Nuclear physics at the edge of stability

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Context

The physics at the drip line is a relatively new topic in which French scientists have a very good experimental visibility and expertise, both on the neutron or proton-rich sides of the valley of stability and using different experimental techniques and instruments. The merit of studying the continuum was realized early in nuclear theory however the challenges still remind tremendous. This broad topic offers many potential new discoveries related to shell evolutions, clustering or halo formation and their medium dependence, evolution of pairing and nuclear superfluidity at the drip line, with connections spanning from others open quantum systems and universality of few-body systems to nuclear astrophysics, of which large swathes largely unknown.

Introduction

The mean field concept, which describes the atomic nucleus in terms of single nucleons moving in an average potential, augmented by two-body or three-body residual interactions, is a very successful tool to describe shell structure and shell evolutions along the chart of nuclei. However, significant limitations arise when treating shell structure near the drip lines, or more generally near the particle emission threshold, which encompasses the description of excited states of well bound nuclei. In particular, the disappearance of traditional magic numbers at the neutron drip line and the emergence of new magic numbers such as N=16 and N=34 partly take root in the change of effective interactions in weakly bound nuclei. In addition to this, in the limit of weak binding, many-body correlations such as pairing or alpha/quartet clustering could no longer be treated as a perturbation on top of a dominant mean field. It follows that cluster states, including 2n and 2p, would be present at the corresponding particle emission thresholds, possibly changing the very nature of the traditional BCS nuclear pairing towards the formation of Bose Einstein Condensates in very dilute systems. Finally, the spectroscopic or scattering properties of unbound or close-to-unbound states can be significantly influenced by the external environment (such as the presence of decaying states or the temperature and density of the surrounding medium) accessible to such open quantum systems. This document was made in strong connection to the GT#1 of the GdR RESANET and reflects the various topics and discussions addressed during the two workshops.

Nuclear shell evolution towards the drip line

Evolution of nuclear structure: understanding the nuclear interaction

L'exploration des propriétés des noyaux les plus riches en neutrons, y compris ceux qui se trouvent au-delà de la dripline, constitue l'un des moyens le plus draconien de tester notre **compréhension de la structure nucléaire et**, le but ultime de tout physicien nucléaire, de **l'interaction nucléaire**. Puisque tous les mécanismes de liaison nucléaire prennent une importance considérable à la dripline, elle constitue un microscope idéal pour notre compréhension du noyau, mais sous certaines conditions : (i) **La théorie a fait des progrès très significatifs ces dernières années** avec la mise au point d'une gamme de modèles sophistiqués (incluant une force nucléaire à trois corps), y compris des approches ab initio et qui, au raffinement final, incorporent explicitement le continuum. (ii) **Les avancées expérimentales**, notamment en termes de **nouvelles installations et de spectromètres**, de cible active, et multi-détecteurs associés (incluant Nebula Plus à RIKEN en 2020 pour la détection de neutrons rapides), permettent depuis quelques années d'atteindre des systèmes très riches en neutrons. Très récemment, les premières étapes de l'exploration des isotopes de l'O et du F les plus riches en neutrons, y compris ceux du continuum, ont été entreprises ($^{26\text{-}28}$O, $^{28\text{-}30}$F). Il est prévu d'étendre ces études à d'autres noyaux non liés comme les quelques exemples décrits ci-dessous.

En ce qui concerne ce programme expérimental à RIKEN sur ce sujet à moyen terme, des études plus complètes et plus détaillées sur les isotopes d'oxygène non liés seront une première priorité. L'exploration des systèmes riches en neutrons autour de N=16 et au-delà pour Z=5-7 devrait s'avérer possible et permettra de mettre en évidence la persistance ou non de la fermeture de sous-couche N=16 révélée dans le ^{24}*O. En particulier, la localisation des états excités du* ^{22}*C (y compris le premier état* 2^+*) ainsi que la première identification de* ^{23}*C devraient être possibles. Des mesures améliorées de* ^{21}*B et* ^{25}*N, y compris l'identification de leurs premiers états excités, sont également à prévoir, avec éventuellement la première identification et étude du* ^{18}*Be.*

A plus long terme, l'augmentation d'intensité de faisceaux primaires à RIKEN d'un facteur 10 à l'horizon 2025 devrait permettre notamment d'approcher la drip line dans la région des Mg-Si Au fur et à mesure de l'augmentation en masse des systèmes qui seront étudiés, la densité plus élevée des niveaux (en particulier dans les systèmes avec Z impair) entraînera naturellement la nécessité d'améliorer à la fois la détection des rayons gamma (multi-détecteur Ge avec tracking) et, à terme, la détection des neutrons (meilleure granularité).

Evolution of proton-neutron force: a binding mechanism for exotic nuclei

Proton-neutron forces are essential to account for shell evolution **far from stability**, in particular for the change of magicity. In the case of neutron-deficient or neutron-rich nuclei, there is a large asymmetry between proton- and neutron-binding energies versus stability. This is depicted by a strong finite-size effect between isotopic and isotonic lines, e.g. from an ^{24}O core, to the right, by adding one neutron makes it unbound then adding of a proton, going up the chart, makes ^{26}F bound thanks to proton-neutron coupling. However, in such extreme condition, it was claimed that the proton-neutron central part of the interaction is weakened by about 30%. A similar effect of weakened effective nuclear force was evidenced in the neutron-deficient ^{16}F, with an observed breaking of the mirror symmetry with ^{16}N with an unprecedented manner.

More cases are needed to explore this reduction of the effective nuclear force for different orbitals and to estimate its effect close and beyond the drip line, also in connection with the damping of S_n oscillations. For instance, it is foreseen that ^{22}N and ^{24}N will be studied at RIKEN, and ^{14}F at GANIL.

Structure of nuclear states at particle emission threshold

α clustering and the embodiment of the Ikeda conjecture

Alpha clustering formation is **expected to occur close to the corresponding decay threshold** (as proposed by the Ikeda conjecture) rather than in ground-states. However, recent Antisymmetrized Molecular Dynamics (AMD) calculations show examples in **light isotopic chains with ground-states** evolving from a compact system to spatially-extended **cluster configurations**, when going towards the neutron dripline. Very recently, important developments in reaction theory have been performed to make use of sophisticated cluster wave-functions. In particular, using the so-called optimized THSR (Tohsaki-Horiuchi-Schuck-Röpke) wave function, ^{10}Be shows a molecular-like structure with two separated α-clusters surrounded by orbiting neutrons. When using this wave-function in DWIA calculations ($E \geq 100$ MeV), a tremendous sensitivity of the calculated proton cross-sections to the $\alpha - \alpha$ inter-cluster distance is evidenced. Hence, measuring such cross-section in this specific example can bring quantitative information on the configuration of $\alpha - \alpha$ correlations.

On the experimental side, a first (p,p α) study has been performed at RIKEN/RIBF on the neutron-rich Beryllium isotopes ^{10,12,14}Be. Further investigation on neutron-rich Carbons are already planned. At RIKEN and GSI, the new tracker device STRASSE, currently under development, will represent a powerful tool for the study of this class of knockout reactions.

Hints of clustering from excited states

In the last 15 years, one of the most remarkable discovery in nuclear structure of light nuclei has been the observation of super-deformed rotational bands, fed by fusion-evaporation, in the N=Z nuclei ^{36}Ar and ^{40}Ca close to the end of the *sd* shell. Interestingly enough, very **deformed cluster bands** are observed in doubly-magic, in principle closed-shell, ^{16}O and ^{40}Ca nuclei. These cluster bands of a m-particle m-hole type, are built on an excited highly-deformed 0^+ state. When moving away from stability into **the island of inversion,** the ground state of the N=20 Ne, Na, and Mg isotopes becomes deformed thus supporting the **possibility of the existence of clusters** in this region.

There are two ideas for the next decade. It is possible that nuclei in the island of inversion have ground state with a cluster structure. This could be tested in experiments using radioactive n-rich beams. Moreover, an evidence of very deformed molecular states can be found by measuring the electromagnetic transitions between states within the band. This has been done only for cluster states in the light nucleus ^{8}Be($\alpha - \alpha$). For heavier nuclei, identifying such transitions is rather challenging since the resonant flux might be spread over several

transitions. Such experiment might be performed in the future using new detector developments for the measurement of gamma-rays and fragments.
An important issue is related to the physical understanding of pre-formed localized clusters inside the nuclei. Many experiments probe clusters emission during nuclear collisions. However, the unambiguous demonstration that the cluster was already pre-formed is rather difficult. Such a demonstration would require to develop theories that can treat (i) the delocalization of nucleons, (ii) the pre-formation clusters together with (iii) a consistent reaction model which will lead to properly trace-back to clusters starting from observables.

Towards a generalized Ikeda conjecture including multi neutron and proton clusters

From the systematic observation of narrow resonant states with clustered structure close to the corresponding particle emission-thresholds, it was proposed that the Ikeda conjecture can be **generalized to two or four nucleon clusters.** In the last three years, adding to the very weakly-bound ^{11}Li that exhibits a two-neutron halo configuration, two remarkable examples of this generalized conjecture have been found in place of ^{15}F and ^{26}O. Both indeed exhibit narrow resonances very close (a few tens of keV) to the respective 2p and 2n thresholds. The properties of these handful of nuclei can be understood in terms of **universal features of few-body systems**. For those loosely-bound systems a lower resolution scale (than nucleons) is sufficient, i.e. an interacting three-body system determined by a few universal parameters, to reproduce observables and understand their correlations as genuine of a few-body system
There is already a significant body of evidence that resonances closed to threshold have been underestimated. This has **significant impact in nuclear astrophysics** because low-lying resonances enhance neutron-capture rates. For instance, in accreting neutron stars is may favor the synthesis of heavy elements. Similarly, the existence of 2p narrow resonances close to the 2p threshold would increase of the proton capture rates in x-ray burst, if very high proton densities are reached.

Other systems are planned to be studied in the future, both on the neutron deficient and neutron-rich side. These states can be produced by resonant elastic scattering, knockout or transfer reactions. For some of them, gamma decay can enter in competition with particle decay, in particular if the cluster lies just above threshold (narrow resonances) or is part of a rotational band. Experimental programs are planned to study such competition. If the frequent presence of narrow 2n(4n) cluster states close to threshold is revealed, this would further indicate that the Ikeda conjecture is intimately linked to open quantum systems.
It is understood that such systems do not encode details of the strong force. However, reaching a complete understanding of these nuclei, of the emergence of the few-body features and the capability to predict them requires both a precise description of nuclear correlations and an accurate accounting of large-distance behavior, currently an active field of research.

From nuclear force in a many-nucleon system to few-body physics and universality

The physic described above shines best in the light of the rich concepts necessary to explain the observations. Since these systems behave like **nuclear microscope**, there is a number of **important questions that can be addressed in close collaboration with theory groups**. 1) High-precision spectroscopic observations can give better insight into **the understanding of the underlying bare nuclear interaction**. Exotic light-nuclei sector, for which ab initio methods are applicable, is a perfect test-bench for our understanding (or lack of) of the nuclear force. 2) Few-body methods and effective field (EFT) theory have underscored that the static and dynamical properties of already a few exotic nuclear states can be described in terms of universal low-energy constants. The treatment of nuclei within EFT also points out that we are dealing with a regime **close those presenting universal properties such as cold atoms**. 3) Considering weakly-bound nuclei with varying separation energy is also a way to change the *s*-wave scattering length between a core and neutron effectively **spanning a discrete set of points in the Effimov trimer plot**. The last value in ^{18}B shows a scattering length of about -100 fm, almost four times the size of the nucleus, more than **five times the free NN value**: an absolute record of the whole nuclear chart.

Among the important questions to be clarified is the importance of the three-nucleon force and possibly higher-order interaction. In order to achieve the goal of predicting the occurrence of few-body phenomenon along the nuclear chart, it is compulsory to develop methods able to treat the continuum with the least phenomenological inputs. The coupling to the continuum is very important in nuclear physic for which many of the developments are ahead of the other field of physics, and effort should be made to continue along those lines.

Nuclear correlations

Nuclear superfluidity: transition from BCS to BEC

A **transition** from BCS (Bardeen Cooper-Schrieffer) to BEC (Bose-Einstein Condensation) **pairing correlations** has been evoked from the modelling of the interior to the surface, respectively, of the neutron-rich nuclei ^{11}Li, ^{6}He and ^{18}C. The search of experimental evidence of such a transition in unbound states is a major motivation. It would imply a change in the relative distance between the neutron or proton pairs, from the size of the nucleus, **eventually forming dineutrons in more dilute nuclei**.

This is planned to be achieved in neutron-deficient and neutron-rich nuclei at GANIL using MUST2/MUGAST/GRIT, at FAIR-R3B and RIKEN using a combination of a spectrometer and neutron walls, respectively, by studying the three-body decay of unbound states (featuring an extended proton/neutron distribution) in view of revealing the momentum correlations (and herewith deducing the fraction of direct over sequential decay) and the sizes of the pairs. This study is complementary to the case of 2p emission (discussed below), in which the pairs may lose their correlations when tunneling through the Coulomb barrier.

Studies of 2p radioactivity

The long-lived (few ms) **two-proton radioactivity** has been established in the decay of **four nuclei** at – or beyond – the proton drip-line: ^{45}Fe, ^{48}Ni, ^{54}Zn and ^{67}Kr. A hybrid three-body model has been developed to compute the 2p decay half-life. While a good agreement is obtained for ^{45}Fe, ^{48}Ni and ^{54}Zn, it fails completely in the case of ^{67}Kr, underlying that **the emission process is not clearly understood**. This has recently trigged some theoretical developments for ^{67}Kr. Two hypotheses have been put forward: (i) the emission occurs in a transition region, between direct (2p) and sequential (1p-1p), depending on energy position of the intermediate state - currently unknown - (ii) the nuclear deformation influences the decay of the two protons. For the latter case, the Gamow coupled channel approach has been applied successfully to ^{67}Kr (with ^{48}Ni as a spherical benchmark). Interestingly, the angular correlations of both models are totally at odd with each other in the *fp* shell nuclei.

In a short/mid-term, it is planned to measure the energy and angular correlations for both ^{48}Ni (at GANIL/LISE3, with a ^{58}Ni beam) and ^{67}Kr (at RIKEN/BigRIPS, with a ^{78}Kr beam), using ACTAR TPC device. Due to the extremely low-production cross-sections, such nuclei are at the limit of what can be reached at current fragmentation facilities. Nevertheless, it would also be interesting to measure ^{54}Zn with a decent statistic and compare it with both theoretical calculations, for a complete experimental set of data on known emitters. This could be achieved at GANIL, or more easily at RIKEN if an intense Ni beam is developed. To go further, we plan to explore the region between the closed shells Z = 28 (Nickel) and Z = 50 (Tin), in order to provide a larger variety of nuclear configurations across a deformation region. This program implies to first identify the new emitters in standard experiments and then to measure correlations in tracking experiments. According to preliminary production rates estimates, such an experimental program could be achieved at GSI-FAIR facility (within the NUSTAR collaboration), with the (Super)FRS.

Investigation of 4p and 4n correlations

The **existence of quasi-bound tetra-neutron resonances**, as an ensemble of four interacting neutrons, was proposed on the basis of experimental results, **in stark contrast with most of the state-of-the-art models** including the most recent ab-initio forces. Even if the existence of a quasi-bound tetra neutron is not confirmed or not existing, the coupling of four neutrons or protons could, alike the two neutrons or two protons cases, play a significant role inside atomic nuclei. The purely neutronic part of both the nucleon-nucleon and three-nucleon (3N) interactions are either poorly or totally **unconstrained by accurate experimental data**, e.g. the T=3/2 part of the 3N force is likely the least understood piece. Even the better understood 2n part suffers from inaccurate experimental data (it can neither be measured directly nor at low-energy). Most theories predict that tetra-neutron resonances are unlikely. Henceforth any experimental signatures that may hint at its existence or any weak effects from a 4n channel coupling, may strongly impact our understanding of nuclei. For instance, the T=3/2 part of 3N force, which is a major contributor to the nuclear saturation properties, contributes to the uncertainties of pure neutron matter.

The search for 4p and 4n resonances has been carried out at in N=1 isotone of ^{7}C, ^{6}B and ^{5}Be at GANIL, using MUST2, and in ^{7}H using the active target MAYA, and at RIKEN. These experiments are presently under analysis. More generally, evidences of 4n correlations will be searched for in the 4n unbound states of ^{17}B, ^{14,16}Be, ^{18}C and ^{28}O to quote a few, at RIKEN, FAIR/R3B, and in ^{12}Be with ACTAR-TPC at GANIL. As for the detection of multi-neutron decays, the use of high efficiency and high granularity detectors (such as e.g. NeuLand) is mandatory.

Neutron-proton pairing, and quartetting

Neutron-proton pairing manifests itself in the binding energies and the delayed alignment phenomena. But **the two-nucleon transfer reactions** are believed to provide the smoking-gun as in the two-neutron pairing case. It requires the systematic measurement of the cross-section for two-nucleon transfer along a full shell to determine the onset of collectivity near the closed shell and the superfluid phase at mid-shell. Recently, the systematic for the stable *sd*-shell nuclei has been extended up to the radioactive *fp*-shell nuclei by measuring ^{56}Ni (p,^{3}Heγ) ^{54}Co and ^{52}Fe(p,^{3}Heγ) ^{50}Mn at GANIL. The results evidence the weakening of the T=0 channel in the *f*-shell that can be traced back to the spin orbit effect, i.e. the large spacing between the *f* orbits reduces the possibility of forming T=0 pairs. Neutron-neutron or proton-

proton pairing are usually included in the energy-density functional theory. There are now extensive efforts to include also proton-neutron pairing. However, n-p pairing is **a very illusive type of correlations**. The standard theory of pairing for two-fermion species (HFB) leads either to n-n and p-p pairing, or n-p pairing but very rarely the two types of pairing simultaneously. Another difficulty is the n-p pairing interaction is very **fragile against the onset of spin-orbit interaction** compared to the particle like pairing. However, **deformation can partially compensate** from the spin-orbit anti-coupling. Lastly, a peculiarity of T=0 neutron-proton pairing is that the pairing strength has two maxima: one for the anti-aligned spins (similar to the anti-aligned scheme in the n-n and p-p pairing) and one for the maximum alignment case, J_{max}. Pioneering work on ^{92}Pd spectroscopy has shown the importance of such aligned pairs in the $g_{9/2}$ orbital.

The role of the spin-orbit in reducing the collectivity in the T=0 channel could be further investigated in heavier nuclei where the strength of the T=0 pairing could overcome the spin-orbit effect. Moreover, the interplay between deformation and n-p pairing in the T=0 and T=1 channels remains to be understood. This program could be started at GANIL with MUGAST-like and EXOGAM set-up and continued in heavier nuclei at RIKEN-GSI with slowed-down beams. These searched for aligned pair coupling could also be more deeply investigated through transfer at high energy or probably more efficiently with knock-out reactions at FAIR/GSI or RIKEN. Finally, the competition between neutron-proton pairs and quartetting (two pairs of neutron-proton) could be investigated by comparing α transfer reactions like (^{7}Li,t) and n-p pair transfer in the fp-shell. Given the very low cross-sections for the former reactions, high intensity beams (>10^7pps) are required and could be performed with MUST2-like or GRIT systems on OEDO line at RIKEN. Another approach could be to knockout pairs at intermediate energies to favor long-range correlations and determine the cross-section associated to n-p pairs and α.
Specific theories beyond the HFB approach like a quartetting theory should be developed. Then a comprehensive quantitative study must be made to figure out which region of the nuclear chart is the more adequate to probe n-p pairing correlations.

Understanding nuclear probes in the vicinity of the continuum

As stated above, understanding the **role of the reaction mechanism** in revealing the existence of correlated pairs in bound atomic nuclei is a **hot topic**. It can be done by comparing the transfer and knockout cross sections of pairs along a chain of isotopes. While both mechanisms probe the nuclear surface, we will use the fact that the knockout is a more sudden process to investigate the increase of surface-localized clustering as compared to BCS pairing, in which nucleons orbit at large relative distance. Another fundamental question arises from the use of the **quasi-free knockout reaction** to suddenly promote nucleon pairs into the continuum. The **central question** seeks to find for **which conditions the reaction convey the structure of the pairs** from the **initial nucleus**. Physical intuition tells us that narrow resonances live long enough to carry their own properties while pairs created by knocking out a deeply-bound nucleon that leads to a very broad resonance, may not survive long enough to distort its properties from within the initial nucleus. So far, little efforts were devoted to bridge the gap between low-energy nuclear structure, particularly for shallow states like exotic cluster or halos, and practical experimental observables. Indeed, many experimental facilities investigate exotic systems in inverse kinematics at higher relative energies than the prototypal low-energy expansion used in microscopic methods. Except for rare, ideal and few-nucleonic systems, there is little hope to achieve a full microscopic calculation of the complicated reaction.

However, a few ingredients used in traditional reaction models can be computed from first principle. For instance, it was established that breakup and knockout reactions are mostly peripherical, e.g. requiring the asymptotic normalization coefficients (ANC) to be correctly reproduced by the microscopic structure method. For the case of exotic states, it has been demonstrated in a few instances that nuclear structure methods which explicitly include the effects of the continuum correctly reproduces ANC. Another important input for high-energy reaction models is the optical potentials between the various fragments and target. Only recently, a few propositions have emerged for optical potentials derived from microscopic theory. However, they all suffer from a poor description of the nuclear absorption. There is room for improvement: we could expect that a unified treatment of the continuum will provide more accurate optical potentials.

In-medium structure and correlations

Nuclei at the edges of their particle stability and close to the drip lines can be produced during the dynamical evolution of heavy-ion collisions (HIC) at intermediate energies. Studying their structure and decay patterns are key to probe in-medium nuclear properties via the EoS, with implications in the properties of compact astrophysical objects (supernovae dynamics, static properties of neutron stars and mergers, etc.). Nuclear systems produced in dissipative HIC represent a dilute, hot and inhomogeneous medium. Its dynamical and thermodynamical features, depending on impact parameter, beam energy and the degree of achieved dissipation, can be probed by correlating observables measured with highly efficient 4π detectors (such as INDRA at GANIL) and more recently developed high-isotopic resolution arrays (such as FAZIA). Thanks to multi-particle invariant mass spectroscopy of the reaction products, several unbound states can be populated in a single reaction. These unbound states include cluster states in alpha-conjugate nuclei (^{8}Be, ^{12}C, ^{16}O, etc.) and states close to or above their decay energy. Moreover, states in nuclei close to the drip lines can be observed and isolated for dedicated studies. These states and their corresponding resonant decays have been commonly used for two different purposes that are intimately interlinked: (a) Resonance decays are used to construct the so-called *excited states thermometers*, from the ratio of the measured population of two different decaying states on the same isotope, when dealing with a well-selected ensemble of thermally decaying systems. One of the most famous examples is represented by the decay of the ground state and first excited state at 16.6 MeV in ^{5}Li decaying, respectively, into $p + \alpha$ and $d + t$ pairs (b) Particle-particle correlations provide information on structure properties of the observed unbound states, such as their positions, width, spin and branching ratios, (c) multi-particle correlations have been used to try to extract direct and sequential decay branching ratios in ^{12}C (with three α particles in the final state) and in the doubly-Borromean nucleus ^{10}C (with two α particles and two protons in the final state). The large amount of observed resonances highlights the complexity of the produced nuclear medium, appearing highly inhomogeneous in charge, mass and in its space-time features. Indeed, these resonances have lifetimes spanning a wide range of values, from tens of fm/c to hundreds of millions of fm/c. In this respect, formation and decay times of resonances may be comparable to reaction and fragmentation times, thus suggesting that they may be interacting with the surrounding medium.

Another related topic concerns the effects of clustering in the low-density nuclear matter in thermodynamic conditions relevant at the neutrinosphere of supernovae explosions. Calculations show that the equation of state of sub-saturation matter is modified by clustering in an important way. Furthermore, masses and binding energies of clusters are expected to change with density under these medium conditions and we can expect that these clustering properties will also affect dynamical transport properties in the astrophysical medium. If confirmed, these considerations may stimulate the development of "in-medium" nuclear structure studies, as has long been the case in hadronic physics.

An experimental program would consist of systematic studies of heavy-ion collisions at various beams energies using the FAZIA array, coupled to a 4π detector to characterize the thermodynamic and dynamical properties of the medium. The use of FAZIA allows to extend charged particle-particle correlation measurements to a large number of cases, thanks to its wide dynamic range, thus approaching the limits of existence of several nuclear species close to the proton drip line. The angular resolution may be improved with position sensitive devices to be coupled to FAZIA telescopes and by adding other correlator arrays such as MUST2/GRIT. Coupling to neutron and gamma detectors would allow to extend even further the physics reach of the project. An energy-scan, between 30 and 90 MeV/nucleon, as well as a mass-scan of different reaction systems (for example collisions between isotopes of Ca, Ni, Xe, Sn as well as reactions induced by LISE exotic beams), would provide different in-medium conditions where resonance decays may be studied systematically. Such studies, scanning measured observables from high to low complexity and comparing them to transport model predictions, will provide unique new information on the evolution of nuclear structure.

Summary of strategies and needs:

Part of the experimental program on the study of cluster formation including the modification of their properties with medium, 2p correlations and n-p pairing can be performed at GANIL. As for charged particle detection, the high-efficiency/granularity detectors FAZIA, GRIT, and ACTAR-TPC are planned to be used, to be competitive worldwide. These detectors should ideally be coupled to ancillary detectors to achieve gamma-ray and fragment detection. Gamma-ray detection is foreseen with a combination of EXOGAM2 and PARIS detectors. Fragment detection at zero degree is available at the focal plane of the VAMOS spectrometer and is foreseen to be obtained at LISE in few years.

As for studies which require neutron detection, the Nebula (and its upgraded version Nebula plus and a highest granularity detector) at RIKEN/Samurai and NeuLAND detector array at FAIR/R3B are the instruments of choice. The construction of FAIR should provide high intensity secondary beam after 2025. However, experiments are already planned there for the study of multi-neutron detection from unbound states of moderately neutron-rich nuclei. From 2025 on, FRIB should start delivering secondary beams. However, the FRIB facility should not be equipped at that time of a large-acceptance and high-rigidity spectrometers as SAMURAI and GLAD at RIKEN and FAIR, respectively.

As far as theory is concerned, progress is generally lagging behind experimental efforts. It is the case either for ab initio or mean field methods. Since models required to treat dynamical or continuum effects are rather involved and very sensitive to nuclear force input, it is essential to have a continuing effort in that direction with an emphasis on transmission of knowledge in the absence of a large national effort on the topic.