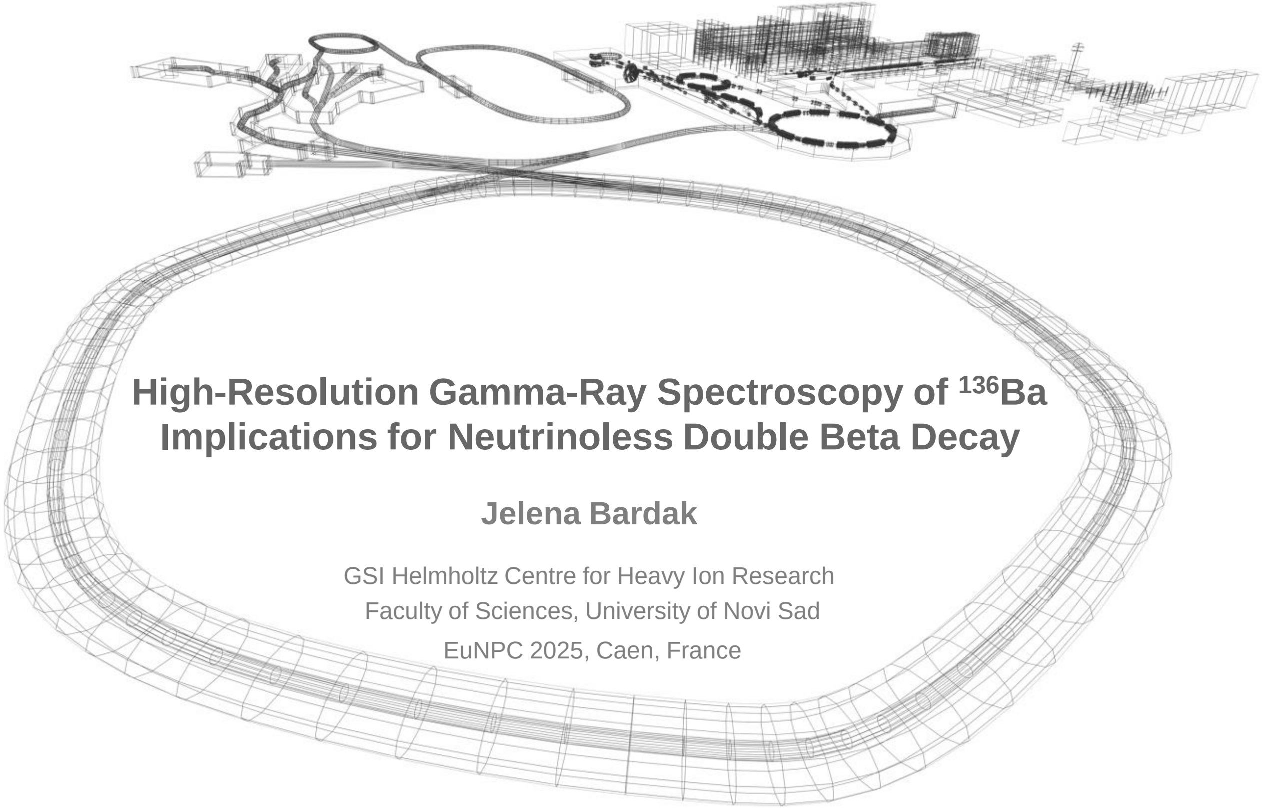


High-Resolution Gamma-Ray Spectroscopy of ^{136}Ba Implications for Neutrinoless Double Beta Decay

Jelena Bardak

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

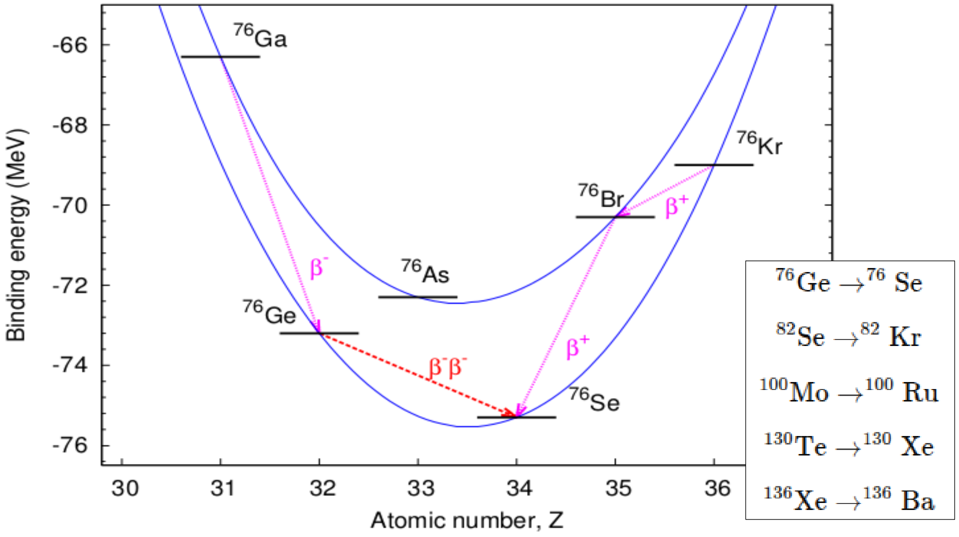
EuNPC 2025, Caen, France

Outline

- Scientific value & motivation for ^{136}Ba investigation
- Experimental setup @ILL,Grenoble
- Ongoing analysis
    - Level scheme
    - Angular correlation measurements
    - Signature of the shape coexistance in A=136
- Summary & Outlook

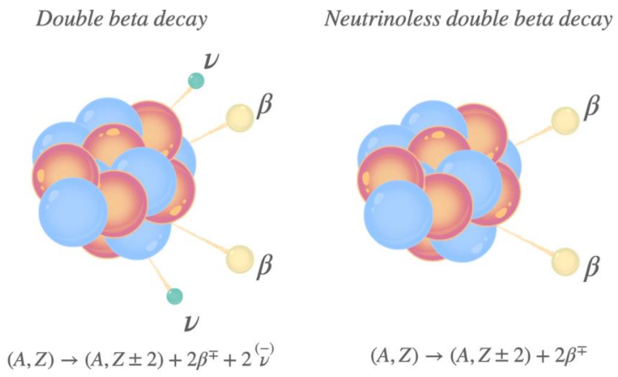
Scientific value and motivation

- Neutrino - Majorana or Dirac particle
- 0uββ decay – second-order weak-interaction process



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

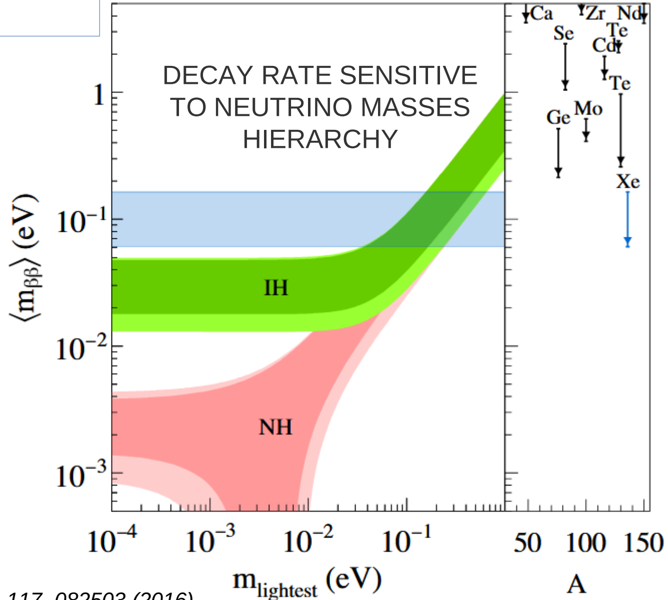
$$T_{1/2}^{0\nu\beta\beta}\left(0^+ \rightarrow 0^+\right)^{-1} = G_{0\nu}\, g_A^4 \boxed{\left|M^{0\nu\beta\beta}\right|^2} \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

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

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

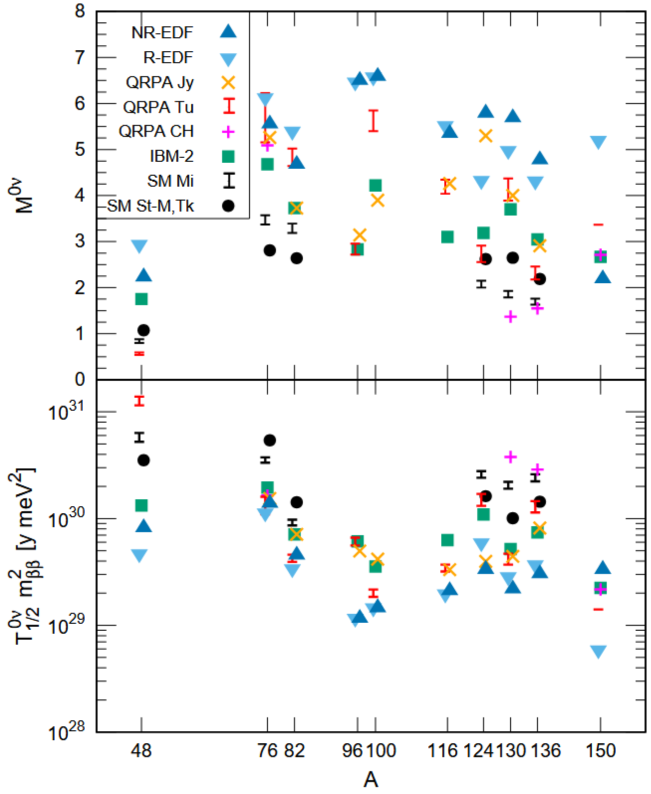
$$T_{1/2}^{0\nu\beta\beta} \geq 10^{26} y$$

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)

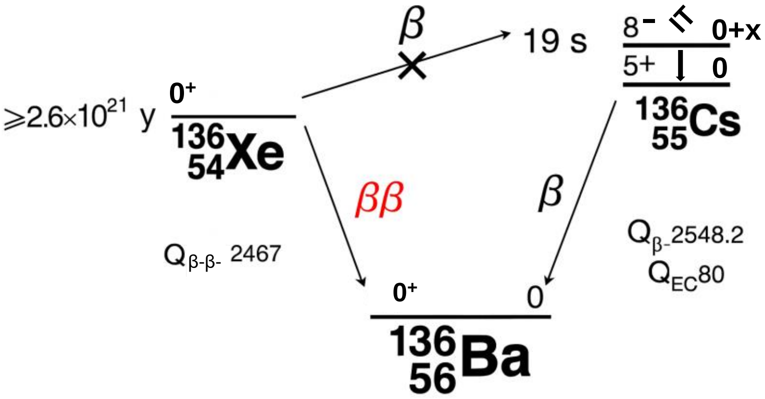


Scientific value and motivation

Goal: the spectroscopy of low-spin states

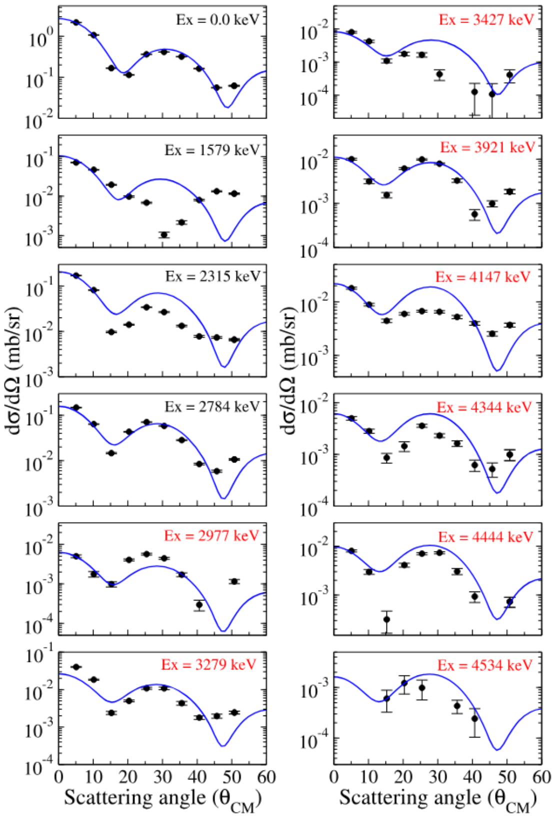
focus on 0^+ in ^{136}Ba

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

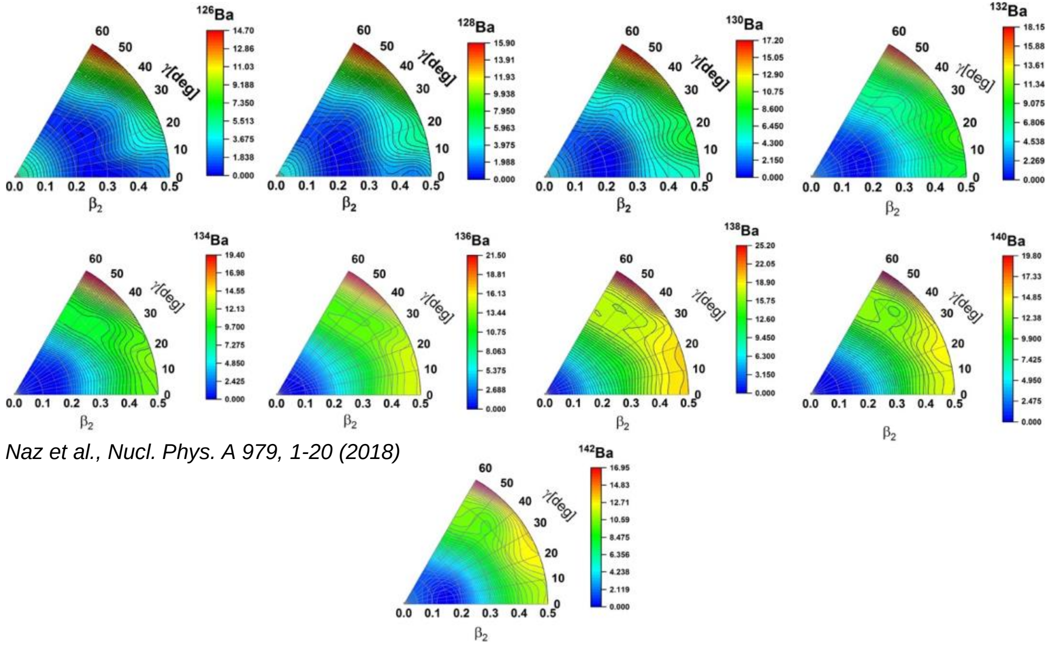


A recent study of the ^{138}Ba(p,t); observed new 0^+ states

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

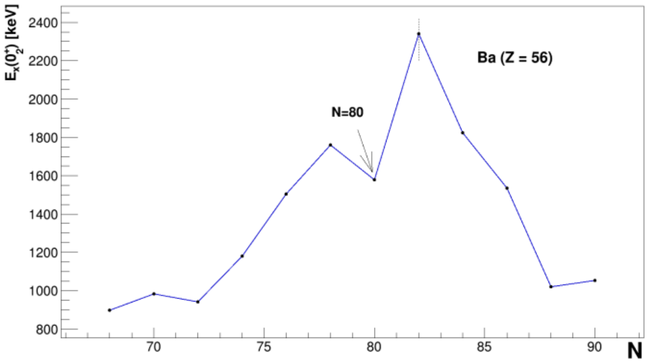


Signs of a SC near N=80 in Ba (Z=56)

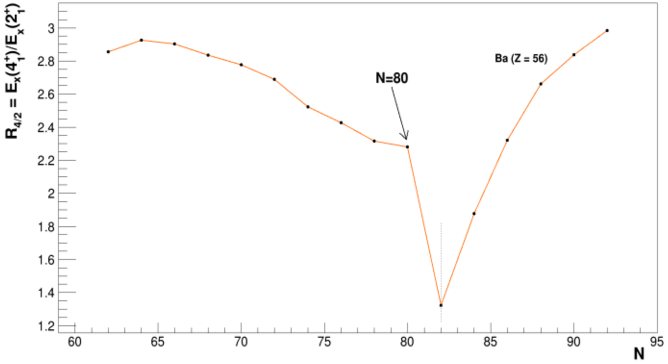


Naz et al., Nucl. Phys. A 979, 1-20 (2018)

Energy of second 0^+ state vs neutron number



$R_{4^+/2^+}$ vs neutron number



PES for ^{136}Ba shows a deep spherical minimum at $\beta_2 \approx 0$

A shallow depression appears around $\beta_2 \approx 0.2$, $\gamma \approx 20–30°$

Experimental apparatus @ILL

https://www.ill.eu/

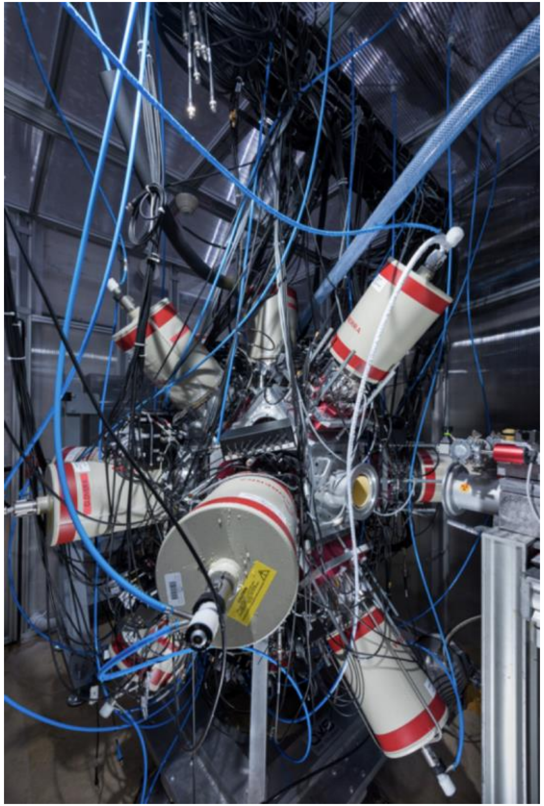
- Reaction studied

  ^{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

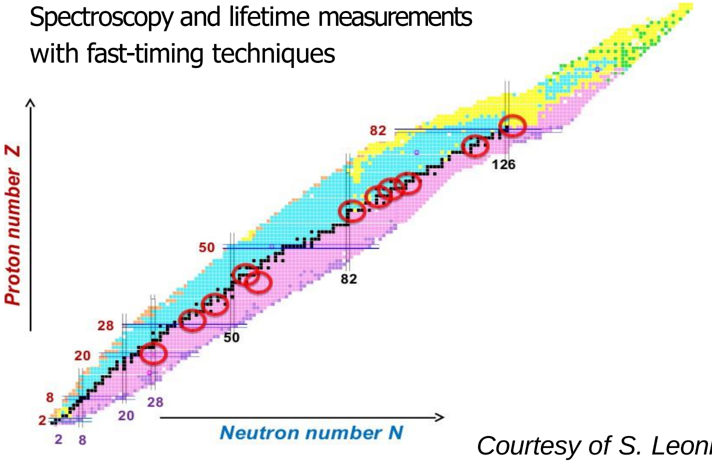
Continuation of the EXILL campaign

gamma ray spectroscopy after slow neutron-induced reactions:

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

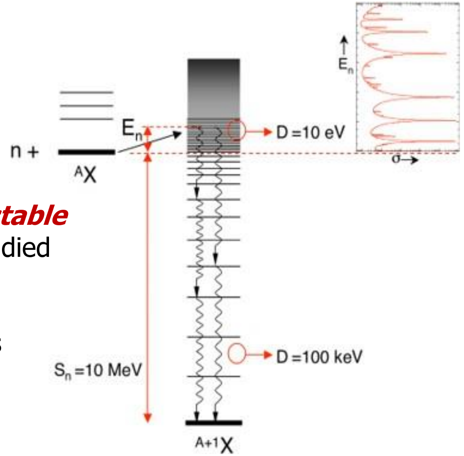
^{46}Ca, ^{48}Ca, ^{68}Zn, ^{70}Zn, ^{77}Se, ^{95}Mo, ^{96}Zr, ^{143}Nd, ^{155}Gd, ^{161}Dy, ^{167}Er, ^{194}Pt, ^{195}Pt, ^{209}Bi

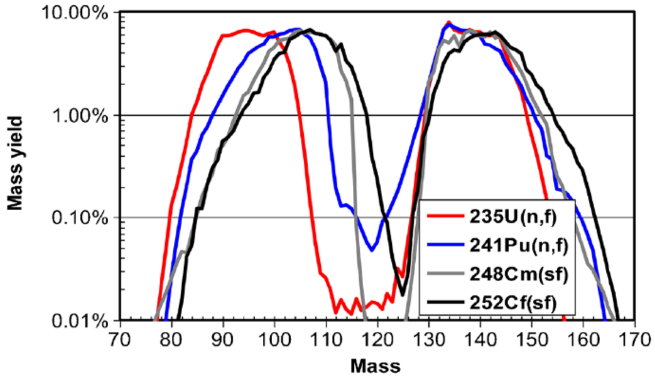
Spectroscopy and lifetime measurements with fast-timing techniques



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





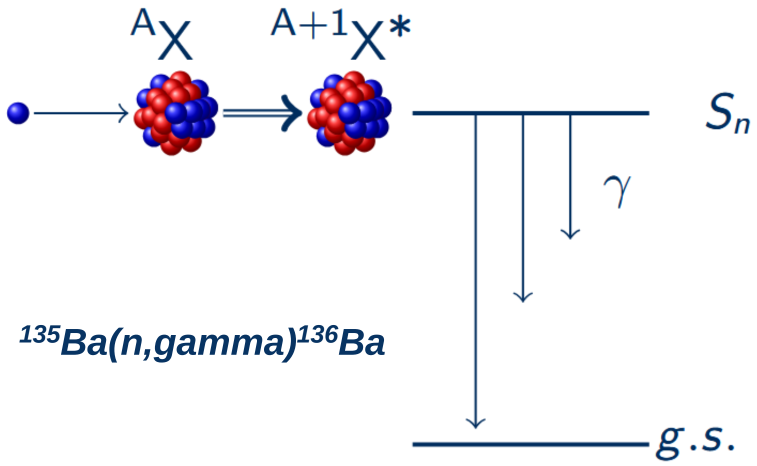
(n,fission) reactions on actinides away from stability; studied fission yields and dynamics, and structure of exotic neutron rich nuclei

Targets

$^{235}UO_2$, σ_f =586 b and

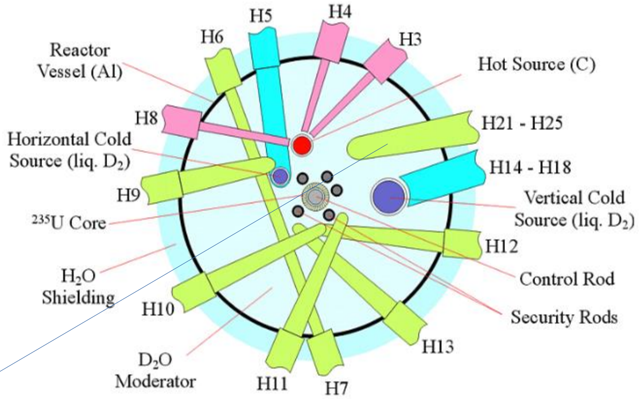
$^{241}PuO_2$, σ_f =1010 b

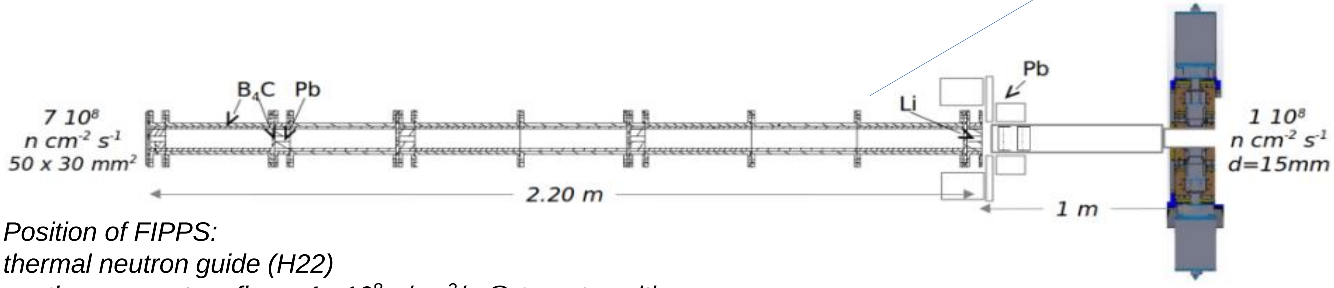
(n,gamma) reactions @ILL

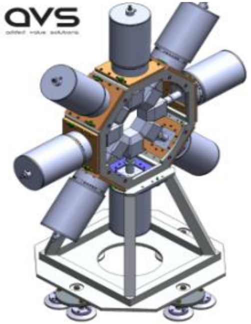


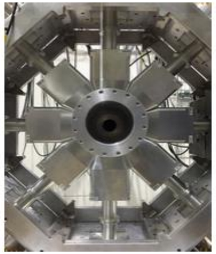
^{135}Ba(n,gamma)^{136}Ba

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







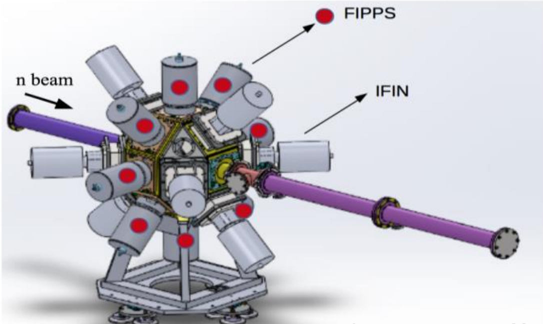


Position of FIPPS:
thermal neutron guide (H22)
continuous neutron flux ~ 1×10^8 n/cm^2/s @ target position

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

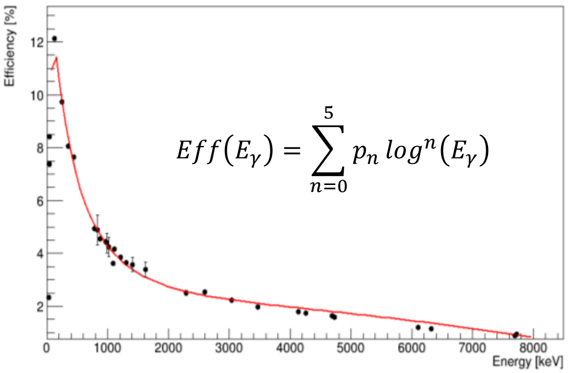
Courtesy of G.Colombi

Absolute eff. ~ 3.5 % @ 1.4 MeV

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

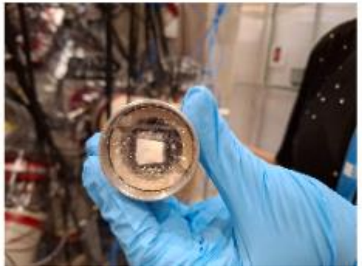
^{27}Al(n,gamma) reaction

^{152}Eu calibration source; 2.72 x 10^5 Bq



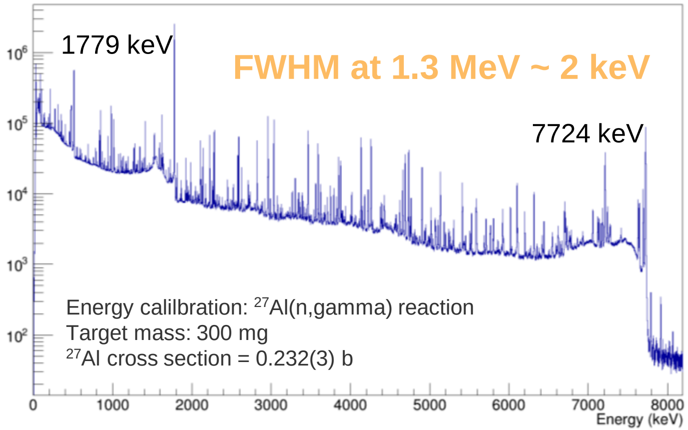
$$Eff(E_\gamma) = \sum_{n=0}^{5} p_n \, log^n(E_\gamma)$$

Courtesy of Z. Chen



Target properties:

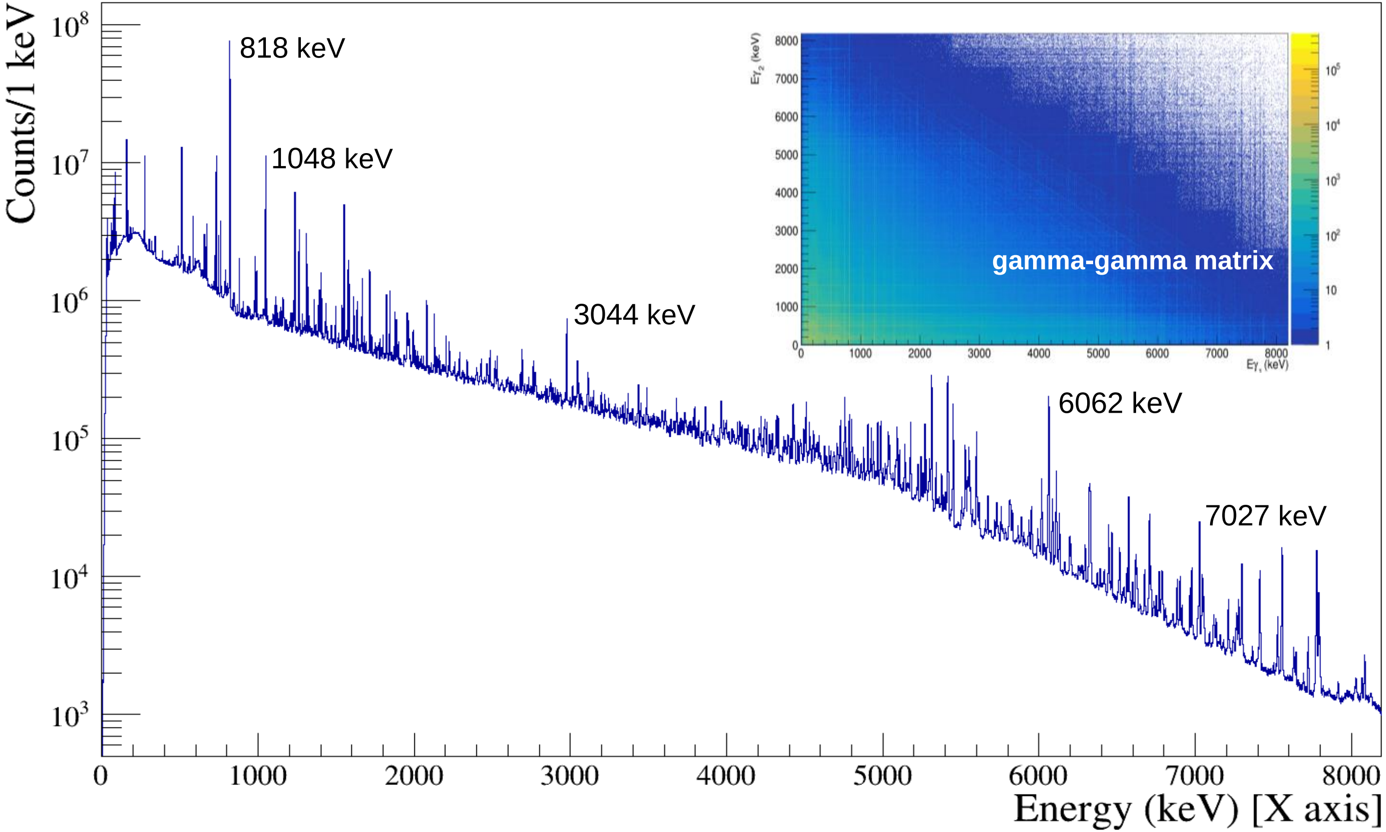
- enriched $^{135}Ba(NO_3)_2$ ≈ 67 mg
- ^{135}Ba cross section = 5.8 b
- neutron capture rate ~ 10^5 reactions/s



FWHM at 1.3 MeV ~ 2 keV

Energy calilbration: ^{27}Al(n,gamma) reaction
Target mass: 300 mg
^{27}Al cross section = 0.232(3) b

^{136}Ba total projection spectra



Ongoing analysis

Level scheme, intensities and BR

gamma cascades following n-capture at ^{135}Ba,
neutron separation energy at 9.1 MeV

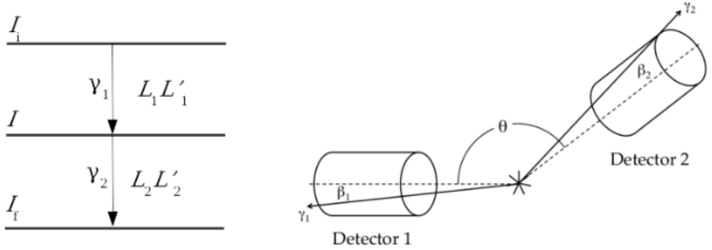
Gamma-gamma matrix for constructing a level scheme of ^{136}Ba

Angular correlation measurements

for spin assignment, determination of mixing ratio

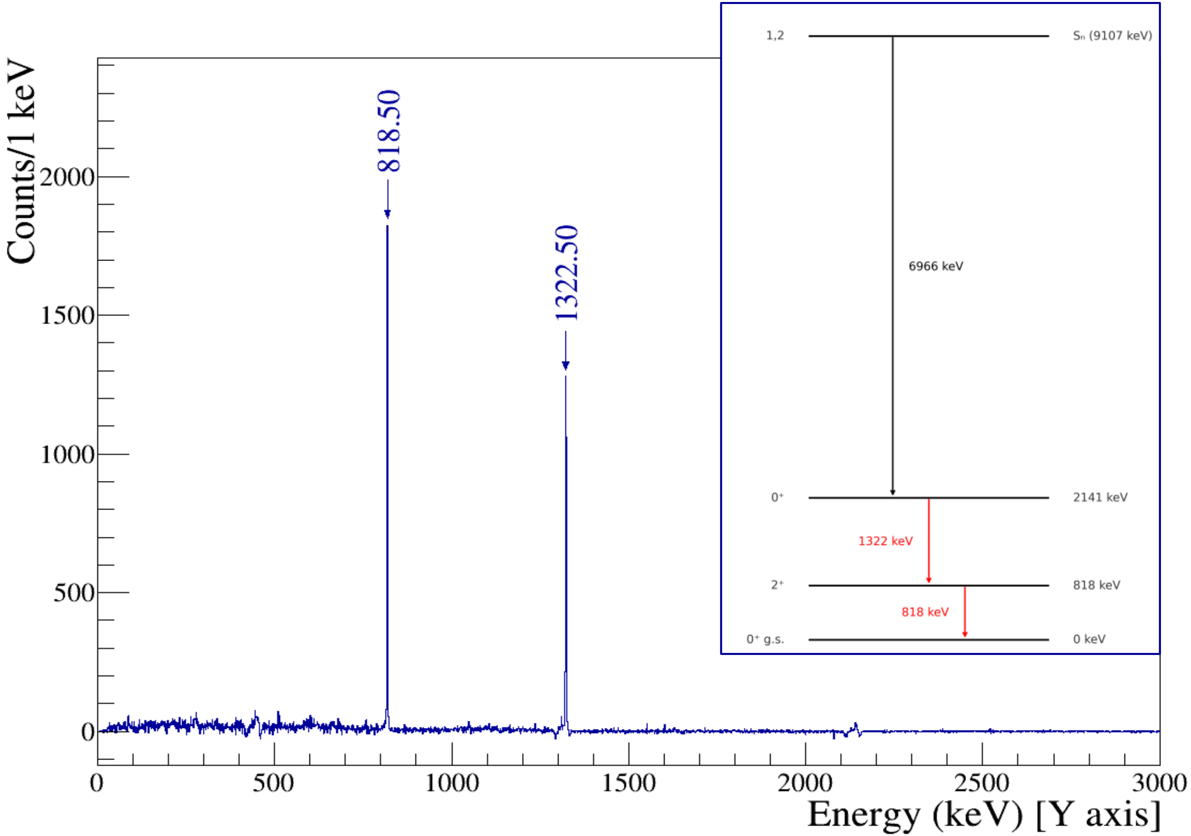
$$W(\theta) = A_0[1 + Q_2 a_2 P_2 cos(\theta) + Q_4 a_4 P_4 cos(\theta)]$$

corrected ang. distribution to the attenuation correction factor;
dependent on the properties and geometry of the detectors



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

^{136}Ba gate @ 6966 keV



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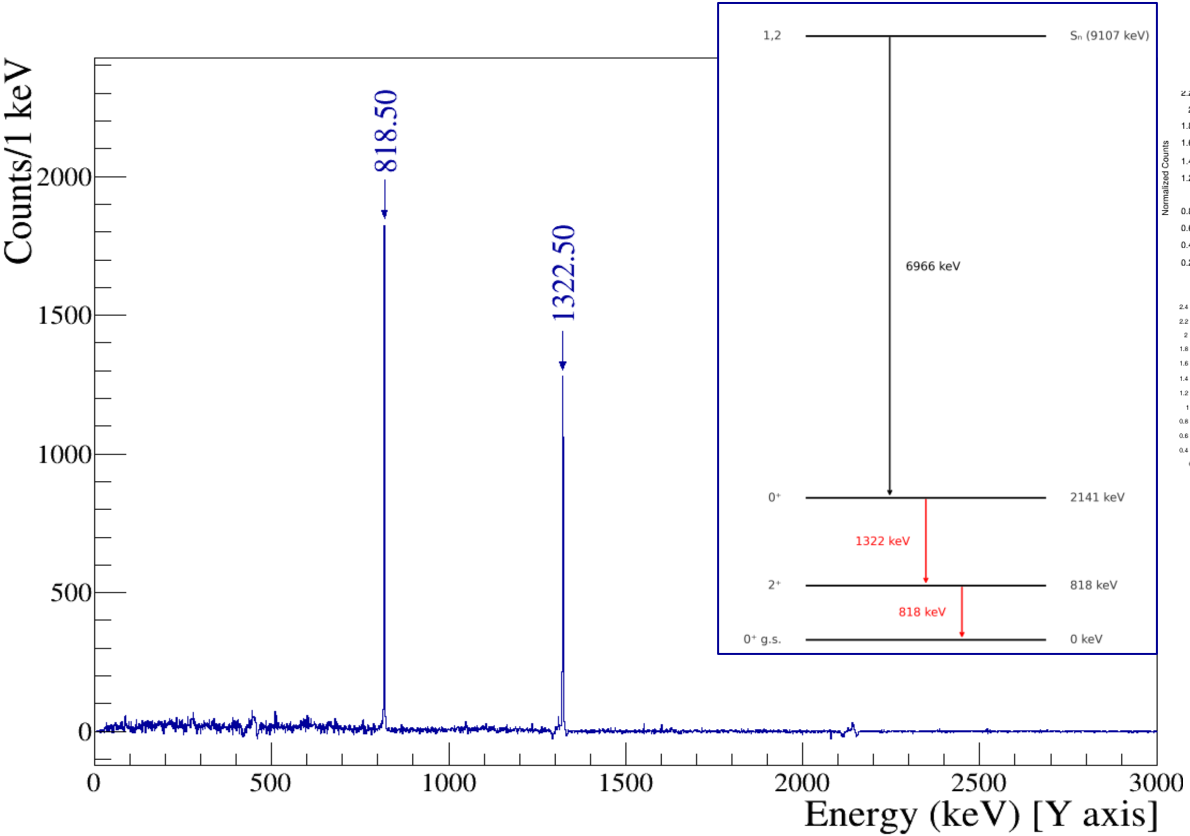
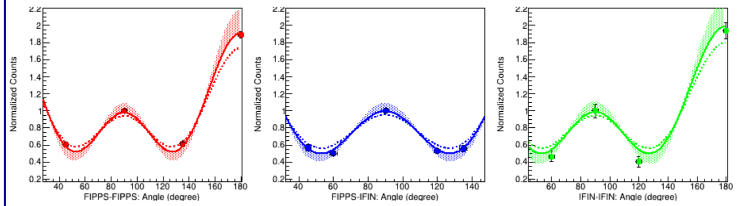
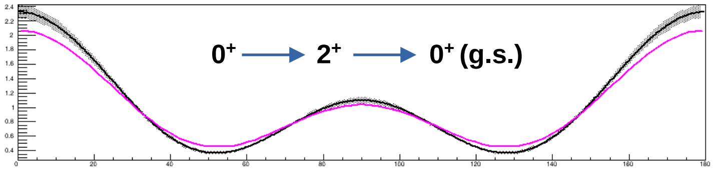
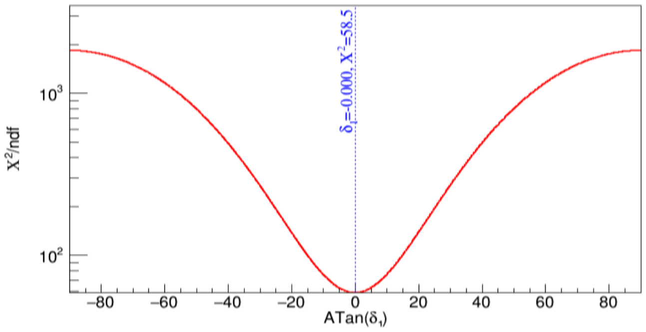


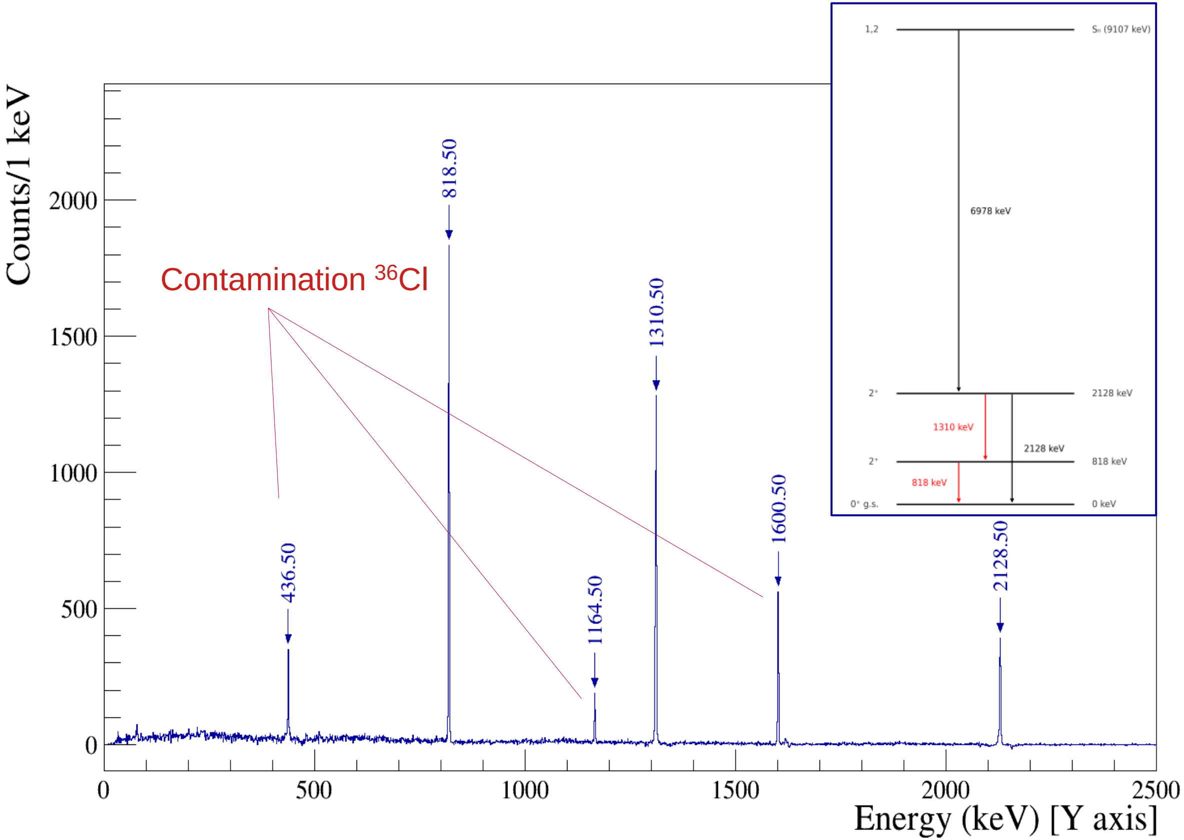
Angular correlations obtained for 1322 keV – 818 keV



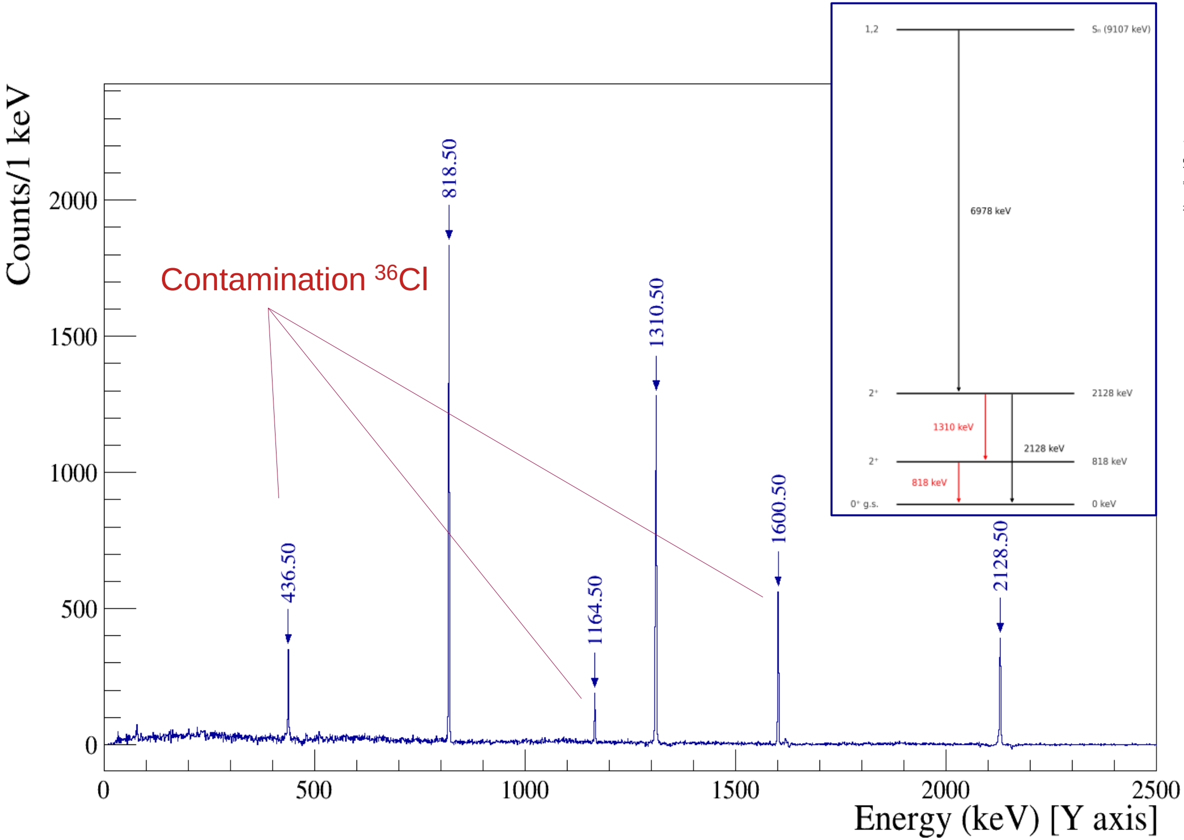




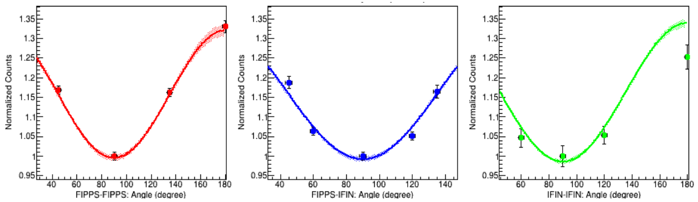
^{136}Ba gate @ 6978 keV

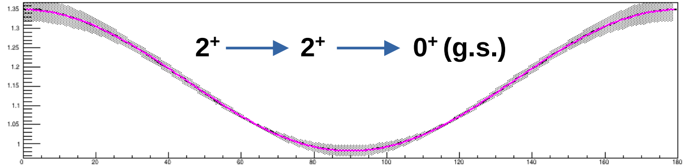


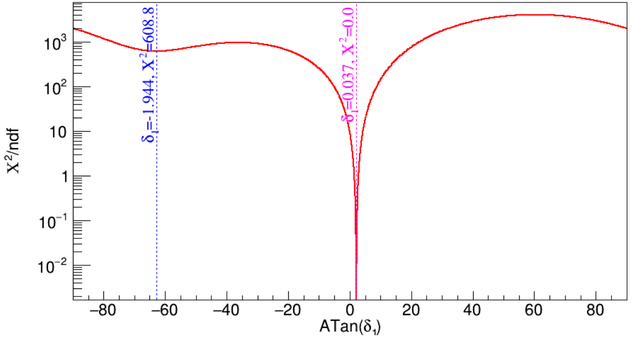
^{136}Ba gate @ 6978 keV



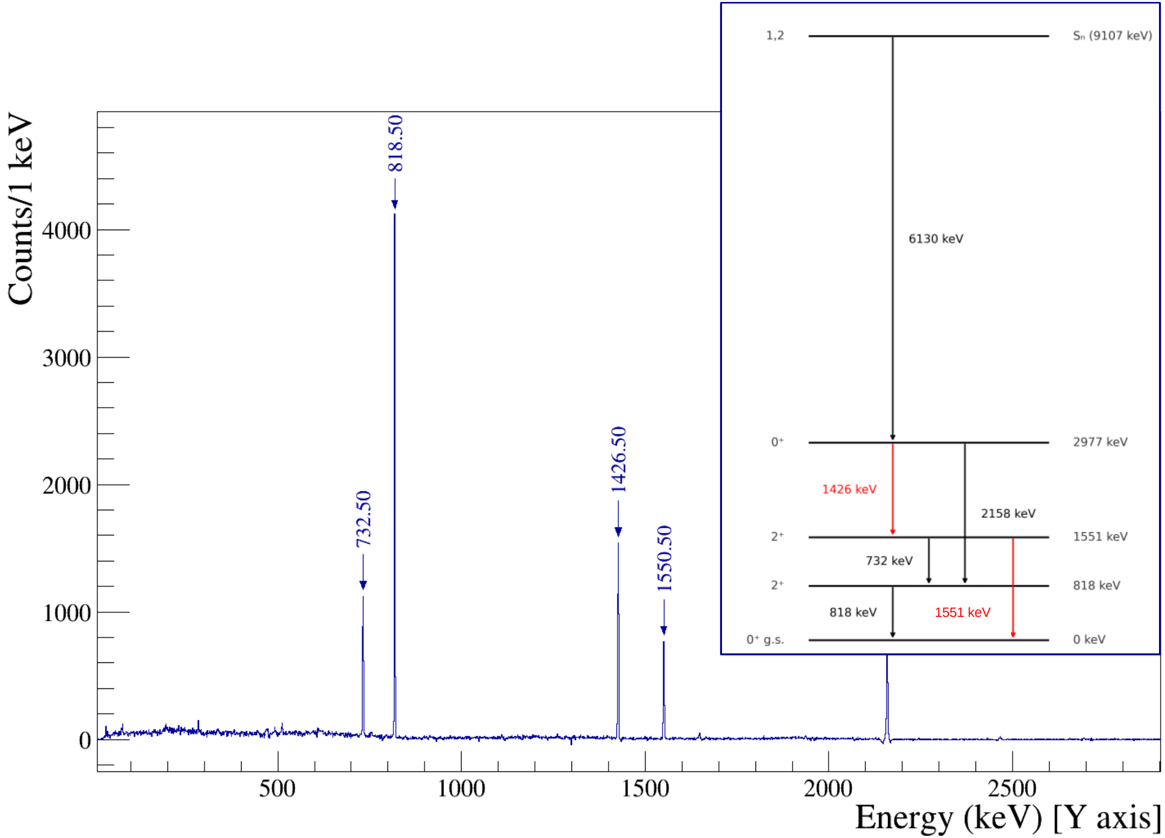
Angular correlations obtained for 1310 keV – 818 keV



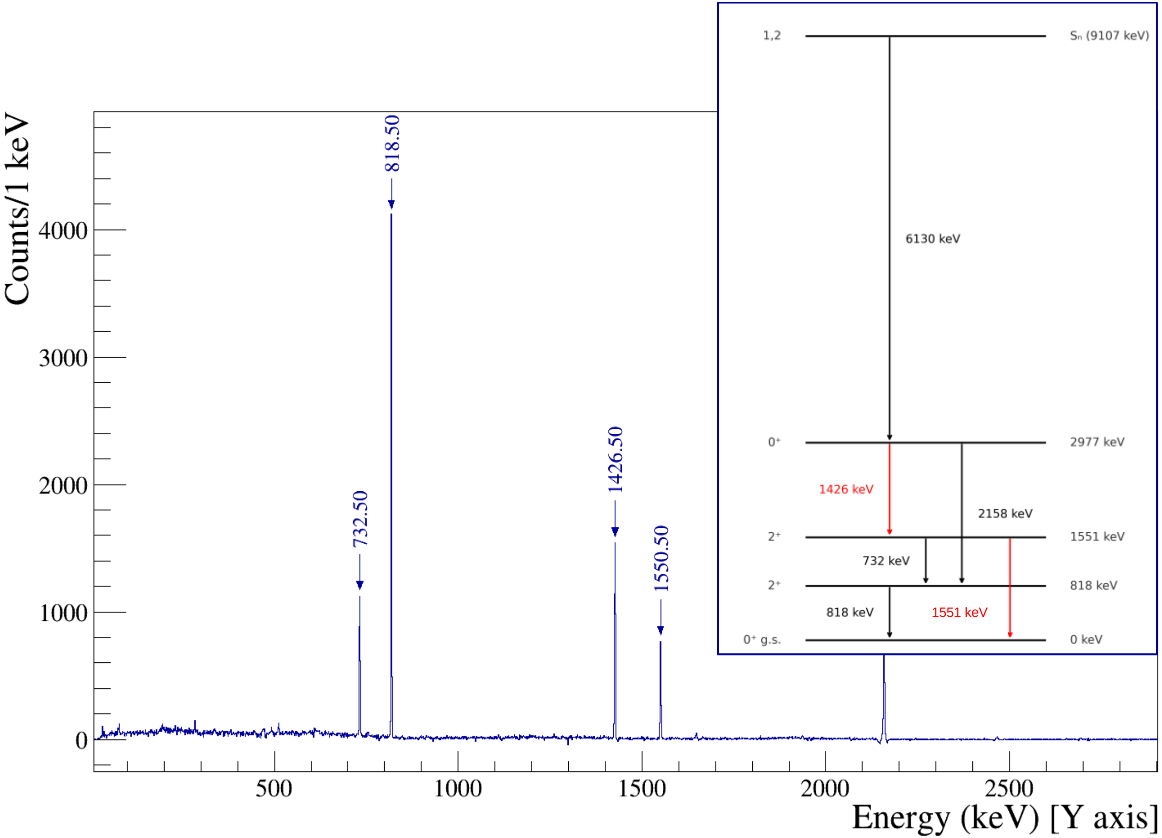




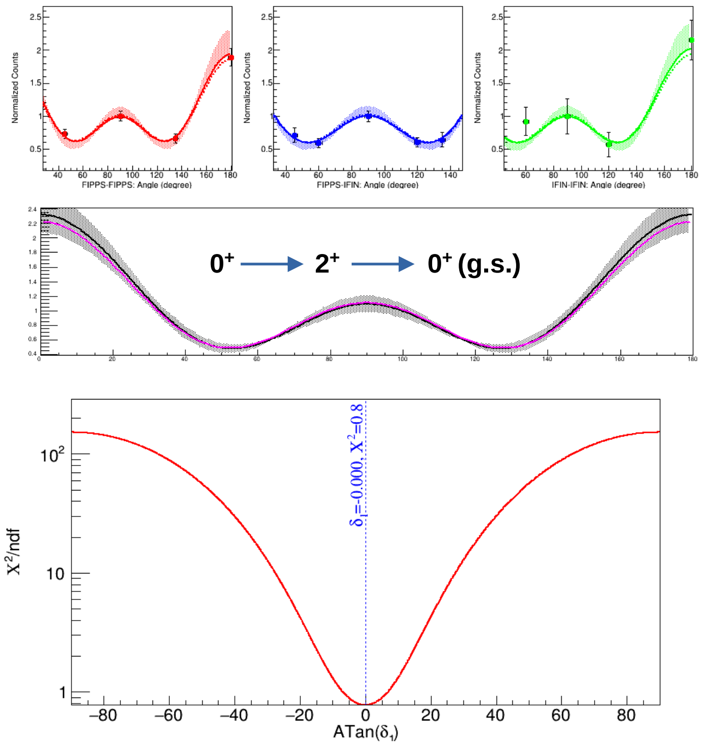
^{136}Ba gate @ 6130 keV



^{136}Ba gate @ 6130 keV

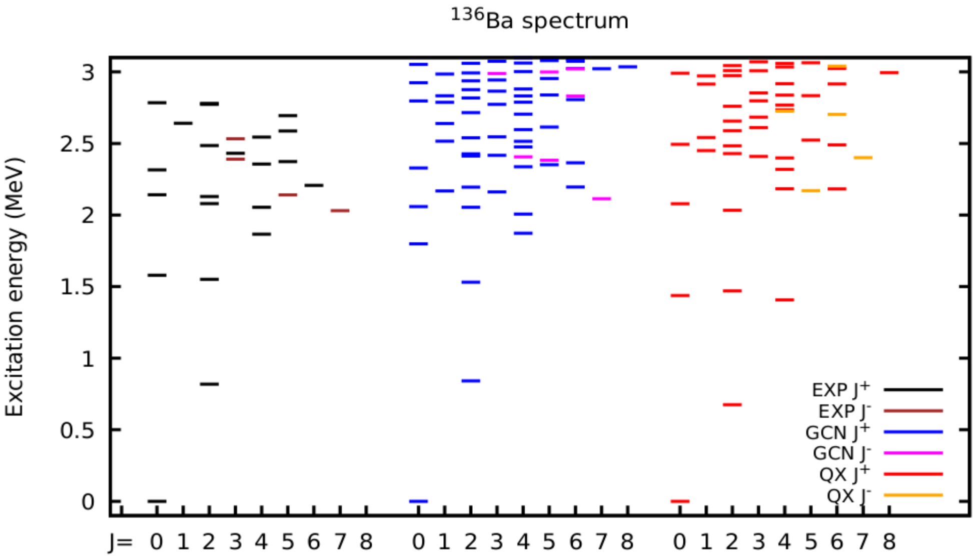


Angular correlations obtained for 1426 keV – 1551 keV

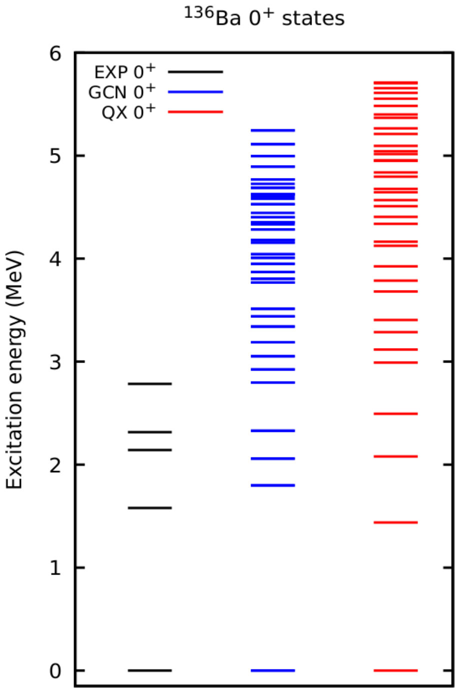


Theoretical calculations

Credits to Javier Menéndez and Dorian Grzegorz Frycz



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

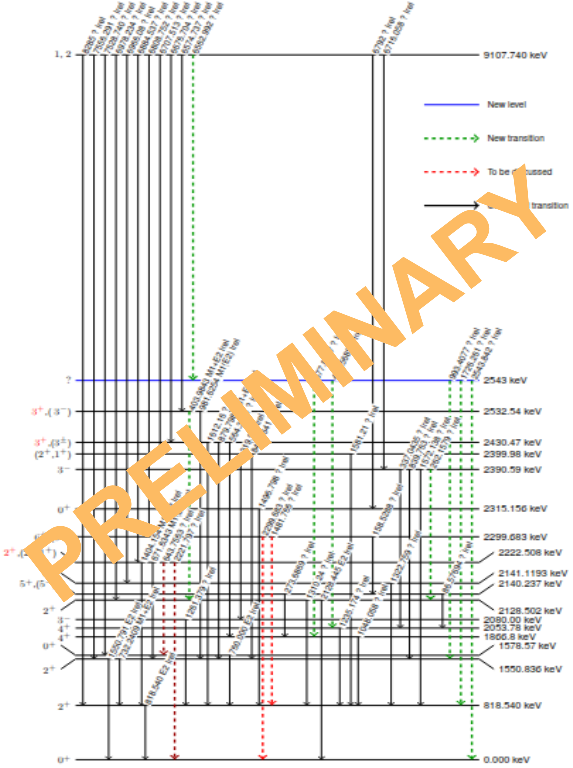


Comparison of experimental J = 0+ states and theory, GCN and QX interactions

Experiment:
up to 3 MeV observed five 0^+ states, additional six 0^+ states from ^{138}Ba(p,t) not included here

Theory:
both GCN and QX predict many more 0^+ states up to 6 MeV; so far the experiment sees limited 0^+, theory predicts a "dense forest"

Summary and Outlook

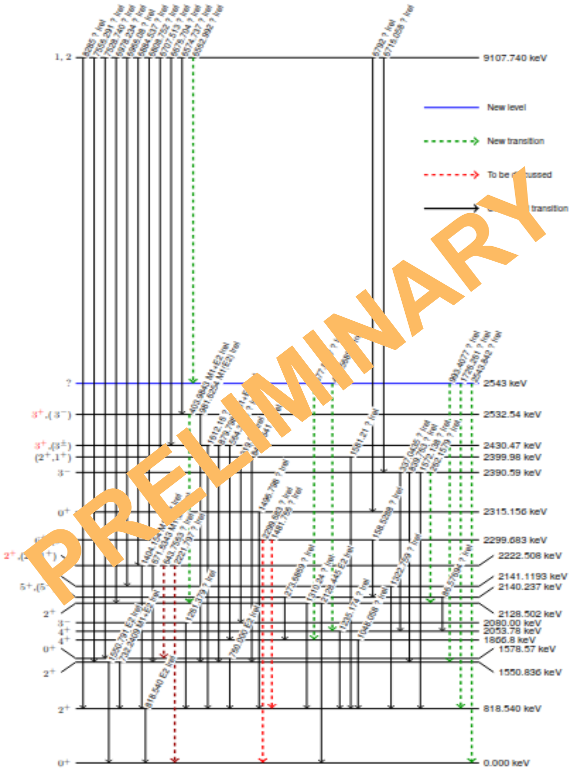


Partial level scheme of ^{136}Ba, here gates applied on transitions between 6 MeV in excitation energy and Sn

Summary

- better understanding of final nucleus of the ^{136}Xe 0νββ decay
- exp. results from (n,gamma) measurements all confirmed
- extracted around 170 gammas and 50 levels
- few 0^+ states observed by B.Rebeiro et all. confirmed
- intensities and BR calculated for observed transitions

Summary and Outlook



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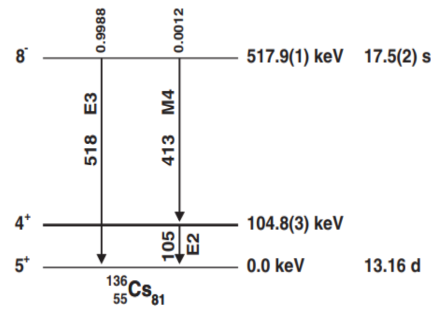
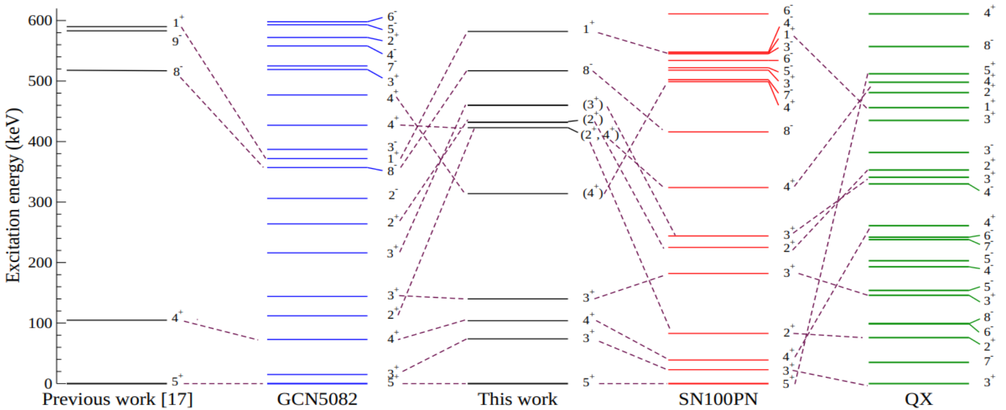


K. Wimmer et al., Phys. Rev. C 84, 014329 (2011)

Outlook

full spectroscopy of ^{136}Cs needed, ^{135}Cs(n, γ) reaction

recent study via ^{138}Ba(d,α) reaction to investigate 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**, Giacomo Colombi,
Lorenco Domenichetti, Dorian Grzegorz Frycz, Corinna Henrich, Ilja Homm, Ulli Koester,
Thorsten Kroell, Caterina Michelagnoli, Javier Menéndez, Erin Peters, Matthias Rudigier,
Marcus Scheck, Chen Zhiqiang, S. W. Yates