Vol. 40 (2009) *ACTA PHYSICA POLONICA B* No 3

THE SPIRAL2 PROJECT: PHYSICS AND CHALLENGES*

Marek Lewitowicz

on behalf of the SPIRAL2 Project Group
and Physics Collaborations

Grand Accélérateur d'Ions Lourds — GANIL CEA/DSM-CNRS/IN2P3
BP 55027, 14076 Caen Cedex, France

(Received January 22, 2009)

The SPIRAL2 project, an important extension of the GANIL facility and one of the ESFRI list European research infrastructures entered recently in the construction phase. In the following, a physics case of the facility based on a use of high intensity stable and radioactive beams is presented. Expected performances and main technical parameters of the facility as well as planned new experimental areas and detectors are introduced.

PACS numbers: 25.60.–t, 29.17.+w, 29.27.Eg, 25.85.–w

1. From GANIL/SPIRAL to the SPIRAL2 facility

The GANIL facility [1] (Caen, France) is one of the major Rare (or Radioactive) Ion Beam (RIB) and stable-ion beam facilities for nuclear physics, astrophysics and interdisciplinary research in Europe. Since the first beams delivered 25 years ago, the performances of the GANIL accelerator complex, was constantly improved with respect to the beam intensity, energy and available detection systems. In recent years, RIBs, *i.e.* beams of synthesized radioactive isotopes, have been recognized by the international scientific community as one of the most promising avenues for the development of fundamental nuclear physics and astrophysics, as well as in applications of nuclear science. Since the beginning of the experimental program of GANIL, the facility delivered RIB produced in-flight at LISE and SISSI/Alpha fragment separators. More recently, in autumn 2001, the SPIRAL facility allowing for the production and post-acceleration of the ISOL-type RIB entered

* Presented at the Zakopane Conference on Nuclear Physics, September 1–7, 2008, Zakopane, Poland.

into operation. The facility, specialized in RIB of rare gases (He, Ne, Ar, Kr but also N, O and F), enlarged importantly the range of experimental possibilities dedicated to study of nuclei far from stability at GANIL.

Available today intensities and energies of the GANIL stable-ion beams ($Z > 5$) limit the use of high intensity RIB to relatively light nuclei ($A < 80$). Since the beginning of the SPIRAL project it was proposed to enlarge the range of accelerated ions by production of high intensity RIB of fission fragments. This idea, after several years of discussions and an important preliminary study phase led, in particular, in the framework of the European RTT Program was concretized in the SPIRAL2 project [2]. The project is following the European road map for RIB facilities defined by NuPECC [3] (Nuclear Physics European Collaboration Committee — an expert committee of the European Science Foundation), which recommended the construction of two complementary next-generation RIB facilities in Europe. One is based on in-flight fragmentation (IF) as proposed for the FAIR facility at GSI (Darmstadt, Germany) and the other on the isotope-separation on-line (ISOL) method, largely developed at the CERN-ISOLDE facility over the last thirty years (the EURISOL project [4]). Because of the time-line for EURISOL as well as of important unsolved yet technological issues, 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 develop applications with RIB. Among the proposed intermediate facilities, SPIRAL2 meets the criteria of European dimension in terms of physics potential, site and size of the investment as it was recognized recently in the ESFRI (European Strategy Forum on Research Infrastructures) roadmap [5]. The SPIRAL2 facility has entered in its construction phase in 2005 and is supported by the EU FP7 through the Preparatory Phase contract since 2008.

2. Scientific case of SPIRAL2

A complete presentation of the scientific case of the facility, going beyond the scope of this contribution, can be found in the White Book of SPIRAL2, Letters of Intent and Technical Proposals for SPIRAL2 (see Ref. [6]). In the following paragraphs, only few examples of a rich and multipurpose scientific program will be shortly discussed.

2.1. Physics of exotic nuclei and nuclear astrophysics

A major part of the experimental and theoretical research program at the SPIRAL2 facility will follow the fundamental motivation of basic nuclear science research, which is trying to establish a bridge between the nucleon–nucleon interaction inside a nucleus and the underlying quarks and gluons

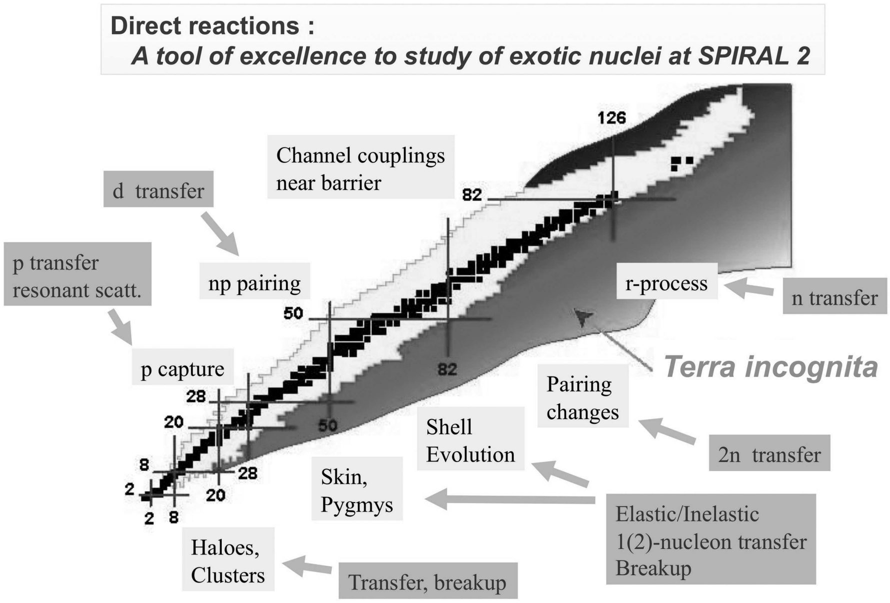

Fig. 1. Topics to be addressed at SPIRAL2 with direct reactions as a tool to study nuclear structure far from stability.

as well as understand the mechanism of interaction between nuclei. This research on the nucleus and on the interactions between its constituents progresses, in particular, using nuclei with unusual neutron-to-proton ratios, artificially produced in laboratories, which open up a considerable field of investigation. By allowing the study of very asymmetric nuclear systems, the nuclei far from stability highlight the phenomena at the origin of the cohesion of the nucleus. SPIRAL2 thanks to very high intensities of RIB will give access to a whole range of experiments (from elastic scattering to fusion-evaporation reactions), which are inaccessible with modest intensity beams of first generation RIB facilities. In particular, new exotic shapes and excitation modes, *e.g.* halo-like and molecular structures, and new modes of nuclear decay are expected to be observed. Tests of fundamental symmetries, testing and refinement of the Standard Model of fundamental interactions, and exploration of the magic numbers of protons and neutrons in very exotic nuclei are all enticing avenues of discovery at SPIRAL2.

Many of explosive nucleosynthesis processes involve radioactive nuclei. Due to their very short lifetimes, most of them have not survived long enough to be present on earth. SPIRAL2 will produce abundantly nuclei lying on or in a close proximity to the r and rp-process paths, opening up new fields of investigation. In particular, a new insight on nucleosynthesis might be achieved using direct reactions (d,p), (p,d), *etc.* These type of reactions are expected to be one of the most powerful tools both for nuclear structure and astrophysics studies at SPIRAL2 (Fig. 1). The facility will match necessary conditions for these kind of measurements namely, high RIB intensities, energy range up to 9 MeV/nucleon for fission fragments and up to 20 MeV/nucleon for neutron deficient nuclei and a full set of efficient detector systems (see below).

The SPIRAL2 beams are equally well suited for studies of new phenomena in the fast-rotating and deformed nuclei produced in fusion-evaporation reactions. Due to higher fission barriers the neutron-rich nuclei are expected to sustain much higher maximum spins of 70–80$\hbar$, leading, most probably, to appearance of new phenomena (Fig. 2).

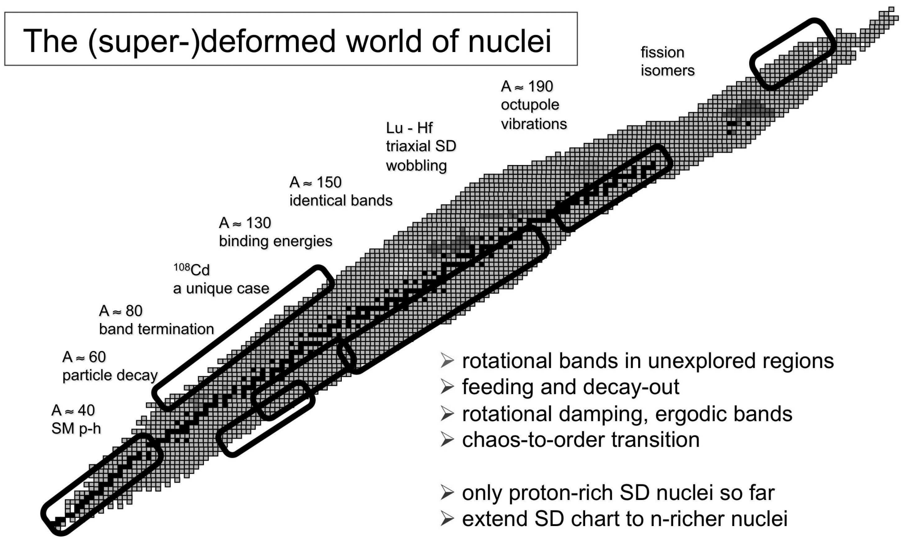

Fig. 2. High optical quality and intense neutron-rich beams from SPIRAL2 will provide access to the so far unexplored regions (solid ovals) of deformed and superdeformed nuclei.

2.2. Neutrons for science at SPIRAL2

One of the interesting possibilities, which will open with the SPIRAL2 facility is related to the production of a high neutron flux in the energy range from several hundreds of keV up to about 40 MeV. The facility will offer a unique opportunity for material irradiations and cross-section measurements, both for fission-related (notably accelerator driven systems (ADS) and Generation-IV fast reactors) and nuclear fusion-related research. The corresponding experiments require specific facilities providing pulsed neutron beams for cross-section measurements or dedicated irradiation station for activation analysis. The high neutron fluxes with high and variable energy spectra available at SPIRAL2 are very attractive to perform the measurements of the cross-sections related to transmutation-incineration of nuclear waste and of minor actinides in particular. The high neutron fluxes would allow the measurements of small reaction cross-sections and/or with very small targets, which might be rare, expensive, and in some cases radioactive. The energy range and conditions offered by SPIRAL2 time-of-flight facility is complementary to other such facilities in Europe, notably GELINA of the European Commission Joint Research Centre in Geel and the CERN based n-TOF facility. More details on this topic can be found in [7].

3. Layout and performances of the SPIRAL2 facility

The SPIRAL2 facility (Fig. 3) is based on a high-power, superconducting linac driver, which will deliver a high-intensity, 40 MeV deuteron beam as well as a variety of heavy-ion beams with mass-to-charge ratio of 3 and energy up to 14.5 MeV/nucleon. A possibility of construction of a second injector for heavy-ions with a mass-to-charge ratio 6–7 is incorporated in the design of facility.

The main RIB production scheme of SPIRAL2 is based on the fast-neutron induced fission of uranium target. Using a carbon converter, a 5 mA deuteron beam and a high-density (up to 11 g/cm^3) 2.3 kg uranium carbide target, the fission is expected to reach a rate of up to 10^{14}/s. The intensities of the post-accelerated RIB in the mass range from $A = 60$ to $A = 140$ will be of the order of 10^6 to 10^{10} particles/s (pps) surpassing by one or two order of magnitude existing facilities. For example, the intensities should reach 10^9 pps for ^{132}Sn and 10^{10} pps for ^{92}Kr. A direct irradiation of the UC_2 target with beams of protons or ^{3,4}He can be used if higher excitation energy leads to higher production rate for a specific nucleus of interest or if much smaller targets with fast release properties is required.

Thanks to the high intensity heavy-ion beams provided by the driver the neutron-rich fission RIB could be complemented by beams of nuclei near the proton drip-line, provided by fusion-evaporation or transfer reactions. For example, an in-flight production of up to 8×10^4 atoms of ^{80}Zr per second using a 200 μA ^{24}Mg^{8+} beam on a ^{58}Ni target should be possible. Similarly, the heavy- and light-ion beams from LINAC can also be used directly on different production targets to produce high-intensity light RIB with the ISOL technique.

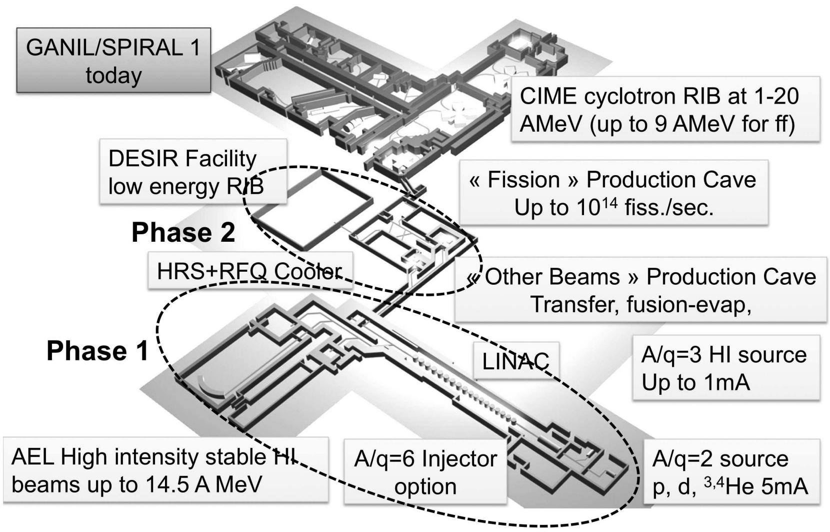

Fig. 3. Layout of the GANIL/SPIRAL1 and future SPIRAL2 facilities.

The extracted 1+ radioactive ions will be subsequently injected to the $1+/n+$ charge breeder (ECR ion source) and post-accelerated to energies of up to 20 MeV/nucleon (up to 7–8 MeV/nucleon for fission fragments) by the existing CIME cyclotron. Thus, using several different production mechanisms and techniques, SPIRAL2 would allow users to perform experiments with a wide range of neutron- and proton-rich nuclei far from the line of stability. One of the important features of the future GANIL/SPIRAL1/SPIRAL2 facility will be the possibility to deliver up to five stable or radioactive beams to different users simultaneously in the energy range from keV to several tens of MeV/nucleon.

A civil construction of SPIRAL2 is divided into two phases (Fig. 3). The first one (LINAC buildings and associated experimental AEL, see below) is going to begin in 2010 with a goal to provide first stable-ion beams in 2012. The second phase (RIB production building and DESIR facility) will start in 2011 aiming in the beginning of operation in 2013–2014. The construction of LINAC is already well advanced with, in particular, the serial production and tests of super-conducting cavities, ion sources and beam-line components.

4. New experimental areas and new detectors for SPIRAL2

In the framework of the SPIRAL2 project two new experimental areas will be constructed. One dedicated to the experiments with high intensity stable beams delivered by linac (Aires Experimentale du LINAC — AEL) and one devoted to research program with low energy RIB proposed recently by the DESIR (Decay, Excitation and Storage of Radioactive Ions) collaboration.

Relatively moderate intensities and high cost of radioactive beams impose a use of the most efficient and innovative detection systems such as the magnetic spectrometer VAMOS, the 4Π gamma-array EXOGAM and AGATA as well as charged particle detectors like MAYA, MUST 2 and TIARA. Several new concepts of the detection systems (ACTAR, DESIR, FAZIA, GASPARD, PARIS) and a new separator/spectrometer S3 located in dedicated experimental AEL hall were recently proposed (Fig. 4). Most of the existing detection systems and the existing experimental area should be adopted to take a full benefit of the high intensity (up to 10^{11} pps) RIB [6]. One of the experimental hall of AEL will host the NFS facility mentioned above. The second hall will be dedicated to the experiments with Super Spectrometer Separator (S3) [8] and in-flight production of exotic nuclei using LINAC heavy-ion beams. The most important physics topics to be addressed with this top-level equipment are nuclear haloes and molecules,

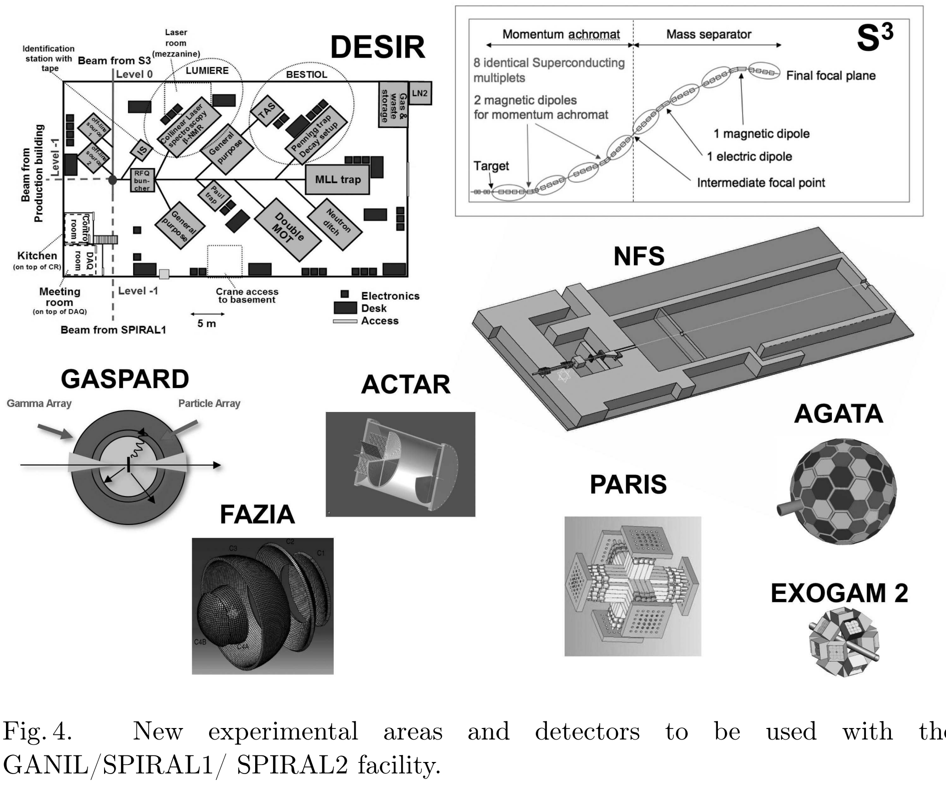

Fig. 4. New experimental areas and detectors to be used with the GANIL/SPIRAL1/ SPIRAL2 facility.

$N = Z$ nuclei, nuclear structure studied via deep-inelastic collisions as well as physics and chemistry of heavy and super heavy nuclei (Fig. 5). The S3 will also provide access to many short-lived isotopes or isotopes of refractory elements which are difficult to produce using ISOL technique. Recent optimisation of the layout of the whole SPIRAL2 facility opened a possibility to use in the DESIR facility low energy beams from the RIB production building, S3 or existing SPIRAL 1 facility.

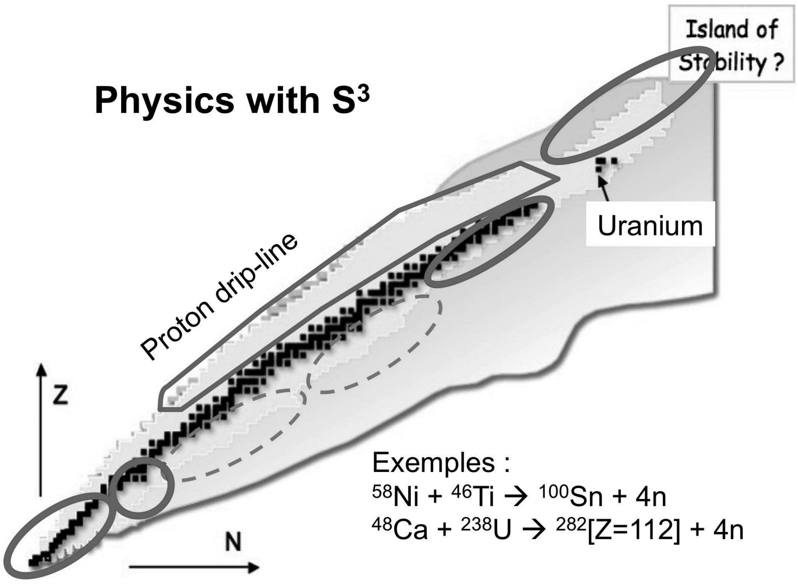

Fig. 5. Main regions of interest to be addressed with the new S3 spectrometer-separator.

A process leading to the definition of the detectors and corresponding collaborations was initiated recently via call for letters of intent for SPIRAL2 (see [6] for details). The evaluation of the letters of intent by the SPIRAL2 Scientific Advisory Committee took place in the end of 2006. A first targeted call for full technical proposals related to the AEL was launched in 2008. The second call related to the DESIR facility and EXOGAM2 is currently going on. Signatures of Memorandums of Understanding related to the construction of new equipment are expected by 2010–2011.

5. Conclusions

The French government approved the construction of SPIRAL 2, a new 200 MEuros RIB facility at GANIL, in 2005. Its construction cost is shared by the French funding agencies CNRS/IN2P3 and CEA/DSM, the regional authorities of Basse-Normandie and international partners. The baseline project as well as new dedicated detectors are supported by the EU FP7 through the Preparatory Phase contract. The construction of the driver accelerator is in progress. The detailed definition of the RIB production building, of the experimental areas and of the dedicated detectors is entering in the final phase. The first beams are expected to be delivered by SPIRAL2 in 2012. The full GANIL/SPIRAL1/SPIRAL2 facility will serve a community of about 700–800 users.

REFERENCES

[1] www.ganil.fr

[2] www.ganil.fr/research/developments/spiral2/origin.html

[3] www.nupecc.org

[4] www.eurisol.org

[5] cordis.europa.eu/esfri/publications.htm

[6] www.ganil.fr/research/developments/spiral2

[7] X. Ledoux *et al.*, Neutrons for Science, SPIRAL2 Technical Proposal, www.ganil.fr/research/developments/spiral2/collaborations.html

[8] H. Savajols *et al.*, S3, SPIRAL2 Technical Proposal, www.ganil.fr/research/ developments/spiral2/collaborations.html