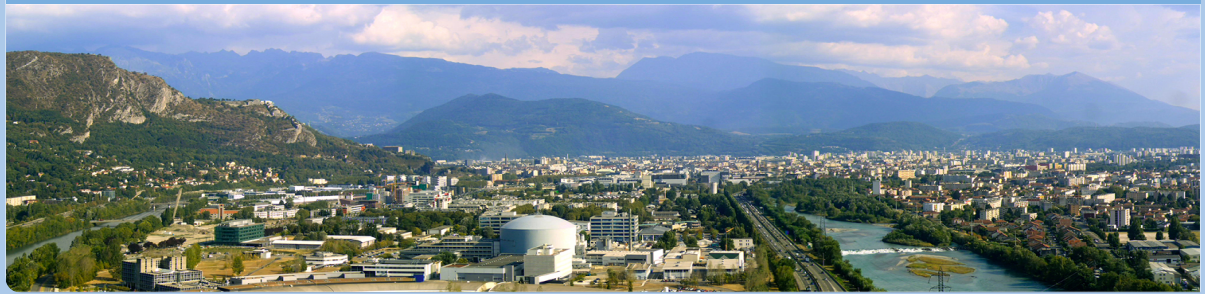
NEUTRONS FOR SOCIETY

Nuclear Structure after slow neutron reactions at ILL

INTRANS 2024 workshop

Caterina Michelagnoli | 23 January 2024

Institut Laue-Langevin



Outline

NEUTRONS FOR SOCIETY

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, ...)

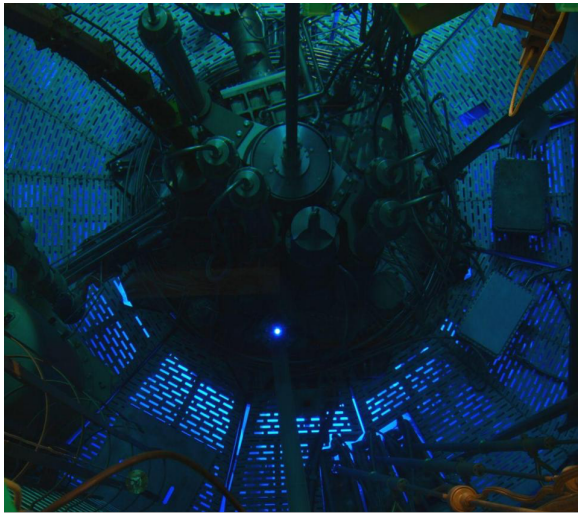
(n,fission) using a *fission tag* -systematic investigations in neutron-rich nuclei

$\approx$ps lifetime measurements via lineshape analysis techniques

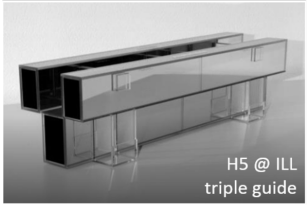
Concluding remarks and future possibilities

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

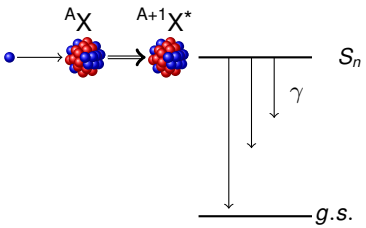
World's highest neutron flux for in-beam experiments



- ✓ up to 1.5 10^{15} n/s/cm^2
- ✓ in-pile irradiation of radioisotopes
- ✓ "slow" neutrons delivered to $\approx$ 40 instruments
- ✓ guided with little losses over hundreds of meters

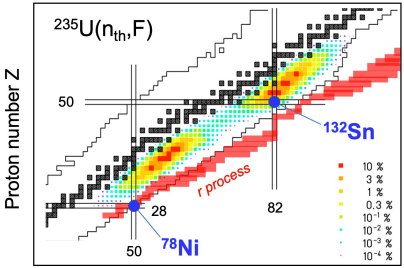


Neutron-induced reactions



Thermal neutron capture reactions

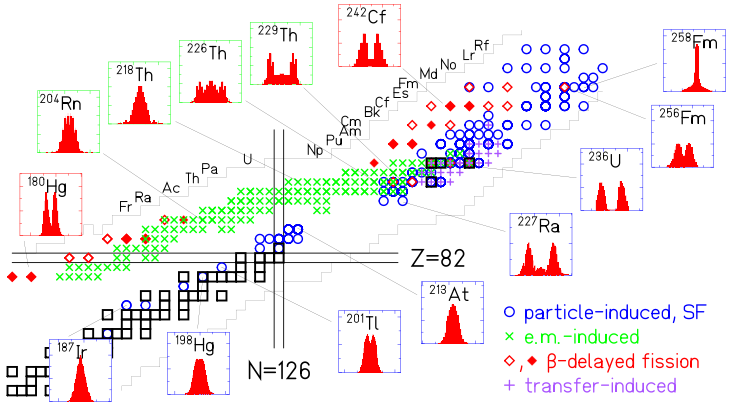
- Structure of nuclei close to stability
- Structure at low spin (below S_n)
- Cross-sections (applications)
- ^{27}Al(n,γ): σ=0.2 b; ^{157}Gd: 2.5 10^5b



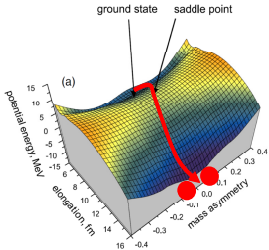
Neutron-induced fission

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

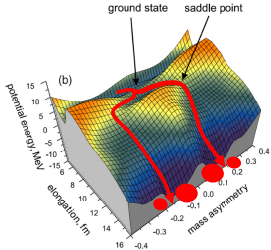
Fission yields



Macroscopic Energy only
(like a Liquid Drop)

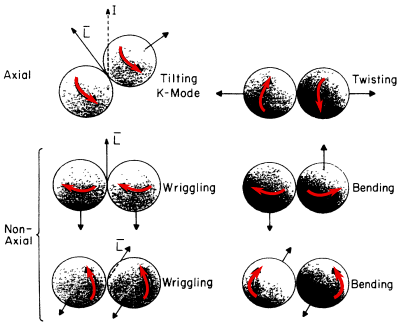


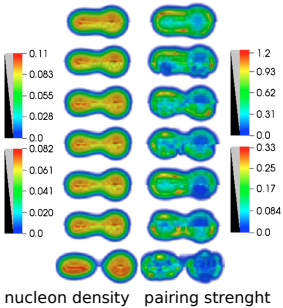
Microscopic effects added
(nuclear shells and pairing)

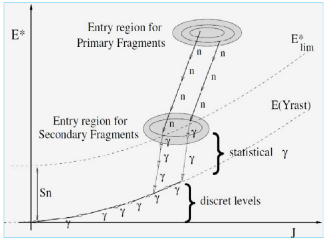


A.N. Andeyev et al., Rep. Prog. Phys. 81 (2018) 016301

Generation of angular momentum in fission





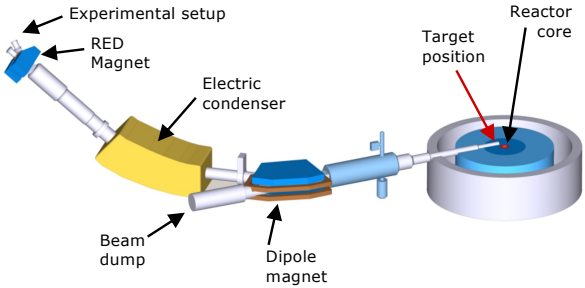


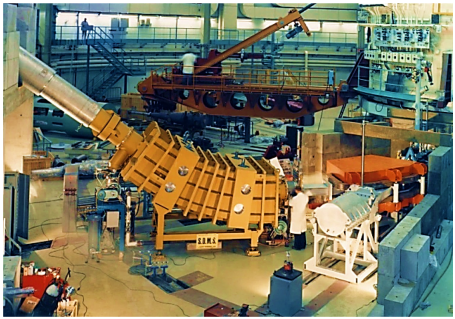
B. Back et al., Phys. Rev. C 41 (1990) 1495; A. Bulgac et al., Phys. Rev. Lett. 116 (2016) 122504; O. Litaize et al., Eur. Phys. J A 51 (2015) 177

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

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

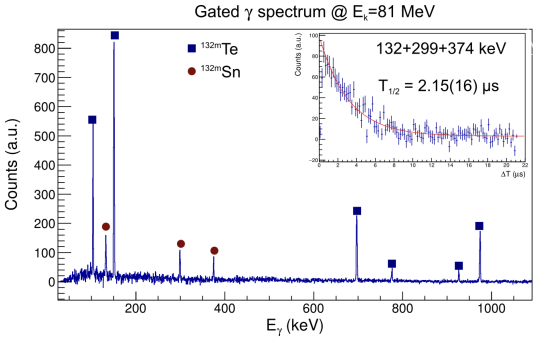
The Lohengrin (PN1) fission fragment separator

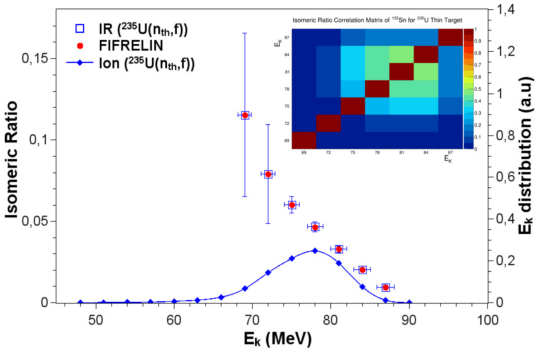




- ✓ Target in-pile, few mg (^{235}U, ^{241}Pu, ^{245}Cm ...)
- ✓ 10^{12} fissions/s $\Rightarrow$ mass-separated fission fragments, up to 10^5 per second, $t_{1/2} \geq \mu s$
- ✓ Up to $A/\Delta A > 1000$, $E/\Delta E > 1000$
- ✓ Detection of γ rays, conversion electrons, and β rays

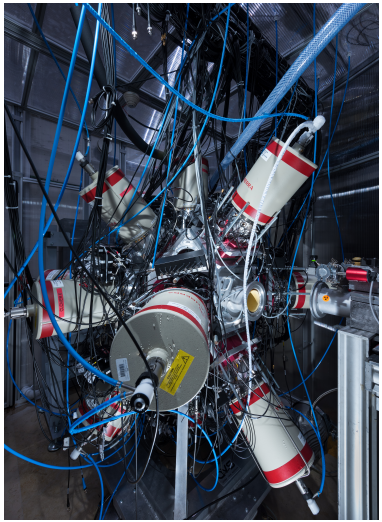
Kinetic energy dependence of fission fragment isomeric ratios for spherical nuclei ^{132}Sn





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

The FIPPS instrument at ILL



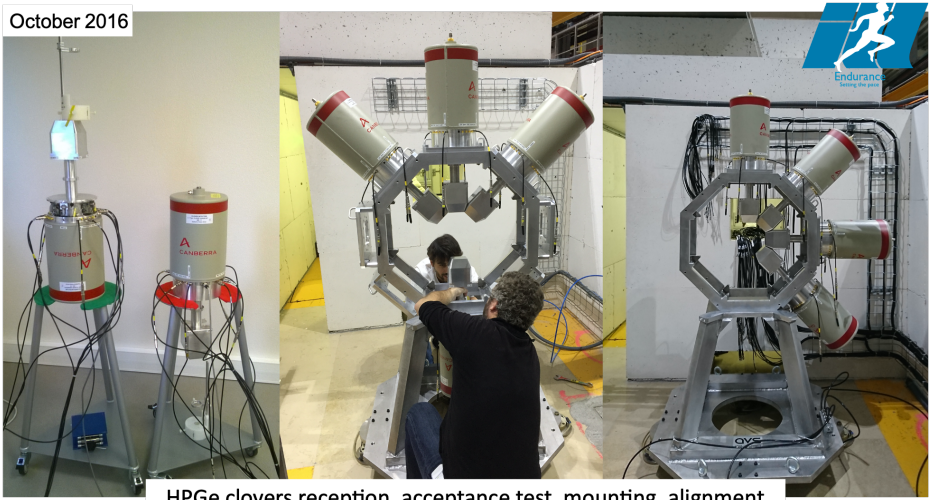
Fission Product Prompt γ-ray Spectrometer

- ✓ 8HPGe clovers+Anti-Comptons (segmented)
- ✓ “pencil-like” thermal neutron beam (1.5cm diam., 5 10^7 n/s/cm^2)
- ✓ digital electronics
- ✓ list mode
- ✓ tight polycarbonate casemate (radioactive targets)
- ✓ possibility to add ancillary detectors: $LaBr_3$, 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

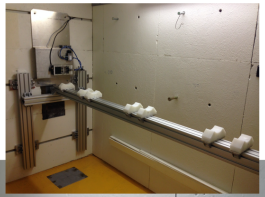
FIPPS Story



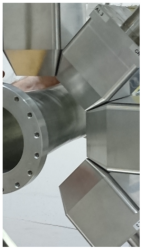
HPGe clovers reception, acceptance test, mounting, alignment

FIPPS Story

October 2016



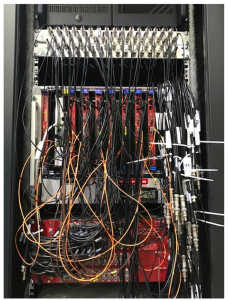
@ H22

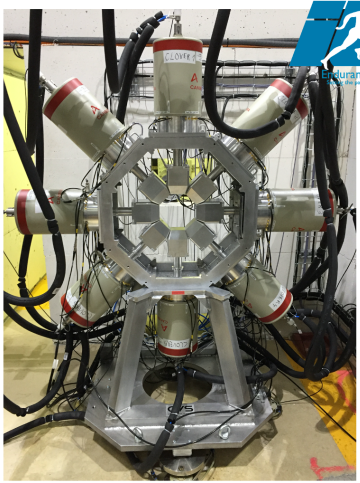


Beam collimation, target chamber and beam stop assembly, mounting, alignement

FIPPS Story

November 2016

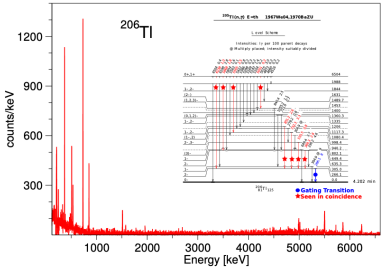




LN2 line, detectors cooling on structure, cabling and electronics connection

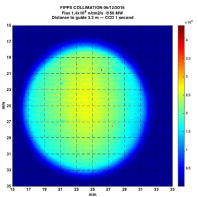
FIPPS Story

November 2016



First user experiment

1.5 cm diameter
10^8 n/s/cm^2



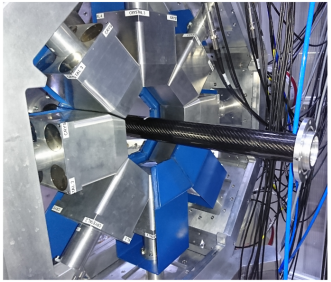
Endurance
Setting the pace

R. Casten as a FIPPS user!

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

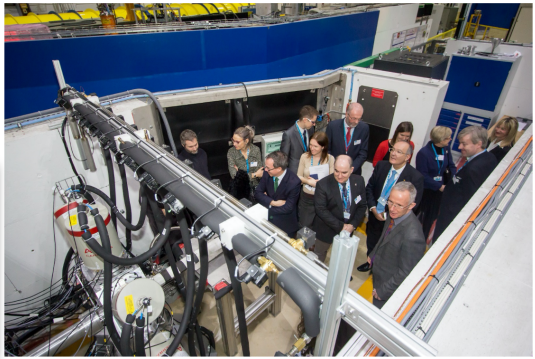
FIPPS Story

January 2017

NEUTRONS FOR SOCIETY

50 YEARS OF SERVICE TO SCIENCE AND SOCIETY

Endurance
testing the pace



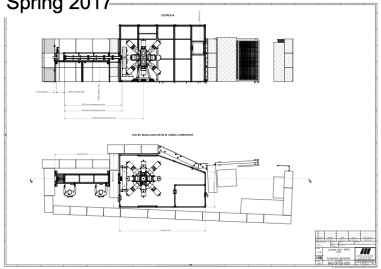
ILL 50th anniversary celebration, FIPPS was there!

FIPPS Story

Nuclear Physics News International 2017: on the cover!

FIPPS Story

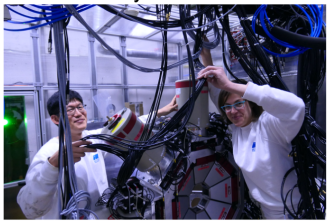
Spring 2017



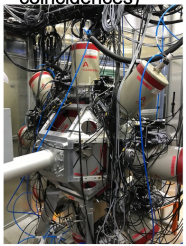
Installation of tight polycarbonate casemate, preparation for new ASI for handling of radioactive targets (signature ASI/DSI March 2018)

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)

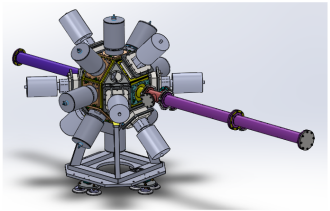


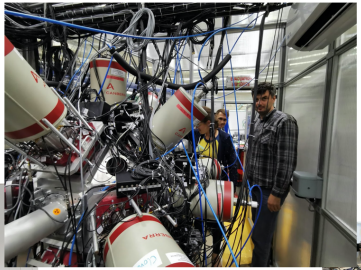
~10 km cables
~80 l LN_2 per day
Up to 70 TB raw data in one cycle

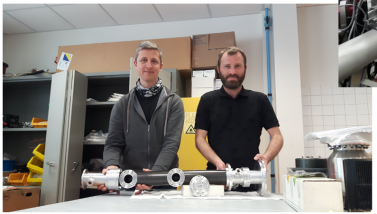
Technical specifications, offers evaluation, reception, installation of antiCompton shields

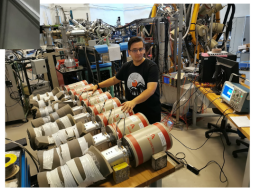
FIPPS Story

2018-2019



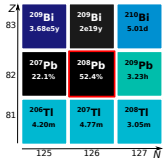


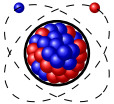




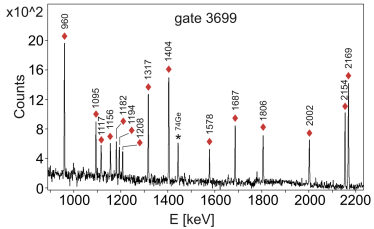
Additional HPGe clovers and ACs from IFIN-HH (RO). Radioactive (actinide) targets experiments

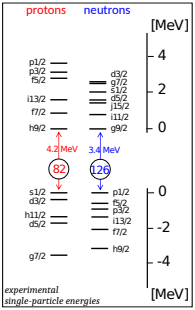
Shell model + realistic interactions around ^{208}Pb

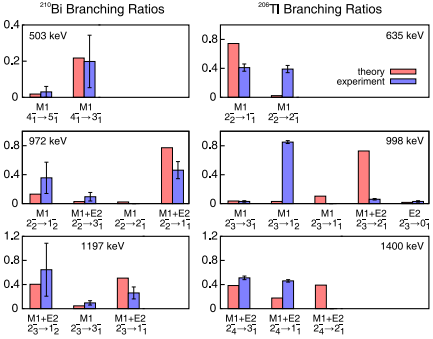




2mg ^{205}Tl target, 9 days beam time
coincidence spectrum with primary γ ray



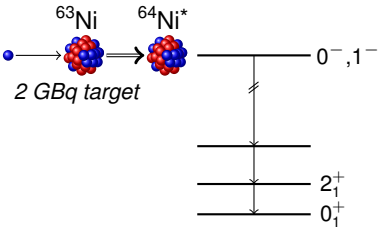


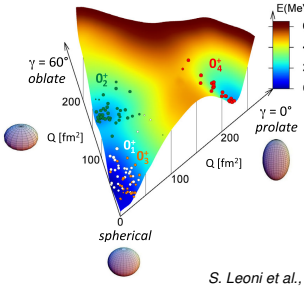


^{206}Tl: Sensitivity to non diagonal matrix elements

N. Cieplicka et al., Phys. Lett. B 802 (2020) 135222

Shape coexistence at zero spin: ^{64}Ni





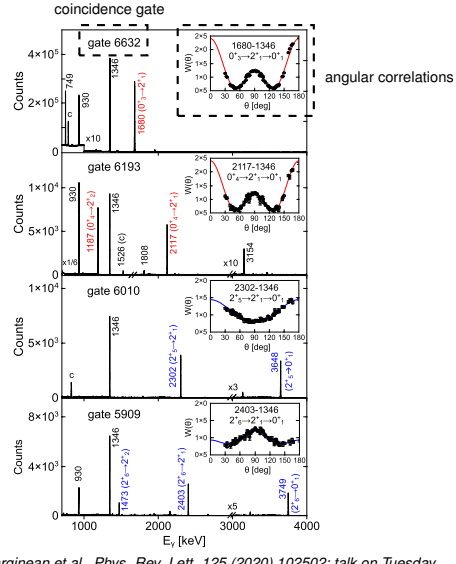
coincidence gate

confirmed 0_3^+

firmly assigned 0_4^+

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

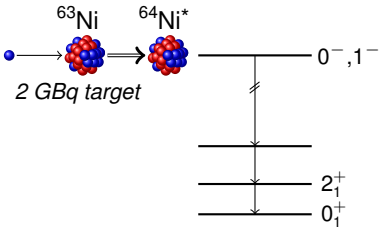
2_6^+: mainly E2 ("hindered")

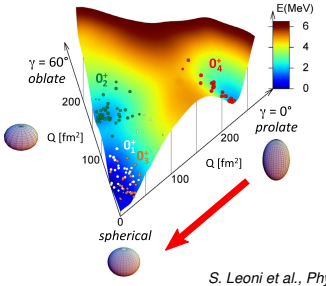


S. Leoni et al., Phys. Rev. Lett. 118 (2017) 162502

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

Shape coexistence at zero spin: ^{64}Ni





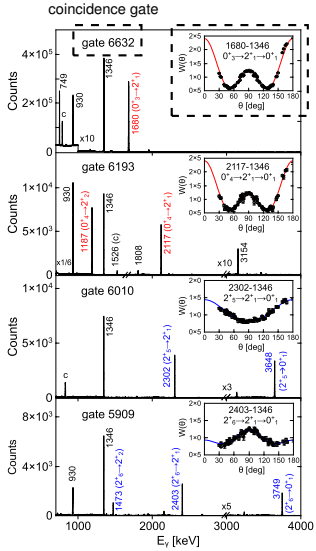
confirmed 0^+_3 ←

firmly assigned 0^+_4 ←

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

2^+_6: mainly E2 (”hindered”) ←

2^+ state in prolate minimum

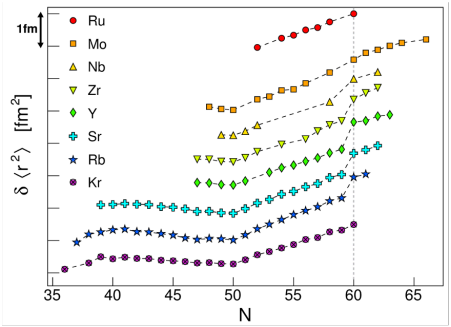


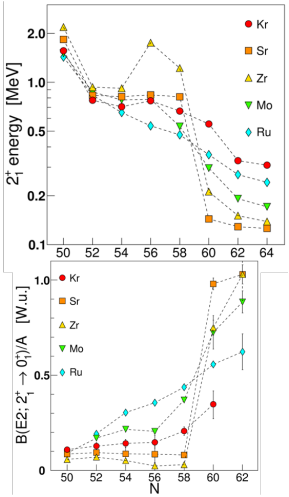
angular correlations

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

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

Shape coexistence in nuclei with A≈100

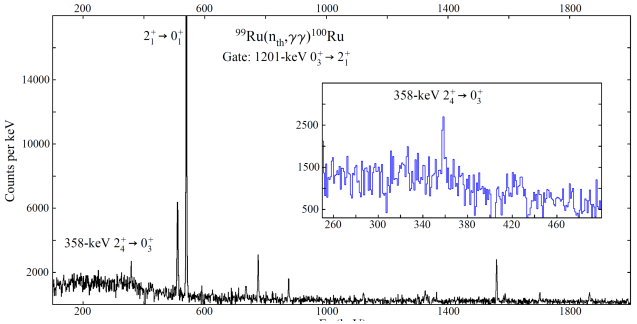


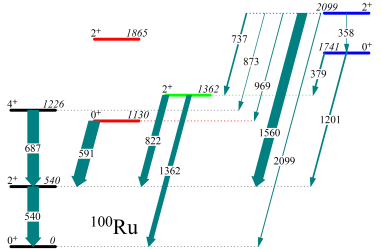


Garrett, Zielińska, Clément, PPNP 124, 103931 (2022)

Shape coexistence in Ru isotopes: structure of ^{100}Ru

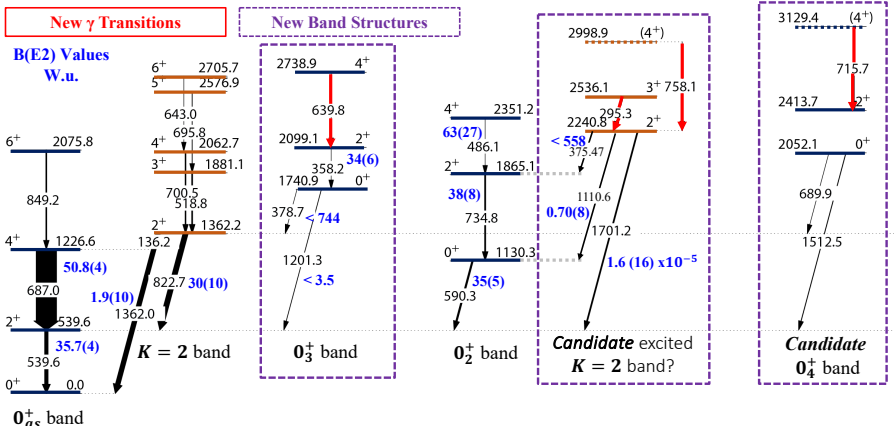
- Previous branching ratio for 358-keV γ ray, 3.1(4)%, leads to 270 W.u. $2_4^+ \rightarrow 0_3^+$ transition – obviously wrong, casting doubt on placement and band assignment
- New branching ratio 0.39(6)%, yielding 34(5) W.u. using half life of 390(70) fs from (n,$n'\gamma$) reaction – $B(E2)$ indicates similar collectivity to gsb that has 35.3(7) W.u.





Courtesy of P. Garret

Band structures in ^{100}Ru



Analysis by S. Pannu (University of Guelph)

0^+ 1828

^{102}Ru(p,t)^{100}Ru Does not observe this state (S. Buck, M.Sc. Thesis, University of Guelph)
&
Current work sees no γ decay from this level

Courtesy of P. Garret

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

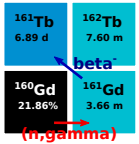
^{161}Gd (Z=64, N=97)

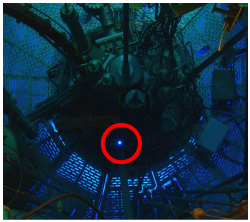
Close to N=90 ”questioned” magic number

Medical interest (^{161}Tb production)

Only few excited states are known

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



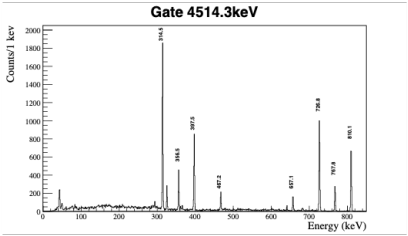


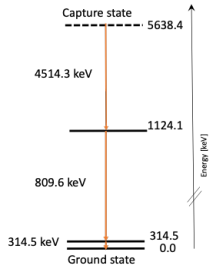
Target produced at the ILL V4 position

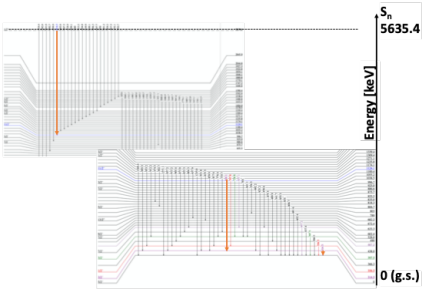
Isotope	σ (b)	A ($\frac{g}{mol}$)	fraction of captures (%)	Compos. (%)
^{155}Gd	60330	155	0.3	$3.3 * 10^{-5}$
^{157}Gd	254000	157	0.8	$4.2 * 10^{-6}$
^{160}Gd	1.4	160	98.9	98.10

A. Saracino, Master Thesis, Univ. Milano ILL

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





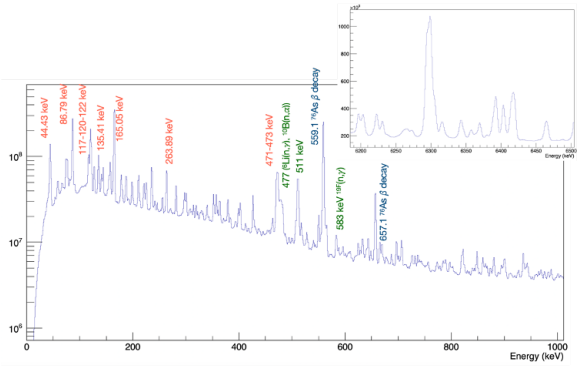


35 new excited levels, 294 new γ transitions found

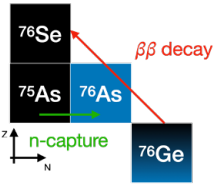
Performed experiment at IFIN-HH (multinucleon transfer)

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

Structure of ^{76}As of interest for ^{76}Ge $\beta\beta$ decay



FIPPS at ILL

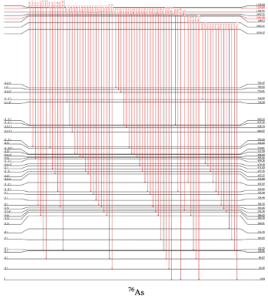


^{75}As(n,γ) measurement (Nov '23)
14 days beam time
3 targets tested (different masses)

E_x : from 1125 to 1034 keV

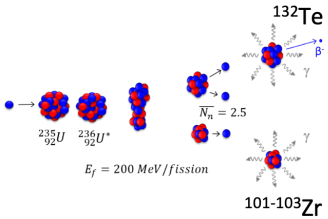
Eight states decay scheme

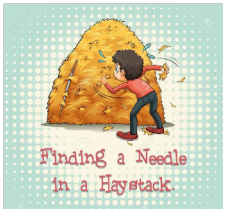
90 keV range, 88 transitions

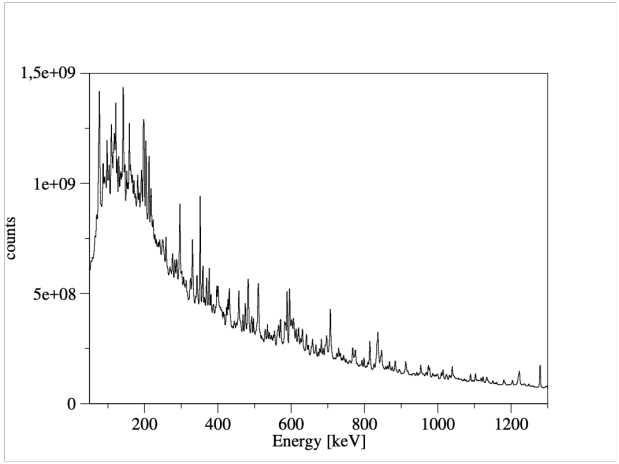


L. Domenichetti, ILL

γ-ray spectroscopy of fission fragments

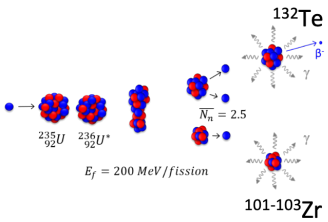


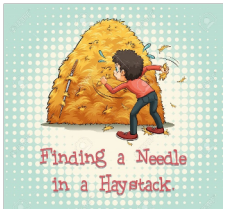


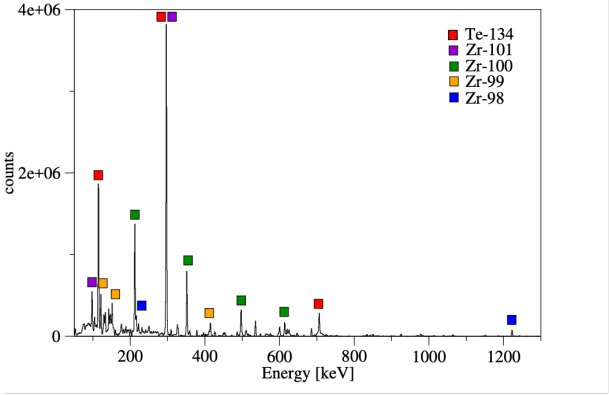


S. Leoni, C. Michelagnoli and J. Wilson, Riv. Nuovo Cim. 45 (2022) 461

γ-ray spectroscopy of fission fragments







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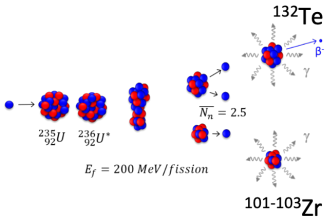
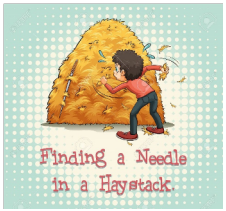
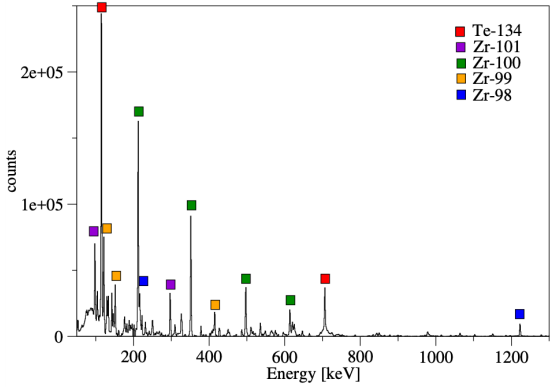
γ-ray spectroscopy of fission fragments







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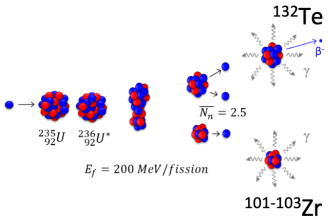

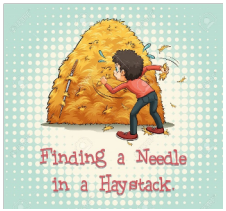

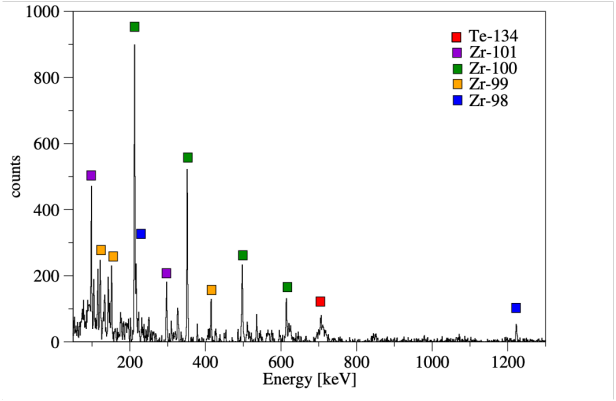

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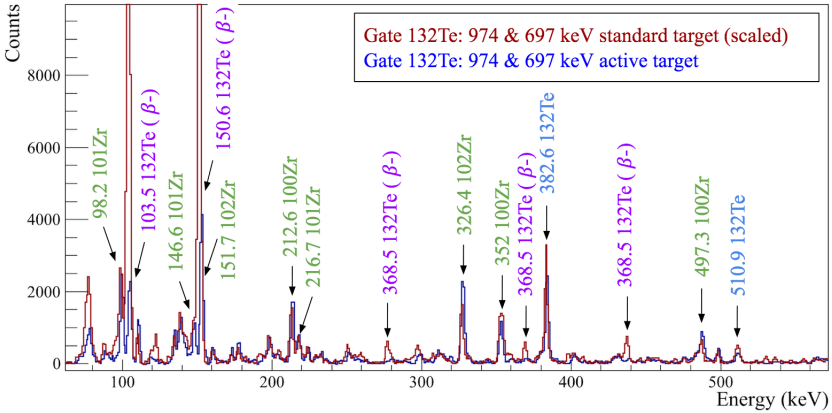
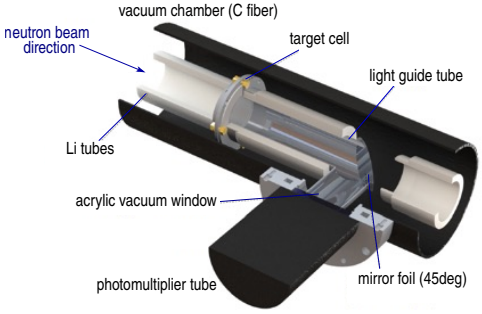
Suppression of β-decay induced background

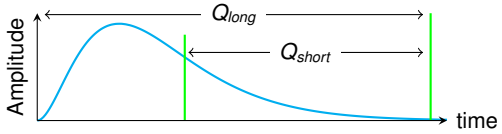


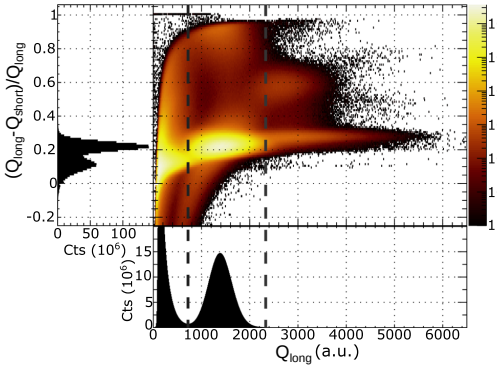
tag of fission events using ^{235}U diluted in liquid scintillator

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

Tag of fission events: Pulse Shape Discrimination

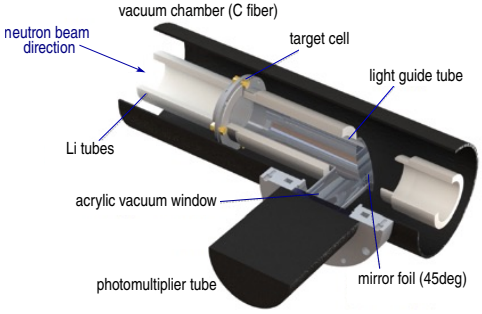


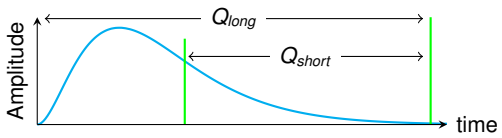


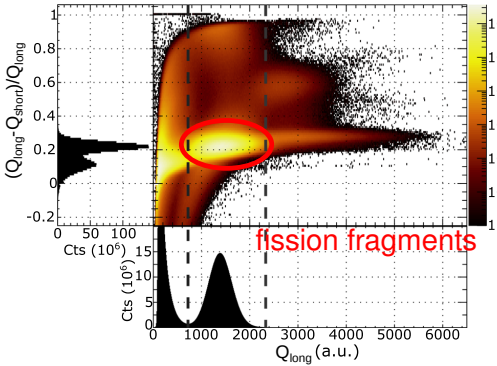


Adapted from Eur. Phys. J A 56 (2020) 207

Tag of fission events: Pulse Shape Discrimination







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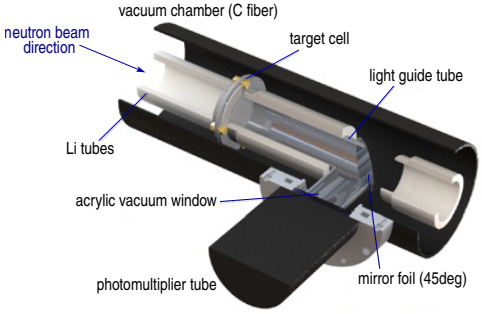
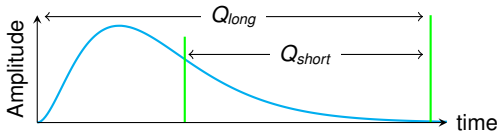
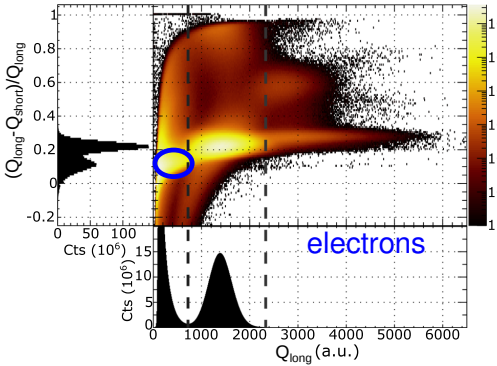
Tag of fission events: Pulse Shape Discrimination



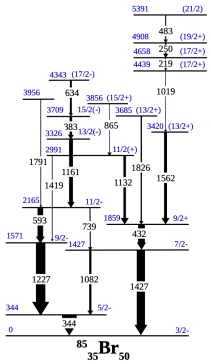


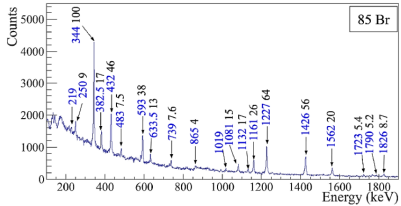


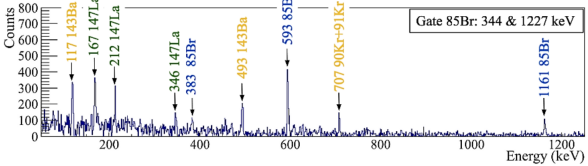
Adapted from Eur. Phys. J A 56 (2020) 207

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

New SM interaction, DNO+SM calculations (F. Nowacki, D. Dao, IPHC Strasbourg). New spectroscopic info up to ^{93}Br. Stay tuned!



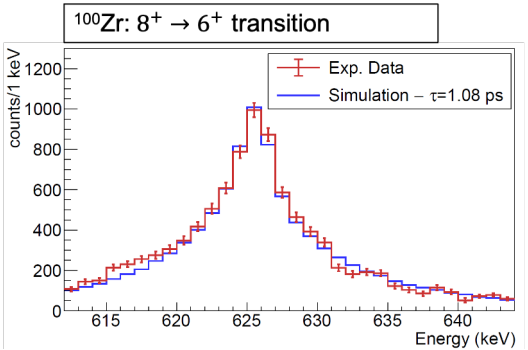


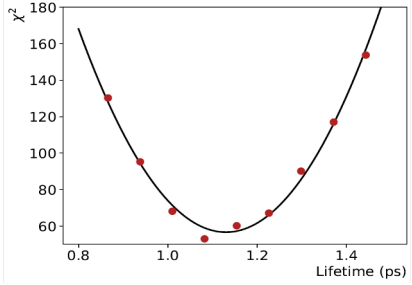


G. Colombi et al., proceedings INPC2022, in press; D. Reygadas, PhD Thesis, Univ. Grenoble-Alpes and ILL, 2021. J. Dudouet, D. Reygadas, G. Colombi et al., to be submitted to PRC

Lineshape analysis on the active scintillator data

Lifetime of medium-high spin states in n-rich nuclei A≈100

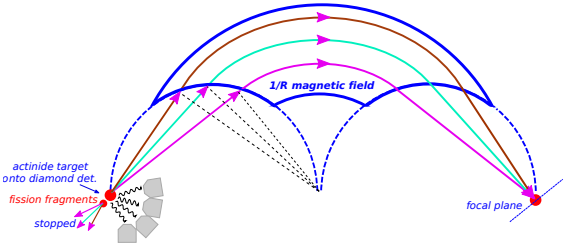


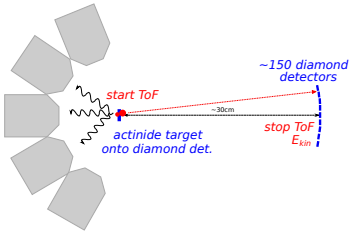


"Full simulation", including FIFRELIN simulations for E_{kin} vs E^* for fission fragments

G. Colombi, PhD Thesis Univ. Grenoble-Alpes, 2023; G. Colombi et al., in preparation

High-sensitivity fission experiments at FIPPS





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

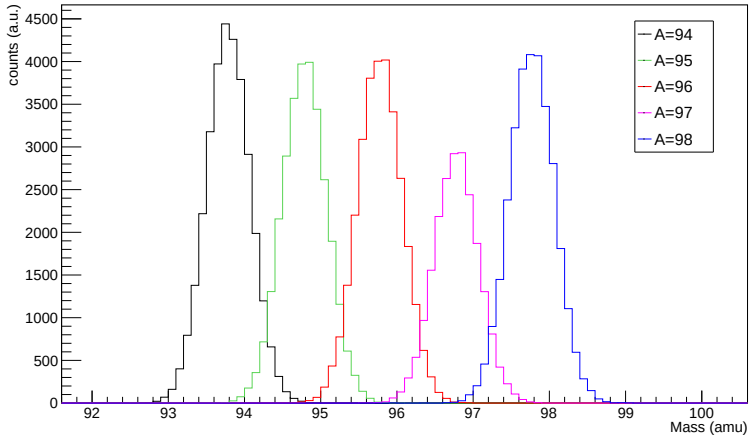
Gas-Filled-Magnet separator

- 1/R field (B_{max} <1.7 T)
- Y focusing ⇒ large acceptance
- same Bρ 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

DAFFI performance



Approved test experiments at FIPPS and Lohengrin

G. Colombi

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 -^{208}Pb, ^{161}Gd, shape coexistence at zero spin -^{64}Ni)
  - structure of neutron-rich fission fragments (shape coexistence, structure at large N/Z asymmetry, ...); lifetime measurements

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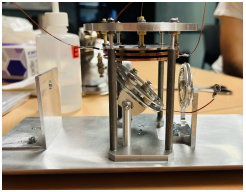
- A fission fragment selection setup at a neutron beam will allow for high-sensitivity prompt spectroscopy of fission fragments (excellent performance expected, diamond technology)
- Many projects/possibilities:
  - plunger setup for fission
  - ^{179}Ta radioactive target (^{180}Ta nucleosynthesis -ILL, nToF, LANSCE)
  - fission data open for LoI
  - diamond-based fission tag
  - possibility for ^{245}Cm(n,fission)
  - other ideas ?? Proposal deadline 25/01 !!!



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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

P. Garret et al., Univ. of Guelph

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

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