GANIL-SPIRAL2 as a Multifaceted Radioactive Ion Beam Facility

Introduction

In this contribution, we[1] present conceptual ideas for the evolution of GANIL-SPIRAL2 as a multifaceted radioactive ion beam (RIB) facility. Given the time needed to bring such ideas to fruition – typically 10-15 years – it is clear that the work towards a future upgrade or new facility needs to begin soon. While the studies of the scenarios presented here are at a very preliminary stage, we believe that each of them has the potential to provide GANIL with unique capabilities and a long term future in a European and wider international context.

Present status of the GANIL-SPIRAL 2 facility

From the outset of its operations in the early 1980's, GANIL was a pioneering facility in the development and exploitation of intermediate energy (~30-90 MeV/nucleon) in-flight fragmentation to produce radioactive beams (using the LISE spectrometer, later supplemented by the SISSI double-solenoid system). Today, the LISE spectrometer, coupled with the intense stable beams provided by the CSS cyclotron complex is still being used for in-flight experiments and, through ongoing upgrades, maintains a competitive physics programme in some specific areas. In 2001, GANIL complemented its in-flight capabilities with an ISOL-type facility – SPIRAL1 – which employs the stable beams from the cyclotron complex to produce relatively intense (with respect to other ISOL installations such as ISOLDE and ISAC-TRIUMF), reaccelerated (<~20 MeV/nucleon) light beams (A<80) for a limited range of elements. These limitations have arisen from the restricted possibilities, both technical, practical and beam time wise, available for beam development[2]. Upgrades of some of the presently available experimental devices will allow GANIL to continue to engage in forefront research in a number of specialised areas. For example, the light SPIRAL1 beams will be employed for the DESIR physics programme, which will, as discussed below, later be supplemented by other production techniques[3,4]. However, it is clear that presently operating facilities (RIBF-RIKEN, HIE-ISOLDE, ISAC2-TRIUMF) and those coming on line in the next few years (FRIB, RAON, FAIR) will diminish very markedly the competitiveness of the existing GANIL facility.

In terms of the so-called Phase 1 of the SPIRAL2 facility, the commissioning of the LINAC has recently begun. As such, the S3 installation[3], which will be the workhorse for the production of RIB – specifically N=Z nuclei and heavy and super-heavy systems – is expected to begin operation in 2023. As discussed in an accompanying contribution, the so-called A/Q=7 upgrade[4] (which will provide for unprecedented intensities of heavy stable ion beams, ranging from Ar to U) will be a vital feature for the long term programmes utilising S3.

[1] A list of physicists supporting the present initiative is provided at the end of this document.
[2] These issues are discussed in more detail in the presentation given in the Jan 2020, Nuclear Physics and Nuclear Astrophysics Town Hall Meeting, accessible at: https://indico.in2p3.fr/event/19748/contributions/78693/
[3] See the contribution "S3 at SPIRAL2/GANIL"
[4] See the contribution "RFQ injector A/Q = 7 for the production of exotic nuclei using fusion-evaporation and multinucleon transfer reactions"

SPIRAL2 - Phase 1 will be completed once the very low energy (eV-keV) beam facility DESIR becomes operational (circa 2024). As described in the contribution focussing on DESIR[5], a range of experimental setups will utilise the RIB from both SPIRAL 1 and the S3-LEB (Low Energy Branch) for a range of investigations, including decay, laser and trap-assisted spectroscopy.

The Phase 2 of SPIRAL2 aimed to provide intense neutron-rich fission fragment beams for both the low energy programmes at DESIR, as well as a broad range of studies employing the reaccelerated (CIME) beams (up to ~10 MeV/nucleon). Apart from funding issues and delays arising from Phase 1, the Phase 2 production system suffered from a number of very significant technical challenges and limitations[2]. In addition, Phase 2 would, if constructed have entered into direct competition with a number of ISOL facilities (HIE-ISOLDE, TRIUMF-ISAC2 and ARIEL, SPES and RAON) without having any significant advantage in terms of beam intensities. The GANIL-SPIRAL 2 community is, as evidenced, for example, by the "IN2P3 Prospectives 2020-30", still particularly interested in having access to neutron-rich beams. Apart from DESIR and the reaccelerated physics programme originally envisioned for SPIRAL2 – Phase 2, the community has identified two broad areas of physics interest and associated facilities that we believe should be considered for the future evolution of GANIL, which require the provision of radioactive beams beyond those furnished by SPIRAL1 and SPIRAL2 - Phase 1. The two programmes encompass very different domains at the forefront of nuclear physics.

Possible physics programmes and associated facilities

I. Probing trapped radioactive nuclei by electron scattering

Electron scattering is one of the fundamental and most well understood techniques to probe nuclei. More specifically, it offers the means to map out the spatially dependent distributions – charge density, transition charge density and magnetic current distributions. Such measurements provide for much more stringent constraints on theory than integral quantities, such as the mean square charge radius and transition probabilities. Moreover, if they could be undertaken with nuclei far from stability they would also allow more complete and deeper insights to be made in our understanding of halo nuclei, neutron skins, centrally-depleted nuclear densities and, more generally, the questions surrounding shell and shape evolution. Indeed, many sophisticated state-of-the-art models (e.g., ab-initio, beyond mean-field) are able to predict charge and transition densities for nuclei far from stability and await to be tested experimentally.

Over the last few years, the SCRIT project at the RIBF-RIKEN has demonstrated that electron scattering may be employed with radioactive nuclei trapped at thermal energies in a ring-type electron accelerator. Preliminary studies have shown that an Energy Recovery Linac (ERL) instead of a conventional ring would allow luminosities of order $10^{29\text{-}30}$ (a factor ~100 higher than SCRIT's present capabilities) to be achieved for RIB with intensities of $\sim 10^6$/s or more[6]. Access to a broad isotopic range of nuclei (from proton to neutron-rich) is highly desirable for the studies enumerated above. In particular, the mapping of charge density distributions and shapes across isotopic chains is of great interest. As such, the proton-rich N~Z beams from SPIRAL2 – Phase 1 need to be complemented by neutron-rich beams well beyond the limited cases available with SPIRAL1. We note, in addition to the relatively simple scattering experiments, more technically demanding measurements may be envisaged, including inelastic and quasi-free scattering as well as electro-fission. Such experiments

[5] See the contribution "DESIR at SPIRAL2/GANIL"
[6] See the contribution "Nuclear structure from electron-ion collisions"

would broaden the scope of the physics programme to cover collective and single-particle aspects of nuclear structure far from stability.

A more detailed description of the goals of the project and the preliminary considerations for the technical options are outlined in a dedicated contribution[6]. An electron-trapped RI collider could be designed, constructed and commissioned in a timescale of some 10-15 years. We note that the design of the ERL could benefit from synergies with other related projects, such as the PERLE demonstrator envisaged for high energy physics applications.

II. Reacceleration of radioactive ion beams up to Fermi Energies[7]

The reacceleration up to intermediate energies (many tens of MeV/nucleon) of both neutron-rich and neutron-deficient radioactive beams, with the production schemes planned for SPIRAL2 – Phase 1 and proposed here, would enable a broad range of physics programmes to be pursued in which the GANIL community has a long standing interest and expertise.

In particular, with energetic fission fragment beams, the shell structure of neutron-rich nuclei in the N=50 and 82 regions, and the related issues of nuclear deformation and r-process nucleosynthesis (with direct links to the neutron star mergers discussed below) could be could be explored using transfer reactions. We note that pick-up and stripping reactions – (d,p) and (p,d) – need to be measured in order to obtain a complete picture of the shell orbital occupancies. Compared to most facilities providing reaccelerated beams, such as HIE-ISOLDE, SPES and ISAC2 and ARIEL which are limited to energies of 10 MeV/nucleon, the higher reaccelerated energies we propose here will allow for the optimal study of very negative Q-value transfer reactions, such as (d,^{3}He) amongst others. The experiments outlined here will be undertaken using combined particle-gamma detector arrays (such as the GRIT Si-array + AGATA) or a TPC (such as ACTAR).

Another approach that has been explored would employ storage-ring based transfer reactions. In this scenario, the post-accelerated RIB (for example using the existing CIME cyclotron for energies of order 5-20 MeV/nucleon) are injected into a storage ring, where they are electron cooled so as to achieve emittances similar to those of tandem beams (~0,05 mm.mrad). High excitation energy resolution transfer reaction studies are thus possible using a thin gas jet target, whereby the very limited target thickness is compensated for by the multiple passages of the circulating beam. While beyond the scope of this nuclear physics based contribution, we note that a broad research programme in atomic physics may also be envisaged[8].

RIB encompassing a broad range of N/Z and reaccelerated to many tens of MeV/nucleon would also provide unique tools to study of the equation of state (EoS) of asymmetric nuclear matter. This subject area has recently seen a dramatically renewed interest following the observation of neutron star mergers through the direct detection of gravitational waves. Understanding and successfully modelling such events requires good knowledge of the EoS over a wide range of densities, temperatures and proton fractions. In this context we note that multifragmentation is strongly connected with the characteristics of the EoS and requires that the role of isospin to be studied. In particular, investigations that should be undertaken include, the limiting temperatures in excited

[7] See also the contribution "Reacceleration of radioactive ions beams up to 60 A MeV"
[8] A similar storage ring was studied for the HIE-ISOLDE based on the Heidelberg TSR. Technical details and possible physics programmes may be found in: EPJ Special Topics **207** (2012) 1.

nuclear systems and the N/Z dependence of nuclear level densities, which are expected to provide unique information about the temperature dependence of the symmetry energy of the EoS.

The intermediate beam energies proposed are also well adapted to study giant resonances in unstable nuclei, which can provide a handle on nuclear compressibility in asymmetric systems. Pygmy resonances, which are believed to play an important role in the r-process, could also be explored.

Another aspect of the post-accelerator proposed here would be the provision of energetic beams of heavy elements. These nuclei could be produced using the S3 spectrometer through fusion-evaporation or few and multi-nucleon transfer reactions[4]. The post acceleration scheme would consist of a first stage composed of a gas-cell and quadrupole mass filter (QMF) both located in the S3 focal plane area or, as discussed below, in a separate production building. The low energy ions would then be transported to a charge breeder before post-acceleration. With sufficient intensities, the post acceleration of such exotic heavy beams would allow secondary reactions (Coulomb excitation, transfer, elastic/inelastic scattering and fission) to be studied and would be unique worldwide.

The programmes outlined here would capitalize on the state-of-the art detection systems already in operation or under construction – ACTAR TPC, GRIT, FAZIA, AGATA and PARIS. In terms of the post-acceleration (beyond CIME energies) two solutions may be envisaged. The first and, in principle, most cost effective one, would employ a superconducting cyclotron. This has some potential drawbacks if frequent energy changes are required and would require CIME or another machine to be available if relatively low-energy beams are required. Issues surrounding the acceleration efficiency also need to be studied. The second solution would be a superconducting LINAC, which is more efficient and versatile (in particular in terms of energy changes and extensions at a later stage to higher energies) but which is much costlier and for which the building requirements might impose a limitation (if a folded configuration is not possible). For both options, the development of a very high efficiency state-of-the-art charge breeder would be essential, to enable high enough charge states to be produced so as to enable reacceleration to be achieved without stripping.

The physics programmes with energetic beams outlined here requires a broad N/Z range of reaccelerated RIB with intensities as high as some 10^6 pps. As such, neutron-rich beams, produced by fission, are a necessary prerequisite to complement the SPIRAL2 – Phase 2 RIB and the existing SPIRAL 1 beams.

Neutron rich beam production by photofission

In order to provide for the neutron-rich beams required for the aforementioned programmes, as well as for DESIR, a driver accelerator independent of the SPIRAL2 LINAC is required. It is important to underline that such an independent driver would allow the necessary beam development programme to be undertaken. The use of the LINAC as a driver could, in principle, be envisaged. However, the nature of the S3 physics programmes (in particular those focussed on the heavy and super-heavy elements) will require the majority of the beam time. In addition, the LINAC beams will also be used for the production of neutrons (NFS facility) and other interdisciplinary research[9].

We believe that the most cost effective and practical solution would be to employ a commercially available high-intensity electron accelerator for photofisson. For example, the “Rhodotron” from IBA is capable of producing 125kW 40 MeV electron beams. Given the experience gained at the ALTO facility, albeit at lower beam power, we believe that such a beam, when coupled with a converter and

[9] See the contribution “A New Interdisciplinary Irradiation Area at SPIRAL2”

thin UCx target technology, should enable fission fragment beams with intensities approaching those available or expected at other facilities. Given the difficulties encountered with the SPIRAL2 - Phase 2 project, notably in terms of the complexity and cost of the production building (related in a greater part to the safety requirements linked to the high intensity energetic deuteron beams and significant quantities of UCx), it is clear that certain limitations must be applied to the scenario proposed if a tractable and relatively cost effective solution is to be implemented. Most importantly, the number of in target fissions should not exceed 10^{13}/sec.

Complementary production methods

The A/Q=7 upgrade of the LINAC should enable the acceleration of unprecedented intensities of heavy stable ion beams, ranging from Ar to U. In principle, these beams could be used in a dedicated production area, rather than S3, for producing (eg., via a gas cell/ISOL/VAMOS-like setups) RIB by fusion-evaporation or deep inelastic reactions that are complementary to the S3 and fission fragment beams. Deep inelastic reactions, for example, have the potential to open up the investigation of neutron-rich nuclei in the region of N=126 as well as possibly very heavy nuclei – both regions of the chart of nuclei that are difficult to reach otherwise.

While the A/Q=7 injector upgrade (which is an essential prerequisite for the schemes described) has a provisional schedule with completion in 2027, the additional dedicated production area outlined here, has not yet been studied technically. This option is presented in more detail in a separate contribution[4]. We note that this production area could be located in the production building proposed below, enabling N=126 and heavy nuclei to also be furnished at low-energies to DESIR, or reaccelerated.

Conceptual layout for the future GANIL-SPIRAL 2 facility

The figure below displays a schematic outline of a possible configuration for the production building. It would be located, with respect to the existing facility and SPIRAL2 – Phase 1 complex, in the area originally allocated for the Phase 2 production building. As shown, this configuration would allow the RIB to be delivered to DESIR, the e^- -RIB collider or to the post-accelerator. In addition to a state-of-the-art EBIS, the fission fragment and heavy beams will require a high-resolution separator (HRS). As may also be seen in the more detailed view of the production area, it would be particularly advantageous if, in addition to the electron driver, it incorporated several versatile production caves. These would enable for the most flexible and optimised utilisation of the beams from both e^- driver and the LINAC using the production methods discussed above – both for production and for the testing and developing of new target ion-source systems and beams.

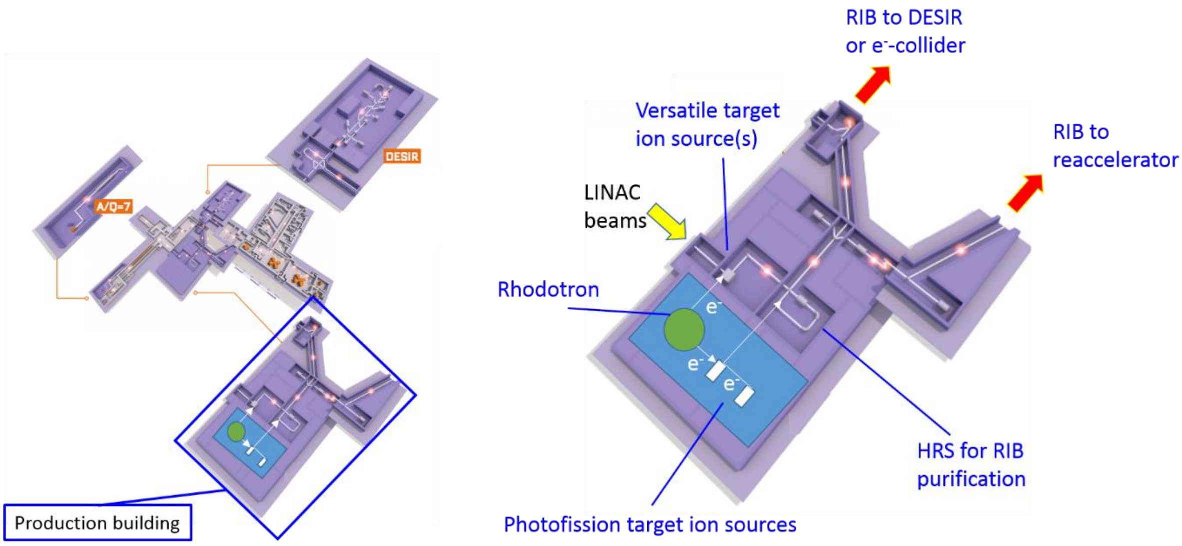

Figure: Layout of GANIL-SPIRAL 2 showing the proposed new production building, including the Rhodotron e- driver as well as a series of ISOL production caves (see text). Importantly such a configuration allows RIB to be delivered to DESIR, the e- collider or to reaccelerator.

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