Nuclear deformation in excited states - Superdeformation at low spins

task coordinators: E. Clément, K. Hadyńska-Klęk (P. Napiorkowski*)

Kasia Hadyńska-Klęk

Heavy Ion Laboratory

University of Warsaw

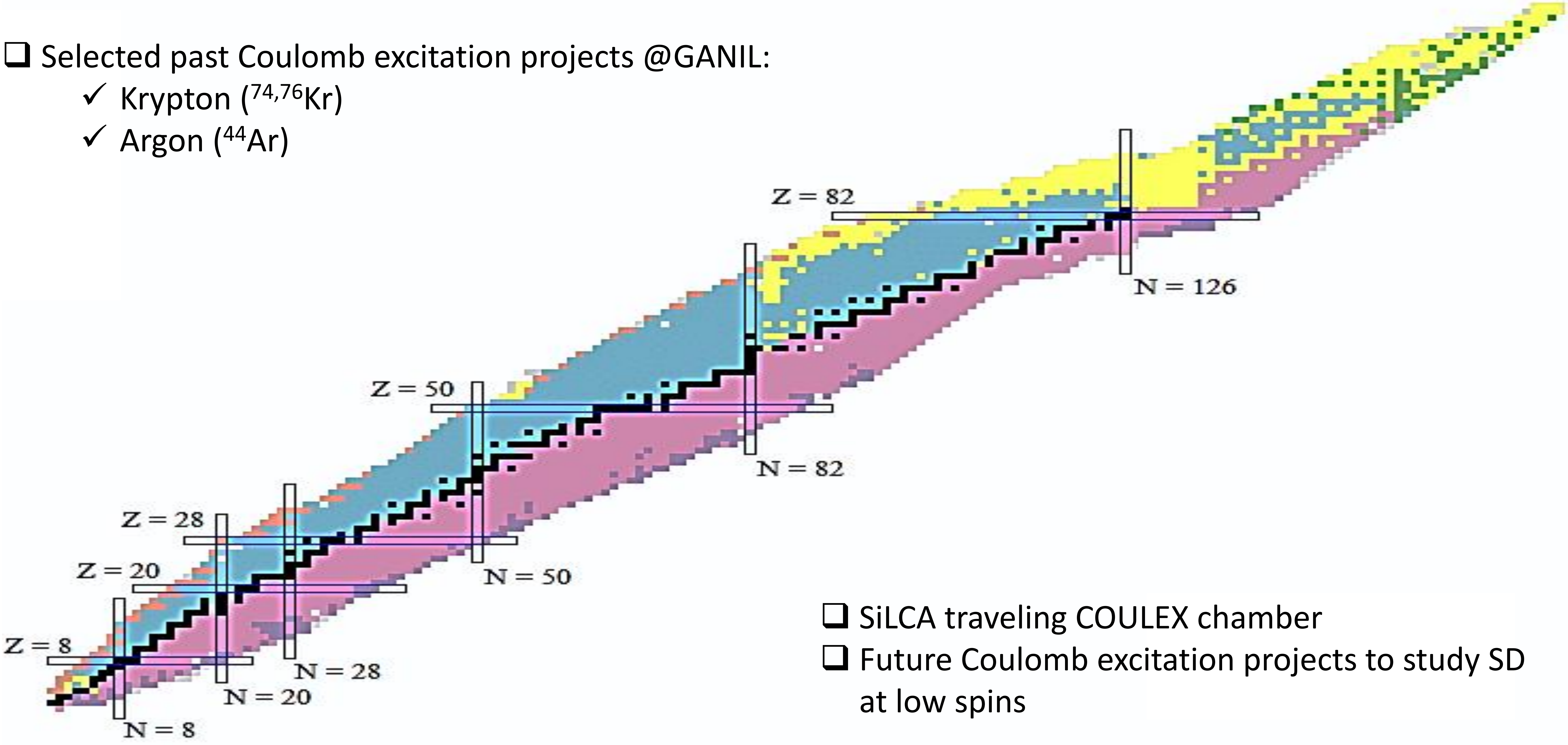
COPIGAL mini-WORKSHOP

28-29 November 2024

Paris, France

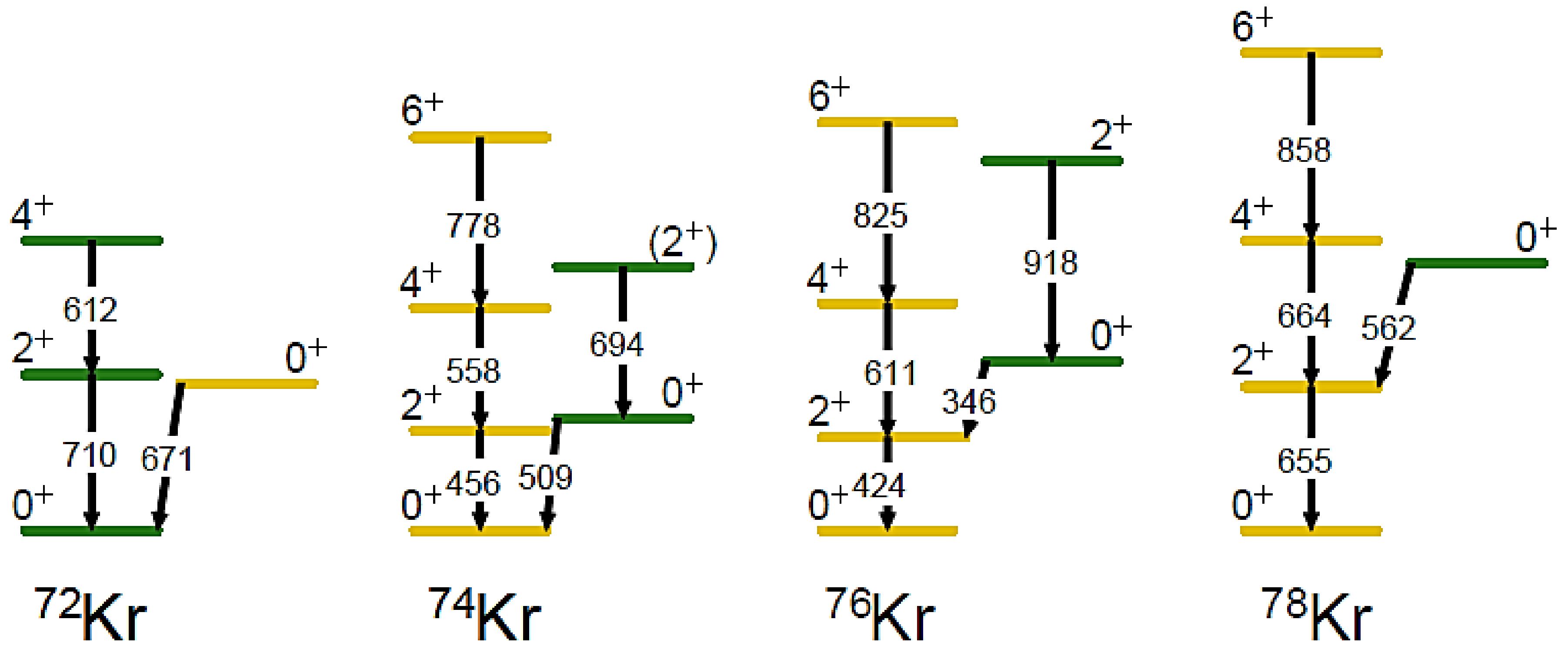
Outline

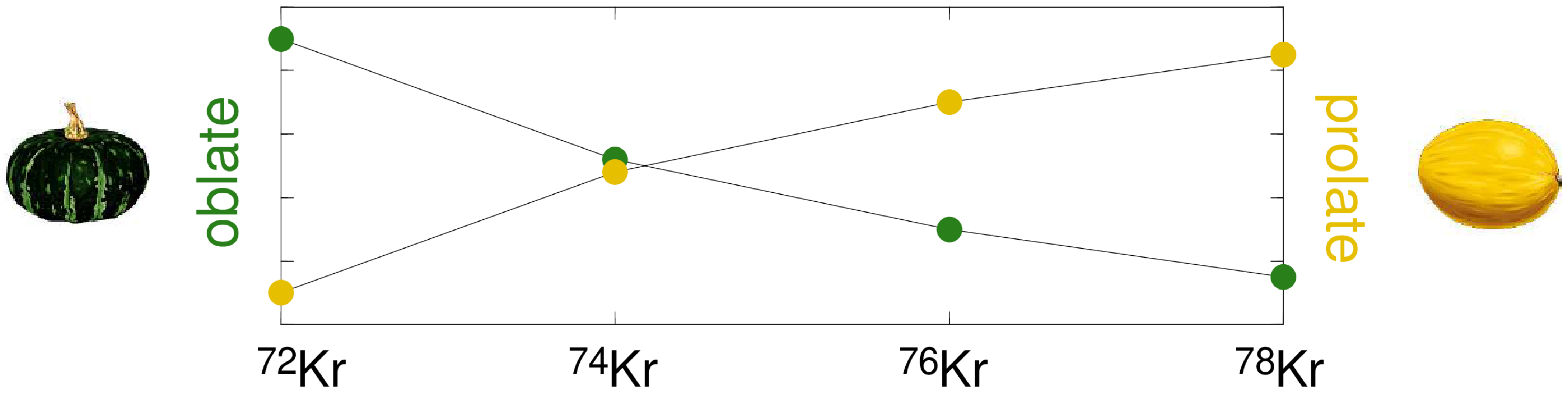
- Selected past Coulomb excitation projects @GANIL:
  - ✓ Krypton ($^{74,76}Kr$)
  - ✓ Argon (^{44}Ar)



- SiLCA traveling COULEX chamber
- Future Coulomb excitation projects to study SD at low spins

Shape coexistence in ^{74,76}Kr @ GANIL [E344S, June 2002+April 2003]





mixing of 0⁺ states deduced from distortion of rotational bands
(E. Bouchez et al. Phys. Rev. Lett. 90, 082502 (2003))

inversion of the ground state and excited 0⁺ states

Courtesy: E. Clement, M. Zielińska

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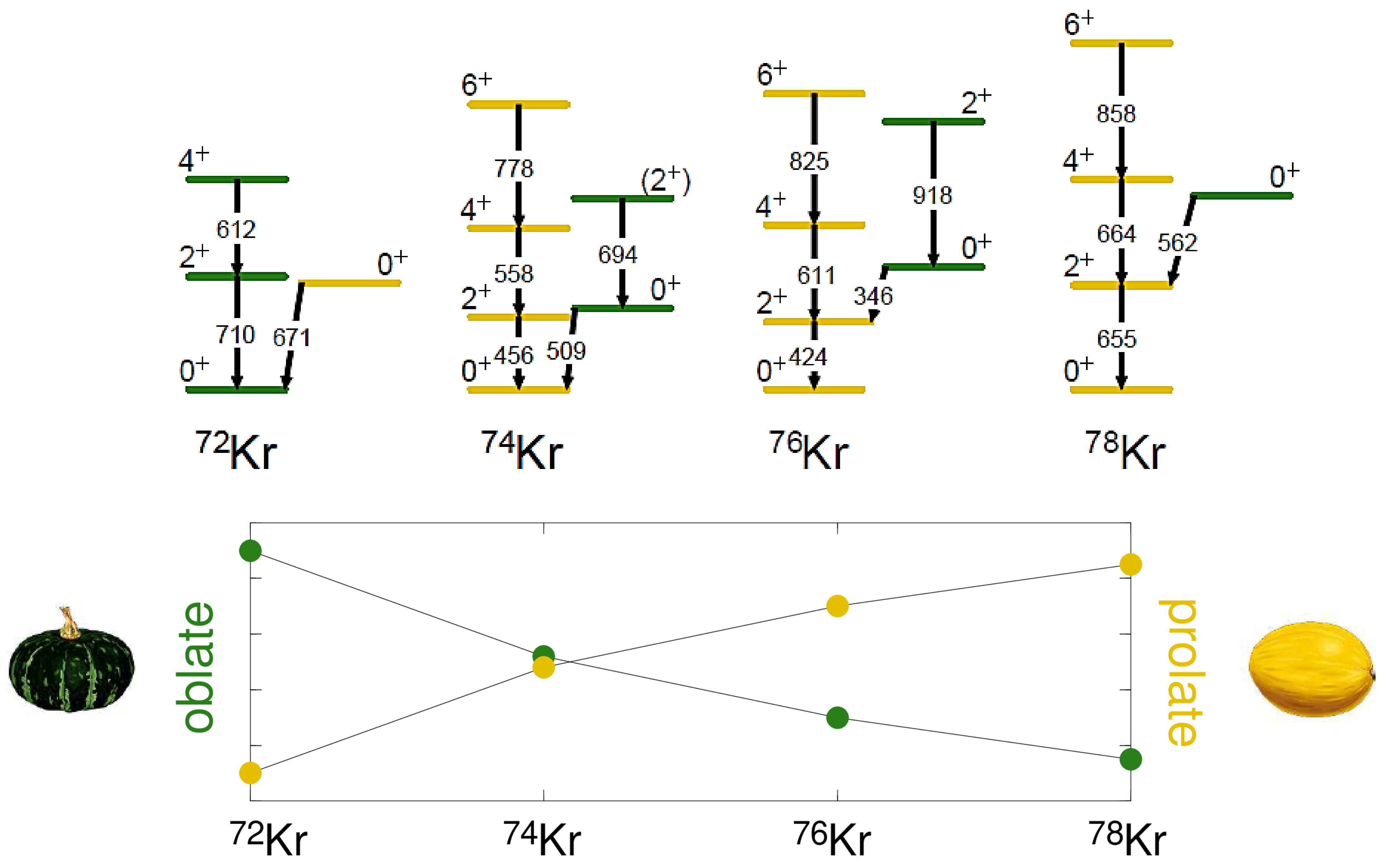

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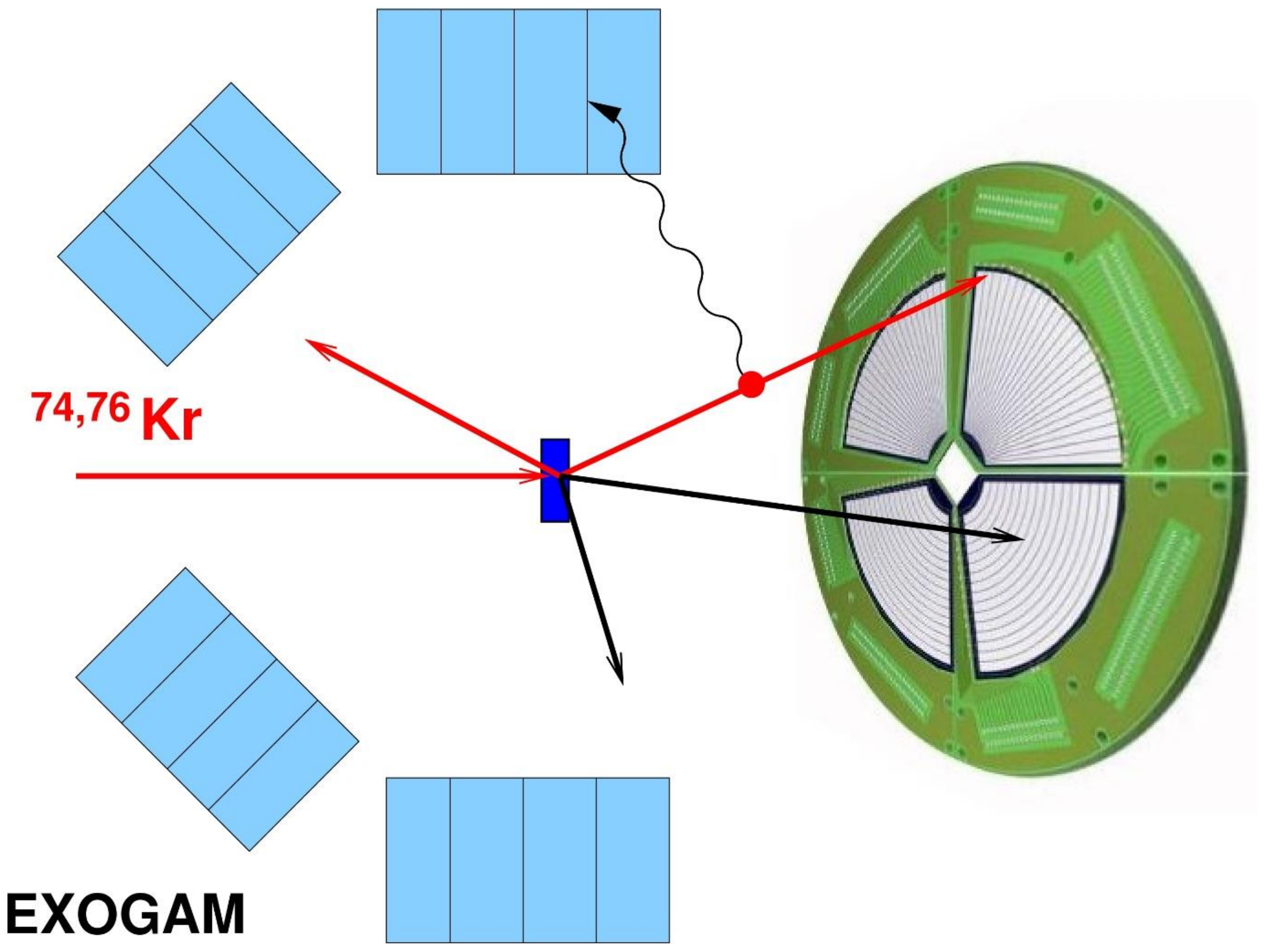
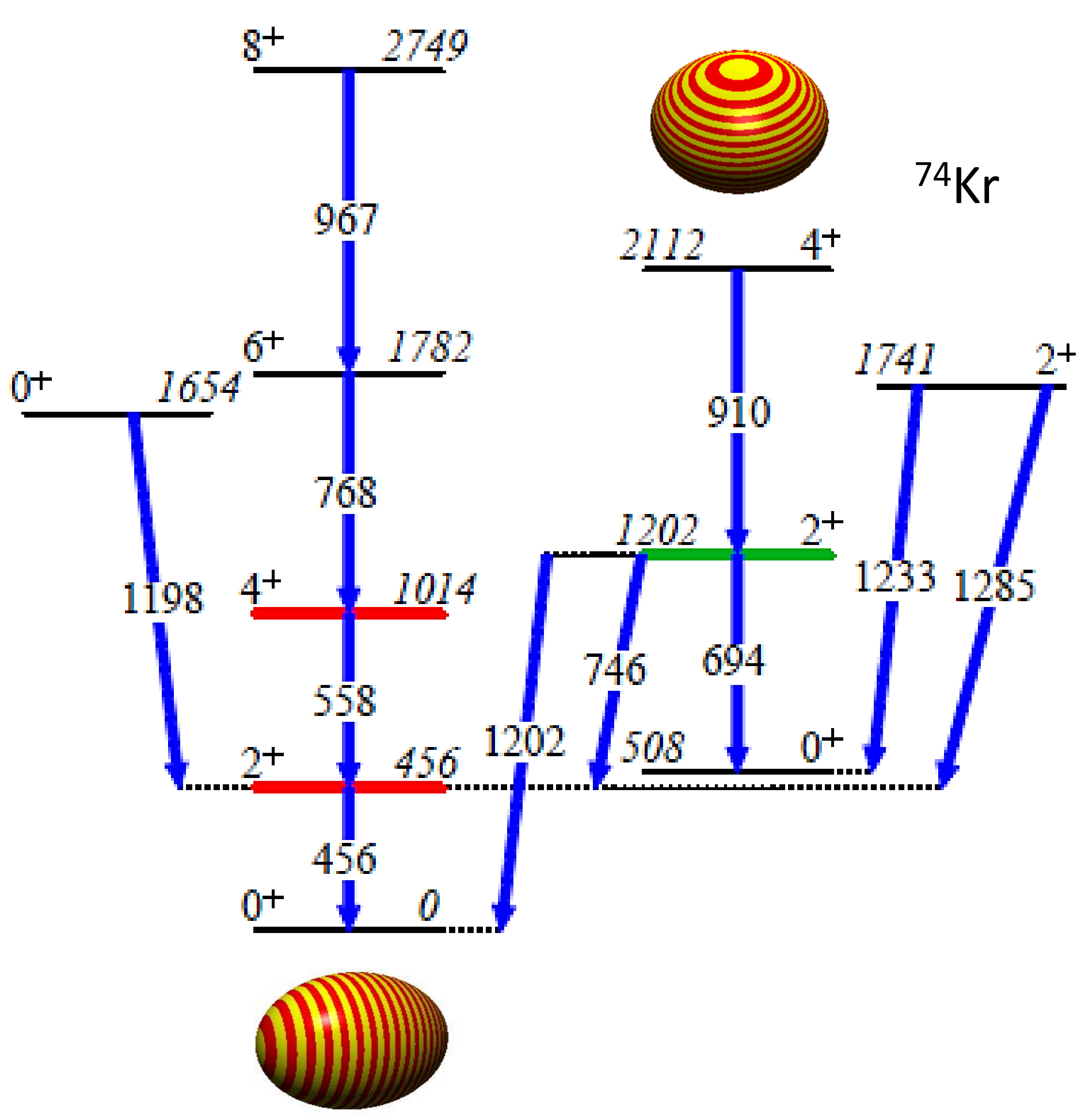


Coulomb excitation to directly determine nuclear shapes in ^{74,76}Kr using SPIRAL beams

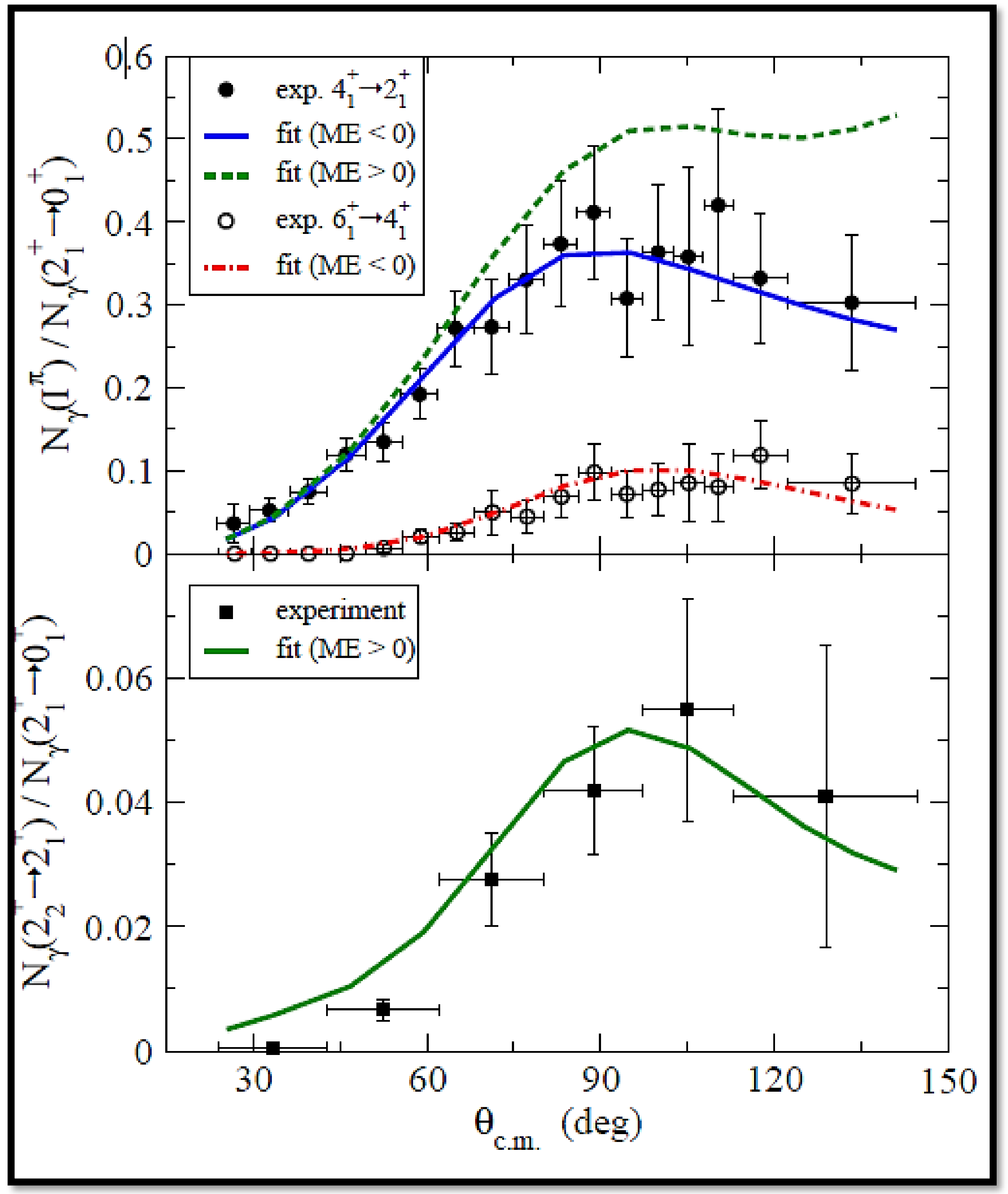
Shape coexistence in ^{74,76}Kr @ GANIL – quadrupole moments

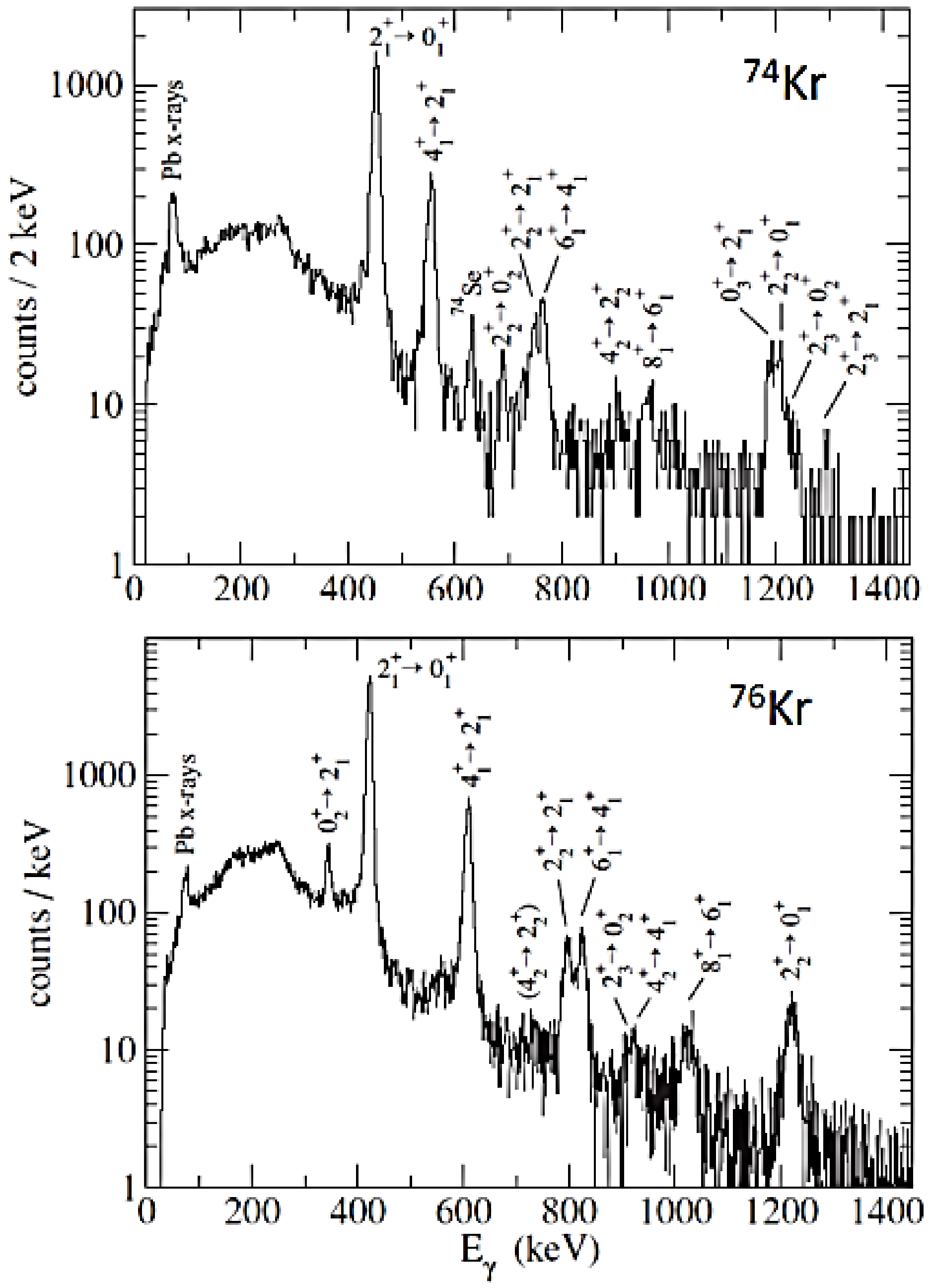


$\langle 2_1^+ \| E2 \| 2_1^+ \rangle = -\,0.70^{-0.33}_{-0.30}$

$\langle 4_1^+ \| E2 \| 4_1^+ \rangle = -\,1.02^{+0.59}_{-0.21}$

$\langle 2_2^+ \| E2 \| 2_2^+ \rangle = +\,0.33^{+0.28}_{-0.23}$

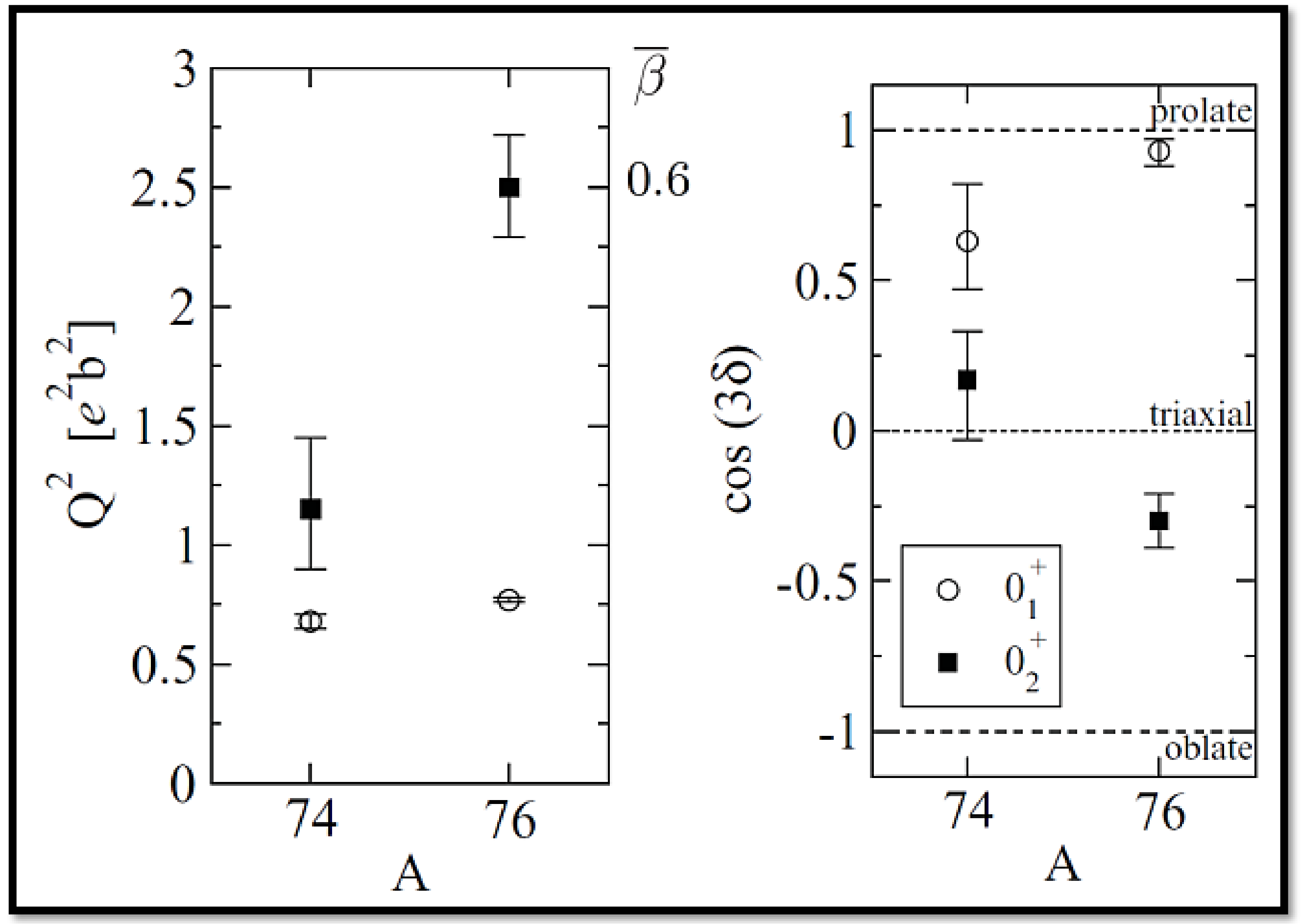




- first determination of quadrupole moments of excited nuclear states using Coulomb excitation of a radioactive beam
- confirmation of the shape-coexistence scenario
- mixing coefficients obtained from measured transition probabilities consitent with those from level energies

Courtesy: E. Clement, M. Zielińska

Shape coexistence in ^{74,76}Kr @ GANIL – sum rules and BMF



❖ ^{76}Kr:
prolate ground state coexists with a less deformed, oblate/triaxial 0^+_2 state

❖ ^{74}Kr:
Strong mixing of 0^+_1, 0^+_2 states leading to more similar, triaxial shapes

Courtesy: E. Clement, M. Zielińska

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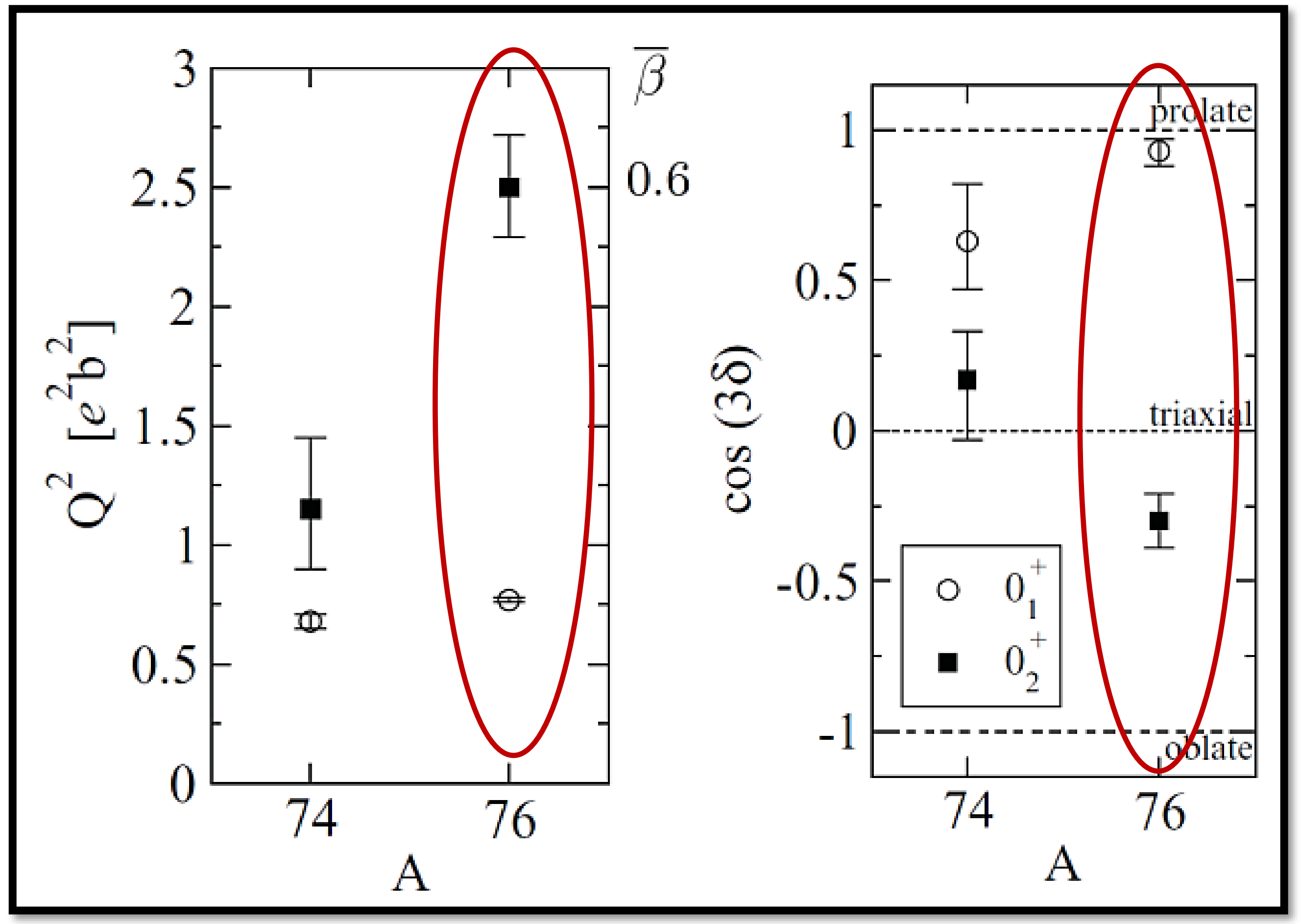

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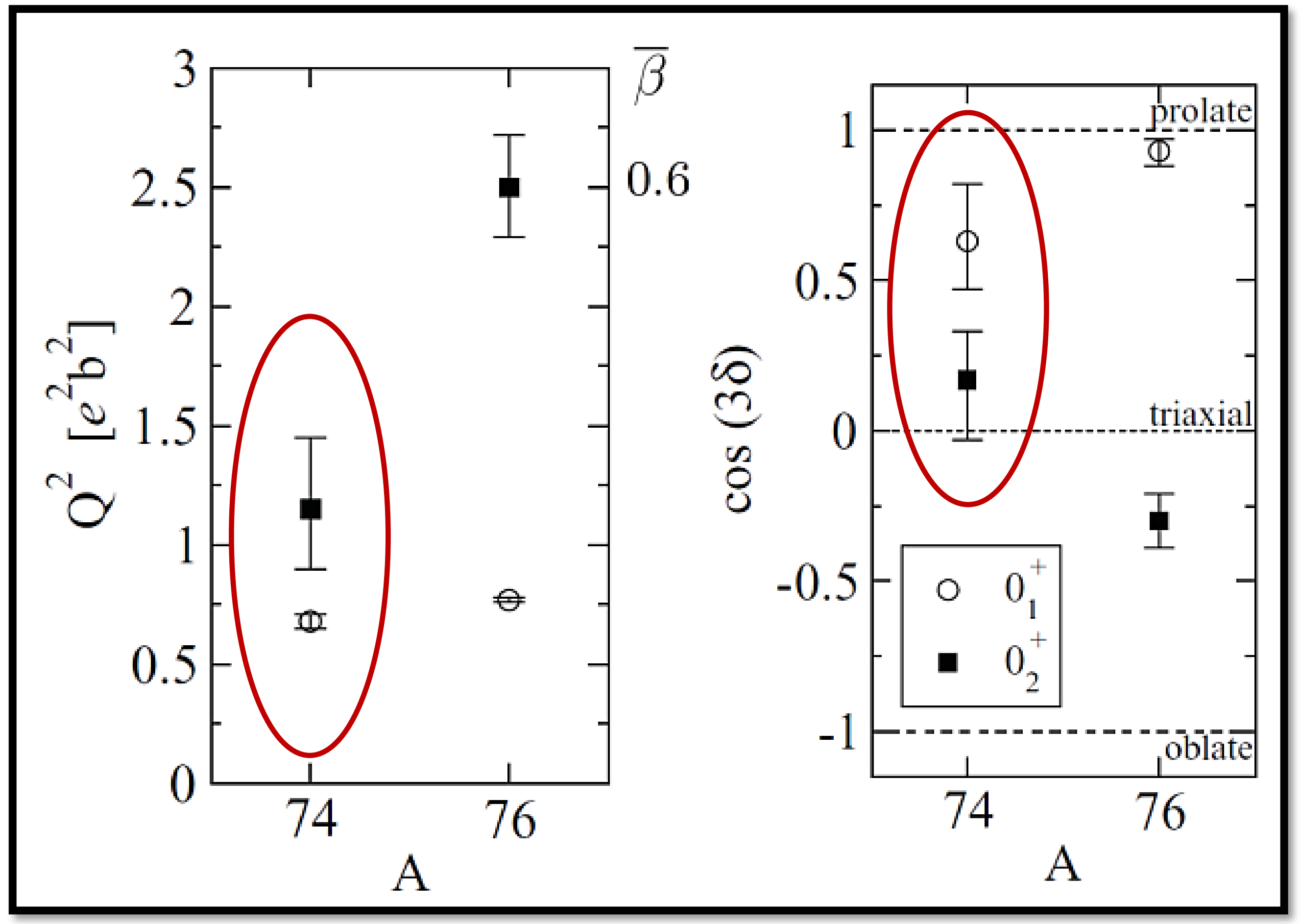

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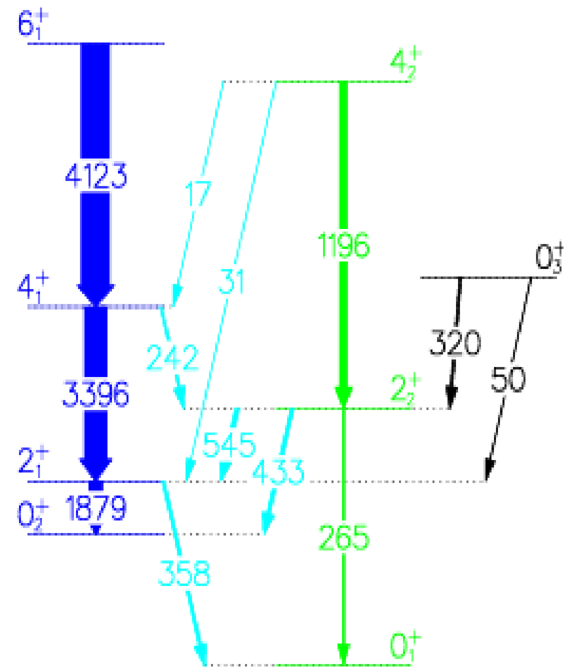
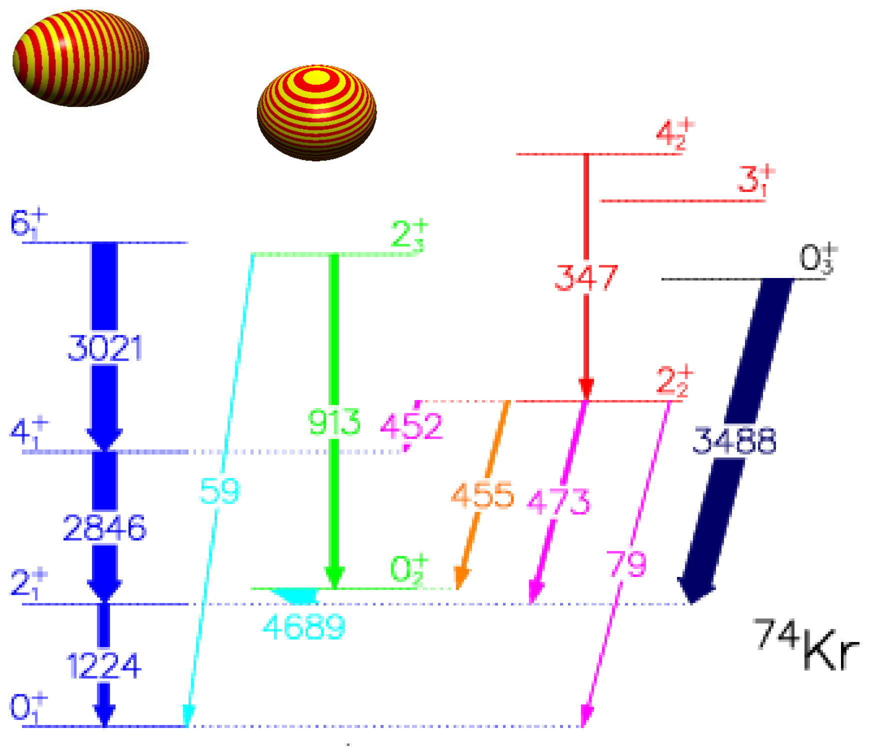
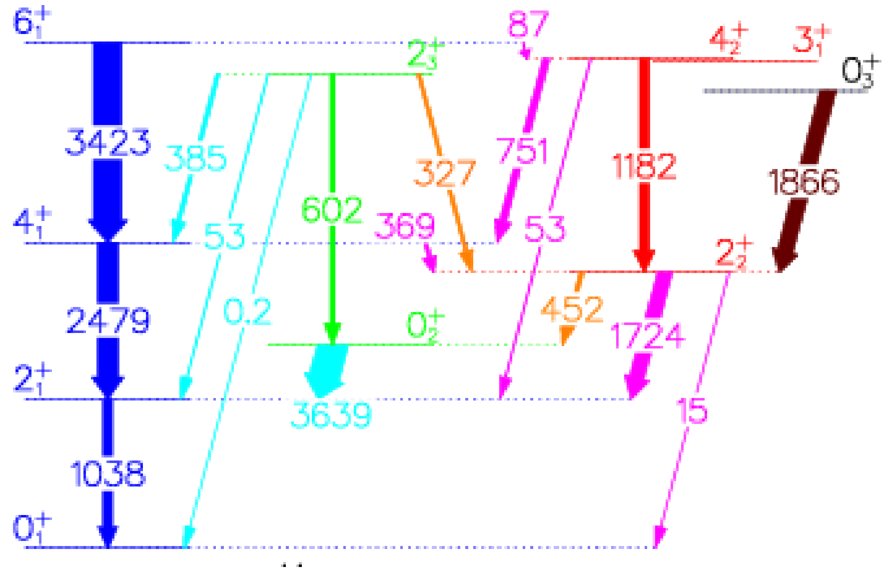


GCM calculation:
axial deformation,
Skyrme SLy6

M. Bender et al. PRC 74, 024312 (2006)

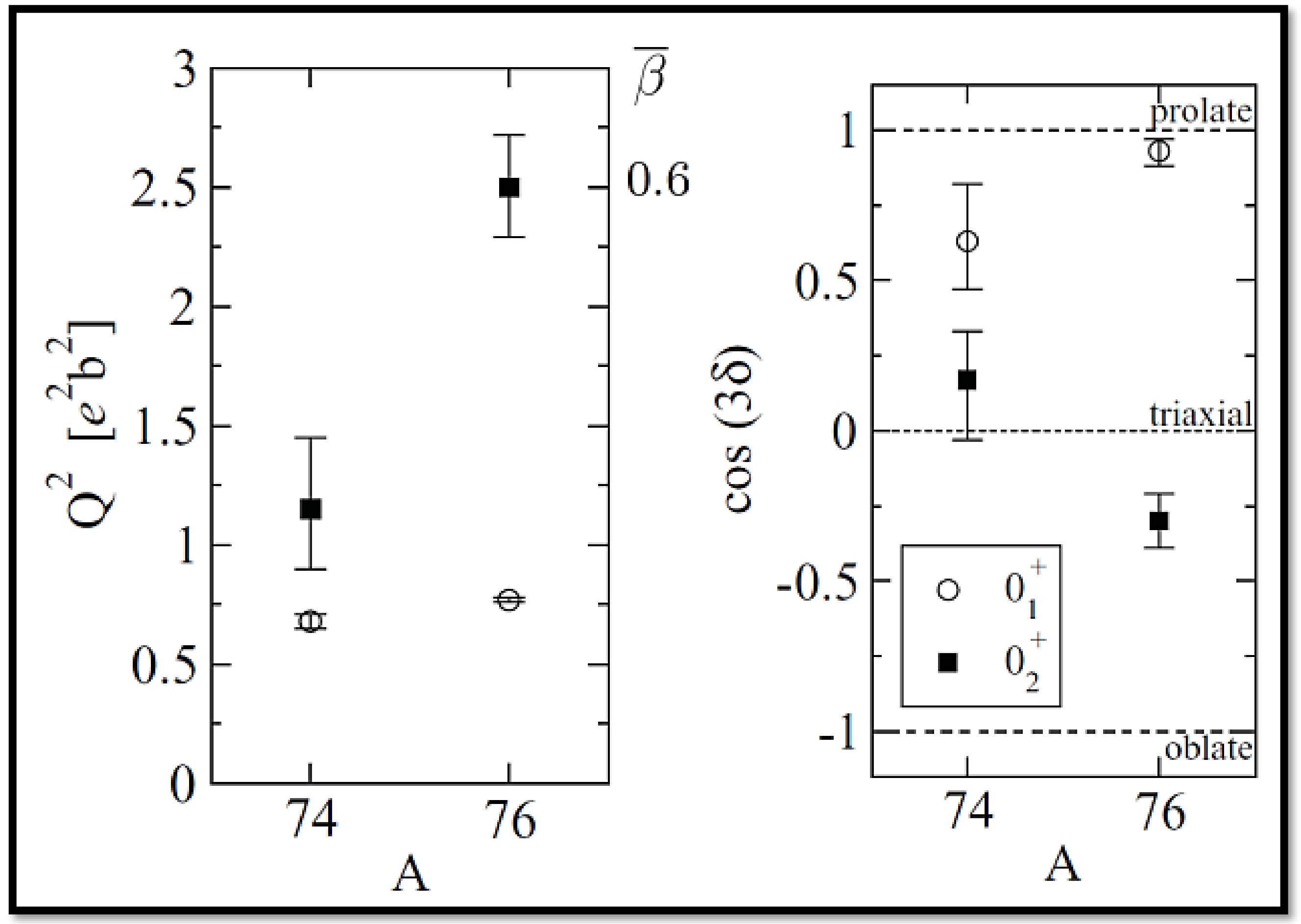


E344S results



GCM (GOA) calculation,
triaxial deformation,
Gogny D1S

M. Girod et al.



- results well described by 5DCH calculations
- bad ordering of states if calculations limited to axial shapes - triaxiality is the key feature!

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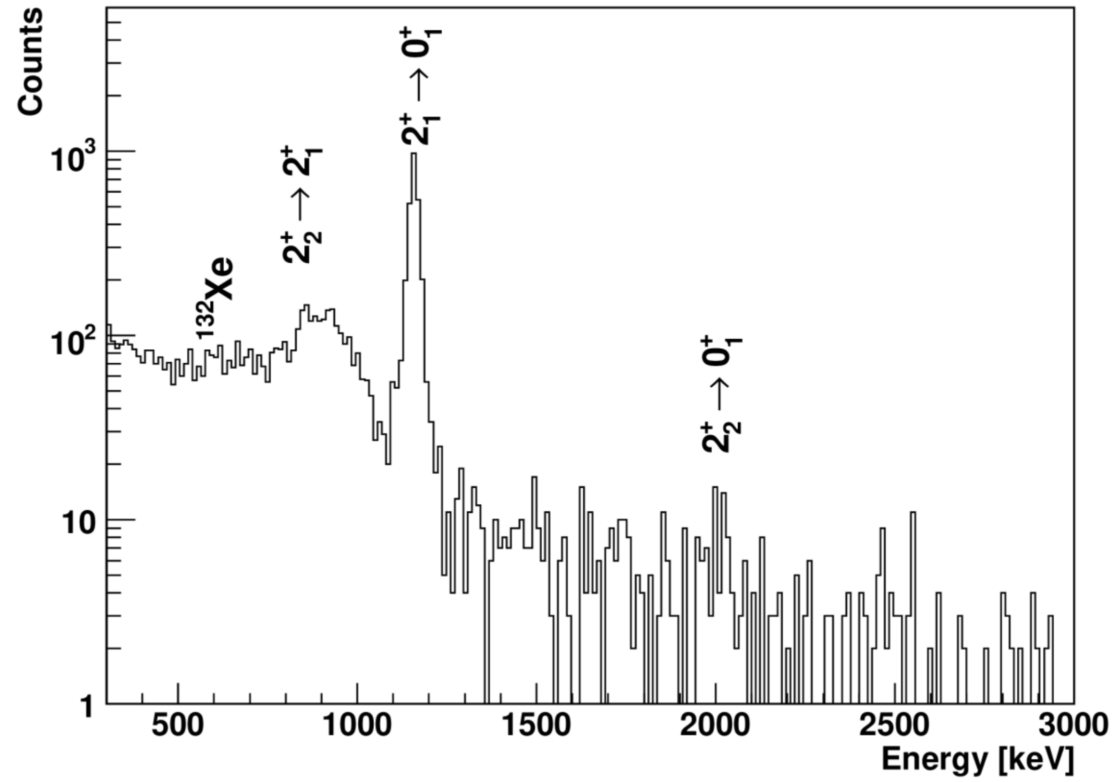
PHYSICAL REVIEW C **75**, 054313 (2007)

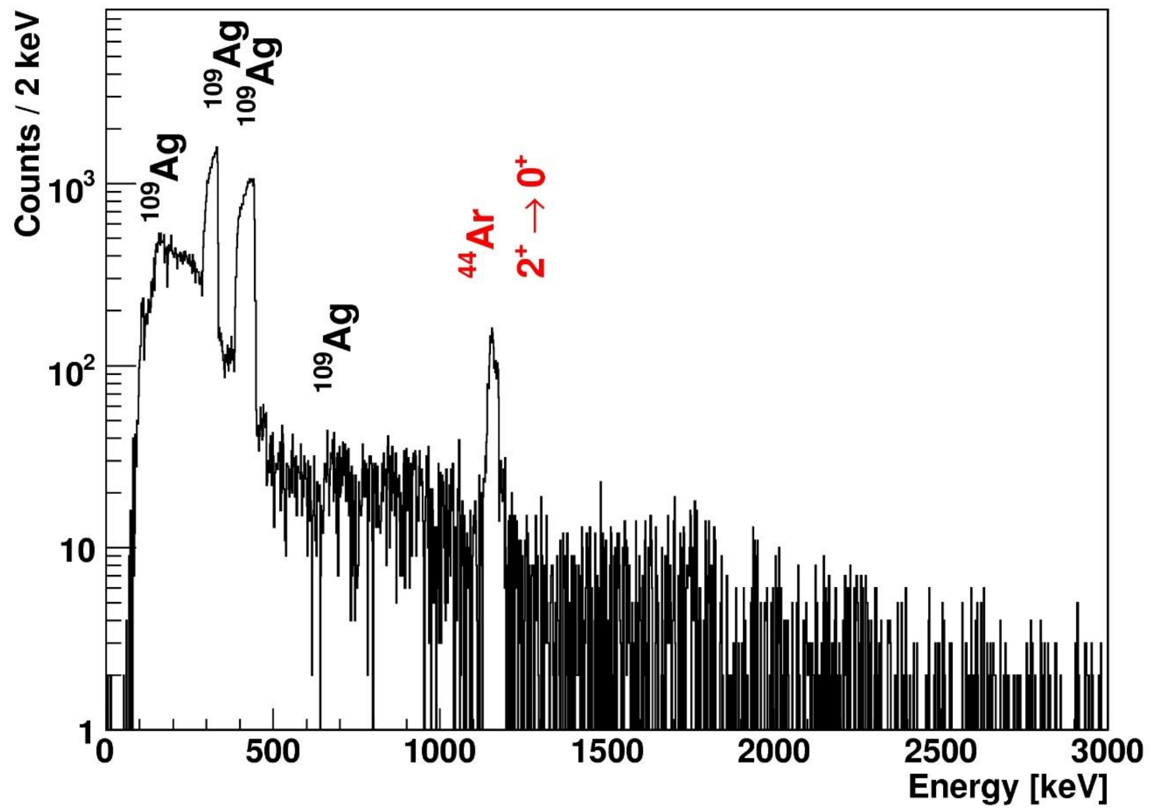
Shape coexistence in neutron-deficient krypton isotopes

E. Clément,[1,*] A. Görgen,[1] W. Korten,[1] E. Bouchez,[1] A. Chatillon,[1,†] J.-P. Delaroche,[2] M. Girod,[2] H. Goutte,[2] A. Hürstel,[1] Y. Le Coz,[1,‡] A. Obertelli,[1] S. Péru,[2] Ch. Theisen,[1] J. N. Wilson,[1,§] M. Zielińska,[1,3] C. Andreoiu,[4,||] F. Becker,[5] P. A. Butler,[4] J. M. Casandjian,[6,¶] W. N. Catford,[7] T. Czosnyka,[3,**] G. de France,[6] J. Gerl,[5] R.-D. Herzberg,[4] J. Iwanicki,[3,4] D. G. Jenkins,[4,††] G. D. Jones,[4] P. J. Napiorkowski,[3] G. Sletten,[8] and C. N. Timis[7]

Courtesy: E. Clement, M. Zielińska

Coulomb excitation of ^{44}Ar @ GANIL [E493S, April 2008]





Courtesy: M. Zielińska

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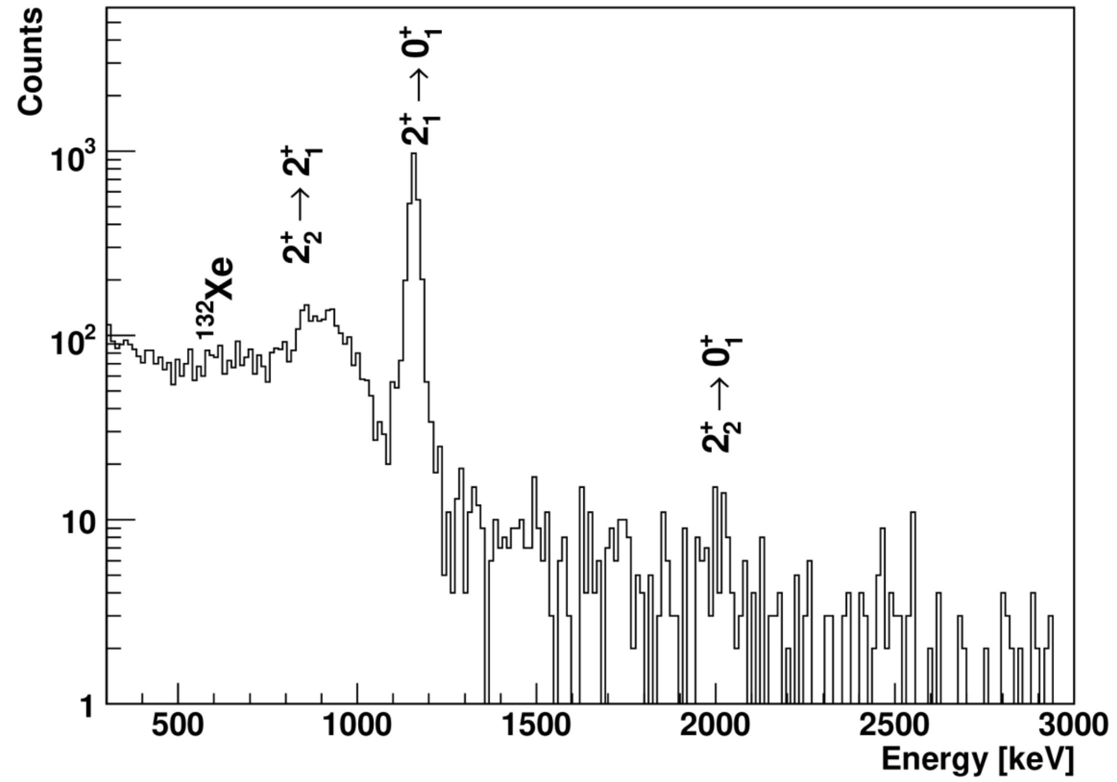
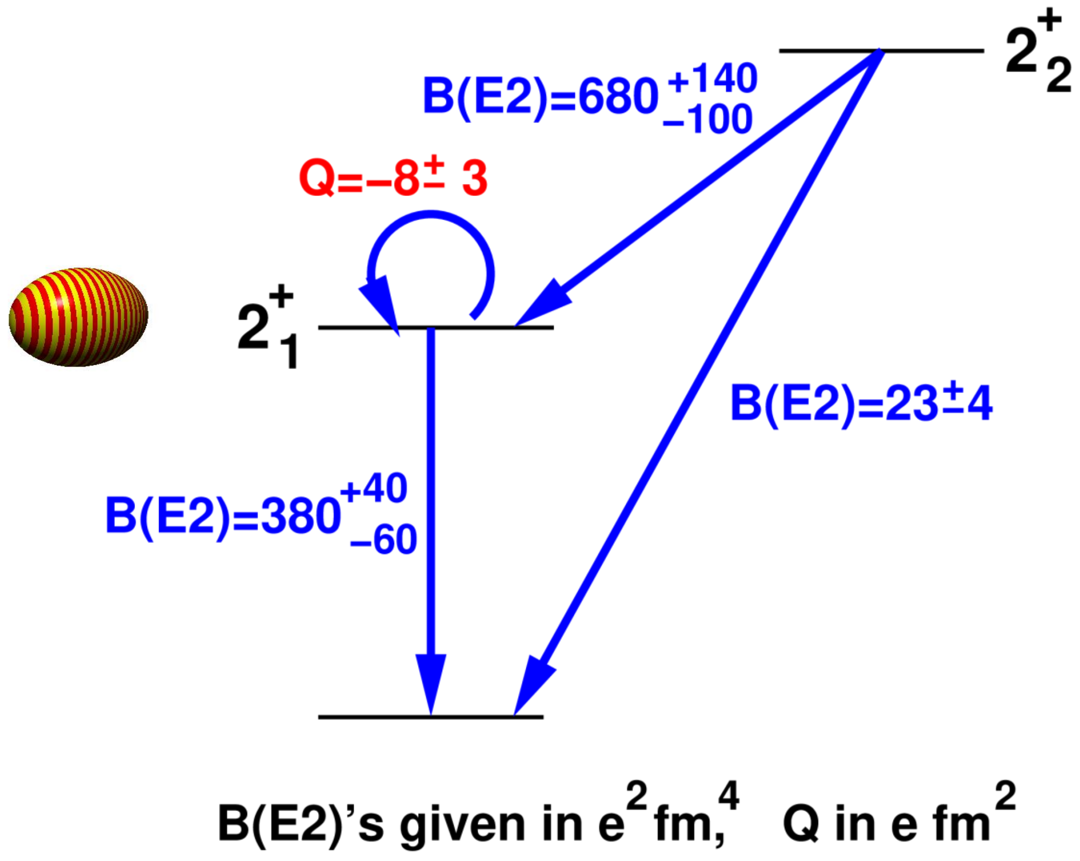
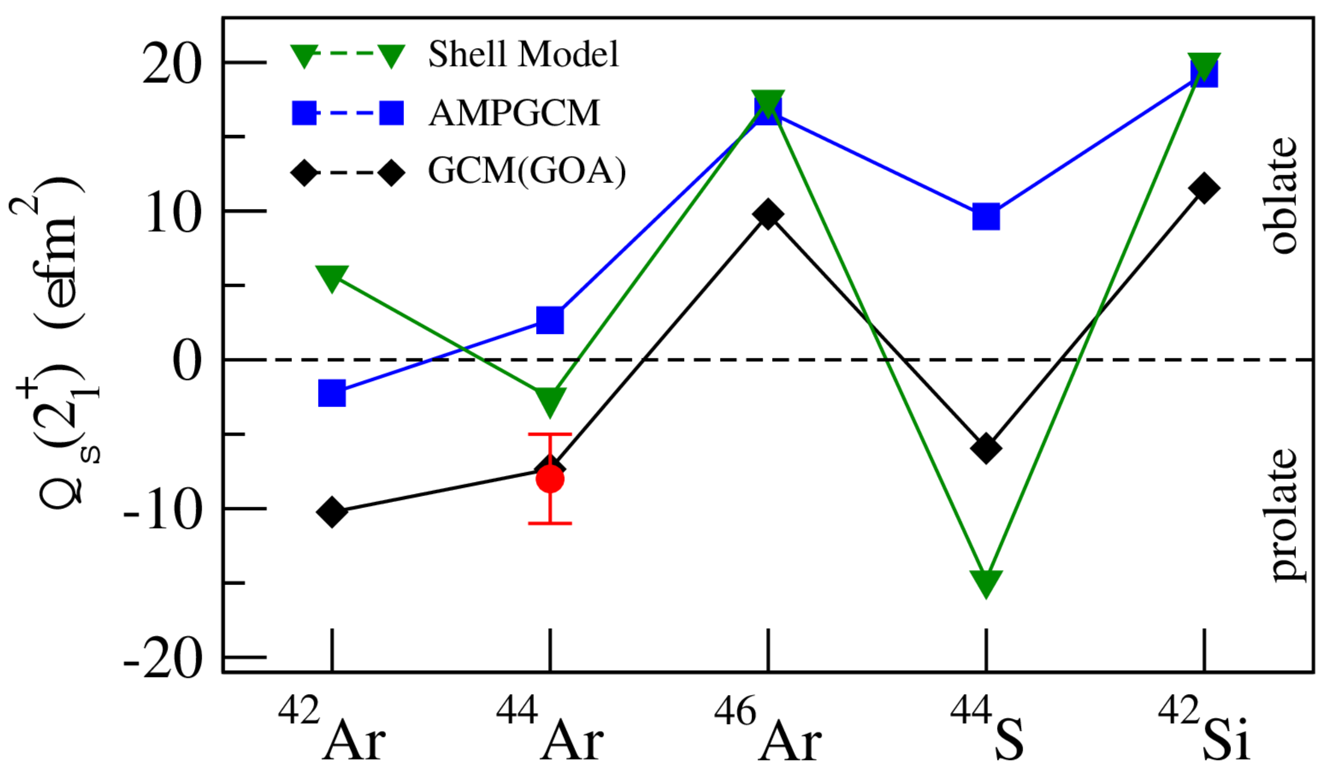
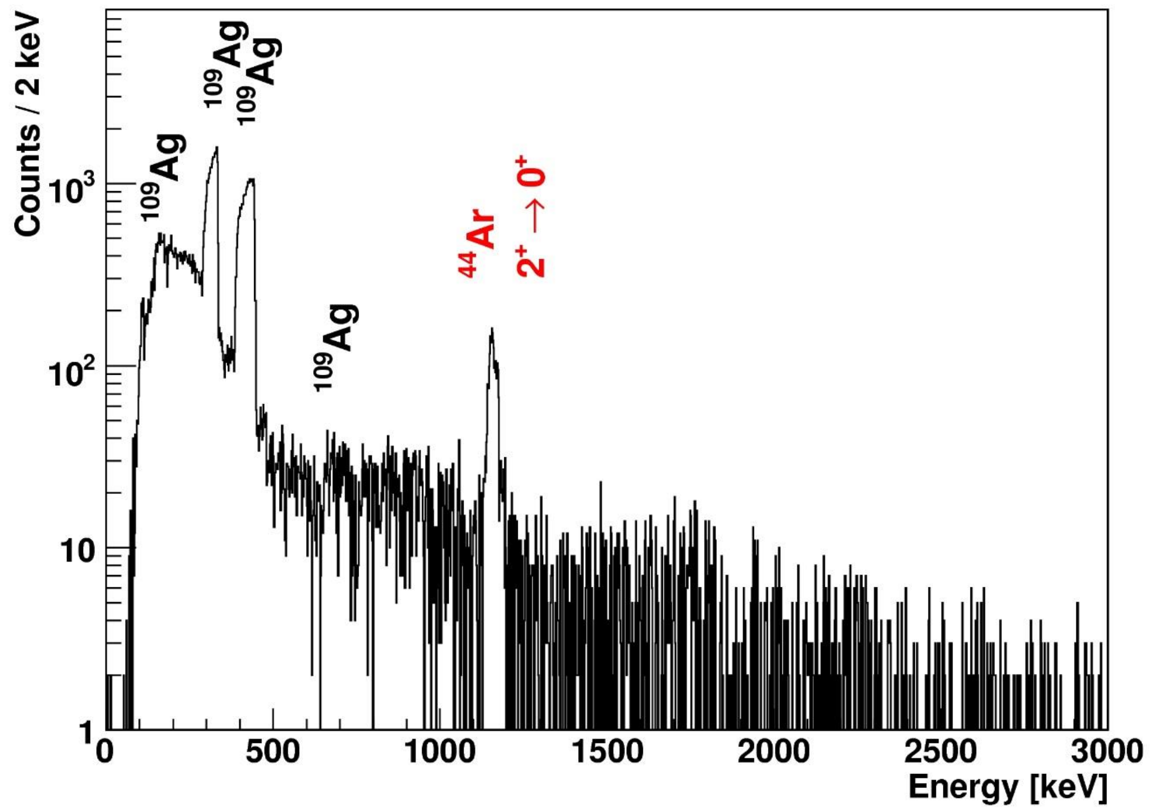








- B(E2; $2^+_1 \rightarrow 0^+_1$) in agreement with the result from intermediate-energy Coulex (345(41) e^2 fm^4)
- quadrupole moment of the 2^+_1 state measured with precision of 35%
- B(E2) values for transitions deexciting the 2^+_2 state measured for the first time
- ground-state β deformation of nearly 0.3 already already two protons and two neutrons away from doubly magic ^{48}Ca
- diagonal matrix element – 50% of the rotational value → triaxiality ?

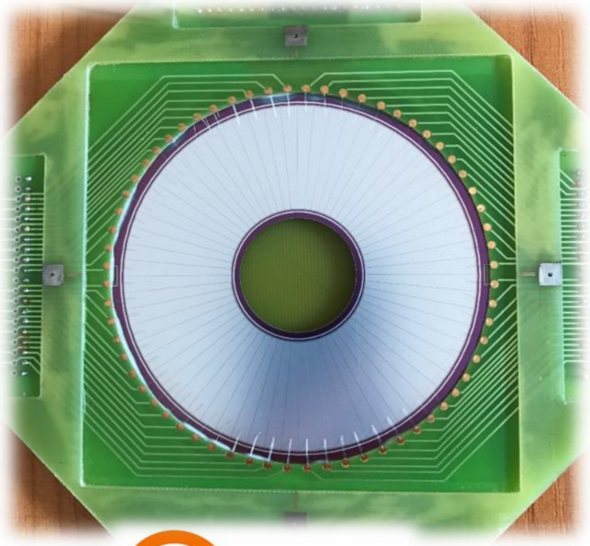
PHYSICAL REVIEW C **80**, 014317 (2009)

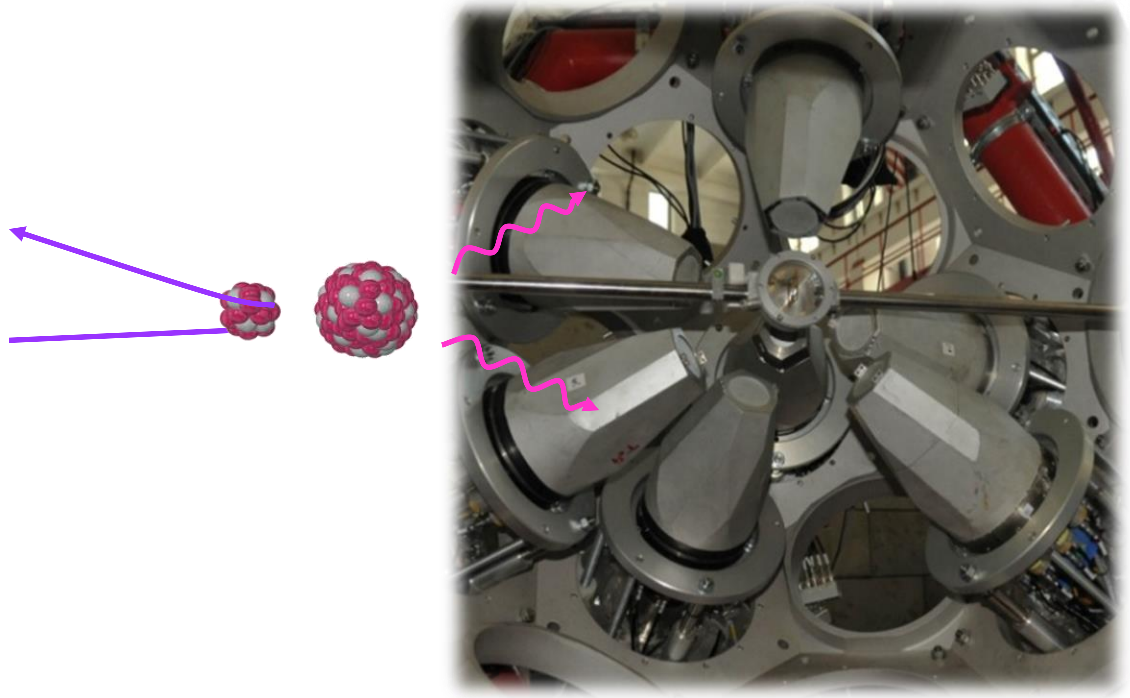
Shape of ^{44}Ar: Onset of deformation in neutron-rich nuclei near ^{48}Ca

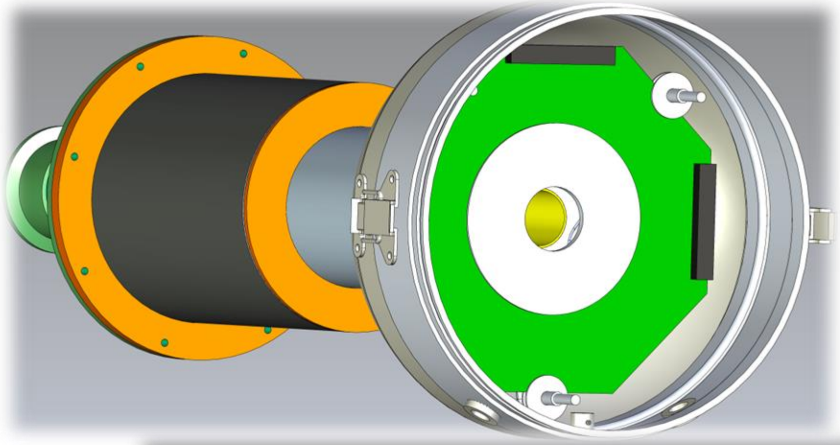
M. Zielińska,[1,2] A. Görgen,[1] E. Clément,[1,*] J.-P. Delaroche,[3] M. Girod,[3] W. Korten,[1] A. Bürger,[1,4,†] W. Catford,[5] C. Dossat,[1] J. Iwanicki,[2] J. Libert,[6] J. Ljungvall,[1,*] P. J. Napiorkowski,[2] A. Obertelli,[1] D. Piętak,[7] R. Rodríguez-Guzmán,[8] G. Sletten,[9] J. Srebrny,[2] Ch. Theisen,[1] and K. Wrzosek[2]

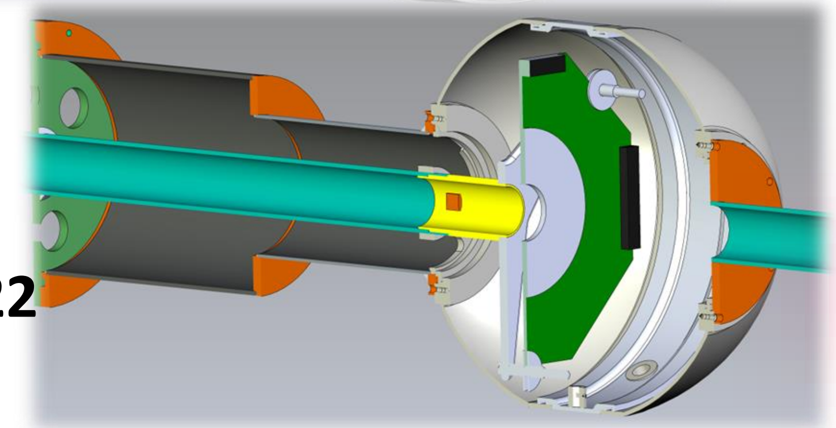
Courtesy: M. Zielińska

SilCA – Silicon Coulex Array









- r_{in} = *1.6 cm*
- r_{out} = *4.2 cm*
- *64 sectors (32 readout)*
- *32 rings (16 readout)*

Spring 2022

October 2022

Project: P. Napiorkowski, J. Iwanicki, A. Iwanicki, J. Mierzejewski, KHK

SilCA – Silicon Coulex Array

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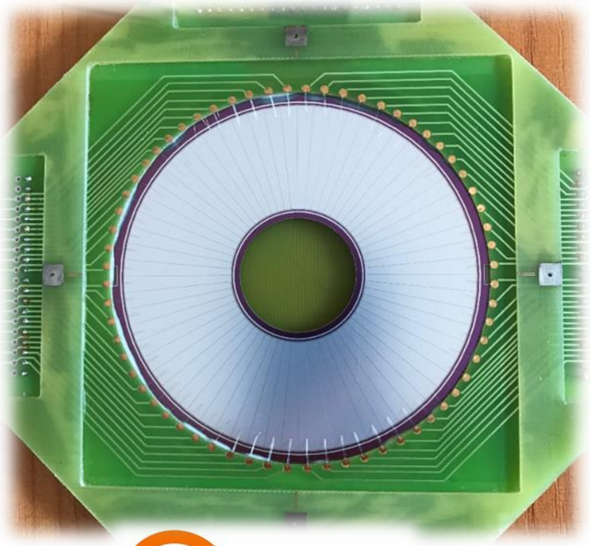

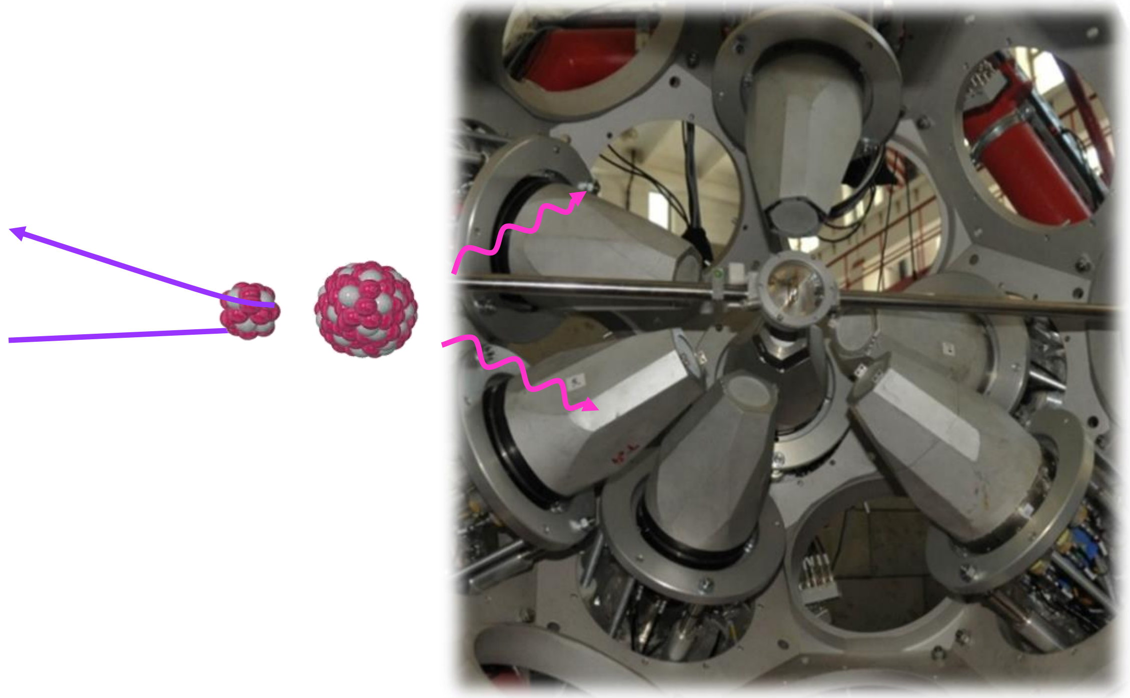

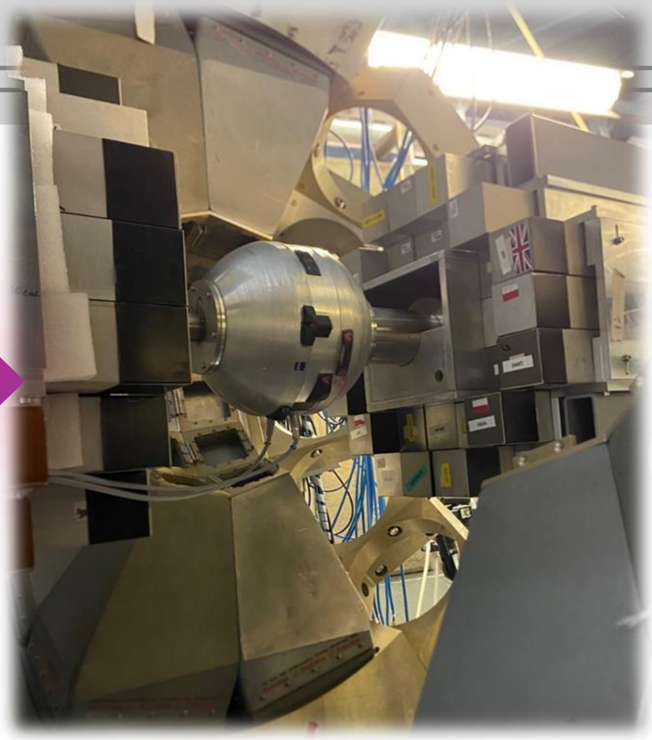

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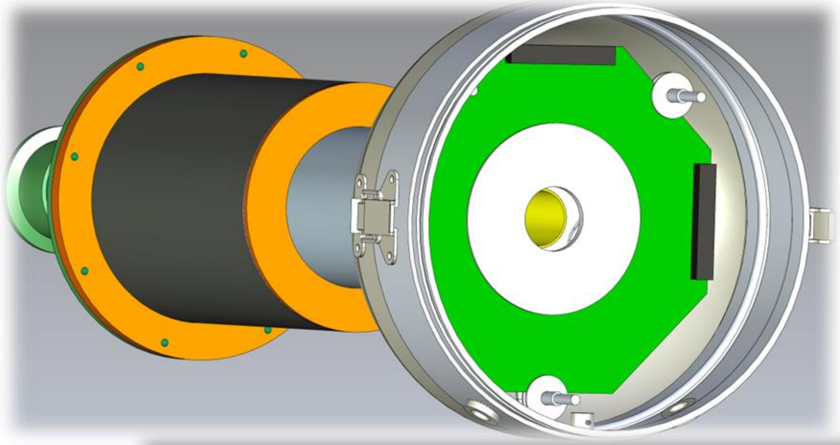

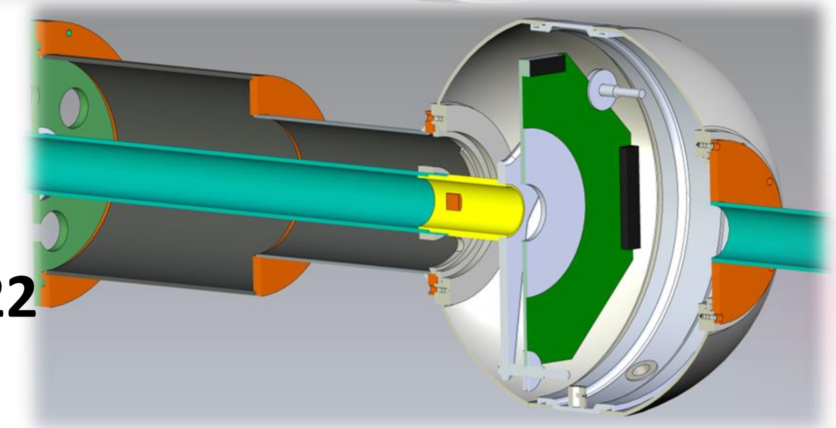

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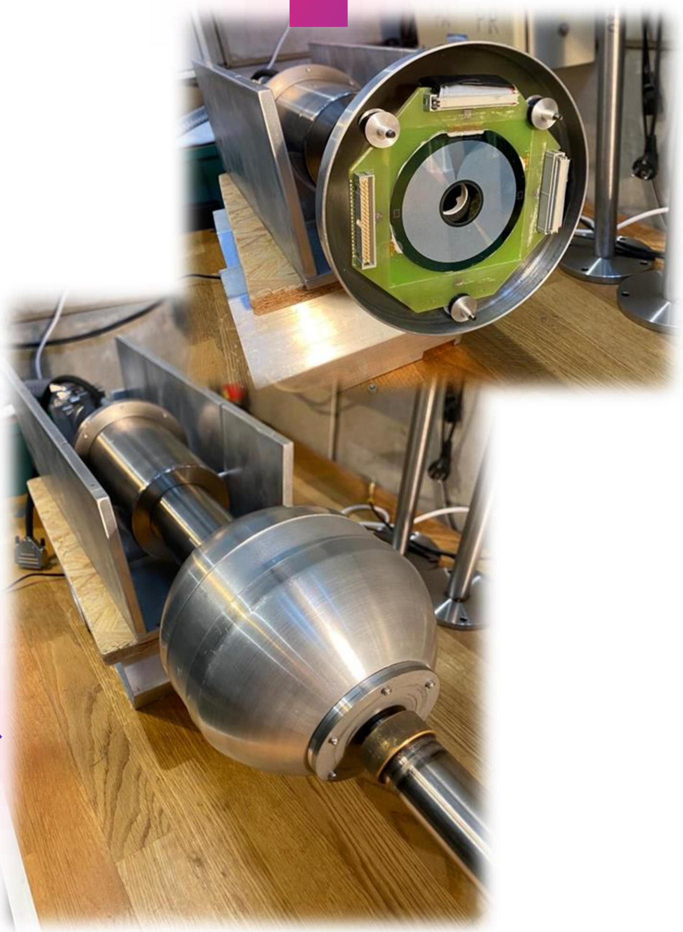

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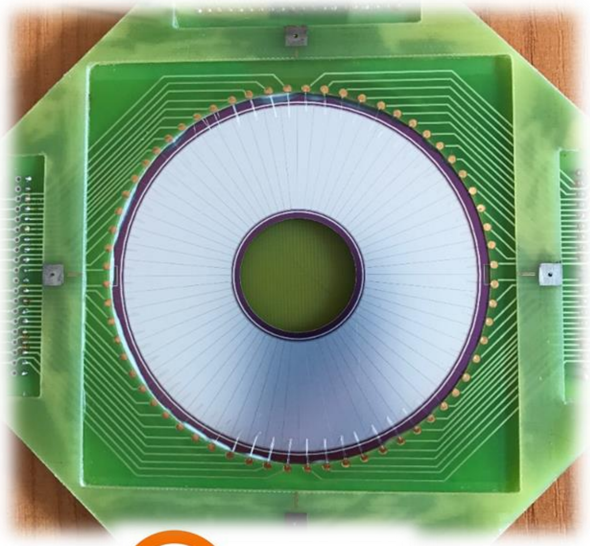
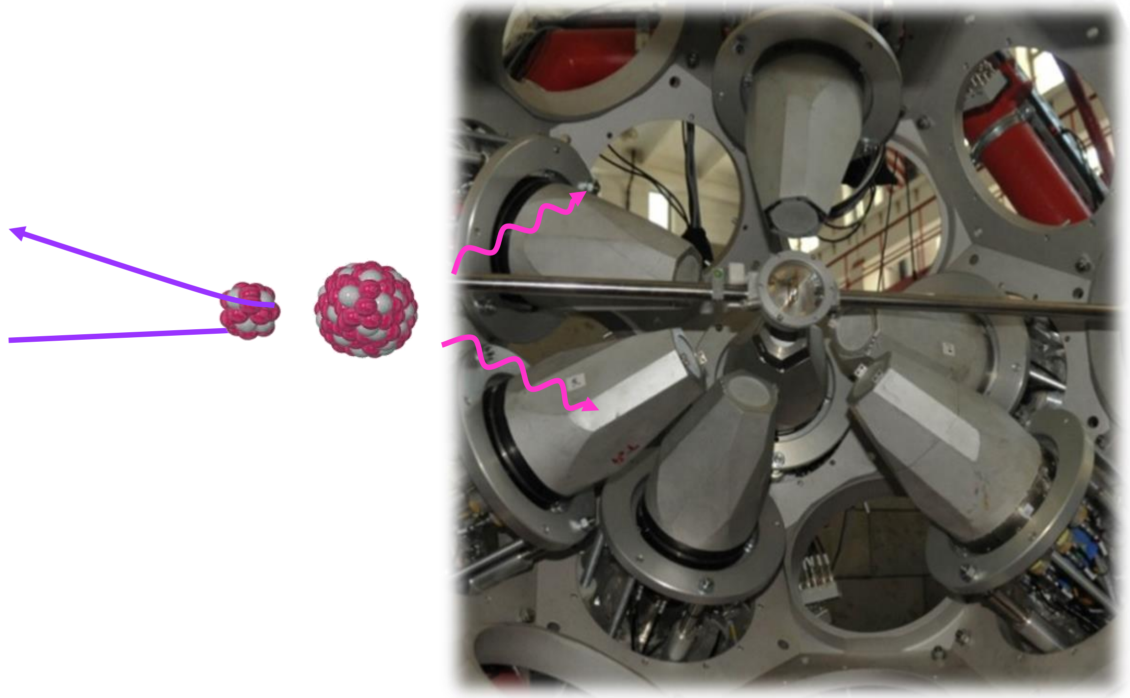
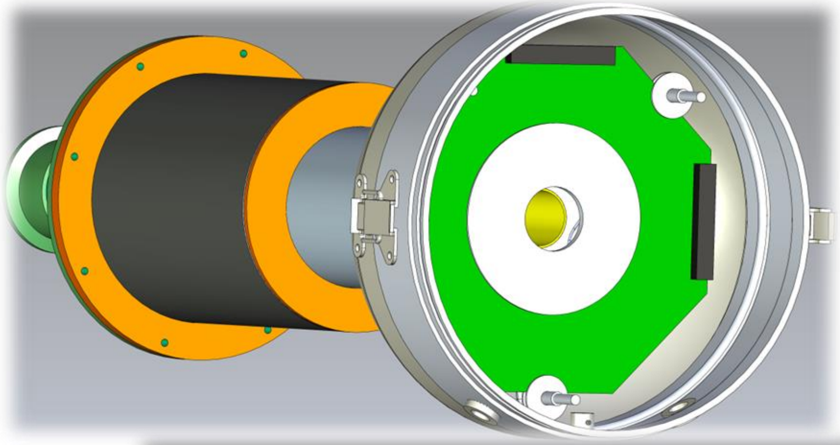
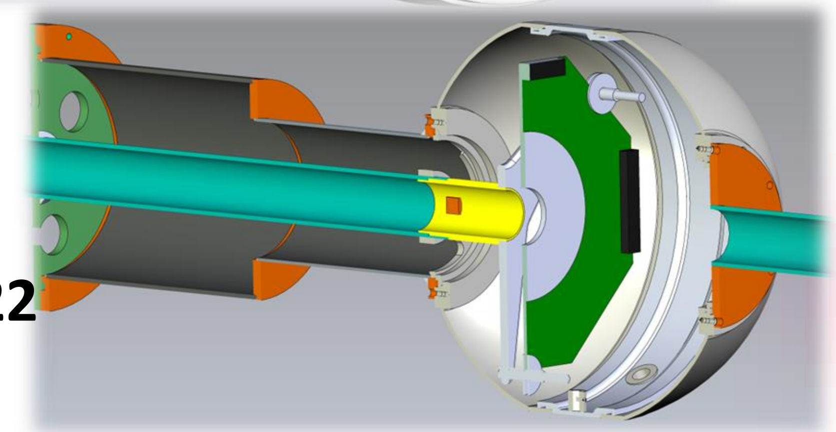


HIL







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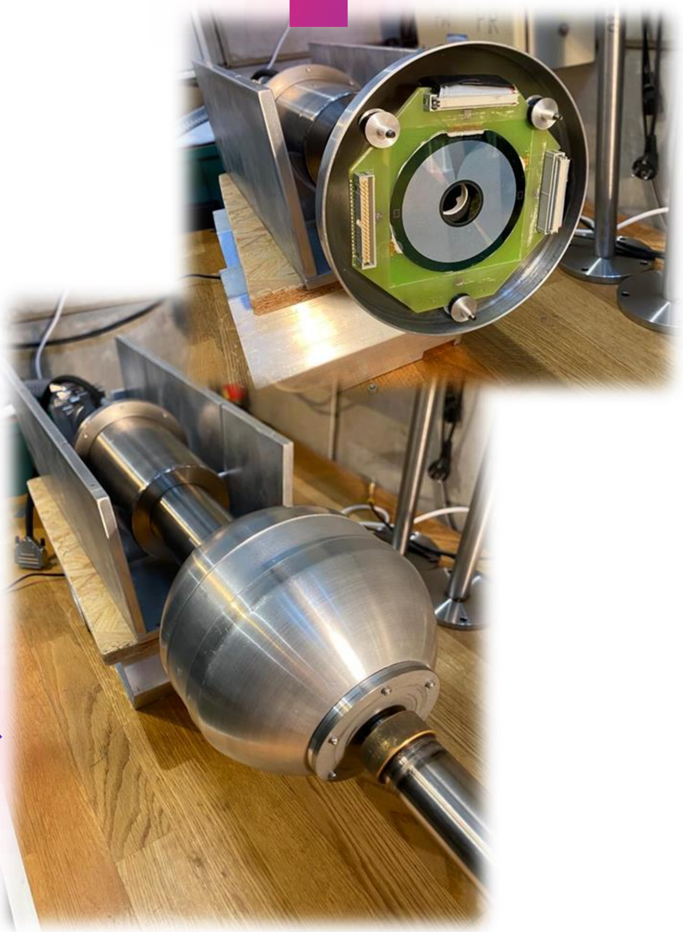
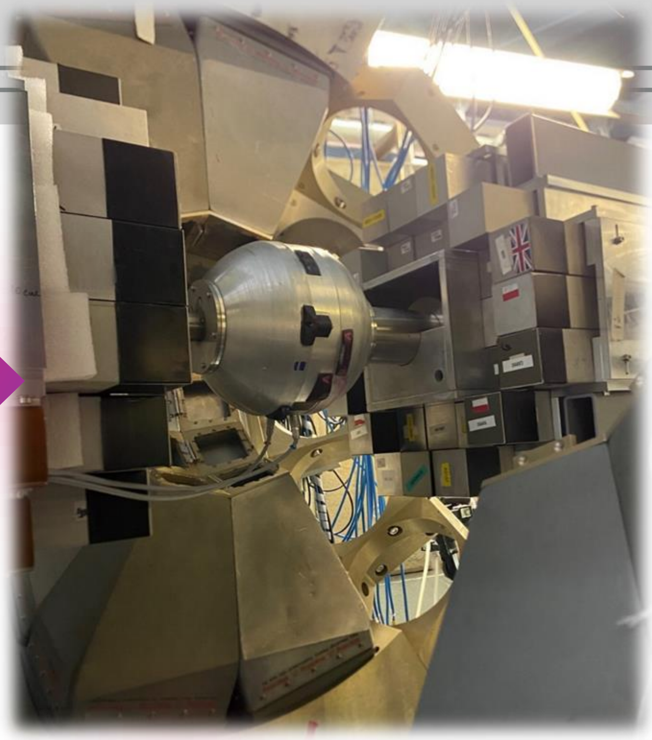


IJCLab Irène Joliot-Curie

December 2022



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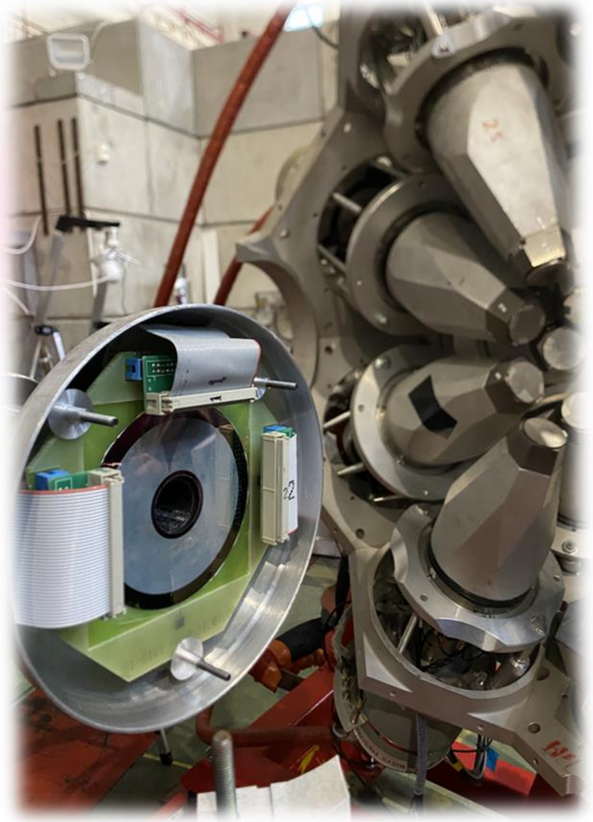

First tests (^{241}Am)**: February 2024**
DSSD+EAGLE (fully digital, CAEN 1725)

Project: P. Napiorkowski, J. Iwanicki, A. Iwanicki, J. Mierzejewski, KHK

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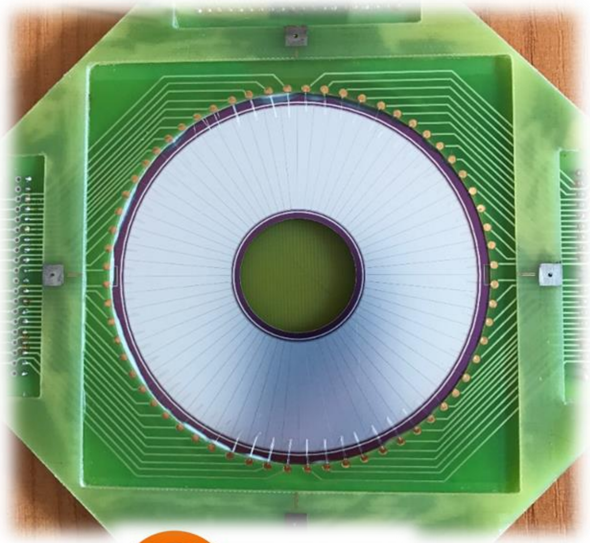

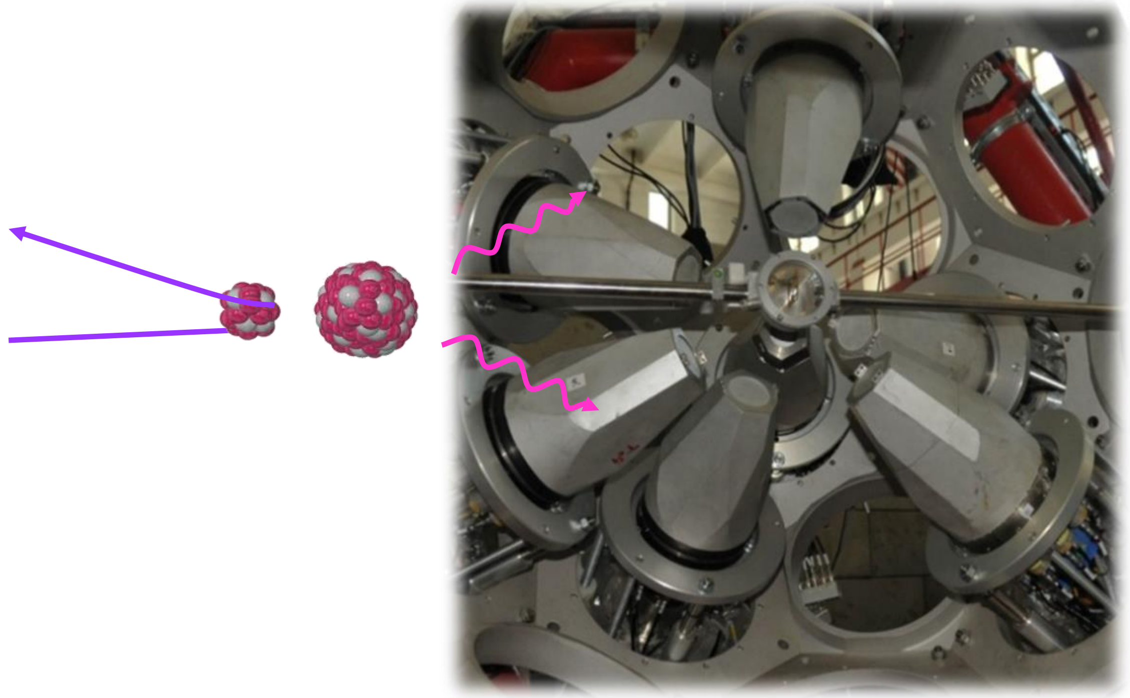

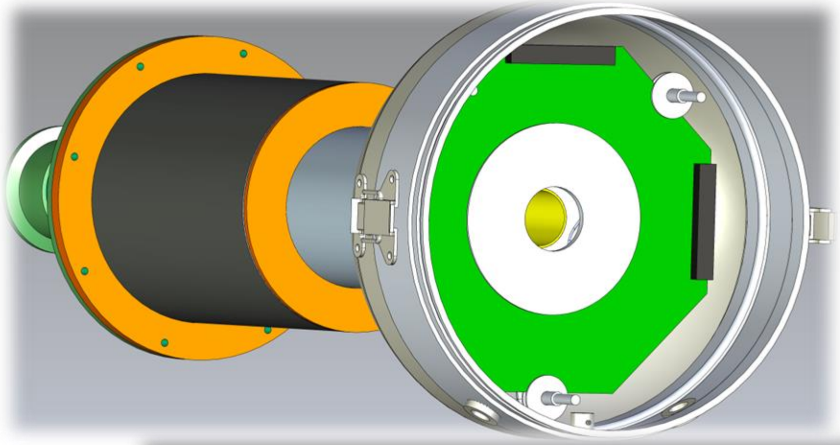

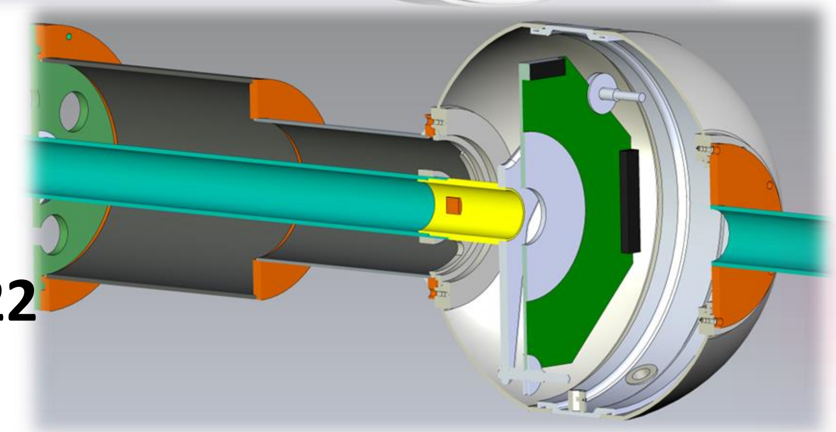

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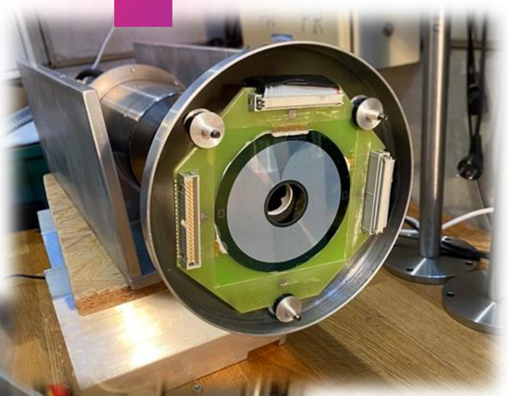

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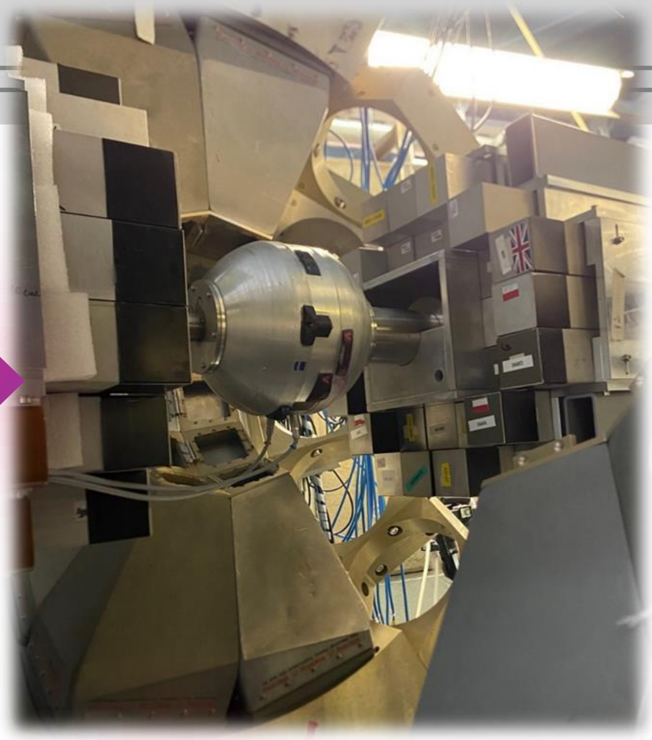

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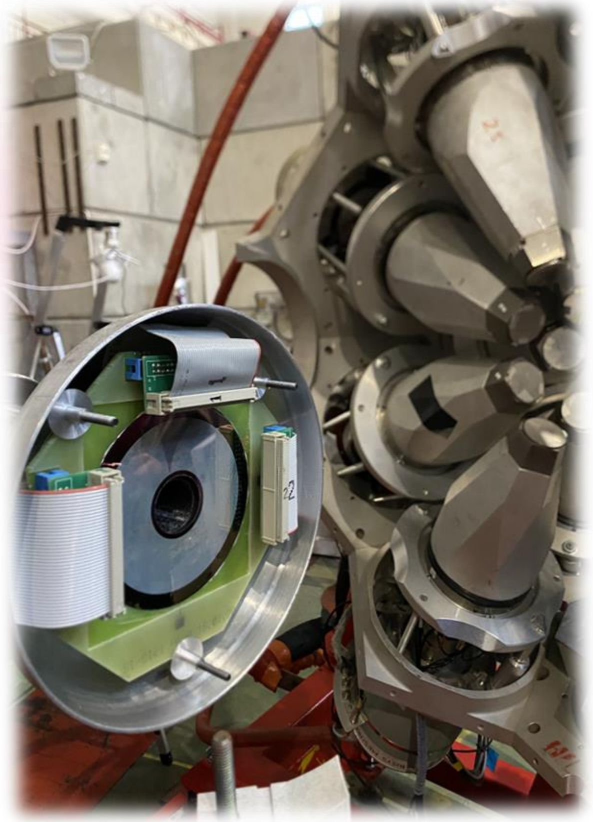

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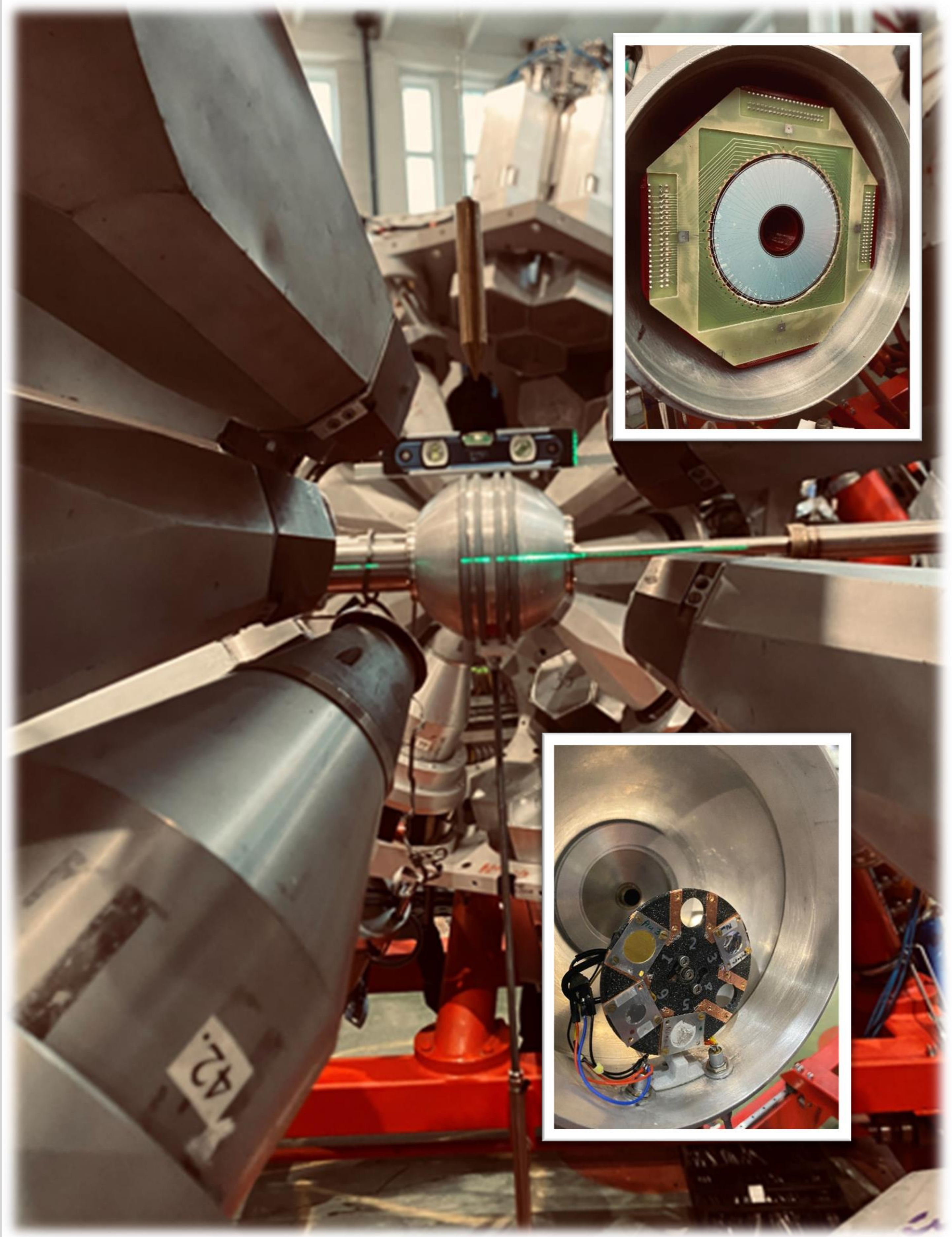
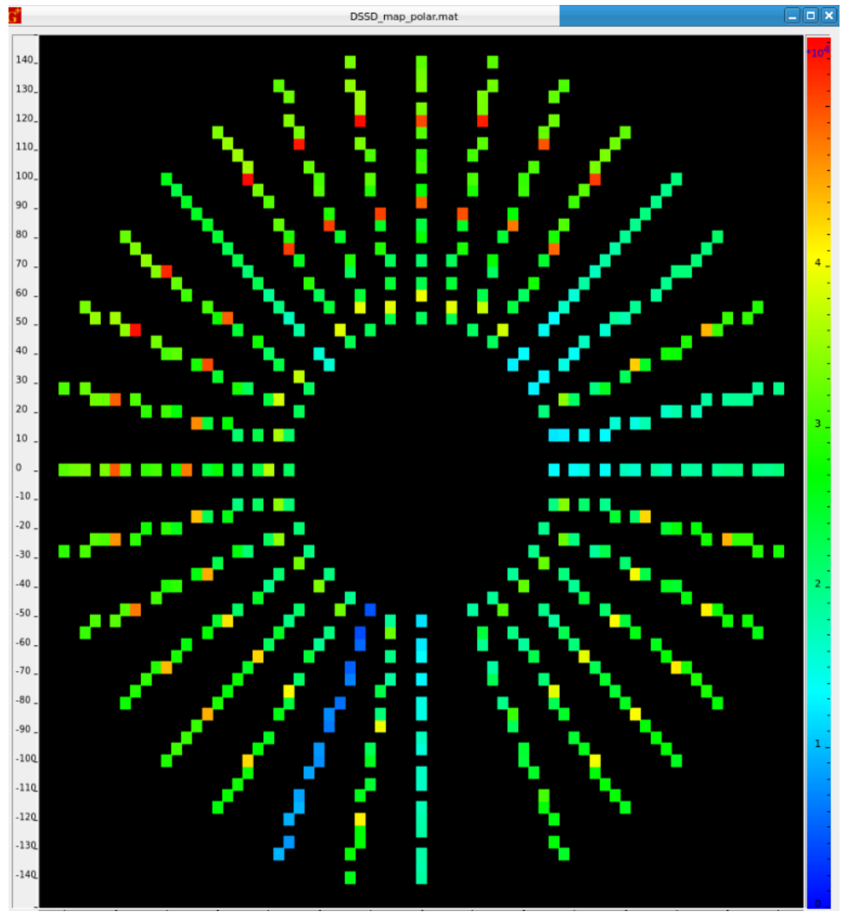
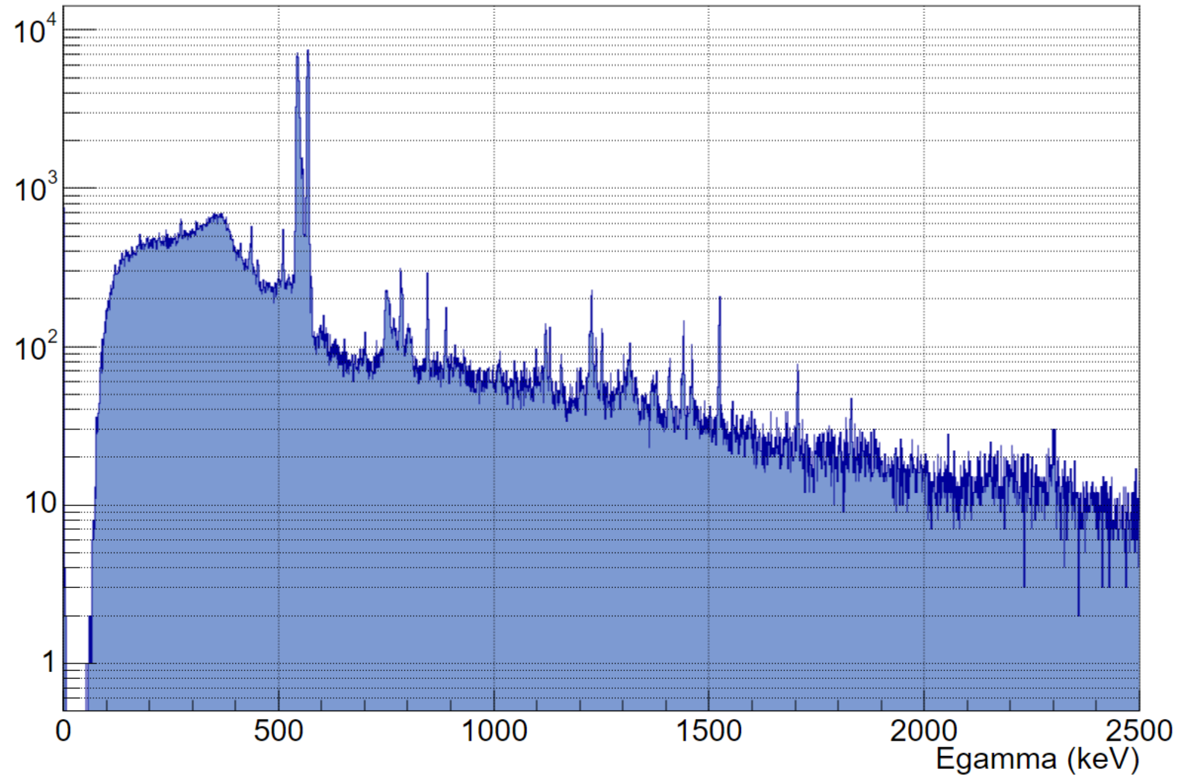
In-beam commissioning of SiLCA+EAGLE performed in November 2024
^{104}Pd + ^{32}S, Coulomb excitation reaction

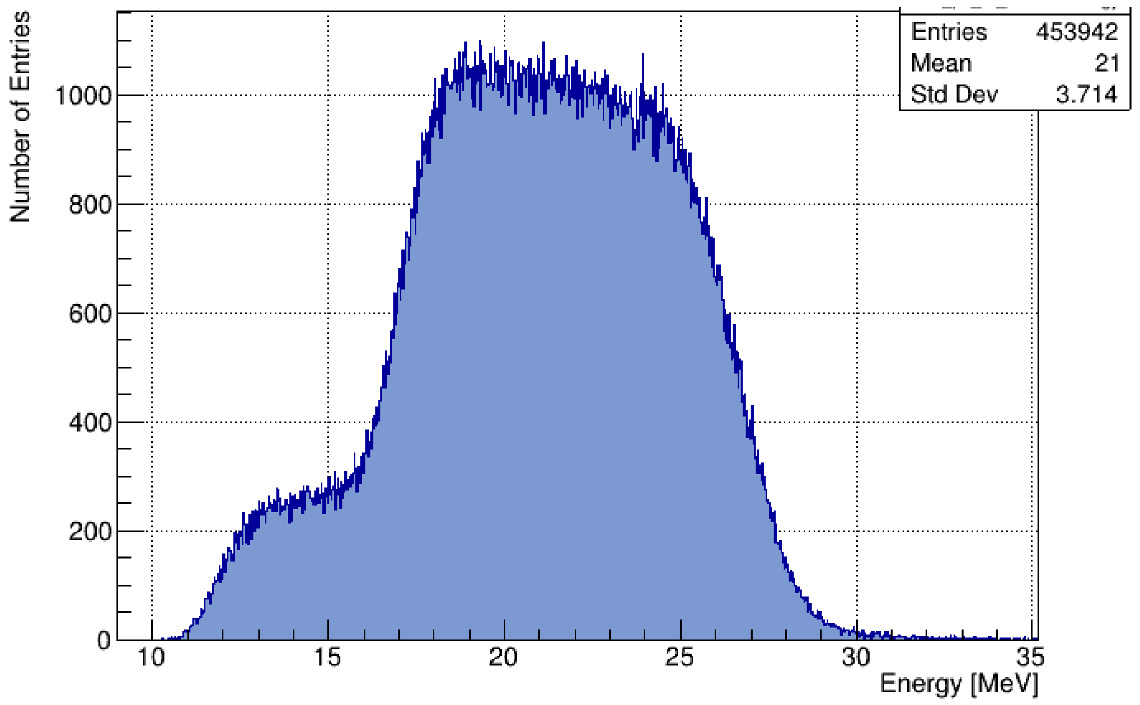
SilCA @ HIL (November 2024) – Coulomb excitation of ^{104}Pd



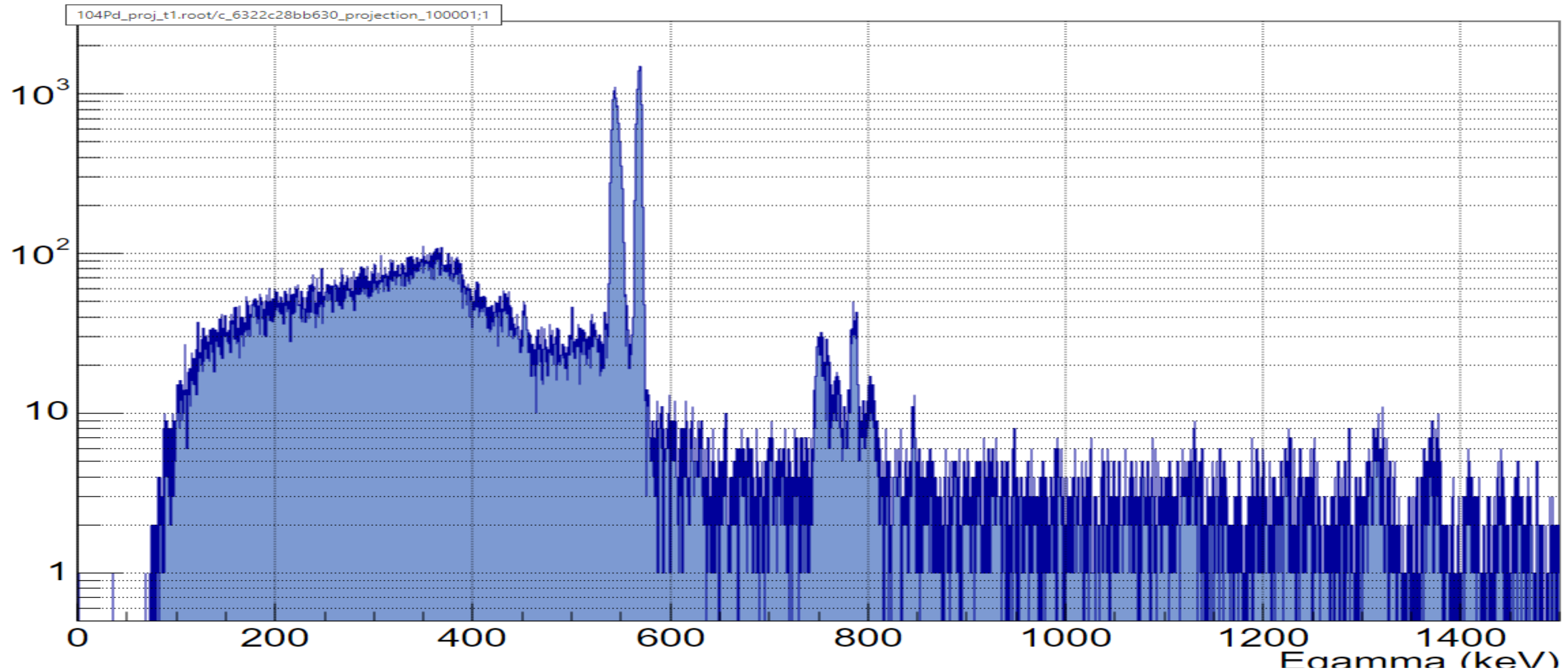
- ^{32}S beam, 90 MeV, 1-2 pnA
- ^{104}Pd (+ natBa and ^{197}Au targets), 1 mg/cm^2 each - on the automatic taget wheel, 6 spots, camera inside
- 4 days (12-15 Nov 2024)
- 13 HPGe (11 GAMMMAPOOL + 2 Phase One)
- SiLCA DSSD – 134-156^o, 4cm from the target
- 31/32 sectors and 16/16 rings were working
- Total dark current increased in-beam from 16 to 22 uA
- CAEN 1725 digitizers – 2 for HPGe + ACS, 3 for DSSD, 1 for NEDA + trigger
- AGAVA for the GTS
- XDAQ (LNL upgrade CERN-based DAQ), particle hardware trigger
- GREWARE + SPY – online visualisation (J. Grębosz, IFJ PAN Krakow)

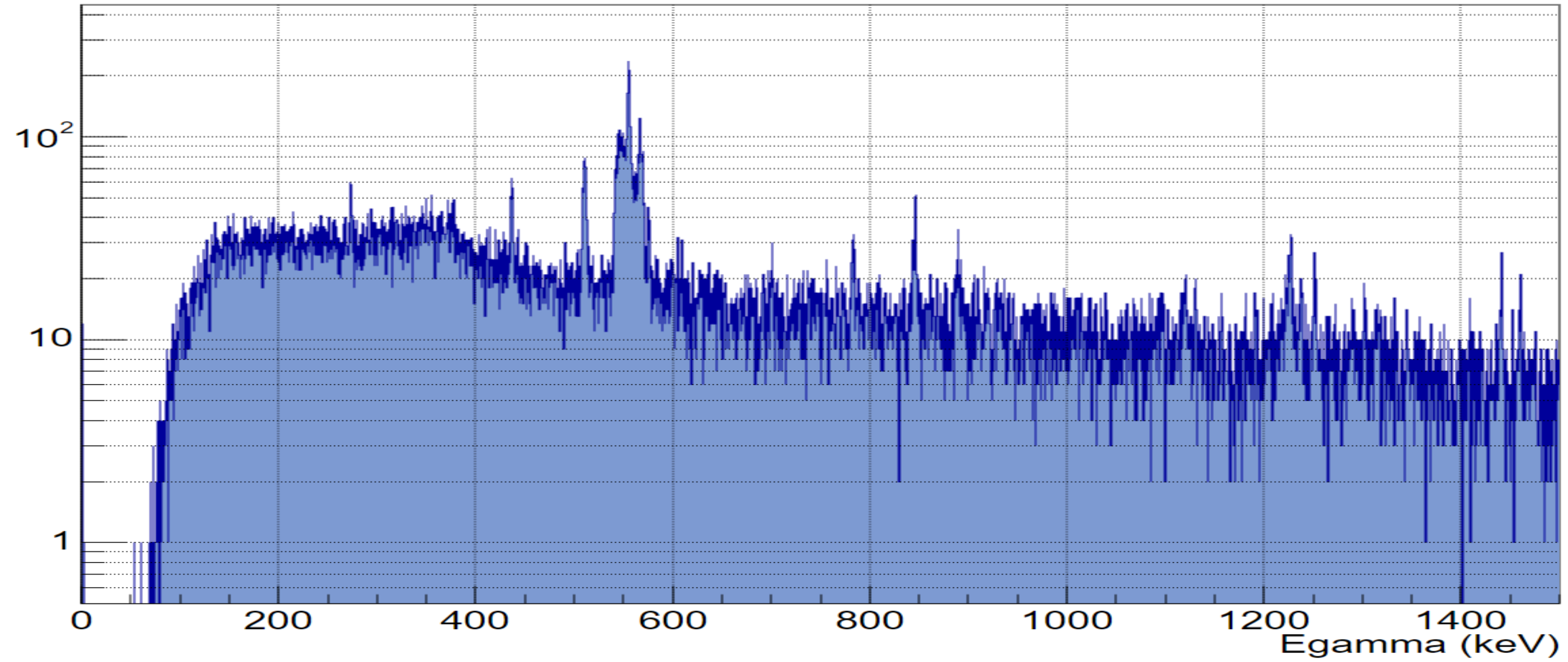


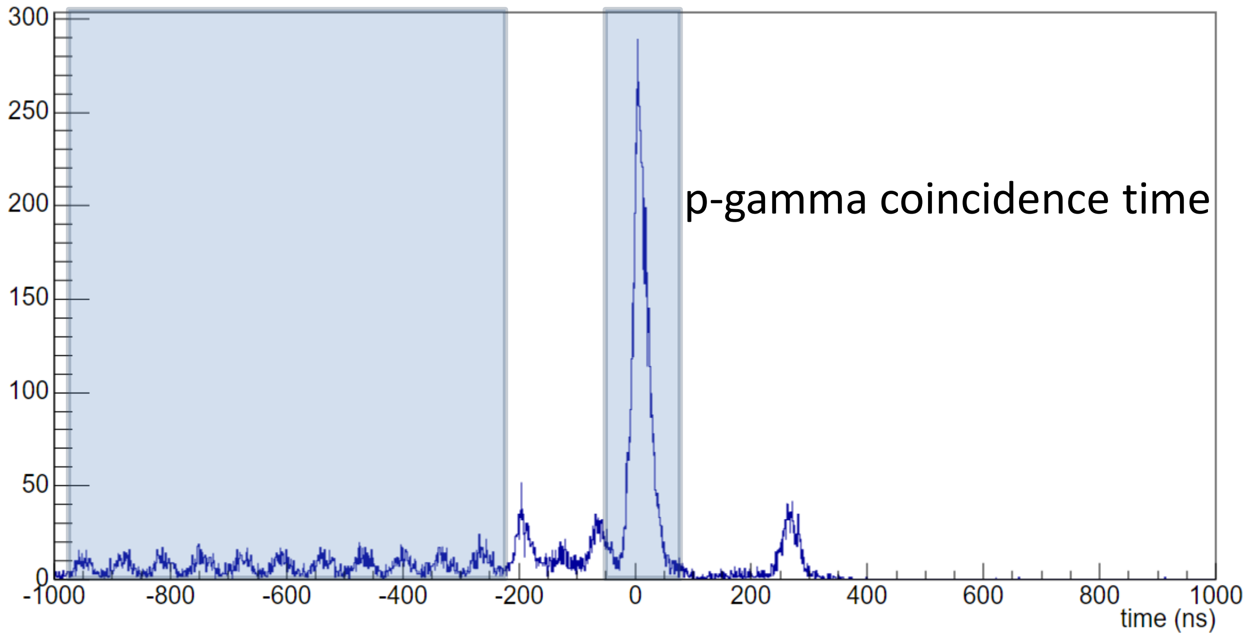


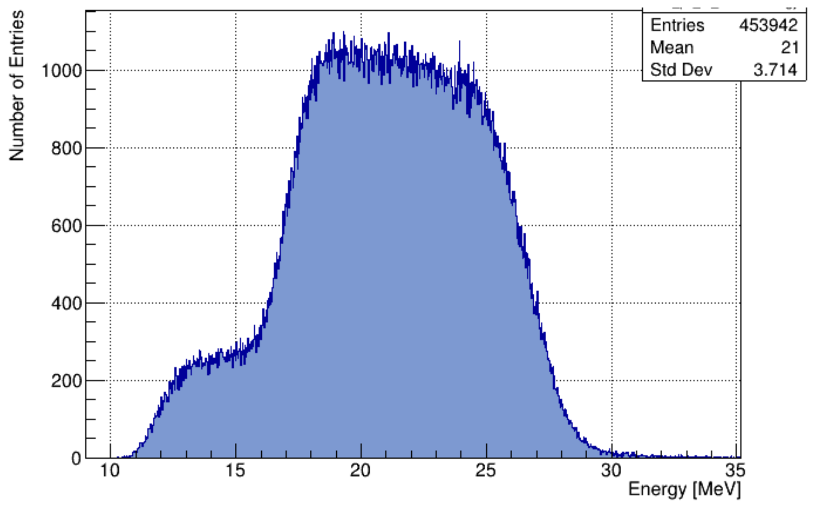


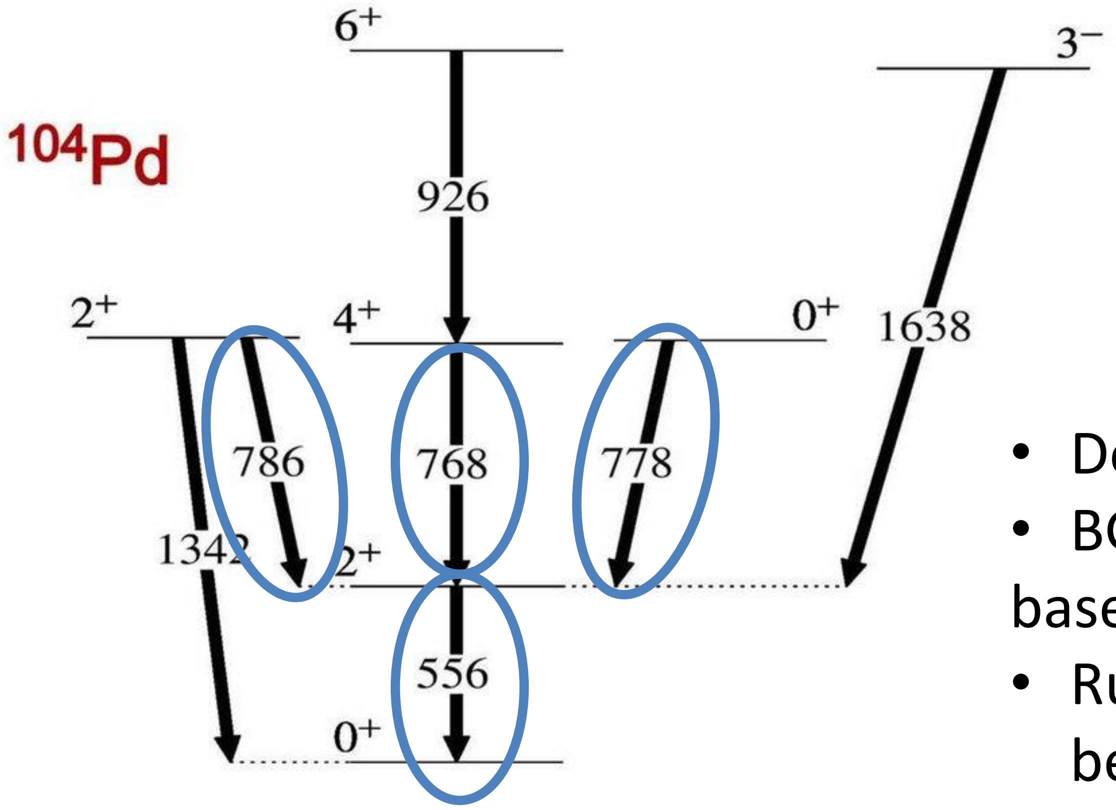
SilCA @ HIL (November 2024) – Coulomb excitation of ^{104}Pd









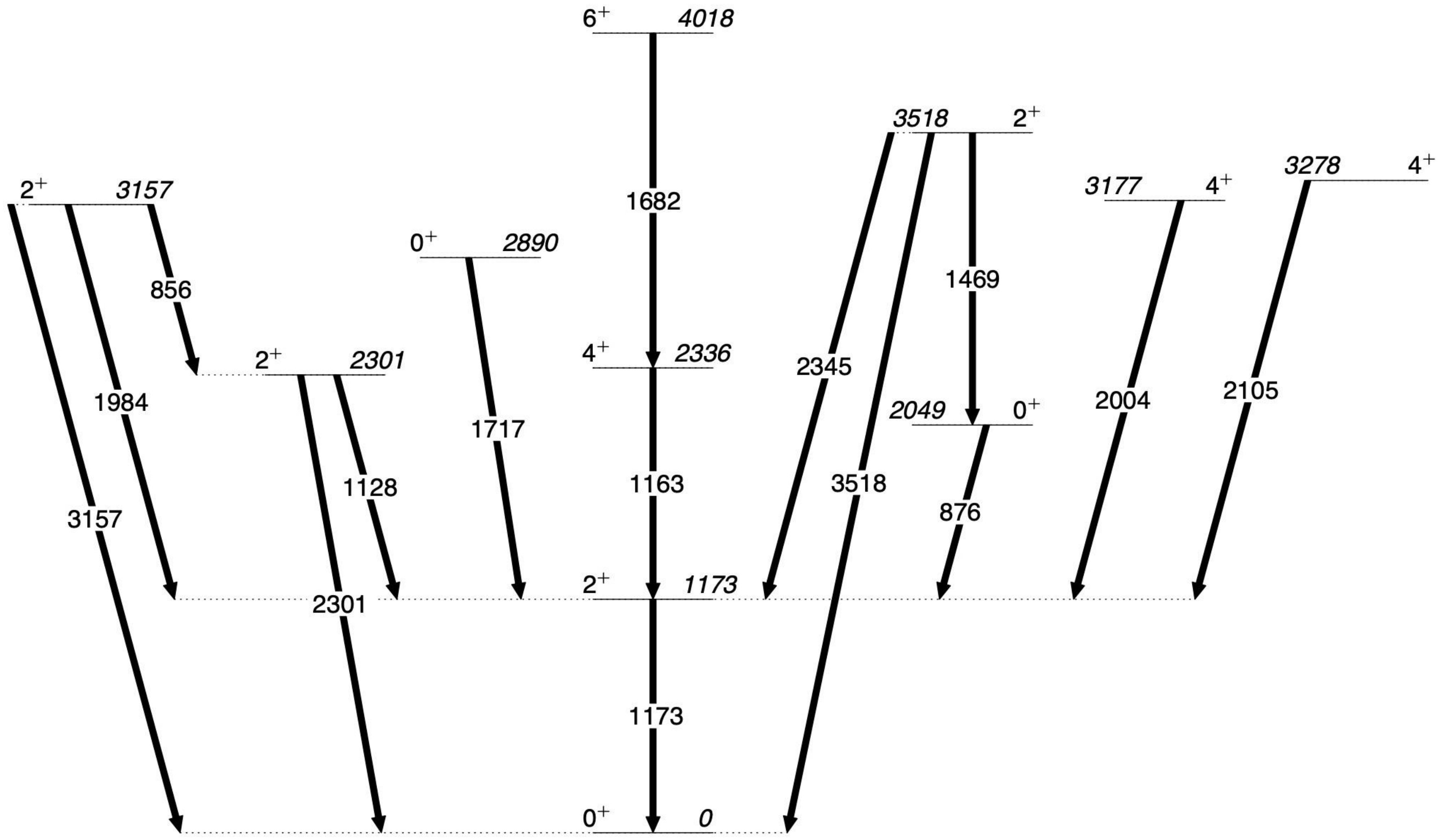


- Doppler Correction – to be done
- BGR subtraction – to be improved: based on the particle spectra + time
- Run-by-run calibration – need to be checked

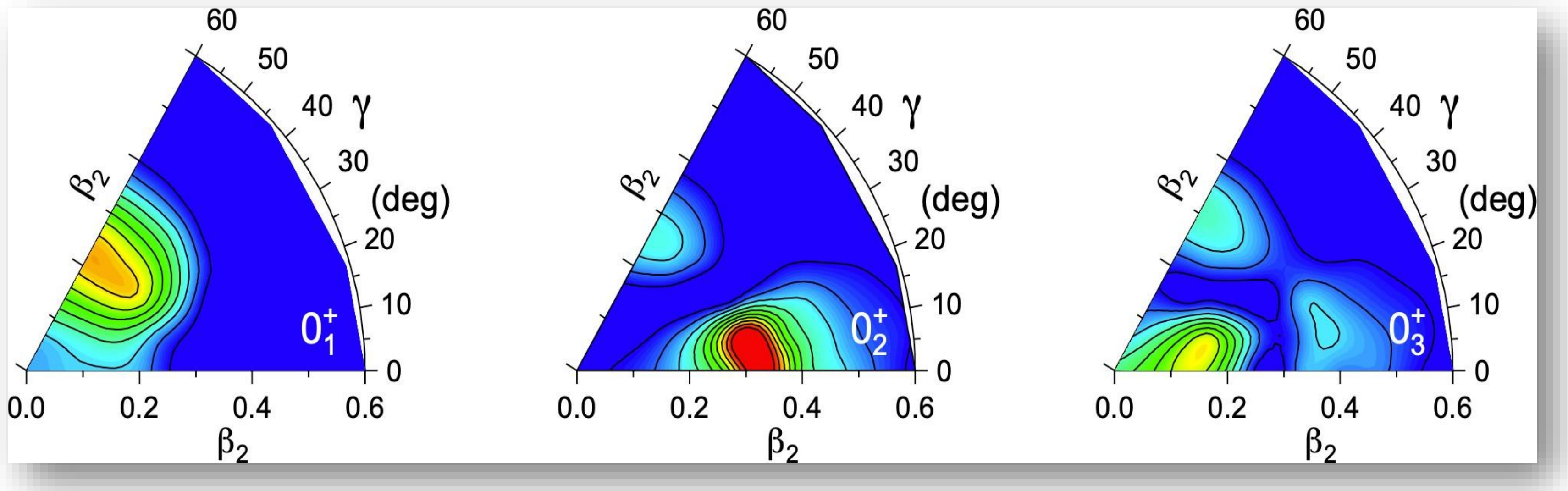
Thanks to (in alphabetical order):

P. Dei, J. Grębosz, C. Hiver, G. Jaworski, M. Komorowska, M. Kowalczyk, A. Krzysiek, A. Malinowski, M. Matuszewski, J. Mierzejewski, P. Napiorkowski, M. Palacz, S. Panasenko, I. Piętka, J. Samorajczyk-Pyśk, P. Sekrecka, K. Solak, A. Spacek, G. Szymanek, K. Wrzosek-Lipska + the target lab (A. Stolarz, J. Kowalska)

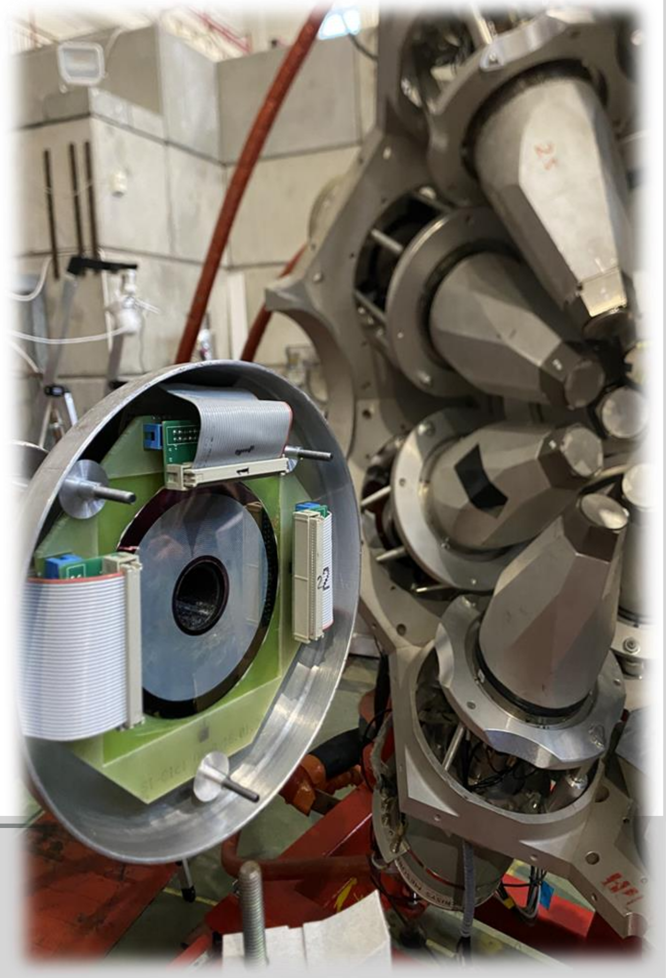
SilCA @ HIL (2025) – Coulomb excitation of ^{62}Ni [HIL 113, accepted]



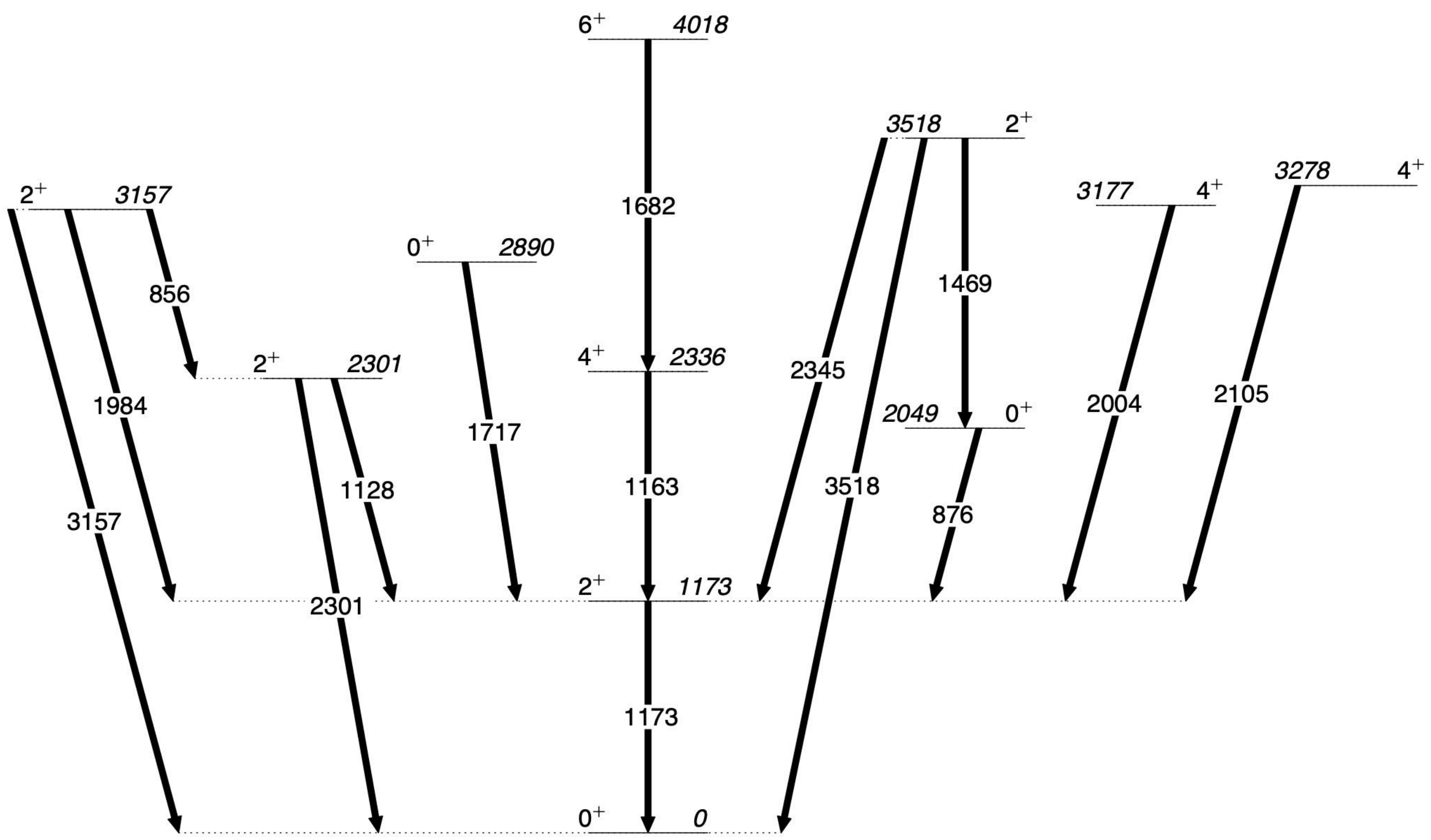
- Safe Coulomb excitation of ^{62}Ni
- Population of 0^+ and 2^+ states needed to understand the low-lying structure of ^{62}Ni
- $Q(2_1^+)$ - weakly known (measured in the reorientation experiment, indicating spherical/slightly oblate GS, but electron scattering is giving completely different value)
- 0_2^+ (2049 keV) - $BE2(0_2^+ \rightarrow 2_1^+)$ known with 55% uncertainty
- 0_2^+ - a 4p-4h excitation of ^{56}Ni core? A band-head of the superdeformed band?
- Triaxiality of 0^+ states - quadrupole moments of the 2^+ states needed
- Continuation of the project with IJC Lab (Orsay)



- ^{62}Ni target, 1 mg/cm^2
- ^{20}Ne beam, 35 MeV, 1 pnA
- 5 days of data taking assumed
- DSSD (127-154^{O}) + EAGLE (1.4% at 1.3 MeV)



SilCA @ HIL (2025) – Coulomb excitation of ^{62}Ni [HIL 113, accepted]



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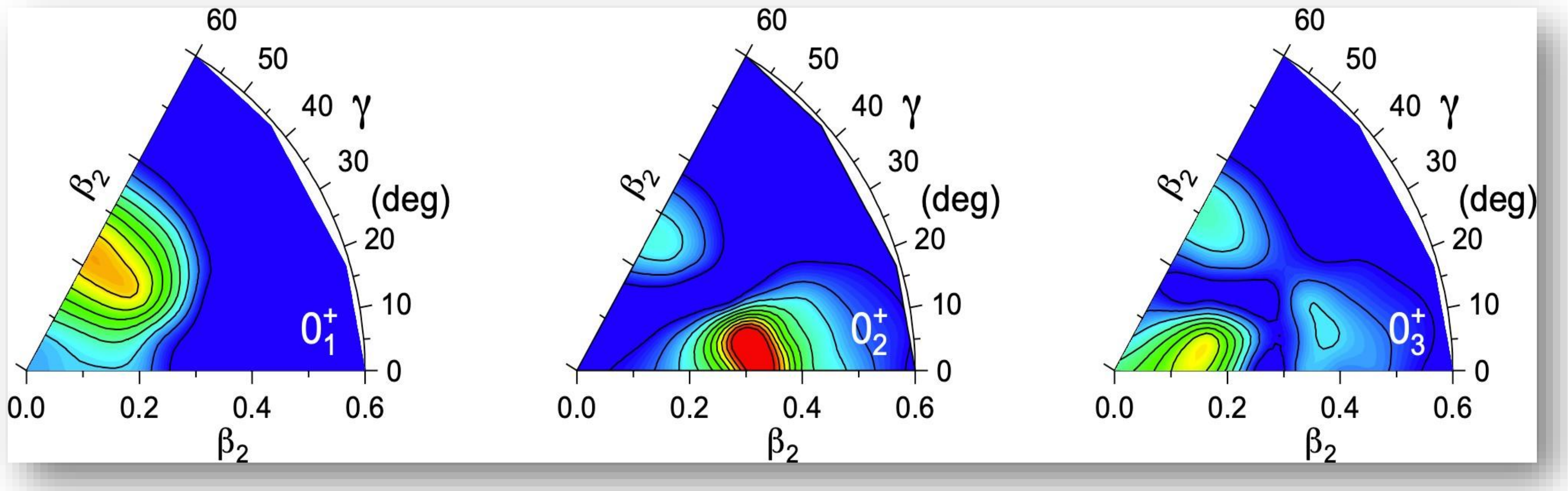

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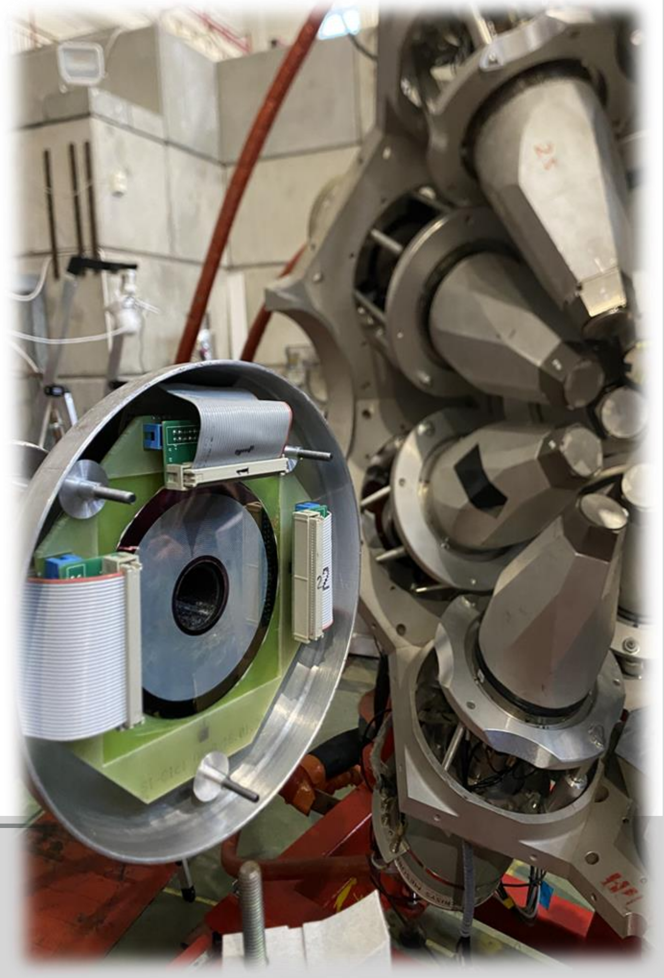
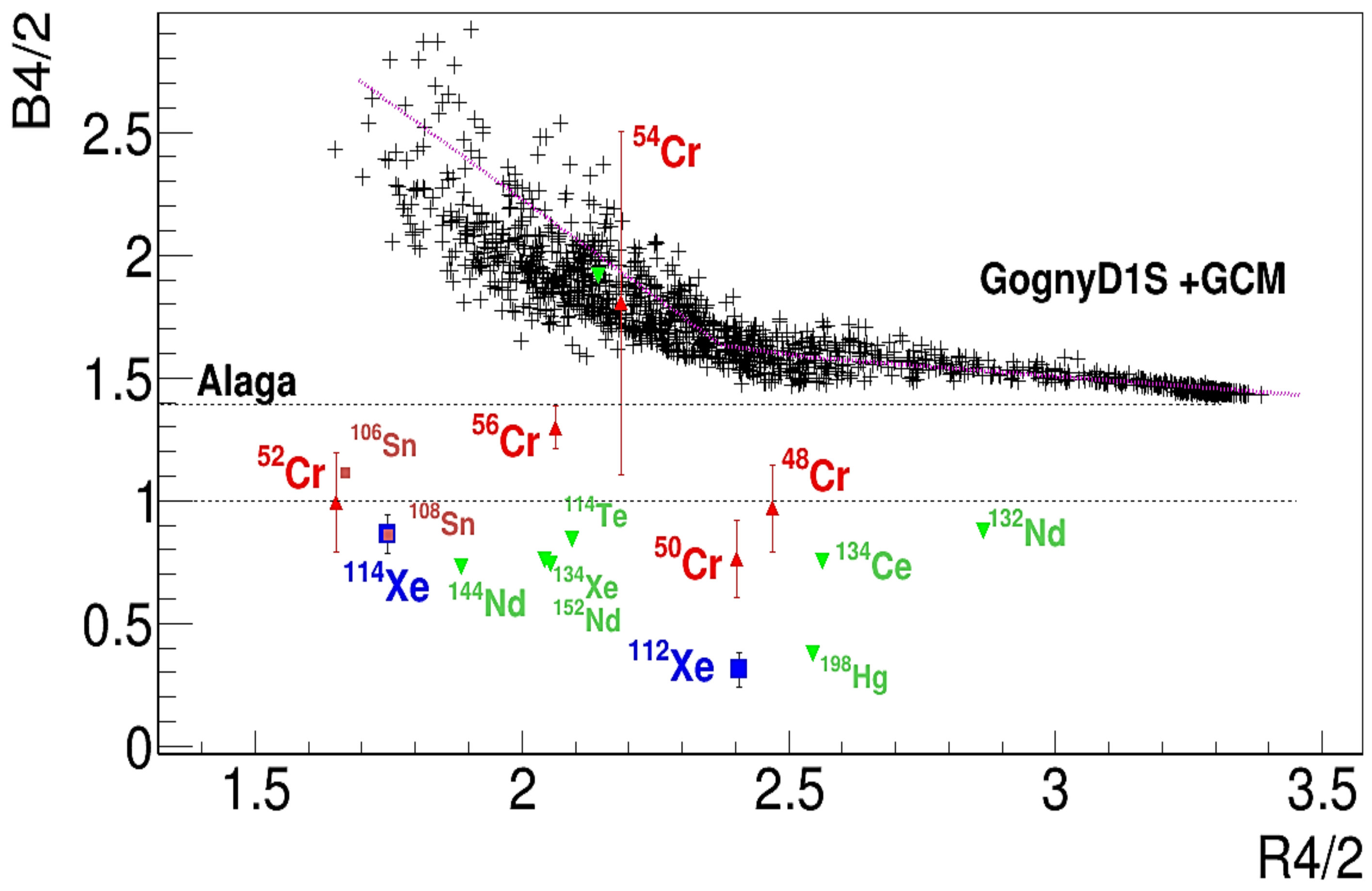
- DSSD (127-154^{O}) + EAGLE (1.4% at 1.3 MeV)

+ 1 accepted: COULEX of ^{34}S
+ 3 new projects submitted to the next HIL PAC

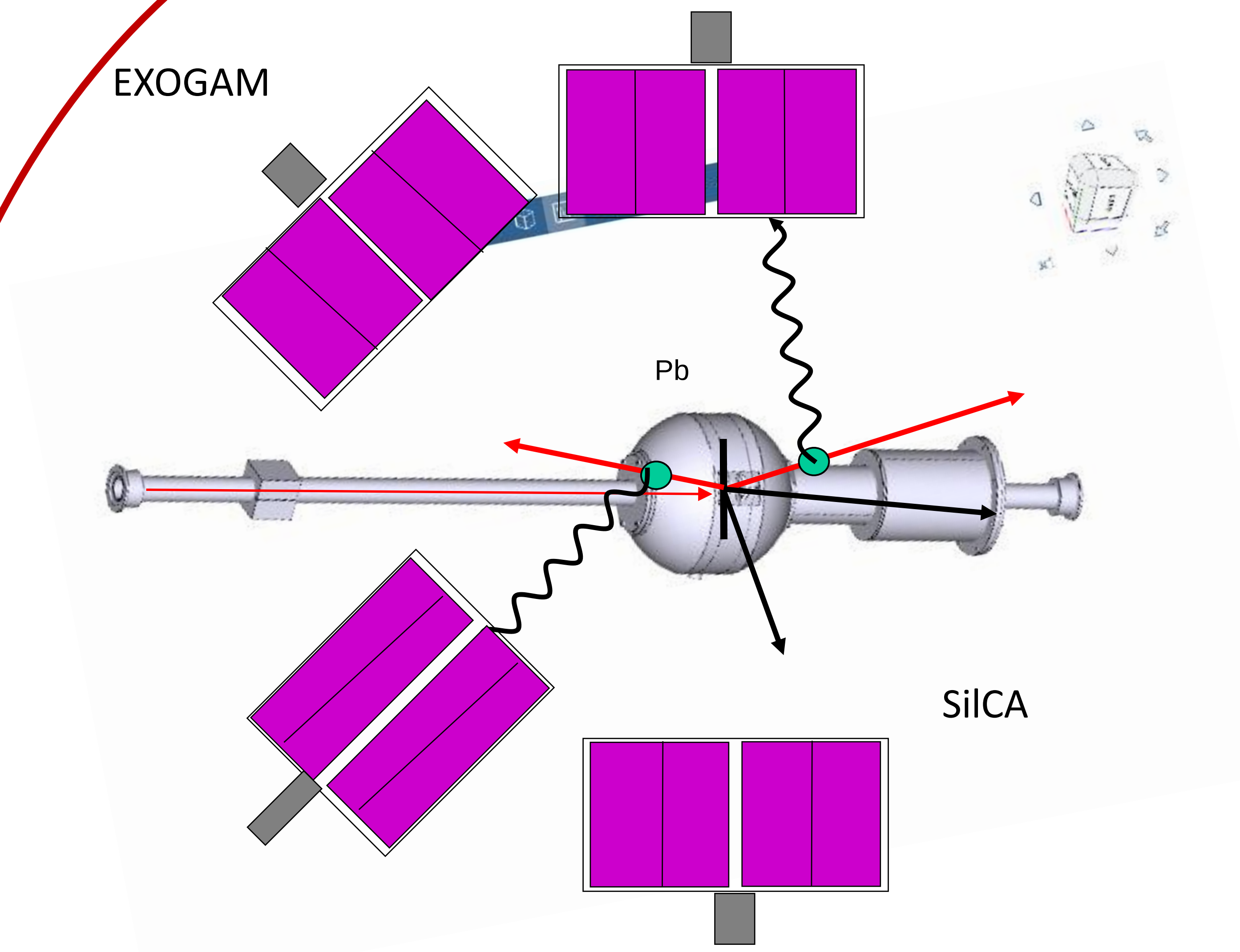


SilCA @ GANIL (2026) – Coulomb excitation of ^{48}Cr [E890_23 accepted]

- Self-conjugate - proton-neutron pairing plays an important role in its structure and collectivity;
- Ideal nucleus to study the alpha-cluster / condensate contribution.
- Milestone in the search for the double neutrino-less beta decay in the A=48 chain.
- The large observed deformation, in a relatively small valence space - comparison between mean-field and shell model approaches



1. An independent measurement of the B(E2,4⁺->2⁺) to study the $B_{4/2}$ anomaly
2. The study of the non-yrast states collectivity
3. A first measurement of $Q_s(2^+, 4^+)$
4. Shape parameters for the 0^+_1



- 1 mg/cm² ^{208}Pb target
- 21 UT
- 6.10^4 pps SPIRAL1 beam at the target position
- GOSIA Analysis – PL-FR-Agreement

Courtesy: E. Clement

SilCA @ GANIL (new projects)

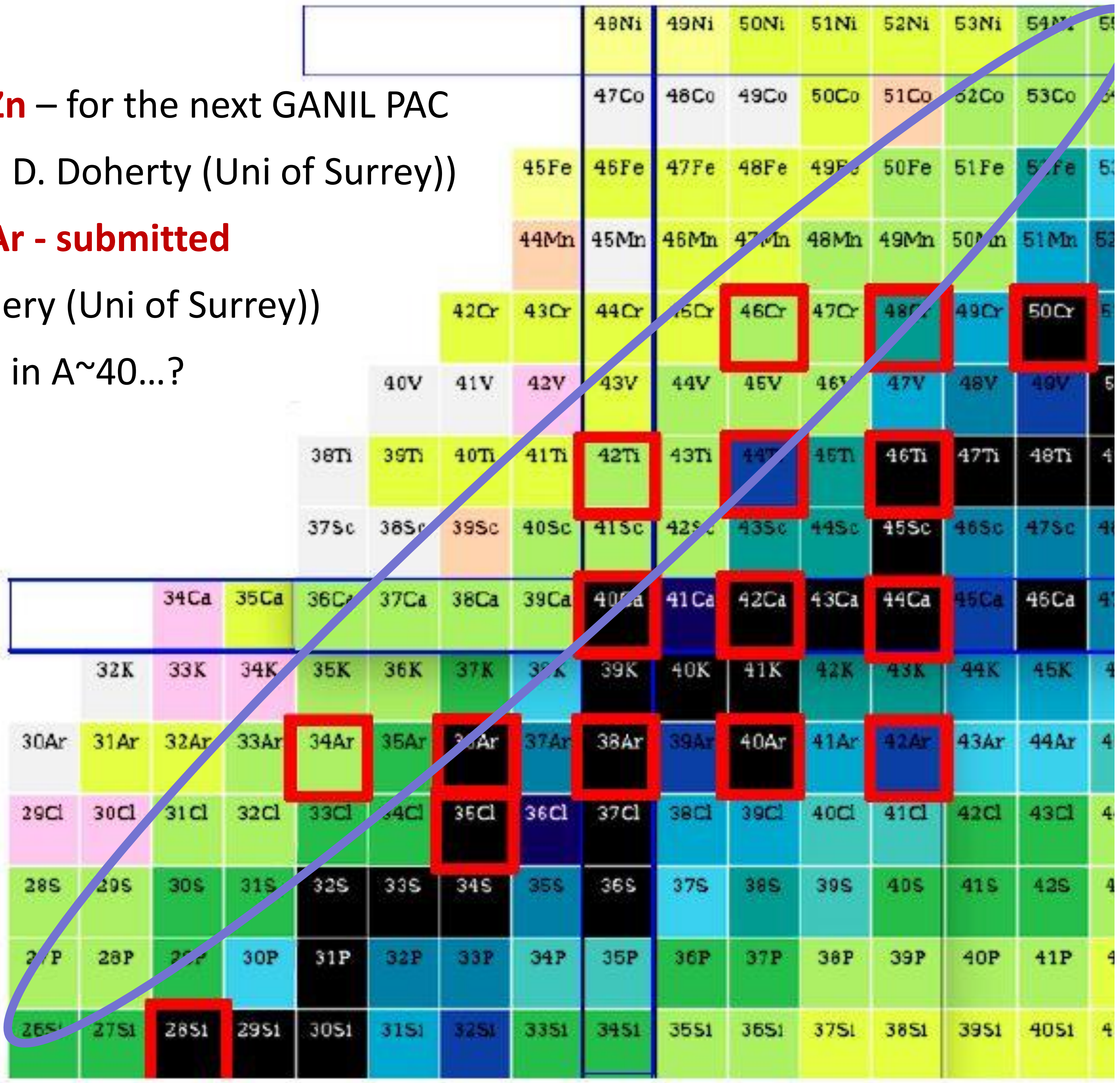
- **^{62}Zn** – for the next GANIL PAC

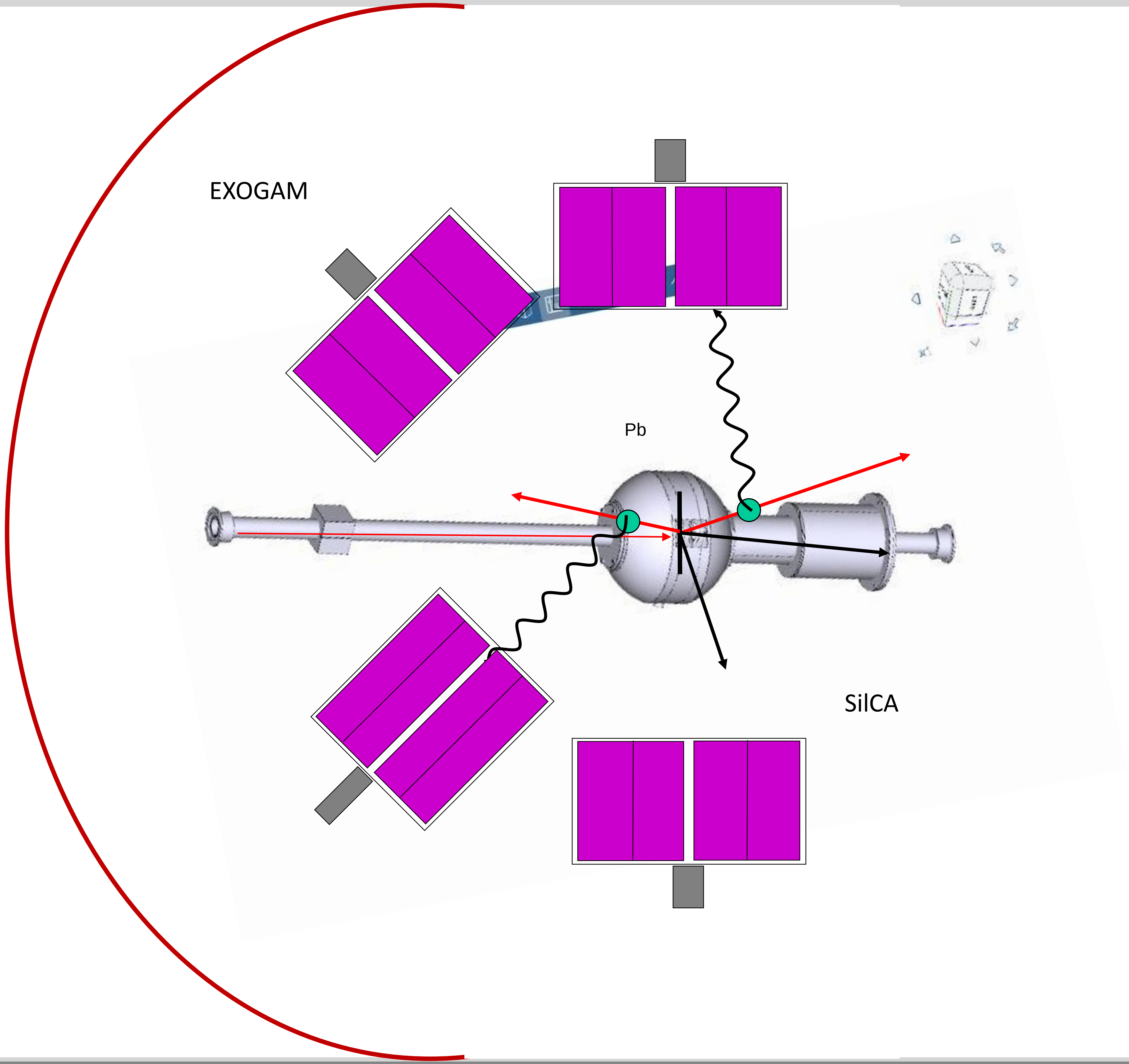
(KHK, D. Doherty (Uni of Surrey))

- **^{34}Ar - submitted**

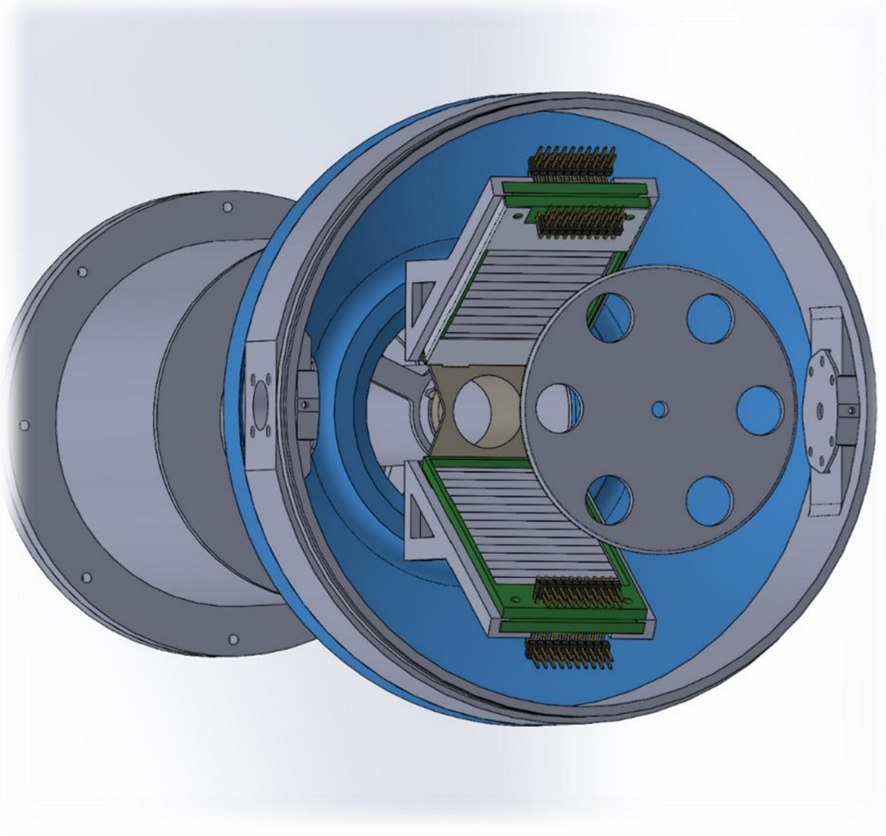
(J. Heery (Uni of Surrey))

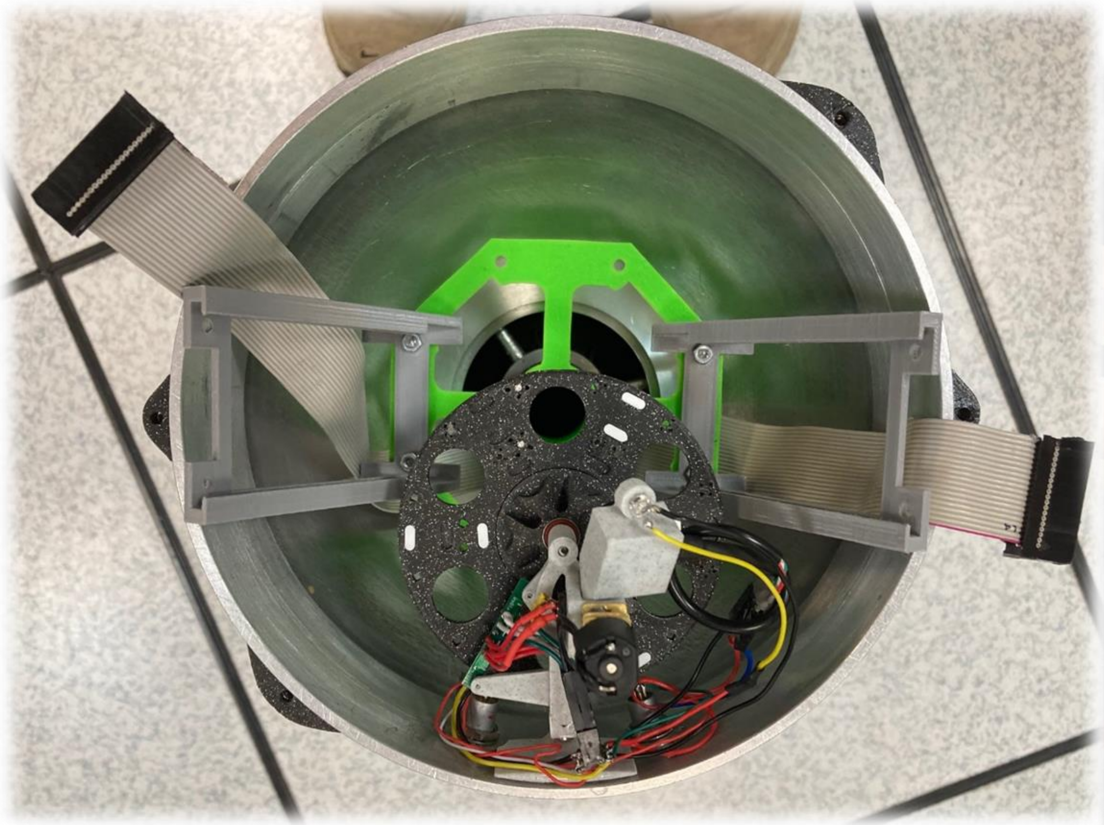
- SD in A~40…?

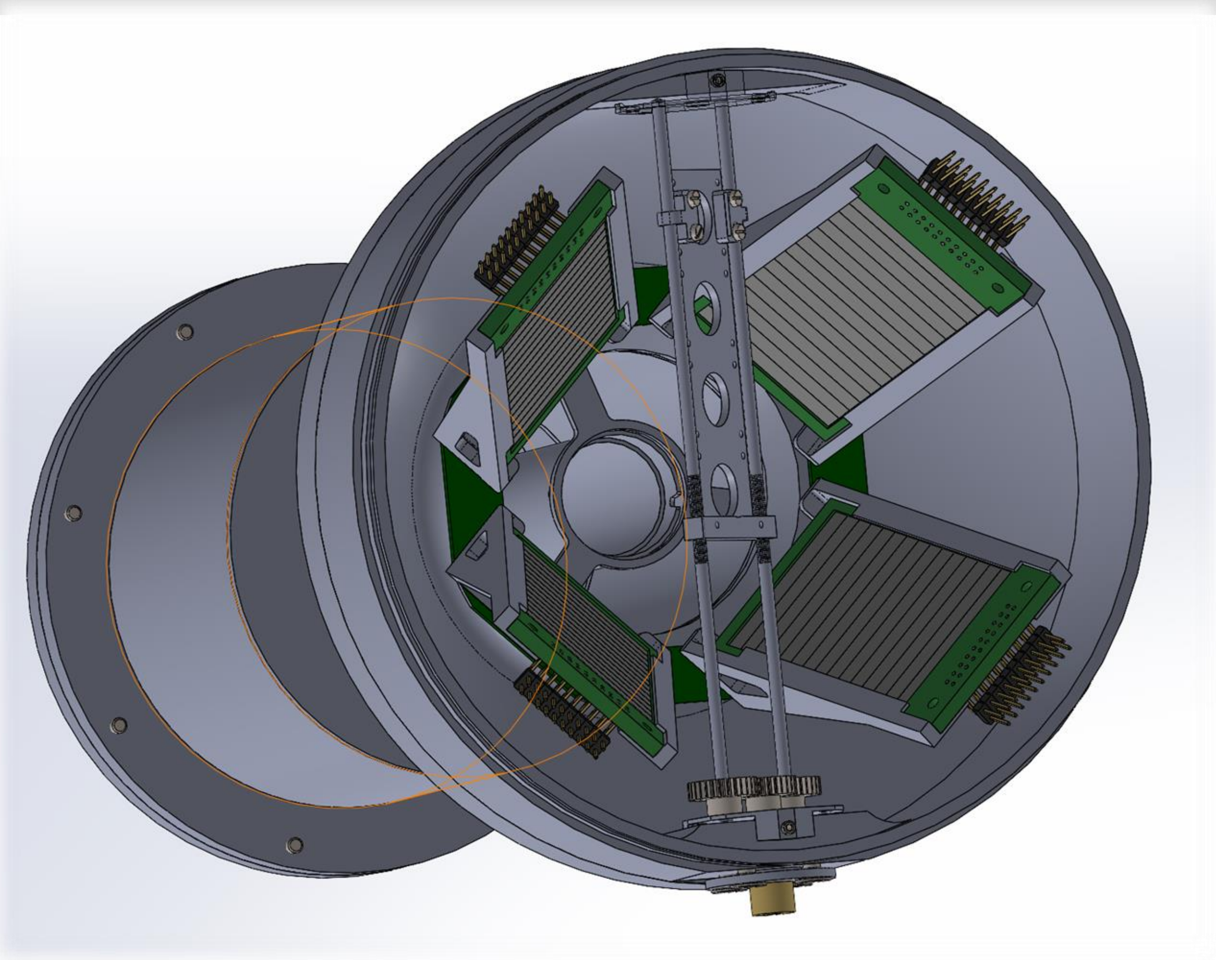


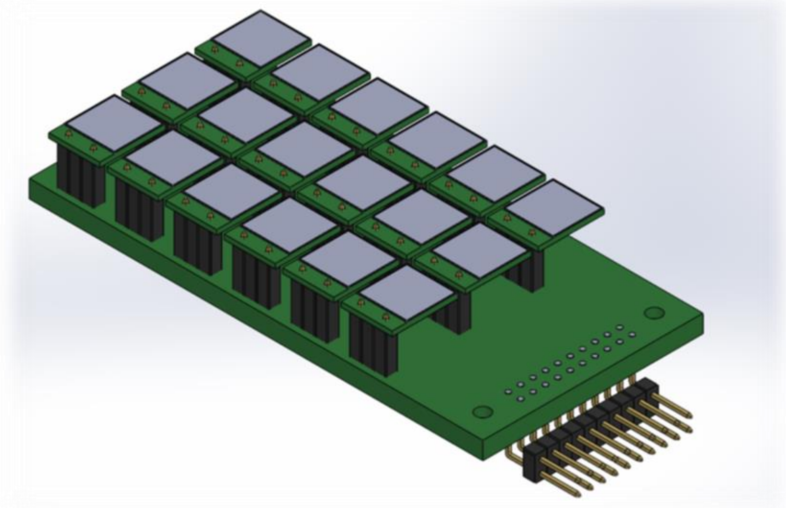


SilCA – DSSD and beyond!

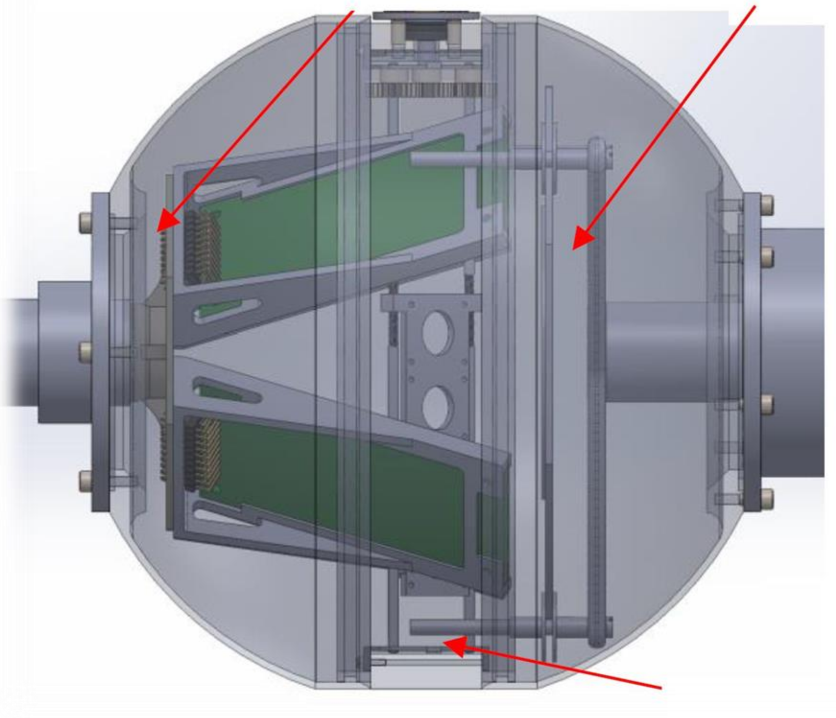








- Position-sensitive DSSD detectors
(Micron X3, 43.3 × 78 mm)
E or E-dE
- A set of pin-diodes
- Scintilators



Project: J. Iwanicki, M. Moukkaddam (IPHC Strasbourg), M. Matejska-Minda (IFJ Kraków), KHK, M. Matuszewski

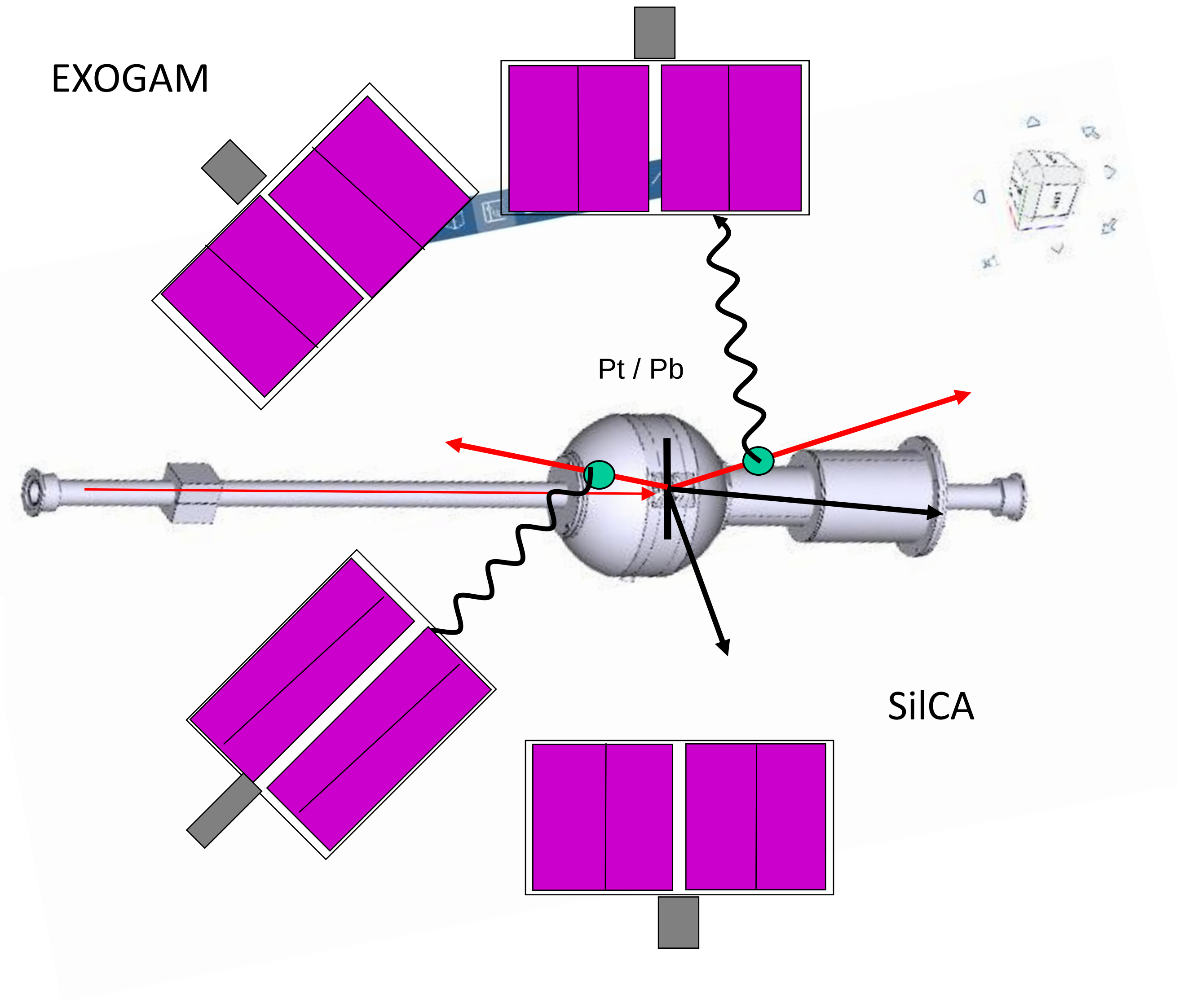
Summary

- PAST – exciting
- PRESENT – steady but busy
- FUTURE – bright

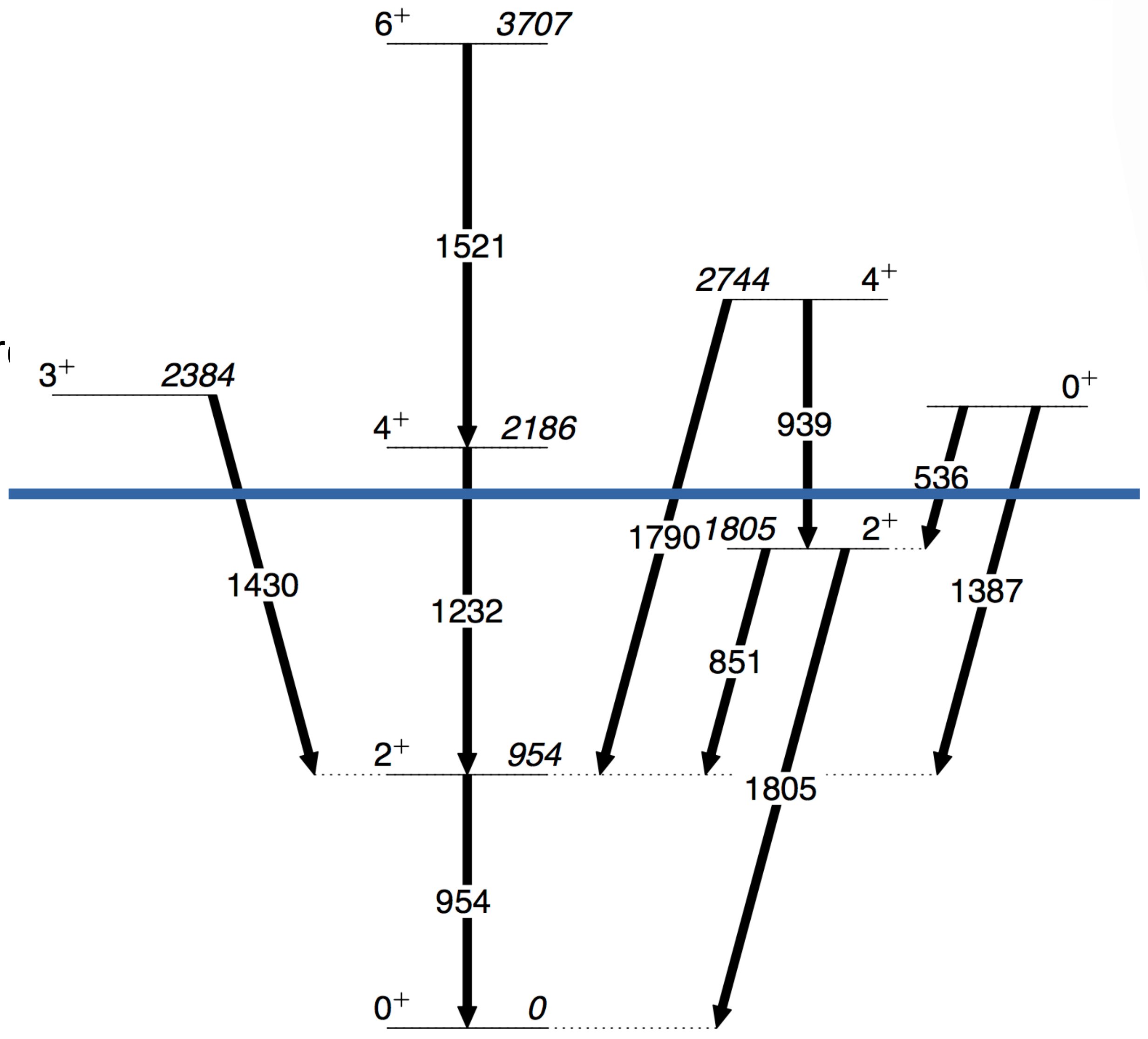
Thank you
Merci
Dziękuję

SilCA @ GANIL (PAC 2026) – ^{62}Zn

- To populate states in the yrast and non-yrast low-spin states in ^{62}Zn with the safe Coulomb excitation
- To extract a complete set of matrix elements (including $Q(2_1^+)$ and $Q(2_2^+)$) in order to describe the low-lying structure of ^{62}Zn
- To determine quadrupole deformation of the 0_1^+ and 0_2^+ states by applying the Quadrupole Sum Rules method – direct measurement of the deformation
- To provide the experimental input in the discussion of the role of nuclear shapes in the astrophysical *rp*-process



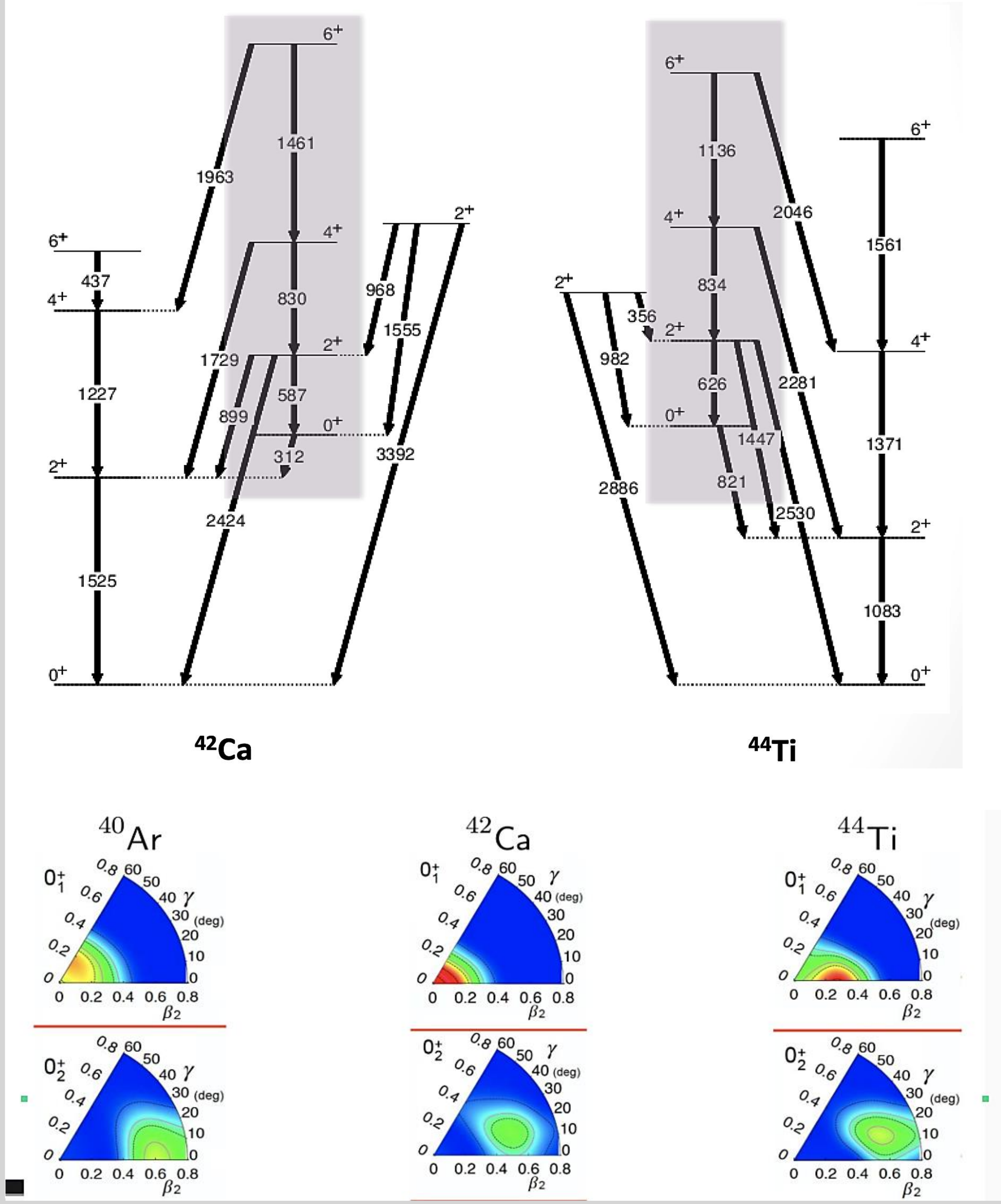
- Excitation of states in ^{62}Zn **above 2 MeV** will help to extract the structure of ^{62}Ge
- States of interest **in ^{62}Ge** – above proton separation energy**: 2053(145) keV** – very low - "exotic" case
- The **quadrupole deformation in ^{62}Zn** is expected to strongly influence **the mirror energy difference** – to be used to predict where these states are placed in **^{62}Ge**
- **The triaxial degree of freedom** has a strong influence **on the binding energies, hence the nuclear masses and the reaction Q values**
- If triaxial deformation is established in *p*-rich nuclei taking part of the *rp* process, this would change dramatically **the recent mass systematics –** masses are unmeasured
- **Shapes in ^{62}Ge** – unknown – so measurement of shapes in ^{62}Zn – the only way to study states in inaccessible ^{62}Ge



Safe Coulomb excitation of ^{62}Zn to be re-proposed at GANIL
KHK, D. Doherty

- EXOGAM2 + SiLCA
- ~10^5 pps SPIRAL1 beam at the target position

Coulomb excitation of ^{44}Ti @ GANIL or @ IJC Lab

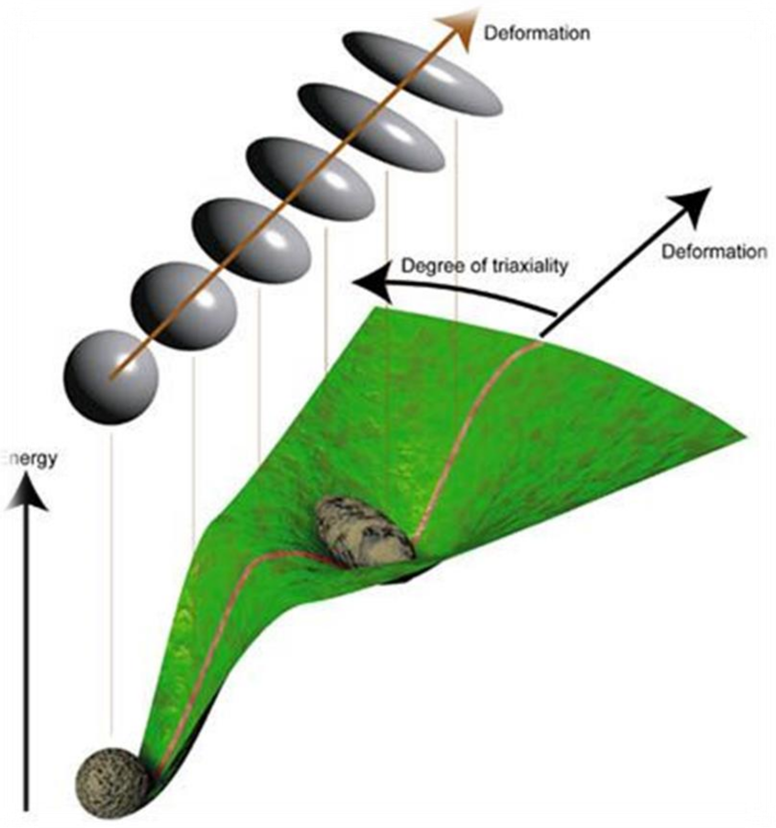


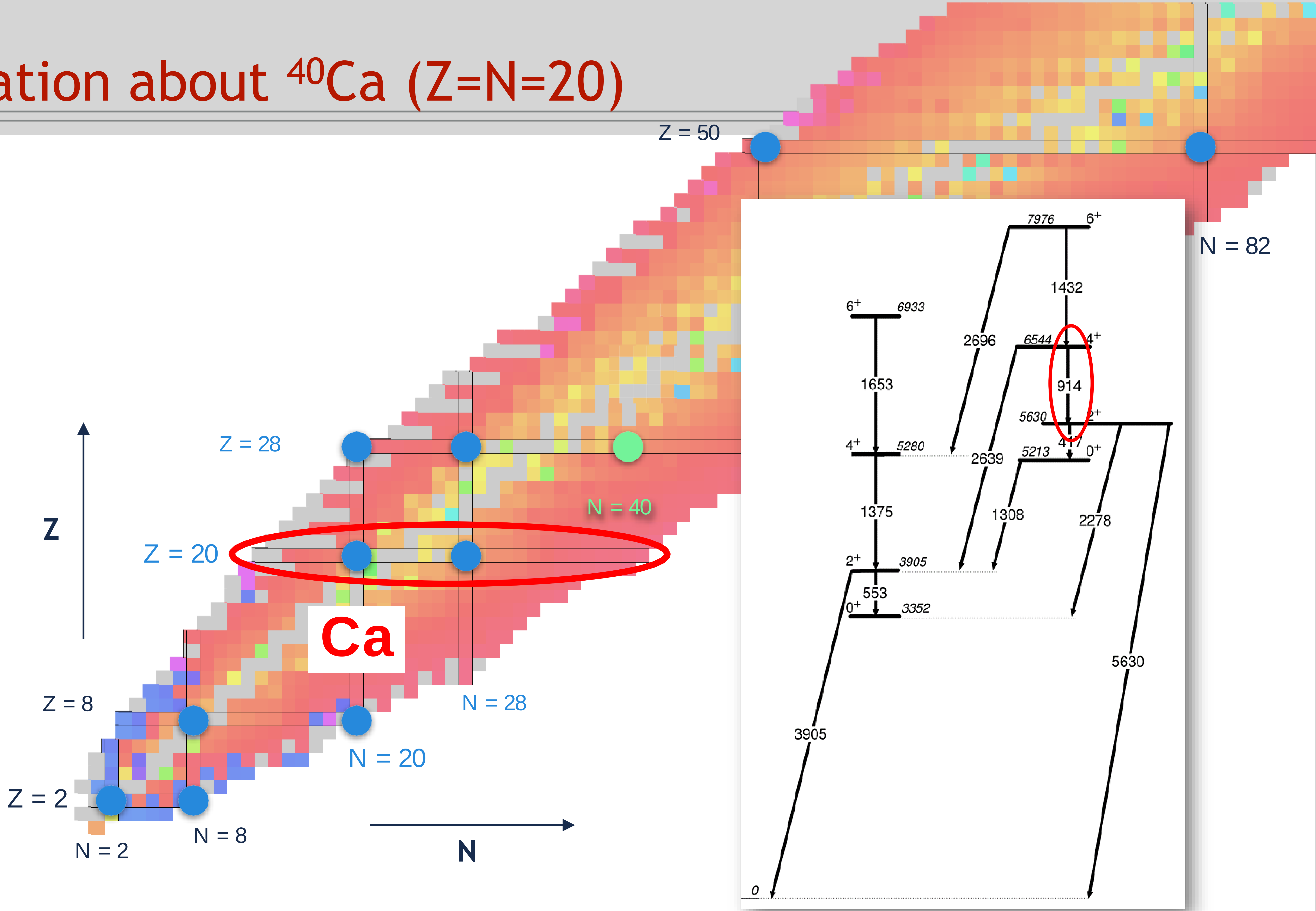
- ✓ A long-lived radioactive nucleus
- ✓ Qs(2^+_1) and Qs(2^+_2) unknown
- ✓ 0^+_2 is localized but the lifetime is unknown
- ✓ The decay of the 0^+_2 is unknown
- ✓ The best option would be to populate side band from GS

Additional motivation: **one of a few cosmic γ-ray emitters** to be observed in our Galaxy - may provide the means to unravel the underlying **explosion mechanism of Type-II Supernovae**

- ✓ expected to be synthesized in the α-**rich freeze out process**, via the **^{40}Ca(α,γ)** reaction
- ✓ how much of the newly produced ^{44}Ti that is caught in the matter of neutron star of a black hole is linked to the hydrodynamics of the star
- ✓ **gamma rays from ^{44}Ti material that falls back will be unable to escape the dense environment and cannot be observed**
- ✓ the **observed ^{44}Ti abundances** by modern-day space-based telescopes vs **predicted production** values will provide a measure of **the location of the mass cut**.
- ✓ large uncertainties in the nuclear reactions responsible for the production and destruction of ^{44}Ti in core-collapse SN make these comparisons extremely difficult
- ✓
- ✓ a key unknown may relate to the **ground state shape of ^{44}Ti**.

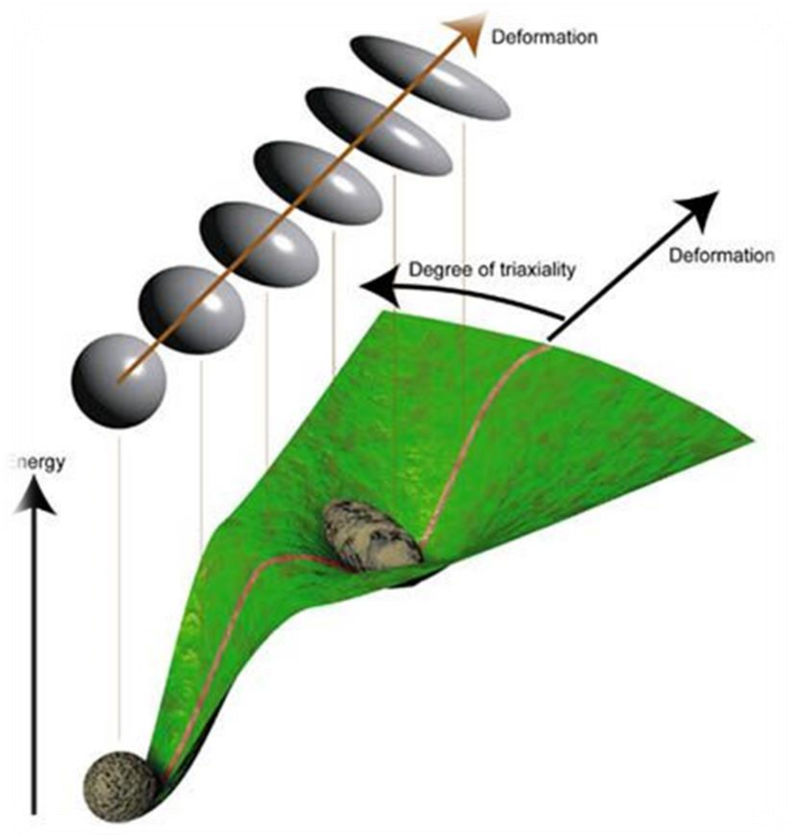
(Super)-Deformation about ^{40}Ca (Z=N=20)

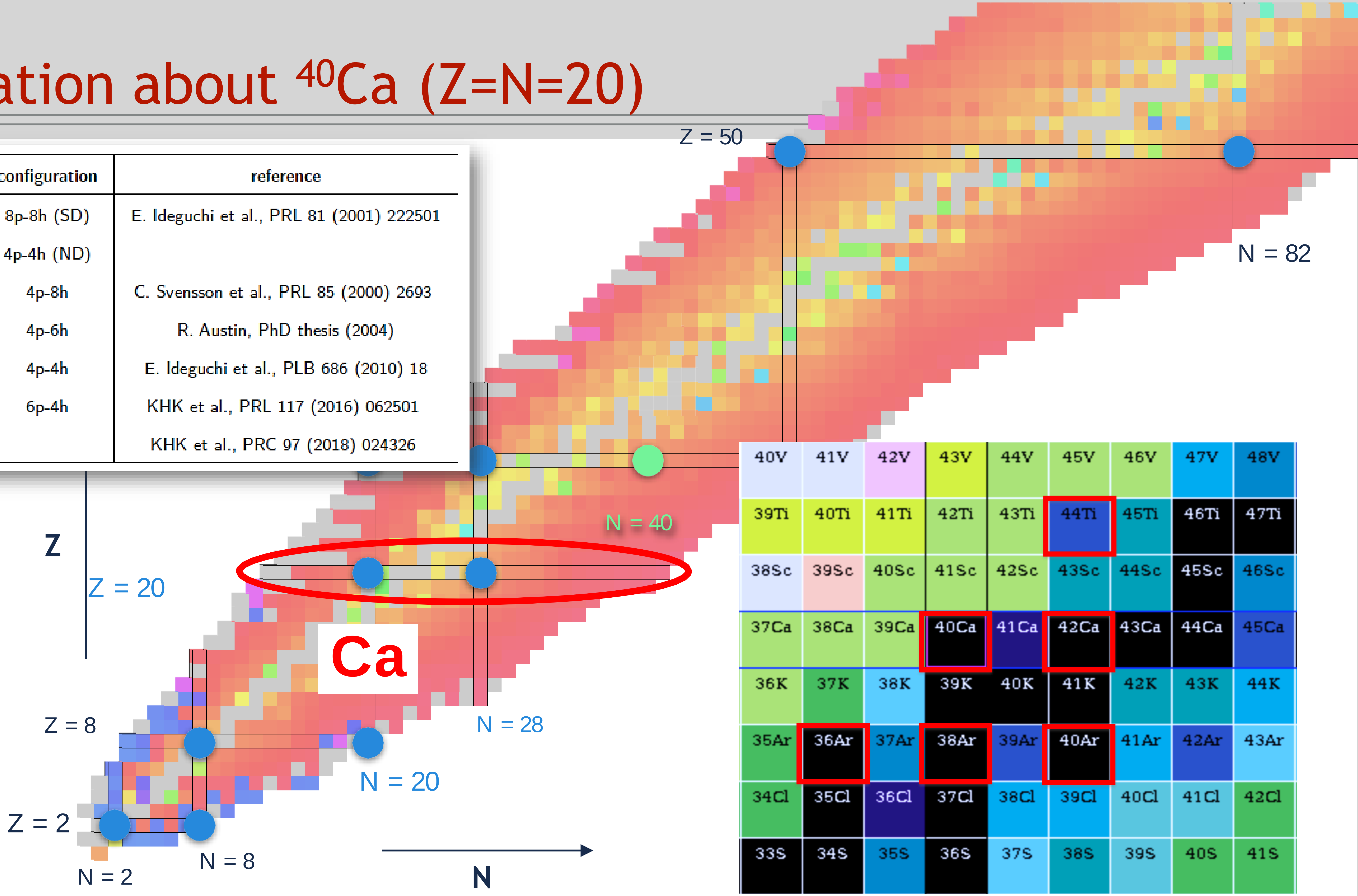




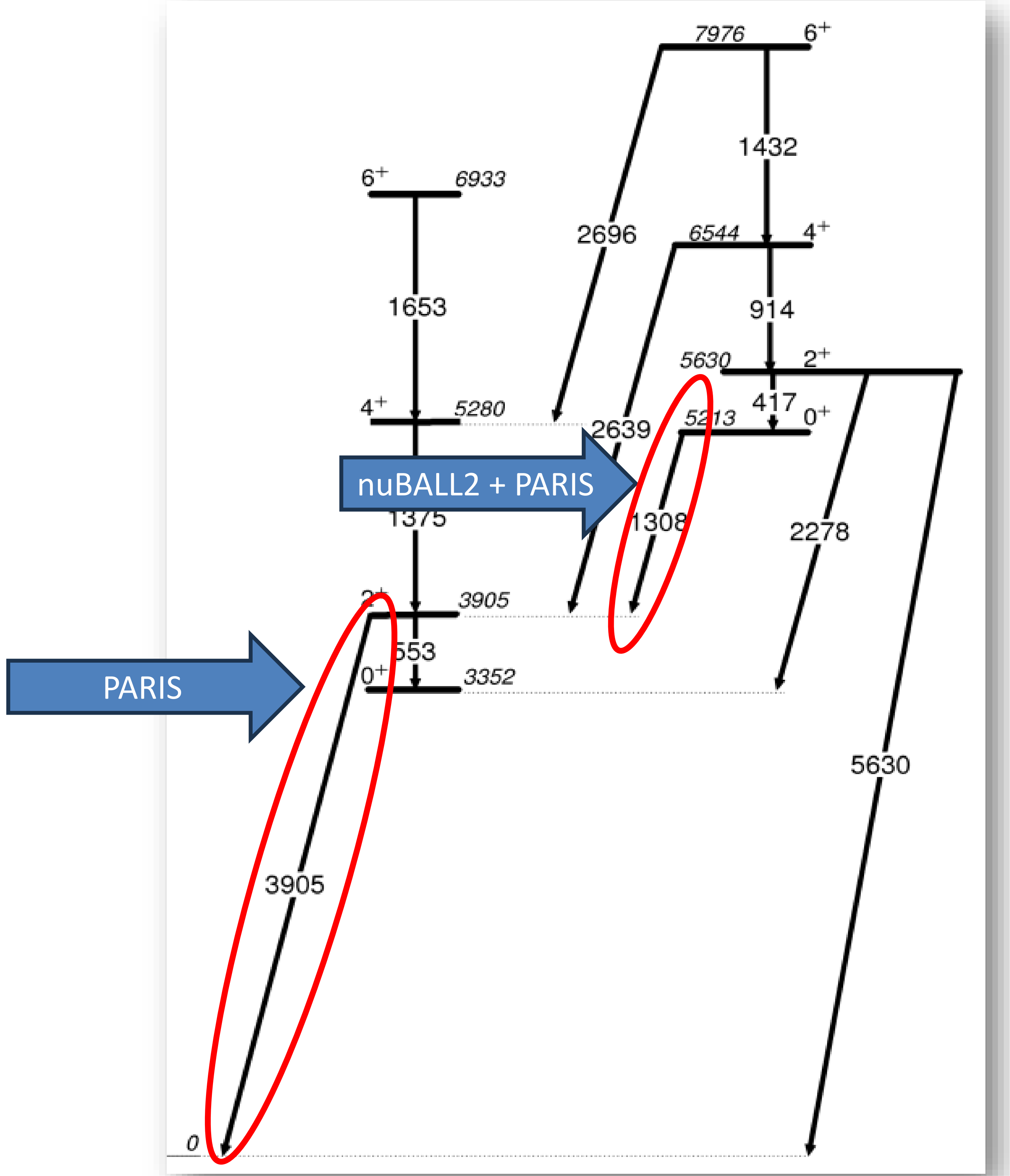
(Super)-Deformation about ^{40}Ca (Z=N=20)

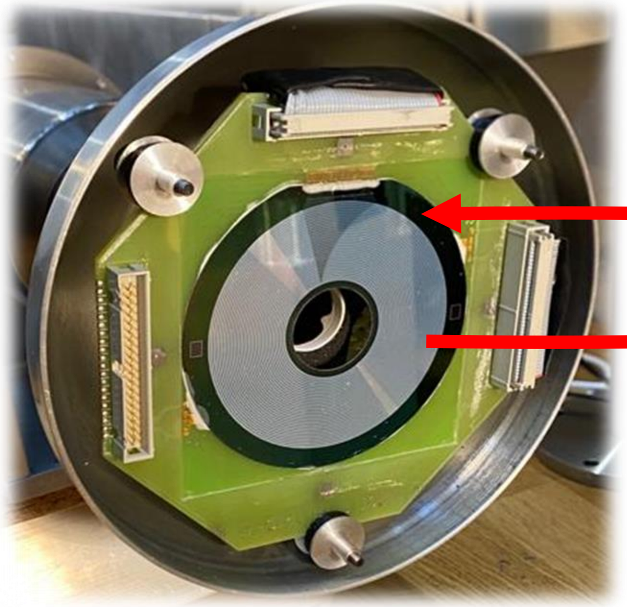
isotope	0^+ energy	experimental β_2	configuration	reference
^{40}Ca	5.2 MeV	$0.59^{+0.11}_{-0.07}$	8p-8h (SD)	E. Ideguchi et al., PRL 81 (2001) 222501
	3.4 MeV	0.27 ± 0.05	4p-4h (ND)	
^{36}Ar	(4.3 MeV)	0.46 ± 0.03	4p-8h	C. Svensson et al., PRL 85 (2000) 2693
^{38}Ar	3.4 MeV	$0.42^{+0.11}_{-0.08}$	4p-6h	R. Austin, PhD thesis (2004)
^{40}Ar	2.1 MeV	$0.48^{+0.16}_{-0.10} \pm 0.05$	4p-4h	E. Ideguchi et al., PLB 686 (2010) 18
^{42}Ca	1.8 MeV	$0.43(4)$ (0_2^+)	6p-4h	KHK et al., PRL 117 (2016) 062501
		$0.45(4)$ (2_2^+)		KHK et al., PRC 97 (2018) 024326

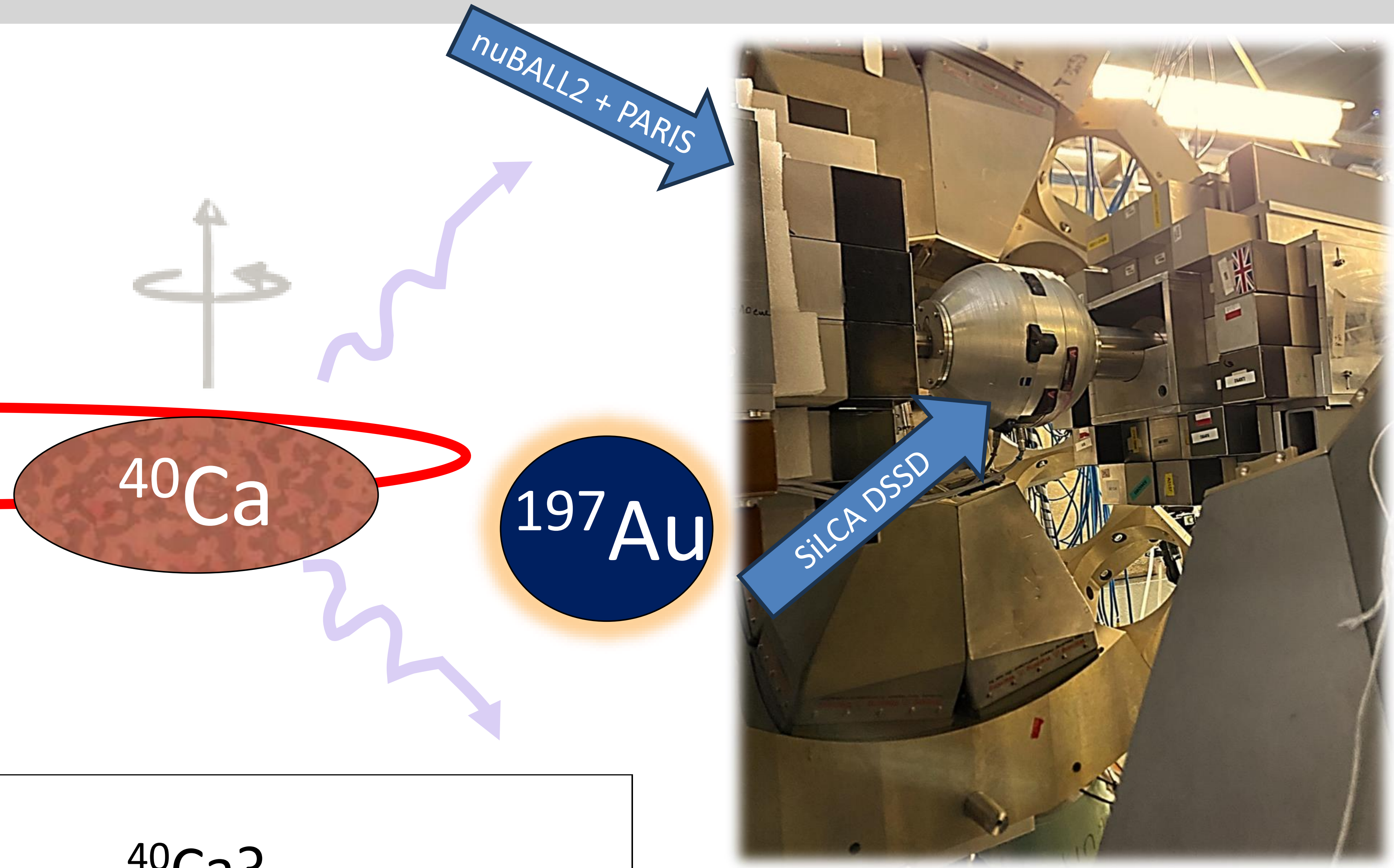


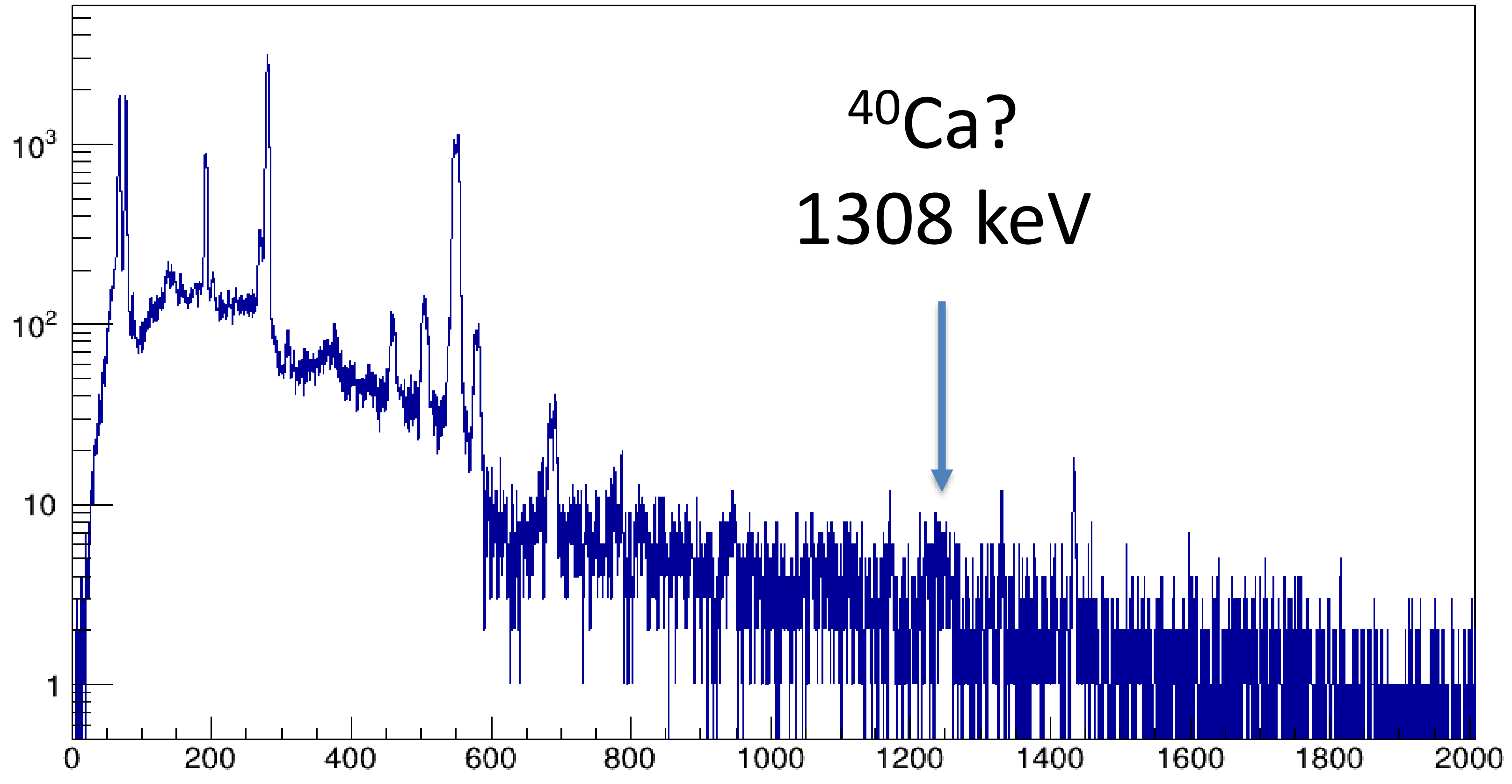


Coulomb excitation of ^{40}Ca @ IJC Lab [N-SI-85]









nuBALL2:

2 rings of 12+12 HPGe CLOVERS + ACS

PARIS:

LaBr3 / CeBr3 + NaI array

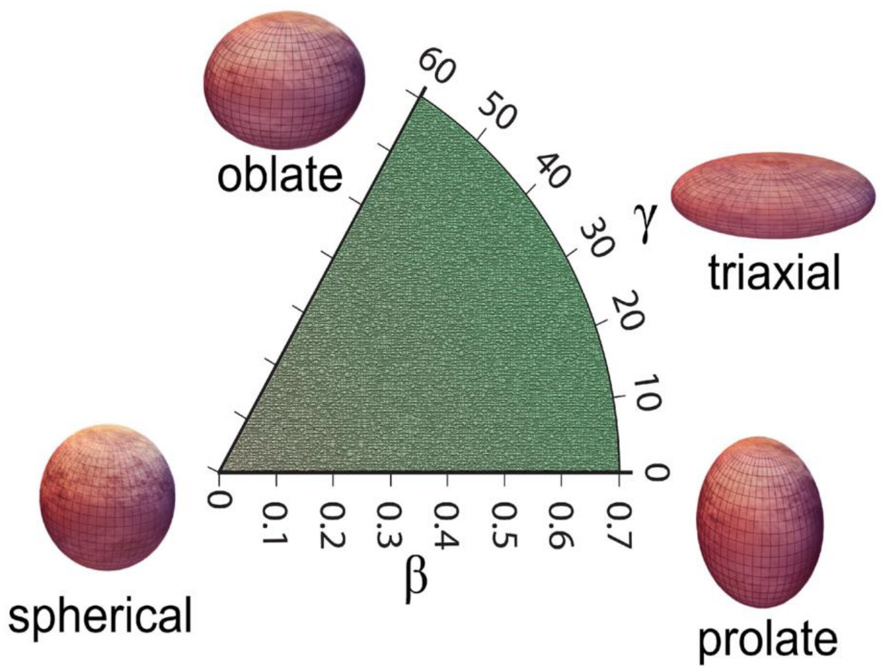
15 cm from the target

SiLCA DSSD:

32 sectors + 16 rings

125-152°

Quadrupole shape invariants

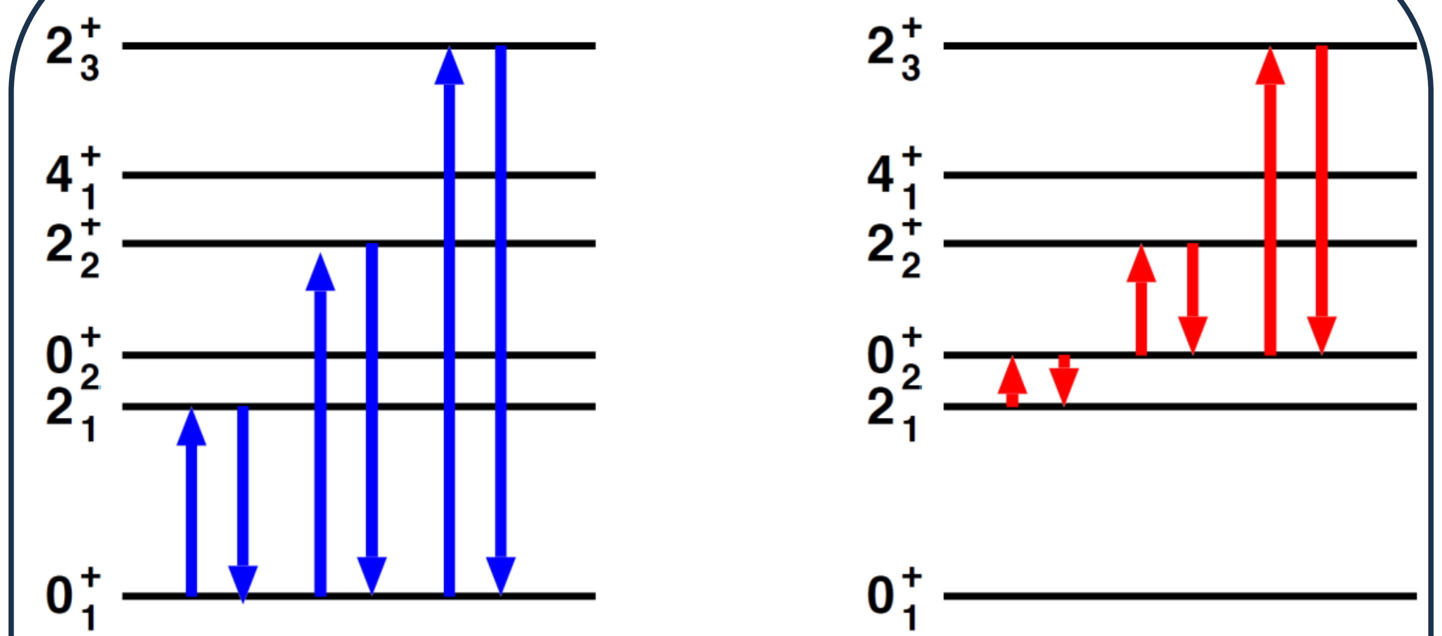


Overall deformation – elongation

$$\frac{\langle Q^2\rangle}{\sqrt{5}} = \langle i||[E2\times E2]^0||i\rangle = \frac{(-1)^{(2I_i)}}{\sqrt{2I_i+1}}\sum_t \langle i||E2||t\rangle\langle t||E2||i\rangle \begin{Bmatrix} 2 & 2 & J \\ I_i & I_i & I_t \end{Bmatrix}$$

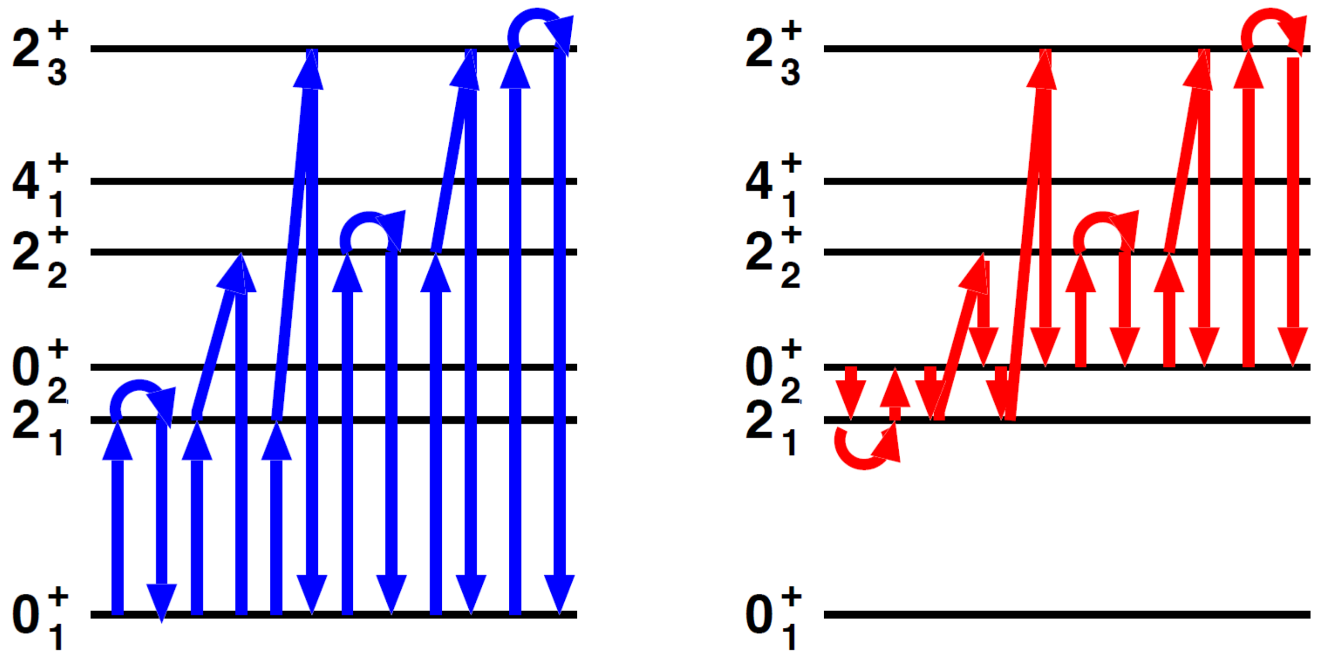
Axial symmetry parameter

$$\sqrt{\frac{2}{35}}\langle Q^3\cos(3\delta)\rangle = \langle i||\{[E2\times E2]^2\times E2\}^0||i\rangle = \frac{(\pm 1)}{\sqrt{2I_i+1}}\sum_{t,\mu} \langle i||E2||u\rangle\langle u||E2||t\rangle\langle t||E2||i\rangle \begin{Bmatrix} 2 & 2 & 2 \\ I_i & I_t & I_u \end{Bmatrix}$$



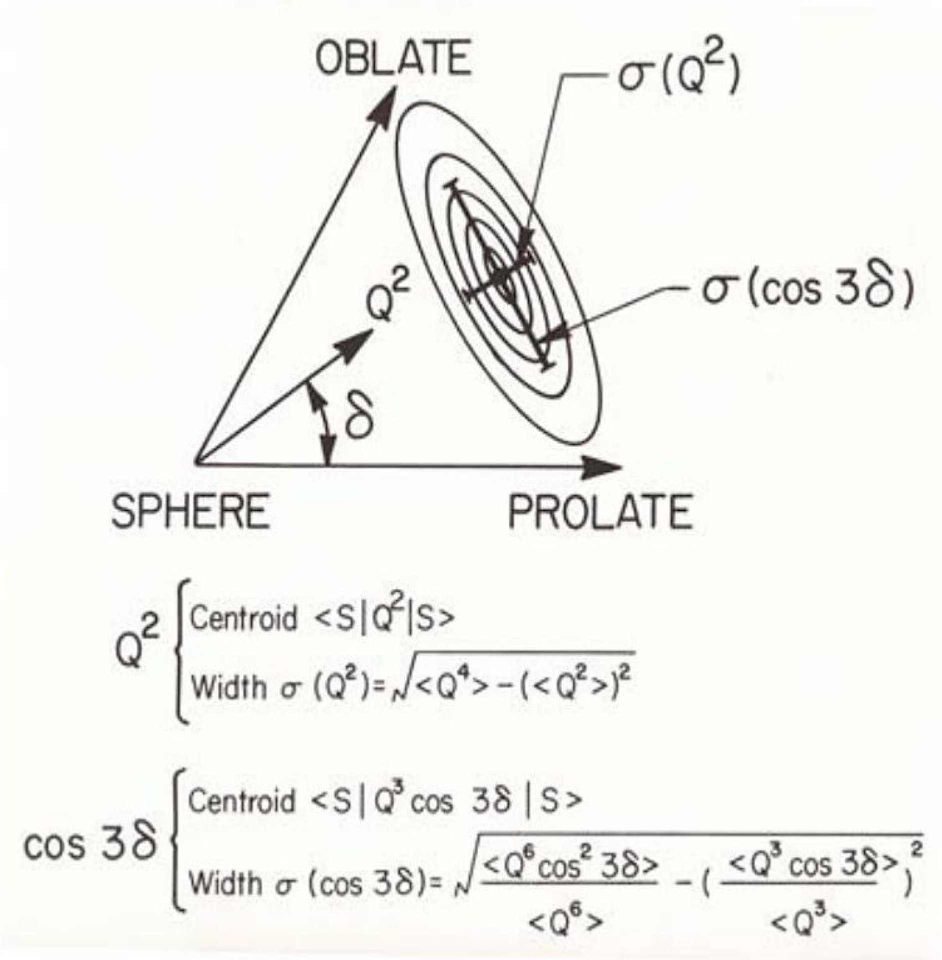
$\langle Q^2\rangle \sim \beta$

$\sim B(E2;\ 0^+_{1/2} \rightarrow\ 2^+_{1,2,3,\ldots})$

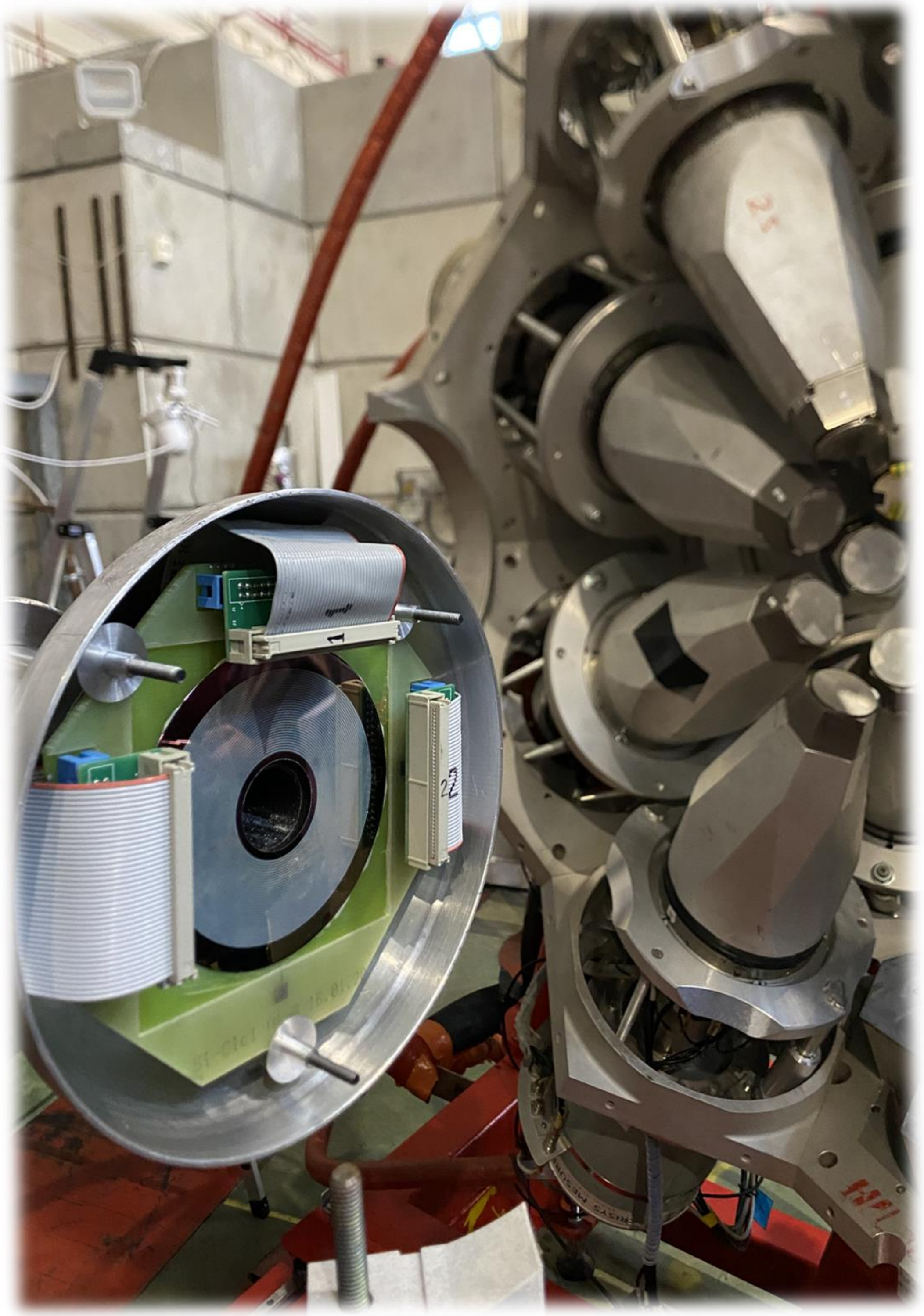


$\langle cos3\delta\rangle \sim \gamma$

$\sim M(E2;\ 0_+ \rightarrow 2_{+j});\ M(E2;\ 2_{+i} \rightarrow 2_{+j})\ [Q_{sp}\ (2_{+j})]$



DSSD tests with ^{241}Am



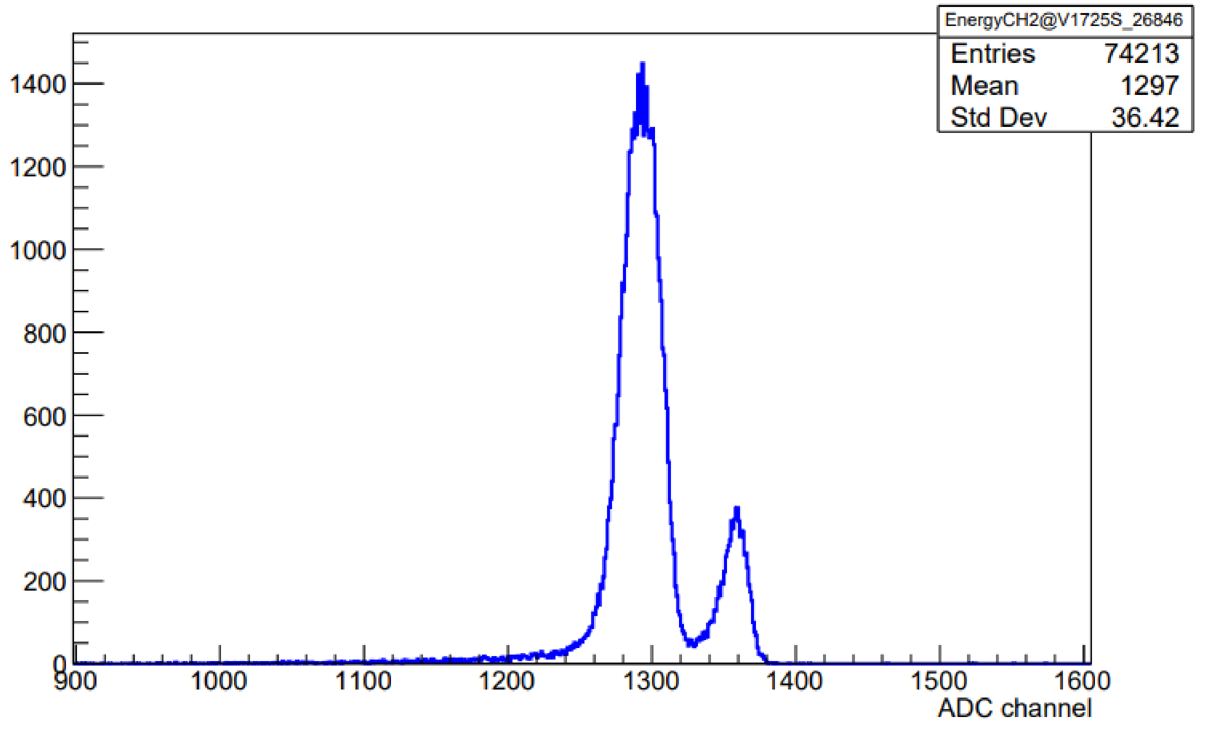
Setup:
- *DSSD detector*
- *64 sectors (32 readout)*
- *32 rings (16 readout)*

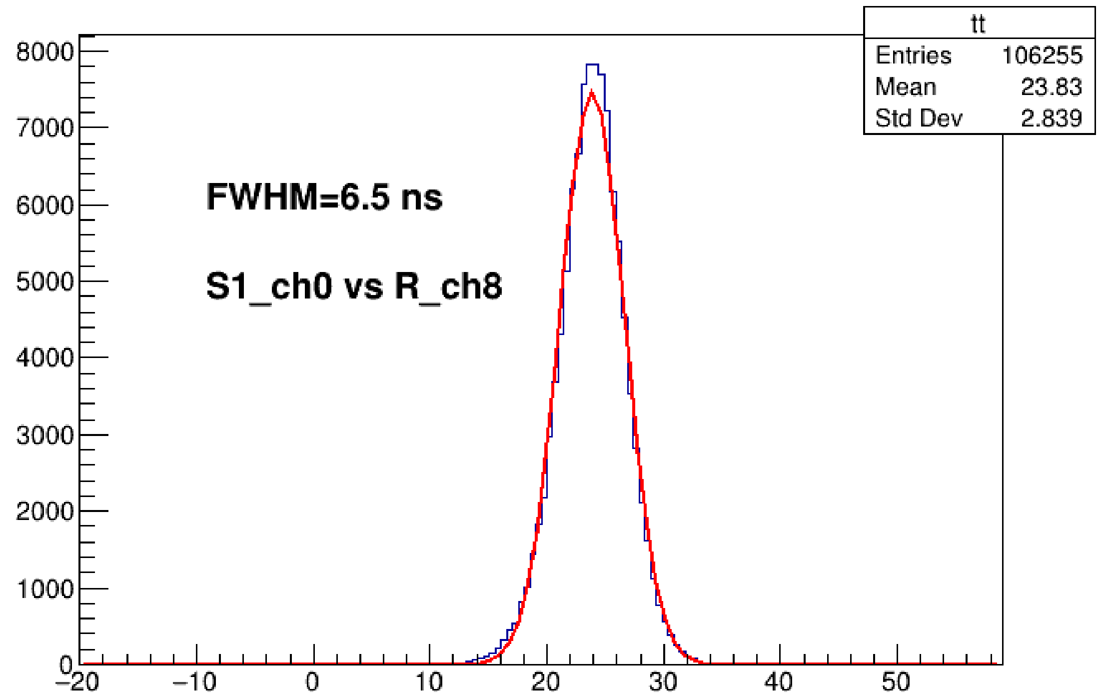
- *3 differential-to-single-ended converters (made at HIL & FUW)*
- *3 CAEN 1725 digitizers*
  16-channel, 14 bit, 250 MS/s

- *^{241}Am source*
- *5.1 MeV Energy*

Data taken with:
- *COMPASS (CAEN software)*
- *xdaq*

Results:
- *Obtained energy resolution: ~50 keV*
- *Obtained sector-ring timing resolution: 6.5-8.5 (1) ns*





In-beam commissioning of SiLCA+EAGLE scheduled: November 2024
^{104}Pd + ^{32}S, Coulomb excitation

Experimental nuclear deformation

- **Nuclear deformation** is one of a central topic in the **COPIN and COPIGAL** collaborations
- Experiments such as **Coulomb excitation** or **gamma-ray spectroscopy** are used to investigate nuclear shapes, including highly deformed or transitional states, to advance the understanding of how atomic nuclei deform and the consequences of these deformations for nuclear structure.

French Institutes:

- **GANIL** (Grand Accélérateur National d'Ions Lourds) in Caen
- **CNRS/IN2P3** (L'Institut national de physique nucléaire et de physique des particules) facilities, including **IJC Lab** (Laboratoire de Physique des 2 Infinis Irène Joliot-Curie) in Orsay
- **CEA Saclay** (Commissariat à l'Énergie Atomique et aux Énergies Alternatives)

Polish Institutes:

- Heavy Ion Laboratory and Faculty of Physics, University of Warsaw
- Institute of Nuclear Physics (IFJ PAN), Kraków

Coulomb excitation studies within COPIGAL

Task: Nuclear deformation in excited states

a. *Superdeformation at low spins* (E. Clement, K. Hadyńska-Klęk, P. Napiorkowski*)
b. *Shape coexistence in A~100 nuclei* (M. Zielińska, K. Wrzosek-Lipska)

Coulomb excitation studies within COPIN tasks:

Task: *Exotic nuclear deformations studied at HIL and ALTO* (J. Wilson, K. Hadyńska-Klęk)