High-resolution γ-ray spectroscopy at a neutron beam: news from FIPPS at ILL

Caterina Michelagnoli

NACRE Workshop, Saclay, 27-28 June 2022

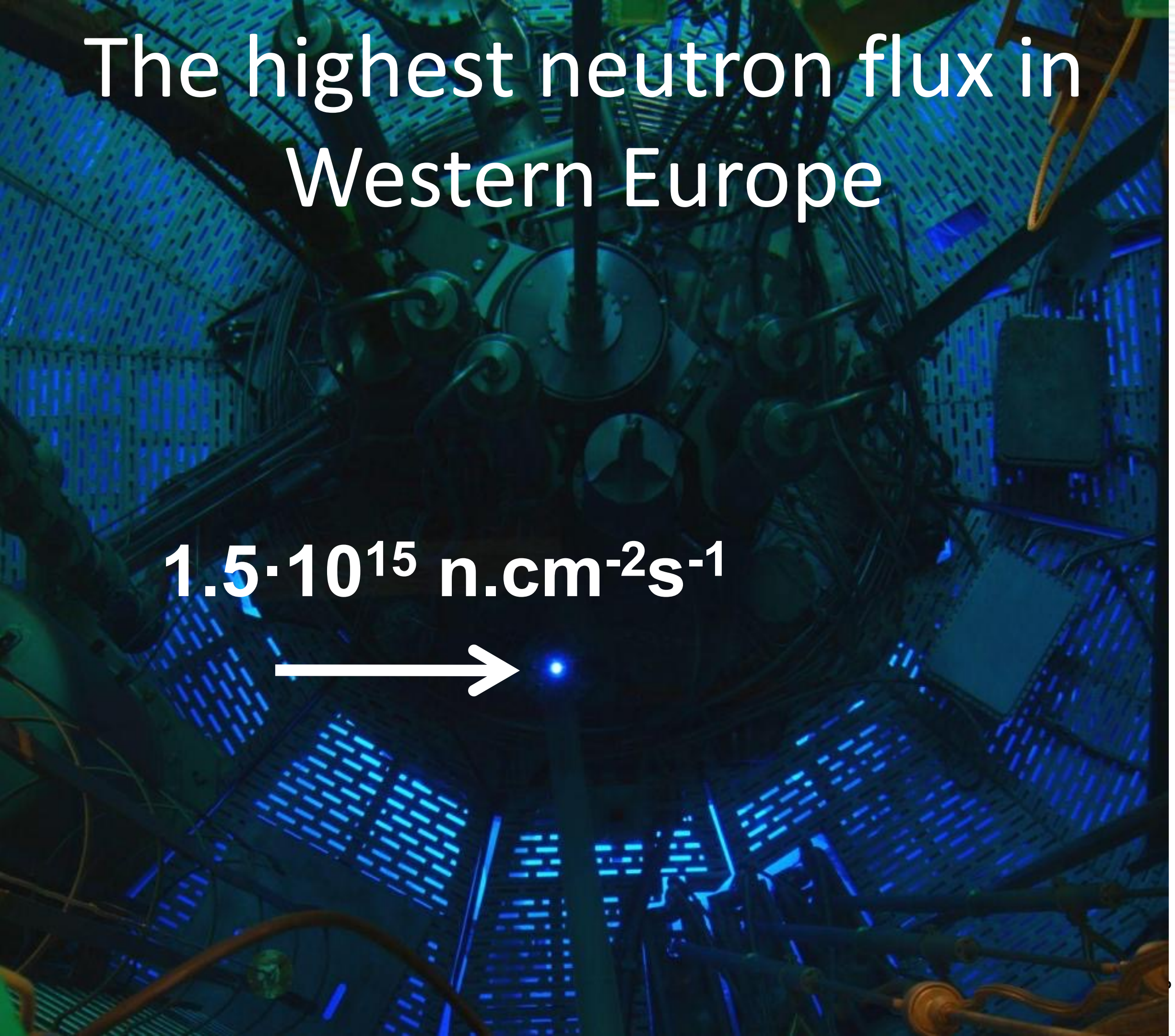
RhôneAlpes Région

Endurance Setting the pace

THE EUROPEAN NEUTRON SOURCE

NEUTRONS FOR SOCIETY

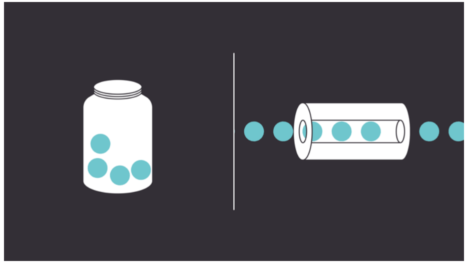
The highest neutron flux in Western Europe



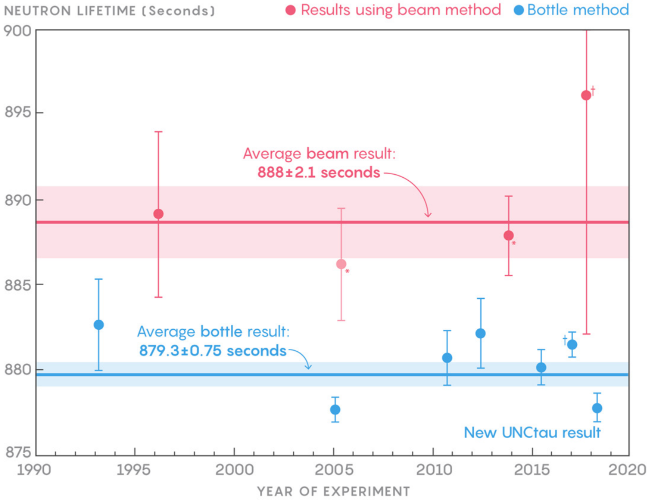
- ✓ In pile irradiations of radioisotopes
- ✓ In pile target experiments
- ✓ <u>World's highest neutron flux for in-beam experiments</u>

The lightest radioactive beam…

Storage (« bottle ») vs
in-beam measurements

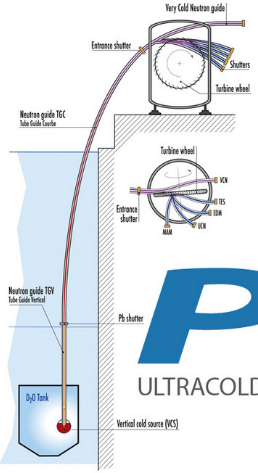


The neutron lifetime puzzle



https://www.quantamagazine.org/

M. Tanabashi et al. (Particle Data Group),
Phys. Rev. D 98, 030001 (2018) and 2019 update



PF2
ULTRACOLD NEUTRONS FOR SCIENCE

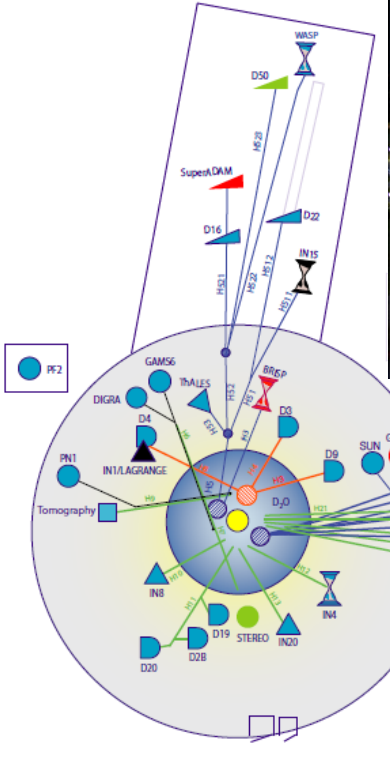
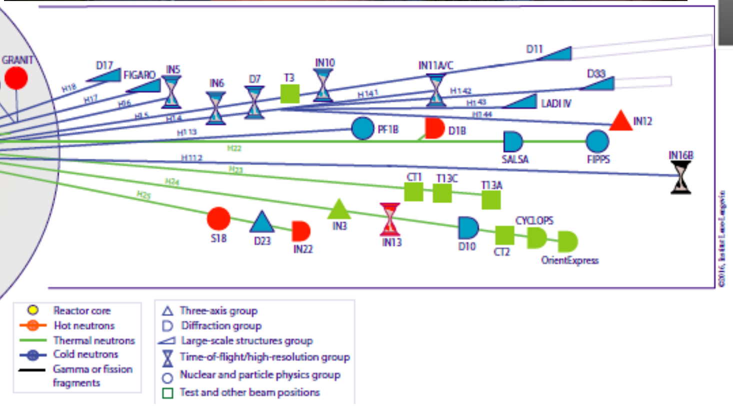
Ultra-Cold-Neutrons experiments @ ILL

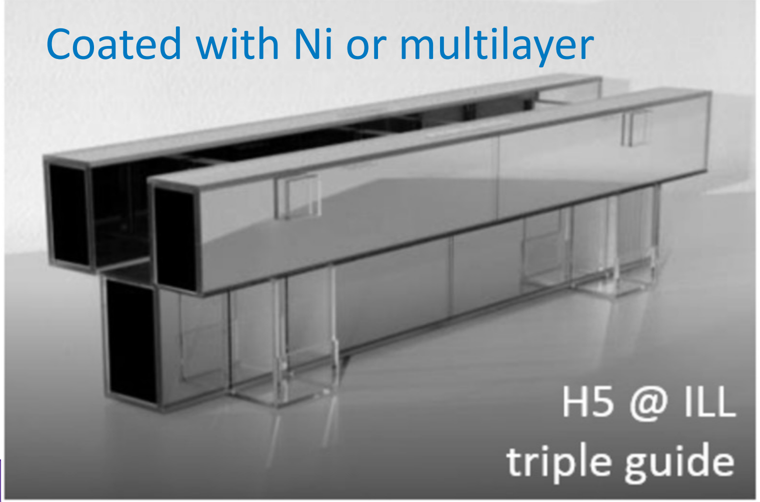
n lifetime
A.P. Serebrov et al., PRC97 (2018) 055503

Search for dark energy
T. Jenke et al., Nature Phys. 13 (2017) 920

Gravity-resonance spectroscopy with neutrons
T. Jenke et al., Nature Phys. 7 (2011) 468

Neutron guides and instruments @ ILL

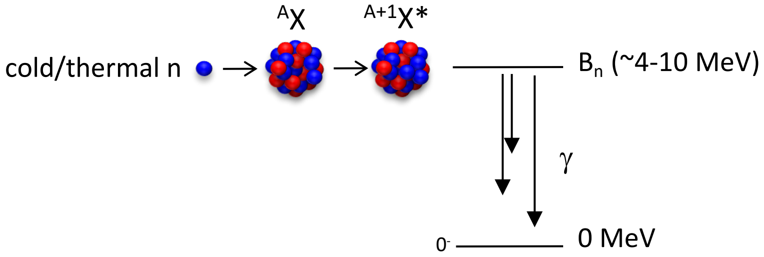


Neutrons can be guided with little losses over 100 m

Clean slow neutron beams (bent guides)

Why using neutrons?

"Slow" neutron-induced reactions



(n,γ) on stable (rare)/radioactive targets

- ➔ close to stability
- ➔ structure at low spin (below n-separation energy)
- ➔ cross-sections (applications)

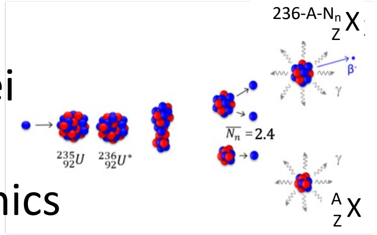
^{27}Al(n,γ) : σ=0.2 b

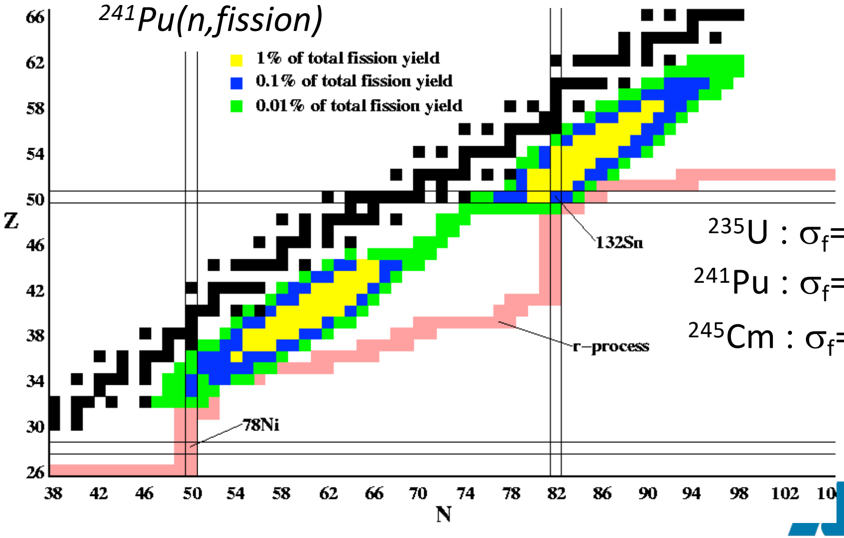
^{64}Ni(n,γ) : σ=1.5 b

^{157}Gd(n,γ) : σ=2.5e5 b

(n,fission) on actinides

- ➔ structure of n-rich nuclei (far from stability)
- ➔ fission yields and dynamics





^{235}U : σ_f=585 b

^{241}Pu : σ_f=1012 b

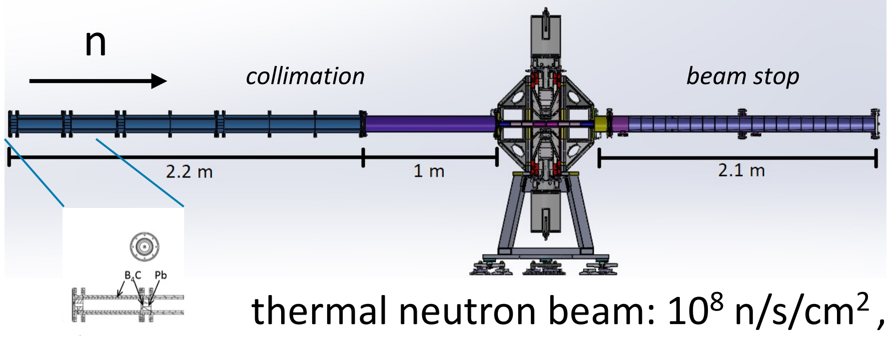
^{245}Cm : σ_f=2141 b

High-resultion γ spectroscopy @ n beam

The Fission-Product-Prompt Spectrometer (FIPPS)

Endurance

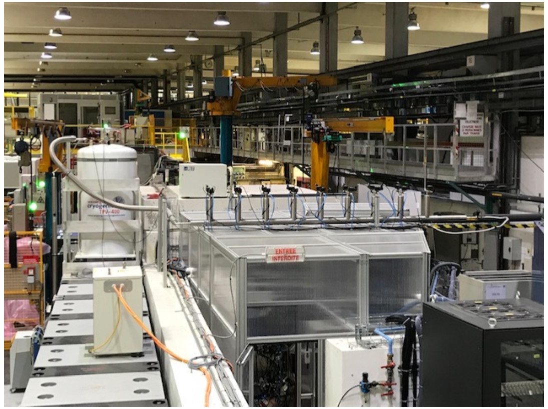
RhôneAlpes Région



8-16 HPGe clovers
+
segmented anti-Compton shields (ACs)

thermal neutron beam: 10^8 n/s/cm^2 , d=15mm

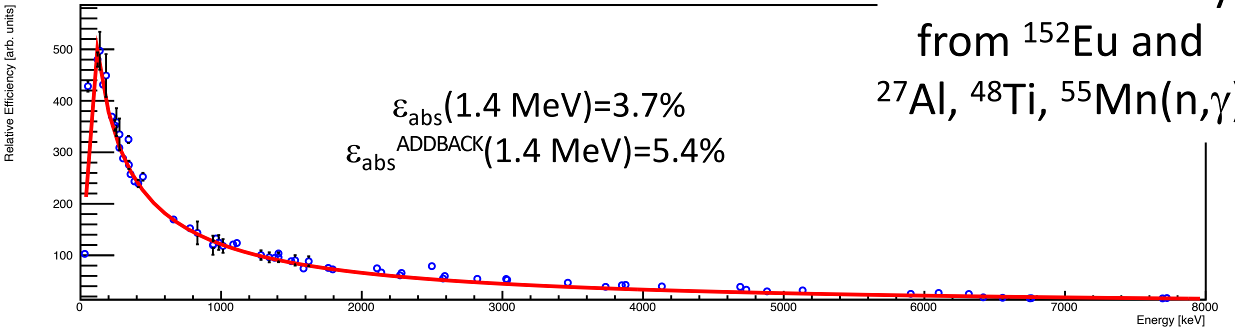
tight polycarbonate casemate for handling radioactive targets

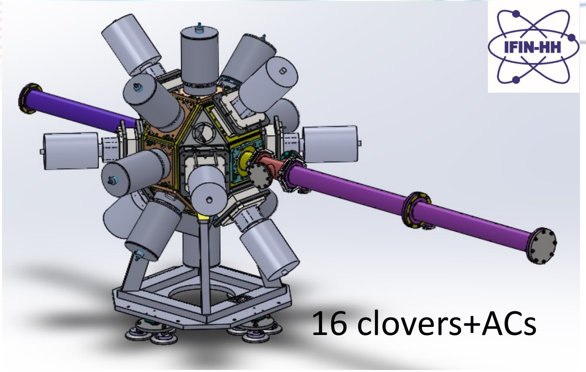


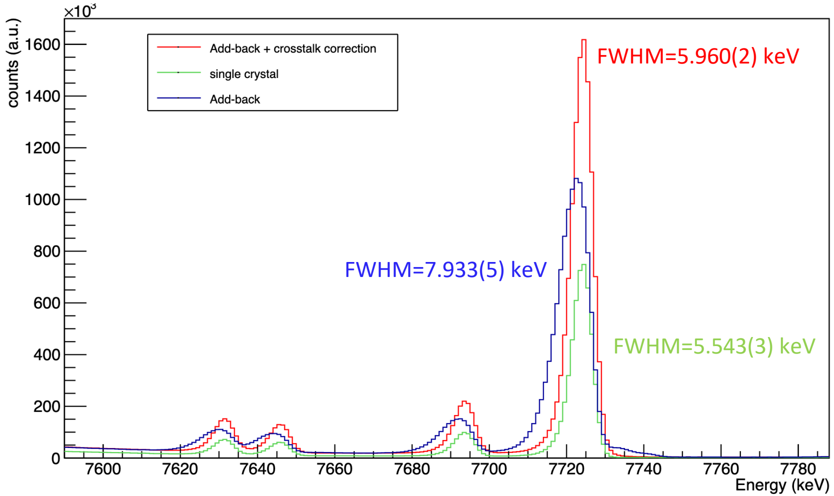
Change of exp zone (larger, H24 guide) next year!

FIPPS performance

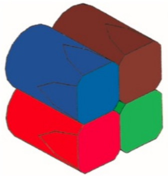
relative efficiency from ^{152}Eu and ^{27}Al, ^{48}Ti, ^{55}Mn(n,γ)







G. Colombi, Mater Thesis, Un. Milan and ILL



- digital electronics

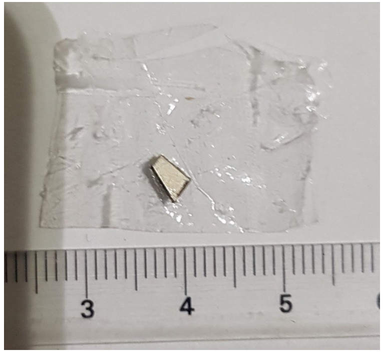
(V1725 CAEN cards, with "home-made" firmware(*) –P. Van Esch, ILL)
  - up to 10-15 kHz/crystal
  - FWHM = 2.1 keV @ 1.4 MeV
  - $Dt_{\gamma\gamma}$ = ~~80ns~~ 30ns(*)
- ancillary detectors ($LaBr_3$,…)

New electronics cards/firmware to be tested

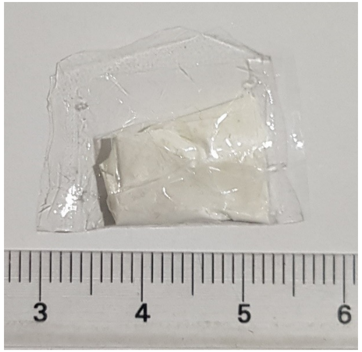
Targets for (n,γ) experiments

*σ*N ~ 2 mmol*barn*

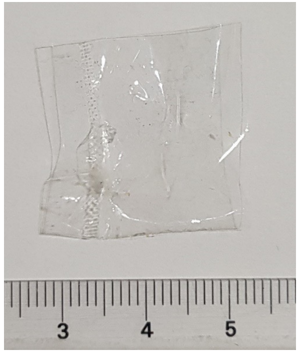
Hold in place by PTFE wiring



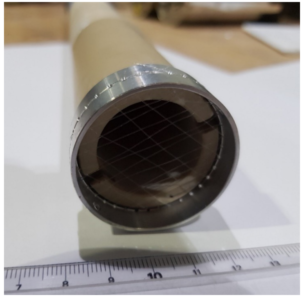
2 mg metal (^{nat}Ti)



120 mg powder

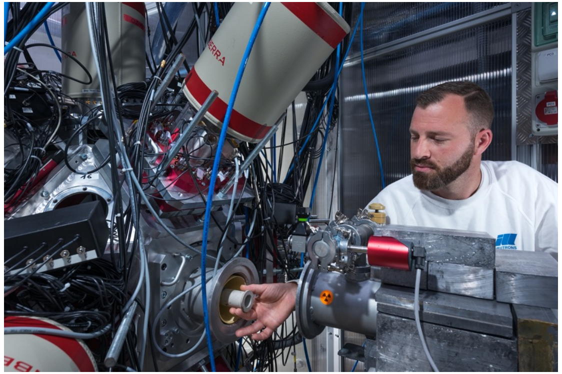


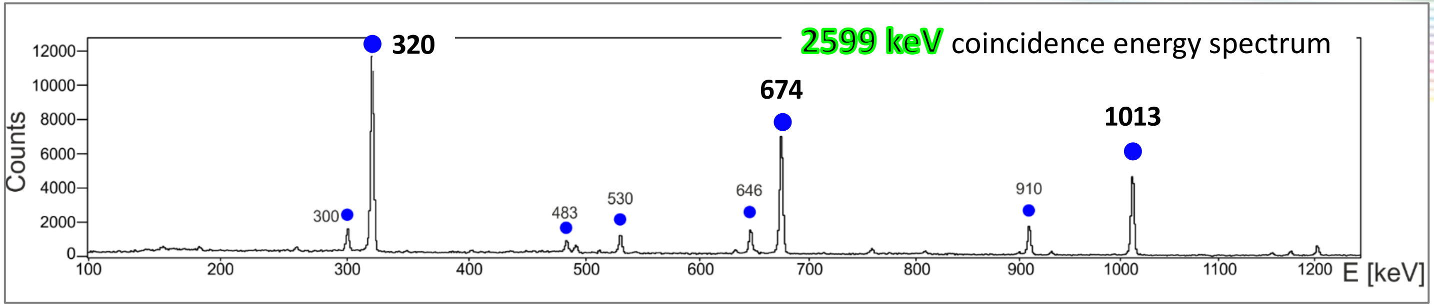
< 1 mg powder

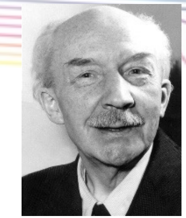


Li target holder against scattered neutrons

3 g powder (^{13}C enriched)



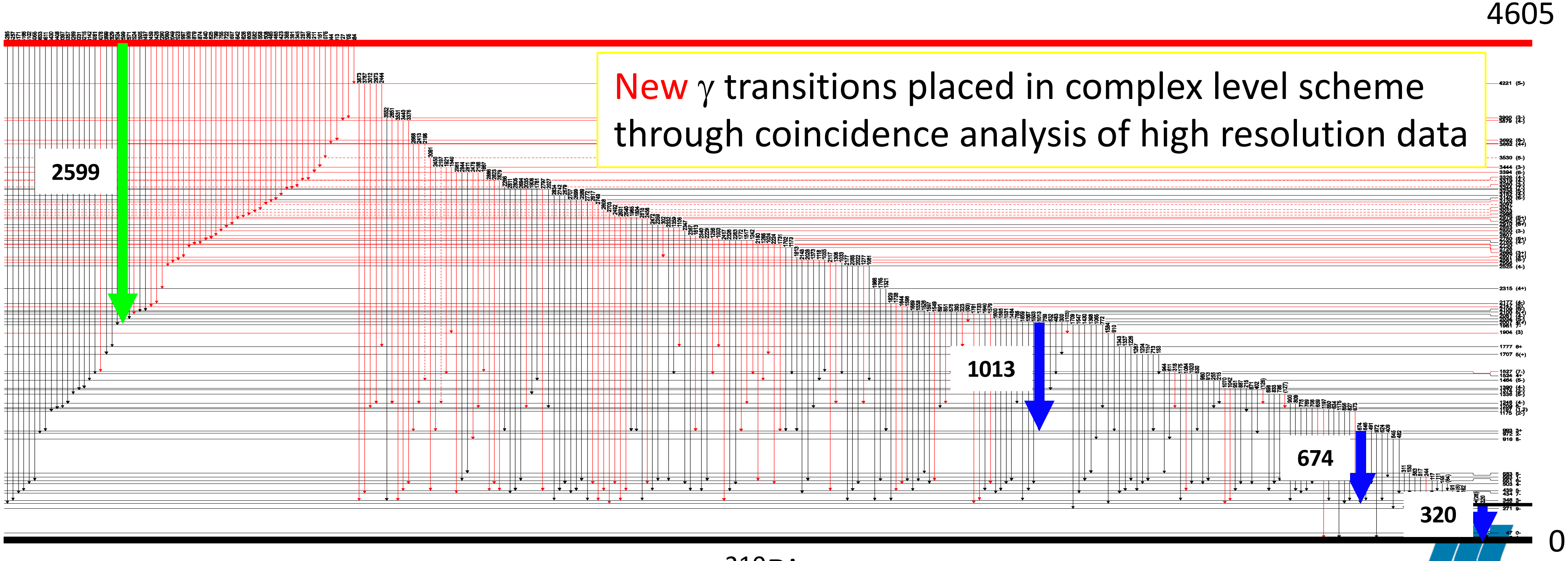




Coincidence method

Walter Bothe

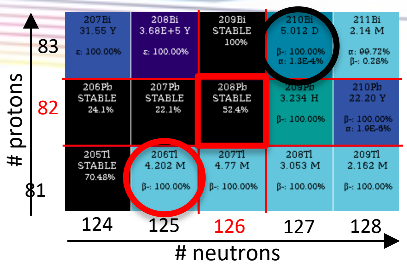
Nobel prize 1954



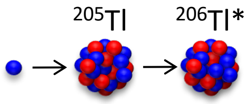
^{210}Bi

N. Cieplicka-Orynczak et al., PRC 93 (2016) 054302

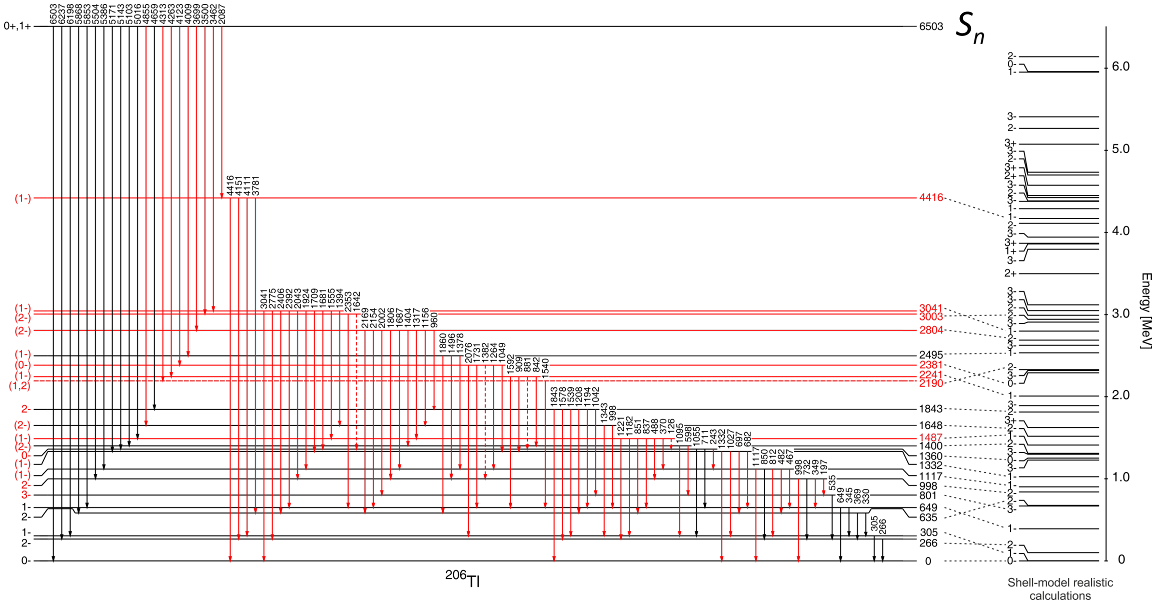
Nuclear structure around ^{208}Pb

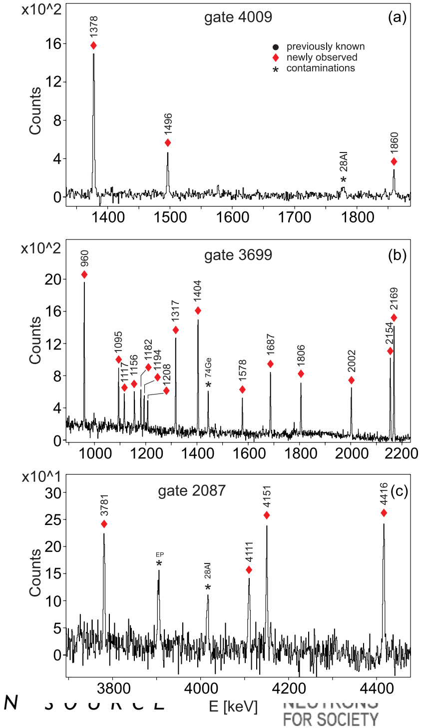


^{205}Tl(n,γ)^{206}Tl –first FIPPS experiment (Dec. 2016/Jan. 2017)



- $I_n = 10^8 n/(s \cdot cm^2)$
- σ = 0.11 b
- 1.9 g of ^{205}Tl (99.9% enriched)
- ~ 10 days



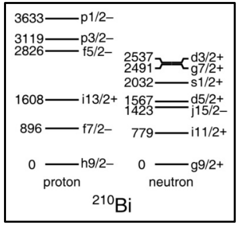


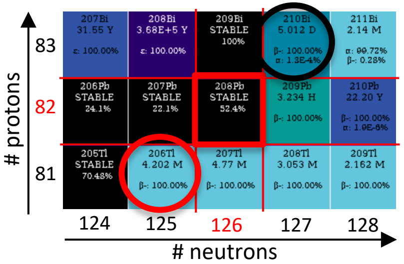
N. Cieplicka et al., PRC in preparation

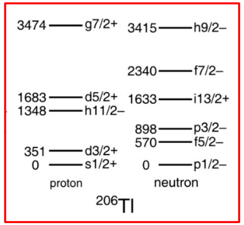
N. Cieplicka et al. Phys. Lett. B 802 (2020) 135222

Test of *realistic* effective interactions

1p-1n (particles/holes) away from ^{208}Pb (doubly magic)

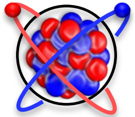






sensitivity to non diagonal matrix elements of the realistic interaction

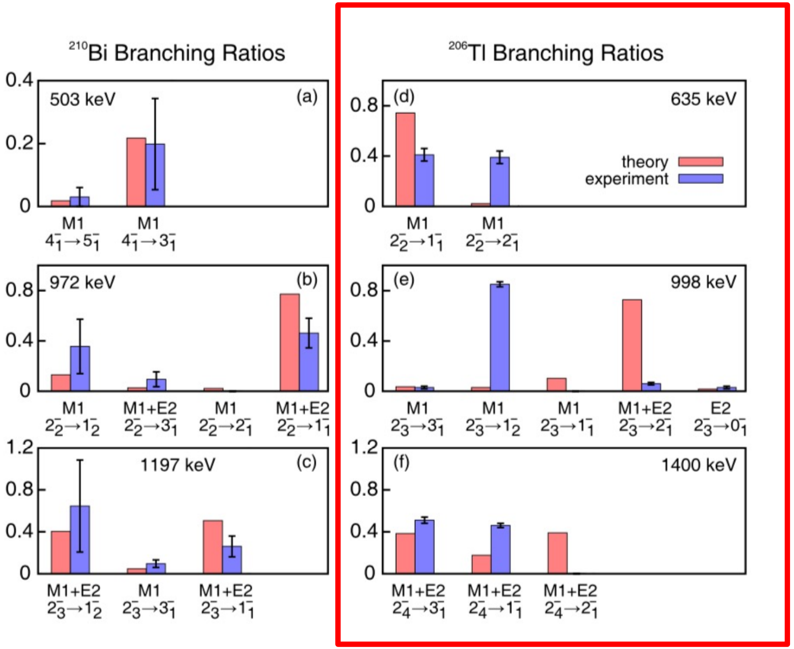
^{208}Pb "frozen" core



+ 2 particles (holes)

$$H = \sum_i e_i n_i + \sum_{ijkl} v_{ijkl} a_i^+ a_j^+ a_l a_k$$

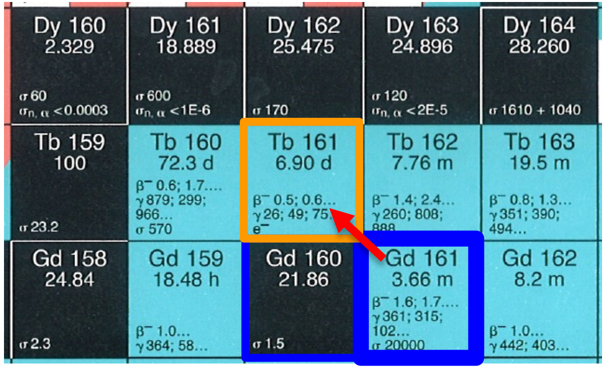
effective nucleon-nucleon interaction



N. Cieplicka, et al. Phys. Lett. B 802 (2020) 135222, PRC 93 (2016) 054302, PRC 93 (2016) 054302

New spectroscopy data for ^{161}Gd

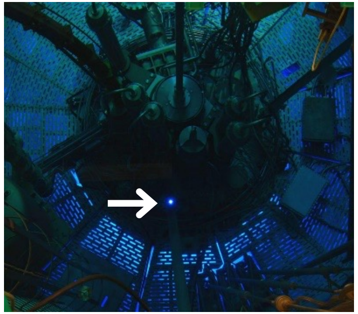
First high-resolution γ spectroscopy experiment usign on a highly isotopically enriched target

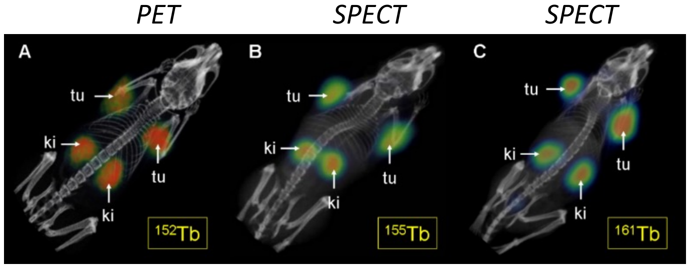


^{160}Gd(n,γ)^{161}Gd (σ=1.5 b)

^{157}Gd(n,γ)^{158}Gd (σ=2.5e5 b)
^{155}Gd(n,γ)^{156}Gd (σ=6e4 b)
^{153}Gd(n,γ)^{154}Gd (σ=2.2e4 b)

^{161}Tb is ideal for targeted radionuclide therapies

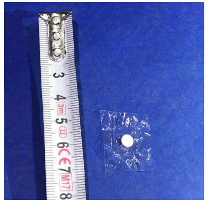




^{161}Gd (N=97) nuclear structure:
deformed Nilsson orbitals around N=96
and search for *scissor modes*

New spectroscopy data for ^{161}Gd

First high-resolution γ spectroscopy experiment usign on a highly isotopically enriched target



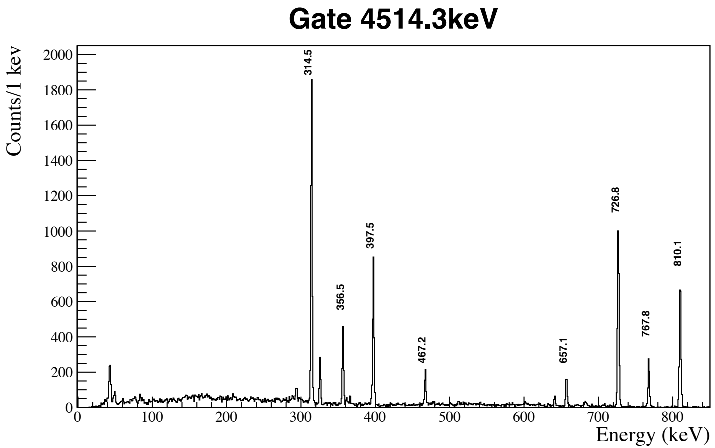
Pill of 98.2% enriched $^{160}GdO_3$

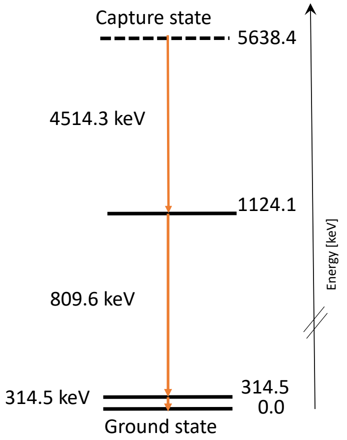
Irradiation in ILL's V4 position

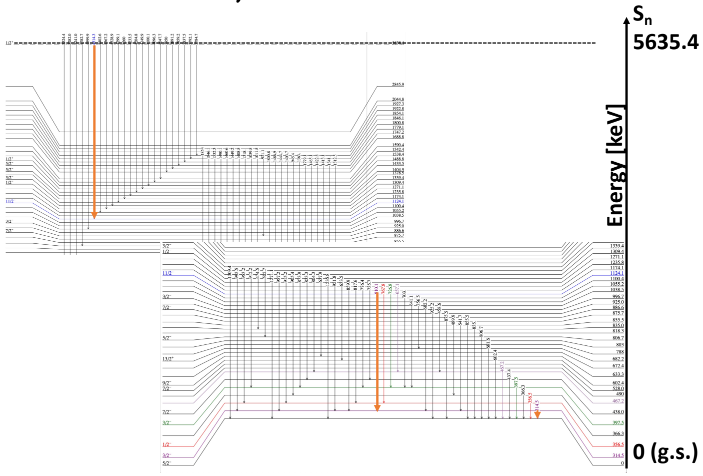
Chemical separation at PSI

7 days beam on target

35 new excited levels and
294 new γ transitions





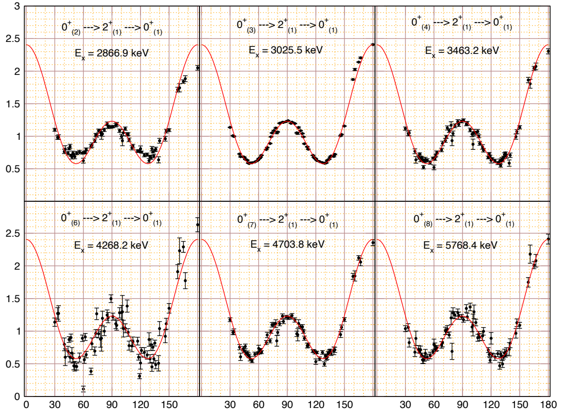


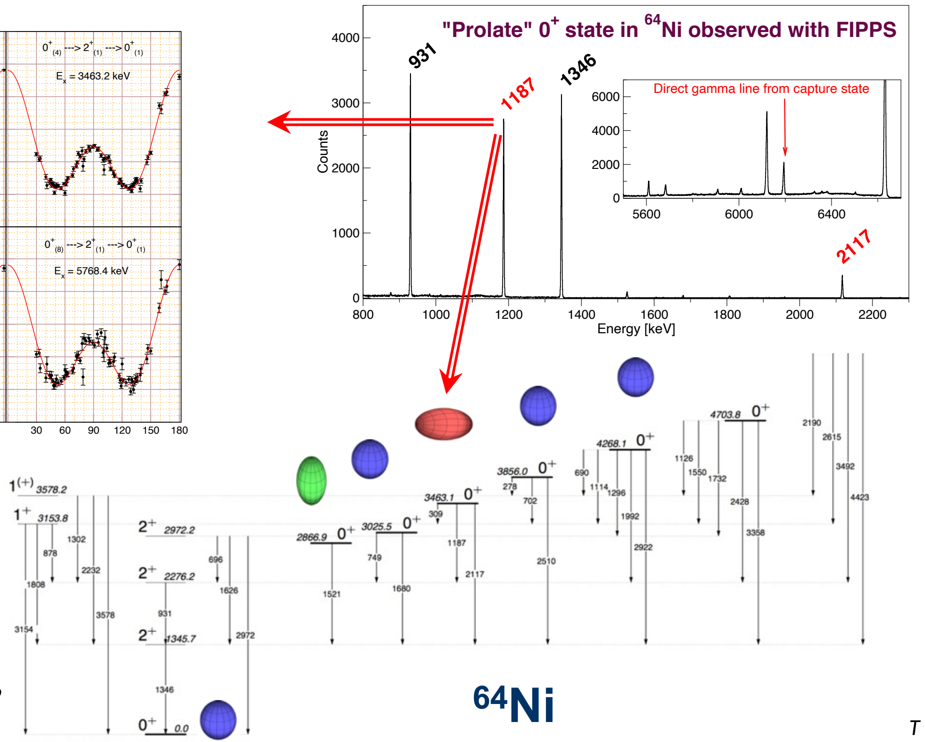
Determination of σ in progress

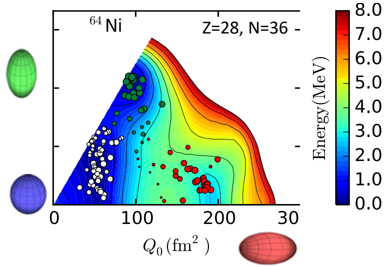
A. Saracino, Master Thesis (Univ. Milan and ILL), paper in preparation

Nuclear *shape isomerism*

Pioneering evidences in light nuclei –(n,γ) on ^{63}Ni radioactive (2GBq) target @ FIPPS+IFIN-HH







Monte Carlo Shell Model Potential Energy Surface

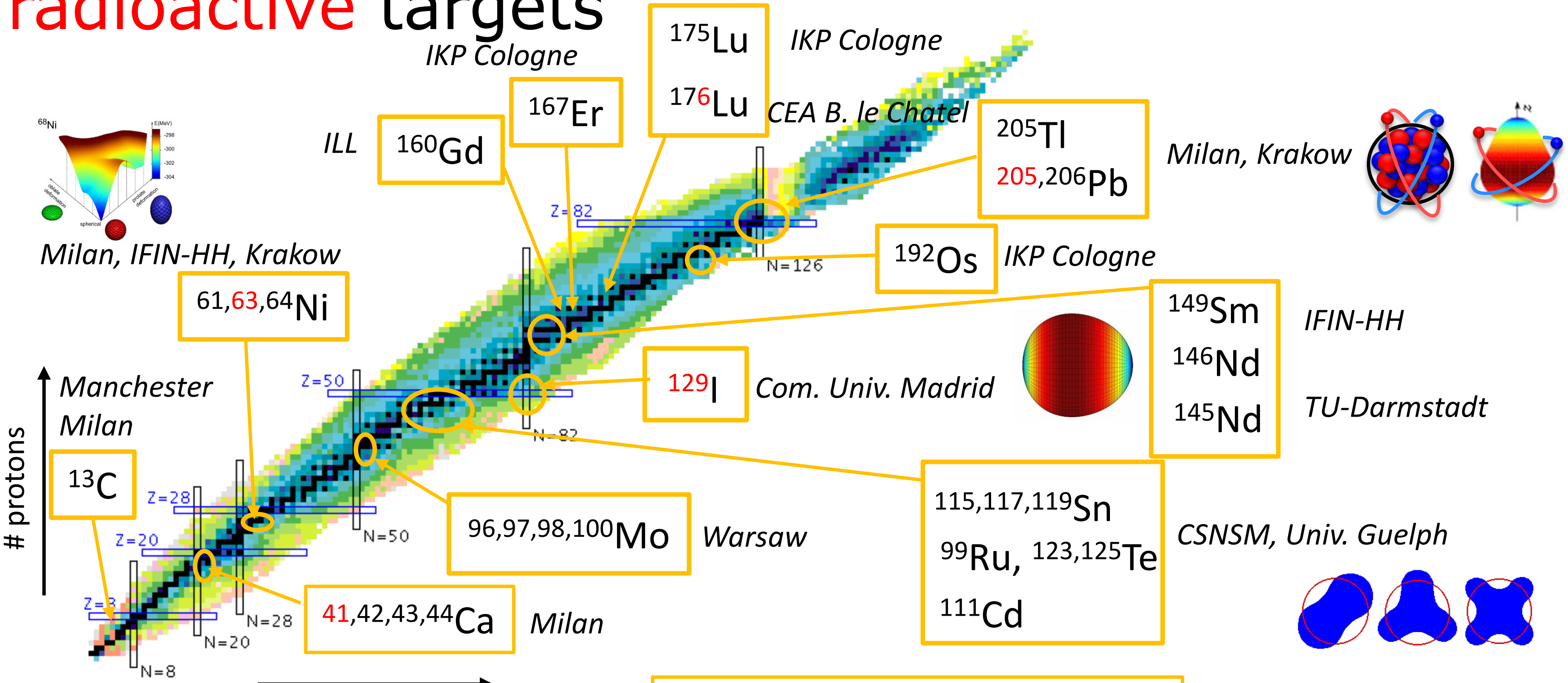
T. Otsuka et al., JPG43 (2016) 024009

Systematics of prolate minimum vs N across N=40

Impact of monopole interaction

N. Marginean et al., PRL125 (2020) 102502
C. Porzio et al., PRC 102 (2020) 064310

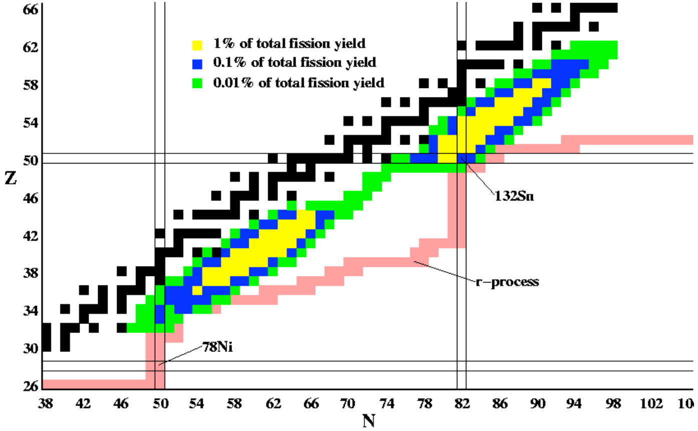
(n,γ) on stable (rare) and radioactive targets

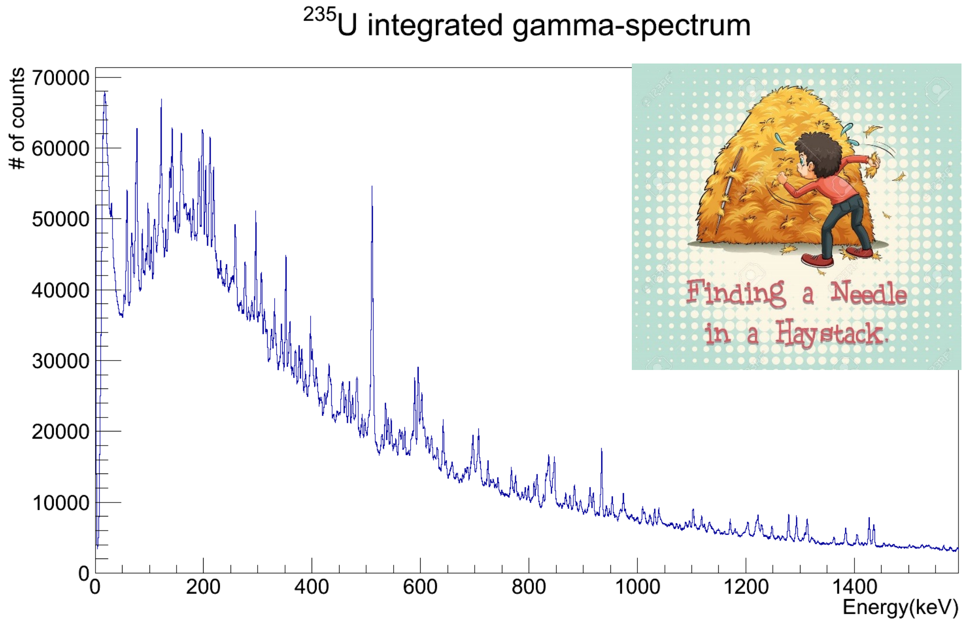


lifetime measurement technique (gas target) *Milan, ILL*

Spectroscopy of fission fragments: a challenge!

More than 150 nuclei emitting γ rays at the same time (excited fission fragments and β-decay products)





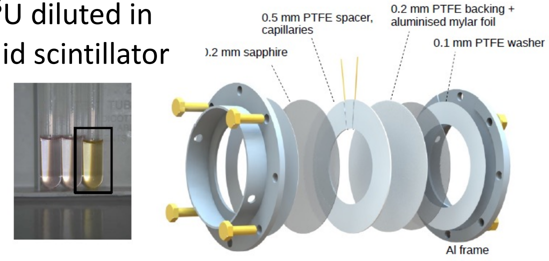
Fission populates exotic nuclei with an « excess » of neutrons important for:

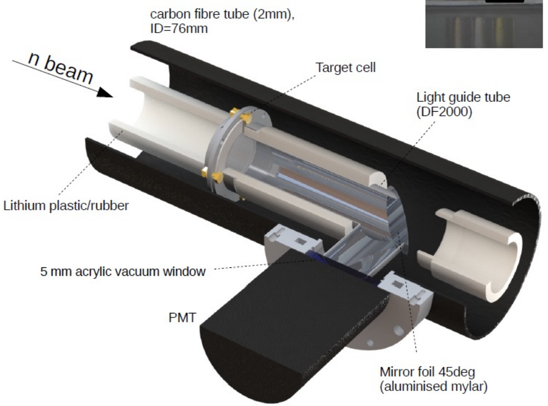
- understanding of nuclear structure far from stability
- modeling of the fission mechanism
- nuclear properties along *r-process* path

Active fission target

FILL2030 postdoc project @ ILL

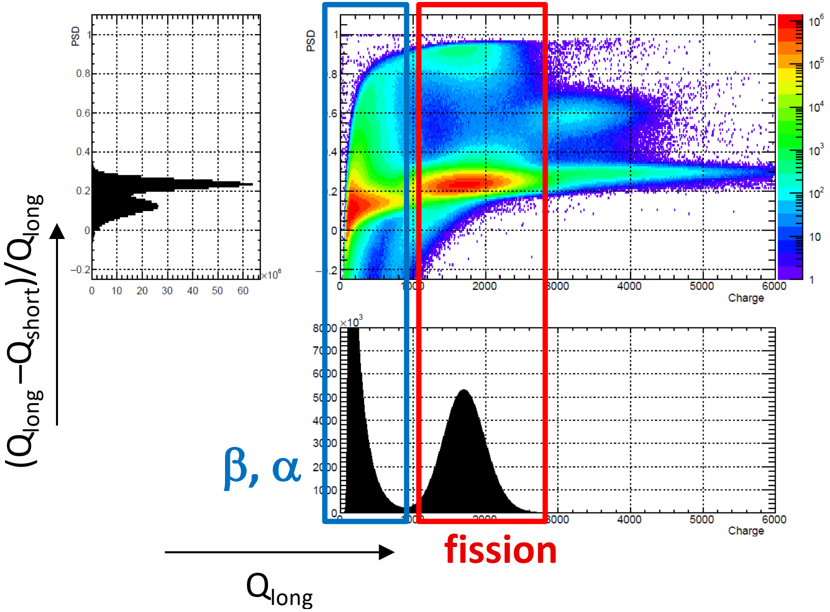
^{235}U diluted in liquid scintillator





target cell

PSD (Pulse-Shape-Discrimination)



F. Kandzia, G. Bélier, et al. EPJA 56 (2020) 207

A diamond-based fission tag has been also tested

G. Colombi, Master Thesis, Univ. Milan and ILL

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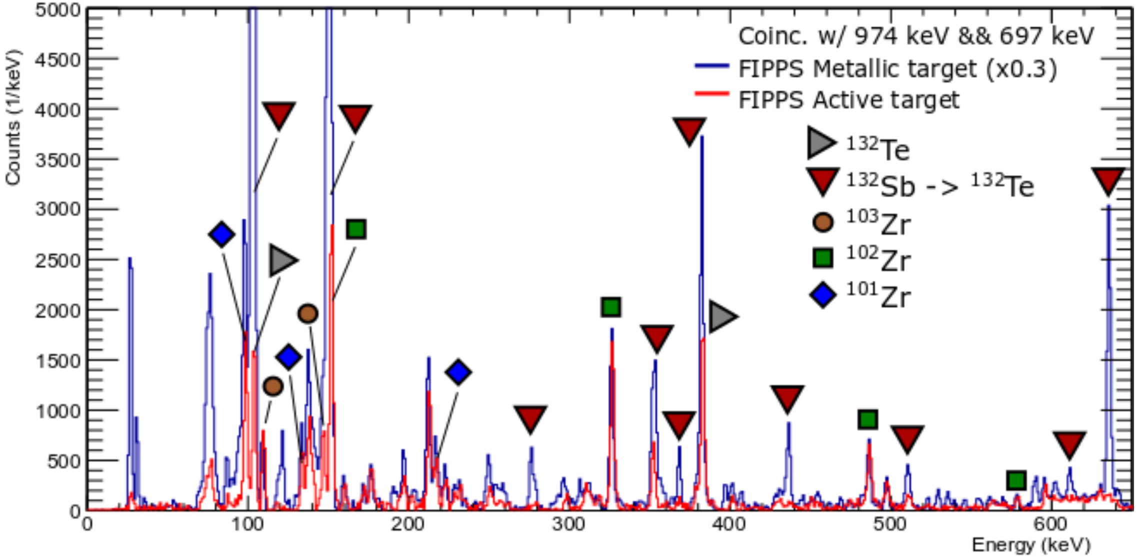
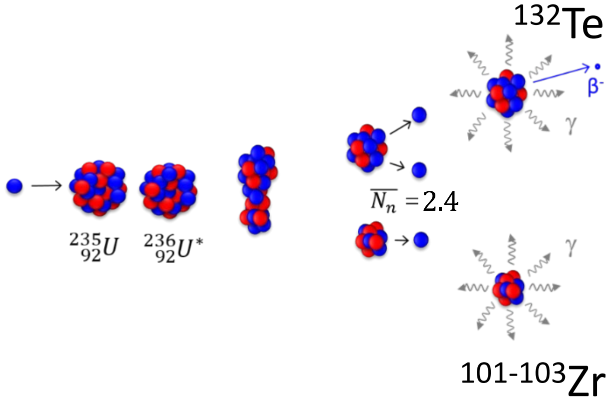
Example of β-induced background suppression

γ–γ–γ analysis (double coincidence gate on ^{132}Te)





Also: increased sensitivity for prompt-delayed coincidence analysis

L. Iskra et al. PRC 102 (2020) 054324

F. Kandzia, G. Bélier, et al. EPJA 56 (2020) 207

Going more and more *exotic*…

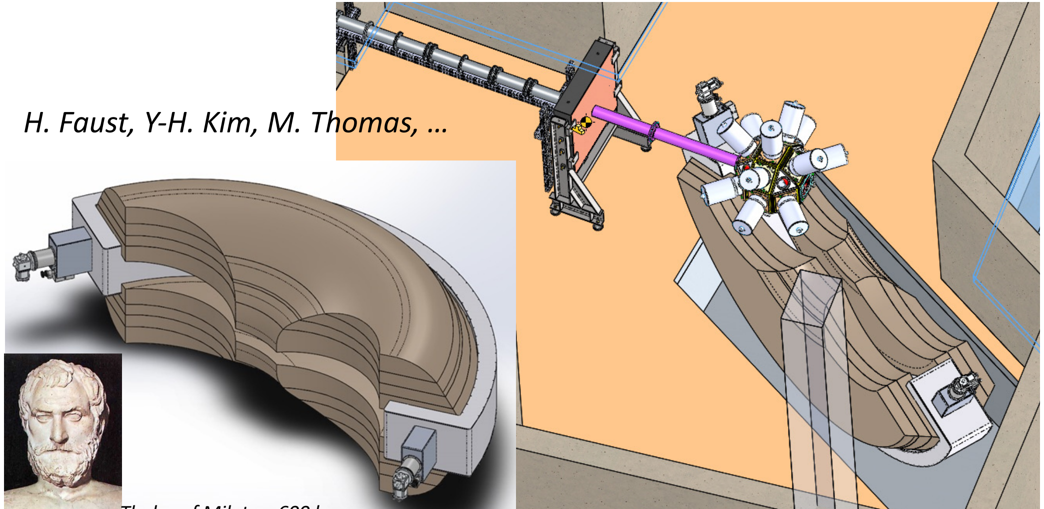
Gain of order of magnitudes in sensitivity for fission studies and spectroscopy of n-rich nuclei using a **Gas-Filled-Magnet (GFM) separator**

HPGe array + fission fragment separator

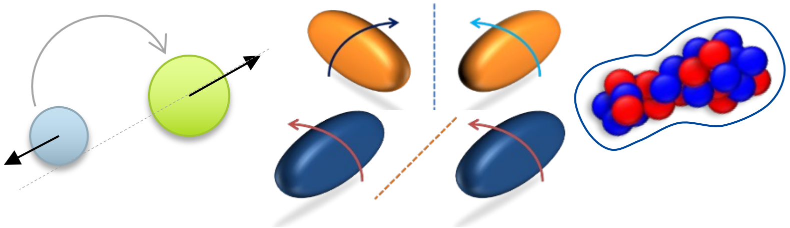
Special geometry:
large acceptance and horizontal focusing indipendent from the ion trajectory

→ Structure of very neutron rich nuclei
→ Understanding of generation of angular momentum and excitation energy in fission

H. Faust, Y-H. Kim, M. Thomas, …



Thales of Miletus, 600 bc



?

- ✓ Pre-design studies
- ✓ Instrument review(s)

Concluding remarks

- Rich Nuclear Physics program at ILL using FIPPS+IFIN-HH/$LaBr_3$ using slow-neutron induced reactions
- ^{235}U(n,f) and ^{233}U(n,f) with *fission tag*: new spectroscopic info on n-rich fission fragments is now available trough multiple gamma-ray coincidences analysis (data are open for LoI)

  → bridge for the science program at FIPPS phase 2 (FIPPS+GFM)

- Food for your thoughts… :

  → "all targets can be used at FIPPS" (or, at least, many…)

  → a plunger measurement with ^{252}Cf is foreseen end of this year

  → a fission run with ^{245}Cm is foreseen for next year

  → diamond base fission tag: (another) test foreseen for next year

Next proposal submission deadline : September 7th 2022

- The physics program and detector developments at FIPPS depend on your input! Hope to see you all soon at ILL…
- … or at least in Grenoble for the **CGS17**

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

CGS17

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July 17 – July 21, 2023
Grenoble, France

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

Deadlines:

- Abstract: 31/05/2023
- Registration: 31/05/2023

Contact:

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

Email: CGS17@ill.fr

F. Kandzia, R. Pommier, ILL

E. Ruiz-Martinez ILL

D. Reygadas (PhD, ILL)

G. Colombi (Master st., now PhD st. ILL)

M. Zanol (Master st.)

A. Saracino (Master st., now PhD st. N.Carolina)

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