
GANIL

Physics results and perspectives

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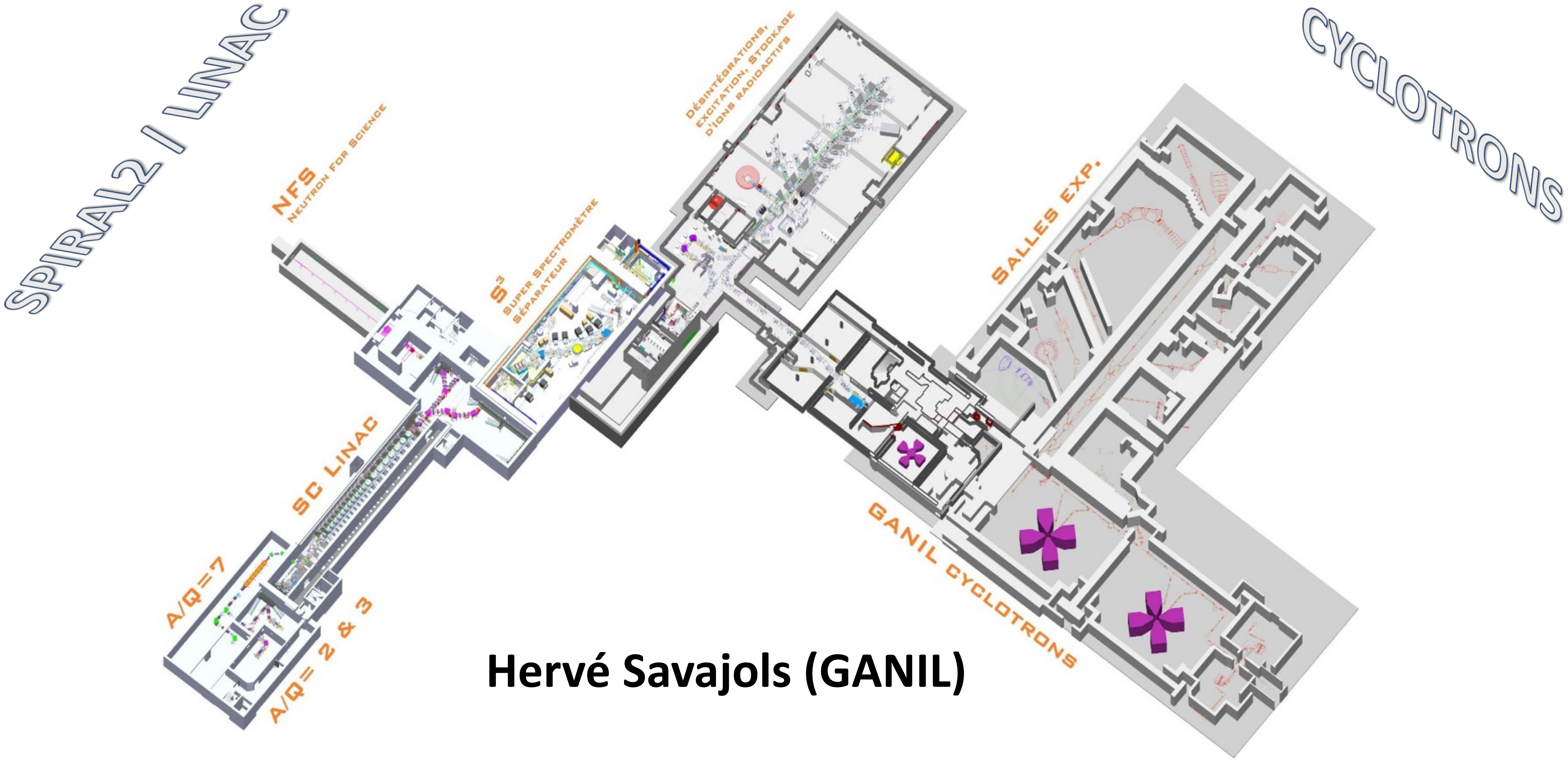


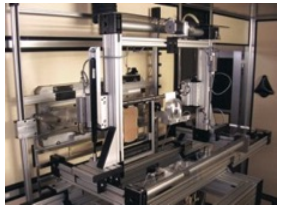
Hervé Savajols (GANIL)

Cyclotrons and their experimental equipment

GANIL

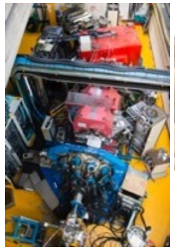
EXOGAM

ACTAR TPC



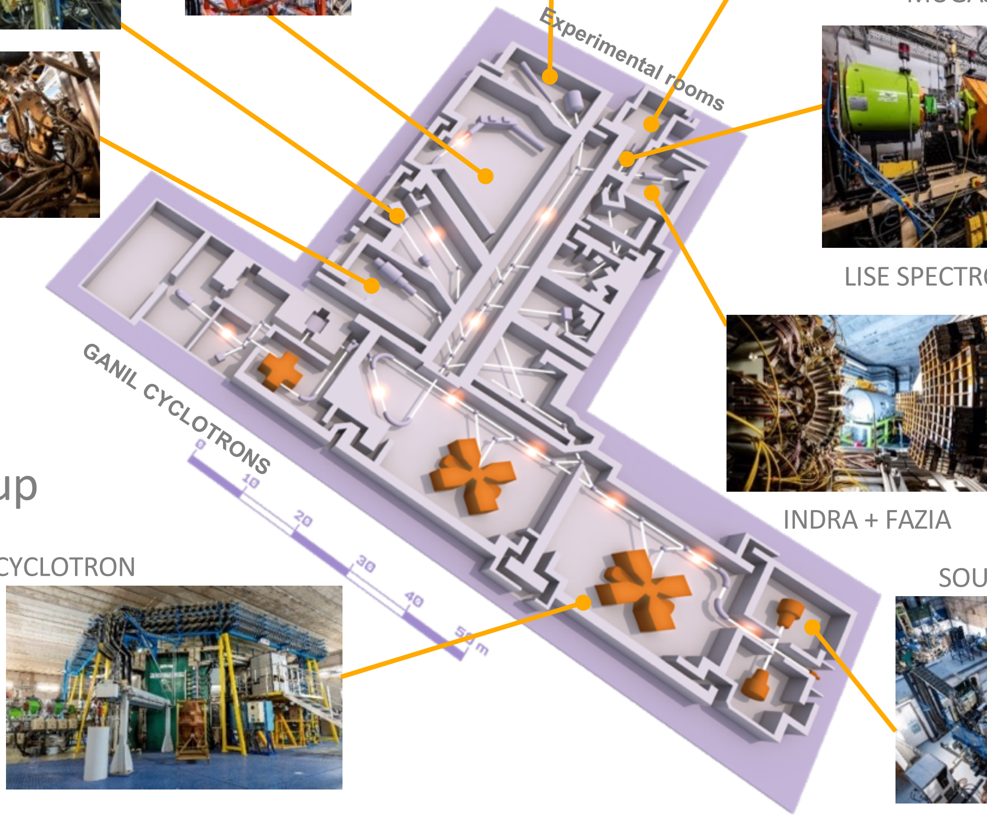
Porte échantillon pour irradiation

MUGAST



VAMOS

AGATA



LISE SPECTROMETER

INDRA + FAZIA

CYCLOTRON

SOURCES

- Beams : ^{12}C à U
- Energy : from <1 MeV up to 95MeV/nucleon
- Up to 3 parallel experiments

A strong program with the large variety spectrometers/detectors :

- VAMOS++ and the fission revival
- LISE and the « tandem » mode
- MUST2/MUGAST campaign
- ACTAR-TPC active target
- INDRA+FAZIA
- AGATA@GANIL.2

New SPIRAL1 beams

But an increase of accelerator failures

=>Cyclotron refurbishing program CYREN

Experiments @ Cyclotrons

Fission

Evolution of fission yields with the excitation energy

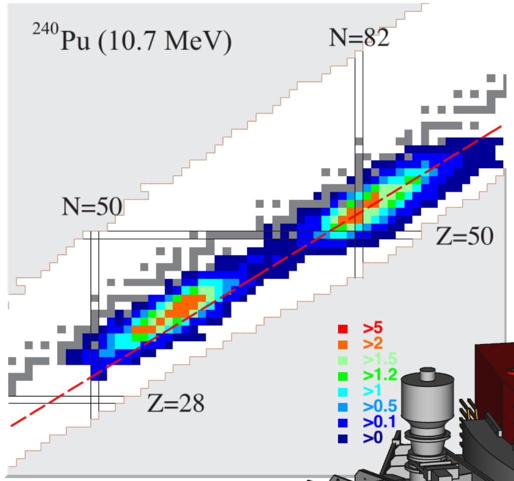
Damping of shell effects in nuclear fission (E850, J. Taieb et al)

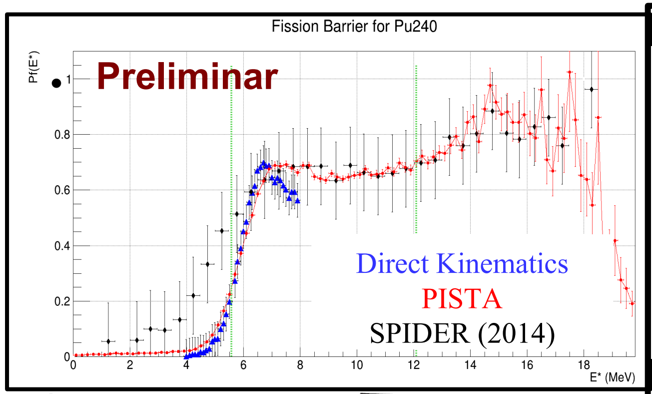
^{238}U beam (6MeV/u) + ^{12}C target → Actinide fissioning systems

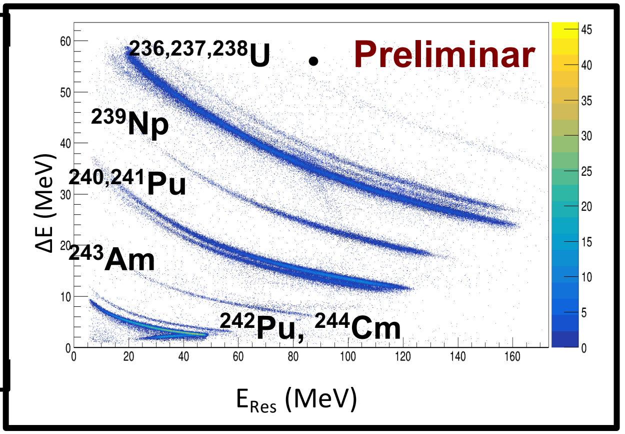
VAMOS

- Isotopic identificaton fo fission fragments
- Full fission fragment distribution
- Fission fragment velocity

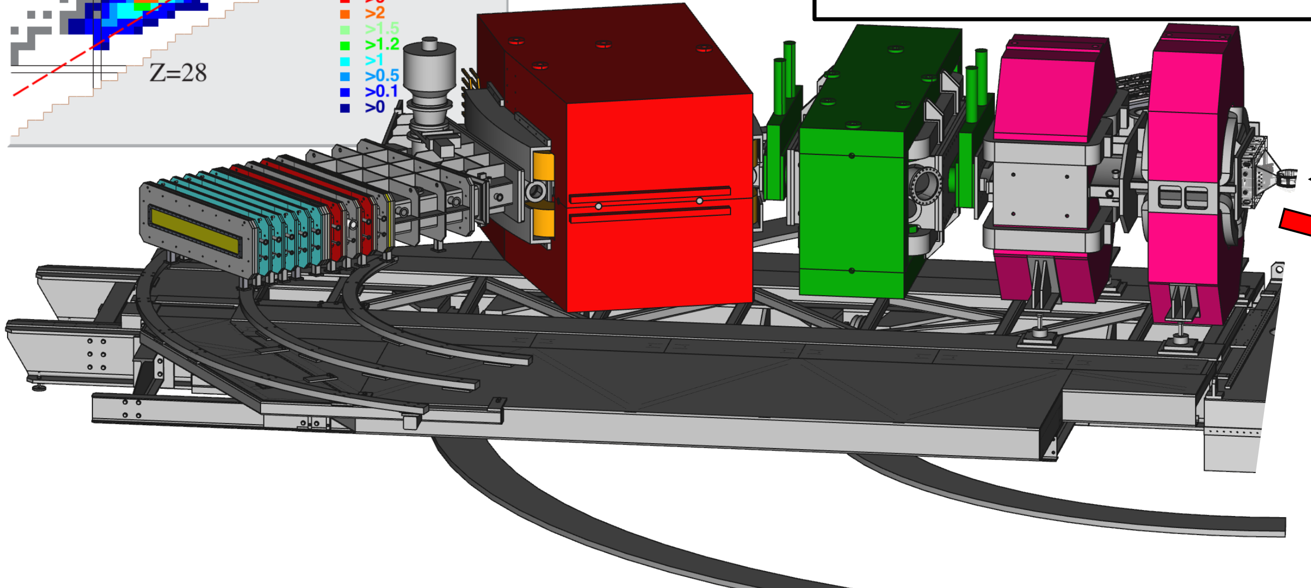
- **PISTA (Silicon Telescope)**
  - Selection of the incoming channel (A, Z, Ex)
  - Fission probability





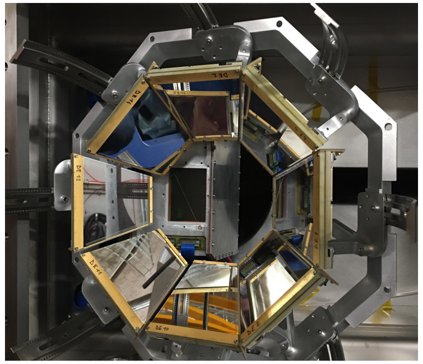


- **VAMOS**



Beam

- **PISTA**



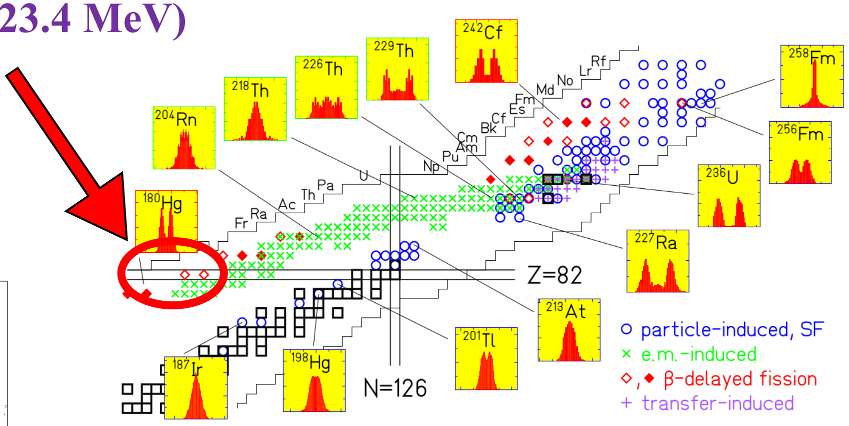
Experiments @ Cyclotrons

Fission

Fission of pre-actinides with VAMOS (E851, A. Lemasson et al)

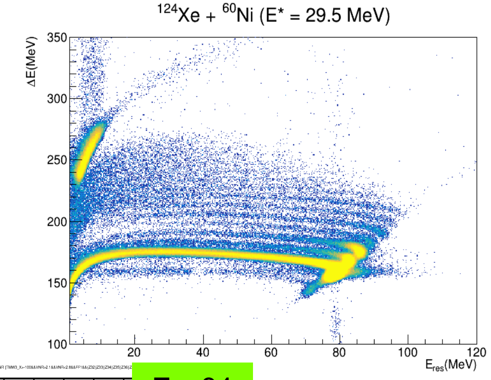
^{124}Xe beam (4MeV/u) + ^{60}Ni target → ^{184}Pb (E_x = 32.3, 29.5, 23.4 MeV)

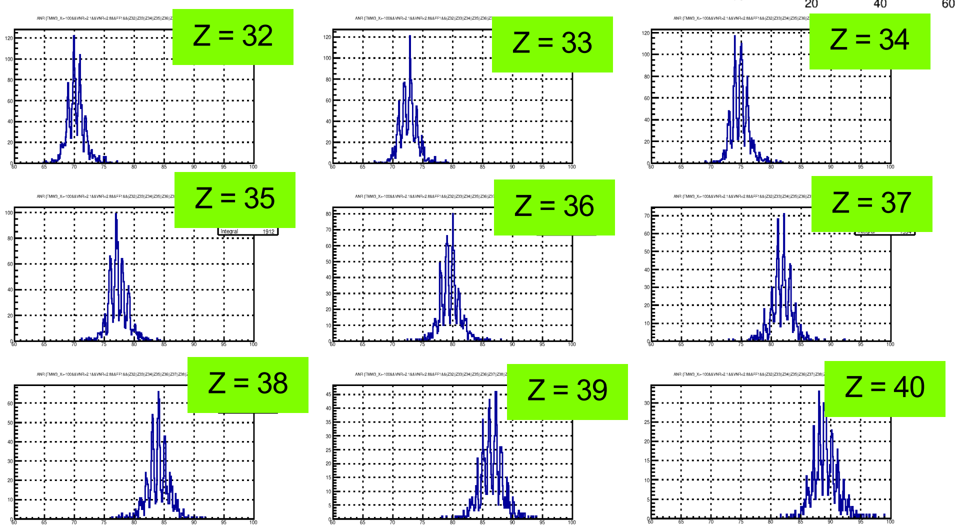
- Study of the island of asymmetric fission in pre-actinides
- Transition from asymmetric to symmetric fission
- Building a coherent picture of microscopic shell effects in fission across the nuclear chart

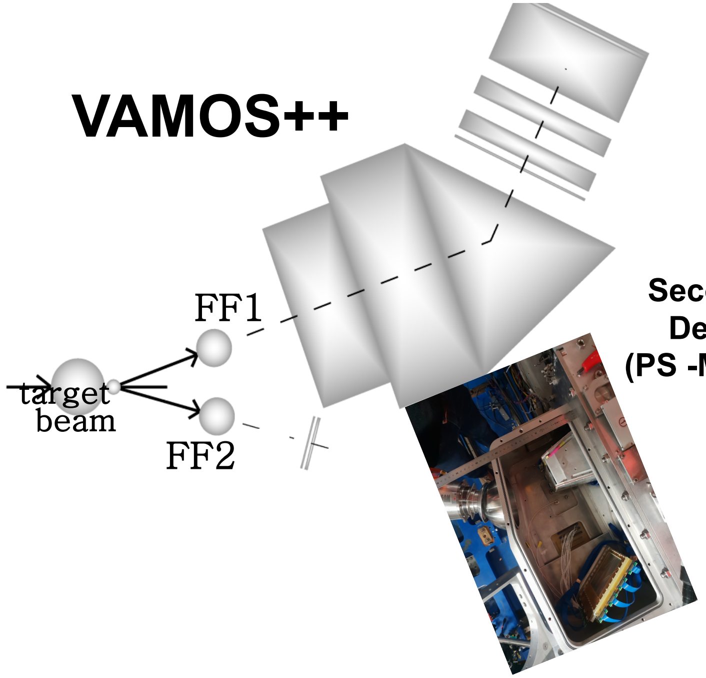


=> Fusion Fission (/!\ low energy)
=> Isotopic Identification of Fission Fragments with VAMOS and second fragment detections

- Isotopic Fission Yields
- <N>/Z
- Pre-evaporation Mass and TKE





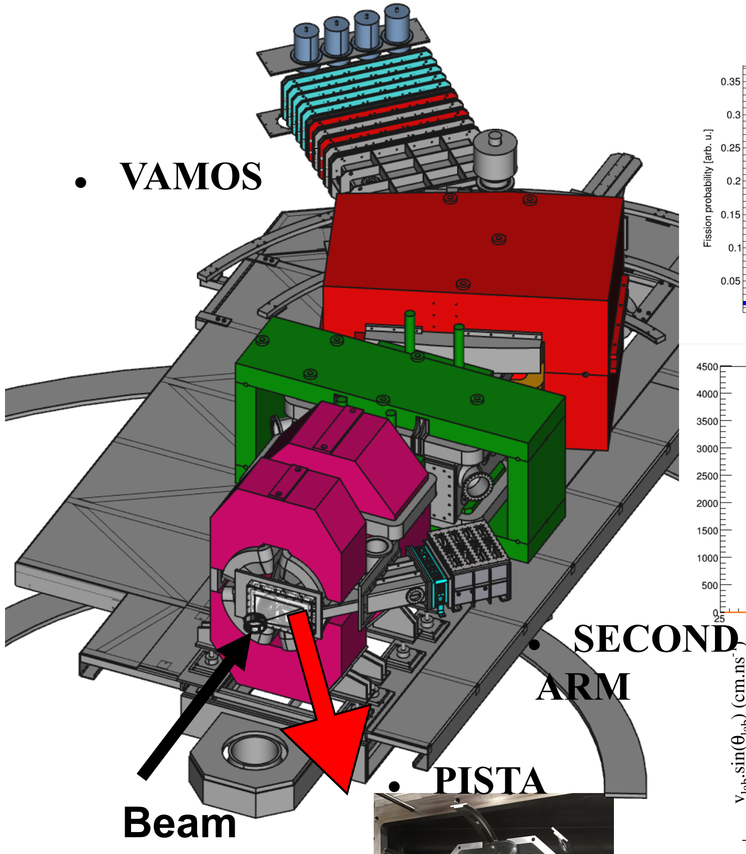


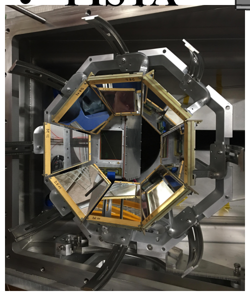
Experiments @ Cyclotrons

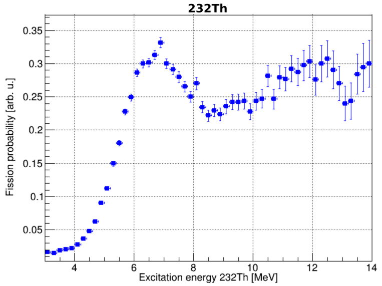
Fission

(E849, D. Ramos et al)

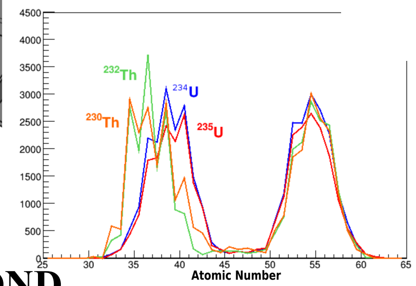
^{232}Th beam (6MeV/u) + ^{12}C target → New fissioning systems around Th



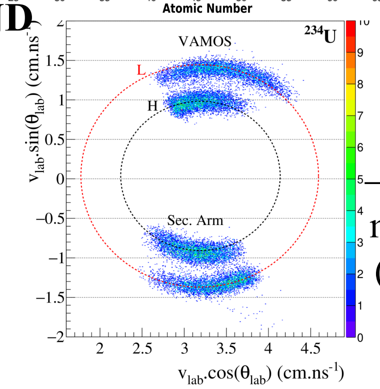




Identification of fissioning system (PISTA)



Isotopic fission fragment identification (VAMOS)

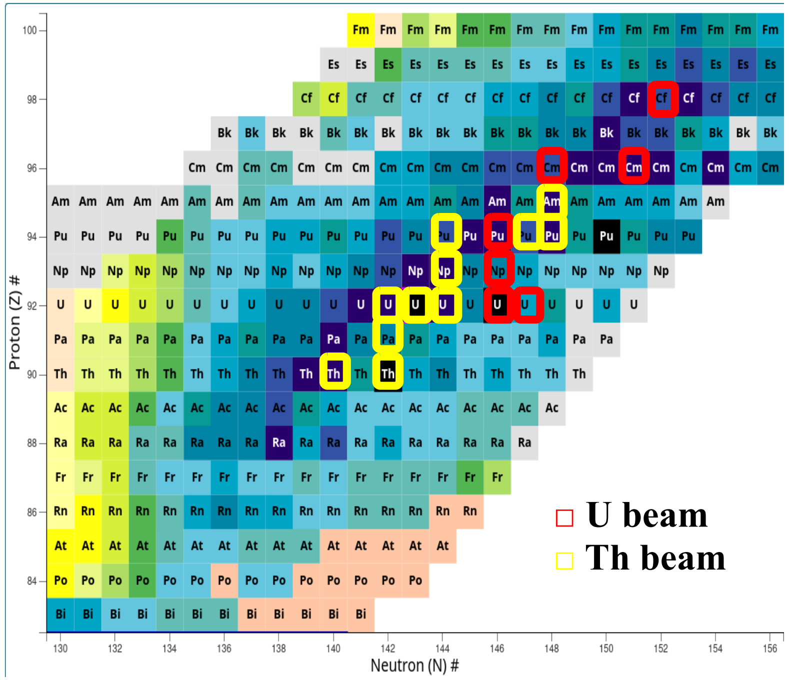


Bofth fission fragments in coincidence

→Fission fragment masses at Scission (SECOND ARM)

New ^{232}Th beam accelerated at GANIL

Access to new region of actinides



Experiments @ Cyclotrons

Clustering

(E870 V. Alcindor)

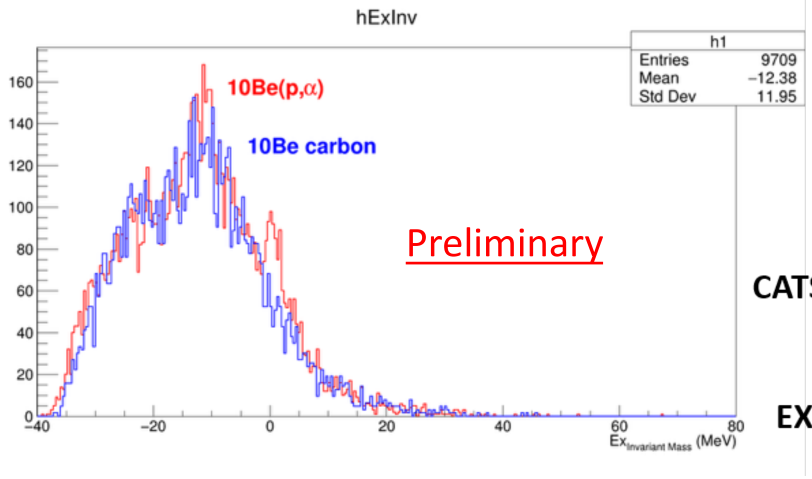
Cluster structure of the gs of light exotic nuclei beyond alpha clustering

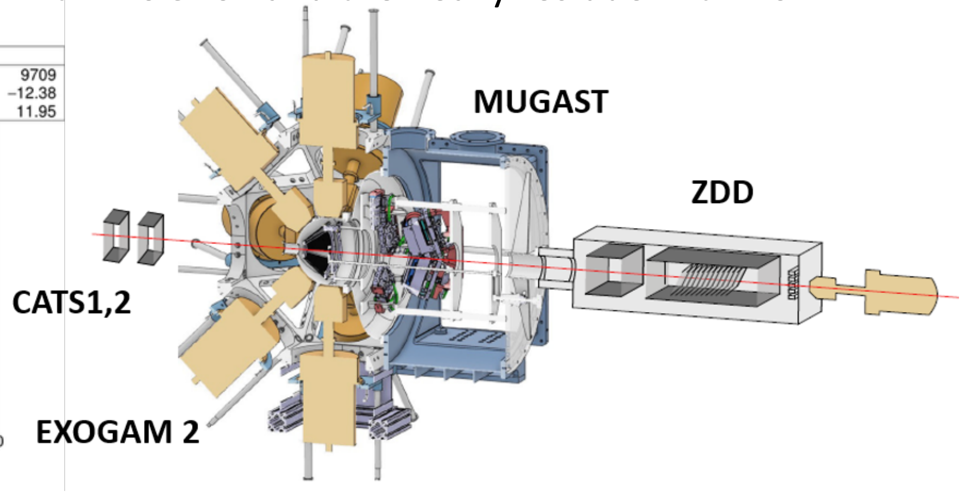
Scientific goal

Test of recent generalized density fonctional theory predicting that the light clusters d, t, ^{3}He and ^{4}He are all formed at approximately 1/10 of the nuclear saturation density, a condition typically reached in the surface region of nuclei. Also prediction of favorable triton formation in n-rich matter.

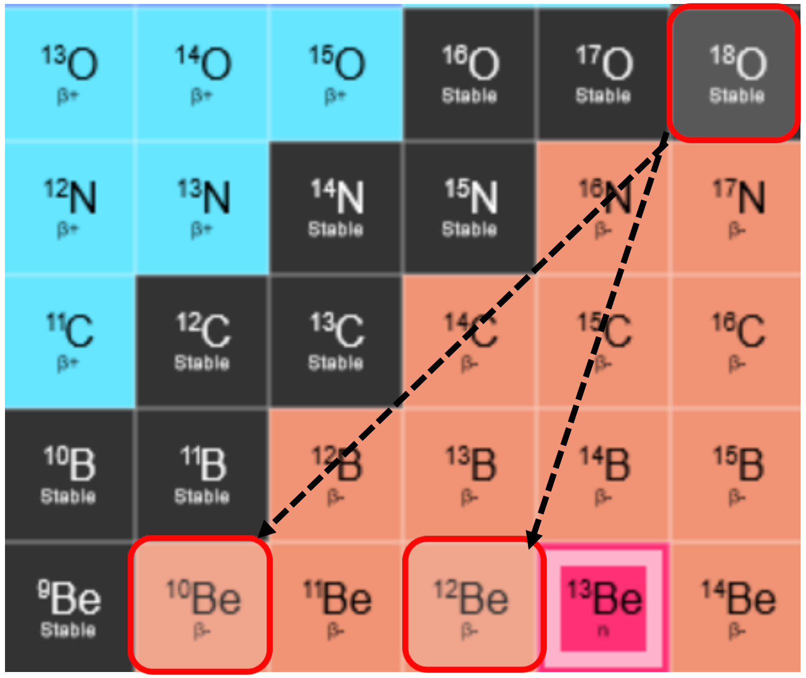
Experimental method

- Cluster removal from ^{10,12}Be on CH_2 and CD_2 targets -> (p,X) and (d,X) reactions
- Detection of light ejectiles (X = α,^{6}Li) with MUGAST and the heavy residue with LISE ZDD





https://people.physics.anu.edu.au/~ecs103/chart/



Preliminary results

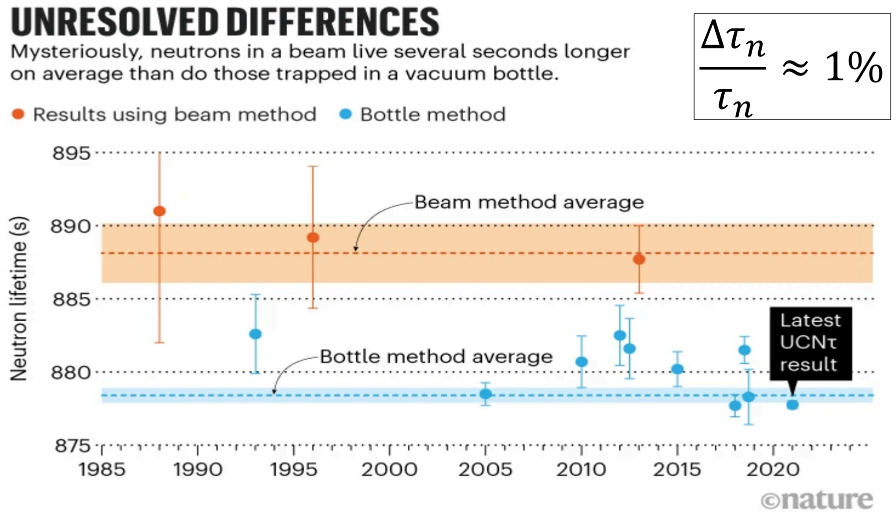
- On line observation of alpha and triton structuration in ^{10}Be : (d,^{6}Li) and (p,α) reactions
- Good hope to observe triton structuration in ^{12}Be

Experiments @ Cyclotrons

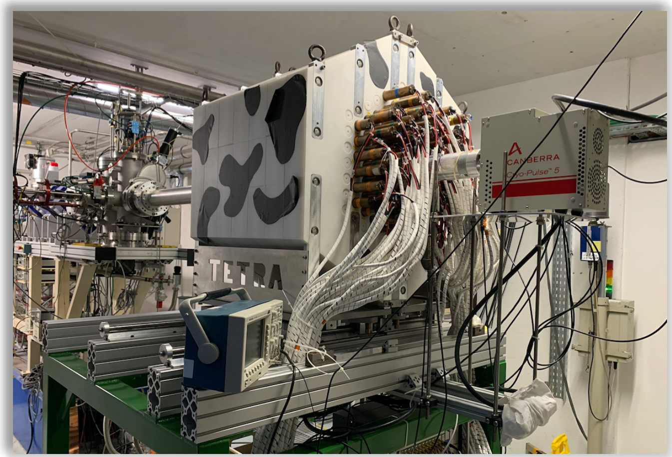
Dark matter

(E819S H. Savajols et al.)

Wietfeldt, https://doi.org/10.3390/atoms6040070 (2018)
Gonzalez, F. M. *et al. Phys. Rev. Lett.* **127**, 162501 (2021)

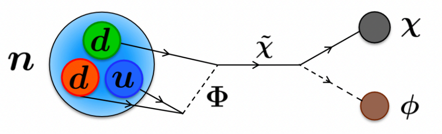


- $^6He^{1+}$ SPIRAL1 world record beam intensity (2×10^8 pps)
- Neutron multidetector TETRA with 50% efficiency

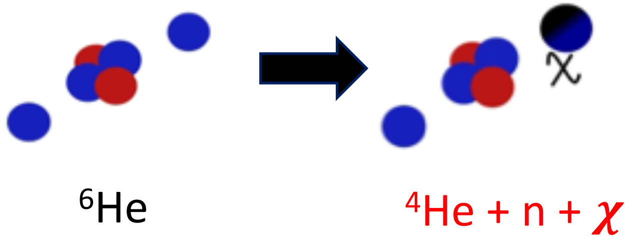


n → dark matter

Fornal and Grinstein, PRL120(2018)191801

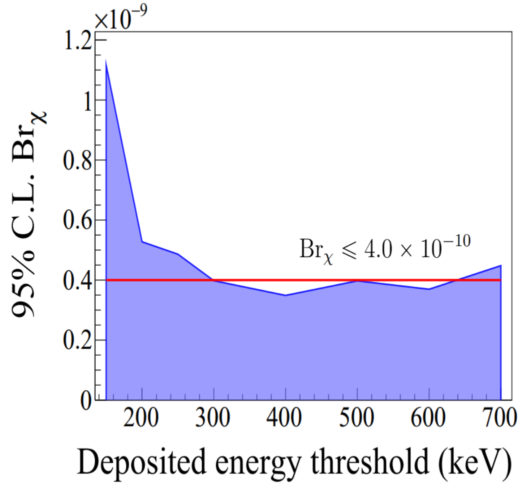


Is there a dark decay of neutrons in ^{6}He ?

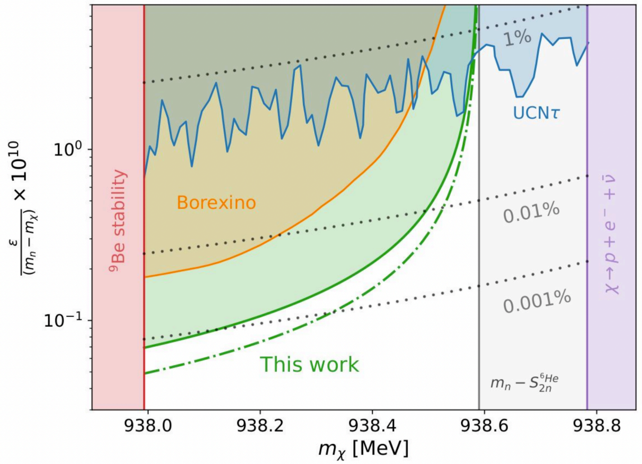


PHYSICAL REVIEW LETTERS 132, 132501 (2024)

Upper limit at 4×10^{-10} (95% C.L.)

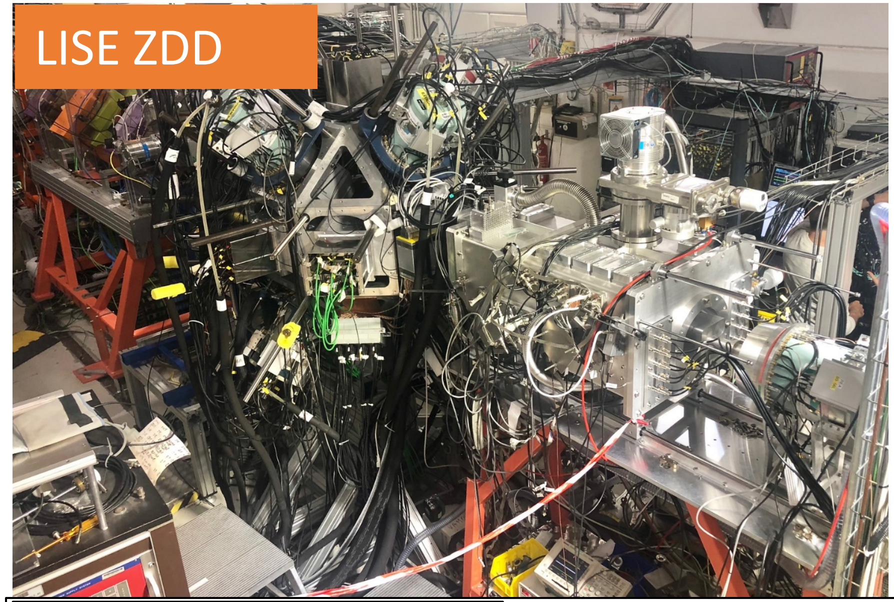


Exclusion Diagram

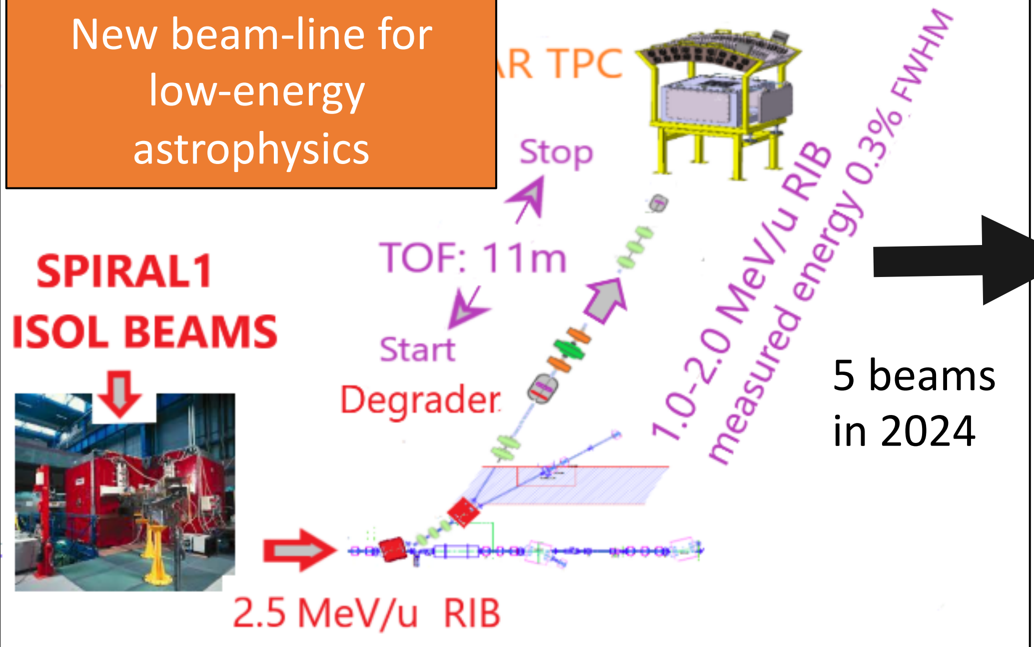


GANIL : a constant upgrade to meet user needs

LISE ZDD

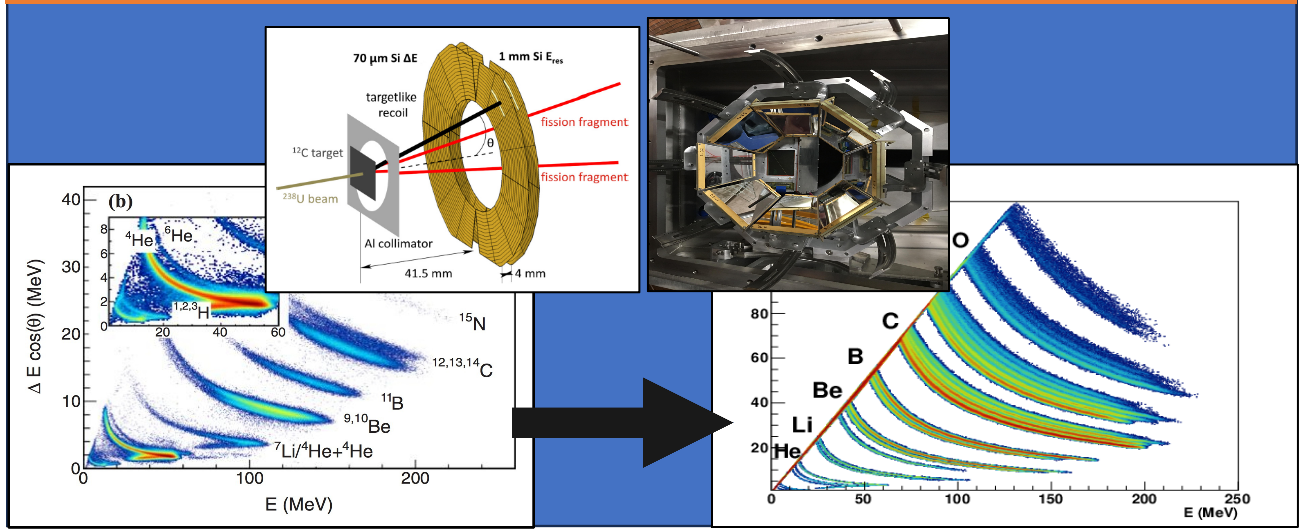


New beam-line for low-energy astrophysics



5 beams in 2024

Improvement of target-point detection set-up @ VAMOS

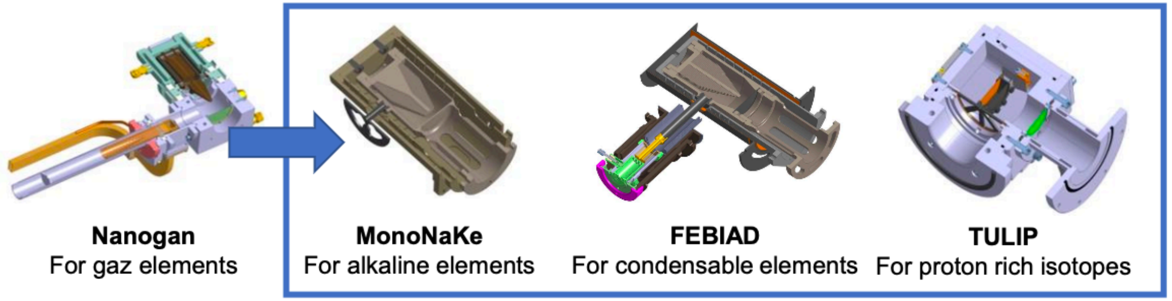


- E837_21 V. Guimaraes et al mars ^{8}He 1.8 MeV/u
- Test B. Jacquot juin ^{16}O 2 MeV/u
- E864_22 M.G. Pellegriti et al juin ^{8}Li 2 MeV/u
- E863_test L. Dienis, C. Fougères... juillet ^{40}Ar 6 MeV/u
- E845_21 G. Georgiev et al sept. ^{22}Ne 5.5 MeV/u

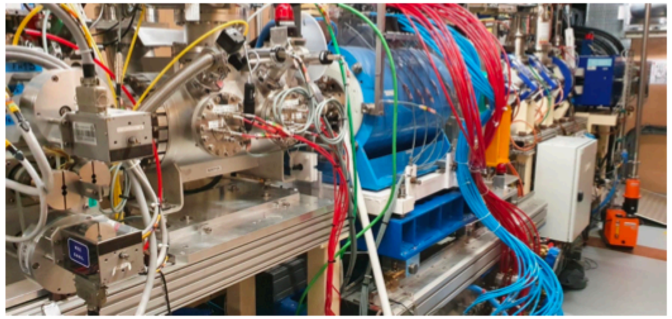
SPIRAL1 upgrade

GANIL

- New target Ion Source Systems (FEBIAD)



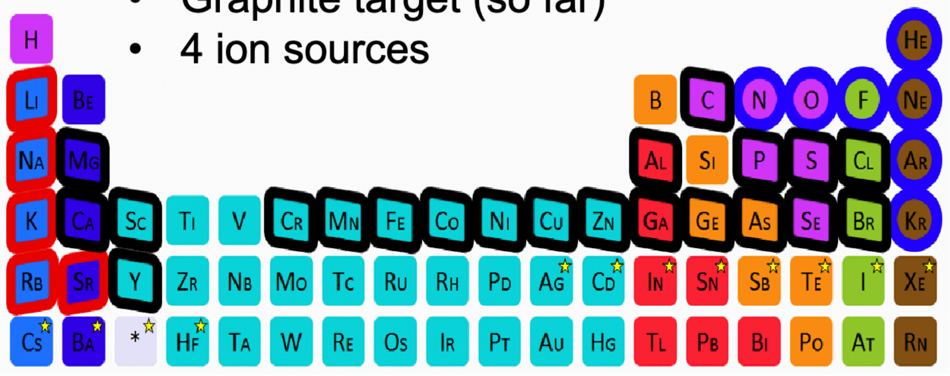
- The charge breeder

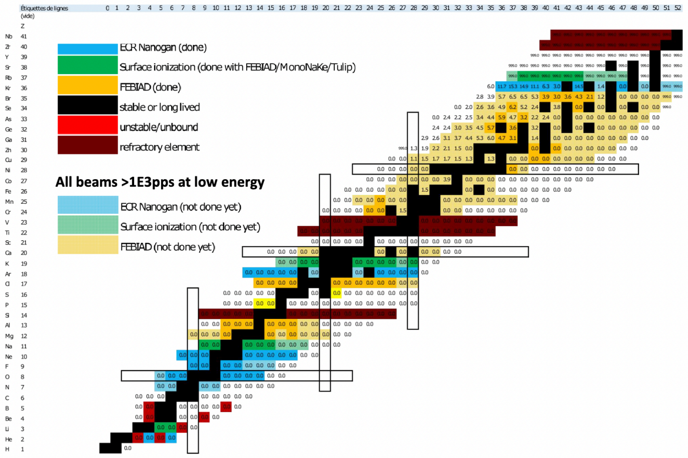


GANIL is putting a strong effort on SPIRAL1 in-beam tests

50 new isomers/isotopes
With intensities suitable for acceleration

- 58 primary beams from ^{12}C to ^{238}U
- Graphite target (so far)
- 4 ion sources





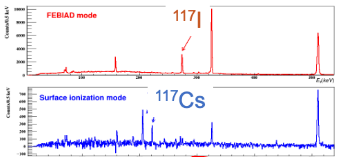
Motivated the AGATA come back in 2029

SPIRAL1 Upgrades

July 2024
^{58}Ni 75 MeV/u
700 W

ION	pps
$^{48}Cr^{1+}$	3.5 10^6
$^{49}Cr^{1+}$	3.5 10^6
$^{52}Fe^{1+}$	4.7 10^6
$^{53}Fe^{1+}$	1 10^7
$^{56}Ni^{1+}$	6.5
$^{57}Ni^{1+}$	2.1
$^{55}Co^{1+}$	2.9

September 2024
$^{129}Xe^{46+}$ beam @ 50 MeV/u,
2 10^{11} pps

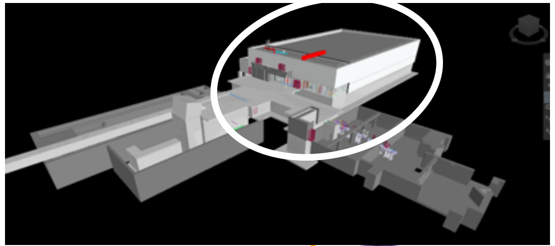


SPIRAL2 and the new experimental rooms

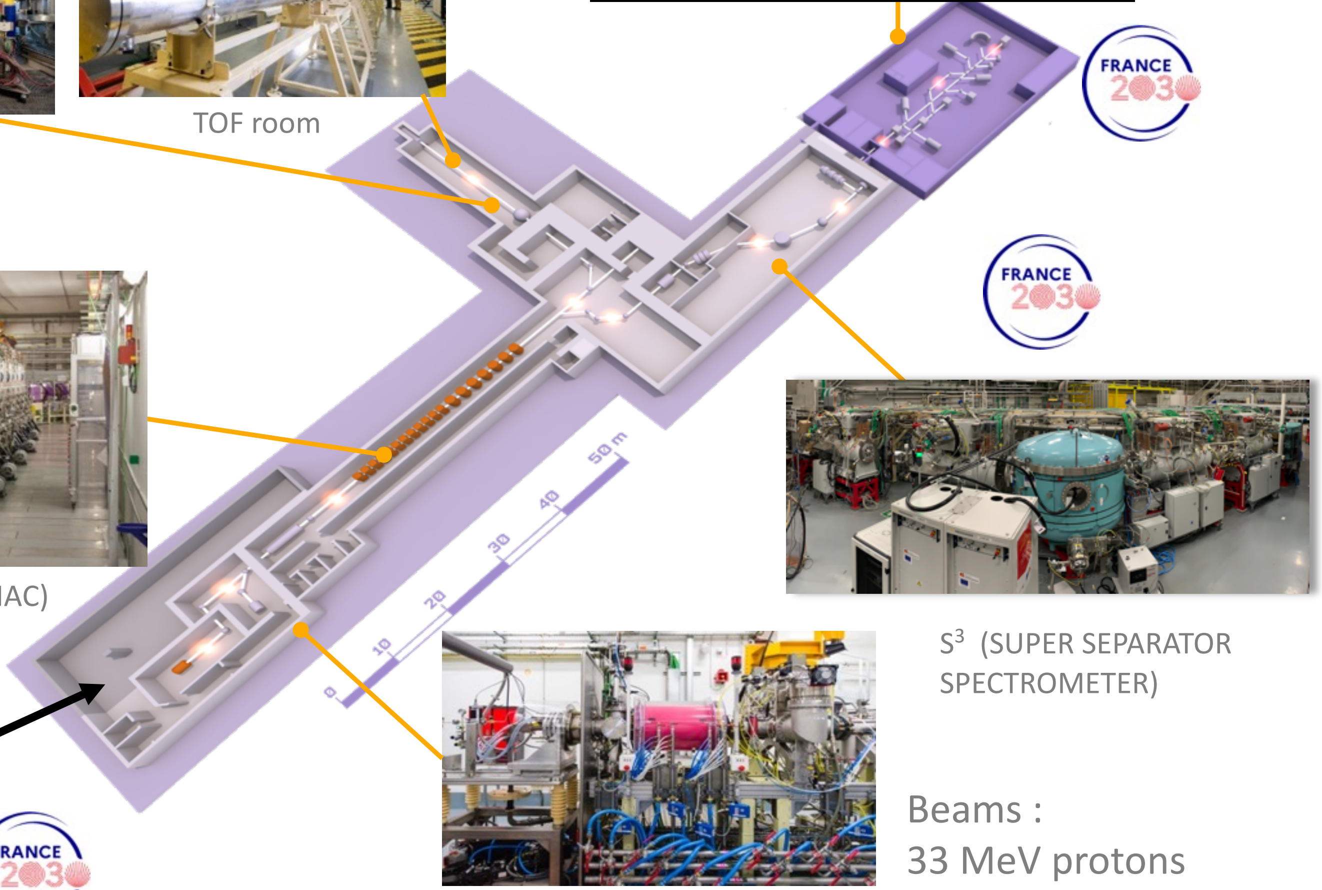
NFS (NEUTRONS FOR SCIENCE)

Converter room

TOF room



DESIR
(Decay,
Excitation and
storage of
radioactive ions)



Accélérateur linéaire (LINAC)

S^3 (SUPER SEPARATOR SPECTROMETER)

ION SOURCE

NEWGAIN
NEW GANIL INJECTOR

A new accelerator ramping up:

First operation experimental area and the first neutrons at GANIL/SPIRAL2: NFS first campaigns and results

Super Separator Spectrometer

DESIR project

Second injector (NEWGAIN)

Beams :
33 MeV protons
40 MeV deutons
<14,5 MeV/nucleon ions lourds

Experiments @ SPIRAL2

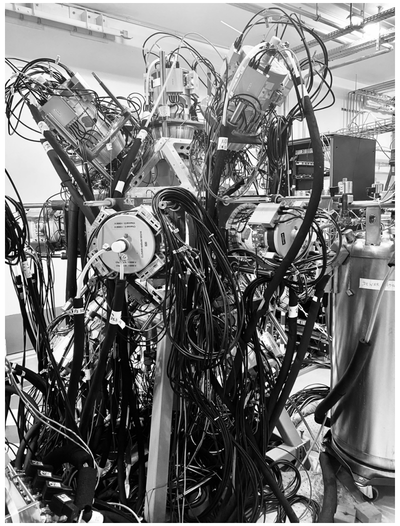
GANIL

E838_21, E. Clément, EXOGAM in TOF hall

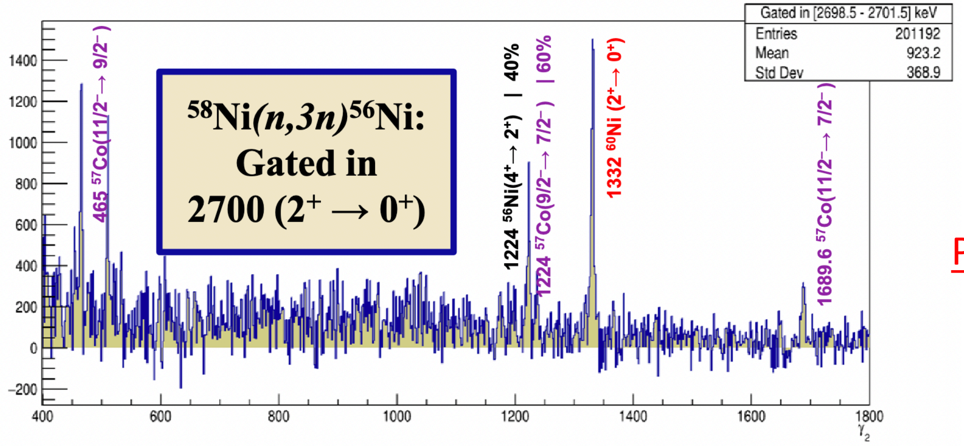
Nuclear structure

Structure of ^{56}Ni using ^{58}Ni(n,3n) reaction

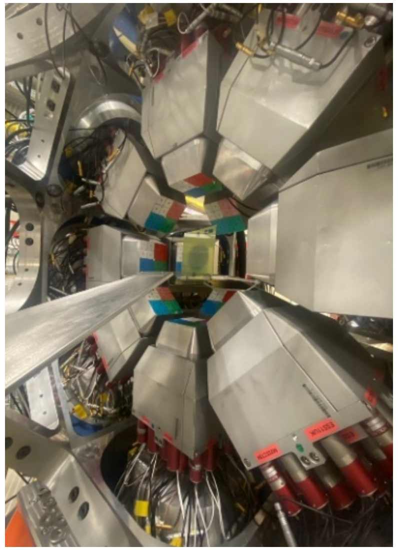
12 EXOGAM clovers placed at 8.6 meters from the production target around Ni target



Successfully observed ^{56}Ni /Neutron excitation selection rules ?
Excitation functions measured



Preliminary



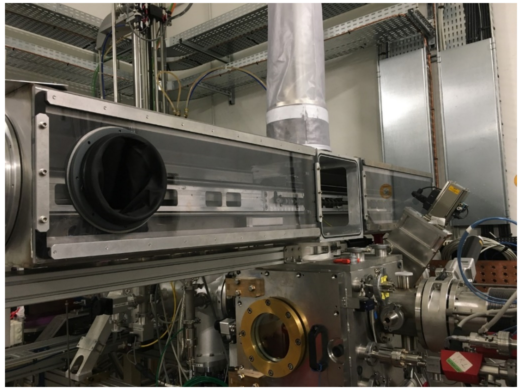
Tests REPARE, G. De France, converter room

Radioisotope

Production of At in NFS converter room with He beam

→ Hardware, soft, beam synchro, vacuum, handling, production yield could be tested
→ but no shipment to ARRONAX…

New beam time in September 2024 : production of At (1 GBq in 3 targets) and shipment to ARRONAX of 2 targets, but At also detected at the SPIRAL2 chimney, outside GANIL authorization (no impact on environment, of the order of nSv)



Experiments @ SPIRAL2

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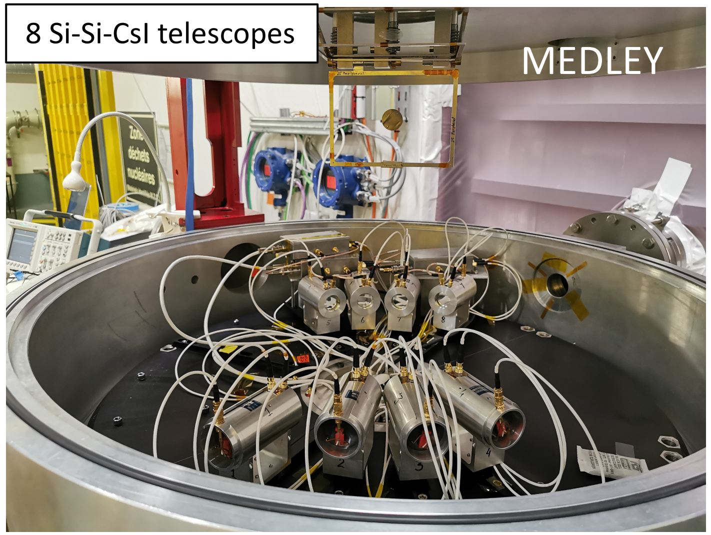
n - induced reaction

- **E858_22 D. Tarrio, MEDLEY**

GARROS: neutron-induced light charged particles emission with MEDLEY
Applications : Energy - electronic SEU
Improvement of reaction models

UPPSALA UNIVERSITET



n - induced activation

- **E835_21 V. Blideanu (DES)**

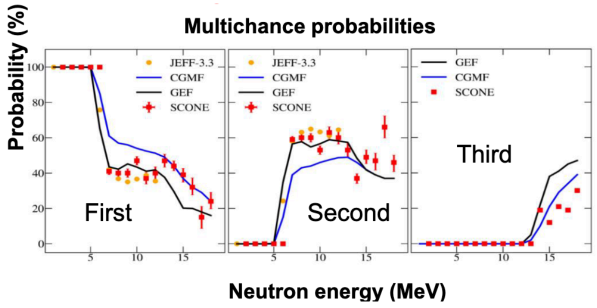
Measurement of the n-induced activation in materials: improvement of nuclear reaction models and decay data libraries for radiation therapy electron accelerators

cea

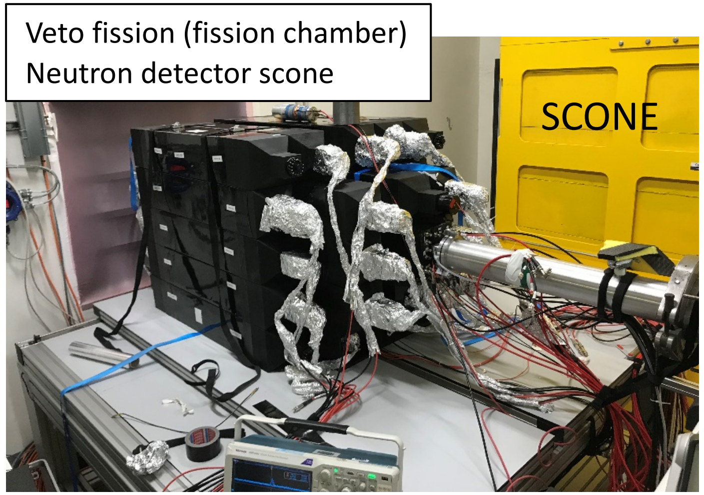
Fission

- **E807 G. Belier et al (DAM)**

(n,xn) and (n,f) for ^{238}U



cea



- **E856_22 G. Belier et al (DAM)**

Study of neutron induced reactions on ^{239}Pu

^{239}Pu fission chamber leaked : stop of experiment and heavy procedures for dismounting and decontamination

Super Separator Spectrometer

GANIL

LINAC beams : He to U
- 1 mA, < 14,5 MeV/A (A/Q=3)
- 1 mA, < 7,5 MeV/A (A/Q=7)

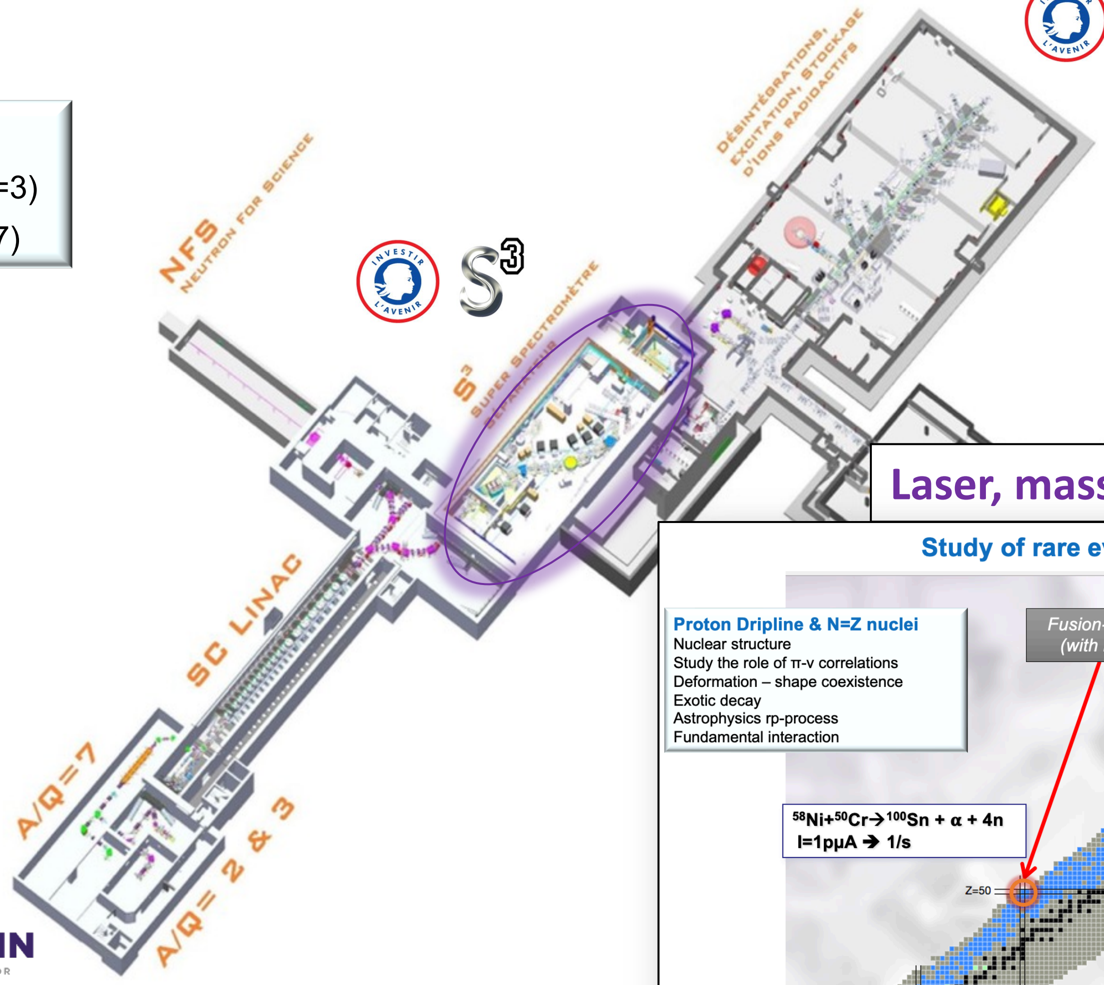
	I for A/Q = 3 (pμA)
^{18}O	80
^{40}Ar	16
^{36}S	2.3
^{40}Ca	2.9
^{48}Ca	1.2
^{58}Ni	1.1
^{86}Kr	0.1
^{136}Xe	0.001

X 5 up to ^{58}Ni
X 10^x for A > 58

NEWGAIN
NEW GANIL INJECTOR

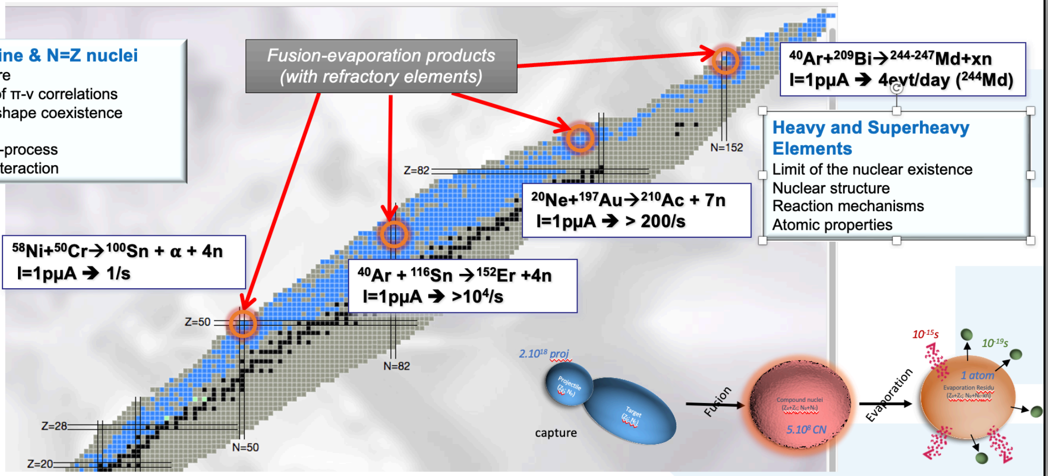
S3

Spiral2 DESIR

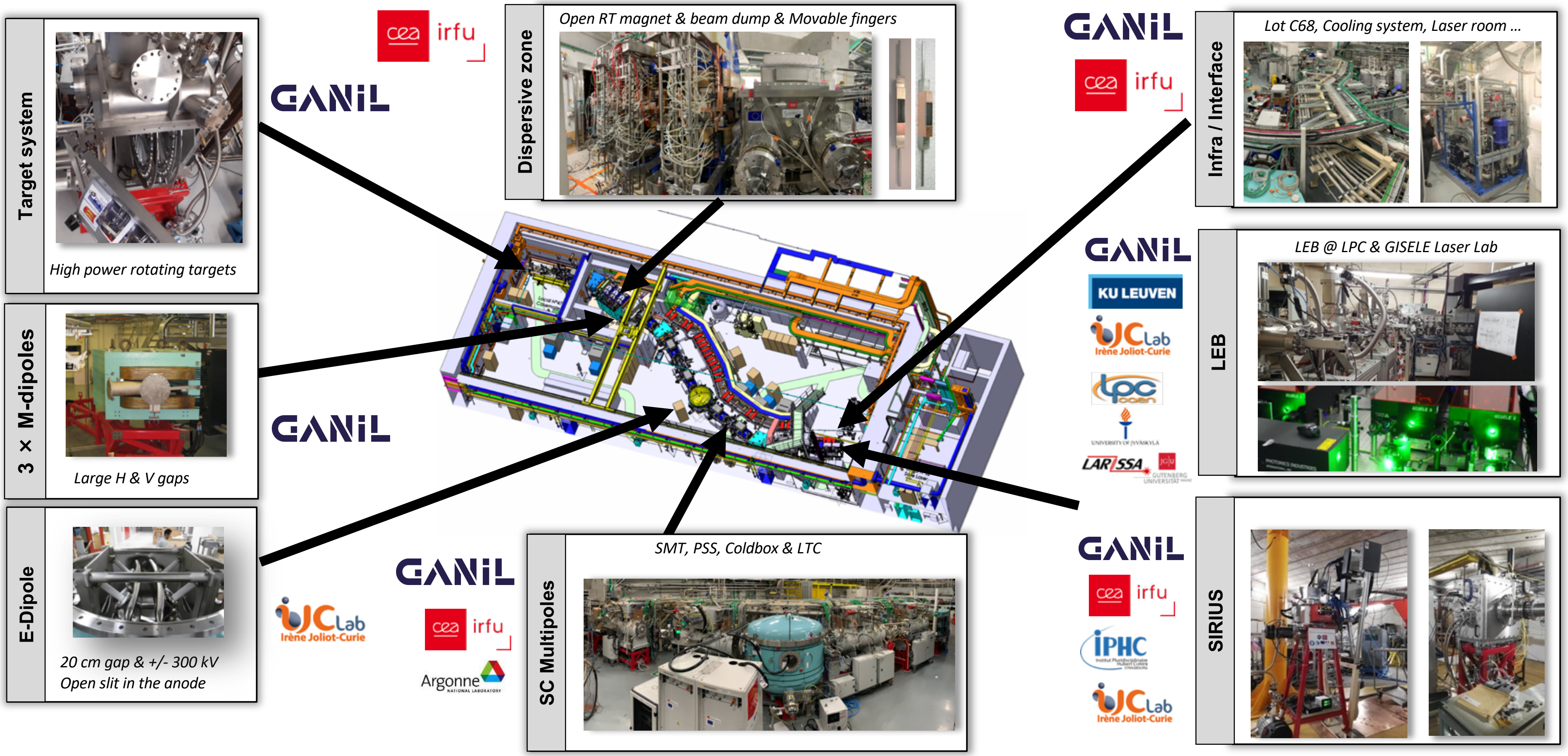


Laser, mass and decay spectroscopy

Study of rare events in nuclear and atomic physics



Super Separator Spectrometer S^3



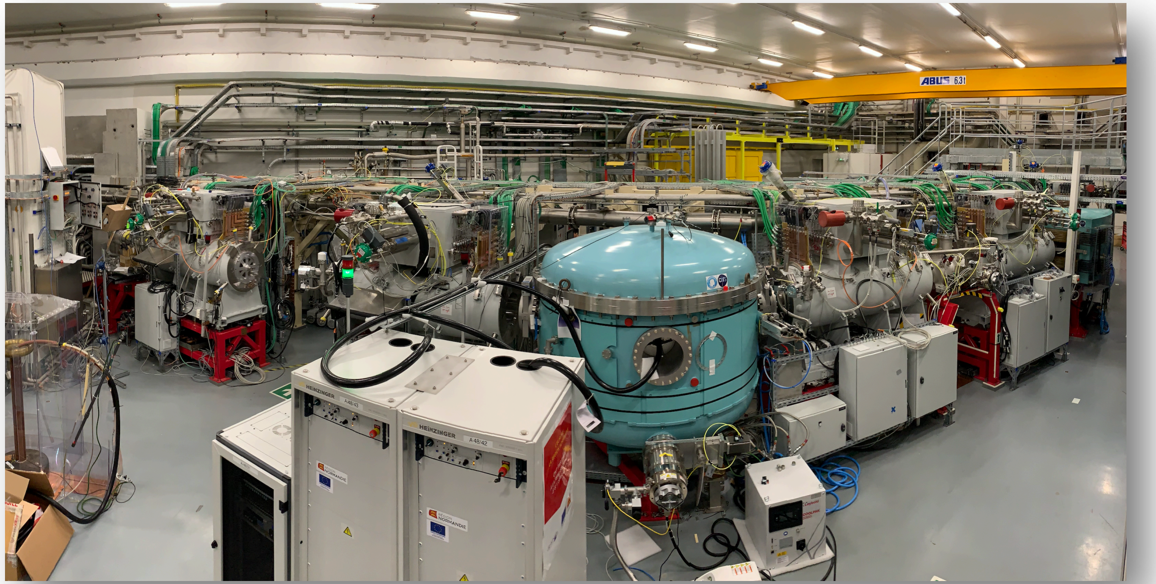
- High selectivity > 10^{13} - High efficiency 50 % - In flight mass separation = 500
- Versatility & unique instrumentation (SIRIUS – LEB)

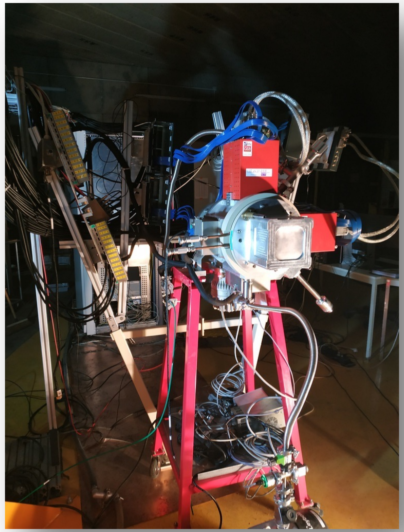
Super Separator Spectrometer

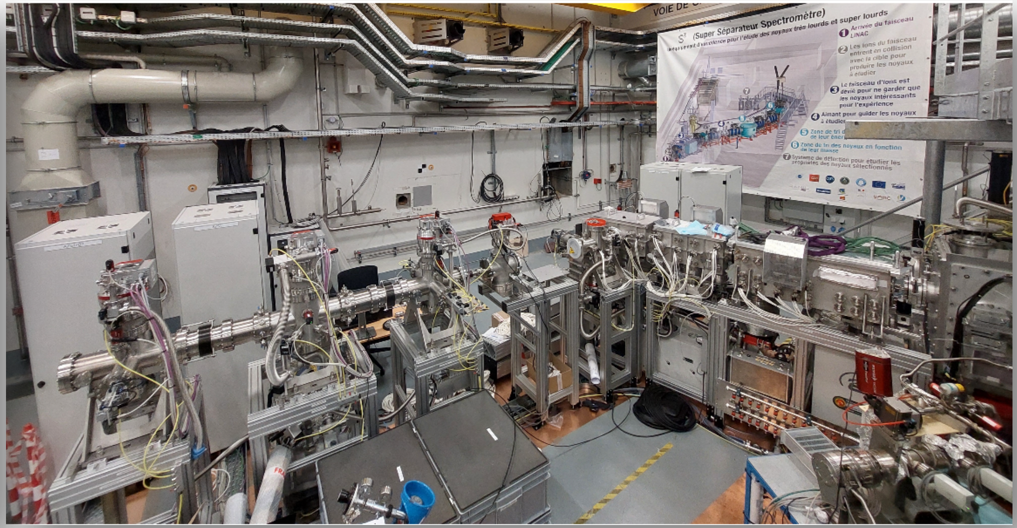
- All major equipments installed
- Cryogenic system tests with 6 SMTs succesfull
- One SMT presents failures : on-going work to repair
- Electric dipole : follow-up of actions to increase high-voltage

- First beam on target : November 21st 2024 !!
- Optical commissioning end 2025

- S^3-SIRIUS (decay spectroscopy of VHE-SHE)
- S^3-LEB (in gas jet laser, mass and decay spectroscopy)





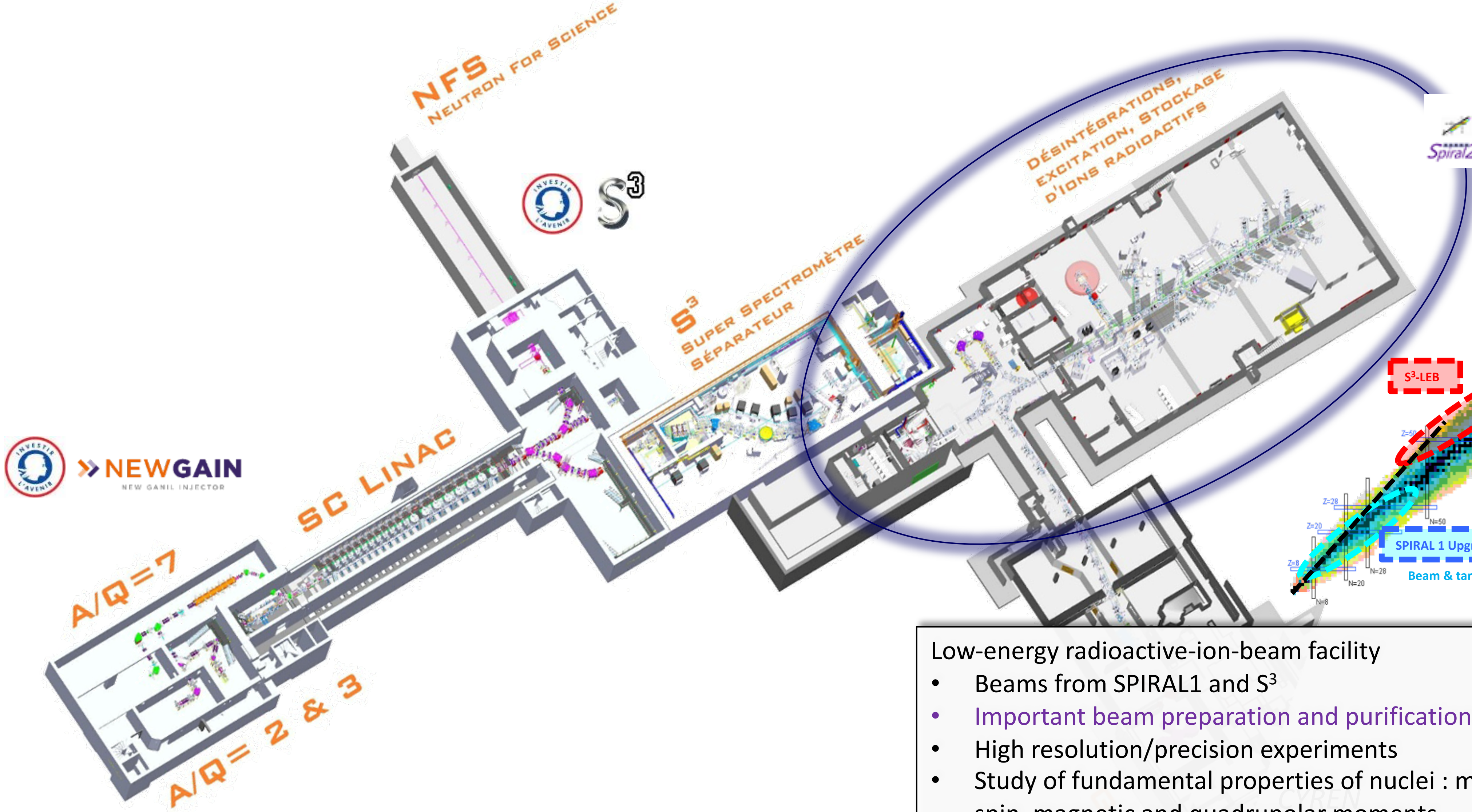


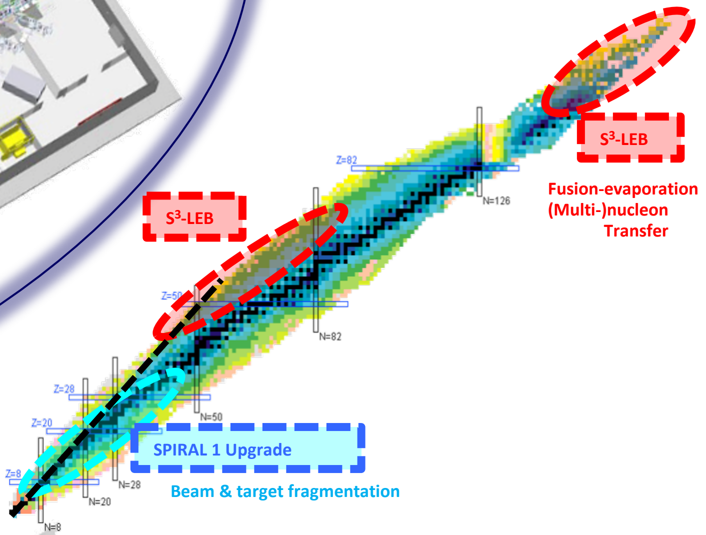
- S^3-LEB moved from LPC to S^3 hall
- New laser lab taking shape
- Perspective online commissioning

2026: Start physics commissioning of S^3

- ^{116}Sn(^{40}Ar, 4n)^{151}Er: Single-particle states and high-spin isomers around the *N = 82* shell closure
- Production of actinium (^{40}Ar + ^{175}Lu and ^{20}Ne + ^{197}Au)
- Production of *N* = *Z* nuclei (^{50}Cr + ^{58}Ni)

DESIR





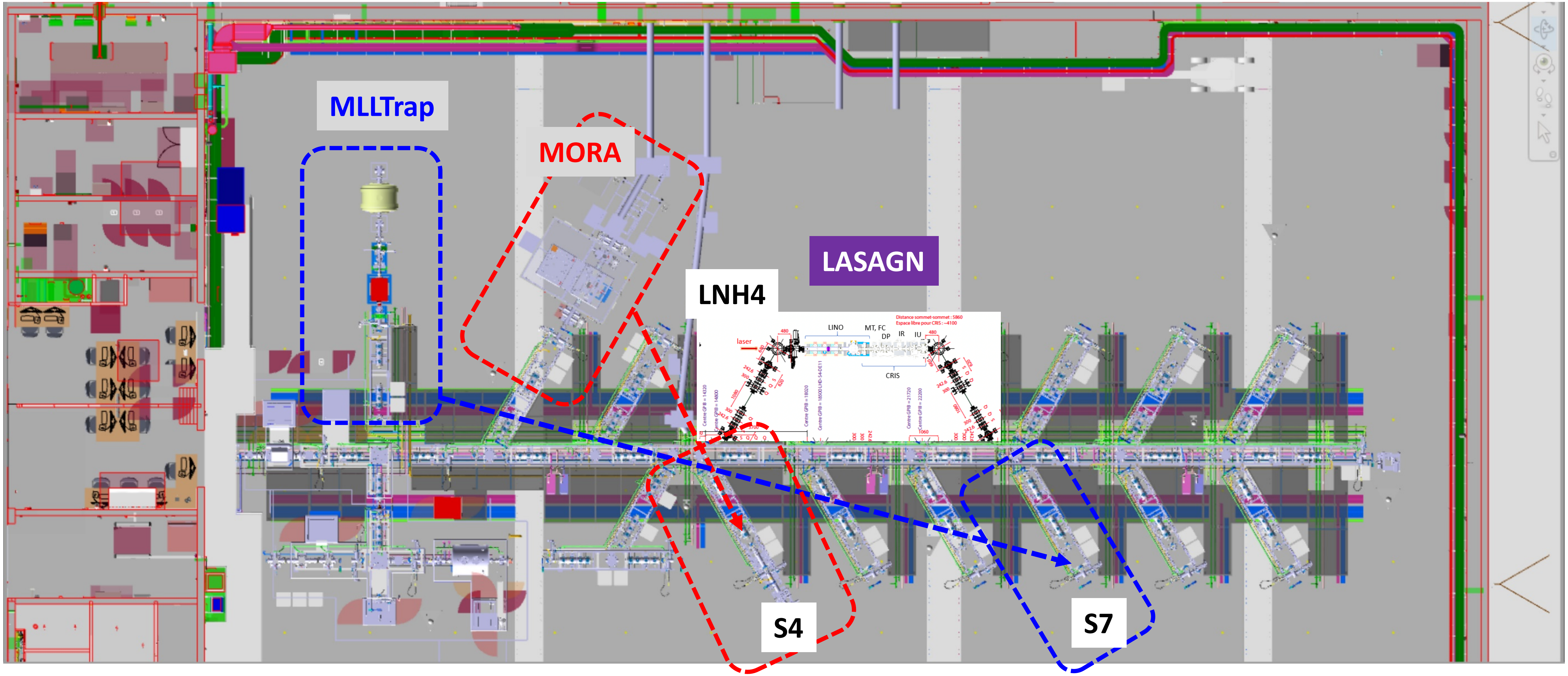
Low-energy radioactive-ion-beam facility

- Beams from SPIRAL1 and S^3
- Important beam preparation and purification capabilities
- High resolution/precision experiments
- Study of fundamental properties of nuclei : mass, life time, decay modes, spin, magnetic and quadrupolar moments
- Nucleosynthesis
- Fundamental interactions, tests of weak interaction standard model

Some pictures on DESIR building site

- Building permit received in June 2023
- Building site inauguration November 10th 2023
- Building infrastructure well advanced
- Building reception 2025
- First test with beam end 2027

Structuration and organization of DESIR experiments



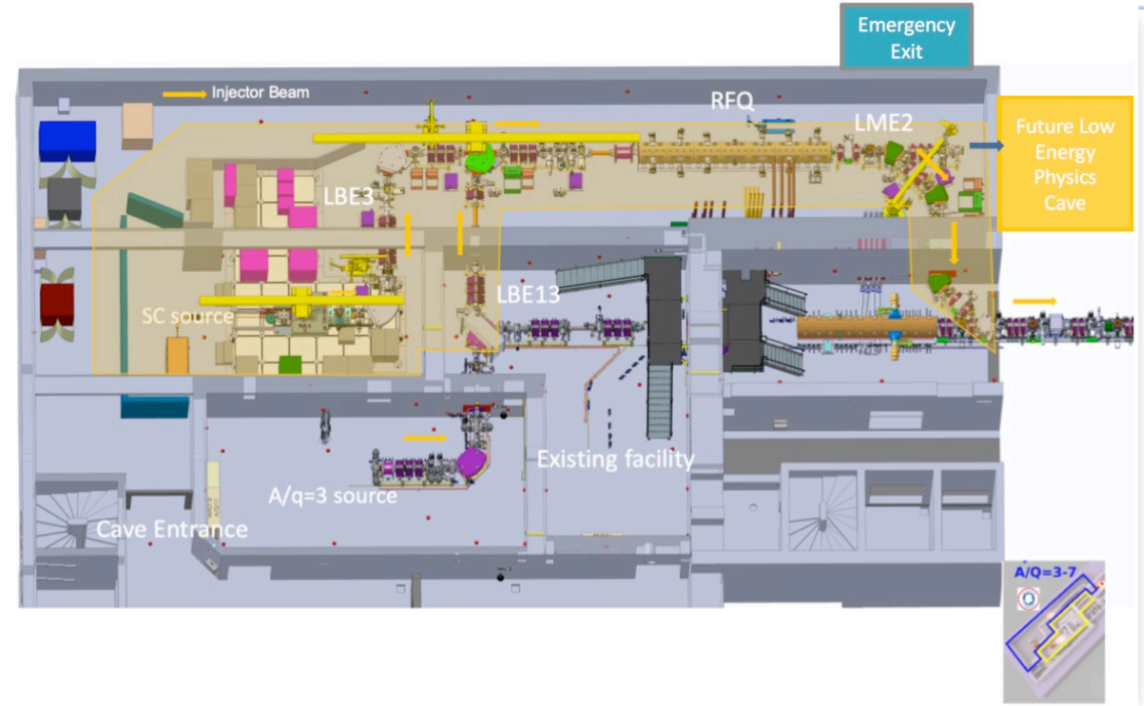
New injector for SPIRAL2: NEWGAIN

NEWGAIN NEW GANIL INJECTOR

GANIL

FRANCE 2030

Floorplan, design intensities and time line



beam intensities	*injector1* *2023*	NEWGAIN *(injector2)* *2028*	*≥ 2030*
Ions	Intensity (pμA) Phoenix V3 RFQ A/Q≤3	Intensity (pμA) Phoenix V3 RFQ A/Q≤7	Intensity (pμA) SC Ion Source RFQ A/Q≤7
^{18}O	80	*	375
^{19}F	>15	>40	>40
^{36}Ar	16	70	45
^{40}Ar	3.6	70	45
^{36}S	2.3	*	*
^{40}Ca	2.9	10	20
^{48}Ca	1.2	10	20
^{58}Ni	1.1	4	**8**
^{84}Kr	0.1	10	**20**
^{139}Xe	0.001	7	**>10**
^{238}U	<<0.001	0.1	**6**

Measured | Estimated

* -> no estimation

NEWGAIN *White Book*

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/accelerators/newgain/

NEWGAIN *time line*

2020	2021	2022	2023	2024	2025	2026	2027	2028

Study Phase → Construction Phase → ***first beam***

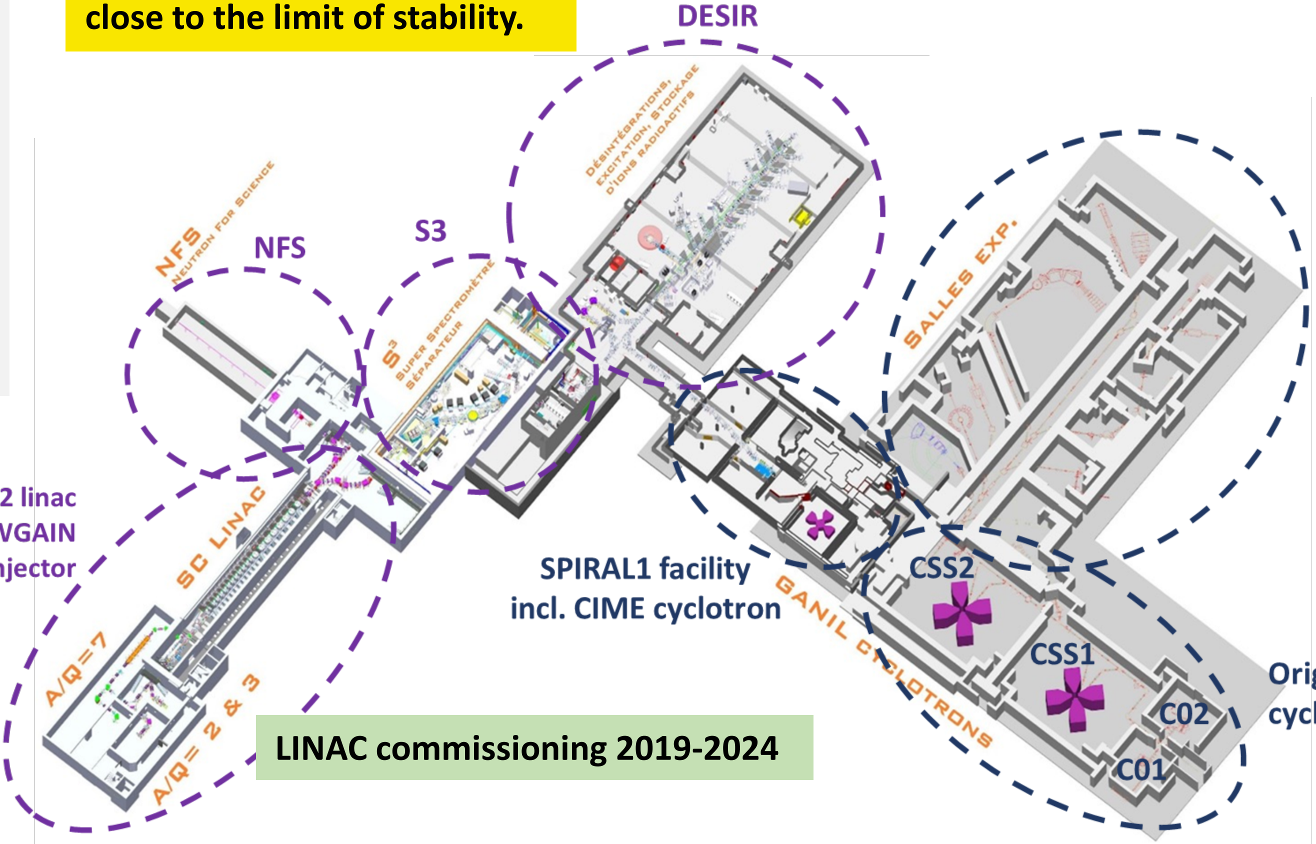
GANIL Spiral2 · IJCLab · IP2I · LPSC Grenoble · IPHC · CENBG · IJCLab

GANIL 2030

Commissioning of the Super Separator Spectrometer (S^3) planned in 2024-2026: nuclei with very low cross sections, such as superheavy elements or neutron deficient nuclei close to the limit of stability.

DESIR in 2027-2028
unique opportunities in terms of exotic nuclei selection and beam purity.
masses, laser spectroscopy, beta-decay spectroscopy, … building construction started in 2023.
First stone ceremony on November 10, 2023

Neutrons for Science (NFS) started operation in 2021. Neutrons produced from protons and deuterons accelerated from the LINAC: mainly fission, but also low-energy excitations, nuclear data,…



AGATA back @ GANIL in 2029

CYREN
Refurbishment of the cyclotrons – by the end of the decade

NEWGAIN, Injector 2:
A/Q =3-7 Increasing beam intensities of heavy (A > 40) and very heavy (Xe, Pb, U) nuclei

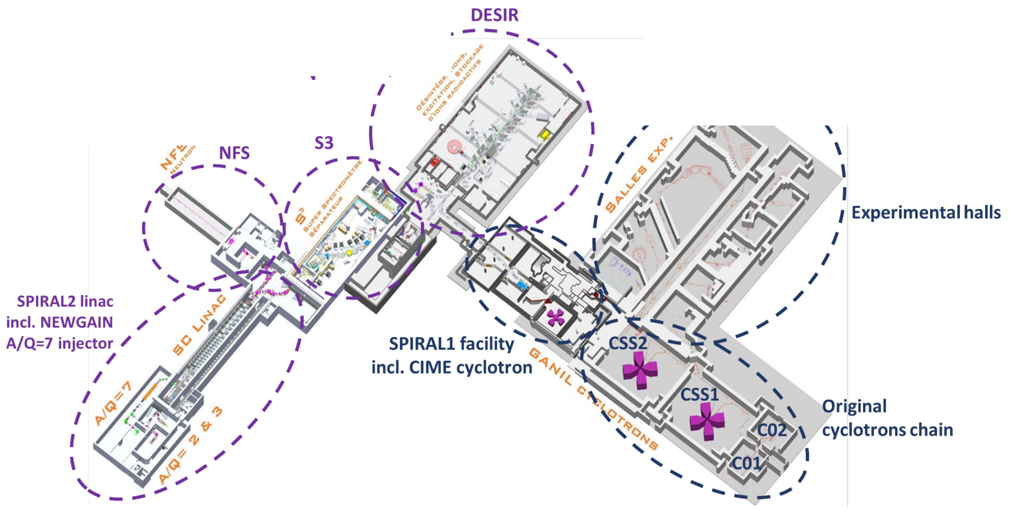
LINAC commissioning 2019-2024

Courtesy M. Grasso

GANIL beyond 2030

International expert committee, chaired by Michel Spiro: vision for the future of GANIL (report provided to CNRS and CEA in December 2021)

Strategy to be defined based on different recommendations and options suggested by the expert committee: new building for production of neutron-rich exotic nuclei, production of radioisotopes, new reacceleration system -> from Coulomb barrier up to 100 MeV/nucleon, ….



On this basis, GANIL direction asked Hanna Franberg and Stéphane Grevy to prepare a document where a few possible scenarios are identified, with:

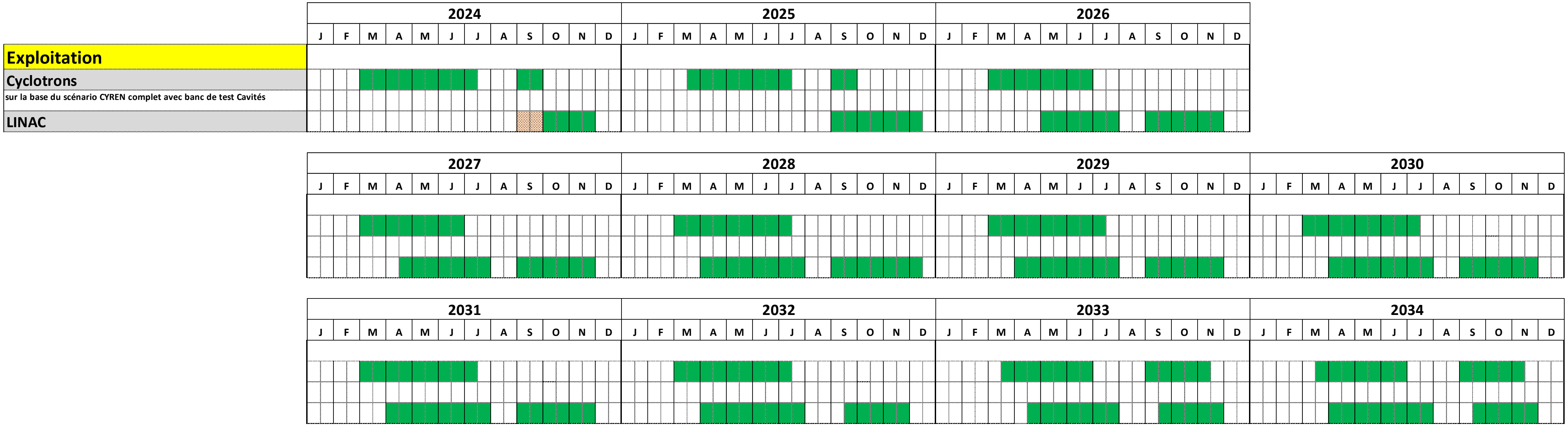
-the description of the physics cases associated with each step

-a budget estimation

CEA and IN2P3 will use this document to establish a strategy

Courtesy M. Grasso

Operation perspectives



18 annual weeks of GANIL cyclotrons operation until 2031

Increasing beam-time for SPIRAL2

Experiments @ SPIRAL2

GANIL

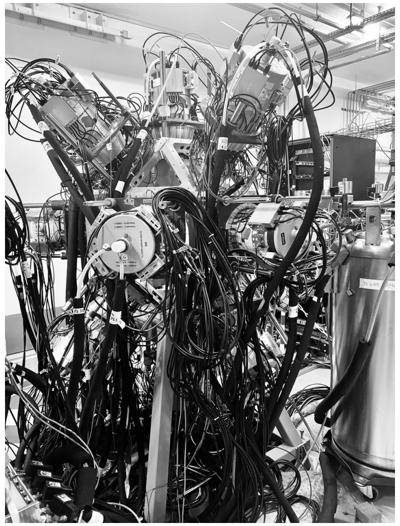
E838_21, E. Clément, EXOGAM in TOF hall

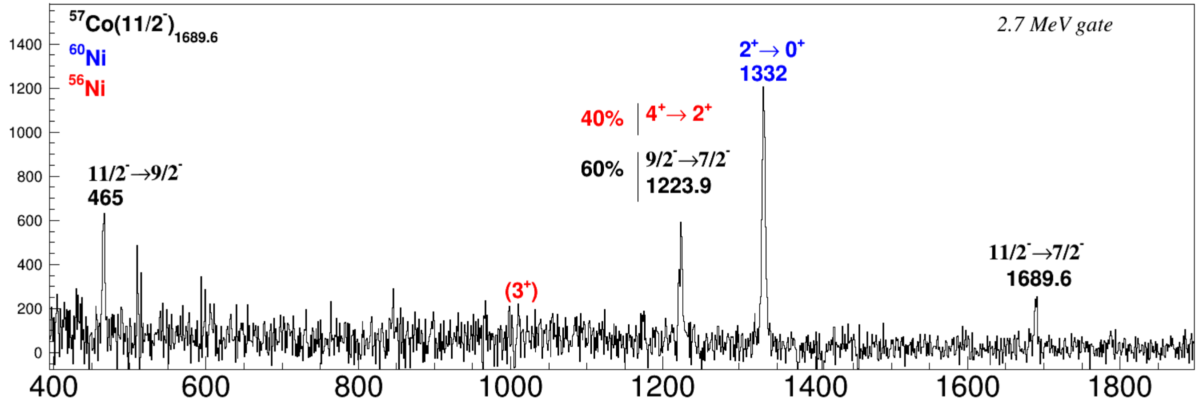
Nuclear stucture

Structure of ^{56}Ni using ^{58}Ni(n,3n) reaction

12 EXOGAM clovers placed at 8.6 meters from the production target around Ni target

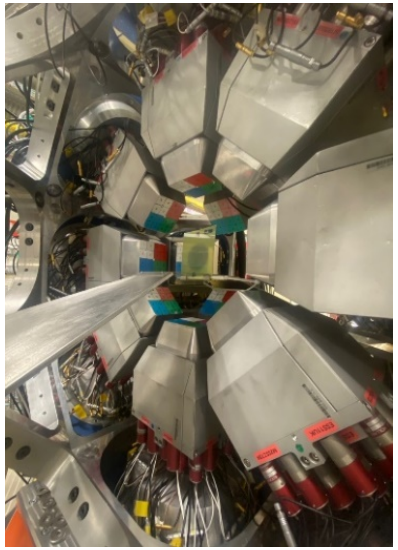
Preliminary





iPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

cea irfu



Tests REPARE, G. De France, converter room

Radioisotope

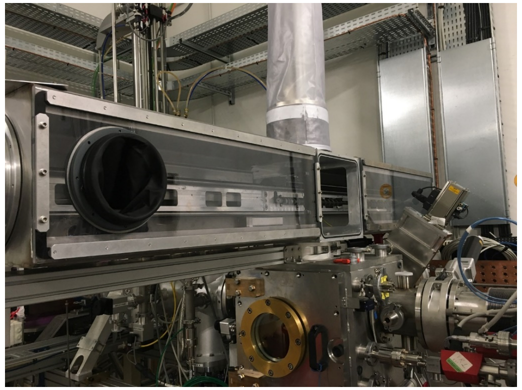
Production of At in NFS converter room with He beam

→ Hardware, soft, beam synchro, vacuum, handling, production yield could be tested
→ but no shipment to ARRONAX…

New beam time in September 2024 : production of At (1 GBq in 3 targets) and shipment to ARRONAX of 2 targets, but At also detected at the SPIRAL2 chimney, outside GANIL authorization (no impact on environment, of the order of nSv)

Subatech

ARRONAX



Experiments @ Cyclotrons

Nuclear structure

GANIL

E869 F. Galtarossa (INFN Legnaro)

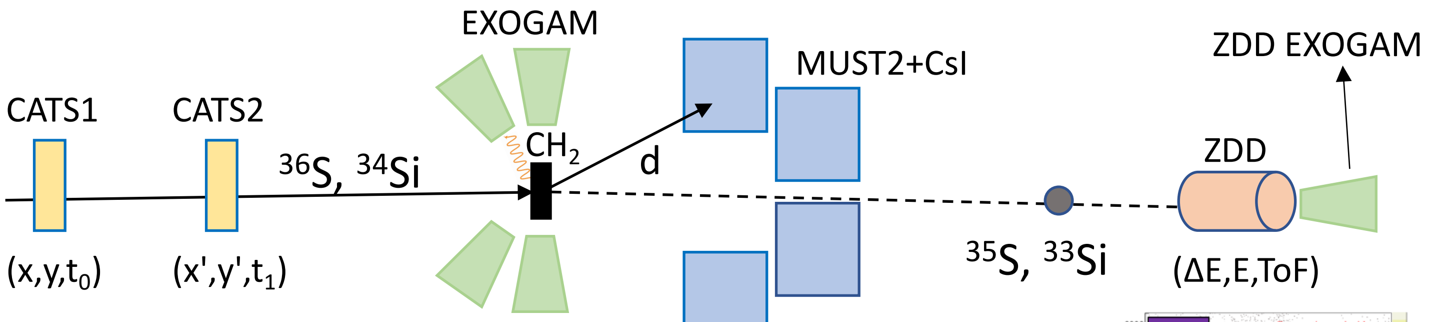
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

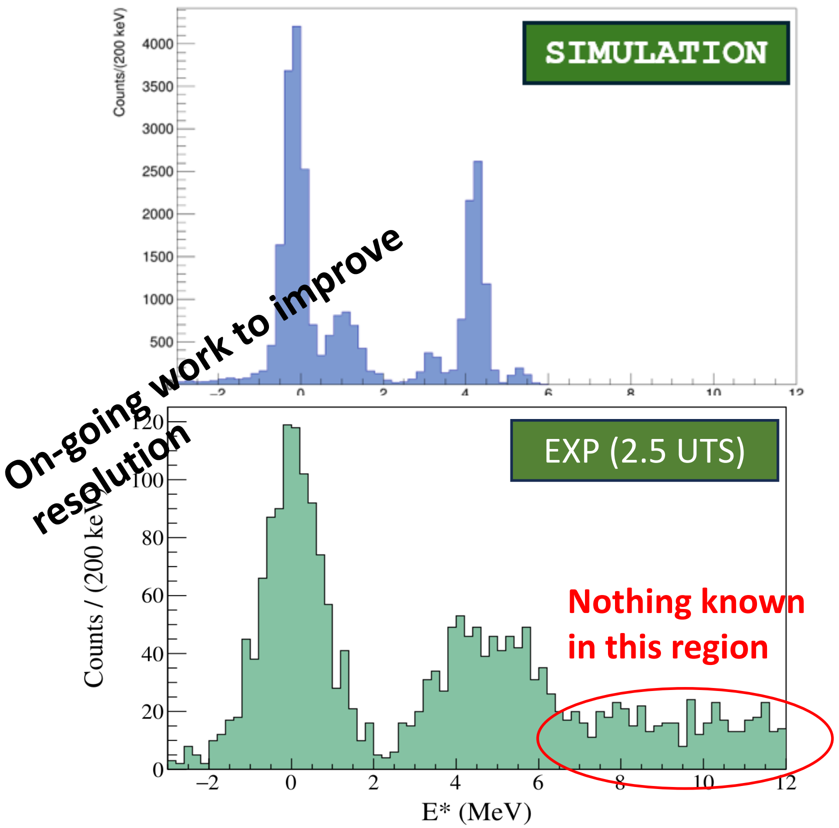
Scientific goal

- Test the spin-orbit component of proton-neutron interaction
- Study the evolution of neutron orbitals in ^{35}S and ^{33}Si

Experimental method

- One-neutron removal in ^{36}S and ^{34}Si on CH_2 target -> (p,d) reaction
- Detection of the light particles with MUST2 and heavy residues (^{35}S, ^{33}Si) in LISE ZDD
- EXOGAM2 to characterize excited states





Preliminary results

- Encouraging in spite of acquisition problems and machine failure (stop of the experiment)

=> experiment will be rescheduled in 2025

NuPECC Long range Plan

Recommendations for nuclear physics infrastructures (heavy ions)

The NuPECC Long Range Plan 2024 resulted in the following main recommendations for infrastructures of importance for nuclear physics:

- The first phase of the international **FAIR** facility is expected to be operational by 2028, facilitating experiments with SIS100 using the High-Energy Branch of the Super-FRS, the CBM cave and the current GSI facilities. Completing the full facility including the **APPA**, **CBM**, **NUSTAR** and **PANDA** programs will provide European science with world-class opportunities for decades and is highly recommended.
- At **GANIL/SPIRAL2** the Super-Separator Spectrometer **S^3** is in an advanced stage of completion and the low-energy **DESIR** facility and heavy-ion injector **NEWGAIN**, will be operational from 2027/28. The refurbishing of the cyclotrons will ensure their operation for the next decades. Timely completion and full exploitation of these GANIL/SPIRAL2 projects is recommended. The plan for a future evolution of the facility towards a very high-intensity reaccelerated RIB facility of up to 100 MeV/u should be actively pursued.
- Nuclear physics opportunities at **CERN** constitute a world-leading research programme. The construction of **ALICE 3** as part of the **HL-LHC** plans is strongly recommended. Continued support for exploitation and new developments are recommended to maximise the scientific output of **ISOLDE**, **n_TOF**, **SPS fixed-target program** and **AD/ELENA**. As the roadmap for the post-LHC future of CERN is developed, a strategy should be prepared to secure future opportunities for continuing world-leading nuclear-physics programmes that are unique to CERN.
- At **ELI-NP** studies will focus on addressing key topics, such as laser-driven ion and electron acceleration. Implementing the gamma beam system to achieve the full completion of the facility to allow breakthrough results in the field of nuclear photonics is of high importance and is strongly recommended.
- Timely completion of the **SPES** facility and continuing coordinated efforts in developing the **ALTO, IGISOL, ISOLDE, SPES, and SPIRAL ISOL facilities** in Europe, will be key to maintaining their world-leading position in many areas of radioactive isotope science and are strongly recommended. Extending these efforts towards future facilities, such as **ISOL@MYRRHA, TATTOOS@PSI,** and **RIB@IFIN**, together with the development of common instrumentation, will secure the European leading position for radioisotope production, separation, and acceleration techniques, and create new avenues for the future and should therefore be actively pursued.
- The exploitation of large-scale **stable beam** facilities, such as **FAIR/GSI, GANIL/SPIRAL2, IFIN, JYFL-ACCLAB, LNL, LNS, NLC (SLCJ and IFJ-PAN),** and smaller ones, such as tandems, underground facilities and AMS systems, should be maximised. It is recommended that synergies between all these facilities, irrespective of size, be reinforced. Developments of novel and more intense beams and capabilities are also recommended to open new opportunities for basic science and applications.
- It is strongly recommended to complete the **AGATA** gamma tracking array to its full configuration as a key instrument for studying atomic nuclei in both stable and radioactive ion beam facilities.