The Neutrons For Science facility at GANIL/SPIRAL-2

X. Ledoux on behalf of the NFS collaboration

1. The NFS facility
2. Neutron beam characteristics
3. First experiments

The Neutrons For Science facility

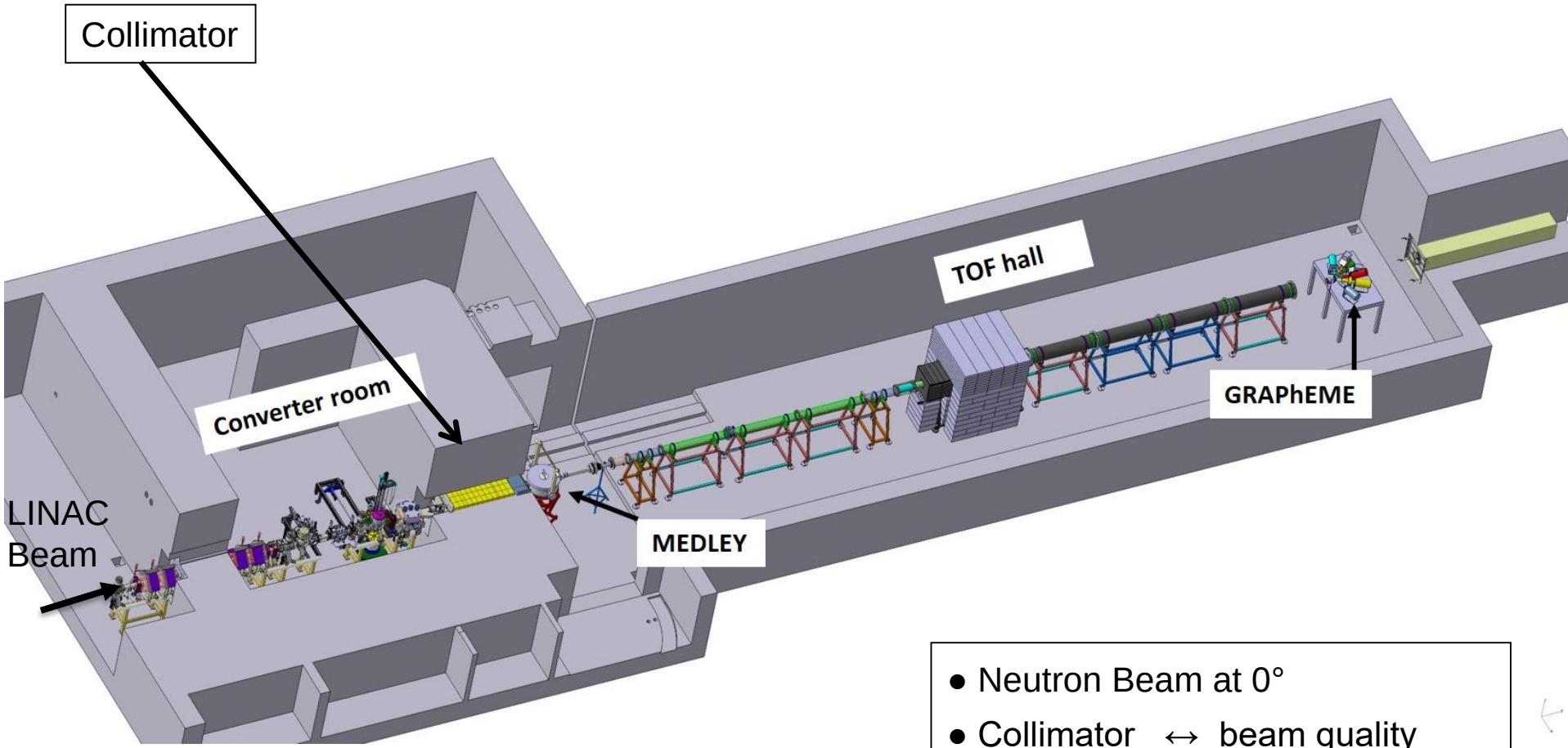
NFS is one of the experimental areas of SPIRAL-2 at GANIL (Caen)

Physics case

- ❑ Fundamental physics
- ❑ Astrophysics
- ❑ New generation of reactor
- ❑ Fusion technology
- ❑ Radioisotopes production for medical applications
- ❑ Biology (cells irradiation..)
- ❑ Development and characterization of new detectors
- ❑ Study of the single-event upsets

International collaboration
50 physicists
15 laboratories
8 partners

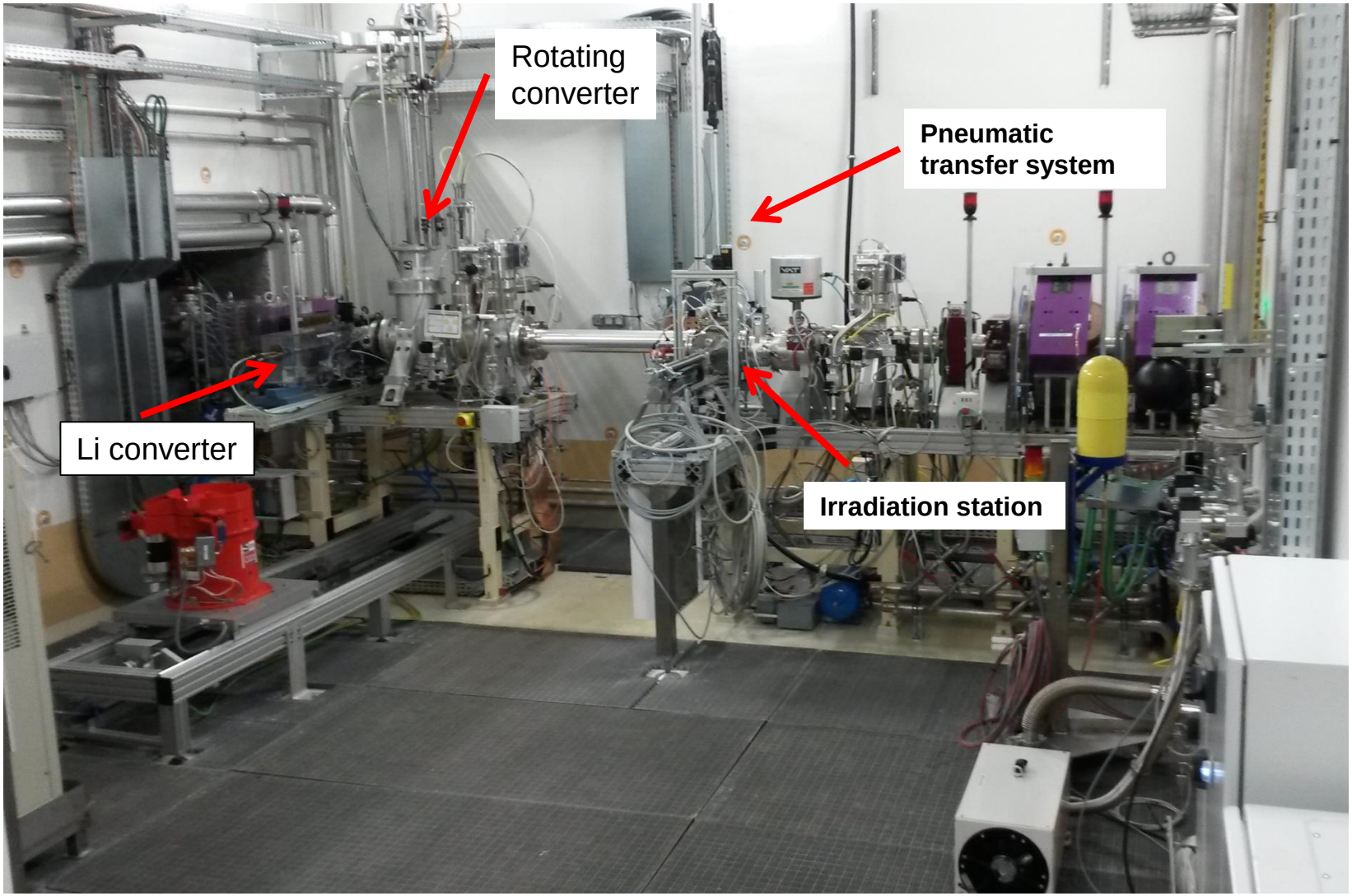
NFS layout



- Ion and neutron induced reactions
- Beam line extension
- Irradiation station (n, p, d)

- Neutron Beam at 0°
- Collimator ↔ beam quality
- Size (L x l) ≃ (28m x 6m)
  - TOF measurements
  - free flight path

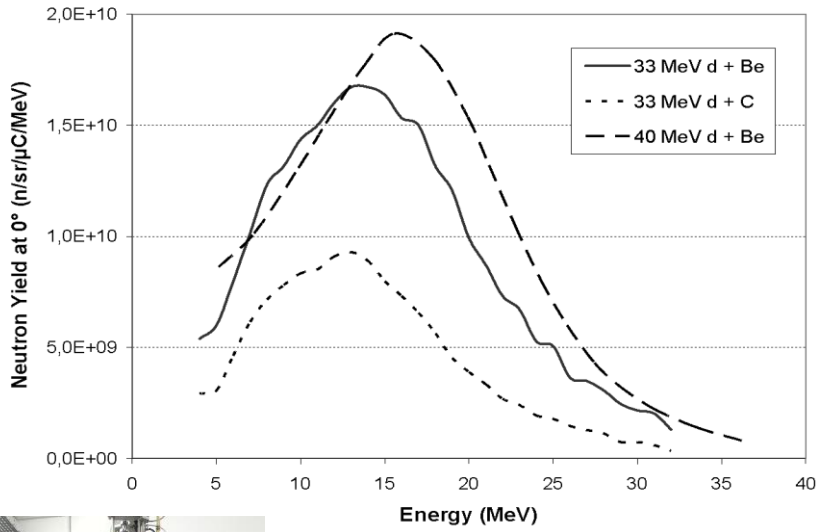
NFS: The converter room

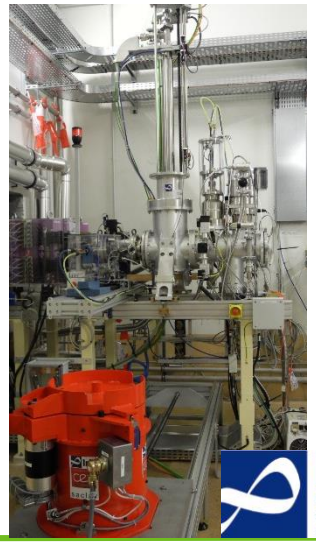


NFS: The TOF area

Neutron production reaction

Continuous spectrum
E_{max} = 40 MeV , <E> = 14 MeV



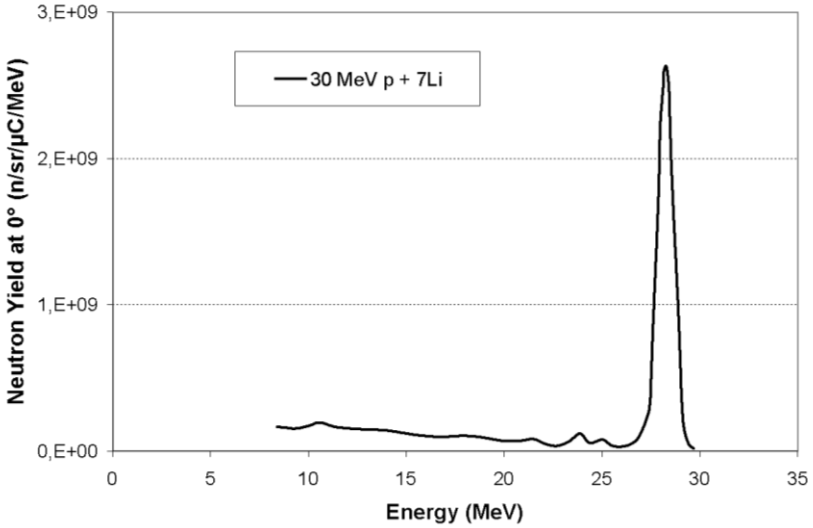


40 MeV d + Be at 50 µA

Rotating converter
thick target C or B (8mm)
P< 2 kW

Irfu
Institut de recherche sur les lois fondamentales de l'Univers

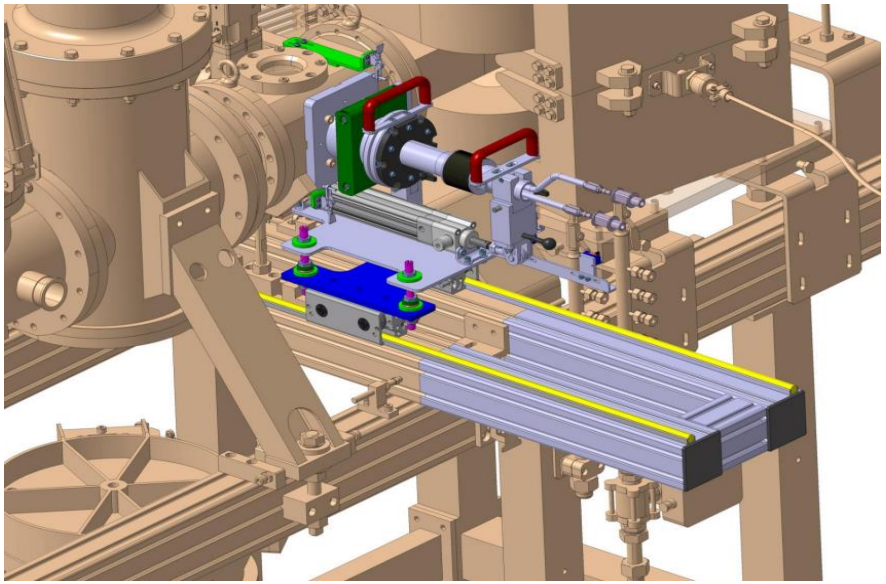
Quasi-monoenergetic spectrum
E_n = up to 31 MeV

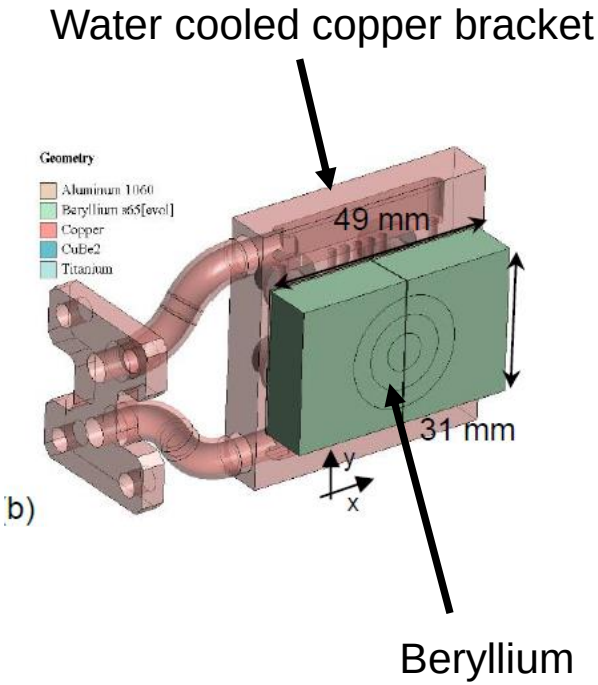


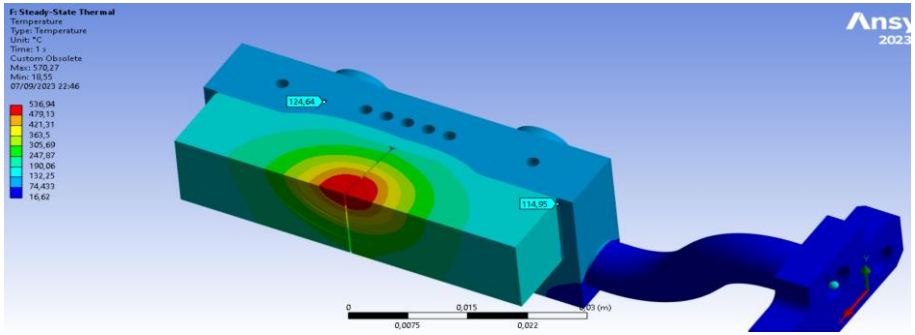
p + Li (1mm) at 20 µA

New beryllium converter

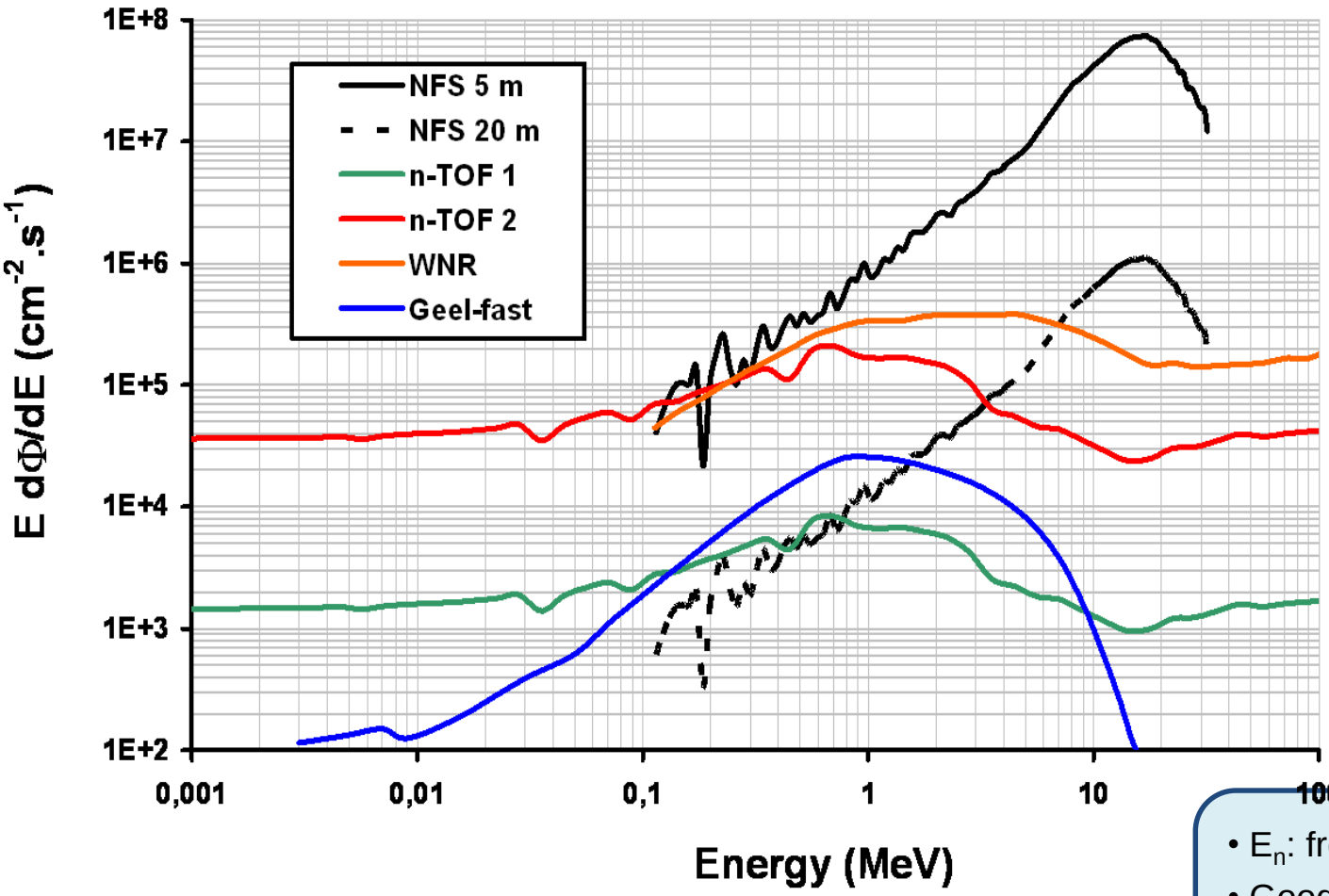
After the failure of the rotating converter in 2021, a new static converter was build







Comparison with other Neutron TOF facilities



NFS : 40 MeV d + Be

WNR : Los Alamos

n-TOF 2 : CERN

n-TOF 1 : CERN

GELINA : Geel

- E_n: from 0,1 MeV to 40 MeV
- Good energy resolution
- Reduced γ flash
- Low instantaneous flux

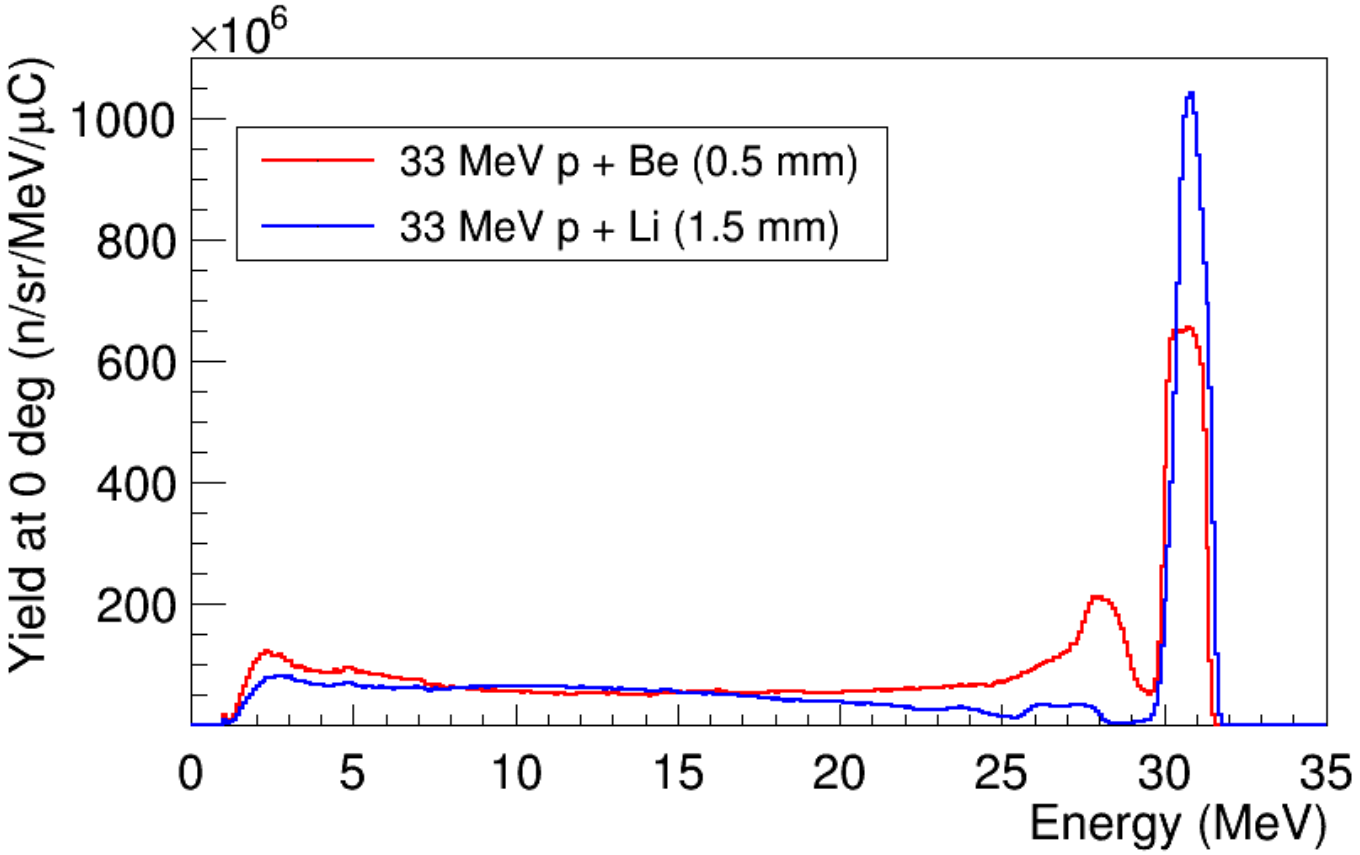
Complementary to the existing facilities

1. The NFS facility

2. Neutron beam characteristics

3. First experiments

Quasi-mono-energetic spectra

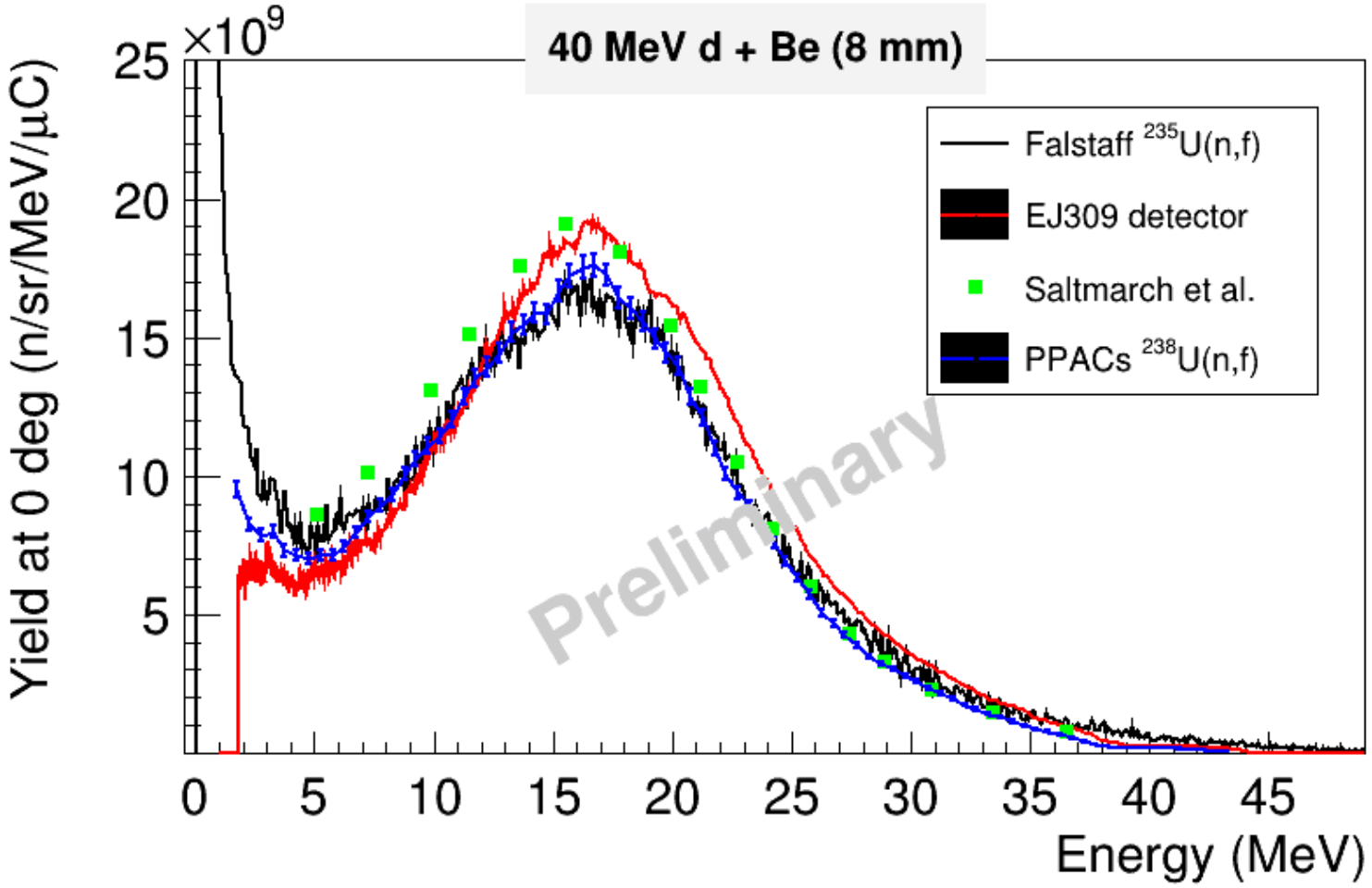


33 MeV p + Li (1,5 mm)

Neutron yield in the mono-energetic peak 1,2 10^9 n/sr/µC

at 20 µA and d=500cm → Φ = 10^5 n/s/cm^2

Continuous spectrum



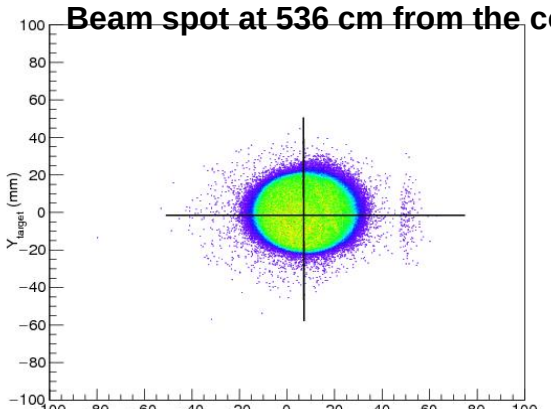
Neutron yield ≈ 3.10^{11} n/sr/µC

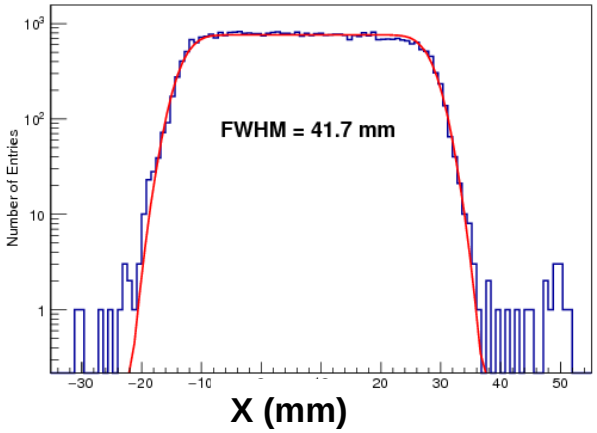
at d=500cm → $\Phi \approx 7.10^{7}$ n/s/cm^2

Neutron beam profile

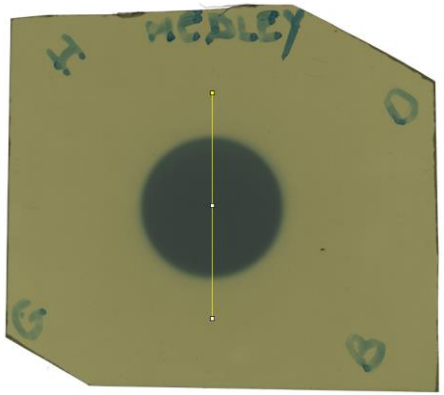
- The beam has a conical shape :
  - r=21 mm at 5 m downstream from the collimator
  - r=28 mm at 29 m

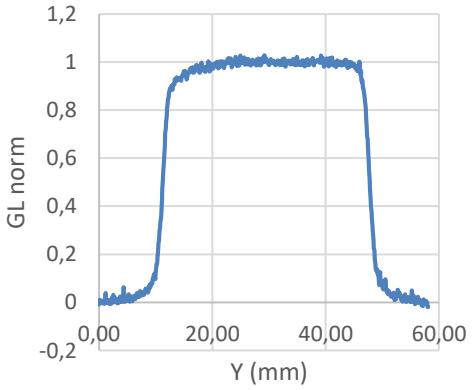
PPAC measurement





Graphchromic film





1. The NFS facility
2. Neutron beam characteristics
3. First experiments

PAC 2020 to 2022 NFS accepted experiments

NUM	Title	Spokesperson	UT Allocated
E799	Excitation functions of short-lived isotopes in proton induced reactions on ^{nat}Fe	E. Simeckova, NPI, Rez	5
E800	LIONS - Light-Ion Production Studies with Medley at the NFS facility	A.V. Prokofiev, Uppsala University	17
E802	GARIC - Gas pRoduction In Chromium by neutrons	A.V. Prokofiev, Uppsala University	21
E804	Measurement of fission cross sections standards relative to elastic n-p scattering at neutron energies 1- 40 MeV	D. Tarrio, Uppsala University	31
E807	Study of the (n,xn) and (n,f) reaction for U238	G. Bélier, CEA-DAM	12
E811	Study of the (n,alpha) reactions of interest for nuclear reactors - the SCALP Project	F. R. Lecolley, lpc Caen	12
E814	235U Fission fragment study with FALSTAFF at NFS	D. Doré, CEA/IRFU/DPhN	11
E832	Deuteron activation of natMo - focus on short-lived products	E. Simeckova, NPI, Rez	4
E833	Pygmy dipole resonance in 140Ce using the (n,n'g) reaction at NFS	M. Vandebrouck, CEA Saclay	23
E835	Measurement of the neutron induced activation in materials	V. Blieanu, CEA Saclay	3
E838	Shedding new light on the structure of 56Ni using (n,3n) reaction at NFS	E. Clément, Ganil	22
E856	Study of neutron induced reactions on 239Pu	G. Bélier, CEA-DAM	42
E858	GARROS - Gas production in iron by neutrons	A. Prokofiev, Uppsala University	22
E859	238U(n, 2ng) and (n, 3ng) reaction cross sections measurements	M. Kerveno, IPHC, Strasbourg	31

Performed in 2021

Performed in 2022

Performed in 2023

1 UT = 8h

FISSION

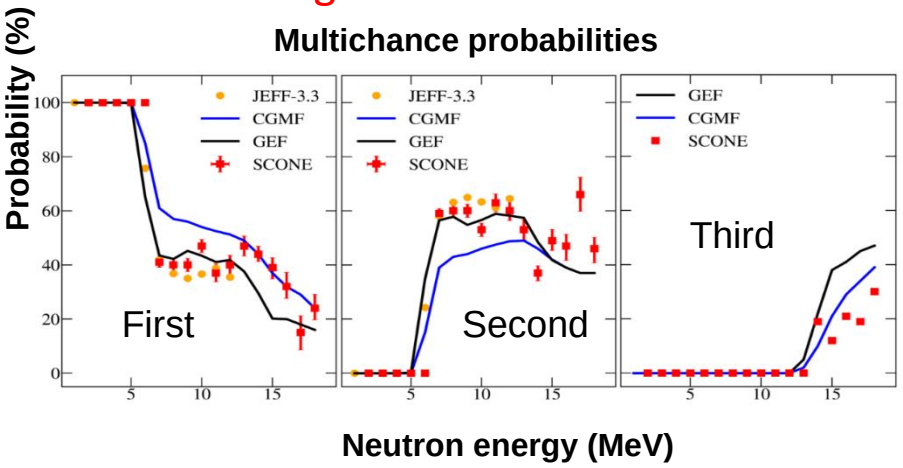
E807: Study of the (n,xn) and (n,f) reaction for U238

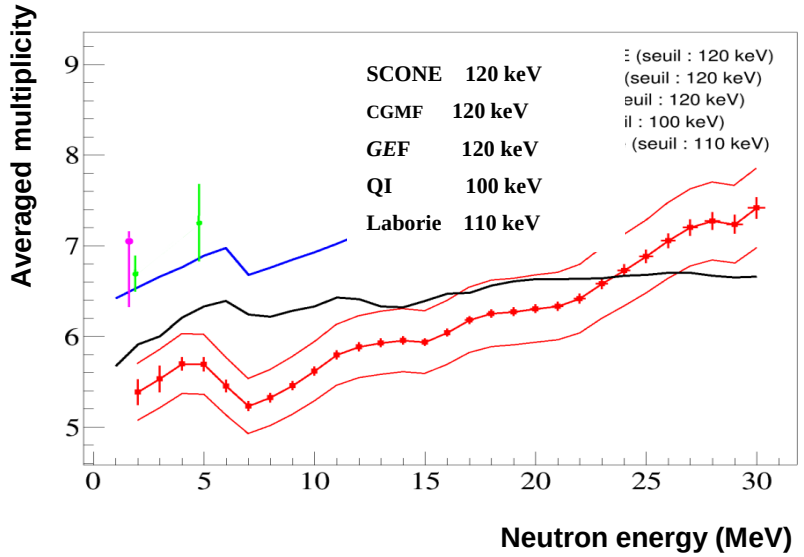
Spokesperson : G. Bélier, CEA-DAM-DIF

- (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<En< 20 MeV

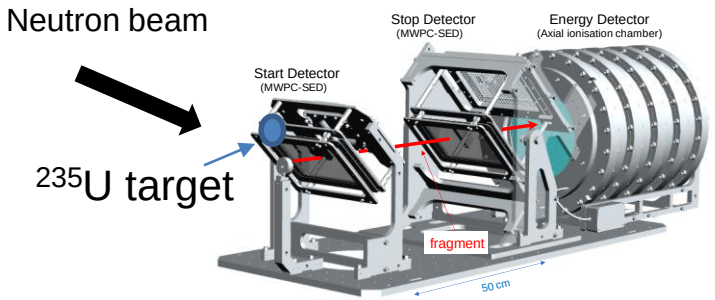




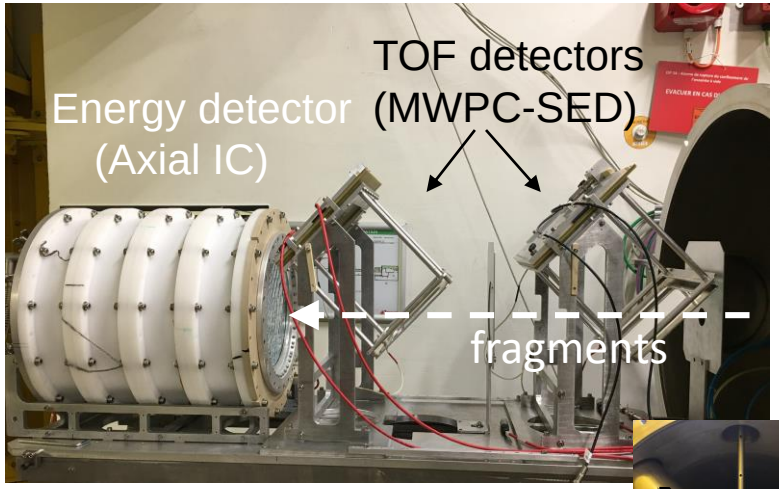
E814: ^{235}U fission fragment study with FALSTAFF at NFS (1/2)

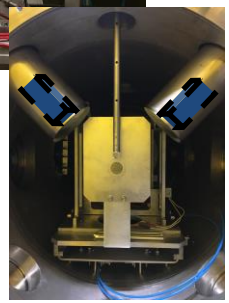
Spokesperson : D. Doré, (CEA Saclay Irfu/DPhN)

Experiment E814 (Nov.-Dec. 2022)

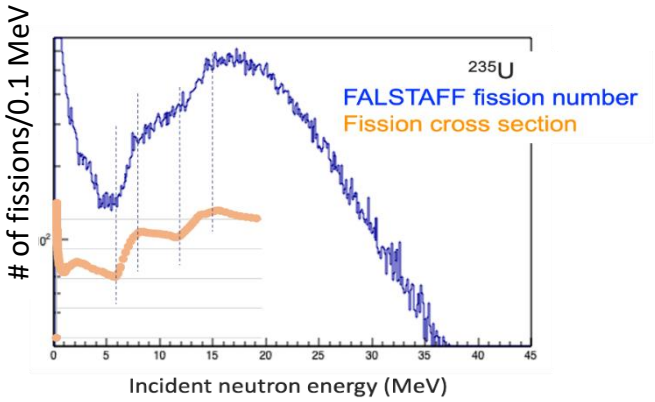


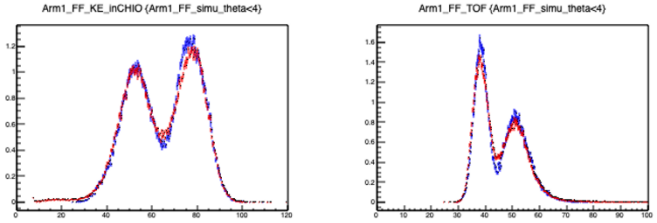
+2 LaBr3 detectors (Subatech, Nantes)



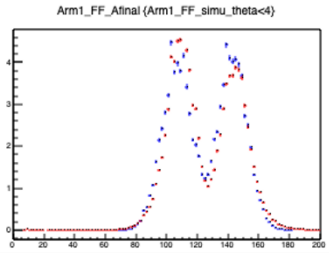


Measurements of time, position and residual energy
→ reconstruction of velocity and kinetic energy
→ determination of post-neutron evaporation fragment mass
over the full NFS neutron energy range :





Data
GEF + G4 + analysis

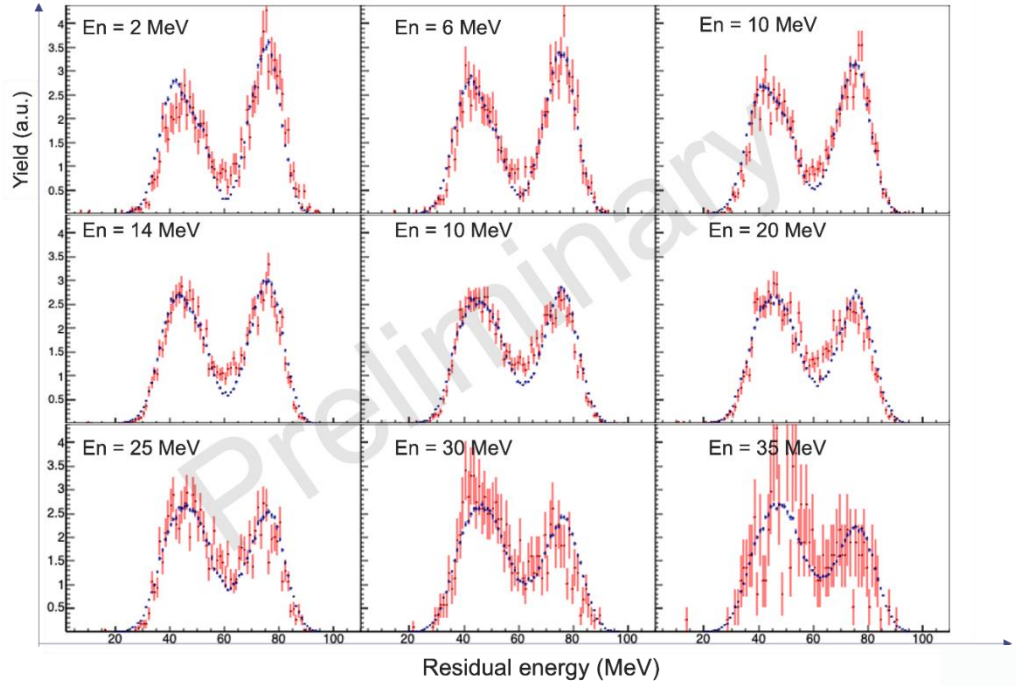


Calibration with Cf-252
- comparison data vs simulations

E814: 235U fission fragment study with FALSTAFF at NFS (2/2)

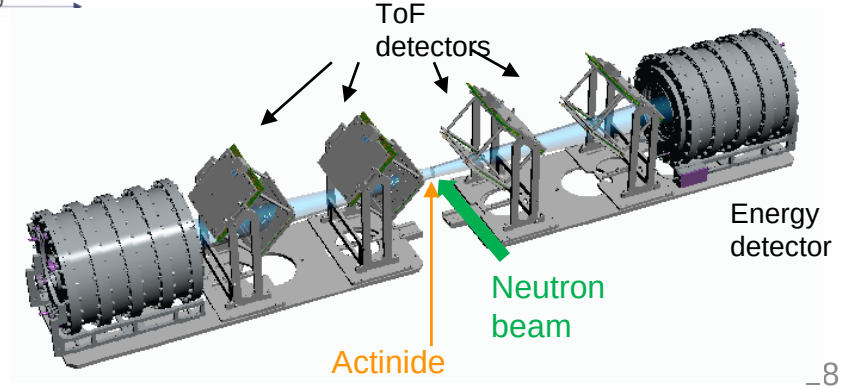
Study of the evolution of kinetic energy, velocity, post-evaporation mass

FALSTAFF
GEF+Geant4



- Expected trends
- Data & Simu in a rather good agreement

Second arm will be tested this Fall
Full setup mounting and tests in 2025
Proposal submitted Oct. 2024 for experiment on ^{235}U with complete setup

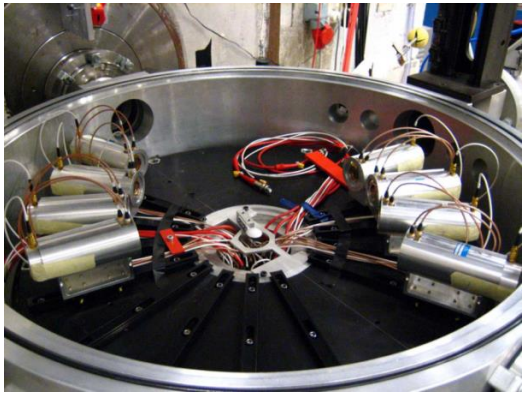


N,X reactions

Ion Production Studies with Medley at the NFS facility

Spokesperson : D. Tario, Uppsala University

- **Neutron-Induced Light charged particles emission with MEDLEY**
  - 8 **Si-Si-CsI** telescopes
  - Double-differential **cross sections** :
  - **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)

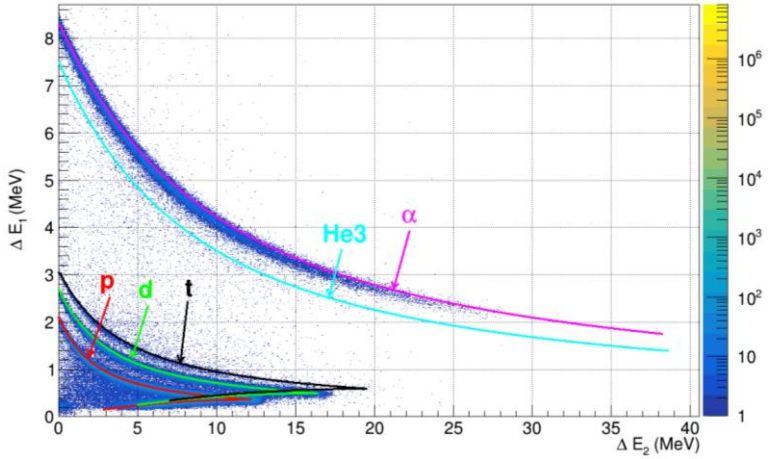


- **Setup tested in fall 2020 and September 2021**
  - High **particle-identification capability**
  - Simultaneous measurement of **charged-particles energy and neutron ToF** (digital

Experiments :
E800, E802, E858

- **One ongoing master project at Uppsala Univ.**

L. de Arruda, D. Tarrío, X. Ledoux et al., submitted to EPJ-Web Of Conf. (2024) (Proc. CNR*24 workshop)

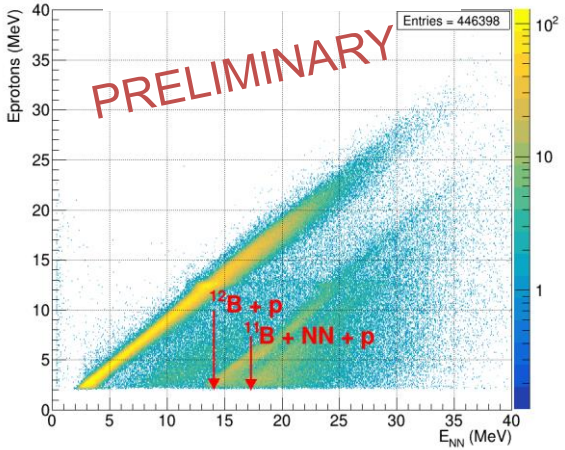


PHD work of Lucas de Arruda (Uppsala Univ., GANIL, Univ. Caen-Normandie)

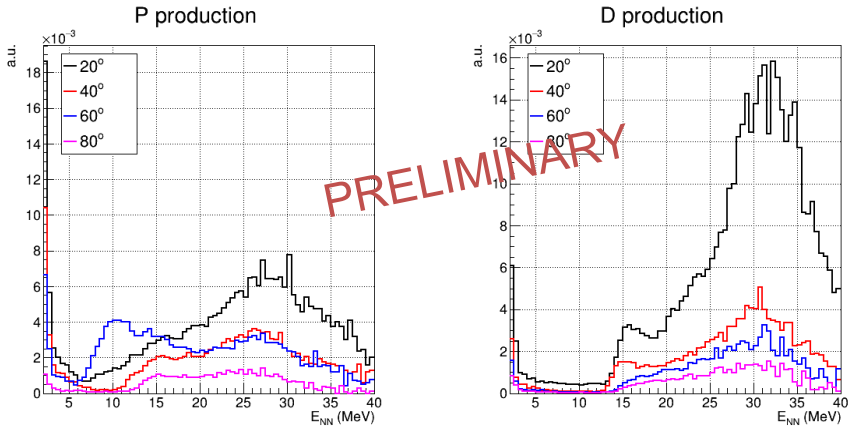
Experimental measurements on light-ion production

Very preliminary cross sections are already being produced

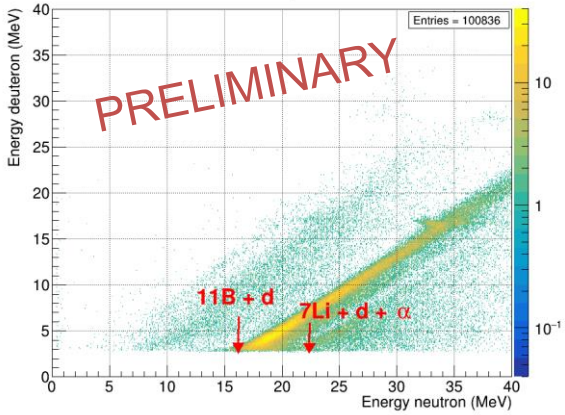
C(n,pX) (at 20º)



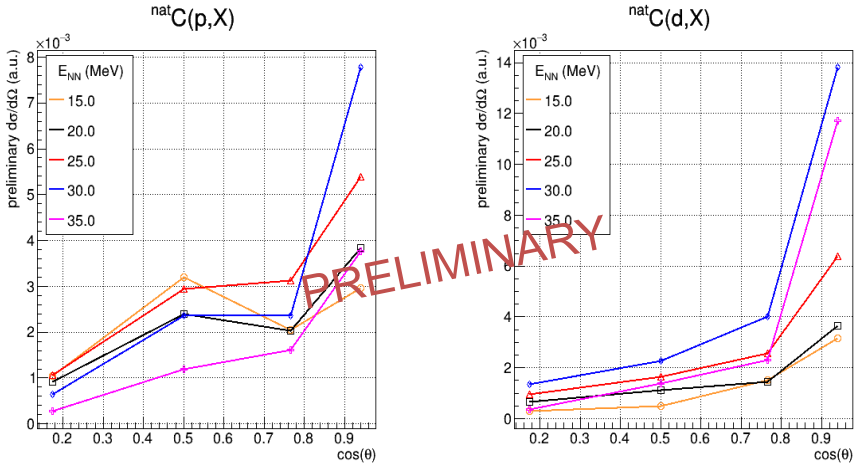
Total spectrum of p and d in ^{nat}C



C(n,dX) (at 20º)



Angular distributions for p and d in ^{nat}C



E811: Study of the (n,α) reactions of interest for nuclear reactors - the SCALP Project

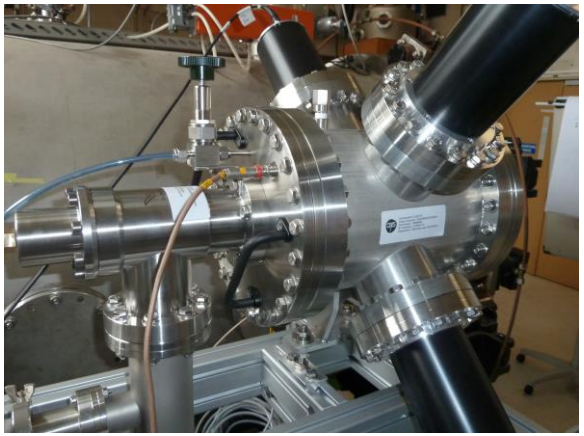
Spokesperson : J. F. Lecolley, LPC Caen

Goals : XS measurement in 7MeV-20MeV range with an uncertainty better than 5%

Active target

Scintillating Ionization chamber

Continuous energy

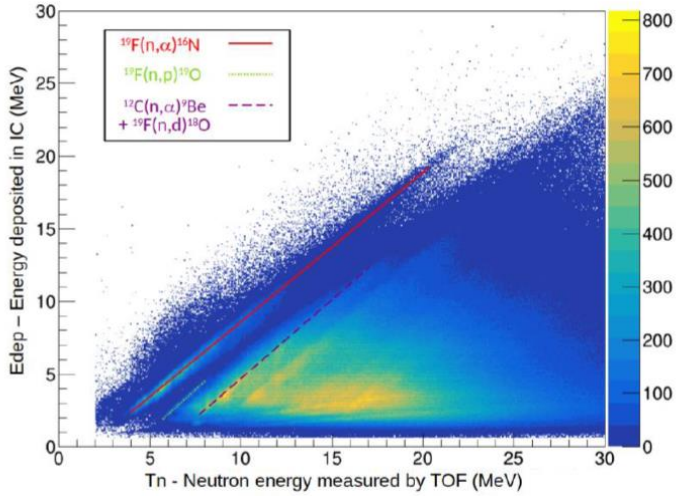


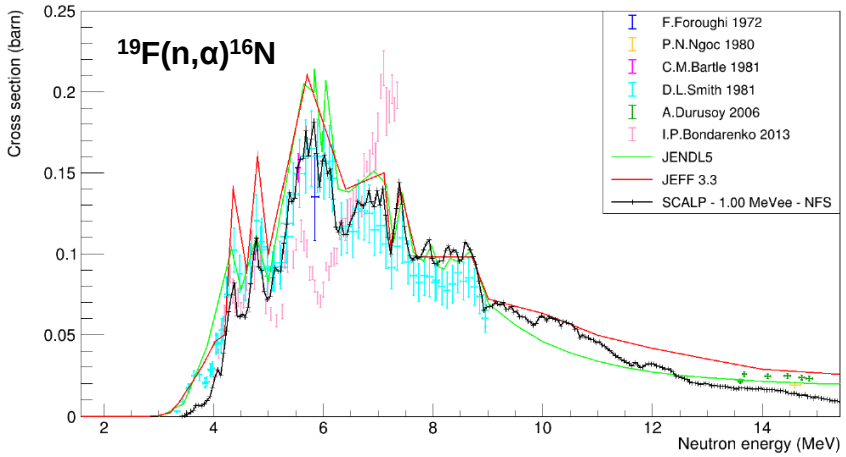
Target composition :

Oxygen → CO_2

Scintillation → CF_4

A lot of Channels to distinguish





Experiment performed in Oct 2021

PHD work of Aurélien Chevalier, LPC Caen

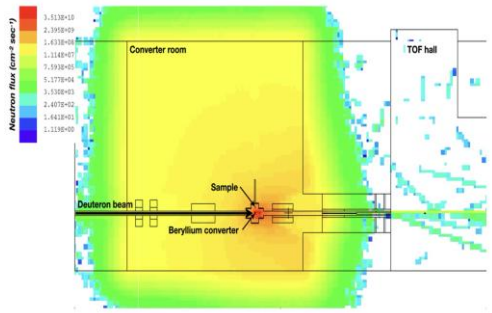
A. Chevalier et al. WONDER 2023 proceeding

E835:Measurement of the neutron induced activation in materials

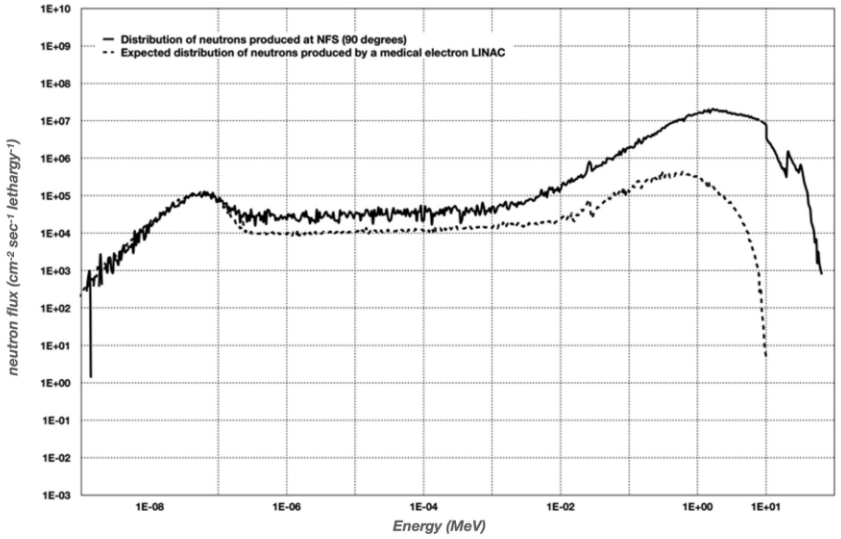
Spokesperson : V. Blideanu (CEA Saclay LIST)

Experimental assessment and analysis of calculations accuracy for the neutron-induced radio-isotopes in copper parts of radiotherapy accelerators

- Need of new data in order to validate the predictive power of the models used
- NFS Neutron spectrum close enough to neutron production in radiotherapy e accelerator
- Measurement by activation method



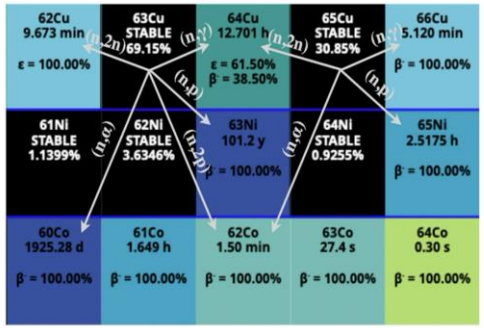
Spatial distribution of neutrons produced at SPIRAL2/NFS by the interaction of 40 MeV deuterons with the beryllium converter.



Simulated energy distribution of neutrons available for sample irradiation at SPIRAL2/NFS, compared to the estimated distribution of neutrons produced by a radiotherapy electron accelerator.

E835: Results

- Activation calculations with MCNP6/FISPACT-II
- Identification of main contributing radio-isotopes to the sample activity
- Comparison simulation - measurement



Main neutron-induced reactions leading to the production of radio-isotopes in copper.

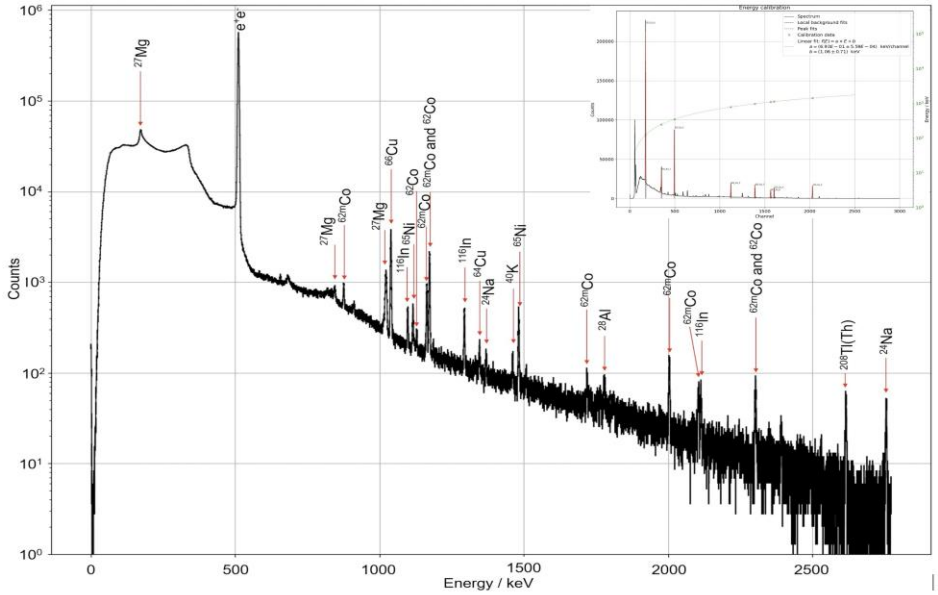


Figure 8: Measured γ spectrum for the neutron irradiated copper sample after background subtraction.

Table 1: Main radio-isotopes created by neutron-induced reactions in the copper sample.

Radio-isotope	Calculated activity/total	Calculated yield/total	Measured yield/total	Ratio Calculated/Measured	Calculation accuracy
^{62}Cu	5,93E-01	1,81E-01	4,96E-01	3,64E-01	7,65 %
^{66}Cu	2,80E-01	4,46E-02	3,59E-03	1,24E+01	7,50 %
^{60m}Co	7,42E-02	2,42E-02	-	-	-
^{64}Cu	3,01E-02	7,17E-01	4,94E-01	1,45E+00	4,83 %
^{62}Co	9,85E-03	4,73E-04	2,36E-03	2,01E-01	27,80 %
^{62m}Co	6,03E-03	2,62E-03	3,51E-03	7,46E-01	17,32 %
^{65}Ni	3,23E-03	1,53E-02	8,70E-04	1,75E+01	23,93 %
^{61}Co	1,84E-03	5,70E-03	-	-	-
^{61}Cu	1,43E-03	9,04E-03	-	-	-
^{63}Co	1,53E-04	2,19E-06	-	-	-

V. Blideanu at al., submitted to NIMB

E833 : Pygmy dipole resonance (PDR) in ^{140}Ce using the (n,n'γ) reaction at SPIRAL2-NFS

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

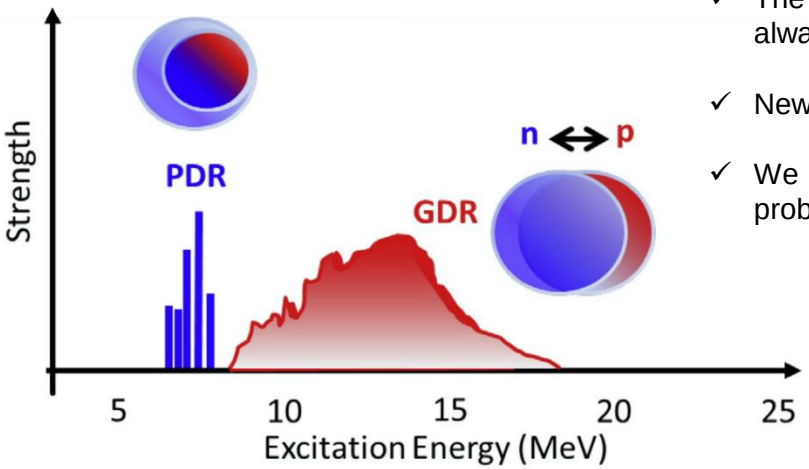
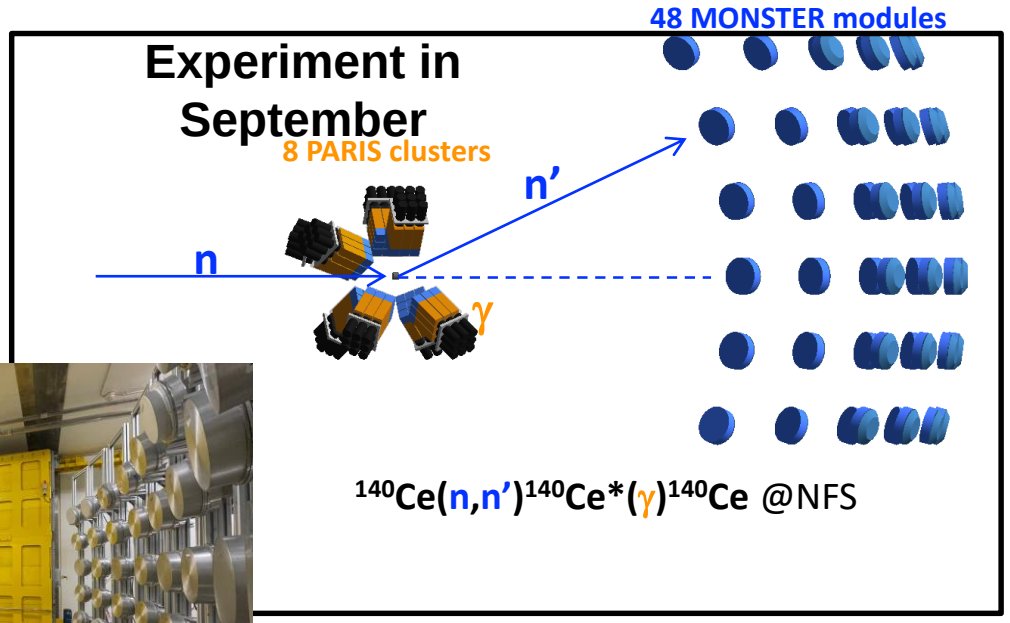


Figure extracted from A. Bracco *et al.* Prog. Part. Nucl. Phys. 106 (2019)

- ✓ 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
- ✓ We propose to use neutron inelastic scattering reaction at SPIRAL2-NFS as a new probe

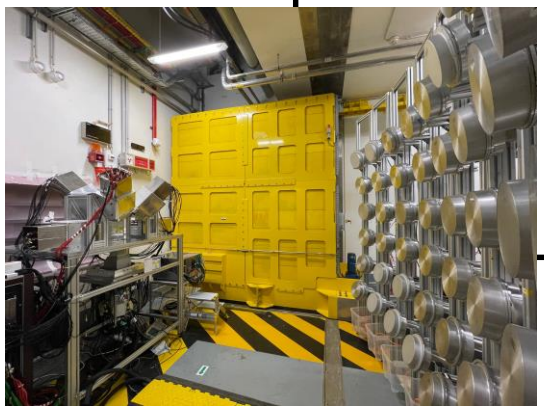


GDR (Giant Dipole Resonance)

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

PDR (Pygmy Dipole Resonance)

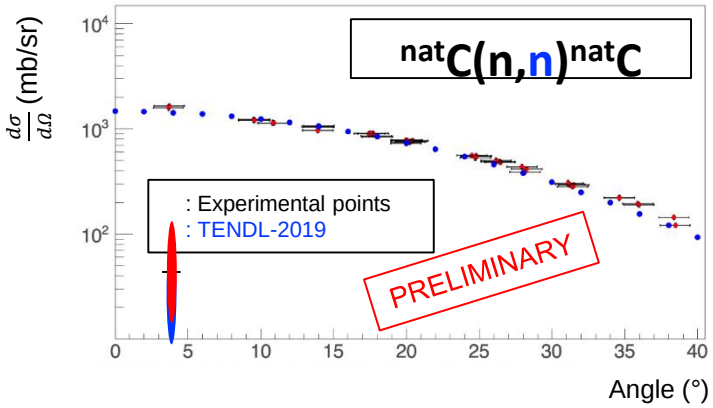
- oscillation of a neutron skin against a symmetric proton/neutron core
- small additional dipole strength at lower energy



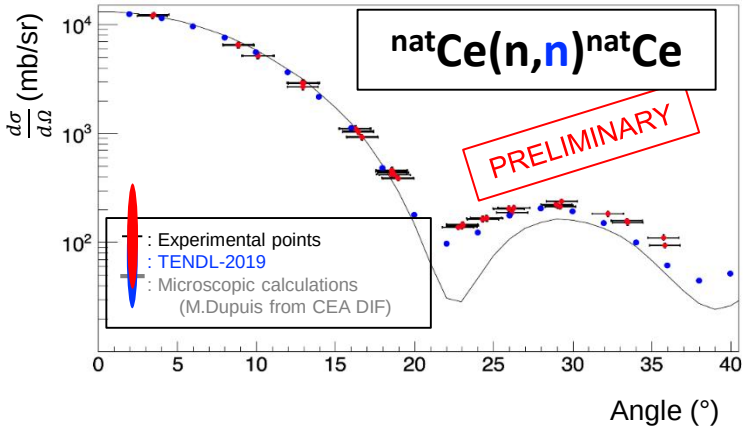
31 MeV neutron beam

E833 : Pygmy dipole resonance (PDR) in ^{140}Ce using the (n,n'γ) reaction at SPIRAL2-NFS

Elastic scattering channel

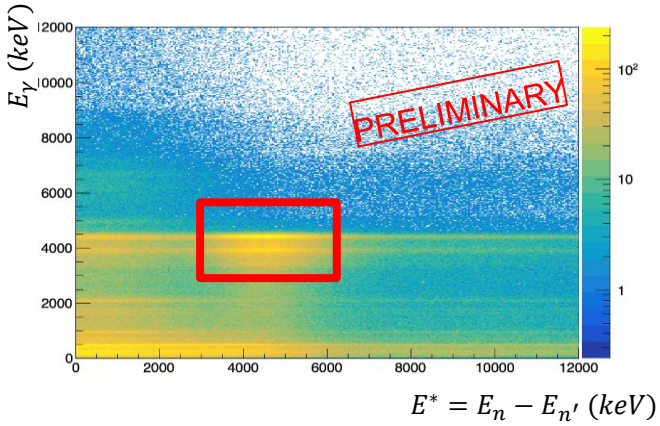


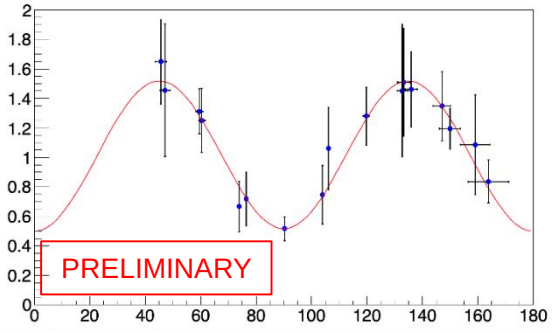
Well known on C -> validates the neutron analysis method



NEW on Ce at 31 MeV

Inelastic scattering channel : benchmark with ^{12}C 4.44MeV excited state





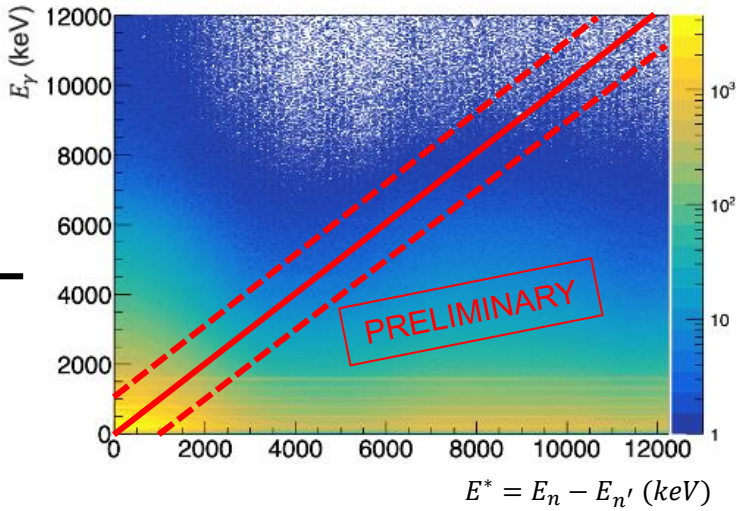
γ angular distribution compatible with 2+ state

PHD work of Périne Miriot-Jaubert (CEA Saclay Irfu/DPhN)

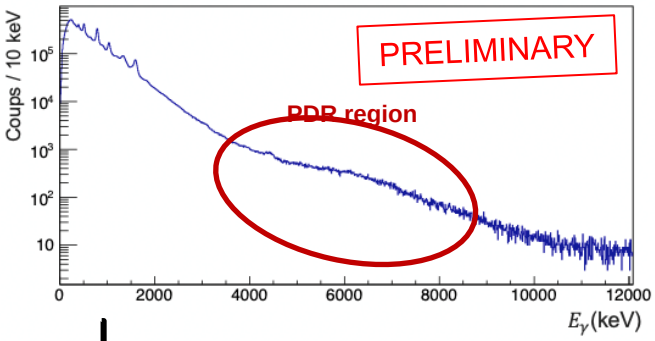
Inelastic scattering channel : ongoing analysis with Ce target

The reaction :
^{nat}Ce(n,n')^{nat}Ce*(γ)^{nat}Ce

1) Coincidence matrix



2) Projection on the energy axes

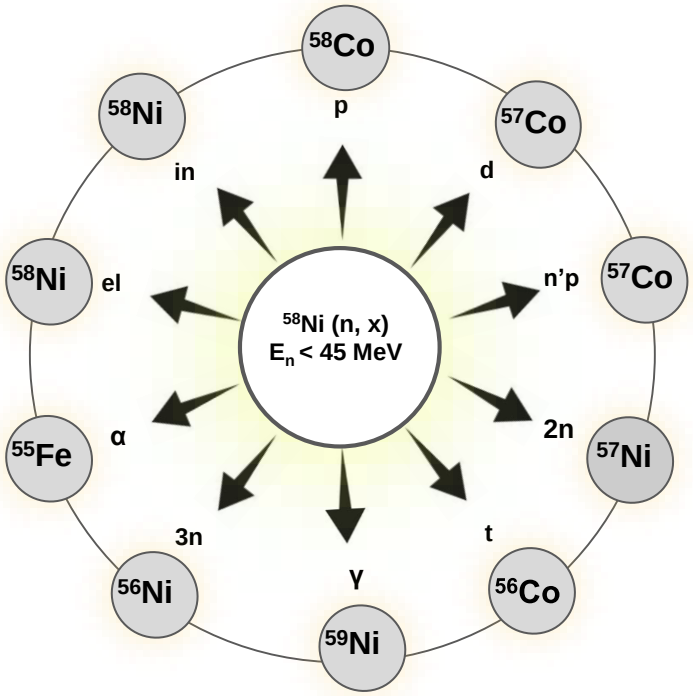


3) Angular distributions for different slices in energy

To be analysed

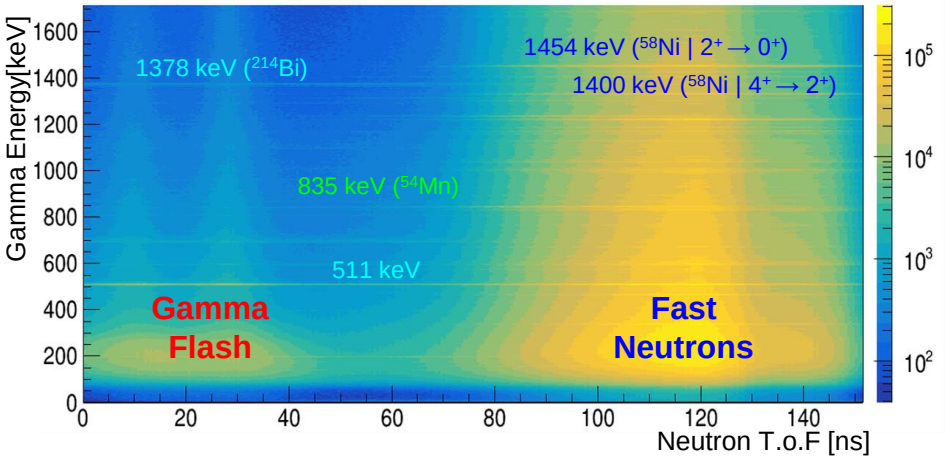
E838 : Shedding new light on the structure of ^{56}Ni using ^{58}Ni(n,3n) reaction at NFS

Spokesperson : E. Clément (GANIL)



- More studies on n-rich Co isotopes from ^{60}Ni isotope in the target to come
- Data also collected for natural Pb target, to be studied

- Pulsed neutron beam – Hard validation by fastest neutron from the T.o.F using the LINAC RF
- EXOGAM (12 Clovers) at 8 meters from converter



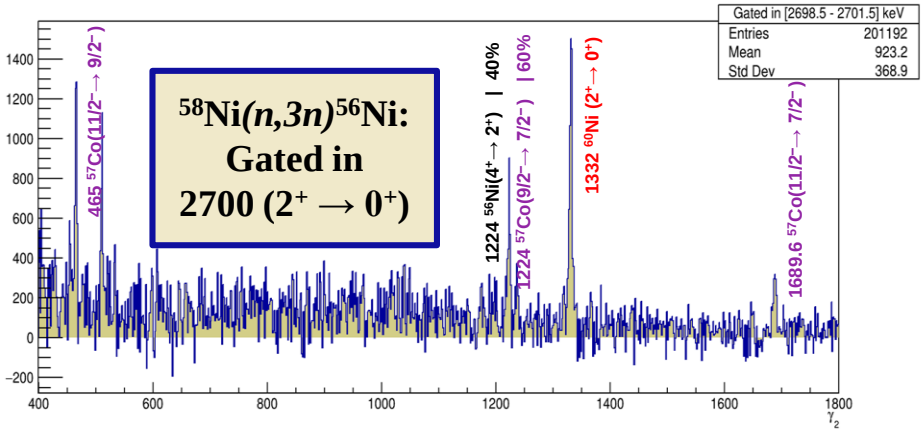
- Can distinguish between gamma flash and prompt gamma from the fast neutrons.
- ~10^{10} γγ coincidences (within a time window of 100ns) recorded in coincidence with fast neutrons after addback.

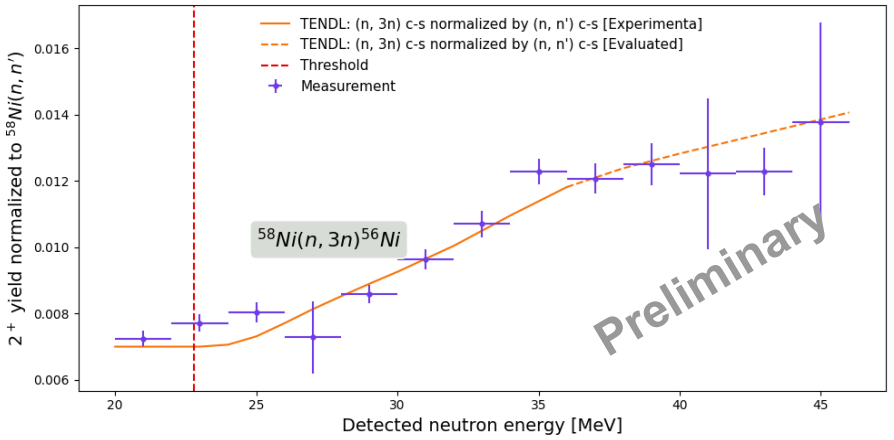
PHD work of Hemantika Sengar (GANIL)

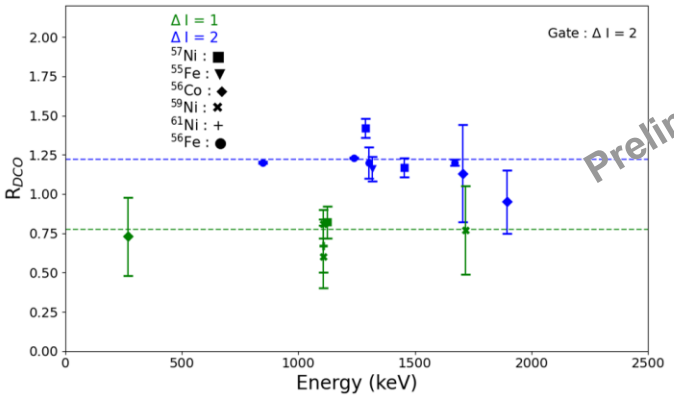
E838 : Shedding new light on the structure of ^{56}Ni using ^{58}Ni(n,3n) reaction at NFS

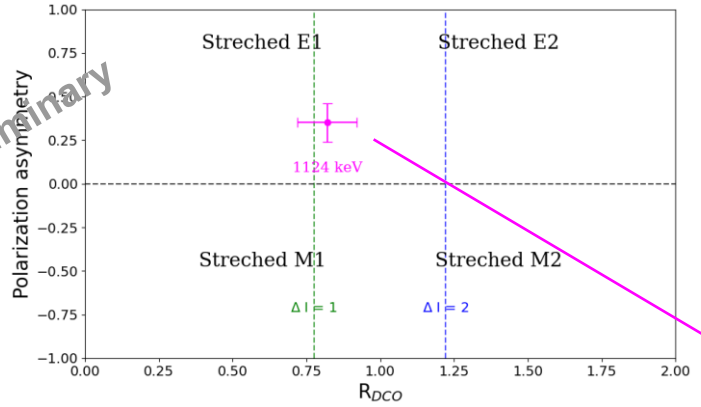
Successfully observed ^{56}Ni in the system!

Additionally, excitation functions measured









- We can verify the neutron energy threshold (~23 MeV) for ^{58}Ni(n, 3n)^{56}Ni.
- R_{DCO} and Asymmetry measurement for the first time in (n,xn) reactions

$9/2^+ \rightarrow 7/2^-$ in ^{57}Ni [3]

Ion induced reactions

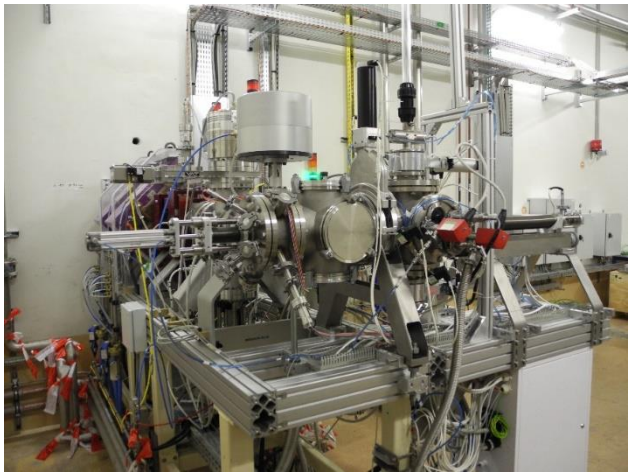
E799: Excitation functions of short-lived isotopes in proton-induced reactions on ^{nat}Fe

Spokesperson : E. Simeckova, NPI, Rez

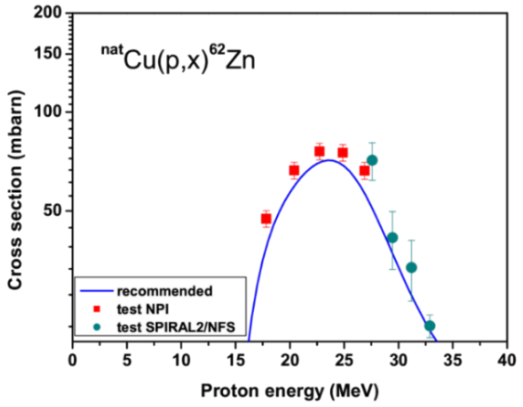
Measurement of reaction cross-sections by activation technique :

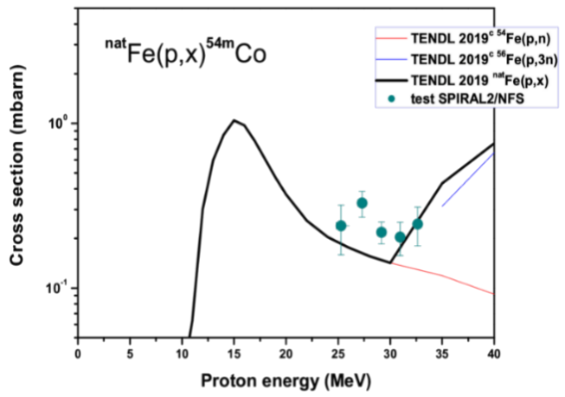
- data for IFMIF facility design
- improvement of reaction model

Goal: measure the ^{58m}Co and ^{58g}Co alimentation



- Commissioning : Irradiation station tested in December 2019
  - **33 MeV proton** beam
  - **80 nA** beam intensity
- Adjustable proton energy (stack foil technique not needed)
- Good agreement between production cross section of 62Zn and recommended values → **proves the validity of the method**
- ^{nat}Fe(p,x) ^{54m}Co measured for **the first time**

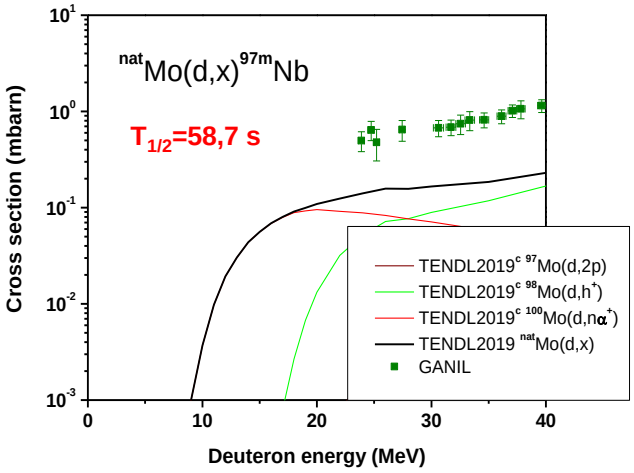


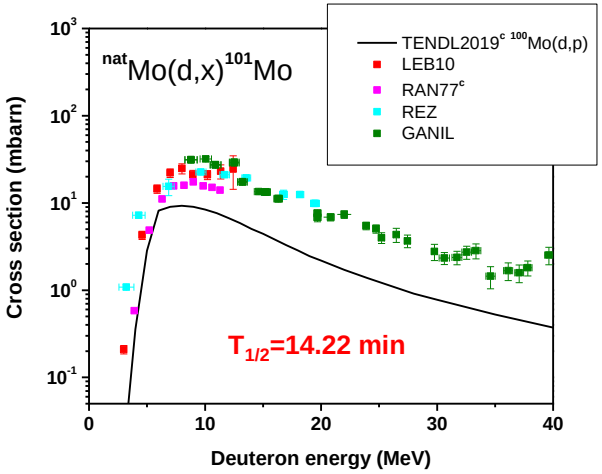


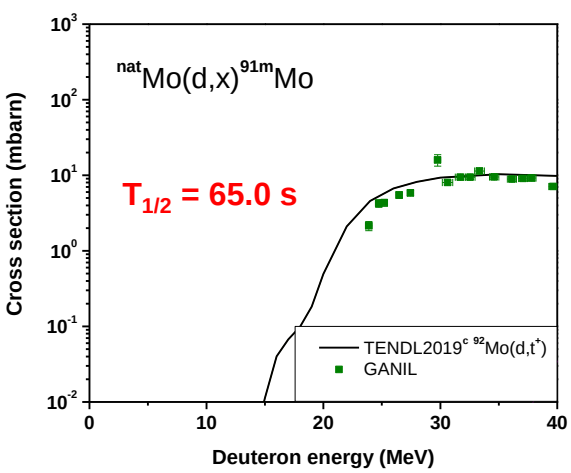
E832 : Deuteron activation of ^{nat}Mo focus on short-lived products

Spokesperson : E. Simeckova, NPI, Rez

- Mo is a component of steel alloy, data needed for fusion projects (ITER, DEMO)
- Natural Mo consists of 7 isotopes.
- Large number of radioactive isotopes (many of them having an isometric state)
- 6 deuteron energies from 15 to 40 MeV







About 30 excitation functions largely in agreement with the preceding works
10 of them determined for the first time.

Part of the results have been published in Journal of Fusion Energy (2024)
https://doi.org/10.1007/s10894-024-00407-w

Study of ^{211}At production

- ^{211}At ($T_{1/2}$ = 7,2h): promising α-emitter for **Targeted α Therapy**
- Production reactions :
  - direct ^{209}Bi(α,2n) ^{211}At Eth=20,564 MeV
  - ^{211}Rn→^{211}At generator
    - ✓ ^{209}Bi(^{6}Li,4n) ^{211}Rn Eth=28,340 MeV
    - ✓ ^{209}Bi(^{7}Li,5n) ^{211}Rn Eth=35,916 MeV

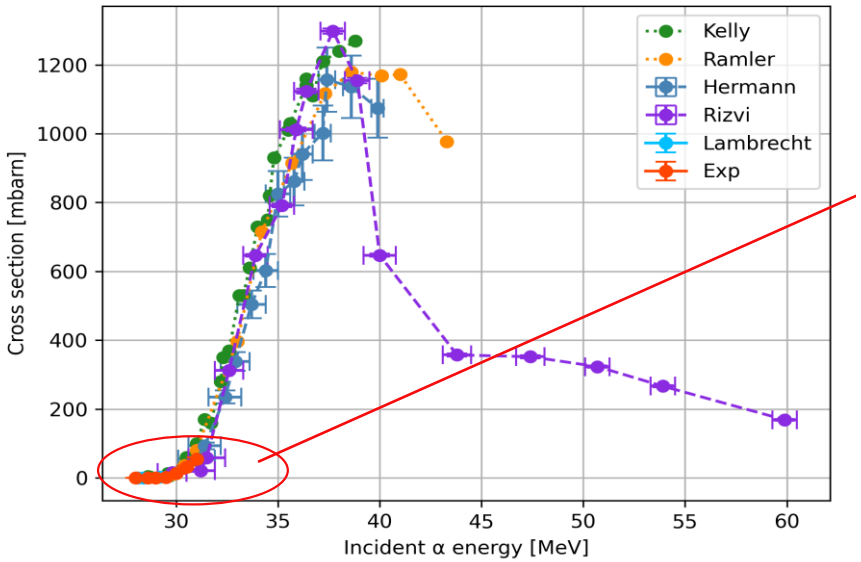
^{209}Bi(α,3n)^{210}At reaction cross-section measurement

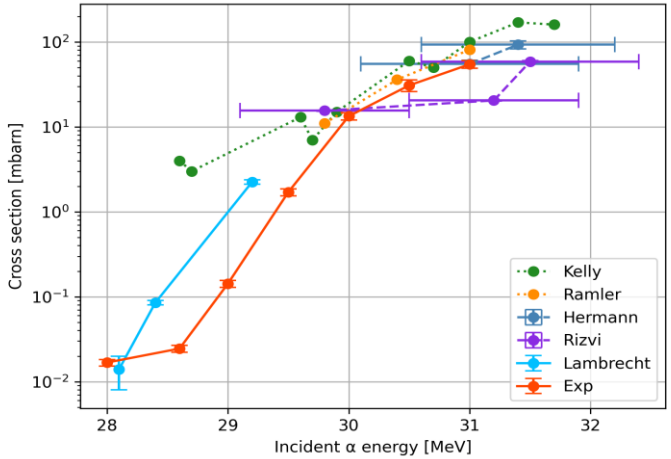
Study of ^{211}At production : REPARE project

$^{209}Bi(\alpha,3n)^{210}At$ excitation function measurement

GANIL, Subatech

- $^{209}Bi(\alpha,3n)\ ^{210}At$ Eth=28,400 MeV
- $^{210}At \rightarrow ^{210}Po$
- It's production must be controlled in the ^{211}At production
- Need of precise measurement around the production threshold NFS allows a fine tuning of Eα
- Measurement by activation technique
- 7 Energies between 28 and 31 MeV
- Activity measured with 2 EXOGAM clovers





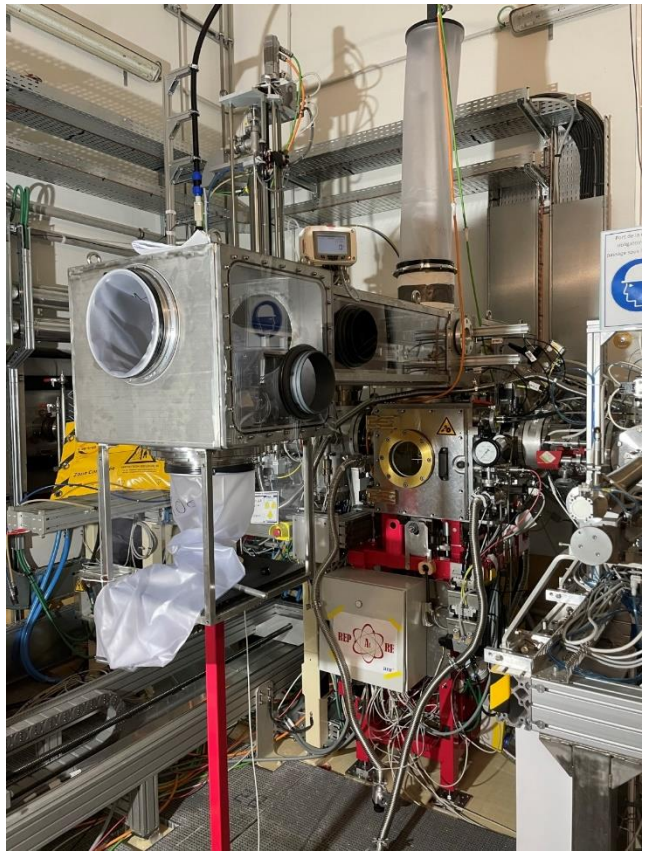
Work of Saba Ansari-Cheveau (Ganil)

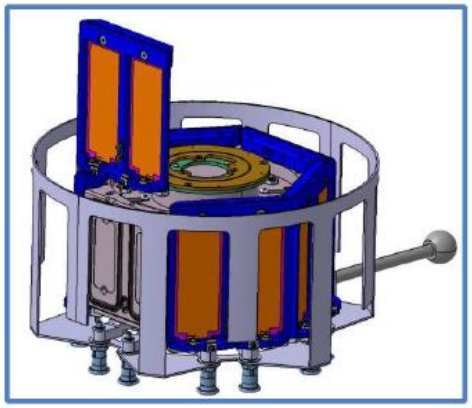
REPARE

Spokesperson : Gilles de France, GANIL

Research and d**E**velopements for the
Production of innov**A**tive **R**adio**E**lements

- Goal: 211At production for medical applications
- Reaction α + ^{209}Bi → ^{211}At + 2n
- 15 h Irradiation in the converter room (September 23-24)
- 3 targets irradiated (≈1 GBq each)
- 2 targets sent to Arronax at Nantes





anr agence nationale de la recherche AU SERVICE DE LA SCIENCE

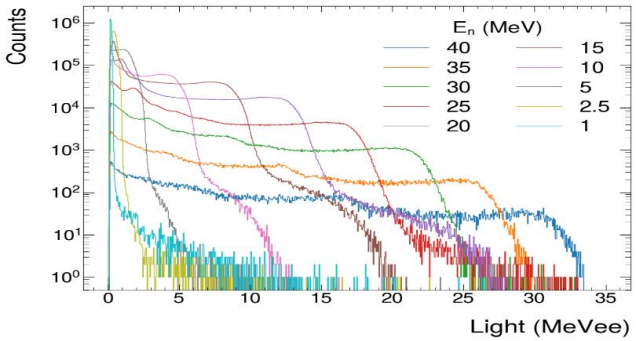
REP At RE

27 EU PRISMAP Medical Radionuclides

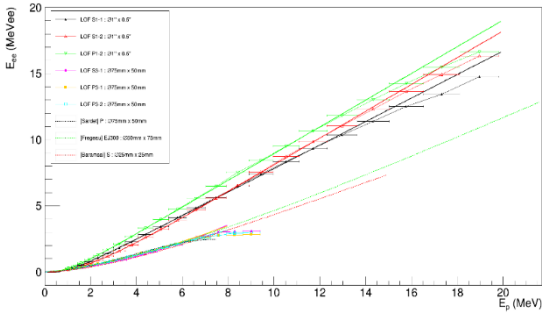
Detector characterization

The characteristics of NFS make it a unique tool for the characterization of certain neutron detectors.

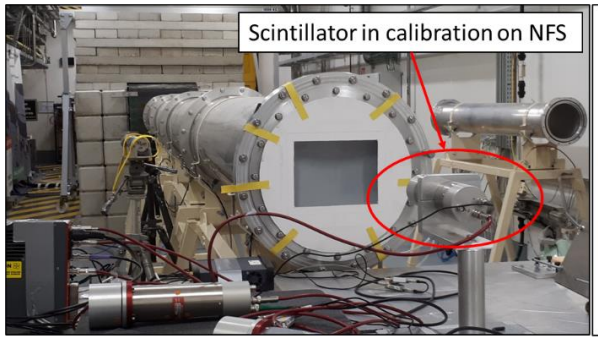
Detector response characterization at a wide energy neutron range of a MONSTER cell
T. Martinez, CIEMAT

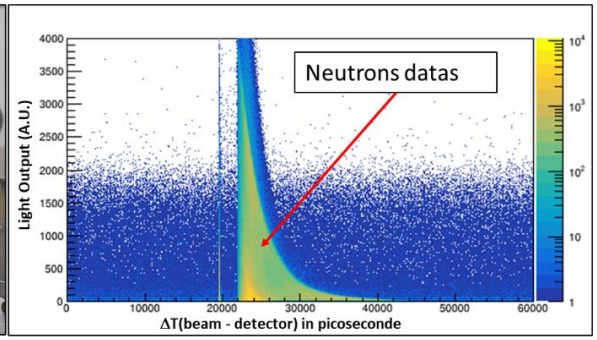


Measurement of the light output function of crystalline organic scintillators as a function of incident neutron energy, G. Lelaizant, CEA-DAM-DIF



Neutrons response determination of scintillators in their operating energy range (i.e. between 100 keV-22 MeV)
M. Petit, LNE-IRSN (LMDN)





Present and future

- 2024 Experiments :
  - E876 : Synthesis of ^{211}At for targeted alpha therapy, G. De France (Ganil)
  - E878: ^{237}Np fission fragment study with FALSTAFF at NFS, J.E. Ducret (Ganil)
  - E859: ^{238}U(n, 2nγ) and (n, 3nγ) reaction cross sections measurements, M. Kerveno (IPHC)
  - E875: Gas production study in copper, I. Ipatova (UKEA)
  - Test of scintillation fibers in the converter room for dosimetry

- Experiment scheduled in 2025 :
  - E877: High resolution γ-ray spectroscopy of fast-neutron induced fission of ^{232}Th, J. Wilson (IJCLab)

- PAC 2024 : 9 proposals and 2 letters of intent submitted

PhD thesis

- Baptiste Fraïsse (CEA-DAM-DIF) , E807, defended in July 2024
- Aurélien Chevalier (LPC Caen) E811
- Lucas Dearruda (GANIL-Uppsala University) E800, E802, E858
- Perine Miriot-Jaubert (CEA-Saclay IRFU) E833
- Hemantika Sengar (Ganil) E838

Publications

Articles and Proceedings:

- “First beams at neutrons for science”, **X. Ledoux et al.,** Eur. Phys. J. A (2021) 57:217
- “Measurement of the neutron-induced activation of materials: testing accuracy of simulation-based assessment methods for radio-isotope creation in the specific case of radiotherapy electron accelerators”, **V. Blideanu at al**., submitted to NIMB
- Study of (n,α) reactions of interest for nuclear reactors: the case of 19F(n,α)16N with SCALP detector”, **A. Chevalier et al**, EPJA294, 01008 (2024), proceeding of WONDER 2023
- “Reconstruction of the GANIL-NFS spectral neutron flux with Medley using elastically scattered protons**”, L. de Arruda et al**., submitted to EPJ-Web Of Conf. (2024) (Proc. CNR*24 workshop
- “Nuclear data measurements with a Solid COunter for NEutrons (SCONE)”, **G. Belier et al.,** submitted to NIMA
- “Study of the pygmy dipole resonance using neutron inelastic scattering at GANIL-SPIRAL2/NFS”, **M. Vandebrouck et al**., Il NUOVO CIMENTO 47 C (2024) 19
- In-beam γ-ray spectroscopy with fast neutron probes at NFS, **H. Sengar et al.**, proceeding of NN2024
- “Modeling of Deuteron-Induced Reactions on Molybdenum at Low Energies”, **M. Avrigeanu et al**., Journal of Fusion Energy (2024) 43:15

Summary

- Neutrons for Science is now operational
- 11 Experiments have already been performed (4 scheduled in 2024)
  - Lcp particle production
  - Fission process
  - n,xnγ reactions
  - Nuclear structure
- 9 experiments proposed at the last PAC
- NFS is in the European Projects (Transnational Access):
  - ~~*ARIEL*~~ → *APRENDE*
  - RADNEXT
  - EUROLABS