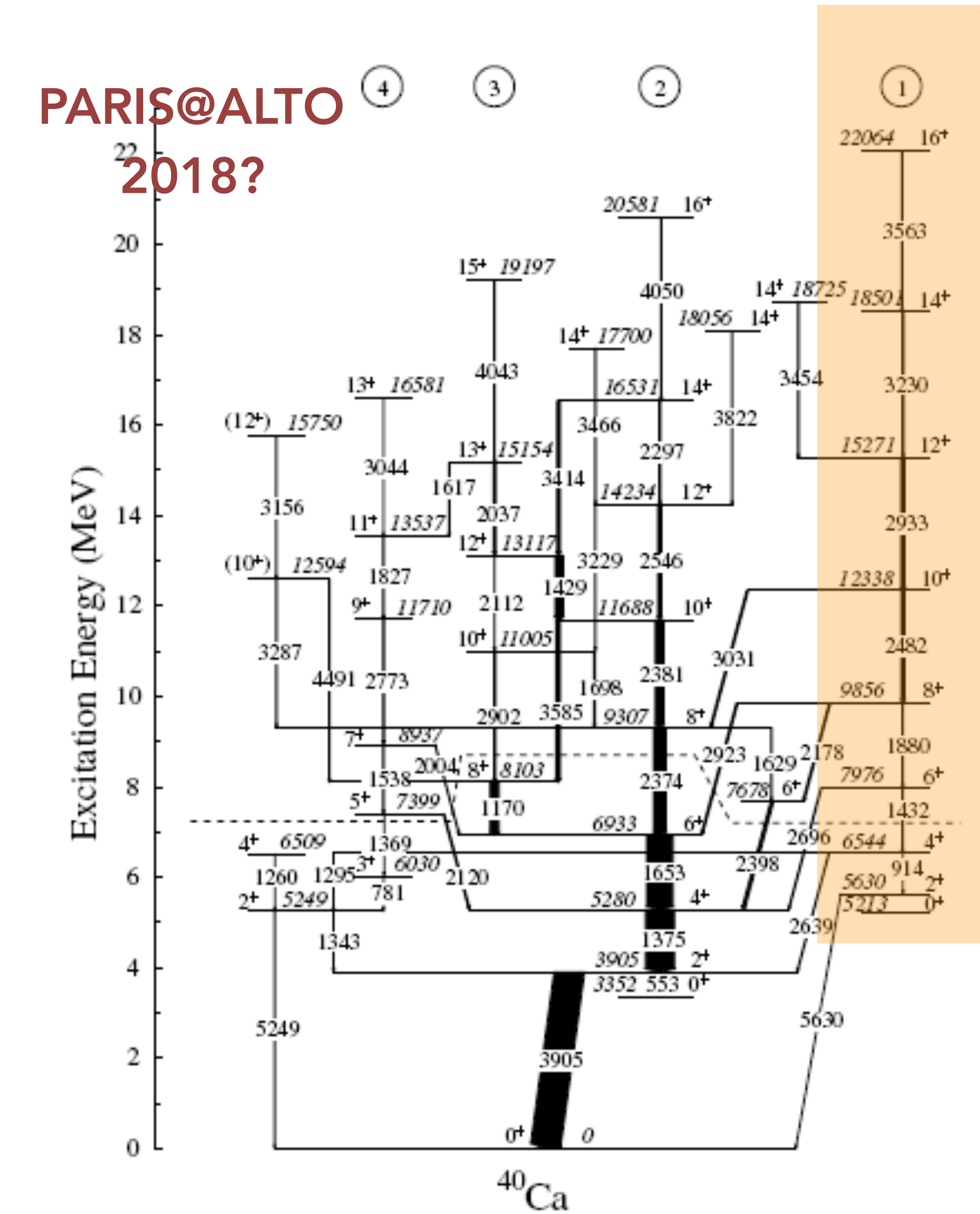
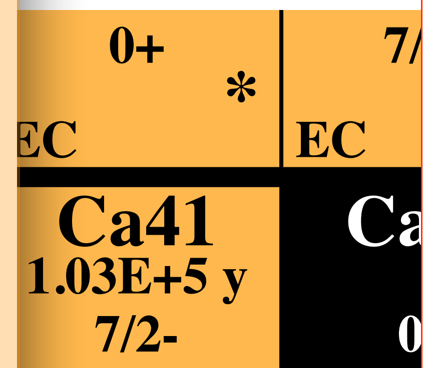
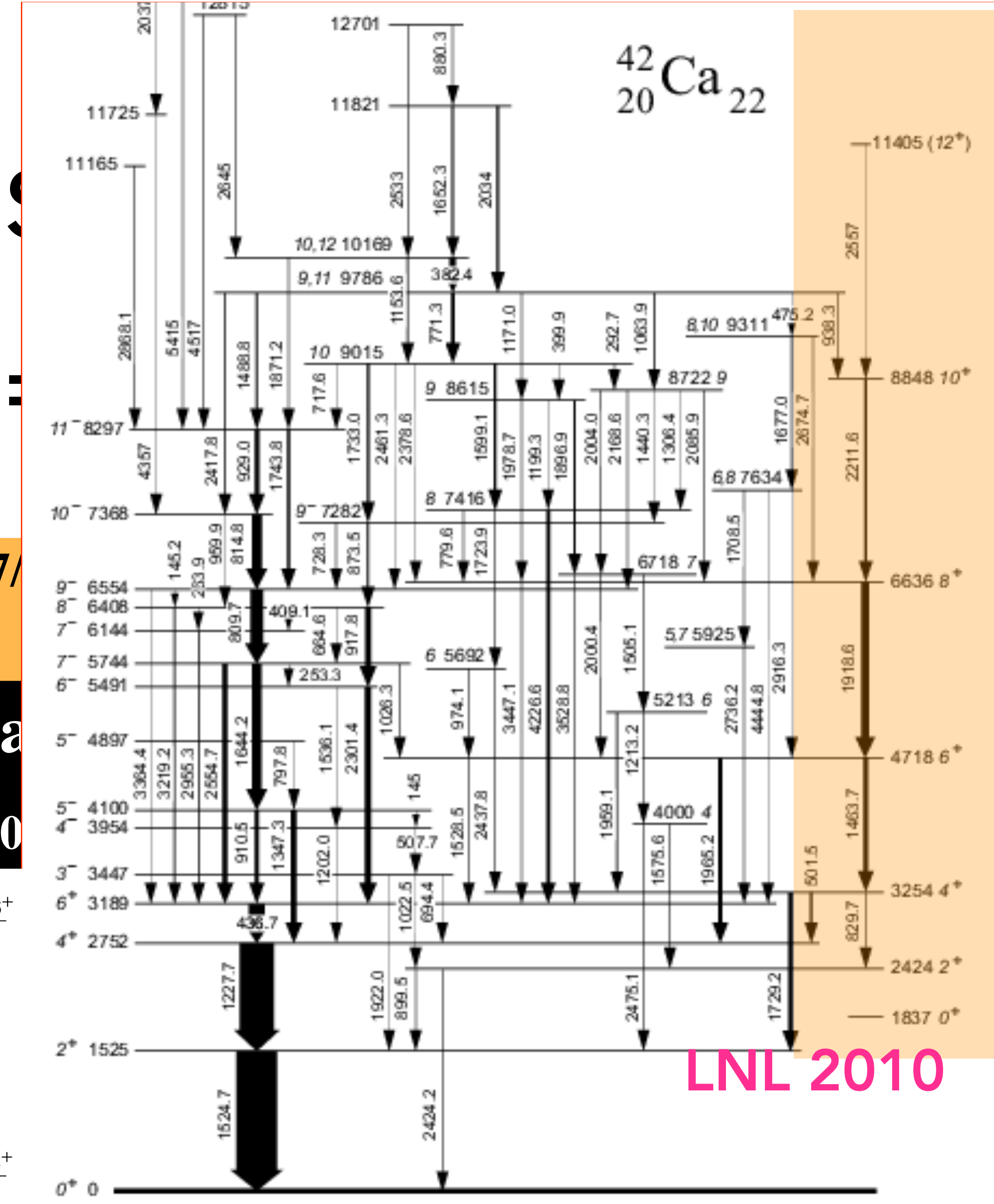
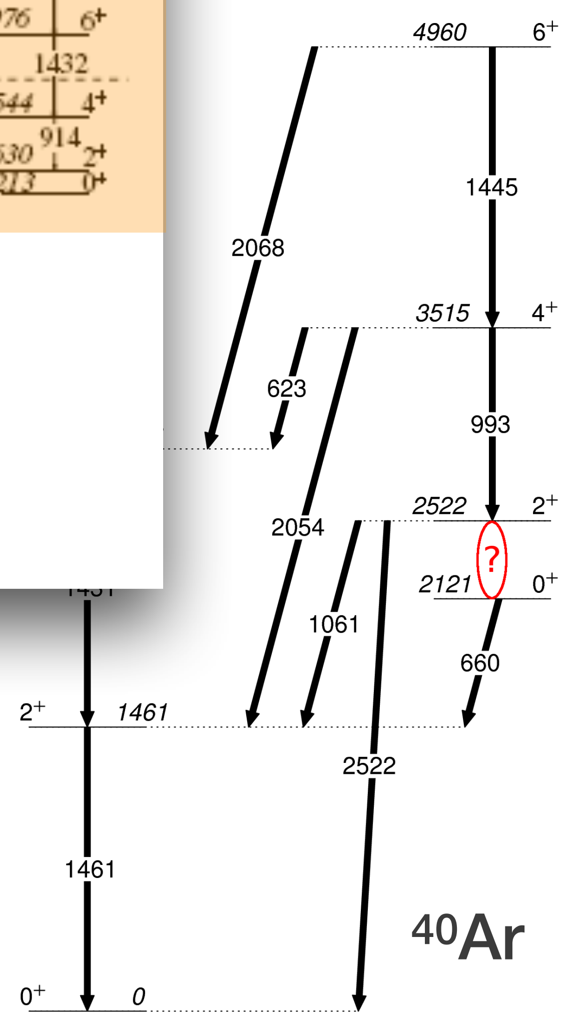
...y of A=...

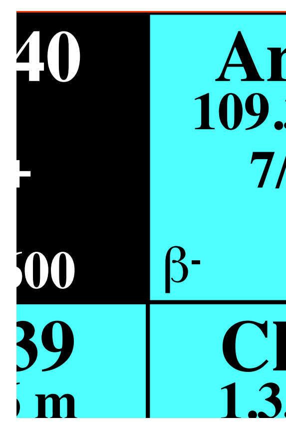


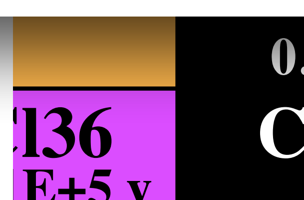




LNL 2010



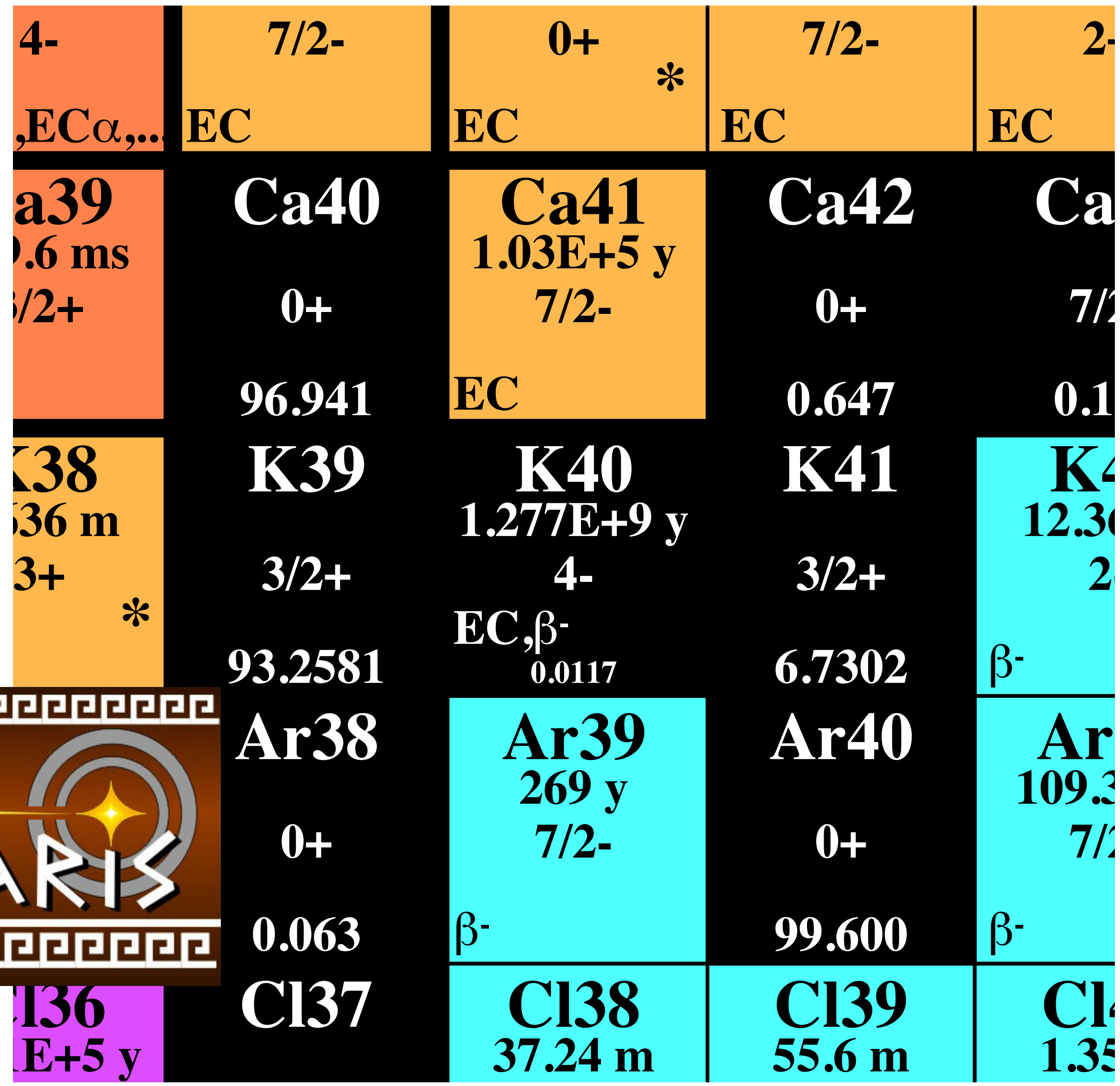




iTEMBA

i ŚLCJ 2015

Super-deformation study in the vicinity of A=40



Summary

- Studies of super-deformation in vicinity of ^{40}Ca are promising thanks to Polish$_W$-Polish$_K$-PARIS collaboration
- Coulex of SD - bands: ^{40}Ca is not end of the story