High resolution spectroscopy of exotic nuclei through direct reactions.

LPC Caen: A. Matta, L. Achouri, F. Delaunay, F. Flavigny, J. Gibelin, M. Marques, N. Orr, M. Parlog
GANIL: E. Clement, G. de France, A. Lemasson, T. Roger, O. Sorlin, M. Rejmund
FLUO: Y. Blumenfeld, M. Assie, A. Astier, D. Beaumel, S. Franchoo, G. Georgiev, J. Ljungvall, R. Lozeva, I. Matea
IPHC: G. Duchene, F. Didierjean, M. Moukaddam
IP2I: J. Dudouet

Scientific Objectives:

The physics opportunities with a high resolution setup for gamma, particle and light nuclei span the fields of nuclear structure, nuclear dynamics and nuclear astrophysics using nuclear reactions.

Low energy experiments probe ground state properties and can give a first glimpse of excited states through isomers or beta-gamma measurements. However, a detailed understanding of nuclear structure requires the complementary measurement of nuclear reactions. On the other hand, processes such as fusion evaporation allow access to a broad range of states and nuclei but they lack selectivity. Linking the observed states to their wave-function content is therefore very indirect.

Studies using a direct reaction mechanism, such as **transfer, knock-out and coulomb excitation**, allow a high selectivity of the populated state, and therefore probe, almost directly, the underlying structure of the populated nuclei through the extraction of transition probabilities and spectroscopic factors. This make such process an essential tool that complement other means of study. Direct reactions have played a central role in constraining the shell model and high-lighting the mechanisms at play in the evolution of the magic numbers N=8, N=20, N=28 and the formation of the islands of inversion.

Weakly-bound systems provide a sensitive test of the nuclear force, and the neighborhood of the drip-lines offers unique opportunities to extend our understanding of this interaction. Light nuclei are a test bench for the most advanced theory approaches (Ab-initio family) and play a key role in nuclear astrophysics. Recent developments in ab-initio many-body methods allow their application to light exotic nuclei in order to perform dedicated tests of nuclear interactions and to determine the input required to best constrain nuclear forces. In turn, very high resolution detailed experimental observations will shed light on the question as to which higher-order terms of the nuclear interaction (3-body, etc.) are essential for a correct description of nuclear matter.

On the proton-rich side of the valley of stability, the instability against spontaneous proton emission is hindered by the Coulomb barrier, allowing these nuclei to have “measurable” lifetimes (μs or longer) and their excited states to decay by γ-ray emission. Therefore, these nuclei are the ideal laboratory to study “particle-unbound” states using γ rays, but also the competition between charged-particle and γ-ray emission. The nuclear structure of ^{100}Sn will be a milestone of the next decade. ^{100}Sn appears to be one of the last doubly magic nucleus to be investigated, and could be the second one without bound excited state with ^{48}Ni (continuum effect etc …). One of the main objectives of the community is to achieve the in-beam spectroscopy of ^{100}Sn and close neighbors using secondary beams of $^{101-102}$Sn or $^{104-106}$Sb. Such measurement will be achieved at RIKEN or FAIR in the next decade.

The N=Z line starting from ^{48}Cr up to ^{100}Sn and higher offers unique opportunity to probe the neutron-proton pairing interaction in the isoscalar channel and its interplay with quartetting. Two- and four-nucleon transfer reactions are the smoking gun to probe this type of correlations. This program spans from Spiral1 and LISE beams for the lower masses to OEDO facility for the intermediate masses.

On the neutron-rich side, phenomena of clusterisation are emerging; near threshold states are of paramount importance in astrophysics (e.g. the Hoyle state in ^{12}C) and continuum states have a large impact on the structure of the nucleus. From the theoretical point of view, their study necessitates the development of a coherent description of structure and reactions. Key reactions will involve beams near the neutron drip-line such as $^{22-24}$O, $^{28-30}$Ne, $^{40-42}$Si, $^{36-40}$Mg for example. Such measurements could be started at GANIL and rapidly carried out at RIKEN on the low energy OEDO line.

In moderately exotic nuclei, high resolution spectroscopy in the vicinity of the doubly magic ^{78}Ni and ^{132}Sn will be a milestone of the study of neutron-rich nuclei. In particular, the onset of collectivity beyond these neutron shell closures could be investigated as a benchmark in the study of shape coexistence in nuclei. Indeed, in the doubly closed-shell nuclei ^{132}Sn and, more recently, ^{78}Ni, rather low-lying collective second $0_2^{\ +}$ states have been discovered exhibiting the presence of correlations which, however, are not strong enough to induce an inversion of the ground-state (g.s.) structure. We propose to perform structure studies around ^{78}Ni and ^{132}Sn, respectively, using several reactions such as Coulomb excitation of RIBs, 1p and 2p knockout reactions, single and few nucleon transfer reactions.

Key experiments would be the safe Coulomb excitation at 5 MeV/A of ^{80}Zn to access states beyond the first 2+. This could be achieved in the next decade at HIE-ISOLDE or ARIEL. Single-nucleon transfer such as (d,p) will help probe the single-particle structure beyond N=50. This could be achieved in the next decade at RIKEN, HIE-ISOLDE, ARIEL or FRIB.

The physics cases proposed with in-beam spectroscopy cover a large variety of physics questions, such as

- Search for the contribution of the three-body interaction to the nuclear force,
- Coupling to the continuum for weakly bound nuclei,
- Isospin symmetry breaking in N~Z nuclei near the drip-line,
- Clusterisation effects and Ikeda conjecture in nuclear matter and the origin of nuclear deformation at the drip-line,
- Proton-neutron pairing near the drip-line,
- Nuclear structure inputs for nuclear astrophysics models
- Nuclear structure of doubly magic ^{100,132}Sn and ^{78}Ni nuclei and beyond

<u>Experimental Facilities :</u>

An ideal facility to study ^{78}Ni and ^{132}Sn would have been the second phase of the SPIRAL2 project, ideally equipped to produce high quality, high purity, ISOL beams at the needed energy of a few MeV per nucleon. This installation however does not exist now and would take at least 15 years to be completed. On the other hand, other laboratories have well advanced or completed installations to deliver similar beams. The bulk of the program, probing the shell and shape evolution in the fission fragments around ^{78}Ni and ^{132}Sn, could be performed at ISOLDE, SPES and ARIEL over the next decade.

In-flight fission of intense Uranium beam provides high intensity, high energy beams, ideally suited for nucleon removal studies, at RIKEN today and tomorrow at FAIR and FRIB. In-flight beams will also allow the study of lighter masses, close to drip-lines, to constrain ab-initio and cluster models. The “slowing-down” technique of in-flight RIB such as the OEDO project at RIKEN and similar project for FAIR will allow to approach the ideal beam energy for nucleon transfer. This type of beam, with respect to post-accelerated ISOL beams, will allow reaching even more exotic nuclei in these regions at the cost of lower quality beams, meaning more complex analyses yielding larger uncertainty.

The study of light nuclei, could be performed at the LISE Separator and SPIRAL1 facility in GANIL, with a program spanning the next 5 years. The availability and design of suited experimental devices is essential for those program to be successful.

High resolution should be also combined with high statistics and good beam quality. A long term prospective should be started on how to gain several orders of magnitude of intensity with the ISOL beams. MWatt primary targets was the options retained in the EURISOL facility conceptual design.

Finally, over the next two decades, moving towards the higher resolution electron probe should be considered a prime option for measuring the observable at play in our field of studies. This unexplored territory is easier to access with less exotic beams and high Z, making fission fragment a good place of the nuclear chart to start.

Experimental methods:

Nuclear reactions are an essential tool to probe the nuclear structure. Thanks to their selectivity, single-particle contributions, cluster structures and collective properties can be measured and used as high resolution spectroscopic benchmark of many modern nuclear models.

We propose to combine the high resolution of ɣ-ray spectroscopy with the high selectivity of the direct reaction probe to constrain the nuclear interaction in weakly-bound nuclei and exotic nuclei between Z=28 and Z=50 in the close vicinity of ^{100}Sn, ^{132}Sn and ^{78}Ni.

While techniques relying solely on the detection of the light particle probe exist, such as using a solenoid device to identify the reaction product, or an ACTIVE target experimental setup, they are not compatible with large ɣ-ray tracking arrays. The high resolution and high efficiency of such array allows reaching an un-matched resolution of a few keV.

More importantly, direct reactions are essentially selective to the orbital momentum of the transferred nucleons ΔL. The selectivity of the ɣ-ray decay path yields essential information on the total angular momentum of the populated states J.

Additionally such a set up allows the use of “special” targets (DSAM, cryogenic, polarized …) which is difficultly conceivable with solenoids or active targets. The power of the ɣparticle coincidence method has been demonstrated by the recent MUST2-TIARA-EXOGAM campaign at LISE and the current MUGAST-AGATA campaign at VAMOS.

Therefore, where possible, we anticipate using the association of a light particle detector such as GRIT with AGATA for low beam energies, or STRASSE with AGATA/MINIBALL/GRETINA for higher energies. The full realization of GRIT and the extension of the solid angle of AGATA are essential milestones for the accomplishment of our physics program.

Transition probabilities and spectroscopic factors, g-factors, are extremly sensitive probes of the nuclear wave functions. High resolution studies (Electromagnetic moments, nucleon or clusters transfer cross section) of bound states near the particle threshold or of unbound states in light exotic nuclei will provide precision tests of the nuclear interaction. While challenging, a large HPGe array, will allow studying EM decays from nearly unbound and unbound states (e.g. resonances or just below threshold) with typical decay branches of 10^{-3} possibly up to 10^{-5}.

The latter constitute an almost unexplored territory, ideal for investigations with high resolution ɣ-ray detectors coupled to a state of the art light charged-particle detectors, such as GRIT, and a magnetic spectrometer at zero degree, such as VAMOS or ZDS, using ISOL and in-flight beams.

The mechanism of **addition** of nucleons and clusters is only possible at intermediate energies around 10 MeV. These types of reactions insure a high selectivity and sensitivity to population of single-particle and cluster states. Such states are typically the base used to describe the nuclear wave function in most modern nuclear models and therefore the best constraints on such models. Measurements of spectroscopic factors in single-particle or cluster-transfer reactions in inverse kinematics at energies below and around the Coulomb barrier will also complete the high resolution description of these nuclei to benchmark the so-called ab-initio calculations.

The reduced electromagnetic transition strengths, e.g., B(E2) or g-factor values, are sensitive to the shell-model description of the excitation in nuclei. In certain cases, such experiments can be performed with low beam intensities (down to 1000 atoms/s), but would require highly efficient ɣ-ray spectrometers with high position sensitivity.

Combining transfer reaction and gamma-ray spectroscopy, a large set of transition probabilities, spectroscopic factors and spectroscopic quadrupole moments, g-factor in yrast and non-yrast states will shed new light on nucleonic correlations in light nuclei at the drip-line and the coupling of low-lying bound states to the continuum.

Finally all those studies will take advantages of the development of new cryogenic targets, such as the window less deuterium target CHyMEN or newly build He target.

Collaborations on theory :

Interaction with theorists are essential in shell-model, ab-initio, coupling to continuum and reaction theory with exotic nuclei. A consistent approach between structure and reaction is necessary to reach the desired precision in linking experimental observable such as cross-section to the wave-function component of the populated nuclei. The limited number of theorist specializing in reaction theory, worldwide in general, and particularly in France, despite a very active experimental community is a concern. Ongoing collaborations with shell model experts will be continuing as describes in their topical contribution on “structure of exotic nuclei, weak processes and astrophysical issues”.

Strategy :

In the current international context GANIL can no longer be considered a world leader for the provision of accelerated RIBs. The strategy proposed benefits from the existing facilities and instruments in which IN2P3 has a leading role. After the end of the MUGAST-AGATA campaign in 2021 at GANIL, a dedicated campaign using a reconfigured MUGAST array coupled to EXOGAM, focused on light nuclei, can be carried out at the LISE and SPIRAL1+ facilities. In Europe, the ISOL fission-fragment facility SPES will be put in operation ~2023. It is foreseen that the AGATA array will be installed at SPES from 2021 until the FAIR facility starts in ~2027. The GRIT project is a partnership between France and Italy and other European countries. Therefore, a campaign at SPES with GRIT-AGATA and PRISMA is a realistic and thrilling project. As soon as FAIR will deliver beams, an AGATA campaign is foreseen at NUSTAR.

Meanwhile, in order to cover the physics cases at higher energies (knockout), beyond ^{132}Sn and around ^{78}Ni, the IN2P3 community must have a leading role in RIKEN and ARIEL facilities. Our expertise in detectors, simulation, analysis but also available manpower on ISOL beam development should be key to the development of fruitful collaborations.

This type of study will be carried out at FRIB within the British led DRACULA collaboration, synergy between this project and GRIT are to be studied. RAON might offer a long term solution, and collaboration opportunities should be scrutinized over the next few years.