GANIL : present and short term activities of cyclotrons executive summary

By the use of the CSS1 and CSS2 cyclotrons, and from the availability of a wide range of state-of-the-art spectrometers and instrumentation, GANIL presently offers large opportunities in nuclear physics and many other fields from the use of stable, fragmented and re- accelerated radioactive beams.

The main asset of the GANIL-Cyclotrons beams concerns the study of exotic nuclei produced either in-flight by projectile fragmentation using the LISE spectrometer, or produced by the ISOL technique using the SPIRAL1 facility and post-accelerated by the CIME cyclotron. These studies cover the main scientific questions that are currently discussed in the nuclear physics community like halo nuclei, cluster, shell evolution, dripline phenomena, soft/giant modes…

The energies of secondary beams in LISE, between 30 and 50 MeV per nucleons, are perfect to perform tertiary reactions like transfer of nucleons, nuclear and Coulomb excitations, and therefore it constitutes a “niche” to develop an ambitious experimental program for the forthcoming years. It should be noted that these studies have already started and benefited from the use of highly efficient an sensitive detector arrays like MUST2/MUGAST for the detection of light particles in the transfer reactions, EXOGAM2 and the Chateau de Cristal for the associated gammas and for Coulomb excitation experiments and the active target ACTAR-TPC for the study of nuclear reactions and decays. The technical developments that are ongoing (LISE QD6 and the Zero Degree Detection) will in a near future open the possibility to perform experimental campaigns using a “brochette” mode allowing to perform two experiments in one using ACTAR-TPC at the first focal point and a second setup after QD6, therefore increasing the duty cycle and/or optimizing the mounting and commissioning of the experiments. A first possibility would be to make the combined study of soft and giant modes in exotic nuclei, such as for example ^{34}Si which is known to be candidate for a bubble “bubble” nucleus, but which is also a key nucleus in between the N=20 spherical region (^{36}S) and the deformed N=20 island of inversion (^{32}Mg). Another possibility would be to perform transfer experiments and to study at the same time (^{3}He,d) and (d,^{3}He) reactions. It is also important to note that the Wien Filter of LISE allows developing specific scientific programs dedicated to the study of proton-rich nuclei that are hardly accessible in other facilities. It is worthwhile to remind the 2-proton radioactivity has been discovered at GANIL and that future experiments using ACTAR-TPC will allow to study the angular correlation of the emitted protons.

The SPIRAL1 facility, coupled to the CIME cyclotron, allows to produced post-accelerated exotic beams at energies between ~1 and 20 MeV/u, many with high intensities and all with very good optical qualities. The newly developed FEBIAD ion source allowed to produce new beams of condensable elements (Na, Mg, Al, P Cl and K) and the use of a primary beam of ^{58}Ni will allow to investigate the production of interesting nuclei like ^{56,57}Ni, ^{48}Cr, ^{55}Co and Sc isotopes. These developments will offer in the coming years new possibilities for transfer reactions, “safe” coulomb excitation and resonant elastic scattering experiments.

A full program of transfer reactions has been proposed for example using the ^{56}Ni beam (^{56}Ni is not available elsewhere and is one of the main objectives for the Spiral1 R&D in the coming years). For Coulomb excitation, a scientific program has been proposed in the *pf* shell from ^{40}Ca to ^{56}Ni. The safe Coulomb excitation of ^{48}Cr for example will shed light on the collectivity development between ^{40}Ca and ^{56}Ni and the role of the proton-neutron pairing. Another program in the area of shape coexistence at A~80 with the development of Se and Sr beams can be anticipated. SPIRAL1 post-accelerated beams are also particularly well adapted to perform resonant elastic scattering reaction in order to study unbound states above the particle emission threshold. Such studies will benefit from the recently developed ACTAR-TPC active target.

The second asset of the GANIL-cyclotrons beams concerns the use of stable beams at energies around the coulomb barrier using the VAMOS spectrometer. Indeed, the large solid angle magnetic spectrometer VAMOS, in combination with a gamma multidetector, is an ideal setup to perform multi nucleon transfer. It allows in-beam nuclear structure studies of n-rich heavy species and three programs of interest could be investigated in a near future : the study of octupole phonon in the ^{208}Pb region using lifetime measurements, the evolution of the N=126 shell closure and the study of neutron -rich actinides and transfermium isotopes.

The study of the fission process could also be a very interesting program in the forthcoming years. Indeed, only inverse kinematics at Coulomb energies, as used in VAMOS/GANIL, can perform an accurate fragment identification and a precise determination of the initial excitation energy in the same setup. This information is crucial to study the influence of intrinsic degrees of freedom and underlying nuclear structure on the fission process. Future programs could cover the measurement of the kinetic energy for both fragments using VAMOS++ spectrometer in conjunction with the second arm of VAMOS and the continuation of the study of fission and quasi-fission using transfer- and fusion-induced fission.

Another interesting development is the use of VAMOS as a gas-filled separator to be used for fusion-evaporation reactions. Indeed, VAMOS is a large acceptance device therefore a huge transmission is expected in particular for the heaviest elements leaving the target with a large angular distribution. The second motivation is related to the opportunity for its coupling with state-of-the-art gamma-ray detectors (the new generation gamma-tracking array AGATA and other arrays such as EXOGAM2 or PARIS).

The medium energy stable beams of GANIL can also be use without magnetic spectrometer. Indeed, fusion evaporation reactions is a powerful tool for the production of the N~Z nuclei. Such measurements are performed with a large Germanium array (AGATA, EXOGAM), coupled to a neutron and charged particles arrays for tagging the reaction. In these nuclei nuclei enhanced correlations arise between neutrons and protons that occupy orbitals with the same quantum numbers. Such correlations have been predicted to favour unusual type of nuclear superfluidity, termed isoscalar T=0 neutron–proton pairing, in addition to normal isovector T=1 pairing. At GANIL, first evidence of the influence of this pairing channel was evidence in ^{92}Pd. Systematic investigation of other N=Z nuclei from low to high spin, from level scheme to g-factor measurements are needed to provide high resolution constrains on the T=0 contribution.

At higher energies, the INDRA-FAZIA collaboration has developed over the years a long-term program dedicated to the study of the nuclear dynamic at low densities and various temperatures. It is mainly focused on the study of the density dependence of the symmetry energy, to radial flow measurement and to the study of the equation of state at very low density.

Finally, the stable beams are also used by a large interdisciplinary research community to study the mechanisms of ion – atom collisions, their consequences on the atomic arrangements, on the physical and chemical properties.

GANIL : present and short term activities of cyclotrons

Written by S. Grévy – may 2019
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Introduction

By the use of the CSS1 and CSS2 cyclotrons delivering ions from carbon to uranium at energies up to 95 MeV/u, and from the availability of a wide range of state-of-the-art spectrometers and instrumentation, GANIL presently offers large opportunities in nuclear physics and many other fields that arise from stable, fragmentated and re- accelerated radioactive beams.
The first part of the report will be dedicated to the studies performed using the in-flight radioactive ions beams produced by the LISE spectrometer. Different topics will be addressed covering beta decay, nuclear and coulomb excitation as well as transfer reaction on both neutron-rich and neutron-deficient nuclei. The second part of the report will focus on re-accelerated radioactive ion beams produced by the SPIRAL1 facility, with a focus on coulomb excitation measurements, elastic scattering experiments and transfer reactions. The third part of the report will be dedicated to the studies performed using medium energy stable beams, mainly using the VAMOS spectrometer covering multi nucleon transfer reactions, fission and fusion-evaporation, but also for experiments which do not require the use of a magnetic spectrometer. The fourth part of the report will report on the use of high energy stable beams used in conjunction with the INDRA-FAZIA detectors whereas the fifth and sixth sections will be dedicated to interdisciplinary researches and industrial applications. Some indicators will finally be given in the last part of this report.

1- In-flight Radioactive ion beams from fragmentation in LISE

The LISE separator is one of the main spectrometers of GANIL. It allowed since the beginning of the 80's many fragmentation type experiments to be performed in different domains covering the discovery of new isotopes, the study of ground- and excited-state properties, decay properties, study of isomers, exotic radioactivities, nuclear moments, haloes and clusters… This studies have been perform using different experimental methods such as beta decay, Coulomb excitation, knockout reaction, in-beam spectroscopy, transfer reactions, "active-target" type experiments…
Since its initial installation at the beginning of the 80's, the LISE spectrometer was upgraded several times : addition of the velocity filter at the beginning of the 90's and the corresponding beam line, the possibility of using an angle on the target in 1991 to produce polarized beams, addition of a second beam line LISE2000 (2001), the high-intensity target CLIM (2007) and more recently the shielding of the beam pipe after the production target.
Since the start of the RIBF facility at Riken, the physics program performed at LISE cannot compete for the study of the most exotic nuclei. Nevertheless, thanks to the energies of the secondary beams produced at LISE (few tens of MeV/u whereas RIBF beams are produced at few hundreds of MeV/u), there is an increasing interest of using radioactive beams to perform secondary reactions in the D6 room, being direct reactions, Coulomb or nuclear excitations. For this purpose, two complementary technical developments were initiated in 2017-2018 : the implementation of tracking and identification detector ensembles at zero degrees and the reconfiguration of the LISE optical equipment after the Wien filter with the LISE QD6 project. The latest has been completed and successfully used in the first run of 2019.

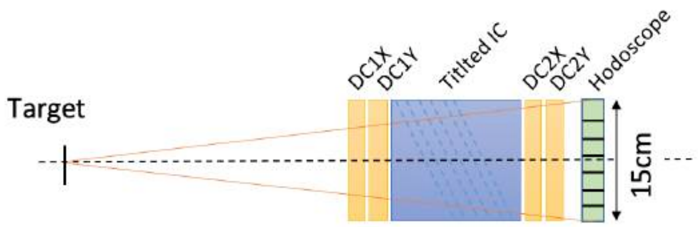

Fig 1 : Scheme of the Zero Degree Detection to be implemented at the end of the LISE spectrometer

Concerning the zero degree detection, the aim is to identify the heavy ion residues and determine their emission angles after the reaction target. For this purpose, it is necessary to measure the energy loss, the residual energy and the transverse positions, such as represented on Fig. 1, for a high counting rate (>10^5 pps) and with a angular acceptance of +- 5°.

In the following we will briefly highlight some experimental results obtained in the last 4 years, with the idea of showing the various technical and scientific assets of the facility and of its related instrumentation. Experiments were performed using different techniques such as beta-decay, Coulomb and nuclear excitations, and transfer reactions. These experiments cover various scientific motivations related to a better understanding of nuclear forces, shell evolution, soft collective modes, halo or cluster nuclei, study of the fundamental interactions and new phenomena at the drip-line.

A- Transfer reactions

Transfer reactions are powerful tools to study the shell structure of the nuclei, giving access to the excitation energy, the spin and the spectroscopic factor of the populated states. The GANIL energies are particularly well suited to perform transfer reaction and they have been used intensively in inverse kinematics during the last decade to study the structure of the exotic nuclei. Nevertheless, very efficient detection systems (both for light particles and gammas) are required in order to compensate for the low beam intensities. This is achieved by using charged particles multi-detectors such as MUST2 or MUGAST and gamma arrays like EXOGAM2.

a) Overlap between neutron rich Be and Li isotopes

This aim of this experiment performed in July 2017 was to study the change in cross section between cluster, drip line or halo nuclei in the vicinity of ^{11}Li. This is a follow-up of a previous campaign of experiments performed at Riken, which showed that the proton transfer cross section between ^{11}Li and ^{10}He was reduced by a factor of 10 as compared to simple expectations. After careful analysis and theoretical development, performed in collaboration with the University of Surrey, it was established that the halo nature of the neutron wave function could explain in part this large reduction. In principle, in a neutron rich nucleus, it is expected that the deeply bound valence proton occupies the lowest shell available fully, therefore the spectroscopic strength should be maximal when performing a proton transfer. We showed however, that in the case of unbound, or halo nuclei, the rapidly changing wave function of the valence neutron between the initial and final state of the system play a major role in reducing the amplitude of the cross section.
The aim was here to measure the cross section between ^{12}Be and ^{11}Li, as well as between ^{10}Be and ^{9}Li for comparison. Nuclei of interest were produced in fragmentation reactions using the LISE spectrometer. The beam position and angle were reconstructed on a CD2 target using the two position sensible CATS detectors. The light reaction products were detected by 8 MUST2 telescopes, capable of measuring time, energy and direction of the light particle, and identifying them using various methods (time-of-flight, E-ΔE). Around zero degree an ionization chamber was combined to a plastic to detect and identify the heavier reaction products. This detection was of paramount importance, as the light particles produced by the reaction of interest (d,^{3}He), have the same mass as the ones produced in the concurrent reaction mechanism (d,t). The separation between these two reactions channel was successfully achieved using this detector and its digital electronics.

As shown in Fig. 2, it is possible to reconstruct a preliminary excitation spectrum for ^{11}Li, however the reduction factor is found to be of about 7 in a first estimation, so more than twice as large as expected. The resolution of the experimental setup is now being improved by correcting the energy spreading of incident beam using their event-by-event time-of-flight information. This should improve both the excitation energy resolution and reduce the background, by allowing a better time-of-flight separation of the ^{3}He and t ejectiles.

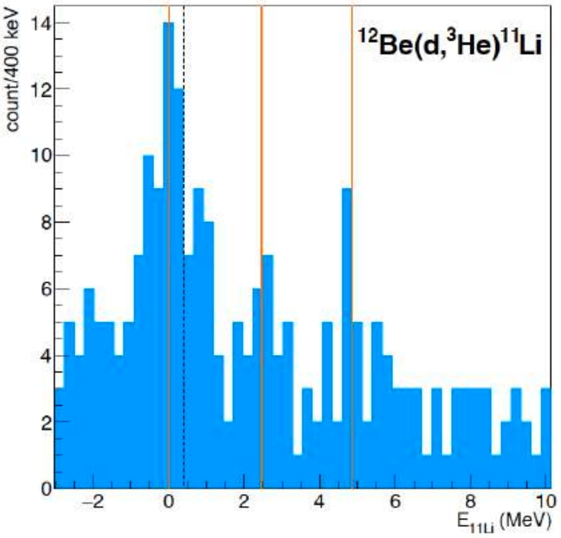

Fig 2: Preliminary excitation energy spectrum of ^{11}Li produced by (d,3He) transfer reaction.

b) Perspectives for transfer reactions with MUGAST@LISE

The MUGAST detector is actually installed in front of the VAMOS spectrometer and coupled to the AGATA array for an experimental campaign in 2019 and 2020 (see §2-C-c). An important upgrade of the MUGAST setup will be undertaken to allow performing particle-gamma measurements at LISE. A new configuration based on the use of EXOGAM2 and on a compact, large solid-angle configuration of the trapezoid detectors of MUGAST/GRIT will be implemented. A scheme of the system is shown in Fig.3.

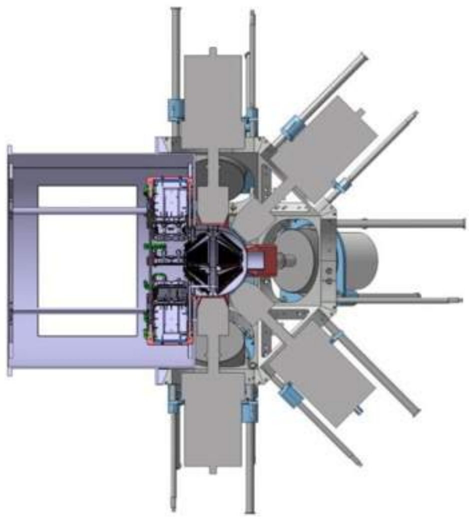

Fig 3 : the MUGAST@LISE configuration.

A new chamber hosting eight trapezoid telescopes has been designed at LPC Caen. 12 EXOGAM segmented HPGe detectors will be placed around the target at 15cm. As in MUGAST@VAMOS, the MUST2 electronics will be used for readout. A new connectics for linking the trapezoid detectors to the front-end board will be built. The development of a second layer of Silicon detectors, 1.5mm thick, has been undertaken in order to improve particle identification and extend the dynamical range for light particles. With this powerful configuration, direct reaction experiments using the versatile fragmentation beams delivered by LISE can be studied. Furthermore, beams delivered at LISE take now benefit of the possibility to use the full intensity of primary beams by hint of the recent upgrade of the LISE production target area. Several reactions studies have suggested within the collaboration such as the study of (d,p) reaction in proton-rich nuclei of interest for the rp-process or the (p,^{3}He) reaction on fp-shell, N=Z nuclei to investigate np pairing or quartetting. Several studies using a slowed-down ^{56}Ni fragmentation beam could be undertaken if the production with SPIRAL1 is found to be insufficient.

B- Coulomb excitations

Coulomb excitation of exotic nuclei in inverse kinematic, in which the nuclei are excited by the Coulomb field of the target, have been performed at LISE, mainly to study regions of shape coexistence where a transition is observed between a classical independent particle structure near the shell closures to regions where the correlations drive the nuclei towards collective nature and therefore deformation. Such measurements have been performed at N=20, 28 and 40 shell closures in the past years.

a) Coulomb excitation of ^{44}Ca and ^{46}Ar

The evolution of the N = 28 shell closure has been investigated far from stability using several experimental techniques. Experimental results suggest that a progressive onset of deformation occurs below ^{48}C. Mean field approaches as well as shell model calculations predict a close-to-spherical ^{46}Ar, a shape mixing or shape coexistence in ^{44}S, and a large oblate deformation in ^{42}Si. The reduced transition probabilities B(E2; $0^+_{g.s.} \rightarrow 2^+_1$) of the ^{46}Ar and ^{44}Ca nuclei were studied using the Coulomb excitation technique at intermediate energy at LISE (Cal16). The in-flight γ rays, emitted after the Coulomb excitation of their first 2^+ states, were detected in an array of 64 BaF2 crystals. The present B(E2 ↑) value for ^{44}Ca, 475(36) e2fm4, agrees well with the value of 495(35) e2fm4 obtained by averaging results of previous experiments. Consistent B(E2; $0^+_{g.s.} \rightarrow 2^+_1$) values of 225(29) e2fm4 and 234(19) e2fm4 have been obtained for ^{46}Ar from an absolute and a relative measurement, normalized to the ^{44}Ca value. Both results agree with the ones obtained with the same experimental technique at the NSCL facility but are a factor of 2 smaller than the shell model predictions. The drop in B(E2; $0^+_{g.s.} \rightarrow 2^+_1$) in the Ar chain at N = 28, confirmed in this experiment, shows that ^{46} Ar is sensitive to the N = 28 shell closure.

b) Perspectives : example of the Coulomb excitation of ^{34}Si

The ^{34}Si with 14 protons and 20 neutrons is a nucleus of particular interest in the region of the N=20 shell closure. Indeed, this so-called “bubble nucleus” is located between the spherical ^{36}S (Z=16) and the emblematic deformed ^{32}Mg which is dominated in its ground state by intruder configurations originating from *fp*-orbitals. Therefore, it is at the verge of the island of inversion and traces of deformed structures were found in its level scheme.

The experimental results on the $0^+_{1,2}$ states in ^{32}Mg [Wim10] and ^{34}Si [Rot12] obtained at ISOLDE and GANIL/LISE have brought further credit to the description in which a crossing between normal and intruder regime occurs between these two nuclei. Moreover, a candidate for the spherical 2^+ state at 5.3 MeV has been proposed recently from a precise measurement of the beta decay of ^{34}Al [Lic18] whereas the spherical 2+ is known at an energy of 3 MeV.

Future Coulomb excitation experiment can determine the reduced transition probabilities of these two states with high accuracy and therefore help to better understand how the deformation progressively dominates the structure of the most exotic N=20 isotones.

C- Study of the pygmy and the giant resonances

Nuclear reactions at the Fermi energies are perfect tools to study the different collective modes that can be at play in the nucleus. Among them, both the isoscalar giant resonances (monopole, dipole and quadrupole) and the pigmy dipole resonance (PDR) have been studied at LISE and could in a near future benefit from the recent development of the ACTAR-TPC detector.

a) Study of the isoscalar giant resonances in ^{58,68}Ni

Among the different giant resonance modes in nuclei, the isoscalar response, which is characterised by the in-phase motion of protons and neutrons, is of particular interest. For instance, the isoscalar monopole resonance, a compression-dilatation vibration called the “breathing mode”, is related to the incompressibility parameter of the nucleus, which, in turn, can be linked to the incompressibility modulus of the infinite nuclear matter. The latter is an important ingredient in the Equation of State (EoS) of nuclear matter and thus plays a crucial role in very fundamental processes, from nuclear-scale ones such as heavy-ion collisions, to the cosmic-scale collapse of heavy stars in supernovae explosions, or the description of neutron stars. The recent simultaneous observation of both gravitational and gamma-ray radiation from a neutron star merger has raised additional interest in this topic.

Despite significant progress in our understanding of the nuclear incompressibility, both theoretically and experimentally, the determined incompressibility modulus remains associated to large uncertainty (20%). To improve on it, measurements of isoscalar modes are being carried out on isotopic chains towards exotic nuclei with a large proton to neutron asymmetry.

Measurements of the isoscalar giant resonances (monopole, dipole and quadrupole) in unstable nuclei were so far only performed in the Ni isotopic chain (^{56}Ni and ^{68}Ni), at the LISE spectrometer using a pioneering technique with the Maya active target. Indeed, the active-target method is necessary to measure the low-energy products of inelastic scattering in inverse kinematics while having a reasonable target thickness.

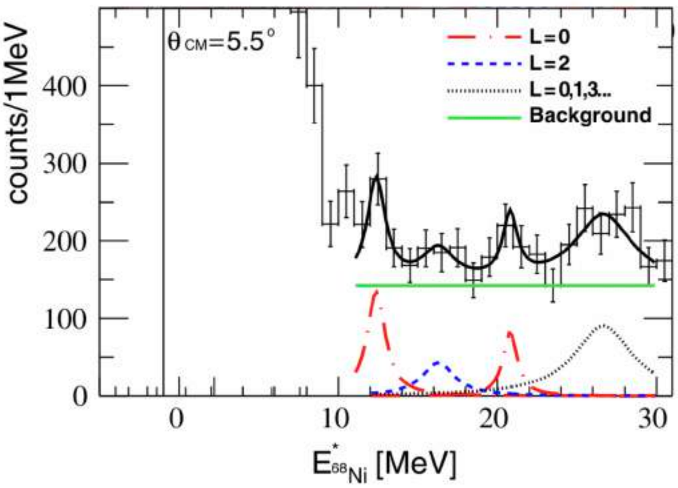

Fig 4: Excitation energy spectrum of ^{68}Ni, obtained in the ^{68}Ni(a,a’)^{68}Ni* reaction, showing the different resonances populated in the region of the giant resonances (from Van14).

The inelastic scattering of deuteron and alpha particles, on the unstable nuclei ^{56,68}Ni in inverse kinematics, were used as isoscalar probes. The centroids and the widths of the isoscalar giant resonances were extracted. As presented in figure 4, the isoscalar giant monopole resonance in the ^{68}Ni was identified at 21.1 MeV. Moreover, in the case of ^{68}Ni, there was an indication of the presence of the soft monopole mode around 13 MeV, which was predicted at lower energy than the isoscalar giant monopole resonance in neutron-rich unstable nuclei but never observed before.

However, if this experimental approach has been validated, the limited resolution has prevented to provide real constraints on the incompressibility modulus.

b) Future plans with ACTAR-TPC

The recently-commissioned ACTAR-TPC detector aims at a significant improvement in energy resolution (a factor 5 or better) in comparison with the Maya detector, inducing a reduction of the uncertainty on the nuclear incompressibility. A further goal is the study of the soft part of the monopole mode, the breathing mode at lower frequency of which an indication was observed in the last experiment with Maya. In the same way, it would be interesting to couple an active detector such as ACTAR-TPC to gamma detectors (such as the PARIS array) in order to study the PDR.

Beyond the measurement of the isoscalar giant resonances and the soft monopole mode in ^{68}Ni with ACTAR, which has been accepted by the Ganil PAC and will be performed in 2019 with the ACTAR-TPC detector, it would be interesting to study these modes even further from the valley of stability, in ^{70}Ni for example, thus extending the measurements along the Ni isotopic chain. In addition, other kinds of compression modes, like the compression of the "bubble nucleus" ^{34}Si, are predicted and could be studied using this method.

D- Beta decay studies of proton rich nuclei

Fragmentation reactions are a very efficient way to produce the most neutron deficient nuclei but the secondary beams are particularly difficult to purify because of a tail in the low energy momentum distribution. The LISE spectrometer, thanks to its Wien Filter located in D6 can very efficiently purify the beams and is therefore particularly well suited to perform such studies. It is worthwhile to remind that the two-proton radioactivity has been discovered at LISE and that the first observation of the 2p decay ion a Time Projection Chamber has also been observed first at GANIL.

a) Precision measurements of the beta decay half-life and branching ratios of ^{30}S

High precision measurements of studies of particular beta decay transition can be used to test the conserved vector current (CVC) hypothesis of the standard model and to constrain the unitary of the Cabbibo-Kobayashi-Maskawa quark-mixing matrix. It is for example the case of the super-allowed $0^+ \rightarrow 0^+$ of ^{30}S which is part of the Tz=-1 nuclei. ^{30}S is of special interest since the nuclear- structure dependent corrections, that need to be applied to the ft value of the super-allowed decay branch in order to extract its vector component, are the second largest of all Tz=-1 super-allowed emitters. Therefore, the precise measurement of the ^{30}S $0^+ \rightarrow 0^+$ ft value would thus allow testing the various theoretical models used to correct the ft values of the entire set of super- allowed beta-decay emitters. The $0^+ \rightarrow 0^+$ decay in ^{30}S proceeds to the 0^+_1 excited state of ^{30}P at 678 keV. The beta-decay Q-value being know already with a high precision, the aim of the experiment was to measure with an improved precision of a factor 3 to 4 the partial half-life of the $0^+ \rightarrow 0^+$ decay branch ($t_{1/2}(0^+ \rightarrow 0^+) = T_{1/2}/BR(0^+ \rightarrow 0^+)$). The LISE facility is well suited for such measurements thanks to the almost pure (>99%) and low-energy (< 30 MeV/u) beam of ^{30}S that can be obtained in the fragmentation of ^{32}S projectiles in a Be target. The latter property allowed collecting the ^{30}S ions in a thin movable tape and transporting the activity in a background- free environment, where β–γ coincidences were measured by repeating a number of implantation and decay cycles.
The analysis procedure is similar to the one of a previous experiment performed at LISE in the past dealing with the $0^+ \rightarrow 0^+$ beta decay study of ^{38}Ca [Bla14]

b) Beta decay of Tz=-2 nuclei

The radioactive decay of nuclei far from stability is usually the first access to information such as masses, half-lives, branching ratio and structure information, or even the only access for the most exotic ones. On the proton-rich side of the nuclear chart, exotic decay modes occur, that involve the emission of charged particles (protons, alpha…). The standard technique consists in implantation-decay in silicon detectors.
An original and powerful way to determine the isospin impurities in nuclear states is provided by beta-delayed proton emission from the isobaric analog state (IAS) of neutron-deficient nuclei. Such decays involve transitions proceeding via isospin-symmetry breaking and thus are of particular interest to constrain the isospin non-conversion terms in the nuclear interaction.
In particular, it was shown in [Smi17] that the experimental proton to gamma-ray branching ratio for the IAS populated in beta decay of a precursor, supplemented by theoretical proton and gamma-ray widths, can be used to extract spectroscopic factors for isospin-forbidden proton emission.
In this context, an experiment was performed in order to determine these branching ratios and establish the complete decays schemes of the Tz=-2 ^{48}Fe, ^{44}Cr and ^{52}Ni nuclei produced in LISE. The nuclei of interest were implanted in a 300 um DSSSD detector, allowing to correlate in time and position the charged particle decay event with the implantation event, surrounded by 4 EXOGAM

germanium detectors. A strong γ-transition, candidate to the decay of the IAS, has been observed at 2.1 MeV.

c) Use of the active gas detector ACTAR-TPC

The use of an active gas detector (such as ACTAR TPC) is often the only way to measure the emitted charged particles, especially at low energy. As an example, the β-delayed proton decay allows to study resonances above the proton emission threshold that are involved in astrophysical radiative capture processes [San16](1). In such case, the low energy protons (few 100 keV), emitted with a small branching ratio, are emitted in a very large β background. While almost insensitive to β particles, a gas detector is perfectly suited to measure these decays [Saa11]. A similar situation is encountered for the βpα and βαp decays [Bla08,Gri15], that provide an indirect method to study (α,γ) and (p,γ) reactions(2).

The study of very exotic decay modes (involving protons emission) is explicitly part of the ACTAR TPC physics case. In particular, for the study of the 2-proton radioactivity, TPC detectors are needed to measure correlations of the emitted protons [Gio07,Mie07], while the use of silicon detectors does not allow to measure the properties of individual protons. Up to now, only the decay of ^{45}Fe has been measured with good statistics, and other nuclei such as ^{48}Ni and ^{54}Zn are accessible at GANIL/LISE [Gio16]. The device has been successfully used in a recent experiment (may 2019) at GANIL that aimed to measure proton emissions in the decay of isomeric states in ^{54}Ni and ^{53}Co [Rud15].

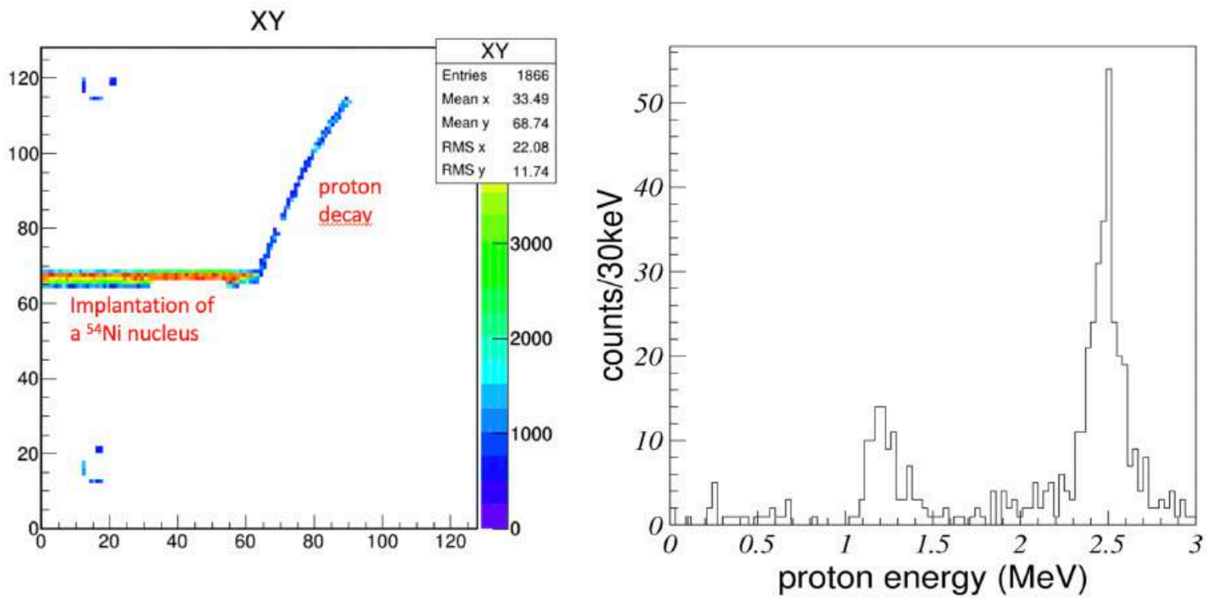

Fig. 5 : 2D reconstruction from the time projection chamber of the implantation of a 54Ni nucleus followed by the emission of a proton (left) and proton spectrum reconstructed from the lengths of the proton tracks in the ACTAR detector showing the presence of two proton decay channels (only one was known up to now).

In addition to the nuclear structure studies of this experiment, it represents a proof of principle for these protons decay experiment. In a similar way, ACTAR TPC is adapted to the measurement of beta-delayed multi-proton emission. While ^{31}Ar has already been extensively studied, other nuclei such as ^{35}Ca or ^{43}Cr decay by β-1p, -2p or even -3p. They can be produced with good rates at the LISE facility, and the various decay branches can be easily identified with ACTAR TPC, providing a large variety of information: branching ratios of interest for astrophysics processes (competition with γ de-excitation), Gamow-Teller strength distributions on a large energy window, and search for a correlated 2-proton emission from excited states.

For decay studies at fragmentation facilities, in addition to a clear identification of emitted protons (or alpha), and a good separation from the beam signal or from β particles, the intrinsic efficiency of this kind of detector is almost 100%.

(1) for example, the βp decay of ^{23}Al for radiative capture $^{22}Na(p,\gamma)^{23}Mg$ (nucleosynthesis in novae), of ^{31}Cl for $^{30}P(p,\gamma)^{31}S$ ($^{30}Si/^{28}Si$ ratio), of ^{46}Mn for $^{45}V(p,\gamma)^{46}Cr$ (abundance of ^{44}Ti produced in SN)
(2)for example $^{9}C(\beta p\alpha)\alpha$, $^{13}O(\beta p\alpha)^{8}Be$, $^{17}Ne(\beta p\alpha)^{12}C$, $^{23}Si(\beta p\alpha)^{18}Ne$, $^{21}Mg(\beta p\alpha)^{16}O$

E- INDRA-FAZIA program

While the INDRA-FAZIA detector has been used up to now at GANIL with stable beams (see section 4), it could be also installed in LISE an benefit from the exotic nuclei produces at Fermi energies.

a) Symmetry energy studies

The energies of the secondary beams produced by LISE (30 to 60 MeV/u) are very well suited for investigations of the symmetry energy in peripheral and mid-peripheral reactions. Since these beams are characterized by N/Z asymmetries that are not available with stable beam facilities, one can explore the extremes of isospin asymmetry in the EoS, profiting from the fact that the effects of the symmetry energy are expected to increase with the square of N/Z asymmetry. Therefore, a natural extension of the stable beam programs is envisioned by the collaboration in near future.
Furthermore, recent efforts to profit from a multi-purpose array to be used for several physics cases at the LISE facility, have suggested the intriguing opportunity to couple the FAZIA detector, placed at forward angles, $\vartheta<10^o$, to an array of silicon strip detectors, such as MUST2, characterized by high energy and angular resolution and covering larger angles, $\vartheta<30^o$, aimed at detecting light particles in coincidence to the heavier residues. Similar studies would represent an extension of the INDRA-VAMOS campaigns where the forward rings of INDRA, $\vartheta<8^o$ were replaced by the acceptance of the VAMOS spectrometer to study $^{40,48}Ca+^{40,48}Ca$ collisions at 35 MeV/u. This campaign has provided good measurements of isotopic distributions of the residual QP systems in peripheral collisions, allowing to explore the surface and volume contributions to the symmetry energy. However, a number of limitations existed in the performed measurements: the acceptance of the VAMOS spectrometer was reduced to 10% and only between $\vartheta\sim2°-7°$, forcing to perform measurements over a range of fixed B-rho values; the angular resolution of the INDRA detector at $\vartheta>8^o$ was limited by the azimuthal segmentation of about $\Delta\phi\sim15°$, preventing to obtain a very good reconstruction of the excitation energy, mass and charge of the initial QP produced during the collisions; furthermore, light particle emitted in the very forward direction and entering the VAMOS spectrometer were not detectable in coincidence with the heavy QP residue, leading to a reduced efficiency in studying the whole range of impact dissipation available at the studied energy regime in peripheral reactions.
The granularity of the forward FAZIA demonstrator will therefore represent the advantage of providing multi-particle detection over the same experimental run in the forward direction. The FAZIA performances have revealed a very high isotopic resolution up to Z~24 that will certainly allow to well reconstruct a large number of midperipheral events the decay of QP fragments is observed. The coupling to MUST2, extensively used at the LISE beam line, thanks to its high energy and angular resolution, will allow not only very good investigations of the symmetry energy in peripheral reactions, but also unique measurements of two- and multi-particle correlations. This capability is complimentary to that of FAZIA (capable of detecting and identifying heavy fragment with reduced angular resolution).

b) In-medium structure and resonance decays

The multi-particle detection capability of MUST2 and FAZIA will allow to reconstruct the decay of short- and long-lived resonances emitted by the dilute and hot medium produced during heavy-ion collisions between N/Z asymmetric systems. Among them we mention resonances corresponding to internal states in ^{5}Li (via proton- α and deuteron-^{3}He correlations), in ^{10}C (via 2p-2α correlations), in ^{12}C (via three α correlations) and several other examples. Some of these unbound states can be used to deduce

temperatures of the hot and dilute medium, as well as their densities. Moreover, the experimental setup will allow to probe properties of these resonances such as their spin, branching ratios, etc… By varying beam energy, projectile-target combinations and impact parameter, these resonances can be produced and explored under different in-medium conditions (densities, temperatures, etc.). Furthermore, the availability of very N/Z asymmetric beams at LISE will allow exploring also the mentioned structure properties at various N/Z asymmetry of the hot and dilute medium. In-medium alpha clustering effects can also be explored by studying collisions induced by neutron-rich isotopes (produced with LISE) of α conjugate nuclei.
These topics are interesting for nuclear structure studies, as a complimentary way to produce unbound states in exotic nuclei. However, the study of the EoS at low density, important also for symmetry energy investigations, requires a detailed study of how these unbound states are produced, especially when dealing with alpha clustering phenomena emerging in very low density nuclear matter.

2- ISOL Radioactive ion beams from Spiral1

During the past decade, SPIRAL at GANIL has been delivering radioactive ion beams of unique intensity and purity for physics experiments, making use of the so-called “Isotope Separation On Line” technique [Intr1]. Ionized in ion sources, ISOL beams have an optical quality which is comparable to this of the stable beams. Thanks to the CIME cyclotron, these beams can be accelerated up to 20AMeV for the lightest nuclides accelerated allowing for a large variety of studies. From the beginning, SPIRAL has been technically limited to the production of radioactive ion beams of gaseous elements, thus limiting the physics opportunities. A project of upgrade was formed in 2009 to complement the ion beam production capabilities towards condensable elements.

A- Spiral1 Upgrade

The SPIRAL 1 upgrade makes use of the charge breeding technique to enlarge the capabilities of radioactive ion beam production. The charge breeding is a competitive and cost-effective solution compared to the stripping foil technique. It has benefited from multiple studies and from the development of facilities using this technique at ISOLDE, TRIUMF or more recently ANL. Because of the continuous mode of operation and of the intrinsic resolving power of the cyclotron CIME, an ECR charge breeder has been found better suited than a pulsed EBIS. The ECR charge breeder of the SPIRAL upgrade is a Phoenix booster donated by the Daresbury Laboratory and which was tested at ISOLDE from 2003 to 2008 [CB1,CB2] and which has been upgraded to obtain the best performances with this device. Due to the diversity of the beams requested in the letters of intent, a FEBIAD source developed recently at ISOLDE, the so-called VADIS [Feb1] was found to be the ion source of condensable elements to be coupled in priority with the SPIRAL targets. The upgrade was also aiming at extending the safety authorizations for a number of combinations of primary beams and targets. The previous authorizations were limited to projectile fragmentation on graphite targets. In the frame of the upgrade, these authorizations were extended in order to include target fragmentation and fusion evaporation reactions.

a) FEBIAD R&D and status

The FEBIAD target ion source has undergone several modifications and optimizations since its first on-line tests in 2011. In the end of 2013, it was successfully tested on-line at SPIRAL 1 at nominal power. Many beams could be produced with average ionization efficiencies around 5% for the condensable elements Na, Mg, Al, P, Cl, K. Following these results, the FEBIAD target ion source was consolidated off-line for more reliability. During the startup of the upgraded facility, in 2018, an unexpected failure occurred on-line at the very beginning of the source conditioning. An insulator was incriminated. A spare ion source was modified to protect the faulty insulator. This permitted to undertake two test beam times to prepare for a ^{38m}K experiment, to investigate further the elements produced in 2013 and to perform a first charge breeding test with ^{37}K. A preliminary charge breeding efficiency of 5% was obtained in a couple of hours of beam tuning. A margin for improvement of a factor of two is expected.

b) Status of the upgrade

The upgrade is mostly operational at the required performances, although the FEBIAD source still requires some work on the off-line test bench for final adjustments, before on-line validation. The validation of the FEBIAD target ion source consists in demonstrating that its lifetime can exceed two weeks of reliable on-line operation. Experience has been gained in 2018 for the beam transport and acceleration for the different modes of operation. In may 2019, the first experiment with ^{38m}K has been successfully performed and a first beam production/acceleration/purification test in the region of ^{56}Ni, which has gathered many interests from the community, is planned for June 2019.

c) Perspectives for the upgraded SPIRAL1

The upgraded SPIRAL 1 facility offers many perspectives for developing new radioactive ion beams which have been evaluated during different calls for letters of intents. Different R&D are presently being pursued to follow the priorities given by the physics community:
* The aforementioned production test of ^{56}Ni, ^{48}Cr, ^{55}Co, ^{57}Ni and Sc beams from the fragmentation of a primary beam of ^{58}Ni. Many of these beams may be contaminated so that stripping will be required.
* The production test using a primary beam of ^{86}Kr, in order to explore the production of heavier isotopes (^{79}Se, ^{60}Fe, ^{67}As for example).
* The development of new targets, consisting mainly of:
* A combination of a fusion-evaporation target with different ion sources (FEBIAD, surface ionization and Electron Cyclotron Resonance sources) for optimizing / enabling the production of neutron deficient nuclei (^{74}Rb, ^{114}Cs, and future prospects for DESIR around ^{100}Sn)
* A Nb target coupled to a FEBIAD source, which would optimize the production of heavy beams by fragmentation (A>60), such as ^{67}As, ^{72}Kr, ^{74}Kr, ^{74}Rb, ^{71}Br, ^{66}Ge, $^{74-76}Ge$, ^{78}Sr, ^{79}Se...
While the development of the Nb target is being undertaken mostly by GANIL internal resources, the fusion evaporation targets are being developed in a staged approach in collaboration with IPN Orsay ("TULIP" project).

B- Low energy beams experiments

The low energy beams program has been examined by the previous IN2P3 scientific council dedicated to the ISOL part in November 2017 and it is not in the scope of the present report. Nevertheless, it is important to remain here that the primary driver of SPIRAL1 being the stable beams accelerated by CSS1+CSS2, this program is totally linked to the existence of the cyclotrons.
It is the case for the existing experimental program developed by the LPC Caen on the LIRAT beam line with the installation of the LPCTrap setup in order to test the standard model of the weak interaction using the beta decay, but it will be also the case on the horizon of 2023 with the start of the DESIR installation. Indeed, 50% of the letter of intent which have been submitted for DESIR are requesting SPIRAL1 beams, the other 50% being linked to fusion-evaporation beams produced with the future S3 spectrometer.

C- Post accelerated beams

As explained before, the radioactive nuclei produced by the SPIRAL1 facility can be post-accelerated using the CIME cyclotron at energies up to 15-20 MeV/u.

a) Coulomb excitation

Safe Coulomb excitation is a very clean experimental technique to address the electromagnetic properties of exotic nuclei. Using a pure electromagnetic process, exotics nuclei can be excited up to relative high spin and cross sections measured with an accuracy better than 5%. From these cross sections, transition probabilities (B$\lambda\mu$) and spectroscopic quadrupole moments (Qs) can be deduced. At GANIL, using the SPIRAL1 ISOL facility, the Coulomb excitation technique was successfully used to measure, for the first time ever, spectroscopic quadrupole moments of short-lived excited states in exotic ^{74,75}Kr in the framework of the shape coexistence study at the N~Z line [cle07] and to probe the collective properties of ^{44}Ar near the doubly magic ^{48}Ca [zie09]. The SPIRAL1 facility was upgraded from 2013 to 2018 and the first Safe Coulomb excitation experiment with the newly developed beam of ^{38}K^{m} was performed in 2019. This experiment was aiming at measuring directly the isospin mixing (see next section) in this N=Z nuclei from the ratio of reduced transition probabilities deduced from Coulomb excitation cross section [def19]. The spectroscopic data (transition probabilities and spectroscopic quadrupole moments) deduced from safe Coulomb excitation experiments are benchmarking most of the subjects in nuclear structure and nuclear astrophysics. Such measurements shed light on the collective properties of doubly magic nuclei and neighboring isotopes, shape coexistence scenario, isospin symmetry breaking and pairing interaction, high order symmetries (triaxiality, γ-softness, octupole correlations and beyond…), link between super deformation and weak deformation in semi-magic nuclei and lifetime of excited states relevant for astrophysical process. The future of the technique at GANIL is intimal related to the beam development at the SPIRAL1 facility. In the next years, experimental programs in the pf shell from ^{40}Ca to ^{56}Ni and in the area of shape coexistence at A~80 with the development of Se and Sr beams can be anticipated. Cr and Ni beams would be unique worldwide. Safe Coulomb excitation of ^{48}Cr will shed light on the collectivity development between ^{40}Ca and ^{56}Ni and the role of the proton-neutron pairing. The first ever safe Coulomb excitation of ^{56}Ni will provide information on its doubly magic character and how large collective structures rise with excitation energy in this isotope. Finally, safe Coulomb excitation of Se and Sr beams will complete the study performed on the Kr isotopes in the field of the shape coexistence between prolate and oblate symmetries, the role of the triaxial degree of freedom and the role of the g9/2 orbit in the fast evolution of the shape properties as a function of the proton and neutron number and excitation energy in this mass region.

b) Study of renonant reactions and cluster states

The nuclear structure close to stability is mainly affected by well-studied two-body forces. While moving close to the drip lines and beyond, or similarly for states close to particle emission threshold, other components of the nuclear force such as three-body forces or the coupling to the continuum become more and more important, giving rise to many interesting phenomena such as mirror symetry breaking or nuclear clustering, which are of primary importance to constraint nuclear models. On the neutron deficient side of the nuclear chart, light nuclei also play an important role in nuclear astrophysics.

One efficient way to populate unbound nuclei, or states above the particle emission thresholds, is to use resonant reactions. This kind of reaction consists in studying the compound system formed by the projectile and the target, through the measurement of the excitation function of the fusion-evaporation reaction. With radioactive beams, this technique is used in inverse kinematics and is known as the thick target in inverse kinematics method [Gol93]. Classically, a solid target is used to continuously slow down the beam and perform the reaction at different energies without changing the energy of the incident beam. The light recoil is usually detected in a solid state detector or a spectrometer, while the scattered heavy partner is stopped in the target.

This technique has been used widely at GANIL, using either fragmented LISE beams or re-accelerated radioactives beams produced by SPIRAL1.

Search for 2p clusters in ^{15}F

In the Ikeda conjecture, clusters are found systematically at the corresponding threshold energy. They are often viewed as narrow resonances, such as the 3α Hoyle state in ^{12}C that lies just above the corresponding 3α energy threshold. It was proposed by Okolowicz et al. (Oko12) to generalize this conjecture to 2n and 2p clusters at the corresponding S_{2n} and S_{2p} thresholds, respectively. Soon after, it was found in the work of de Grancey et al. (Gra16) that a very narrow resonance was indeed present in the proton unbound nucleus ^{15}F, about 4.5 MeV above its proton-unbound ground state, only 50 keV above S_{2p}. This state was interpreted to be due to a 2p cluster ($1/2^-$), formed as a ^{13}N+2p in the $s_{1/2}$ orbital.

Further investigations of 2p cluster states have been investigated in ^{15}F in 2018 with three goals. The first was to characterize the decay of the $1/2^-$ and see if it could decay by a E1 gamma transition to the unbound $1/2^+$ ground state, rather than by one or two proton emissions. Intuitively, we would expect a strong 2p emission in case of a cluster configuration, but the phase space allowed for the two protons is so small that this resonance decays slowly (herewith accounting for its narrow width) by one proton emission and perhaps by gamma emission. Guided by the structure of the mirror nucleus ^{15}C, the second goal was to discover other states at higher energy, also predicted to be have narrow widths by Fortune (For11). The third goal is to quantify and characterize their 2p decay emission, such as their energy sharing and their decay mode (sequential or direct).

An ^{14}O beam at 7.5 MeV/u from SPIRAL 1 impinged on a CH2 target to form the unbound nucleus ^{15}F in the resonant elastic scattering process. Protons were detected in five MUST2 detectors placed at forward angles. The preliminary analysis confirms the presence of the early discovered 1/2- resonance and proves the existence of a 3/2- resonance at about 6.3 MeV.

Nevertheless, the drawback of this method is the difficulty to identify the reaction channels : three reaction parameters (the reaction energy, the center of mass angle and the excitation energy in the final state) need to be determined in order to fully characterize the reaction, which is impossible to do while measuring the light partner only. Active targets, such as ACTAR TPC permit to measure the heavy fragment and hence completely determine the reaction. Such studies moreover require to have rather pure beams at low energy (typically 5A MeV), which fits with SPIRAL1 beams at GANIL.

Direct measurement of ^{14}O(α,p)^{17}F (M. Aliotta- Edinburg University - UK)

The use of active targets is particularly interesting when studying reactions close to the thresholds. As an example, the ^{14}O(α,p)^{17}F reaction is believed to play an important role in hot (T9 ~ 0.1 – 1.0) and dense (ρ ~ 10^2 - 10^5 g/cm3) astrophysical environments, such as X-ray bursts, as a major breakout reaction from hot CNO cycle. The aim of such an experiment would be to investigate the ^{14}O(α,p)^{17}F reaction (Q = 1.191 MeV) by a direct measurement of its cross section in the energy region between Ecm ~ 1.0 – 2.5 MeV. This will help constraining its astrophysical rate with a firmer experimental ground. The resonant elastic reaction ^{14}O(α,α)^{14}O can be measured simultaneously and be used to constrain the analysis. A first experiment was performed at GANIL without success due to a high pollution of protons produced during the slowing down process of the incident ions inside the degrader located in front of the helium gas target. The active target ACTAR-TPC can be used instead of the degrader and helium gas target. In that case, it is used both to slow down the beam and induce reactions at decreasing energies as the vertex is closer to the target exit. The new detector could be used to determine the vertex for a better energy resolution and for a reduction of the proton background.

c) Study of transfer reactions

The high-resolution direct reaction program is currently ongoing at GANIL, based on the coupling of the state-of-the-art gamma detector AGATA, the VAMOS spectrometer and a specifically-developed charged–particles Silicon array called MUGAST. This program, which is of great importance for both nuclear astrophysics and nuclear structure was set as high priority by the Scientific Council of GANIL, in agreement with evaluations issued by the GANIL PAC. In 2019, after commissioning test of this unique setup, a first experiment aiming to pinpoint the gamma decay of between unbound resonances populated through the ^{14}O(p,p) was successfully performed.

Picture / small text

During the forthcoming second run of 2019, the α + ^{15}O capture reaction, crucial for explosive nucleosynthesis at the surface of neutron stars will be investigated using the ^{15}O SPIRAL1 beam and the $^{15}O(^{7}Li,t)$ α-transfer reactions. This reaction is thought to be the main route for break-out from the Hot CNO cycle in X-ray bursters or common envelope systems, the latter being a likely precursor of neutron star mergers. The determination of the alpha transfer cross-section to a specific resonance in ^{19}Ne will allow to determine the conditions under which the thermal runaway commences, and the conditions of the subsequent rp-¬process. On the side of nuclear structure, an experiment involving the unique ^{3}He target system integrated in MUGAST will be performed, with the goal of extracting the amount of proton excitations and clarify the role of the neutron-proton interaction in ^{47}K, by probing directly the proton wave functions through the proton transfer reaction (^{3}He,d) induced by a SPIRAL1 beam of ^{46}Ar.

For 2020, MUGAST was again set as priority to run with AGATA in the GANIL call for experiments. An experiment accepted at the last GANIL PAC investigating anomalous dripline location in Oxygen isotopes, and the suggested role of 3-body forces will be performed. In this pioneering work, a lifetime measurement of the 2^{+}_{2} and 3^{+}_{1} states in the neutron-rich nucleus ^{20}O will be performed using the Doppler Shifted Attenuation Method, after selective population of the states of interest using the ^{19}O(d,p) reaction. Further transfer reaction experiments has been recently discussed during the AGATA pre-PAC meeting in view of submission to the forthcoming PAC meeting to be held in October 2019.

3- Medium energy stable beams from CSS1

A- Experimental program with VAMOS

The recent developments of the detection systems of the VAMOS++ large acceptance spectrometer towards an improved identification coupled with the heavy stable ion beam of GANIL allow unique studies in the field of fission dynamic and structure of heavy nuclei (from lead to neutron rich actinides).

In the last 5 years, several upgrade of the detection system (including large size position sensitive Multiwire Proportional Chambers, high pressure ionization chamber), electronic readout (Upgrade to digital electronics) and trajectory reconstruction methods have been carried out. These resulted in an improved identification in terms of atomic charge (1/70) and mass resolutions (1/500) but also in an increased counting rate capability.

a) Multi Nucleon Transfer in heavy neutron-rich nuclei

An ideal set-up for perform Multi-Nucleon-Transfer and, in particular, in-beam nuclear structure studies of n-rich heavy species is provided by the large solid angle magnetic spectrometer VAMOS in combination with the multi-detector γ-tracking array AGATA. The mass resolution of ΔA=1/500, recently achieved for VAMOS, together with a Z identification by X rays or complementary fragment measurement should provide the necessary identification in A and Z to extend isotope-tagged γ-ray spectroscopy.

Such studies using Multi-Nucleon Transfer (MNT) could cover the following topics :

1) Observation of octupole phonon in the ^{208}Pb region using lifetime measurements in the ^{207}Pb and ^{209}Pb.

The population of high spin state in the MNT is a unique opportunity to study the occurrence of octupole phonon states. The measurement of the mass of the heavy reaction product in conjunction with the AGATA spectrometer would allow a precise measurement of the lifetime of these states (using Recoil Distance Doppler Shift method) otherwise very difficult to populate.

2) Evolution the N=126 shell closure below Pb using MNT transfer.

It was shown at GANIL, that the MNT is a very competitive to populate neutron-rich heavy nuclei [Wat15]. These experimental finding corroborates for the first time recent predictions that multinucleon transfer reactions would be the optimum method to populate and characterize neutron-rich isotopes around N=126 which are crucial for understanding both astrophysically relevant processes and the evolution of “magic” numbers far from stability. Such an experiment would aim at the first spectroscopy of several neutron rich N=126 nuclei like ^{204}Pt or ^{202}Os.

3) The study of neutron-rich actinides and trans-fermium isotope :

The investigation of the region of the heaviest nuclei is one of the major challenges in nuclear physics. In particular, the unique feature of those species being stabilized only by quantum mechanics and so-called shell effects makes them an ideal laboratory to study, and to put constraints on our understanding of the strong nuclear interaction by spectroscopic means [Ack17]. Despite the recent success in synthesis of new elements, the perspectives to push the applied reaction scheme of fusion-evaporation even further are rather limited. In particular, neutron-rich actinides and trans-fermium isotopes cannot be produced in complete fusion reactions due to the lack of sufficiently neutron-rich projectile-target combinations. An alternative method to produce neutron-rich heavy systems has been proposed [Zag05, Zag06], with the use of deep-inelastic collisions of heavy nuclei. In an early chemistry experiment Schädel et al. [Sch78, Sch82] could observe the production of isotopes from Pu to Fm in a cross-section range from mbar to nbarn in the reactions ^{238}U+^{238}U and ^{248}Cm. The neutron-rich part of these isotope chains reaches into close vicinity of the N=152 sub-shell closure. In a recent investigation of the reactions ^{70}Zn,^{136}Xe+^{238}U at the combination of the magnetic spectrometer PRISMA at LNL and the AGATA demonstrator a rotational band could be established up to 20-24 for ^{240}U [Bir15]. The heaviest uranium isotope, ^{242}U, for which the first 2+ state is known, is two neutrons away from N=152 [Ish07]. To extend the reach of this type of measurements to higher Z heavier actinide targets like e.g. ^{248}Cm will be required.

b) Study of the Fission Process

1) Main challenges in the fission process studies

Nowadays, fission can only be studied through the measurement of the initial characteristics of the fissioning system and the final characteristics of the fission products. However, the accurate determination of a wide set of these properties is difficult: Fixed target installations, such as n_TOF/CERN or NFS/Spiral2, can perform an accurate determination of the initial excitation energy but cannot perform isotopic identification of the fragments. Inverse kinematics at high energy, employed in SOFIA/GSI, can identify the fragments in mass and atomic number but with a coarse assignment of the initial excitation energy and a poor resolution in the fissioning system reference frame and the scission point. Only inverse kinematics at Coulomb energies, as used in VAMOS/GANIL, can perform an accurate fragment identification and a precise determination of the initial excitation energy in the same setup.

The information about the atomic number and neutron content, and their correlation with other observables such as the initial excitation energy, is crucial to study the influence of intrinsic degrees of freedom and underlying nuclear structure on the fission process. In addition, the measured distributions of these observables are stringent tests for current fission models and theoretical descriptions.

However, these recent improvements are far from exhaust the experimental information that can be extracted from the fission process. In general, both the fissioning system and the emitted fragments can be affected by evaporation, which might change the mass and the excitation energy before and after the process. Experimentally, the evaporation can be address with neutron and gamma detection, as well as improved accuracy on the kinetic properties of the fragments.

Besides the challenges related with the measurement of fission observables, a full picture of the fission process can only be obtained with large systematics of accurate measurements for a wide range of fissioning systems, where the evolution of the influence of nuclear structure shapes the fragment distribution from symmetric to asymmetric fission. The development of new beam species and the use of different reaction channels is here a key to expand the collection of fissioning systems in both neutron and proton content.

2) Summary of recent results and strengths

At GANIL, the use of fusion-, transfer-induced fission is a well-established program. The VAMOS++ spectrometer provide a unique isotopic identification of the full fission fragment distribution, along with accurate kinematical information and a precise assignment of the initial excitation energy.

The combination of intense uranium beams and the use of transfer and fusion channels in inverse kinematics provides a unique opportunity to measure isotopic fission yields for systems heavier than uranium and for different initial excitation energies [Ram18]. These measurements are complementarity to the results from SOFIA/GSI, which, together with VAMOS/GANIL, are the only fission campaigns able to measure full isotopic fission yields: whereas SOFIA/GSI explores neutron-deficient systems below uranium, VAMOS/GANIL explores neutron-rich systems above uranium with a larger range of excitation energy.

The campaign VAMOS/GANIL was first to provide complete isotopic fission yields [Caa13], comprising atomic numbers and post-evaporation masses and neutron content fragment distributions. The correlation of these observables was used to present the study of the N/Z as a new parameter, sensitive to nuclear structure. In addition, these measurements were done for a wide collection of systems and controlled excitation energies. Such collection of observables allowed to explore the fission dynamics, the survival of structure effects [Ram19], and to reconstruct the fragment masses at the scission point and the neutron evaporation from low to high energy fission [Caa15]. These results are also unique in extracting the energy balance partition between the fragments and rendering the potential surface at scission available from experimental measurements [Caa17]. Fission barriers were also studied with the evolution of the fission probability with the initial excitation energy [Rod14]. In general, every observable measured in the campaign can be explore as a function of the excitation energy [Ram17].

3) Proposed program

A possible program could consist of the following main topics:

1) Measurement of the kinetic energy for both fragments using VAMOS++ spectrometer in conjunction with the Second Arm of VAMOS. So far, the characteristics of fission fragments were measured for one fragment per fission event within VAMOS, and thus the reconstruction of properties such as the Total Kinetic Energy (TKE), the neutron evaporation, and the scission configuration was performed with average quantities. With the coincident measurement of both fragments, these properties can be determined with greater accuracy and in an event-by-event basis. While preliminary data was acquired for this setup, a dedicated program including the measurement in the $^{238}U+^{9}Be$ reaction would lead to the isotopic TKE measurement for a set of systems produced in different reaction channels (fusion: ^{247}Cf, alpha transfer: ^{242}Cm, neutron transfer: ^{239}U)

2) Continuation of the study of fission and quasi-fission using transfer- and fusion-induced fission: The use of several targets together with intense heavy-ion beams allows to widen the set of produced fissioning systems and the range of excitation energy. In addition, less asymmetric combinations of beam-target are prone to produce quasi-fission reactions, giving us the chance to apply the expertise gained with the fission campaign to study the same observables in quasi-fission reactions. The measurement of the emission angle in the reference frame of the compound system allows to study time evolution of any observable within the process. The evolution of the fragments atomic number, neutron content, and N/Z can be measured for the first time in the VAMOS/GANIL campaign.

3) Currently, the variety of systems that can be studied within the VAMOS/GANIL campaign is limited by two factors: the gap between uranium and lead beams produced at GANIL, and the targets that can be exploited in VAMOS. The first limit can be overcome with the development of thorium or radium beams, with energies around the Coulomb barrier. Concerning the targets, the mains limitation is the detection setup used to measure the target-like products in transfer-induced fission. So far, the setup is optimized for the detection of forward-emitted target-like particles. The use of lighter targets increases the probability of emission of the target-like recoils at large angles, and thus the need of a more versatile detection system around the target point. In addition, a wide variety of beams and targets would permit to measure fission from the same fissioning system but produced through different channels, allowing us to test the dependence of the fission characteristics on the initial conditions and the basic assumptions behind the use of surrogate methods.

B- Experimental program with VAMOS-GF

While VAMOS in a dispersive vacuum mode [Pul08] is the perfect tool for the mass and charge identification of reactions products away from zero degree (transfer products, fission fragments, ...), it is not adapted to reactions were the nuclei of interest are concentrated around zero degree, such as fusion-evaporation reactions. Indeed, for these reactions one has to evacuate the beam in order to allow the ions detection and identification. Unfortunately, this is not possible with a magnetic dipole only, due to the overlap of the beam and fusion-evaporation residues magnetic rigidities. This function can be realized with a combination of magnetic and electric fields, such as done with S3, or filling the apparatus with a low gas-pressure, thus providing a « gas-filled separator ».
The reversible upgrade of VAMOS as a gas-filled separator was guided by mainly two motivations. First VAMOS is a large acceptance device therefore a huge transmission is expected in particular for the heaviest elements leaving the target with a large angular distribution. The second motivation is related to the opportunity for its coupling with state-of-the-art gamma-ray detectors (the new generation gamma-tracking array AGATA [Akk12] and other arrays such as EXOGAM2, PARIS…).

The feasibility and the potential of VAMOS-GFS have been established in a test experiment performed in 2009 [Sch10]. Excellent performances in terms of fusion-evaporation residue transmission and background rejection have been obtained for the ^{40}Ca + ^{150}Sm collisions around the Coulomb barrier. Thus, the modifications required to transform the VAMOS vacuum spectrometer into a gas-filled separator, that were of provisional character during the test, were undertaken. These modifications have now been completed in a GANIL-CEA Saclay collaboration, making available to a widespread community a fully operational device, with the best performances for a large range of reactions and a smooth operation.
The physics case covered by the VAMOS-GFS includes all in-beam spectroscopy experiment where it is mandatory to physically filter the rare nuclei of interest lost in a huge background of parasitic reactions, plus eventually to tag the nuclei using their characteristic decay (Recoil Tagging and Recoil Decay Tagging techniques). Besides the region of the actinides and Super-heavy nuclei, the foreseen experiments will also cover the ^{100}Sn region, nuclei at the proton drip-line, and the neutron-deficient lead region.
To give a flavour of the interest, Figure 7 summarizes the experiments gathered in a AGATA+VAMOS-GFS letter of intent by a community of ~ 200 physicists from ~ 30 laboratories, which shows that VAMOS-GFS project responds to a large demand from the nuclear scientific community.

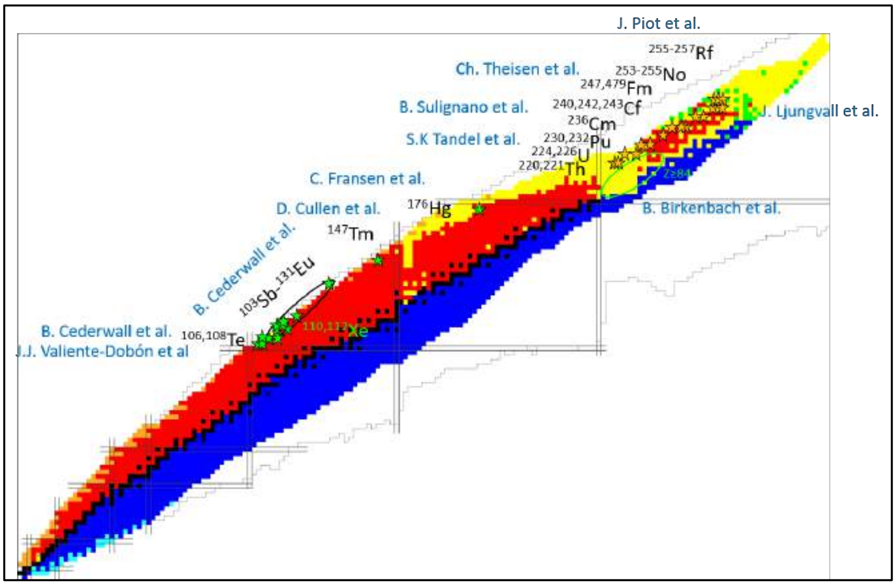

Figure 7 : Sample of nuclei of interest discussed, as discussed in 2016 within an AGATA+VAMOS-GFS LoI .

Besides fusion-evaporation reactions which concentrate the vast majority of the proposals, the deep inelastic reactions are of great interest. These reactions provide a promising tool for the population of a wide range of nuclei in the very-heavy and super-heavy region with sufficient high cross sections. Indeed, theoretical calculations [Zag15,Kar17] predict large cross-sections for neutron-rich heavy elements production close to zero degrees and recent experiments performed at GSI using decay-spectroscopy only [Nit18,Dev19] show exciting results and perspectives for in-beam spectroscopy.
In a longer term, fusion-evaporation reactions used in conjunction with exotic beams will permit to reach exotic isotopes, and/or still un-explored regions of the (angular momentum L, excitation energy E*) phase space. The interest in fusion-evaporation for reaction dynamics studies is obvious, giving access to the evolution of the system as driven by rotation and/or temperature.
It is important to stress that the VAMOS-GFS focal plane geometry (beam dump and detection) is versatile and optimized case by case to obtain the largest dispersion between the beam and the recoils and therefore the best rejection. This is not possible with any other gas-filled separator for which the detection is in the optics axis (fixed). The main peculiarities of VAMOS-GFS compared to its competitors are its large acceptance, the large range of reactions to be used (fusion-evaporation reactions with different asymmetries including possibly inverse kinematics, but also deep-inelastic collisions), and its coupling with the most efficient gamma-ray arrays.
The project, which is now ready for operation, is awaiting programming schedule. In a very competitive context with the AGATA strong attractiveness, we have not yet been able to be schedule. In addition, the project was launched when there were about 8 months of beam available per year, which is no longer the case. VAMOS-GFS has been designed using numerous simulations, it is possible to predict the transmission with a good level of confidence. However, the beam rejection factor which is the most sensitive point for the success of the experiments cannot be simulated. Therefore, commissioning a separator requires a long beam time and long-term work, not compatible with the current operation in conjunction with AGATA. We are confident the beam-time requirement will be met in a near future, providing a major tool for a large community in Europe and possibly beyond.

C- Fusion evaporation reactions

Stable ion beams at medium energy can also be used without magnetic spectrometer. As matter of example, fusion evaporation reaction with high intense stable beams at the Coulomb barrier is a powerful tools for the production of N~Z nuclei. Such measurements are performed with a large Germanium array (AGATA, EXOGAM), coupled to a neutron and charged particles arrays for tagging the reaction.

The GANIL had a significant contribution in the recent years in the field of the so-called "N~Z nuclei" where proton and neutron occupy similar orbits [ced11, zeh13, Gha14.1, Gha14.2, bos18, ert18]. Being self-conjugated nuclei, there are ideal for the study of specific aspects of the nuclear interaction such as the concept of isospin symmetry and the nucleon-nucleon pairing interaction. These nuclei are typically produced in complete fusion reaction of heavy-ions at the Coulomb barrier. The very exotic isotopes produced in the reaction are identified on the basis of the number of proton, alpha and neutron evaporated after the complete fusion. This program aims at performing high resolution spectroscopy of nuclei with N~Z nucleons from mass ranging from A~20 to 100. Such measurements are performed with a large Germanium array (AGATA, EXOGAM) for gamma-ray spectroscopy, coupled to a neutron (NEDA/NWALL) and charged particles arrays (DIAMANT) for tagging the reaction.

The isospin symmetry concept is based on the fact that protons and neutrons are nearly identical particles, and that nuclear forces are nearly charge independent. However, it is known that isospin symmetry is broken by the strong interaction. First observation of this concept of isospin symmetry breaking is visible in so-called "mirror nuclei", having same mass but for which the number of protons and neutrons is exchanged [bos18]. The isospin symmetry-breaking lead to each observed nuclear state having mixed contribution of T=0 and T=1 isospin. The amount of isospin mixing, as derived from experiment data (level scheme, electromagnetic properties), can be understood as a measure of the magnitude of the symmetry violation. The breaking of the isospin symmetry by the Coulomb force increases with Z and for a given mass it is at its maximum for N=Z nuclei. The study of the heavier nuclei with N≈Z is thus of fundamental interest and in particular beyond the *fp* shell where there is a lack of experimental data.

In this N=Z nuclei enhanced correlations arise between neutrons and protons that occupy orbitals with the same quantum numbers. Such correlations have been predicted to favour an unusual type of nuclear superfluidity, termed isoscalar T=0 neutron–proton pairing, in addition to normal isovector T=1 pairing. Such strong, isoscalar neutron–proton correlations would have a considerable impact on the nuclear level structure and possibly influence the dynamics of rapid proton capture in stellar nucleosynthesis. At GANIL, first evidence of the influence of this pairing channel was evidence in ^{92}Pd [ced11]. Systematic investigation of other N=Z nuclei from low to high spin, from level scheme to g-factor measurements are needed to provide high resolution constrains on the T=0 contribution. Indeed, evidence are never direct as there is a mix with the well-known T=1 pairing channel and its contribution is revealed by the comparison with high resolution spectroscopic data and advanced theoretical model.

Finally, the N=Z line is composed by the majority of the doubly magic nuclei and therefore are ideal to probe the shell evolution with few nucleons of valence. High resolution spectroscopy determining spin/parity of excited states by angular correlation measurement, reduced transition probabilities all along the N=Z line will give information on nucleon-nucleon interaction on the proton deficient isotopes [zeh13, Gha14.1, Gha14.2, ert18].

The development of the AGATA array towards 4π will allow reaching more and more exotic N=Z nuclei. AGATA coupled to 1π neutron detector and a charged-particle array will allow spectroscopy towards doubly-magic ^{100}Sn, to determine transition probabilities by lifetime measurement up to ^{96}Cd and angular distribution and polarization measurements up to ^{92}Ru.

4- High energy stable beams from CSS1+CSS2

a) Density dependence of the symmetry energy

The density dependence of the nuclear symmetry energy will be accessed with a number of observables, including binary dissipative reactions around the Fermi energies. The INDRA-FAZIA array can fully measure the mass number for the reaction products emitted in such dissipative reactions (projectile-like fragments, IMFs with Z>3, light charged particles). This will allow performing high quality studies of isospin drift, occurring through the low density neck region, and isospin diffusion driven by the N/Z difference between colliding projectile and target nuclear systems. These investigations, already started with the first INDRA-VAMOS campaigns and now continuing with the ongoing INDRA-FAZIA array, need to be extended to a wide range of systems in order to better constraint the density dependence of the symmetry energy. State-of-the-art microscopic models will be improved thanks to the possibility of comparing their predictions to new observables measured with the FAZIA array.

b) Radial flow measurements

The path of nuclear colliding nuclei towards the low density region of the EoS is made possible by the radial flow phenomenon occurring in central collisions at GANIL energies. Mean kinetic energies of emitted fragments contain a thermal and a radial collective contribution. Thanks to the detailed measurement of their kinetic energies and the capability of identifying them in mass with FAZIA, it will be possible to deduce the velocity of this fragments and that of the radial motion. This quantity is linked to the incompressibility of nuclear matter around saturation density and allows to better understand the dynamical and thermodynamic properties of the studied systems.

c) Vaporization and EoS at very low densities

Vaporization of hot nuclei consists of their complete explosion into light particles (neutrons and Hydrogen and Helium isotopes). The yields and the average kinetic energy of the different species suggest that a reasonable degree of thermodynamic equilibrium has been achieved. In the last decade, many improvements have been made from the theoretical side in order to describe the mixing of clusters in a low density nucleon gas at finite temperature. These developments have been motivated by the modeling of core-collapse supernova matter, particularly the composition of the neutrino-sphere which is the warm low-density nuclear matter region where the last scattering of neutrinos occurs. Since neutrinos carry most of the supernova energy and their dynamics is believed to trigger the supernova explosion, a precise understanding of the energetics and composition of matter at high temperature (~5 MeV) and low density ($\sim\rho_0/10$) is of foremost importance for the astrophysics of dense objects. Furthermore, the so-called neutrino wind passing through the neutrino-sphere induces important nucleosynthesis phenomena. The kinetic energy of neutrinos and their opacity in the neutrino-sphere dependeof the EoS of this very low density nuclear matter region
Collisions induced by high-energy neutron-rich beams will profit from the the performance of the FAZIA telescopes in terms of angular and isotopic resolution to extend vaporization measurements to neutron-rich sources. With the measurement of mass (A) and charge (Z) up to calcium/nickel, we will be able to study the continuous evolution between multifragmentation and vaporization and also generalize the definition of vaporization as a mixing of clusters (clusterization) in a low density nucleon gas at finite temperature.

5- Interdisciplinary researches

The interdisciplinary researches at GANIL can be defined along different topics whose objective is to study the mechanisms of ion – atom collisions, their consequences on the atomic arrangements, on the physical and chemical properties, no matter what is the atomic arrangement. Also the target consist of atoms, molecules (biologic or not), clusters, surfaces and materials of all types. These researches are mainly focused on the effects of the electronic excitations produced by multi-charged ions whatever it is at high- or low-velocity [http://iopscience.iop.org/1742-6596/629/1]. Until 2008, CIRIL (Centre for Interdisciplinary Research with Heavy ions) was the name of the laboratory that lead the interdisciplinary research at the GANIL facility, since a clusterization with other research teams of Caen, a larger laboratory is born under the name CIMAP "Centre of research on Ions, MAterials and Photonics", where CIRIL is one of the teams, in charge of the GANIL interdisciplinary research user platform.

Since 1983, because of the exceptional opportunities offered by GANIL, CIRIL has continued to invest for the benefit of the interdisciplinary research community. First, by increasing the number of beam lines devoted to interdisciplinary research: the medium energy beam line in 1989; a very low energy beam line, with multi-charged ions delivered by ECR sources (LIMBE in 1999 extended to ARIBE in 2005); IRRSUD (meaning irradiation toward south) line built in 2004 taking advantage of the "free" compact cyclotron for material irradiation. Since 2005, CIRIL has therefore experiment stations in all the acceleration steps of the GANIL ions: ARIBE at the ion sources, IRRSUD after the first cyclotron (C0), SME after the second cyclotron (CSS1) and D1 at full energy. Secondly, by developing unique in-situ instruments (online X-rays diffraction, AFM in UHV condition, time-resolved optical spectrometer SPORT, IGLIAS setup: ultrahigh vacuum chamber equipped with a cold head which provide the possibility to prepare samples of simple or mixed ices (up to four components) and the analysis of irradiation or thermal effects by both infrared and UV-visible spectroscopy, COLIMACON, ….and many others).
The research area of interdisciplinary research at GANIL facility is the study of excited matter and radiation damage including:

- interaction of ions with dilute matter ranging from isolated molecules to atomic or molecular clusters;
- fundamental developments in the science of materials submitted to dense excitation with swift heavy ions or slow multi-ionized ions;
- characterization of radiation-induced defects in various materials and their consequences on the physical and chemical properties;
- theoretical approaches to simulate phenomena occurring in excited materials;
- development of new material by irradiation, nanostructuration, ion-beam shapping
- radiobiology

Interdisciplinary research at GANIL facilities cover a broad range of topics and in order to get a comprehensive approach of ion/beam interaction the use of different beamline at different energy is crucial. One of the major strength of GANIL facility for our community is the choice of ion species and energy range (HE, SME, IRRSUD and ARIBE; from a few hundreds of eV to GeV), which permit to deliver a broad range of ENSP (electronic to nuclear stopping power ratio) and many kinds of charged ions. It is also important to maintain such an offer to give to the interdisciplinary community sufficient ion beam time access to build ambitious and diverse research programs.
Concerning the specific case of radiobiology, related to hadrontherapy, GANIL is one of the few places in the world where researchers could find a large range of ions (C, Ne, Ar) at an energy high enough to reach the cells in there feading liquid, together with a specially developed sample holder (designed and constructed by CIMAP) as well as a fully equipped biology laboratory hosted in CIMAP building. These exceptional conditions attract several national and international teams and are one of the reasons why Caen has been chosen to host the future C-400MeV cyclotron of CyclHad.

6- Industrial applications

A- Mid-term perspectives for industrial applications with the G41 beam line

a) Description of the G41 activity

G41 beam line is dedicated to industrial applications. The two main fields for these applications are:

- irradiations of electronic components and systems for tests and certification for aerospace uses
- microporous (and nanoporous) membrane R&D and production for various uses

Medium energy (CSS1) and high energy (CSS2) beams are used for these applications, and the irradiations are performed in the air, which allows very rapid changes of systems and samples.
The companies testing electronic components and systems come to Ganil for Single Event Effects testing with high energy and high LET heavy ions (from Kr to Pb or U).
For the membrane R&D and production, the main and important advantage of Ganil beams lies on the beam intensity stability, which is a major criterium as far as pore homogeneity is concerned.
A team of 6 expert operators is dedicated to these experiments, they run 8 hour shifts together with the industrial users, in order to offer a permanent technical support to the teams who pay for the beam time.
During standard operation periods (9-10 months a year), the aerospace companies come usually twice a year, with six months in between 2 experiments. Presently, with one 3-4 months operating period per year, coming twice a year is very constraining, and most of them come once a year and go to other facilities (USA) for the second test period. The beam time allocated to electronic components tests has thus been reduced to 20-25 UTs these last 2 years, instead of 30-40 UTs in the preceding period. Moreover, the industrial companies have to know the number of beam periods before the end of the year preceding their experiments, for budget reasons.
As far as the membrane production is concerned, Ganil had several large volume demands these last years (15 UTs as a whole), which led us to consider the possibility in the future to produce microporous membranes with the CIME cyclotron. The goal would be to allocate more beam time for space industry applications, from which demand is higher that beam availability, and to run membrane production in parallel to nuclear physics experiments.

b) Perspectives

A development program was started in 2015 with a Chinese medical company, in order to go progressively towards the production of large quantities of microporous membranes. The production tests are very positive in terms of pore density homogeneity, and some very preliminary studies were performed considering the use of CIME cyclotron for the membrane production (mechanical study, machine study with CIME beam).
Moreover, the use of microporous and nanoporous membranes is growing, with the development of many new applications in various domains, in particular in the energy domain or water desalting field. A market study on the membrane production with the use of ion beams in thus being started in the frame of the European Project IDEAAL, in order to evaluate the interest to have a dedicated facility (with CIME cyclotron when not operating for radioactive beams) and its rentability. A business plan on this subject will be delivered at the end of the IDEAAL project. As a first step, the experimental room would remain the same (G4 cave), thus keeping strong operation constraints; subsequently, in order to have large scale industrial contracts, the idea would be to place the irradiation set-up either at the exit of the CIME cyclotron or in a new irradiation cave. These studies could be carried out after the end of the IDEAAL project, if the market study is promising, and it would be an ideal subject to study and build in collaboration with a company.

7- Indicators

a. Number of experiments and beam time availability

The number of accepted/rejected experiments between 2008-2018 is presented in Fig. 8. The ratio of accepted/proposed experiments is typically around 0.5.
The number of hours of beam available for physics is potted in Fig. 9. The operating rate is 93% on average, and stable over the years. To keep the failure rate below 10% a dozen technical support teams are available on-call 24 hours a day during operation, covering all the technical fields of GANIL (electricity, fluids, ventilation, computing, etc.) Let us note that the GANIL cyclotrons are running only 4 months per years during the past few years. This decrease beam time is mainly due to the choice

made by the GANIL directors following the request of GANIL funding agencies to concentrate efforts on the construction of SPIRAL2.

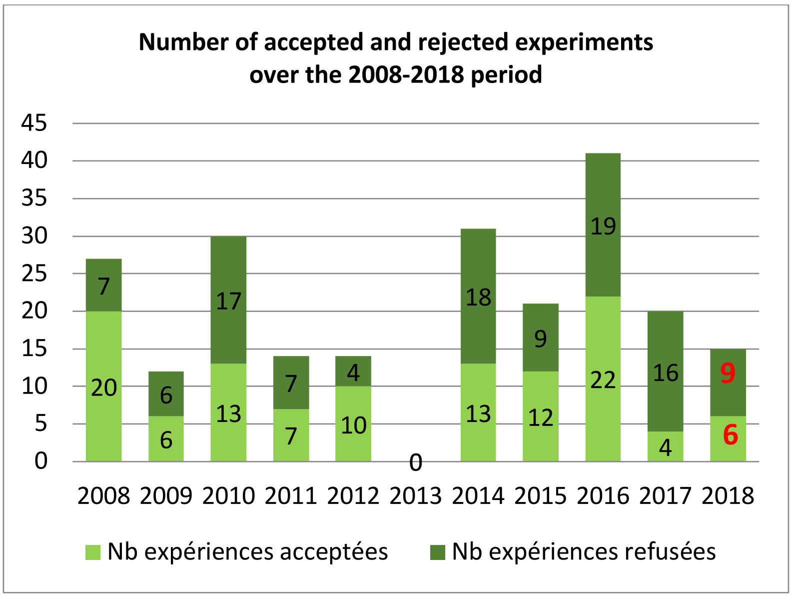

Fig. 8 : Number of accepted and rejected experiments over the 2008-2018 period

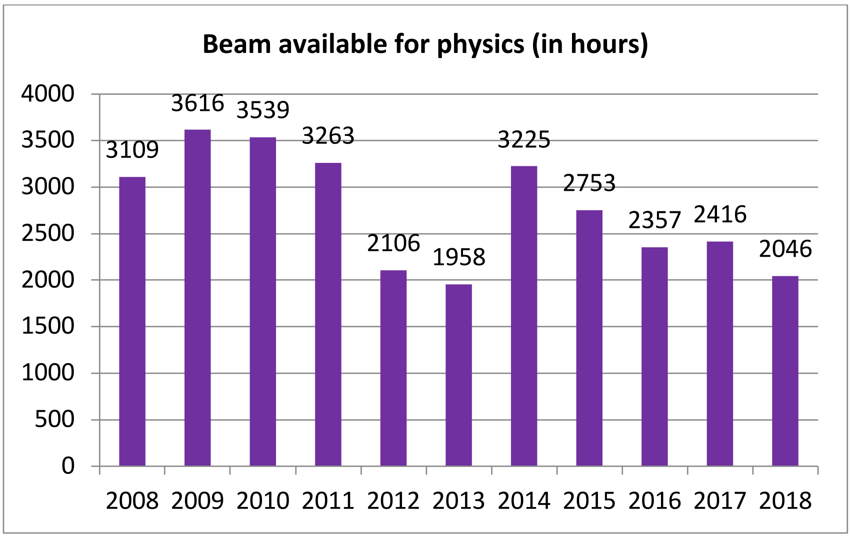

Fig. 9 : Number of accepted and rejected experiments over the 2008-2018 period

b. Scientific production

During the last period of the HCERES review (1st of January 2011 – 31th of June 2016), the GANIL physics group was involved in 351 papers in peer-reviewed journals and 325 in conference proceedings, see Fig. 10. In the period 2017-2018, the GANIL physics group was involved in 150 papers in peer-reviewed journals and 109 in conference proceedings

The analysis based on SciVal® shows the high impact of the publications: 1.75% of the papers reach a number of citations which places them among the top 1% of the most cited papers, and 12.5% are among the top 10%.

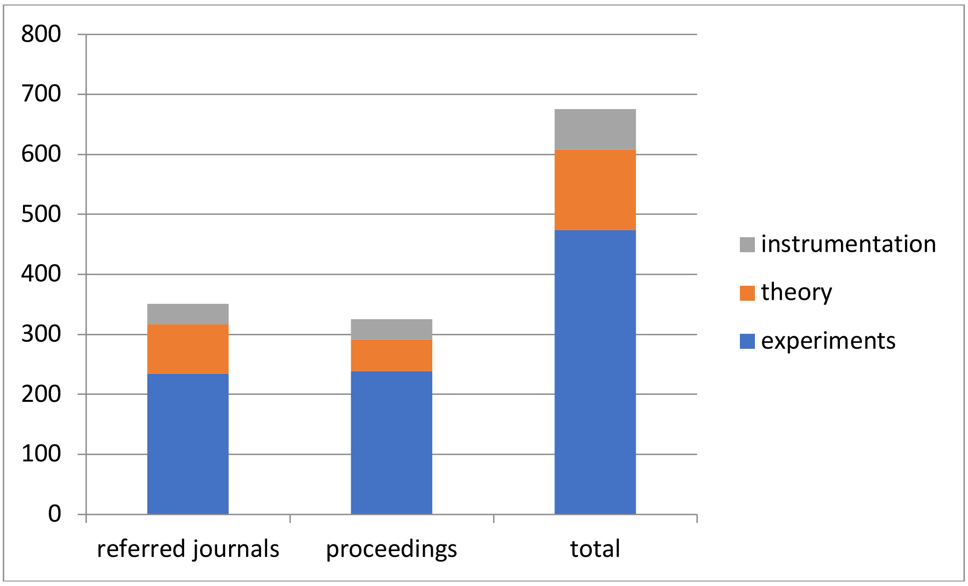

Fig. 10 : Number of publications depending on the topic

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