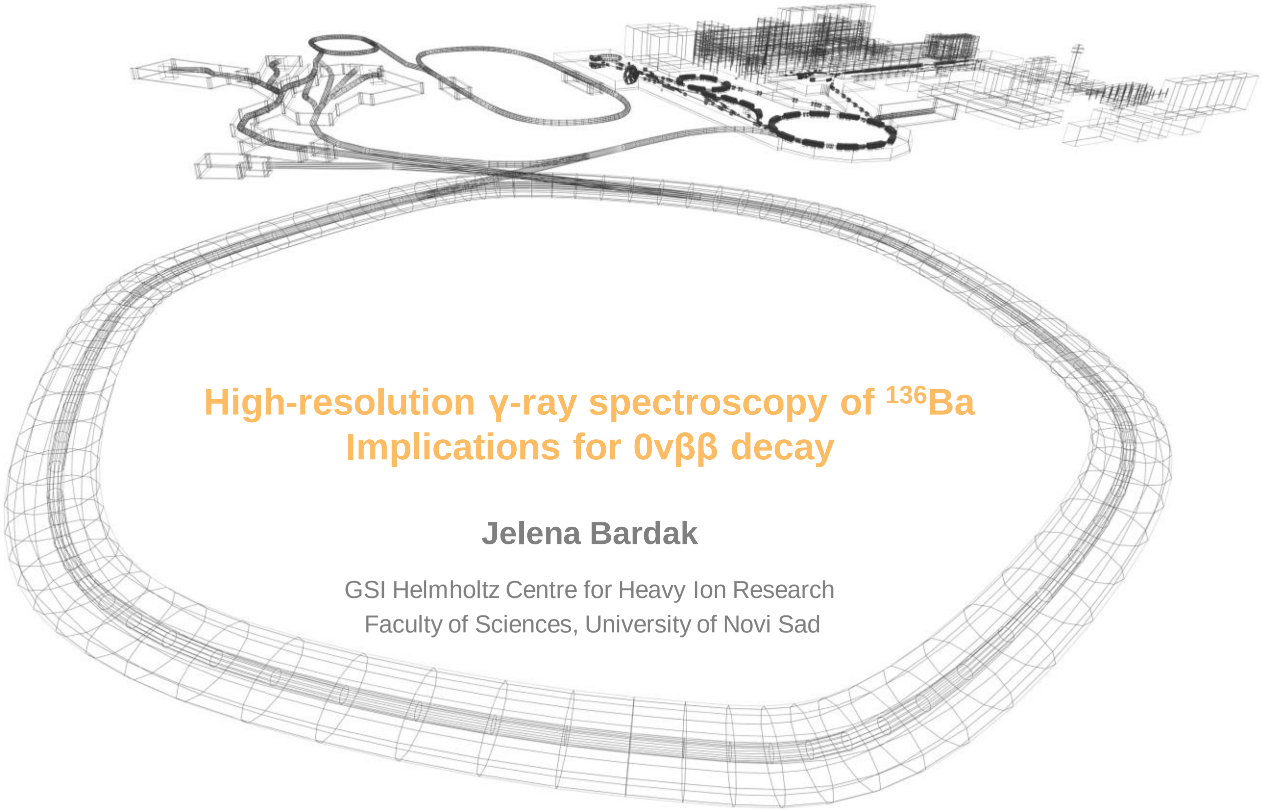


# High-resolution γ-ray spectroscopy of $^{136}$Ba Implications for $0\nu\beta\beta$ decay

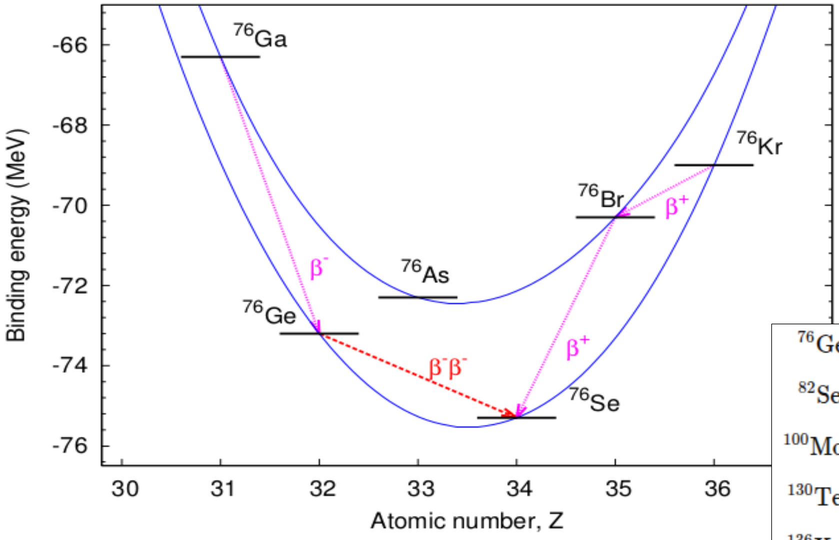
**Jelena Bardak**

GSI Helmholtz Centre for Heavy Ion Research
Faculty of Sciences, University of Novi Sad

- Scientific value & motivation for $^{136}$Ba investigation
- Experimental apparatus at ILL, Grenoble
- Low-spin spectroscopy of $^{136}$Ba
  - Level scheme
  - Angular correlation measurements
- Shell-model interpretation
- Summary & Outlook

# Scientific value and motivation

- Neutrino - Majorana or Dirac particle
- $0\nu\beta\beta$ decay – second-order weak-interaction process




$^{76}Ge \to ^{76}Se$

$^{82}Se \to ^{82}Kr$

$^{100}Mo \to ^{100}Ru$

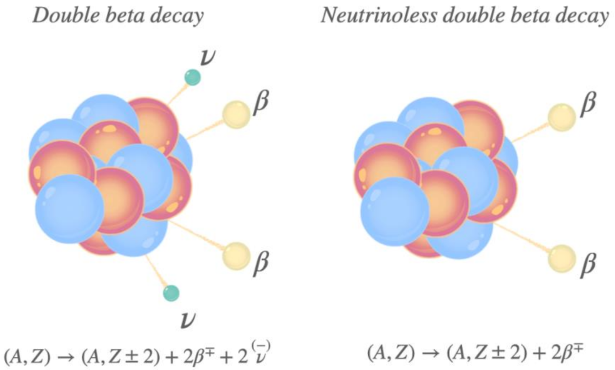
$^{130}Te \to ^{130}Xe$

$^{136}Xe \to ^{136}Ba$

*J. Menéndez, Nuclear Effects in Neutrinoless Double-Beta Decay, presented at Neutrino-Nucleus Interactions, CERN (2022)*

*© V. Palušová, JGU*

*source: https://nudoubt.uni-mainz.de/public.php*




Only observable in nuclei where:

- β-decay is forbidden energetically due to nuclear pairing interactions or
- where β decay is very suppressed by ΔJ angular momentum change

# Scientific value and motivation

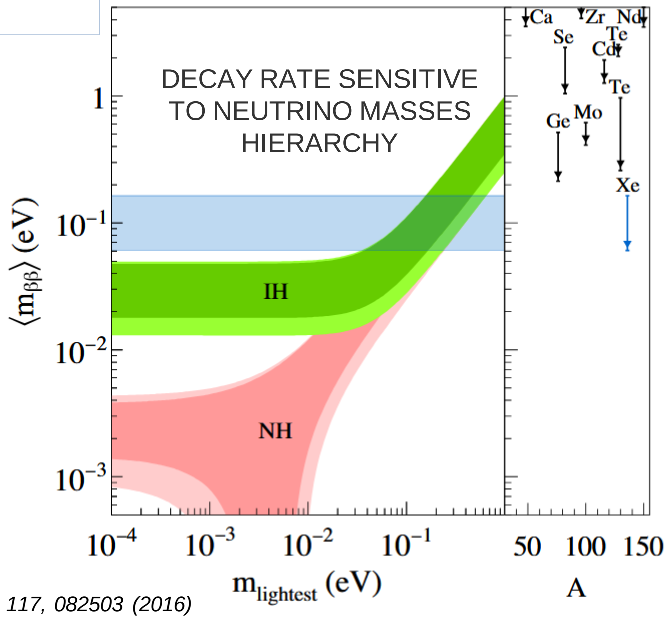
$$T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+)^{-1} = G_{0\nu}\, g_A^4 \boxed{|M^{0\nu}|^2} \left(\frac{|m_{\beta\beta}|}{m_e}\right)^2$$

EXTRACTING NEUTRINO MASS FROM LIFE-TIME MEASUREMENTS NEEDS ACCURATE CALCULATED NME

$^{76}$Ge(GERDA,Majorana)
$^{130}$Te(CUORE)
$^{136}$Xe(EXO,KamLand-Zen)

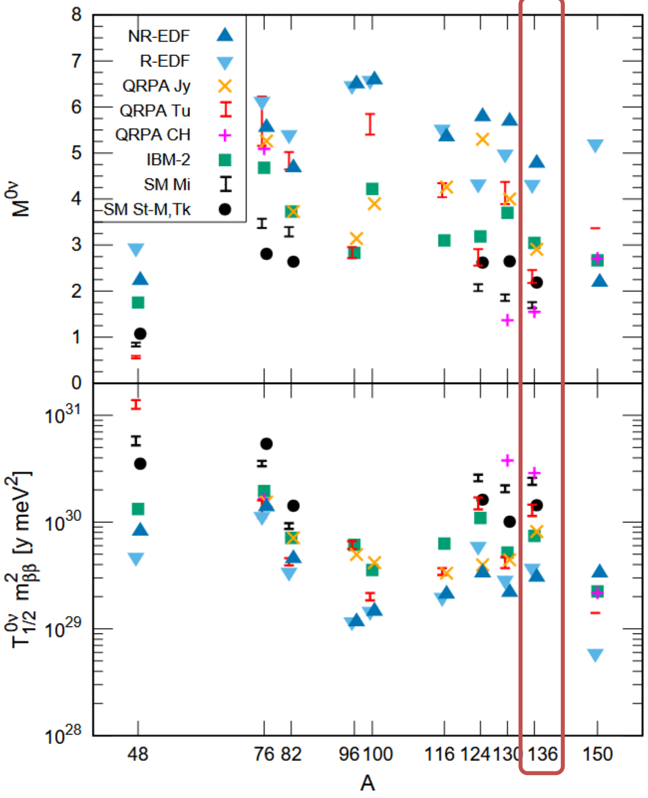
$$T_{1/2}^{0\nu\beta\beta} \geq 10^{26} y$$

DECAY RATE SENSITIVE TO NEUTRINO MASSES HIERARCHY




A. Gando, Y. Gando, H. Hachiya et al., Phys. Rev. Lett. 117, 082503 (2016)

J. Engel and J. Menéndez, Rep. Prog. Phys. 80, 046301 (2017)

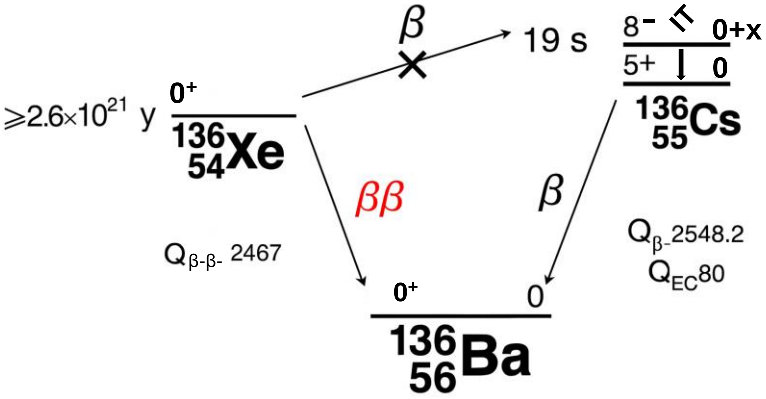


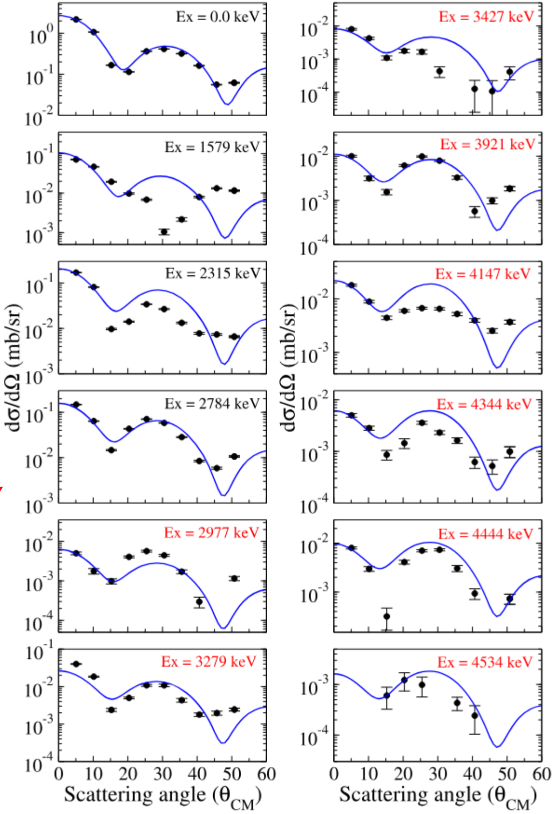
# Scientific value and motivation

**Goal:** the spectroscopy of low-spin states

focus on $0^+$ in $^{136}$Ba

as a final nucleus in $0\upsilon\beta\beta$ of $^{136}$Xe to provide additional constraints on NME




*A recent study of the $^{138}$Ba(p,t); observed new $0^+$ states*

*B. M. Rebeiro, S. Triambak et al., Phys. Lett. B 809, 135702 (2020)*

# Experimental apparatus @ILL

https://www.ill.eu/

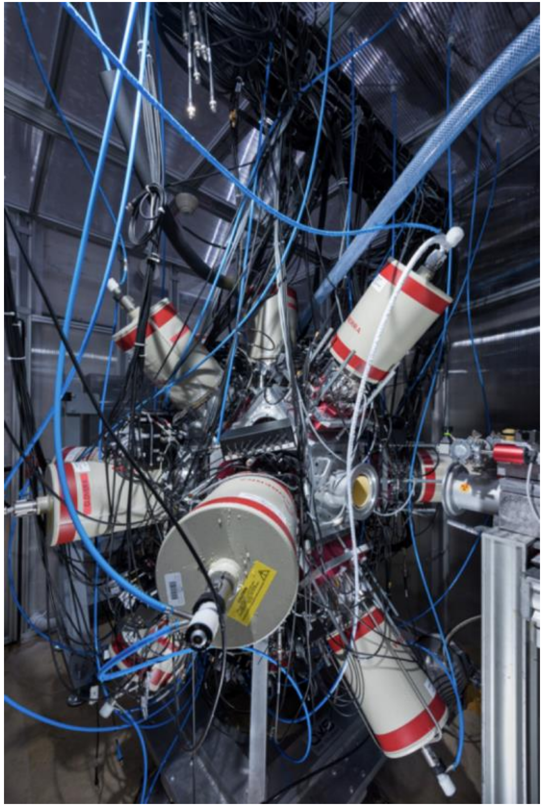
- Reaction studied

  $^{135}$Ba(n,gamma) $^{136}$Ba reaction

- Instrumentation

  FIPPS - a high-resolution HPGe detector array

- Measurement setup & target properties



*Courtesy of L. Thies*

# Reactions studied @ILL

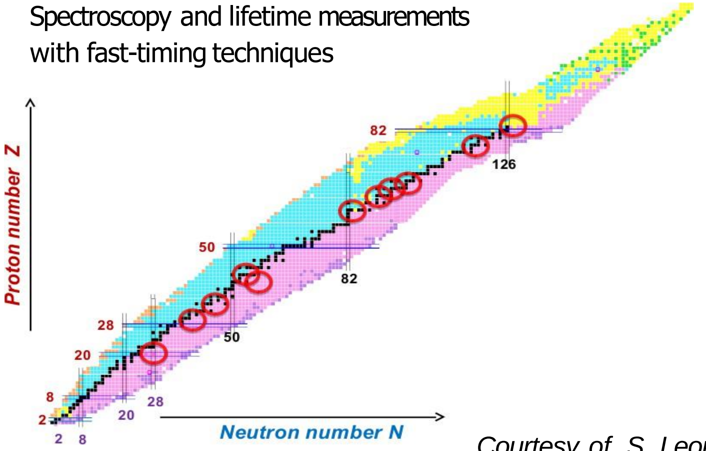
FIPPS
Continuation of the EXILL campaign

***gamma ray spectroscopy after slow neutron-induced reactions:***

***(n,γ) reactions on (rare) stable targets***

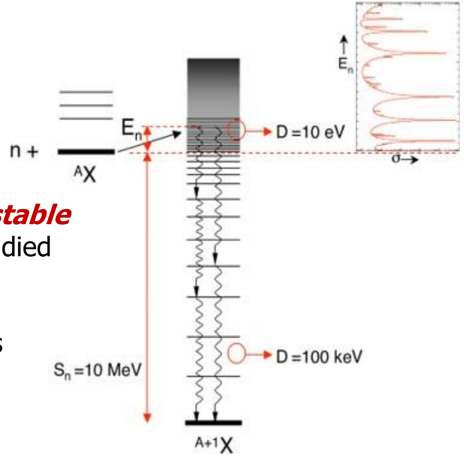
$^{46}$Ca, $^{48}$Ca, $^{68}$Zn, $^{70}$Zn, $^{77}$Se, $^{95}$Mo, $^{96}$Zr, $^{143}$Nd, $^{155}$Gd, $^{161}$Dy, $^{167}$Er, $^{194}$Pt, $^{195}$Pt, $^{209}$Bi

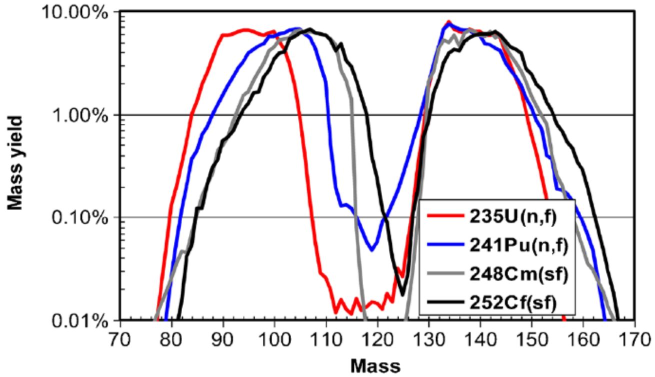
Spectroscopy and lifetime measurements
with fast-timing techniques




*Courtesy of S. Leoni*

***(n,gamma) reactions on stable targets*** close to stability; studied structure at low spin
(below n-separation energy)
cross-sections measurements

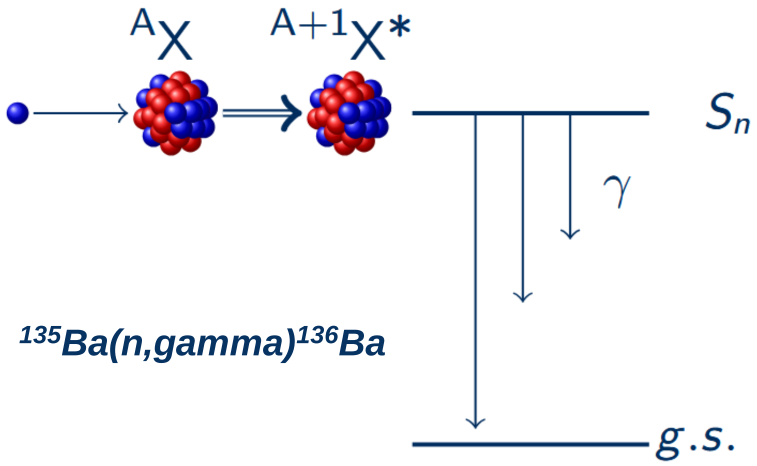



***(n,fission) reactions*** on actinides away from stability; studied fission yields and dynamics, and structure of exotic neutron rich nuclei

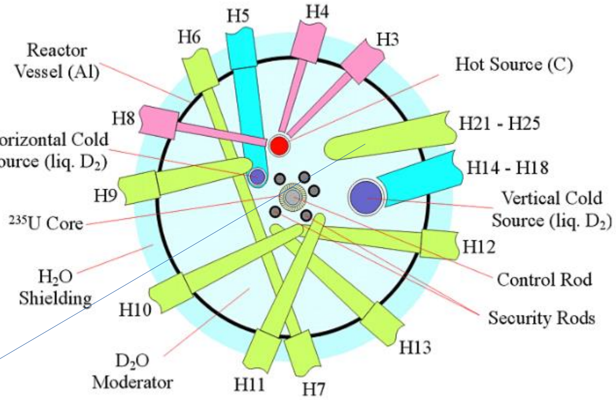
Targets
$^{235}UO_2$, $\sigma_f$ =586 b and
$^{241}PuO_2$, $\sigma_f$ =1010 b

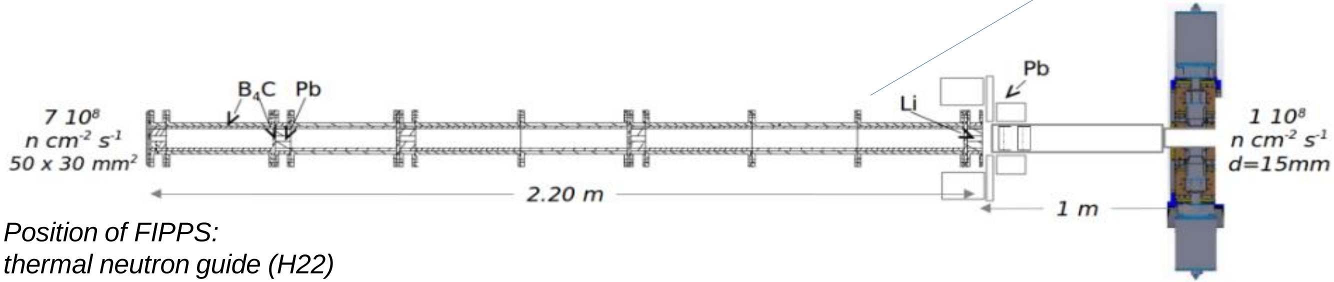
# (n,gamma) reactions @ILL

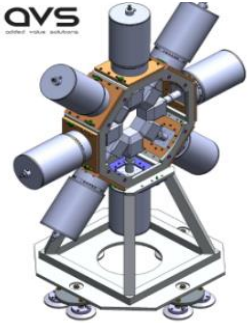


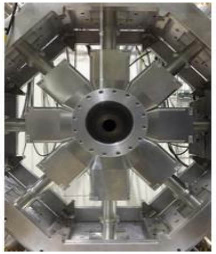

***$^{135}$Ba(n,gamma)$^{136}$Ba***

**ILL reactor core** with different beamlines: Red (fast neutrons), Green (thermal neutrons) and Blue (Slow neutrons)



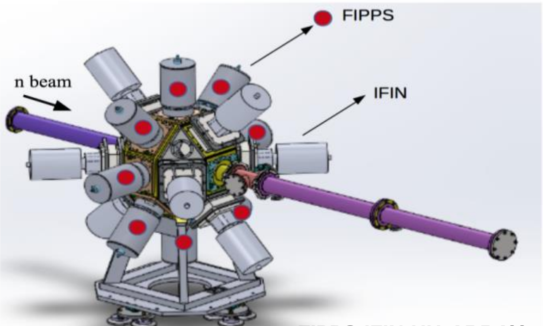



*Position of FIPPS:*
*thermal neutron guide (H22)*
*continuous neutron flux ~ $1\times10^8$ n/cm$^2$/s @ target position*

# Experimental setup & target

## FIPPS-IFIN-HH ARRAY

8 FIPPS clover detectors with ACs with 5 IFIN-HH (from collaboration) clover detectors



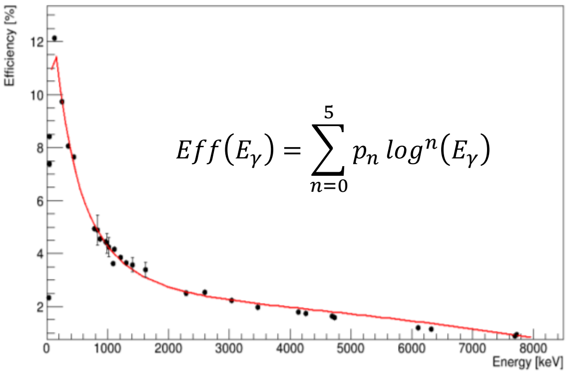

**FIPPS-IFIN-HH ARRAY**

*Courtesy of G.Colombi*

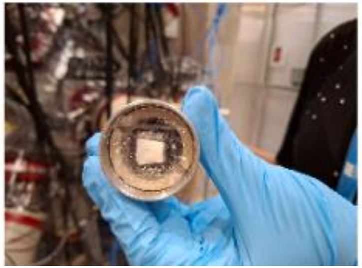
**Absolute eff. ~ 3.5 % @ 1.4 MeV**

Combined data from $^{152}$Eu and $^{27}$Al(n,gamma)

$^{27}$Al(n,gamma) reaction
$^{152}$Eu calibration source; 2.72 x $10^5$ Bq

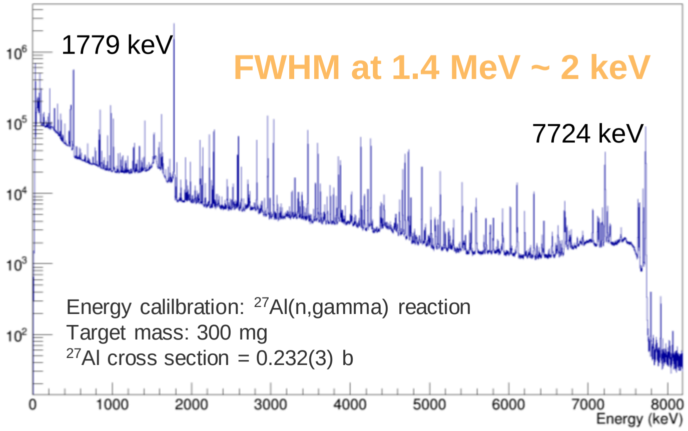



*Courtesy of Z. Chen*

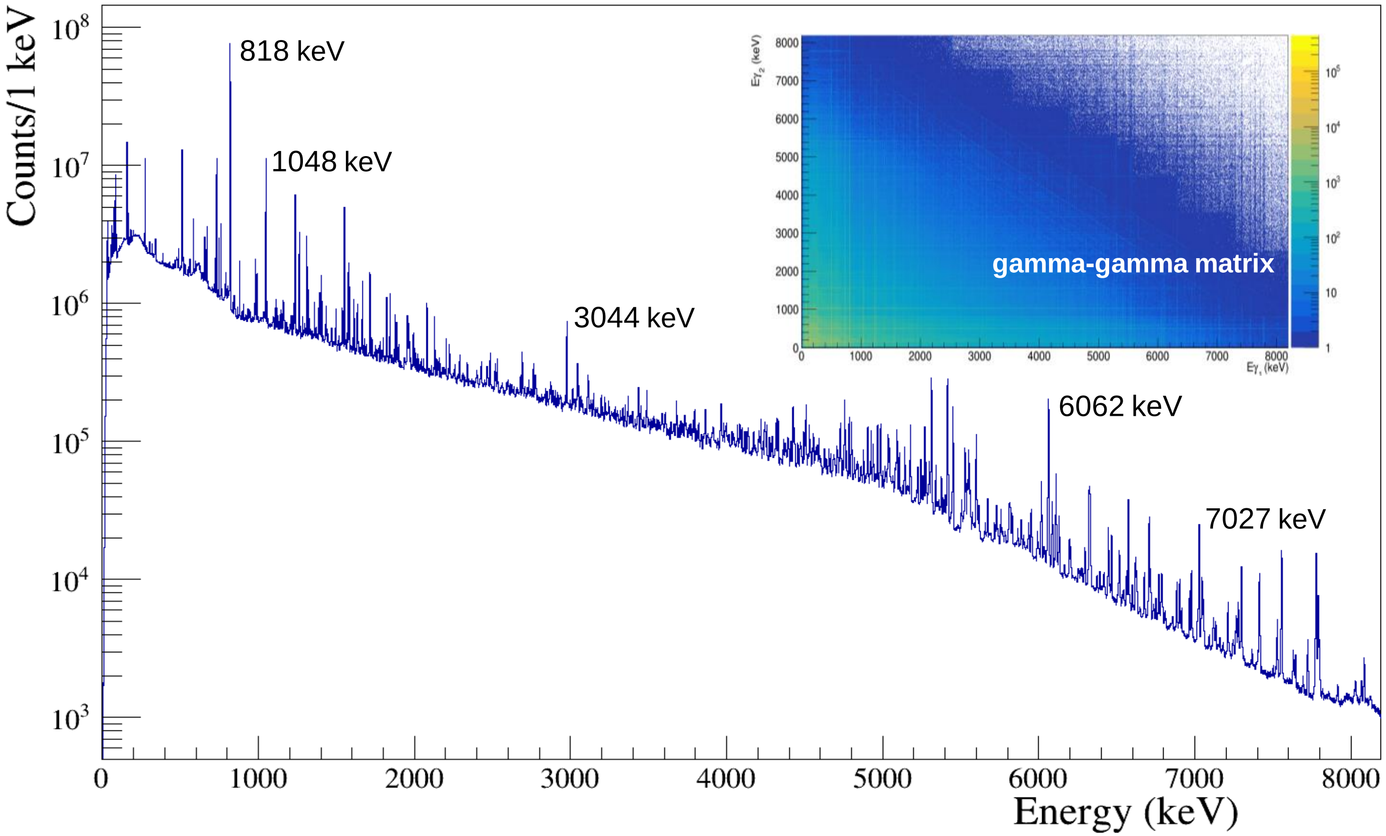


Target properties:

- enriched $^{135}$Ba(NO$_3$)$_2$ ≈ 67 mg
- $^{135}$Ba cross section = 5.8 b
- neutron capture rate ~ $10^5$ reactions/s



# $^{136}$Ba total projection spectra



# Spectroscopic analysis

## Level scheme, intensities and BRs

γ-ray cascades following n-capture on $^{135}$Ba

$$S_n(^{136}Ba) \approx 9.1 \text{ MeV}$$

γ-γ coincidences

- ✓ construction of the $^{136}$Ba level scheme
- ✓ transitions intensities and branching ratios

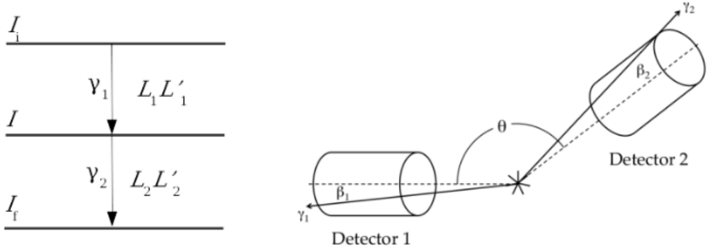
## Angular correlation analysis

γ-γ angular correlations

- ✓ spin assignments
- ✓ multipole mixing rations δ

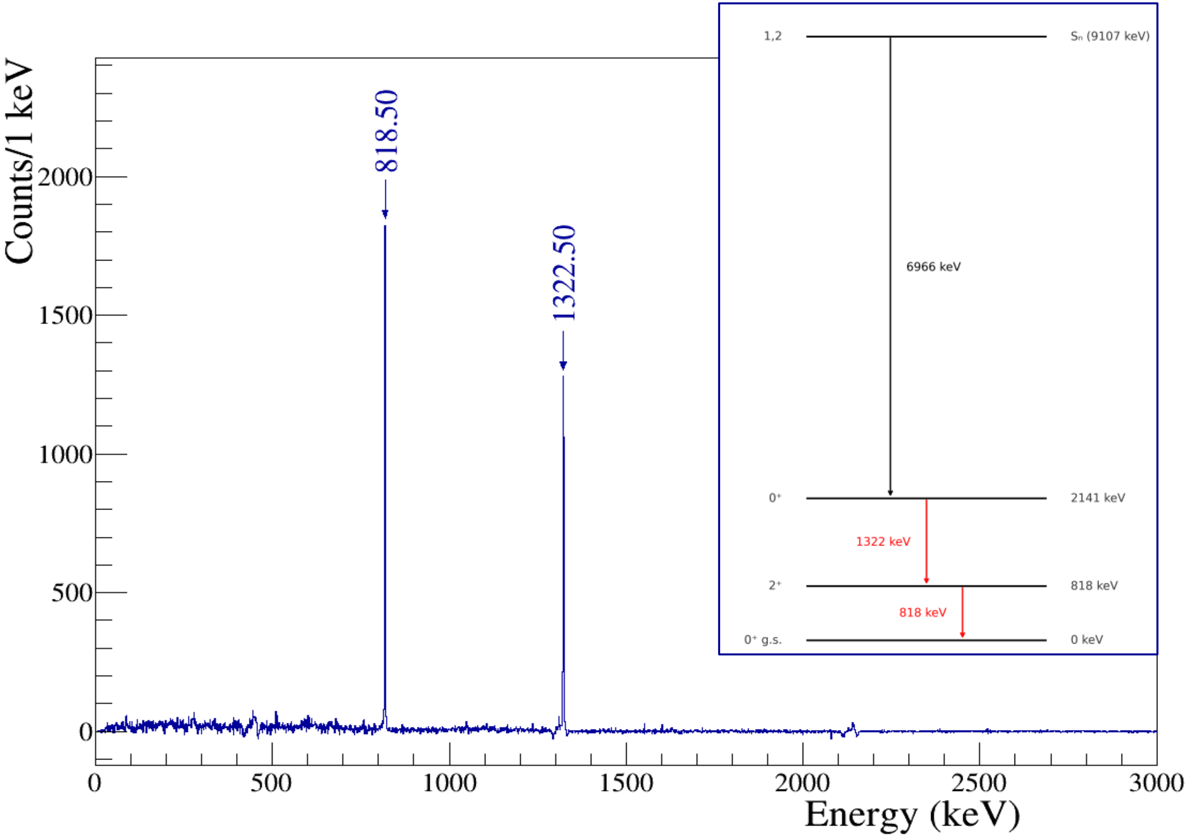
$$W(\theta) = A_0[1 + Q_2 a_2 P_2 cos(\theta) + Q_4 a_4 P_4 cos(\theta)]$$

finite-detector geometry accounted for by attenuation coefficients $Q_{\mathrm{k}}$ .

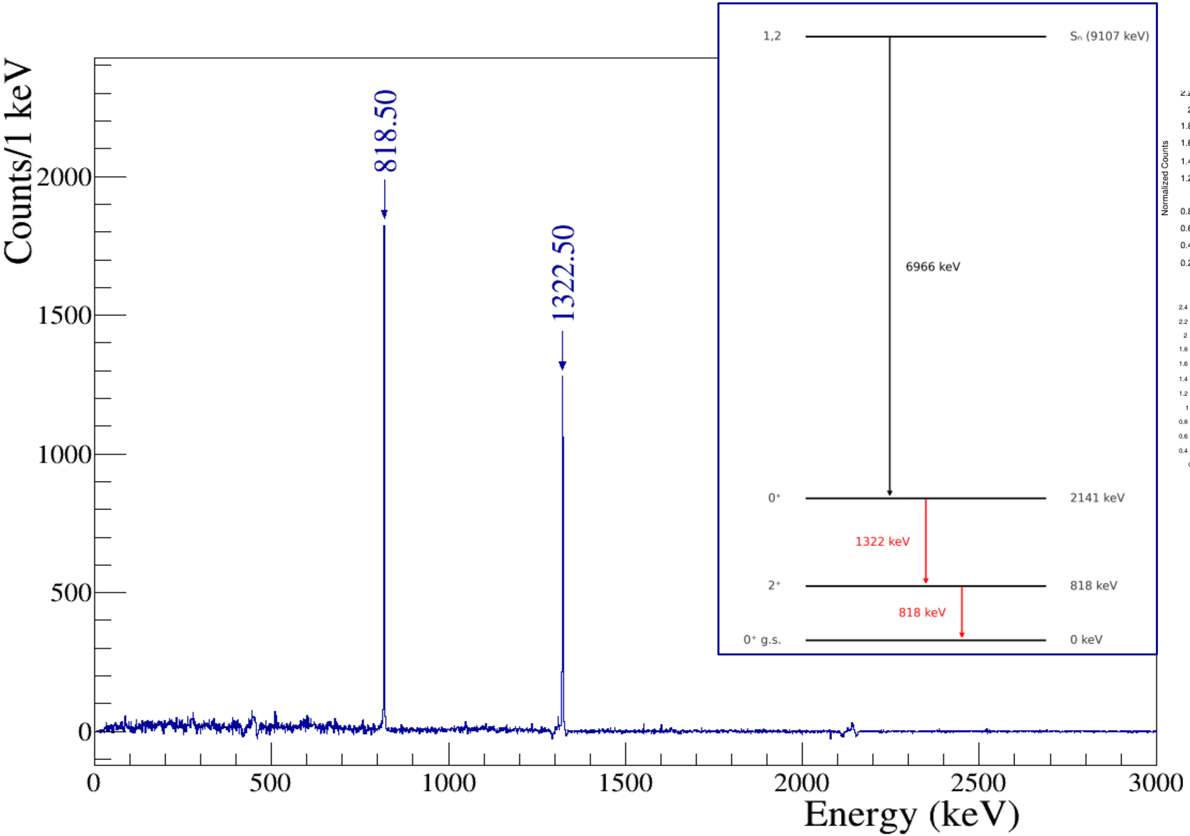



Schematic diagram of two γ rays in a cascade, emitted with relative angle θ

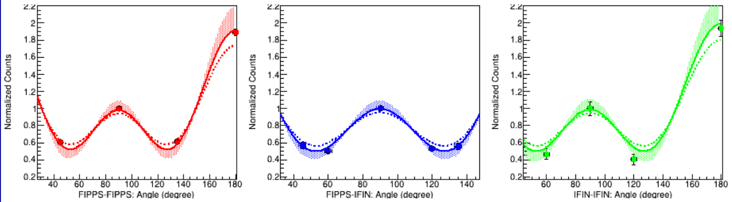
# $^{136}$Ba gate @ 6966 keV

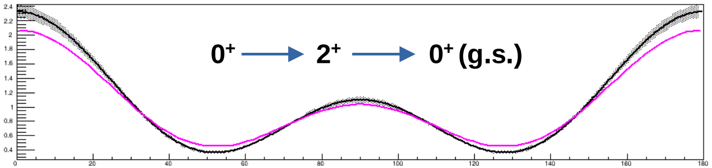


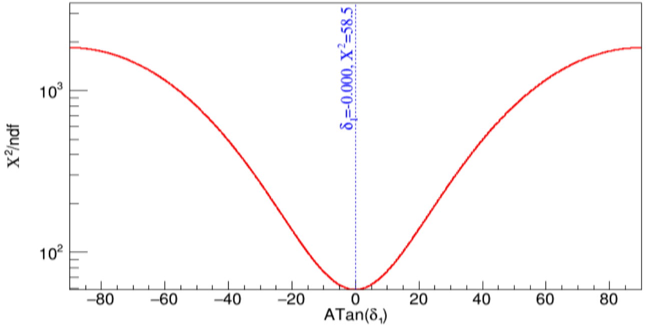
# $^{136}$Ba gate @ 6966 keV



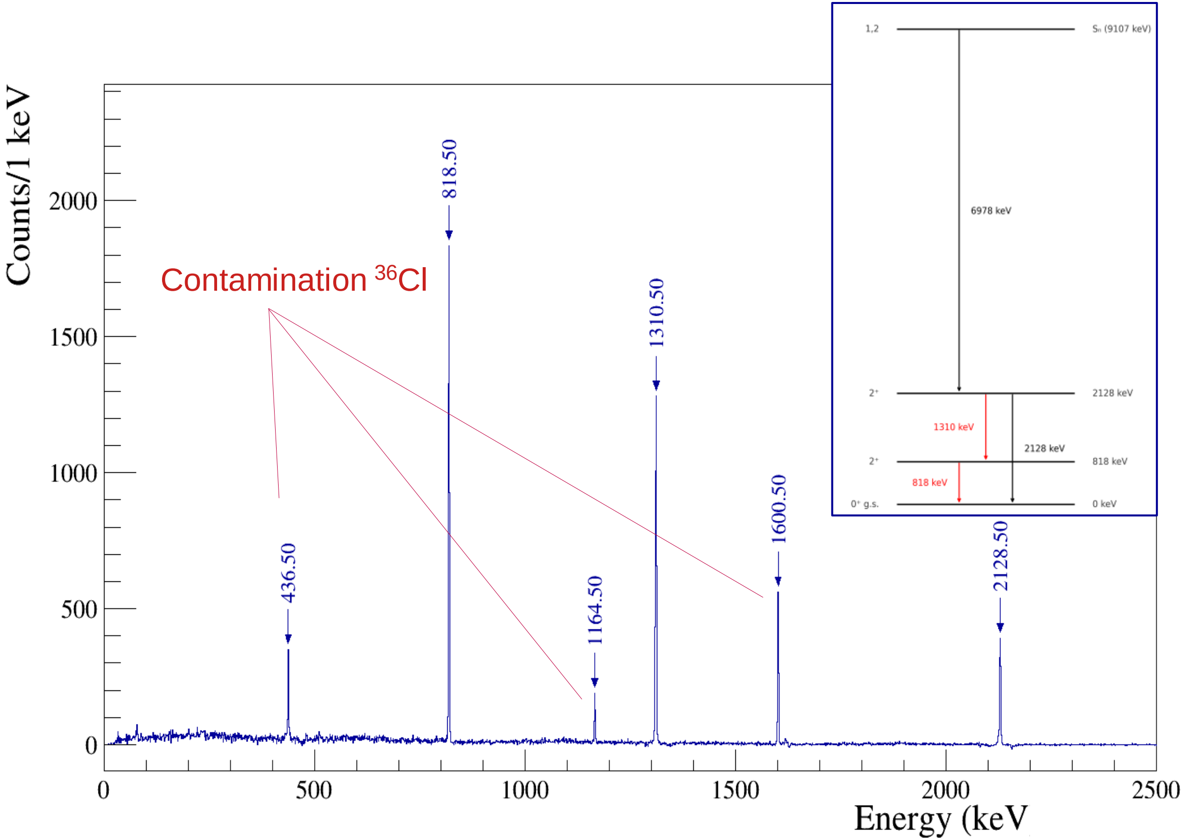

## Angular correlation: 1322 keV – 818 keV cascade



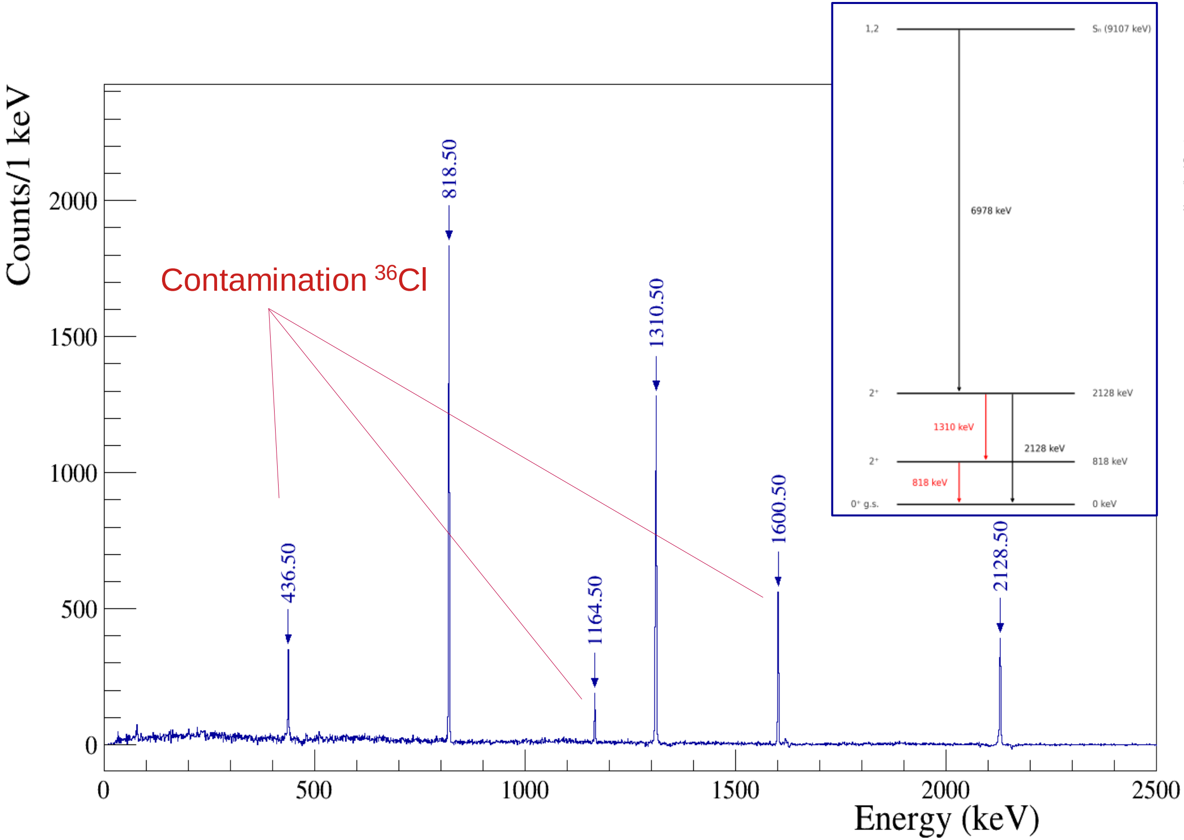



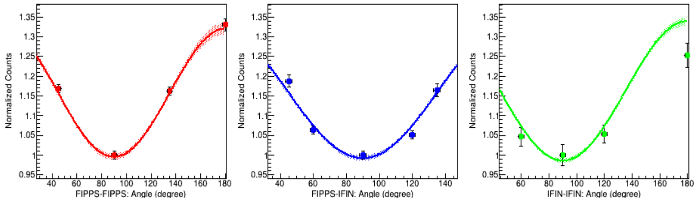
# $^{136}$Ba gate @ 6978 keV

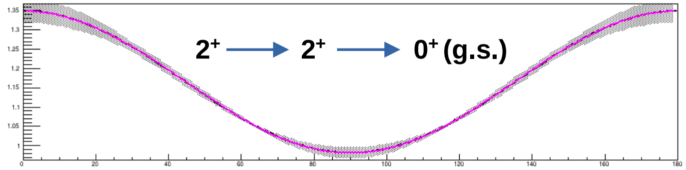


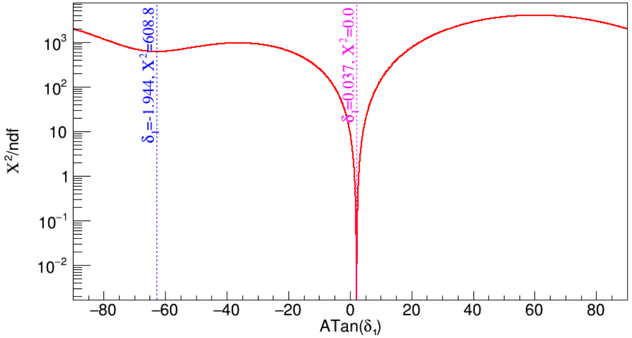
# $^{136}$Ba gate @ 6978 keV



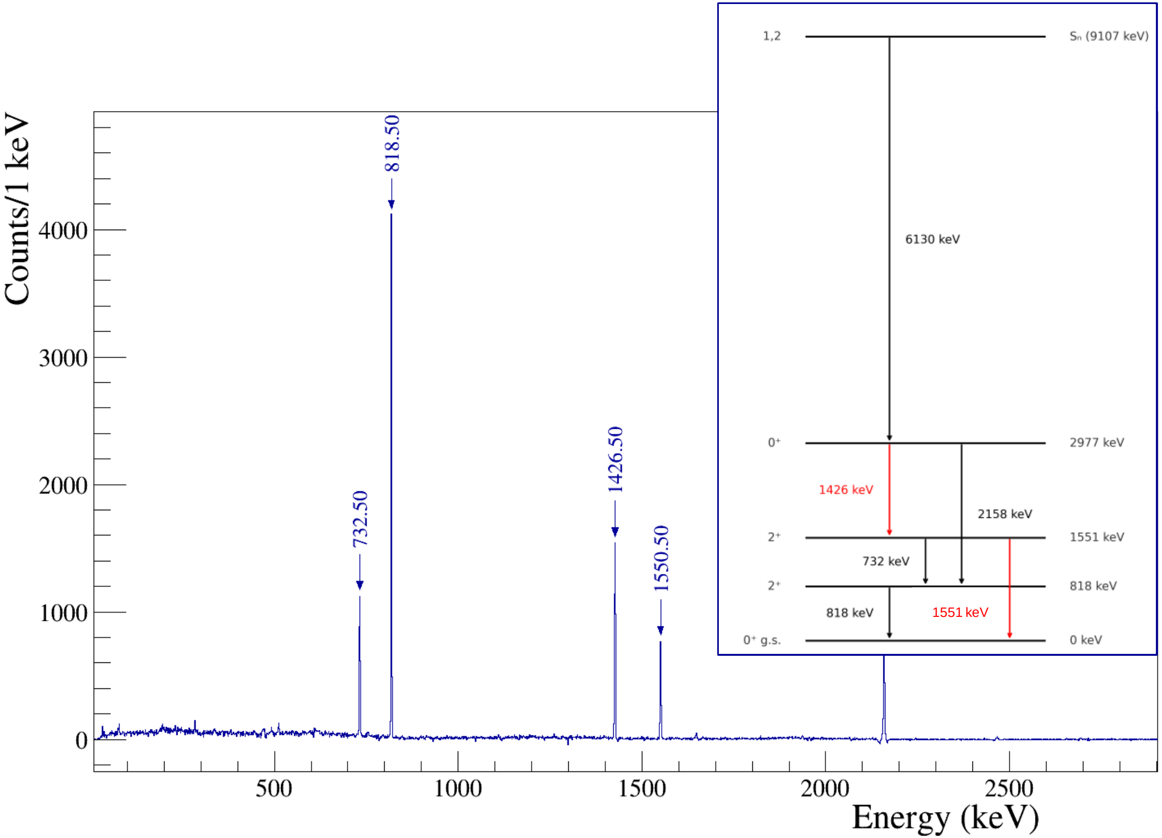

Angular correlation: 1310 keV – 818 keV cascade



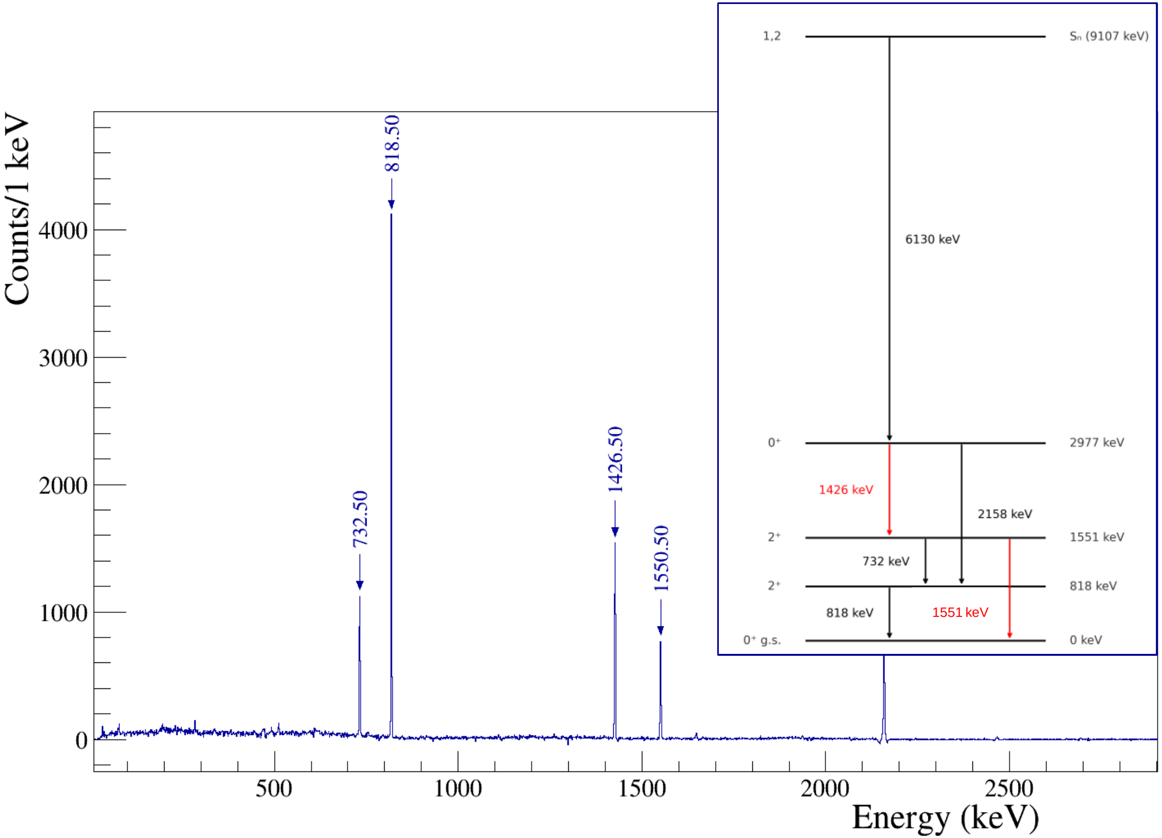



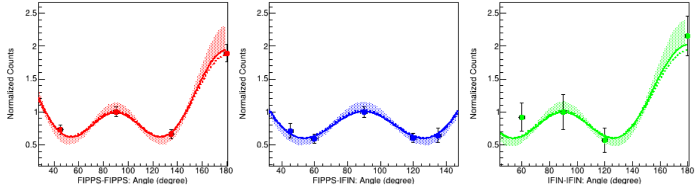
# $^{136}$Ba gate @ 6130 keV

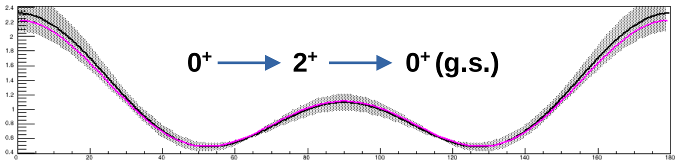


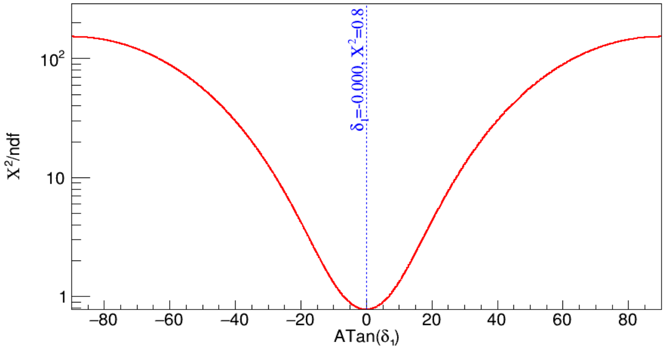
# $^{136}$Ba gate @ 6130 keV




## Angular correlation: 1426 keV – 1551 keV cascade



# Shell-model description of $^{136}$Ba

*Credits to Javier Menéndez and Dorian Grzegorz Frycz*

valence space: ***50 < Z,N < 82***

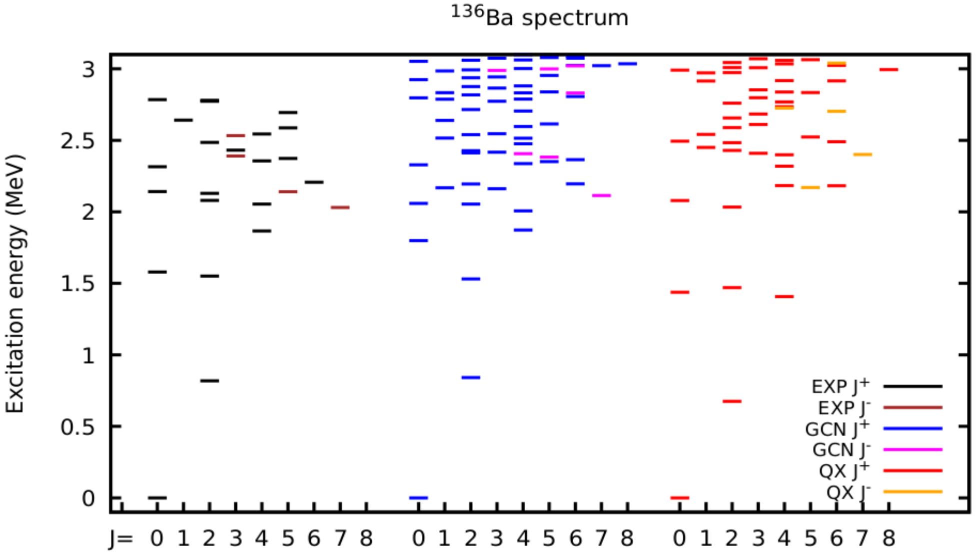
$\{0g_{7/2}, 1d_{5/2}, 1d_{3/2}, 2s_{1/2}, 0h_{11/2}\}$
for both neutrons and protons

$^{136}$Ba: 6 valence p + 2 n holes

GCN and QX interactions

$E_x$, $J^\pi$, wave functions

***B(E2), B(M1), μ***




Comparison of experimental states (only NNDC) and theory up to 3 MeV,
+/- parities are represented with different colors

# Excited $0^+$ states in $^{136}$Ba: exp. vs theory

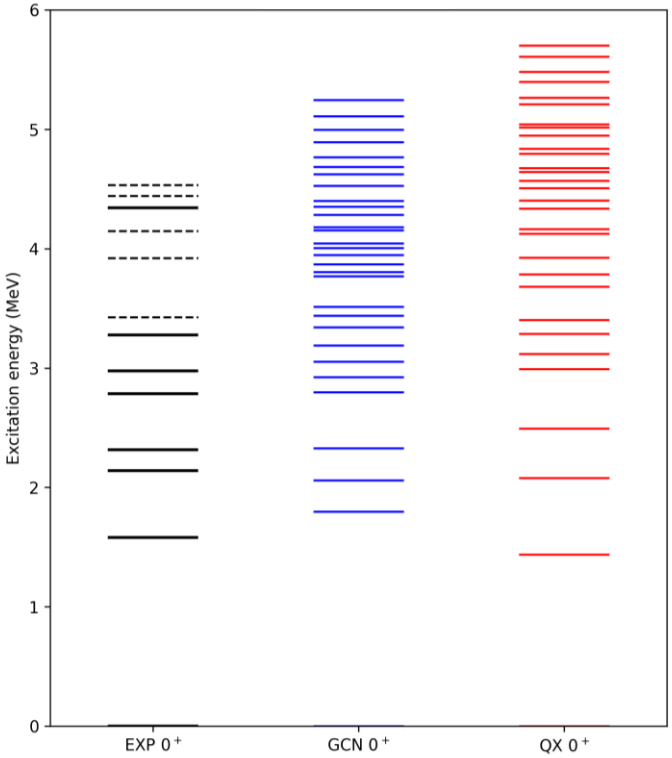
*Credits to Javier Menéndez and Dorian Grzegorz Frycz*

***Experiment:***
*extended experimental $0^+$ spectrum*
*solid black line – observed/confirmed in this work*
*dashed black line – previously reported, not confirmed in the present analysis*

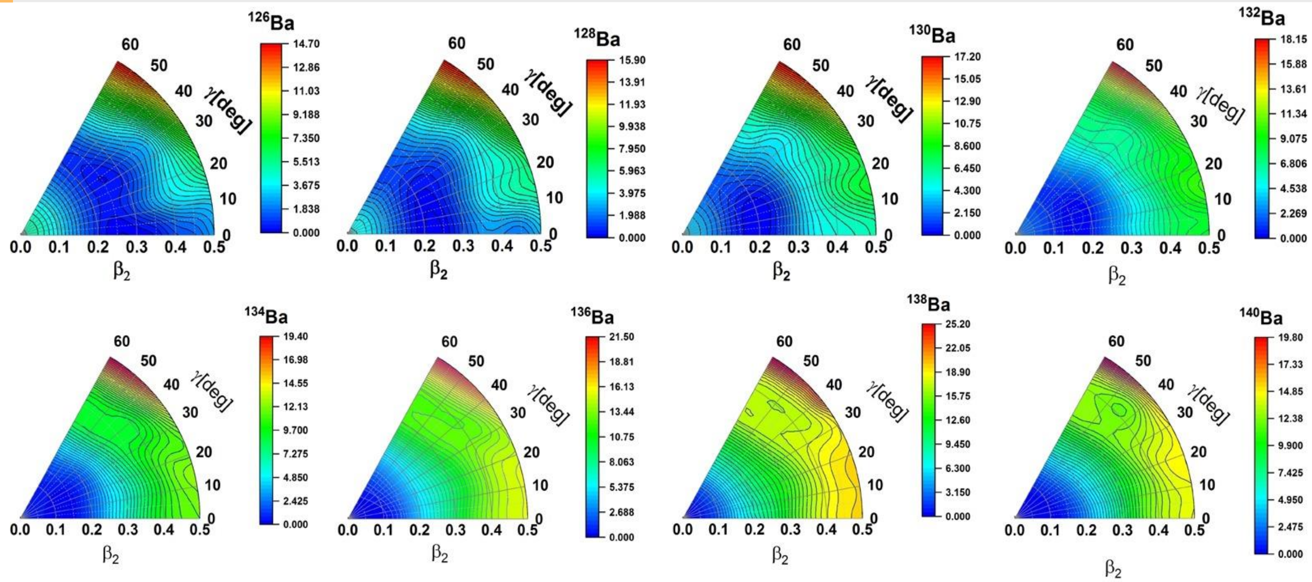
***Shell model calculations:***
*both GCN and QX predict a considerably higher density of $0^+$ states*

*What is the structural origin of the excited $0^+$ states?*

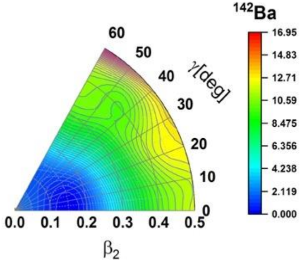
- *possible role of shape coexistence and configuration mixing ?*



# Structural evolution of Ba isotopes




*Naz et al., Nucl. Phys. A 979, 1-20 (2018)*

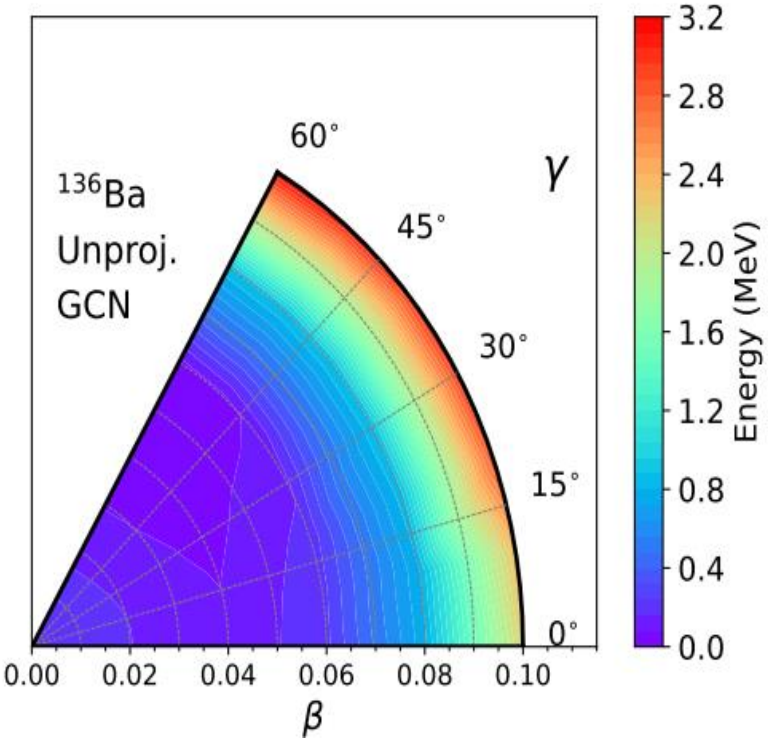


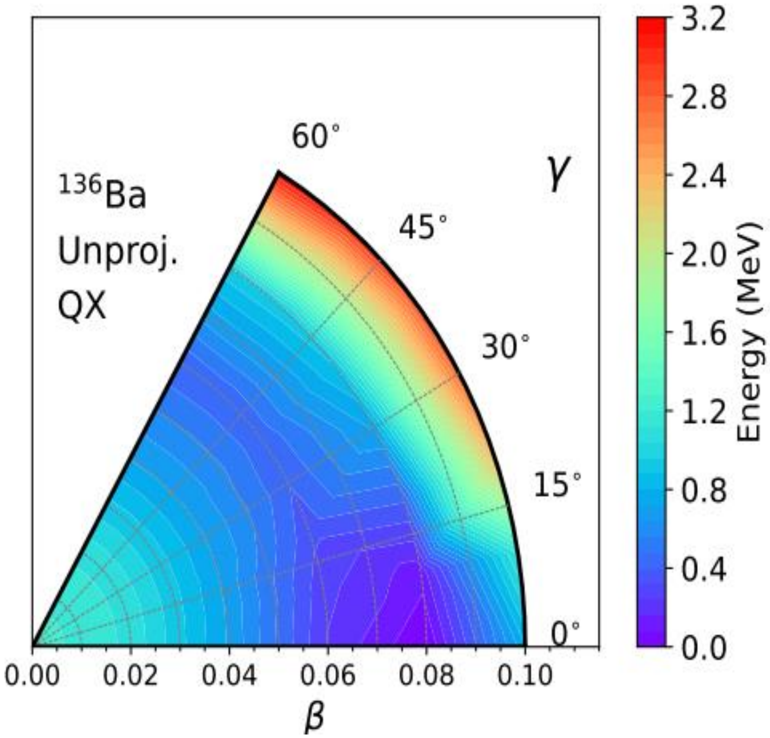

Mean field PES for the nuclei $^{126\text{-}138}$Ba in the (β,γ) plane, obtained from a triaxial RHB calculations with DD-ME2 parameter set. The color scale shown at the right has the unit of MeV, and scaled such that the ground state has a zero energy.

The shape transition from γ-unstable (prolate) $^{126}$Ba to spherical $^{138}$Ba.

# Mean-field calculations (GCN and QX) of $^{136}$Ba

Credits to Javier Menéndez and Dorian Grzegorz Frycz

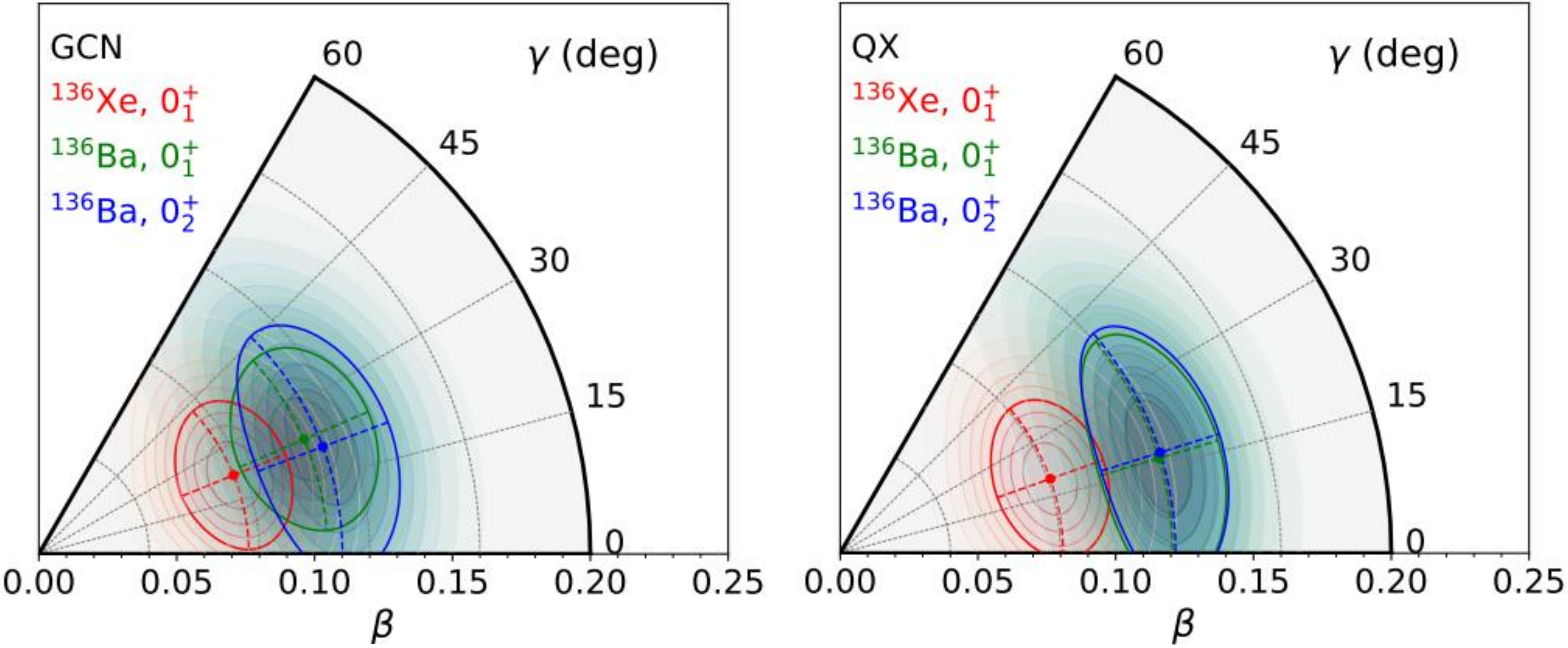



$^{136}$Ba is predicted to be nearly spherical, with $\beta<0.1$, the GCN gives more spherical minimum, while QX predicts slightly larger deformation. No indication of a shape-coexisting minimum is observed in the calculated energy surfaces.

# Full shell-model shape invariants of $^{136}$Ba

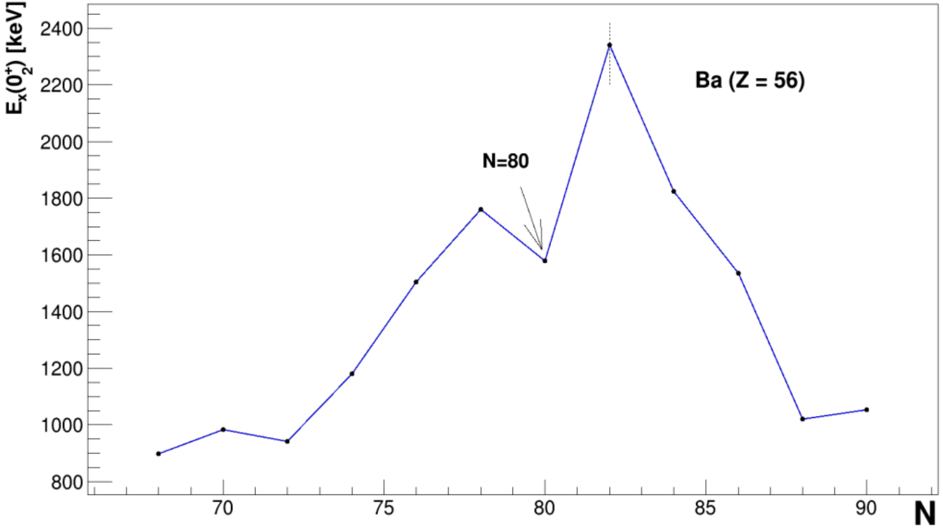
Credits to Javier Menéndez and Dorian Grzegorz Frycz




Full shell-model shape invariants indicate larger β values, nevertheless, the $0_1^+$ and $0_2^+$ excited states populate strongly overlapping regions of the deformation plane. No clear separation into two distinct intrinsic shapes.

# $^{136}$Ba: an intriguing $0_2^+$ state evolution

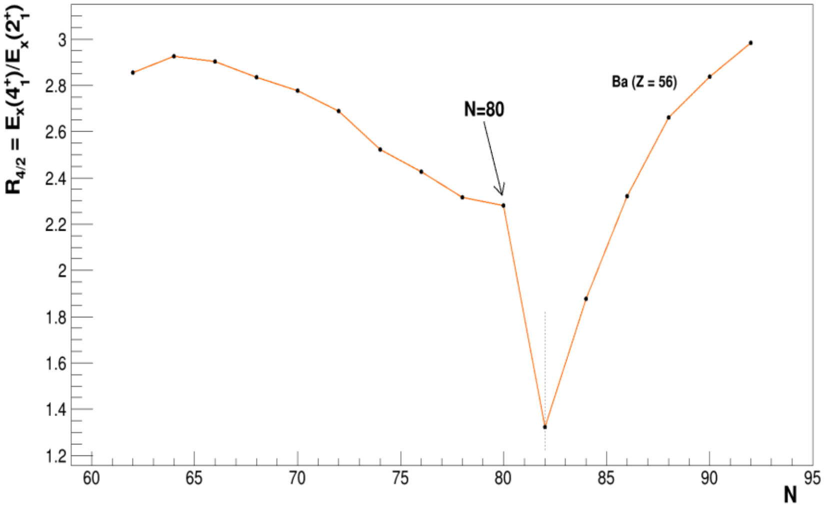
**Energy of second 0$^+$ state vs neutron number**



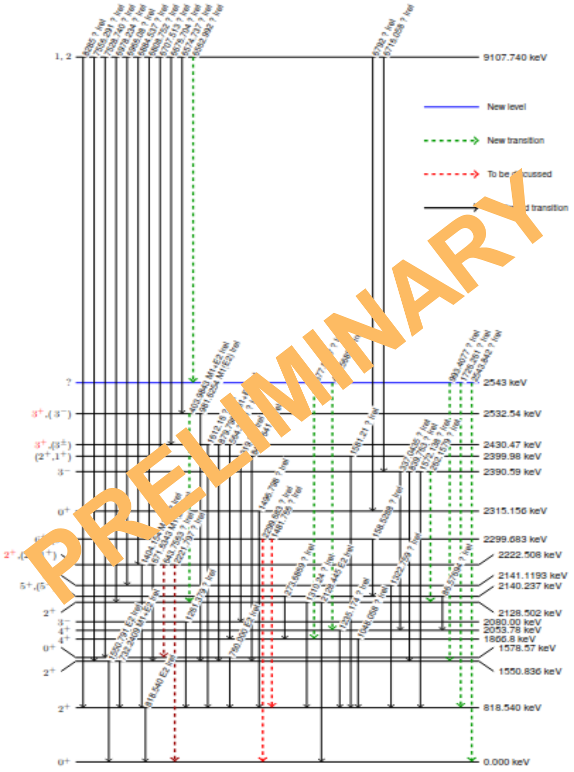

Experimental systematics show a pronounced kink in $0_2^+$ energy at $\mathrm{N} = 80$.

The ratio $R_{4/2}$ is consistent with a nearly spherical structure.

**R$_{4^+/2^+}$ vs neutron number**



# Summary and Outlook




Partial level scheme of $^{136}$Ba, here gates applied on transitions between 6 MeV in excitation energy and Sn

## *Summary*

- detailed low-spin spectroscopy and better understanding of the final nucleus of the $^{136}$Xe 0νββ decay via $^{135}$Ba(n, γ) reaction
- in total 140 levels extracted; 77 observed for the first time
- $J$ assignments and mixing ratios from angular correlations
- new constrains on excited $0^+$
- exp. vs theory: theory predicts a much denser $0^+$ spectrum

# Summary and Outlook

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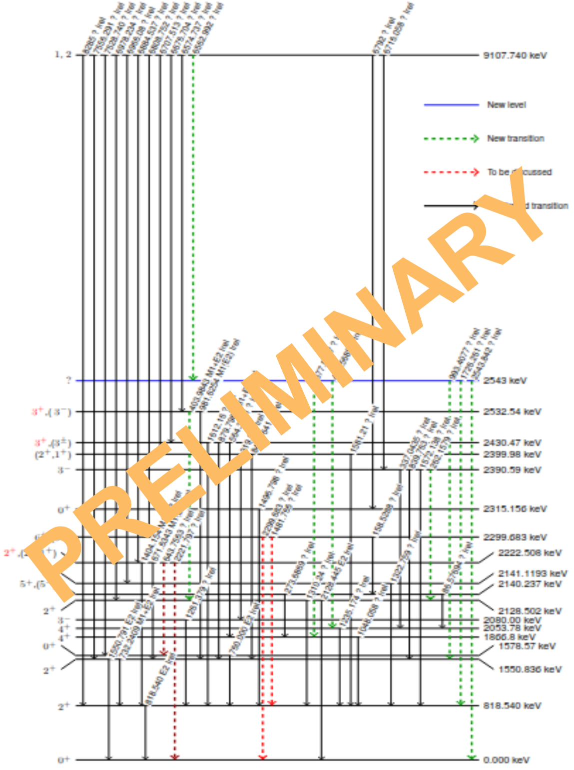
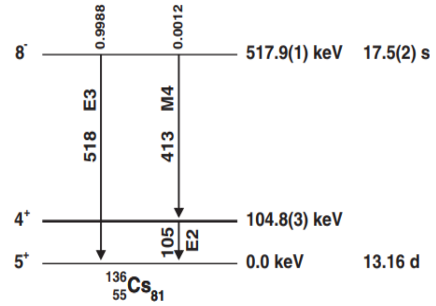



Partial level scheme of $^{136}$Ba, here gates applied on transitions between 6 MeV in excitation energy and Sn

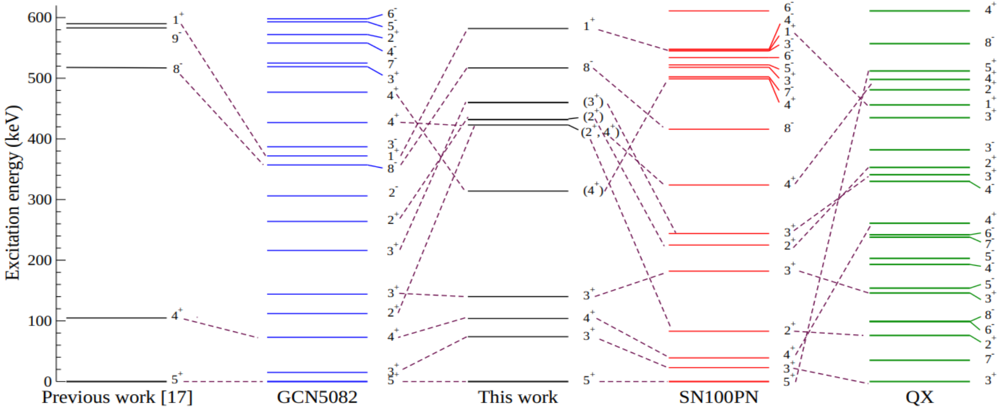



*K. Wimmer et al., Phys. Rev. C 84, 014329 (2011)*

## *Outlook*

- spectroscopy of $^{136}$Cs via $^{135}$Cs(n, γ) reaction

***complementary information from the recent $^{138}$Ba(d,α) study; states in $^{136}$Cs up to ~2.5 MeV***




*B. M. Rebeiro et al., Phys. Rev. Lett. 131, 052501 (2023)*

# THANK YOU FOR YOUR ATTENTION!

**Jelena Bardak**, Kathrin Wimmer, Nikola Jovancevic, Javier Menéndez, Dorian Grzegorz Frycz, Giacomo Colombi, Lorenco Domenichetti, Caterina Michelagnoli, Corinna Henrich, Ilja Homm, Ulli Koester, Thorsten Kroell, Erin Peters, Matthias Rudigier, Marcus Scheck, Chen Zhiqiang, S. W. Yates