

# The Neutrons For Science Facility at GANIL – SPIRAL2

X. Ledoux and the NFS collaboration

## Outline

- The Neutrons For Science Facility
- First Experiments



## ❑ Strong need of nuclear data measurements

- New generation of reactor
- Fusion technology
- Study of the single-event upsets
- Medical applications



- (n,xn)
- (n,fission)
- (n,lcp)

## ❑ Interesting probe for fundamental physics

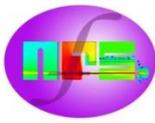
- Nuclear structure
- Reaction mechanism

## ❑ Few and few available neutron beams in the 1-40 MeV range

## ❑ Interest of GANIL/SPIRAL-2

- Ion beams particularly well suited for neutron production
  - ✓ Proton, deuteron
  - ✓ Energy , intensity, time structure
- Laboratory experienced in hosting complex experiments

International collaboration : 50 physicists, 15 laboratories, 8 partners



NFS (NEUTRONS FOR SCIENCE)



Converter room



TOF room



Linear Accelerator (LINAC)  
26 supraconducting cavities



2 ION SOURCES



RFQ : 88 MHz

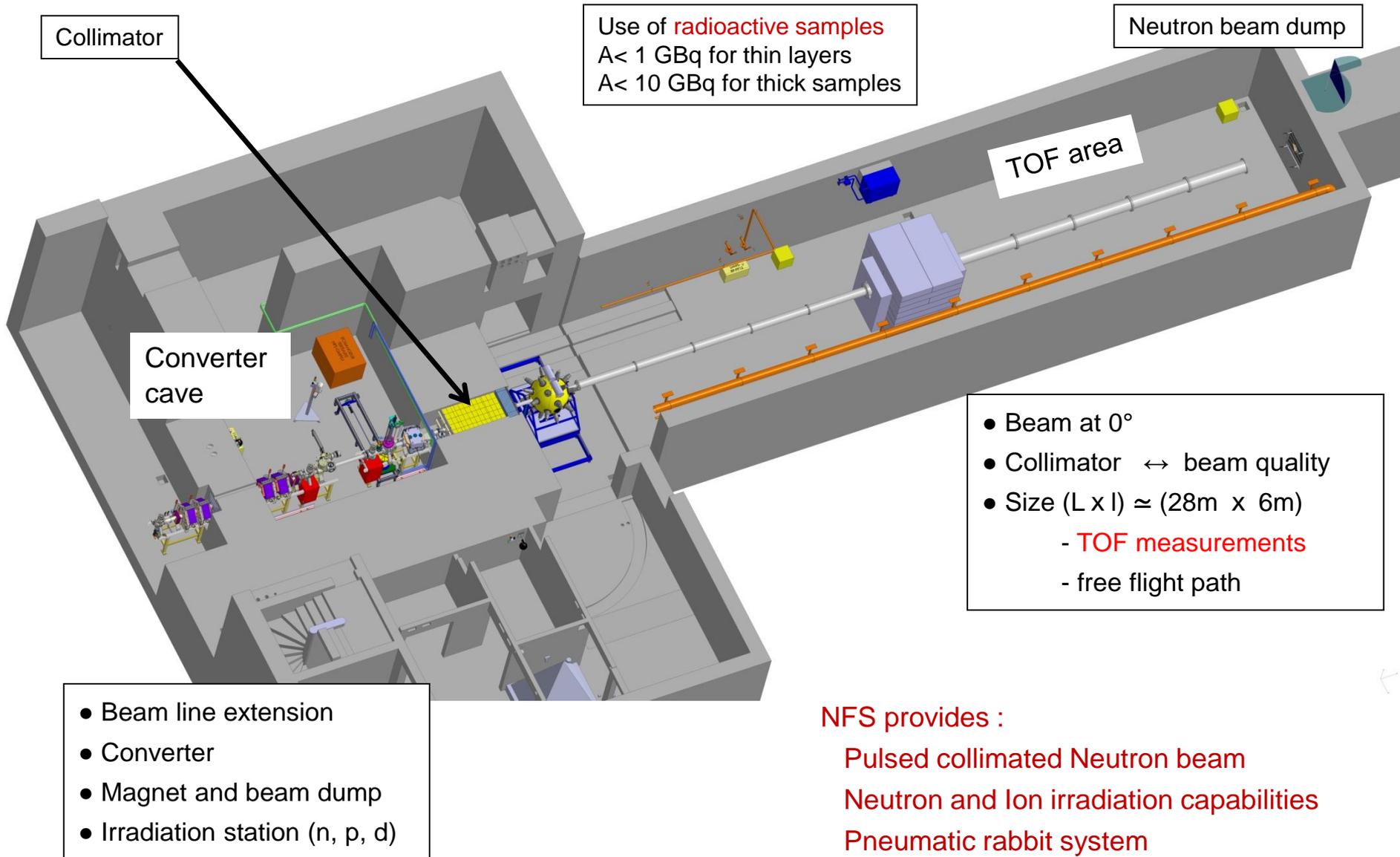
DESIR  
(Decay, Excitation and storage of radioactive ions)



S<sup>3</sup> (SUPER SEPARATOR SPECTROMETER)

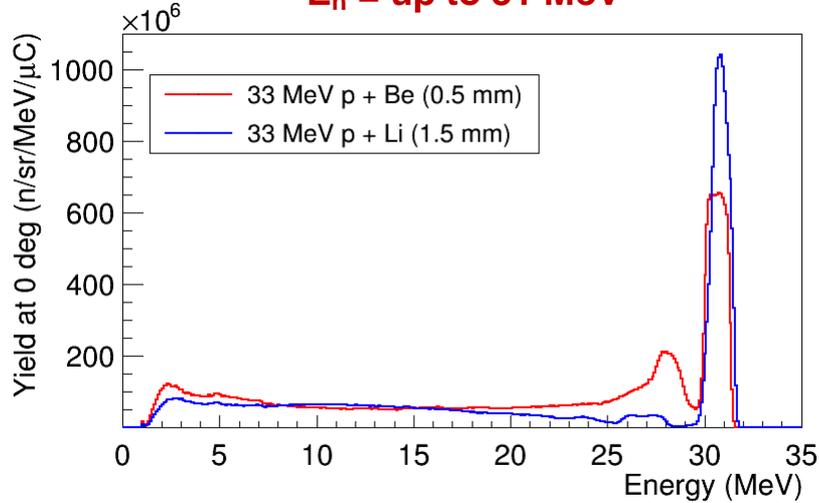
	Q/A	I (mA)	Energy (Mev/u)	CW max beam Power (KW)
Protons	1/1	5	2 - 33	165
Deuterons	1/2	5	2 - 20	200
Ions	1/3	1	2 - 14.5	45
Ions (option)	1/6	1	2 - 8	48





## Quasi-mono-energetic spectrum

$E_n = \text{up to } 31 \text{ MeV}$

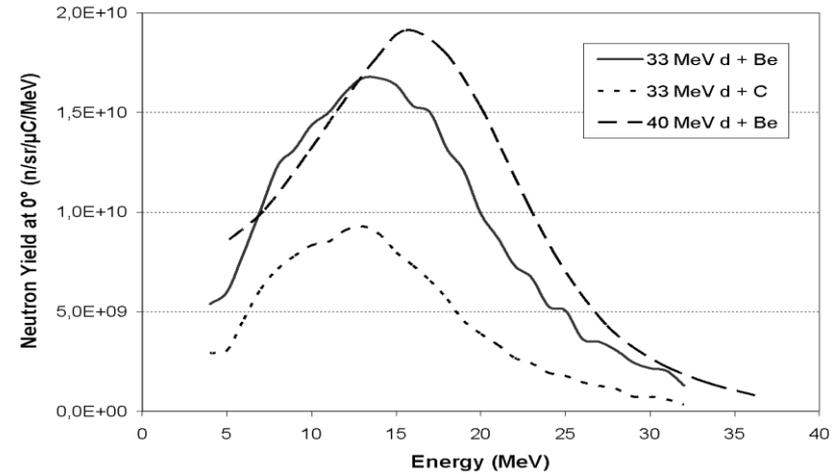


$p + \text{Li (1.5 mm) at } 20 \mu\text{A}$



## Continuous spectrum

$E_{\text{max}} = 40 \text{ MeV}, \langle E \rangle = 14 \text{ MeV}$



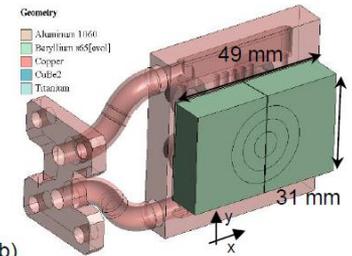
$40 \text{ MeV d} + \text{Be at } 50 \mu\text{A} \rightarrow P=2 \text{ kW}$

Rotating converter  
thick target Be (8 mm)

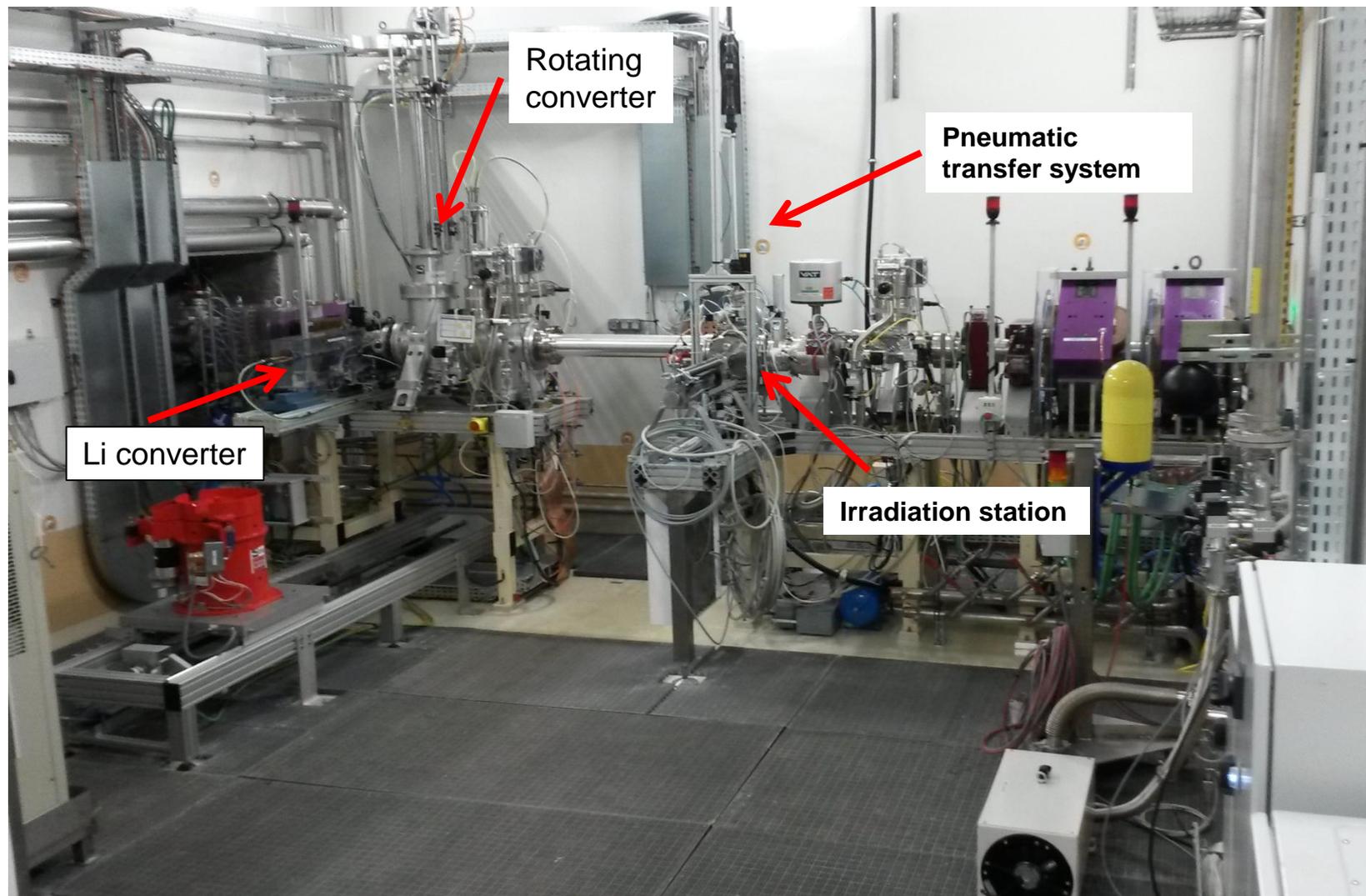


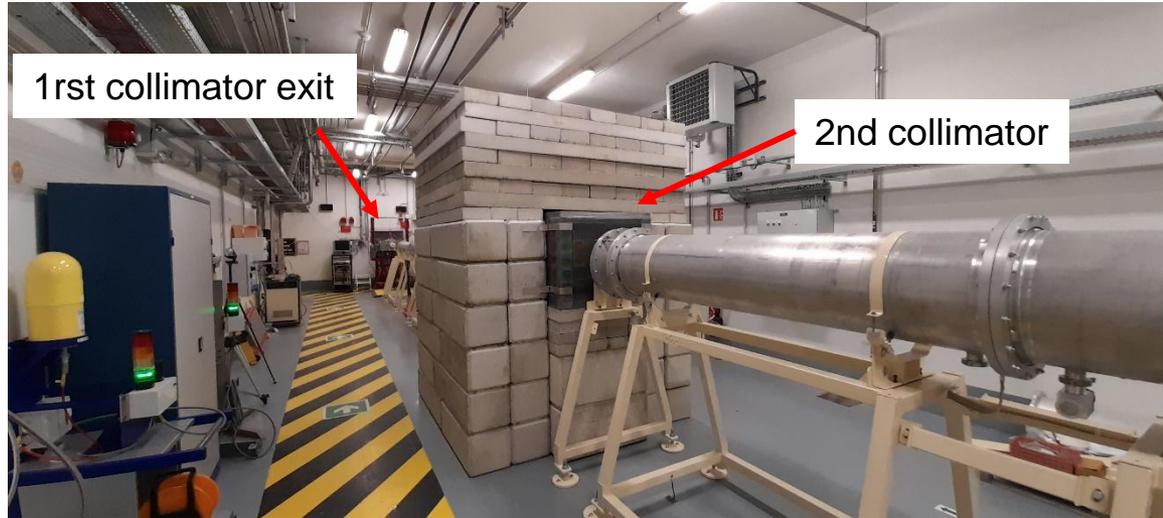
Institut de recherche sur les lois fondamentales de l'Univers

Static converter  
thick target Be (11 mm) + Cu



Fast chopper  $F = F_{\text{linac}} / N$  with  $N > 100 \rightarrow I_{\text{max}} = 50 \mu\text{A}$

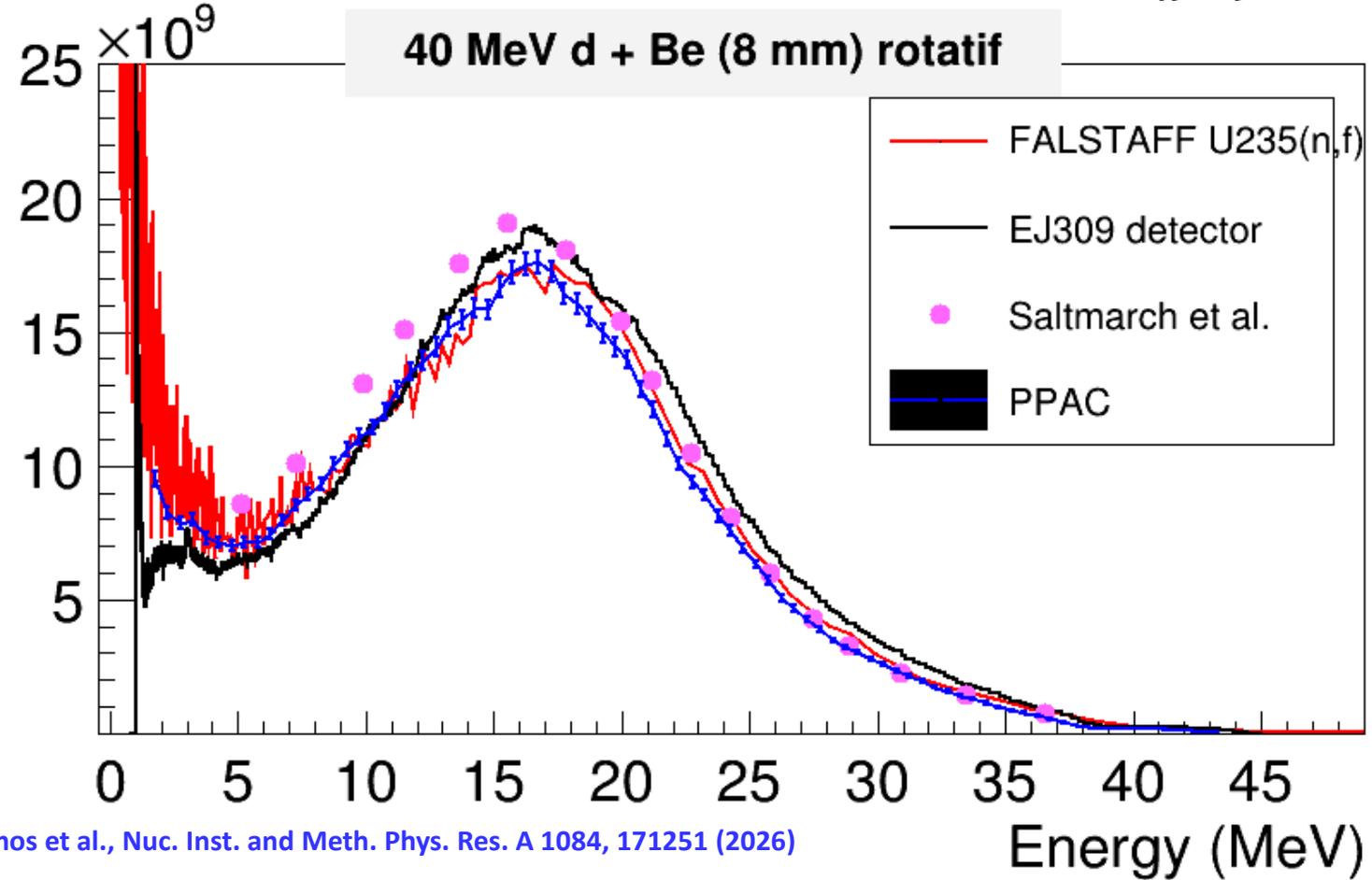
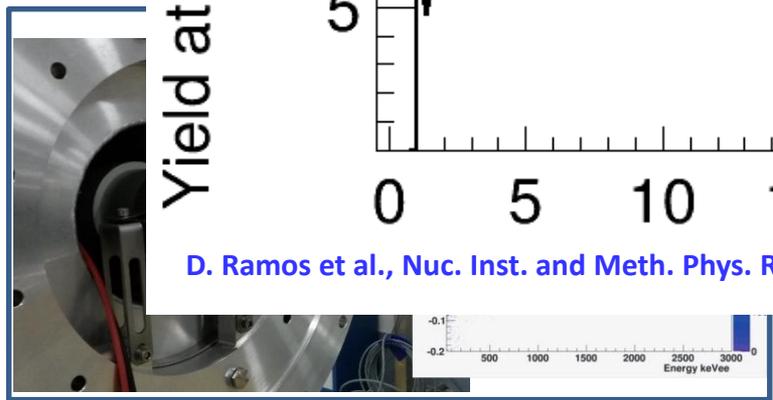
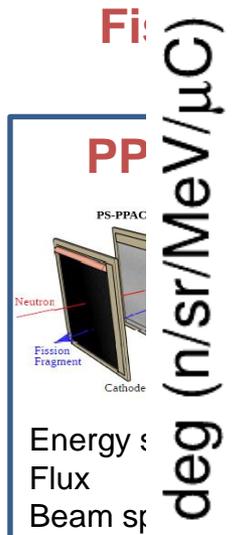






Dedicated monitors

Detectors used during experiments



D. Ramos et al., *Nuc. Inst. and Meth. Phys. Res. A* 1084, 171251 (2026)





### □ Large time-of-flight area

- High flux : d=5 m
- High energy resolution d>20 m
- Several experiments at the same time

### □ Quasi-mono-energetic neutrons :

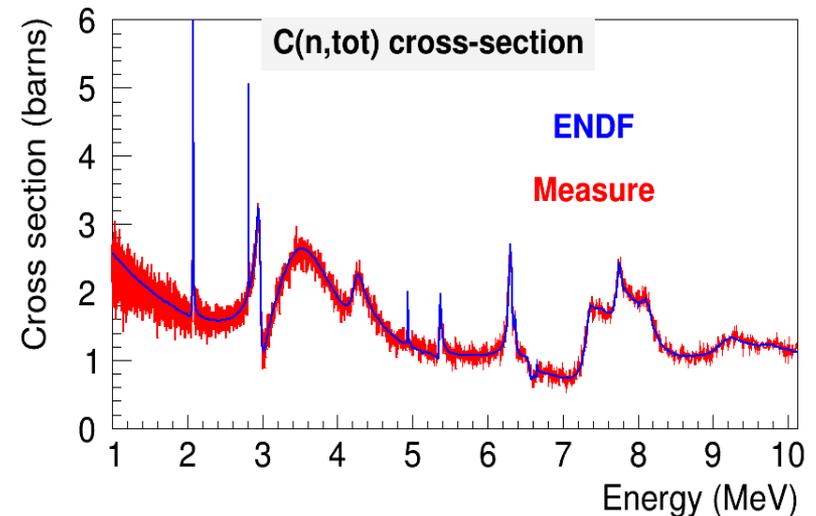
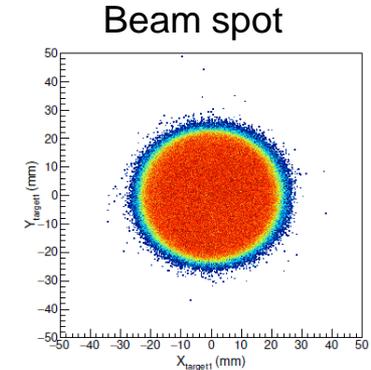
- p+Li
- up to 31 MeV
- Yield in the mono-energetic peak  $1,2 \cdot 10^9$  n/sr/ $\mu$ C
- at 20  $\mu$ A and d=500cm  $\rightarrow \Phi = 10^5$  n/cm<sup>2</sup>/s

### □ White energy spectrum

- d+Be
- E<sub>max</sub>= 44 MeV
- <E>=15 MeV
- $8 \cdot 10^7$  n/cm<sup>2</sup>/s at 5 m

### □ Beam

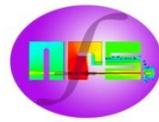
- Small  $\gamma$  flash
- Spot size : r=1,7 cm at 5 m
- Frequency < 1 MHz
- Burst duration < 1 ns



Cross-section measurement by transmission



1. The Neutrons For Science Facility
2. First Experiments



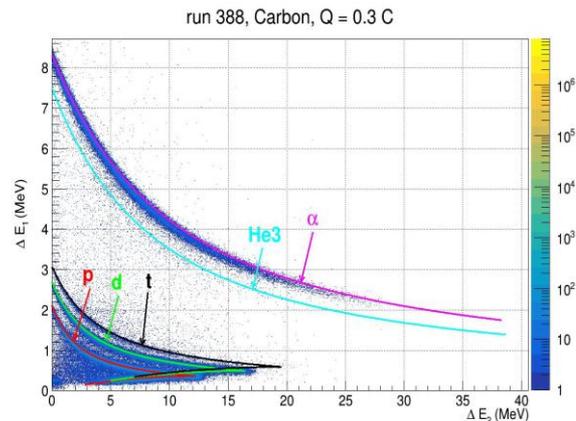
**Spokespersons : D. Tario, Uppsala University, I. Ipatova, UKEA Culham**

## Neutron-Induced Light charged particles emission with MEDLEY

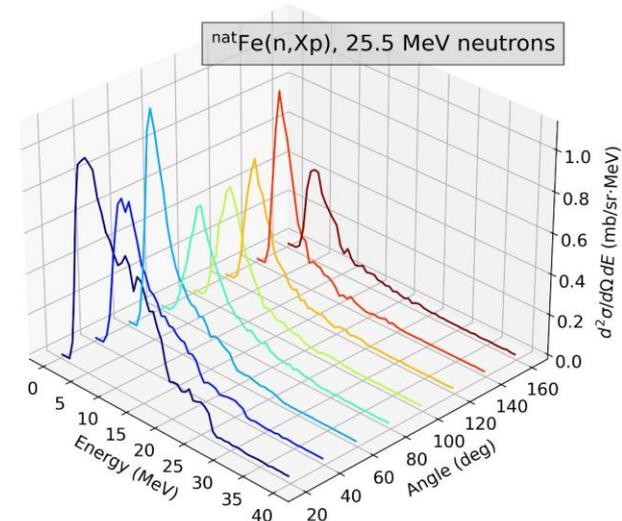
- **Cancer therapy and dosimetry** (H,C,O, Ca...)
- **Radiation effects** in microelectronics (Si, O)
- Energy applications: **Gen-IV or fusion reactors** (building materials, fuel, coolants, etc)
- Studied targets: C, Fe,Cr, Cu63

## MEDLEY

- 8 **Si-Si-CsI** telescopes
- Double-differential **cross sections** :
- High **particle-identification capability**
- Simultaneous measurement of **charged-particles energy and neutron ToF**
- GANIL digital acquisition



See D. Tario's talk last Monday



**Spokesperson : G. Bélier, CEA-DAM-DIF**

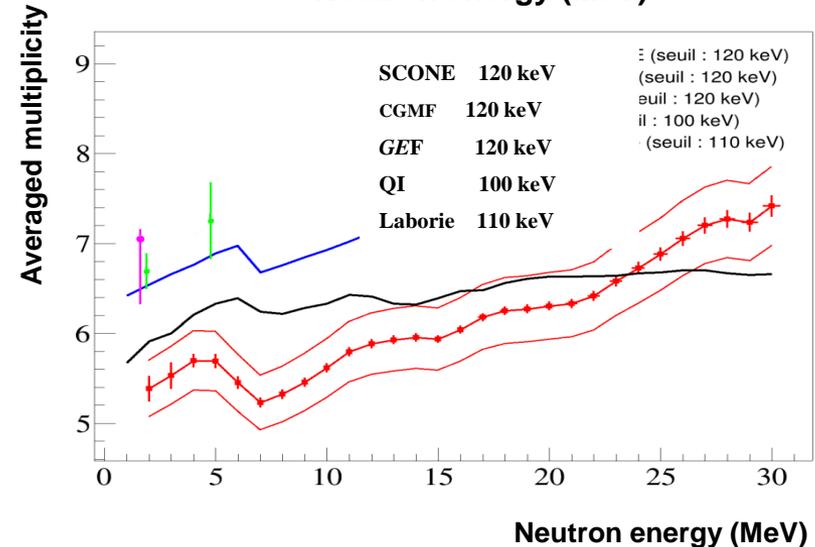
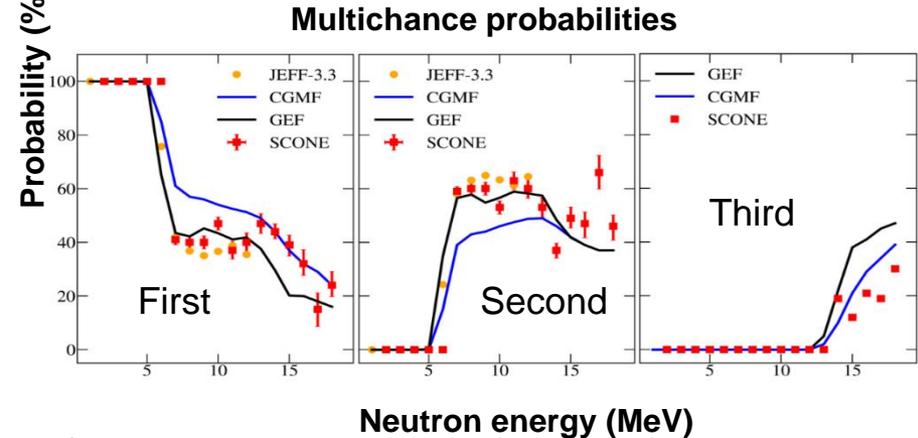
- ❑ (n,xn) reaction are important channels in the 5-50 MeV range
- ❑ Competition with fission
  - radioactive sample
  - prompt neutron fission

**Experimental technique :**

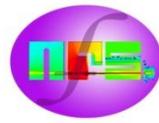
- ❑ Veto fission (fission chamber)
- ❑ 4π neutron detector SCONE
- ❑ 6 MeV < E<sub>n</sub> < 20 MeV



See G. Bélier's talk last Monday

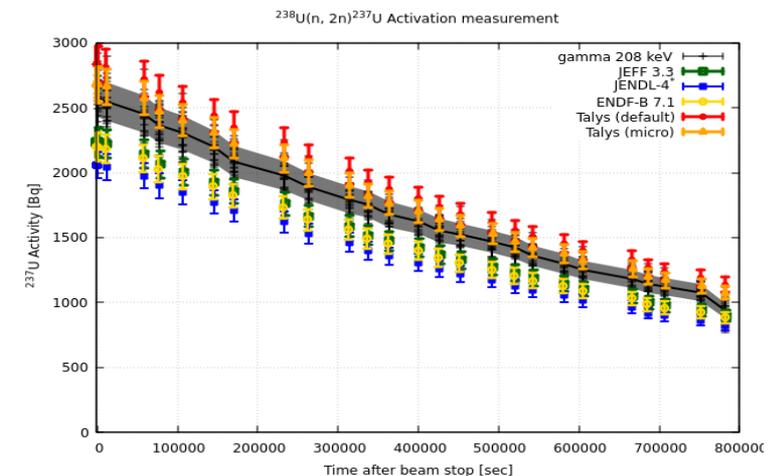
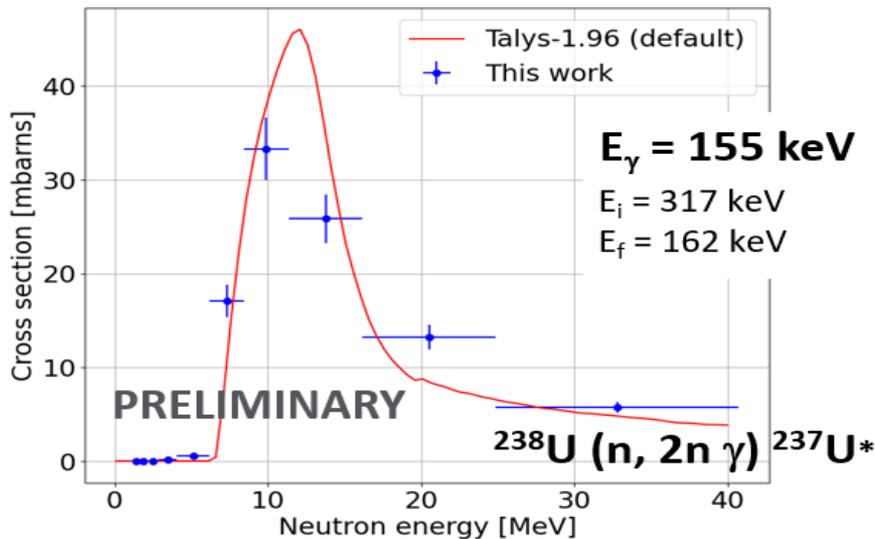
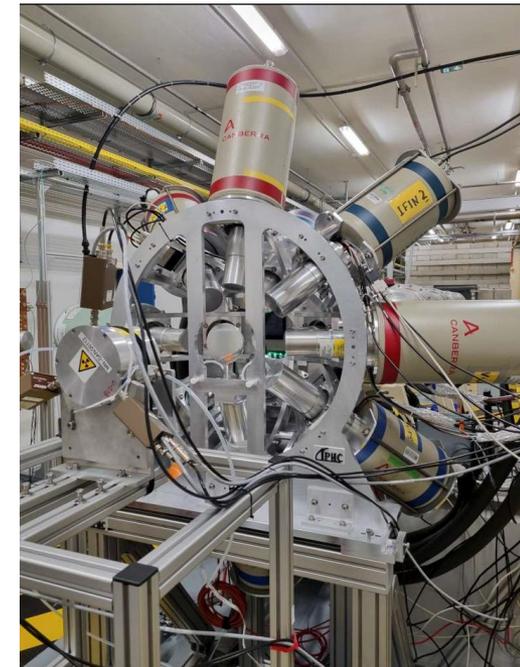


G. Belier et al., NIMA 1072 (2025) 170225



### Spokesperson : M. Kerveno, IPHC Strasbourg

- ❑ Prompt g-ray spectroscopy & Activation technique
- ❑ Detection set-up :
  - GAINS (JRC-Geel): 4 large volume HPGe
  - IFIN-HH : 2 large volume HpGe
  - Grapheme (IPHC Strasbourg): 6 planar detectors
  - Sample : 14 g of depleted U
  - U238 fission chamber
- ❑ Neutron white spectrum
- ❑ Neutron energy measurement by TOF
- ❑ 2 weeks in-beam, 16 days of decay observation.

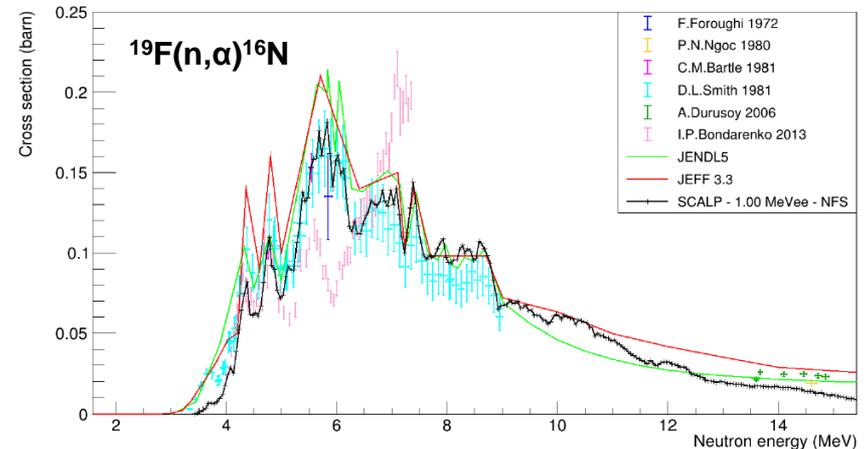
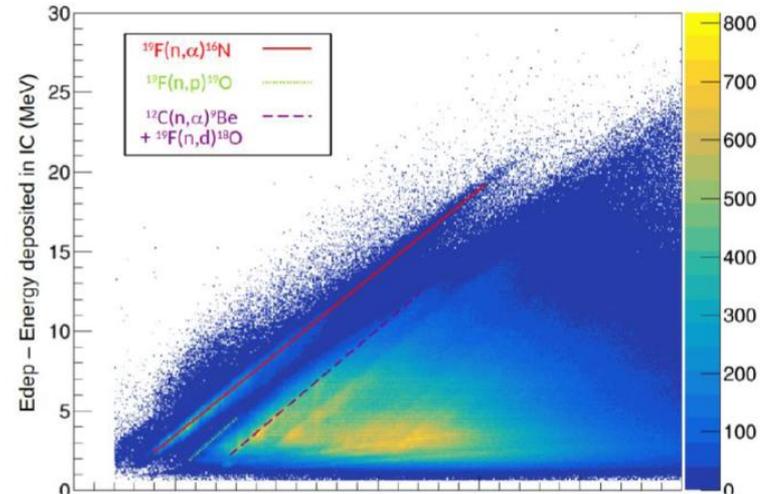
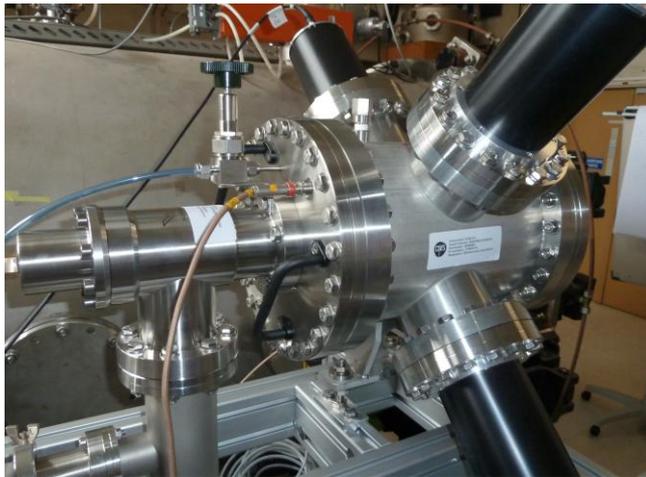


**Spokesperson : F. R. Lecolley, LPC Caen**

**Goals : XS measurement from threshold to 20MeV range with an uncertainty better than 5%**

- ❑ Active target
  - Ionization chamber : E measurement
  - Scintillation : En measurement by TOF
- ❑ Continuous spectrum : whole excitation function
- ❑ 2 measurements :
  - CF<sub>4</sub> for fluorine XS
  - (3%) CO<sub>2</sub>+CF<sub>4</sub> for oxygen XS after fluorine subtraction

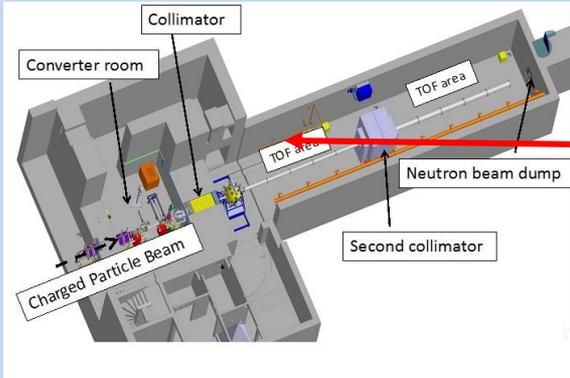
**A lot of Channels to distinguish : Eres vs TOF**



A. Chevalier et al. WONDER 2023 proceeding

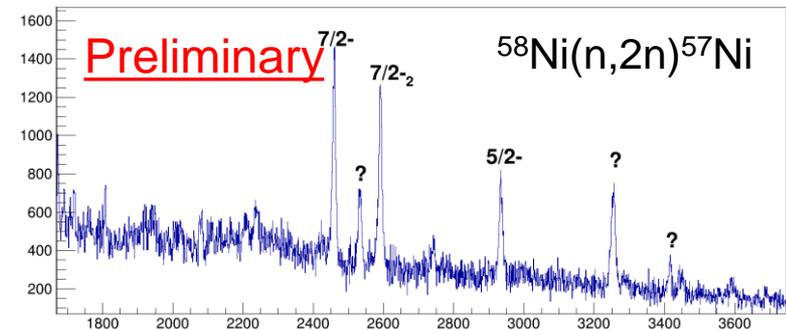
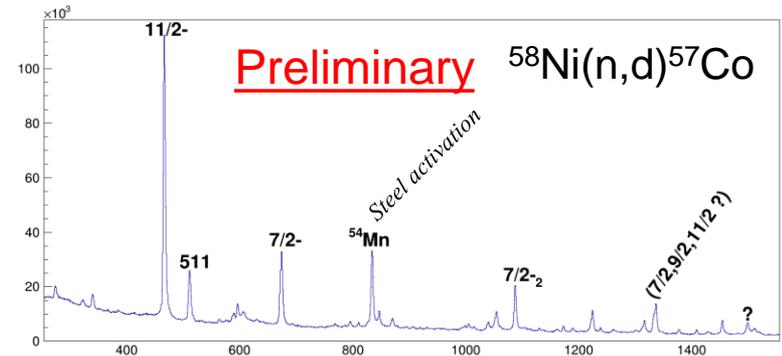
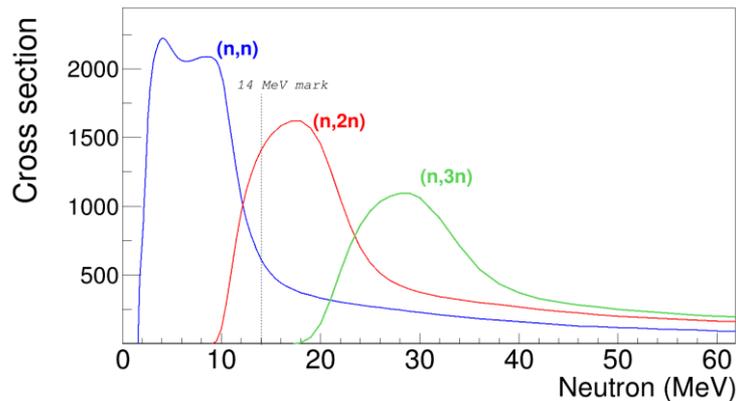


Spokesperson : E. Clément, GANIL



12 exogam clover at NFS

- EXOGAM clovers placed at 8.6 meters from the production target
- Using 10 mA of 40 MeV deuteron beam on the thick Be target  
→ 100 Hz of  $^{56}\text{Ni}$  with a 1mm target
- Triggered in gg in coincidence with the fastest neutrons (> 25 MeV)



- New states probably observed in  $^{57}\text{Ni}$
- $^{56}\text{Ni}$  decay was observed
- From the easiest (n,d/t) channels, it seems that different states than b-decay, fusion of heavy ions or direct transfer reaction using protons beam are populated with high cross section (?)

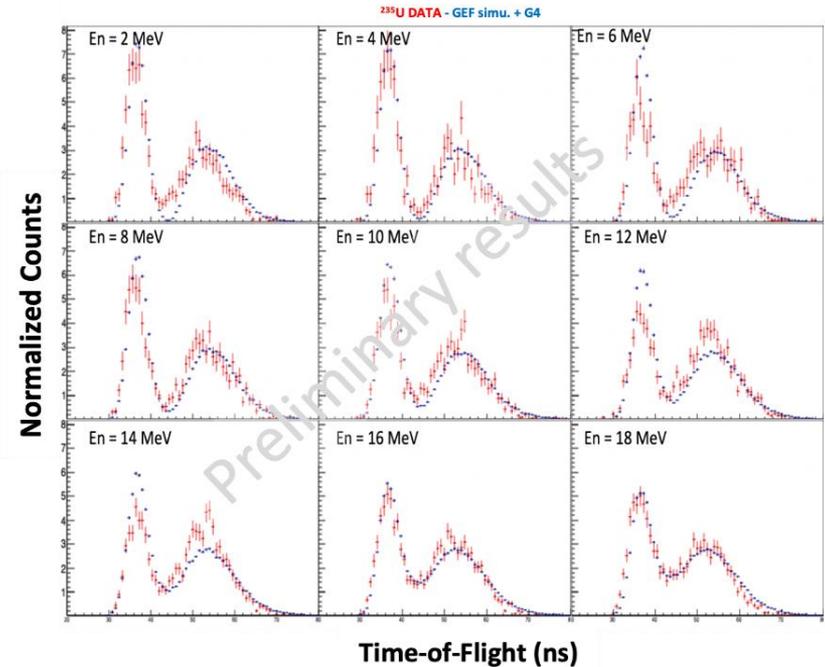
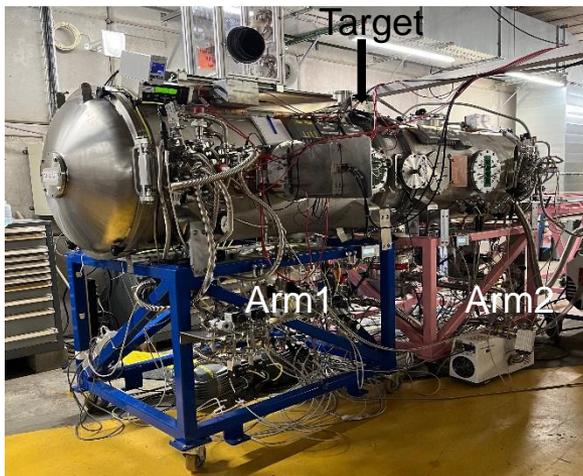
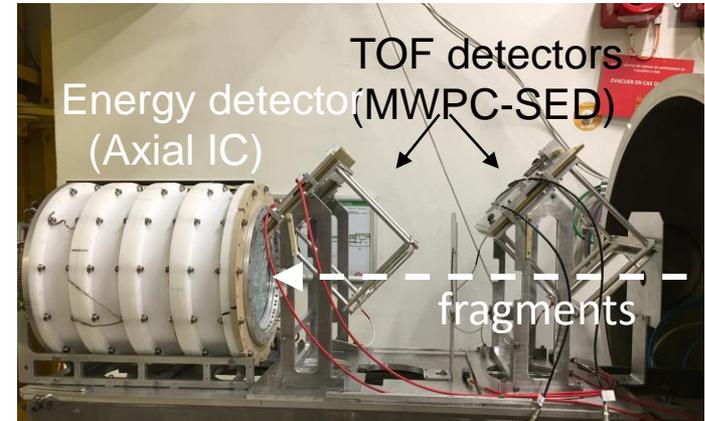
**Spokespersons : D. Doré (CEA Saclay Irfu/DPhN), J.E. Ducret (GANIL)**

Perform experiments in the **fast domain** to characterize actinide fission fragments

- ❑ Mass and energy distributions as function of  $E_n$
- ❑ Neutron Sawtooth Curve
- ❑ Important piece of information about scission
  - Excitation energy sharing
  - Shell effects
  - Energy balance

**Measurements with 1 arm : U235 in 2022, Np237 in 2024**

**Next measurement in 2026 : U235 with 2 arms**



Spokespersons : Marine VANDEBROUCK (CEA Saclay Irfu/DPhN) and Iolanda MATEA (IJCLab)

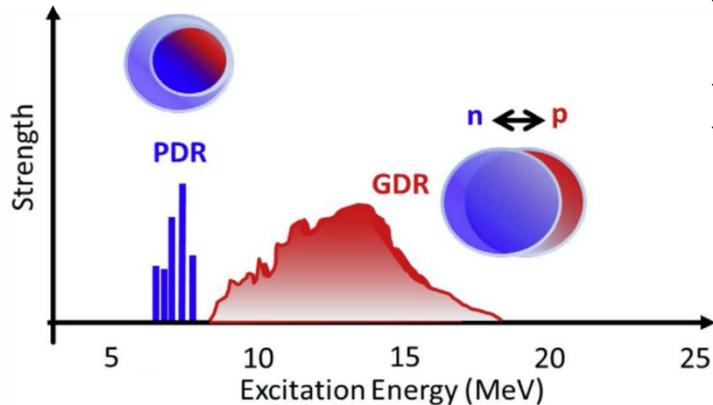


Figure extracted from A. Bracco *et al.* Prog. Part. Nucl. Phys. 106 (2019)

- ✓ The use of different reactions to excite the PDR showed different responses, not always compatible with the neutron skin picture
- ✓ New probes are necessary to resolve the complexity of the PDR structure
- ✓ Neutron inelastic scattering reaction at SPIRAL2-NFS was used as a new probe

### ○ GDR (Giant Dipole Resonance)

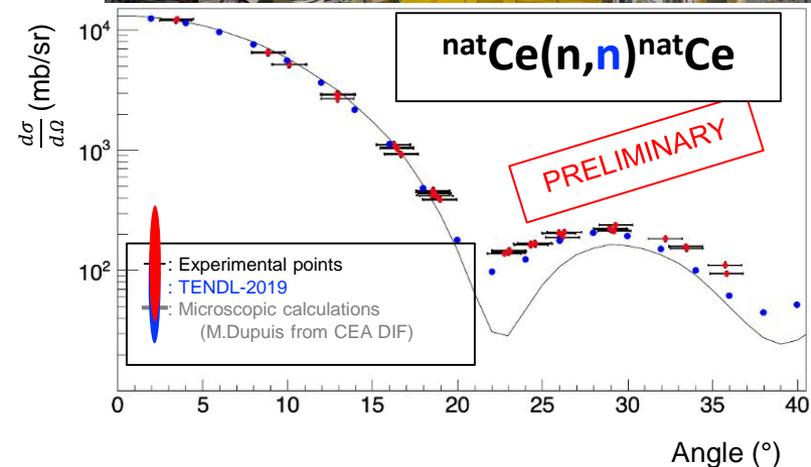
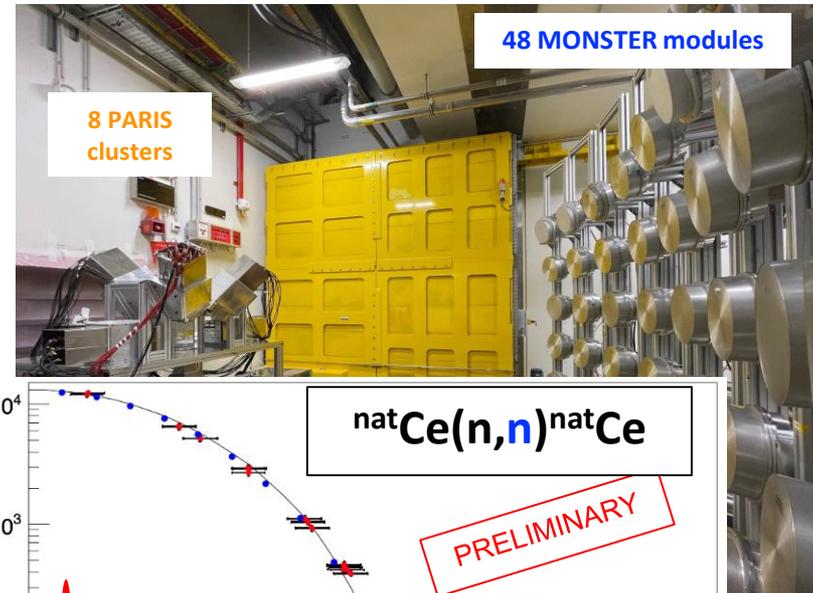
- oscillation of neutrons against protons
- exhausts ~ 100% of the dipole strength

### ○ PDR (Pygmy Dipole Resonance)

- oscillation of a neutron skin against a symmetric proton/neutron core
- small additional dipole strength at lower energy

### ○ Experimental details:

- 31 MeV neutron quasi-mono-energetic beam
- Neutron detectors : 48 BC501 cells of MONSTER array
- $\gamma$ -rays detectors: 8 Paris Clovers (LaBr3)



"Neutron elastic scattering at 30.8MeV on  $^{nat}\text{Ce}$ ", Mirit-Jaubert P., submitted to EPJA

NEW on Ce at 31 MeV

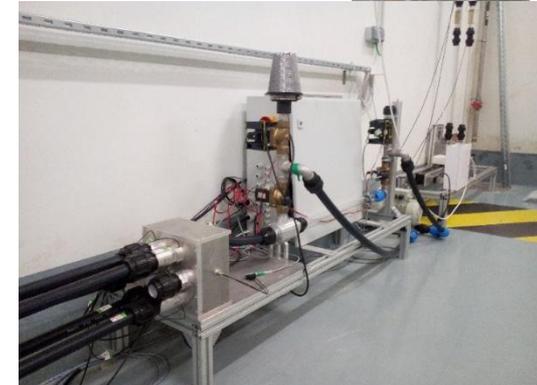
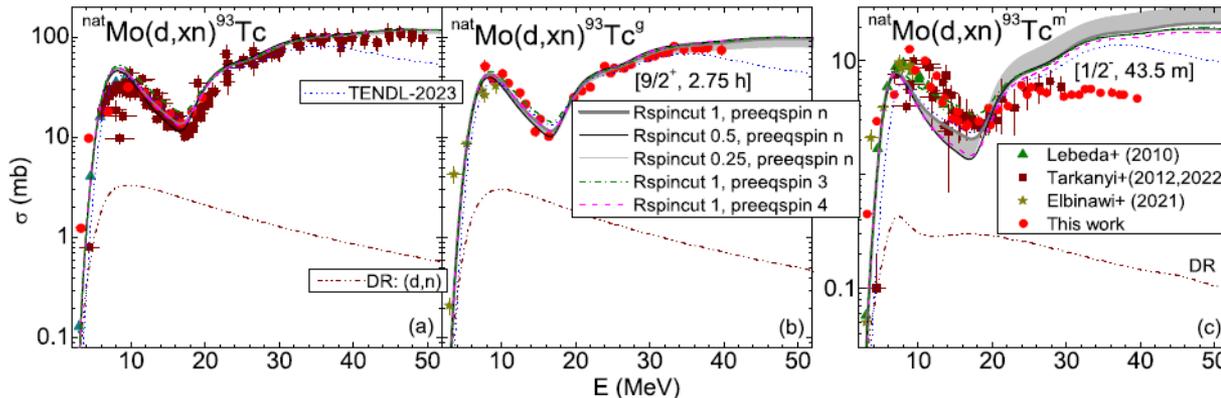
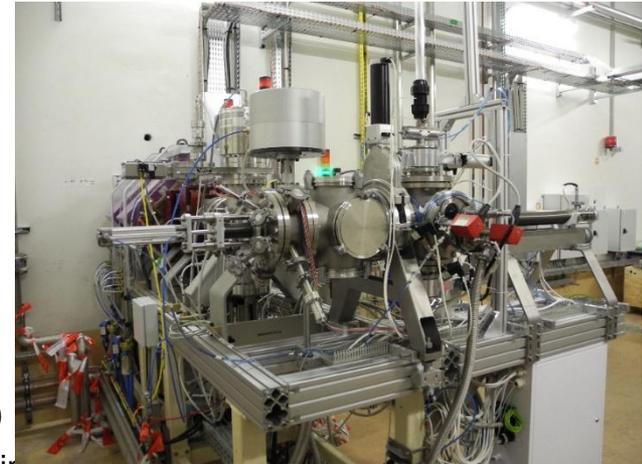


### Measurement by activation technique:

- Irradiation station
- Rabbit system (short half-live measurement)
- Adjustable proton energy (stack foil technique not needed)

### Excitation functions measurement:

- Data for IFMIF facility design
- Improvement of reaction model
- $p + \text{Fe}$  :  ${}^{\text{nat}}\text{Fe}(p,x) {}^{54m}\text{Co}$  measured for **the first time** (*E. Simeckova, NPI*)
- $d + \text{Mo}$  : 30 excitation functions measured on Mo 10 of them for the first time

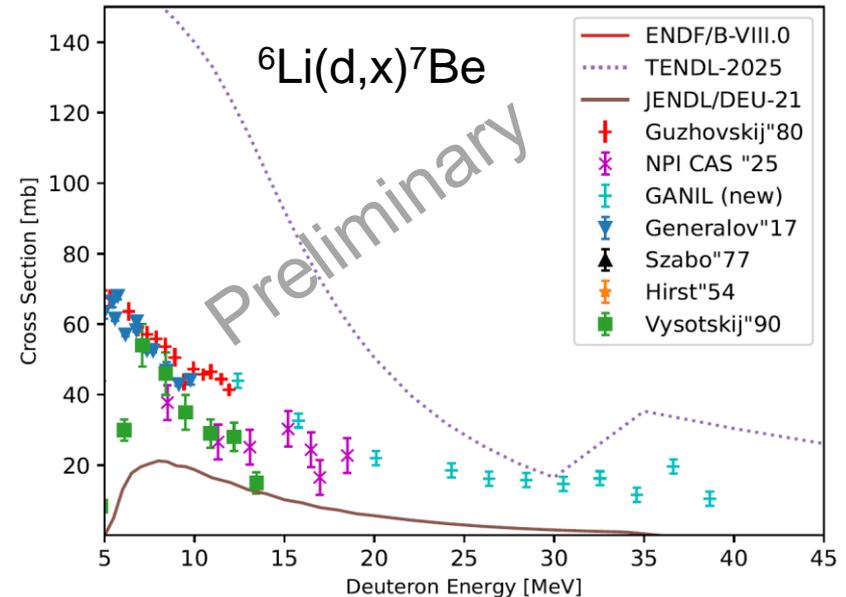
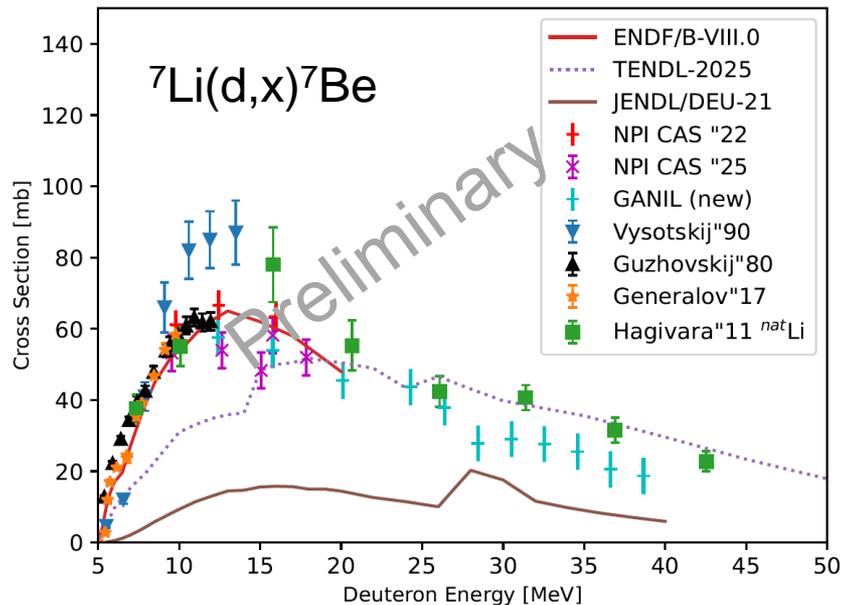


- Journal of Fusion Energy, vol 43, article15 (2024) <https://doi.org/10.1007/s10894-024-00407-w>
- PRC111, 044612 (2025)



### Experiment perform in September 2025

- ${}^6,{}^7\text{Li}(d,x){}^7\text{Be}$  and  $\text{Li}(d,x){}^3\text{H}$  (D. Koliadko, KIT)
- $\text{Fe}(d,x)$  and  $\text{Cr}(d,x)$  (E. Mendoza, CIEMAT)
- 11 Deuteron energies between 14 and 40 MeV





## □ $^{211}\text{At}$ ( $T_{1/2} = 7,2\text{h}$ ): promising $\alpha$ -emitter for Targeted $\alpha$ Therapy

### ○ Cross-section measurement :

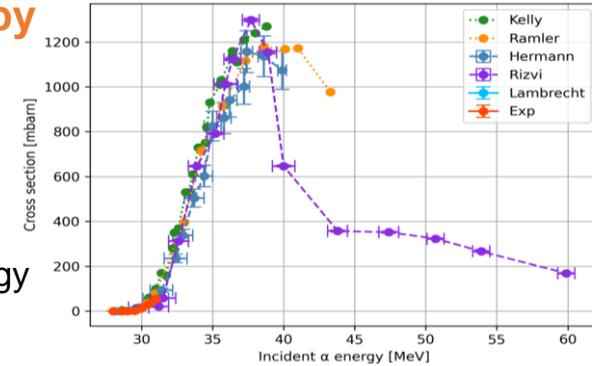
- Production reaction :  $^{209}\text{Bi}(\alpha,2n) ^{211}\text{At}$   $E_{th}=20,564$  MeV
- Unwanted reaction :  $^{209}\text{Bi}(\alpha,3n) ^{210}\text{At}$   $E_{th}=28,4$  MeV
- $^{209}\text{Bi}(\alpha,3n) ^{210}\text{At}$  Excitation function measurement near the energy threshold
- Saba et al., Applied Radiation and Isotopes 225 (112061)  
<https://doi.org/10.1016/j.apradiso.2025.112061>

### ○ Production test :

- REPARE project : 3 GBq produced in 15 hours at NFS
- Rotating target : 10 kW
- 2 GBq sent to Arronax (Nantes)

## □ Tb155 production cross section (IJCLab, NPI, GANIL)

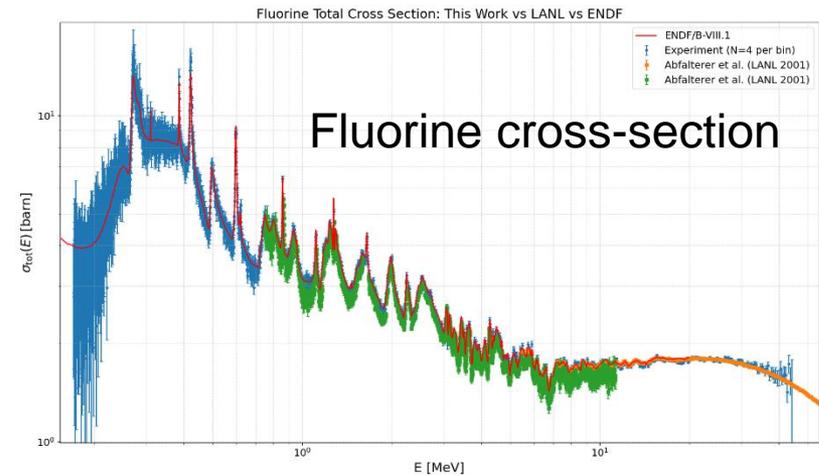
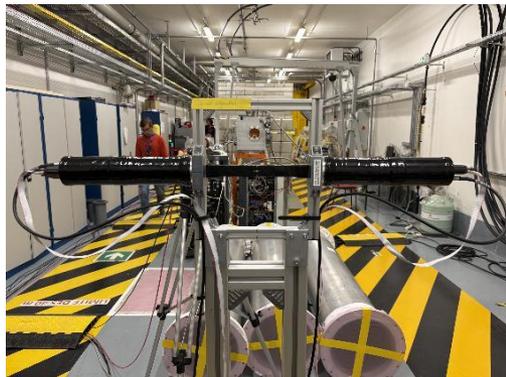
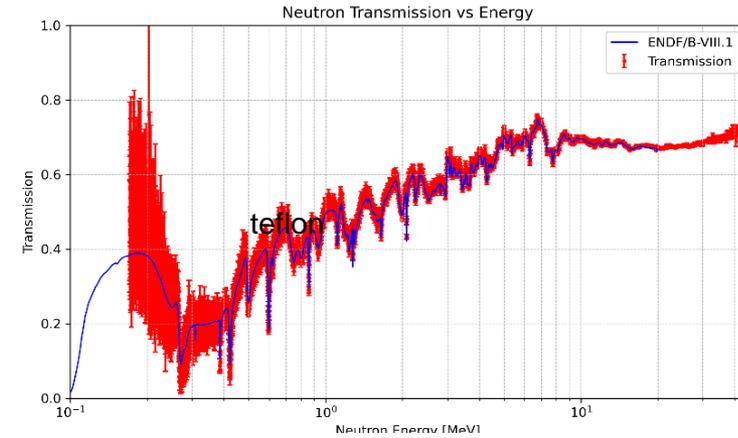
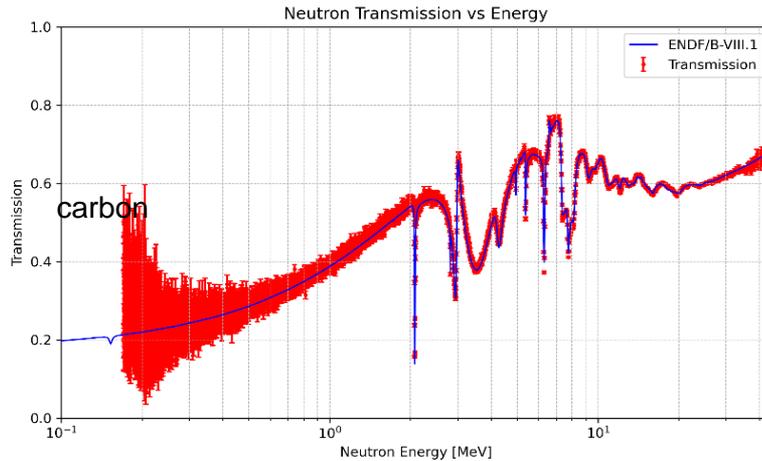
- Gd-155(p,x)Tb-xxx reaction between 7 and 24 MeV
- Activation technique with irradiation set-up
- M. Boutecluet et al., Applied Radiation and Isotopes 229 (112375)  
<https://doi.org/10.1016/j.apradiso.2025.112375>





- E912\_25: Elastic and inelastic neutron scattering measurements using Vendeta at NFS, P. Morfouace (CEA/DIF)
  - ➔ Development of low energy neutron beams
- E913\_25: Neutron-induced direct transfer reactions: an alternative window into proton orbital structures, C. Paxman (GANIL)
- E914\_25: Probing low energy dipole strength in  $^{88}\text{Sr}$  with  $(n,n'g)$  reaction at NFS, I. Mataea (IJC lab)
- E916\_25: Nuclear-moment measurements with the nfs, R. Loveza (IJC lab)
- E917\_25 Measurement of  $^{238}\text{U}(n,xn)$  reaction cross-sections using the SCONE detector, G. Bélier (CEA/DIF)
- E918\_25: Toward prompt gamma-rays from fragments in fast neutron-induced fission of  $^{238}\text{U}$  at NFS with the SFyNCS array, C. Fougères (CEA/DIF)
- E919\_25 New insights into the structure of the  $^4\text{He}$  nucleus, A. Chbihi (GANIL)
- E921\_25: Neutron Transmission measurement of  $^{20}\text{Ne}$ , A. Junghans (HZD Rossendorf)

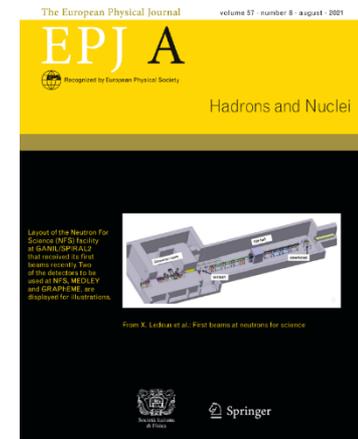
Transmission measurements test performed in September 2025 on  
carbon and teflon during 9 h



E921\_25: Neutron Transmission measurement of Ne20, A. Junghans (HZD Rossendorf)  
scheduled in 2026



- ❑ **Neutrons for Science is now operational**
  - Intense fast neutrons flux
  - Pulsed and well collimated beam
- ❑ **Studied reactions**
  - Light-Charged-Particles production
  - Fission process
  - n,xny reactions
  - Excitation function measurement of ions induced reactions
- ❑ **Applications**
  - Radioisotopes for medicine
  - Irradiation of chips
  - Detector characterization
- ❑ **Everyone can propose an experiment**
  - 1 PAC session per year; next PAC submission deadline (September 2026)
  - GANIL web site “proposing an experiment” and contact me
- ❑ **NFS is in the European Projects (Transnational Access):**
  - APRENDE
  - RADNEXT
  - EUROLABS





Thank you for your attention

