GANIL-SPIRAL2: a new era

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Abstract. GANIL presently offers unique opportunities in nuclear physics and in many other fields that arise from not only the provision of low-energy stable beams, fragmentation beams and re-accelerated radioactive species, but also from the availability of a wide range of state-of-the-art spectrometers and instrumentation. A few examples of recent highlights are presented. With the construction of SPIRAL2 over the next few years, GANIL is in a good position to retain its world-leading capability. As selected by the ESFRI committee, the next generation of ISOL facility in Europe is represented by the SPIRAL2 project to be built at GANIL (Caen, France). SPIRAL 2 is based on a high power, CW, superconducting LINAC, delivering 5 mA of deuteron beams at 40MeV (200KW) directed on a C converter+ Uranium target and producing therefore more $10^{13}$ fissions/s. The expected radioactive beams intensities in the mass range from A=60 to A=140, will surpass by two order of magnitude any existing facilities in the world. These unstable atoms will be available at energies between few KeV/n to 15 MeV/n. The same driver will accelerate high intensity (10μA to 1 mA), heavier ions (Ar up to Xe) at maximum energy of 14 MeV/n. Under the 7FP program of European Union called *Preparatory phase*, the SPIRAL2 project has been granted a budget of about 4M€ to build up an international consortium around this new venture. The scientific pillars of the future facility, the status of the construction of SPIRAL2 accelerator and associated physics instruments in collaboration with EU and International partners will be presented.

1. Introduction
Since its beginning in 1983, GANIL [1] has been involved in active research in the field of exotic nuclei. With the LISE spectrometer and its successor LISE3 some 50 new nuclei have been observed. In addition, in 1994, the physicists developed SISSI, a dual superconducting solenoid system for producing high-energy beams of exotic nuclei. At GANIL the available stable ion beams range from $^{12,13}$C to Kr isotopes with intensities up to 2μA for $^{13}$C at 95MeV/n and 0.1μA for Kr at 50 MeV/n (beam power between 3 to 6 KW on target). For heavier ions (Lead and Uranium) an energy range between 5-25 MeV/n with $10^{10-11}$pps can be achieved. Light and medium mass ion beams raised to high energy are fragmented on a thin target, giving rise through the “fragmentation process” to light exotic nuclei. The successful program of the physics of “exotic “ nuclei produced by the so-called “in-flight “ method was extended recently towards new possibilities offered by high-quality, low-energy Radioactive Ions Beams (RIB) at the SPIRAL facility [1] using the “ISOL” production method. This SPIRAL facility, which became operational in September 2001, can be summarized as follows: the high energy, high power extracted beam from the three GANIL accelerators C01 (2)-CSS1-CSS2 is sent to a carbon target. The incident nuclei are fragmented by nuclear reactions in this target, generating a population of radioactive nuclei which diffuses out of this hot target (2000°C). After
ionization in an ion source, the particles are injected into the CIME cyclotron to be accelerated to energies from 1.7 to 25 MeV per nucleon. Since its start-up, various ions have been produced and accelerated in the SPIRAL facility, ranging from exotic nuclei as light as $^8\text{He}$ to heavier nuclei like $^{76}\text{Kr}$. About 200 shifts per year are devoted to experiments with SPIRAL beams. At GANIL, the rather unique capabilities, using both “In flight” and “ISOL” techniques, to produce a large variety of light and medium “exotic” species have boosted the scientific program.

2. Exotic nuclei at GANIL: recent highlights

As intensities of secondary radioactive beams are usually four or five orders of magnitude lower than typical intensities of stable beams, physics with secondary RIBs requires very specific detection devices. Reactions and Structure studies of “exotic” nuclei are carried out using intensively the high energies of the fragmented “in flight” RIB from GANIL, the post accelerated ISOL- SPIRAL1 RIB and low energy (5-10 MeV/n) intense Uranium beams. The beams are coupled to spectrometers like LISE, VAMOS and/or $4\pi\gamma$-array called EXOGAM, charged particle detectors like MUST and TIARA. Those combinations are ideal tools for the studies of nuclear structure and reactions. In the following we will present a few recent highlights of the physics results achieved in the last few years.

2.1 Reaction studies with neutron rich dilute matter are also of strong interest.

A modern variation of the Rutherford experiment to probe the tunneling of exotic nuclear matter from the measurement of the residues formed in the bombardment of $^{197}\text{Au}$ by extremely neutron-rich $^8\text{He}$ nuclei was carried out. Using a novel off-beam technique the most precise and accurate measurements of fusion and neutron transfer involving reaccelerated unstable beams are reported. The results are displayed in Fig.1 and reveal an unusual behavior of the tunneling of $^8\text{He}$ compared to that for lighter helium isotopes, highlighting the role of the intrinsic structure of composite many-body quantum systems and pairing correlations [4].

![Figure 1: Fusion cross-sections of $^4,^6,^8\text{He}$ on gold.](image)

2.2 Quest for shell structure changes far off stability.

Experiments on shell structure evolution around magic number 8, 20 and 28 have been recently investigated using both “in flight” and ISOL RIB via knock out or transfer reactions associated to gamma spectroscopy.

For the $N=28$ neutron shell, the energies of the excited states in very neutron-rich $^{42}\text{Si}$ and $^{41-43}\text{P}$ have been measured using in-beam $\gamma$–ray spectroscopy from the fragmentation of secondary beams of $^{39,40}\text{Si}$ at 39 MeV/n. The low 2+ energy of $^{42}\text{Si}$, 770(19) keV, together with the level schemes of $^{41-43}\text{P}$ provide evidence for the disappearance of the $Z=14$ and $N=28$ spherical shell closures, which is ascribed mainly to the action of proton-neutron tensor forces [5]. Recent investigation, of the neighboring
Two dimensional spectrum of $\Delta E$ vs. $E_{\text{total}}$ in the $^{238}\text{U} + ^{12}\text{C}$ system at beam energy of 1.45 GeV. The inset shows the associated mass spectrum for the Xe isotopes.

Measurements of prompt Doppler-corrected de-excitation $\gamma$-rays from uniquely identified fragments formed in the above mentioned reaction was also achieved through gamma-fission fragment coincidences. These very promising results open a new window in the spectroscopy of very neutron rich fission fragments [7, 8].

3. SPIRAL2: Status and Perspectives
Since the beginning of the SPIRAL project it was proposed to enlarge the range of RIB produced through the fission of uranium target and the delivery of high intensity neutron–rich fission fragments. This idea is now being implemented in the SPIRAL2 project [9]. The importance of the RIB’s has been underlined by NuPECC [10] (Nuclear Physics European Collaboration Committee - an expert committee of the European Science Foundation) which recommend the design and construction of the ultimate-generation RIB ISOL facility EURISOL [11].
Because of the time-line for EURISOL (2020), NuPECC recommends the construction of intermediate-generation facilities that will benefit the EURISOL project in terms of R&D and that will give the community opportunities to perform research and applications with RIBs. Among the proposed intermediate facilities SPIRAL2 at GANIL (Caen, France), meets in terms of physics potential, site and size of the investments, the criteria of European dimension as it was recognized recently in the ESFRI (European Strategy Forum on Research Infrastructures) roadmap [12]. The construction of SPIRAL 2 started in the middle of 2005 and is supported by the EU FP7 through the Preparatory Phase contract since 2008. The first beams are expected in the years 2012-2013. As an added bonus, the facility will also produce over $10^{15}$ neutrons/s, making it the world’s most powerful source of fast neutrons for several years.

3.1 The Science Drivers of SPIRAL2

A rather complete presentation of the scientific case of SPIRAL2 facility can be found in the White Book of SPIRAL2, Letters of Intent and technical proposals for the facility (see Ref [9]). In the following only few examples of a rich and exciting scientific program will be shortly illustrated.

3.1.1 $N=Z$ Proton Drip Line and Super-Heavy Elements

Very intense stable heavy ions beams will be available at the exit of the LINAG accelerator. These heavy ions (from He to Ca), will reach intensities from 1pµA up to 1pmA using new PHOENIX ion sources in combination with A/Q=1/3 RFQ injector and later A/Q=1/6 for heavier ions (Kr to U). Reaching such beams intensities will open a wide range of physics experiments not accessible to day. Super Heavy Elements synthesis, spectroscopy and chemistry, spectroscopy of $N=Z$ nuclei or beyond the proton drip line, multi-nucleon transfer and deep inelastic scattering, production and study of isomers, access to many short-lived isotopes or isotopes of refractory elements which are difficult to produce with ISOL technique. For example, a production of up to $8\times10^4$ atoms of $^{86}$Zr per second using a 200 µA $^{24}$Mg$^{8+}$ beam on a $^{58}$Ni target should be possible. A new device, S3 (for Super Separator Spectrometer, see Ref [13] has been proposed for experiments with the very high intensity stable beams of SPIRAL2 coming from the LINAG accelerator. Most of the physics cases listed above can be seen as either the study of rare processes or as the study of a secondary reaction with exotic ions produced in a first step reaction.

3.1.2 Physics of “Very Neutron Rich Isotopes” and Nuclear Astrophysics

The SPIRAL2 facility at GANIL will produce radioactive isotopes ranging from the lightest to very heavy elements beyond uranium. Different production mechanisms will be utilized: fission of $^{238}$U to produce medium-mass, neutron-rich isotopes, fusion evaporation for medium-mass, transfer and deep-inelastic reactions for light to heavy nuclei closer to the line of stability. Thanks to very high intensities, SPIRAL2 will give access to a whole range of experiments which were not feasible with the first generation of RIB facilities. New exotic shapes and excitation modes, halo-like and molecular structures, single particle properties and new magic numbers, new modes of nuclear decay have been recently observed, while studies of fundamental symmetries, tests of the Standard Model and of fundamental interactions in very exotic nuclei have all a huge potential of discovery.

A fundamental challenge in Nuclear Astrophysics is our lack of understanding of the formation of transferric elements. The site for the production of many of the elements heavier than iron, including gold, platinum and uranium is still unknown. Nuclear physics is needed to provide the data required to understand the underlying reaction processes. The future SPIRAL2 facility will contribute prominently to several areas of active research in nuclear astrophysics, such as explosive hydrogen burning, s-process and r-process nuclear synthesis, which are linked to astrophysical observations (novae, X-ray bursts, type2 supernovae, etc...). The (d,p) reaction can be used to simulate the (n,γ) capture on medium-mass nuclei at SPIRAL2 near the r-process possible paths. The neutron rich isotopes of Sn and Cd nuclei are excellent test cases.
3.1.3 Neutrons for Science at SPIRAL2
In addition, let us stress that, thanks to the high energy and high intensity neutron flux available at SPIRAL2, the facility will offer a unique opportunity for material irradiations and cross-section measurements both for fission (notably accelerator driven systems (ADS) and Gen-IV fast reactors) and fusion related research, tests of various detection systems and of resistance of electronics components to irradiations, etc. The scientific opportunities discussed above are just a few examples among many exciting avenues which can be investigated with SPIRAL2.

4. Layout, performances and construction of the SPIRAL2 facility
The SPIRAL 2 facility (Figure 3.) is based on a high power, superconducting driver LINAC, which will deliver a high intensity, 40 MeV deuteron beam as well as a variety of heavy-ion beams with mass over charge ratio equals to 3 and energy up to 14.5 MeV/n. Using a carbon converter, the 5 mA deuteron beam and a uranium carbide target, fast-neutron induced fission is expected to reach a rate of up to $10^{14}$ fissions/s. The RIB intensities in the mass range from $A=60$ to $A=140$ will surpass by one or two order of magnitude any existing facilities in the world. A direct irradiation of the UC$_x$ target with beams of deuterons, $^{3,4}$He, $^6$Li, or $^{12}$C can be used if higher excitation energies were to lead to higher production rate for a nucleus of interest.

The stable heavy-ions available at the exit of the linac accelerator will reach intensities from 1pμA to 1pmA. These heavy ions beams will be used to induce fusion and deep inelastic processes leading to the production of neutron and proton rich isotopes. Similarly, the heavy- and light-ion beams from the linac driver on different production targets can be used to produce high-intensity light RIB with ISOL technique. The extracted RIBs will be subsequently accelerated to energies of up to 20 MeV/n, (typically 6-7 MeV/n for fission fragments), by the existing CIME cyclotron. Thus using different
production mechanisms and techniques SPIRAL 2 would allow performing experiments in a wide range of neutron- and proton-rich nuclei far from the line of stability (see Figure 1).

One of the important features of the future GANIL/SPIRAL/SPIRAL 2 facility will be a possibility to deliver up to five stable or radioactive beams simultaneously in the energy range from KeV to several tens of MeV/n.

SPIRAL2 has also a remarkable potential for neutron-based research both for fundamental physics and various applications.

The civil construction of SPIRAL2 has started. It is divided into two phases. Phase 1 includes the LINAC building and associated experimental areas (AEL) and is planned to be completed by 2012 with the commissioning of first beams from LINAC. The second phase (RIB production building and dedicated area low energy ISOL facility, DESIR) will start in 2012 aiming to be ready by 2014. Moreover all the components of the LINAC are under construction including serial production of super-conducting RF cavities, ion sources, injection and other beam-line components.

5. New experimental areas and detectors for SPIRAL2

A process leading to the definitions of the new experimental areas, detectors and associated collaborations was initiated in March 2006 by the Scientific Advisory Committee (SAC) of SPIRAL2. A call for Letters of Intent was launched and the corresponding evaluation took place at the end of 2006. A first targeted call for full technical proposals related to two new experimental vaults S3 and NFS and using directly intense heavy ions and p,d beams from the linac was launched in 2008.

Figure 4: New experimental areas and detectors to be used with GANIL/SPIRAL1/SPIRAL2 facility

Within the SPIRAL2 project these two new experimental areas (Aires Experimentales du LINAC-AEL) will host, respectively, the Neutron for Science facility (Neutron converter and time of flight hall) and the Super Separator Spectrometer (S3) devoted to in flight production of exotic nuclei and to Super Heavy Elements (SHE) using intense heavy ions linac beams (see figs 3 and 4).

Another experimental area devoted to the low energy RIBs has been proposed by the DESIR (Decay, Excitation and Storage of Radioactive Ions) collaboration. At SPIRAL2 and its low-energy beam
facility DESIR, there is an opportunity of building a diversity of apparatus to try to cover the whole nuclear chart.

In addition to these new experimental areas, the Letters of Intent process has induced the formation of new collaborations around detectors the 4Π-γ array EXOGAM2 and AGATA, the active target gas detector ACTAR, the large charge particle arrays FAZIA and GASPARD and the gamma calorimeter PARIS (see Figure 4). These new instruments dedicated to SPIRAL2, for the R&D phase, are supported by the EU FP7 trough the Preparatory Phase contract. Signatures of Memorandums of Understanding (MoU) related to the construction phase are expected by 2010-2011.

6. Conclusions

Nuclear physics has been revolutionized by the recent development of the ability to produce accelerated beams of radioactive nuclei. For the first time it will be possible to study reactions to produce the 6000 to 7000 nuclei we believe exist.

SPIRAL2 is a major expansion of the SPIRAL facility at GANIL, which will help maintain European leadership in ISOL (Isotope Separation On Line) development, aiming at two orders of magnitude increase of the secondary beams available for nuclear physics studies. The technical challenges of the high power accelerator, targets and experimental equipments will provide essential knowledge on the road toward EURISOL, the most advanced nuclear physics research facility presently imaginable and based on the ISOL principle. The scientific program, proposes the investigation of the most challenging nuclear and astrophysics questions aiming at the deeper understanding of the nature of matter.

The construction cost of SPIRAL2 amounts to 200 M€ (including personnel and contingency), and will be shared by French funding agencies CNRS/IN2P3 and CEA/DSM, the Region of Basse Normandie and international partners. The first beams are expected to be delivered by SPIRAL2 in 2012. The full GANIL/SPIRAL1/SPIRAL2 facility will be operational by the end of 2013 and will serve a community of about 800 users.

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