Nuclear physics for basic science and applications

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1. Foreword and Summary

In this contribution, the DPhN presents its priorities for the evolution of GANIL. Saclay physicists are currently conducting experiments along three main scientific axes:

1) properties of nuclei at the extremes of isospin asymmetry, excitation energy and shape,
2) heavy and super-heavy nuclei at extreme masses,
3) neutron-induced reactions notably for the study of fission in actinides, with applications for nuclear data.

Regarding the scientific future of GANIL, DPhN physicists propose along these three axes the construction of three new scientific tools, which will ensure that GANIL will continue to be a worldwide competitive facility:

- *An installation for studying nuclear structure with electron-ion collisions*, that will provide a new original probe to study charge distributions in radioactive nuclei,
- *a facility capable of delivering a wide range of radioactive beams*, both on the neutron- and proton- rich sides, at energies up to ≈ 60 A.MeV, and
- *the construction of an RFQ A/Q = 7 injector* for enhancing the intensity of ion beams ranging up to U. This upgrade will be vital for the long-term programme of S^3 and will also allow the production of new neutron-rich nuclei through multi-nucleon transfer.

The scientific cases for these contributions have been extensively discussed at many topical meetings, and were already integrated in the projects proposed in the framework of the GANIL-2025 prospective (launched in 2015 by the GANIL 2025 core group). The future of GANIL is an ongoing concern for the physicists of our department. However, the current availability of beams does not meet the needs of our scientific community, either in terms of available time or beam variety. For this reason we are currently involved in experimental programmes developed at other facilities worldwide. We conduct experiments with stable beams at incident energies around the Coulomb barrier at the University of Jyväskylä and at ANL, with beams of exotic nuclei at RIKEN, GSI, Isolde, ANL and TRIUMF and with neutron beams at ILL and n_TOF. In the near future the new SPES facility at Legnaro and the FAIR facility at Darmstadt are expected to be operational in the next years. Furthermore, we are committed to experiments motivated by nuclear physics applications through the production and use of neutrons, so far mostly at n_TOF, even though NFS will offer unique perspectives. We also participate in the evaluation and consolidation of nuclear data libraries.

2. Physics objectives

The nucleus is a complex *N*-body mesoscopic system described in terms of the fundamental interactions between protons and neutrons anchored in the theory of the underlying strong interaction. DPhN theoreticians are strongly contributing to theoretical efforts via their world-leading program on the *ab initio* description of atomic nuclei. In this endeavour, they vigorously take part and benefit from the framework of the *"Space for Structure and Nuclear reaction Theory*" (ESNT), a virtual laboratory of CEA DRF and DAM.

From the experimental side, the complexity of nuclear systems translates into a wide variety of phenomena in a broad range of energetic and dynamic scales. Many fundamental questions remain unanswered, like the question of the limits of stability of nuclear matter, the nature of shell effects in yet unexplored regions, or even the validity of the concept of "magic numbers" for loosely bound objects. This consequently requires the use of a large variety of beams, instruments and facilities. Our experimental studies address the following issues:

- *Study of exotic nuclei with strongly N/Z-asymmetric systems mainly on the neutron-rich side*: evolution of the nuclear structure (nuclear shells and their filling, nuclear densities) with the isospin degree of freedom, exploration of new structures in the "*terra incognita*" and the evolution of their shape (e.g. shape coexistence).
- *Study of the properties of very-heavy and super-heavy nuclei*: this region of very fragile objects aggregates key questions on shell effects, reaction dynamics and the boundary of the nuclear matter and of the Mendeleiev table.
- *Study of fission reactions*: Fission is a subject that combines all the difficulties mentioned above: shell effects, extreme masses, extreme shapes and dynamics. *De facto*, its theoretical description is tremendously complex. Fission fragment yields, excitation energy, kinetic energy, angular momentum and neutron multiplicity are studied with the aim of both modelling the fission process and contributing to nuclear data evaluations.

3. Instrumentation and techniques

In the context of a long-term vision to ensure that GANIL will continue to be a worldwide competitive facility, new experimental devices are proposed.

Very high intensity heavy beams for fusion-evaporation and multinucleon transfer reactions

A new radiofrequency quadrupole (RFQ) injector with A/Q = 7 has been proposed since the birth of the SPIRAL2 project. This ensemble will allow the experimental possibilities presently offered by LINAG, the superconducting linear accelerator at GANIL, to be enhanced very significantly for heavy (A > 40) and very heavy (Xe, Pb, U) beams. New experiments with very low cross sections will be conducted, focussed notably on two experimental approaches:

- Fusion-evaporation reactions that produce heavy and super-heavy nuclei with very low cross sections and poor statistics. The study of those nuclei is the core of the physics program of S^3, whose ambition is to be one of the most powerful devices worldwide in that domain, with a panoply of experimental tools[1].
- Multinucleon transfers are unique reactions that can produce very heavy neutron-rich nuclei, in the (trans-)actinide region as well as heavy nuclei in the N =126 region below Pb. A specific experimental area would be necessary to optimize the production and purification of the beams[2].

Radioactive ion – electrons collisions

A new experimental facility allowing the study of nuclear structure of exotic nuclei with electron-ion collisions is proposed. This experimental facility will allow us to go well beyond traditional nuclear radii measurements by determining form factors and deducing charge density distributions, and this will be a prime with radioactive nuclei. If the luminosity is large enough, inelastic scattering (e,e'X), electro-fission (e,e'F) and (e,e'p) scattering would be performed as well. The only operating electron-ion collider in the world, SCRIT at RIKEN, has limitations in luminosity that will strongly limit its reach. Although there are currently several

[1] Additional details can be found in the contribution "S^3 at SPIRAL2/GANIL"
[2] See the contribution "RFQ injector A/Q = 7 for the production of exotic nuclei using fusion-evaporation and multinucleon transfer reactions"

projects worldwide like DERICA at Dubna and ELISe at FAIR (both not yet launched), we believe that, if undertaken now, this project will provide GANIL with a worldwide competitive machine. The long-term physics program opened by this experimental installation is explained in a separate contribution[3]. To be relevant, this facility should be “fed” with a large choice of radioactive beams. Consequently, considering the means of production of these beams is also essential (see below).

Neutron-induced reactions

NFS will be unique in Europe in its energy range and complementary to other neutron source installations limited to thermal neutrons (ILL) or more focused on for spectroscopy in the resonance region (n_TOF at CERN). On the other hand, neutron-induced reactions are limited to stable targets, or those close to the stability and do not allow for studies of exotic nuclei. This could be overcome by using surrogate transfer reactions, (d,p) for example, in a storage ring filled with well identified stable and radioactive isotopes.

Evolution of existing instrumentation

To complete this part of the document it should be kept in mind that detectors are either in use at GANIL or under construction, also requiring funding and support in terms of human resources. Among the most noteworthy detectors for carrying out experiments are:

- AGATA, for gamma-ray spectroscopy, is a nomad European array that should be completed towards 4π in the forthcoming decade. It has been used for many successful experiments in the last years at GANIL and will soon move to LNL. Without a doubt it will return to GANIL in the mid and long term.
- The FALSTAFF device should soon be finalized with the completion of its second arm. Intended to be used at NFS/SPIRAL2 it will be a unique device for the complete characterisation of fission fragments and therefore of the fission process.
- The VAMOS spectrometer can be used in a gas-filled mode (VAMOS-GFS) for in-beam spectroscopy studies. Physicists are currently expecting the GANIL management’s authorization to carry out the planned campaign. In the meantime, different alternatives are being explored at the University of Jyväskylä or ANL.

4. Beam production

Radioactive ion beams

As discussed above, the A/Q=7 RFQ is a critical asset to produce very- or super-heavy nuclei. However, neutron-rich nuclei are also at the core of the DPhN experimental program. Presently, the SPIRAL1 facility does not produce beams fulfilling our needs.

It is clear that the former SPIRAL2-Phase2 has to be revised to optimize the cost/production ratio. We have no *a priori* preference concerning the future method of production of exotic nuclei, namely d + uranium or photo-fission of uranium, although the former benefits from the already existing LINAG driver which is optimized for deuterons.

Whatever the means of producing radioactive nuclei, it would be a significant asset for GANIL to be able to deliver good quality reaccelerated beams (neutron-rich, but also proton-rich and very heavy nuclei from S^3, or from a multinucleon transfer target –ion source) with incident energies from below the Coulomb barrier to ~60 A.MeV[4].

Neutron beams

The LINAG deuteron driver, built for the SPIRAL2-Phase2 project, is designed to reach a power of 200 kW. This objective can be revised downwards in order to meet present safety

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[3] See the contribution “Nuclear structure from electron-ion collisions”
[4] See the contribution “Reacceleration of radioactive ions beams at GANIL”

constraints, still resulting in substantial production of exotic nuclei. In this context, assuming e.g. a ~50 kW production target, the remaining power could be used for other applications such as neutron production, radioisotope element production, etc. The most efficient way would be a real-time distribution sharing the beam simultaneously between different experimental areas. As mentioned in the foreword, neutron beams are extensively used for basic science research (fission as a complex phenomenon, stellar and primordial nucleosynthesis) and applications (fission for energy, nuclear data). Experiments performed at ILL and n_TOF, CERN, will soon be followed up by experiments at NFS, SPIRAL2. Neutron beams from NFS will be unique in their energy range. Despite this uniqueness, the NFS intensity is not sufficient for exclusive measurements using multidetectors e.g. FALSTAFF with gamma-ray detection. An increase of the intensity by a factor of ten or more (i.e. ≈ 50 kW on target) without degrading the time structure of the beam (to keep the energy information from a time-of-flight measurement) would be beneficial.

Irfu also has growing activities in the development of compact neutron sources that are expected ultimately to replace several existing research reactors[5]. Investigations into using these neutron beams for basic science are also under way.

5. General remarks

Unique instruments and beams are essential for GANIL to be competitive. This implies "niches" e.g. an electron-ion collider or re-accelerated actinides as described above. The installation must however retain a "standard" character in order to appeal to the maximum number of users (i.e. stable beams at the Coulomb barrier). *Obviously, the installation must deliver the appropriate beam time, i.e. at least 8 months per year.* It should be remembered in this context that the "Cour des Comptes" was concerned that the facility was not widely used by the French community[6].

Considering the attractiveness of GANIL, we believe that the governance model should also be reconsidered. GANIL currently operates with host physicists who ensure, with the technical staff, the smooth operation of the experimental areas. This model also deserves discussions. The endless discussions about the change of the guesthouse (which has a notorious reputation in the community) into an international welcome center of true accommodations should come to a successful conclusion.

An increasing weight of industrial and societal applications (applications using neutron beams, irradiation stations, isotope production for medicine, etc.) is essential for the long-term survival and public acceptance of GANIL.

The facility should be such that any instrumentation should benefit from any beam. New instrumentation is usually not included in the budget when building a new facility. The risk here is to have beams of the requested quality without relevant instruments.

The existing cyclotrons have a limited lifetime and a high operation cost (electricity). It would be a mistake not to consider their future, either their decommissioning, refurbishment or replacement by an accelerator with a lower operating cost.

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[5] See also the contribution "A new Interdisciplinary Irradiation Area at SPIRAL2"
[6] https://www.ccomptes.fr/fr/publications/les-tres-grandes-infrastructures-de-recherche-tgir