

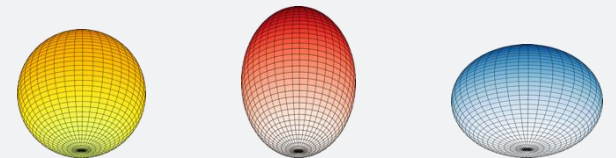


Science and  
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Facilities Council

Technology

# Shape coexistence in neutron-deficient nuclei

Philippos Papadakis  
UKRI-STFC

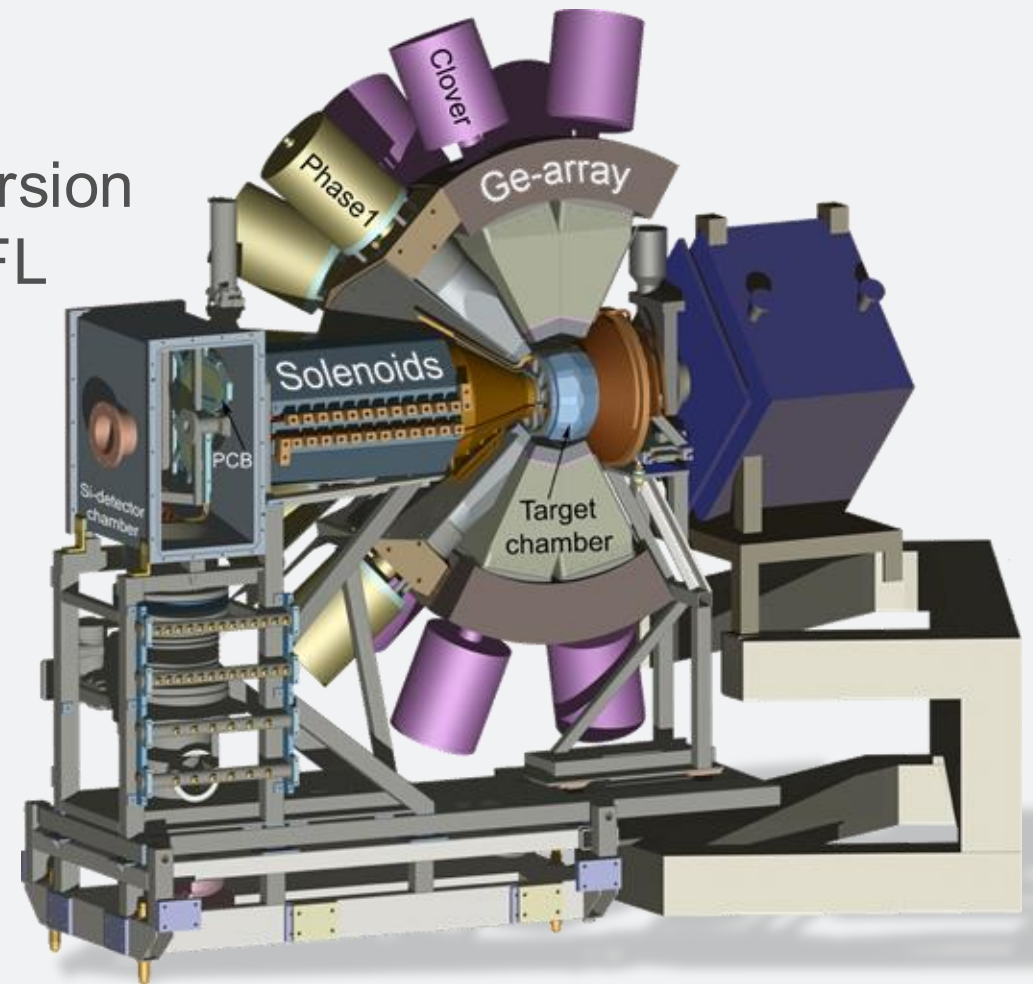


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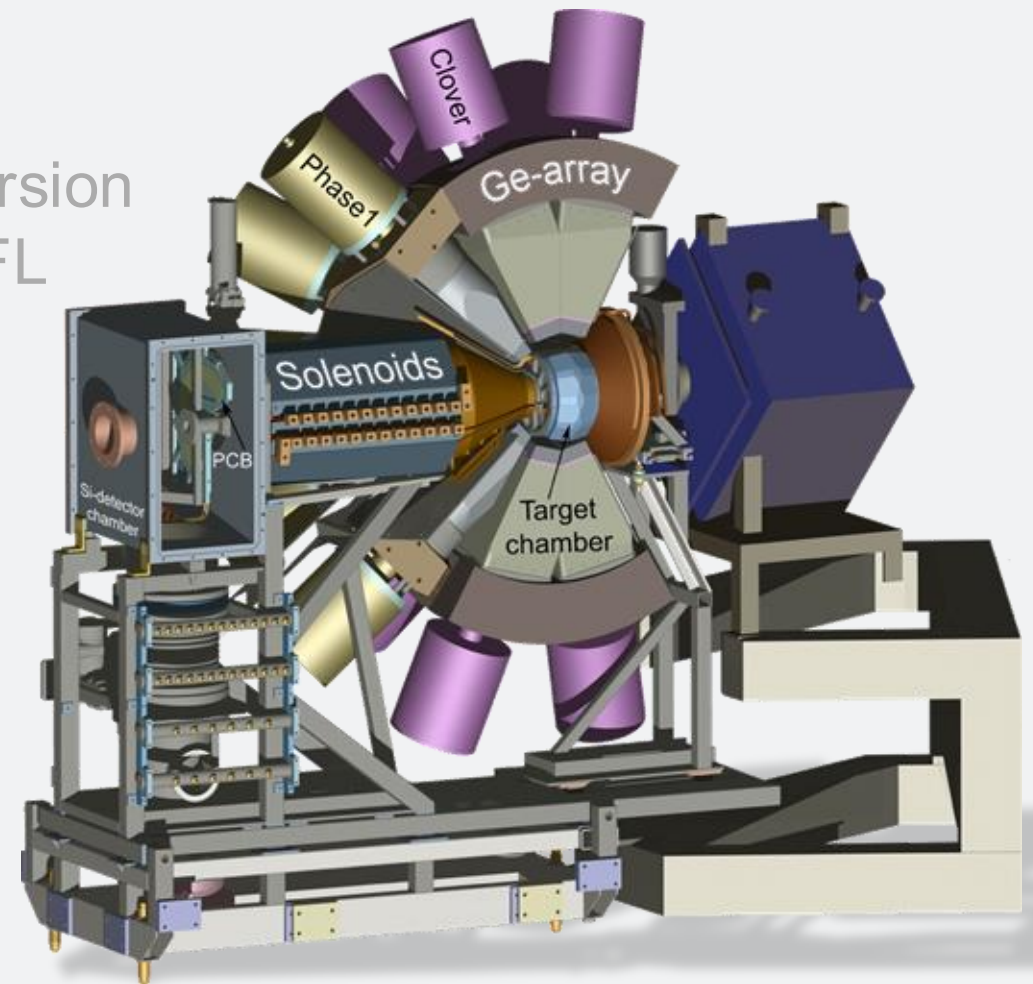
# Outline

- Motivation
- Experimental methods
  - Simultaneous in-beam  $\gamma$ -ray and conversion electron spectroscopy with SAGE@JYFL
  - Lifetime measurements with a plunger
- Shape coexistence in even-even neutron-deficient lead isotopes



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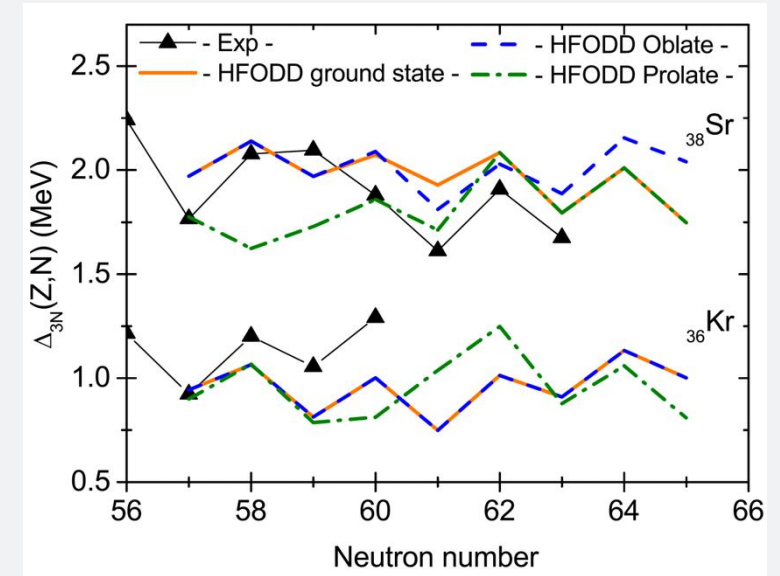
# Motivation – Global perspective

- Nuclei exhibit a wide range of diverse and interesting phenomena, e.g.:
  - Magic numbers and shell structure
  - Nuclear pairing leading to odd-even staggering
  - Deformation
  - Shape coexistence
  - ...



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A. de Roubin *et al.*, Phys. Rev. C **96**, 014310 (2017)

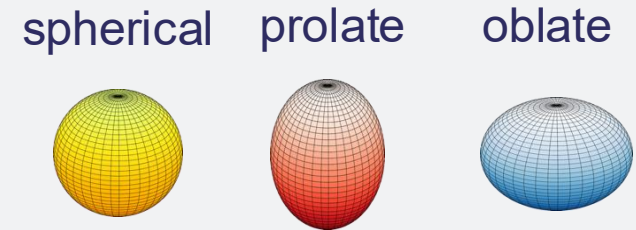
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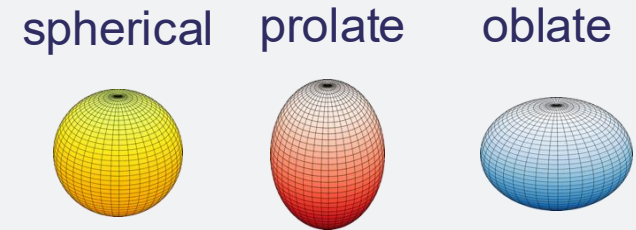
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  - ...
- Some main drivers:
  - single-particle motion (nucleons move independently in nuclear potential)
  - nucleon pairing (two nucleons forming correlated pairs)
  - collectivity (many nucleons acting coherently)



# Motivation – Global perspective

Questions

What are the mechanisms that drive the emergence of new structural phenomena in exotic nuclei?

- Single-particle motion, nucleon pairing, collectivity, others...
- What nuclear interactions take place?
- How do different mechanisms interact?
- When does each dominate?

How does nuclear structure evolve in exotic nuclear systems?

- What new phenomena emerge far from stability?

Needs

Produce and study these exotic nuclear systems.

Theoretically interpret our observations.

- Sufficient quantities
- Resolve from background
- Study before they decay
- Resolution, timing etc.

- Nuclear interactions
- Solve many body problem
- Computing power

# Motivation – Global perspective

What are the mechanisms that drive the emergence of new structural phenomena in exotic nuclei?

Questions

- Single-particle
- What nuclear
- How do differ
- When does

My view in a nutshell:

Understand how nucleons interact within the nucleus to create all the phenomena we observe across the nuclear chart.

How does nuclear

In extension:

- What new p

- What influence this has on other fields?
- What are its real-world applications?

ity, others...

systems?

Needs

Produce and study these exotic nuclear systems.

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# Motivation – Shape Coexistence

What is it?

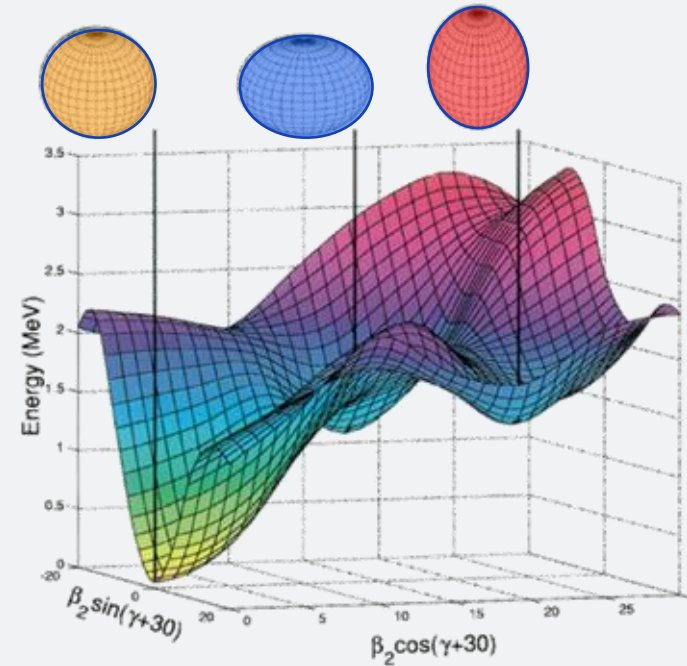
- “Nuclear shape coexistence is the phenomenon in which distinct shapes occur within the same nucleus and at a similar energy”

P. Garrett, M. Zielinska, E. Clément, *Prog. Part. and Nucl. Phys.* **124**, 103931 (2022)

In which nuclei can we find it?

- “While shape coexistence has, to date, only been established or inferred in a few hundred nuclei, there are compelling reasons to believe that it is a **universal feature of (almost) all nuclei.**”

K. Heyde and J.L. Wood, *Physica Scripta* 91, 083008 (2016)



A.N. Andreyev *et al.*, *Nature* **405**, 430 (2000)

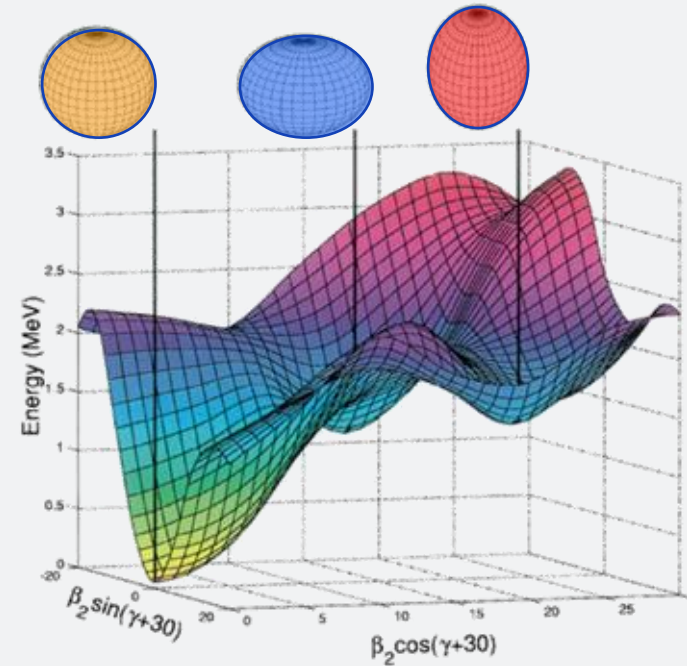
# Motivation – Shape Coexistence

Is it interesting outside nuclear physics?

- “It is now understood that it is even the feature of nuclear structure that is ‘responsible for us all being here’: the Hoyle State is the result of  $^{12}\text{C}$  possessing shape coexistence.”  
K. Heyde and J.L. Wood, *Physica Scripta* 91, 083008 (2016)
- Sounds a bit dramatic but shows how large of an impact something we observe in a specialised experiment may have.

Why study it?

- Because it’s really interesting 😊
- It’s a tricky interesting puzzle to solve!

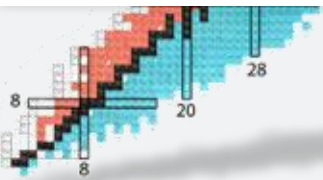
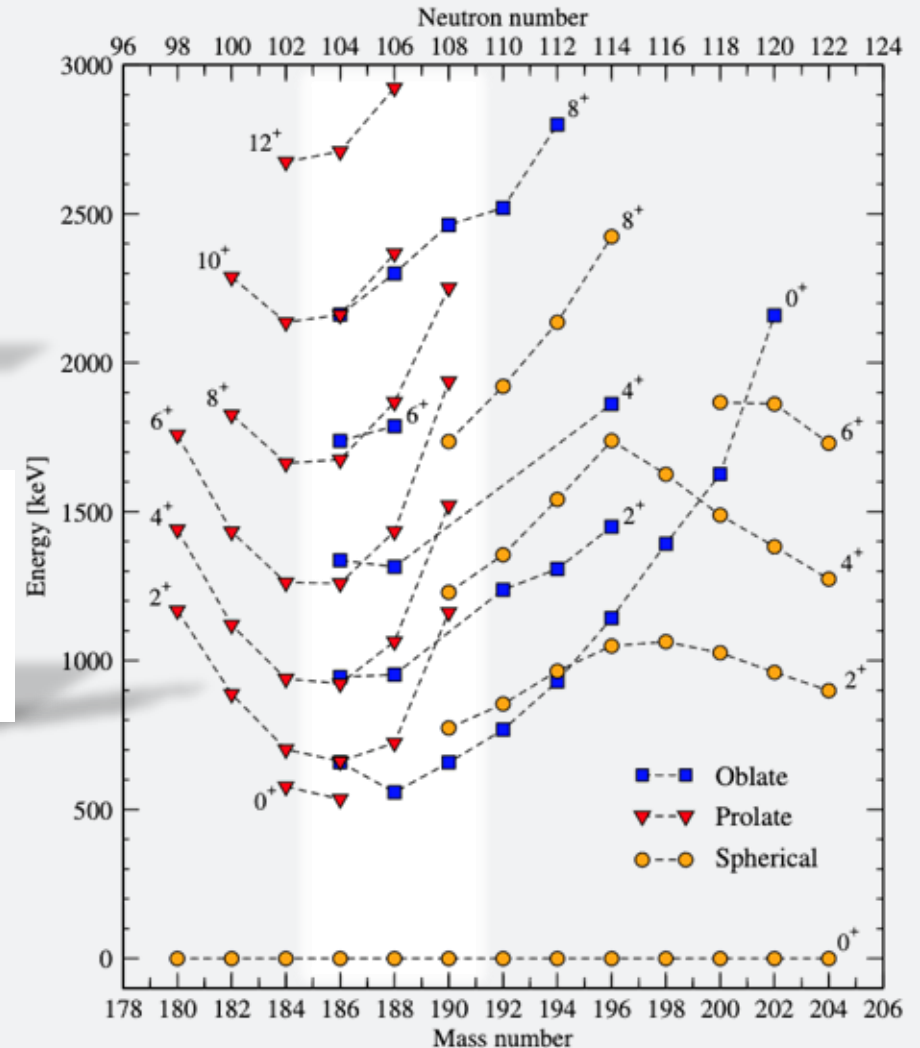


A.N. Andreyev *et al.*, *Nature* **405**, 430 (2000)

# Shape coexistence in light Pb isotopes



- Spherical ground states
- Intruder states associated with different deformation
- Energy minima around neutron  $N=104$  mid-shell



# Shape coexistence in light Pb isotopes

## Aims – Questions

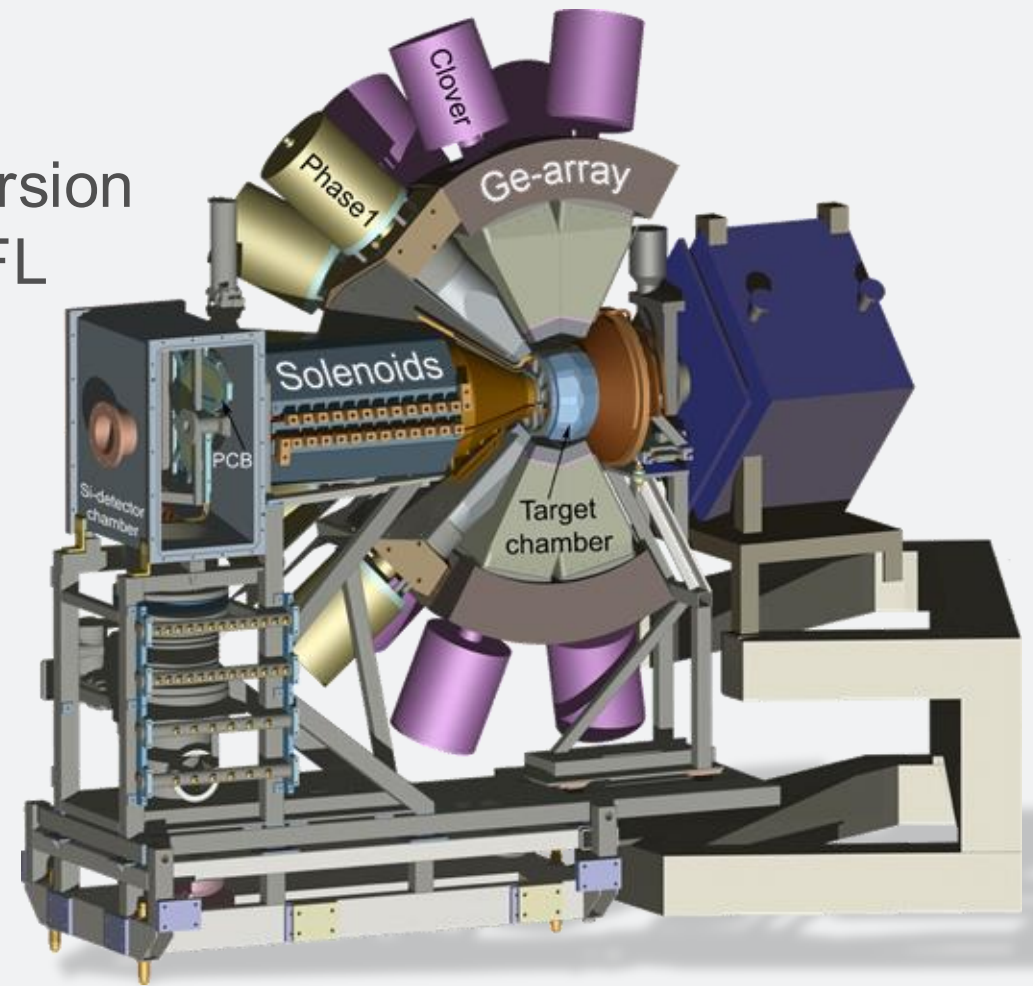
- Where are the prolate and oblate minima?
- What is the level of configuration mixing?
- Are the states observed correctly assigned?
- Where are the spherical excited states?
- What can we learn from monopole strengths?
- How to assess multipole mixing of inter-band transitions?

## Techniques – Answers

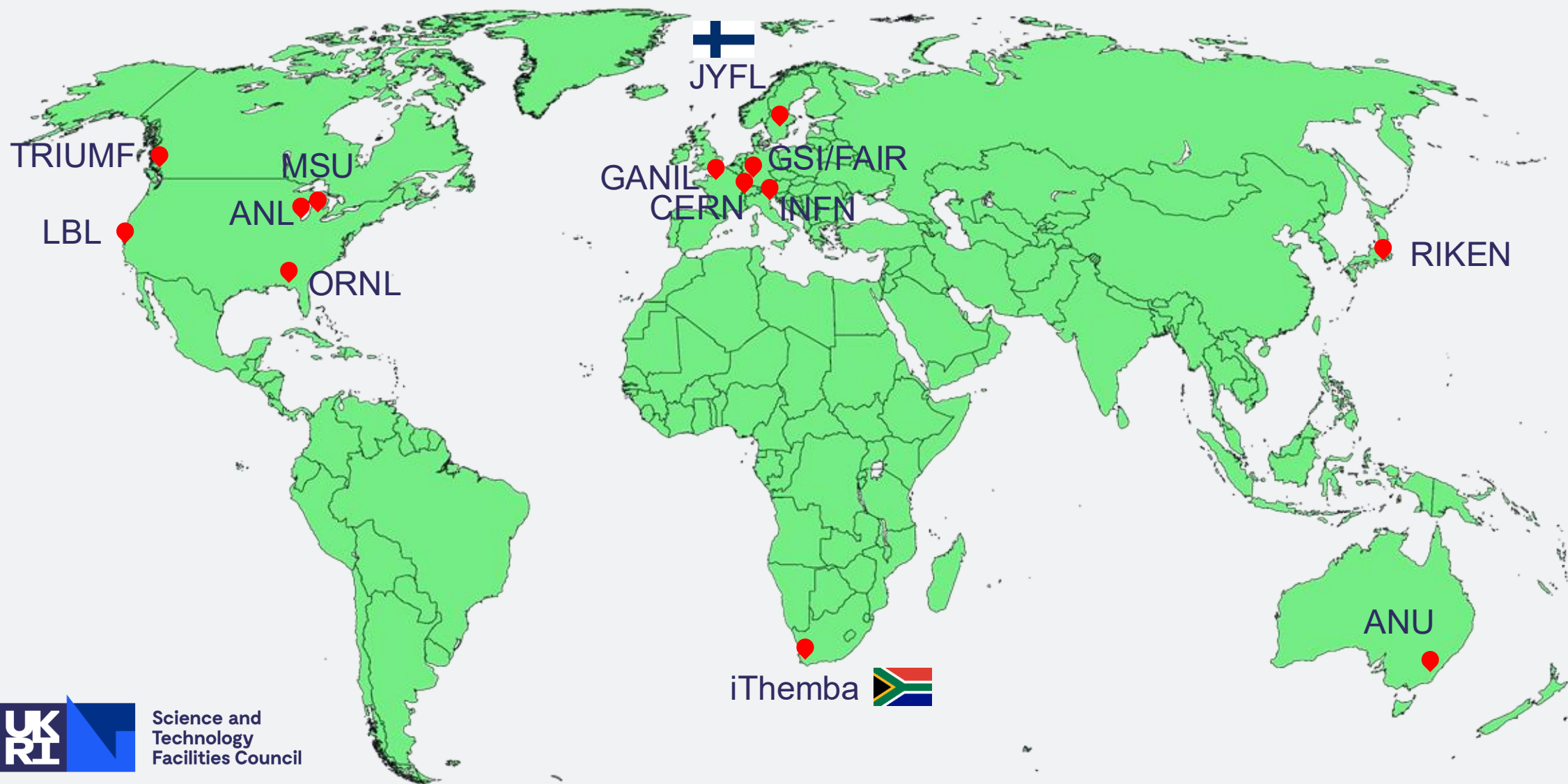
- In-beam spectroscopic techniques
  - Simultaneous  $\gamma$ -ray and electron spectroscopy
  - Lifetime measurements
  - Coulomb excitation with radioactive beams
- Decay spectroscopy
  - $\alpha$ - and  $\beta$ -decay experiments
- Laser spectroscopy
  - ground states and isomers
- New approaches, e.g.:
  - Recoil shadow method

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# Experiments – University of Jyväskylä (JYFL)



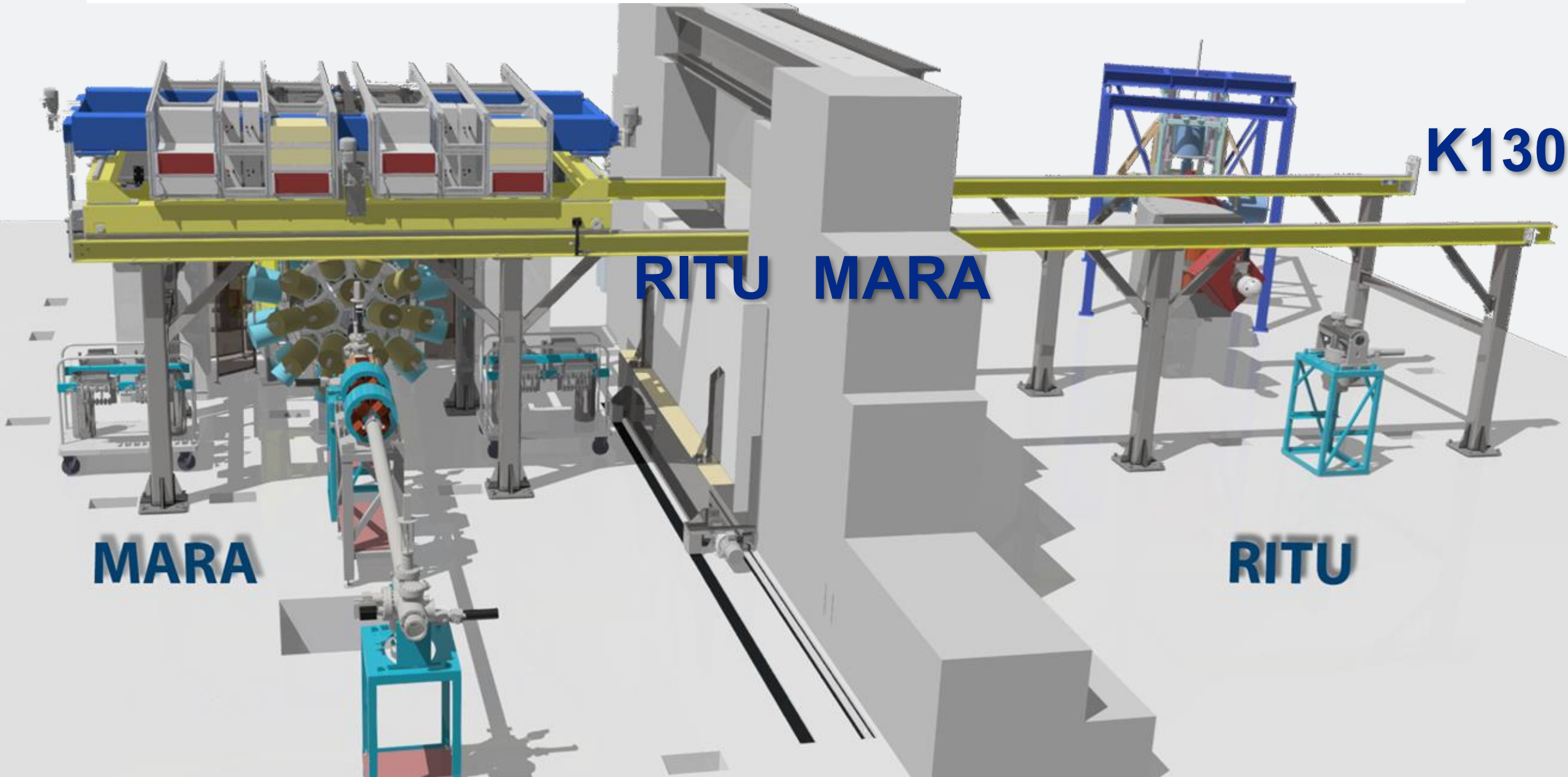
# Experimental Programme at JYFL

**RITU MARA**

A detailed 3D architectural rendering of the JYFL experimental facility. The image shows a complex layout of rooms and corridors, each containing various pieces of scientific equipment. In the center, a large room is labeled 'RITU MARA' and contains a prominent yellow and blue structure. To the right, another room is labeled 'K130' and features a large yellow box. Other rooms contain smaller instruments, control panels, and structural elements like ladders and scaffolding. The overall scene is a comprehensive virtual tour of the facility's experimental capabilities.

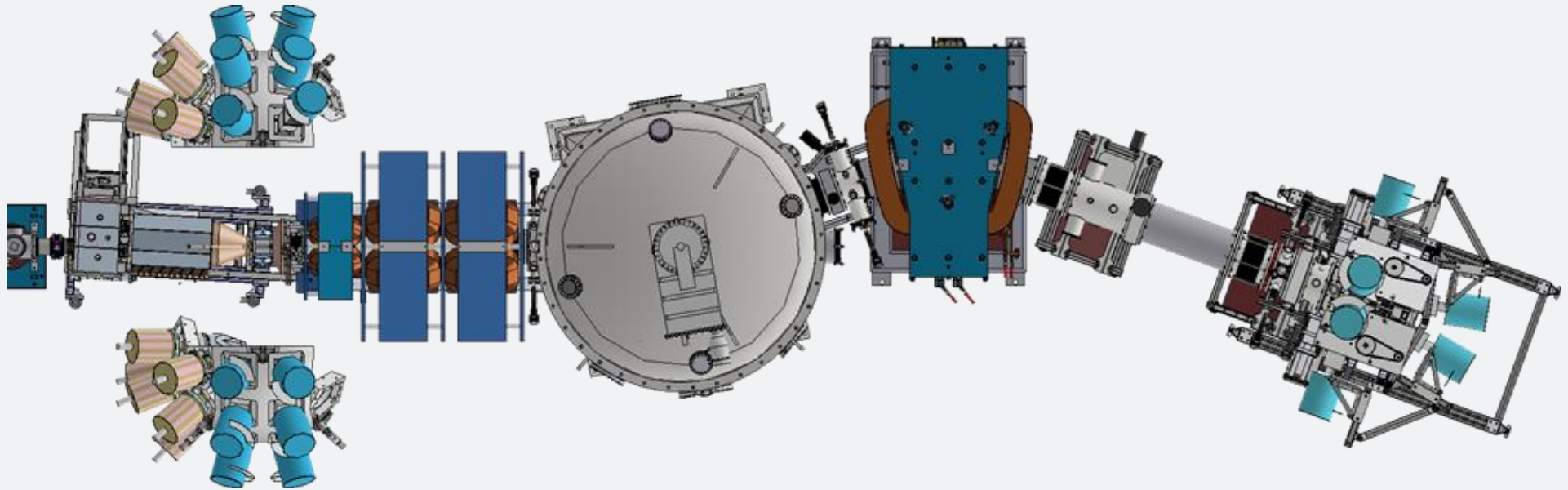
**K130**

# Experimental Programme at JYFL

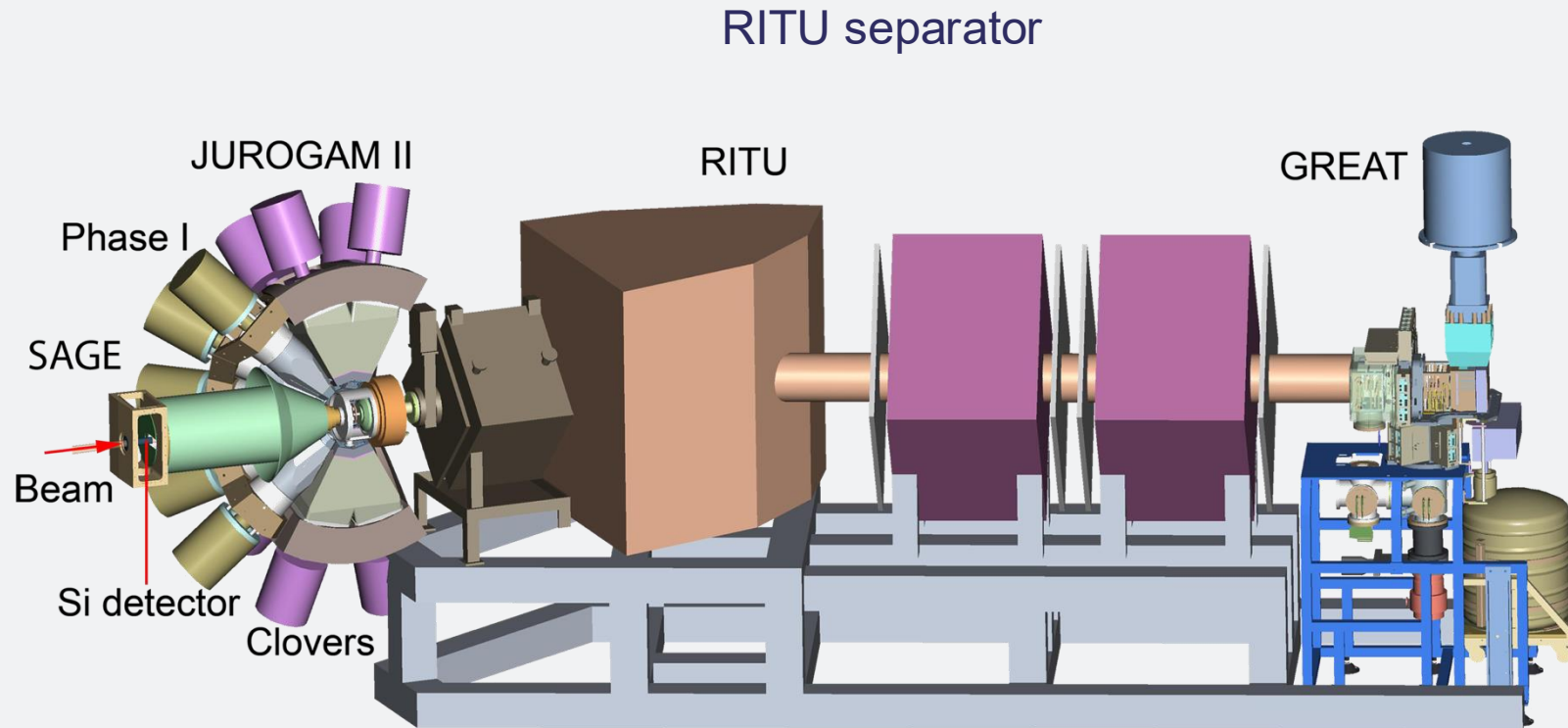


# The SAGE Spectrometer

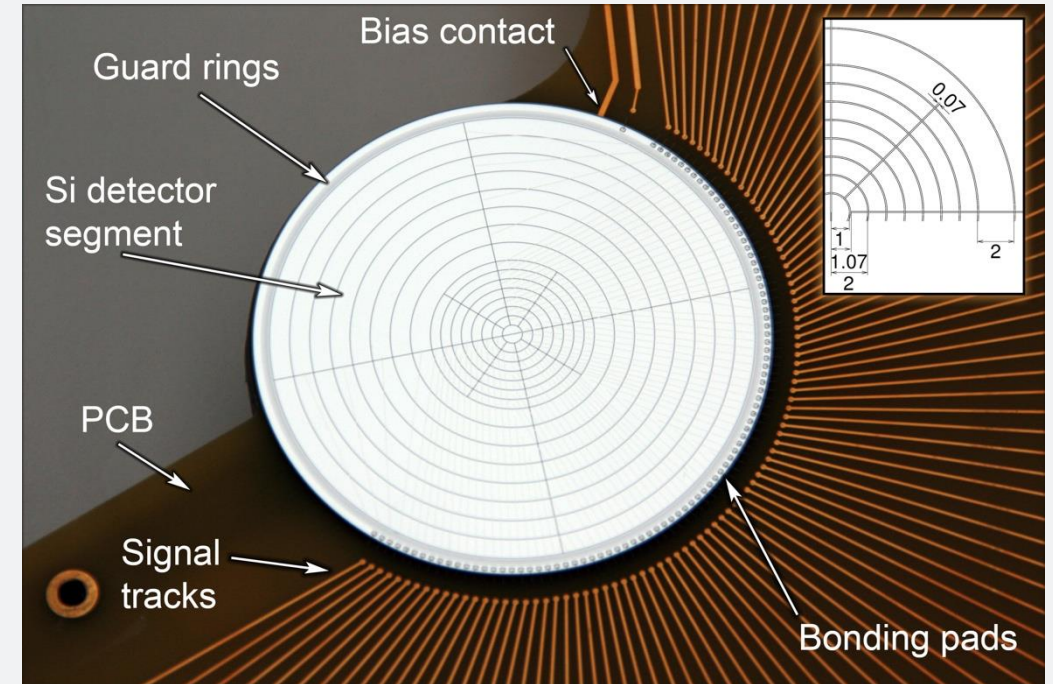
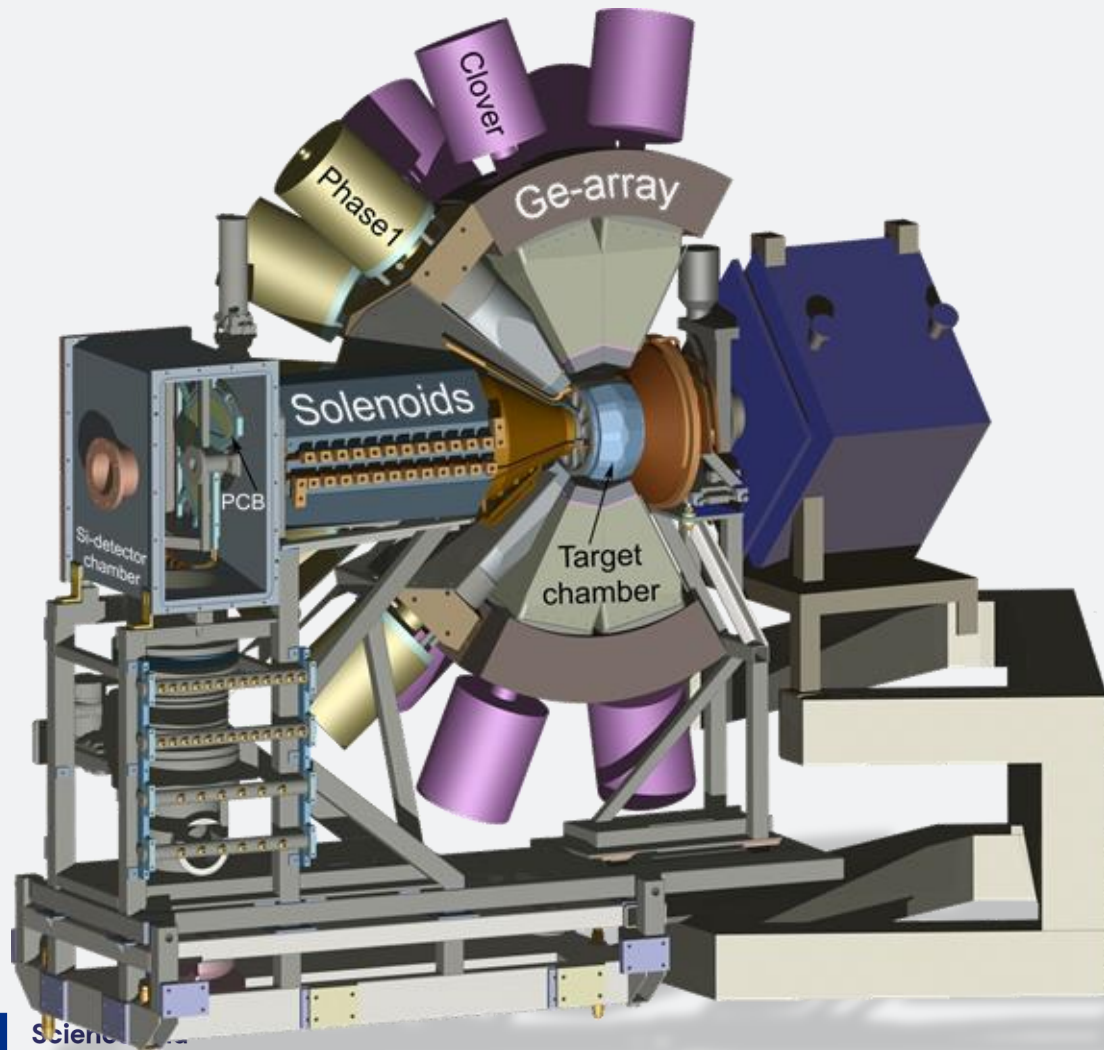
MARA separator



# The SAGE Spectrometer



# The SAGE Spectrometer



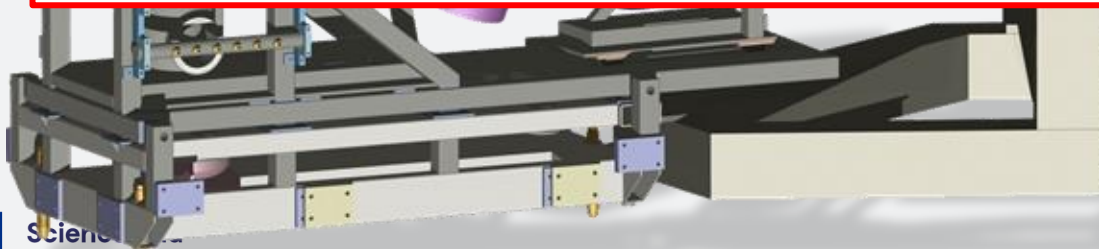
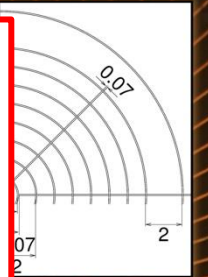
# The SAGE Spectrometer



$E0$  transitions associated with:

- Nuclear radius, changes in nuclear radius, and compressibility of nuclear matter
- Isotope and isomer shifts
- Monopole degree of freedom, i.e. radial density oscillations
- Wave function of the  $0^+$  states, deformation and different modes of excitations

**Unique probe of shape changes and shape coexistence in nuclei**

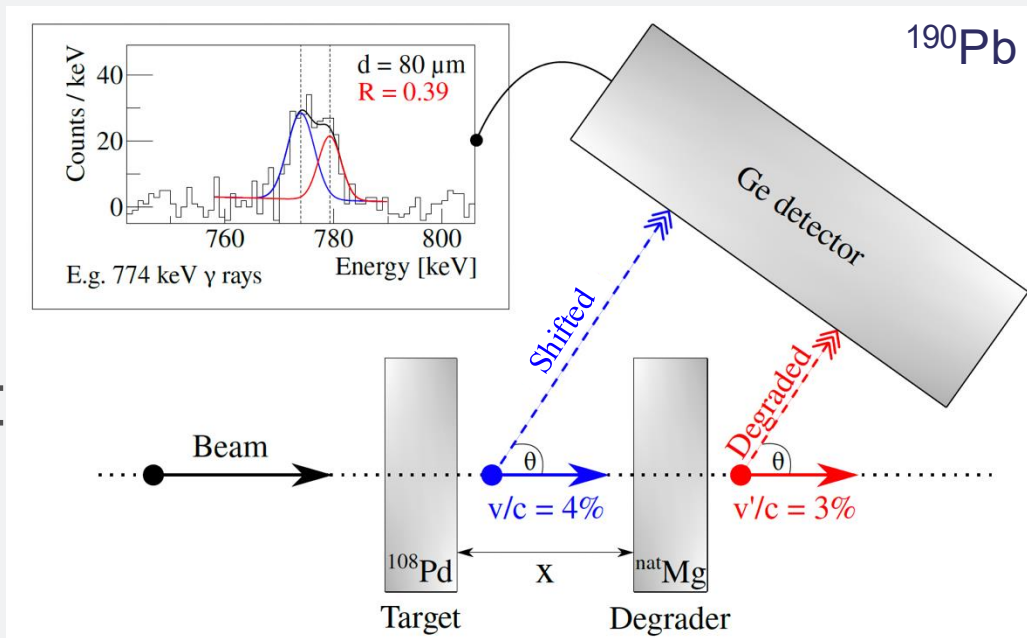


# Plunger lifetime measurements

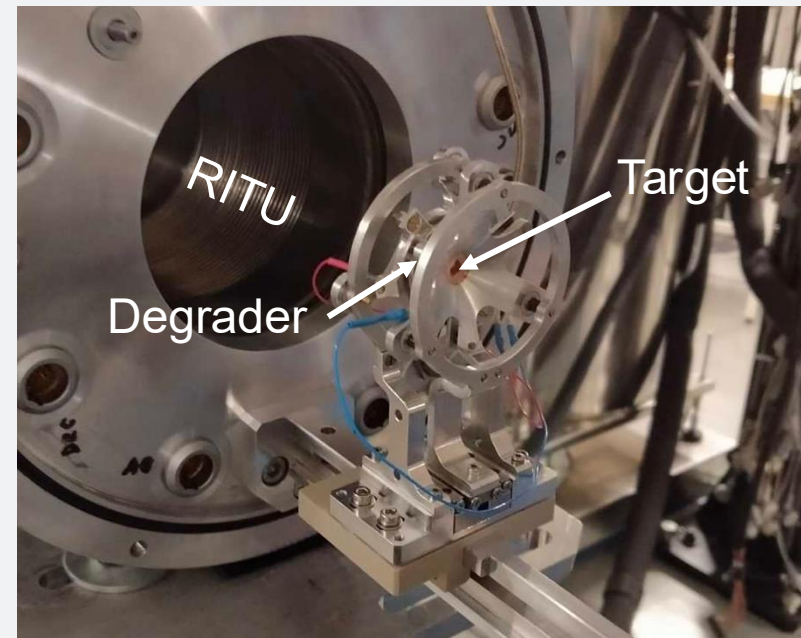
Measure state lifetimes (ps – ns)

- B(E2) values inversely proportional to state lifetime
- B(E2) values indicative of state collectivity and degree of deformation
- B(E2) values associated with different behaviour → shape coexistence

Recoil Distance  
Doppler-Shift



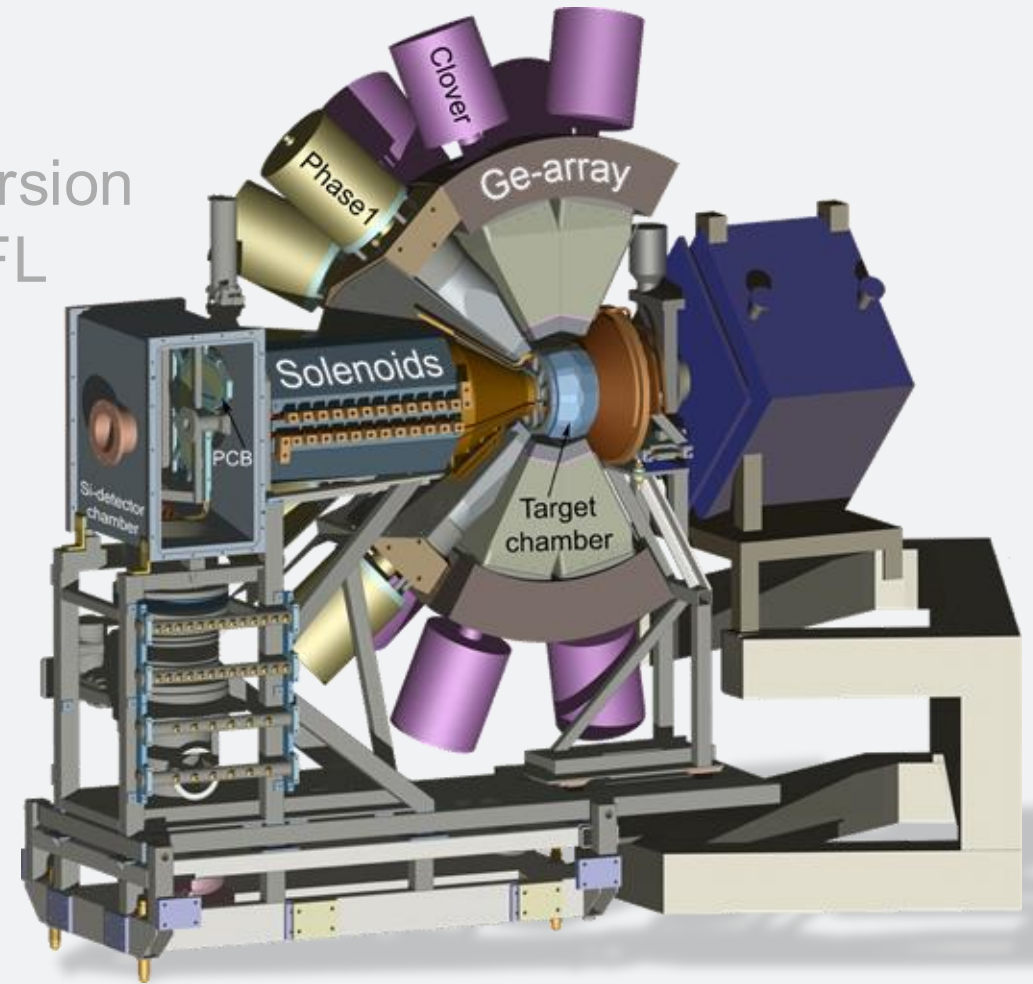
APPA plunger at  
RITU in JYFL



$$E' = E_{rest} \left( 1 + \frac{v}{c} \cos\theta \right)$$

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# Experiments overview

	<sup>186</sup> Pb	<sup>188</sup> Pb	<sup>190</sup> Pb	
<b>Instrumentation</b>	SAGE+RITU+GREAT	SAGE+RITU+GREAT	SAGE+MARA+MARA_FP	APPA+RITU+RITU_FP
<b>Channel selection</b>	Recoil-decay tagging	Recoil gating	Recoil gating	Recoil gating
<b>Reaction</b>	$^{106}\text{Pd}(^{83}\text{Kr},3n)^{186}\text{Pb}$	$^{160}\text{Dy}(^{32}\text{S},4n)^{188}\text{Pb}$	$^{159}\text{Tb}(^{35}\text{Cl},4n)^{190}\text{Pb}$	$^{108}\text{Pd}(^{86}\text{Kr},4n)^{190}\text{Pb}$
<b>Beam energy</b>	365 MeV	165 MeV	164 MeV	378 MeV
<b>Beam intensity</b>	~5 pnA	~13 pnA	~10 pnA	~2 pnA
<b>Beam on target</b>	108 h	129 h	320 h	~250 h
<b>Target thickness</b>	1 mg/cm <sup>2</sup>	500 μg/cm <sup>2</sup>	350 μg/cm <sup>2</sup>	0.95 mg/cm <sup>2</sup>
<b>Production cross section</b>	75μb	1100μb	~10mb	~10mb

SAGE

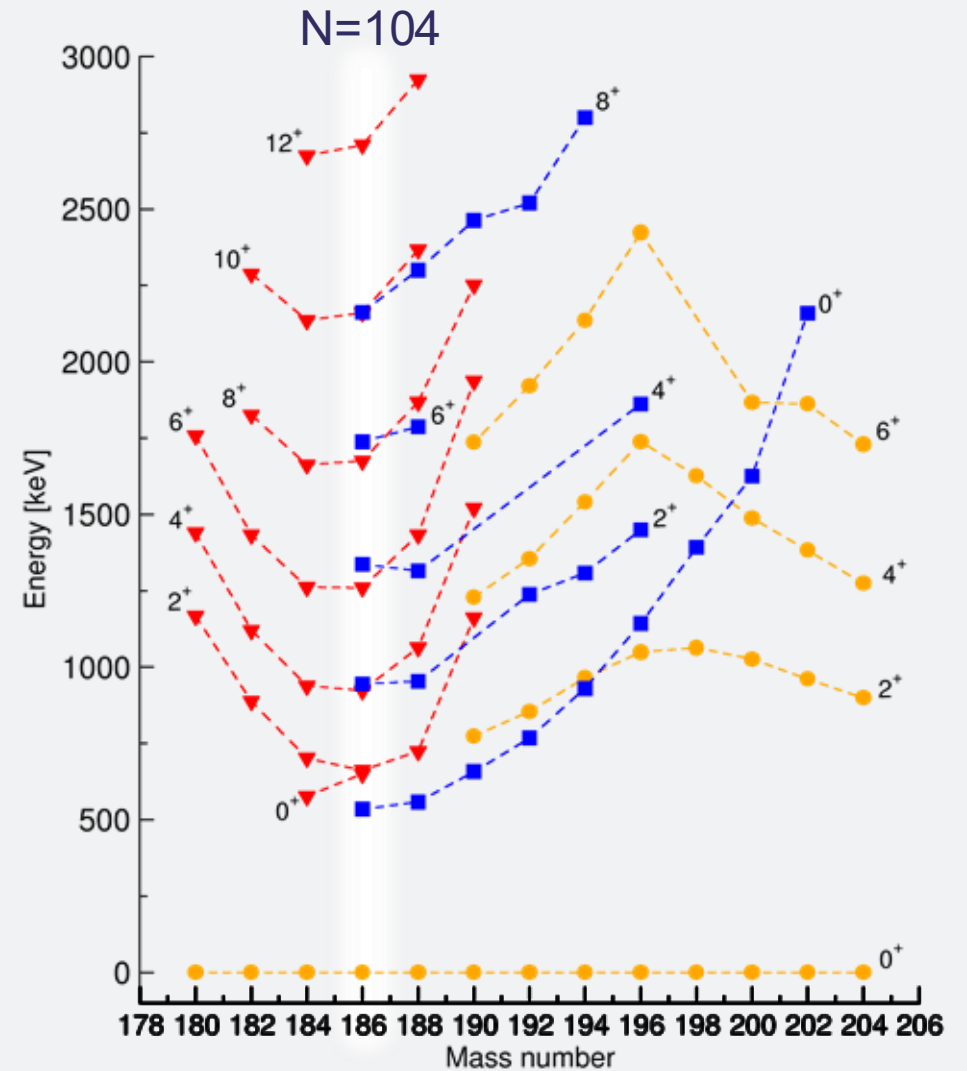
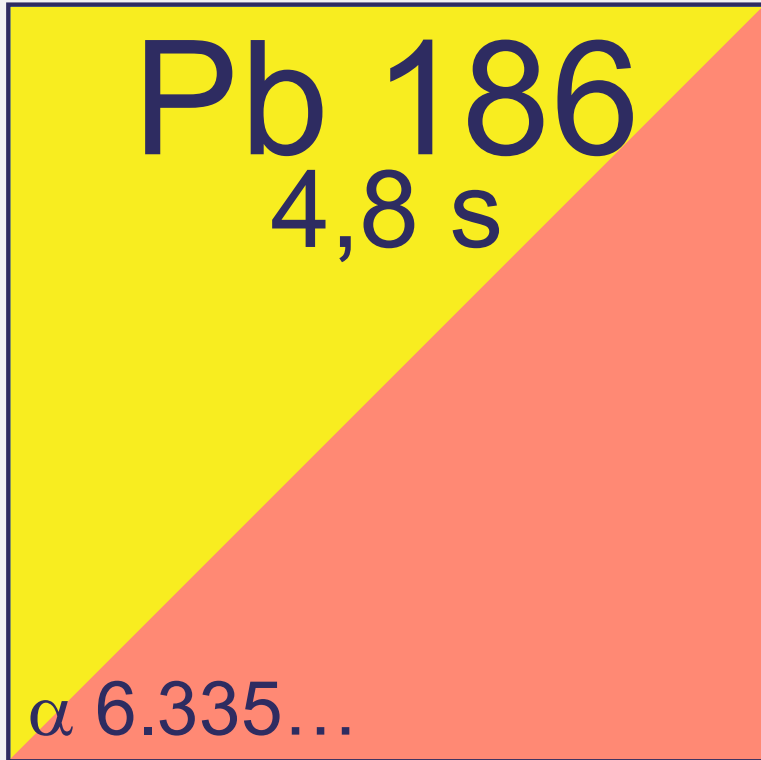
APPA

## Additional complementary in-beam experiments:

JR4: A recoil-gated plunger lifetime measurement of <sup>188</sup>Pb with JUROGAM and the RITU separator

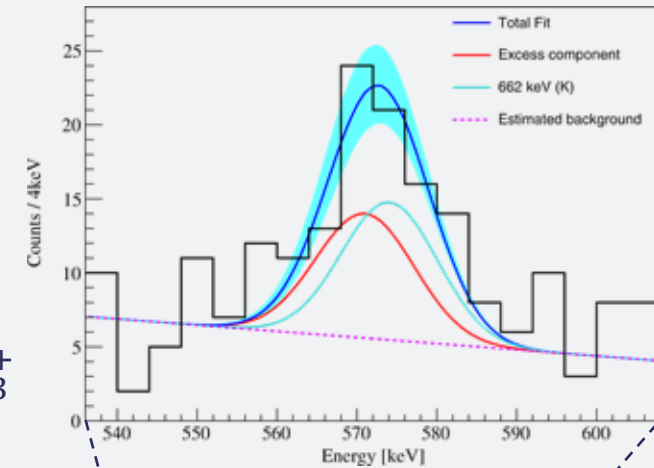
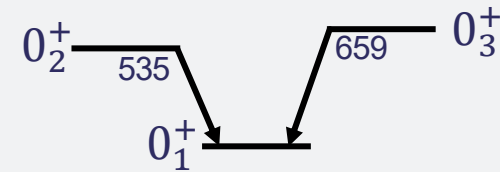
JR33: A recoil-decay tagged plunger lifetime measurement for the yrast levels of <sup>186</sup>Pb

# $^{186}\text{Pb}$ – At the $N=104$ neutron mid-shell

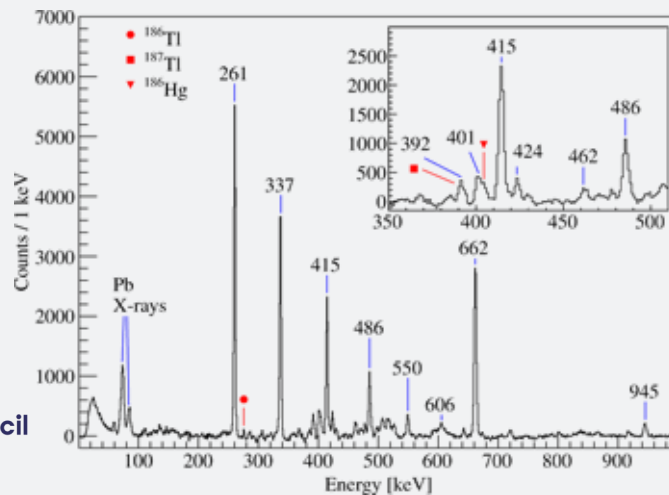


# $^{186}\text{Pb}$ – $\gamma$ and electron spectroscopy

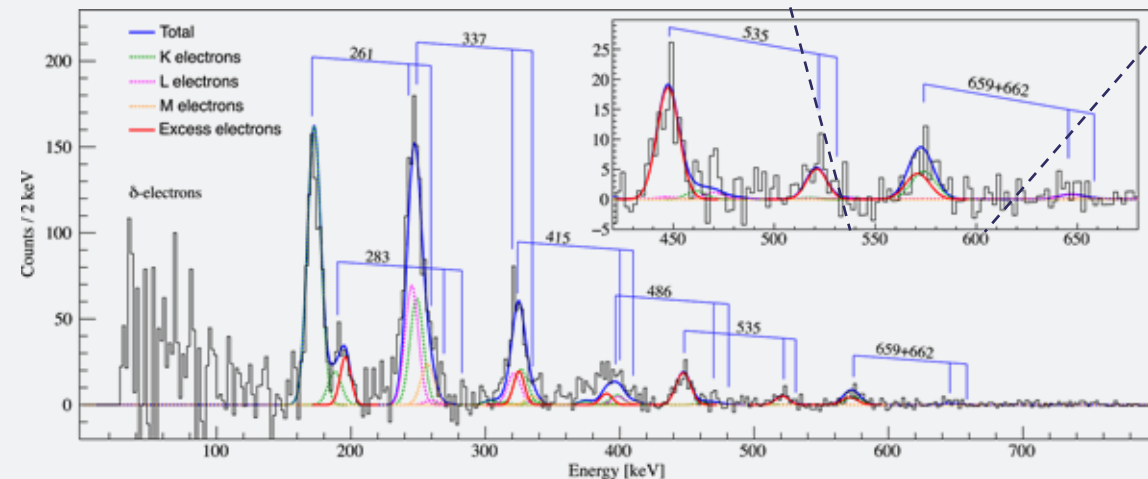
- Very clean  $\gamma$ -ray and electron energy spectra
- Calculated electron energy spectra show excess counts  $\rightarrow$  associated with E0 transitions
- The first direct measurement of the  $0_2^+ \rightarrow 0_1^+$  and  $0_3^+ \rightarrow 0_1^+$  transitions in  $^{186}\text{Pb}$



$\gamma$ -ray singles energy spectrum



Electron singles energy spectrum



# $^{186}\text{Pb}$ – Reassigning shapes of $0^+$ states

Based on  $B(E2; 2_1^+ \rightarrow 0_1^+) = 6(2)$  W.u. (from lifetimes)

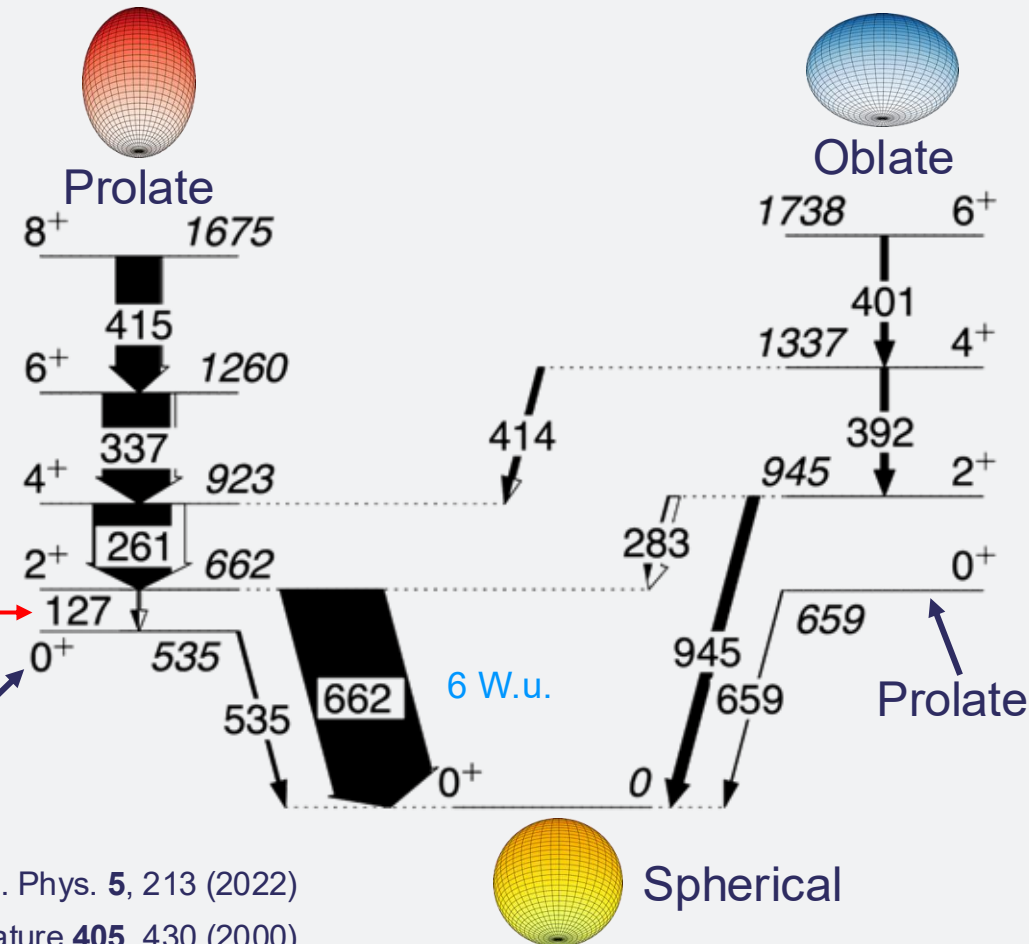
and the measured branching ratio  $\frac{I_\gamma(2_1^+ \rightarrow 0_2^+)}{I_\gamma(2_1^+ \rightarrow 0_1^+)}$

Suggestion:  $0_2^+$  state a **prolate** band member

- Reduced transition probability:  
 $B(E2; 2_1^+ \rightarrow 0_2^+) = 190(80)$  W.u.
- Typically in this region:  
 $B(E2; \text{prolate in-band}) = 390(40)$  W.u.
- Transitional quadrupole moment:  
 $|Q_t(2_1^+ \rightarrow 0_2^+)| = 7.7(33)$  eb
- Typically in this region:  
 $Q_t(E2; \text{prolate in-band}) = 9.0(5)$  eb

$B(E2) = 190(80)$  W.u.  
 $Q_t = 7.7(33)$  eb

~~Oblate~~  
Prolate



# $^{186}\text{Pb}$ – Reassigning shapes of $0^+$ states

Assuming  $B(E2; 2_2^+ \rightarrow 0_1^+) = 5 \text{ W.u.}$

and if  $0_2^+$  predominantly oblate  $B(E2; 2_2^+ \rightarrow 0_2^+) = 50 \text{ W.u.}$

- $I(2_2^+ \rightarrow 0_2^+) = 19(2)$  ( $I_\gamma(2_1^+ \rightarrow 0_1^+) = 1000$ )

does not fit with observations

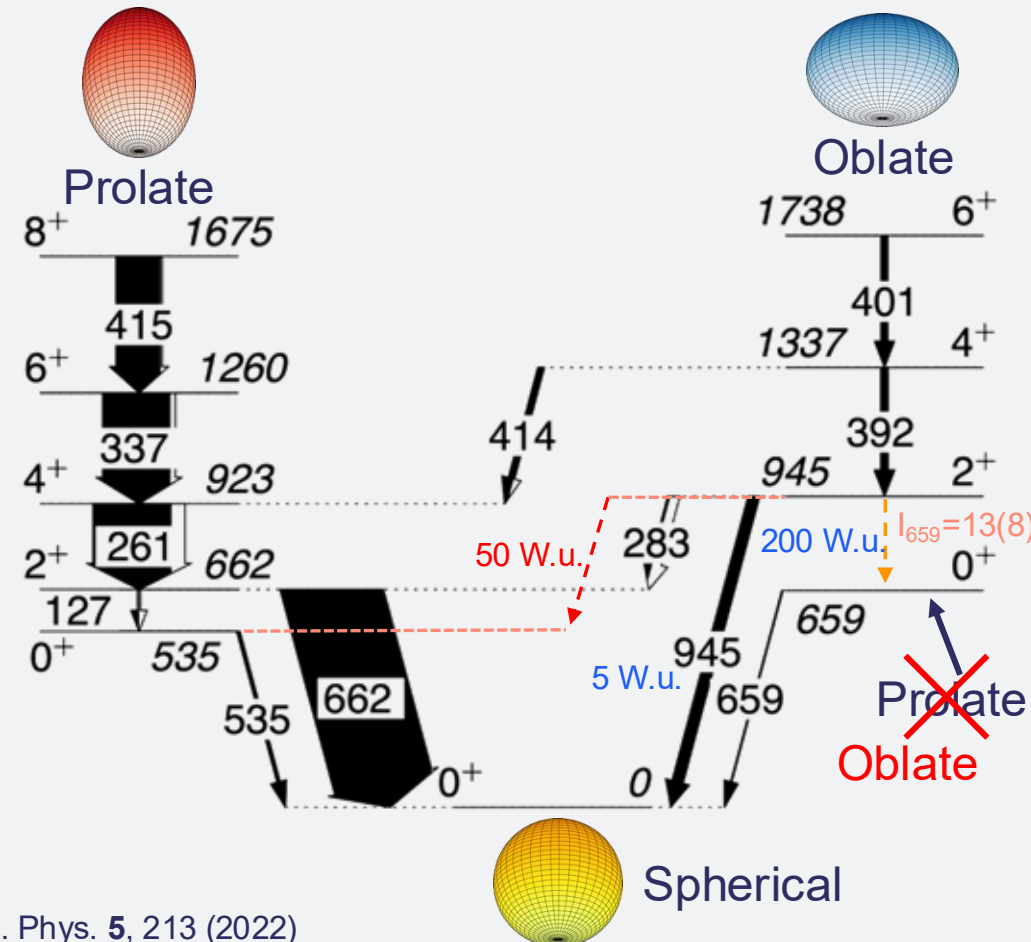
- The  $0_2^+$  state does NOT have a notable oblate component.

Assuming  $I(2_2^+ \rightarrow 0_3^+) = I(0_3^+ \rightarrow 0_1^+) = 13(8)$

and  $B(E2; 2_2^+ \rightarrow 0_1^+) = 5 \text{ W.u.}$

- $B(E2; 2_2^+ \rightarrow 0_3^+) = 200(120) \text{ W.u.}$
- $2_2^+ \rightarrow 0_3^+$  a collective (oblate) in-band transition.

Based on observed intensity balances and calculated monopole strengths  $\rightarrow$  small mixing between  $0_2^+$  and  $0_3^+$



# $^{186}\text{Pb}$ – Reassigning shapes of $0^+$ states

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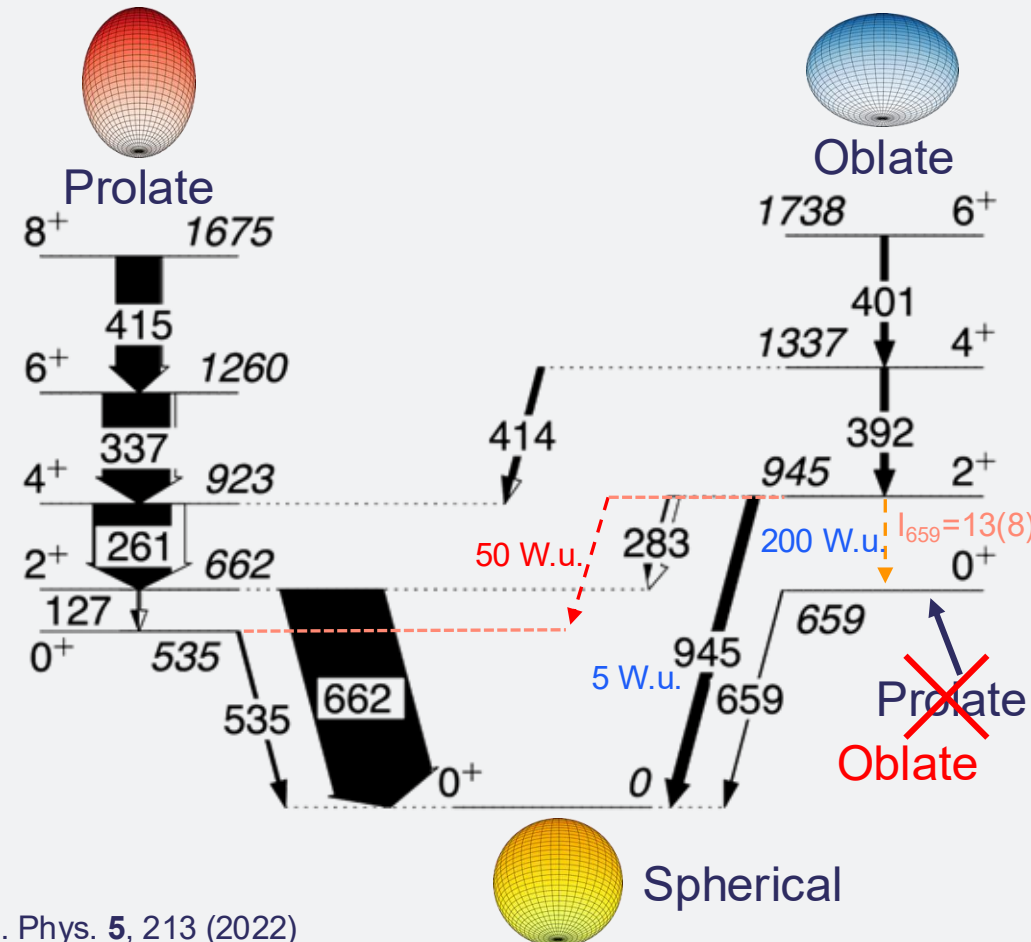
- **Conclusion:**

- $0_2^+$  band-head of band associated with predominantly **prolate** shape
- $0_3^+$  band-head of band associated with predominantly **oblate** shape

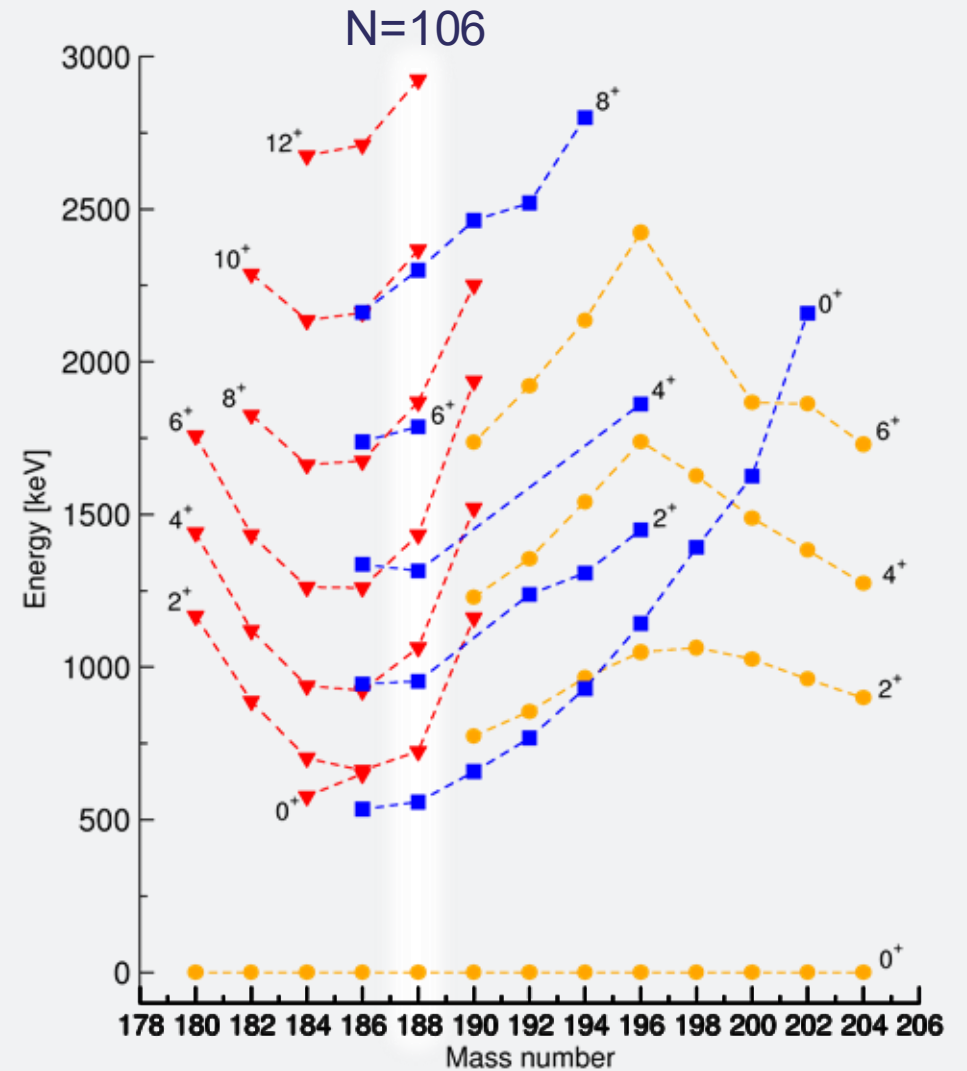
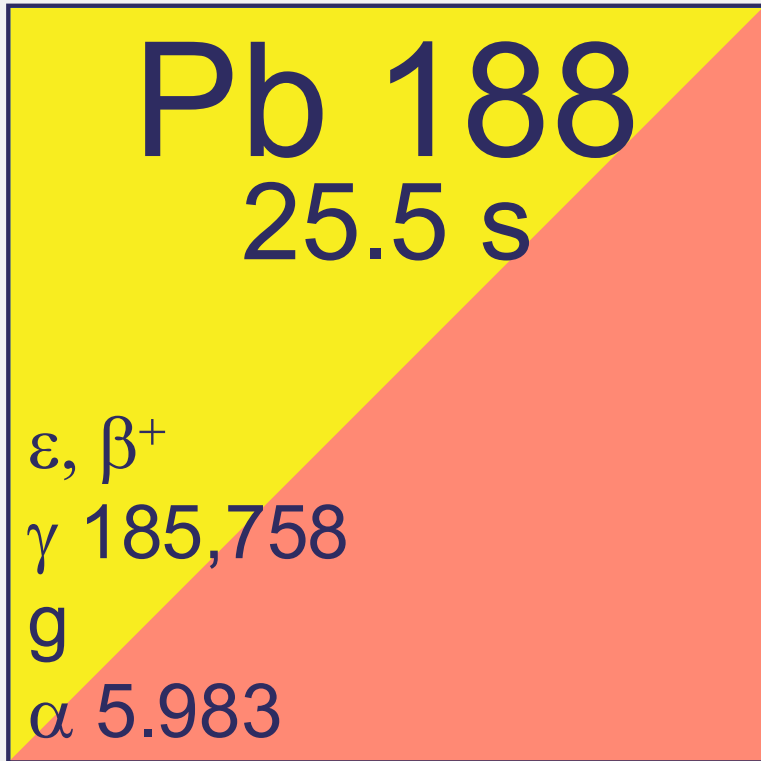
Assu  
and

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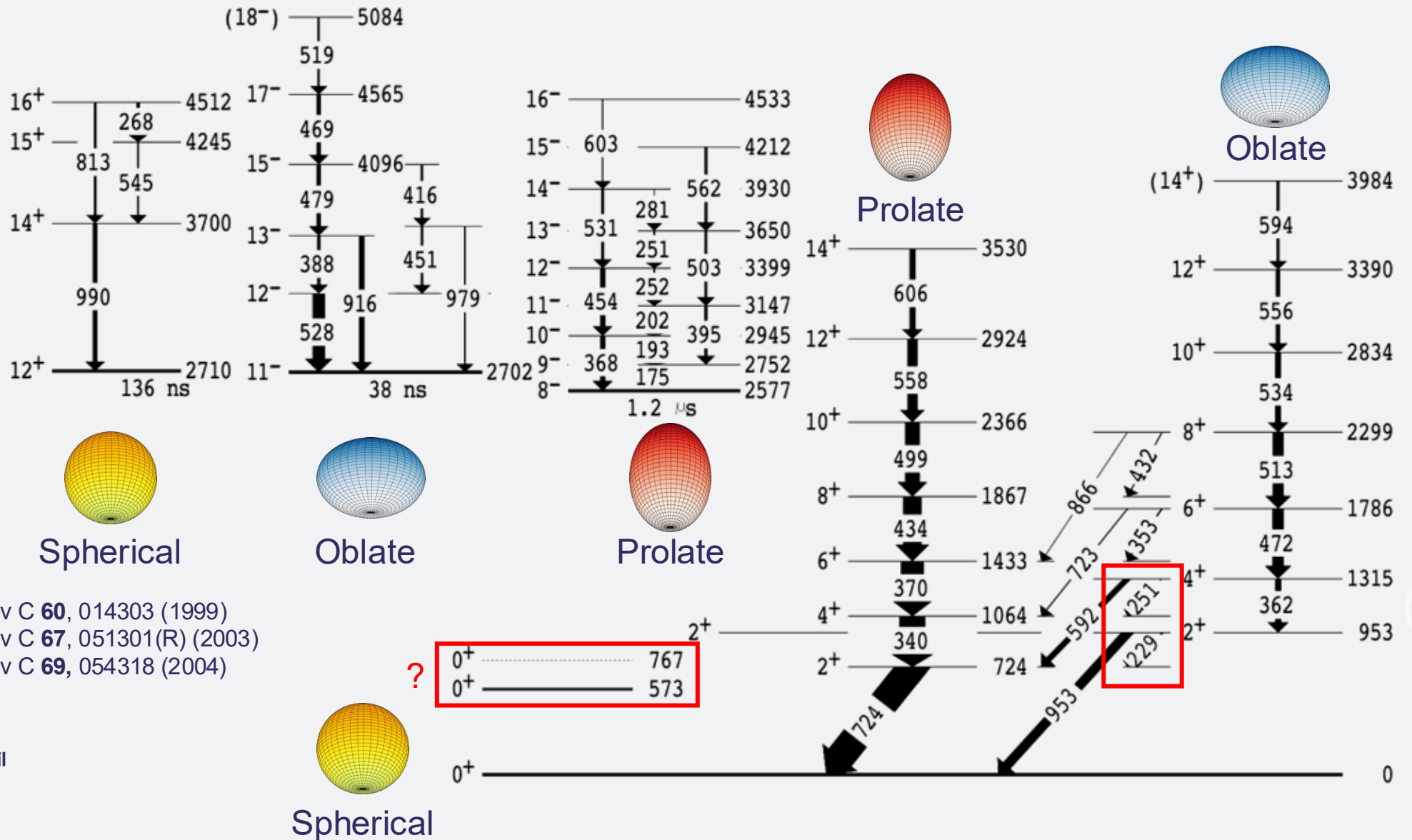
Based on observed intensity balances and calculated monopole strengths  $\rightarrow$  small mixing between  $0_2^+$  and  $0_3^+$



# $^{188}\text{Pb}$ – Mixing of configurations



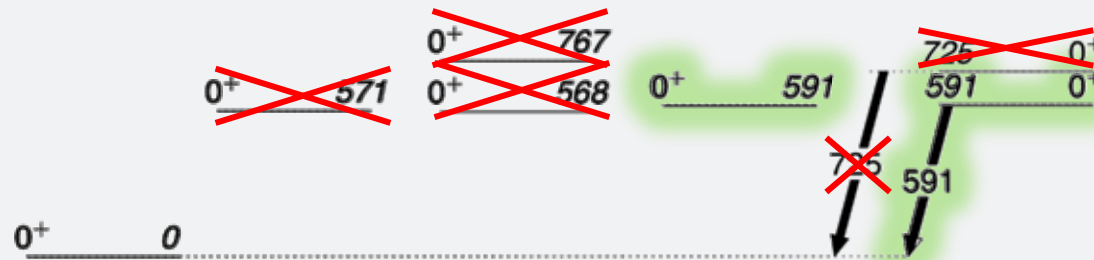
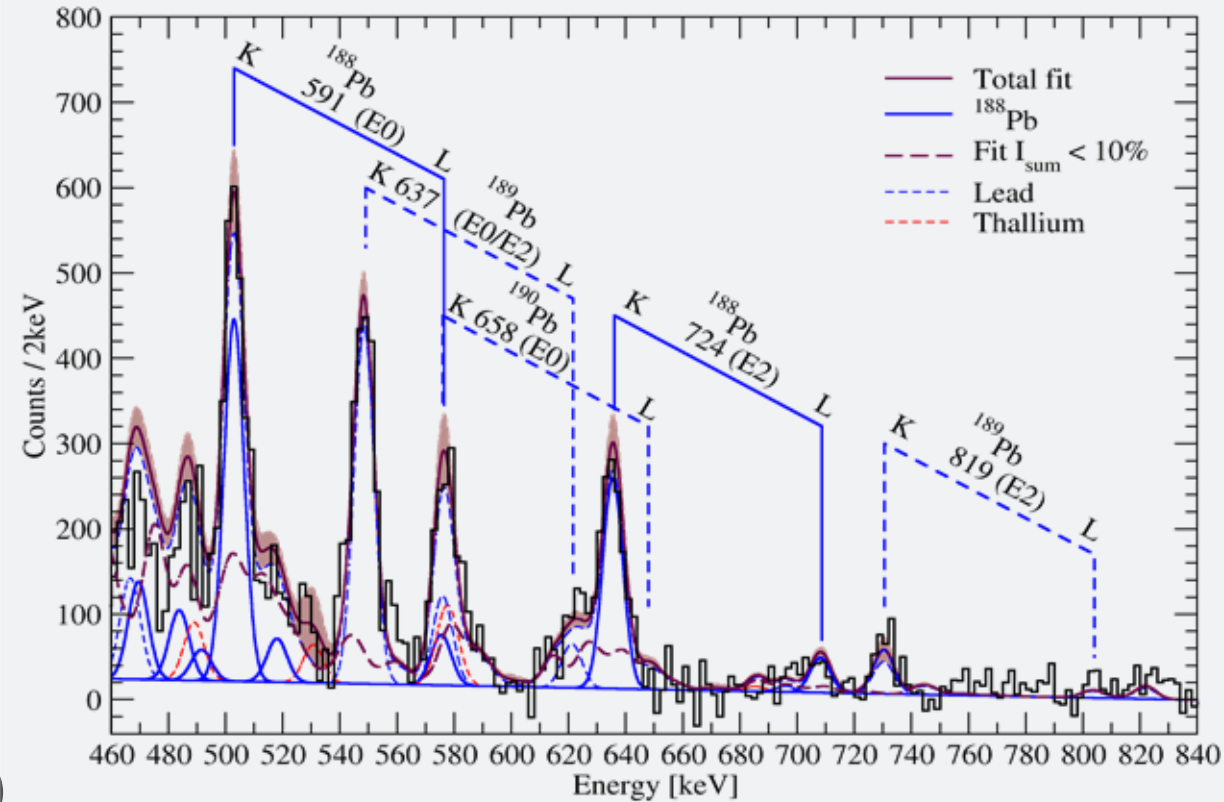
# $^{188}\text{Pb}$ – In-beam $\gamma$ -ray spectroscopy



G.D. Dracoulis *et al.*, Phys. Rev C **60**, 014303 (1999)  
 G.D. Dracoulis *et al.*, Phys. Rev C **67**, 051301(R) (2003)  
 G.D. Dracoulis *et al.*, Phys. Rev C **69**, 054318 (2004)

# $^{188}\text{Pb}$ – The conundrum of $0^+$ energies

- Deconvolution based on observed  $\gamma$ -rays
- Includes 200+ individual components
- Excess electrons  $\rightarrow$  E0 transitions
- Direct observation of  $0_2^+ \rightarrow 0_1^+$  transition at 591(2)keV
- No indication of  $0^+$  state at 767keV
- All intensity around 724keV assigned to the  $2_1^+ \rightarrow 0_1^+$  transition
- Confirm observations by:  
Van de Vel *et al.*, PRC **68**, 054311 (2003)



# $^{188}\text{Pb}$ – Shape assignment of the $0_2^+$

Feeding from the prolate band (133keV):

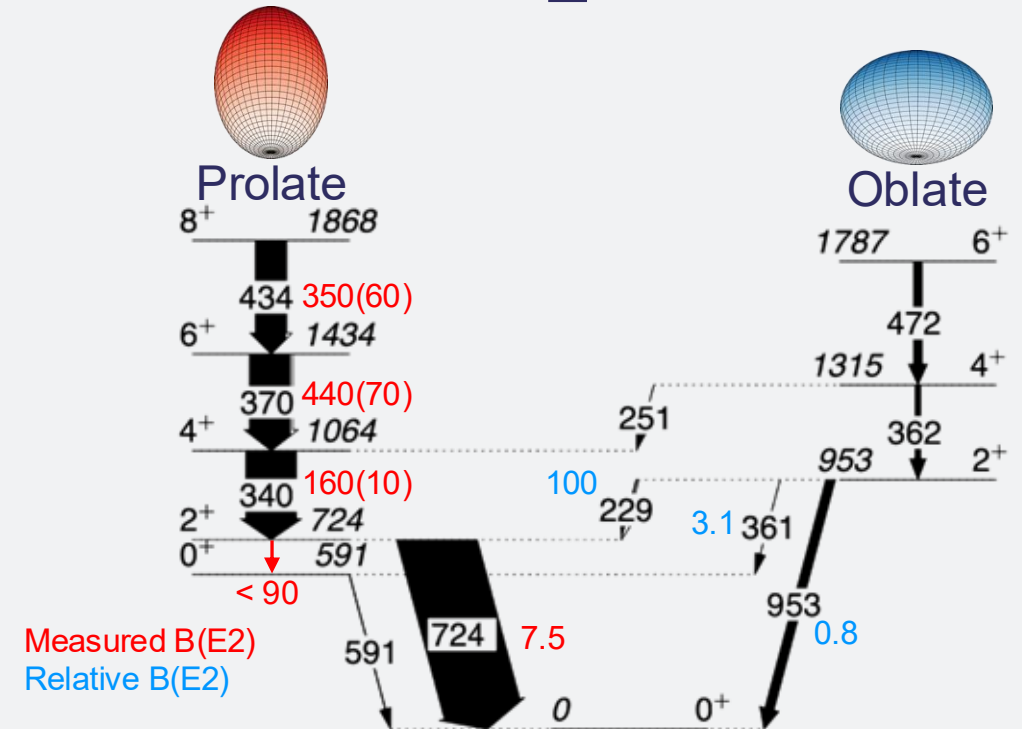
$$\bullet I_\gamma(E2; 2_1^+ \rightarrow 0_2^+) < \frac{I_{tot}(E0; 0_2^+ \rightarrow 0_1^+) - I_{tot}(E2; 2_2^+ \rightarrow 0_2^+)}{1 + \alpha_{tot}(2_1^+ \rightarrow 0_2^+)} = 1.5$$

$$(I_\gamma(2_1^+ \rightarrow 0_1^+) = 1000)$$

- Taking  $B(E2; 2_1^+ \rightarrow 0_1^+) = 7.5(30)$  W.u.  
 $\rightarrow B(E2; 2_1^+ \rightarrow 0_2^+) < 90$  W.u.  $\rightarrow$  collective

Feeding from the oblate band (361keV):

- $I_\gamma(2_2^+ \rightarrow 0_2^+) = 3.4(12)$  and  $I_\gamma(2_2^+ \rightarrow 0_1^+) = 117(7)$
- Taking  $B(E2; 2_2^+ \rightarrow 0_1^+) = 0.8$  W.u.  
 $\rightarrow B(E2; 2_1^+ \rightarrow 0_2^+) = 3.1$  W.u.  $\rightarrow$  hindered



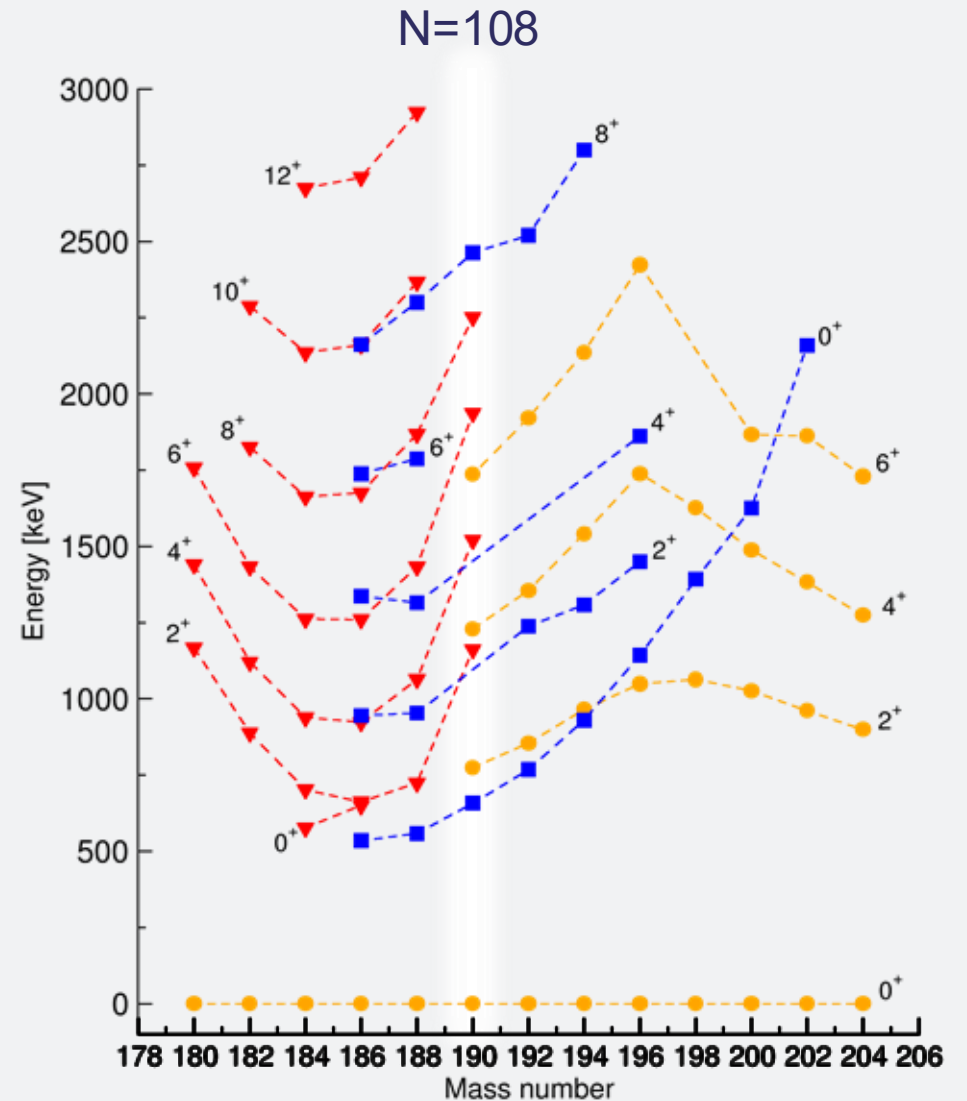
Conclusion:

- Collective intra-band transition from prolate band
- Hindered inter-band transition from oblate band
- ∴ the  $0_2^+$  state fits better with the predominantly prolate band  $\rightarrow$  Reassignment of configuration

# $^{190}\text{Pb}$ – Combining three techniques

**Pb 190**  
71 s

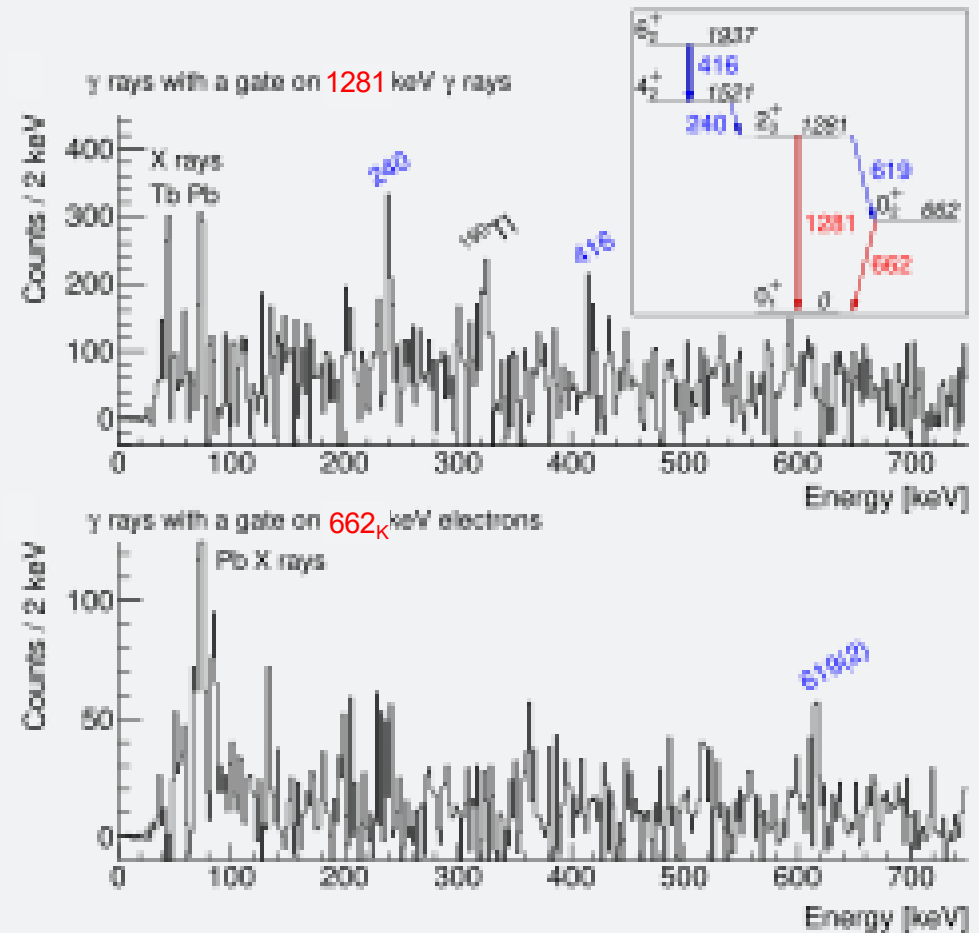
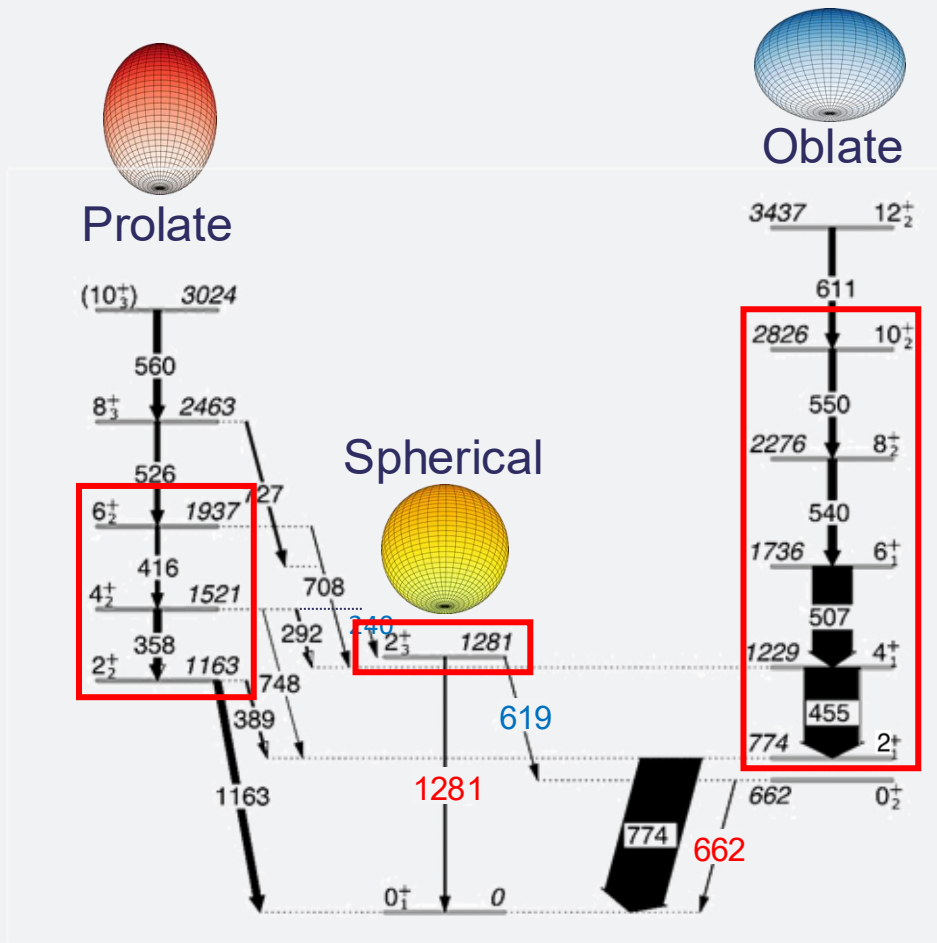
$\epsilon$   
 $\beta^+$  2.0, 2.9  $\square$   
 $\gamma$  942, 151, 598..., g  
 $\alpha$  5.581...



# $^{190}\text{Pb}$ – Direct measurement of deformations

- Prompt  $\gamma$ - $\gamma$  and  $\gamma$ -electron coincidence spectroscopy
    - Study of highly-converted transitions
    - New transitions (and their properties)
  - Delayed  $\gamma$ -ray spectroscopy
    - De-excitation of isomeric states
  - RDDS lifetime measurements
    - State lifetimes
- Reduced transition probabilities,  $B(E2)$
- Assignment of configurations and deformations
- Configuration mixing

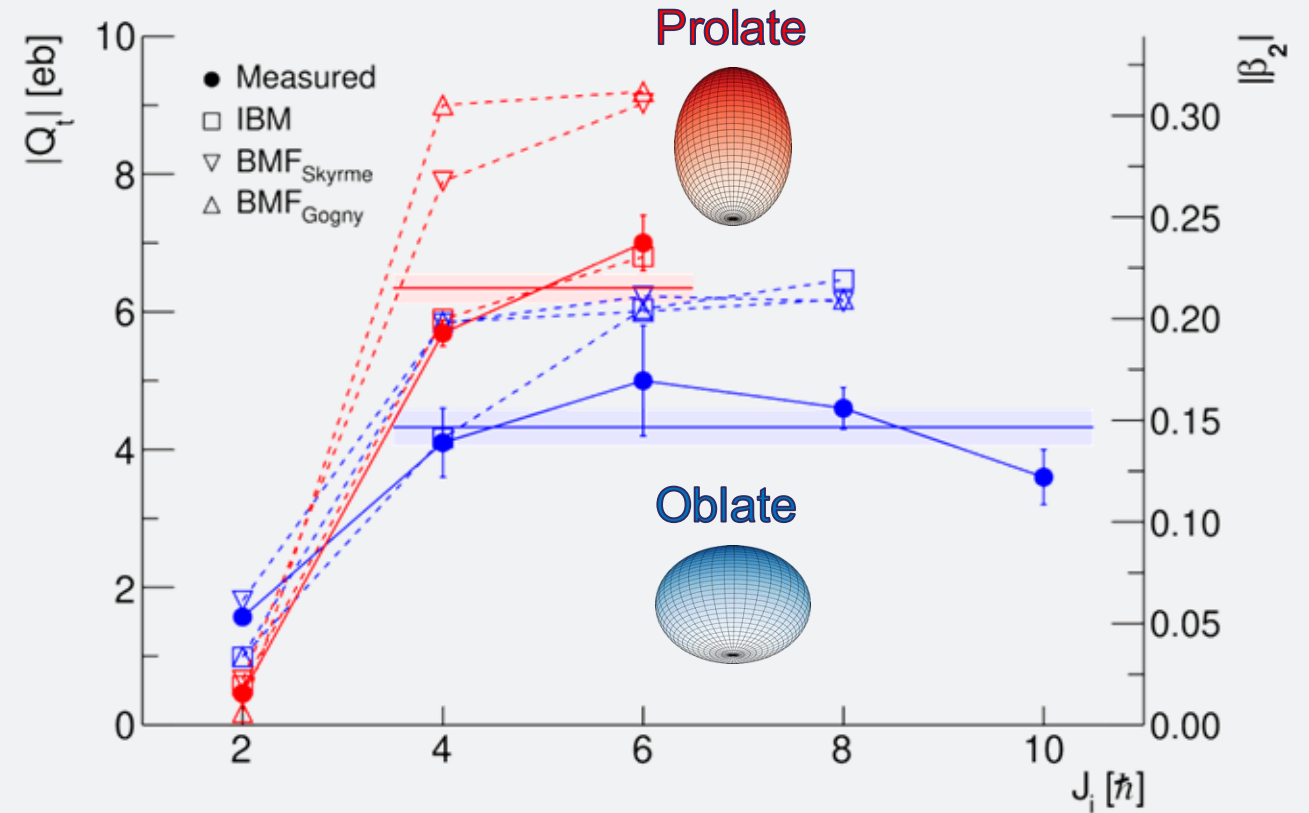
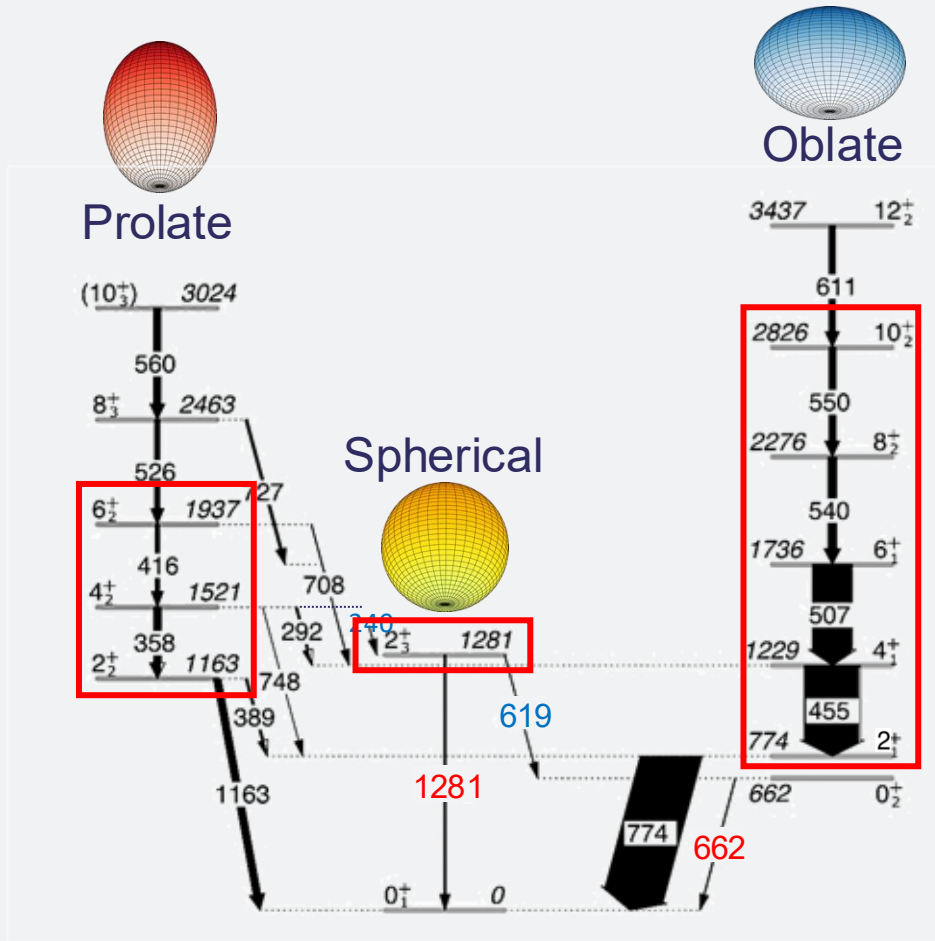
# $^{190}\text{Pb}$ – Direct measurement of deformations



- Discovery of several new transitions
- Discovery of the candidate spherical  $2_3^+$
- Lifetimes obtained for many states

- Reassignment of the  $0_2^+$  and  $2_1^+$  as oblate
- Direct measurement of the  $E0$  transitions:  $\rho^2(2_2^+ \rightarrow 2_1^+)$  and  $\rho^2(4_2^+ \rightarrow 4_1^+)$  determined

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# Summary

- Shape coexistence an almost global phenomenon
- Pb region one of the most fertile for its study
- $\gamma$ -e spectroscopy a powerful tool for its study ( $E0$  transitions unique probes)
- Complimentary techniques are needed
  - Disentangling of complex de-excitation paths
  - Discovery of new states
  - Assignment of state configurations
- $^{186}\text{Pb}$ : Reassignment of excited  $0^+$  configurations
- $^{188}\text{Pb}$ : Clarity on location of  $0_2^+$  state and reassignment of configuration
- $^{190}\text{Pb}$ : Reassignment of  $0_2^+$  configuration, discovery of excited spherical  $2^+$

# Pb@SAGE collaboration

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# Thank you



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