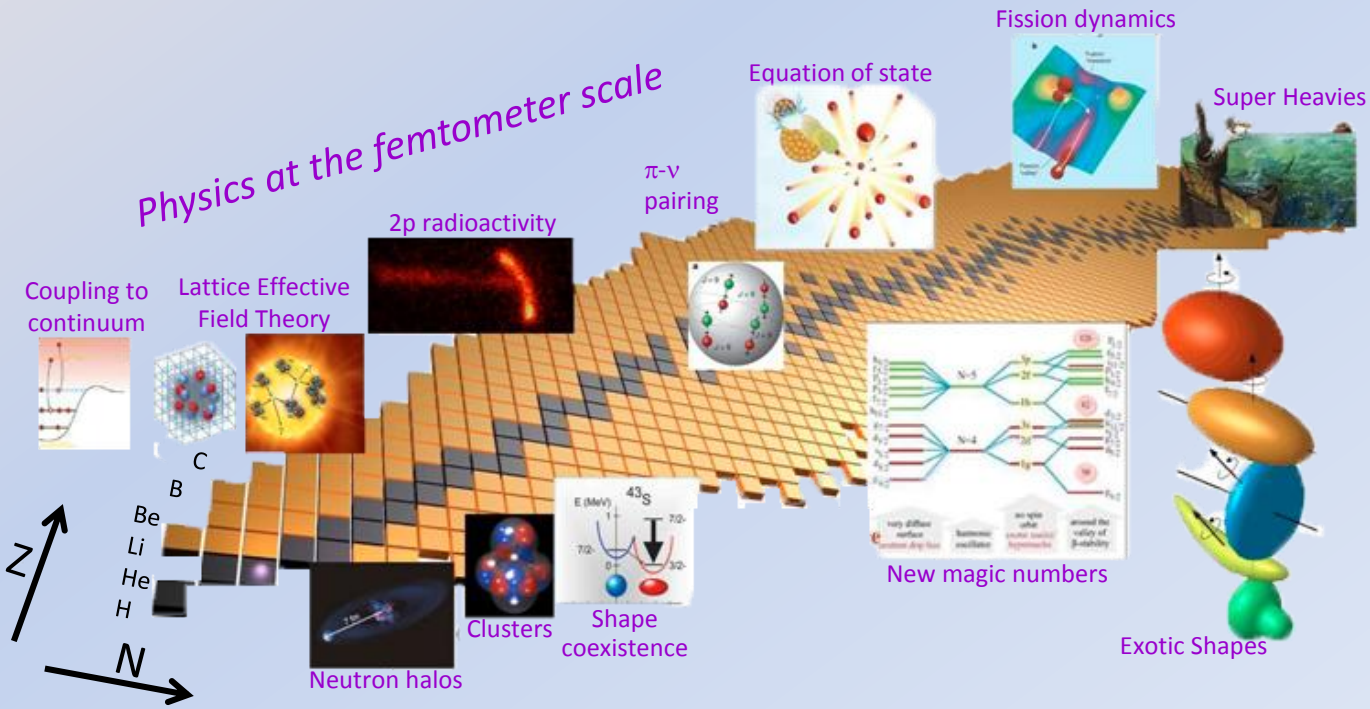
GANIL : present and short term activities of cyclotrons

Conseil Scientifique de l'IN2P3 - 26 juin 2019

Stéphane Grévy



GANIL : present and short term activities of cyclotrons

❑ Outlook

Key questions in nuclear physics that are adressed using the GANIL cyclotrons

The GANIL-cyclotrons facility and the associated experimental setups

- Variety of beams
- Experimental setups : spectrometers and detectors

Scientific highlights and perspectives

- Nuclear astrophysics
- Nuclear structure
  - Evolution of the shell structure
    - *using transfer reactions*
    - *using Coulomb excitation*
    - *using "in beam" gamma spectroscopy*
  - Study of exotic decays
- Study of fission mechanisms
- Study of reaction mechanisms
- Other GANIL physics with the cyclotron beams
  - Other γ-spectroscopy studies
  - Interdisciplinary researches
  - Industrial applications

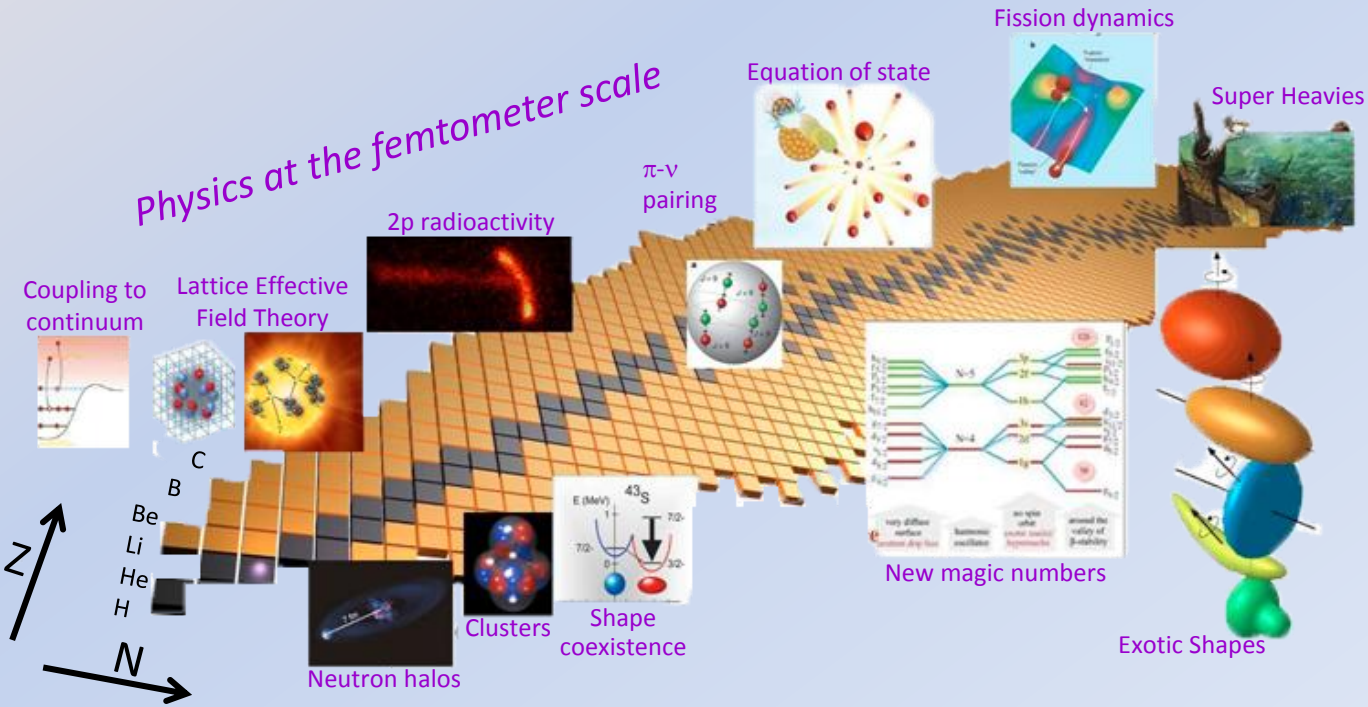
Beam time / number of users

Implication of french community

GANIL : present and short term activities of cyclotrons

❑ Key questions in nuclear physics that are adressed using the GANIL cyclotrons

THEMATICS	
- Fundamental Interactions	➢ What are the limits of the Standart Model?
- Nuclear astrophysics	➢ How are synthetized the chemical elements in the universe ? What are the mechanisms responsible of the explosion of stars in SN ?
- Nuclear structure - Super heavy nuclei	➢ How change the shell effects (magic numbers, shapes) ? What are the limits in isospin and mass ?
- Reaction mechanism	➢ What is the equation of state of the nuclear matter How to obtain a microscopic description of the fusion, fission and nuclear reactions ?



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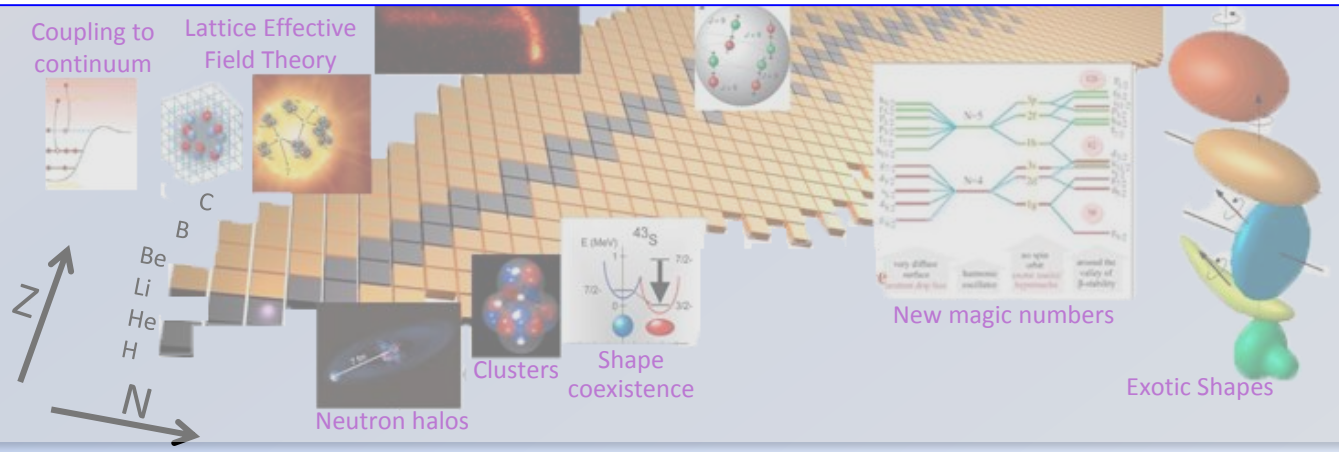
- Nuclear structure
- Super heavy nuclei
  - ➢ How change the shell effects (magic numbers, shapes) ?
    What are the limits in isospin and mass ?

- Illustrate *some* of these questions with highlights, recent works (non published) and perspectives
- From the french community (leader or in collaboration)
- Typical examples illustrating the "GANIL cyclotrons" strenghts (beams, spectrometers, detectors)
- Non exhaustive of the experimental work performed at GANIL !!



GANIL : present and short term activities of cyclotrons

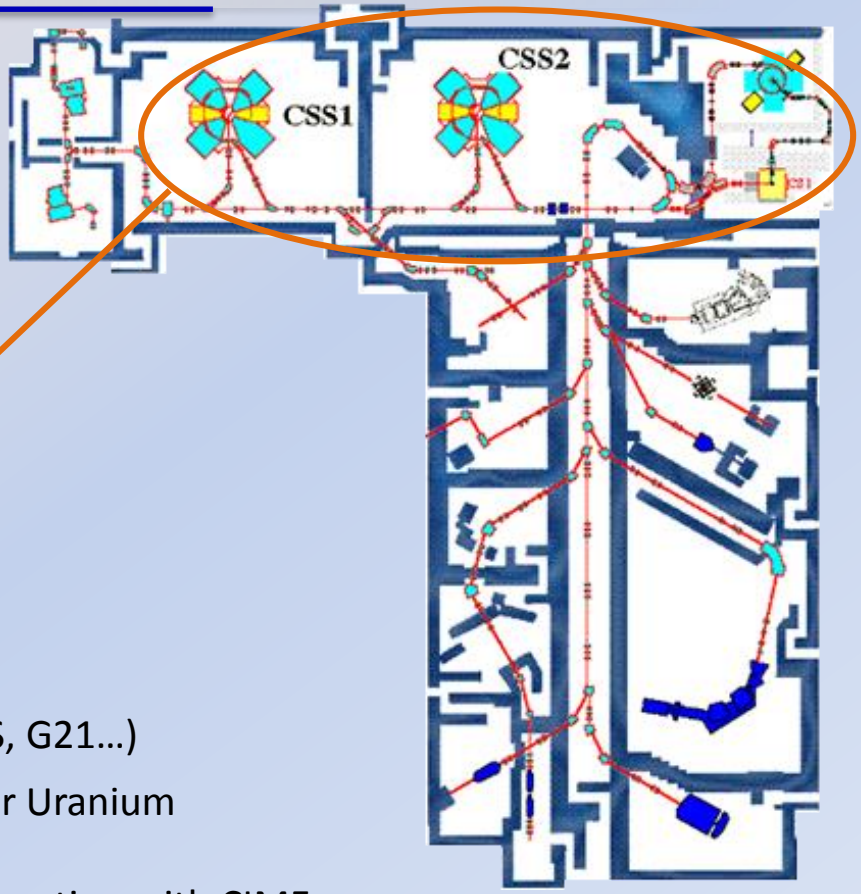
❑ The GANIL/cyclotrons facility and the associated detectors

THEMATICS

- Nuclear astrophysics
- Nuclear Structure (shell evolution and exotic decays)
- Study of fission mechanisms
- Study of reaction mechanisms
- Other studies

BEAMS

- Stable CSS1 / CSS1+CSS2
- ISOL Spiral1 + CIME
- Fragmentation LISE



Stable beams :

→ large diversity : Carbon to Uranium
→ high intensities : up to tens of µA

CSS1 : up to few MeV/u

→ studies at the Coulomb barrier (VAMOS, G21…)

CSS1+CSS2 : up to 95 MeV/u for Carbon, 35 MeV/u for Uranium

→ projectile fragmentation in LISE
→ ISOL production in SPIRAL1 / post acceleration with CIME
→ reaction mechanism studies with INDRA/FAZIA
→ interdisciplinary researches
→ industrial applications

Upgrade of SPIRAL1 (2012-2019) → use of new beam/target combination
→ use of a FEBIAD source
→ Developement of the 1+/N+ booster

} enlarge the variety of ISOL beams

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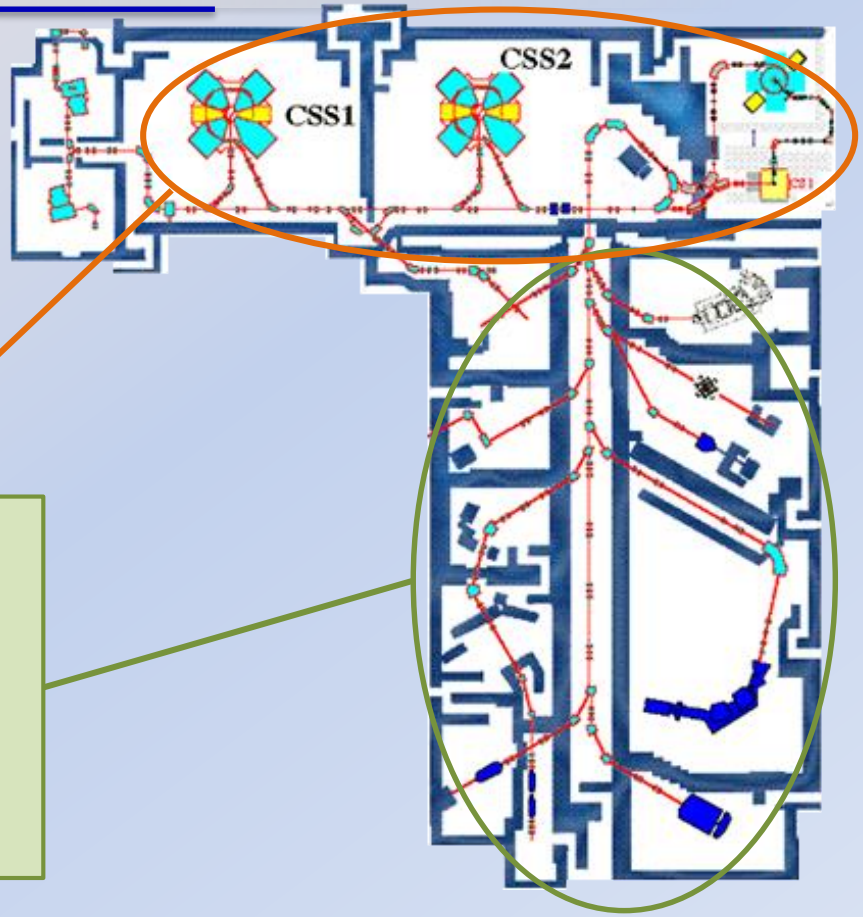
ROOMS & SPECTROMETERS

- D1 → Interdisciplinary researches
- D5 → INDRA/FAZIA
- D6 → LISE spectrometer
- G1 → VAMOS spectrometer
- G2 → multi purpose room
- *G3 → SPEG (actually not used)*
- G4 → industrial applications



LISE
- → stable beams from 5 to 95 MeV/u
- → production of radioactive beams by fragmentation (15-50 MeV/u - possibly polarized)
- → selection by Bρ-ΔE-Bρ-velocity filter / identification ΔE-TOF-tracking
- → radioactive SPIRAL1 beams (stripper foil for purification)

VAMOS
- → Stable beams around Coulomb Barrier energies
- → Large Acceptance Magnetic Spectrometer
- → Complete Isotopic Identification ΔA/A = 1/500 and ΔZ/Z ~1/70
- → Spiral1 Radioactive Ion Beams (5-10 MeV/u)

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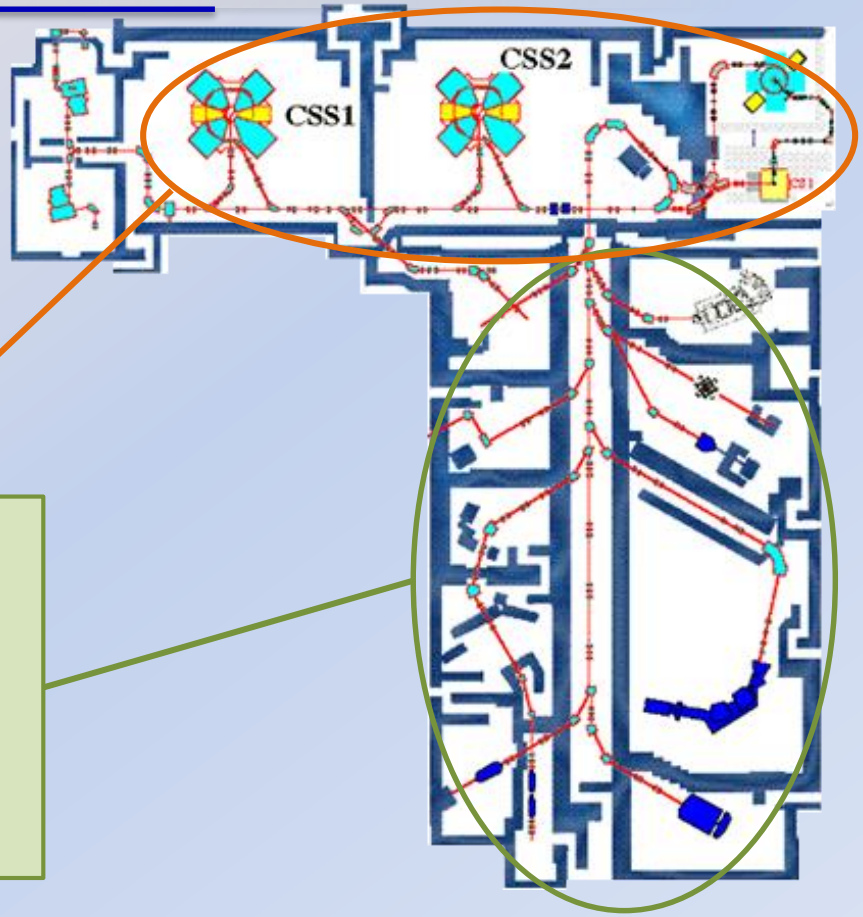

LISE upgrades

→ better identification : use of TOF detectors (CATS, CAVIAR….)
→ better selection and focalisation in D6 : new triplet of quadrupoles in D6 (2015-2018)
→ Zero degree detection : identification of the ejectile (2019-…)

VAMOS upgrades

→ increase the acceptance : larger focal plane detectors (2015)
→ increase the kinematic reconstruction : time detector after the target (2017)
→ increase the counting rate capabilities : digital electronics (2018)

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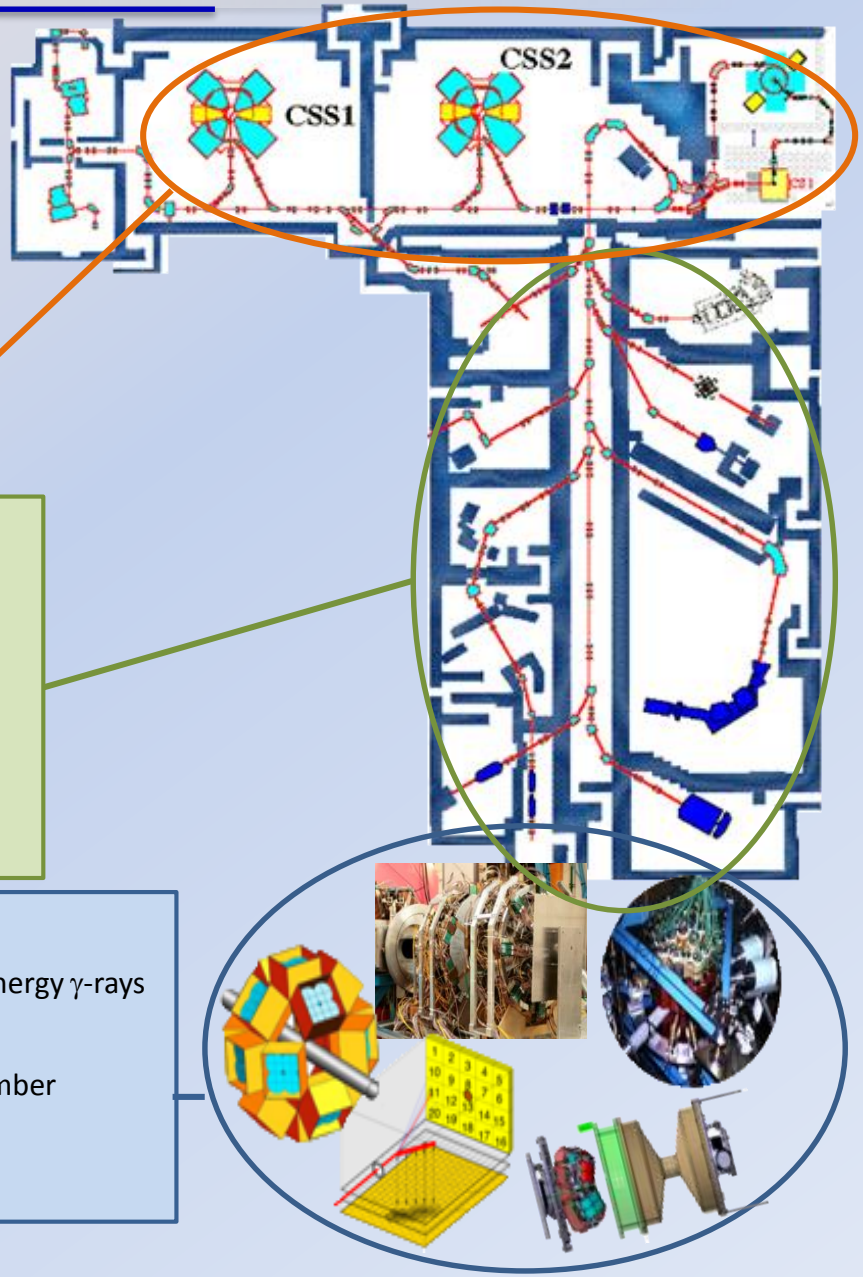
DETECTION SYST.

- AGATA/Exogam2 : high resolution γ-rays
- PARIS/Château de cristal : high efficiency/energy γ-rays
- MUGAST/Must2 : light charged particles
- ACTAR-TPC : active target / time projection chamber
- INDRA-FAZIA : 4π charged particles
- NWall/NEDA : neutron detectors



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Beam time / number of users

Implication of french community

F. De Grancey et al,
PLB, 758, 26-31. (2016)

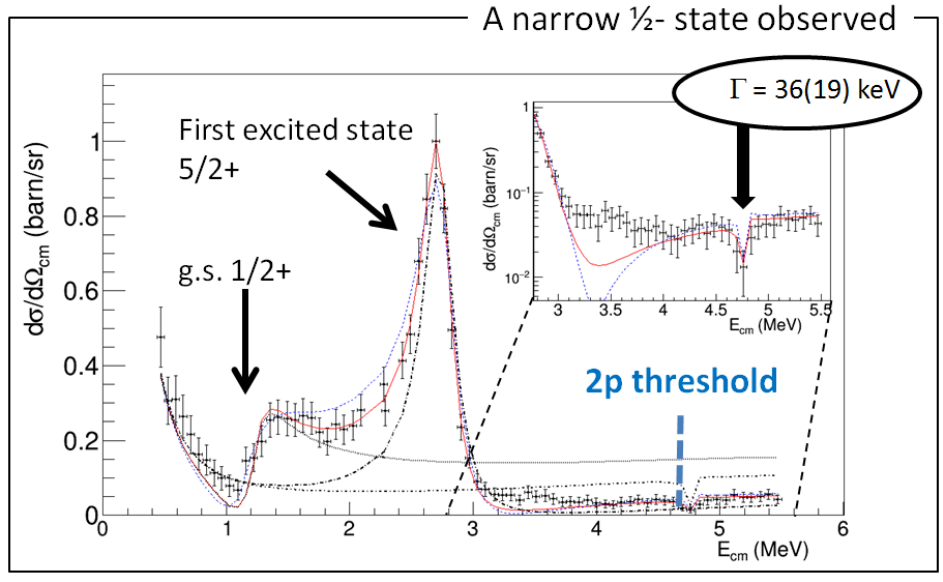
Nuclear astrophysics

General motivations :

- Study of key reaction to understand the astrophysical processes

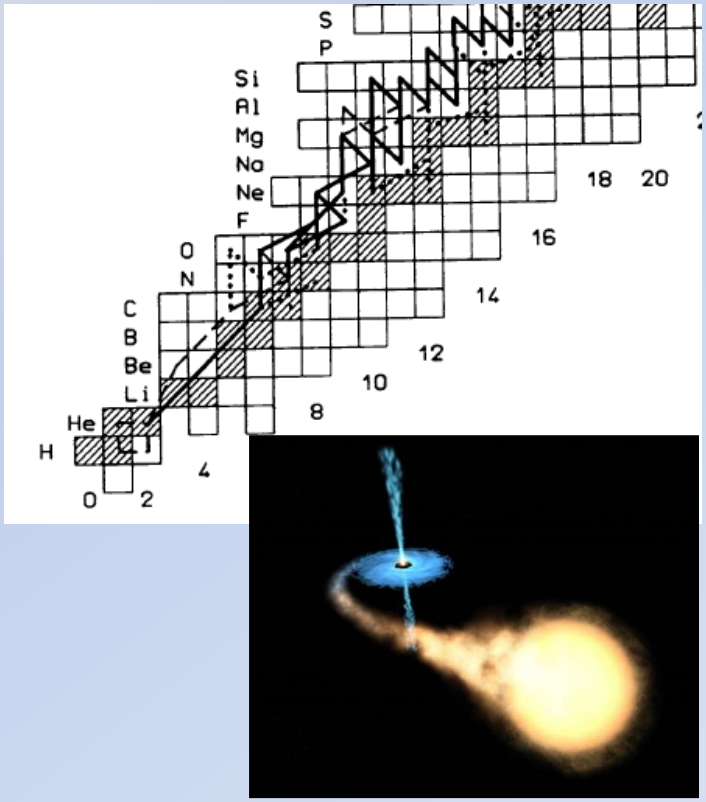
→ Elastic resonant scattering in inverse kinematics using **intense SPIRAL1 beamsc**

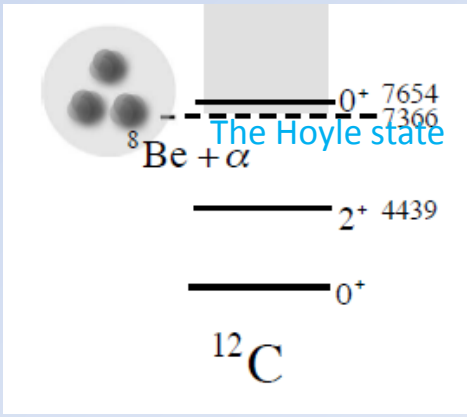
^{15}F studied with ^{14}O(p,p)^{14}O



Unexpected ½- narrow resonance
just above the 2p threshold Q_{2p} = 129 keV

$E_R = 4.757(6)(10)$ MeV $\Gamma = 36(5)(14)$ keV



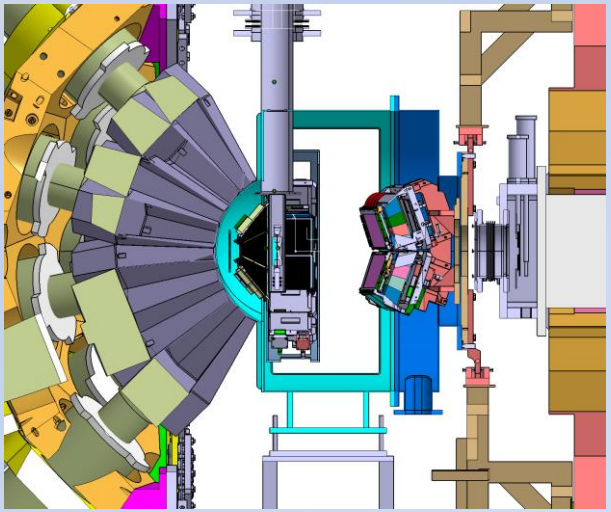


Generalized Ikeda conjecture: the coupling to a nearby cluster decay channel induces cluster correlations

Nuclear astrophysics

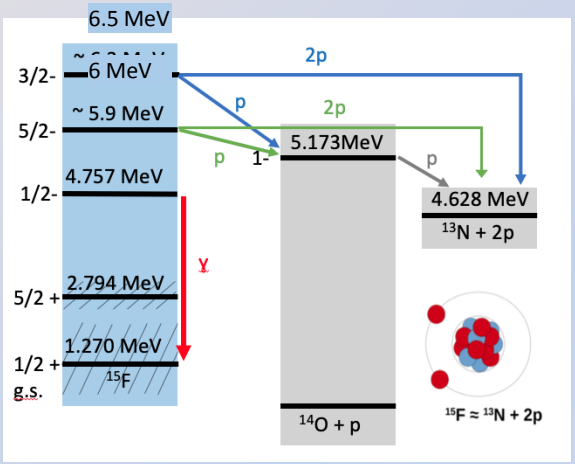
Study of ^{15}F by ^{14}O+p reaction

AGATA MUGAST VAMOS



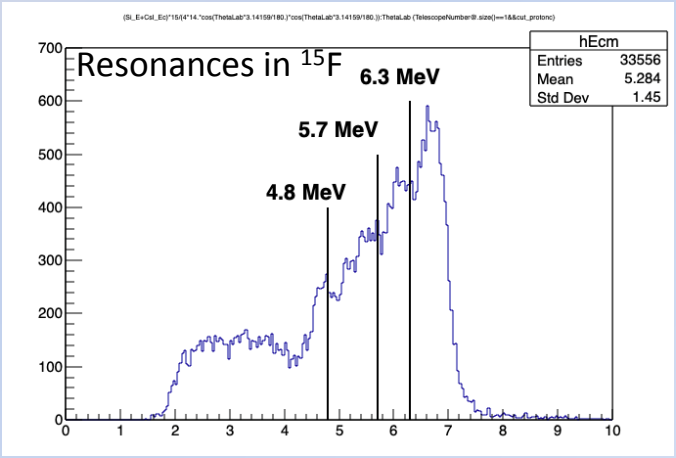
General motivations :

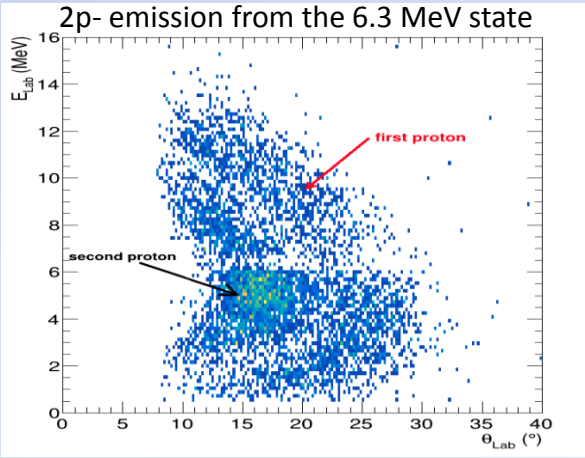
- Study of key reaction to understand the astrophysical processes
- Study of cluster states



Goals of the experiment :

- Measure new states in ^{15}F
- Observe two proton emission from those new states
- Observe the possible gamma emission from the 1/2- to the ground state





❑ Perspectives for nuclear astrophysics

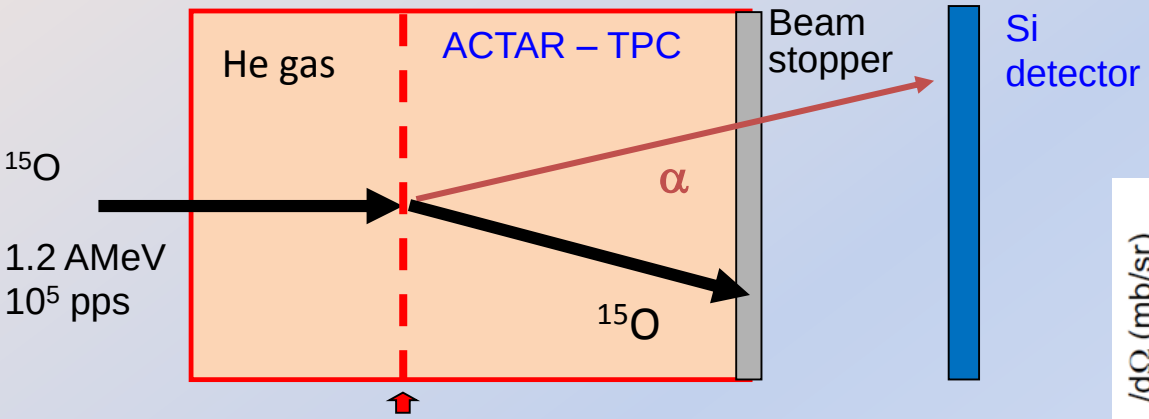
X-ray burst: several important reactions

→ direct measurement of **^{14}O(α,p)^{17}F** with ACTAR-TPC

Emission of 511 keV transitions in novae explosions

most important reaction ^{18}F(p,α)^{15}O

→ direct measurement of **^{15}O(α,α)^{15}O** with ACTAR-TPC



Exact position measurement

- Background suppression
- Identify / remove Inelastic processes
- If Resolution=1mm/length=20 cm

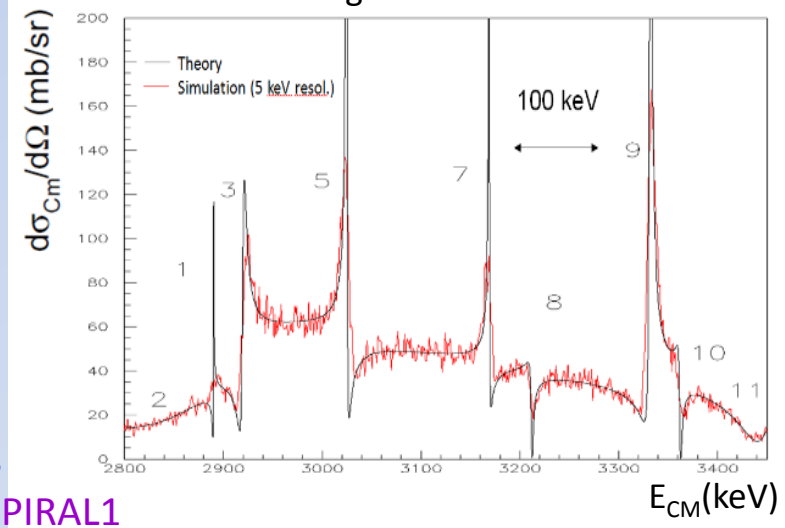
→ resolution CM < 5 keV ∀ **angle**

REACTIONS THAT IMPACT THE BURST LIGHT CURVE IN THE MULTI ZONE X-RAY BURST MODEL.

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	^{15}O(α,γ)^{19}Ne	D	16	1
2	^{56}Ni(α,p)^{59}Cu	U	6.4	1
3	^{59}Cu(p,γ)^{60}Zn	D	5.1	1
4	^{61}Ga(p,γ)^{62}Ge	D	3.7	1
5	^{22}Mg(α,p)^{25}Al	D	2.3	1
6	^{14}O(α,p)^{17}F	D	5.8	1
7	^{23}Al(p,γ)^{24}Si	D	4.6	1
8	^{18}Ne(α,p)^{21}Na	U	1.8	1
9	^{63}Ga(p,γ)^{64}Ge	D	1.4	2
10	^{19}F(p,α)^{16}O	U	1.3	2
11	^{12}C(α,γ)^{16}O	U	2.1	2
12	^{26}Si(α,p)^{29}P	U	1.8	2
13	^{17}F(α,p)^{20}Ne	U	3.5	2
14	^{24}Mg(α,γ)^{28}Si	U	1.2	2
15	^{57}Cu(p,γ)^{58}Zn	D	1.3	2
16	^{60}Zn(α,p)^{63}Ga	U	1.1	2
17	^{17}F(p,γ)^{18}Ne	U	1.7	2
18	^{40}Sc(p,γ)^{41}Ti	D	1.1	2
19	^{48}Cr(p,γ)^{49}Mn	D	1.2	2

[a] Up (U) or down (D) variation that has the largest impact
[b] $M_{LC}^{(i)}$ in units of 10^{38}ergs/s

Simulation of high resolution measurement



Experimental program based on the GANIL cyclotons strengths

→ variety and intensity of radioactive ion beams : SPIRAL1

→ *ideal* beam energies

→ use of ACTAR-TPC

GANIL : present and short term activities of cyclotrons

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Beam time / number of users

Implication of french community

G. Burgunder et al, PRL1125(2014)042502

Evolution of the shell structure

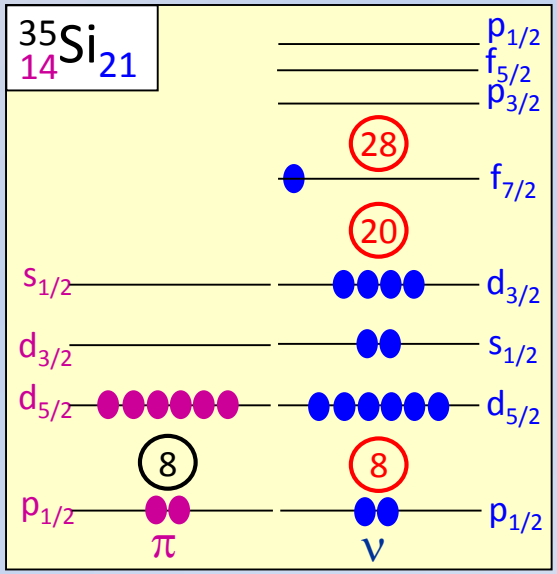
Spectroscopy of ^{35}Si by ^{34}Si(d,p) transfer reaction

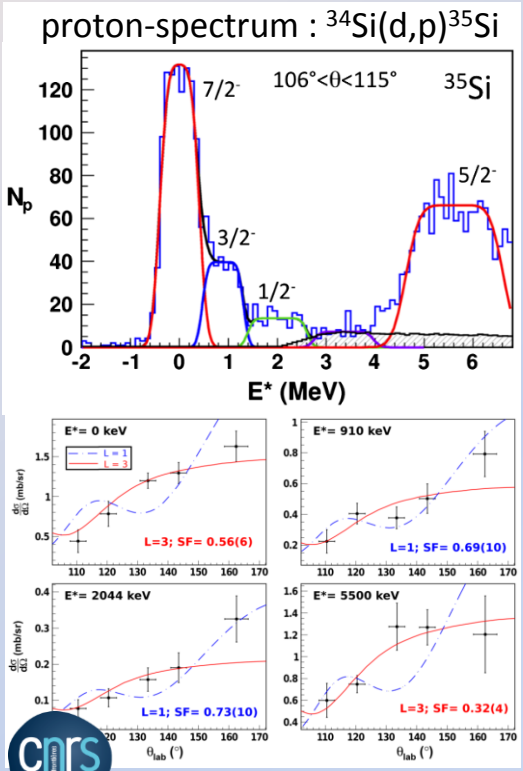
PRL 112, 042502 (2014) PHYSICAL REVIEW LETTERS week ending 31 JANUARY 2014

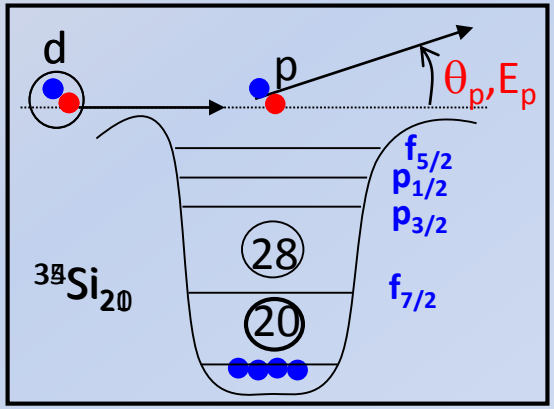
Experimental Study of the Two-Body Spin-Orbit Force in Nuclei

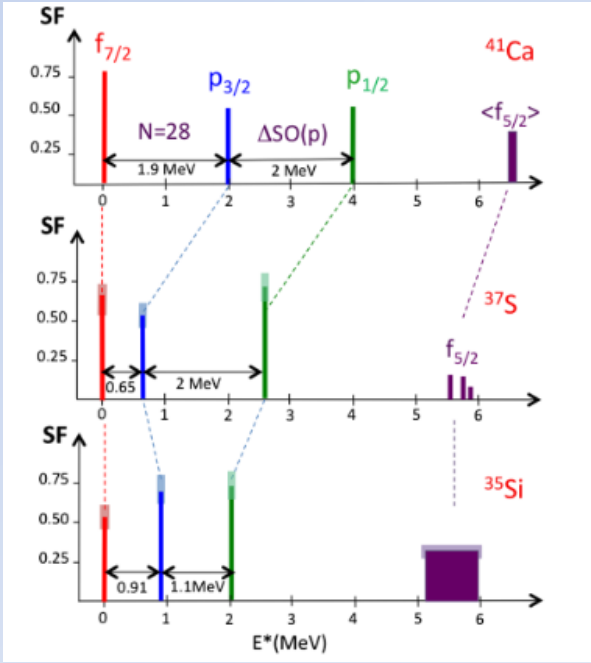
Goals of the experiment : Study of N=28

- by measuring the E* and SF of the first excited states in ^{35}Si
  → (d,p) transfer reaction
- By quantifying the evolution of the $f_{7/2}$-$f_{5/2}$ and $p_{3/2}$-$p_{1/2}$ spin orbit slitting between between Ca and Si isotopes









Evolution of the shell structure

Spectroscopy of ^{17}C by ^{16}C(d,p) transfer reaction

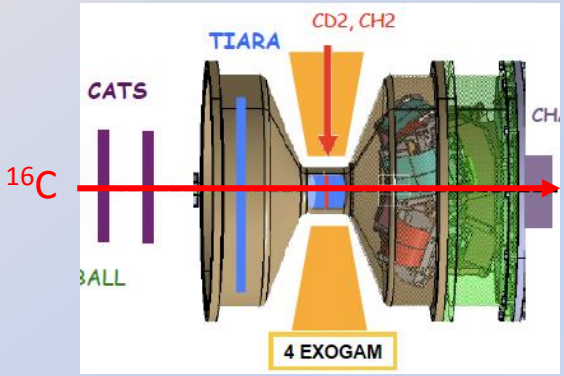
General motivations :

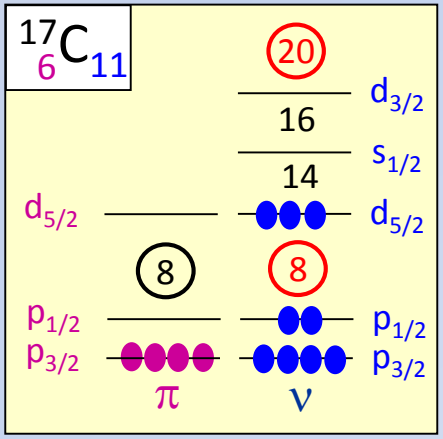
- Study of the N=14 and 16 shell evolution
- Search for a halo candidate in ^{17}C

Goals of the experiment :

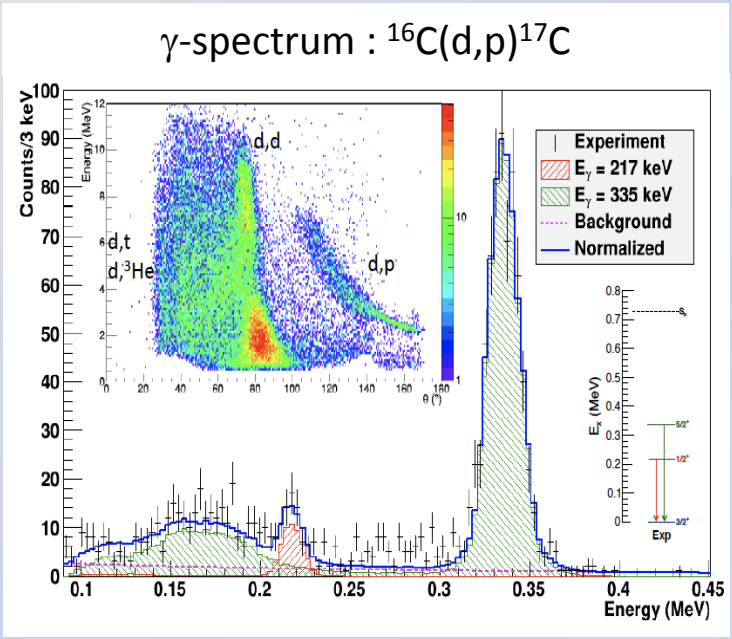
- Measure the E* and SF of the first excited states in ^{17}C

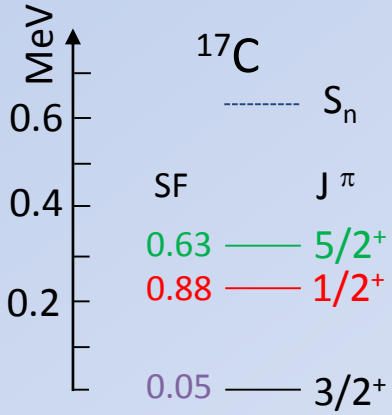
→ (d,p) transfer reaction





γ-spectrum : ^{16}C(d,p)^{17}C





Two states with large SF values from $d_{5/2}$ and $s_{1/2}$ orbits

→ reduction of the N=14 gap

The $1/2^+$ has a large spectroscopic factor

→ good candidate for a halo structure

S. Calinescu et al, PRC93(2016)044333

❑ Evolution of the shell structure

Coulomb excitation of ^{46}Ar

General motivations :

- Study of the shells evolution and deformation

Goals of the experiment :

- Measure the reduced transition probabilities B(E2)

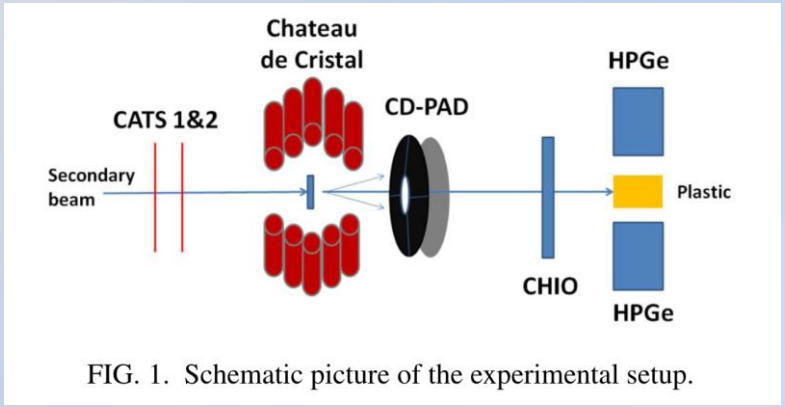


FIG. 1. Schematic picture of the experimental setup.

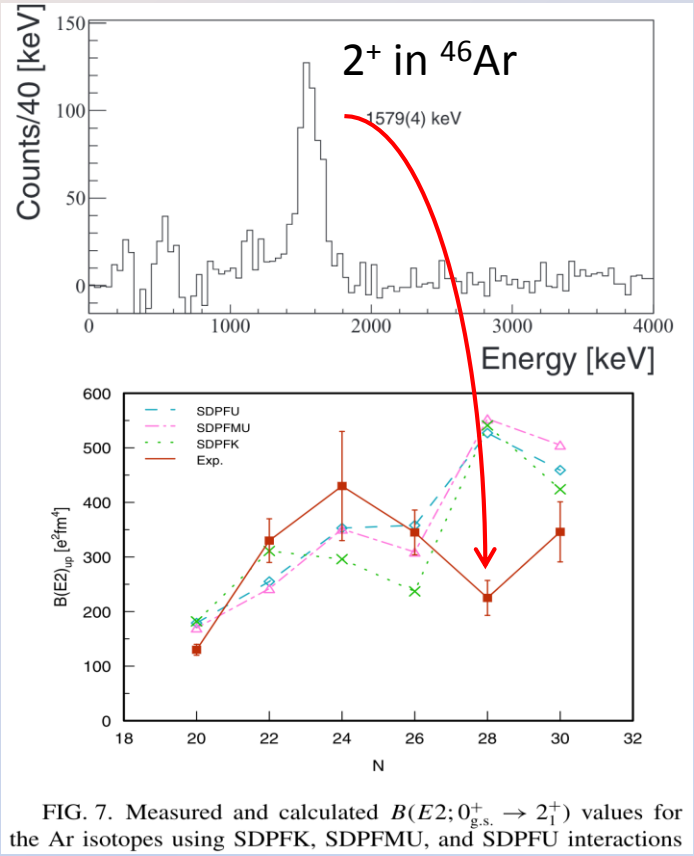
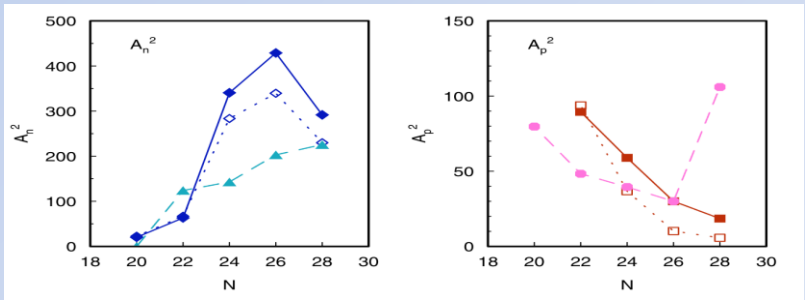


FIG. 7. Measured and calculated $B(E2; 0^+_{g.s.} \rightarrow 2^+_1)$ values for the Ar isotopes using SDPFK, SDPFMU, and SDPFU interactions

Discrepency between experiment and shell model calculations

→ insight on the role of the protons in the developement of the deformation at N=28



→ New transfert experiment at GANIL ^{46}Ar(^{3}He,d) (2019)

SPIRAL1 ^{46}Ar beam on cryogenic ^{3}He target

VAMOS+MUGAST+AGATA

(campaign 2019-2020)

Evolution of the shell structure

Perspectives for transfer reactions and Coulomb excitation experiments with RIB

Experimental campaigns based on the GANIL cyclotons strengths

→ variety of radioactive ion beams : LISE and SPIRAL1
→ *ideal* beam energies
→ availability of powerful charged particles and gamma arrays { γ : EXOGAM2/AGATA-PARIS ; pc : MUST2/MUGAST }

Exemple of possible experiments

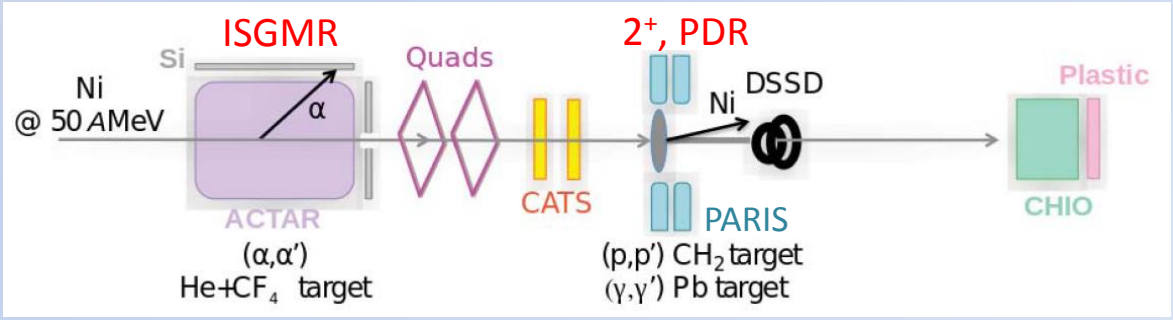
- Beams of nuclei around ^{56}Ni produced by SPIRAL1
  → evolution of shell closure in N=Z nuclei, pairing…

- Beams around ^{68}Ni produced by LISE
  → recent SM calculation for a new "island of inversion between ^{68}Ni and ^{78}Ni

F. Nowacki et al., Phys. Rev. Lett. 117, 272501

- Beam of ^{34}Si produced by LISE
  → study of the developement of the deformation between ^{36}S and ^{32}Mg
  → study of the compression modes in the "bubble" nucleus ^{34}Si

Campaign combining study of soft and giant modes in exotic nuclei (‘brochette’ mode)



Transfer experiments (MUST2/MUGAST) in combination with ACTAR – TPC :
e.g. perform (d,^{3}He) and (p,d) or (p,t) reactions in the same experiment

- Nuclear astrophysic
- Nuclear structure
- Study of the fission mechanism
- Other studies

- Stable CSS
- ISOL Spiral1/CIME
- Fragmentation LISE

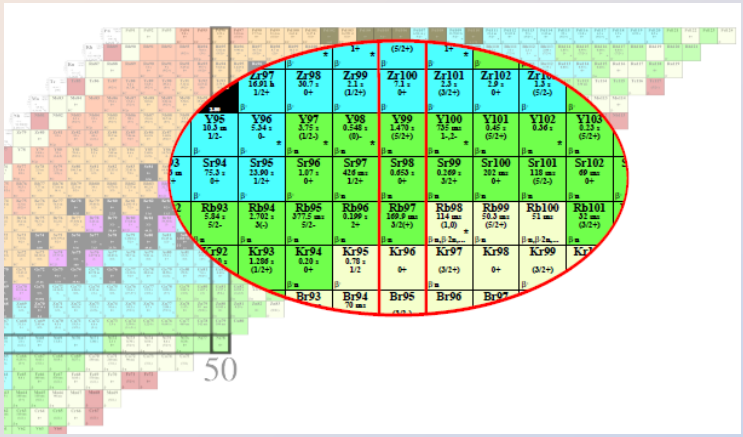
- LISE
- VAMOS

- AGATA/Exogam2
- PARIS/Château de cristal
- Must2/MUGAST
- ACTAR-TPC
- INDRA-FAZIA

J. Dudouet et al, PRL118(2017)162501

Evolution of the shell structure

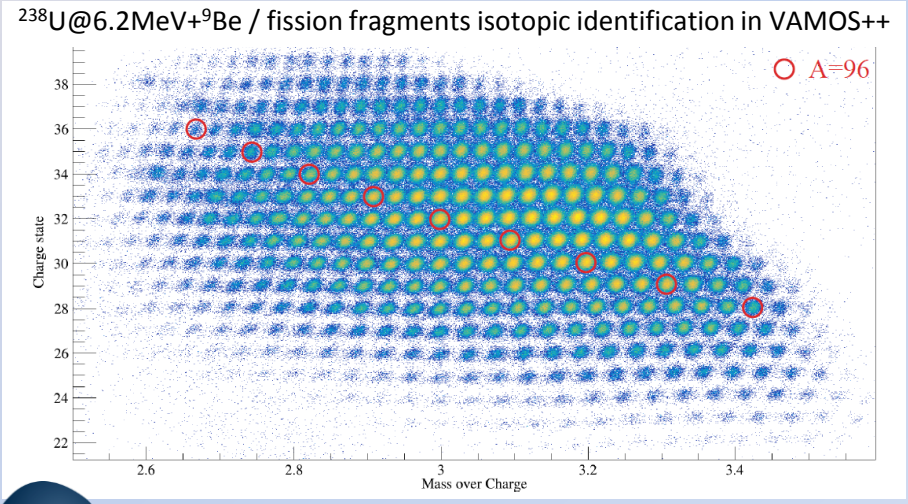
Study of deformation at N=60 in ^{96}Kr



→ In beam gamma spectroscopy of fission fragments with AGATA and VAMOS

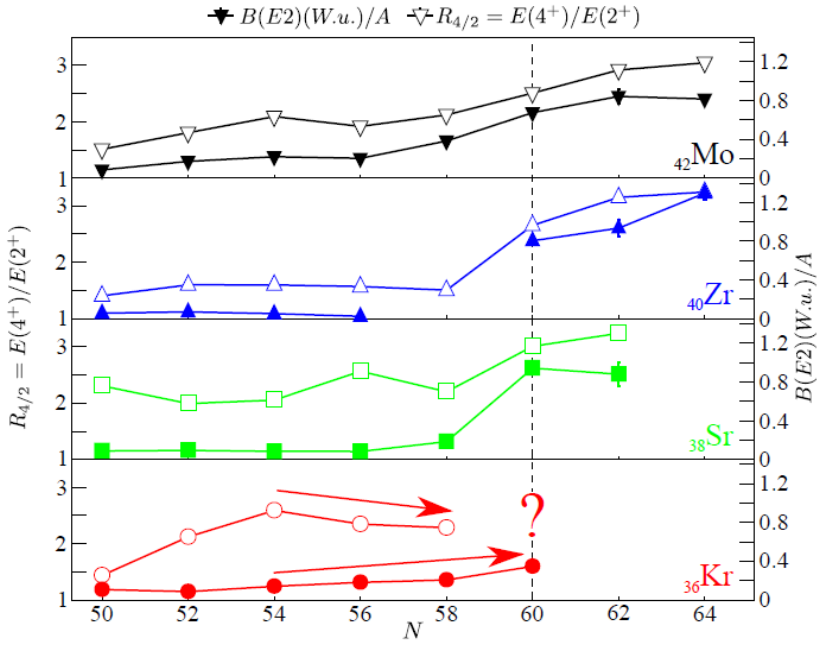
(heavy stable beams at Coulomb energies)

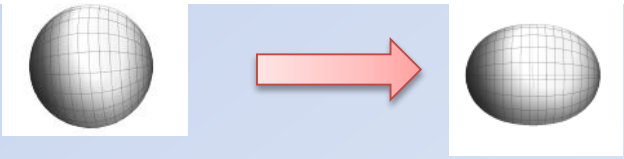
^{238}U@6.2MeV+^{9}Be / fission fragments isotopic identification in VAMOS++



PRL 118, 162501 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

$^{96}_{36}Kr_{60}$–Low-Z Boundary of the Island of Deformation at $N = 60$

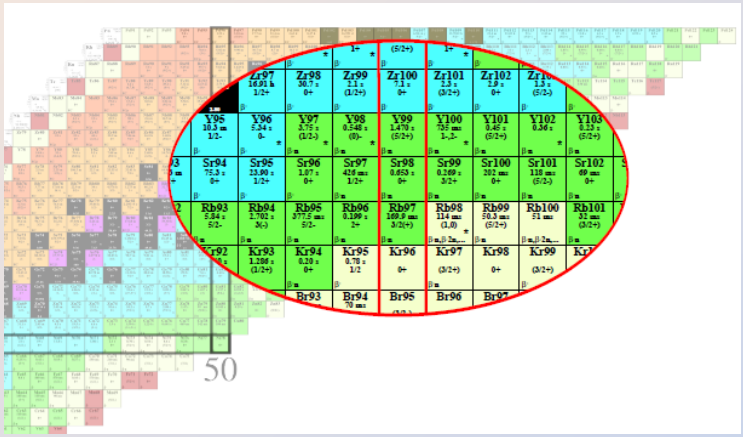




J. Dudouet et al, PRL118(2017)162501

Evolution of the shell structure

Study of deformation at N=60 in ^{96}Kr



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PRL 118, 162501 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

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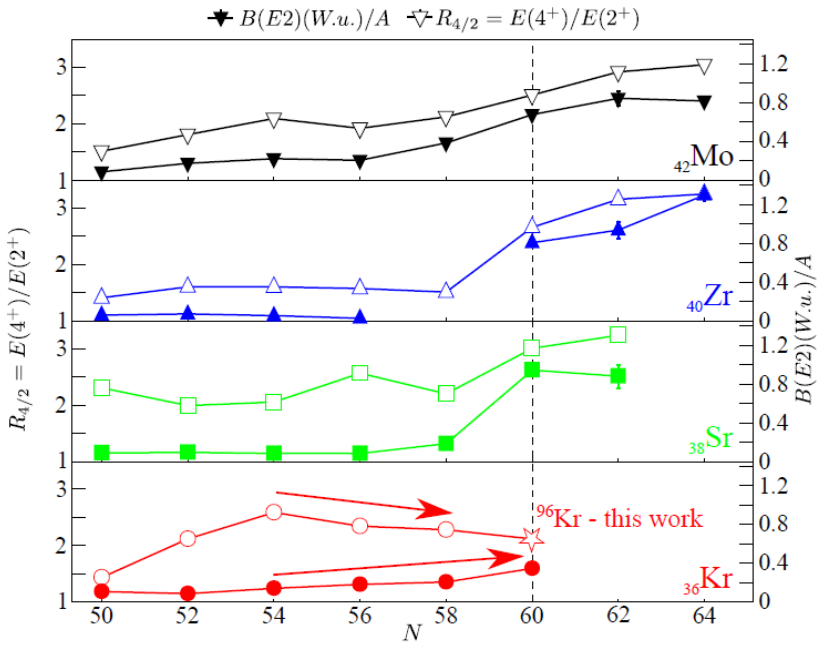
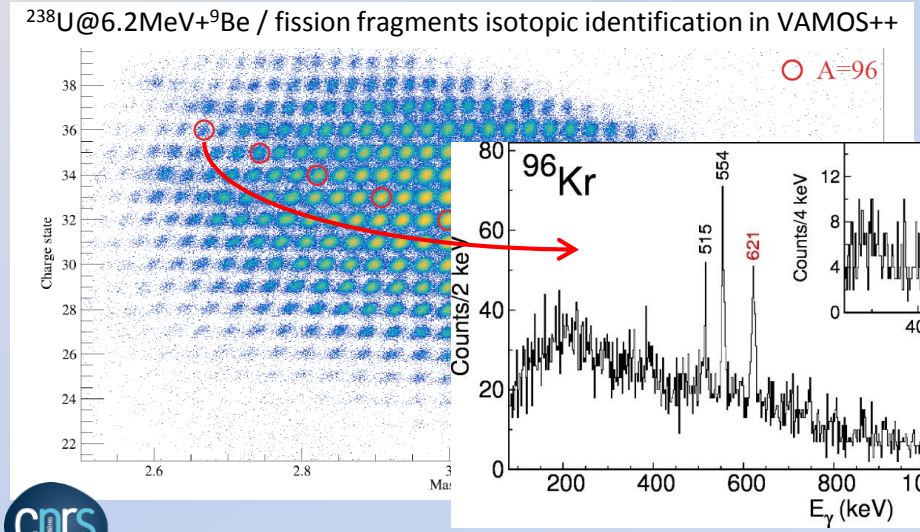
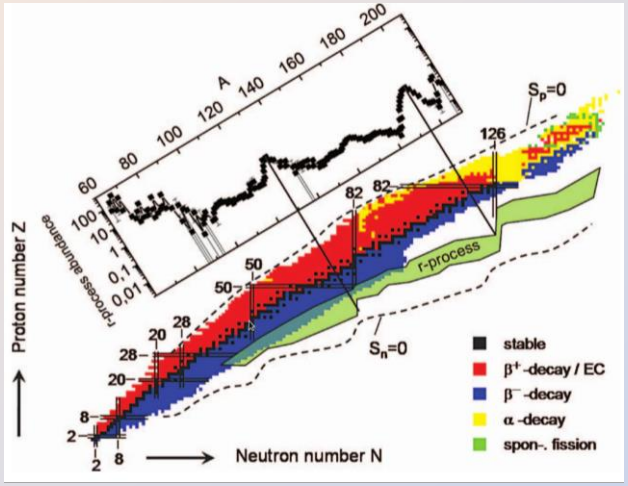




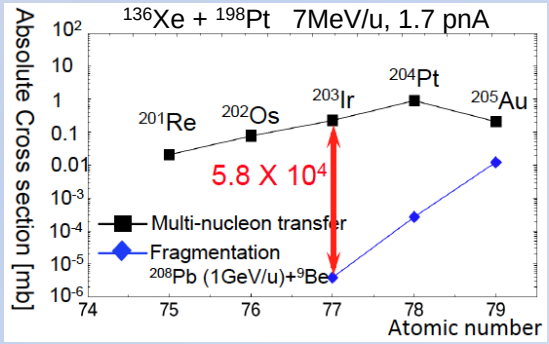
^{96}Kr lies outside of the island of deformation

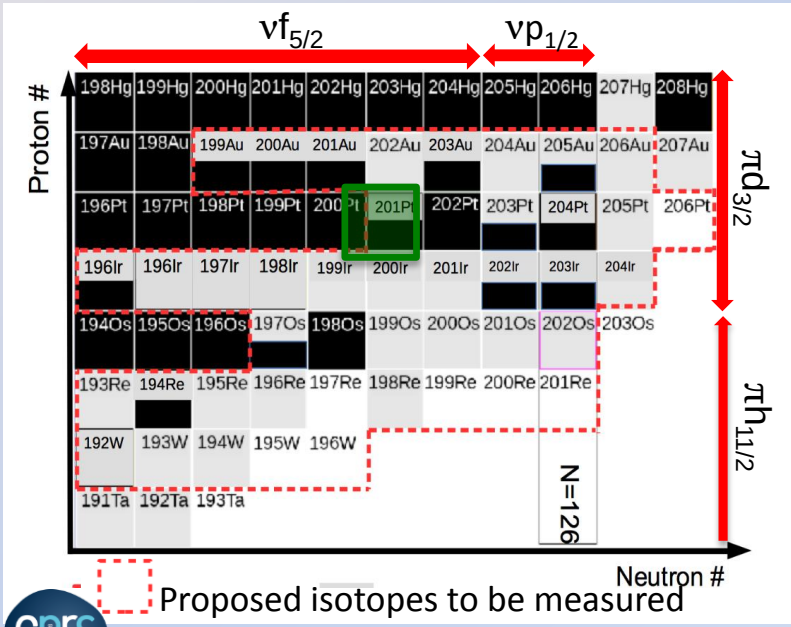
Evolution of the shell structure

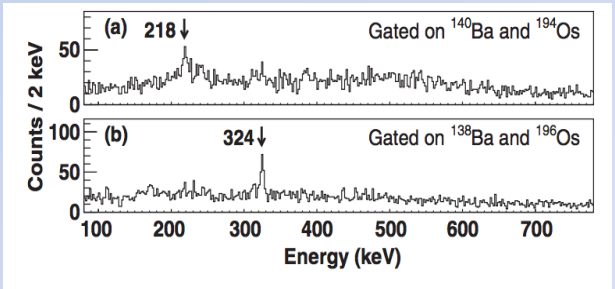
Perspectives : Exploring nuclear structure in "Blank Spot" in nuclear chart



- Evolution of nuclear structure for N=126 neutron rich nuclei
- Relevant to the last bottle neck of r-process: A~195 peak
- "Less studied" → Difficult to access by conventional methods (fragmentation, fission)
  → use of MNT (multi nucleon transfer) reactions
  → "high spin" gamma spectroscopy







Y.X. Watanabe, *et al.*,
PRL **115**, 172503 (2015)

GANIL : present and short term activities of cyclotrons

❑ Outlook

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  - Interdisciplinary researches
  - Industrial applications

Beam time / number of users

Implication of french community

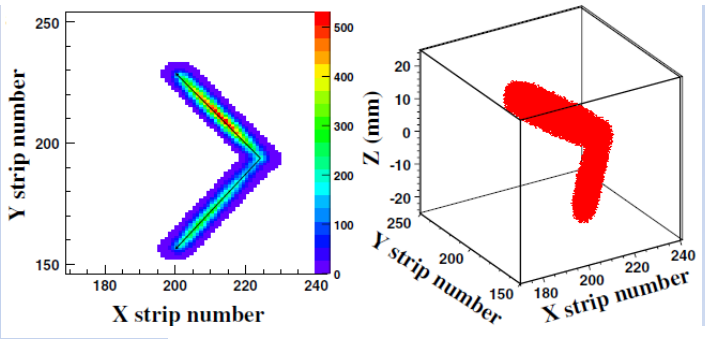
P. Ascher et al., PRL107(2011)102502

Evolution of the shell structure

Study of exotic radioactivities

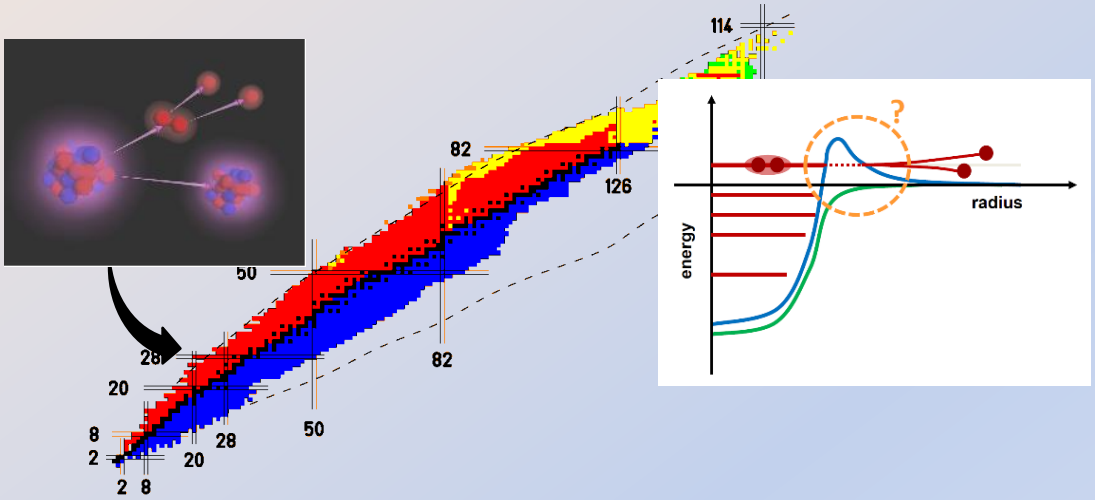
PRL 107, 102502 (2011) PHYSICAL REVIEW LETTERS week ending 2 SEPTEMBER 2011

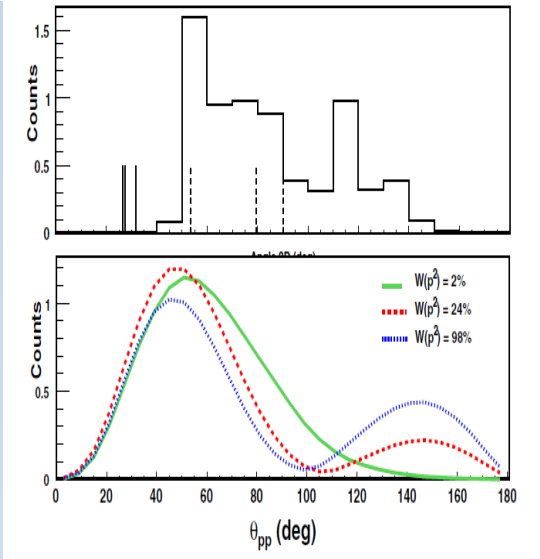
Direct Observation of Two Protons in the Decay of ^{54}Zn



Two protons radioactivity :

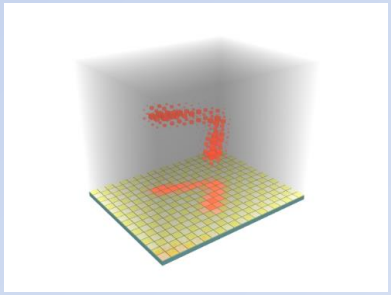
- discovered at GANIL in 2002 (^{45}Fe) (B. Blank, J. Giovinazzo et al.)
- observed in ^{45}Fe (GANIL/GSI), ^{48}Ni (GANIL/NSCL), ^{54}Zn (GANIL), ^{67}Kr (RIKEN)





Physics motivations

- nuclear structure at and beyond the drip line
- pairing
- tunnel effect



Perspectives :

New emitters (FAIR)

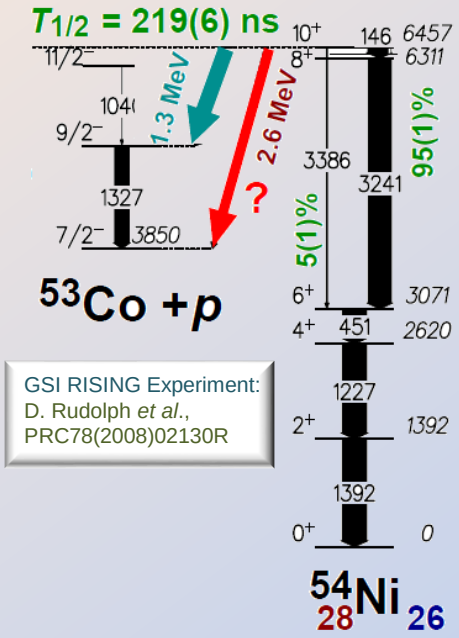
higher statistic for ^{48}Ni/^{54}Zn → angular correlations

(upgrades LISE and ACTAR-TPC)

Evolution of the shell structure

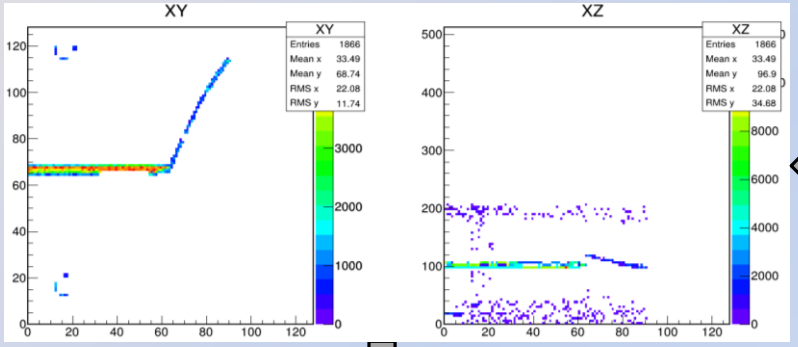
Study of exotic radioactivities

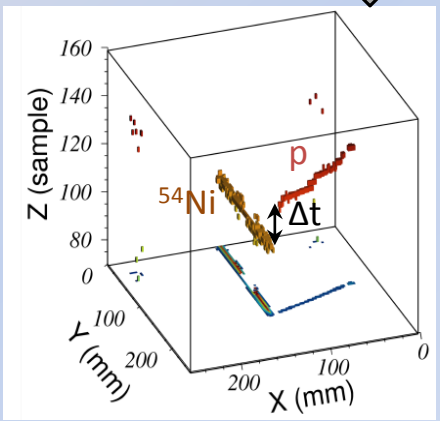
One and two protons emission from $^{54}Ni^{m}(10^{+})$:

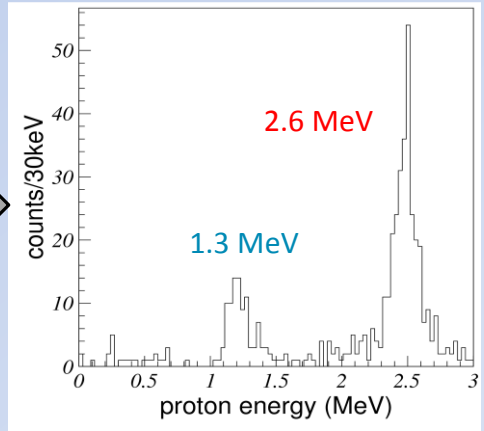


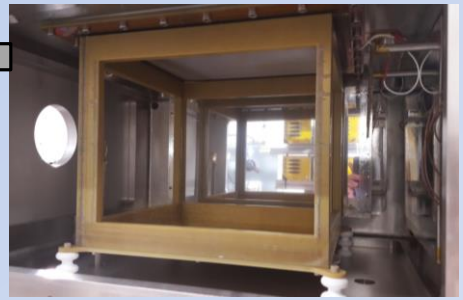
GSI RISING Experiment:
D. Rudolph *et al.*,
PRC78(2008)02130R

LISE/ACTAR-TPC (may 2019)









Open question : how can the protons carry =5 and =6 angular momentum ?

Perspectives : experimental program based on the GANIL cyclotons strengths

→ production *and selection* of neutron deficient RIB : LISE and the Wien Filter

→ ACTAR-TPC active target

GANIL : present and short term activities of cyclotrons

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Beam time / number of users

Implication of french community

Study of the fission mechanism

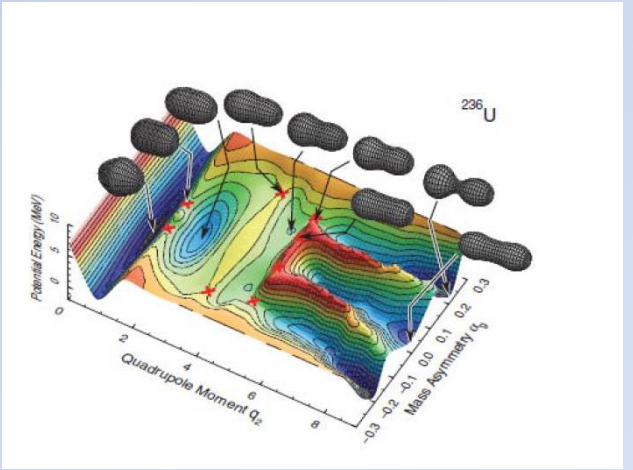
2019 : 80 years of the discovery of Fission (as CNRS !) L. Meitner and O. Hahn (1939)

Key Open Questions :

- Dynamical evolution of complex quantum system
- At the crossroad of many research topics of nuclear physics with essential interplay between structural and dynamical properties of nuclei.
- Fully microscopic description of the whole fission process is not yet available

Societal motivations for Nuclear Energy

- Accurate and precise data beyond the evaluated data
- New data



Relevant observables for what ?

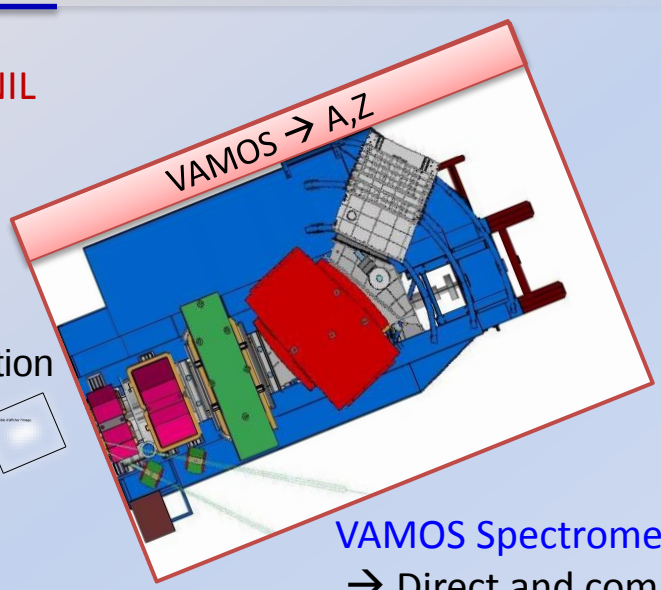
- Direct isotopic (A,Z) fission fragments data
- Complete fission yields
  => Probing the role of shell effect in fission and dissipation
- Kinetic energies and excitation energies of the fission fragments
  => Probing the scission configurations (A,Z,energy sharing)
- Fission Barriers (evolution as function of excitation energy):
  => Probing the the potential energy surface as function of E*
  => Exploring the fission paths (different modes of fission)

Study of the fission mechanism

What is unique and what can be done at VAMOS/GANIL

Inverse Kinematic using beams of ^{238}U around Coulomb Barrier

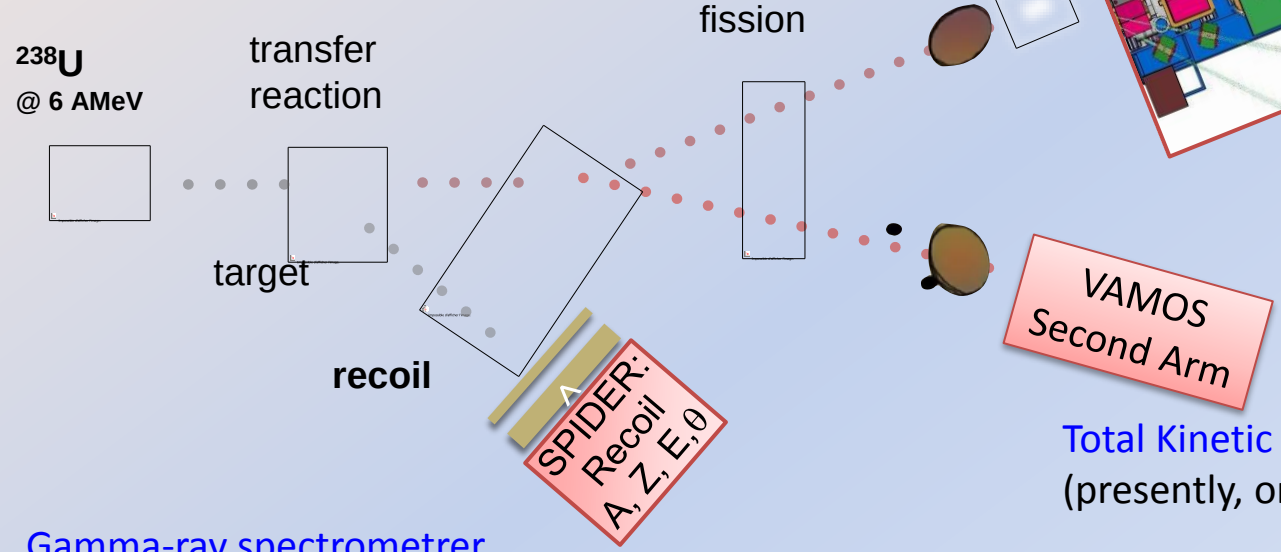
→ Access to « exotic » fissionning systems heavier than ^{238}U



VAMOS Spectrometer

→ Direct and complete isotopic FF yields

→ Precise center-of-mass FF velocities



Total Kinetic energies isotopically

(presently, only averaged without second arm)

Gamma-ray spectrometrer

→ Excitation energy sharing between FF

Surrogate reactions (transfer induced fission)

→ Selection of the fissionning system

→ Measurement of the excit. energy

Study of the fission mechanism

What is unique and what can be done at VAMOS/GANIL

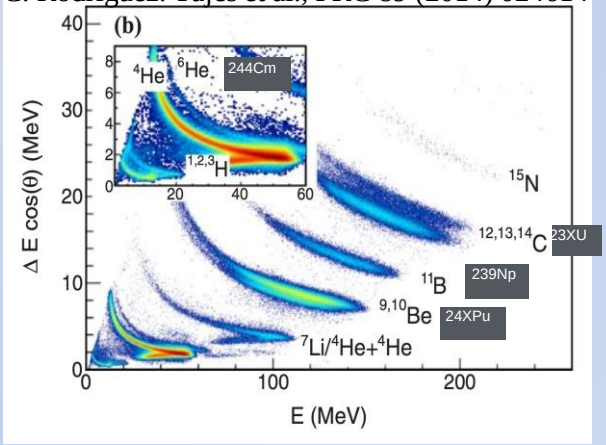
VAMOS spectrometer

→ isotopic identification and complete yields of FF

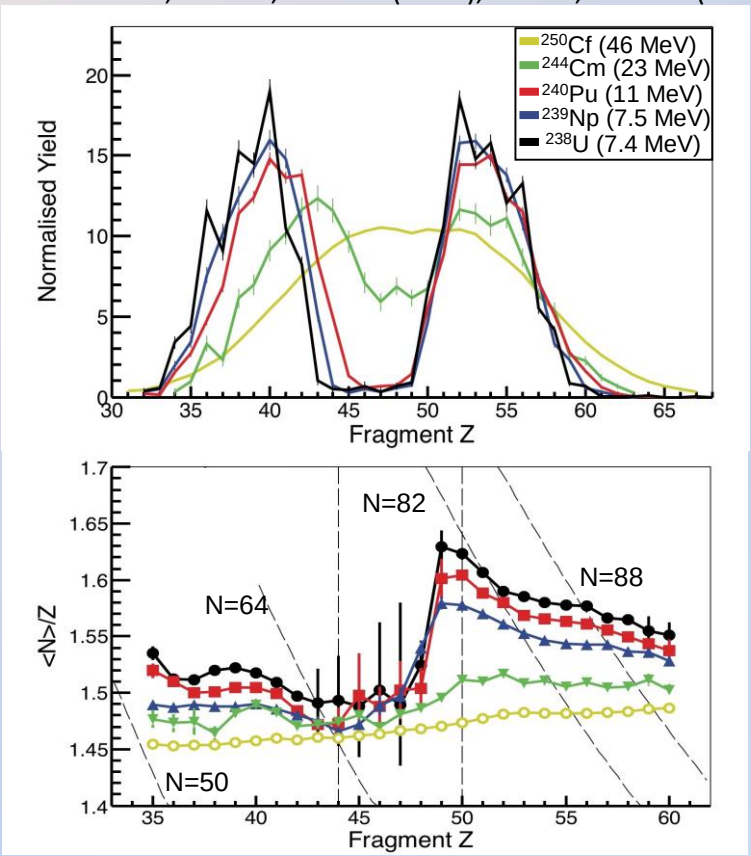
SPIDER annular segmented dE-E silicon telescope

→ selection of the fissioning system and excitation energy

C. Rodríguez. Tajes et al., PRC 89 (2014) 024614



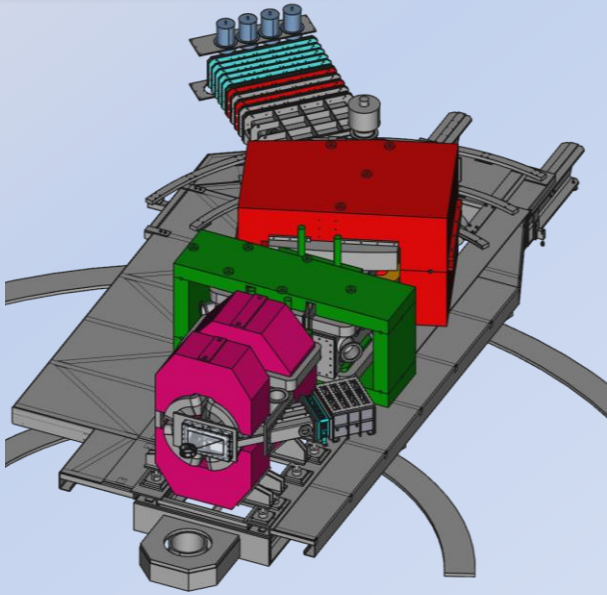
D. Ramos et al., PRC 97, 054612 (2018), PRC99, 024615 (2019)



Fragment neutron excess (N/Z)

→ Signature of structural effects (Z=50, N=82) only accessible with isotopic distrinution

Study of the fission mechanism
perspectives with VAMOS



Unique and ideal experiments at GANIL to constrain the dynamical evolution of quantum many body systems on its path to fission

→ Second Arm of VAMOS :
isotopic velocities of both fragments to probe scission configurations

→ Upgrade the detection of target like nuclei
improve the excitation energy resolution of the fissioning system from 2 MeV => 500 keV

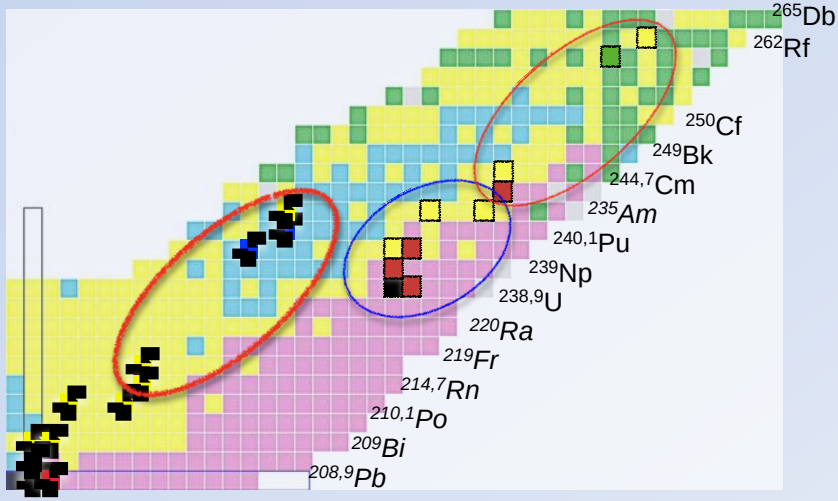
Extend the accessible reaction channels to probe unique and relevant fissionning systems :

→ Li Target : neutron rich Pu chain

→ Heavier targets (Al, Mg, …) : MNT reactions leading to a isotopic chains of fissioning systems

→ Thorium beams : ^{233}Pa (1 proton transfer) relevant to Th cycle

There is a huge gap between useful beams : ^{238}U, ^{208}Pb, ^{181}Ta.



GANIL : present and short term activities of cyclotrons

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Beam time / number of users

Implication of french community

❑ Study of rection mechanism

General motivations :

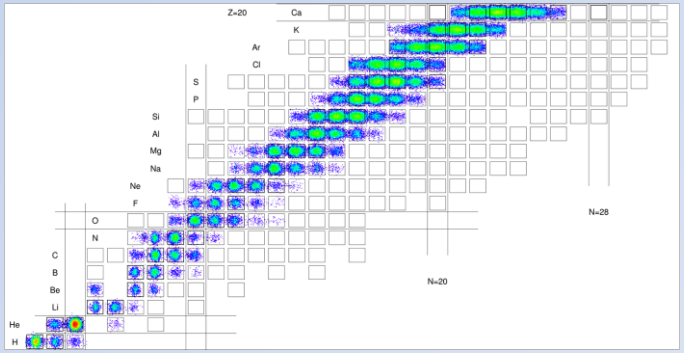
- Study the equation of state of the nuclear matter → reaction mechanism at intermediate energies

Experimental setup :

- INDRA-FAZIA array : 4π charged particle array

INDRA : Ionisation Chamber + CsI + Si
→ Z identification

FAZIA : 192 High-Quality Si-Si-CsI telescopes from 2 to 14 deg.
+ dedicated Full Digital Electronics
→ Isotopic identification up to Z=20



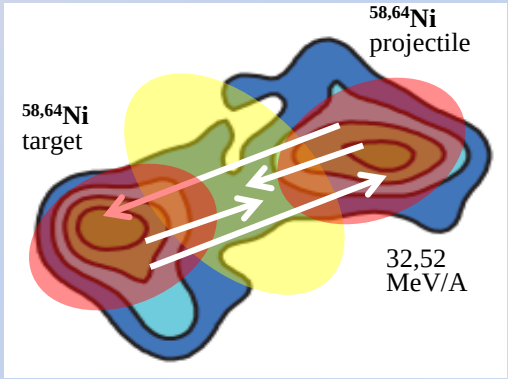
Study of rection mechanism

2019 : First INDRA-FAZIA campaign

Aim : better constrain the isovector component of the EoS and study the density dependence of the Symmetry Energy

→ Energy impact parameter dependence of the isospin transport (N/Z) around the Fermi energy
→ use of different beams and targets at different energies

Isospin transport :
Redistribution of protons & neutrons between projectile, target & neck during the reaction (10^{-22}-10^{-20} sec.)



Experimental method :

- Measure Z & A for projectile fragments (FAZIA)
- Measure intermediate energy fragments (INDRA-FAZIA)
- Impact parameter selection (INDRA)

Perspectives at GANIL

- EOS : density dependence of the Symmetry Energy
- Fragmentation Dynamics : spinodal Instabilities and multifragmentation
- Clusterisation in nuclear matter : from multifragmention to vaporisation

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Beam time / number of users

Implication of french community

B Cederwall et al.
Nature 469 (2011) 68

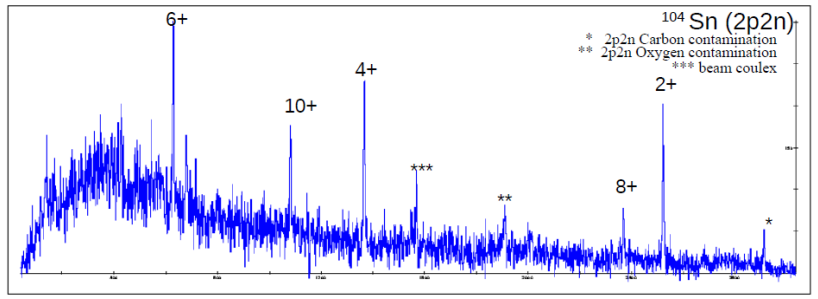
❑ Other studies

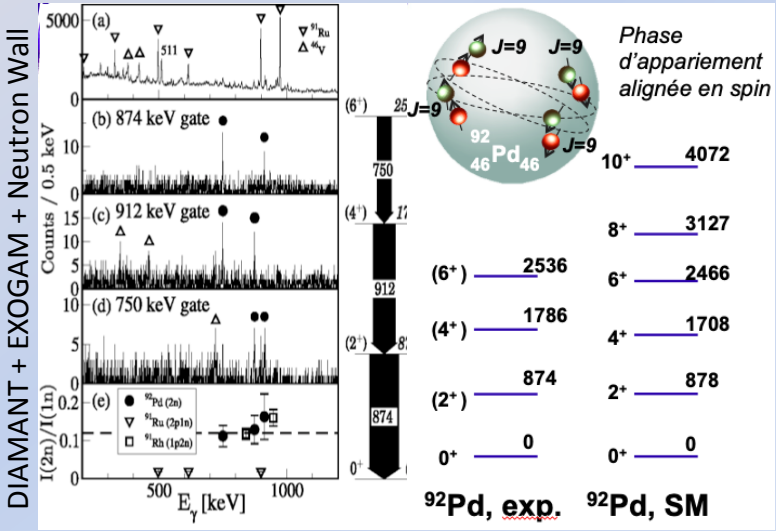
Medium energy : CSS1

- Spectroscopy of N=Z nuclei

→ fusion evaporation reactions

AGATA-NEDA-DIAMANT campaign in 2018





High energy : CSS1 + CSS2

- Interdisciplinary researches

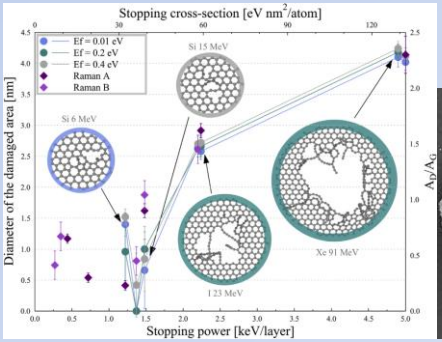
→ Radiobiology : hadrontherapy, LET effects…

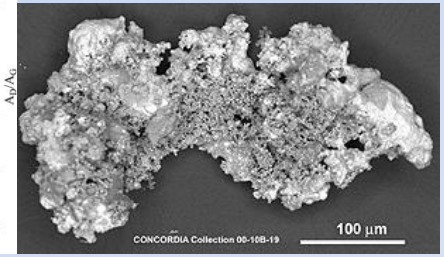
→ Atomic, molecular and plasma physics

→ Radiochemistry

→ Material science

→ nano structuration





- Industrial applications

→ Irradiation of electric components and systems : tests and certification for aerospace uses

→ microporous and nanoporous membrane R&D and production : growing activity

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Beam time / number of users

Implication of french community

- Nuclear astrophysic
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- Other studies

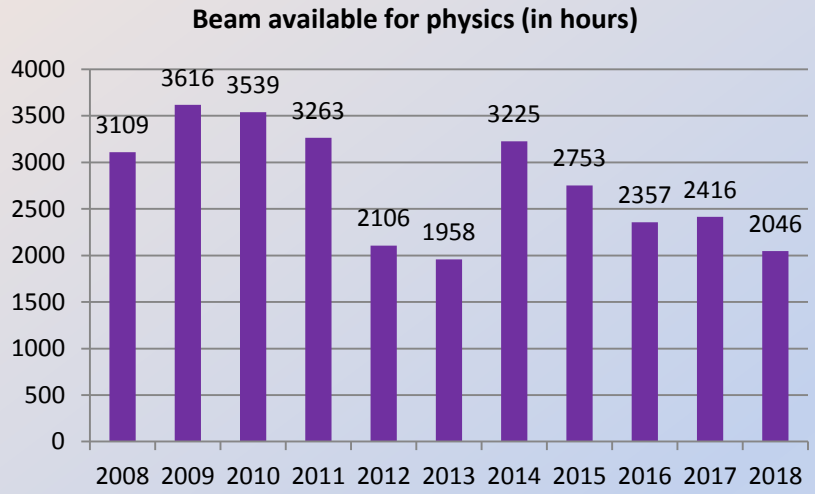
- Stable CSS
- ISOL Spiral1/CIME
- Fragmentation LISE

- LISE
- VAMOS

- AGATA/Exogam2
- PARIS/Château de cristal
- Must2/MUGAST
- ACTAR-TPC
- INDRA-FAZIA

Beam time

- The "cyclotrons" beam time has been reduced in the last five years (priority on S2 construction)



- Clear objective to increase it from 2021 (parallel running of cyclotrons and LINAC)

2018 : 4 months cyclotrons
2019 : 4 months cyclotrons + 2 months LINAC (C)
2020 : 3 months cyclotrons + 6 monts LINAC (C+E)
2021 : 5 months cyclotrons + 6 months LINAC (2 in parallel)
2022 : 5 months cyclotrons + 6 months LINAC (2 in parallel)

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- LISE
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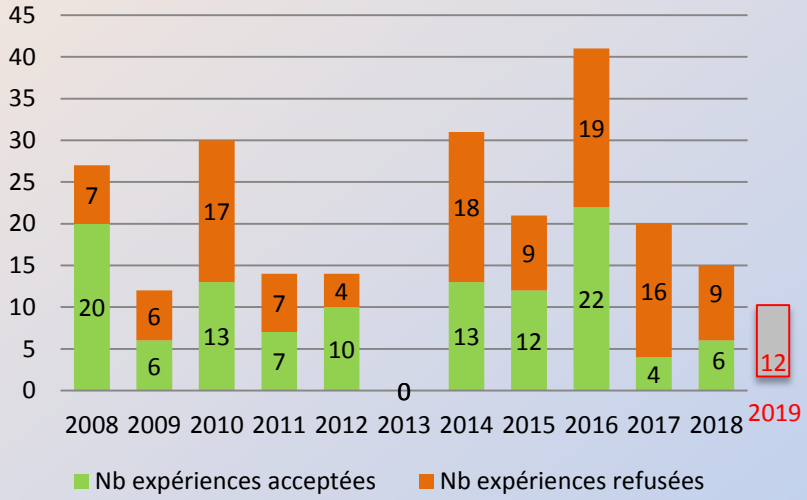
Users

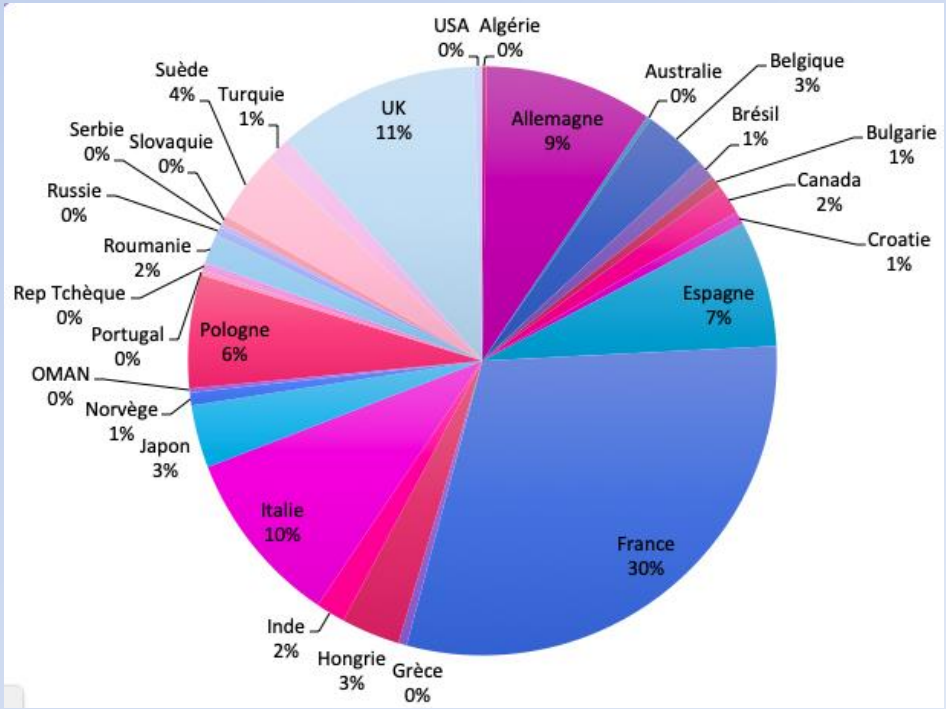
- Number of accepted and rejected experiments



- Number of users :

Nuclear Physics - without GANIL members

	2016	2017	2018	2016-2018
Foreign users	67	143	94	304
French users	36	51	38	125
Total	**103**	**194**	**132**	**429**



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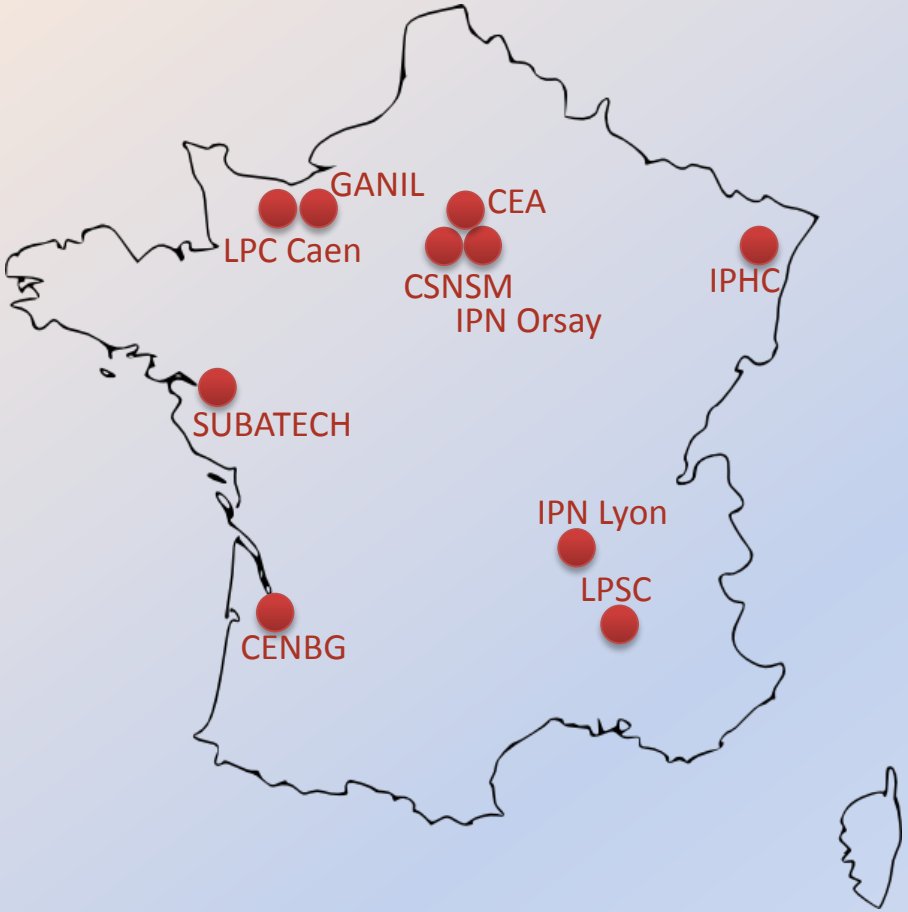
- INDRA-FAZIA

Implication of the french community



→ For the experiments

Nombre de CODE	Étiquettes de colonnes			
Étiquettes de lignes	2016	2017	2018	Total
CEA DAM DIF	2		1	3
CEA SACLAY	7	8	5	20
CENBG	8	8	5	21
CSNSM ORSAY	6	7	9	22
GANIL	2	1	1	4
IPHC STRASBOURG	2	9	2	13
IPN LYON	4	2	2	8
IPN ORSAY	5	16	13	34
Total	**36**	**51**	**38**	**125**

Number of visitors for Nuclear Physics experiments (without Caen)

→ For the development of detectors used at GANIL

- ACTAR-TPC
- AGATA
- PARIS
- MUST2/MUGAST
- NEDA
- …