The SPIRAL2 Project and experiments with high-intensity rare isotope beams

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Abstract. The SPIRAL2 facility at GANIL, which entered recently in the construction phase consists of a new superconducting linear accelerator delivering high intensity, up to 40 MeV, light (proton, deuteron, 3He) beams as well as a large variety of 14.5 MeV/nucleon heavy-ion beams and the associated Rare Isotope Beam facility. Using a dedicated converter and the 5 mA deuteron beam, a neutron-induced fission rate is expected to approach 10^14 fissions/s for high-density UC_x target. The energies of accelerated RIBs will reach 5-10 MeV/nucleon for fission fragments and 20 MeV/nucleon for neutron-deficient nuclei. The physics case of SPIRAL2 is based on the use of high intensity RIBs & stable-ion beams and on possibilities to perform several experiments simultaneously. A use of these beams at a new low-energy ISOL facility (DESIR) and their acceleration to several MeV/nucleon as well as of high neutron flux at the n-tof-like facility will open new possibilities in nuclear structure physics, nuclear astrophysics and reaction dynamics studies. The high intensities (up to 10^11pps) and a high cost of RIBs impose a use of the most efficient and innovative detection systems like ACTAR, FAZIA, GASPARD, HELIOS, NEDA, PARIS and a new separator/spectrometer S^3.

1. Introduction
The SPIRAL2 facility [1], an ambitious extension of the GANIL accelerator complex, has entered recently in the construction phase. SPIRAL2 is the most advanced Isotope Separation On-Line (ISOL) – type facility under construction in Europe aiming, in particular, in the production of the most intense Radioactive Ion Beams (RIB) of fission fragments in the world. The physics case of SPIRAL 2 based on the use of high intensity RIB and stable light- and heavy-ion beams as well as on possibilities to perform several experiments simultaneously. In particular, a use of these beams at the low-energy ISOL facility (DESIR) and their acceleration to several MeV/nucleon as well as of high neutron flux at the n-tof-like facility will open new possibilities in nuclear structure physics, nuclear astrophysics, reaction dynamics studies. The SPIRAL2 facility was selected by the European Strategy Forum on Research Infrastructures (ESFRI) as one of the 45 most important EU research infrastructure projects [2].
2. The SPIRAL2 facility
The SPIRAL2 facility layout, which includes main characteristics of the accelerated beams and new experimental halls, is shown in figure 1. In the frame of the SPIRAL2 project, a new superconducting linear accelerator (LINAC) delivering high intensity, up to 40 MeV, light (proton, deuteron, $^3$He) beams as well as a large variety of heavy-ion beams with mass over charge ratio equal to 3 and energy up to 14.5 MeV/nucleon is being constructed. The LINAC beams can be used directly for the production of high neutron flux for the new Neutron For Science (NFS) facility or in the new recoil separator spectrometer S3 for in-flight production of exotic nuclei. The main RIB production technique at SPIRAL2 will use dedicated graphite rotating converter and the 5 mA deuteron beam in the RIB production building. A neutron-induced fission rate is expected to approach $10^{14}$ fissions/s for high-density UC$_x$ target. The versatility of the SPIRAL 2 driver accelerator will also allow using fusion-evaporation, deep-inelastic or transfer reactions in order to produce very high intensity RIB and exotic targets. The ISOL RIB production schemes include most of possible combinations of target (UC$_x$ and other highly resistive materials) - ion sources (ECR, surface ionization, laser, FEBIAD). More detailed information on the production of RIB at SPIRAL2 was presented at this conference in the Poster # 421 of H. Franberg - Delahaye et al.

The 1+ RIB after will be separated in mass in the low-resolution (mass resolving power $M/\Delta M$ of few hundreds) and high-resolution ($M/\Delta M \approx 20000$) mass separators. The RIB can be subsequently used in a dedicated low-energy facility (DESIR) or, after charge breeding, injected into existing CIME cyclotron for acceleration. The energies of accelerated RIB will reach typically 5-7 MeV/nucleon for fission fragments (maximum about 10 MeV/nucleon) and 20 MeV/nucleon for neutron-deficient nuclei.

After acceleration with the CIME cyclotron, which plays also a role of an additional mass separator with $M/\Delta M$ of typically 4000, the RIB from SPIRAL2 or from SPIRAL1 can be used in the existing experimental halls of GANIL.

Recent detailed estimations of the RIB intensities available in the beginning of operation of SPIRAL2 are shown on the example of Cu, Ga, Zn and Kr fission fragments in figure 2. In the calculations a 280g low-density UC$_x$ target and 50kW deuteron beam power were assumed. Nominal RIB intensities
produced with a 2kg high-density UC₄ target and 5mA deuteron beam should be about 15 times higher.

The whole GANIL/SPIRAL1/SPIRAL2 accelerator complex is expected to deliver up to two RIB (one for DESIR facility and one post-accelerated) and three stable-ion beams (at different energies) simultaneously. After reaching its nominal performances SPIRAL2 will deliver up to 44 weeks of LINAC beam time per year. Together with the existing GANIL/SPIRAL1 (35 weeks of beam time/year) the whole facility will provide to the users up to 53 weeks of ISOL RIB beams per year.

![Graphs of rare-isotope beam intensities](image)

**Figure 2.** Examples of rare-isotope beam intensities expected in the beginning of operation of SPIRAL2 for the Cu, Ga, Zn and Kr fission fragments. The 1+ rates (diamonds) and n+ rates (squares and triangles) correspond to those expected after mass separation and after acceleration with the CIME cyclotron correspondingly. Several points for the same isotopes correspond to the production of ground-state and isomeric RIB.

### 3. Physics with Radioactive & Stable-ion High-intensity Beams at 0-20 MeV/nucleon

The scientific programme of SPIRAL2, prepared by more than six hundred physicists proposes the investigation of the most challenging questions in nuclear physics and astrophysics aiming at the deeper understanding of the nature of matter. SPIRAL2 will contribute to the physics of nuclei far from stability, nuclear fission and fusion based on the collection of unprecedented detailed basic nuclear data, to the production of rare radioisotopes for medicine, to radiobiology and to materials science. In the following only main topics of physics of nuclei far from stability with SPIRAL2 are presented. A detailed Physics Case of SPIRAL2 can be found in [3].

The most important nuclear physics issues to be studied at SPIRAL2 can be summarized in the following list: single-particle structure and modification of nuclear shells, nuclear pairing, structure of very-heavy nuclei, nuclear clustering and nuclear molecules, isospin in reaction mechanisms and applications to astrophysics.

High-intensity and large variety of RIBs produced by SPIRAL2 as well as SPIRAL1 (see figure 3) in the energy range from about 1 to 20 MeV/nucleon are perfectly suited for most of nuclear reactions extensively used (and well known) with stable-ion beams in the past. These “standard” tools of nuclear
physics like elastic, inelastic & resonant elastic scattering, transfer reactions ((d,p), (p,d), (p,t)…),
coulomb excitation, breakup, fusion-evaporation, deep-inelastic and fission will gain new dimension
with the SPIRAL2 RIB intensities reaching $10^8 - 10^{11}$ pps. They will allow either on very precise
measurements using the highest and so far unreached intensities for some RIB or the first
measurements for the most neutron-rich or neutron-deficient isotopes - typically 2-3 mass units
beyond the currently known nuclei.
All exotic nuclei produced at SPIRAL2 will be available also at the keV energies in the Decay,
Excitation and Storage of Radioactive Ions (DESIR) facility.
In order to fulfill the requirements of experiments on nuclei far from stability the
GANIL/SPIRAL1/SPIRAL2 facility is and will provide users with ISOL RIB beams of high intensity,
optical quality & purity. It will ensure possibilities to use light and heavy-ion, high-intensity stable-ion
beams, multi-beam capabilities, many months of beam-time every year as well as world-class arrays
and detectors.

4. New detectors for SPIRAL2
Relatively moderate intensities and high cost of radioactive beams impose a use of the most efficient
and innovative detection systems as currently used at GANIL the magnetic spectrometer VAMOS, the
4H gamma-array EXOGAM as well as charged particle detectors like MAYA, MUST 2 and TIARA.
Several new concepts of the detection systems: AGATA and EXOGAM2 gamma-arrays, ACTAR
active target, FAZIA charged particle array, HELIOS and GASPARD light-particle and gamma array,
PARIS gamma-ray calorimeter, NEDA neutron detector and a new Super Separator Spectrometer S3
located in dedicated experimental halls are currently under design. More detailed description of the
detectors mentioned above can be found in [1].
S3 is an innovative device designed for fundamental physics experiments with the very high intensity
stable beams of the SPIRAL2 LINAC. Heavy-ion beams delivered by SPIRAL2 with rates above
$10^{13}$ions/s will be among the highest intensities in the world used for nuclear physics research in the
Coulomb-barrier energy regime. These unprecedented intensities combined with the unique S3 facility
will open new horizons of research in the domains of rare nuclei and low cross-section phenomena at
the limit of nuclear stability as well as in atomic ion-ion collisions research.
The existing detection systems and spectrometers (like VAMOS, EXOGAM and LISE) and the
current GANIL experimental area will be adopted to take a full benefit of the high intensity (up to
$10^7$pps) RIB. The necessary modifications of the vacuum system, beam dumps, electronics etc. will
take into account new radioprotection, safety and background issues due to use of high-intensity long-
lived exotic nuclei.
The most exotic species – many of which will be produced for the very first time at SPIRAL2 –
might be transmitted to the DESIR facility for experiments at low energies that will determine their
fundamental, ground-state properties such as decay mode, half-life, mass, charge radius and shape. In
addition, DESIR can also receive beams from the existing SPIRAL1 facility. Finally, DESIR is also
meant to receive beams from S3. The S3 separator will produce exotic nuclei by fusion-evaporation and
deep-inelastic reactions. The main asset of S3 is the fact that it can also produce exotic nuclei of
refractory elements and very short-lived isotopes that are not available from SPIRAL1 and SPIRAL2
due to the use of thick production targets. This production mode is also the most important asset of
DESIR as compared to other ISOL RIB facilities. The equipment to be installed at DESIR comprises
different ion and atomic traps for high-precision mass measurements, for studies dealing with
nucleosynthesis scenarios and the standard model of weak interaction, and for the high-purity
preparation of radioactive species for decay studies. The LUMIERE facility, the laser-spectroscopy
facility of DESIR, will allow measurements of static properties of the exotic nuclei ground and long-
lived isomeric states like their magnetic moment, their quadrupole moment and thus their deformation
as well as their spin and parity.
Figure 3. Radioactive ion beams and nuclei far from stability accessible with SPIRAL1 & SPIRAL2 with different reaction mechanisms and production techniques.

The BESTIOL facility will enable to perform precision measurements in nuclear beta decay to study fundamental properties like decay modes, half-lives, branching ratios, spins and parities of these exotic nuclei. Finally, the basement of the DESIR facility will contain a highly protected room for high-intensity experiments devoted to material science and industrial applications.

5. Status of the SPIRAL2 construction phase

The SPIRAL2 Project entered in the construction phase in 2006. The construction of SPIRAL2 is going to last about 7 years (2006-2014) and is separated into two phases:

1. Linear accelerator with S3 and NFS experimental halls - commissioning expected in 2012;
2. Radioactive Ion Beam production hall and DESIR low-energy RIB facility – commissioning expected in 2014.

All essential sub-systems of LINAC were ordered and many of them, in particular super-conducting cavities, were already delivered and successfully tested. The heavy-ion injector of LINAC was recently mounted and tested at LPSC laboratory in Grenoble. The light-ion injector is currently under assembly in the Irfu/DSM/CEA laboratory at Saclay. All major LINAC components fully tested will be moved to GANIL once the SPIRAL2 buildings are available. The civil construction of Phase 1 is expected to begin in the end of 2010.

A detailed design study of SPIRAL2 Phase 2 (the RIB production building, the DESIR hall and associated instrumentation) is largely advanced and should be ready by 2011.

The main components of the facility are constructed by large consortium of main French CEA/DSM and CNRS/IN2P3 laboratories with contributions from international (mainly EU) partners.

A total construction cost of the baseline project (without detectors) estimated to 196 M€ is shared by CEA/DSM, CNRS/IN2P3, local authorities in Normandy, European Commission and international partners.
6. Conclusions
The construction of SPIRAL2 is currently following the initial schedule. The first stable-ion beams from LINAC expected in the end of 2012/beginning 2013 should allow starting experimental program in 2013. The first RIB should be available about 2 years later.

A very intense R&D work on the new detectors for SPIRAL2 is in progress and a preparation of the corresponding Memoranda of Understanding is entering in a final phase.

Following a recent call for letters of intent (LoI) for Day 1 experiments with high-intensity stable-ion beams with NFS and S3 facilities 22 LoIs were submitted and evaluated by the SPIRAL2 Scientific Advisory Committee. This in turn allowed to define specifications of the first beams to be delivered by LINAC and to set priorities for the SPIRAL2 Phase 1 on the construction of the S3 and NFS experimental halls.

Recently a new call for letters of intent for the first experiments at SPIRAL2 with RIB was launched with a deadline for the submission of the LoIs December 17, 2010.

The SPIRAL2 project is an essential intermediate step toward EURISOL, the most advanced nuclear physics research facility presently imaginable and based on the ISOL principle. It is expected that the realisation of SPIRAL2 will substantially increase the know-how of technical solutions to be applied not only for EURISOL but also in a number of other European and world projects. In a mid-term perspective towards EURISOL the GANIL/SPIRAL2 facility might considered an intermediate step aiming in a post-acceleration of fission fragments to about 150 AMeV.

The current negotiations with international partner countries should allow them to join the ongoing construction of the base-line project and associated detectors as well as the future operation phase, turning the present GANIL into a fully international legal entity. This transformation is the main goal of the ongoing EU Framework Program 7 SPIRAL2 Preparatory Phase contract (25 partners from 13 countries, EC contribution of 3.9M€).

References
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