Nuclear Structure at NFS

Emmanuel Clément (GANIL)

GCM - 2022

Letter of intent for NFS@GANIL

Nuclear structure measurement at NFS: γ-rays spectroscopy and lifetime measurement

A. Dijon *et al.*
NFS workshop
March, 31th 2014

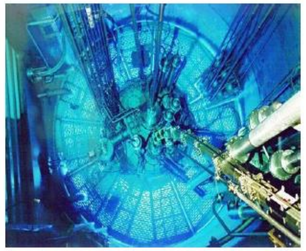
In the past…

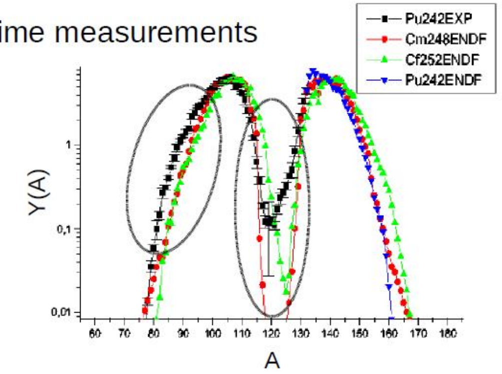
- Spontaneous fission (^{252}Cf, ^{248}Cm sources)
  EUROGAM/EUROBALL or GAMMASPHERE : ~ 250 fission fragments

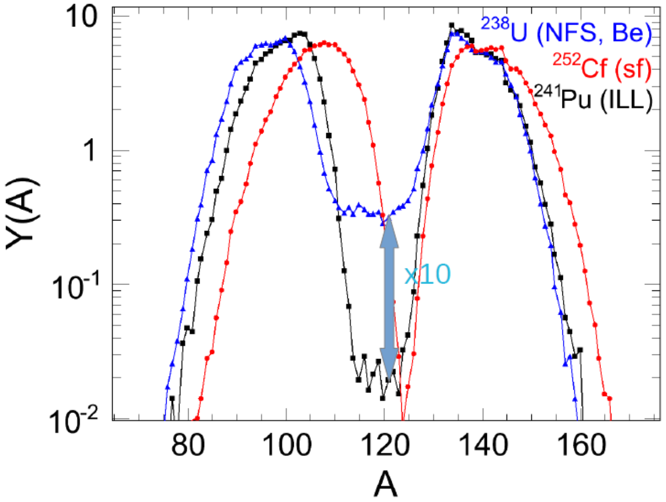
- Induced fission
  - Fusion-fission: VAMOS@GANIL (^{238}U+^{12}C)
  - Thermal neutron beam: EXOGAM@ILL (winter 2012-2013)

30 new nuclei unreachable with spontaneous fission

Mainly prompt spectroscopy and lifetime measurements







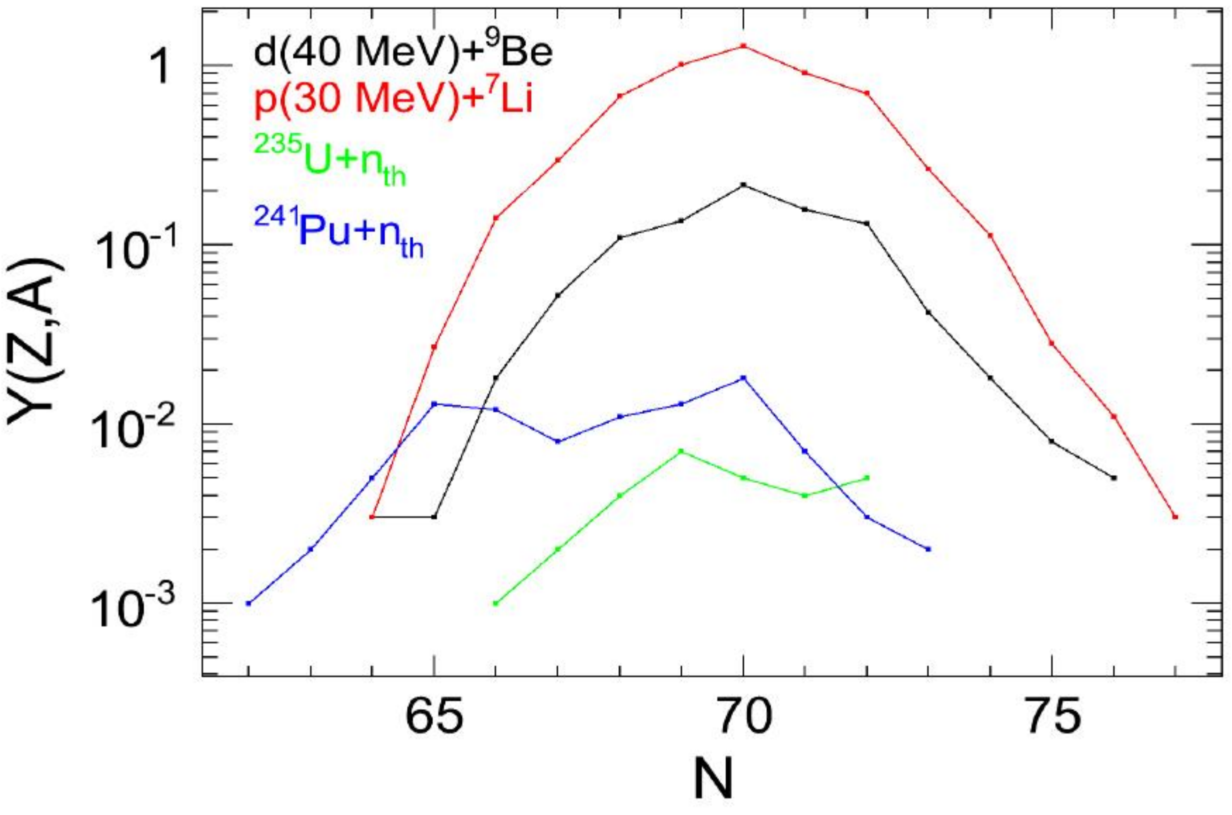
Y(A) 10x higher in the A≈110-130 region

Possibility to use ^{232}Th target to produce lighter fission fragments

Isotopic yields for Pd chain

A. Dijon courtesy

GEF calculations

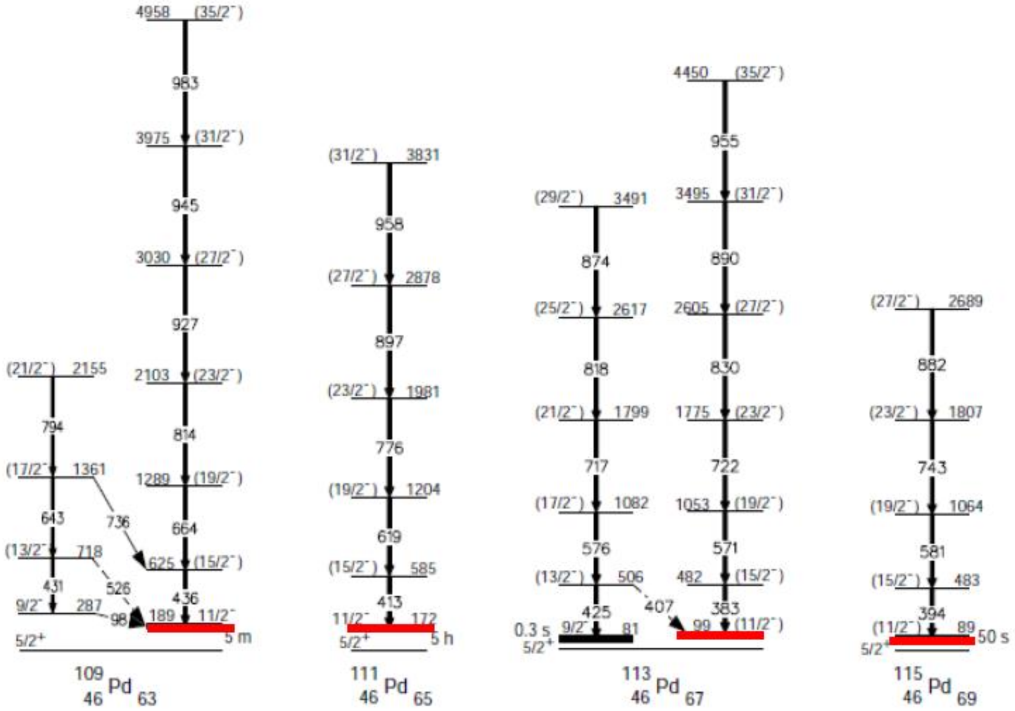


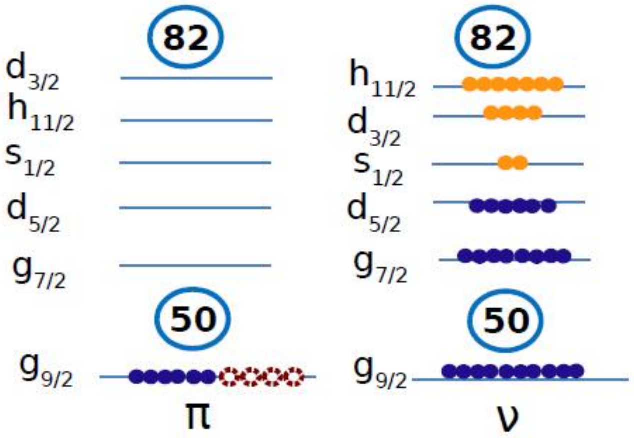
Physics motivations: $^{110-123}$Pd (Z=46, N>60)

A. Dijon courtesy

Influence of neutron orbital $h_{11/2}$:

- intruder state
- deformed isomeric state





Evolution of **isomer** going toward N=82

M.Houry et al., EPJA 6, 41 (1999)

Since :

- LICORNE at Orsay using fast neutron (< 4 MeV)

https://alto.ijclab.in2p3.fr/installation/alto-heb/neutrons-licorne/

- FIPPS at ILL using thermal neutron

https://www.ill.eu/users/instruments/instruments-list/fipps/description/instrument-layout

- AGATA-VAMOS++ - Several Data set since 2015

(+ plunger, + LaBr3, +DSSD), future : see Antoine's presentation

- RIKEN –high energies RIB (Pd case covered by BigRIPS)
- HIE-ISOLDE – Post-Accelerated RIB

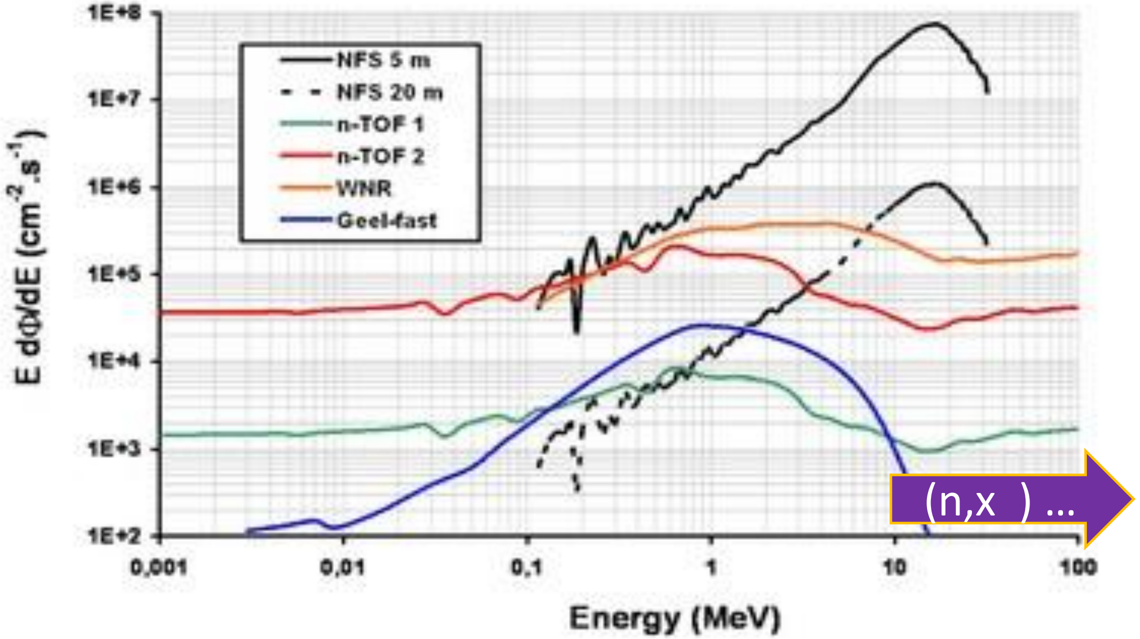
Soon FRIB, SPES,

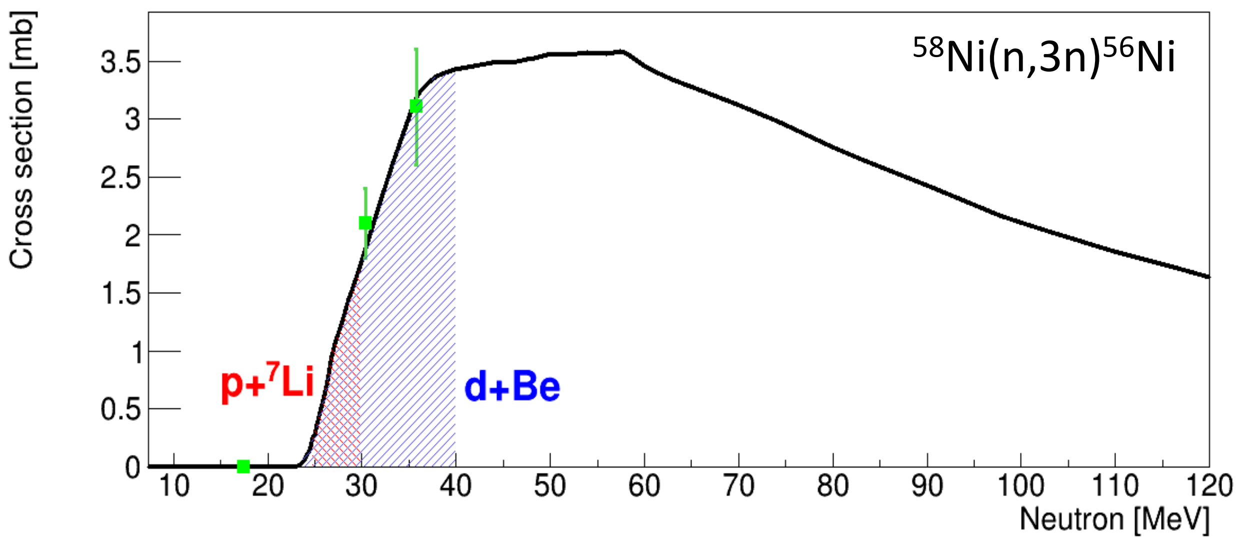
Very strong competition for prompt spectroscopy in the framework of nuclear structure

Nuclear structure spectroscopy using fast neutron beams

laboratoire commun CEA/DRF spiral2 CNRS/IN2P3

- NFS offers unique opportunities with the highest neutron flux > 10 MeV world-wide
- Unique flux for (n,xn), (n,p) (n,d) and (n,α) reactions → known technique in the framework of the design of the Generation-IV nuclear reactors.
- Most of the studies are on heavy elements for nuclear fuel (U, Th) or structural materials (^{nat}Fe, Cr, Mg/Na, W) with focus on the cross section measurements to improve models included in reaction codes such as talys.
- What can we learn in nuclear structure spectroscopy using this reaction ?





Nuclear structure spectroscopy using fast neutron beams

laboratoire commun CEA/DRF CNRS/IN2P3

https://www.nndc.bnl.gov/

Dataset
Select All
ADOPTED LEVELS, GAMMAS
56CU EC DECAY (93 MS)
57ZN ECP DECAY:47 MS
9BE(57NI,56NIXG)
24MG(32S,X)
28SI(32S,2P2NG)
28SI(36AR,2AG)
40CA(28SI,3AG)
54FE(3HE,N),(3HE,NG),(A,2NG)
54FE(16O,14C),(12C,10BE)
56NI(D,D'):GIANT RES
COULOMB EXCITATION
58NI(P,T)

^{56}Ni

(shape coexistence close sdf)

Dataset
Select All
ADOPTED LEVELS, GAMMAS
39SC P DECAY:?
39TI ECP DECAY (28.5 MS)
24MG(16O,2NG)
36AR(3HE,N)
36AR(3HE,NG)
COULOMB EXCITATION
40CA(P,T)

^{40}Ca(n,3n)^{38}Ca never measured

(shape coexistence close sd)

ADOPTED LEVELS, GAMMAS
76RB EC DECAY (36.5 S)
77SR ECP DECAY (9.0 S)
COULOMB EXCITATION
78KR(P,T)
78KR(4HE,6HE)
(HI,XNG)

^{78}Kr(n,3n)^{76}Kr never measured

^{70}Ge(n,3n)^{68}Ge never measured

Retrieve selected ENSDF datasets:

PDF Version ENSDF text format

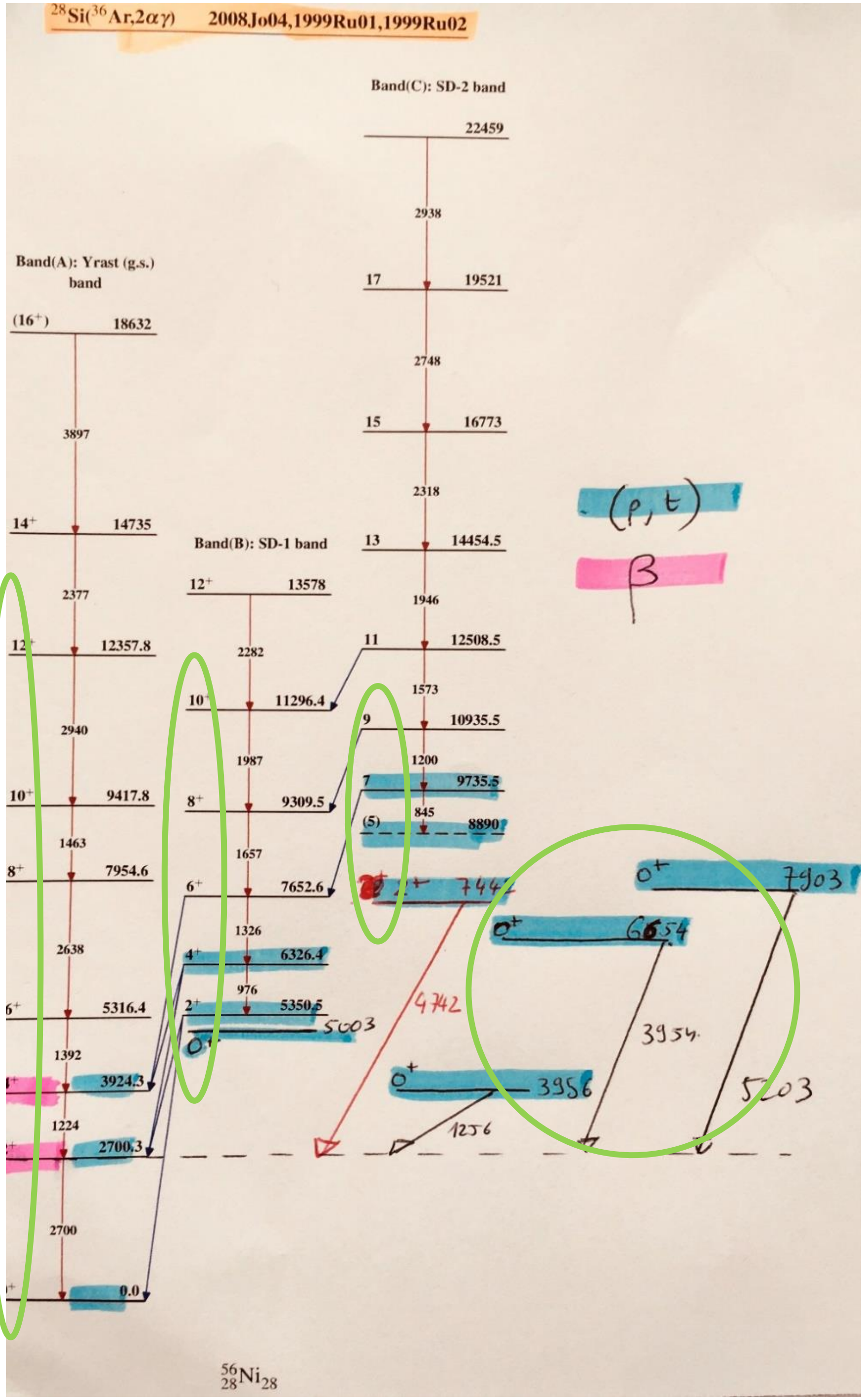
Here are the XUNDL datasets which came in after the last ENSDF publication.

Nuclide	Dataset
	Select All
^{76}Kr	54FE(28SI,A2PG):XUNDL-1
	54FE(28SI,A2PG):XUNDL-2
	40CA(40CA,4PG):XUNDL-3
	40CA(40CA,4PG):XUNDL-4
	76RB EC DECAY:XUNDL-5
	COULOMB EXCITATION:XUNDL-6
	76RB EC DECAY:36.5 S:XUNDL-7

(shape coexistence open pfg)

(p,t)
Low angular momentum
From gs to Sn
Yrast (90%) / non-yrast (10%)

Test case : ^{56}Ni



laboratoire commun CEA/DRF CNRS/IN2P3

^{56}Ni is a doubly magic nuclei, therefore all spectroscopic information's are relevant for nuclear structure studies.

^{56}Ni has an extended level scheme populated by :

- ^{58}Ni(p,t)^{56}Ni H. Nann and W. Beneson Phys. Rev C 10, 1880 (1974)
- ^{54}Fe(^{3}He,n)^{56}Ni J. Blomqvist et al, Z. Phys. A322, 169 (1985)
- Heavy ions reactions, D. Rudolph et al, Phys. Rev. Lett. 82, 3763 (1999)
- β-decay, R. Borcea et al, Nucl. Phys. A 695, 69 (2001)

❑ Heavy ions fusion reaction populate to high spin the GSB and the 2 SD band.

❑ β-decay has very strong selection rules ^{56}Cu($J^{\pi} = 4^{+}$)

❑ (p,t) reaction is limited to low angular momentum and highly selective
But shed light on many non-yrast structures, **i.e 4 excited 0^{+} states**.
No feeder or band structures have been observed later.
→ observing the 2^{+} states feeding these states is of great interest

Test case : ^{56}Ni

Nuclear structure (level scheme, including levels' spin, parity and lifetime, as well as transitions' intensity and multipolarity) is a key input of nuclear reaction codes (e. g. Talys), it needs to be as complete as possible.

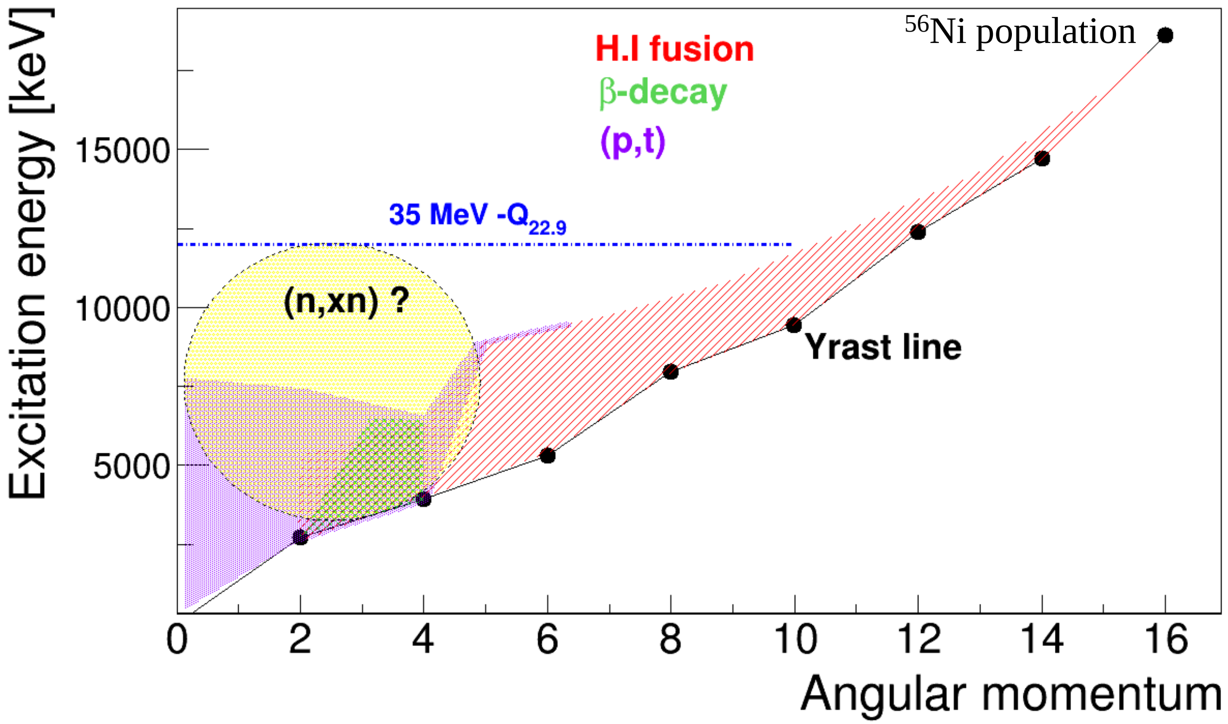
Uncertainty on transition branching ratios and unknown states affects negatively the quality of the calculations.

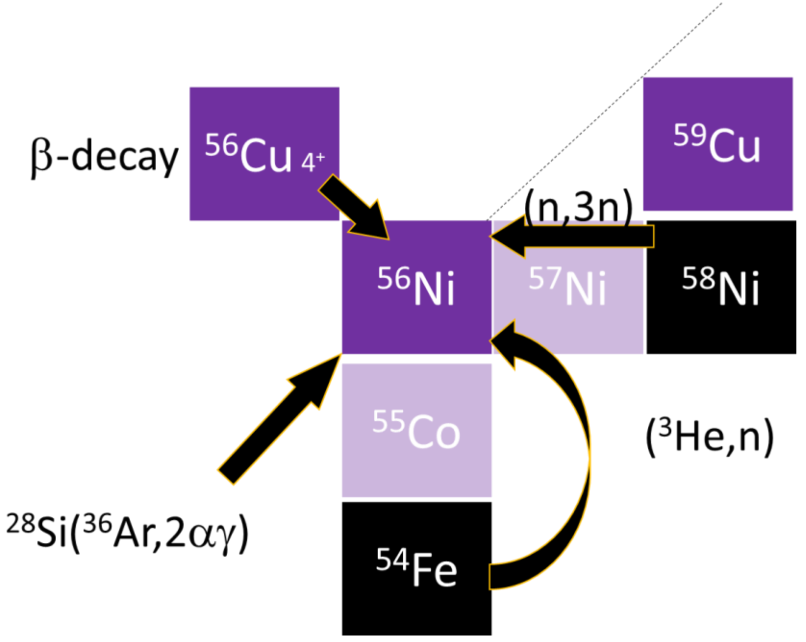
The IPHC - JRC-Geel - IFIN collaboration has highlighted the shortcomings in terms of nuclear structure that prevent the production of accurate (n,xn) cross section from the measured (n,xn g) ones.
M.Kerveno et al., European Physical Journal N 4, 23 (2018)

Many level spectroscopy studies are done via charged particles induced reactions or decay reaction, the selectivity in angular momentum and excitation energy of these channels may leave some area of the J, E* plane unexplored, leading to a limited knowledge of the level scheme there.

Direct comparison for ^{58}Ni with
H. Nann and W. Beneson Phys. Rev C 10, 1880 (1974)

Test case : ^{56}Ni





The basic questions are :

Which states are populated in the (n,xn) reaction from the nuclear structure point of view ?

Which area of the Yrast surface is populated ? (Angular momentum generated vs E*?)

Is this so different from the (p,t) reaction ? → Direct surrogate method validation

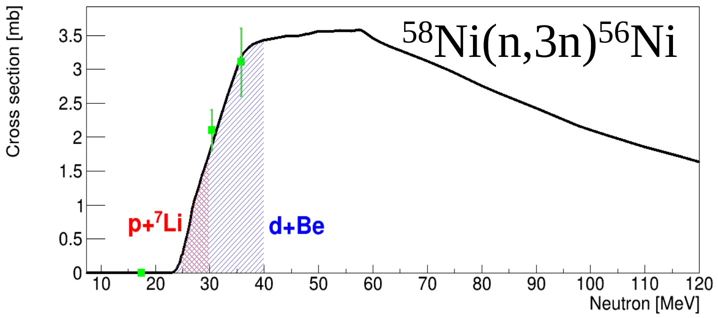
Could we access unknown low spin, high excitation energy states such as the 2^+ states built on the $0^+_{2,4,5}$?

Experiment #1

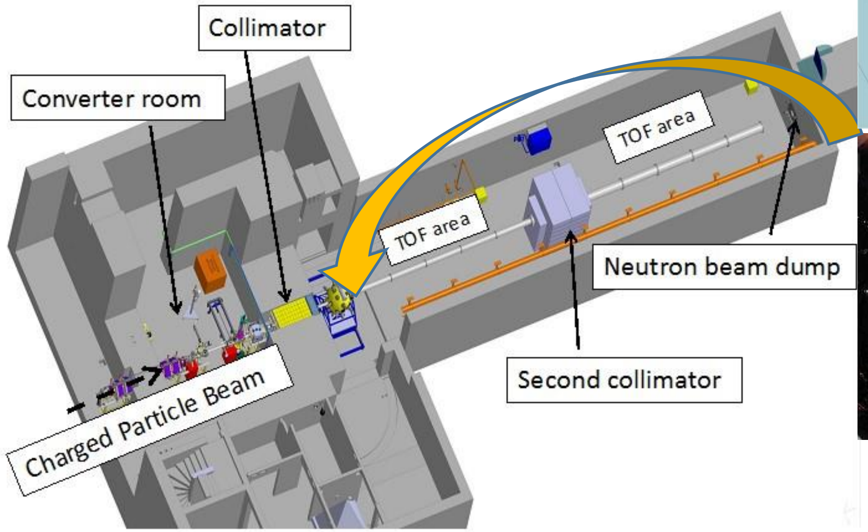
Methodology

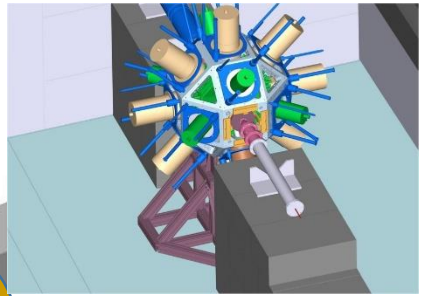
- 12 EXOGAM clover detectors placed at 5 meters from the production target
- Using 45μA of deuteron beam on the thick Be target
  →700 Hz of ^{56}Ni with a 1mm target
- Triggered in γγ in coincidence with the fastest neutrons

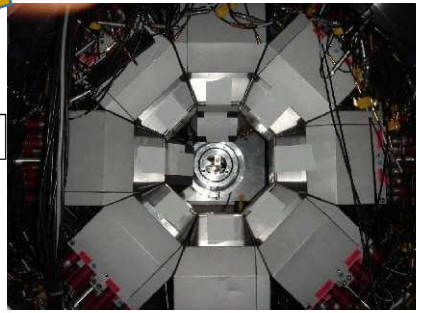
With 21 UT of beam on target → ~5.10^{6} γγ coincidences

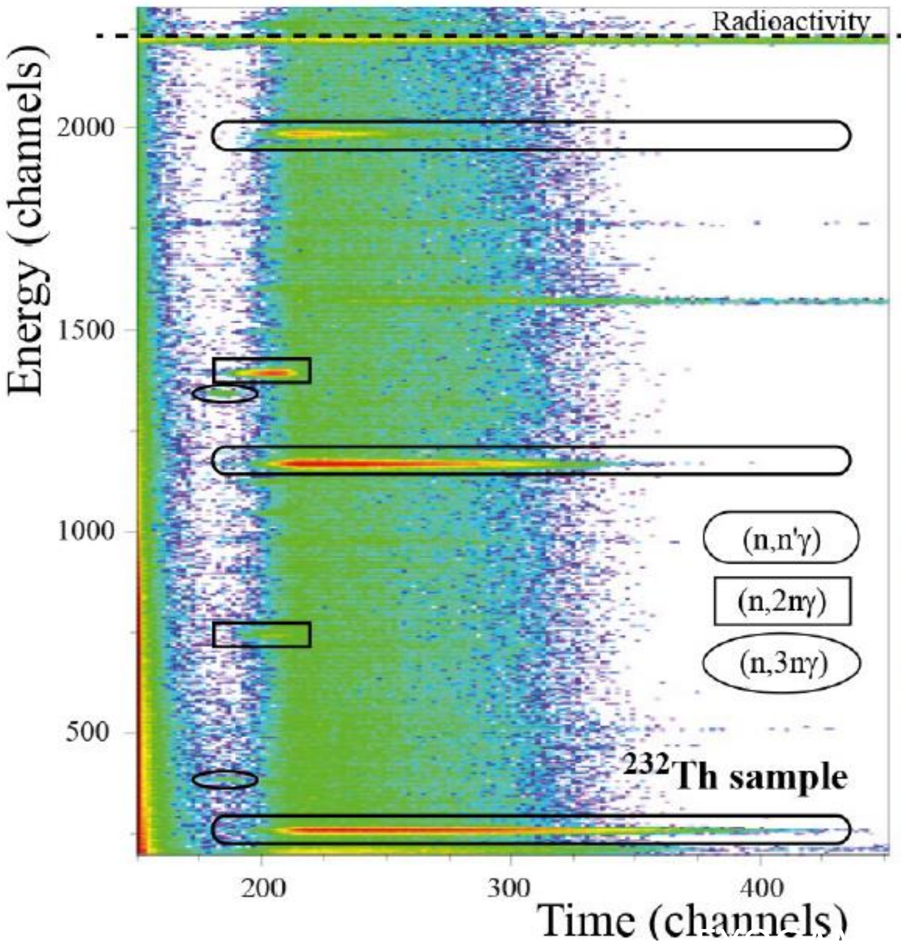


J. Vrzalova et al NIM A, 726 (2013)84-90





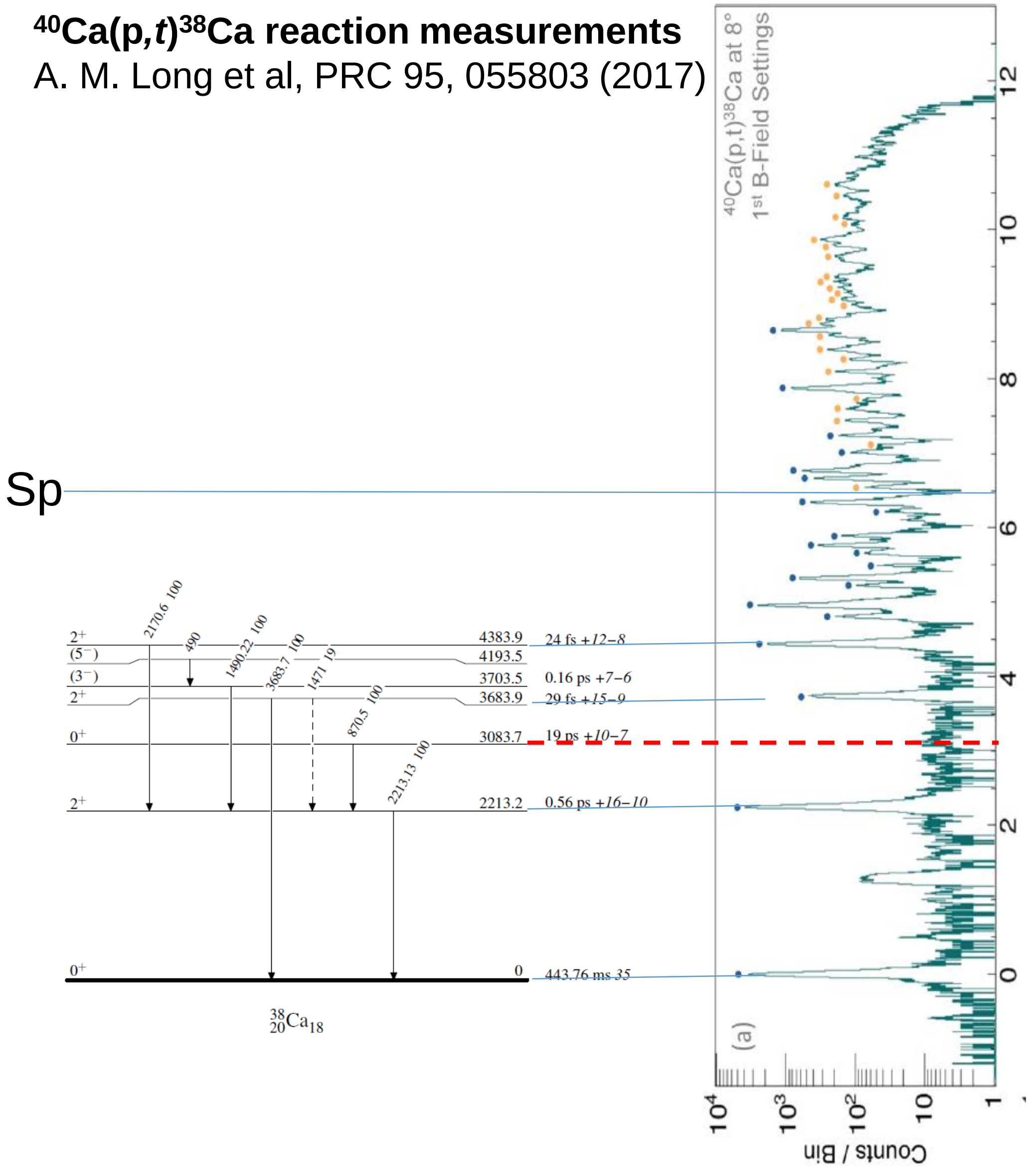




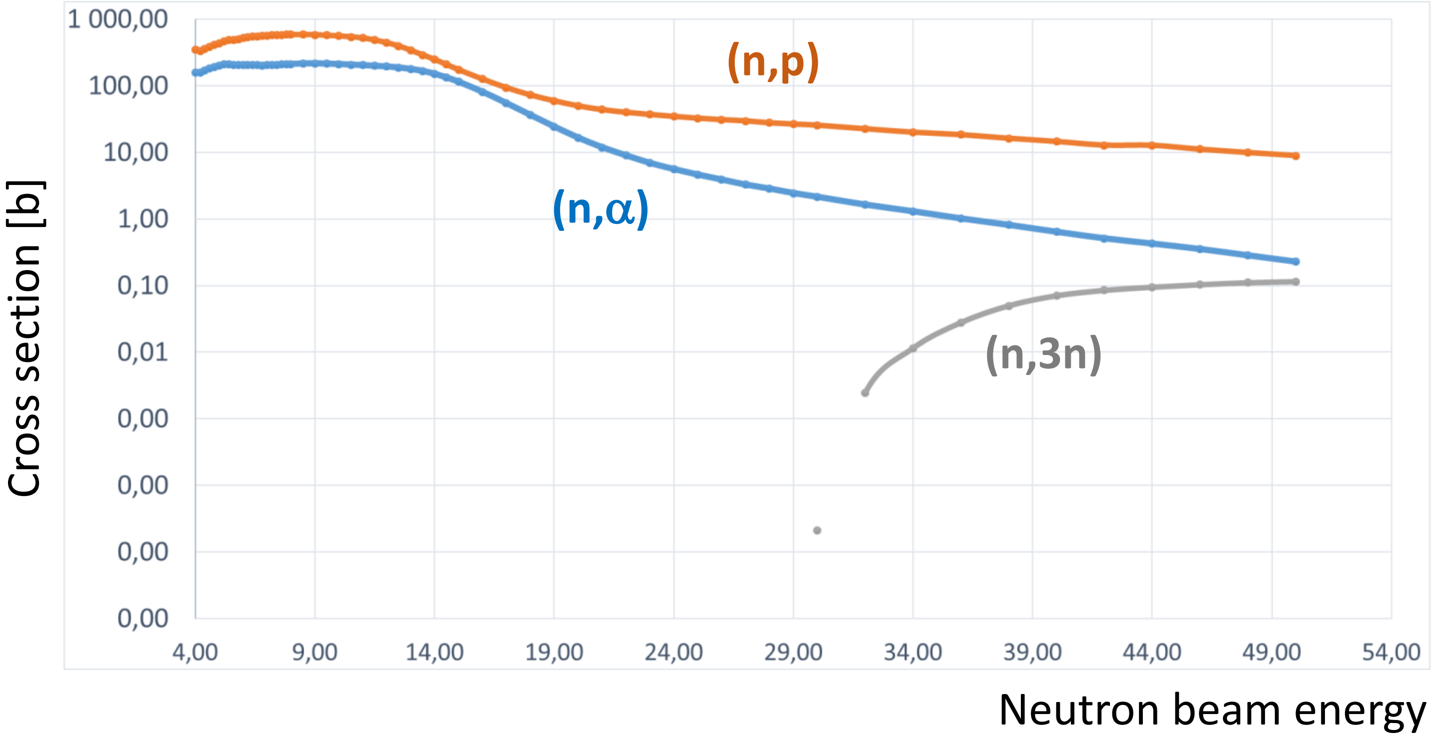
M. Kerveno et al Eur. Phys. J. A (2015) **51**: 167

Experiment #2

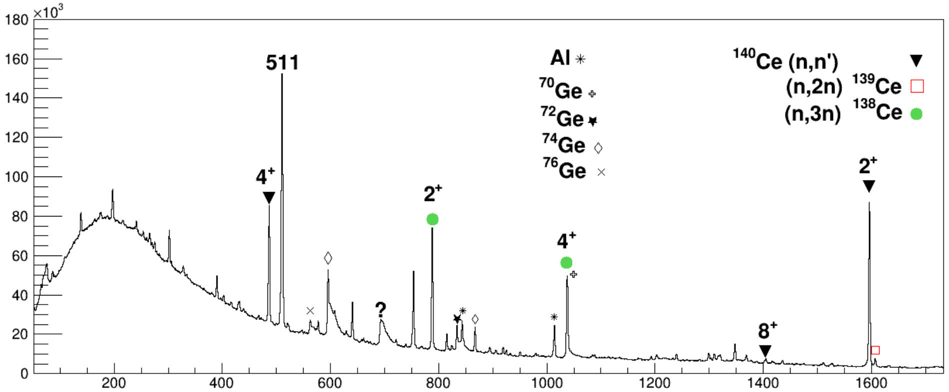
^{40}Ca(p,*t*)^{38}Ca reaction measurements
A. M. Long et al, PRC 95, 055803 (2017)

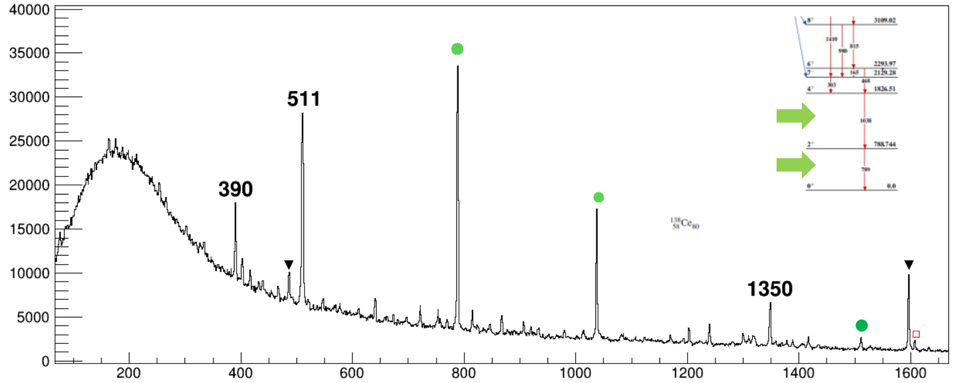


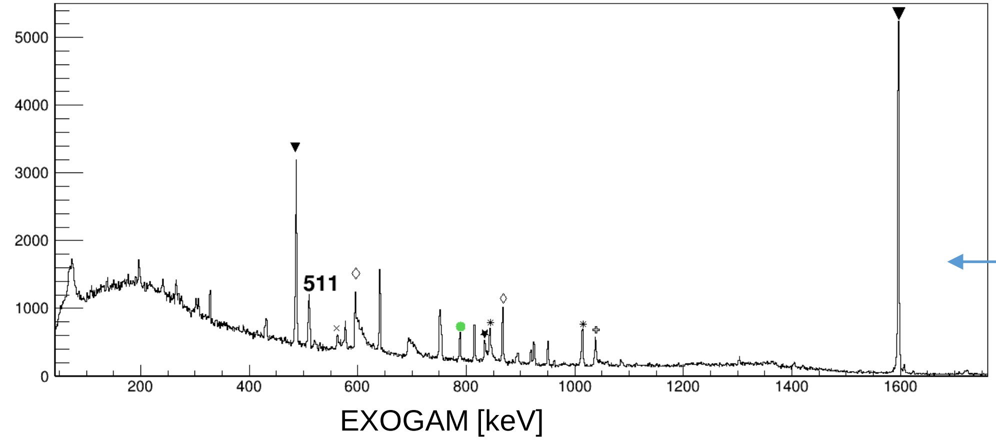
Second proposal could be ^{40}Ca(n,3n)^{38}Ca



Experiment #0 *E. Clément (GANIL)*

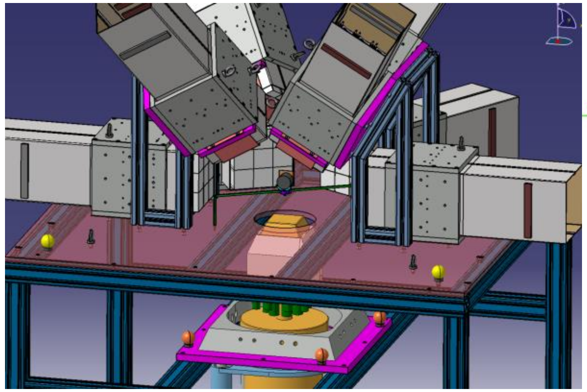


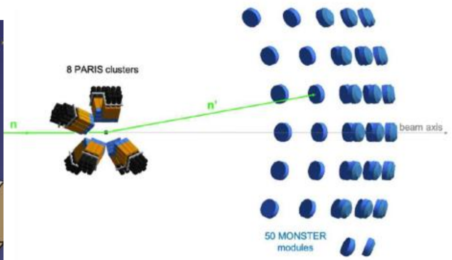




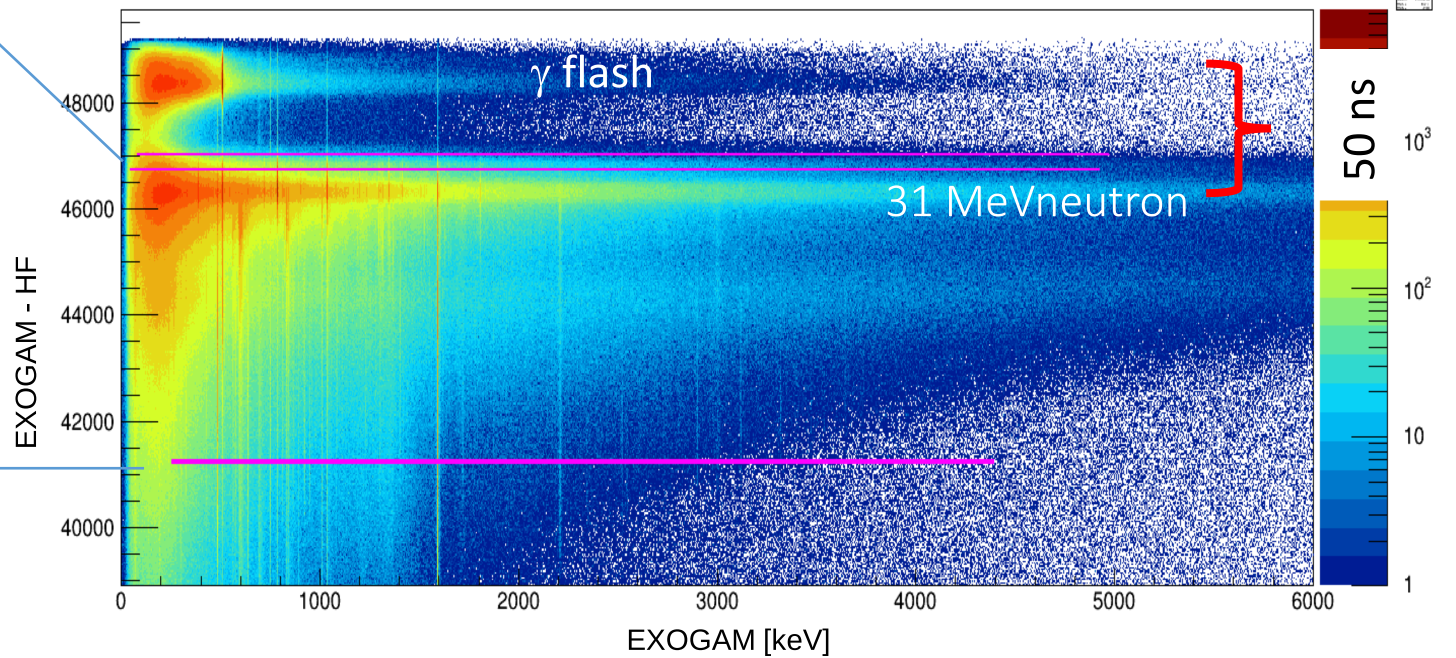
Pygmy dipole resonance in ^{140}Ce using the (n,n'g) reaction at NFS

1 EXOGAM clover at 5 meters from the convertor





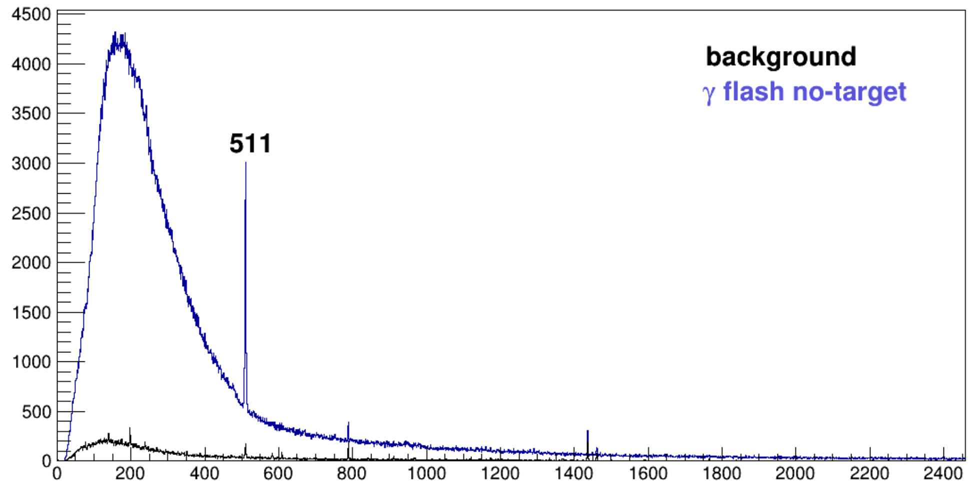
M. Vandebrouck(CEA)
I. Matea (IJClab)
September 2022 @ 5 meters

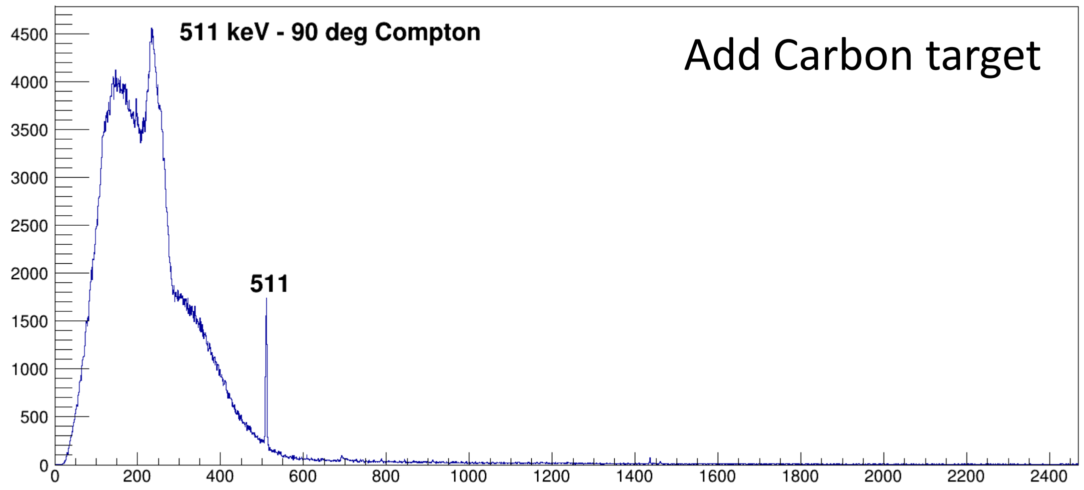


Experiment #0 *E. Clément (GANIL)*

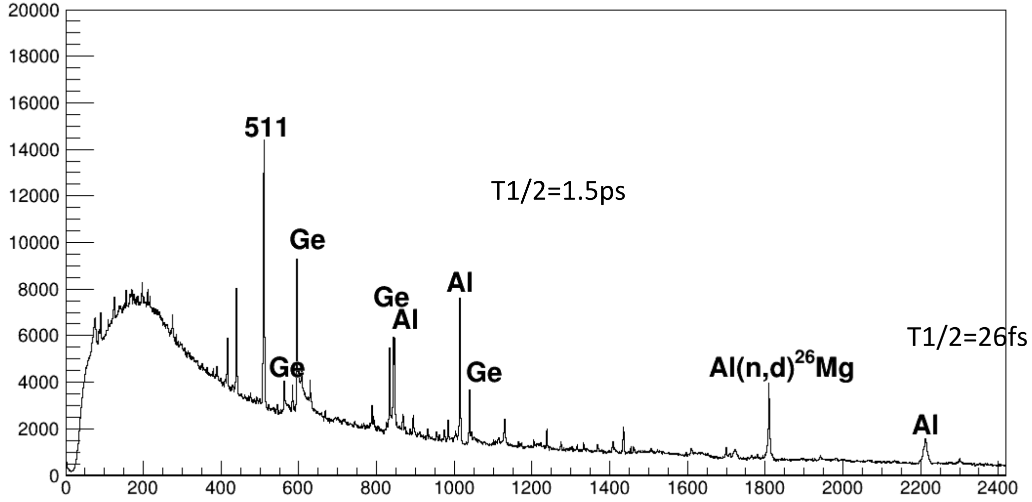
GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3

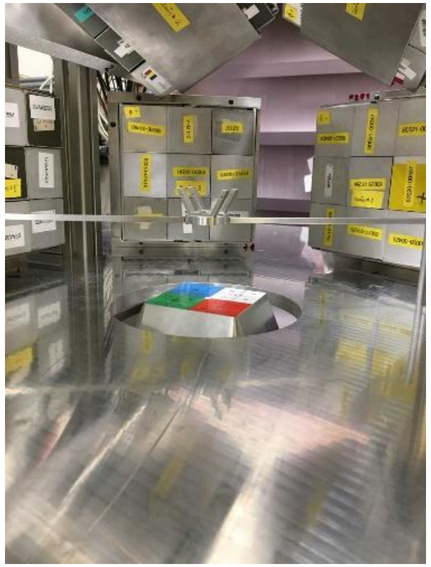
Grazing measurement of the γ-spectrum with neutron beam





In coincidence with fast neutrons

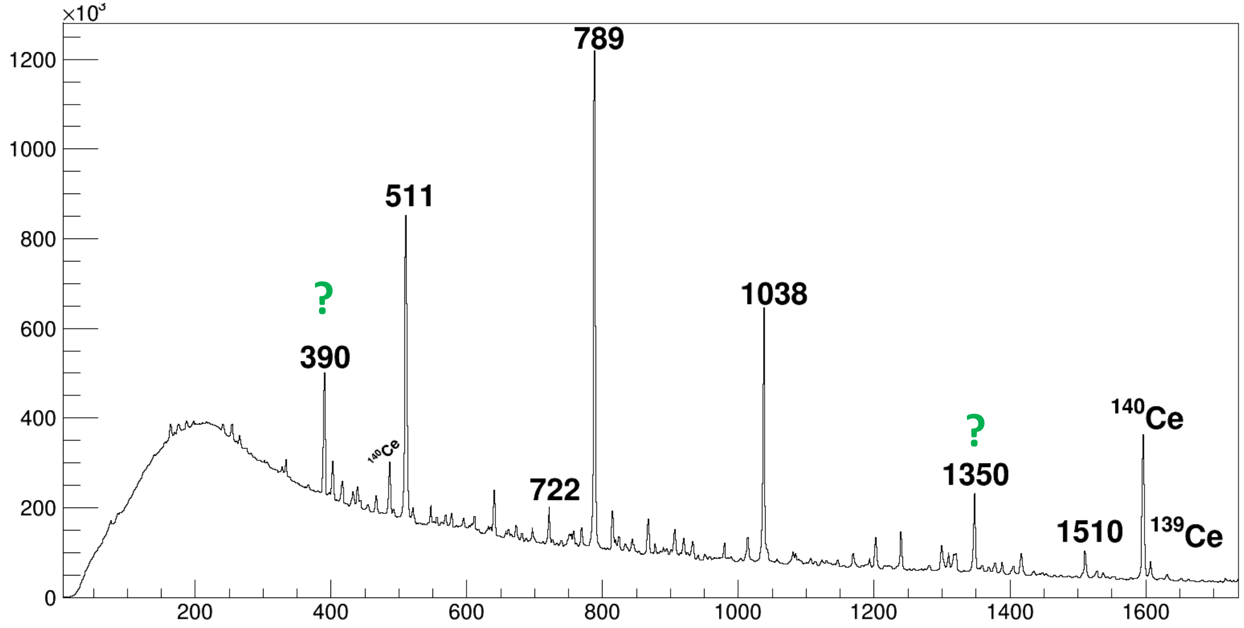




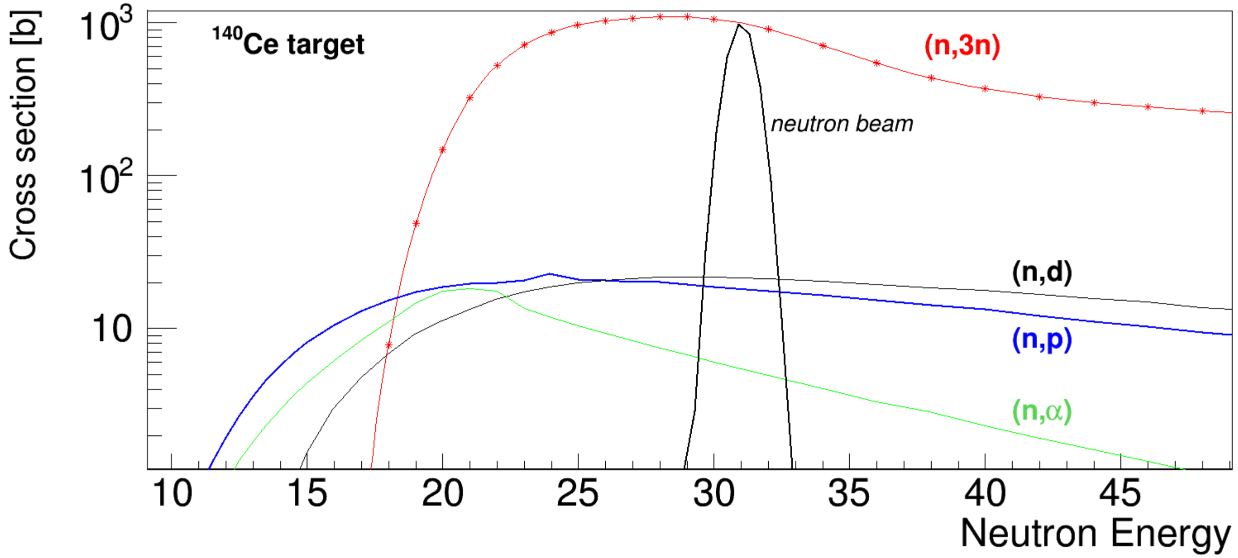
Picture by D. Ramos

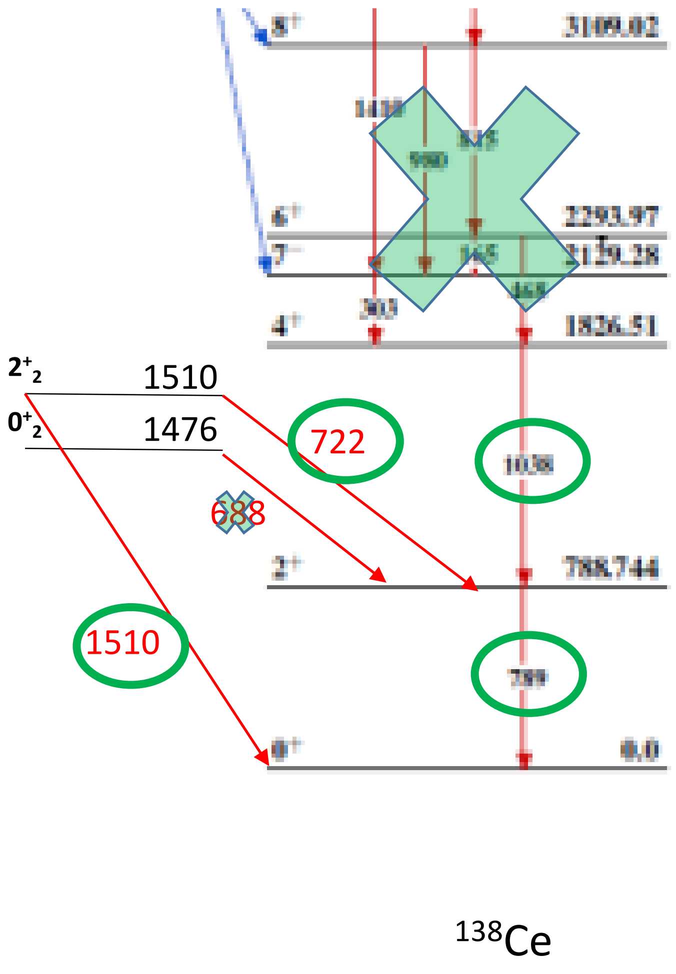
Experiment #0

E. Clément (GANIL)

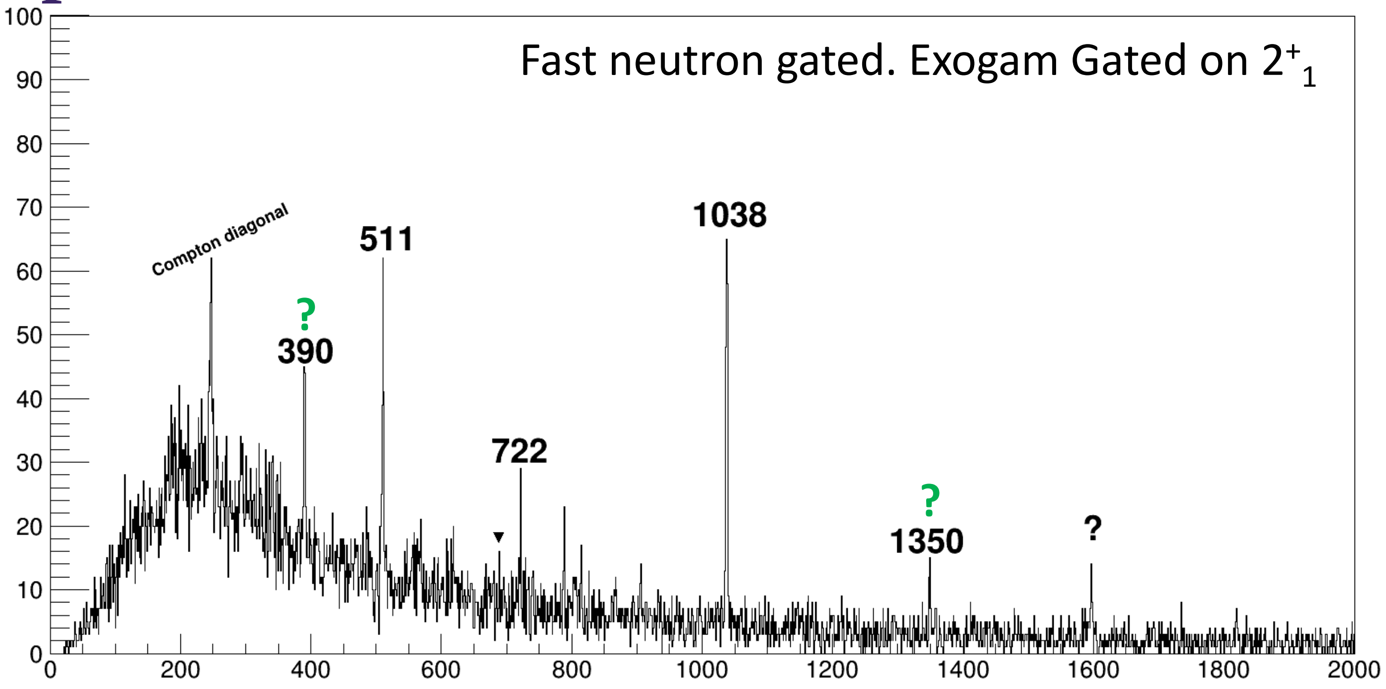


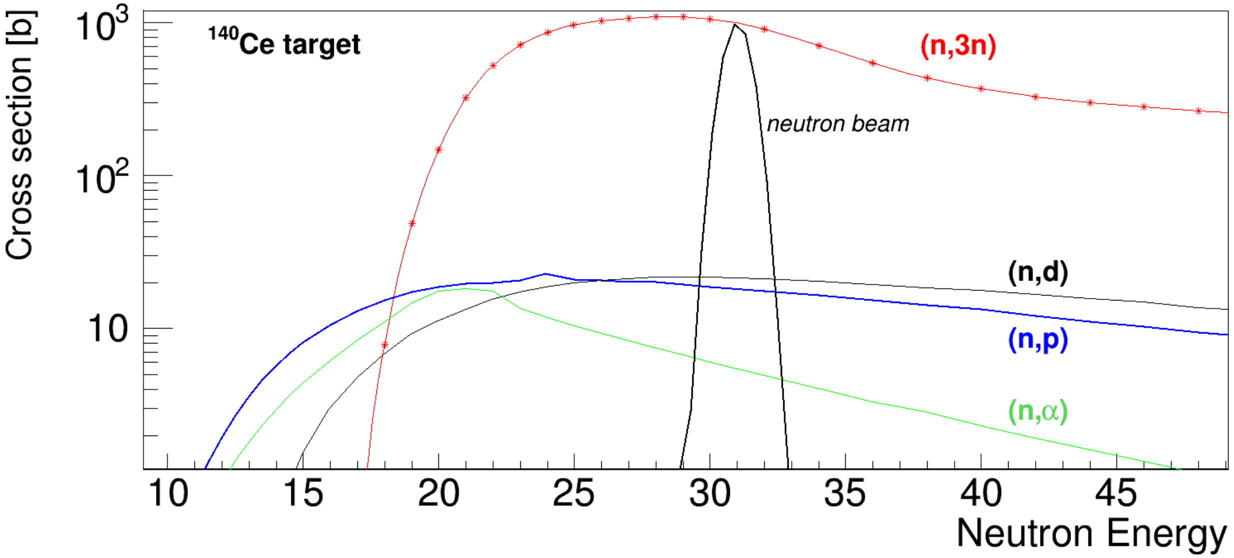
Fast neutron gated. Exogam Total projection

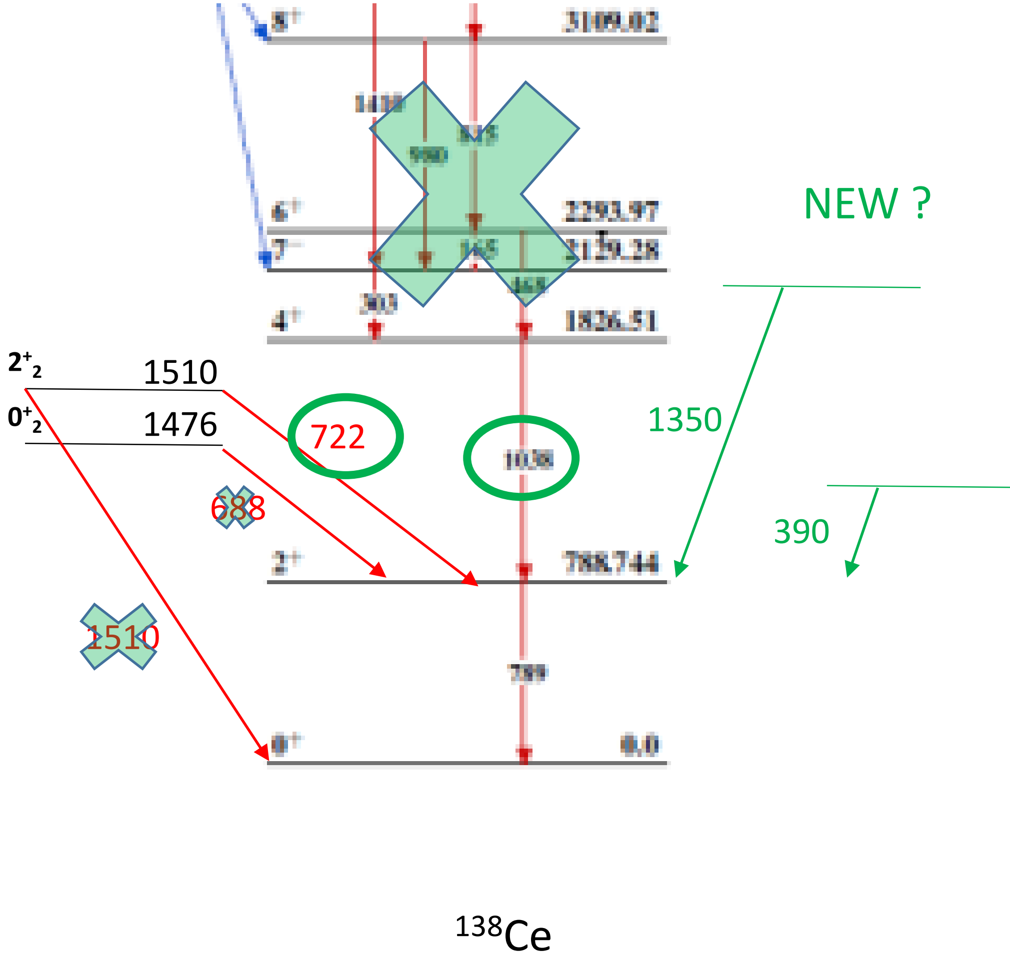




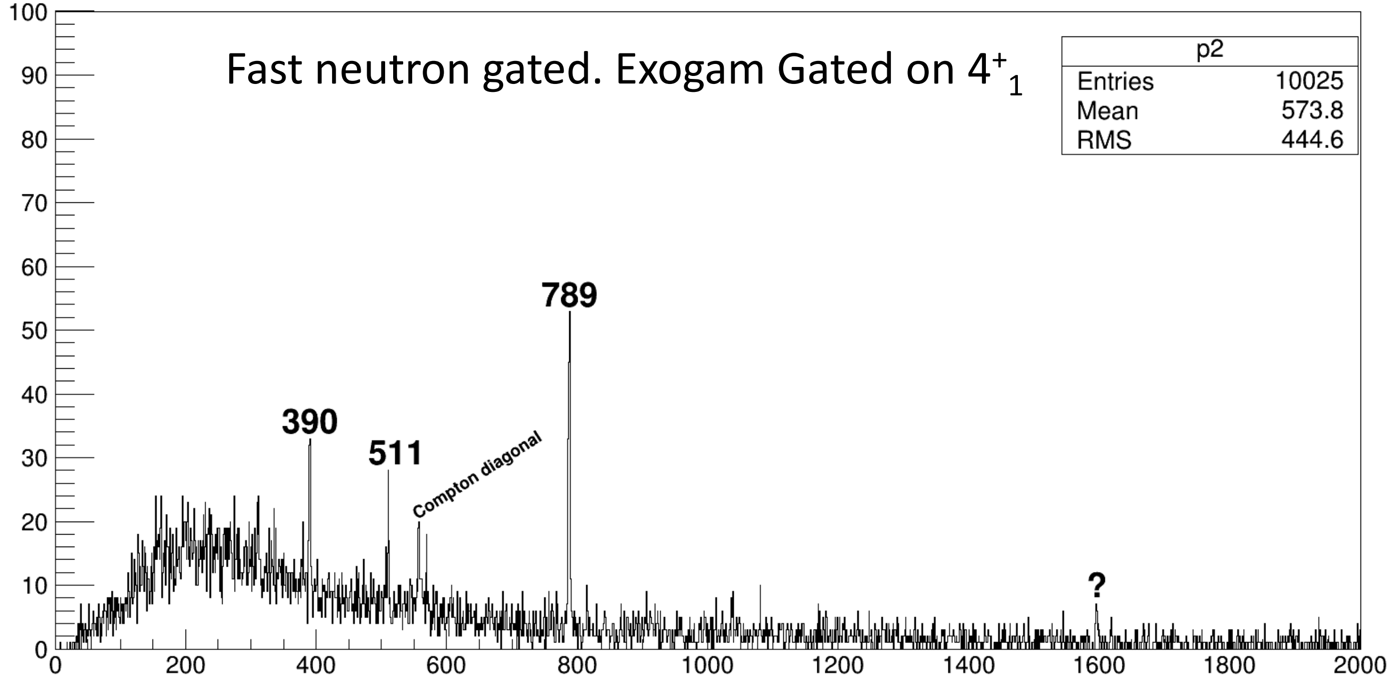
Experiment #0 *E. Clément (GANIL)*

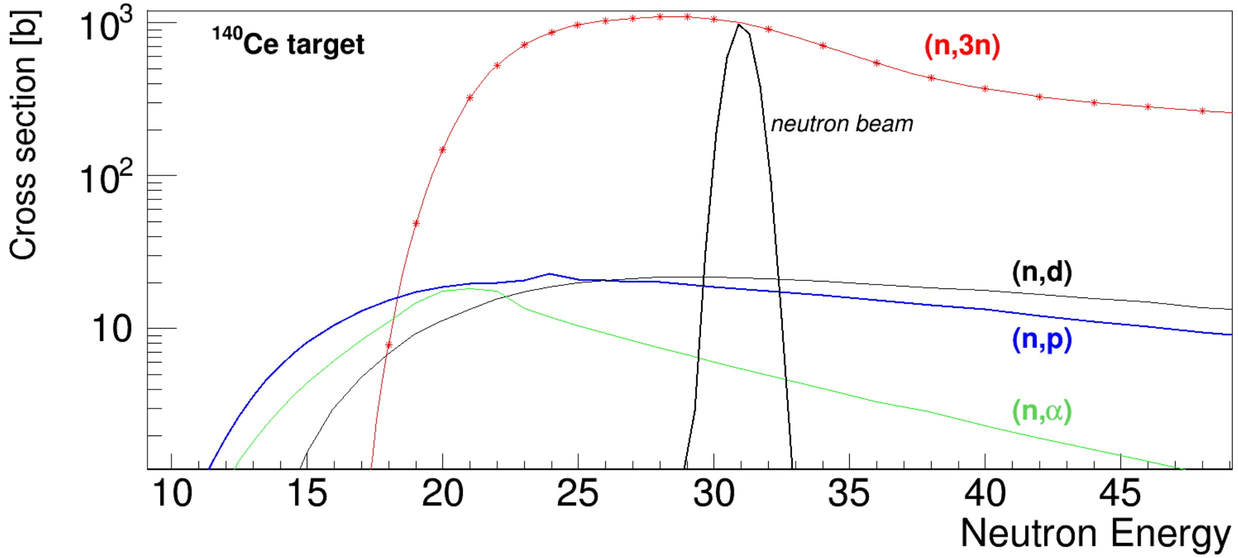


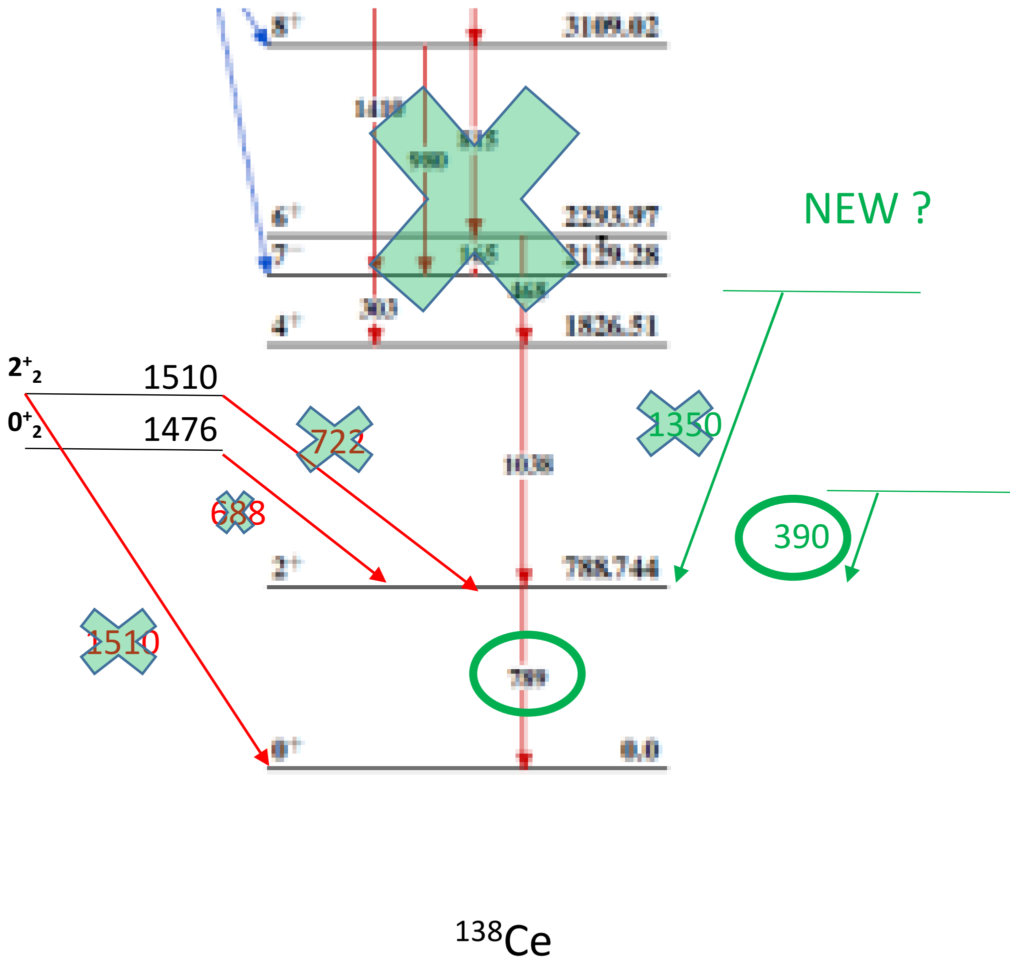




Experiment #0 *E. Clément (GANIL)*







Experiment #0

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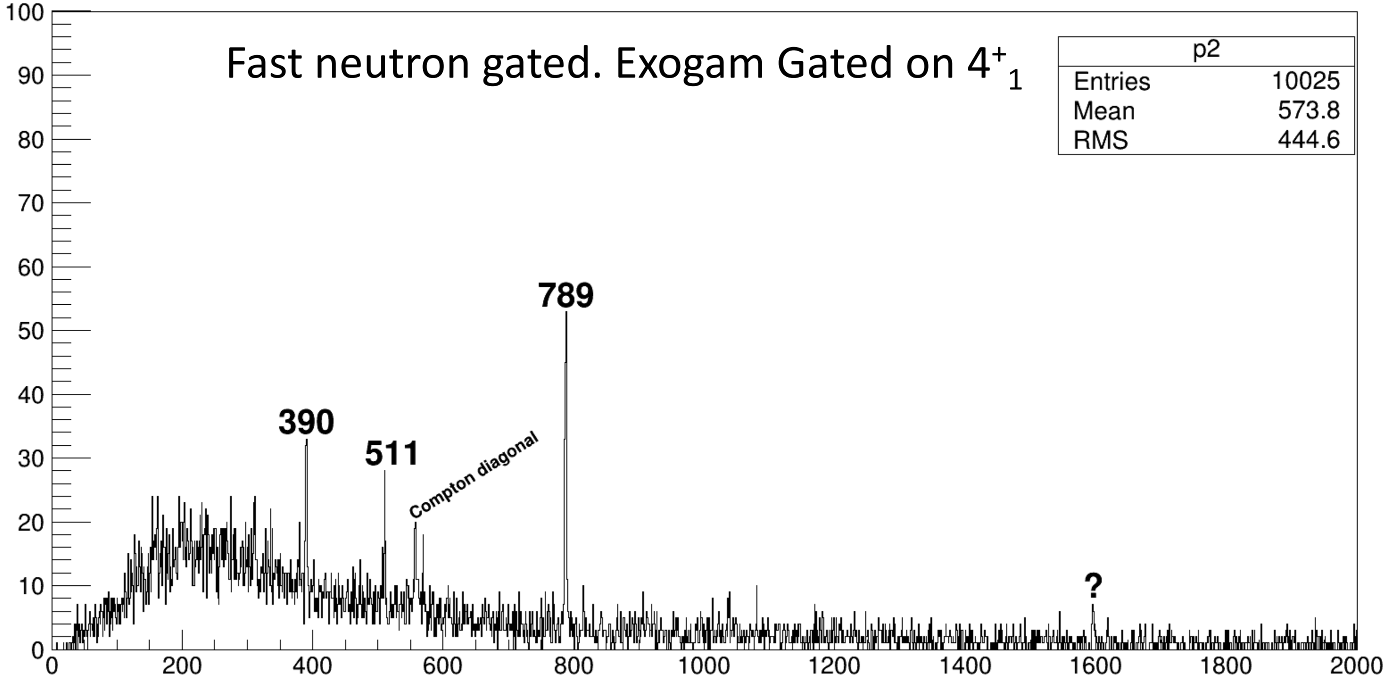
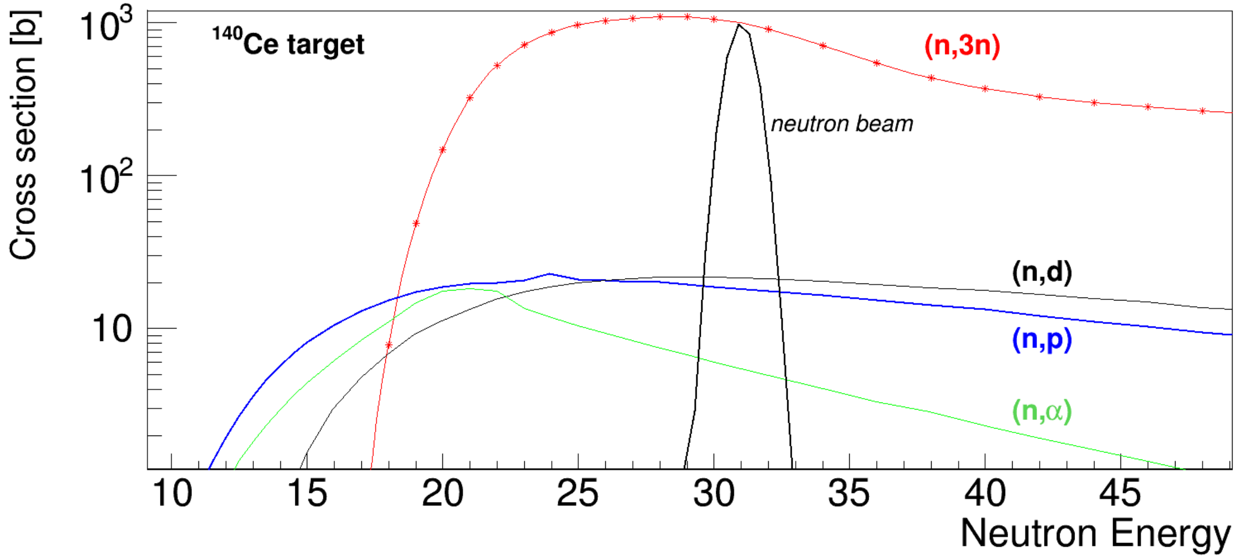
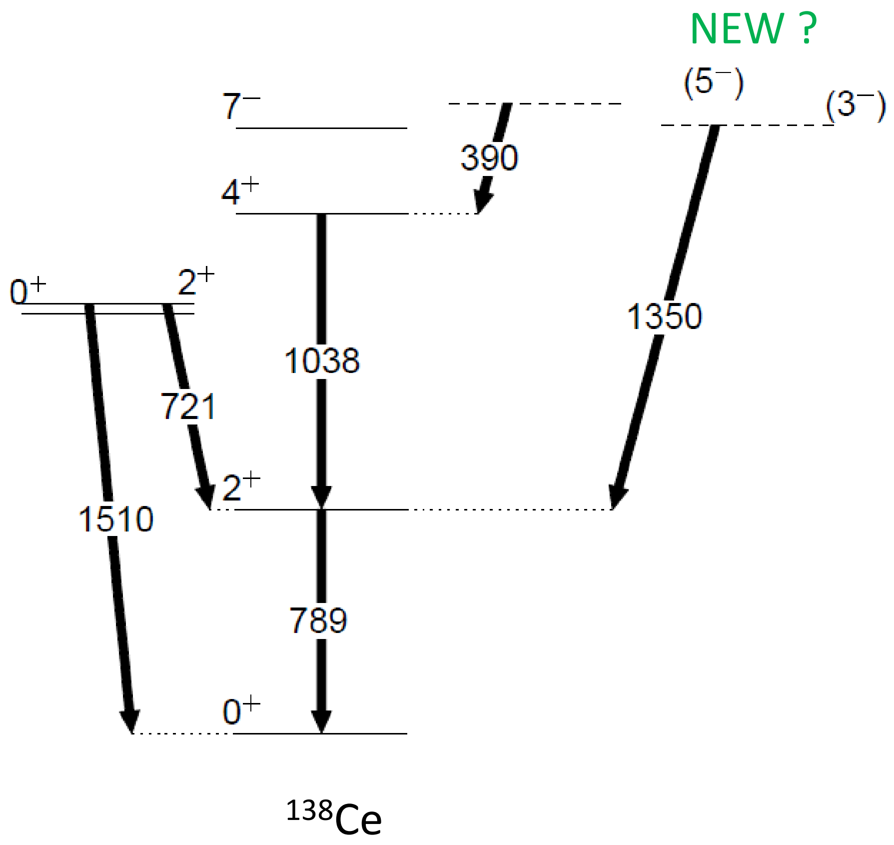
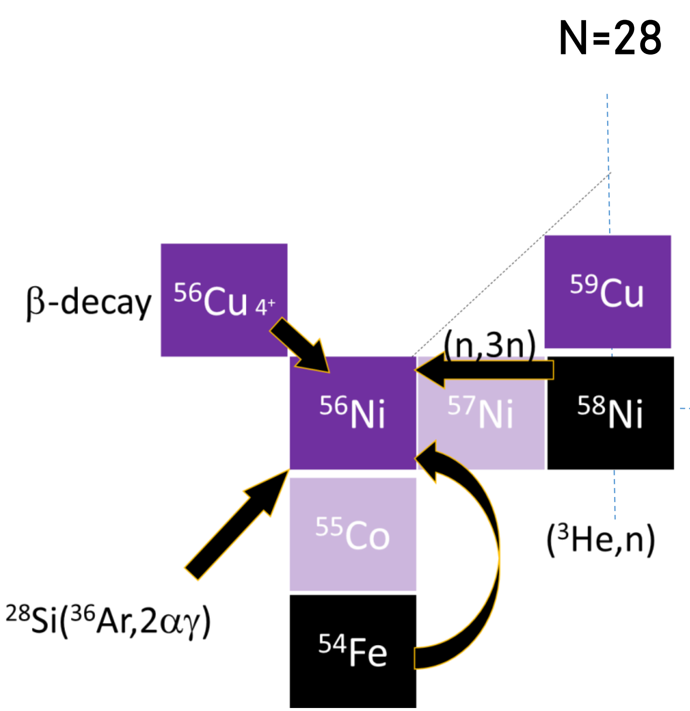
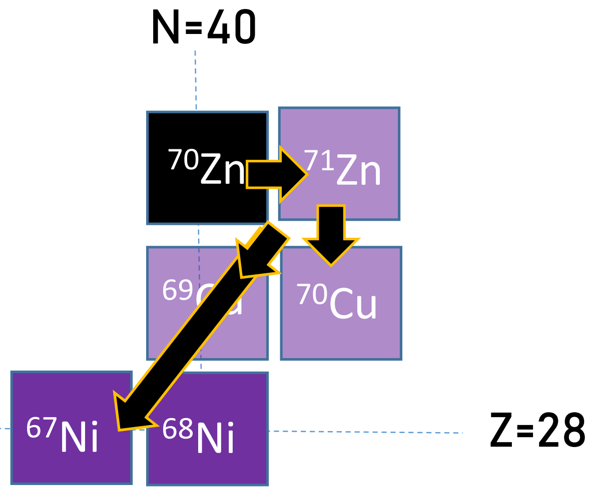




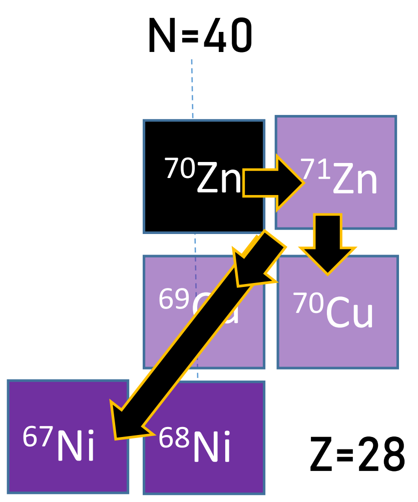


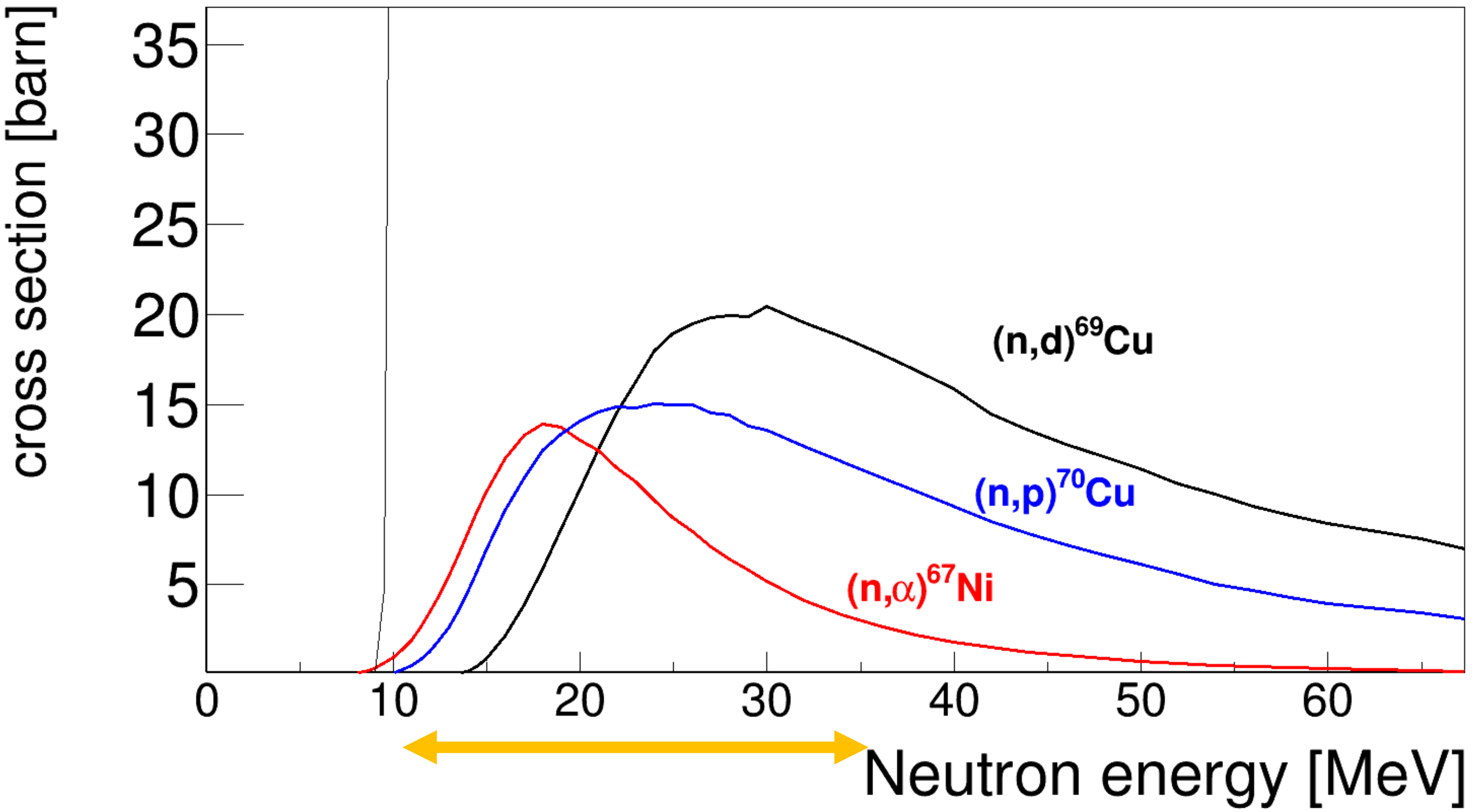
Beyond : n-rich side ?



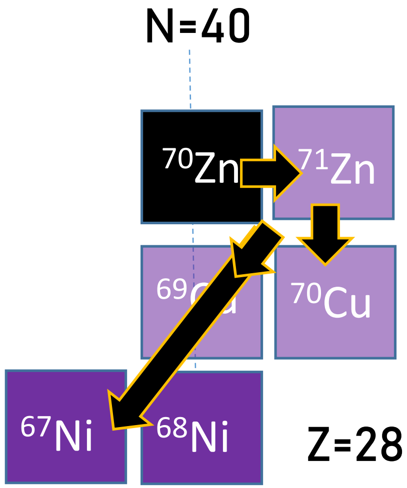


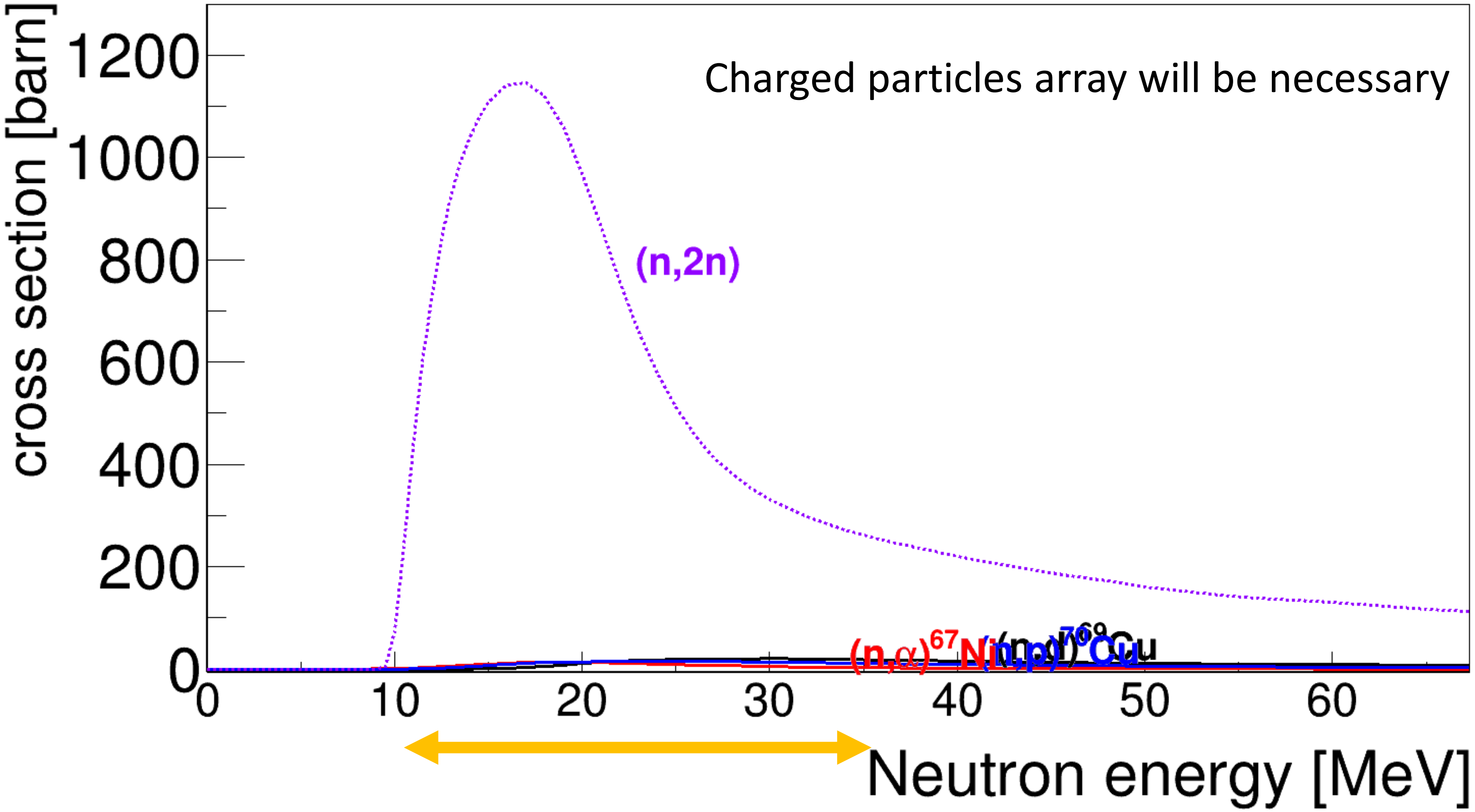
Beyond : n-rich side ?





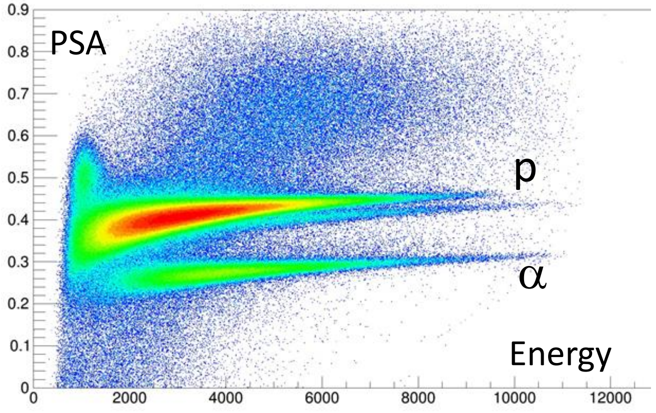
Beyond : n-rich side ?

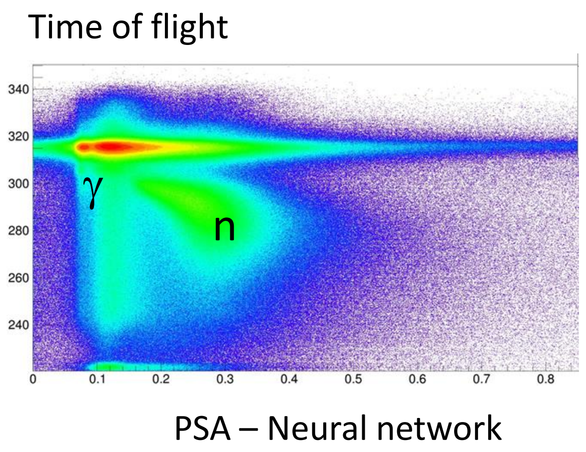


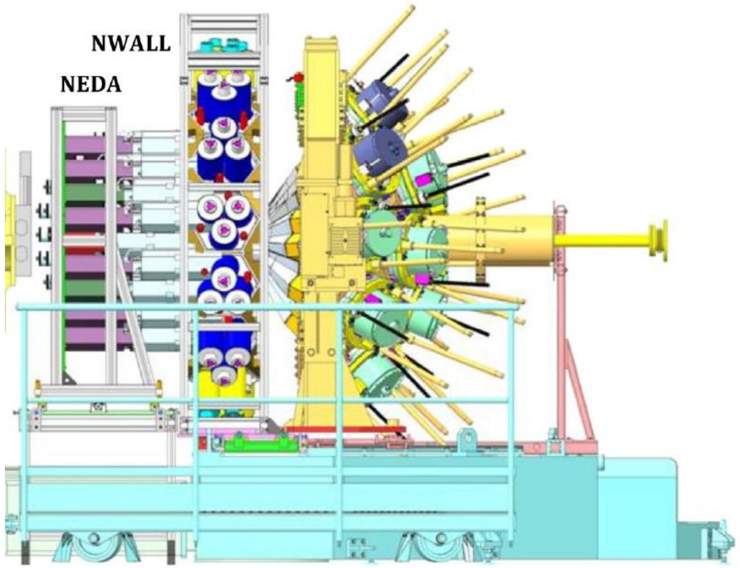


Beyond : n-rich side ?

2018 run AGATA - NEDA campaign







DIAMANT and NEDA in full digital system making use of the NUMEXO2 boards and coupled to AGATA with the AGATA GTS system

J. J. Valiente-Dobón et al., Nucl. Instr. Meth. A927 (2019) 81,

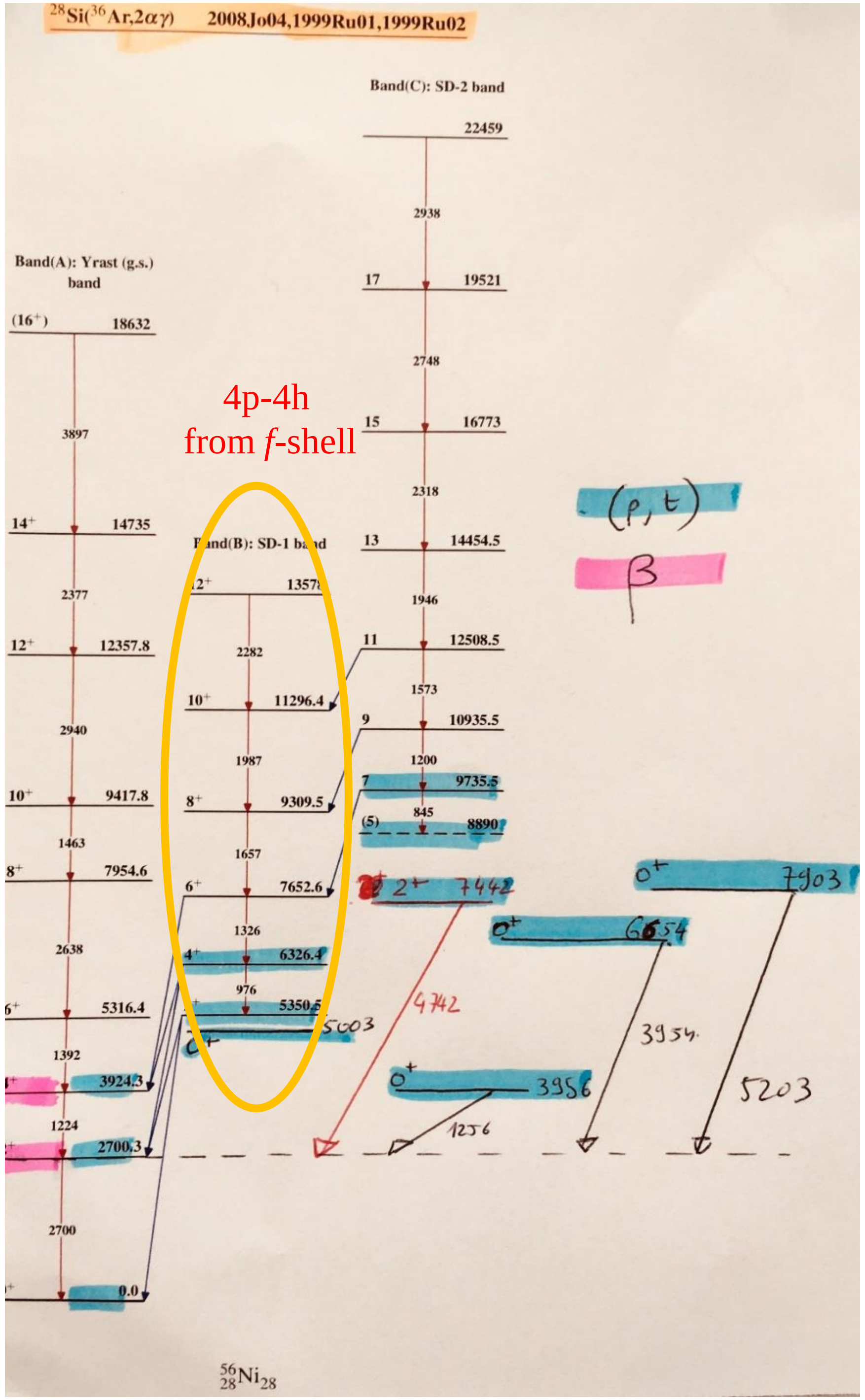
Conclusion

- NFS is unique in term of flux at the (n,x….) energies.

- GANIL gathers State-of-the-art instrumentations

- The proposition is a (longer) EXOGAM@NFS campaign starting in 2023, possibly coupled to large neutron and charged particles arrays

Test case : ^{56}Ni



The Yrast structure of ^{56}Ni is rather well understood with the ground state band of a doubly magic nuclei and a shape coexistence scenario at 5 MeV based on a 4p-4h configuration from the *f*-shell.

State-of-the-art Shell Model calculations :
Low-lying 0$^+$ states calculated (exp.) at 3.6 (3.9) , 4.94 (5.0) , 6.16 (6.6) , and 6.8 (7.9) MeV.

Not clear interpretation for the 1st , 3rd and 4th excited 0$^+$ states.

The 3.9 MeV state is proposed as a two-phonon structure but no experimental confirmation

Others ?

→ Need for more spectroscopic data

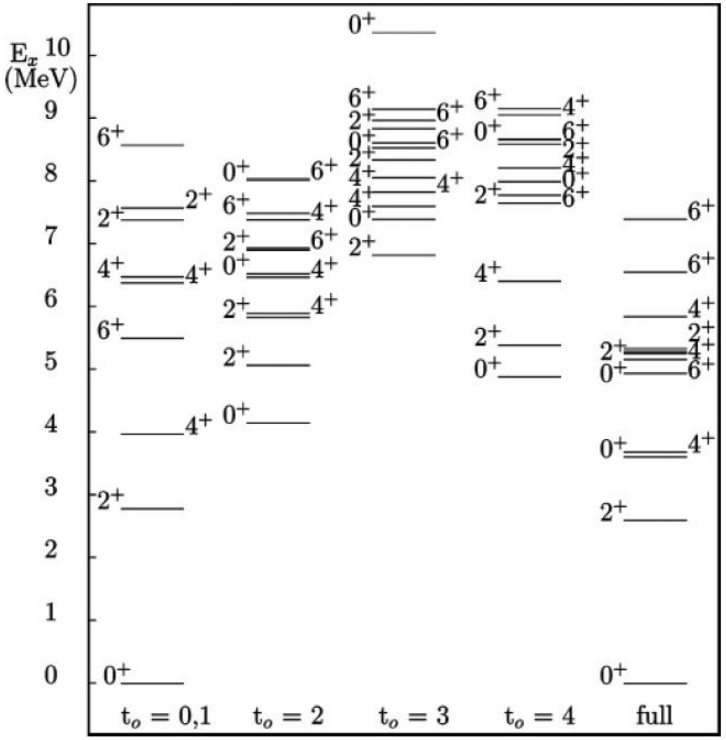


FIG. 2. The first three 0^+, 2^+, 4^+, and 6^+ states for the pure t_o configurations.

M. Horoi, B. A. Brown, T. Otsuka, M. Honma, and T. Mizusaki, Phys. Rev. C ***73****, 061305(R) (2006)*

Experiment #0

E. Clément (GANIL)