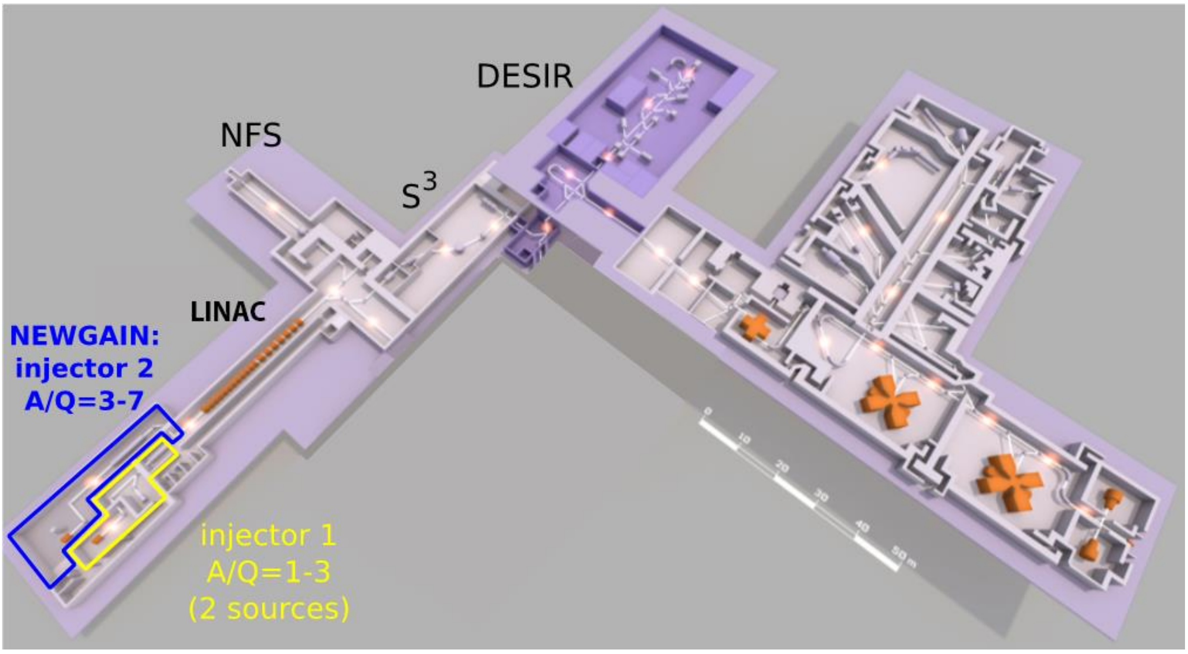
WHITE BOOK

SCIENCE REQUIREMENTS



Work Package Physics

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[1]GANIL, [2]CENBG, [3]USC, [4]IPHC, [5]CIMAP, [6]INSP, [7]IJCLab, [8]IP2I, [9]IRFU

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PREAMBLE

*The new injector for **SPIRAL2** at **GANIL**, **NEWGAIN** is presently in its design phase. The major constraints for its technical concepts are determined by the requirements of its future users, the national French and the international scientific communities. The facility will offer heavy ion beams of unmatched intensity for fundamental and applied research.*

*This document reports on the specific requirements of the scientific communities in terms of beam energy, intensity, time structure and other features which are needed to conduct the envisaged research programs at the experimental installations which are or will be coupled to the linear accelerator of the **SPIRAL2** facility at **GANIL**. It aims at fostering the information exchange between the scientific community and the technical and engineering team who is designing, planning and constructing **NEWGAIN**.*

*The document has been elaborated by the members of the Work Package Physics (WPP) of the **NEWGAIN** project, consisting of the scientific coordinators of the institutions contributing to and participating in **NEWGAIN**, and representatives of the various scientific collaborations engaged in the exploitation of the **SPIRAL2** accelerator facility.*

The document is organized with active links to sections, subsections, figures, tables and literature references integrated in the text.

Caen, in June 2021

NEWGAIN
PROJECT SUMMARY

SPIRAL2 (***S****ystème de* ***P****roduction d'****I****ons* ***RA****dioactifs en* ***L****igne de* ***2****e génération*) is a new accelerator facility, presently in an advanced stage of commissioning at the ***G****rand* ***A****ccélérateur* ***N****ational d'****I****ons* ***L****ourds* (**GANIL)**. **GANIL** is a **TGIR** (Very Large Research Infrastructure) with a prominent positioning in the national and international strategy of the Ministry of Research, **CEA** and **CNRS**. GANIL-**SPIRAL2** is also a *Landmark* facility in the ***E****uropean* ***S****trategy* ***F****orum on* ***R****esearch* ***I****nfrastructures (***ESFRI***)*. The main equipment is a state-of-the-art superconducting *LIN*ear *AC*celerator (***LINAC***), presently equipped with a single injector producing ion-beams having mass to charge state ratios (A/q) ranging from 1 to 3. The proposed project ***NEW GA****nil* ***IN****jector* **(NEWGAIN)** aims at the construction of a second injector with A/q=7, so as to produce very intense heavy-ion beams up to uranium, well beyond the performance of the existing injector. With the addition of this new injector, the **SPIRAL2 LINAC** will deliver, within its energy range of operation, the most intense beams in the world over a large variety of ions (ranging from protons to uranium). This upgrade of the **LINAC** will increase the international competitivity of **GANIL** both in fundamental science and associated applications. These ion beams will be exploited by three associated state-of-art experimental facilities:

- The **S**uper **S**eparator **S**pectrometer $\mathbf{S^3}$, expected to take first beams in 2023/2024 will initially exploit beams of medium mass produced by the existing A/q=3 injector (however with lower intensity). Measurements of rare events at S^3 will benefit substantially and especially from the very high intensity beams having a mass number greater than 40 that will be delivered by the proposed **NEWGAIN** (A/q=7) injector project. The proposed project will be of crucial importance to further enhance the international impact of S^3.
- The low-energy facility **DESIR (D**ésintégration, **E**xcitation et **S**tockage d'**I**ons **R**adioactifs**),** presently in its design and construction phase, is expected to come online in 2026 with radioactive ion beams. Its large variety of instrumentation will be used for the investigation of fundamental nuclear and atomic properties of exotic ions produced by S^3 and SPIRAL1
- The **N**eutrons **F**or **S**cience (**NFS**) facility will mainly use light ion and neutron beams. A First commissioning experiment has already been performed using the design energy value of the proton beam provided by the **SPIRAL2 LINAC** in December 2019. **NFS** will also substantially profit from the pulsed operation mode within the framework of the **NEWGAIN** project.

The expected exceptionally high beam intensities with the new A/q=7 injector and the associated experimental equipment at the SPIRAL2 facility, will lead to a very high discovery potential. Its principal impact will be on open problems in the investigations of **S**uper **H**eavy **E**lements (**SHE**) and nuclei far from stability having equal or very similar neutron and proton numbers (**N=Z**) in the neutron-deficient region around ^{100}Sn. Both these topics which contribute to the understanding of nuclear structure at the limits of stability, rely on the investigation of exotic nuclear species having very low production cross-sections. Among others, the long-standing questions, among others, concerning location and stability of the so-called *island of stability of* **SHE** and the nature of the proton-neutron interaction, will be addressed.

Interdisciplinary research, in particular related to atomic physics, applied science and industrial applications are also part of the program at **SPIRAL2**. Apart from potential transfer of know-how to industry, experimental setups like **FISIC (**Fast Ion – Slow Ion Collision**)** at S^3 for atomic physics and those at **NFS** and **DESIR** will investigate, among others, questions related to nuclear energy, nuclear data, nuclear structure condensed matter physics and medical applications.

The **NEWGAIN** project will substantially increase the capabilities of the **SPIRAL2 LINAC** with the construction of a second injector able to produce and accelerate ion beams with mass to charge-state ratios ranging from A/q=3 up to A/q=7. This second injector will be designed to be fully compatible with

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the existing facility and to further enhance its 'multi-user' capabilities. It will be composed of the following:

- A high-performance superconducting ion source
- A first low energy beam transport (LEBT) line connecting the superconducting ion source to the **R**adio **F**requency **Q**uadrupole **(RFQ).**
- A second LEBT line connecting the existing ion source to the **RFQ**
- A **RFQ** that will accelerate heavy ions with minimal beam losses up to the injection energy for the superconducting **LINAC**
- A medium energy beam transport (MEBT) line for the connection the **LINAC**

In comparison to the existing LINAC injector with a mass to charge ratio up to A/q=3, NEWGAIN will provide substantially increased beam intensities for masses A≈40 and higher. Ion species with masses A>60 can only be provided with the new A/q=7 injector (see ***Figure*** *3*).

NEWGAIN is presently, after the **P**reliminary **D**esign **S**tudy (**PDS**) phase was completed, at the beginning of the detailed **T**echnical **D**esign **S**tudy (**TDS**) phase which will last 18 months. The construction phase is planned to begin in January 2023, for a duration of five years, including a commissioning phase that will be performed simultaneously with the operation of the existing **SPIRAL2** facility. The global cost of this project is estimated to be around 16.5 M€. The building and infrastructure (electrical power, cooling power, etc.) are already constructed and installed since 2014, as a part of the **SPIRAL2** project.

An EQUIPEX+ grant request was been submitted to the ANR in June 2020 for a total amount of 16.5 M€. This NEWGAIN EQUPEX+ proposal is supported by GANIL, IRFU, LPSC, IP2I, IPHC, CENBG, IJCLAB and CMAP and was evaluated A+ (maximum) in December 2020. After a formal acceptance of the proposal the final negations with ANR are ongoing right now.

GENERAL INTRODUCTION

The heart of the *Système de Production d'Ions Radioactifs en Ligne de 2^e^ generation* (SPIRAL2) is a superconducting linear accelerator (LINAC) which will deliver ion beams of unmatched intensity ranging from protons and deuterons up to the heaviest nuclei. This LINAC accelerated its first proton beams in 2019 and is presently pursuing its commissioning phase. An overview of the complete GANIL accelerator complex is given in ***Figure 1***, including the cyclotrons and their experimental areas as well as the layout of the new SPIRAL2 facility. It shows on the lower left part the two injectors, one of which (injector 1) is already operational and is served by two ion sources with a mass to charge-state ratio A/q up to 3, while the second (injector 2), with a maximum A/q of 7, is the subject of this NEWGAIN (*NEW GAnil INjector*) project. The three experimental areas served by the LINAC are also shown: NFS, which produced its first test neutrons in December 2019, S^3, which is presently in the final construction phase, and DESIR, which is in its final design and integration phase. The NFS experimental program will start in September 2021. S^3 is expected to start its commissioning phase with beam mid 2023 and to start its first experimental campaign in 2024, while DESIR envisages early science operation by 2026.

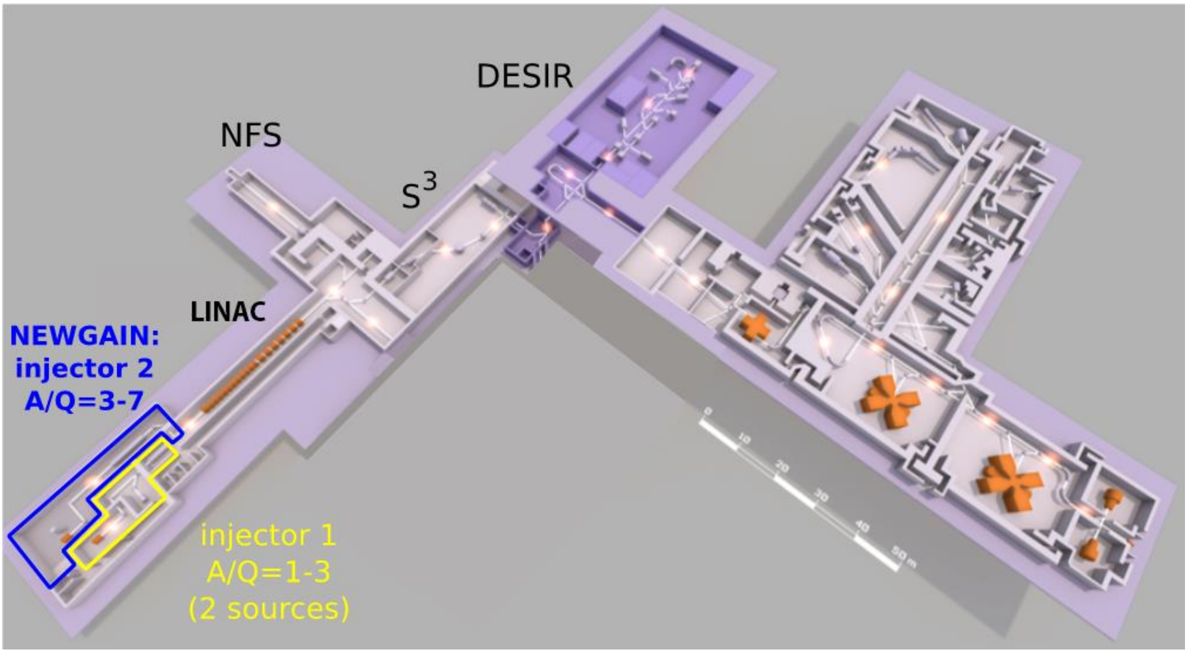

Figure 1*: Overview of accelerator and instrumental installations at GANIL/SPIRAL2 (see text).*

PROJECT – SCIENTIFIC AIMS

The scientific goals of the NEWGAIN project can be divided into two parts:

- Expand and reinforce the existing A/q ≤ 3 physics program. This concerns mainly the SHE and N=Z physics research programs based on the fusion-evaporation reaction products selected by the S^3 spectrometer, connected to a series of instrumentation set-ups like SIRIUS, FISIC at S^3, S^3-LEB and DESIR. All those facilities are in various phases of construction, but all are scheduled to be commissioned before the construction of NEWGAIN.
- Prepare the development of an ambitious physics program. This includes the use of high-intensity beams up to uranium and reaction mechanisms such as deep-inelastic, fusion-fission and fusion-evaporation in inverse kinematics. This physics program is, the well-defined scientific projects for S^3, NFS and DESIR, under development. New installations have to be implemented to take full advantage of the high beam intensities and the wide range of projectiles offered by NEWGAIN. Some of them will be constructed after NEWGAIN is started. The most relevant heavy beams under discussion are Xe, Pb, Bi and U.

SHE and N=Z research are part of the comprehensive list of research fields, including the investigation of exotic nuclear structure in the vicinity of the proton dripline, basic properties of atomic nuclei, applications in the fields of isotope and energy production and advanced studies of the atom itself. The versatile tool park includes three major experimental sites, one of them, NFS, by now in operation, the second, S^3, presently under construction, the third, DESIR, being implemented in the nearest future:

- The separator-spectrometer set-up (S3) with the SIRIUS decay station, its Low Energy Branch (S3-LEB) and the future atomic physics installation FISIC. Its in-beam commissioning planned to start in the mid 2023.
- The Neutrons For Science (NFS) facility, presently operational, with a first p-beam experiment performed in December 2019, employing for the time being the existing injector of LINAC
- The low-energy ISOL facility DESIR, presently in its final design study at GANIL with its construction scheduled to start in the first half of 2022.

Table 1*: Comparison of the maximum design beam intensities for relevant facilities around the world. The first column shows the expected intensities for the existing SPIRAL2 injector1 (A/q=3) coupled with the Phoenix V3 source. The second, third and fourth column show the projected intensities for the NEWGAIN project with the Phoenix V3 source coupled with A/q≤7, a new superconducting (SC) source coupled with A/q≤6 and a new superconducting (SC) source coupled with A/q≤7 respectively. The fifth column lists the projected intensities for the SHE factory of FLNR, Russia. The sixth and seventh columns the intensities provided by the accelerators of RIKEN, Japan, and the eighth column the expected intensities from the UNILAC upgrade at GSI Germany (priv. com. W. Barth et al., GSI). The best intensities for the given projectile are shown in red. This comparison is particularly adapted for SHE research.*

Beam intensities puA (6.2e+12 pps)	**SPIRAL2 * GANIL, Caen**				SHE factory** FLNR, Dubna	RIKEN Nishina Center Wako (Tokyo)		GSI *** Darmstadt
	LINAG A/q≤3 Phoenix v3	**NEWGAIN A/q≤7 Phoenix v3**	**NEWGAIN A/q≤6 SC source**	**NEWGAIN A/q≤7 SC source**	DC-280	RILAC	RRC (RILAC(2) injector)	UNILAC
^{18}O	**80**	**>64**	**300**	**300**	**16**	**10**	**-**	**1**
^{40}Ar	**16**	**56**	**56**	**56**	**10**	**10**	**1**	**8**
^{36}S	**2.3**	**30**	**30**	**30**	**-**	**-**	**-**	**-**
^{40}Ca	**2.9**	**16**	**16**	**16**	**-**	**-**	**-**	**-**
^{48}Ca	**1.2**	**8**	**16**	**16**	**10**	**3**	**0.3**	**4**
^{58}Ni	**1.1**	**3.2**	**6.4**	**6.4**	**-**	*****	*****	**2.2**
^{86}Kr	**0.1**	**8**	**16**	**16**	**-**	**10**	*****	**0.2**
^{136}Xe	**0.001**	**5.6**	**>8**	**>8**	**16**	**10**	**0.3**	**1**
^{238}U	**<<0.001**	**0.06**	**0.4**	**4.8**	**0.008**	**0.2**	**0.5**	**0.06******
*	80% total transmission assumed							
**	http://flerovlab.jinr.ru/index.php/2017/03/23/she-factory/							
***	for CW-LINAC project, CAPRICE ion source, 50% total transmission, mode: CW, priv. com. W. Barth et al., GSI							
****	VARIS ion source, 80% Alvarez-transmission, mode: 2 Hz/0.1 ms, priv. com. W. Barth et al., GSI							
*****	beams not delivered							
-	intensities not provided							

With this instrumentation panoply, including a low-energy irradiation station placed directly at the exit of the NEWGAIN RFQ, a number of science topics and applications will be addressed:

- Atomic and nuclear structure, and synthesis of SuperHeavy Nuclei (SHN), with the option to investigate the chemistry of SHE
- Nuclear structure of the heaviest nuclei with N=Z
- Atomic and nuclear physics in the low-energy domain
- Properties of atoms in Fast Ion–Slow Ion Collisions with the FISIC setup at S^3
- Investigation of deep inelastic reactions from multi-nucleon transfer (MNT) to fission
- Interdisciplinary research of fundamental as well as applied science topics, including the production of radio-isotopes.

These research programs will profit from the high intensities for medium mass and heaviest projectiles provided by NEWGAIN with its capability of efficiently accelerating ions with a mass to charge state ratio of A/q ranging from 3 to 7 (see ***Table 1***) with a maximum energy of 7.5 MeV/A for A/q=7. The most relevant beams are ^{40}Ca, ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{50}Cr, ^{70}Zn in the near future for SHE and N=Z research. The target system is designed for 10 pμA of ^{70}Zn at 5 MeV/A incident beam. An A/q maximum of 6 would be sufficient to satisfy this request. The heaviest species such as lead or uranium isotopes require A/q=7. Those heavy beams are at the center of attention for the development of a new physics program at GANIL. Beams of this kind are needed for studies of fission and deep-inelastic reactions, but they are foremost necessary for production schemes as envisaged for future rare-isotope beam facilities, based on deep inelastic reactions, fusion-fission and fusion-evaporation reactions in inverse kinematics. Therefore, it has been decided to design the NEWGAIN injector for A/q up to 7.

After presenting the technical outline of the NEWGAIN project in the next subsection and some details on beam production and target technology in section **BEAM PRODUCTION AND TARGETS**, the special requirements related to the instrumentation to be used and the science topics to be studied with NEWGAIN will be discussed in sections **REQUIREMENTS – DETECTION INSTRUMENTATION** and **REQUIREMENTS – PHYSICS**, respectively. In the final section **SUMMARY BEAM REQUIREMENTS** those requirements are summarized. As compared to other parts of the document, more room has been dedicated to the section T, including details which are not reported elsewhere in the project documentation, but which are relevant and important, in particular, concerning the special challenges posed for the target technology by the high beam intensities provided by NEWGAIN.

PROJECT – TECHNICAL DESCRIPTION

The new injector for the GANIL/SPIRAL2 LINAC is based on a standard conceptual design as far as the various system functions are concerned, but requires the development of new and very high-performance prototypes as far as some major components are concerned. It will be fully located in an existing cave in the SPIRAL2 building, the design of which has been anticipated to host such an injector. Its ancillaries will be placed in various rooms of the SPIRAL2 building as well, since extra room has been reserved for this equipment.

The NEWGAIN injector components are shown with their location in their dedicated cave in ***Figure 2*** with:

- **Ion source**: the performance of the novel installation is essential to achieve the goal of highest beam intensities. It will be equipped with a set of superconducting magnets, operating at 4K and requiring a substantial design study, and with two frequency generators (18 GHz and 28 GHz). This electron cyclotron resonance (ECR) ion source will be the first one of its kind in France and the second in Europe after the SERSE project of LNS, Catania, Italy [S. Gammino et al., Rev. Scient. Instr. 72 (2001) 4090]. It is aiming at higher performances than similar sources already existing in USA, Japan or China. For an updated summary of highest intensities achieved worldwide see ***Figure 3***.

- **The Low Energy Beam Transport (LEBT)** section will allow transporting the ion beam towards the RadioFrequency Quadrupole (RFQ). It will be equipped with standard magnetic or electrostatic elements used to match the beam characteristics to be accelerated then by the RFQ. It will also include one or several components that will allow variations of the beam intensity, either to adapt the instantaneous maximal intensity to the user needs, and/or to tune the time structure of the beam sent into the various experimental areas (for the so-called multi-user operation of the beam). Some beam time structure equipment such as the buncher will need a development phase. This LEBT will include a section connecting the already existing ion source Phoenix V3 (placed at the first SPIRAL2 injector and located in a contiguous cave) to this new injector, allowing operation of NEWGAIN with the Phoenix V3 source, before the SC source will be available.

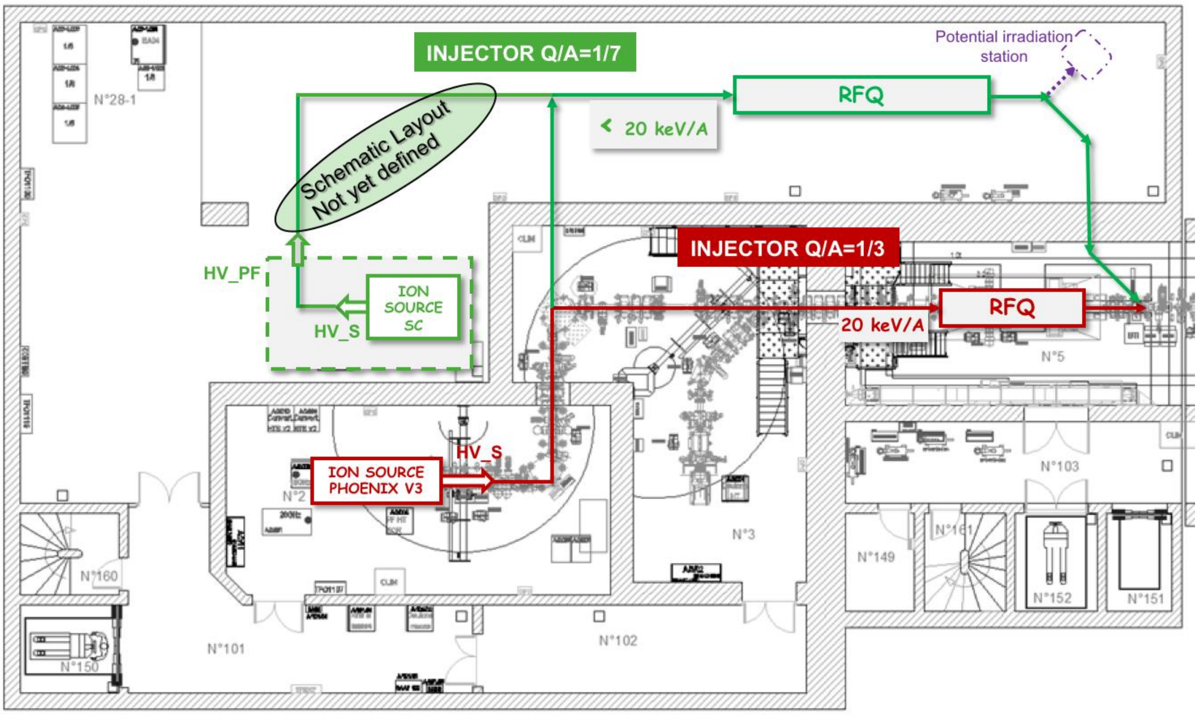

Figure 2: Schematic view of the NEWGAIN injector (green lines) including the planned connection of the existing Phoenix V3 ion source to the NEWGAIN RFQ.

- **The Radiofrequency Quadrupole (RFQ)** is the second major component of the injector. It will be able to accelerate high intensity heavy ion beams with very low beam losses (less than a few percent), which cannot be accelerated by the existing SPIRAL2 injector which was designed for light ion beams. This equipment has to be fully designed from scratch, and the technical solution chosen at the end of the preliminary design phase will be the best compromise between technical performances, manufacturing cost and electrical power consumption. This new RFQ will be the first of its type in France and in Europe, and it will allow SPIRAL2 to be the first facility worldwide having the capability to accelerate high intensity ion beams from protons to uranium.
- **The Medium Energy Beam Transport (MEBT)** section will connect the RFQ exit to the existing superconducting linear accelerator of the SPIRAL2 facility, and will ensure some beam characteristics tuning and time structure for the various user requirements (see REQUIREMENTS – DETECTION INSTRUMENTATION and REQUIREMENTS – PHYSICS). It will be equipped with standard magnetic elements and rebunchers used to match the beam characteristics to the LINAC entrance. This section will also host a new bunch selector system, required by some experiments which need to use

a different beam time structure. It will be designed in order to allow the commissioning and the future operation (pre-tuning) of the new injector in a completely independent way from the existing injector, a fundamental feature to maximize the experimental time for users in the future.

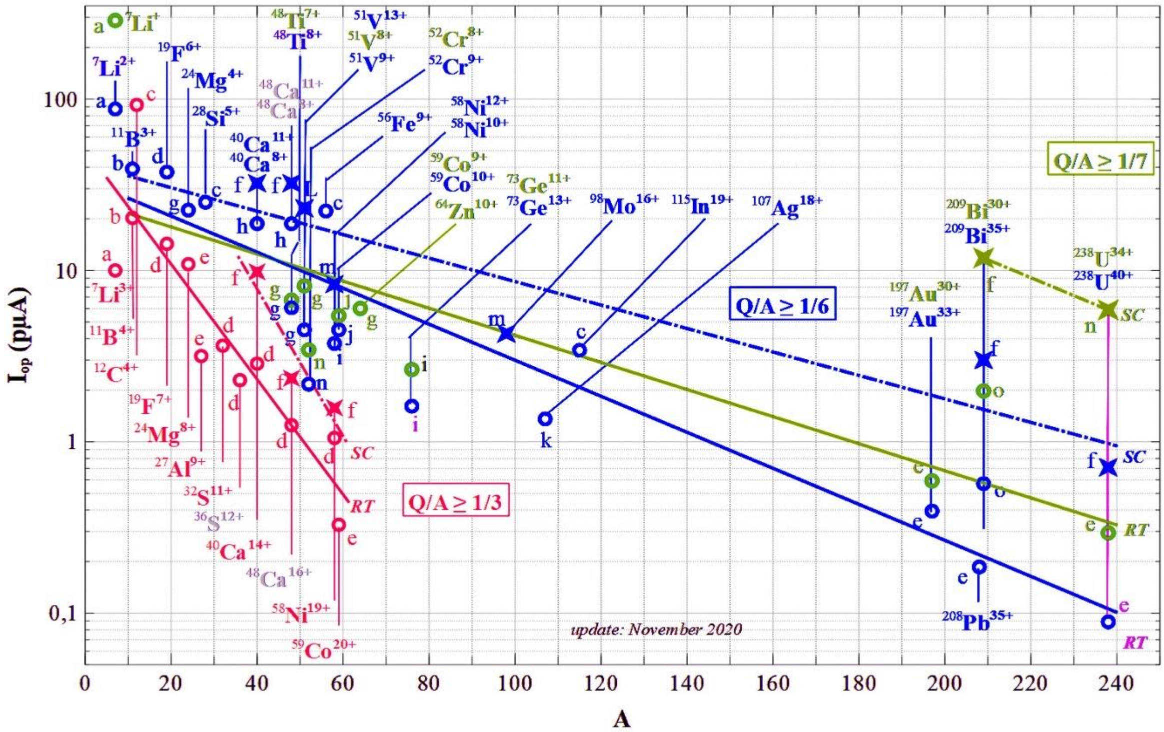

Figure 3: *(Courtesy of Ch. Barué, GANIL) Highest beam intensities obtained for metallic for Q/A=1/3, Q/A=1/6 and Q/A=1/7. The circles refer to room temperature (RT) ion sources and stars refer to superconducting (SC) ion sources. References are identified by a letter beside the dots:*

[a] R. Ernst, Nuclear Instruments and Methods in Physics Research A287 (1990) 337-340.

[b] H. Koivisto et al., Proceedings of the Workshop on the Production of Intense Beams of Highly charged ions, Catania (2000).
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H. Koivisto et al., Proceedings of 23rd ECRIS workshop (Catania 2018).
http://accelconf.web.cern.ch/AccelConf/ecris2018/papers/moa3.pdf
HIISI 18+14+8-14 GHz/16O6+ 1040 µA (74.3 pµA)/data in the report
HIISI 18+14+8-14 GHz/40Ar14+ 195 µA (13.9 pµA)/data in the report
HIISI 18+14+8-14 GHz/129Xe26+ 300 µA (11.5 pµA)/data in the report
H. Koivisto et al., to be published.
https://wiki.jyu.fi/display/ensar2/Meetings (V. Toivanen ENSAR2/MIDAS workshop at GANIL 2019)
HIISI 18+14+8-14 GHz/129Xe43+ 1 µA (0.023 pµA)/extrapolated from graph

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Permanent magnet Kel2 10 GHz/12C4+ 740 µA (185 pµA)/Gaz C2H2/spectrum in the report
A. Kitagawa et al., Proceedings of 19th ECRIS workshop (Grenoble 2010).
http://accelconf.web.cern.ch/AccelConf/ECRIS2010/papers/mocobk03.pdf
http://lpsc.in2p3.fr/Indico/getFile.py/access?resId=11&materialId=slides&confId=467
28Si5+ 250 µA (50 pµA)/MIVOC Si(CH3)4/data in the talk only
Source ?/56Fe9+ 400 µA (44.4 pµA)/MIVOC Fe(C5H5)2/data in the talk only
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Permanent magnet Kel2 10 GHz/115In19+ 130 µA (6.84 pµA)/MIVOC In(C5H5)/data in the talk

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PHOENIX-V2 18 GHz/19F7+ 200 µA (28.6 pµA)/Gaz SF6/not in the report (internal report GPI-2012 013)
PHOENIX-V2 18 GHz/32S11+ 80 µA (7.3 pµA)/32S12+ 55 µA (4.6 pµA)/Gaz SF6/data in the report
Phoenix V3, not yet published.
PHOENIX-V3 18GHz/40Ca14+ 80 µA (5.7 pµA)/40Ca16+ 40 µA (2.5 pµA)/resistive oven
PHOENIX-V3 18GHz/58Ni19+ 40 µA (2.1 pµA)/resistive oven

[e] Z.Q. Xie et al., Proceedings of the 13th ECRIS workshop (College Station 1997).
AECR-U 14+10 GHz/59Co20+ 13.1 µA (0.65 pµA)/resistive oven/data in the report
AECR-U 14+10 GHz/197Au33+ 26.0 µA (0.79 pµA)/197Au30+ 35.5 µA (1.18 pµA)/resistive oven/data in the report
AECR-U 14+10 GHz/209Bi35+ 20 µA (0.57 pµA)/209Bi31+ 29.3 (0.95 pµA)/resistive oven/data in the report
AECR-U 14+10 GHz/238U40+ 7 µA (0.18 pµA)/238U34+ 20 µA (0.59 pµA)/resistive oven/data in the report
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http://dx.doi.org/10.1063/1.1425781
AECR-U 14+10 GHz/24Mg8+ 174 µA (21.8 pµA)/resistive oven/data in the report
AECR-U 14+10 GHz/27Al9+ 57 µA (6.3 pµA)/resistive oven/data in the report

[f] H.W. Zhao et al., Proceedings of 18th ECRIS workshop (Chicago 2008)/paper not received.
SECRAL 18 GHz/40Ca16+ 75 µA (4.7 pµA)/Resistive oven?/data in the talk only
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SECRAL 18 GHz/58Ni19+ 60 µA (3.2 pµA)/Resistive oven?/data in the talk only]
L.T. Sun, Proceedings of 21st ECRIS workshop (Nizhny Novgorod 2014).
http://accelconf.web.cern.ch/AccelConf/ECRIS2014/papers/tuommh03.pdf
SECRAL 24+18 GHz/209Bi35+ 210 µA (6.0 pµA)/209Bi30+ 710 µA (23.7 pµA)/resistive oven/spectrum in the report
H.W. Zhao et al., Proceedings of the 17th ICIS (Geneva 2017), Rev. Sci. Instrum. 89, 052301 (2018).
http://dx.doi.org/10.1063/1.5017479
SECRAL 24+18 GHz/40Ca14+ 270 µA (19.3 pµA)/resistive oven?/data in the report
SECRAL 24+18 GHz/40Ca11+ 710 µA (64.5 pµA)/resistive oven?/data in the report
SECRAL II 28 GHz/16O6+ 6700 µA (1117 pµA)/data in the report
SECRAL II 28+18 GHz/40Ar14+ 1040 µA (74 pµA)/40Ar12+ 1420 µA (118 pµA)/ data in the report
SECRAL II 28+18+45 GHz/86Kr28+ 146 µA (5.2 pµA)/86Kr18+ 1020 µA (57 pµA)/data in the report
SECRAL II 28+18+45 GHz/129Xe43+ 10 µA (0.23 pµA)/129Xe26+ 1100 µA (42 pµA)/spectrum in the report
W. Lu et al., Proceedings of the 18th ICIS (Lanzhou 2019), to be published in Rev. Sci. Instrum.
SECRAL II 28 GHz/238U40+ 60 µA (1.5 pµA)/inductive oven

[g] R. Lang et al., Proceedings of 15th ECRIS workshop (Jyvaskyla 2002).
CAPRICE 14 GHz/26Mg5+ 140 µA (28 pµA)/resistive oven/data in the report
CAPRICE 14 GHz/51V9+ 115 µA (12.8 pµA)/51V8+ 160 µA (20.0 pµA)/resistive oven/spectrum in the report
CAPRICE 14 GHz/68Zn10+ 120 µA (12.0 pµA)/resistive oven ZnO/data in the report
K. Tinschert, Proceedings of 20th ECRIS workshop (Sydney 2012).
CAPRICE 14 GHz/48Ti8+ 97 µA (12.1 pµA)/resistive oven/spectrum in the report

[h] D. Hitz et al., Proceedings of the 12th ECRIS workshop (Riken 1995).
CAPRICE 14 GHz/40Ca8+ 300 µA (37.5 pµA)/resistive oven/data in the report

[i] C. Barué et al., Proceedings of the Workshop on the Production of Intense Beams of Highly charged ions, Catania (2000).
ECR4M 14 GHz/58Ni10++ 75 µA (7.5 pµA)/MIVOC Ni(C5H5)2/spectrum in the report
P. Lehérissier et al., Nuclear Instrum. and Methods B211 (2003).
http://www.sciencedirect.com/science/article/pii/S0168583X03012138
ECR4 14 GHz/76Ge13+ 45 µA (3.5 pµA)/oven and then recycling with SF6/spectrum in the report

[j] S.L. Bogomolov, Physics of Particles and Nuclei Letters, Vol. 12, n°7 (2015).
https://www.researchgate.net/publication/286522922
see update of this article https://aip.scitation.org/doi/10.1063/1.5128172
ECR4M 14GHz?/59Co10+ 90 µA (9.0 pµA)/MIVOC/spectrum in the report

BEAM PRODUCTION AND TARGETS

BEAM/SOURCE

INTRODUCTION ON HIGHEST INTENSITY STABLE HI BEAMS

Intense beams of ^{48}Ca paved the way for the synthesis of the heaviest known elements and enabled their discovery: moscovium (Mc, Z = 115), tennessine (Ts, Z = 117) and oganesson (Og, Z = 118) validated recently. They also opened a wide range of spectroscopic studies at the shores of the region of SHE nuclei, with its archetype ^{254}No or with ^{257}Db studied recently at GANIL. Intensities up to 0.6 to 1.5 pμA (= 9×10^{12} pps) of ^{48}Ca and ^{50}Ti on target can be maintained over rather long operating times in several world leading laboratories. The study of heavier nuclei needs a significant increase in the available intensities to compensate the drastic decrease of reaction cross sections in the heavy element region. Due to low cross sections at the limit of stability, the study of nuclei with identical proton and neutron number in the region around the doubly magic nucleus ^{100}Sn (N=Z physics near ^{100}Sn) also requires highest possible beam intensities, typically for more neutron-deficient projectiles with A ≈ 40 to 60.

Intense beams of medium mass to heavy ions like ^{50}Ti, ^{51}V, ^{54}Cr, the work horses for the near-future SHN/SHE structure studies and synthesis, more neutron-deficient isotopes for N=Z research and the heaviest species like Pb, Bi and U are mandatory to achieve the outstanding physics program foreseen with the Super Separator Spectrometer (S^3) at GANIL and for the preparation of the presently discussed future facilities (see TOPIC: FUTURE FACILITIES). The existing heavy-ion source constructed SPIRAL 2 which is limited to A/Q=3, is not optimal for these heavy beams. Moreover, it does not allow the use of Metal Ions from Volatile Compounds (MIVOC) method. The carbon content of the organic compounds that bring the metal into the ECR plasma generates a parasitic beam of substantial intensity, forbidding the use of this versatile and low-consumption method. High temperature oven developments are being performed both at GANIL with a resistive oven operating at 2000°C, and at IPHC with an inductive oven foreseen to operate up to 2500°C. These ovens will be compatible with the NEWGAIN ion source feeding its plasma with enriched metallic material. This should lead to the 10 pμA needed on target in the near future at GANIL.

COMPARISON WITH WORLD-LEADING INFRASTRUCTURES

Since the earliest times of the LINAC project of SPIRAL2 the option of an RFQ injector with a maximum mass to charge-state ratio of A/Q 6 or 7 was considered, in order to gain access to highest-possible intensity beams for accelerated ions up to uranium. The existing injector limits the possible beams to masses below 40 to 50, and it provides a moderate intensity increase with respect to state-of-art heavy ion accelerators worldwide. With the present project, the gain in intensity with respect to an injector with A/Q=3 is of the order of 5 to 6. This would place the SPIRAL2 facility at a world class level competing effectively with the leader in the field, the SHE Factory of the Flerov Laboratory of Nuclear Reactions/Joint Institute for Nuclear Research (FLNR/JINR) in Dubna, Russia, that started operation in fall 2020.

A comparison of the maximum design beam intensities of the SPIRAL2 LINAC for A/Q=3 to 7 with the world-wide competing facilities is given for some key ion species in ***Table 1***. The intensities provided by the NEWGAIN project combined with the S^3 capabilities, such as the high transmission and the mass identification (ΔM/M < 1/350), will make SPIRAL2 a unique facility for the study of SHE nuclei. (See TOPIC: SHE RESEARCH)

For the study of N=Z nuclei around ^{100}Sn, the beam intensities delivered by the NEWGAIN project will allow the study of nuclei beyond the N=Z symmetry line, providing access to the proton drip-line. The combination of the highest possible intensities provided by NEWGAIN with the detection capabilities of S^3, in particular, S^3-LEB and DESIR will enable the study of specific phenomena, present in the region around ^{100}Sn. To produce the nuclei of interest the most important projectiles are mass 40-60 ions such as ^{40}Ca, ^{50}Cr and ^{58}Ni with the heavier ones profiting from the implementation the NEWGAIN project (see e.g. ^{58}Ni in ***Table 1***). The beam intensities delivered will being highly competitive around the ^{100}Sn region with those from from the final phase of the next generation RIB facility FRIB. E.g. for the flagship nucleus ^{100}Sn SPIRAL2/NEWGAIN could deliver ~30 s^{-1} for S^3 LEB measurements, while FRIB will reach ≈3 s^{-1}. For for the lighter Z=45 nuclide ^{90}Rh for which ~1000 s^{-1} will be available for S^3 LEB measurements compare with ≈70 s^{-1} at FRIB. (See TOPIC: STRUCTURE OF N=Z NUCLEI)

The NEWGAIN project will also give access to world best intensities for the heaviest beams, in particular, for uranium projectiles which are expected to become available with 10 times higher intensities as compared to other facilities (see ***Table 1***). This will enable production of numerous new SHE isotopes by means of multinucleon transfer reactions. The SPIRAL2 physics community is presently developing a new physics program for those beams at LINAC energies studying production schemes for radioactive species on the basis of reaction mechanisms such as fusion-fission and deep-inelastic reactions (see TOPIC: DEEP INELESTIC COLLISIONS/MULTI NUCLEON TRANSFER STUDIES).

PRODUCTION METHODS

HIGH TEMPERATURE OVENS

Titanium and uranium metals or oxides have a very high boiling point. It is therefore very difficult to inject them in an ECR plasma in order to generate intense metallic ion beams. A resistive oven faces the problem of large Laplace forces due to the usage of high current in the ECR high magnetic field. In the last 5 years, several laboratories worldwide initiated the development of an innovative dedicated high temperature ovens. The GANIL new high temperature oven successfully uses a current collinear to the magnetic field axis to limit mechanical constraints. This oven was tested in 2020 in an existing ECR source and was operated continuously several weeks at 2000°C.

IPHC Strasbourg initiated the development of an inductive micro-oven. It is based on the inductive oven developments done in collaboration with JYFL (University of Jyväskylä, Department of Physics) 10 years ago. It is designed to operate up to 2500°C. The demonstrator phase proved the concept in 2020 and a prototype is being prepared in order to be tested in GANIL ECR ion sources in 2021.

MIVOC

The method based on Metallic Ions produced by means of Volatile Organic Compounds (MIVOC) was initiated by Matti Nurmia at JYFL. MIVOC is a versatile method enabling quite intense beams with rather low material consumption. A revival of this method was implemented by IPHC with the development of isotopic beams of ^{50}Ti and ^{54}Cr used in several laboratories worldwide. Nowadays, it appears that these ^{50}Ti, ^{51}V and ^{54}Cr MIVOC developments represent the best approach to produce new superheavy elements. In the framework of NEWGAIN the ECR ion source will again be compatible with the MIVOC method for some of these strategic beams, enabling many spectroscopic studies of SHE at GANIL with S^3.

TIMELINE

There is a historical strong collaboration between IN2P3 laboratories, JINR Dubna and JYFL around these developments that finds a natural continuation in the NEWGAIN project. Both the high temperature and MIVOC methods will be ready for use within the timeframe of the NEWGAIN ion source development project. The different solutions will be tested at GANIL with the local ion sources experts. This will enlarge the panel of available beam production methods. During the exploitation phase, the most efficient production method will be chosen beam per beam.

TARGETS

GENERAL INTRODUCTION

To meet the demands of various applications in nuclear physics, targets with high quality are a major ingredient for the success of experiments. The quality resides in the intrinsic characteristics of the targets: thickness, homogeneity, purity and geometry but also in their capacity to withstand intense irradiation as provided by NEWGAIN project.

With the unprecedented high intensity beams expected from the NEWGAIN injector coupled to the SPIRAL2 LINAC, , their large heat deposit will induce a major increase of radiation damage, i.e. a weakening of the material by modification of the solid lattice. The consequent limited lifetime of the targets could become the principal impediment to the realization of experiments. In order to keep the structural integrity of the target, the dissipation of the high power deposited into them by the primary beam is a major challenge. Although target stations are designed for targets to sustain such intensities (more than 10 pμA at S^3 – see ***Table 1***) in terms of heating, up-to-date development on target preparation can be envisaged with the potential to go beyond present technologies.

GENERAL REQUIREMENTS

INTRINSIC PARAMETERS OF TARGETS

Below are a few examples of the conditions that targets have to fulfill in the case of superheavy element research at S^3 which can also be applied to other physics cases: considering the following specifications:

- Thickness, over a surface of few cm^2, should be around 400 µg/cm^2
- Inhomogeneity not exceeding 7% at FWHM
- High chemical and isotopical purity
- In the case of radioactive material, given the limited amount of the isotopically purified material, the fabrication technique yield needs to be nearly 100% and recovery of used target material must be possible in case of target failure during irradiation with intense beams.

→ For each physics case, the intrinsic target parameters with their tolerances have to be specified: thickness, homogeneity over the surface, chemical and isotopic purity, tolerated contaminants, restrictions on backings.

These parameters will help in choosing the ideal target fabrication technique which should use limited material efficiently and substrates that do not interfere with detecting the decay events of reaction products. The techniques should also allow production of targets or target segments in case of a target-wheel configuration with reproducible characteristics and long-term stability, and enable remote operation.

In parallel to the target preparation, one has to consider the effects that induce a limited lifetime of the material under intense irradiation. A suited design of the target installation (wheel, beam wobbler, control features of the beam spot dimensions etc.) is mandatory optimize the target performance. The distructive effects have various origins: thermal, mechanical, radiation.

→ For each physics case, the beam characteristics, i.e. energy, intensity and spot size have to be specified

Coupled to the target parameters, one can estimate the radiation damage and temperature and then design a system according to the technological limits. Inputs in thermal calculations are the deposited power and the thermodynamic properties of the material (emissivity, thermal conductivity, specific heat, fusion and boiling temperature)

THIN SOLID TARGETS FOR NUCLEAR PHYSICS EXPERIMENTS

Thanks to the S^3 spectrometer, the observation of very exotic nuclei in the SHE region (Z>104, SHE) or at the drip line will become possible. Such nuclei are produced by fusion-evaporation reaction of heavy ions at the Coulomb barrier using thin (≈300 µg/cm² up to few mg/cm²) isotopically enriched targets, made either of stable material (Pb, Bi, Ni, …) or of actinides (Cm, Pu, Am….).

In a vacuum spectrometer, such as S^3, an additional solid thin carbon foil (thickness: few tens of µg/cm²) placed a few centimeters downstream of the targets, aims at equilibrating the charge state of the produced nucleus.

STABLE TARGETS

Techniques for fabrication of stable targets are rather well known (thermal evaporation, rolling, deposition, sputtering …) and can be optimized case by case. According to the material and required thickness, targets are either self-supporting or deposited on a backing.

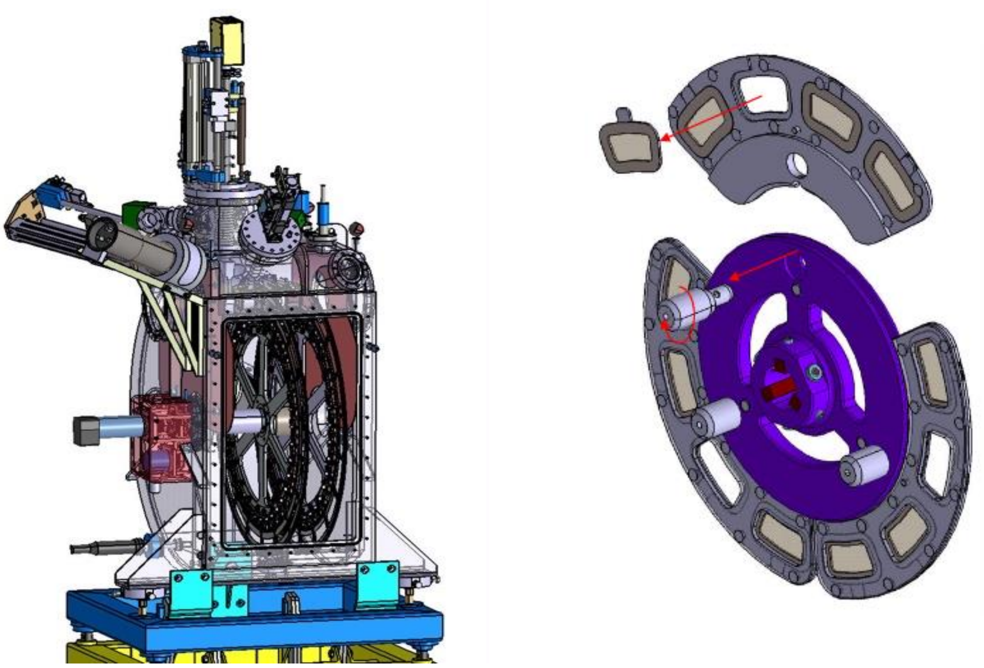

Figure 4: *Left panel: S^3 stable target station. Right Panel: S^3 prototype actinide wheel. (Details see text).*

ACTINIDE TARGETS

Actinide targets are essential for SHE or fission and nuclear data studies. Nevertheless, due to their scarcity and radiochemical constraints, efficient methods of production and specific, dedicated facilities are needed to manufacture them. Currently, the most widely applied process for the production of thin actinide layers is molecular plating [K. Eberhardt et al, NIM A 521 (2004) 208]. This method is known to quickly produce deposits of acceptable uniformity and adherence with rather high yields. But this method requires “thick and conductive” backings, limiting their choice.

- To pursue this common production method, radiochemists at IJCLab conduct detailed studies on the deposition mechanism, coupled with precise characterization of the layers at each step of the process.
- We propose also to reduce the thickness of the backing and to study of alternative material to limit the heating of the target and to favor the adhesion of the layers.
- A novel method, called Drop-on-Demand (DoD) inkjet printing technique [R. Hass et al, NIM A 874 (2017) 43], has been developed recently. It enables the production of targets of varying size and geometry on different substrates.

Another efficient and novel approach was conducted at Dubna in collaboration with PSI considering intermetallic targets [I. Usoltev et al, NIM B 318 (2014) 297].

The continuation of the latter studies in collaboration with our international colleagues are of high interest for our community.

***Table 2:** Parameters of two test cases, ^{48}Ca+^{238}U and ^{70}Zn+^{209}Bi.*

Case 1: ^{48}Ca on sandwich target Ti - ^{238}U - C			E [MeV]	P [W]
beam (I = 10 pμA)	^{48}Ca	5 MeV/A	240	2400
			ΔE [MeV]	ΔP[W]
target wheel components (sandwich)	Ti	2 μm	12.24	122.4
	^{238}U	0.15 μm	2.12	21.3
	C	0.05 μm	0.20	2.0
	total power deposit			**145.7**
Case 2: ^{70}Zn on sandwich target C - ^{209}Bi - C			E [MeV]	P [W]
beam (I = 10 pμA)	^{70}Zn	5 MeV/A	350	3500
			ΔE [MeV]	ΔP[W]
target wheel components (sandwich)	C	0.13 μm	1.03	10.3
	^{209}Bi	0.46 μm	6.06	60.6
	C	0.05 μm	0.35	3.5
	total power deposit			**74.4**

IRRADIATION STATIONS

For solid targets, rotating systems are often considered in order to profit from the cooling by radiation over a large surface. The surface (diameter of the wheels) is estimated according to the melting point of the considered material. The rotation speed is estimated according to the acceptable gradient of temperature between the beam impact and cooling by rotation.

In the case of S^3, for stable targets, metallic bismuth as one of the materials with lowest melting point irradiated by a 10 pμA ^{70}Zn (5 MeV/A) beam, is the limit case for which a rotating wheel of 67 cm diameter and 3000 rpm was designed [M. Michel, *Tenue thermique cibles stables S3.* S3-NT-8514-I035728V2.0 (2014)]. It is presently being commissioned at GANIL (see

Figure 4, left panel).

For actinide targets, a prototype actinide target station (see ***Figure 4***, right panel, for the actinide target wheel) was used for material irradiation and for commissioning the diagnostic systems (electron gun, scattered particle detectors…). As melting points of actinides are high (> 1000 °), for a beam of 48Ca @ 10 pµA, the wheel was designed with a diameter of 15 cm and a rotation velocity of 5000 rpm [F. Pellemoine, Technical Report On thermal calculation for S3 target. (2008)]. For each system (projectile @10 pµA/target) the total power loss is given in ***Table 2***

Figure 4 together with the details of the two example cases. The maximum acceptable power loss values 145.7 W for the uranium and 74.4 W for the bismuth target were established on the basis of the material melting points and to guarantee a limited temperature difference for the heating/cooling cycle which is important to avoid destructive thermal stress of the target foils.

→ With rotating targets, a time structure of the beam has to be considered to prevent irradiation of frames.

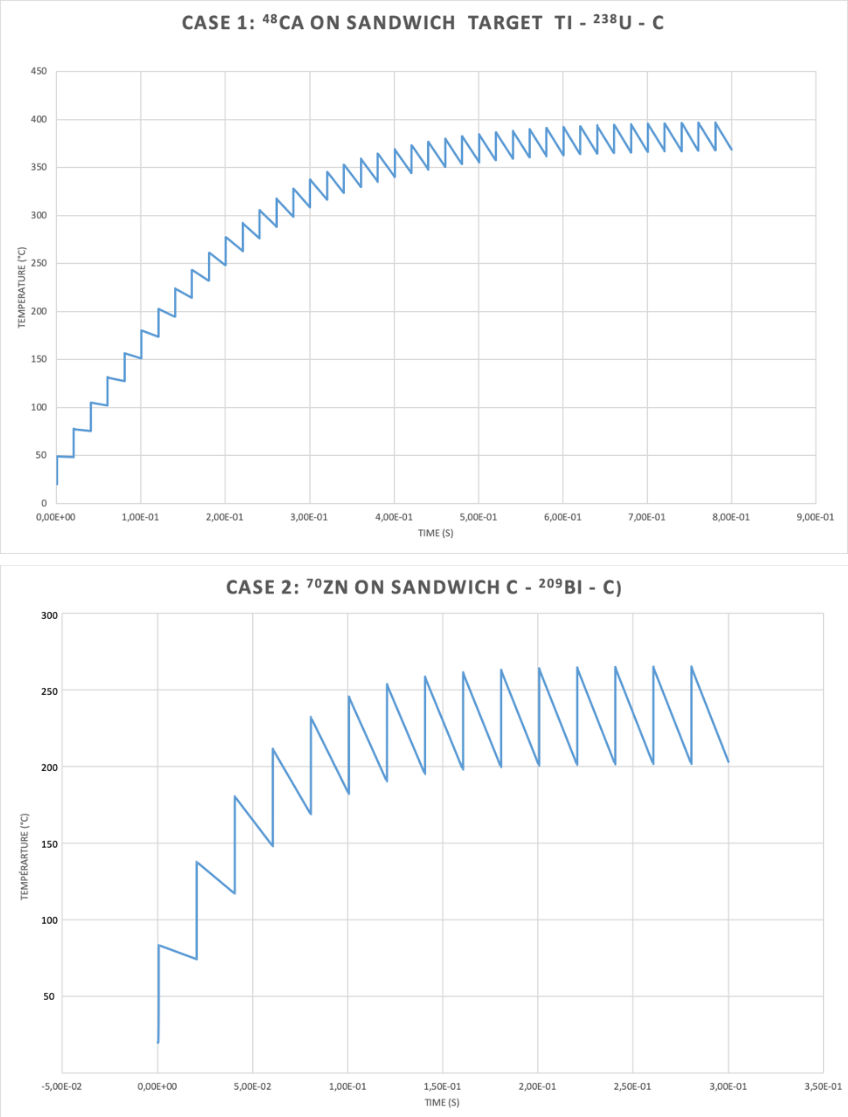

***Figure 5**: Temperature vs time, simulated for ^{48}Ca on a Ti-^{238}U-C (upper panel) sandwich target and a ^{70}Zn on a C-^{209}Bi-C sandwich (lower panel). For both cases the beam profile is assumed to be Gaussian with widths of σ = 0.5 mm in x and 2.5 mm in y direction. A wheel diameter of 670 mm and a rotation frequency of 3000 rpm were chosen for both cases.*

In ***Figure 6*** maximum beam currents and energy loss calculations are shown for two example cases of target wheel configurations for the whole projectile mass range up to A=238 for uranium. For the case of stable material, a bismuth target foil sandwiched in between a carbon backing and a carbon cover layer was chosen as one of the materials with lowest melting point (see above). Thicknesses for these calculations were the same as given in ***Table 2*** with 0.133 μm for the carbon backing, 0.46 μm for the ^{209}Bi target and 0.044 μm for the carbon cover, mounted on a wheel with the same diameter of 67 cm as used for the calculations in ***Figure 5***. For the limit power loss of ΔP=74.5 W, maximum beam intensities of 15 pμA for ^{48}Ca @5 MeV/A and 10 pμA for ^{70}Zn @ 5 MeV/A are obtained. Even for uranium projectiles intensities of >2 pμA can be sustained by targets of this kind. The situation could be improved substantially by using instead of the metallic bismuth, with a melting point of 271°C, the higher melting point material $^{209}Bi_2O_3$ with T_{fus}=817°C, as it is done in standard irradiations in the field of SHE/SHN research.

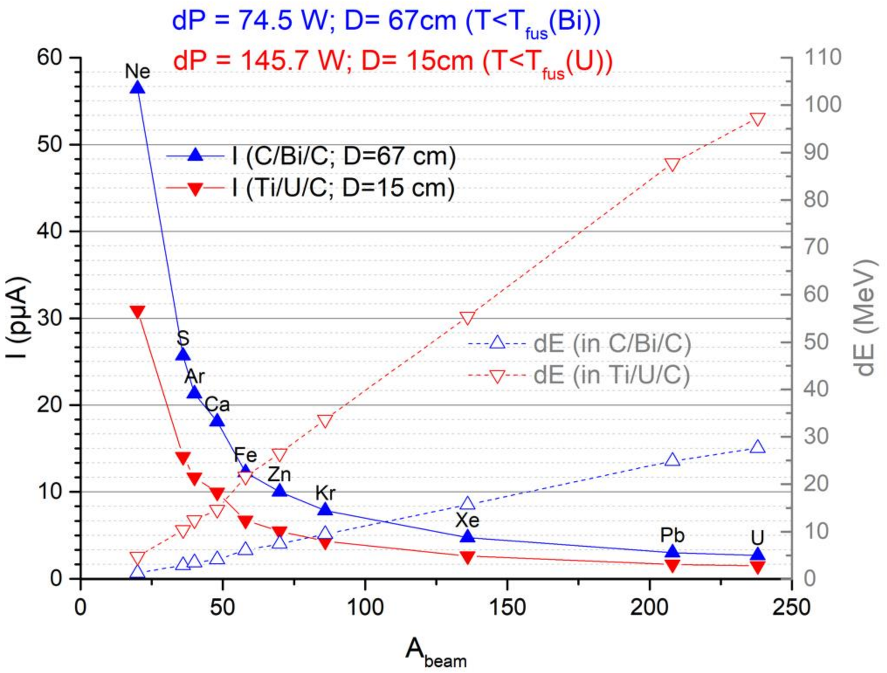

Figure 6: *Beam intensity and energy loss calculations for a projectile range from lowest masses A up to 238 for uranium projectiles, for the two sandwich-target wheel configurations consisting of the layers carbon-bismuth-carbon and titanium-uranium-carbon, respectively. The wheel diameters were D=670 mm for the bismuth and D=150 mm for the uranium target.*

As a demonstration case for actinide targets the same calculations have been performed for a titanium-^{238}U-carbon sandwich on a wheel with 15 cm diameter with thicknesses of 2 μm, 0.15 μm and 0.05 μm, respectively. The power loss limit for the higher melting point material was taken as ΔP=145.7 W. Under these conditions, the calculations in, right panel, show that for projectiles like ^{48}Ca and ^{70}Zn maximum beam intensities of 10 pμA and 5 pμA, respectively, can be reached. New target production techniques like e.g. the drop-on-demand method as developed by K. Eberhart et al. from the Johannes Gutenberg-University of Mainz, Germany, (see ACTINIDE TARGETS) can allow replacing the thick titanium backing required by classic electro-plating by thinner material, reducing the power deposit in the target material substantially.

For S^3, because of the thin material, cooling by radiation is considered only. In addition, cooling by conduction and by convection (for vacuum spectrometer for instance) can be envisaged. Cooling by radiation is more effective with material of higher emissivity, carbon layers at each side of the target are an ideal solution to be used for stable material. Cooling by conduction is often implemented for thicker targets in contact with higher conducting material such as copper cooled by water circulation. Cooling by convection was tested at GSI, SHIP [S. Antalic et al, NIM A 530 (2004) 185] employing stationary He-gas as well as He-gas flow. It helps in accepting higher beam intensity up to a factor of 10 depending on the applied gas pressure.

In and around the target stations some systems are implemented to monitor the target behavior under irradiation. Some are described in [J. Kallunkathariyil et al, AIP Conf. Proc. 1962 (2018) 030002; Ch. Stodel et al, Jour. Rad. Nucl. Chem. 305 (2015) 761; Ch. Stodel Eur. Phys. Jour. Web Conf. 229 (2020) 02001].

RADIATION DAMAGE AND SPUTTERING

The surface structure of irradiated targets will be affected by radiation damage and sputtering of material, while spectrometer requirements often request homogeneous spatial properties for sufficiently well-defined kinematic properties of particles passing the material.

Concerning radiation damage, high electronic excitations in radiation of metallic targets with swift heavy ion beams at the Coulomb barrier play a dominant role in the damaging processes of some metals. The thermal spike model, applied to some projectile-target combinations [Ch. Stodel et al, EPJ Web Conf. 229 (2020) 05001] (and references therein) allows to understand that some metallic targets were deformed due to a fast and local temperature increase while others were unaffected. The model enables to predict reliably the sensitivity of targets to the electronic slowing down of heavy ions by considering fundamental parameters such as the energy loss and the electron-phonon coupling factor determined by some experimental studies of sputtering yields. Estimations employing this model prior to experiments will help to adjust some parameters, i.e. beam energy, target material form and surface of irradiation, to prevent the damages.

Concerning the loss of material, calculations on the emission rate of target atoms by elastic diffusion and atomic plus nuclear sputtering were performed using LISE and SRIM codes for a fusion-evaporation reaction (^{48}Ca + ^{248}Cm). These estimations were compared to experimental data reported in [S. Hofmann et al, Eur. Phys. Jour. A 48 (2012) 62]. By measuring the activity of ^{248}Cm in the carbon foil equilibration charge state, we can deduce the ratio of ejected atoms per incident ion: at_{ej}/ion_{inc} = 1.6% and the rate for an initial thickness normalized to the number of incident ions of 10^{18}: at_{ej}/at_{ini} (@10^{18} incident) = 0,061%. These experimental results agree with simulations and were extrapolated for a LINAC beam (10 pμA; 10 days: ion_{inc} (^{48}Ca) = 5.4*10^{19} ions) and a target of larger surface (30,2 cm^2, m_{ini} (^{248}Cm) = 14 mg). The number of ^{248}Cm atoms collected on the stripper is then at_{ej} = 7,9*10^{17}, and the sputtering ratio is at_{ej}/at_{ini} (@5.4*10^{19} incident) = 2.5 %. In conclusion, with a material loss of only 2.5 % after an irradiation time of 10 days, long-term experiments with irradiation times of weeks or months are feasible with a limited number of interventions for target change. Moreover, this figure for the loss of radioactive material is an important input to establish the necessary safety procedures, in accordance with the safety authorities.

CONCLUSION

The developments, in terms of target fabrication and irradiation station, associated to each of the cases described above are different and have to be evaluated one by one.

Research and development to improve target production are major issues and substantial in-beam testing time is mandatory. There is a need to develop new methods of fabrication techniques, and search for alternative solutions compared to the present ones. In particular, a fully equipped target laboratory infrastructure is essential for an accelerator institution like GANIL/SPIRAL2 to efficiently sustain the experimental program envisaged at SPIRAL2 with S^3, NFS and DESIR.

REQUIREMENTS – DETECTION INSTRUMENTATION

TOPIC: S^3

TECHNOLOGY AND SCIENCE INTRODUCTION

Exotic nuclear structure features at the edges of nuclear stability for extremely proton rich nuclei with similar to equal proton and neutron numbers (N=Z) and SHE with the highest atomic numbers are often characterized by rare events and extremely low production probabilities. Their exotic nuclear structure features are at the heart of the scientific program at S^3. The unique combination of high beam intensities, in particular for masses around and beyond A=50 provided by the SPIRAL2 LINAC, equipped with the NEWGAIN injector, with the separation/spectrometry capabilities and high efficiency of S^3 are essential for this ambitious research program. Further details regarding the science to be pursued at S^3 are discussed in section REQUIREMENTS – PHYSICS, and various subsections in there like TOPIC: SHE RESEARCH, TOPIC: STRUCTURE OF N=Z NUCLEI and TOPIC: LOW ENERGY PHYSICS @ S3LEB AND DESIR.

S^3 DETECTION I: SIRIUS

SIRIUS [N. Karkour et al., *IEEE Nuclear Science Symposium, Medical Imaging Conference and Room-Temperature Semiconductor Detector Workshop (NSS/MIC/RTSD)* (2016) 1] is designed to study the decay of rare isotopes produced in fusion-evaporation reactions, selected and identified in the focal plane of S^3. It will establish the nuclear mass of the reaction products by measuring the position at the focal plane of S^3 being operated in dispersive mode, by means of a double-sided silicon strip detector (DSSD). After implantation, energy, time and position of subsequent decays will be measured with resolutions that allow clean identification of extremely rare events. Completed with a silicon detector array, forming a box- or tunnel-like geometry upstream from the DSSD, and surrounded by a set of high-purity germanium detectors in close geometry, the set-up will provide highly efficient photon and particle detection. This will allow detailed α, γ, conversion-electron and spontaneous fission spectroscopy for the investigation of exotic nuclei up to the heaviest ones accessible in fusion-evaporation reactions [D. Ackermann and Ch. Theisen, Phys. Scr. 92 (2017) 083002]. Thanks to digital electronics, the array is capable of separating short decays, with life-times of the order of $\leq 1\mu$s, and sustaining the high rates made available by NEWGAIN.

S^3 DETECTION II: LOW ENERGY BRANCH (S^3-LEB)

S^3-LEB is an installation designed to study radioactive isotopes by low-energy experimental techniques. The fusion-evaporation recoils of S^3 will be stopped in a gas cell filled with Ar or He and neutralized, then extracted in a supersonic gas jet. A state-of-the-art laser system will allow resonantly ionizing the species of interest in the supersonic jet and performing laser spectroscopy with a spectral resolution of a few 100 MHz. A proof of principle of in-jet laser spectroscopy has been performed at the LISOL facility in Louvain-la-Neuve [R. Ferrer et al., Nature Comm. 8,14520 (2017)]. The ions produced by laser ionization will be transported through a system of RFQs to a detection area combining a mass spectrometer called PILGRIM and an alpha/conversion-electron/γ-ray detection station called SEASON. The two stations will be used either for counting the number of ions as a function of laser frequency, or directly in order to perform mass measurements and decay spectroscopy. In addition, a transport line will allow delivering the laser ions to DESIR, where a number of high-resolution measurement techniques will be available for dedicated experiments. In this sense, the LEB will act as an experimental installation and as a radioactive-ion source for DESIR, the combination of neutralization and superior spectral resolution allowing it to deliver isomerically pure beams.

As a new development to enhance radioactive ion stopping, extraction and neutralization in the S^3-LEB gas catchers is foreseen with the aim to extend nuclear-structure studies by laser spectroscopy on short-lived isotopes (new ANR project: FRIENDS3). In a later stage of S^3-LEB, a fast and universal gas cell will be installed, allowing to directly extract radioactive species without requirement of laser ionization. It will allow to extract all the chemical elements and isotopes with shorter lifetimes, in the order of 10 to 20 milliseconds. An ANR proposal (FUGACE : Fast and Universal GAs CEll) has been submitted in 2021 proposing to develop a cryogenic gas cell able to reach an efficiency above 70%. The ions will then be transported to DESIR and purified by the available mass separators (see also following topic).

Apart from these two detection set-ups, additional complementary installations are envisaged at S^3 like the FISIC program aiming at atomic physics studies (see TOPIC: ATOMIC PHYSICS (FISIC @ S3)).

BEAM REQUIREMENTS

The beam requirements are governed by low cross sections demanding high intensities of ions including mass regions which cannot be served efficiently by the existing A/q = 3 injector.

For the ions of interest for S^3 refer to the lists given for the various physics topics in Requirements – Physics.

SPECIAL REQUIREMENTS

- Horizontal (X) beam spot size: 0,5 mm < RMS(X) < 1 mm.
- Vertical (Y) beam spot size: 1 mm < RMS(Y) < 2,5 mm.
- Horizontal position (X) stability (center of gravity): 0,25 mm.
- Vertical position (Y) stability (center of gravity): 0,25 mm.
- The beam size on target should be adjustable between 0.5mm ≤ RMS(X) ≤ 2.5mm and 1mm ≤ RMS(y) ≤ 2.5mm.
- Energy stability and dispersion <0,1%(RMS).
- Intensity stability: maximum intensity should not exceed the average intensity by more than 10%, $I_{max} < I_{ave}+10\%$

.

More details will be discussed in the respective subsections of section **REQUIREMENTS – PHYSICS**.

TOPIC: DESIR

TECHNOLOGY AND SCIENCE INTRODUCTION

DESIR (Désintégration, Excitation et Stockage des Ions Radioactifs = Decay, excitation and storage of radioactive isotopes) is presently in its final design study, and construction is scheduled to start before the middle of 2022. It is destined to become GANIL’s low-energy ISOL facility with the start of its radioactive beam program in 2026.

Research at DESIR will include radioactive decay studies, laser spectroscopy and experiments with different trapping devices, allowing high-precision measurements to be performed with ultra-pure samples. The experimental program at DESIR will tackle questions concerning the structure of atomic nuclei, questions linked to the nucleosynthesis and the energy production in different stellar environments, and to the nature of fundamental interactions. The DESIR research program will also include interdisciplinary research.

Envisaged experimental studies request basically all nuclei of the Segré chart of radioactive isotopes. While light species (up to mass A=40 or 50) are efficiently produced by fragmentation reactions with SPIRAL1, heavier nuclei and, in particular, nuclei from refractory elements, which are not available from SPIRAL1, will be produced by S^3 and its low-energy branch LEB. The main reaction type to be used will be fusion-evaporation reactions for the production of proton-rich, heavy and super-heavy nuclei. But deep inelastic or multi-nucleon transfer reactions can also serve for the production of moderately neutron-rich isotopes.

Further details regarding the science to be pursued at DESIR are discussed in section REQUIREMENTS – PHYSICS and subsection TOPIC: LOW ENERGY PHYSICS @ S3LEB AND DESIR.

BEAM REQUIREMENTS

DESIR has no specific beam requirements from LINAC, except general requirements, which apply to all S^3-LEB experiments. A fast and efficient preparation of the exotic beams is essential for DESIR, as most experiments deal with short-lived isotopes produced in limited amounts.

List of projectiles of interest:

$^{16,18}O$, ^{20}Ne, ^{24}Mg, ^{28}Si, $^{32,36}S$, $^{36,40}Ar$, $^{40,48}Ca$, $^{46,50}Ti$, $^{50,54}Cr$, ^{54}Fe, ^{58}Ni, $^{64,66}Zn$, ^{78}Kr

TOPIC: NFS

TECHNOLOGY AND SCIENCE INTRODUCTION

Apart from the main working horse, the neutron, the use of ions is also envisaged at the NFS facility. Neutron production features in heavy ion induced reactions (yield and energy distributions) are poorly known (and sometimes never measured). They are key parameters for radioprotection purposes. The NFS characteristics allow very precise measurements of the yield and energy distribution of neutrons emitted at 0 degrees, if the incident beam has a dedicated time structure: beam burst duration of the order of 1 ns with a beam frequency lower than 500 kHz. The implementation of adequate beam tuning instrumentation within the NEWGAIN project would make such studies possible.

NFS IN PARALLEL OPERATION

80% of the proposed NFS experiments use the neutron time-of-flight facility. In this kind of experiments, 1% of the beam intensity is used to avoid burst overlaps for time-of-flight measurements. This means that 99% of the machine time is lost, when the beam is sent onto the beam dump. A pulsed operation of a second injector and of the SPIRAL2 LINAC with an effective pulse selection will allow the parallel operation of the applied science and research program at NFS with minimal impact on experiments at S^3 and DESIR. The use of two injectors in parallel, in a typical scenario where the A/q=3 injector is serving NFS while the NEWGAIN injector is serving S^3/DESIR, would provide a free choice of beam species, energies and intensities. This is an option presently being discussed which needs, however, modifications of the LINAC which are not part of the NEWGAIN project.

TOPIC: SHE RESEARCH

SCIENCE INTRODUCTION

When the liquid drop fission barrier vanishes in the fermium-rutherfordium region only the stabilization by quantum mechanics effects allows the existence of the observed heavier species. Those in turn provide an ideal laboratory to study the strong nuclear interaction by in-beam methods as well as decay spectroscopy after separation [D. Ackermann and Ch. Theisen, Phys. Scripta 92 (2017) 083002].

Theoretical predictions of a so-called "island of stability of superheavy elements (SHE)" for the next proton and neutron shell closures beyond ^{208}Pb, the first dating back to more than half a century, initiated worldwide efforts towards ever refined experimental techniques aiming at ever higher sensitivities pushing the limits to ever lower cross sections. These efforts, which were rewarded by the synthesis of the heaviest nuclei up to ^{294}Og with Z=118 and N=176, remain however still short by few neutrons and possibly protons to set foot onto the island of shell-stabilized nuclei suggested by various models at Z =114, 120 or 126 and N=184 [Y.T. Oganessian, A. Sobiczewski, and G.M. Ter-Akopian, Phys. Scr. 92 (2017) 023003]. The key ingredient for further progress and eventual success, apart from optimized detection efficiency, is highest-achievable beam intensity which is pursued world-wide by accelerator projects aiming at this goal. The cross-section level reached (see ***Figure 7***) is typically in the pbarn range, resulting with state-of the art performance of existing instrumentation in an average event rate of 1 per week.

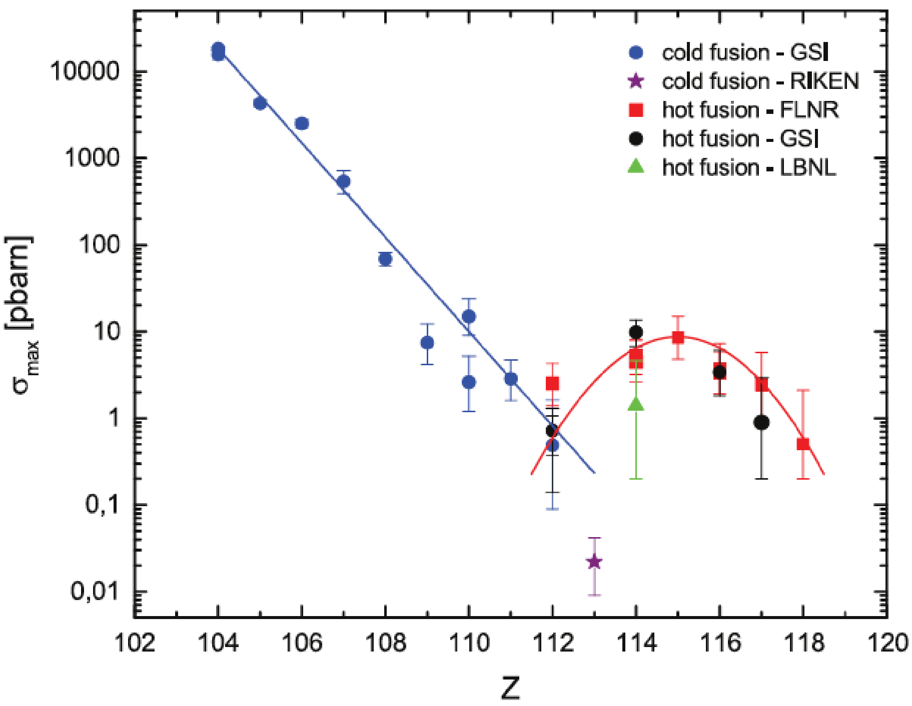

Figure 7: *Maximum cross sections for SHE synthesis (figure taken from [D. Ackermann and Ch. Theisen, Phys. Scripta 92 (2017) 083002].*

The experimental approaches include reaction mechanism as well as nuclear structure studies of superheavy nuclei (SHN) which demand, apart from the highest intensities, specific requirements for the ion beams employed to produce the species of interest. These include features concerning the time structure of the beam as well as specific intensity and energy control, which are listed in the following subsection BEAM REQUIREMENTS, together with the ion species needed. This rare event research with highest discovery potential, would profit from world leading intensities for projectiles like ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{70}Zn. For those species, which are the workhorses for the production of SHE beyond Z=112 up to the synthesis of the hitherto unknown elements 119 and 120, the gain in intensity compared to an injector with A/q=3 is of the order of 5 to 6. Being able to provide these beams would place the SPIRAL2 facility on a world class level competing effectively with the leader in the field, the SHE Factory of the Flerov Laboratory of Nuclear Reactions/Joint Institute for Nuclear Research (FLNR/JINR) in Dubna, Russia, presently initiating operation. A comparison of the maximum design beam intensities of the SPIRAL2 LINAC for A/q=3 to 7 with the world-wide competing facilities is given for some key ion species in ***Table 1.*** The intensities provided by the NEWGAIN project combined with the S^3 capabilities, such as the high transmission and the mass identification ($\Delta M/M$ < 1/350), will make SPIRAL2 a world-leading facility for SHN/SHE research.

Table 3*: Production calculations for Day 1 pre-proposal event rates. The values were generated on the basis of Table 6 in ref. [D. Ackermann and Ch. Theisen, Phys. Scripta 92 (2017) 083002] using the following assumptions: Target thickness = 0,4 mg/cm2; beam intensity limited to 11 pμA if LINAC output is higher to respect the presently assumed acceptance capabilities of the wheel-mounted targets (see SUBSECTION T; transmission of LINAC = 72%; transmission of S3 = 40%.*

Nuclide and production reaction	Cross-section (pb)	I_{beam} on target (pμA)		Rates			
				[pps]		per 7 days	
		A/Q=3	A/Q=7	A/Q=3	A/Q=7	A/Q=3	A/Q=7
^{208}Pb(^{48}Ca,2n)^{254}**No**	2×10^6	0.9	7.9	5.2	46	3.2×10^6	2.8×10^8
^{208}Pb(^{50}Ti,2n)^{256}**Rf**	17×10^3	1.8	4.3	8.9×10^{-2}	2.1×10^{-1}	5.4×10^6	1.3×10^5
^{207}Pb(^{64}Ni,1n)^{270}**Ds**	13	0.72	3.2	2.7×10^{-5}	1.2×10^{-4}	16	73
^{207}Pb(^{70}Zn,1n)^{276}**Cn**	0,5		4.3		6.3×10^{-6}		3.8
^{243}Am(^{48}Ca,3n)^{288}**Mc**	10	0.9	7.9	2.2×10^{-5}	2.0×10^{-4}	13	118

In June 2018 in a meeting of the scientific community interested in performing experiments at S^3 a number of pre-proposals for the early exploitation phase ("day 1") were discussed. The proposed measurements were addressing both detection installations foreseen in the focal plane of S^3, SIRIUS and S^3-LEB (see subsections S3 DETECTION I: SIRIUS and S3 DETECTION II: LOW ENERGY BRANCH (S3-LEB)) at equal shares of 11 pre-proposals for each of the two. For experiments concerning SHE/SHN research, envisaging the investigation of heavy and superheavy nuclei up to ^{260}Sg and in the vicinity of the N=162 neutron subshell closure, beams of medium mass isotopes were requested. In ***Table 3*** event rates are given for a number of selected isotopes which were estimated for certain experimental conditions on the basis of beam currents expected for the two options A/q=3 and 7 in the early implementation phase of SPIRAL2/NEWGAIN (see columns 2 and 3 in ***Table 1***). With the NEWGAIN installation fully completed the facility with its world-leading intensities will be highly competitive in all aspects of SHE/SHN research, including the search for new elements beyond Z=118 with a high chance of their successful synthesis (see projected beam intensities in ***Table 1***).

BEAM REQUIREMENTS

List of projectiles of interest:

^{12,13,14}C, ^{16,17,18}O, ^{20,21,22}Ne, ^{23}Na, ^{24,25,26}Mg,^{27}Al, ^{28,29,30}Si, ^{35,37}Cl, ^{38,40}Ar, ^{38,39,40}K, ^{40,42,43,44,46,48}Ca, ^{46,47,48,49,50}Ti, ^{51}V, ^{50,52,53,54}Cr, ^{55}Mn, ^{54,56,57,58}Fe, ^{59}Co, ^{58,60,61,62,64}Ni, ^{63,65}Cu, ^{64,66,67,68,70}Zn, ^{74,76}Ge, ^{86}Kr

SPECIAL REQUIREMENTS

The specific needs for SHE research are due to target related issues and specific experiment types like e.g. the measurement of excitation functions. They are listed in the following:

Beam energy and tuning

- The generally low cross-sections experienced in the field of SHN/SHE research require long irradiation times from weeks to months with the consequence that long-term stability in terms of beam energy and intensity as well as of other beam properties like beam spot location and size is crucial.
- Energy loss in the target is an issue demanding for beam spot size control, in particular in y-direction (extension of the order of 0.5 cm to 1 cm (±3 rms)), while the extension in x will be achieved by the rotation of the target wheel.
- For the use of actinide targets presently thick target backings (2 μm) are needed leading to an additional energy loss of typically **2 MeV/u**, leading to the requirement of a maximum beam energy of 7.5 MeV/u (New target production techniques (e.g. drop-on-demand (DOD) could use thinner carbon backings).
- In order to measure excitation functions and infer the optimal energy for SHE production energy variations down to ΔE = 1 MeV in an energy range of up to 20 MeV around Coulomb barrier energies (≈ 5 MeV/u) with minimum time (1-2 h) for the energy change are desired.

Beam intensity

- As mentioned above the low cross sections require the highest achievable intensities in the limit of sustainability by the targets which are currently subject of research and development aiming for continuous improvement (see section T).
- Intensity variations from lowest (1 pnA) to maximum (≥ 10 pμA), e.g., for the ”baking-in” procedure of actinide targets.

Time structure

- The capability to block the beam, e.g. for back-ground free detection after specific decay detection, requires the control from experimental side. To this end slow chopping in the ms to s range is needed.
- In cases when a ToF measurement cannot be based on transmission detection only, e.g. for slow recoils, a start(stop) signal is required from the accelerator side, asking for a beam-pulse length of a few tens of ns with a pulse separation (beam pause) of the order of the flight time through the separator of up to tens of μs.

TOPIC: STRUCTURE OF N=Z NUCLEI

SCIENCE INTRODUCTION

Neutron-deficient nuclei close to the proton drip line, in particular ^{100}Sn and its neighbors along the N=Z line, have reinforced the interest of the worldwide physics community thanks to the large variety of different nuclear phenomena occurring in this region.

The fact that protons and neutrons occupy the same shell-model orbitals translates into a maximum overlap of the wave functions of the two fermionic systems; thus proton-neutron pairing plays a predominant role in this area of the nuclear chart. The inherent symmetry of these nuclei makes them excellent candidates for the study of proton-neutron pairing correlations and isospin breaking symmetry. Moreover, the magicity of ^{100}Sn and its effect on neighboring nuclei is decisive for the course and the end of the astrophysical rapid-proton capture process. In addition, the nuclei in the region above ^{100}Sn are known for presenting different types of radioactivity, i.e. (super-allowed) α, one or two proton emission, and cluster radioactivity predicted but not yet observed up to date in the region. Current facilities can fill in some of the gaps in mass measurements, but only a facility like S^3 can reach nuclei such as ^{99,100,101}Sn, ^{98,99}In, ^{95,96}Cd, that have very small production cross section and many strong parasitic reaction channels. A nice overview of the physics of the region can be found in [T. Faestermann, M. Gorska and H. Grawe, Prog. Part. Nucl. Phys. 69 (2013) 85), Celikovic, I. et al., Phys. Rev. Lett. 116 (2016) 162501 and D. Lubos et al. Phys. Rev. Lett. (2019) 122.222502].

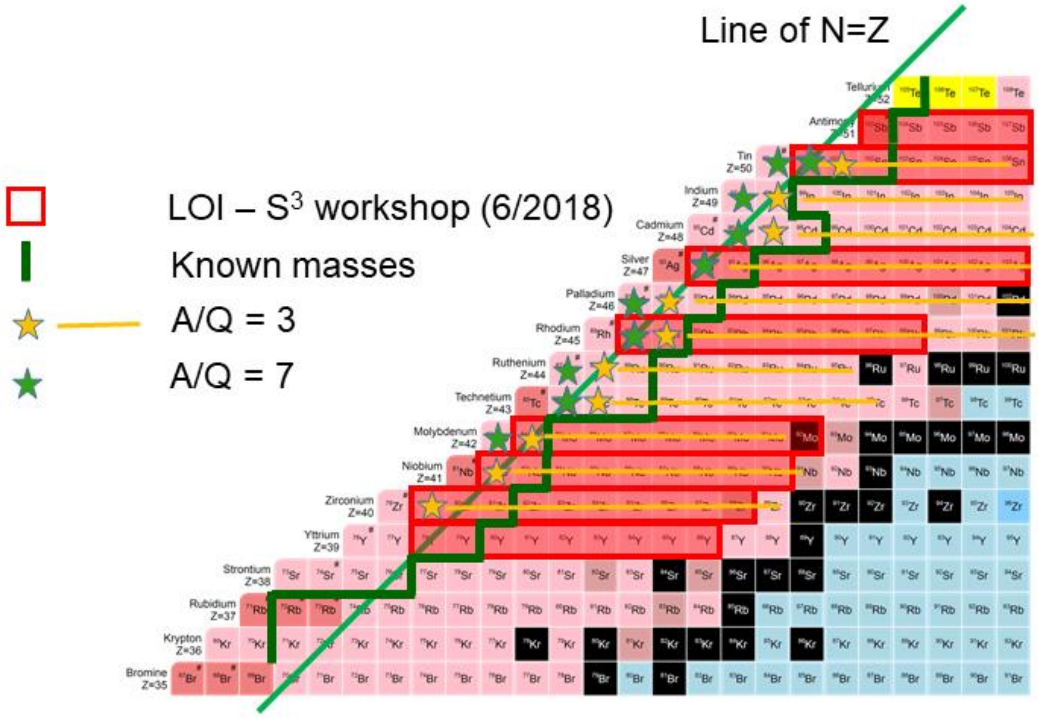

Figure 8: Region of interest along the N=Z line in the vicinity of ^{100}Sn. Stars indicate the most neutron deficient nuclide to be reached with A/q=3 and 7, respectively. The isotopes covered by Letters of intent (pre-proposals) in the S^3 meeting in June 2018 are indicated as well by red frames.

The nuclei reachable with the help of the installation of the NEWGAIN injector are illustrated in ***Figure 8.*** These nuclei will be studied by laser spectroscopy (a status of this type of measurements can be found in [P. Campell, I.D. Moore, M.R. Pearson, Prog. Part. Nucl. Phys. 86 (2016) 127)], mass measurements of the ground and isomeric states and decay spectroscopy at S^3-LEB as well as at DESIR.

The meeting of the scientific community interested in performing experiments at S^3 in June 2018 mentioned in the previous subsection TOPIC: SHE RESEARCH addressed N=Z physics as well. Similarly, to experiments concerning SHE/SHN research, mainly beams of medium mass isotopes were requested for subjects addressing nuclear structure issues around ^{100}Sn. ***Table 4*** maximum production rates expected for SPIRAL2/NEWGAIN (see columns 2 and 3 in ***Table 1***) with those to be achieved at FRIB in its various stages of completion.

BEAM REQUIREMENTS

The list of beams required to accomplish the Day1 physics program are listed below, these beams will serve for later programs as well:

^{18}O, ^{22}Ne, ^{28}Si, ^{36}Ar, ^{40}Ar, ^{40}Ca, ^{48}Ca, ^{50}Cr, ^{58}Ni

SPECIAL REQUIREMENTS

The beam requirements are detailed in the subsection SPECIAL REQUIREMENTS of the next section TOPIC: LOW ENERGY PHYSICS @ S³LEB AND DESIR

Table 4: *Comparison of the maximum production rates in pps at S^3-LEB for neutron-deficient isotopes relevant for N=Z studies. The first column shows the expected production for the existing SPIRAL2 injector1 (A/q=3) coupled to the Phoenix V3 source. The second column shows the projected production from beams delivered by NEWGAIN (cross sections from [B. Blank et al., NIM B 416 (2018) 41]). The third, fourth and fifth columns show the expected production of stopped beams from FRIB in its different phases (from https://groups.nscl.msu.edu/frib/rates/fribrates.html). The highest intensities for a given projectile are shown in red.*

Intensities [pps]	S^3 LEB (A/q=3)	S^3 LEB (A/q=7)	FRIB1	FRIB2	FRIB Final
^{100}Sn	7	**34**	0.05	0.2	4
^{101}Sn	170	**850**	3	10	161
^{97}In	0.2	**2.6**	0	0	0
^{98}In	4	**11**	0.02	0.09	4
^{99}In	80	**800**	2.7	13	316
^{100}In	740	7,400	231	1,150	**18,400**
^{98}Cd	3600	18,000	505	2,520	**105,000**
^{97}Cd	19	95	6.4	32	**2,030**
^{96}Cd	3	15	0.24	1.2	**89**
^{95}Cd	0.4	**2**	0.004	0.02	**1.6**
^{94}Ag	136	**680**	0.04	0.2	20
^{95}Ag	870	4350	30	152	**14,700**
^{91}Pd	81	**405**	0.02	0.12	27
^{92}Pd	810	**4,050**	1.7	8	1,870
^{90}Rh	210	**1,050**	0.02	0.09	52

TOPIC: LOW ENERGY PHYSICS @ S^3LEB AND DESIR

SCIENCE INTRODUCTION

Low-energy experiments generally refer to studies based on laser and decay spectroscopy, and mass spectrometry. These studies allow accessing ground-state properties of nuclei like their mass, spin, charge radius and electromagnetic moments, as well as decay properties such as their half-life, branching ratios and excitation probabilities. The S^3-LEB is conceived as a versatile installation capable of addressing these topics from the lightest to the heaviest nuclei produced by S^3 and serving the dual role of experimental installation and low-energy-beam preparation and delivery system. Its science program and physics requirements thus follow the major topics of research outlined in this White book for S^3 (see TOPIC: SHE RESEARCH and TOPIC: STRUCTURE OF N=Z NUCLEI).

Complementing these topics, another region of interest concerns intermediate-mass nuclei approaching the proton dripline, between the Sn and Pb isotopic chains. The upper part of this region, in particular (masses 160 - 180), will allow the study of the phenomenon of shape coexistence and the effect of the N=82 shell closure (beyond the proton dripline) on the shape of very neutron-deficient nuclei. For this region, as shown in ***Figure 9***, the most exotic isotopes of interest will require primary beams in the mass range 70-90. High primary-beam intensities are additionally motivated by the decreasing half-life of the nuclei in the region, which will lead to losses by in-cell decay prior to extraction. This also calls for the development of faster gas cells.

The physics cases of DESIR cover basic nuclear structure topics by measuring the sequence of single-particle orbitals for nuclei far from stability and their occupancies, separation energies and Q-values, which together with half-lives and decay properties of neutron-deficient and neutron-rich nuclei are important inputs for simulations of stellar evolution and nucleosynthesis, and for studies of the fundamental interaction, most notably of the weak interaction. The focus will be set e.g. on regions around closed major shells (N=Z=28, N=Z=50), but also around deformed shells (e.g. N=Z=40) or on long chains with only one shell closed.

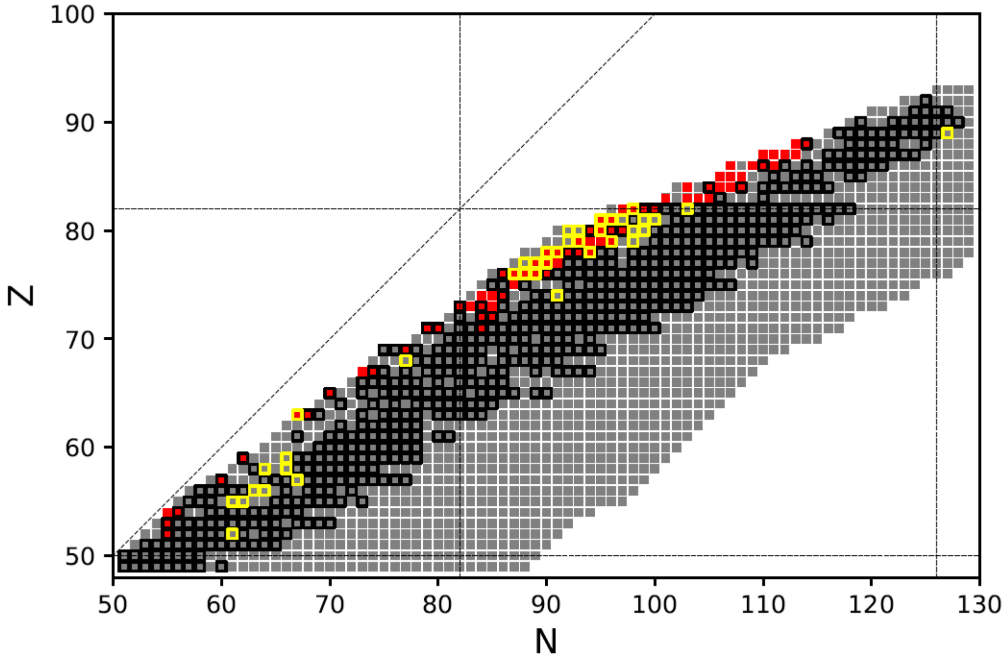

Figure 9: Intermediate mass region of the nuclear chart. The nuclei in the online GANIL database of beams available for S³ (https://u.ganil-spiral2.eu/chartbeams/) are emphasized by open squares. The yellow open squares denote cases requiring projectiles heavier than Ni. Red squares mark isotopes of half-life below 250 ms.

Some of the lighter nuclei (A>20) of refractory elements are also of particular interest, as these nuclei have exotic decay properties like βp and β2p decays, which are the reverse of interesting astrophysical reactions important for the evolution of stars. Input for these astrophysics' reactions can be gained by studying the above-mentioned decay branches.

Weak-interaction studies will deal with N=Z nuclei up to the ^{100}Sn region for the determination of the V_{ud} quark-mixing matrix element of the CKM matrix, but also with other specific nuclei to test for exotic currents in the weak sector of the standard model of particle physics. For example, nuclei like ^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar, ^{36}Ca allow the search for scalar currents in the weak interaction via the kinematics of their decay.

BEAM REQUIREMENTS

List of projectiles of interest: In addition to those mentioned for SHE and DESIR: ^{78}Kr, ^{84,86}Sr, ^{90}Zr,^{92}Mo at energies between 4-5 MeV/u.

SPECIAL REQUIREMENTS

- For some reactions with light beams provided by the A/Q = 3 injector very asymmetric projectile-target mass ratios lead to very slow recoils, posing difficulties for injecting them in the gas cell (ultrathin window required). Reactions in inverse kinematics would be interesting because they lead to more energetic recoils. They would be, however, difficult e.g. for light gaseous elements as for the very asymmetric reactions proposed for the Day 1 experiments using O and Ne as projectiles.

Beam energy and tuning

- It is constrained by the physics and true also for the A/Q = 3 injector.
- Some experiments require slight energy retuning between different isotopes to optimize cross section to be done once every few UTs, depending on the time needed to complete the measurements on one isotope. This fine adjustment requires an energy precision of 1% or better.
- For cases with poorly known cross-sections (like N = Z nuclei), excitation function measurements might be needed requiring frequent and fast energy changes.

Beam intensity

- In general, maximum primary beam intensities are required due to low production cross sections for the exotic nuclei. Count rate limitations might however become necessary, when plasma effects in the LEB gas-stopping cell would risk a loss in efficiency, leading to intensity reductions of 10% or 1%.
- Intensity stability is very important for scans, demanding ideally 1% stability. During the laser scans primary-beam intensity monitoring is essential for normalization.

Time structure

- Even with a fast gas cell, the S^3-LEB or DESIR programs will not be sensitive to any primary-beam time structure on the µs level or below.
- Beam chopping on the 1-100 ms scale is sufficient.
- In various situations (background reduction, change of experiment mode etc.) controlling/stopping the beam from experiment side will be necessary.

TOPIC: INTERDISCIPLINARY RESEARCH

SCIENCE INTRODUCTION

The interdisciplinary physics that is proposed using the NEWGAIN injector corresponds to the one already performed at GANIL on the IRRSUD beamline adding new experiments but taking advantage of the world's best beam intensities. IRRSUD, developed in 2002 at the instigation of CIMAP-CIRIL, profits from the provided beams, from C to U in the energy range 0.3 to 1 MeV/A, beams highly requested by broad physics communities such as material sciences (inorganics, semiconductors, nuclear materials, polymers), astrophysics/astrochemistry and atomic physics often related to radiobiological interests. There are many scientific interests for these beams as i) ^{12}C or ^{13}C at 1 MeV/A is near the Bragg peak for molecules of biological interest, ii) the energy available for A≈90 (^{86}Kr 0.86 MeV/A) and A≈140 (^{136}Xe at 0.71 eV/A) corresponds to the one of fission products in nuclear reactors, iii) for heavy ions (around A>86), the energy losses are above the threshold for the formation of latent tracks in many materials allowing studies of dense electronic excitations, and iv) high fluencies can be reached, thus some displacements per atom are added to the electronic excitations, being of high interest for the nuclear materials community as well as for the target materials community. Also, in-situ and online analysis are possible due to sophisticated available equipment attached to the beamline (e.g., X-ray diffraction, absorption/vibration spectroscopy, heating and cooling stage, etc.). However, a major limit at IRRSUD is that time resolved measurements are not really possible, at least not well optimized, which works against the interests of some experiments. NEWGAIN would help to overcome these limitations by providing better beam time-structure capabilities. Indeed, pump probe or time-of-flight experiments require pulsed beams and time resolved characteristics, which would be available at NEWGAIN.

Another advantage of NEWGAIN is the intensity, higher than currently available. It will allow reaching even higher fluencies providing more displacements per atom expected for example for the simulation of high-power targets of accelerator facilities. Moreover, experimental conditions at NEWGAIN such as beam sweeping or defocused beam, flux measurements, automatic sample changer, could allow to perform many of the experiments presently conducted at IRRSUD and will substantially increase the availability of beam time. A dedicated irradiation station located close to the NEWGAIN RFQ exit is presently being discussed.

A comprehensive overview of interdisciplinary research activities using ion beams is given in an issue of the Journal of Physics' conference series, entitled "*CIRIL, 30 years of interdisciplinary research at GANIL"* [Jour. Phys. Conf. Ser. 629 (2015)].

BEAM REQUIREMENTS

BEAM REQUIREMENTS

List of ions of interest - a broad range of ions in A and Z is needed:

Ar, Kr, Xe, Pb, U

SPECIAL REQUIREMENTS

- Varying the beam intensity is requested from low flux (10^5 $cm^{-2}s^{-1}$) up to high flux (>10^{11} $cm^{-2}s^{-1}$).
- A beam time structure with pulse length/repetition rate between 500 ms/1 Hz and 1 µs/100 kHz is required for the irradiation station of the RFQ.

TOPIC: ATOMIC PHYSICS (FISIC @ S^3)

SCIENCE INTRODUCTION

The Fast Ion–Slow Ion Collisions (FISIC) setup is foreseen to be coupled to S^3 with the goal of studying atomic interactions in beam-beam collisions [D. Schury et al., *The low energy beamline of the FISIC experiment: current status of construction and performance,* J. Phys.: Conf. Ser.1412 162011 (**2020**)]. A low energy beam (a few keV/A) is planned to be injected under 90 degrees into S^3 at the achromatic point to interact with the SPIRAL2 beam (a few MeV/A). For the fast ions, a dedicated beam line equipped with a magnetic dipole, quadrupoles and a beam dump will help to separate the different charge state products. This arrangement will provide a unique facility to study ion-ion interaction in the energy regime where the ion stopping power reaches its maximum [F. Aumayr et al., *Roadmap on photonic, electronic and atomic collision physics: III. Heavy particles: with zero to relativistic speeds - Chapter 3 - Collisions involving heavy projectiles,* J. Phys. B: At. Mol. Opt. Phys. 52 171003 (**2019**)]. The knowledge of atomic cross sections in this regime is important since this is where the strongest effects on material modifications (including biological material) are observed and where ion-ion collisions play an important role in various plasmas, such as inertial confinement fusion plasmas or stellar and interstellar plasmas. This scientific program is led by a group at the Institut des Nanosciences de Paris of Sorbonne Université and FISIC is part of the EQUIPEX S^3.

Ions from carbon to xenon will be delivered by the SPIRAL2 LINAC (the "high energy" beam), where the new A/q=7 injector would be essential for providing the high intensities needed for the collisions with the "low-density target" of the thermal ions coming from the FISIC injection. With energies ranging from 4 to 14 MeV/A, depending on the A/q ratio, the S^3 charge-state selected fast ions would collide with the slow ions, from helium to argon, delivered by an Electron Cyclotron Resonance (ECR) ion source (the "low energy" beam) connected to a dedicated low-energy ion beam line.

BEAM REQUIREMENTS

List of projectiles of interest:

Ar, Ni, Kr, Xe

SPECIAL REQUIREMENTS

- Ion beams of high intensities and the possibility to vary the ion charge state.

TOPIC: DEEP INELESTIC COLLISIONS/MULTI NUCLEON TRANSFER STUDIES

SCIENCE INTRODUCTION

Deep-Inelastic Collisions (DIC) [W.U. Schroeder, J.R. Huizenga Damped Nuclear Reactions, D.A. Bromley (Ed.), Treatise on Heavy-Ion Science, Springer, N.Y./London (1985), pages 113-726] between complex nuclei were first observed in the 1960s, but it was not until the early 1970s that the importance of such reaction mechanisms was recognized by experimental groups and that theoretical concepts were developed for their description. These processes acquired the name *deep-inelastic collisions*, or *damped collisions* or *multinucleon transfer reactions*. Characteristic features of deep-inelastic collisions (DIC) include: formation of a di-nuclear system which rotates almost rigidly, **exchange of nucleons** governed by N/Z equilibration, **damping of the relative kinetic energy** between the reaction partners**, transfer of relatively high angular momentum** into the intrinsic spin of the reaction products, and, eventually, separation into two fragments.

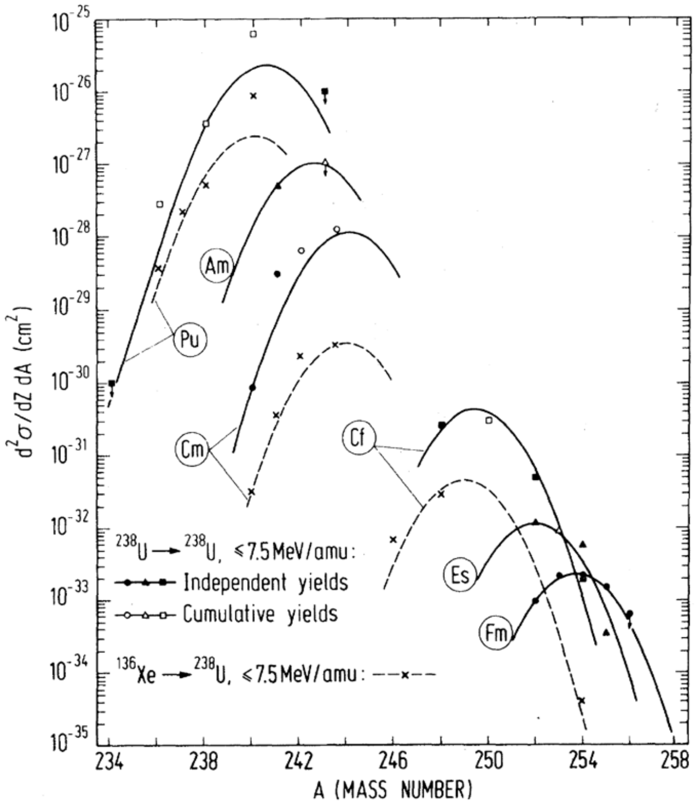

Figure 10: *Actinide production using the $^{238}U+^{238}U$ and $^{136}Xe+^{238}U$ reactions [M. Schädel et al. PRL 41 (1978) 469].*

DIC have been widely exploited in the 1980s using radiochemistry techniques for the study of transactinide nuclei [J.V. Kratz, W. Loveland and K.J. Moody, Nucl. Phys. A 944 (2015) 117 and references therein]. An example among many others is shown in ***Figure 10***. This figure highlights two important issues. First, the highest cross-sections are achieved using the heaviest beam: the ^{238}U beam is superior to that of ^{136}Xe by about an order of magnitude. Second, a beam energy of ≈7 MeV/A must be used.

However, the use of the radiochemistry technique declined because it was not applicable for decay after separation (DSAS) or in-beam spectroscopy (since the products were stopped in the thick target). There was more recently a renewal of interest for multinucleon transfer reactions with the work of Zagrebaev and Greiner, predicting very attractive production cross sections using the heaviest beam on the heaviest target, possibly also at angles close to zero degrees [V. Zagrebaev and W. Greiner, Phys. Rev. C 83 (2011) 044618 and Phys. Rev. C 87 (2013) 034608].

Recent experimental studies using LISE [I. Stefan et al. Phys. Lett. B 779 (2018) 456] showed that the deep-inelastic reaction mechanism is also an effective mechanism to produce light neutron-rich nuclei not only at grazing angle but also at forward angles. In fact, the forward angle is where the production of the exotic nuclei is the most favored. In addition, this reaction mechanism can be used to create neutron-rich isotopes of very heavy elements with N ≈ 126 for studies of interest to the formation of the A ~ 195 abundance peak in the r-process, a region that can be hardly produced by other reactions: see e.g. [G. Savard et al., Nucl. Inst. Meth. B 463 (2020) 258; Y.X. Watanabe et al., Phys. Rev. Lett. 115 (2015) 172503].

While an extensive program is ongoing on the theoretical side, as well as experimentally at several facilities where such experiments are performed at small angles (GSI, ANL, LISE, etc.), the zero-degree program is still in its infancy [J.V. Kratz, W. Loveland and K.J. Moody, Nucl. Phys. A 944 (2015) 117][G.G. Adamian et al., Eur. Phys. J. A 56 (2020) 47 and references therein]. Moreover, the use of 0° separators is limited due to the large angular and momentum distribution characterizing the fragments produced by this mechanism. In the case of S^3, its usefulness is furthermore limited by the kinematic limitations imposed by the electric dipole. Therefore, to take advantage of this mechanism, it is necessary to develop new devices. Such a device could be a new target-ion source that would produce exotic heavy nuclei using DIC, fusion-evaporation and fusion-fission reactions. This setup will benefit from the highest intensity heavy beams from the injector A/Q = 7 as described in more detail in section TOPIC: FUTURE FACILITIES.

See also:

- *RFQ injector A/Q = 7 for the production of exotic nuclei using fusion-evaporation and multinucleon transfer reactions,* Contribution to the future of GANIL, available here.
- *Production of trans-lead and actinide nuclei – the benefits of a target-ion source and A/Q=7 LINAG beams,* Ch. Theisen, 2020, “Mission Spiro” working document.
- *Radioactive Ion Beam production,* P. Delahaye et al., “Mission Spiro” working document.

BEAM REQUIREMENTS

List of projectiles of interest:

^{18}O, ^{36}S, ^{40,48}Ca, ^{70}Zn, ^{76}Ge, ^{86}Kr, ^{98}Zr, ^{124}Sn, ^{138}Xe, ^{208}Pb, ^{209}Bi, ^{238}U[1]

SPECIAL REQUIREMENTS

- New separation/selection device e.g.

[1] This list is dependent of the specifications of new devices not yet defined.

- Separator/spectrometer with high acceptance and high Eρ capability (e.g. a gas-filled separator).
- Target ion source followed by separation/selection device: gas-cell, magnet, MR-ToF

- Radioactive targets such as ^{248}Cm

TOPIC: FISSION STUDIES

SCIENCE INTRODUCTION

Fission is one of the most complex and extreme scenarios for nuclear matter that we can study in the laboratory. A process where nuclei are deformed to the extreme by forces that tear them apart, driven by dissipative heat exchanges and the influence of shell structure in the nascent fragments. A full understanding of the interplay between macroscopic and microscopic properties, and the dynamics involved is still a challenge for theoretical models [M. Bender *et al*. J. Phys. G: Nucl. Part. Phys. **47**, 113002 (2020)], but also for experimental techniques that feed them with large systematics of relevant observables [A.N. Andreyev, K. Nishio and K.-H. Schmidt, Rep. Prog. Phys. **81**, 016301 (2018); K.-H. Schmidt and B. Jurado, Rep. Prog. Phys. **81**, 106301 (2018)]. From the experimental point of view, the use of inverse kinematics with heavy beams between ^{208}Pu and ^{238}U has rekindled the interest in fission research by providing new, key observables. In addition, the same technique can be applied to the study of the dynamics of quasi-fission, which are also relevant for the production of super-heavy nuclei. Recent experimental efforts include the VAMOS/GANIL campaign, which mainly uses fusion and transfer reactions, and the SOFIA campaign at GSI, which measures Coulomb-induced fission in relativistic heavy beams. It is worth mentioning that both campaigns use a magnetic spectrometer to measure and identify the fission products.

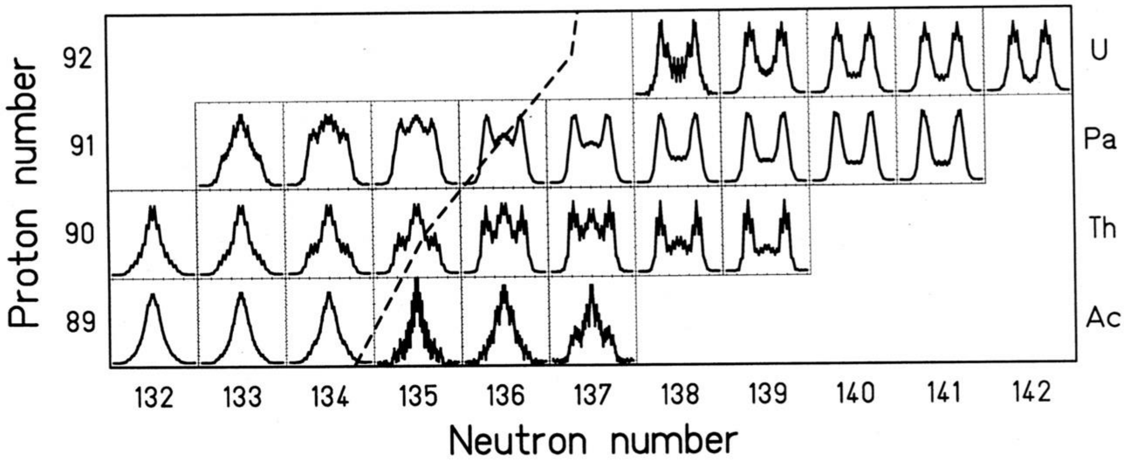

Figure 11: *Isotopic yields for e.m.-induced fission of low actinides. The dashed-line shows the theoretical transition between asymmetric and symmetric fission. We can observe how both the neutron and proton contents affect the symmetric or asymmetric character of the fission yields. Figure from [K.-H. Schmidt et al, NPA 665, 221 (2000)].*

While the typical cross sections for induced fission are relatively high (from tens to hundreds of mb), the reaction probability for a particular reaction channel is distributed among a large set of multi-parametric combinations of fragment properties (mass, charge, energy, etc.) and initial fission conditions (excitation energy, angular momentum, etc.). A detailed study of the process as a function of these parameters can only be achieved with a substantial increase of the incident beam current for reasonable measurement times and target thickness. The improved statistics would also help to contribute to higher-precision fission yields for nuclear data-bases and nuclear applications. High-intensity beams will also permit reaching rare combinations of fragment properties, such as symmetric or extremely asymmetric splits, which carry valuable and hitherto inaccessible information due to their low probability ***Figure 11*** shows a classical example of the relevance of symmetric splits: a transition from asymmetric to symmetric fission appears in the actinide region, which is governed both by the structural characteristics of the fissioning system and fragments, and by the dynamics of the process.

Besides the intrinsic study of fission and quasi-fission dynamics, the use of these reactions with high-intensity heavy beams at energies above the Coulomb barrier is also interesting as a source of neutron-rich nuclei for spectroscopic measurements. For instance, the low production cross section of fragments approaching ^{78}Ni can be overcome with the high intensities expected from the NEWGAIN injector and combinations of heavy beams and relatively light targets.

Concerning experimental setups, fission in inverse kinematics is typically used in combination with magnetic spectrometers in order to obtain full isotopic identification. Although this option is particularly curtailed with the present layout and the optical limitations of S^3, future techniques or modifications, such as changes in the velocity acceptance or the use of degraders at the entrance of the spectrometer, can be considered in order to bypass these limitations. Other approaches may include the use of gas cells, where fragments can be stopped and further analyzed, or even the construction of additional lines to receive the fission products at off-beam angles. This discussion is detailed in the following section on TOPIC: FUTURE FACILITIES together with alternative approaches for possible future extensions of GANIL.

BEAM REQUIREMENTS

List of projectiles of interest:

^{197}Au, ^{208}Pb, ^{209}Bi, ^{232}Th, ^{238}U

SPECIAL REQUIREMENTS

- Beam energy scans: As in the case of TOPIC: SHE RESEARCH, the possibility of changing the beam energy in steps of ≈0.5 MeV/A within a reasonable time would be required for systematic studies on the initial conditions of excitation energy.

TOPIC: FUTURE FACILITIES

SCIENCE INTRODUCTION

A world-class heavy-ion accelerator facility such as SPIRAL2, once upgraded with the NEWGAIN injector, providing high-intensity beams up to uranium, could be used as basis to prepare for future instrumentation and accelerator development projects at GANIL. These aspects are currently being discussed by the nuclear physics community, through the present French national prospective exercise, which will define in 2021 the national strategic priorities for the next 10 years in the field, and through an additional CNRS and CEA initiative coordinated by Michel Spiro to explore GANIL's future [https://indico.in2p3.fr/event/20534/]. The main possible projects currently under discussion in this context are the following:

- A new target-ion source based on multinucleon transfer reactions, fusion-evaporation in inverse kinematics and fusion-fission reactions.
- An electron-radioactive ion collider. This project will be enhanced by the very high beam intensities delivered by NEWGAIN.
- A new RIB post-acceleration facility at GANIL. This project will be enhanced by the very high beam intensities delivered by NEWGAIN injector.

The reactions mechanisms under consideration for the future GANIL upgrade are: Fusion-evaporation in inverse kinematics, multi-nucleon transfer (MNT) and fusion-fission reactions.

A new target-ion source based on multinucleon transfer reactions, fusion-evaporation reactions and fusion-fission reactions.

The project is dealing with the development of a new target-ion source that would produce exotic heavy nuclei using multi-nucleon transfer reactions and exotic fragments from fusion-fission reactions. The multi-nucleon transfer reactions are unique to synthesize neutron-rich nuclei, such as those approaching the super-heavy island of stability or at N=126 of interest for the formation of the A≈195 abundance peak in the r-process, whereas they cannot be populated by fusion-evaporation reactions and they are populated less efficiently by fragmentation. As seen in **,** for multinucleon transfer reactions, the production cross section of heavy and superheavy nuclei is very much enhanced for projectiles with high in A and Z, favoring the use of the heaviest available beams. Therefore, this proposed setup will highly benefit from the highest intense heavy ion beams from the NEWGAIN A/q=7 injector.

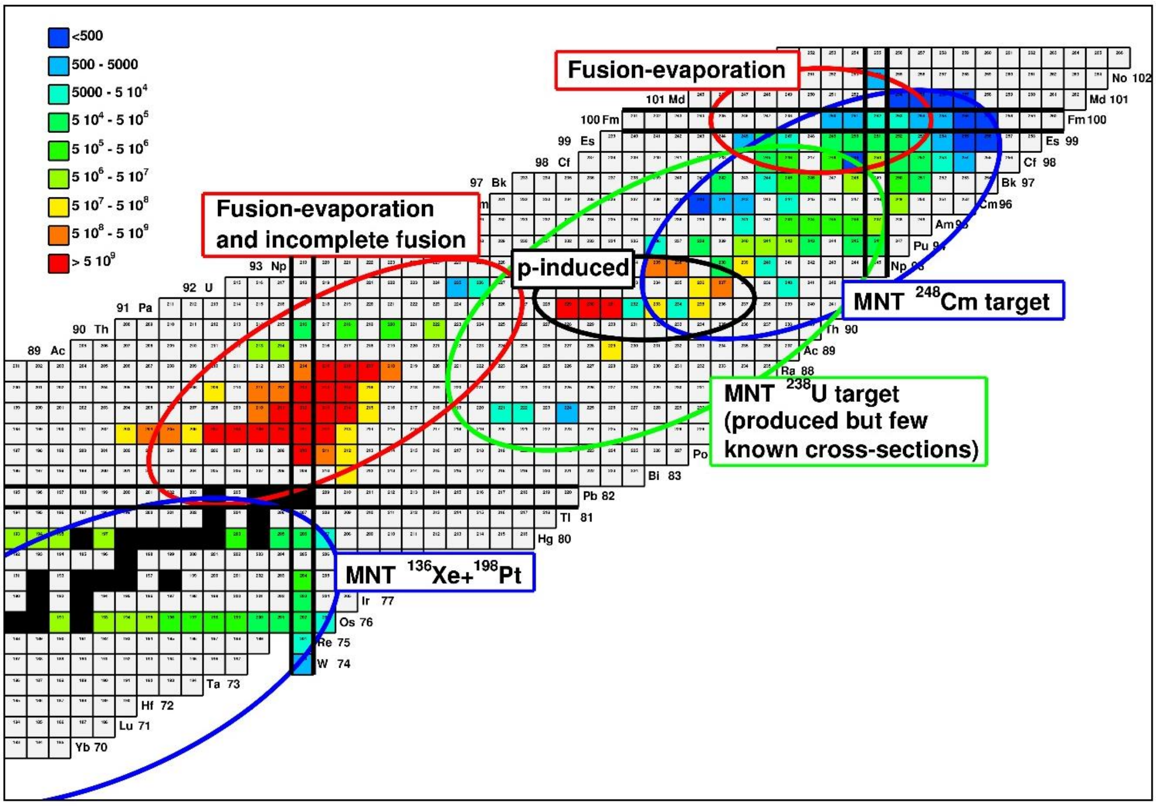

Figure 12: *Estimated production rates at the primary target for very-heavy elements using LINAG beams. Other nuclei must also be populated, but the cross-sections have either not been measured or are not reported in literature.*

While the possibility of using S³ as a production and separation facility has extensively been discussed, it presents severe limitations for MNT and inverse kinematics reactions in terms of transmission and rejection. Having for objective the highest possible production and thus the highest beam intensities, S³ also presents limitations in terms of target, notably thickness. Therefore, it would be advantageous to benefit from a new target ion-source devoted to MNT reactions, but also fusion-evaporation and fusion-fission reactions, installed in a dedicated yellow cave. Devices suitable for MNT reactions have been already proposed as N=126 factories by the Argonne National Laboratory [G. Savard et al.,IMB 463 (2020) 258] and KEK [Y. Hirayama et al., IMB 412 (2017) 11], [KISS Web page]. These devices are typically a gas catcher followed by a mass separation (magnet, MR-TOF). Adaptations, or even a new concept, are needed for fusion-evaporation and fusion-fission reactions.

Fusion-evaporation reactions using inverse kinematics would benefit greatly from the intense heavy beams delivered by the A/Q=7 injector. Since thicker targets can be used inverse kinematics, production rate ~50 times higher can be obtained using heavy beams such as ^{208}Pb, ^{209}Bi, ^{238}U. As an example, using direct kinematics, production rates of 10^8 pps correspond to cross sections of 200 mb while in inverse kinematics similar production rates can be reached with cross sections ~50 times lower.

Typical radioactive ion production rates are the following:

- ^{214}Ra (fusion evaporation in inverse kinematics): $6.3 \cdot 10^9$ pps

- ^{248}Bk (MNT): $3.3 \cdot 10^6$ pps

- ^{50}Ca (MNT): $4 \cdot 10^7$ pps

- ^{30}S (Transfer reaction): $2 \cdot 10^8$ pps

Figure 12 summarizes the expected production rates for heavy elements.

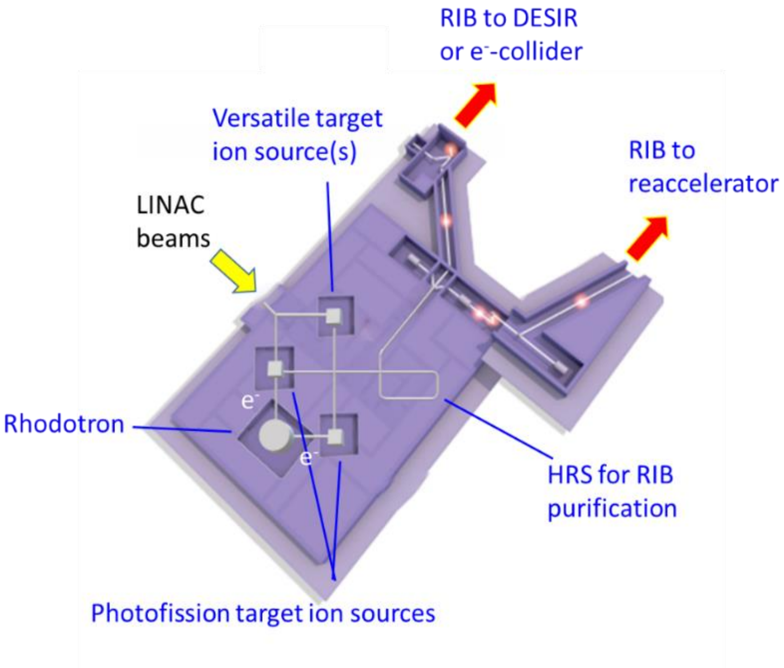

Figure 13: *Sketch of a possible future production building as discussed in [Radioactive Ion Beam production, P. Delahaye et al., 2020, "mission Spiro" working document].*

A possible implementation of the target-ion source is shown in ***Figure 13*** (versatile target ion source(s)), in the context of a future SPIRAL2 upgrade.

The produced exotic nuclei could be used, after selection, to perform the spectroscopy after decay or to study ground state properties (mass measurement, laser spectroscopy). The produced ions could therefore benefit from the S^3-LEB instrumentation (RFQ buncher, laser spectroscopy REGLIS and multi-reflection time-of-flight spectrometer PILGRIM) and could be sent to the DESIR hall, in the same way as it is already planned for the S^3 products. The produced ions might be reaccelerated and used either for secondary nuclear reactions or to induce electron-ion collisions detailed here below.

The heaviest beams, like Au, Pb, Bi, U would be essential for this installation and depend on the construction of an RFQ injector with A/q=7, a necessary ingredient for their production.

An electron-radioactive ion collider

Scattering electrons from nuclei provides access to the spatial distribution of fundamental properties like charge density, transition charge density and magnetic current distributions. An intense electron beam combined with a high flux of nuclei far from stability would allow for detailed investigation of nuclear matter features far from stability like halo nuclei, neutron skins, centrally-depleted nuclear densities and, more generally, the questions surrounding shell and shape evolution. Charge and transition densities for nuclei far from stability predicted by many sophisticated state-of-the-art models (e.g., ab-initio, beyond mean-field) could be tested by such measurements, providing stringent constraints on theory.

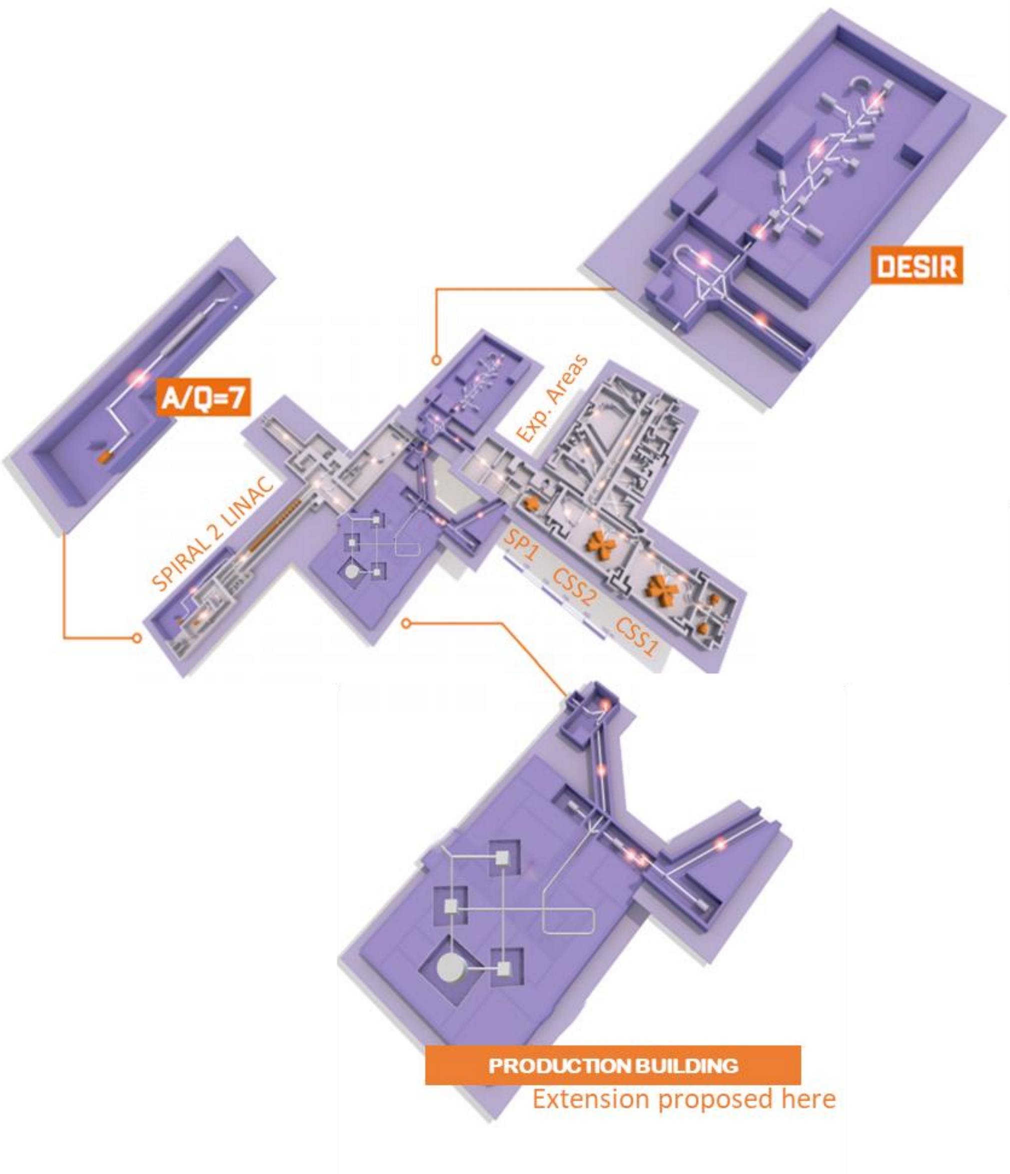

Figure 14: *Layout of GANIL-SPIRAL 2 showing the proposed new production building.*

The working group which proposes an electron-trapped RI collider as a possible future installation at GANIL sustains that such a facility could be designed, constructed and commissioned in a timescale of some 10-15 years.

More details are provided in the working group document “Electron scattering on radioactive ions at GANIL” (2020).

A crucial point for this project is the production of the radioactive ions. The NEWGAIN project can deliver the beams, particularly the uranium beam that can be used to produce the radioactive ions as detailed above to be studied with the collider.

Re-acceleration of exotic ions.

The re-acceleration of exotic ions was widely discussed within the Spiral2025 think tank and was then considered a priority. This possibility has again been discussed in numerous contributions to the future of GANIL in such as P. Delahaye et al. [GANIL-SPIRAL2 as a Multifaceted Radioactive Ion Beam Facility] and the working document "GANIL future report to the international expert committee - Working group on "post-accelerated radioactive ion beams" (2021)". While several facilities may in the future produce heavy elements using MNT reactions, no project so far envisages the reacceleration of these beams for reaction or structure studies. This statement holds also for exotic nuclei produced though fusion-evaporation reactions. As far as heavy elements are concerned (including the neutron-rich N=126 region) it is proposed to perform Coulex/inelastic scattering (spectroscopy, quadrupole moment measurements, spectroscopy of the second/third well), transfer reactions (detailed spectroscopy, spectroscopic factors, fission barrier measurement, fission dynamics, spectroscopy of the second well), or more simply spectroscopy after implantation. The minimum intensities needed for these studies are about 10^3 pps (Coulex), 10^3-10^4 pps (detailed spectroscopy using transfer reactions), 10^4 pps (fission probabilities) and 10^6 pps (fission fragment distribution characteristics).

A possible sketch of the infrastructure updated from this reference is shown in ***Figure 14***.

BEAM REQUIREMENTS

List of projectiles of interest:

^{18}O, ^{36}S, ^{48}Ca, ^{70}Zn, ^{76}Ge, ^{98}Zr, ^{124}Sn, ^{138}Xe, ^{208}Pb, ^{209}Bi, ^{238}U[2]

[2] This list is dependent on the specifications of new devices not yet defined.

SUMMARY BEAM REQUIREMENTS

MAIN BEAM CHARACTERISTICS

In order to maximize beam time for physics experiments and to fulfill their requirements, the NEWGAIN injector should provide the following general performance items:

- Accelerate all ions of interest with A/q from 3 to 7, to maximum energy of existing LINAC for each kind of ion considering requested minimum and maximum intensities.
- Have a design that allows connecting at the exit of the RFQ a future additional beamline and irradiation area.
- Be connected to the existing LBE1 heavy ion source Phoenix V3 (presently dedicated to A/q=3 ions for the first injector) so that also ions from this injector can be accelerated by the NEWGAIN RFQ.
- Have a technical design allowing existing and future injectors to operate simultaneously and independently in order to facilitate commissioning of the new injector and future operation (pre-tuning) particularly for metallic ions. Most of the equipment and ancillaries have to be independently dedicated to each injector (RF amplifiers, magnet power supplies, electric power supplies…).
- Consider specific beam time structure and energy dispersion requested by scientific users. A first list of these requirements was presented in the report to the NEWGAIN TAC at its first meeting in February 2021.
- The impurity of the beam, given the high intensities, is required to be kept to a minimum, ideally close to zero. Possible contaminants, often occurring due to matching A/q ratios with respect to the wanted beam species, have to be discussed case by case. One measure to avoid those contaminants is the use of a slightly less probable charge state leading to an acceptable intensity reduction.
- Regarding contaminants which have very similar A/q like e.g. the case $^{12}C^{4+}$ and $^{48}Ca^{16+}$ with A/q = 3 and 2.997, respectively, pose a problem for the existing A/q=3 injector. This can be overcome at NEWGAIN by choosing a lower charge state for the desired beam species. For the heaviest beams like Pb and U the major impact of impurities comes from the additional contribution of those impurities to the total beam power. In this respect, the number of impurity ions should not exceed 10-20% of the number of ions for the desired species. In rare cases of exceedingly high cross sections of reactions induced by the impurities, special measures which are difficult to anticipate presently, have to be taken case by case.

OTHER REQUIREMENTS:

In the following the special requirements presented in the various sections throughout the White Book are summarized here (for details see the description in the BEAM REQUIREMENT subsections of the various sections):

Beam energy and tuning

- Long-term stability in terms of beam energy and beam properties like beam spot location and size
- Energy stability and dispersion <0,1%(RMS)
- Enable beam spot size control up to widths of 0.5 cm to 1 cm (±3rms)
- Energy steps down to ΔE = 0.5 to 1 MeV in an energy range of up to 20 MeV at ≈ 5 MeV/A
- Time needed for energy change ≤ 1-2 h
- Capability of energy retuning for fine adjustment with an energy precision of 1% or better

Beam intensity

- Highest intensities, in particular for medium-heavy projectiles (A ≤ 70 to 90)
- Intensity stability for long term experiments (months) within 10%
- Intensity stability for short periods (hours to days) ideally within 1% or best achievable

- Intensity stability limitation: maximum intensity should not exceed the average intensity by more than 10%, $I_{max} < I_{ave}+10\%$
- Intensity variations from lowest (1 pnA) to maximum (10 pμA or more)
- Intensity variations for low-E beams (interdisciplinary irradiation station after NEWGAIN) from low flux (10^5 cm^{-2} s^{-1}) up to high flux (>10^{11} cm^{-2} s^{-1})
- Ion beams of high intensities and the possibility to vary the ion charge state
- Beam intensities have to be measured with a precision of 10%.

Time structure

- Possibility to stop the beam from experiment side
- Variable beam-on/beam-off time structures down to 1 µs periods
- Short pulse ($n \times 10$ ns) operation with µs pulse separation[3]
- Beam timing for the irradiation station of the RFQ between 500 ms/1 Hz and 1 µs/100 kHz

Beam geometry

- Horizontal (X) beam spot size: 0,5 mm < RMS(X) < 1 mm
- Vertical (Y) beam spot size: 1 mm < RMS(Y) < 2,5 mm
- Horizontal position (X) stability (center of gravity): 0,25 mm
- Vertical position (Y) stability (center of gravity): 0,25 mm
- The beam size on target should be adjustable between 0.5mm ≤ RMS(X) ≤ 2.5mm and 1mm ≤ RMS(y) ≤ 2.5mm

Table 5: *List of major beam characteristics required for the envisaged physics program*

Ion species	
List of projectiles of interest:	^{12,13,14}C, ^{16,17,18}O, ^{20,21,22}Ne, ^{23}Na, ^{24,25,26}Mg, ^{27}Al, ^{28,29,30}Si, ^{32,34}S, ^{35,37}Cl, ^{38,40}Ar, ^{38,39,40}K, ^{40,42,43,44,46,48}Ca, ^{46,47,48,49,50}Ti, ^{51}V, ^{50,52,53,54}Cr, ^{55}Mn, ^{54,56,57,58}Fe, ^{59}Co, ^{58,60,61,62,64}Ni, ^{63,65}Cu, ^{64,66,67,68,70}Zn, ^{74,76}Ge, ^{78,86}Kr, ^{84,86}Sr, ^{90}Zr, ^{92}Mo, ^{136}Xe, ^{197}Au, ^{208}Pb, ^{209}Bi, ^{232}Th, ^{238}U
Beam Energy	
Energy Range (end of LINAC)	4 MeV/A – 7,5 MeV/A
Energy dispersion	0,8% to 1%
Energy step	± few 100 keV
Time needed for E change	Few hours
Peak beam intensity	
Min	1 pnA
Max	>10-15 pμA for all ions (more if possible for some A/q)
Stability	±10 pnA
Time needed for I variation	minutes
Max experiment duration	weeks to months

Beam time structure specifications:		
Condition	Frequency	Bunch length
#1	between 1 Hz and 1 kHz	From 1 μs to CW
#2	≤MHz	500 ns to 1 μs (50% beam on-off)
#3	between 1 Hz and 100 kHz	from 0,5 s @ 1Hz to 1 μs @ 100 kHz
#4	MHz	$n \times 10$ ns[3]

[3] Regarding the time structure, a beam pulse width of few tens of ns separated by beam-off periods of the order of μs is needed for the Time-of-Flight (ToF) measurements in separator experiments in case transmission detectors cannot be employed.

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