

Probing nuclear structure with slow neutrons: news from ILL

Vllth Topical Workshop on Modern Aspects in Nuclear Structure - Bormio 6-11 February 2023

Caterina Michelagnoli | 8 February 2023

Institut Laue-Langevin



Thermal neutrons: how and why?

An introduction to a *complementary* probe for nuclear structure, astrophysics and fission

High resolution γ -ray spectroscopy after thermal neutron induced reactions

(n, γ) reactions on stable (rare) and radioactive targets
(shape coexistence, realistic Shell Model interactions, ...)

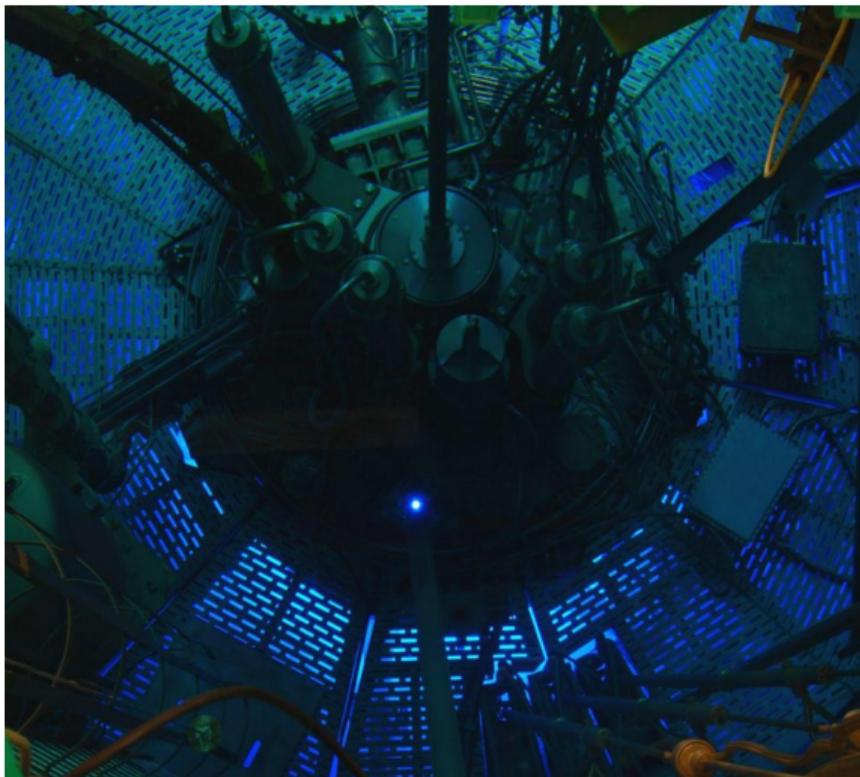
(n,fission) using a *fission tag* -systematic investigations in neutron-rich nuclei

Concluding remarks and future possibilities

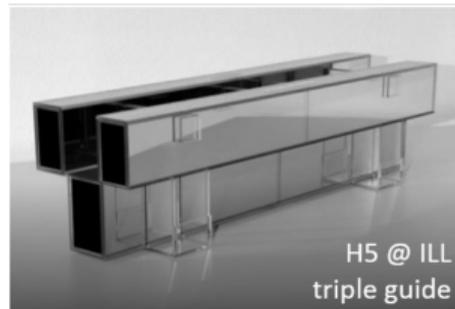
“The future” for high-resolution prompt γ spectroscopy after thermal neutron induced fission

Ideas for the (approaching!) proposal deadline

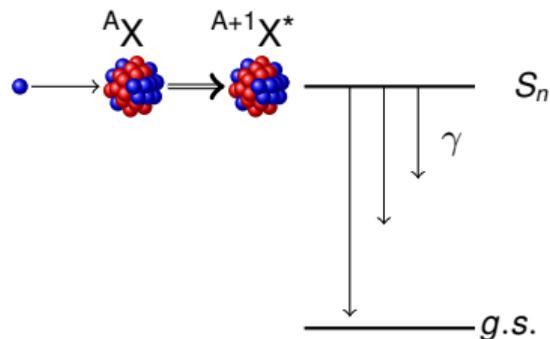
World's highest neutron flux for in-beam experiments



- ✓ up to $1.5 \cdot 10^{15}$ n/s/cm²
- ✓ in-pile irradiation of radioisotopes
- ✓ "slow" neutrons delivered to ≈ 40 instruments
- ✓ guided with little losses over hundreds of meters

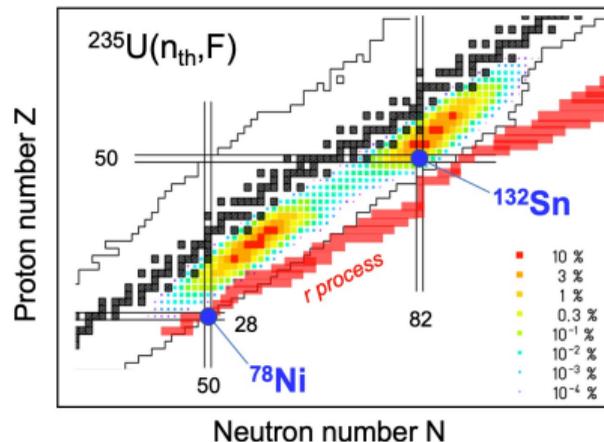


Neutron-induced reactions



Thermal neutron capture reactions

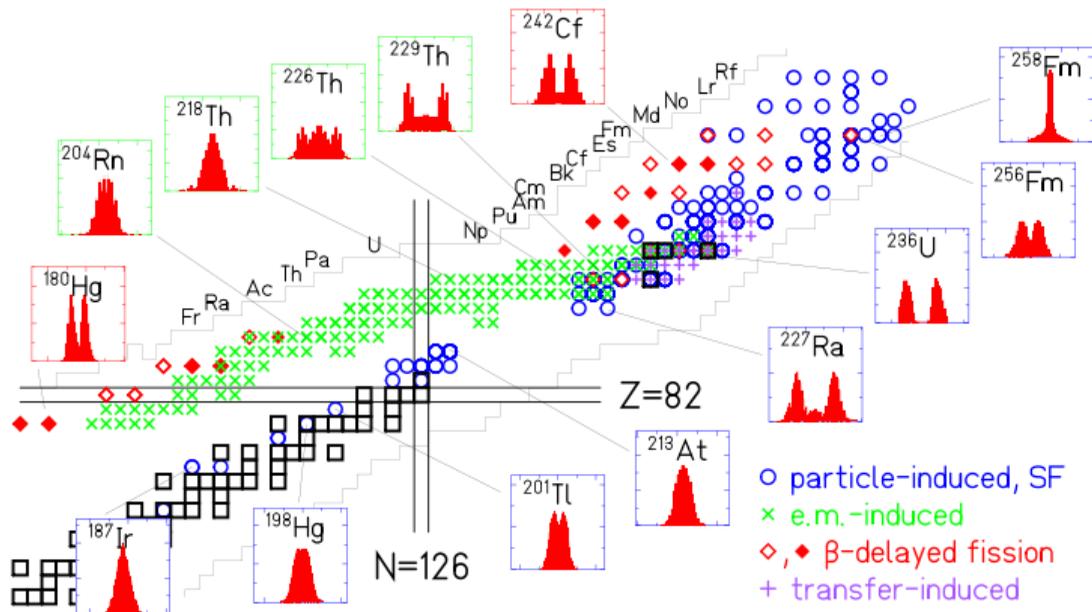
- ◇ Structure of nuclei close to stability
- ◇ Structure at low spin (below S_n)
- ◇ Cross-sections (applications)
- ◇ $^{27}\text{Al}(n,\gamma)$: $\sigma=0.2$ b; ^{157}Gd : $2.5 \cdot 10^5$ b



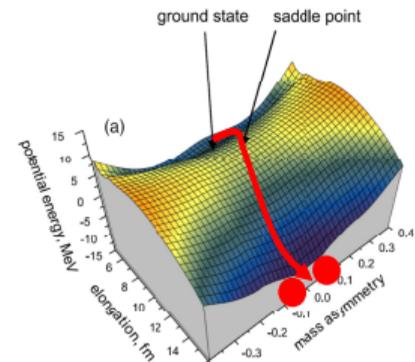
Neutron-induced fission

- ◇ Structure of n-rich nuclei (far from stability)
- ◇ Fission yields and dynamics
- ◇ ^{235}U : $\sigma_f=585$ b; ^{245}Cm : $\sigma_f=2141$ b

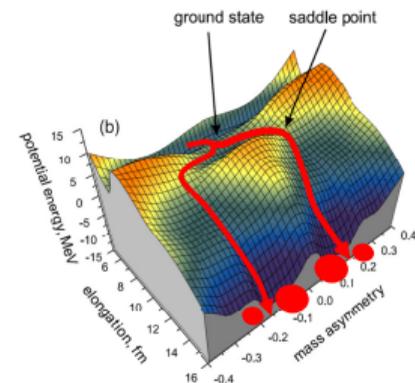
Fission yields



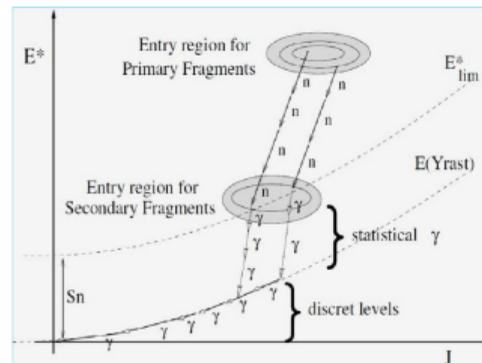
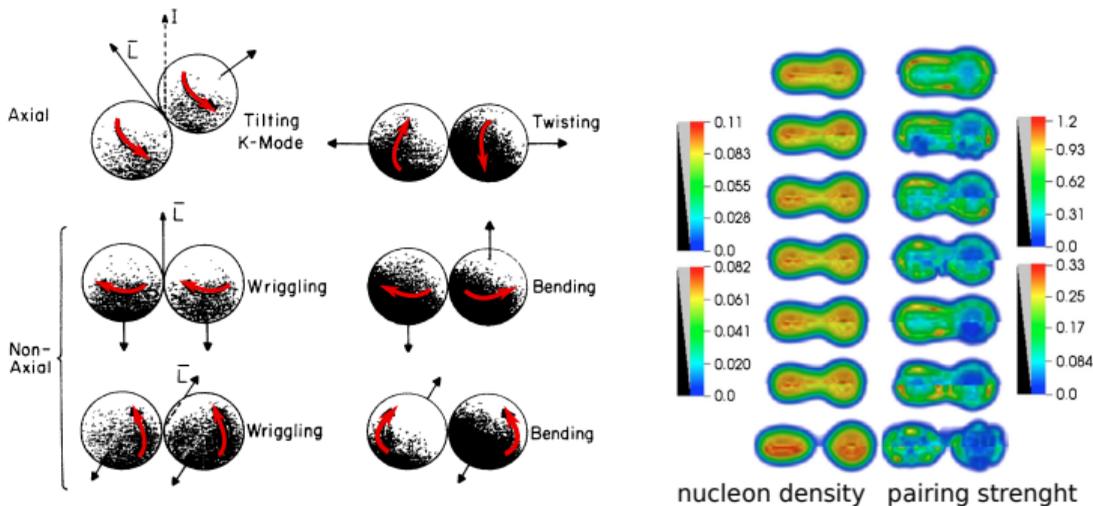
Macroscopic Energy only
(like a Liquid Drop)



Microscopic effects added
(nuclear shells and pairing)



Generation of angular momentum in fission

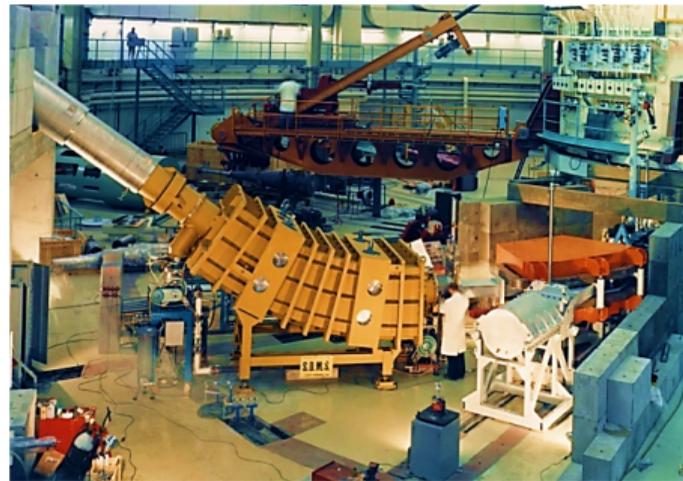
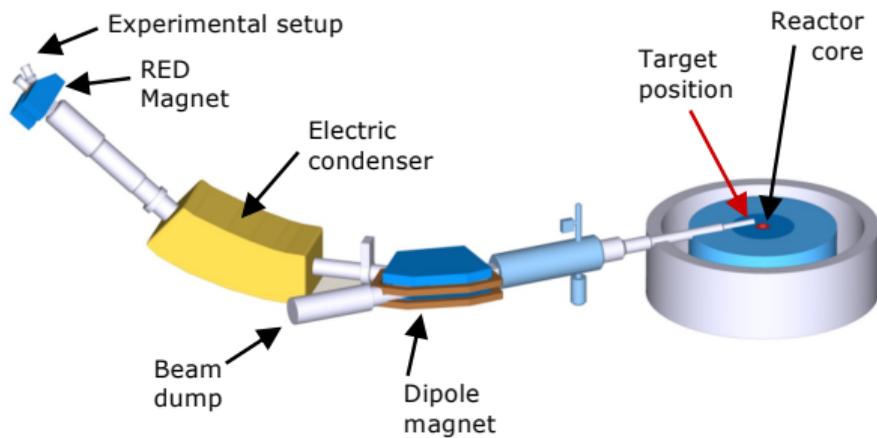


B. Back et al., Phys. Rev. C 41 (1990) 1495; A. Bulgac et al., Phys. Rev. Lett. 116 (2016) 122504; O. Litaize et al., Eur. Phys. J A 51 (2015) 177

Determination of *isomeric ratios* and/or detection of prompt γ rays from fission fragments

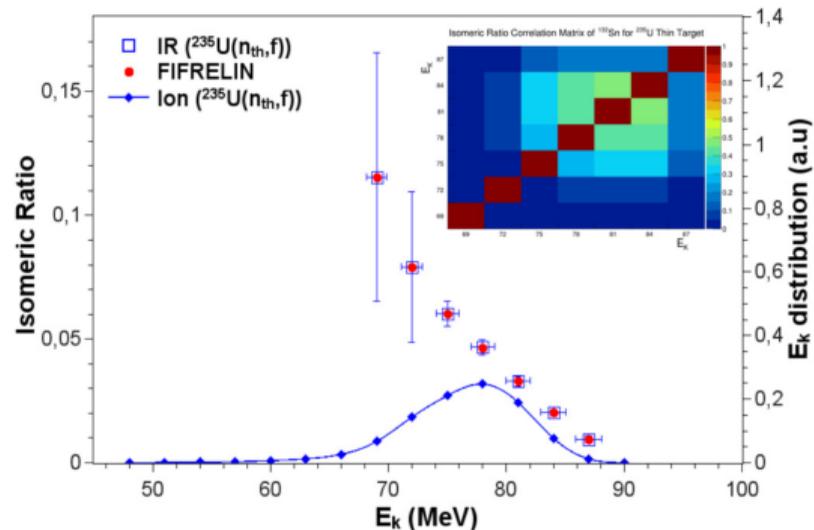
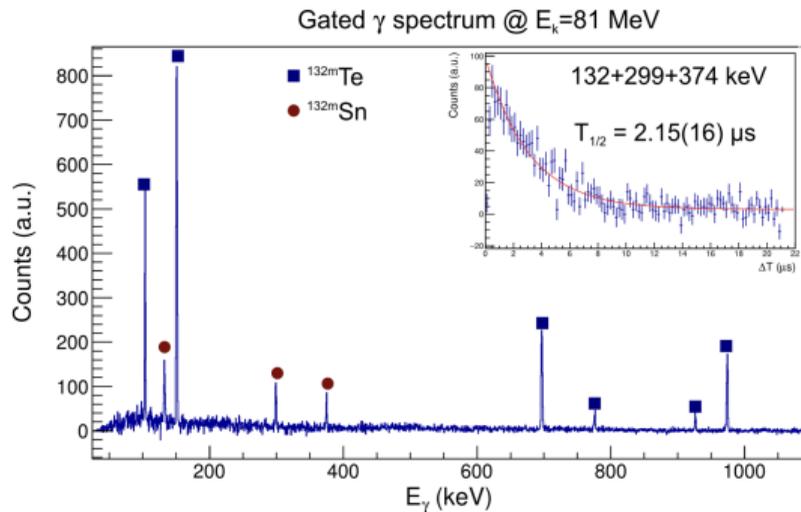
Shape of the fission fragments. Correlation between E^* and J .

The Lohengrin (PN1) fission fragment separator



- ✓ Target in-pile, few mg (^{235}U , ^{241}Pu , ^{245}Cm ...)
- ✓ 10^{12} fissions/s \Rightarrow mass-separated fission fragments, up to 10^5 per second, $t_{1/2} \geq \mu\text{s}$
- ✓ Up to $A/\Delta A > 1000$, $E/\Delta E > 1000$
- ✓ Detection of γ rays, conversion electrons, and β rays

Kinetic energy dependence of fission fragment isomeric ratios for spherical nuclei ^{132}Sn

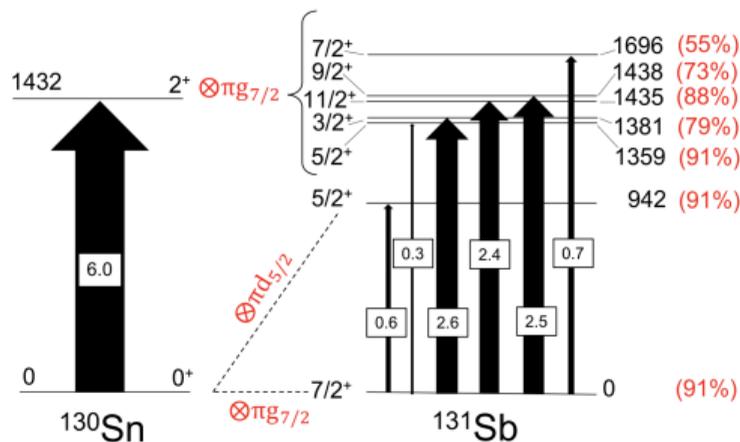
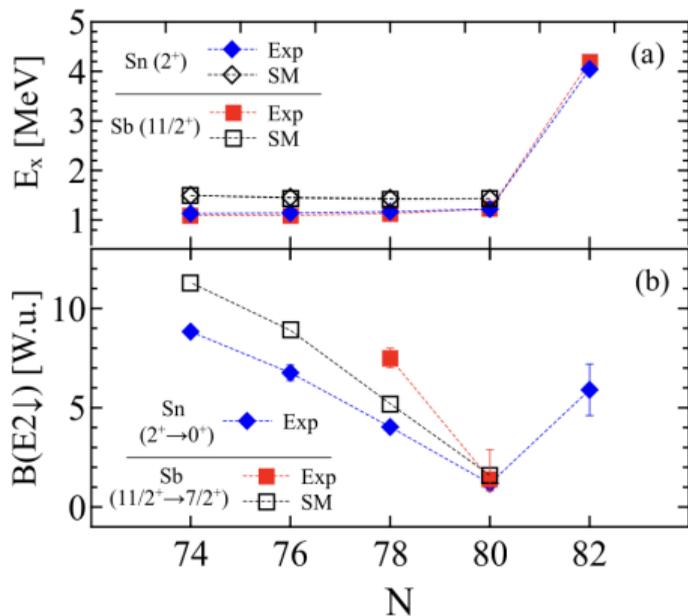


A. Chebboubi et al., Phys. Lett. B 775 (2017) 190

Realistic shell model calculations around ^{132}Sn

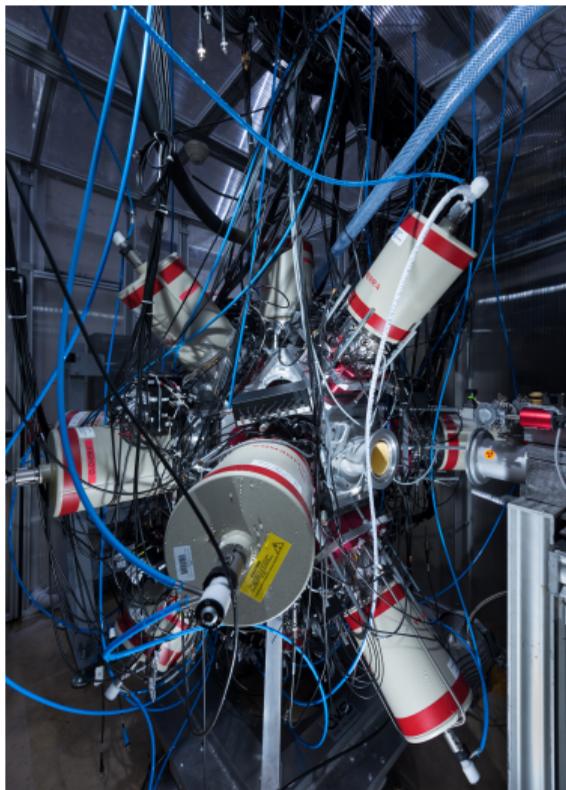
Lifetime measurement of the $11/2^+$ state in ^{131}Sb via fast-timing techniques.

Shell Model calculations with realistic interactions.



S. Bottoni et al., Phys. Rev. C 107 (2023) 014322; see poster!

The FIPPS instrument at ILL



Fission Product Prompt γ -ray Spectrometer

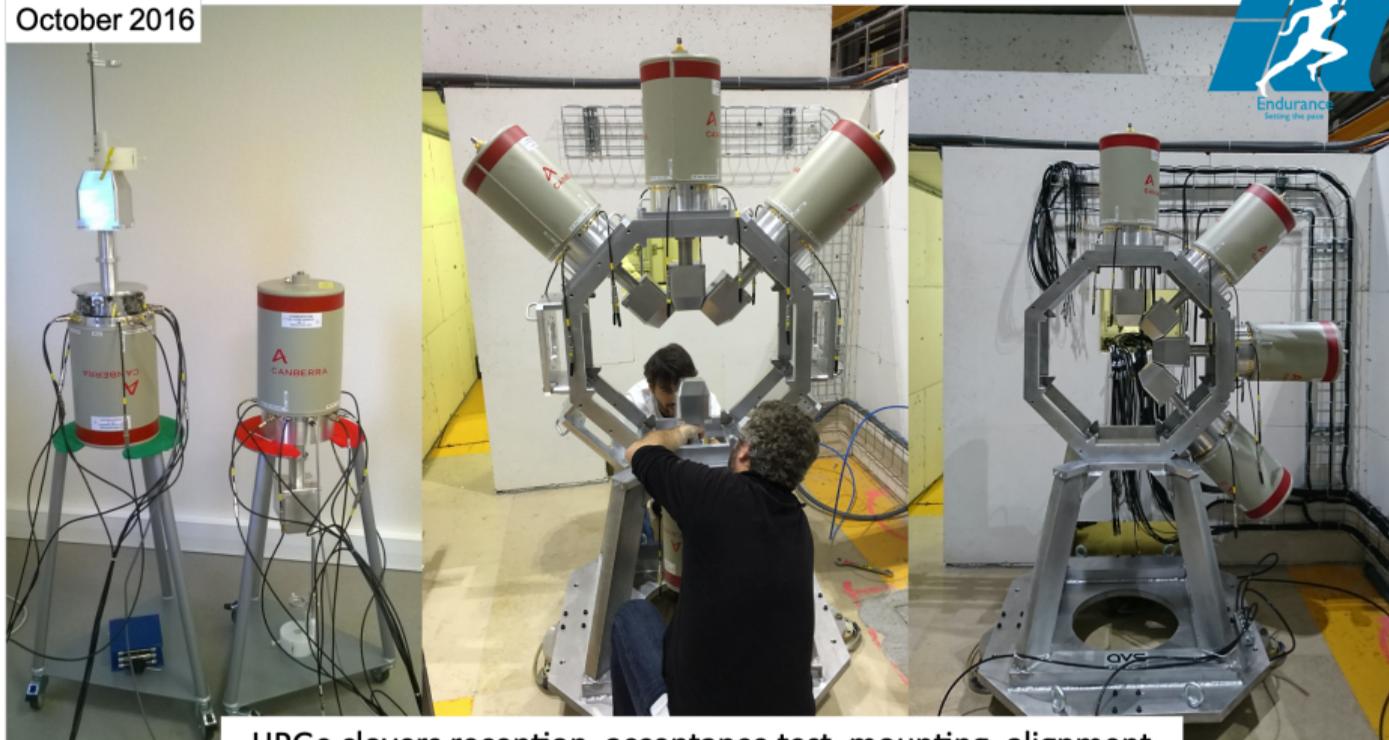
- ✓ 8HPGe clovers+Anti-Comptons (segmented)
- ✓ “pencil-like” thermal neutron beam (1.5cm diam., $5 \cdot 10^7$ n/s/cm²)
- ✓ digital electronics
- ✓ list mode
- ✓ tight polycarbonate casemate (radioactive targets)
- ✓ possibility to add ancillary detectors: LaBr₃, additional clovers from IFIN-HH, ...

C. Michelagnoli et al., EPJ Web Conf., 193 (2018) 04009; many Master/PhD theses

G. Colombi et al., in preparation

FIPPS Story

October 2016



HPGe clovers reception, acceptance test, mounting, alignment

FIPPS Story

October 2016



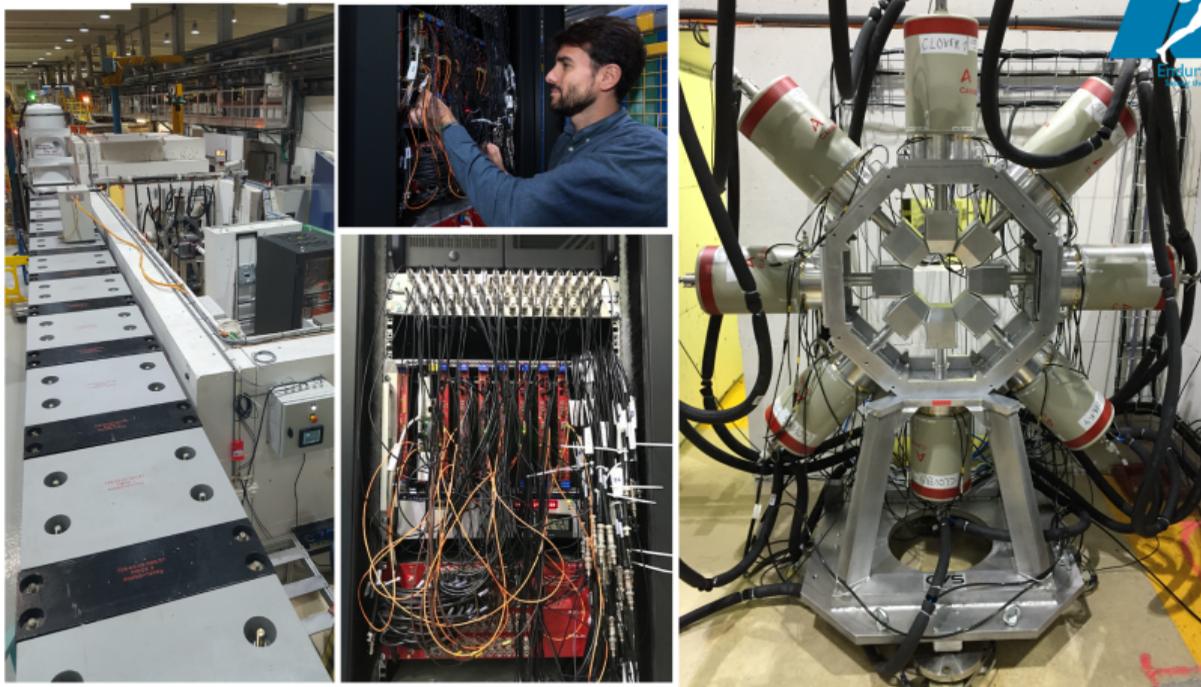
@ H22



Beam collimation, target chamber and beam stop assembly, mounting, alignment

FIPPS Story

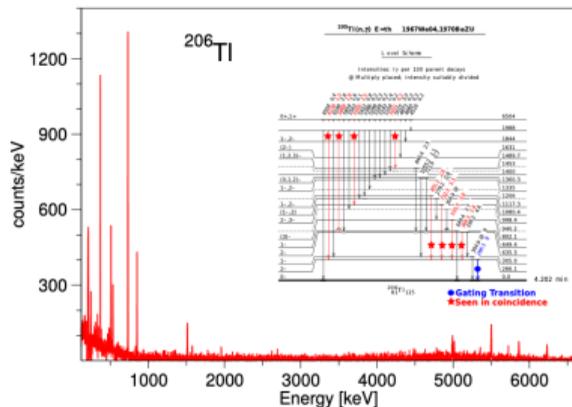
November 2016



LN2 line, detectors cooling on structure, cabling and electronics connection

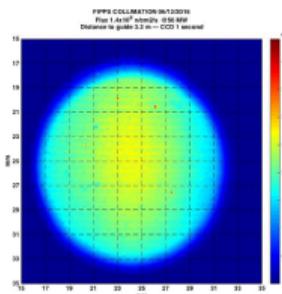
FIPPS Story

November 2016



First user experiment

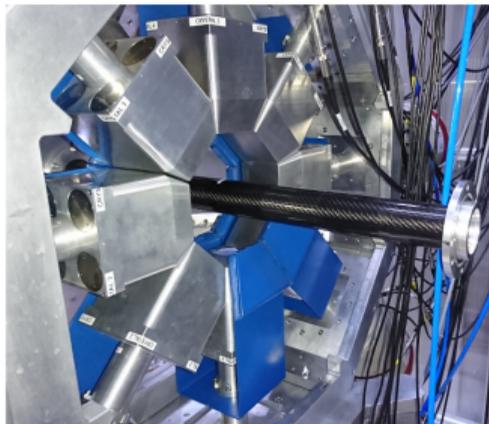
1.5 cm diameter
 10^8 n/s/cm²



DSI signature and in-beam commissioning. First happy users.

FIPPS Story

Learning from commissioning



Carbon fiber vacuum chamber



Li-plastic target holder
Teflon sample support

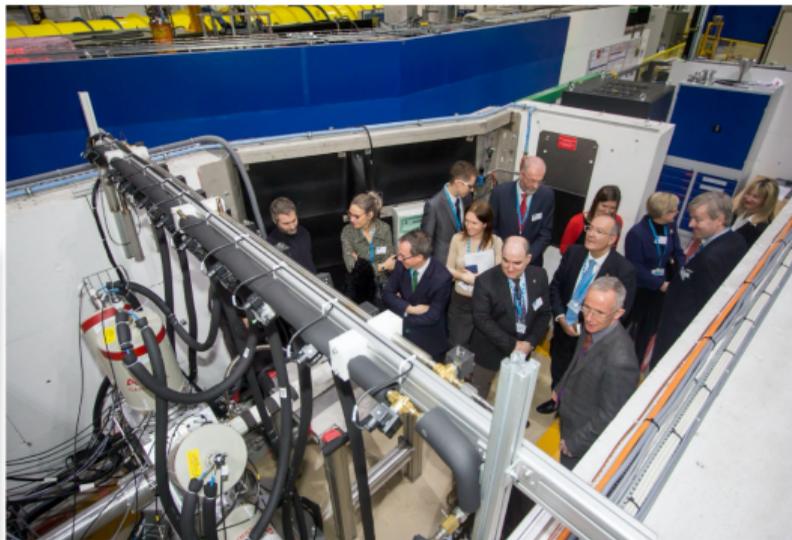
"Fighting" against n-induced gamma background

FIPPS Story

January 2017



50 YEARS OF SERVICE TO SCIENCE AND SOCIETY



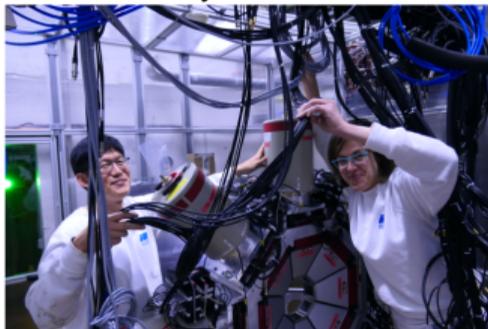
ILL 50th anniversary celebration, FIPPS was there!



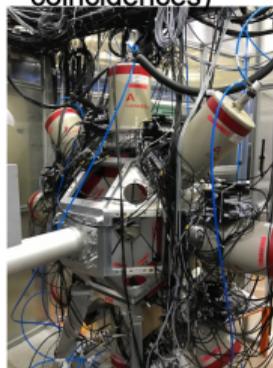
Nuclear Physics News International 2017: on the cover!

FIPPS Story

End 2018-Early 2019



40% improvement
in peak-over-
Compton
background ratio
(gain of a factor of 6
in quality of γ - γ
coincidences)



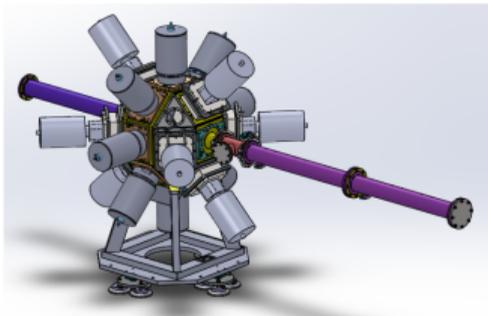
~10 km cables
~80 l LN₂ per day
Up to 70 TB raw data in one cycle



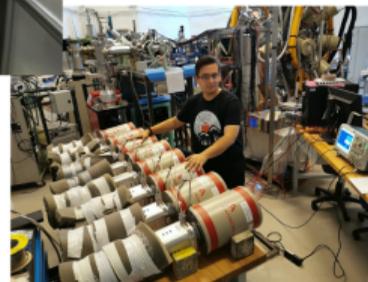
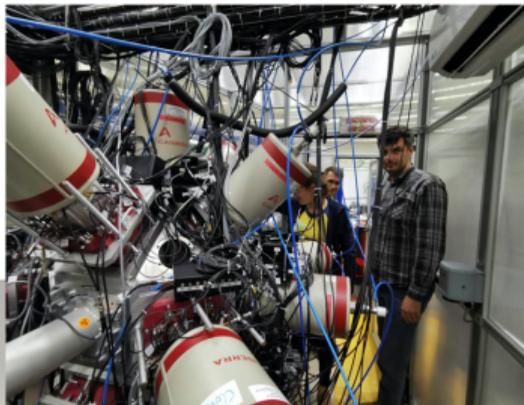
Technical specifications, offers evaluation, reception, installation of antiCompton shields

FIPPS Story

2018-2019

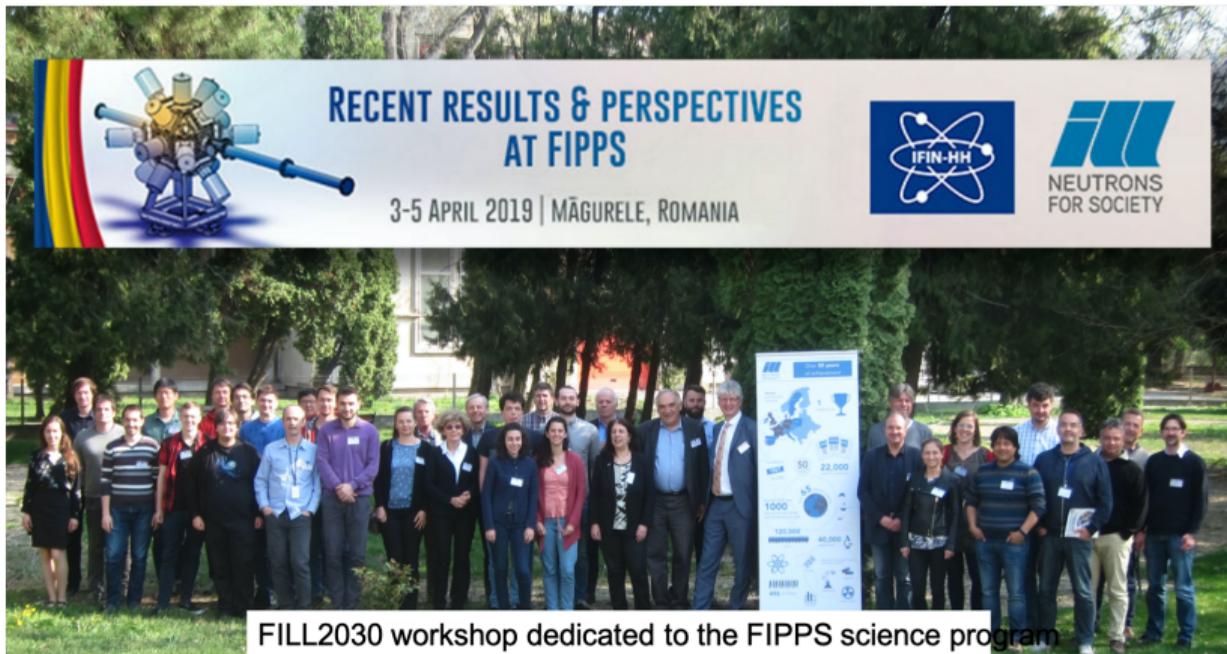


Rhône-Alpes



Additional HPGe clovers and ACs from IFIN-HH (RO). Radioactive (actinide) targets experiments

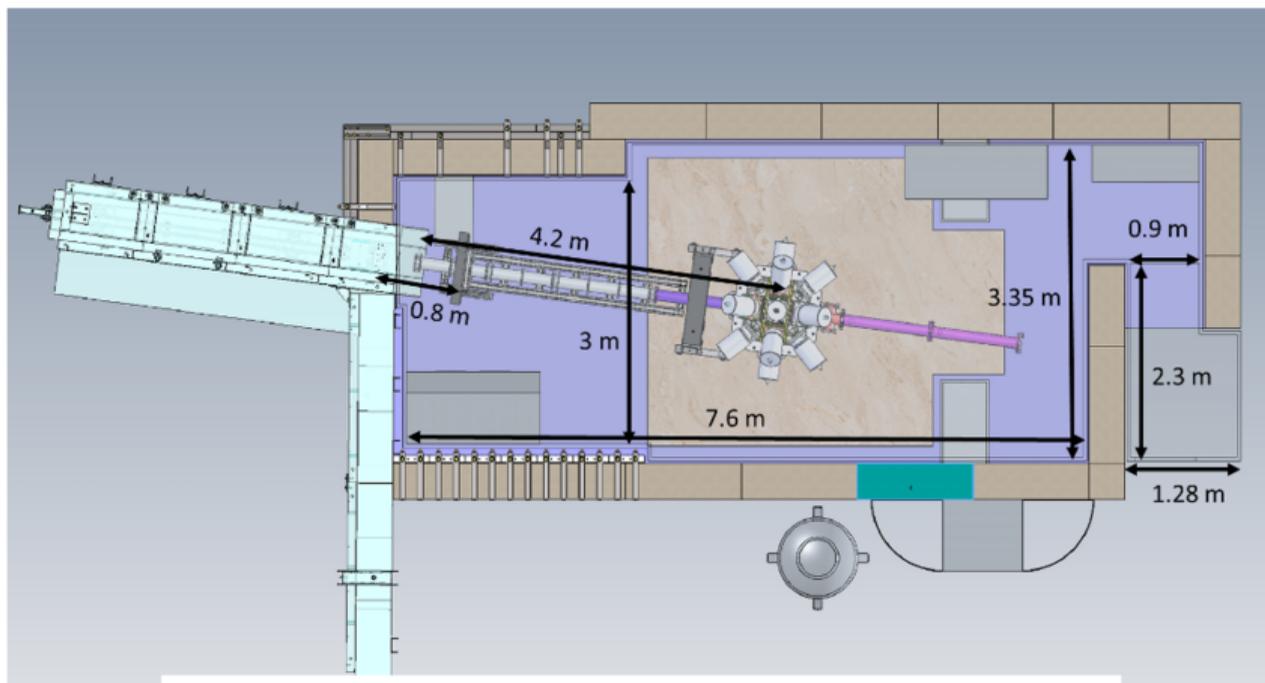
FIPPS Story



FILL2030 workshop dedicated to the FIPPS science program

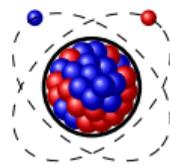
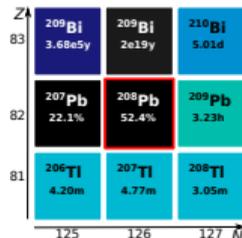
Very rich user program!

FIPPS Story

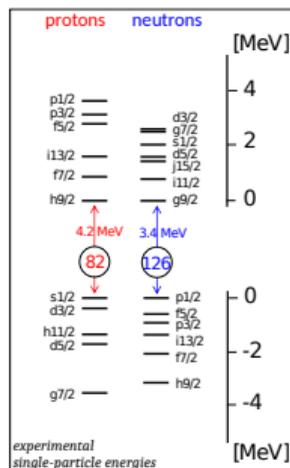
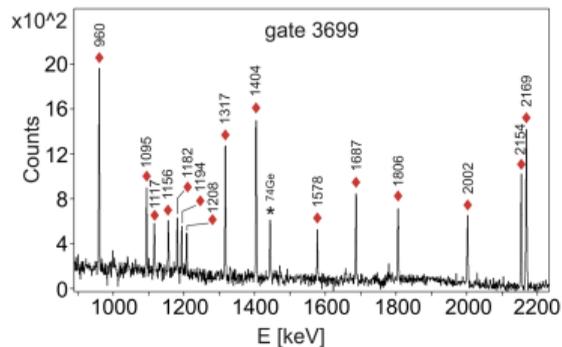


Soon FIPPS will move to a new end-guide position (more space and more flux)

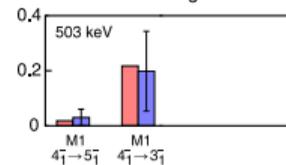
Shell model + realistic interactions around ^{208}Pb



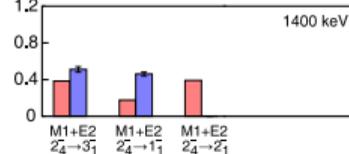
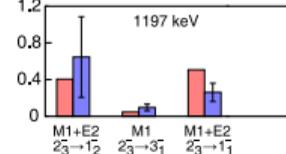
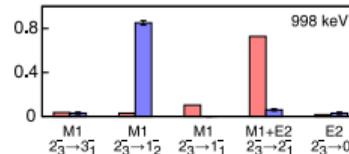
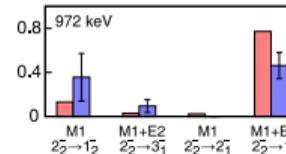
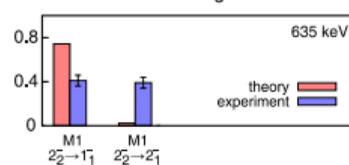
2mg ^{205}Tl target, 9 days beam time
coincidence spectrum with primary γ ray



^{210}Bi Branching Ratios

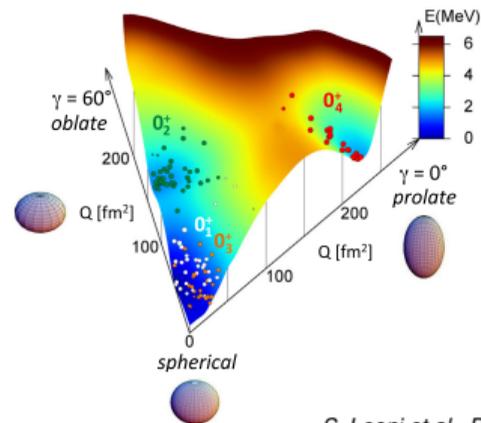
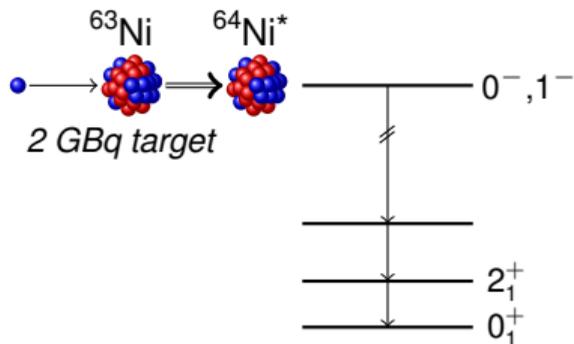


^{206}Tl Branching Ratios



^{206}Tl : Sensitivity to non diagonal matrix elements

Shape coexistence at zero spin: ^{64}Ni



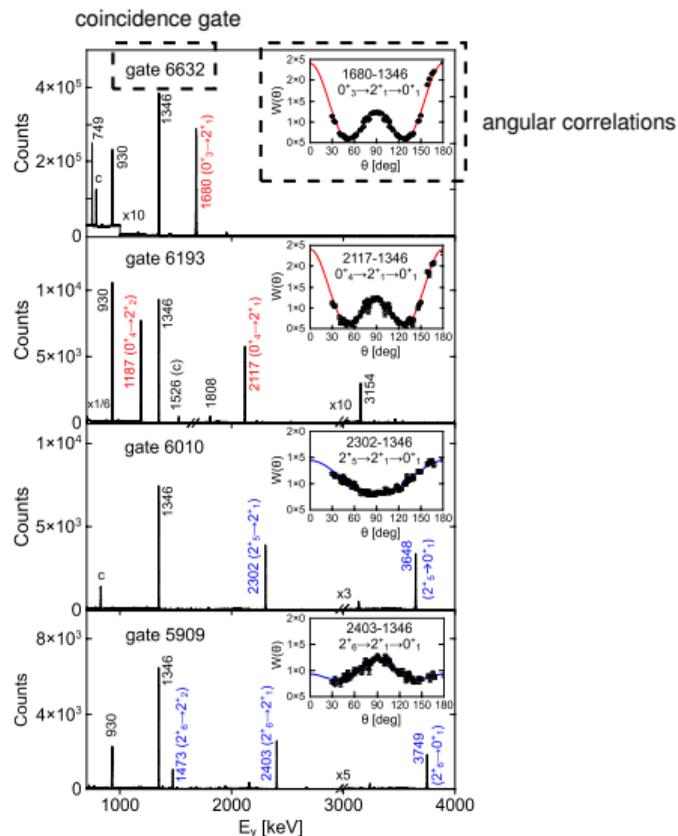
S. Leoni et al., *Phys. Rev. Lett.* 118 (2017) 162502

confirmed 0_3^+ ←

firmly assigned 0_4^+ ←

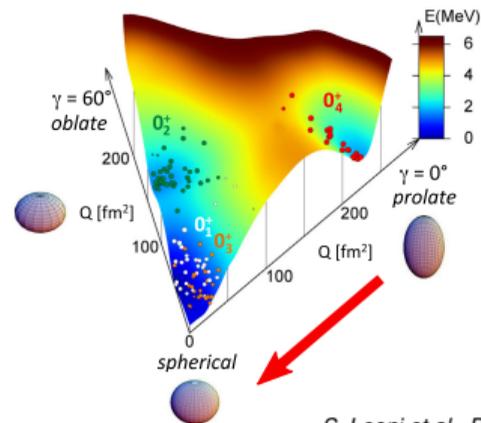
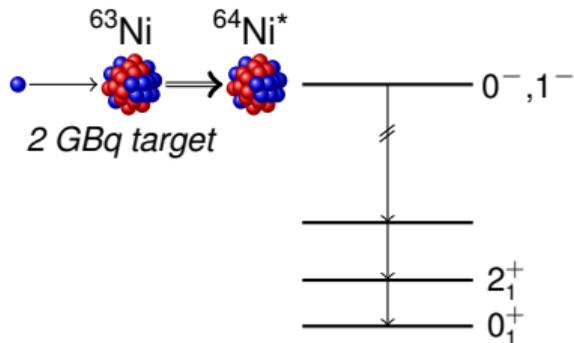
$2_{4,5,7}^+$: mainly M1 ("enhanced") ←

2_6^+ : mainly E2 ("hindered") ←



R. Marginean et al., *Phys. Rev. Lett.* 125 (2020) 102502; talk on Tuesday

Shape coexistence at zero spin: ^{64}Ni



S. Leoni et al., *Phys. Rev. Lett.* 118 (2017) 162502

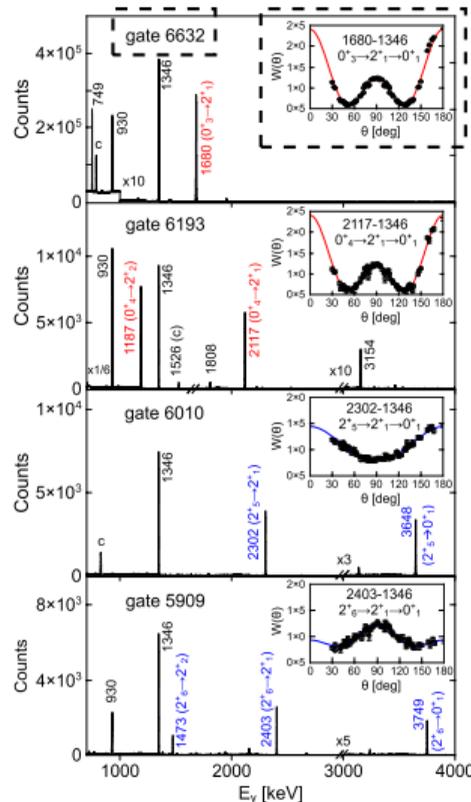
confirmed 0_3^+ ←

firmly assigned 0_4^+ ←

$2_{4,5,7}^+$: mainly M1 ("enhanced") ←

2_6^+ : mainly E2 ("hindered") ←

coincidence gate



angular correlations

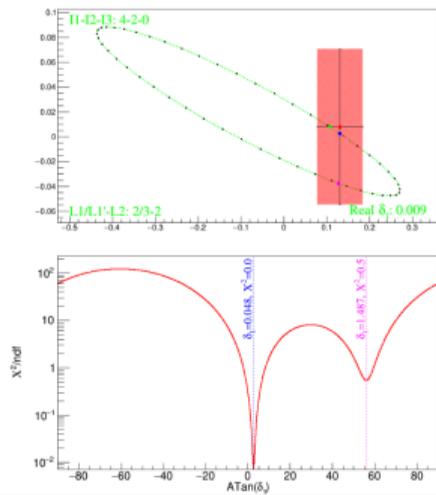
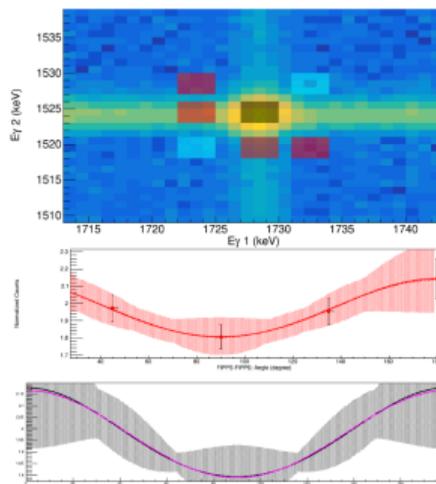
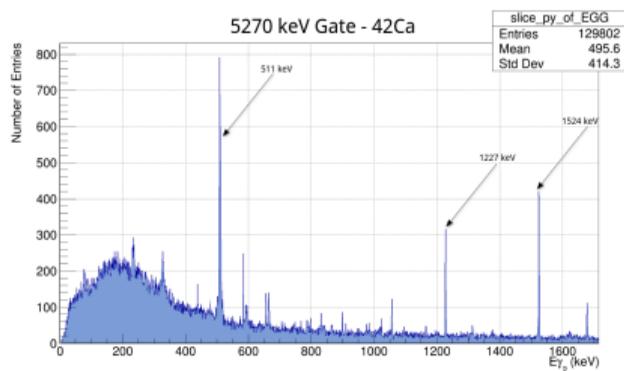
R. Marginean et al., *Phys. Rev. Lett.* 125 (2020) 102502; talk on Tuesday

Shape coexistence in Ca isotopes

≈20% of existing enriched ^{41}Ca (radioactive)!

Coincidence with primary γ ray

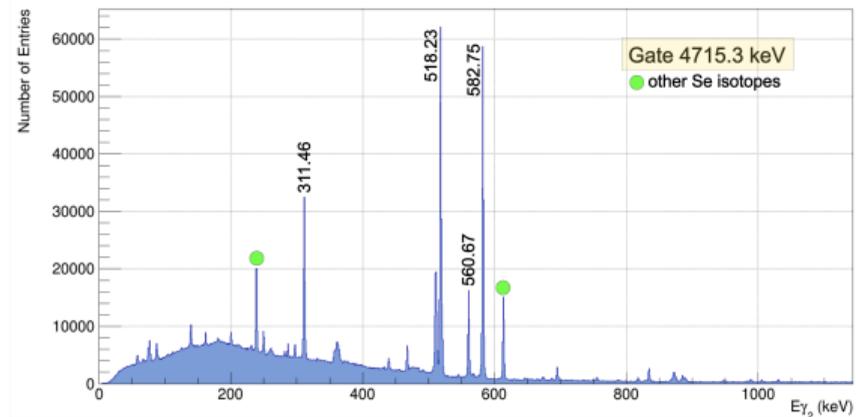
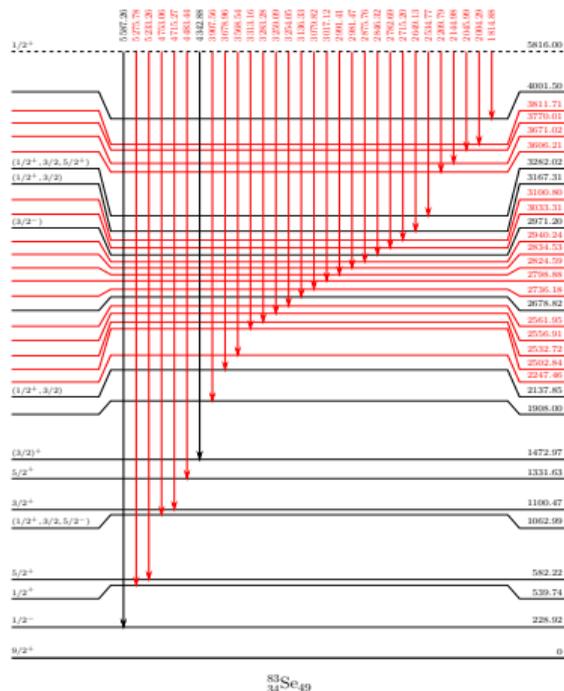
$4^+ \rightarrow 2^+ \rightarrow 0^+$ angular correlation



M. Luciani, Univ. of Milan (Master thesis work)

$^{82}\text{Se}(n,\gamma)^{83}\text{Se}$: shape coexistence around N=50

Same active proton orbitals as the neutron ones in $^{62-66}\text{Ni}$. Background reference for ^{82}Se double-beta decay. ^{82}Se target 95.3% provided by the CUPID collaboration ($\sigma = 0.044$ b).



F. Conca, Univ. of Milan (Bachelor thesis work)

Structure of rare-earth nuclei: the case of ^{161}Gd

Rare-earth nuclei (Dy, Gd, Eu, ...)

Nuclear structure between $Z=50$ and $Z=126$

Single-particle orbitals in deformed potential

Scissor modes

Very complex level scheme

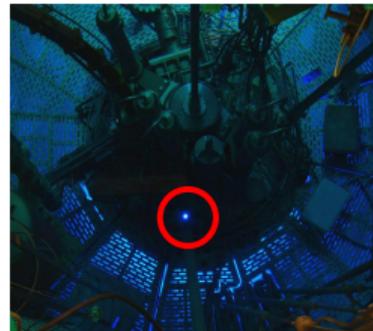
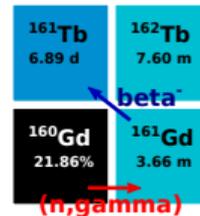
^{161}Gd ($Z=64$, $N=97$)

Close to $N=90$ "questioned" magic number

Medical interest (^{161}Tb production)

Only few excited states are known

$^{160}\text{Gd}(n,\gamma)^{161}\text{Gd} \Leftrightarrow$ highly isotopically pure target

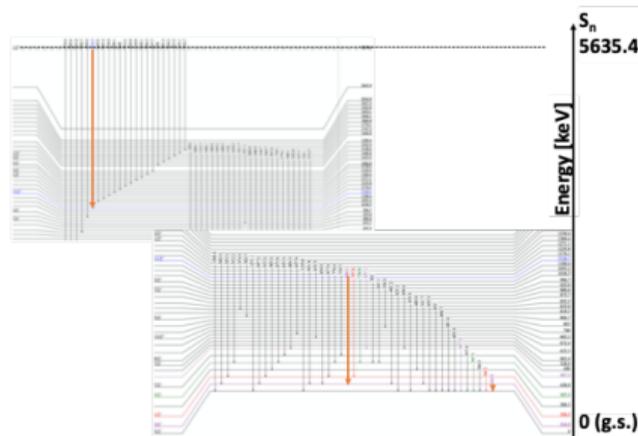
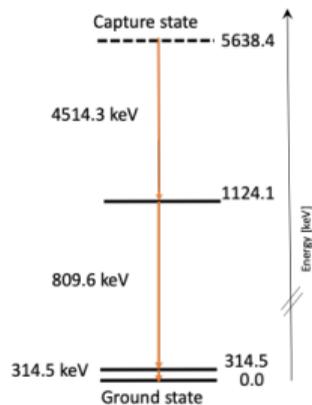
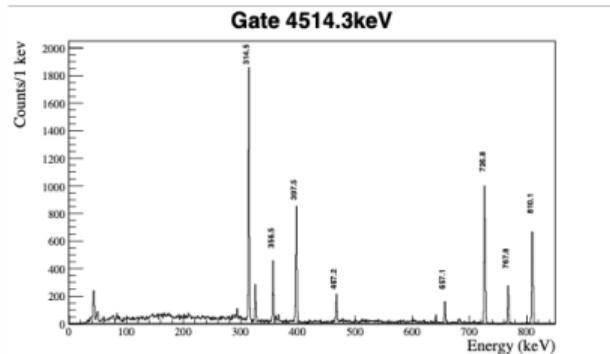


Target produced at the ILL V4 position

Isotope	σ (b)	A ($\frac{g}{mol}$)	fraction of captures (%)	Compos. (%)
^{155}Gd	60330	155	0.3	$3.3 \cdot 10^{-5}$
^{157}Gd	254000	157	0.8	$4.2 \cdot 10^{-6}$
^{160}Gd	1.4	160	98.9	98.10

A. Saracino, Master Thesis, Univ. Milano ILL

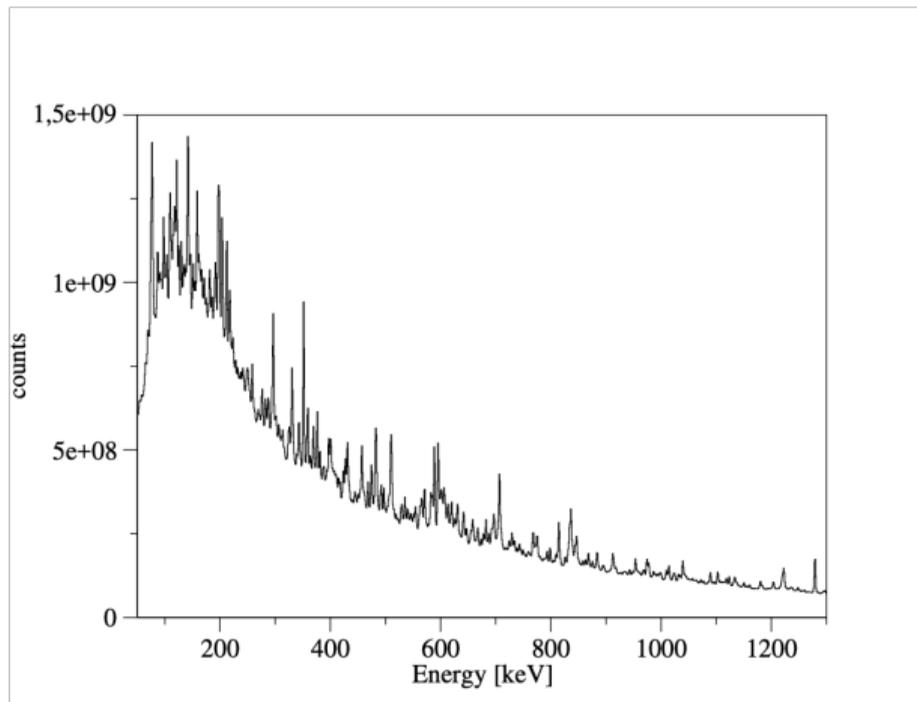
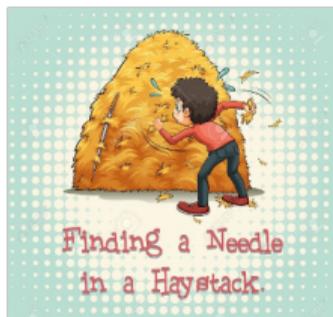
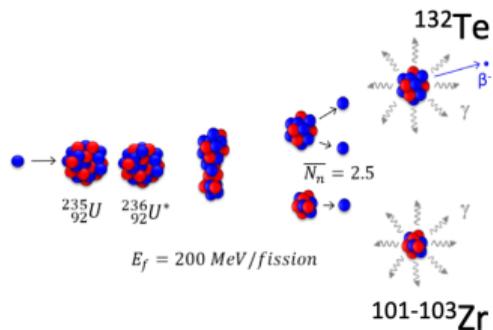
(Almost) complete spectroscopy of ^{161}Gd at low spin



35 new excited levels, 294 new γ transitions found
Accepted experiment at IFIN-HH for multinucleon transfer experiment

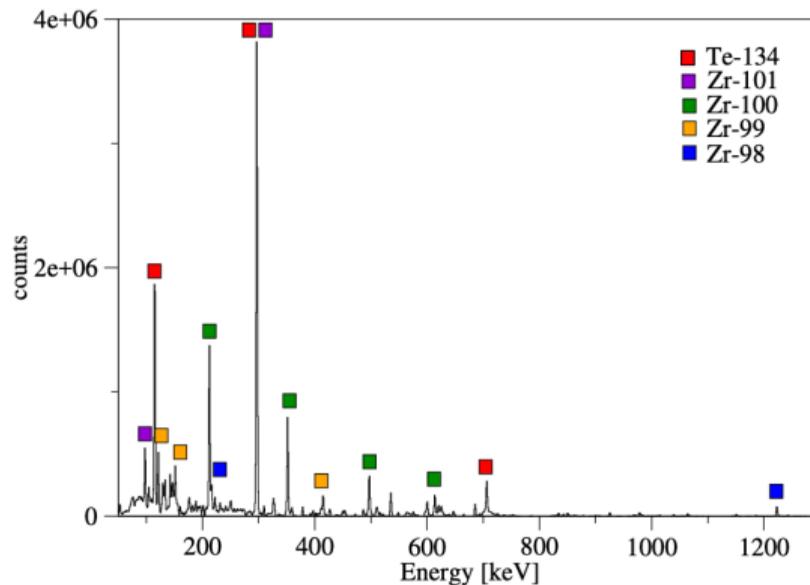
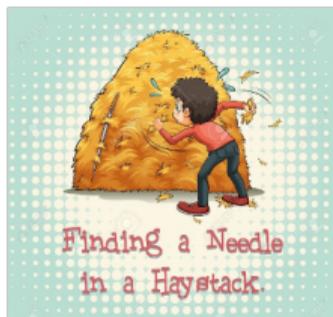
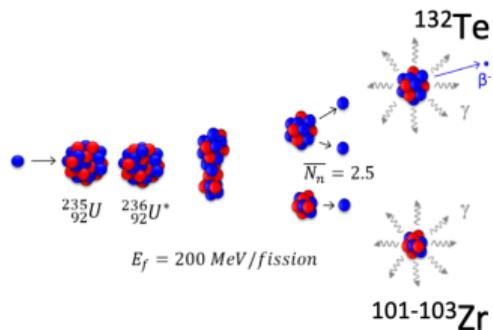
A. Saracino, Master Thesis, Univ. Milano ILL; A. Saracino et al., to be submitted to Phys. Rev. C

γ -ray spectroscopy of fission fragments

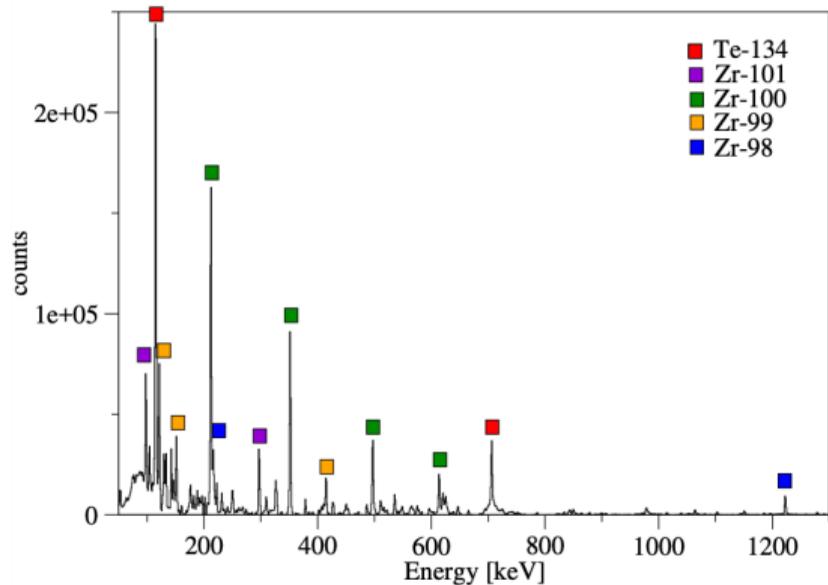
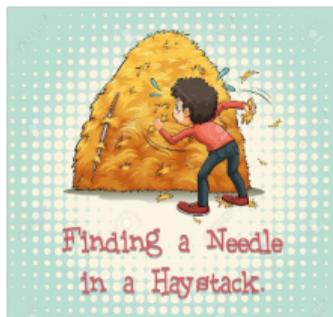
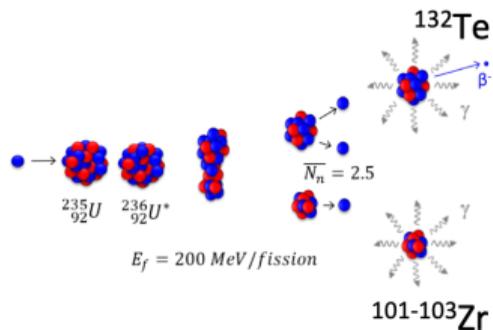


S. Leoni, C. Michelagnoli and J. Wilson, Riv. Nuovo Cim. 45 (2022) 461

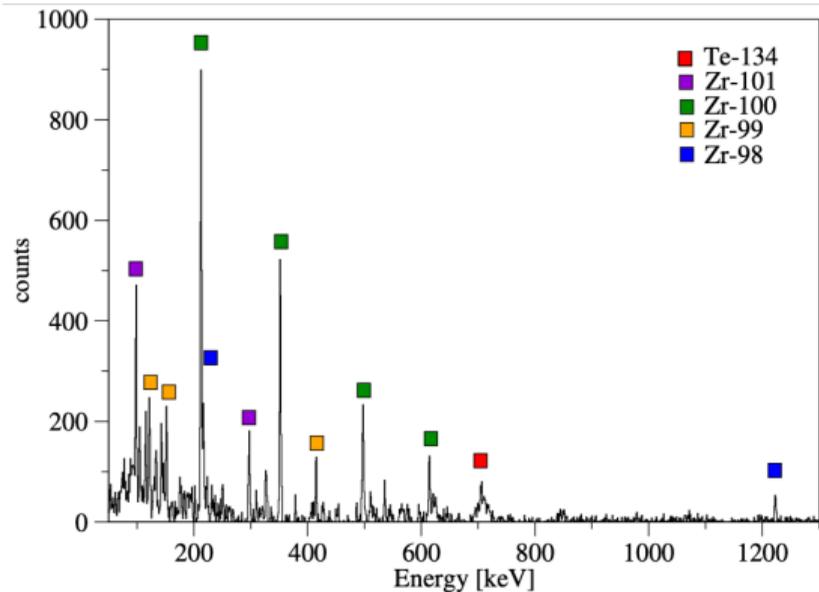
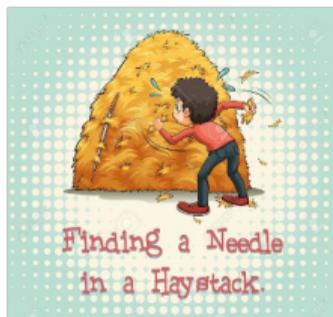
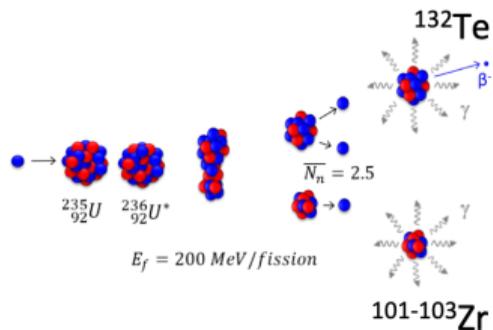
γ -ray spectroscopy of fission fragments



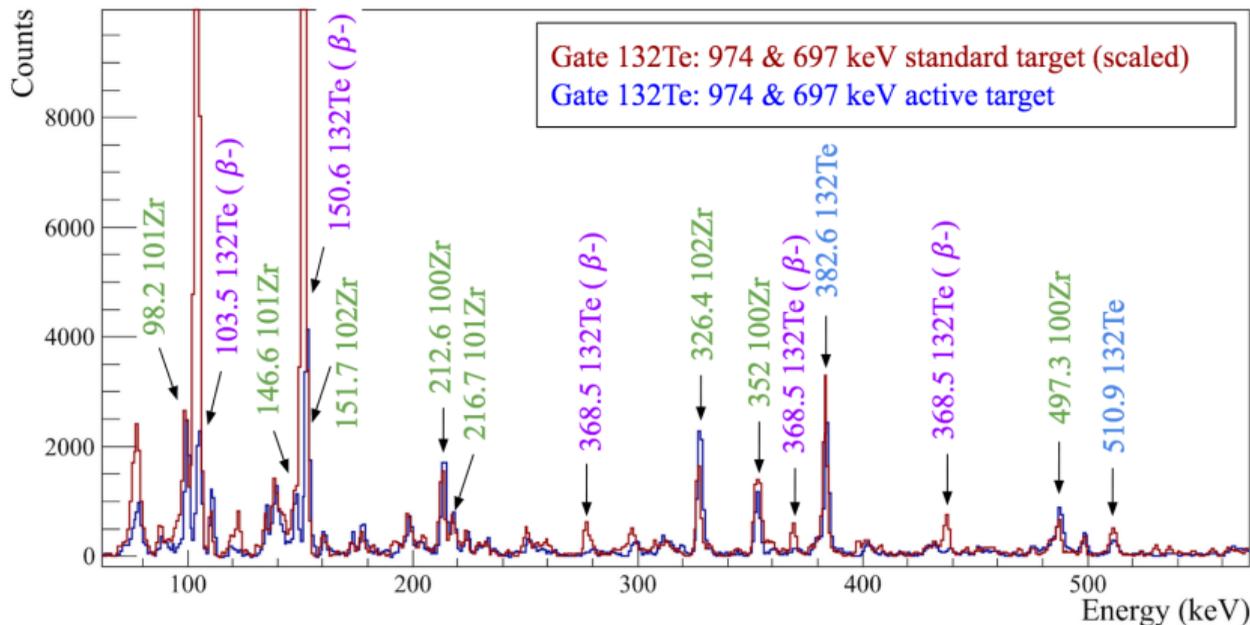
γ -ray spectroscopy of fission fragments



γ -ray spectroscopy of fission fragments



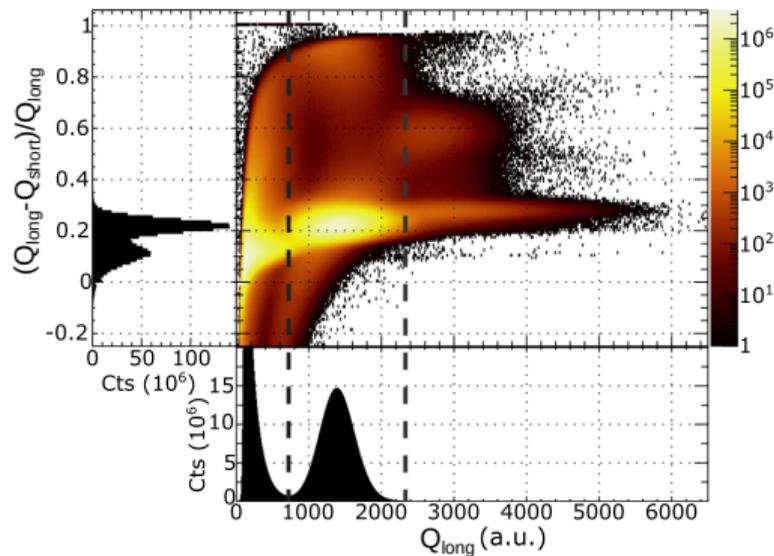
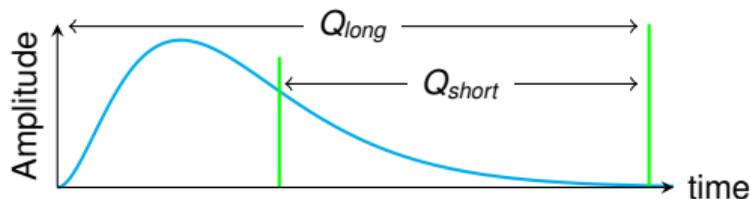
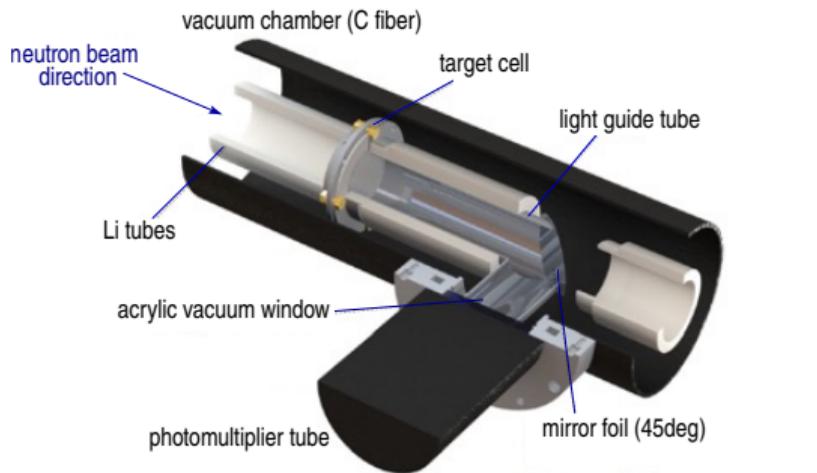
Suppression of β -decay induced background



tag of fission events using ^{235}U diluted in liquid scintillator

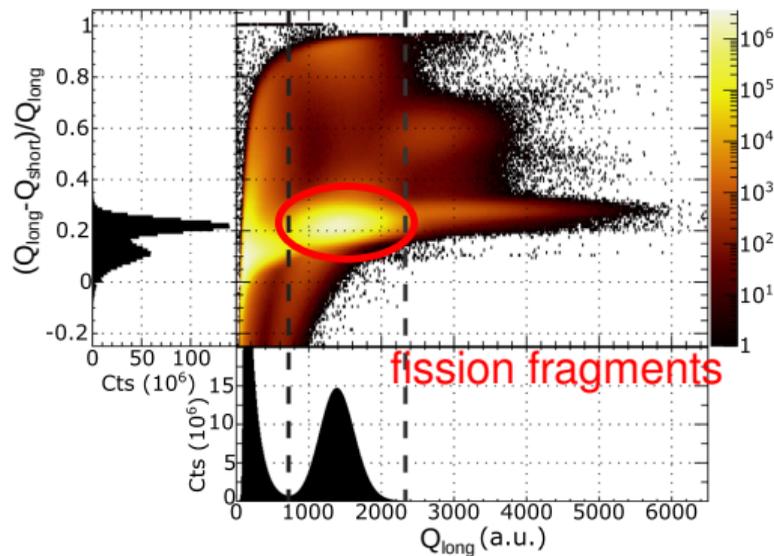
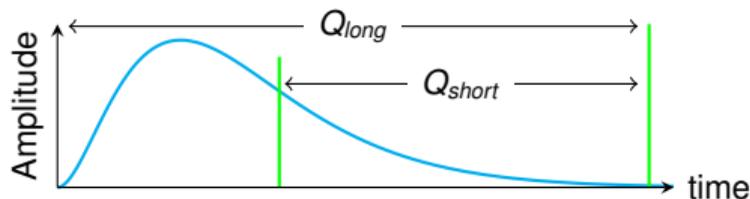
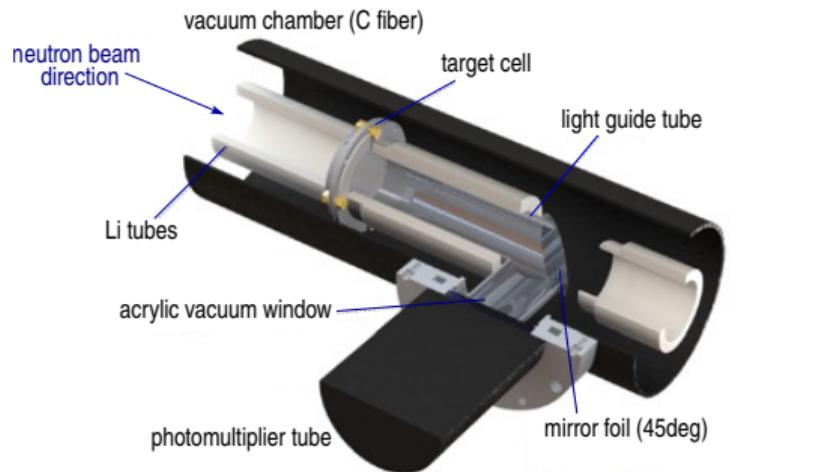
D. Reygadas et al., PhD Thesis Univ. Grenoble-Alpes and ILL

Tag of fission events: Pulse Shape Discrimination



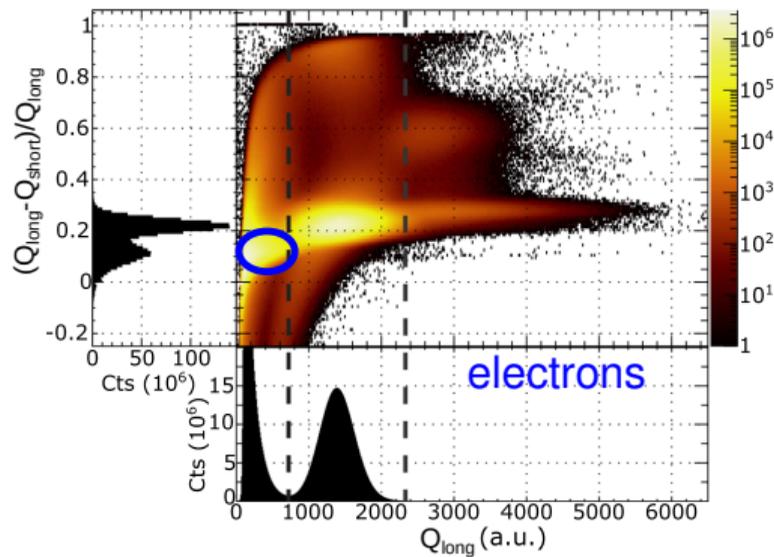
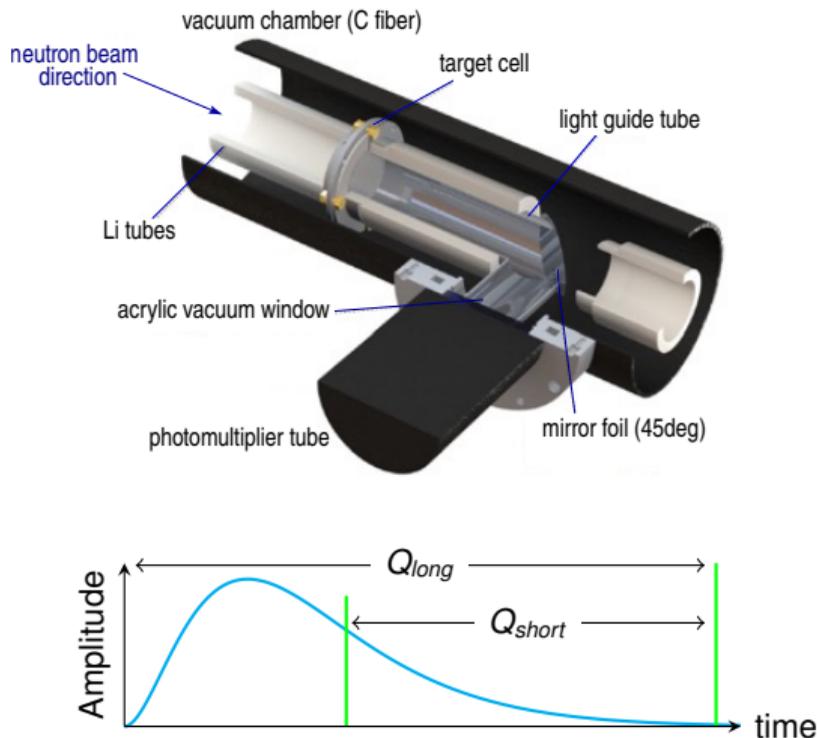
Adapted from *Eur. Phys. J A* 56 (2020) 207

Tag of fission events: Pulse Shape Discrimination



Adapted from *Eur. Phys. J A* 56 (2020) 207

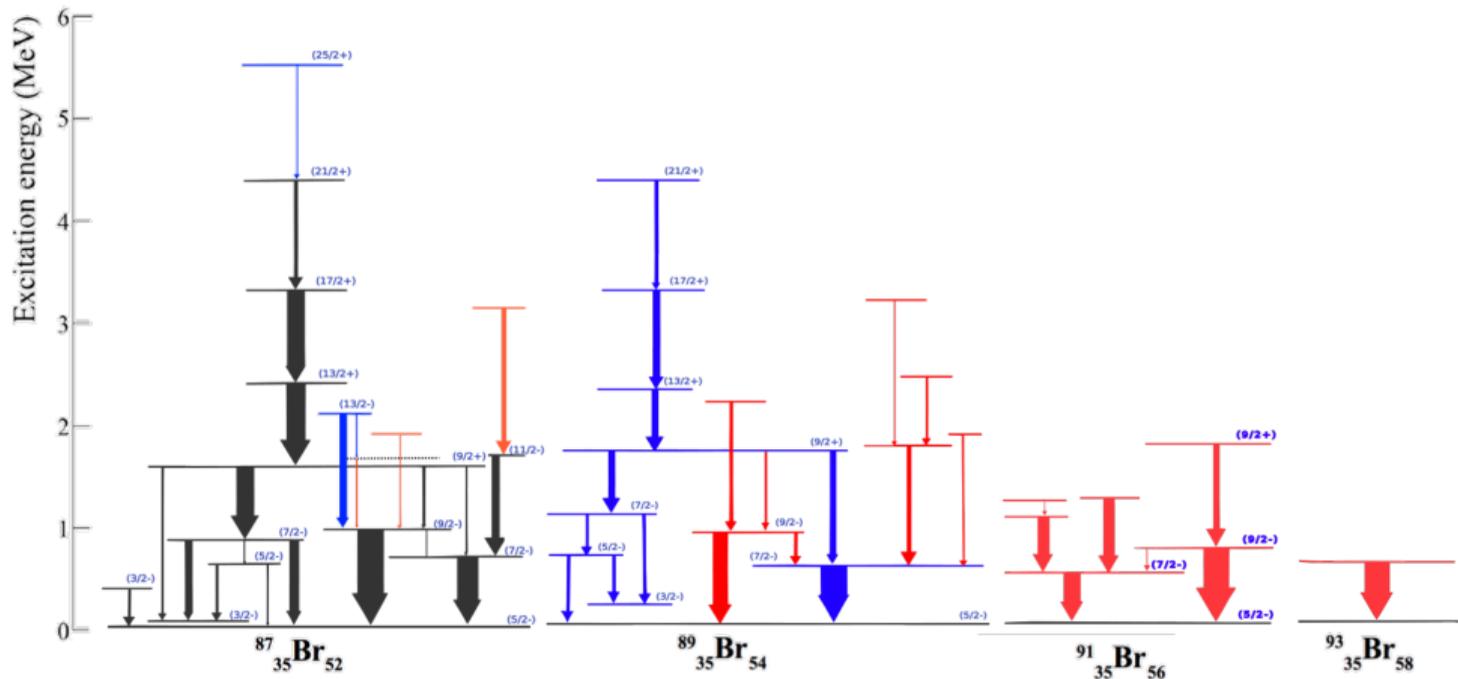
Tag of fission events: Pulse Shape Discrimination



Adapted from *Eur. Phys. J A* 56 (2020) 207

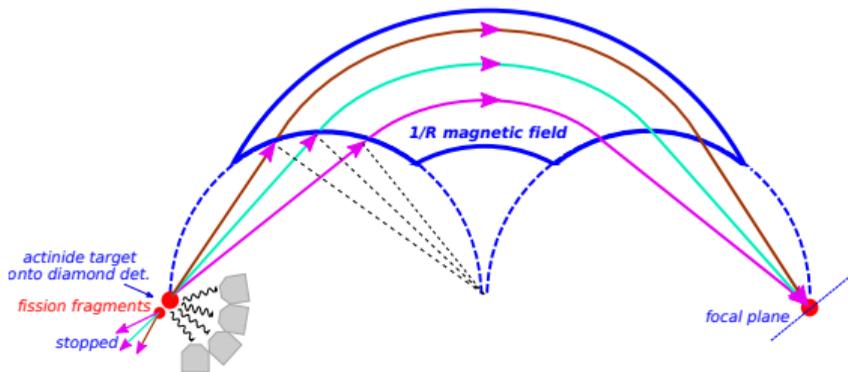
Systematics of n-rich Br isotopes: combined analysis of FIPPS and AGATA+VAMOS data

New SM interaction (F. Nowacki, D. Dao, IPHC Strasbourg). Stay tuned!



D. Reygadas, PhD Thesis, Univ. Grenoble-Alpes and ILL, 2021. D. Reygadas, J. Dudouet, G. Colombi et al., to be submitted to PRC

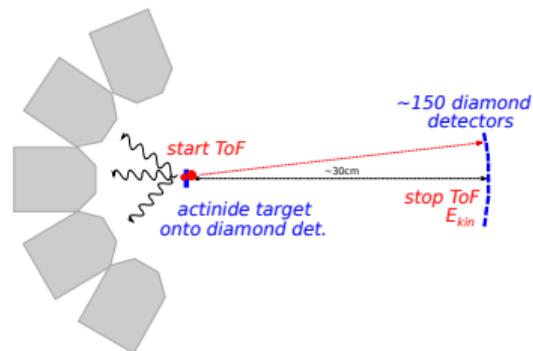
High-sensitivity fission experiments at FIPPS



Y.H. Kim et al. NIM B 463 (2020) 269

Gas-Filled-Magnet separator

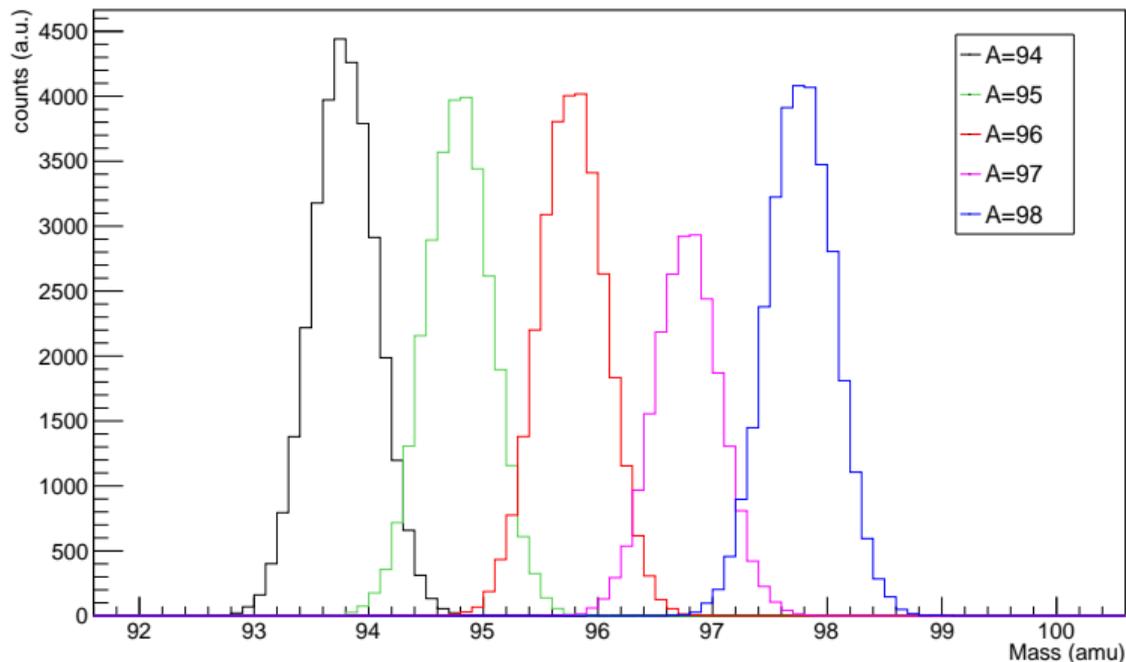
- ◇ 1/R field ($B_{max} < 1.7$ T)
- ◇ Y focusing \Rightarrow large acceptance
- ◇ same $B\rho$ for all trajectories
- ◇ horizontal focusing (Thales circles)



Diamond Array for Fission Fragment Identification (DAFFI)

- ◇ Fission fragment id via time-of-flight
- ◇ Technical development in collaboration with CEA (Cadarache and Saclay), CNRS Lyon and Grenoble (ANR project)

DAFFI performance



Approved test experiments at FIPPS and Lohengrin

Concluding remarks and future perspectives

- ◇ The **slow neutrons produced by the ILL high flux reactor** can be used for investigating nuclear structure, fission and astrophysics (complementary to other facilities)
 - ◇ nuclear structure close to stability (single particle vs collective degrees of freedom -²⁰⁸Pb, ¹⁶¹Gd, shape coexistence at zero spin -⁶⁴Ni, [N. Marginean's talk](#))
 - ◇ structure of neutron-rich fission fragments (shape coexistence, structure at large N/Z asymmetry, ...) [L. Iskra's talk](#) - lifetime measurements [G. Colombi's talk](#)

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- ◇ **Next ILL proposal deadline** February 15th 2023 -FIPPS, Lohengrin, PF1B (10^{10} cold neutrons/cm²/s, polarized 10^9 n/cm²/s)



17th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics - CGS17



July 17 – 21, 2022 Grenoble, France



- Nuclear Structure
- Nuclear Reactions
- Nuclear Astrophysics
- Fundamental Interactions and Symmetries
- Nuclear Data
- Experimental Techniques and Facilities
- Interdisciplinary Studies and Applications

Deadlines:

- Abstract: 28/02/2023
- Registration: 31/03/2021

Contact:

<https://workshops.ill.fr/event/188/>

Email: CGS17@ill.fr



Activities: History, Mountains, Sport,...



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Belledonne Mountains



Saint-Antoine
l'Abbaye



Lac Paladru



Vercors Mountains



Acknowledgements

G. Colombi, L. Domenichetti, R. Pommier, E. Ruiz-Martinez, M. Jenstchel, U. Köster, H. Faust, Y.H. Kim, J.-M. Daugas and other ILL colleagues and services

J. Dudouet et al. IP2I Lyon

N. Marginean, C. Mihai, A. Turturica et al., IFIN-HH

S. Leoni, S. Bottoni et al., University and INFN Milan

B. Fornal, N. Cieplicka et al., PAN Krakow

J.M. Regis, L. Knafla et al., IKP Cologne

and many many other collaborators!!!

Acknowledgements

