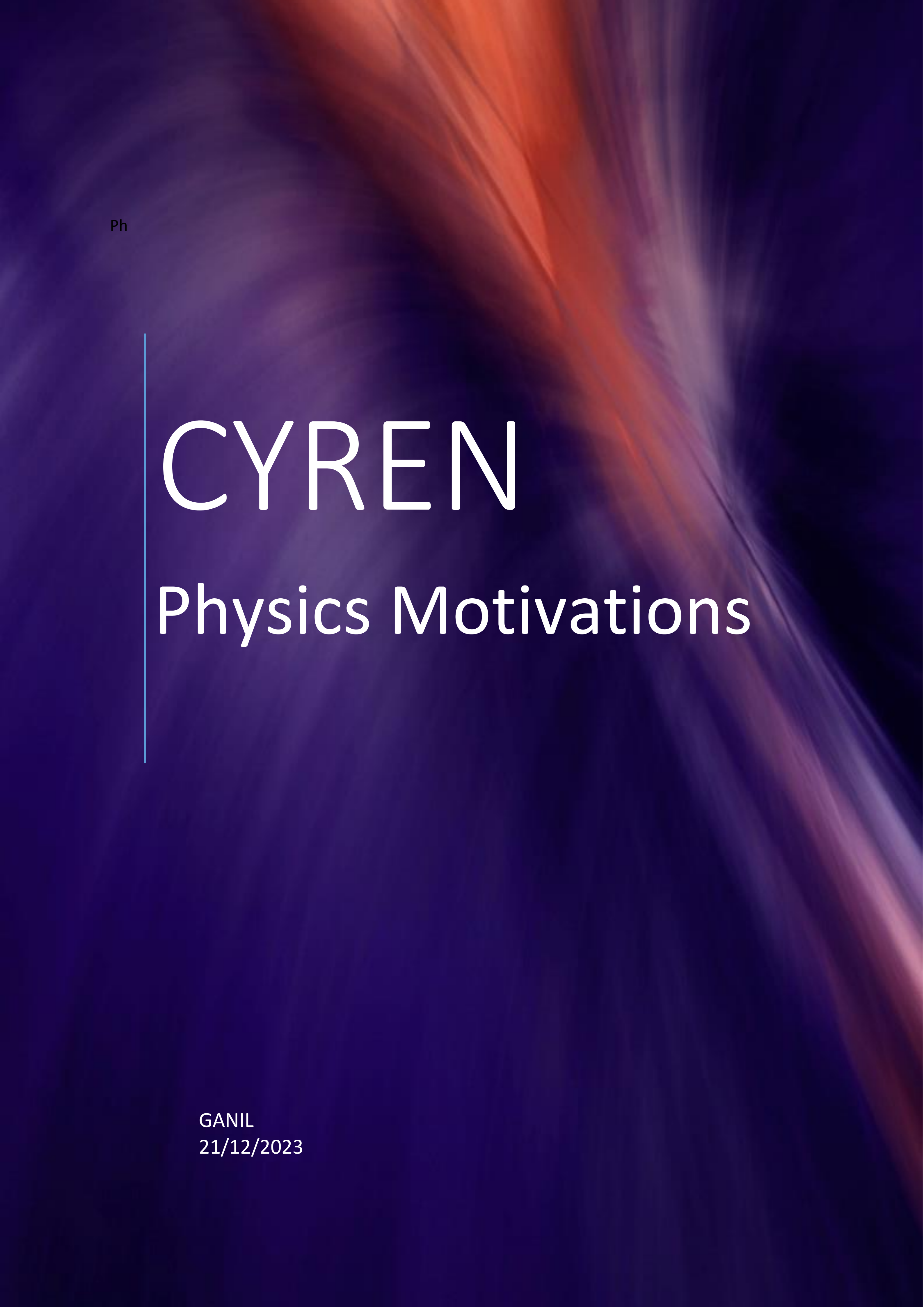

Ph

CYREN

Physics Motivations

GANIL
21/12/2023

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Introduction

GANIL's cyclotrons deliver ion beams ranging from carbon to uranium, with energies covering a range from 0.25 to 95 MeV/A, depending on the desired accelerator-beam combination. These beams are guided to experimental areas where dedicated and varied detection systems are installed. Users of these beams can be broadly divided into two main physics fields: nuclear physics and interdisciplinary physics. For these communities of physicists, GANIL's cyclotrons are indispensable tools for carrying out diversified research programs such as, in nuclear physics, the structure and production mechanisms of heavy nuclei, the shapes and symmetry of nuclei, the structure of nuclei at the limit of their existence, the study of reaction mechanisms and nuclear dynamics, nuclear astrophysics and physics beyond the Standard Model. One of GANIL's unique features is SPIRAL1, which can take full advantage of its upgrade thanks to the very high intensity of the primary beams available. The use of radioactive beams from SPIRAL1 (post-accelerated or not) is one of GANIL's assets that needs to be developed, but this can only be done if cyclotron operation is secure. One consequence of this is, of course, the DESIR scientific program, part of which also relies on SPIRAL1 beams. For the decade following its start-up (2027-2037), these beams will be essential for conducting ground-breaking experiments not only in the field of fundamental symmetries and interactions, but also for measuring the masses of exotic nuclei to probe shell closures far from stability, and for studying exotic modes of radioactivity at the limit of matter's existence, such as $\beta-$(x)p decay.

An extensive fission program is also underway at VAMOS using CSS1. Light nuclei produced by fragmentation at LISE may also be close to the dripline, and studies of near-threshold transfer reactions are relevant to both nuclear structure and nuclear astrophysics. Finally, and without being exhaustive, one can also mention studies of the thermodynamic properties of hot, dilute nuclear matter with high neutron-proton asymmetry, an essential ingredient for understanding compact astrophysical objects (neutron star, supernova). As far as interdisciplinary physics is concerned, apart from molecular and atomic physics whose activities are mainly carried out at ARIBE, the themes concerned are the study of inorganic and organic materials, astrochemistry and radiobiology. The community of physicists working in these fields is very strong at GANIL, and the trend is growing. The needs of these two communities are therefore similar, with the need for beams of varied nature and covering a wide energy range, more beam times and for interdisciplinary physics on a regular basis, varied and high-performance instruments and finally the generalization of parallel/auxiliary mode operation. All these fields of research require optimal cyclotron operation.

1. Nuclear physics

1.1. Fundamental interactions

Since the 1930s, the theory of the weak interaction has been progressively built up and refined through a large number of experiments probing the fundamental symmetries of the nuclear beta decay process. Despite the successes of the Standard Model of elementary particles, in line with the experimental tests carried out to date, there are still clear indications of the existence of a new physics manifesting itself at a different energy scale. These include the problems of dark matter, mass hierarchies, matter/antimatter asymmetry, etc. In this context, the study of nuclear beta decay via high-precision measurements is today a tool of choice to search for signs of this physics beyond the Standard Model, or to better constrain some of its hypotheses. This approach, which complements the high-energy experiments carried out at the LHC, is mainly implemented at ISOL-type facilities providing radioactive beams that are both intense and pure, well suited to the targeted precision measurements.

The questions addressed in this framework can be classified into three research themes: i) the search for exotic weak interaction currents of scalar (*S*) and tensor (*T*) types, ii) tests of the unitarity of the CKM matrix and of the CVC (conserved vector current) hypothesis, iii) the search for time-reversal symmetry-violating processes.

1.1.1. Exotic currents and correlation measurements

Two of the main hypotheses that formed the foundations of the Standard Model - maximum parity violation and the vector (*V*) axial-vector (*A*) character of the weak interaction - are partly the result of detailed studies of the nuclear β-decay process. The β decay spectrum reveals various correlations between kinematic variables, the precise measurement of which makes it possible to constrain the nature of the interaction. To solve the "τ–θ puzzle", the hypothesis of a weak interaction violating parity was put forward in 1956 by Lee and Yang. The following year, Chien-Shiung Wu and his team provided experimental confirmation of this hypothesis, by measuring the β emission asymmetry in the decay of polarized ^{60}Co nuclei. This asymmetry, usually referred to as A_β , is an angular correlation between the direction of electron/positron emission and the spin of the nuclei. In 1958, Feynman and Gell-Man formulated the *V* - *A* theory. The nature of the interaction was finally confirmed in 1959 by Allen et al., who measured the $\beta - \nu$ angular correlation, $a_{\beta\nu}$, after various controversial measurements, in the decay of ^{6}He, ^{19,23}Ne and ^{35}Ar nuclei. The neutrino's negative helicity was determined by Goldhaber et al. by studying the decay of ^{152m}Eu.

In general, the existence of exotic currents of scalars (*S*) and tensors (*T*) can be respectively constrained by the measurement of correlations in Fermi- and Gamow Teller-type transitions. At GANIL, measurements of the β–ν angular correlation ($a_{\beta\nu}$) to an accuracy of the order of 1% were carried out from 2005 to 2013 by the LPCTrap experiment. Analysis of the latest experiments, using SPIRAL1 beams ^{6}He, ^{35}Ar and ^{19}Ne, should provide competitive constraints for this type of measurement on the existence of tensor and scalar interaction. More recently, a measurement of the Fierz interference term (b_F) deduced from the β spectrum of ^{6}He has been undertaken as part of the bSTILED project. Aiming for an accuracy of a few ‰, this experiment should be highly sensitive to the existence of *T* interaction.

At DESIR, the MORA trap (see 1.1.3) will enable the measurement of $a_{\beta\nu}$ for mirror nuclei. For these transitions, the correlation value can be used to determine the Fermi / Gamow Teller mixing ratio, under the assumption of a purely *V*, *A* interaction. With correlation measurements performed to the per-mile, the Ft values of corrected mirror transitions would achieve an accuracy on the absolute value of the first CKM matrix element, $|V_{ud}|$, almost equivalent to those of $0^+ \to 0^+$ transitions ($\sim 6 \cdot 10^{-4}$, see 1.1.2). Conversely, by making the CVC assumption (constant corrected Ft value for mirror transitions, and consistent with that deduced from $0^+ \to 0^+$ transitions, see 1.1.2), these measurements enable the search for tensor or scalar exotic currents in β-decay. These measurements concern ^{21}Na, ^{23}Mg, ^{29}P, ^{33}Cl, ^{37}K, ^{39}Ca and ^{41}Sc nuclei.

1.1.2. CVC tests and determination of $|V|_{ud}$

Combined measurements of Q_β (mass difference between parent and daughter nuclei), half-life and branching ratio of super-allowed Fermi-type beta decays $0^+ \to 0^+$ provide the most accurate test of the weak current vector conservation hypothesis (CVC hypothesis). In this hypothesis, by analogy with the theory of the electromagnetic interaction, the vector current is not influenced by the strong interaction and is therefore identical whatever the emitting nucleus. Consequently, the strength of these purely vector transitions, noted Ft, must be independent of the nuclei involved, after Z-dependent radiative corrections linked to nuclear structure and the non-conservation of isospin by the strong interaction are taken into account. If CVC is confirmed, then we can deduce the value of the vector coupling constant G_V, related to $|V_{ud}|$, the most important element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. This matrix element plays a crucial role in testing the unitarity of the first row of the CKM matrix, another basic assumption of the Standard Model. A deviation from unitarity would be evidence of new physics beyond the Standard Model, involving a fourth flavor of quarks, or a charged Higgs boson.

With the CVC assumption currently satisfied at the level of $6 \cdot 10^{-4}$, the Ft values of these decays provide the most accurate measurement of the $|V_{ud}|$ element of the CKM matrix. This precision on $|V_{ud}|$ today depends largely on the uncertainties and systematic effects associated with the calculations of the radiative corrections mentioned above. These corrections can be tested by extending the list of candidates used for the determination of $|V_{ud}|$ (currently 15 nuclei, from ^{10}C to ^{74}Rb). A large part of this program is planned for isotopes with masses above 80 at S3-LEB. However, a number of elements whose chemistry is favorable to the ISOL method at SPIRAL1, are likely to achieve competitive production rates for mass, lifetime and branching ratio measurements at DESIR. Parallel developments of target-source assemblies for fusion-evaporation (TULIP-type) and of a Nb target for fragmentation, both underway, open up interesting prospects for ^{10}C, ^{34}Ar, ^{18}Ne, ^{46}Cr, ^{50}Fe, ^{54}Ni, ^{58}Zn, ^{62}Ge, ^{66}As, ^{70}Br, ^{74}Kr beams, currently off the list for measuring $0^+ \rightarrow 0^+$ transitions participating in the determination of $|V_{ud}|$. Other light isotopes that can only be produced at SPIRAL1, such as ^{10}C whose Ft value is particularly sensitive to the existence of scalar currents, could be undertaken as part of dedicated developments (CaO target, Al_2O_3 for example for the ionization of CO molecules).

As mentioned in 1.1.1, the test of CVC and nuclear corrections can be extended to mirror nuclei, by determining the Fermi/Gamow Teller mixing ratios of transitions using precise correlation measurements with the MORA trap at DESIR. These measurements will be complemented by high-precision mass measurements ($M/\Delta M \sim 10^{-8}$) using the double Penning traps PIPERADE and MLLTrap. PIPERADE will also enable ultra-pure samples of the nuclei of interest to be prepared, so as to improve the precision of branching and half-life ratio measurements, with the aim of reducing uncertainty in Ft values associated with mirror transitions (Figure 1). SPIRAL1 production capabilities and the instrumentation available in the future DESIR hall will thus offer unique opportunities to test the CVC hypothesis and the unitarity of the CKM matrix using intense radioactive beams of ^{21}Na, ^{23}Mg, ^{29}P, ^{33}Cl, ^{37}K, ^{39}Ca and ^{41}Sc.

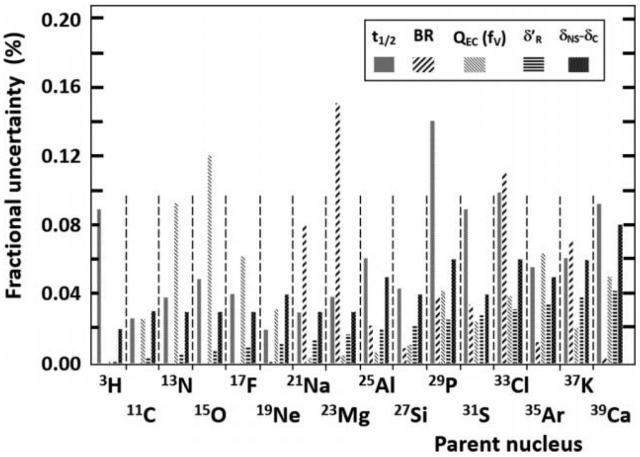


Figure 1: Share of experimental and theoretical uncertainties in the evaluation of Ft for mirror transitions up to A=39 (N. Severijns et al., Phys. Rev. C 107, 015502(2023)).

1.1.3. Time-reversal symmetry violation and the MORA experiment

The possibility of using laser polarization with DESIR trapping techniques will give access to correlations such as the β asymmetry, A_β (see 1.1.1), which is sensitive to exotic currents, and to the Fermi/Gamow Teller mixing ratio. It will also provide access to the triple correlation D, a non-zero value of which would be a sign of time reversal violation, and via CPT invariance, of CP violation. Precise measurement of D is the objective of the MORA experiment, whose experimental program has begun at Jyväskylä. A large CP violation, several orders of magnitude larger than that introduced in the Standard Model via the CKM matrix, is a necessary ingredient to explain the matter-antimatter abundance asymmetry observed in the universe. At Jyväskylä, the proof-of-principle of laser polarization is underway. The measurement of D, carried out from the nuclear β–decay of ^{23}Mg and ^{39}Ca, is currently encountering a difficulty: heavy contamination of the beams by the stable isobars ^{23}Na and ^{39}K. Various ways of reducing contamination are currently being tested. Once this difficulty has been overcome, the intensities available should make it possible to achieve a sensitivity of the order of 10^{-4} on a non-zero value of *D* which would push back the current limits deduced from the of the neutron β-decay. At DESIR, MORA will benefit from advanced purification facilities, and production rates more than two orders of magnitude higher (> 10^7 pps), at least for ^{23}Mg already produced at SPIRAL1. The ^{39}Ca beam is the subject of dedicated R&D. Under these conditions, measurement sensitivity should be improved by an order of magnitude, of the order of a few 10^{-5}. At this level, MORA will be sensitive to CP violation linked to the existence of Leptoquarks, or right-handed currents, complementing neutron electric dipole moment measurements. MORA will also, for the first time in this type of measurement, probe the so-called final-state interactions, sensitive to weak magnetism.

1.2. Mass measurement of neutron-rich light nuclei

The association of SPIRAL1 with the purification and preparation facilities for radioactive ion beams to be set up at DESIR offers a unique opportunity to study the evolution of nuclear structure as the imbalance between the number of protons and neutrons in the atomic nucleus increases. The availability at SPIRAL1 of stable ion beams naturally rich in neutrons, such as ^{36}S and ^{48}Ca, means that radioactive isotopes very rich in neutrons can be produced in the vicinity of shell closures at N=16, 20 and 28. These will be pre-selected using DESIR's high-resolution separator ($M/\Delta M \sim 2.10^4$), cooled and bunched using the GPIB radio-frequency quadrupole, before being injected into the first part of the PIPERADE ion trap for optimum purification. The second part of the trap will be used to measure the mass of ultra-pure isotopic samples with very high precision. Imaging techniques such as the PI-ICR (Phase-imaging ion-cyclotron resonance) method will be used to perform these measurements, provided their lifetime exceeds around fifty milliseconds and their intensity around ten particles per second. Increasing the intensity of the stable ion beams feeding SPIRAL1 and improving the performance of the ion sources used will thus be decisive for the study of the most exotic isotopes.

1.2.1. Disappearance of shell closure N=28

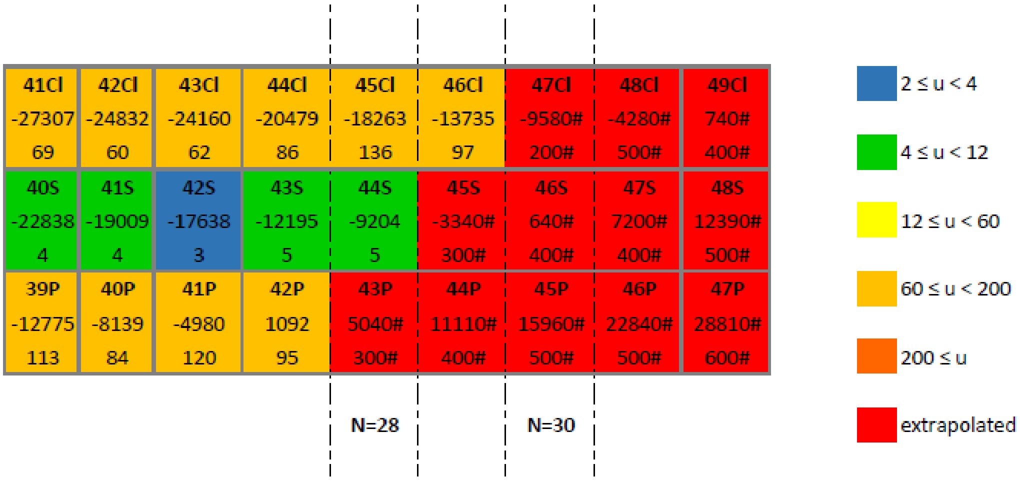
Studying the evolution of shell closures as they approach driplines is a powerful way of probing nuclear forces and refining the theoretical description of nuclear structure. Magic numbers associated with spherical shell closures can evolve far from stability. The special case of the spin-orbit magic number N=28 has been intensively studied in various types of experiments: decay spectroscopy, gamma-ray spectroscopy, isomer decay electron spectroscopy, transfer reactions, or mass measurements. These measurements have revealed a loss of magicity in nuclei below ^{48}Ca.

One possible interpretation for this evolution is that of an interaction between the collectivities induced by protons and neutrons: the addition of neutrons to go from ^{40}Ca to ^{48}Ca induces mixing of orbitals generating quadrupole excitations. On the other hand, removing protons reduces the attractive interaction between active orbitals, thus pushing back the f7/2 quantum level, reducing the N=28 gap and further promoting quadrupole excitations. However, it is possible that other effects, such as the 3-body force or continuum coupling, play a dominant role in these nuclei far from stability. The changes in nuclear structure in this region are therefore not yet clearly understood.

From mass spectrometry, we can derive the separation energy of two neutrons (S2n), an indicator of the evolution of the shell structure obtained by comparing neighboring nuclei. A more relevant indicator is the measurement of the gap itself, defined as the difference in neutron separation energies at, and two neutrons after, the closed layer: S2n(Z,N) - S2n(Z,N+2). The masses of the N=30 isotones are therefore needed to derive this quantity at N = 28. At Z=18, a recent mass measurement of ^{48}Ar showed a persistent gap at N=28, which would mean that the collapse below Z=18 could be even more abrupt than expected. As the masses of the N=30 isotones below Z=18 are still unknown, it will only be possible to clarify these questions by carrying out mass measurements, in particular the masses of ^{47}Cl, ^{46}S, ^{45}P.

More generally, and as can be seen from figure 2, the uncertainties in mass measurements are large (>50 keV) and do not allow a better understanding of the mechanisms involved in shell evolution far from stability, neither to constrain theoretical models. To achieve this, we need to measure the masses of $^{41\text{-}46}$Cl and $^{39\text{-}44}$P with an order-of-magnitude improvement in precision.

As sulfur is chemically reactive, it is difficult to produce in beam form using the ISOL method. Their mass is therefore measured by time-of-flight, where production is not limited by chemistry. Another possibility is to measure the mass of S isotopes by the decay of P isotopes in a trap. This technique was demonstrated at ISOLTRAP with the measurement of the mass of ^{34}Si after the decay of ^{34}Al.



41Cl -27307 69	42Cl -24832 60	43Cl -24160 62	44Cl -20479 86	45Cl -18263 136	46Cl -13735 97	47Cl -9580# 200#	48Cl -4280# 500#	49Cl 740# 400#
40S -22838 4	41S -19009 4	42S -17638 3	43S -12195 5	44S -9204 5	45S -3340# 300#	46S 640# 400#	47S 7200# 400#	48S 12390# 500#
39P -12775 113	40P -8139 84	41P -4980 120	42P 1092 95	43P 5040# 300#	44P 11110# 400#	45P 15960# 500#	46P 22840# 500#	47P 28810# 600#

Figure 2: Part of the nuclei map showing masses and measurement uncertainties (keV, AME2020). The masses of the N=30 isotones are all extrapolated (in red), while some masses of the N=28 isotones have large uncertainties. Both are needed to deduce the N=28 gap.

1.2.2. Proton-neutron interaction far from stability

Because of their particularly simple structure, the two nuclei ^{26}F and ^{22}N are unique examples for probing the pn interaction far from stability. The former has a neutron in the d3/2 orbital and a proton in the d5/2 orbital, while the latter has a neutron in s1/2 and a proton in p1/2.

The ^{26}F nucleus is a particularly suitable case for studying the various components of the proton-neutron interaction. The binding energies of the ground and excited states (1^+, 2^+, 3^+, 4^+) have been measured. These measurements were used to extract the interaction energy resulting from the coupling between the proton and the single neutron, and were compared with calculations performed within the framework of coupled cluster theory, using interactions derived from chiral effective field theory. The inclusion of the 3-body force and continuum coupling in the calculations reproduces the data very well.

However, the multiplet resulting from the d3/2-d5/2 coupling is based on the binding energy of the ^{26}F ground state measured by Jurado et al. It is very likely, however, that the atomic mass measured corresponds to a mixture of the ground state 1^+ and the isomeric state 4^+. Consequently, a new measurement of this mass is crucial to confirm the very good agreement between model and data.

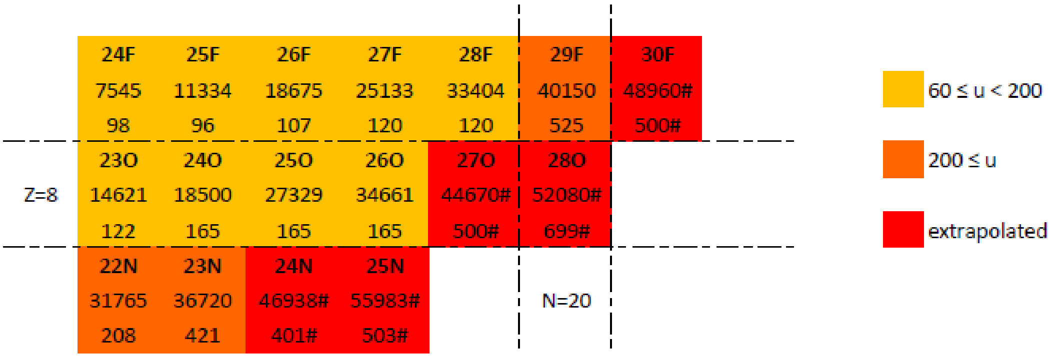
In the same context, the isotope ^{22}N was studied in order to extract the pn interaction force resulting from the coupling between the p1/2 proton orbital and the s1/2 neutron orbital. The advantage of this particular case is that the two-body spin-orbit force is more directly probed, since there is no tensor component. The interaction term $V^{pn}_{p1/2-s1/2}$ was determined using the ^{22}O kernel and compared with the same term extracted from the spectroscopy of ^{16}N. Assuming an $A^{1/3}$ dependence of the monopole interaction, the two values should be equal. However, the value obtained for ^{22}N turned out to be over 600 keV greater than that deduced for ^{16}N. As binding energies are well known in the neutron-deficient region, the most likely explanation for this discrepancy is that the masses used to extract the interaction, i.e. ^{22}O, ^{23}O, ^{22}N and/or ^{21}N, are not correct. In addition, the same calculation was made with a ^{24}O nucleus, resulting in a positive interaction force, i.e. a repulsive monopole interaction.

As nitrogen is extremely difficult to extract from ISOL sources, mass measurements of its isotopes (like S) are more suited to in-flight radioactive beam facilities. Oxygen and fluorine, on the other hand, are perfectly suited to a facility like SPIRAL1.

1.2.3. Search for new exotic phenomena

Measuring fluorine isotope masses as far from stability as possible is also of great interest in the search for two-neutron radioactivity or new halo nuclei. Extrapolating S2n to/beyond the neutron dripline gives a first indication of whether or not these phenomena exist. In both cases, the absolute value of S2n must be sufficiently low in relation to the centrifugal barrier. For two-neutron radioactivity, the last two neutrons must be unbound, i.e. S2n<0, while in the case of halo nuclei the nucleus is bound, i.e. S2n>0.

Figure 3 shows the region of the masses to be measured and the associated uncertainties. From ^{24}F, the uncertainty is already high. As far as oxygen isotopes are concerned, not only are the uncertainties large, but the values themselves are probably wrong.



	24F 7545 98	25F 11334 96	26F 18675 107	27F 25133 120	28F 33404 120	29F 40150 525	30F 48960# 500#
Z=8	23O 14621 122	24O 18500 165	25O 27329 165	26O 34661 165	27O 44670# 500#	28O 52080# 699#	
	22N 31765 208	23N 36720 421	24N 46938# 401#	25N 55983# 503#		N=20	

🟨 60 ≤ u < 200

🟧 200 ≤ u

🟥 extrapolated

Figure 3: Mass measurements and uncertainties (in keV, AME2020) in the neutron-rich fluorine isotope region. Masses in red are all extrapolated.

1.3. Nuclear structure and astrophysics

Understanding the properties of nuclei far from stability is a central theme of current nuclear physics. These properties are difficult to predict because the nuclear interaction is still poorly understood in many respects and the N-body problem is hard to solve. Exotic nuclei, rich in protons or neutrons, are also in the path of the astrophysical processes involved in nucleosynthesis, so studying their properties is essential for understanding the evolution of the universe from its origin to the present day.

Various methods are used to study these properties, starting with measurements of the static properties (masses, moments, half-lives, radii, etc.) of the fundamental or isomeric states. In this section, we discuss an approach based on the study of direct reactions, mainly transfer reactions induced by radioactive ion beams (RIBs) delivered to GANIL by SPIRAL1 and LISE.

Much of our current knowledge of stable nuclei comes from studies using direct kinematic reactions. In addition to the selective spectroscopy of nuclear states, these reactions provide crucial information on the wave function of the final states, which are populated thanks to their superposition with the initial states, and which are used as input data for the nuclear structure in cross-section calculations. The use of inverse kinematics, in which a beam of heavy nuclei interacts with a target of light ions (hydrogen or helium), opens up the possibility of extending these studies to more interesting and hitherto inaccessible isotopes, both stable and radioactive (all those with which it is possible to produce a beam).

Single-nucleon transfer reactions involving hydrogen isotopes are well-characterised probes of single-particle states (and their mixing), enabling excitation energies to be determined, spin and parity to be assigned, and spectroscopic information on the populated levels to be obtained. These are powerful tools for studying the evolution of the shell structure (Fig. 4). Stripping and pick-up reactions can be used to probe the occupancy of neutron orbitals beyond the Fermi surface. They also make it possible to measure the size of the gaps separating the shells, as well as their evolution as a function of the filling of neutron and/or proton orbitals. In addition, they provide direct access to components of the nuclear force, such as the central, spin-orbit and tensor parts.

Two nucleon transfer reactions, although more complex as a reaction mechanism, are the best way to study pairing correlations and in particular nuclear superfluidity. They can provide information on the collectivity or shape coexistence.

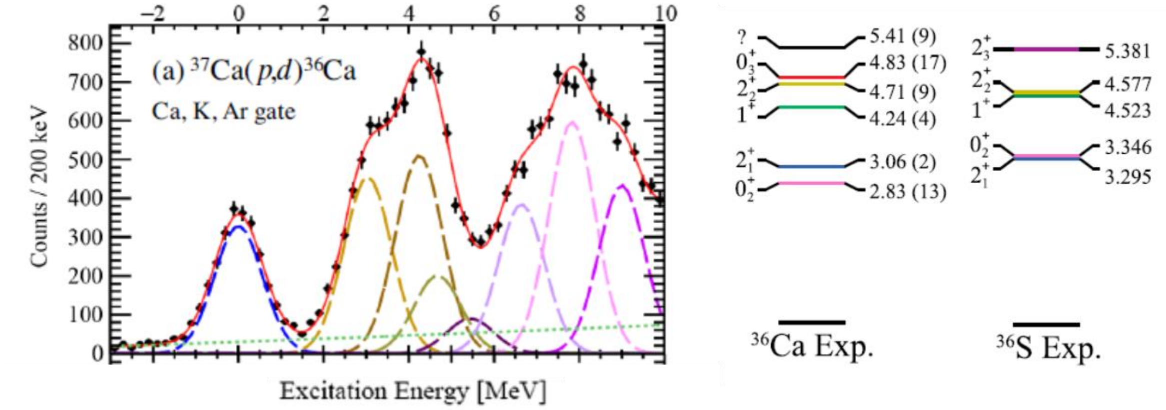


Figure 4 : (Left) Excitation energy spectrum of ^{36}Ca obtained from the (p,d) transfer reaction at LISE+MUST2. (Right) Compared to its mirror system ^{36}S, it has the largest MEDs ever observed. The present work is expected to serve as a benchmark case for ab-initio calculations that are supposed to rigorously treat all ISB effects of the nuclear force. L. Lalanne et al, Phys. Rev. Lett. 129, 122501 (2022)

More generally, exclusive measurements of charged particles, gamma rays and the heavy transfer residue using a spectrometer (typically the AGATA-GRIT-VAMOS coupling) give access to level schems (levels, lifetimes, branching ratios) and spectroscopic factors (Fig. 5). These observables can be used to study the shell structure and its evolution in light and intermediate mass nuclei. In this area, the high-resolution spectroscopy made possible by the AGATA-GRIT coupling is particularly promising, enabling us to probe the most elaborate theories (ab-initio, continuum-coupled shell model, etc.).

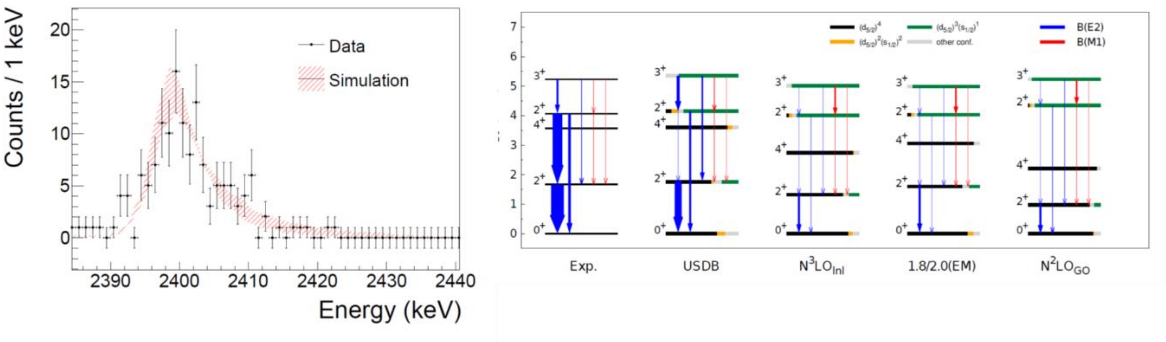


Figure 5: High resolution γ-rays spectroscopy of ^{20}O using AGATA-VAMOS-MUGAST and SPIRAL1. (Left) Excited states in ^{20}O are populated using the $^{19}O(d,p)^{20}O$ reaction at 8 MeV/u and the shape of the transitions corresponding to the γ-decay of the states is compared to simulation to deduce its lifetimes in the fs range. (Right) The deduced B(E2) and B(M1) are compared to state-of-the-art ab-initio calculations showing for the first time their spectroscopic accuracy. I. Zanon et al Accepted Phys. Rev. Let. (Nov. 2023)

The excitation energy and properties of single-particle and low-spin states often play a decisive role in the rate of thermonuclear reactions in astrophysical environments, which has an impact on the elemental and isotopic abundances produced in astrophysical phenomena (stars, novae, X-ray bursts, etc). The properties of states measured by nucleon transfer reactions make it possible to constrain the properties of certain states that are particularly important from an astrophysical point of view in order to be able to deduce reaction rates, and that are experimentally unreachable today (Fig. 6).

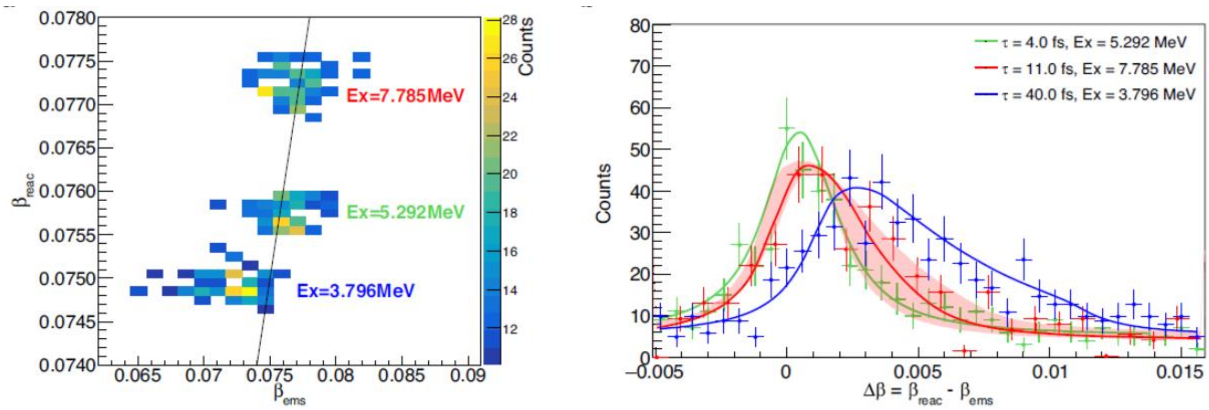


Figure 6: Study of the transition probabilities in 23Mg to probe the 22Na burning in astrophysical process. (Left) The ^{23}Mg velocity at the time of reaction ($^{24}Mg + {}^{3}He \longrightarrow {}^{27}Si^{*} \longrightarrow {}^{23}Mg + {}^{4}He$) is shown against the velocity at the time of the γ-ray emission in AGATA for three excited states. (Right) the corresponding angle-integrated velocity difference profiles for the three states compared with simulations (continuous lines). It shows unambiguously that the key state (in red) has a lifetime $4 < \tau < 40$fs. This transition rate constrains the astrophysical model to scrutinise with unprecedented precision the process of disappearance of ^{22}Na, a radioactive isotope of sodium. This isotope, which scientists hope to detect in the deflagration of novae, could play a key role in validating theories explaining how these colossal detonations take place. Ch. Fougère et al. Nature Communications (2023)

While inverse kinematics provides access to a greater diversity of radioactive nuclei, it comes with a number of experimental challenges, including low beam intensities, increased loss of resolution induced by the target, background noise from fusion-evaporation reactions (particularly from the carbon in plastic targets) and kinematic compression. Several detection strategies have been implemented to overcome, at least in part, these difficulties. Active targets compensate for low beam intensities by using a very thick target and reduce target-induced broadening by accurately reconstructing the vertex position. The elements with small atomic number Z of which they are composed offer low stopping power to light charged particles, giving access to very low energy detection thresholds. The simultaneous detection of particles and gamma rays makes it possible to discriminate between states that are very close in excitation energy, thanks to the very high-resolution detection of germanium gamma-ray detectors. Triple coincidence measurements using an additional zero degree detection also enable background noise to be suppressed by rejecting fusion-evaporation events.

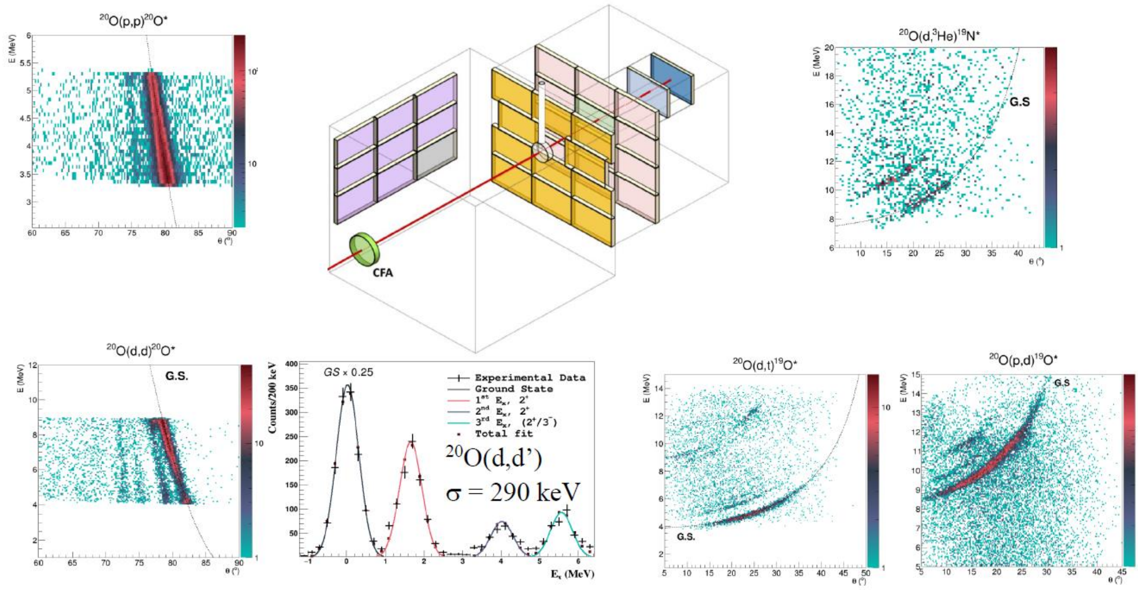


Figure 7: Transfer reaction with ACTAR using RIB (J. Lois Fuentes PhD thesis, U. Santiago de Compostella)

However, there are few light atom targets, which is a major obstacle. Single or double neutron transfer reactions such as (d,p), (d,t) and (p,t) can be carried out using either plastic (deuterated) targets (with the drawbacks mentioned above) or H^2 and D^2 gases for active targets (although mixed with a small amount of gas such as isobutene, Fig. 7). The ease with which these targets can be used has stimulated the study of neutron wave functions and thus, for example, the evolution of neutron shells, neutron capture rates or neutron-neutron pairing.

Homologous proton transfer reactions represent a real experimental challenge and have been a major obstacle to the study of the evolution of the proton shell structure. The (d,n) proton transfer reactions, which would enable progress to be made on studies of the evolution of proton shells, suffer from the difficulties associated with neutron detection (low efficiency and energy resolution, poor granularity for angular distributions). Transfer reactions (d,^{3}He), (^{3}He,d) and (^{3}He,p) represent the best alternatives for probing proton shells. Today, it is possible to detect and identify ^{3}He particles produced in (d,^{3}He) pick-up reactions by analysing the shape of the pulses delivered by new-generation silicon detectors, and projects are underway to develop sufficiently thick ^{3}He targets, whether gaseous or cryogenic, to study (^{3}He,d) and (^{3}He,p) proton stripping reactions. These developments, combined with the development of the SPIRAL1 and LISE beams, have made it possible to develop major scientific programmes, some examples of which are detailed below.

1.3.1. Evolution of proton shells in neutron-rich nuclei

The study of neutron shell evolution has shown that nuclear forces lead to a new paradigm in the existence of magic numbers: N=8, 20, 28 shell closures all collapse away from stability, while N=16 appears at both ends of stability. Are such drastic changes also present for proton shell closures, and if not, why not? This question can be answered by studying the evolution of single-particle states along isotopic chains such as those of Si or Ni by measuring the evolution of gaps at Z=16 and Z=28 and by studying the role of the spin-orbit and tensor components of the nuclear force in this evolution. These studies on the evolution of shell closures will be extended to the appearance of islands of inversion at N=40 and N=50.

1.3.2. Spectroscopy of unbound proton rich nuclei

The charge independence of the strong interaction is a fundamental assumption in nuclear physics. Properties such as energy, spin and parity, or spectroscopic factors should be identical in mirror nuclei due to isospin symmetry. The Coulomb interaction violates this symmetry, resulting in level shifts in proton-rich nuclei. Larger shifts occur in light nuclei and are associated with low angular momentum orbitals. This is known as the Thomas-Ehrman shift where the mirror asymmetry is induced by a weakly bound proton, particularly for nuclei where the outermost proton is in an s1/2 state. This symmetry breaking has been attributed to a weakening of the Coulomb potential due to the spatial expansion of an s-wave. Recent interpretations of this effect claim that differences in single-particle energies could lead to an asymmetry in the single-particle wave functions of neutrons and protons. A key nucleus in which this symmetry breaking could be studied is ^{25}P, which has a closed sd shell and a proton dominated by a 1s1/2 configuration. This nucleus is not yet known.

More generally, precision measurements in light nuclei close to or beyond driplines will make it possible to constrain ab-initio structure and reaction models, as well as to probe the influence of coupling to the continuum.

1.3.3. Neutron-proton pairing in N=Z nuclei

Pairing correlations are at the heart of superconductivity and superfluidity in strongly interacting N-body quantum systems. For most known nuclei, the superfluid states are neutron and/or proton pairs (nn or pp pairs) singlet spin (T=1). But in N=Z nuclei, the large overlap between the neutron and proton wave functions favours another type of Cooper pair made up of neutrons and protons (np pairs) of two different types: either spin singlet (T=1) pairs similar to neutron-neutron or proton-proton pairs or spin triplet (T=0) pairs, « deuteron-type pairs ». While the strength of the T=0 pairing is strong enough to bind a deuteron, the question of the existence of a superfluid state of neutron-proton pairs remains open.

Some indications are obtained from static observables such as the masses of odd-odd N=Z nuclei or rotational behaviour. But the most relevant approach is undoubtedly the neutron-proton pair transfer reaction. Indeed, the (p,t) and (t,p) pair transfer reactions revealed the superfluid behaviour of Sn isotopes and pair vibrations in lead isotopes near the closed shell. The same arguments apply to neutron-proton pair transfer.

In this case, two components come into play: the transfer of a T=0 pair and the transfer of a T=1 pair. Their relative importance is established by measuring the feeding of J=1^+, T=0 and J=0^+, T=1 levels in the residual odd-odd nucleus populated in the pair transfer reaction (stripping and pick-up) from an even-odd nucleus N=Z, (J=0^+,T=0). The (^{3}He,p) reaction, which has a positive reaction Q, is best suited to low-energy beams, while the (p,^{3}He) reaction, which has a very negative reaction Q, is only accessible with high-energy beams.

The N=Z≈64 region is the most promising for observing competition between the isoscalar and isovector channels. Although this region is out of reach, heavy proton-rich nuclei may favour the correlated phase due to the higher degeneracy of the orbitals involved. The next step would be to measure the two-nucleon transfer reaction ^{60}Zn(^{3}He,p), with the ^{60}Zn beam produced by the SPIRAL1 facility.

Another aspect of np pairing is the search for new types of pairing, such as aligned pairs. These aligned pairs on J=7 in the f7/2 layer can lead to a 7^+ state that could be identified by (^{3}He,p) transfer reactions.

1.3.4. Clustering and the generalised Ikeda conjecture

The narrow resonances of the α cluster states present in the ^{12}C and ^{16}O nuclei are essential to produce the refined ^{16}O/^{12}C ratio that allows life to develop in the Universe. On the basis of experimental observations, Ikeda conjectured the appearance of cluster states close to the corresponding emission thresholds in the nuclei. This phenomenon is thought to be a common feature of open quantum systems, and its existence has recently also been conjectured for two-neutron or two-proton clusters. The archetype of two-neutron clustering is the ^{11}Li halo nucleus, whose ground state is about 300 keV below the emission threshold of two neutrons. Several other cases have recently been discovered, as shown in Figure 8.

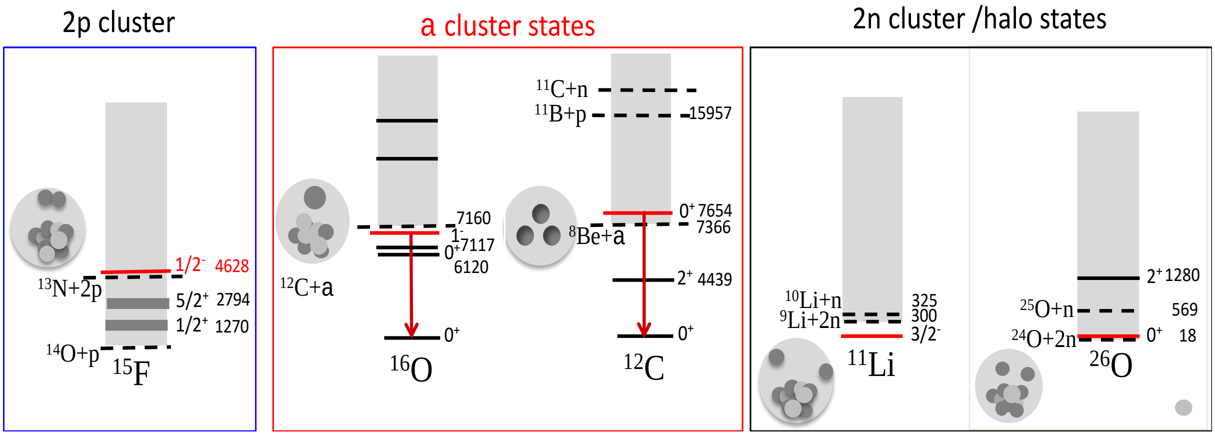


Figure 8: The central panel shows the cluster states α (in red) in the nuclei ^{12}C and ^{16}O, very close to the emission thresholds 3α (above) and α (below), respectively (dotted lines). In the left-hand panel, a narrow resonant state has been observed in ^{15}F at around 50 keV above the two-proton emission threshold, while narrow states are also identified close to the two-neutron separation energy in bound ^{11}Li and unbound ^{26}O (right).

It is important to understand the mechanism leading to the appearance of such narrow resonances, particularly in the context of weakly correlated fermion pairs of the Bardeen-Cooper-Schrieffer (BCS) type or of the Bose-Einstein condensate (BEC) type. It would also be extremely interesting to see whether this conjecture applies to a system of 4 neutrons. The systematic appearance of narrow two-neutron resonances close to the two-neutron emission threshold could also play an important role in nuclear astrophysics, as it could significantly accelerate neutron capture in rapid-capture nucleosynthesis.

In addition, tritium and ^{3}He clustering are expected to take over from a clustering in neutron-rich and neutron-deficient nuclei, respectively. The search for these fermionic clusters and their ability to form quasi-molecular states when other nucleons are added is of major interest and will be a challenge for nuclear physics over the next decade. Such studies can be carried out using transfer reactions with radioactive beams in which light particles are detected using detectors such as GRIT and/or ACTAR-TPC.

1.3.5.Nuclear astrophysics

Type I X-ray bursts are explosive events that occur in binary systems consisting of a neutron star accreting material from a main sequence star (or a more evolved star). With a neutron star as the underlying compact object, the temperatures and densities in the accreted envelope reach typical high temperature and density values: Tpeak>10^9 K and $\rho \sim 10^6$ g.cm^{-3} leading to a thermonuclear runaway and a sharp increase in X-ray emission. During this thermonuclear explosion, the nucleosynthesis of heavy elements up to A ~100 develops around the proton dripline through αp and rp processes (rapid proton captures and β+ decays). The main challenge in studying X-ray bursts is understanding the observed light curves and the associated nucleosynthesis. Several recent sensitivity studies have shown that among the thousands of reactions involved, the reaction rates of just a few dozen (α,p) and (p,γ) reactions have a major impact.

The reaction rates of $^{59}Cu(p,\gamma)^{60}Zn$, $^{56}Ni(p,\gamma)^{57}Cu$ and $^{57}Cu(p,\gamma)^{58}Zn$ are those that have a significant effect on the shape of the calculated X-ray burst light curve, with the first of the three having by far the greatest impact, as shown in Figure 9. This results from competition with the $^{59}Cu(p,\alpha)^{56}Ni$ reaction due to the lower α emission threshold in ^{60}Zn compared with the proton emission threshold.

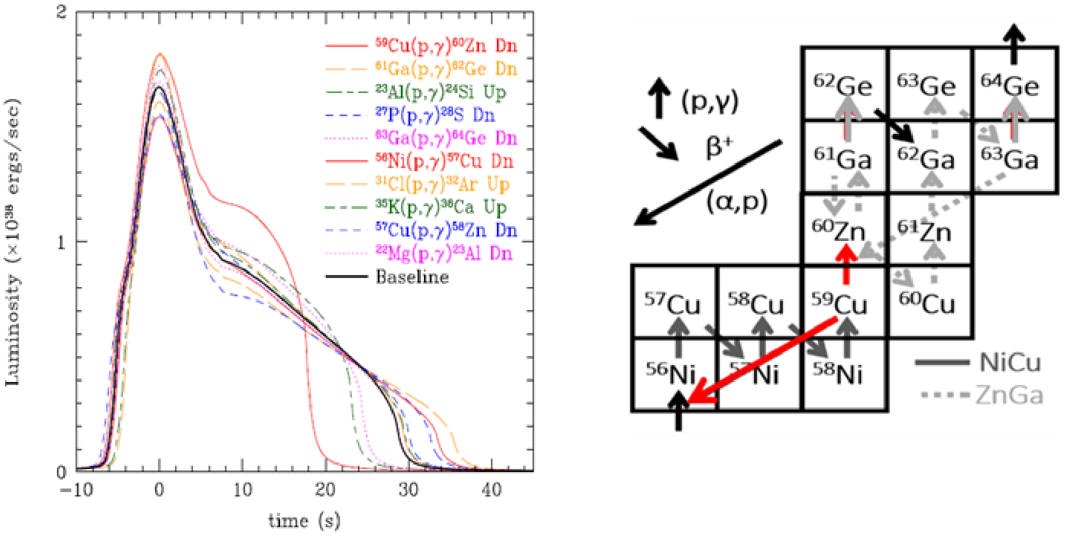


Figure 9: (Left) Light curves calculated for X-ray bursts at different reaction rates (coloured curves), and the scenario using the unmodified ReaclibV1.0 database (black curve). Dn (Up) indicates a downward (upward) variation of a factor of 100. (Right) Part of the reaction sequence of the rp process showing the NiCu and ZnGa cycles.

Consequently, a low $^{59}Cu(p, \gamma)^{60}Zn$ reaction rate combined with a high $^{59}Cu(p,\alpha)^{56}Ni$ reaction rate leads to the formation of a strong Ni-Cu cycle (Figure 4) that limits the synthesis of heavier nuclei, strongly affects energy generation and the shape of the X-ray burst light curves. It is therefore particularly important to measure not only $^{59}Cu(p,\alpha)^{56}Ni$ but also $^{59}Cu(p,\gamma)^{60}Zn$ to understand the Ni-Cu cycle in X-ray bursts. Because of the low intensities of the proton-rich beams, the thickness of the ^{3}He targets and the detection threshold of the recoil deuteron, these measurements are possible with an active ^{3}He target.

Several astrophysical experiments or letters of intent have recently been proposed at GANIL, which will probably be carried out over the next few decades. GANIL's great advantage over other accelerators in the world is the ability to produce excellent quality post-accelerated radioactive beams, at relatively low energies that are often very relevant for these astrophysical experiments (see, for example, the recent $^{15}O(^{7}Li,t)^{19}Ne$ alpha transfer experiment carried out with VAMOS and AGATA). GANIL is also highly suitable for direct measurements of astrophysical cross sections at low energies (< 2 MeV/u). With a very simple technical set-up (degrader and time-of-flight measurement) and the use of very high-performance detectors (ACTAR-TPC, for example), it will be possible to directly measure several key reactions for X-ray bursts ($^{15}O(\alpha,p)^{17}F$, $^{34}Ar(\alpha,p)^{37}K$ in particular).

1.4. Fission

Nuclear fission is a complex process in which a heavy nucleus evolves from a compact form to a configuration in which two or more fragments are produced, accompanied by the emission of fast neutrons and gamma radiation (and possibly electrons and antineutrinos). Most of the energy is released in the form of the kinetic energy of the fragments, while the fast neutrons emitted before the beta decays play a major role in applications such as energy production.

The dynamics of the nuclear system from the formation of the compound nucleus to the acceleration of the Fission Fragments (FF) and the rapid emission of particles is too fast to be resolved experimentally. On the other hand, the time scale for weak interactions, which governs the decay of FFs towards stability, varies from a few seconds to a few minutes. These dynamics (including the emission of delayed neutrons and gammas) can therefore be decoupled from the initial, fast part, which is governed solely by the strong interaction. The measurement of fragment properties has been the subject of numerous studies. However, experiments that measure the mean neutron multiplicity as a function of the number of neutrons at the pre-fission stage, which can be used to assess energy sharing between fission fragments, are rarer, and for a limited number of reactions (spontaneous fission or fission induced by thermal neutrons).

Historically, fission fragment yields were measured using the activation technique. This involves irradiating a sample with a mono-energetic neutron flux, followed by a cooling period and then spectroscopy to identify the fission fragments. However, this technique is only sensitive to long-lived nuclei and only gives access to cumulative yields, which means that shell effects cannot be studied.

With the development of spectrometers, in-flight identification of fragments has become possible, thereby removing one of the intrinsic limitations of the activation technique. Remarkable data has been obtained using the Lohengrin spectrometer at ILL, such as the isotopic yields of ^{235}U and ^{239}Pu fissions. However, no information on the excitation energy dependence of the fission yields could be established since only thermal neutrons were used. Furthermore, isotopic identification remains limited at $Z<40$, due to the low kinetic energy of the fragments, which makes their detection particularly difficult. The use of faster neutrons (above thermal energy) is limited by other major experimental difficulties - the drastic fall in fission cross-section and available neutron flux.

An alternative approach to access the fissioning system of interest is to use a surrogate reaction in inverse kinematics. At GSI, the SOFIA collaboration is using coulomb excitation to induce fission of the nuclei making up the secondary beams delivered by the FRS spectrometer.

At GANIL, two complementary approaches are being pursued to study fission: firstly, the study of fission induced by transfer reactions in inverse kinematics using the VAMOS spectrometer and the PISTA (Particle Identification Silicon Telescope Array) detector, and secondly, the simultaneous measurement of the two fission fragments using the VAMOS spectrometer with a second arm for studies of fission induced by heavy ions or using the FALSTAFF device equipped with two arms for fission induced by neutrons. Neutron-induced fission has been studied mainly using thermal neutrons in reactors such as the ILL. Very little data exists in the field of faster neutrons, the reasons for this being, on the one hand, the difficulties associated with identification and, on the other hand, those associated with the low cross sections requiring high neutron fluxes. However, these data are crucial for gaining an understanding of the fission mechanism, the scission configuration, energy sharing between fragments, shell effects, pairing, etc., information that is highly complementary to the data from fission reactions induced by heavy ions. These experiments will also provide essential nuclear data for future generation IV reactors, for waste management, for improving calculation codes such as FIFRELIN, and for the production of exotic nuclei. They will complement the heavy-ion induced fission experiments which are described in the following.

1.4.1. Fission induced by transfer and fusion reactions in inverse kinematics

The use of transfer reactions induced by ions in inverse kinematics gives access to the measurement of the excitation energy of the fissioning system, particularly exotic actinides. The VAMOS-PISTA coincidence will make it possible for the first time to measure the fission fragment distributions for exotic systems produced in reactions of the type ^{238}U+Be/C and ^{232}Th+Be/C, with control of the mass, charge and excitation energy (A,Z,E*) of the entry channel thanks to PISTA. A first exploratory measurement could be carried out with the SPIDER detector in coincidence with VAMOS in the ^{238}U+^{9}Be reaction. The fission fragments will be isotopically identified by the VAMOS spectrometer (see Fig. 10). This combination of detectors will make it possible to obtain fission yields as a function of the excitation energy of the fissioning system with unprecedented precision. The data obtained will be used to study the open questions surrounding the fission process, such as the universality of shell effects, dissipation effects, the role of angular momentum in fission, pairing, etc. Accurate measurement of the excitation energy of the system will make it possible to obtain fission yields as a function of excitation energy and to provide nuclear data for new-generation reactors.

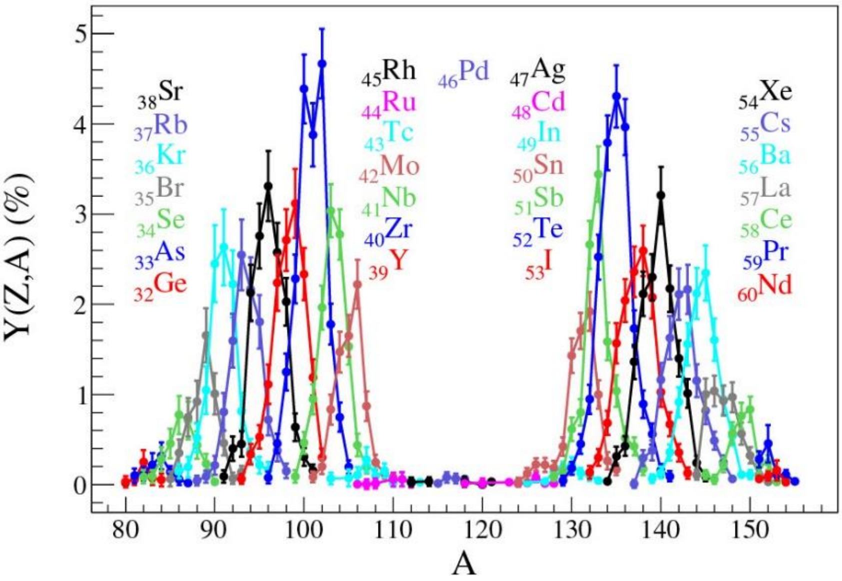


Figure 10 : Isotopic mass distribution measured with VAMOS +SPIDER in the $^{238}U+^{9}Be$ reaction

At the same time, considerable efforts have been made to simultaneously measure the energies and velocities of the two fragments, with the aim of achieving resolutions of less than one mass unit and charge. GANIL plans to develop a second time-of-flight arm to detect the second fragment at the exit of the first VAMOS quadrupole. Taking these measurements at the coulomb barrier is a unique opportunity to determine fission observables at scission. Measurement of the velocity vector of the second fragment will enable us to reconstruct the mass of the fragments at scission as well as their kinetic energy. Coupling with isotopic measurements in VAMOS will make it possible, for the first time, to determine isotopic observables at fission (isotopic distribution, kinetic energies, evaporation neutron multiplicities), which will place unique constraints on current fission theories.

In order to extend our understanding of the fission mechanism, an experimental programme is being developed to measure fission observables (isotopic yields, kinetic energies, neutron multiplicities see Fig. 11) for nuclei fissioning with isotopic contents (N/Z) different from those of actinides. In the coming years, various studies covering the regions of neutron-rich and neutron-deficient fissioning nuclei, as well as nuclei at the fissile limit, are planned. These studies will be based on the use of Xe, W and Pb beams on targets with intermediate masses. In addition, a gaseous target (He or H) will be used to accurately populate nuclei fissioning at very low excitation energies.

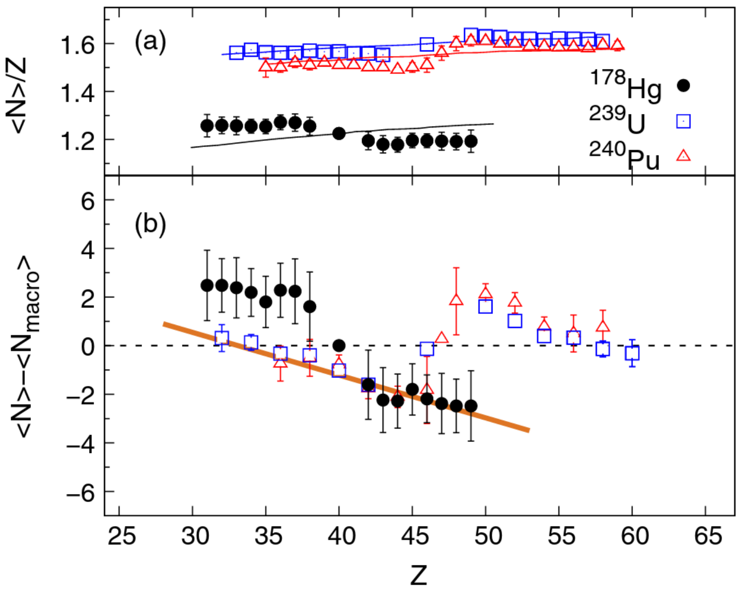


Figure 11 : (a) Neutron content of fission fragments from ^{178}Hg (black dots), ^{239}U (blue squares), and ^{240}Pu (red triangles) measured at VAMOS. (b) Microscopic component of the neutron content of fission fragments.

These various measurements will provide a global view of fission and shell effects by changing the isospin (N/Z) of the fissioning nuclei. This will make it possible to determine the asymmetric fission island that occurs in pre-actinide nuclei. The measurements required to characterise the mechanism behind this asymmetry are measurements of the isotopic yield of fission fragments for pre-actinides, kinetic energies, isospin and neutron multiplicities. Full identification by mass and charge is therefore essential.

The fission of neutron-rich pre-actinide nuclei populated in low-energy inverse kinematic fusion reactions such as Pb+^{4}He or Pb+^{4}H can be measured using a gas cell. The major interest in this type of reaction is the possibility of probing the population of fission systems at very low excitation energies.

Finally, another area of fission research is the study of the fission of light systems (Z<60) to explore new shell effects and their implications for fission.

1.4.2. Structure of exotic nuclei produced by multi-nucleon transfer reactions

Deeply inelastic transfer reactions make it possible to populate neutron-rich nuclei. These reactions, which have already been used with the VAMOS spectrometer in the past, will enable experimental programmes to be carried out in the spectroscopy of heavy exotic nuclei in order to study the evolution of the shell structure and collectivity in nuclei.

Several experimental programmes have been identified to date. The first concerns spectroscopy near the N=126 layer closure. The nuclei of interest are produced in deeply inelastic transfer reactions (Xe+^{198}Pt). The measurement of the two reaction products with VAMOS and a second detection arm (CATLIFE, a project under discussion with South Korea) will enable the identification of the nuclei as well as the prompt and delayed spectroscopy of exotic nuclei (with detectors such as AGATA or EXOGAM). A pioneering experiment carried out with AGATA is currently being analysed.

A second programme focuses on the spectroscopy of nuclei close to ^{208}Pb, the heaviest double magic nucleus and the cornerstone of the layered model. One crucial question in particular is the competition between collective aspects and single-particle excitation. These nuclei are populated by deep inelastic transfer reactions of the ^{208}Pb+^{92}Mo type, and beyond the availability of lead beams, the unique mass identification capabilities of the VAMOS spectrometer for nuclei of mass ~ 200 have been demonstrated. This performance will make it possible to measure the gamma-ray spectroscopy of these difficult-to-produce nuclei.

Finally, a third line of research focuses on the study and spectroscopy of heavy actinides beyond ^{238}U using multinucleon transfer reactions. These studies use the same experimental set-up as above and will make it possible to establish the spectroscopy of these heavy nuclei.

1.5. Nuclear dynamics and thermodynamics: the equation of state for nuclear matter

The nuclear equation of state (EoS) characterises the properties of nuclear matter subjected to extreme conditions of temperature T, density ρ and isospin δ=(N-Z)/A. It is the equation of state that conditions the collective response of nuclei such as the compressibility of nuclei (via the incompressibility modulus K) and the collective modes of monopole (GMR) or dipole (GDR) oscillations in the isoscalar mode (depending only on the density ρ), or in the isovector mode via the symmetry energy term (depending on the proton density ρp and neutron density ρn). On the other hand, the collapse phase of protoneutron stars (type II supernova) and the associated cooling phase are intimately linked to the characterisation of the volume, surface, coulomb and symmetry parameters and their dependence in terms of density, temperature or isospin.

With experiments on Earth, there are two main approaches to constraining the EoS parameters: heavy ion collisions and the measurement of giant resonance properties. These methods are complementary: giant resonances probe the parameters of the EoS through excitations close to the saturation density using structure information, while heavy ion collisions probe a much wider range of energies and excitation densities.

At GANIL, it is the second approach that is mainly used, measuring nuclear reactions at different energies from above the Coulomb barrier to the Fermi regime. Recent studies have focused on the role of structure effects on the EoS, in particular the persistence of cluster effects at high excitation energies and low densities.

Moving away from stability, i.e. maximising the δ isospin asymmetry, is valuable for constraining the isospin dependence and hence the isovector part of the EoS, the parameters of which are currently poorly determined. It is therefore crucial to have access to both stable and radioactive ion beams in order to carry out studies that shed light on the different terms of the equation of state and to understand the evolution of symmetric nuclear matter towards asymmetric matter. These studies require high-quality post-accelerated beams with energies ranging from the Coulomb barrier to around 50-60 A MeV, well suited to creating asymmetric excited nuclear systems and low-density fragments in heavy-ion collisions.

Interest in the EoS of dense neutron-rich matter has recently been rekindled by the detection of gravitational wave signals from the merger of two neutron stars with the LIGO and VIRGO interferometers, opening a new multi-messenger era for the fields of astronomy, nuclear physics, general relativity and astrophysics. New constraints for better understanding the macro- and microscopic properties of such compact objects are expected from the analysis of the waveform of gravitational waves and the subsequent electromagnetic radiation produced by their merger.

Understanding these cataclysmic events requires knowledge of the EoS over a wide range of densities, temperatures and proton fractions. These astrophysical sites provide unique opportunities to confront the understanding of the nuclear phase diagram obtained from research laboratory, through studies of nuclear structure and reaction mechanisms, with new observations. For example, the inhomogeneous matter in the outer layers of neutron stars is expected to play an important role in their evolution and dynamics. Light and heavy clusters are expected to form in three main astrophysical sites: neutron star mergers, core-collapse supernovae and the crust of neutron stars. These clusters affect the mean free path of neutrinos and, consequently, their transport properties. Consequently, the cluster composition of neutron-rich matter below saturation density plays an important role in both the post-bounce dynamics of core-collapse supernovae, and in the cooling rates of proto-neutron stars.

Although the very neutron-rich matter involved in astrophysical processes is far from accessible in terrestrial laboratories, such extreme conditions can to some extent be reproduced (on a microscopic scale) by heavy ion collisions. Neutron-rich projectiles at energies ranging from below to above the Fermi energy are needed to produce low-density systems of potentially exotic clusters, as well as particles, in order to probe the EoS of nuclear matter. In such an environment, the properties of nuclei ground state are modified, which has a direct and important impact on the models describing the evolution of compact stellar objects.

The availability of a rich palette of beam/energy combinations and high-performance detectors are key ingredients for a comprehensive study of the nuclear EoS. Most of the information on the role of neutron-proton asymmetry in the interaction phase, in the production of hot fragments and in the subsequent statistical de-excitation has so far been obtained using various isotopic combinations of beams and stable targets. For future plans on this topic, radioactive beams will be valued as they will allow exploration of the thermodynamic and transport aspects of nuclear reactions with neutron-rich nuclei at both low and intermediate energies (~10-60 A MeV). The exploration can provide information on the isospin (N/Z) dependence of the equation of state by studying in particular the properties of the nuclear interaction medium, the effective mass separation, the mean free path and the production of clusters.

Below, we highlight three topics specific to heavy-ion collisions, which appear in the European medium-term strategy.

1.5.1. Exploring the properties of clusters in dilute systems

Light clusters play an important role in hot, low-density nuclear matter such as can be found in core-collapse supernovae or in neutron star mergers. The main role played by these clusters is to affect the weak interaction rates, and therefore the dynamical evolution of these violent events. In neutron star mergers, their abundance has a direct influence on the fraction of ejecta that is converted into r-process elements, or on the evolution of the accretion disc after the merger, and therefore on the amount of matter that is detached from it.

Recent work in the field of heavy ion collisions has provided new information on the production of clusters in low-density nuclear matter. This is done by determining chemical equilibrium constants, which describe the rates of cluster production in a gas of protons and neutrons at equilibrium and finite temperature (see Fig. 12). The equilibrium constant $K_c(A,Z)$ depends only on the temperature and density of the system (proton, neutron and cluster densities). Consequently, if such quantities can be experimentally extracted from nuclear data, they can be applied to CCSN (Core Collapse SuperNova) simulations, for example.

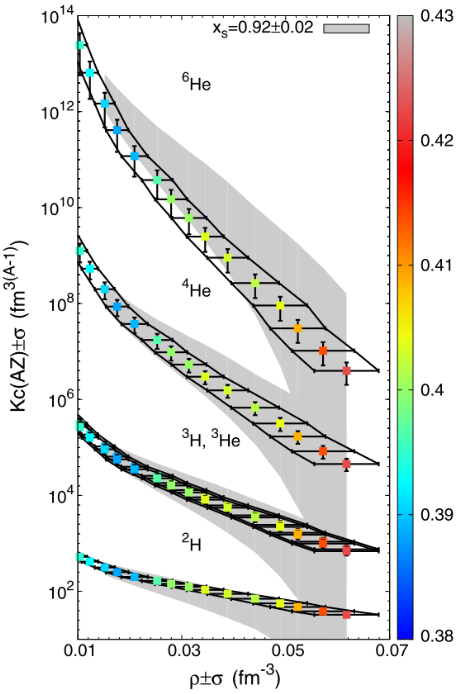


Figure 12 : Chemical equilibrium constants for H and He isotopes as a function of density deduced from INDRA data for central collisions of 136Xe+124Sn at 32 MeV/nucleon bombarding energy. The colour code represents the global proton fraction. Gray bands are the equilibrium constants for clusterised nuclear matter calculated in a RMF approach at the average temperatures, densities and proton fractions deduced from data. The model parameter x_s measures how much the medium affects the binding of each cluster and was tuned to best reproduce the data (Phys. Rev. Lett. 125, 012701 (2020)

Chemical equilibrium constants can be used to constrain changes in the properties of clusters in the medium by fixing the coupling of scalar mesons in a phenomenological approach of the Relativistic Mean Field (RMF) type.

In the future, the availability of stable and radioactive ion beams, and the improvement of experimental set-ups (such as the FAZIA-INDRA configuration in particular after the recent INDRA upgrade), will make it possible to extend these studies to heavier clusters (A ~ 12) to better constrain the models. The use of high energies for these studies is mandatory to produce relatively large nuclear systems at low density in semi-central collisions. Clearly, the opportunity of (stable and radioactive) beams at energies as high as 60 A MeV would make it possible to study both the multifragmentation and the vaporisation of dilute (low density), neutron-rich nuclear systems.

1.5.2. Neutron-proton equilibrium and transport processes in semi-central collisions

The empirical parameters involved in the series expansion of the EoS of nuclear matter are not all well constrained experimentally, particularly for the isovector part (Lsym, Ksym, Qsym, etc.). Given that these parameters are also used in the EoS to model astrophysical objects, it is essential to constrain them further by exploiting different observables that are accessible experimentally.

For example, several transport models predict that isospin diffusion, which occurs when two nuclei of different N/Z collide, is mainly sensitive to Lsym when a low-density zone forms during the interaction. The smaller the value of Lsym (smoother equation of state), the faster the isospin diffusion rate because the symmetry energy remains relatively large (close to the saturation value). Experimentally, by varying the isotopic composition (N/Z) of the projectile and target nuclei and by selecting the centrality of the events (thus varying the interaction times, the deformations and the yields of the different reaction channels) we can achieve extreme conditions (in terms of temperature, isospin and density) similar to those found in the crusts of neutron stars, for example (Fig. 13). Comparing different experimental observables with different parameterisations of the EoS in theoretical models (variation in the value of Lsym, for example) would provide more constraints.

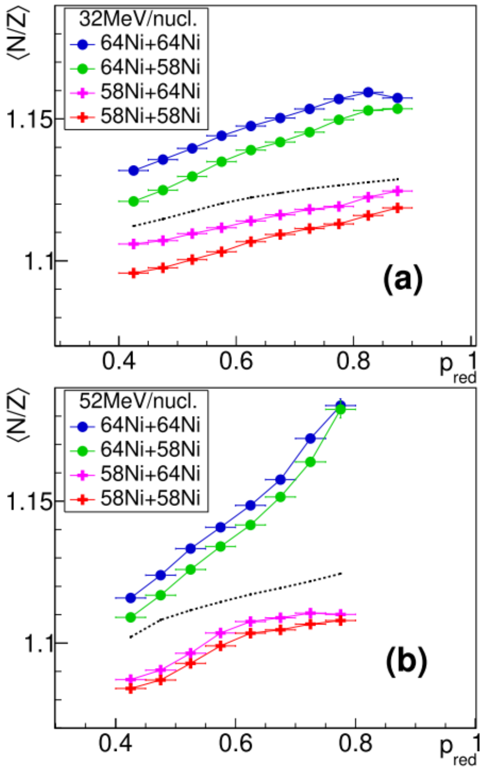


Figure 13 : Experimental results of the first INDRA-FAZIA experiments at GANIL: mean N/Z ratio of quasiprojectile (QP) residues for the 8 reactions of 58,64Ni+58,64Ni at 32 and 52 MeV/nucleon, as a function of $p_{red}=p_{QP}/p_{beam}$, the measured QP momentum expressed as a fraction of the beam momentum. Smaller p_{red} values correspond to more central collisions. The dashed lines represent the expected <N/Z> for evaporation residues with Z equal to the mean, <Z>, measured for each p_{red} bin (Ciampi et al., Phys. Rev. C106, 024603 (2022))

For many years now, the INDRA-FAZIA collaboration has been engaged in a scientific programme on this subject mainly with beams of stable nuclei, hence with a reduced range of isospin, δ, asymmetries. Characterising the properties of this extreme nuclear matter requires the detection of all the reaction products (Z, A, E, velocity vector...) and therefore requires a 4π device with good granularity and isotopic resolution. This is precisely what the combined INDRA and FAZIA detectors are now capable of doing. Complementarily, radioactive ion beams with a large N/Z would bring even greater sensitivity to experimental analysis and also, hopefully, the ability to go beyond this by constraining the higher-order parameters of the EoS, such as Ksym and Qsym. In this case, these analyses would benefit from neutron-rich radioactive beams in the Fermi energy range.

1.5.3. Thermodynamics of very exotic systems in central collisions

This research is more strictly linked to the availability of radioactive isotope beams (beyond the stable reference beams) to produce hot exotic nuclei or nuclear systems and then study their dynamic and thermodynamic properties. The research focuses on limiting temperatures in excited nuclear systems, the

N/Z dependence of nuclear level densities and the EoS symmetry energy term. Clearly, to achieve these goals, a post-accelerator reaching bombardment energies as high as 60 A MeV is needed for future plans, although some parameters can also be addressed at energies closer to the Coulomb barrier (10-15 A MeV) to produce heavy hot nuclei via fusion-type reactions.

1.5.3.1. Chemical instabilities in multifragmentation

Beyond their astrophysical interest, the behaviour of extremely excited sources formed in central high-energy collisions is the main framework for studying the phase transition of low-density nuclear matter associated with multifragmentation. The data indicate that this multifragmentation occurs when nuclear matter is driven, through a compression-expansion cycle, towards a low-density region of spinodal instability occurring within the coexistence region associated with a first-order phase transition. Interestingly, for asymmetric matter (N/Z=1.5-2.0), theoretical calculations predict the appearance of a new spinodal region linked to chemical instabilities (fluctuations in proton concentration). In this region, a process known as isospin fractionation is predicted to enrich the liquid phase (fragments) with symmetric matter and the gas phase with neutron-rich matter.

1.5.3.2. Study of the limiting temperature and level density in fusion-type reactions

Low-energy exotic beams (~15 A MeV) make it possible to study the low-energy branch of nuclear matter by producing hot compound nuclei with different N/Z asymmetries. By measuring their temperature as a function of their excitation energy, we can explore the N/Z dependence of the limiting temperature, Tlim, i.e. the maximum temperature that a nuclear system can withstand before ending its existence and decomposing into its constituent parts. Some results suggest that the limiting temperature depends on the mass of the nuclear system. With the combined effects of the Coulomb interaction and symmetry energy, we also expect to find a lower limiting temperature as we move away from the valley of stability, producing both proton-rich and neutron-rich excited compound nuclei. The isospin dependence of Tlim also provides important links with the isovector part of the effective nucleon-nucleon interaction. Future experiments in this field will require systematic measurements of given observables along extended isotopic chains (for example using Ar or Ni beams from stable to unstable isotopes).

The study of the same fusion channel, also induced by both stable and radioactive beams, can also provide important information on the N/Z dependence of nuclear level densities. This quantity plays an important role in the formation of compound nuclei, in the production of fragments, and in the determination of thermonuclear rates in astrophysics (nucleosynthesis and supernova dynamics). Studies of the nuclear level density and its dependence on the N/Z isospin will provide a better understanding of the temperature dependence of the symmetry energy. In order to constrain this parameter, complete data on the evaporation of asymmetric and hot systems must be compared with Hauser-Feshbach and Weisskopf type calculations.

1.5.4. Persistence of structure effects at high excitation energies

The previous paragraph also introduces a question that is receiving increasing attention: do the properties of nuclei in terms of cluster structures persist at high excitation energies and do they play a role in fragment production? Both experimental and theoretical efforts are attempting to connect analysis of reaction mechanisms with studies of nuclear structure. In this context, the INDRA-FAZIA detector at GANIL, which allows complete determination of events (in mass and charge), is a unique tool. As in the previous paragraph, this research is based on the precise measurement of evaporation chains emitted in the de-excitation of hot nuclei formed under well-controlled conditions.

Comparison of the de-excitation properties (branching ratios, light charged particle production rates and angular distributions, thermal properties) with a refined statistical model prediction would reveal effects beyond the mean-field hypothesis (or the shell model framework). The possibility of carrying out particle-fragment correlation analysis can provide important information in this type of research: in fact, it is possible to reconstruct excited levels and relative populations of nuclei beyond the particles separation energies with high excitation energies and spins, where the signatures of correlations and collectivities are more obvious. Among these correlations, those constructed by alpha particles are the best known; they are well documented for light nuclei at relatively low energies. On the other hand, the limits of alpha-fragments correlations at high energies and in medium-sized nuclei have received little attention. For these investigations, stable and radioactive beams up to Ar-Ca at Fermi energies are required.

2. Interdisciplinary Research

Interdisciplinary research has been part of the GANIL facility's scientific ambition since its inception. The first interdisciplinary research experiments took place at GANIL in 1983 on the Ligne d'Ions Super Epluchés (LISE), an experimental area dedicated to the spectroscopy of ions with very few electrons, and in room D5 thanks to a low-temperature materials irradiation chamber (IRABAT, later moved to D1). Right from the start, in the 1980s, a number of significant results were obtained (ion spectroscopy, channelling, description of the morphology of traces and their use in the manufacture of nanostructured polymer membranes, the first experiment in radiobiology, etc.). This very active community was quickly limited by access to beam time to answer emerging scientific questions. So, in the late '80s, a new project, based on an earlier idea known as GANIL INTER, was launched by CIRIL and GANIL to increase beam access time. This project led to the development of the Medium Energy Output (SME), which increased the beam time available to GANIL/CIRIL users by a factor of ten, and extended access to a range of energies at maximum electronic stopping power. Several other beamlines were subsequently built (LIMBE then ARIBE and IRRSUD), drastically extending the energy and ion ranges and the number of experiments taking place simultaneously. Today, up to 4 simultaneous experiments can be hosted using the 4 beamlines dedicated to interdisciplinary research (HE, SME, IRRSUD, ARIBE) at GANIL. This multi-user configuration enables different interdisciplinary research communities to meet up, leading to the emergence of new projects. Simultaneous use of the lines is only possible thanks to the very specific configuration of the GANIL gas pedal, with its 3 cyclotrons (C0, CSS1 and CSS2) in cascade (for HE, SME and IRRSUD) and the presence of two C0 injector cyclotrons. Thanks to parallel operation for several users, interdisciplinary research has access to beam times comparable to, or even superior to, nuclear physics.

In addition, over the years, continuous effort has been put into developing *in-situ* characterisation techniques for users: X-ray diffraction, IR/Visible/UV emission/absorption photon spectroscopy, on-line gas analysis. Devices for low-temperature and/or high-temperature irradiation, under ultra-high vacuum or in a controlled atmosphere have also been built, expanding the range of studies using accelerated ions. The construction of the biology sample preparation laboratory, LARIA, has improved the facilities for radiobiology experiments and attracted new experimenters. GANIL's success is due to this original and unique instrumentation, much of which has been funded by calls for projects (ANR, regional projects, Labex projects, Equipex) or from CIMAP resources.

In addition to GANIL's success in attracting interdisciplinary research, great efforts have been made to raise its visibility. To structure and energise the communities, CIMAP has coordinated the GDR PAMIR and c-PAMIR, the EMIR&A Federation and the European infrastructure networks LEIF and ITS-LEIF. CIMAP was a partner in Labex EMC3, INFRA France-Hadron and the SPIRIT and RADIATE European infrastructure networks, and recently applied for IBISA accreditation for its radiobiology platform.

Over the past 40 years, the topics we cover have continually evolved as a result of expanding possibilities (beamlines and on-line instrumentation) and the emergence of new subjects. GANIL's beams are also used by a wide variety of communities (topological insulators, 2D materials, additive manufacturing, astrophysical ice, etc.). To date, GANIL's beams remain highly attractive to the interdisciplinary community. They will continue to be so, at least over the next two decades, as detailed below for the main interdisciplinary physics themes using GANIL's cyclotron cascade: (i) materials science: inorganic materials, (ii) materials science: organic materials, (iii) astrochemistry and (iv) radiobiology and (v) atomic and molecular physics.

2.1. Materials science at GANIL: inorganic materials

The study of inorganic materials is one of GANIL's historical subjects. In materials science, irradiation with swift heavy ions provided by GANIL makes it possible to simulate extreme environments and modify the properties of materials in a controlled way. Whatever the application envisaged, we need to be able to predict the modifications induced by these ion beams, which requires multi-scale approaches combining experimental data from beam experiments (from in-situ characterisations, possibly under irradiation, or from advanced post-irradiation characterisations) with advanced numerical simulations. While many studies have been carried out over the past 40 years, recent improvements in characterization instruments with increasing resolution, acquired in particular through the GENESIS equipex (Groupe d'Etudes et de Nanoanalyses des Effets d'Irradiations), combined with improvements in numerical simulations, are enabling a better description, understanding and even prediction of defect creation mechanisms for model systems. This opens up new areas of experimentation in both fundamental and applied materials research.

For the study of condensed matter and inorganic materials, the benefits of working on the GANIL facility are clear, as the control of irradiation parameters such as energy, ion, charge state and intensity are essential to these studies. The four beam lines, ranging from very low energy (ARIBE), low energy (IRRSUD), medium energy (SME) to high energy (HE), allow specific selection of particular conditions for energy loss in matter, depending on the desired position around the Bragg peak: by interaction with electrons (predominantly electron stopping power, Se), or by interaction with atoms (predominantly nuclear stopping power, Sn), or with a variable Se/Sn ratio to explore possible coupled Se-Sn effects. Very few facilities in the world allow such a range of energy, with a magnitude of more than 6 orders of magnitude (ARIBE a few keV/u - HE 100MeV/u, see Fig. 14).

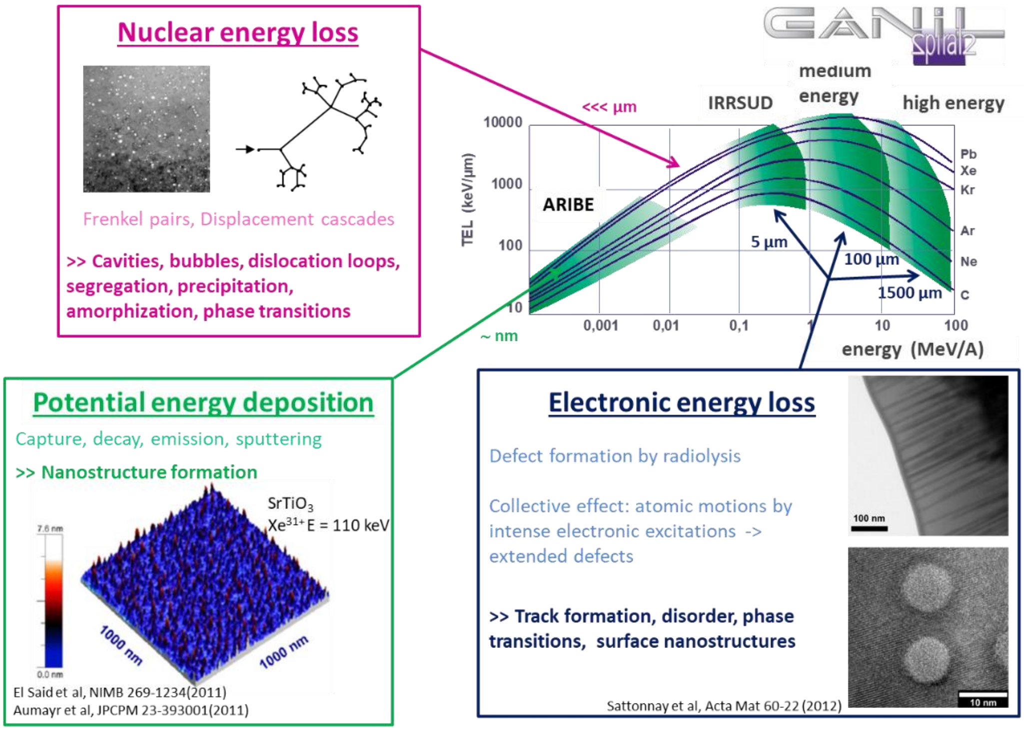


Figure 14 : Predominant energy loss mechanisms on GANIL's various beam lines

This energy range also means that the path of the ions in the material can be varied widely (down to a few millimetres for HE, around a hundred micrometres for SME and around ten micrometres for IRRSUD). The higher energy ions, because of their long path through the material, allow experiments to be carried out in an extracted beam or in a controlled atmosphere. Moreover, the choice of ion, ranging from carbon to uranium, enables us to finetune energy losses at different points around the thresholds of electronic stopping power required to create latent traces. The choice of the charge state of the projectile around the charge state at equilibrium is also an advantage, making it possible, for example, to vary the diameters of traces on the surface of materials. Intensity is also a relevant variable experimental parameter, since for the study of individual ion effects a few 10^6-10^7 pps/cm2 are sufficient, whereas for collective effects requiring high doses the maximum of 10^{10}-10^{11} pps/cm2 supplied by the machine is used (it may even sometimes be insufficient to keep within reasonable irradiation times). In addition to these beam-related parameters, the CIMAP laboratory, through its CIRIL platform, has developed a number of devices for varying the experimental conditions in terms of beam incidence angle (normal 90° to grazing close to 0° with a precision of 0.2°), temperature (cryogenic head or high-temperature furnace) for working in the 4K-1600K range and atmosphere (vacuum, inert, oxidising or reducing gas). These conditions can be coupled with devices for in-situ analysis of the modifications induced, which can be adapted to various beamlines: X-ray diffraction, electrical resistivity, UV-Visible spectrophotometry, IR spectrophotometry, atomic force microscopy, Raman spectrometry and creep measurements in particular.

One of the characteristics of the swift heavy ions produced by the GANIL facility and their successive accelerations through the various cyclotrons is the intense energy density they deposit in solids, driving the local atomic and electronic structure away from the equilibrium state. Irradiation-induced phase or structure transitions are observed with ultra-fast kinetics, including transient or permanent damage, involving changes in the material that are otherwise unattainable. These modifications induced along the path of fast heavy ions, due to intense electronic excitations, form what are commonly known as latent traces. They are highly anisotropic and the energy deposition is largely inhomogeneous along the ion's path. Experiments using GANIL's swift heavy ions therefore induce changes in matter with a very high geometric aspect ratio over a very short time scale, making it possible to simulate extreme conditions found in different contexts (space, nuclear or accelerator in particular).

Research programmes involving the national, European and international community are carried out on GANIL's interdisciplinary beamlines. The various current and future projects fall into 3 main themes:

- Detailed study of the modifications induced and prediction of ageing under irradiation of materials

The mechanisms leading to the formation of latent traces and the combined effects of the various energy loss processes (possibly in terms of temperature) are still relatively poorly understood in the energy range of the ions accelerated by GANIL's cyclotrons. Similarly, while latent traces have been described in many materials, little is known about their evolution at high fluence or temperature. Model materials - oxides, nitrides or metal alloys, insulators or semiconductors - are being studied in order to better describe or even predict changes in properties. The cutting-edge tools acquired as part of the GENESIS equipex are then used to characterise materials resulting from experiments carried out on beamlines and permit detailed study of irradiation induced changes along the ion path (damage profile).

Numerous studies are therefore underway or planned. Without being exhaustive, here are just a few of them:

- Fine characterisation of traces in nitride semiconductors, in particular it is planned to explore the effects in quantum dots or quantum wells in the coming years and to combine simulation and characterisation by transmission electron microscopy (TEM) and electron energy loss spectroscopy (EELS) to study the effects at interfaces (see Fig. 15).

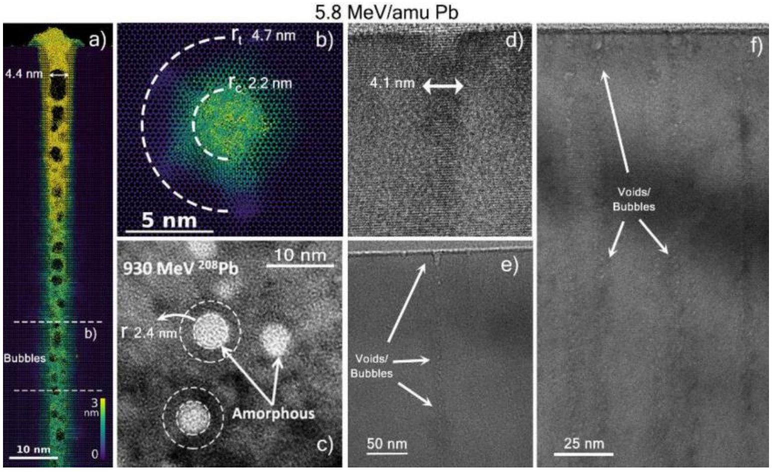


Figure 15 : Simulation and TEM observation of traces in Pb-irradiated GaN on the SME. The simulation predicted a strong tendency towards recrystallisation, which decreases with increasing stopping power. TEM observations confirm the simulations with the presence of bubbles that decrease in size with depth [M.C.C. Sequeira, Small 18 (2022) 2102235].

- Resistance to irradiation at very high doses of targets used in high-power accelerators (FermiLab, CERN, etc.) via the international collaboration RADIATE (Radiation Damage In Accelerator Target Environment) and Fermilab. As part of projects to increase the energy and intensity of future very high energy accelerators, interceptive devices will be subjected to high fluences. Ensuring their reliability requires a study of the damage induced at high power, as these extreme doses can be reached by lower-energy ion beams, particularly on the IRRSUD line.

-Effect of densification on mesoporous materials including silicas or MOFs (metal organic frameworks). In addition to understanding the defects produced and the consequences on the dimensional variation of these materials, these studies also aim to assess the possibility of densification. The separation and immobilisation of radionuclides or radioactive gases in these materials is envisaged as part of a two-stage process involving firstly their incorporation into the mesopores, whether functionalised or not, of these materials and then the closure of the porosity by irradiation.

- Study of the ageing of nuclear materials. Numerous studies have been carried out on GANIL cyclotron lines on model materials such as UO_2, B_4C, MgO, SiC, SiC fibres, ODS, etc. For several years now, mechanical parts have been easily produced by additive manufacturing. The impact of this new manufacturing process on performance under irradiation remains to be explored. The beams of the IRRSUD line (a line producing ions typical of fission products), coupled with high-temperature furnaces, can be used to simulate real operating conditions and estimate their resistance.

- Controlled modification of material properties. By adjusting beam parameters, the structural, optical, electronic, thermal, magnetic and other properties of materials can be adapted by the controlled insertion of defects (punctual, complex or extensive such as latent traces). The wide range of energies available at GANIL is perfectly suited to clarifying the specific contributions of electronic and nuclear energy loss in the creation of these defects. One example is the study of large-gap semiconductors for applications as new coherent quantum bits that could complement the well-known NV centres in diamond. Irradiation with fast heavy ions makes it possible to create and/or activate point defects or gaps in the trajectory of the ions and to modulate their spatial distribution. For these experiments, which require work in a controlled atmosphere (inert to oxidising), the use of medium-energy beams is essential. Studies of magnetic properties, electronic states and spin transitions are underway on a wide range of materials: materials for quantum applications, Mott insulators or topological insulators, superconductors and van der Waals heterostructures on the nanometric scale. Other areas have not yet been fully explored, such as thermoelectric materials, since the introduction of defects can strongly influence the mobility and concentration of carriers, as well as modifying thermal conductivity. In addition, the non-equilibrium conditions induced by ion beams can allow access to states that cannot be reached in the equilibrium energy landscape. This gives access to new phase transitions and unique states, as well as unprecedented control possibilities. Access to these states logically brings new challenges, as characterisation of the final adiabatic state is no longer sufficient. Pump-probe experiments combining short ion pulses of different types and laser-triggered detection systems would be needed to treat, for example, ion-induced transient electronic states, the formation of intermediate species or the dynamics of crystal lattice evolution, and are in the long-term prospects of the community with the development of new time-resolved characterisation techniques.

- Nanostructuring of materials. As materials are modified in latent traces (for those that have them), GANIL's ion beams (IRRSUD, SME and HE) are the tools of choice for modifying matter on a nanometric scale (on cylinders a few nanometres in diameter and up to several hundred micrometres in depth). Furthermore, the properties of GANIL's swift heavy ion beams make it possible to carry out surface nano-engineering using electronic excitations (Fig. 16). By using special irradiation geometries, at grazing incidence with an angle of less than 5° between the projectile and a surface, it is possible to manipulate and control the surface structuring of materials, the formation processes of which are at the heart of the research conducted at GANIL. Understanding thickness effects (by moving from 2D materials to lamellar and then massive materials) can lead to a better understanding of ion/matter interaction and the mechanisms inducing defects or surface modifications. This can lead to applications such as, for example, the study of 2D materials under extreme conditions, which has led to the manufacture of filters with nanometre-sized pores.

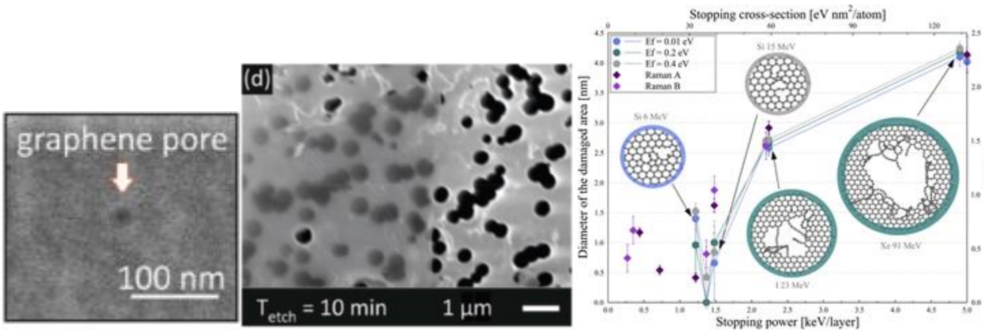


Figure 16 : Observation and simulation of nanopores created by irradiation in graphene deposited on polymer as a function of the stopping power of the ions according to V. Vàzquez et al Carbon114 (2017) 511 and L. Madauss et al, Nanoscale 9 (2017) 10487.

2.2. Materials science at GANIL: organic and hybrid materials under irradiations using GANIL ions

Organic materials subjected to ionising radiation are modified by bond breaks and the molecular reorganisation that follows. Two main types of defect are formed in these materials: macromolecular defects and their gaseous counterparts. Macromolecular defects, formed on a molecular scale, influence the different levels of organisation of organic materials and molecules, depending on their positions and concentrations. So, depending on the degree and conditions of irradiation, properties of use can be tuned. GANIL's accelerated ions have the particularity of introducing these modifications in a very small cylindrical space (diameter of a few tens of nanometres to a few microns), along their path, called the trace; this leads to localised modifications of the materials. The work carried out at GANIL over the last forty years on organic materials has made it possible to study the ageing of organic materials and the underlying mechanisms, to provide important information to the nuclear power industry by demonstrating the equivalence of certain ion beams with actinide particles but with a better path, and finally to develop new materials and new applications through the modification of materials on a nanometric scale via ion Track Technology (ITT).

Regardless of the field under consideration, of the three areas mentioned above, there is still a great deal of work to be done, which requires GANIL's cyclotrons. As detailed in the previous paragraph, the wide range of ions and energies available and the in-situ analysis facilities developed by CIMAP make it possible to study the influence of the amount of energy deposited per unit distance (TEL), the dose and the dose rate, provide access to a very wide range of radial dose distributions and allow the irradiation of thick samples.

The difficulty in studying the behaviour of polymers under ionising radiation lies in their different levels of organisation, their composition in terms of additives (which varies from one supplier to another) and the influence of the working atmosphere (oxygen pressure and humidity). Rather than studying the wide variety of polymers individually, over the last ten years or so the aim has been to study the main processes involved in the behaviour of these materials as a function of 1) the functional groups of the molecules forming the macromolecular chain or potential additives, 2) the microstructure, and 3) the environment. The long-term objective is to develop a predictive model of evolution under irradiation.

Polymer materials are usually used in air, i.e. under oxidising conditions. Polymer oxidation is one of the most deleterious processes in the ageing of polymer-based materials and in the loss of their properties in use. A new and ambitious programme to study the radiation-induced oxidation of polymers, combining theory and experiment, has just been launched by several CEA laboratories. The aim of the programme is to develop a model for predicting the level of oxidative ageing of polymers as a function of their chemical structure, microstructure and irradiation conditions. Access to this model requires an excellent understanding of the kinetics of the chain reaction leading to the formation of oxidation defects, determination of the efficiency of each of the numerous reactions in this reaction chain and knowledge of the associated reaction constants. To do this, it is planned to monitor online the creation and consumption of radicals, which are the main reaction intermediates in the oxidation chain reaction, as well as the consumption of other species, by building an analysis platform combining EPR spectrometry (which will be unique in the world under oxidation conditions) and FTIR, UV and mass spectrometry (more traditional). This initially very fundamental study is perfectly suited to applied research needs in the electronuclear industry, in the field of hadrontherapy or non-conventional radiotherapy, and in the field of chemical recycling of polymers:

- In the field of the nuclear power industry, future needs are organised on the one hand around the prediction of the stability of MA-VL (medium activity-long life) waste packages from the point of view of gaseous emission during the operating period and from the point of view of hydro-oxidative degradation (complexation of radionuclides and diffusion in the geosphere) for longer periods, as part of the CIGEO project (French deep disposal project for radioactive waste), and also in reverse engineering for the characterisation of old waste drums whose initial compositions and changes are not known. The degradation of organic materials over long periods mainly concerns the hydrolysis of products of radiation-induced oxidation at high doses and their evolution in the presence of water (liquid or vapour).

- In the field of hadrontherapy, it is obviously necessary to study the behaviour of the cells, but it is just as important to study the evolution of the extra-cellular matrix of the tissues through which the accelerated ions will pass. These studies began years ago and are set to continue through various collaborations with Canada, Japan and other French laboratories. The aim is to understand the mechanisms by which tissues evolve by studying the behaviour of the main proteins in the tissues concerned, but above all to determine how radiation-induced modifications will affect tissue properties (biomechanical properties for cartilage, for example) and ultimately the consequences of these changes on patients' quality of life.

- The problem of recycling polymers needs no introduction. One of the groups of polymers currently posing recycling problems are polyolefins, due to the absence of oxidised or polar groups in their chemical structures. These oxidative groups must therefore be introduced beforehand. It has been shown by an American team, and confirmed very recently at CIMAP (2021), that although the photo-oxidation of polymers is considered to be homogeneous, it is far from being so. Indeed, the microstructure of polymers, combining amorphous zones permeable to oxygen and therefore subject to oxidation, and crystalline zones impermeable to oxygen and therefore not subject to oxidation, leads to an oxidation profile very similar to that induced by heavy ions in terms of the spatial distribution of defects (Fig. 17). Studies focusing more on the chemical recycling of polymers will therefore have to be combined with research into the prediction of the radio-oxidation of organic materials.

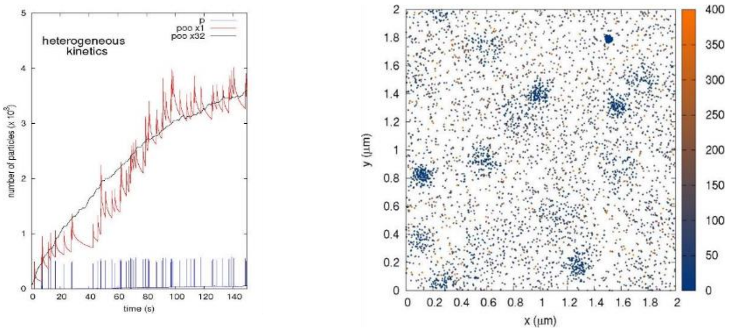


Figure 17 : Simulation of the radio-oxidation of a polymer: evolution of radicals after irradiation with He@5 MeV ions. The event map shows that in the steady state, the distribution remains inhomogeneous. The colour scale represents the age of the radicals (B. Gervais, Y. Ngono, E. Balanzat, Polymer degradation and stability 185 (2021) 109493).

A field of application research aimed at developing new materials that can be integrated into new equipment for analysing or extracting metals from the environment is flourishing in France, thanks to access to GANIL's very energetic beams. New European environmental standards have prompted research into new chemically modified membranes at the ITT. Demand from industrial companies (e.g. TotalEnergies, Vinci) for laboratories at the forefront of this activity is continuing unabated and should continue to grow. The current trend in medical analysis is to obtain results quickly so that appropriate treatments can be put in place as quickly as possible. With this in mind, the use of instrumental devices to control single-ion irradiation on the chosen surface is extremely useful in the miniaturisation of analysis equipment (Labs-on chips). By way of example, Sébastien Balme's group at the University of Montpellier has set up a device for analysing a single chain of proteins (applicable to neurodegenerative diseases) and aims, in the future, not only to work on the specification of these devices for the many functional groups of interest in proteins, based on the key/lock model, but also to integrate machine learning (which requires a large amount of data) into the application deployment of their devices.

2.3. Interdisciplinary research in laboratory astrophysics : studies of irradiation effects on molecular ices in various spacials environments

Organic molecules and ice are ubiquitous in space. Ices are mainly composed of simple molecules such as H_2O, CO, CO_2, NH_3 and others. They are present on comets, the satellites of certain planets, trans-Neptunian objects and on grains of dense molecular clouds in the interstellar medium. They are constantly exposed to complex and diverse radiation composed of photons, electrons, protons, helions and heavier ions of varying energies. For several decades, laboratory studies have been carried out to study analogues of astrophysical ices by subjecting them to weakly ionising radiation such as photons (VUV, XUV) or irradiation with light ions (H, He) of energies ranging from a few keV to a few MeV, using small laboratory accelerators. GANIL has opened up a new energy window to simulate the interaction of these analogues with the fast heavy ions of galactic cosmic rays. The specific effects of heavy ions with high kinetic energy have proved to be very important for various processes such as sputtering, amorphisation, compaction and fragmentation, due to the high energy deposition. The data obtained on the IRRSUD, SME, LISE and ARIBE beamlines, for example, have made it possible to obtain an electronic stopping power scaling law for the sputtering and destruction of molecules. GANIL's beams have also enabled major advances to be made in calculating the desorption rates of molecules, leading to the unexpected observation of molecules in the gas phase (in molecular clouds), and estimations of the survival times of organic molecules in space. Since the end of the 2000s, experimental astrochemistry has become a very active area of research at GANIL. The opening of the CASIMIR device (an infra-red spectrometer for the on-line analysis of irradiated samples at 15K), initially developed for the study of polymers, followed by the development of the IGLIAS device (an ultra-high vacuum device for the deposition of ice with access to the ion beam for irradiation and on-line analysis, at 8K, using infra-red and UV-visible spectroscopy, funded by an ANR and regional co-funding), offered the astrophysics community unique opportunities to study various aspects of ion irradiation in relation to astrochemistry. Three main areas of research were investigated:

(1) Chemistry induced by galactic cosmic rays in interstellar ices. In-depth studies have focused on ice radiolysis and sputtering, providing information on molecular complexification, sputtering yields and the branching ratio of the sputtered species that feed the gas phase. Data such as radiolytic cross sections and sputtering efficiencies have been extrapolated to the full range of energies and ions present in galactic cosmic rays. They have been made available to feed complex chemical models and are a valuable aid to interpreting radio astronomy observations.

(2) Ion irradiation at the surface of small, atmosphere-free bodies in the solar system. The solar wind, energetic solar particles, ions trapped in the magnetospheres of giant planets and cosmic rays are the main sources of ions that irradiate and modify the surface of objects to varying degrees. The wide range of energies of these ions, from 1 keV/u to several GeV/u, leads to ion implantation depths of from a few tens of nm to several metres and doses of up to several hundred eV/atom, in the absence of any surface renewal process. Ion-surface interactions include both elastic (ballistic collisions) and inelastic (electronic excitation) regimes, and lead to complex chemical and structural transformations of materials at the surface. The flux, dose and nature of ions in the local environment of planetary bodies are estimated from satellite and space-based measurements, but experiments remain essential to test and explain the chemical effects of irradiation and their consequences on their optical signature. The experiments carried out at GANIL have provided new information on the main species synthesised by radiolysis on the icy surfaces of trans-Neptunian objects, on their spectral properties (albedo, reddish surface) and new data to help explain the origin of Pluto's Ctulhu organic belt.

(3) Radiolytic formation of carbon compounds in primitive asteroids and comets. This subject concerns two new scenarios proposed for the origin of nitrogen-rich Antarctic micrometeorites (UCAMMs) and insoluble organic matter in primitive chondrites.

Radiolysis of molecular ices leads to the formation of new molecular species, including complex organic molecules. The origin of primitive organic matter is a central question in modern astrophysics. The precursors of organic matter are observed in the dense regions of the interstellar medium. These molecules are injected into protoplanetary discs and evolve under radiation (UV, X-rays and ions) in their cold, dense phases. Primitive organic molecules are also constantly being formed on the surface of small bodies (asteroids and comets). These various organic components are constantly being transported from interplanetary space to the planets via micrometeorites and carbonaceous meteorites, for example. Consequently, these primitive organic molecules could constitute the building blocks of prebiotic molecules on the young Earth. Thanks to the IGLIAS equipment developed at CIMAP in collaboration with the community (see Fig. 18), the chemical or physical evolution of different ices of astrophysical interest subjected to the action of ions is being studied.

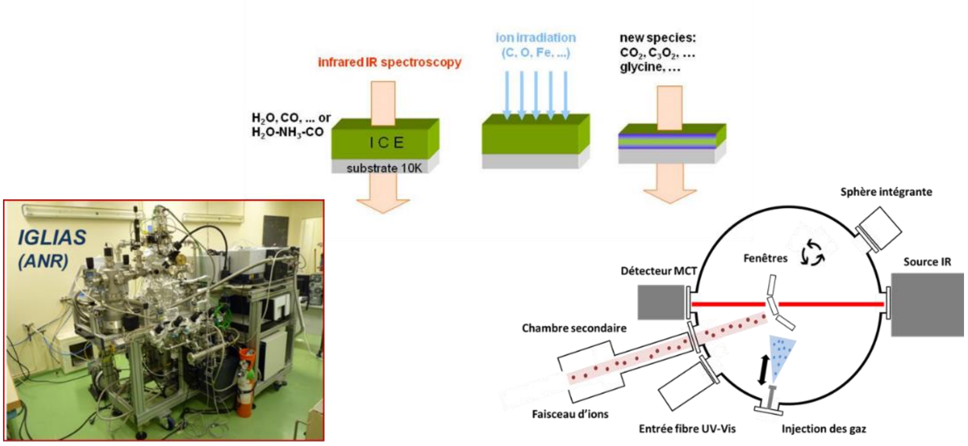


Figure 18: scheme of the IGLIAS setup at CIMAP

During the irradiations, the ices are analysed in-situ using a combination of Fourier transform infrared (FTIR), UV- Visible (Vis-UV) and mass spectrometry (during the annealing phase). The instrumental systems developed on GANIL's beamlines are highly competitive and enable large-scale interdisciplinary studies. Since the first exploratory experiments in 2008, the number of users has risen sharply and now includes users from various laboratories (Marseille, Grenoble, Orsay, Paris, Rio de Janeiro, Darmstadt, Debrecen) whose work has produced more than 70 articles in peer-reviewed journals between 2009 and 2023. There are still many experiments to be carried out in this area. In particular, the astrophysics community has proposed the development of a multibeam chamber (MIRRPLA), which will be funded by the PEPR ORIGINS (Life and Universe) programme. The aim of this platform is to overcome the remaining limitations in research into astrophysically interesting ices, the most limiting of which is the failure to take into account any synergy or antagonism in the effects of the different types of radiation to which these ices are subjected. Indeed, it should be borne in mind from what has been presented upstream that irradiations, until now, have always involved only one type of beam. The MIRRPLA platform (Fig. 19) consists of an ultra-high vacuum chamber, combining four types of radiation (UV photons, energetic electrons of a few keV, ions of a few keV and ions from GANIL's cyclotrons) and the associated in-situ analysis devices.

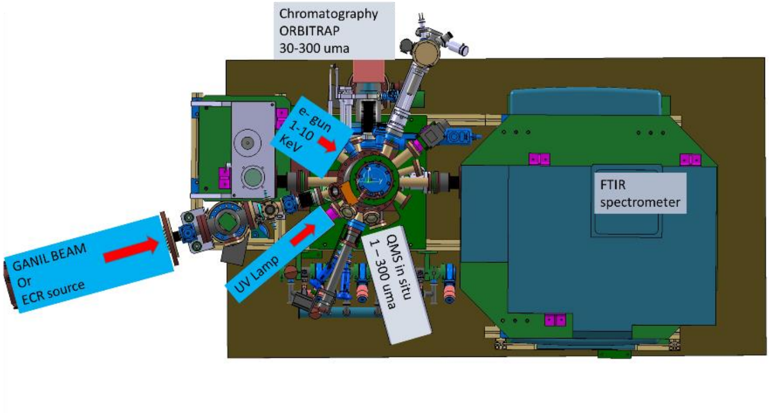


Figure 19: MIRRPLA: Multi-beam irradiation platform to study the origin and evolution of organic matter in the solar system

It is important to emphasise the unique nature of this new setup, which should make GANIL even more attractive to the astrophysics community.

2.4. Radiobiology

In radiobiology research, GANIL has considerable advantages in attracting national and international research teams. In fact, it is the only facility in France with high-energy ions (other than protons) whose long path through matter enables them to pass through biological supports, with very limited energy loss, before reaching the cellular models, which are thus preserved in their sterile environment. Since the installation of LARIA in 2002, the facility has benefited from a fully equipped laboratory for cell biology experiments (cell culture with or without hypoxia, microscopy, etc.), biochemistry and molecular biology. Many French and international teams use GANIL's radiobiology beam times for their research activities with various ions relevant to radiobiology (Carbon; Neon; Oxygen; Calcium; etc.). Most of the proposed research projects focus on cancer, with a view to improving radiotherapy protocols and, in particular, testing the conditions for treatment with carbon ions, more commonly known as carbon therapy. At the same time, research is being carried out into the effects of space radiation by simulating the high TEL radiation conditions encountered by astronauts on space missions. Hadrontherapy, which includes therapy with carbon ion beams, is ideally suited to the treatment of radioresistant and non-operable tumours. However, although numerous studies have been launched on this subject over the last decade or so, there are still many unknown factors in our understanding of the processes involved, which are necessary either to target tumours more effectively or to optimise the dose and the conditions under which it is delivered. It therefore seems essential to continue, and even accelerate, research into innovative radiotherapies, in particular by exploring ions with lower atomic numbers, between protons, whose relative biological effectiveness (RBE) is slightly greater than 1, and carbon, whose production cost is very high. Fundamental studies of the biological effects of ions heavier than carbon (O, N, Ne, etc.) could also be of great interest for clinical transfer, thanks to their higher RBE and lower lateral diffusion. The TEL and intensity of the beams also make it possible to achieve dose rates in the field of FLASH radiotherapy (≈ 100 Gy/s).

Research in hadronbiology, carried out by local or external teams using GANIL's heavy ion beams, can be divided into three main areas: 1) acquisition of biological data to improve the simulation models used to calculate the biological dose used in treatment planning, 2) study of the effects of $^{12}C^{6+}$ ion beams on cancer cells, and 3) study of the effects of accelerated heavy ion beams on healthy tissue.

Acquisition of biological data

In recent years, in response to strong demand from the international radiobiology community, studies have evolved to allow new types of analysis, and certain developments are underway and should continue in the more or less distant future. The first is to ensure that the results of biological research are correlated with clinical results by studying models that are closer to tumours. This is particularly important in the fields of hadrontherapy and FLASH therapy. With this objective in mind, the community is gradually implementing its traditional two-dimensional cell culture models with three-dimensional culture and organoids. One development involves preserving and reducing the biological variability of three-dimensional models during irradiation by using a thermostatic chamber and more precise control of irradiation characteristics.

Research into the effects of $^{12}C^{6+}$ heavy ions on cancer cells is aimed at specifying the influence of high energy transfer (HET) on molecular response, cancer progression, metastasis and the development of possible radioresistance in radiotherapy. In addition, the search to optimise the local effects of the dose deposited on cancer cells has led to the development of protocols combining different processes. These may involve increasing the radiation dose in fractions (hypo-fractionation), or highly localised insertion of chemical radiosensitisers (metallic nanoparticles) or biological radiosensitisers (PARP inhibitors, KRAS, cetuximab, immunotherapy, etc.). In this context, animal models with xenografted or syngeneic tumours will be adopted to study the efficacy of hadrontherapy combined with promising adjuvant treatments such as immunotherapy. These models will also be used to monitor the formation of metastases/secondary cancer. Varying the dose rate applied to tumours is also one of the ways in which radiotherapy treatments can be improved, through Flash radiotherapy (high dose rate for a very short time). In order to implement this type of therapy using ion beams, it is first necessary to understand and control the influence of very high dose rates (around 10 Gy/ms) on cellular response. These developments are very recent and will require major research over the coming decades, with the dual aim of understanding the mechanisms involved and determining the crucial parameters in terms of total dose, dose rate and dose fractionation.

Studying the effects of ions on healthy tissue is a major challenge in several areas. The main one concerns the study of the side effects of hadrontherapy treatments. During treatment, the maximum dose is deposited at the heart of the tumour. However, the therapeutic ion beam first passes through healthy tissue, depositing energy. Although the TEL of the particles is lower and the resulting dose is small compared with the dose deposited in malignant cells, it is essential to study the evolution of these healthy tissues. Another side effect of radiotherapy is the bystander effect. This relates to the development of cells that have not been penetrated by the beams but have suffered damage in the immediate vicinity of the irradiated cells. Studying this bystander effect, which is mediated by biological stress messengers, is therefore an important part of our understanding of the biological effects of irradiation. The study of the effect of ion beams on healthy tissue is also relevant to space research. In this field, despite the data already acquired, fundamental questions about the mechanisms of degenerative changes induced by heavy ions (such as iron ions) in space are still open and risk assessment is incomplete. Future work will focus on the influence of low doses (up to 1 mGy) and low dose rates (up to 1 cGy/min) in order to get as close as possible to the characteristics of space irradiation.

The forthcoming use of metallic nanoparticles in targeted therapies and Flash irradiation hold out the promise of major advances in cancer treatment. This is far from being the case in France or elsewhere, and requires the implementation of irradiation systems, beam controls and dosimetric controls adapted to the new needs of radiobiologists.

Over the years, CIMAP engineers have developed several devices and sample holders for the irradiation of new cell models, with the aim of keeping up to date with standard and modern experiments in radiobiology. LARIA's cell culture laboratory, located within the INB zone, enables fast and efficient experiments to be carried out, which meet the best conditions that can be expected and guarantee the quality of the results.

2.5. Atomic and molecular physics at GANIL

For more than 35 years, the atomic and molecular collision physics community has used the GANIL facility for countless experiments carried out as part of numerous national and international collaborations. These experiments have focused on the study of the interaction of ions with dilute matter ranging from isolated atoms and molecules to molecular aggregates and nanoparticles. The originality of the GANIL facility is that it offers complementary beamlines producing a variety of ion species ranging from light ions (up to protons) to heavy ions (up to uranium) with a wide range of charge states and energies. GANIL is therefore the most versatile facility in Europe, if not the world. This versatility is an essential feature for the atomic and molecular collision physics community, as this field of research requires systematic studies as a function of the energy and/or charge state of the incident ion. For example, the ratio between the energy transferred to the target electrons (electronic energy loss in soft collisions) and the energy transferred to the target nuclei (nuclear energy loss in hard binary collisions) depends on the speed of the ion and, to some extent, on the initial charge state of the projectile. Thanks to the wide range of projectile energies and species available on GANIL's different beamlines, elementary processes such as electron capture, ionisation and excitation have been extensively studied. For some years now, the relaxation processes of the collision partners have been another source of specific interest.

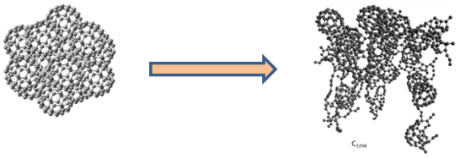


Figure 20 : Fragmentation of C60 aggregates and formation of new structures (R. Delaunay et al., Carbon 129 (2018) 766)

A major objective of current and future experiments at GANIL is to study the stability and fragmentation dynamics of multi-atomic systems after their excitation/ionisation by ion impact at speeds ranging from a few tenths to several atomic units (Fig.20). These studies will provide a better understanding of radiation damage processes by describing - at the molecular level - the initial physical stages of ion-induced excitation and ionisation of molecular systems and their subsequent fragmentation. Another emerging priority objective is to study the formation of new molecular species in excited and ionised molecular aggregates, in order to gain a better understanding of the molecular growth that occurs during the interaction between solar/stellar wind ions and the interstellar medium and planetary atmospheres.

The studies carried out are very fundamental, but provide data for other communities, for example for studies into the understanding of astrophysical or atmospheric phenomena, or in the context of hadrontherapy:

- In the context of ices of astrophysical interest, the community is considering a multi-scale experimental approach to identify the processes induced by ions at the molecular level and to understand the role of cosmic rays in the evolution of ices in the interstellar medium. Irradiating molecules with the same species of ions in the gas and solid phases promises to be a systematic way of exploring the various mechanisms involved. Another essential part of this project will be to study, at the molecular level, the primary interaction between ions and matter using experiments dedicated to ion-molecule collisions in the gas phase. The impact of ions leads to the fragmentation of molecules. Most of the fragments ejected have a low kinetic energy (of the order of one eV or less) and play a key role in subsequent chemical reactions in the irradiated matter. We therefore plan to exploit GANIL's various beamlines to irradiate a wide variety of complex organic molecules in the gas phase, to complement studies in the condensed phase.

- In the context of hadrontherapy, experimental collision physics techniques coupled with mass spectrometry are being used to identify the molecular products of isolated collagen peptides formed during direct irradiation with carbon ions. This has made it possible to observe the formation of specific small molecules that could be toxic to cartilage cells and provide an explanation for the arthritis observed after radiotherapy of cartilage. In addition, the specific triple helix structure of collagen is damaged by 1 MeV/u carbon ions. This result was obtained thanks to an international collaboration involving the University of Groningen. This collaboration is also studying the effects of ionising radiation on DNA, and in particular the role of specific duplex or G-quadruplex structures on single- and double-strand breaks. It has been shown that these bond breaks play a crucial role in the death of cancer cells under radiotherapy. This is why many efforts are now being made to increase the number of double-strand breaks during radiotherapy and hadrontherapy, in particular by using radiosensitisers such as metallic nanoparticles. The latter have been shown to be a source of secondary electrons that increase the number of double-strand breaks. Recent theoretical work has shown that electron emission from nanoparticles results from different types of collective electron excitation. These processes are thought to depend on the size of the nanoparticles, but also to vary significantly with the energy of the projectile ion. At CIMAP, to quantify these processes, the recent ANR IMAGERI project (Fig. 21) aims to measure the absolute cross sections of electron emission from isolated metallic nanoparticles, and to compare the results obtained on the different GANIL beamlines and for different nanoparticles (in size and chemical composition).

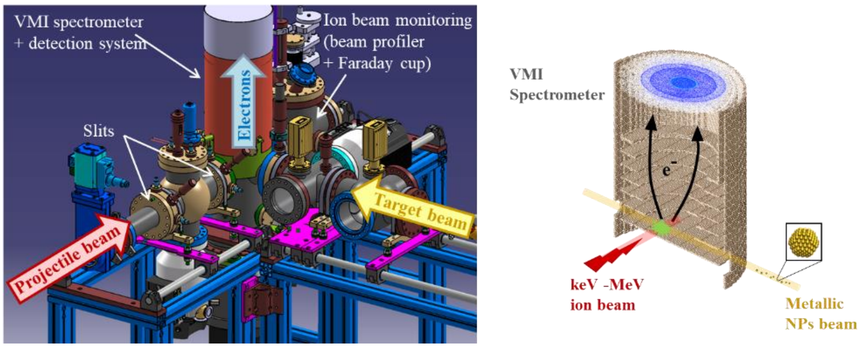


Figure 21 : 3D diagram of the IMAGERI device designed at CIMAP and simulation of the VMI (Velocity Map Imaging) spectrometer

For the majority of future experiments, the ion beams delivered by the SME and HE beamlines will be of particular interest, as they correspond to the energy of the ions when they interact with healthy tissue during hadrontherapy. Our aim is to extend the work done on proteins and DNA to higher energy domains (IRRSUD). In addition, on IRRSUD, numerous experiments will have to be carried out with carbon ion beams at different charge states, in order to study the effect of charge on the processes induced, bearing in mind that the charge state decreases rapidly with the depth of penetration into the tissue around the Bragg peak.

2.6. Conclusions and outlook

Interdisciplinary research at GANIL involves around 70 experiments a year, in which more than 150 French and international scientists take part. In the 40 years of its existence, more than 2,500 publications have been produced by the scientific communities involved in interdisciplinary research at GANIL. One of GANIL's major assets, because of its many lines of research, is the fact that it can be a meeting place for specialists from different disciplines, which leads to cross-fertilisation between research fields and the emergence of new projects (hadrontherapy is one example, with an approach combining physicists, chemists and biologists).

Some of the topics presented above still require at least a decade of research and involve numerous teams. For all these projects, it is essential to maintain regular access to these high-quality beams. Renovating the cyclotrons will ensure that the community is able to pursue and develop major new research programmes over the next twenty years.

GANIL's interdisciplinary user community remains dynamic and has recently proposed or supported various projects to develop GANIL's lines or associated instrumentation in order to continue to develop GANIL's capabilities around the cyclotrons. In addition to the current projects presented above (MIRRPLA, IMAGERI, etc.), the following projects are currently under study:

- Project for a new electrostatic "small accelerator" DIAPASON :

Over the last few years, the community has been reflecting on the supply of beams at GANIL. It has led, within the EMIR&A federation, to a proposal to build a new accelerator coupled to one of GANIL's current lines (the DIAPASON project submitted in 2020 in response to the PIA3 equipex+ call for proposals; well evaluated but not financed). This tool would make it possible to extend the beam possibilities on the GANIL site, by integrating an accelerator with an intermediate energy range between those of ARIBE and those of IRRSUD in room G3, for example. The main advantages would be

1) to have a double beam combining a "low energy" beam and a "high energy" beam giving simultaneous access to the main types of particle/matter interactions (nuclear and electronic). The choice of medium- or high-energy ion beams with electron stopping powers above the trace creation threshold (Se_{th}) optimises the study of the coupled effects of nuclear (Sn) and electron (Se) stopping powers. This combination of $Se > Se_{th}$ / ballistic collisions would be unique in the world and would enable major advances to be made in understanding the coupled effects of Se/Sn on the behaviour and ageing of materials under irradiation (damage, healing of defects, etc). This multi-beam device would enable a more detailed study of the expected synergies, particularly in nuclear materials. It would also make it possible to simulate irradiations in space for which the field of radiation to which materials are exposed is complex, UV, e-, ions (H, He, C, O, S, Fe, etc.) of various energies (some of which are very energetic), and for which the effects of synergy have been little or not studied.

2) to carry out in-situ characterisations by RBS (Rutherford Backscattering Spectroscopy) using the new accelerator to produce the probe beam. Here again, in this energy range (ME-HE), this device would be unique in the world and would complete the range of on-line characterisations developed at CIMAP, for a better understanding of the fundamental aspects of ion/matter interaction.

3) to have a new irradiation line to extend the range of energies available at GANIL and to open up GANIL's offer to ion beam analysis.

- Support for the C02 injector renovation project:

Having a more efficient injector would allow greater flexibility in programming the HE line, which would increase the time available for IRRSUD. On the other hand, some experiments are currently limited by the beam intensity available and would benefit from having a more powerful injector (in particular for heavy experiments in SME and HE or on IRRSUD). The technical upgrade of existing cyclotrons and a new injector would make it possible to deliver very high dose rates in very short and intense ion pulses. This would be of great interest to radiobiologists in understanding the effects of Flash irradiation with carbon ions, but also to the atomic and molecular collision community, because of the possibility of time-resolved pump-probe experiments with ions and/or lasers, which have not yet been carried out. These experiments could shed light on the dynamics of ion-induced denaturation of proteins and DNA, a totally unexplored area.

- New in-situ devices project:

A new electron paramagnetic resonance (EPR) analysis device has just been acquired by CIMAP-CIRIL, which will not only complete the possible characterisations. Once it is online, this equipment will be made available to the interdisciplinary physics community. This spectroscopic technique, which can detect species with mismatched electrons, will enable the study of the creation of defects such as radicals in organic materials, F centres in transition metal materials or any material with paramagnetic species; at temperatures ranging from 8 K to 500 K, in materials. Studies of the electronic structures of the transient species, their concentrations and the characteristics of their reactions (activation energy, kinetics, etc.) as a function of the irradiation environment and/or temperature will be carried out. This device is at the heart of future work planned to predict the ageing of organic materials, as described in the following section, since it will provide access to the reaction intermediates. In addition to this analysis device, other ideas include the installation of an in-situ Raman spectrometer, which would be an advantageous addition to the IRTF spectrometer, in order to remove certain remaining obstacles to the production of damage profiles on the ion trajectory and thus predict changes in properties. It should also be remembered that the IRRSUD and SME lines are open to experiments by communities in the EMIR&A research infrastructure and research federation, the national network of accelerators for the irradiation and analysis of molecules and materials, and that the ARIBE-IRRSUD-SME lines, in addition to the historical iPAC committee, are open to the European community via the ARIE European network.