Nuclear physics at GSI/FAIR

1. Introduction

One of the greatest challenges of contemporary subatomic physics is to understand the strongly interacting many-body system of the atomic nucleus. This requires investigating how the nuclear properties change when varying the number of protons and neutrons of the nucleus, its internal (excitation) energy and angular momentum. The advent of radioactive ion beam facilities has made possible to approach more and more the limits of existence of elementary matter: along the proton and neutron drip lines where protons and neutrons become unbound and in the region of heavy elements, the limit in mass and charge. Nuclear reactions are essential to produce exotic nuclei far from stability, to investigate ground-state nuclear properties, as well as to modify the excitation energy and angular momentum of the nucleus and study its structure and behavior under different conditions. The exploration of the nuclear landscape by varying the proton and neutron number has shown that established entities such as magic numbers cease to be valid when going towards the drip-lines; exotic shapes and decay modes appear, as well as new collective phenomena.

Nuclear physics is intimately related to astrophysical processes and the understanding of the elemental abundances in the Universe, and is also relevant for applications like nuclear medicine and the production of energy.

In this contribution we will describe different nuclear physics projects coordinated by IN2P3 researchers to be conducted over the next five years at the GSI/FAIR facility. The research topics of all the French projects are covered by the NUSTAR collaboration [NUS19], which is concerned with the study of NUclear STructure, Astrophysics and Reactions, and is one of the four pillars of GSI/FAIR.

2. The GSI/FAIR facility

The Facility for Antiproton and Ion Research (FAIR) is an international accelerator facility under construction in Darmstadt, Germany [FAI19]. It is based upon an expansion of the existing GSI Helmholtz Centre for Heavy Ion Research [GSI19]. The first important element of the GSI facility is the UNIversal Linear ACcelerator UNILAC. It provides beams of accelerated ions of elements from hydrogen to uranium with energies up to 11.4 A MeV. The UNILAC is used to send beams to experiments like the SHIP velocity filter or as injector of stable ions to the heavy-ion synchrotron SIS18, where the beams are further accelerated, up to 1 A GeV for ^{238}U. Secondary radioactive beams are produced via fragmentation and fission reactions at a primary production target. The secondary beams can then be identified and selected in-flight in the FRagment Separator (FRS) and transferred to the different experimental areas (e.g. cave C), as well as to the ESR storage ring, see Fig. 1.

The FAIR accelerator complex largely extends the current GSI facility, it will be unique by offering beams of all ion species and antiprotons at high energies with unprecedented high intensities (e.g. about 5×10^{11} p/s of ^{238}U at 1.5 A GeV) and quality (i.e. with very precise energy and very small emittance). As shown in Fig. 1, the FAIR facility has a number of additional components. A new storage ring already in operation, the CRYRING, is coupled to the ESR. Beams from the SIS18 synchrotron can be directly sent to the target station of the Superconducting Fragment Separator (Super-FRS) or be further accelerated via the new SIS100 synchrotron and sent to various beam lines for detailed spectroscopy and mass measurements. The Super-FRS provides a few times larger acceptance for radioactive isotopes as compared to the existing FRS at GSI, which together with the enhanced primary beam intensities, leads to an intensity gain factor of about 1000. Short-lived nuclei in the ground and excited states of all elements up to uranium will be delivered to two branches at the exit of the Super-FRS, see Fig. 1. The high-energy branch will lead to the R3B set-up where reaction studies with complete kinematics will be carried out. The low-energy branch (LEB) will lead to different experimental areas for high-precision in beam and decay spectroscopy such as HISPEC/DESPEC/gSPEC, as well as precision measurements with energy-bunched beams stopped in a gas cell such as MATS/LASPEC.

The HISPEC (High-resolution In-flight SPECtroscopy) setup will include the AGATA 4pi germanium-detector array [AGA19] to measure γ rays arising from nuclear states excited in the course of secondary reactions of the radioactive beams. France is part of the AGATA project, which will be discussed in a dedicated contribution of this scientific-council meeting.

To provide the increased energies and intensities and to ensure an appropriate injection into the SIS100, the UNILAC and SIS18 are being upgraded [Spi18]. The construction phase of FAIR is expected to end in 2025. Until the end of the construction of FAIR, the existing GSI facility will be operated to conduct experiments within the so-called «FAIR phase 0», which will benefit from the continuous upgrades and increased intensities.

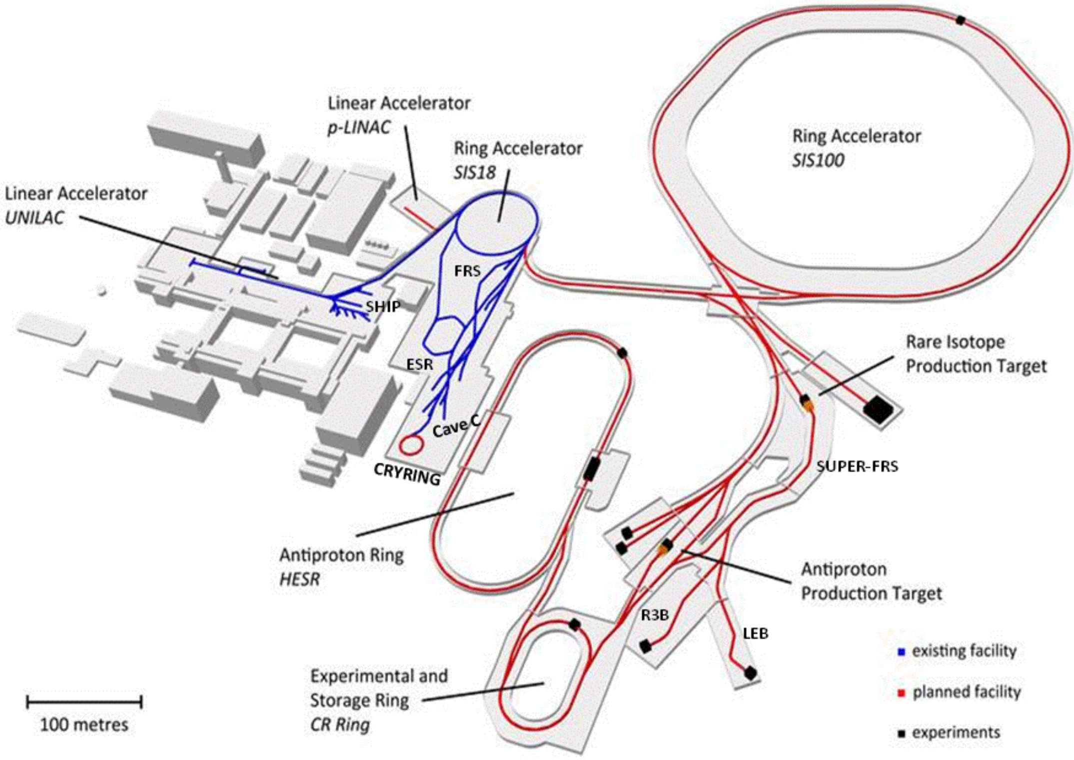

Figure 1: The GSI/FAIR facility, the existing GSI facility is shown in blue.

French scientists from the CNRS/IN2P3, CEA and French Universities work at GSI and on the planning and realization of FAIR since many years. France is one of the ten shareholders of FAIR. The CNRS and the CEA hold each half of the French shares, which accounts for 2.6% of the total FAIR shares. With its participation France enables its scientific community the access to FAIR. In this contribution, we will show that the GSI/FAIR facility offers unique possibilities for addressing a number of relevant open questions in nuclear physics, which will be described in the next sections.

3. French nuclear-physics experiments at GSI/FAIR

3.1. Insight into nuclear super-fluidity from di-neutron and tetra-neutron correlations towards the neutron drip line

Coordinator: O. Sorlin, GANIL

3.1.1. Motivation

Pairing interactions play a crucial role in atomic nuclei and in quantum many-body physics in general, and this, even if di-neutron or di-proton systems are not bound. Two-neutron and/or two-proton pairing are responsible for the odd-even staggering observed in the binding energy of atomic masses, for the fact that all even nuclei have a $J=0^+$ ground state, and for their small moment of inertia as compared to a rigid body. More generally, pairing correlations imply a smoothing of the level occupancy around the Fermi energy surface, an enhancement of pair transfer probabilities, as well as a superfluid behavior in the nuclear rotation and vibration. A transition from BCS (Bardeen Cooper-

Schrieffer) to BEC (Bose-Einstein Condensation) pairing correlations is expected as nuclei become more and more neutron rich [Hag07, Hag08].

We also wish to study if the Ikeda conjecture, proposed from the systematic observation of narrow resonant states with clustered structure close to the corresponding particle emission-thresholds, can be generalized to two- or four-neutron clusters [Oko12]. The presence of narrow 2n or 4n cluster states would, if revealed, probably impact the neutron-capture rates in accreting neutron stars, possibly favoring the synthesis of heavy elements.

3.1.2. Previous achievements

Despite its importance, the real observation of the decay of paired or tetra nucleons is still lacking. It is difficult to evidence, and this for two reasons. First, nuclei that would proceed through such type of decay are hard to produce, and second, the detection of multi neutrons is a very difficult task. As for the first point, we have recently proposed an innovative route to study neutron pairing, which consists of suddenly promoting neutrons of the studied nuclei into the continuum (out of the range of the nuclear force) by using knockout reactions on deeply-bound protons [Rev18]. The high-energy beams (500 MeV/A and higher) available at GSI/FAIR make this facility unique to ensure a quasi-free mechanism that, in the case of proton knockout, supposedly leaves the neutrons as they were prior to the reaction. Once in the continuum, we deduce their relative distance and multi-neutron correlations inside the nucleus from the study of their multi-body decay, see [Lau19] for a description of the method. The experimental results at GSI by [Rev18] were obtained from the measurement of the quadri-vectors (energy and momentum) of the incident and the residual nuclei, as well as of the neutrons, detected at that time in the Land detector. As a key result of our experiment, we have observed that the decay of the ^{18}C nucleus into ^{16}C + 2 neutrons exhibits an extremely high degree of neutron correlation, i.e. twice as large as the largest ever observed. The neutrons decay in about 90% cases as correlated pairs, up to an available energy of 12 MeV.

3.1.3. State of the art/perspectives

Despite the success of this previous work, we encountered several limitations. *First*, the granularity of the LAND detector limited the neutron energy resolution and did not allow the detection of four neutrons. Indeed, with the insufficient granularity, four neutrons were never seen as four, but rather as two or three neutrons. *Second*, the intensity of the secondary beams was not high enough to reach nuclei closer to the drip line, where a possible change of regime of the superfluidity to the BEC is expected.

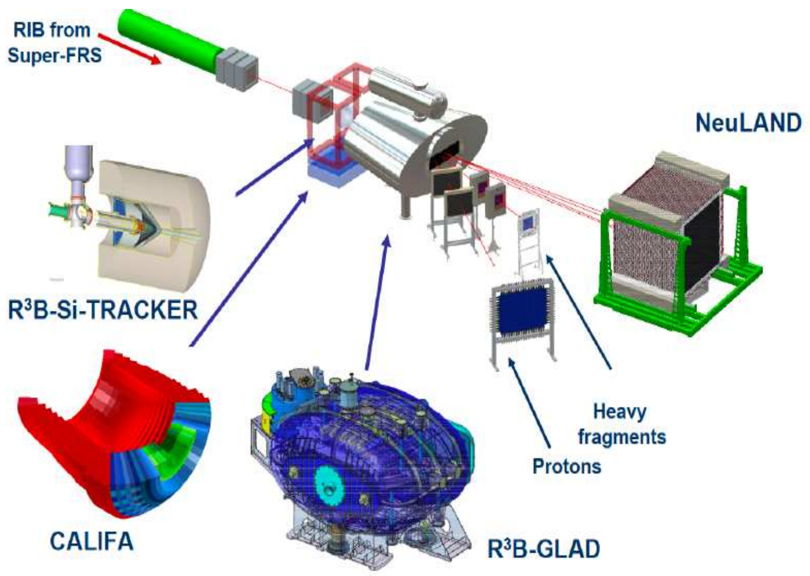

Figure 2: Schematic layout of the R3B set-up.

With the starting operation of the NeuLAND detector (see figure 2), the situation has already changed dramatically. Its increase in granularity leads to an improvement of the energy resolution by a factor of 3 and a further gain by a factor of 3 will be reached once the detectors will be placed at their final distance from the target in few years (35 meters instead of 13 meters). With this increased granularity, the detection of 4n correlations becomes possible. A detection efficiency for 4n multiplicities of about 10-20 % is expected with 12 panels of the NeuLAND detector, which is unique worldwide. The intensity of the primary beam ^{40}Ar is planned to be increased by a factor of 3 in a first step, before the starting of FAIR. To increase the luminosity (by a factor of about 8), we plan to use a 15 cm-thick Liquid Hydrogen (LH) cryogenic target, in construction at the CEA Saclay, to induce knock-out reactions and detect the vertex of the reaction in two-stages of Si-strips tracker detectors around the target.

We have an accepted proposal to study the evolution of pairing correlations (neutron-neutron distance and amount of direct decay) as a function of the proximity of the drip line for a cocktail of nuclei produced after the FRS, such as ^{14}Be, ^{17}B and ^{20}C. The other goal is to search for possible four-neutron correlations that would indicate a contribution to the description of the superfluid character of the nuclei. Finally, the much-improved energy resolution of the neutron detectors will allow us to study nuclear spectroscopy at the drip line and in particular the search of very narrow resonant state (linked to generalized Ikeda conjecture) close to the corresponding emission thresholds (2n or 4n).

3.1.4. Timeline and scientific production

2011: Participation to experimental campaign with Aladin/LAND

- **2016:** Study ^{26}F and probe the strength of the proton-neutron interaction, 1 publication
- **2018:** Neutron pairing in ^{18}C and ^{20}O, 1 publication (PRL)
- **2019:** The multiple facets of the ^{12}Be nucleus, PhD thesis, work in progress

2017: Proposal approved by the GSI PAC to investigate several nuclei close to the drip line

- **2020:** Expected schedule of the experiment

2021-…: Participation to experiments of the collaboration, new proposals to be presented.

3.1.5. Resources

There is so far neither technical implication nor financial contribution of the IN2P3 to the R3B project, even though we have strongly benefited from this collaboration (full access to data from the previous campaign, possibility to present a proposal at the GSI-PAC in 2017). There is also a significant investment by the CEA for the delivery of the LH target and mechanical supports.
The R3B line is not yet fully equipped. Due to major cuts in the budget, the CALIFA detector, supposed to detect gamma-rays around the target, as well as knocked out particles (mostly protons and neutrons), is not complete. Moreover, the NeuLAND detector is not yet completely funded as well. About 1/3 of the panels (8) are missing, which is a problem for the detection of 4n correlations that request the full detector to act as a calorimeter. It would be greatly appreciated by the R3B collaboration that the IN2P3 participation to R3B experiments would be associated to financial support of some of the missing detectors. For information, the purchase of 1 double panel (DP) of the NeuLAND detector costs 155 k€. It is also requested to pay 1 k€ per year per senior scientist with a student working on the data analysis, which we have not paid so far. This is a contribution to the running costs, in case there is a need to repair a detector.

Type	**2020**	**2021**	**2022**	**2023**	**2024**	**total**
NeuLAND double planes or Califa detectors	**30 (1)**	**30**	**30**	**30**	**30**	**150 k€**
Travel (k€)	**3 (2) +1.5 (3)**	**2.5 (3+4)**	**2.5 (3+4)**	**2.5 (3+4)**	**2.5 (2)**	**14.5 k€**
PhD (k€)		**40**	**40**	**40**		**120 k€**
Senior with student	**1**	**1**	**1**	**1**	**1**	**5 k€**
Total (k€)	**35.5**	**73.5**	**73.5**	**73.5**	**33.5**	**289.5 k€**

(1) Yearly contribution to buy 1 double plane of NeuLAND or two rings of CALIFA array in 5 years.
(2) For running our accepted experiment supposed to be scheduled in 2020.
(3) For 2 yearly R3B collaboration meetings (6 people in total).
(4) For the participation of the IN2P3 researchers to other experiments of the collaboration.

3.1.6. Human resources

Human resources	**2020 etp**	**2021 etp**	**2022 etp**	**2023 etp**	**2024 etp**	**Total etp**
Researchers **GANIL: F. de Oliveira, A. Chbihi, G. Verde** **LPC: M. Marques** **IPNO : M. Assié, D. Beaumel, F. Flavigny**	**0.8**	**0.2**	**0.2**	**0.8**	**0.2**	**2.2**
Spokesperson : O. Sorlin	**0.3**	**0.2**	**0.2**	**0.3**	**0.2**	**1.2**
PhD	**0.9**	**0.9**	**0.9**	**0.9**	**0.9**	**4.5**
Total etp	**2**	**1.3**	**1.3**	**2**	**1.3**	**8.9**

Note: It is assumed that the experiment proposed in 2017 will be scheduled in 2020. If any shift occurs, the human resources should be also shifted accordingly. Estimated time is for running experiments, attending R3B meetings, participating to tests or other experimental programs. It is assumed that another proposal will be deposited in the period (2021), with another experiment running in 2023. As for student's work, the time includes data analysis as well.

3.1.7. Competition with RIKEN

The secondary beam intensities at RIKEN are generally about 3 orders of magnitude larger than at FAIR0. Therefore, at GSI, we focus on nuclei that lie close or at the drip line, and not several units further away from the drip line as done at RIKEN (e.g. we study ^{17}B instead of ^{21}B). We propose to study the spectroscopy and decay modes of the ^{14}Be and ^{17}B nuclei at GSI. In spite of the fact that these two latter nuclei are bound in their ground states, the 2n and 4n thresholds lie at only around 2 and 5 MeV, respectively, making the observation of 2n and 4n correlations easily accessible experimentally with the NeuLAND detector. For the time being, the SAMURAI beam line at RIKEN no longer has a neutron detector of such efficiency, making the 4n decay study rather unique at GSI. However, neutron detectors are being constructed/tested at LPC-Caen, to be installed soon at RIKEN. Therefore, a long-term strategy on the study of nuclei at the drip-line and on multi-neutron correlations has to be established between the French teams (including LPC Caen) and the IN2P3 governance, concerning scientific activities at RIKEN and / or GSI.

3.2. Two-proton radioactivity

Coordinator: J. Giovinazzo, CENBG

3.2.1. Motivation

The 2-proton radioactivity is a very exotic decay mode that can occur for nuclei beyond the proton drip-line, with an even atomic number *Z*. Together with the 1-proton radioactivity (for odd-*Z* nuclei), the phenomenon was suggested in the 60's by theoretical prediction [Gol60]. The candidates for such a decay process, located in the *A*~50 mass region, were out of reach at that time, and the experimental observation of 2-proton radioactivity has been possible after the development of projectile fragmentation facilities and the associated fragments separators. The process was evidenced in the decay of ^{45}***Fe*** in experiments at GANIL/LISE3 [Gio02] and GSI/FRS [Pfu02] facilities in 2002.

For candidate nuclei, the last 2 protons are not bound by the strong interaction, but the ground state energy is below the Coulomb barrier, which gives the life-time of the emitter. In addition, they are correlated by the proton-proton pairing effect: a sequential emission of the proton is energetically forbidden, and the correlated protons have to be emitted simultaneously (Figure 3). After the emission by tunnel effect through the barrier, the sub-system (***p-p***, or ^{2}***He***) is unbound.

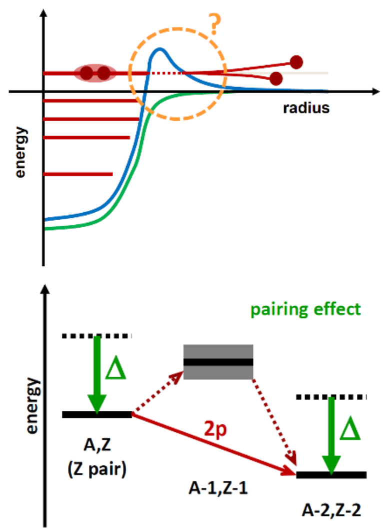

Figure 3: Schematic description of the 2-proton radioactivity decay process.

The study of this decay mode is directly related to the masses of nuclei beyond the drip-line (transition energy Q_{2P}), and to the pairing effect. Calculations performed in a theoretical 3-body framework [Gri08] show that the measured ***p-p*** correlation pattern is sensitive to the orbital configuration of the nuclei. This opens the path to structure studies of nuclei located beyond the drip-line. The experimental observation of 2-proton radioactivity induced several theoretical attempts to describe the phenomenon. Nevertheless, recent results have shown that these descriptions fail to reproduce the experimental results.

Today, only 4 long-lived emitters (in the *ms* range) are known: ^{45}***Fe***, ^{48}***Ni***, ^{54}***Zn*** and ^{67}***Kr***, that have been produced at GSI, GANIL, NSCL and RIKEN, respectively. Since the production rate increases significantly with beam energy, the GSI/FAIR facility (together with the FRS or Super-FRS), with high intensity beams at 1 A *GeV* (to be compared with 95 A *MeV* at GANIL, 160 A *MeV* at NSCL and 350 A *MeV* at RIKEN), offers new opportunities to produce and study possible candidate nuclei up to the ***Z*** = 50 region.

3.2.2. State of the art

The first observations of 2-proton radioactivity were performed using the standard implantation-decay technique in silicon detectors: the decay mode was established for ^{45}Fe first at GANIL and GSI [Gio02, Pfu02], then for ^{54}Zn at GANIL [Bla05], with also an indication for ^{48}Ni [Dos05]. Since the implantation in thick detectors does not permit individual measurements of the protons (that do not escape the detector), the process was evidenced indirectly through the global observables related to the decay: transition energy, half-life, branching ratio (in competition with β-delayed protons emission), decay of the daughter nucleus…

These "discovery" experiments triggered the development of time projection chambers (TPC) as implantation detectors, for a direct measurement of the relative energy and emission directions of the protons. This made possible the first direct observation of this decay process, at GANIL, in the case of ^{45}Fe [Gio07], using a TPC developed at CENBG [Bla08]. For the same nucleus, the first angular correlation pattern was measured at MSU [Mie07], which allowed for the first interpretation in terms of nuclear structure, based on the 3-body model. This experiment used an optical-readout TPC that was also used at NSCL in an experiment that could clearly establish the 2-proton decay of ^{48}Ni [Pom11]. The direct observation of the decay of ^{54}Zn was also achieved [Asc11]. For these 2 nuclei, with only few 2-proton decay events, the statistics did not allow for a precise enough angular distribution measurement. The half-life of the 2-proton emission process of these isotopes, related to the transition energy, was interpreted with a theoretical hybrid model by combining the dynamics description of the 3-body model [Gri08] and the nuclear structure from a shell model approach [Hon04], with fairly good results.

More recently, the 2-proton decay of ^{67}Kr has been established in an experiment at RIKEN [Goi16], using standard silicon detectors. In that case, the different theoretical formalisms fail to reproduce the experimental half-life by about 2 orders of magnitude. Two interpretations of this discrepancy have been proposed: (1) the decay of ^{67}Kr could be at the transition between a direct and a sequential decay, depending on the position of the intermediate resonance [Gri17], (2) the nucleus is located in a region where deformation occurs, which may strongly influence the decay width [Wan18].

Further experiments have been accepted for proton-proton correlations measurements in ^{48}Ni or ^{54}Zn at GANIL (^{48}Ni being doubly magic, with protons in the $f_{7/2}$ orbital), and in ^{67}Kr at RIKEN. This latter measurement should provide more constraints on the decay mechanism, in particular in the case of a sequential emission component. These experiments will be performed using the new ACTAR TPC device [Rog18, Gio18]. This device has been successfully operated in a recent experiment at GANIL (exp. E690) to observe proton decay from isomeric states in ^{54}Ni and ^{53}Co. The design of ACTAR TPC is well adapted for high-energy fragmentation beams such as the ones available at GSI/FAIR.

3.2.3. Objectives and perspectives

The purpose of this experimental program is to search for new candidates for the ground-state 2-proton emission in the region between the magic shells Z=28 (Nickel) and Z=50 (Tin) and, for the identified emitters, to perform proton-proton correlations studies. The candidates are proposed according to the estimates of the 2- and 1-proton separation energies Si_P: the best candidates have $S_{2P}<0$ and $S_{1P}>0$. This will allow us to collect a set of experimental information for nuclei with different structure configurations, across a region where deformation occurs.

The experiments will be performed at the FRS/Super-FRS facility, in two steps: (1) identification of new emitters using standard implantation-decay technique in silicon detectors: this can be achieved with the NUSTAR/DESPEC collaboration (decay spectroscopy) and (2) proton-proton correlation measurements using the ACTAR TPC.

Rough estimates [Bla17] suggest that unprecedented count rates can be obtained with various primary beams (considering 5×10^{11} pps):

- ~70 ^{48}Ni per day with ^{58}Ni beam;
- ~200 ^{67}Kr per day with ^{78}Kr beam;
- ~100 ^{71}Sr, ~60 ^{75}Zr, ~10 ^{79}Mo per day with ^{92}Mo beam;
- ~10 ^{98}Sn per day with ^{134}Xe beam.

These numbers will need to be updated with effective beam intensities available.

This program does not need specific instrumentation and detection. The search for ground state 2-proton emitters can be achieved with standard implantation-decay DSSSD telescopes (such as AIDA, but silicon detectors thinner than 1 *mm* would be preferred), surrounded by an array of gamma detectors. The proton-proton correlation experiments will use the ACTAR TPC. This only requires some technical work for coupling the TPC to the separator detection system (common trigger dead-time, time stamping…).

3.2.4. Timeline

The timeline is difficult to estimate since it strongly depends on the acceptance of the proposals by the GSI/FAIR advisory committee, and the scheduling of the requested beams. Considering the current program on this topic (at GANIL and RIKEN), it is unlikely that this program at FAIR could start before 2021 or 2022. We consider here that the experiment (beam time) could start in 2024.

We thus propose the following timeline:

- **2020-2023**, join the NUSTAR collaboration and submit the proposals for identification experiments, and the letter of intents for the correlation experiments;
- **2024-…**, perform identification experiments, and submit proposals for correlation experiments depending on the identified emitters; prepare the installation of the ACTAR TPC at GSI
- **2025-…**, install the ACTAR TPC device at GSI for the correlations experiments.

3.2.5. Requested resources

The project does not require any important investment for technical developments, since it may use available equipment.

type	2020	2021	2022	2023	2024	…	total
equipment					**10 k€ (ACTAR TPC coupling)**		**10 k€**
travel	**1 k€(1)**	**1 k€(1)**	**2 k€(1)**	**2 k€(1)**	**15 k€(2)**	**15 k€(2) / exp**	**36 k€ (up to 2025)**
PhD					**40 k€(3) × 3 years**	**40 k€(3)**	**120 k€**
total	**1 k€**	**1 k€**	**2 k€**	**2 k€**	**65 k€**	**…**	**166 k€**

(1) for meetings with the NUSTAR collaboration, proposals preparation and PAC meeting.
(2) for the participation of the IN2P3 researchers to the experiments: the year is an indication, but cannot be given precisely.
(3) a first PhD is requested for the participation and analysis of the first experiments, but another PhD will be needed for the ACTAR TPC experiments.

3.2.6. Human resources

The table below only includes the estimated participation of IN2P3 staff. The collaboration from foreign members, either currently collaborating on the 2-proton radioactivity program or members of the ACTAR TPC collaboration is reported in the last line.

	2020	2021	2022	2023	2024	2025+	total
Researchers							
- CENBG	**0.1**	**0.1**	**0.2**	**0.4**	**0.8**	**0.8**	**2.4**
- ACTAR TPC				**0.1**	**0.2**	**0.3**	**0.6**
- other IN2P3					**0.2**	**0.2**	**0.4**
Engineers							
- CENBG				**0.1**	**0.1**	**0.1**	**0.2**
- ACTAR TPC				**0.1**	**0.2**	**0.2**	**0.5**
PhD (if any)					**0.9**	**0.9 (+2026)**	**2.7**
Collab. from abroad (incl. ACTAR TPC)					**0.3**	**0.5**	**0.8**
Total	**0.1**	**0.1**	**0.2**	**0.7**	**2.7**	**3.8**	**7.6**

3.3. Nuclear moments

Coordinator: R. Lozeva, CSNSM

3.3.1. Motivation

Sensitive to the precise configuration of the nuclear states, nuclear magnetic moments are a fingerprint of the nucleus single-particle structure because they depend strongly on the nucleus orbital and total angular momentum, being connected to the nuclear spin via the g factors [Ney03]. Their investigation for exotic nuclei far from-stability provides extremely valuable information on the orbital evolution or any development of collectivity. This is particularly important, in the vicinity of doubly-magic nuclei, where moments can be the only measure of the unpaired-nucleon configuration of the emerging isomeric states [Ney03,Wol05]. Such information often comes from systematics or theoretical calculations and appears to be quite imprecise in barely explored regions. Isomeric states are particularly interesting because their existence often indicates orbital structure changes or other particular features in the de-excitation of the nucleus. In addition to the investigation of the shell evolution, nuclear moments can serve to reveal new nuclear structure or shape phenomena as well.

3.3.2. State of the art

Three key regions of the nuclear chart, rich of isomers and with unknown nuclear moments, are in the primary scope of the present project, called gSPEC: the ^{208}Pb, the ^{100}Sn as well as the ^{132}Sn region. They will be accessed by either heavy-ion fission or fragmentation at the GSI/FAIR facility. In particular, nuclei along Z=82 exhibit a variety of nuclear structures at low excitation energy and *g*-factor measurements will be probing this onset of collectivity and allow us to probe the competition between single-particle and collective excitations and search for their coexistence in some new phenomena. In the A~100 region, a very rapid increase of deformation is expected when varying both N and Z, which will be studied by measuring the valence-nucleon configuration of isomeric states. Besides the relevant single-particle structure and spin/parity assignments, we will investigate the intrinsic properties of the *M1* operator and its suggested quenching at the two extremes of isospin from ^{100}Sn to ^{132}Sn and beyond. Our pioneering works on *g*-factor measurements during the g-RISING campaigns at GSI [Ney03,Wol05,Ili10,Ata10] paved the way for these new investigations allowing 1) spin-aligned isomeric beams to be maintained in-flight and used for nuclear moment measurements 2) heavy-ions of up to A~200 to be fully stripped to allow no loss of orientation, which is a necessity for these investigations 3) nuclear states of different isotopes to be accessed and their wave-function content measured simultaneously, depending on the momentum selections using both fission and fragmentation reactions to produce these cocktail beams [Wol05,Ili10,Ata10,Kmi10]. Employing the highly-performant TDPAD technique when implanting the nuclei in a magnetic field environment, we will measure very exotic nuclei for the first time thanks to the highly-improved beam quality and intensity, and the much better experimental conditions at FAIR [FAI19]. The gSPEC project is tightly linked to HISPEC/DESPEC project and part of the NUSTAR collaboration [NUS19] at FAIR.

3.3.3. Objectives and Perspectives

To meet the scientific and technical goals of our project we plan to proceed in several stages, consisting of 1) full simulations and detector development; 2) design study, preparations of the setup and in-beam tests and 3) experimental campaigns.

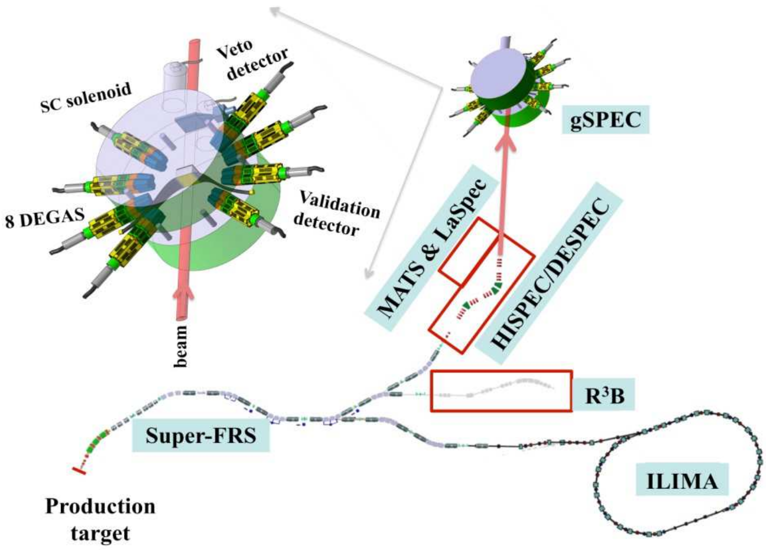

Figure 4: The gSPEC setup at the Super-FRS at FAIR. Similar positioning at the FRS at GSI will be used during the commissioning phase of the project. The main gSPEC setup consists of an electromagnet (SC solenoid), system of HpGe detectors and an ancillary set of detectors as shown in the inset.

Performing dedicated investigations requires the construction of a specific new setup, with measurements in a high magnetic field environment (see Fig. 4). This includes the use of a high-field electromagnet and two types of ancillary detectors for validation and veto of the implanted heavy-particle beam. The magnetic device needs to be well adapted to all physical conditions at GSI/FAIR, including widely-distributed secondary beams, which results in a relatively large cryogenic system.

Our objective is to use a new specially designed superconducting (SC) solenoid, which has already been discussed with suppliers. Its design and production is one of the technical challenges and can serve for all types of measurements planned, and very importantly, can allow very small g-factors to be accessed for the first time. Challenging task by itself, we have started the design study. Provided financial help is available, it can be terminated and produced for gSPEC by 2021, for installation and commissioning in 2022. Carried out by CSNSM, this is considered as the main contribution to gSPEC, associated with DESPEC and part of NUSTAR. The High-purity germanium (HpGe) detectors with a new DEGAS design are developed in close collaboration with GSI and will be provided by partners. Our objective is to perform a specific modification in their cryostats, which according to our simulations, will perfectly suit to gSPEC and the increase of detection efficiency. Such modification is being discussed with our TIFR collaborators, involved in DESPEC and gSPEC.

We foresee to test the DEGAS detectors during the DESPEC campaigns in 2020 and 2021. A modification of our standard setup, subject of multiple collaboration LoIs, requires coupling to existing LaBr3 detectors provided by partners. We have evaluated that these possibilities enlarge the feasibility of gSPEC over the entire chart of nuclei. Together with the ancillary-detector R&D and prototype tests, detailed simulations associated with the project will be performed as soon as possible by a postdoc, foreseen for the project. Our next objectives are preparing the Technical Design Report (TDR) and sending the MoU/LoI of the collaboration to the PAC calls on dedicated experimental runs. In-beam tests of the assembled system are expected to start in 2022, followed up by the commissioning experiment and running the experiment campaigns in 2023-2024 with phase-0. With the further increase of beam intensities, gSPEC will continue in phase-1. Additionally, we consider expanding nuclear moment investigations to the-more-difficult quadrupole moments (providing information on the nuclear shape [Loz11]). The project is foreseen beyond 10y scale and represents a collaboration of scientists from French and international institutions [Loz19], allowing large international cooperation and serious impact on the nuclear physics investigations of exotic nuclei.

3.3.4. Timeline and Scientific production

2017: Start of feasibility studies+magnet design at CSNSM; Kickoff gSPEC, FAIR-France meetings;
2018: P2I vis. grant CSNSM; NUSTAR-Annual meeting; First gSPEC collaboration workshop (RL)
2019: Feasibility studies, simulations of new detector configurations/setups; collaboration agreement CSNSM-GSI; NUSTAR Annual meeting; Hyperfine community meeting (HI19)
2020-2021: TDR, LoI, experimental proposals to GSI/FAIR PAC and construction of set-up
2022 -2023: Detector tests, Commissioning at FAIR-0 (campaign)
2024-2025+: Realization of FAIR-1 experimental campaigns, data analysis, and publication of results
We have organized visio-conferences and presented this project in several meetings/workshops/conf. The first gSPEC publication is online [Loz19], another detailed one is in preparation. Many future articles are expected during the set-up development tests and after the experimental campaigns.

3.3.5. Requested resources

Type of budget	2020	2021	2022	2023	2024	Total
Equipment	**120 k€ detectors (ancillary)+ design magnet**	**780 k€ magnet**	**50 k€ detector+magnet manipulators**	-	-	**950 k€**
Running costs	**10 k€**	**10 k€**	**10 k€**	**10 k€**	**10 k€**	**50 k€**
Travel	**15 k€**	**15 k€**	**15 k€**	**20 k€**	**10 k€**	**75 k€**
Personnel	**PostDoc (75 k€)**	**PostDoc (75 k€)**	**PostDoc+PhD (115 k€)**	**PhD (40 k€)**	**PhD (40 k€)**	**345 k€**

Total	220 k€	880 k€	190 k€	70 k€	60 k€	1420 k€

Important: The total cost of equipment is estimated to 1420 k€ [Loz19], the requested equipment would allow carrying a commissioning experimental campaign in case the ANR/ DFG application for 2020 is not successful.

3.3.6. Available human resources: PhD, post-doc and IN2P3 permanent staff

[etp]	2020	2021	2022	2023	2024	Total
PhD (incl. dem.) **Postdoc (dem.)**	**0.4** **1**	**0.3** **1**	**1** **1**	**1**	**1**	**3.7** **3**
Perm. Researchers *(IN2P3)* ***CSNSM*** *R. Lozeva, G. Georgiev, J.Ljungval* ***IPNO*** *D. Yordanov, V. Manea, S. Franchoo* ***GANIL*** *J.C. Thomas*	**1.6**	**1.8**	**2**	**2**	**1.7**	**9.1**
Engineers **(***Mechanics/ Detectors/ Electronics/ Magnetics)* ***CSNSM*** *H. Ramarijaona* ***IPNO*** *G. Hull, T. Nguyen Trung* ***LAL*** *V. Puill, C. Vallerand*	**0.7**	**0.8**	**0.8**	**0.6**	**0.5**	**3.4**
Perm. Collaborators from abroad ***GSI*** *J. Gerl, M. Gorska, P. Boutachkov* ***ANU*** *A. Stuchbery, G. Lane, T. Kibedi* ***TIFR*** *R. Palit, S.N. Mishra* ***U. Athens*** *T. Mertzimekis*	**1.5**	1.6	**2**	**2**	**2.2**	**9.3**
Eng. from aboad ***GSI*** *I. Kojouharov, H. Schaffner* ***ANU*** *A. Akber* ***TIFR*** *D. Rajneesh* ***U. Athens*** *G. Zagoraios*	1.5	2.3	2.5	**2.2**	**2.2**	**10.7**
Total IN2P3 **(incl. Collaborators from abroad)**	**3.7** **(6.7)**	**3.9** **(7.8)**	**4.8** **(9.3)**	**3.6** **(7.8)**	**3.2** **(7.6)**	**19.2** **(39.2)**

Important: This project has large international participation [gSP18] with core-group researchers and engineering staff from GSI, ANU, TIFR, U. Athens; and some CEA/IRFU participation, in the framework of NUSTAR (W. Korten). Implication of all quoted researchers/staff for 2024+ can be considered similar or higher.

3.4. High-precision decay-probability measurements at storage rings

Coordinator: B. Jurado, CENBG

3.4.1. Motivation

Understanding the de-excitation process of medium-mass and heavy exotic nuclei at excitation energies of about 10 MeV is important for fundamental nuclear physics. In this excitation-energy range, an excited heavy nucleus decays via different competing channels: γ-ray emission, particle emission (e.g. neutrons or protons) and fission (split into two lighter nuclei). The de-excitation process is ruled by fundamental properties of nuclei such as level densities, γ-ray strength functions, particle transmission coefficients and fission barriers. However, when no experimental data are available, the existing nuclear-structure models give very different predictions for these properties [Arn03].

This lack of knowledge strongly hampers our understanding of the synthesis of elements, which are formed by nuclear reactions in different stellar environments. Of particular importance are neutron-induced reactions on short-lived nuclei, which occur during the slow and rapid neutron capture process. These two processes are responsible for the formation of most of the nuclei heavier than iron. The predictions of the neutron-induced cross sections of interest can differ by as much as two orders of magnitude or more, and their measurement is very difficult because neither the radioactive nucleus nor the neutron can serve as a target. Neutron cross sections of short-lived nuclei are also relevant for the design of new-generation nuclear reactors.

The most promising way to access these cross sections is to use surrogate reactions (few-nucleon transfer or inelastic scattering reactions) to produce the nuclei formed by the neutron-induced reactions of interest and to simultaneously measure all the decay probabilities (fission, neutron and γ-ray emission). The measured probabilities are very useful to constrain the models and enable accurate predictions of the desired neutron cross sections [Esc12].

3.4.2. State of the art

The CENBG collaboration has so far used transfer and inelastic-scattering reactions induced by light projectile nuclei in direct kinematics to form nuclei near stability and simultaneously measure the fission and γ-emission probabilities [Duc16, Per19]. Our work has shown that the differences in the angular momentum populated by the neutron-induced and surrogate reactions have to be taken into account. This is complicated and the studies done so far are not sufficient to establish surrogate reactions as a standard tool to infer neutron cross sections in regions where no data exist. This requires building the systematics of decay probabilities over isotopic chains involving nuclei in various mass regions and different reactions. These systematic studies cannot be performed in direct kinematics because of the following limitations: (a) Unavailability of targets from short-lived nuclei. (b) High background from the competing reactions with the target contaminants and backing. (c) The heavy products of the decay of the excited nucleus are stopped in the target and cannot be detected with particle detectors. Therefore, the measurement of γ- and neutron-emission probabilities in direct kinematics relies in the detection of the γ-rays or the neutrons emitted by the excited nucleus, which is very difficult due to the very low detection efficiencies. The limitations (a) and (c) can be elegantly overcome by doing the measurement in inverse kinematics in single-pass experiments, where the heavy radioactive beam passes through a thick target of light nuclei. However, the quality of radioactive beams is too poor and the straggling in the target is too large to allow for an accurate measurement of the emission angle of the reaction residues. The accurate determination of this angle is essential for deducing the excitation energy of the excited nucleus with sufficient precision (few 100 keV). In addition, thick targets often have windows, leading to an unwanted background.

Heavy-ion storage rings offer unique and largely unexplored opportunities to investigate surrogate reactions in inverse kinematics. In a storage ring the heavy ions revolve with high frequencies and pass repeatedly through an electron cooler, which will greatly improve the beam quality and maintain it after each passage of the beam through the internal gas-jet that serves as ultra-thin, windowless target. Under these conditions the emission angle can be accurately measured and the target-window issue is solved.

The GSI/FAIR facility has pioneered and is world-wide leader in the construction and operation of heavy-ion storage rings. GSI/FAIR is the only facility worldwide where two heavy-ion storage rings are connected together (CRYRING@ESR). The ESR is used to slow down and cool the beams that are then injected into the CRYRING, which is optimized for the storage of ions at low energies. The combination of the CRYRING with the ESR is particularly interesting since the CRYRING is used to perform the measurements with the fully stripped, cooled ions, while the ESR prepares the next ion bunch. In this way, no time is lost in the preparation of the beam. The storage of heavy ions needs to ensure a minimum of atomic reactions between the stored beam and the residual gas inside the ring. Therefore, heavy-ion storage beams are operated in ultra-high vacuum (UHV) conditions (10^{-10} to 10^{-12} mbar). This poses severe constraints to in-ring detection systems. For this reason nuclear reactions have started to be measured only very recently at the ESR [Mei15,Glo19].

3.4.3. Objectives

Our objectives are to develop a setup and a methodology to simultaneously measure fission, γ and neutron-emission probabilities induced by surrogate reactions in inverse kinematics at the CRYRING storage ring, and to conduct a first experiment with a ^{238}U beam at 11 A MeV on a deuterium gas-jet target, see [Jur19] for all the details on the project. Even though the physics of this project is clearly within the topics covered by the NUSTAR collaboration, this project is part of the APPA/SPARC collaboration [SPA19], which has a very strong link to the storage rings of GSI/FAIR

The detection system, see figure 5, consists of a particle telescope to identify and measure the kinetic energies and angles of target-like nuclei; a fission detector to detect fission fragments in coincidence with the telescope and a heavy-residue detector to detect projectile-like nuclei produced after γ emission or neutron emission in coincidence with target-like residues. The latter detector is placed after two of the dipoles of the ring, which will separate the beam and the heavy residues according to their magnetic rigidity. We propose original options to cope with the very demanding in-ring vacuum conditions like the use of solar cells, which appear to be a very interesting and cost-efficient alternative to the typically used silicon detectors.

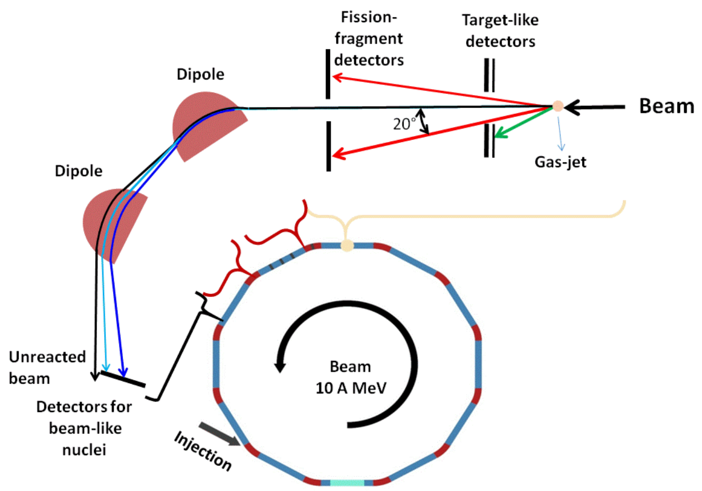

Figure 5: The upper part shows a schematic view of the experimental setup to be developed. The trajectories of the beam-like residues produced after γ and neutron emission are shown in light blue and blue, respectively. They are detected after the second dipole downstream from the target. The CRYRING storage ring is shown in the lower part.

We have performed detailed Geant4 simulations of the set-up that give very positive results. They show that it will be possible to reach an excitation energy resolution of about 300 keV and detection efficiencies close to 100%, much larger than the efficiencies obtained in direct kinematics. These outstanding conditions can only be achieved at the CRYRING. Thus, this work will be the seed of a fruitful long-term program to indirectly measure neutron cross sections of many unstable nuclei (e.g. from fragmentation of a ^{238}U primary beam) available as beams at GSI/FAIR.

3.4.4. Timeline and scientific production

2017: Start of feasibility studies, presentation of the project at the CENBG Scientific Council with the conclusion: *"The scientific council strongly supports this project and their funding request."*
2018: Detailed feasibility studies at GSI within EMMI visiting professor-ship of B. Jurado
2019: Project awarded with a Marie Curie post-doc fellowship and an international PhD of the CNRS, applications sent to French/German funding agencies ANR-DFG and to the ERC (Advanced Grant).
2020-2022: Submission of experiment proposal to the GSI/FAIR PAC and construction of set-up
2023-2024: Realization of first experiment, data analysis and publication of results
We have presented this project in more than 15 workshops and are preparing an article on the use of solar cells, many articles are expected during the set-up development and after the experiment.

3.4.5. Requested resources

Type of budget	**2020**	**2021**	**2022**	**2023**	**2024**	**Total**
Equipment	**380k€ detectors and electronics**	**420k€ reaction chambers and manipulators**	**200k€ beam monitors**			**1030 k€**
Travel	**10 k€**	**10 k€**	**10 k€**	**20 k€**	**10 k€**	**60 k€**
Personnel			**PhD (40 k€)**	**PhD(40 k€)**	**PhD(40 k€)**	**120 k€**
Total	**390 k€**	**430 k€**	**250 k€**	**60 k€**	**50 k€**	**1180 k€**

Important: We have applied for funding to the ANR-DFG and ERC in 2019. In case any of these applications is successful, our requested resources to the IN2P3 will be drastically reduced. See [Jur19] for the details on the needed resources.

3.4.6. Available human resources: PhD, post-doc and IN2P3 permanent staff

	2020 etp	**2021 etp**	**2022 etp**	**2023 etp**	**2024 etp**	**Total etp**
International PhD CNRS CENBG	**1**	**1**	**1**			**3**
Marie Curie postdoc A. Henriques CENBG	**1**	**0.6**				**1.6**
Permanent IN2P3 researchers **CENBG: B. Jurado, L. Mathieu, I. Tsekhanovich, CR** **IPNO: L. Audouin**	**1.1**	**1.25**	**1.25**	**1.5**	**0.7**	**5.8**

Mechanical Engineer T. Chiron CENBG	**0.5**	**0.5**	**0.5**			**1.5**
Electronics Engineer J. Pibernat CENBG	**0.6**	**0.6**	**0.6**	**0.5**		**2.3**
Instrumentation Engineers B. Thomas, P. Alfaurt CENBG	**0.3**	**0.3**	**0.4**	**0.3**		**1.3**
Total ETP	**4.5**	**4.25**	**3.75**	**2.3**	**0.7**	**15.5**

Important: We insist that the above resources are already available; an additional PhD student would increase the total ETP to 17.5. Besides, the project evolves within a strong international collaboration with the GSI/FAIR, the University of Frankfurt and the Max-Planck Institute of Nuclear Physics in Heidelberg. There is also a strong collaboration in France with the CEA. See [Jur19] for the details on the collaboration.

3.5. High-precision nuclear fission studies with SOFIA

Coordinator: L. Audouin, IPNO

3.5.1 Motivation

Fission fragments are a remarkable window on nuclear fission and nuclear structure. Furthermore, many fragment-related observables such as isotopic yields, recoil energy or neutron yields have a direct interest for energy applications, since they impact macroscopic quantities such as the prompt energy, the residual heat and the radiotoxicity of the fuel, or the reactivity of the core. Although fission-fragment mass yields are generally well-known, only a few data exist for isotopic yields. Furthermore, outside of the region of long-lived actinides, data on fission become extremely scarce. Measuring fission on exotic systems would provide a stringent test for models of fission and strongly improve our general knowledge of the nuclear dynamics, while improving the precision and range of nuclear data is very important for the development of new options for nuclear energy. For example, several questions remain pending, such as the origin of asymmetric fission in actinides whose fission-fragment yields are centred at Z=54. This stability at Z=54, has been explained only recently as being due to the softness against octupole deformation of nuclei around Z=54 [Sca18]. Also, the asymmetry observed for very light systems such as ^{180}Hg [And10] can only be understood based on collective effects from the father nuclei [War12]. In order to bring new elements on these subjects, the SOFIA collaboration intends to produce data of unprecedented quality for a large variety of fissioning systems, many of them never-measured previously.

3.5.2 State of the art

An enduring challenge in fission experiments is to reach exclusive measurements, in which both fragments would be fully identified (mass and charge) and the fissioning system would be fully characterized (mass, charge, excitation energy, spin). Direct kinematics measurements offer a complete control on the incident energy; but in spite of recent progresses (especially from the FIPPS array at Lohengrin), they only bring partial information on charges and have a very limited range of systems to explore. The advent of inverse kinematics in the 90s has brought two major innovations: high-precision measurements of nuclear charges and access to a wide range of systems by means of radioactive beams. The previous SOFIA measurements can be considered as state-of-the-art in this field, since they present an unprecedented resolution on nuclear charge and are the only experiments world-wide able to direct identify both fragments in mass and charge. Combined to the identification of the fissioning system, it allows the measurement of neutron yields on an event-by-event basis. The missing parameter in this case is the excitation energy: it is not measurable due to the use of Coulomb excitation. Note that the SOFIA setup is highly complementary with the recent VAMOS fission experiments [Rod14], in which only one fragment is fully identified, but where the detailed reconstruction of the kinematics allows to characterize the fissioning system and its excitation energy.

3.5.3 Objectives and method

The aim of the SOFIA collaboration is to provide high-precision data on isotopic yields for a very large range of nuclear systems, including exotic, short-lived nuclei. To reach this goal, the inverse kinematics technique is used: the fissioning system is the beam. Due to the high velocity of the centre of mass, the fission fragments are strongly forward-focused in the laboratory frame, thus allowing their full identification (mass and charge) within a magnetic recoil spectrometer. Such an experiment is only possible at GSI, the sole facility worldwide where relativistic uranium beams are available. Practically, we take advantage of the secondary beam production by the Fragment Separator (FRS), using a primary ^{238}U beam at 1 A GeV. The nuclei of interest are directed into the cave C where the SOFIA setup is installed, thus allowing the study of isotopes with half-life as short as a millisecond. The fission is triggered in-flight by an electromagnetic interaction on a uranium or lead target. The choice of this interaction mode, rather than a nuclear collision, is motivated by its very large cross section and the low excitation energy it provides: 14 MeV on average, a range in which the structure effects still play a decisive role, and close enough to the excitation induced by a thermal neutron – hence, relevant for applications. The downside is the absence of precise information on the excitation energy on an event-by-event basis: only the global energy distribution is known.

The SOFIA setup revolves around the large-acceptance GLAD magnet, see Fig. 6. It includes 9 detectors (possibly more in the future), to track and identify both the secondary beam and the 2 fission fragments.

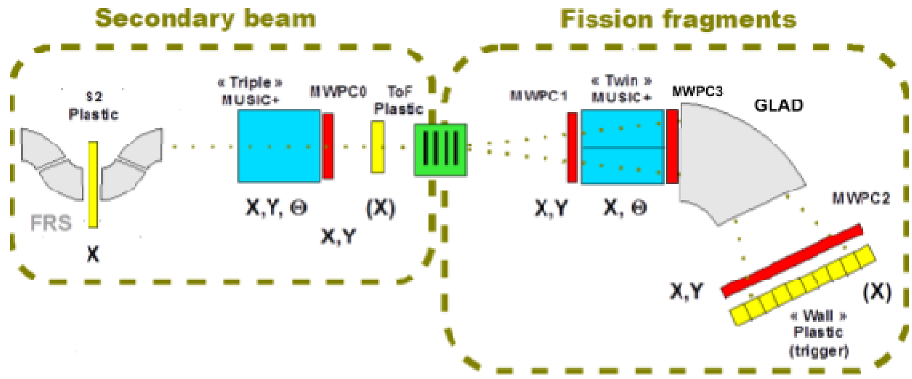

Figure 6: Schematic view of the SOFIA setup. The active target is shown in green, plastic detectors (time of flight and position) in yellow, MWPC (position) in red, ionization chambers (energy loss and tracking) in blue.

The mass and charge identification process is similar for all nuclei: the charge is derived from the energy loss in an ionization chamber, and the mass is derived from the measurement of the magnetic rigidity, time of flight, and charge. The high velocity of the fragments allows for a perfectly clean charge identification (full separation of peaks is achieved). The mass measurement is more challenging: the excellent precision obtained ($\Delta A/A$ as low as 0,55 FWHM) relies on cutting-edge performances on the time-of-flight measurement (resolution better than 30 ps FWHM is routinely achieved).

While CEA-DAM has the leadership of the project, the CNRS/IN2P3 is an essential contributor, with a strong involvement and visibility. IPNO is responsible for the position detectors, namely multi-wires chambers MWPC; they were entirely designed and built locally. Similarly, CENBG is operating the active target. These systems are upgraded between each campaign. For example, the electronics of the MWPC are currently in full refurbishment: one of the chambers has been significantly upgraded mechanically and an additional chamber will be built for the next experiment, scheduled in March 2020. The performance and flexibility of these MWPC are such that it has attracted interest from the Super-FRS community.

SOFIA is not a new project per se: two experimental campaigns already took place (2012 and 2014). The first served as a demonstration for the method [Pel17] and provided data on a wide range of isotopes in the Th-U region. Remarkable consistency was obtained with the sole previous charge yields measurement [Sch00], and the data on the Thorium chain [Cha19] offers insight of a new fission mode. The second campaign was dedicated to a very high-precision measurement of ^{236}U*, the analogue of ^{235}U+n reaction, the most important reaction in nuclear reactors. A third campaign is now scheduled for March 2020, with the ambition to explore fission near the very neutron-deficient Hg isotopes, where fission data are extremely scarce. The 2020 campaign should include two additional fission experiments, one dedicated to a first demonstration of a measurement devoted to energy-dependence of the reaction mechanism; and the other to nuclear astrophysics.

The in-depth exploration of the effect of the excitation energy will be the next step in the fission studies. This would be achieved by coupling the SOFIA setup to a major instrument of R3B, the CALIFA array. Using a hydrogen target, CALIFA allows to measure the excitation energy using (p,2p) reactions as fission trigger, with a resolution expected to reach 1 MeV. Such coupling should be demonstrated in 2020 using primary beam, and a more complete experiment is expected in later years using secondary beams.

Additionally, coupling the NeuLAND detector would allow to directly track neutrons and therefore to assign them to fission fragments, thus permitting further testing of the energy-sorting mechanism [Sch10].

Finally, an exciting challenge for the upcoming years is the use of a ^{242}Pu primary beam, which would allow to study the fission of the whole U-Pu region, most notably ^{240}Pu* (analogue of ^{239}Pu+n, the main reaction of the U/Pu fuel cycle): high-precision data for these nuclei are of paramount importance for nuclear energy. The development of a Pu beam is a major challenge in terms of radioprotection, but the idea is not regarded as out-of-range anymore. One should note that many experiments could also benefit from such a beam, which will necessarily be a one-time opportunity because of the heavy decontamination that will follow its use. However, the technical study for this specific project is not detailed enough to write down a budget or a schedule.

3.5.4 Timeline

2012: First campaign to study the U-Th region (SOFIA-1)
2014: Second campaign focussed on ^{236}U (SOFIA-2)
2020: Construction of a MWPC, revamp of the readout of all MWPC, SOFIA-3 experiment (dedicated to the study of the transition toward asymmetric fission in very neutron-deficient nuclei). Data analysis.
2021: Data analysis
2022: Preparation of the SOFIA-4 experiment (dedicated to the influence of excitation energy on the fission yields for a range of nuclei, possibly the Th chain)
2023: SOFIA-4 experiment and data analysis.
2024: Data analysis and possibly development of the Pu beam

3.5.5 Requested support

The overall investment cost is limited since the SOFIA setup is already a reality. Therefore, only improvements are foreseen.

Type of budget	2020	2021	2022	2023	2024	Total
Equipment	**65 k€ (detectors and electronics)**		**20 k€ (mechanics)**			**85 k€**
Travel	**8 k€**	**2 k€**	**4 k€**	**15 k€**	**10 k€**	**39 k€**
Personnel			**Post-doc (1) (50 k€)**	**Post-doc (1) (50 k€)**		**100 k€**
Total	**73 k€ (2)**	**2 k€**	**74 k€**	**65 k€**	**10**	**224k€**

(1) Considering the lack of manpower at IPNO on the topic of fission, a postdoc position is clearly a priority. Since the 2020 experiment is now a close perspective, we assign it for the next-in-line SOFIA measurement.

(2) Due to the large magnetic field leak of GLAD, an additional MWPC will be built for the 2020 campaign. The largest part of the budget corresponds to a full replacement of the readout of these detectors (1000 channels total). In addition, the 2020 campaign requires a strong presence at GSI.

3.5.6 Human resources

The present human resources dedicated to SOFIA in terms of permanent researchers are fairly limited (mainly 1 MCF at IPNO). While the visibility and impact of CNRS would clearly benefit from an increase in human power, the CNRS has well-identified, non-replaceable responsibilities in the collaboration and gains weight due to the involvement of its technical services.

	2020 (etp)	2021 (etp)	2022 (etp)	2023 (etp)	2024 (etp)	Total (etp)
PhD (expected from Graduate School of Saclay)		**1**	**1**	**1**		**3**

Post-doc (CNRS)			**1**	**1**		**2**
Permanent researchers : **L. Audouin (IPNO)** **B. Jurado (CENBG)**	**0.6**	**0.5**	**0.5**	**0.5**	**0.5**	**2.6**
Instrumentation engineers : J. Bettane, L. Vatrinet (IPNO)	**0.50**		**1**			**1.5**
Electronics Engineer : T. N. Trung (IPNO)	**0.20**					**0.2**
Instrumentation technicians : **M. Imre, L. Seminor, B. Geoffroy (IPNO)**	**1**		**2**			**3**
Total	**2.3**	**1.5**	**5.5**	**2**	**0.5**	**12.3**

3.6. High-resolution laser spectroscopy of Super-Heavy Nuclei

Coordinator: N. Lecesne, GANIL

3.6.1. Motivation

Despite of the prediction of a so-called island of stability, characterized for superheavy nuclei (SHN) by the next proton and neutron shell closures beyond ^{208}Pb, already in the mid-sixties of last century [Sob66, Mel67], the quest for superheavy elements (SHE) is still at the forefront of interest in nuclear chemistry, nuclear and atomic physics research activities. This is illustrated and underlined in [Dul15], covering all aspects of SHE research, and some more recent reviews on SHE synthesis [Oga17] and SHN structure features [Ack17].

The nuclear properties of quantum mechanical origin (shell effects) allow for the stability of SHN beyond Z=100-104. They make the synthesis of nuclei with up to 118 protons possible and are the basis for predictions of the existence of even heavier systems with higher atomic numbers. These features manifest themselves in trends towards high Z of nuclear deformation, metastable states (K-isomers) and other single particle and collective nuclear properties. Some quantities, like nuclear quadrupole moments, charge radii, etc. can be investigated by employing complementary atomic physics methods, such as precise mass measurements in Penning traps [Ram12] and, in particular, laser spectroscopy as highlighted by the first observation of an optical transition in nobelium (Z=102) [Laa16].

The variation of the spectral energy of a given atomic excitation along a chain of isotopes as well as the hyperfine structure (HFS) splitting for isotopes featuring a non-zero nuclear spin (I≠0) has been investigated for $^{252-254}$No [Rae18a]. Those measurements provide access to observables like magnetic and quadrupole moments, and isotope shift, revealing the character of the underlying nuclear configuration. In particular K-isomers combining single particle with collective properties are ideal to benchmark nuclear models, as they are formed by single or multiple 2-quasi-particle excitations built on the basis of an axially deformed nucleus [Mel67].

3.6.2. State of the art

High-resolution optical measurements of the atomic level structure readily yield fundamental and model-independent data on nuclear ground and isomeric states, namely changes in the size and shape of the nucleus, as well as the nuclear spin and electromagnetic moments [Cam16]. Laser spectroscopy combined with on-line isotope separators and novel ion manipulation techniques provides the only mechanism for such studies in exotic nuclear systems.

One challenge is to access the heavy element region of the nuclear landscape, which exhibits rather scarce information from optical studies. This reflects a combination of the difficulty in producing such elements (low production cross sections) and a lack of stable isotopes (thus few optical transitions available in literature). Indeed, the past years have seen a number of exciting developments including optical studies of exotic atoms produced at the level of one atom-at-a-time [Laa16], and high-resolution spectroscopy in supersonic gas expansions [Fer17].

Laser spectroscopy on nobelium was performed in the RADRIS experiments U290 and U293 behind the velocity filter SHIP at GSI. In these experiments an optical $1S_0 \rightarrow 1P_1$ ground state transition in nobelium has been identified for the first time [Laa16]. This transition has been measured for the isotopes ^{252}No, ^{253}No, and ^{254}No. From the obtained isotope shifts in combination with atomic calculations the change in the mean square charge radius has been deduced. This shows that nobelium features a maximal deformation in this region as predicted by nuclear-model calculations and results of in-beam data for nuclear excitations of rotational bands beyond 20 ħ. Further investigations employing laser spectroscopy at SHIP will concentrate on more exotic nobelium isotopes and on the extension of laser spectroscopy towards the next heavier element Lr (Z=103). However, the technique suffers from limitations regarding resolution and the half-life of the investigated nuclides. These limitations can be overcome by performing laser spectroscopy in the gas jet as it was demonstrated recently on-line for short-lived Ac isotopes [Fer17]. A new set-up realizing this concept at the velocity filter SHIP has been designed for high-resolution spectroscopy on short-lived isotopes and isomers and is part of this project as described below.

3.6.3. Objectives

To achieve a higher spectral resolution for the laser spectroscopy in the gas jet effusing from the gas cell, an advanced setup is presently being implemented at the velocity filter SHIP at GSI/FAIR [Rae18b] (see fig. 7). We propose to provide the 10kHz pump laser for the high repetition rate narrow bandwidth laser system that is needed for this purpose. A similar configuration will be implemented in the near future at the super separator spectrometer S^3 low energy branch (S^3-LEB) presently under construction at SPIRAL2 of GANIL [Fer13].

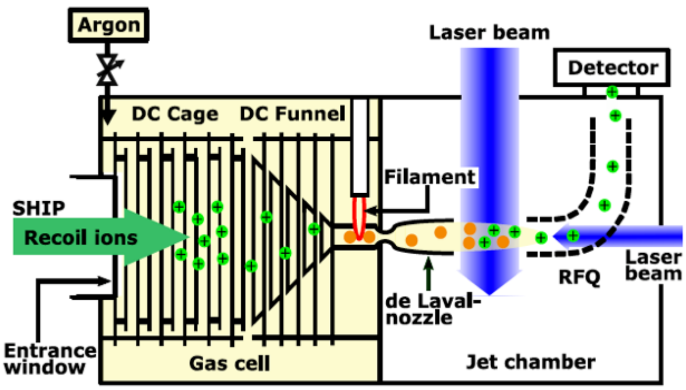

Figure 7: Concept of the gas cell for laser spectroscopy of heavy elements in a supersonic gas jet. The recoil ions (green) are thermalized in the gas cell and guided by electric fields to a filament for neutralization. The neutral atoms (orange) leave the cell through the nozzle and laser spectroscopy is performed by resonant ionization in the low-density and low-temperature gas jet. For details see ref. [Rae18b]. (Figure and caption taken from [Rae18b]).

These improvements will allow us to determine nuclear moments of ^{253}No and ^{255}No with high precision. They will also enable investigations of the $K^\pi = 8^-$ isomer ($T_{1/2}$ = 270 ms) in ^{254}No, for which contradicting interpretations of its quasi-particle excitation configuration have been put forward based on decay spectroscopy, and possibly help to understand the much-debated short-lived $K^\pi = 16^{+/-}$ isomer ($T_{1/2}$ = 200 s) at 2 MeV.

The proposed experiments are a natural continuation of our successful laser spectroscopy program and are presently only feasible in combination with the velocity filter SHIP at GSI. In the future, those experiments will continue at S^3, which will offer higher production rates to access heavier nuclei and a unique Low Energy Branch setup [Fer13], combining high resolution laser spectroscopy with mass measurement capabilities. Those new opportunities were stated in the 2017 IN2P3 Scientific Council: *"S3-LEB offers unique opportunities in terms of beam type and intensities. This installation will be a flagship tool for the community in the coming decade"*.

3.6.4. Timeline

2017: Proposals accepted at the GSI G-PAC for RADRIS and in-gas-jet laser spectroscopy experiments (U313, U314)
2018: Construction of the new detection set-up prototype for high-resolution spectroscopy
2019: Realization of RADRIS studies at SHIP of GSI/FAIR for ^{255}No and first tests for in-gas-jet laser spectroscopy experiments (U313, U314)
2019-2022: Realization of the in-gas-jet laser spectroscopy experiments with an improved setup (high repetition rate narrow bandwidth laser system)
2019-2021: Final construction of the S^3 LEB instrumentation and off-line commissioning at LPC Caen

2022: Mounting of LEB instrumentation at S^3, commission and first test in-beam
2023: Start of Day-1 experimental program at S^3

3.6.5. Requested resources

Type of budget	**2020**	**2021**	**2022**	**2023**	**2024**	**Total**
Equipment	**100 k€ pump laser 10kHz**	**15 k€ Laser consumable**	**10 k€ Laser consumable**			**125 k€**
Travel & meetings (+accord IN2P3)	**2 k€**	**2 k€**	**2 k€**	**2 k€**	**2 k€**	**10 k€**
Personnel	**PhD (40 k€)**	**PhD (40 k€)**	**PhD (40 k€)**			**120 k€**
Total	**142 k€**	**57 k€**	**52 k€**	**2 k€**	**2 k€**	**255 k€**

Important: This contribution covers part of the new laser system needed at GSI and a PhD Student located part time at GSI and at GANIL

3.6.6. Available human resources: IN2P3 and CEA permanent staff

	2020 etp	**2021 etp**	**2022 etp**	**2023 etp**	**2024 etp**	**Total etp**
Permanent staff **GANIL: N. Lecesne, H. Savajols, D. Ackermann, J. Piot, C. Stodel** **IPNO: E. Minaya** **Irfu/DPhN : M. Vandebrouck, B. Sulignano**	**2**	**2**	**2**	**2**	**2**	**10**

Important: The project evolves within a strong international collaboration with the GSI/FAIR, the Helmholtz Institute of Mainz, KU Leuven, the Johannes Gutenberg-University of Mainz, the University of Liverpool, TU Darmstadt, the Ernst-Moritz-Arndt-University of Greifswald, CEA Saclay, IPN Orsay, the Max-Planck Institute of Nuclear Physics in Heidelberg, GANIL and TRIUMF.

4. Summary of scientific objectives and requested support

We have presented six experimental programs conducted by IN2P3 researchers to be realized at the GSI/FAIR facility in the next five years. The different projects aim at investigating nuclear properties and nuclear reactions over a large range of nuclei, going from relatively light systems near beryllium (Z=4) up to super-heavy nuclei (Z=103). The covered topics belong to the physics included in the NUSTAR collaboration. The proposed experimental methods are original and based on cutting edge technology.

Pairing correlations will be investigated at the two edges of the nuclear chart, close to the neutron and the proton drip lines. In the first case, neutron-neutron and four-neutron correlations will be investigated by using knock out reactions and measuring the reaction residues with the R3B set-up. The high energy beams and the NEULAND neutron detector make of GSI/FAIR the ideal place for carrying out these measurements. In the second case, proton-proton correlations will be investigated by measuring the decay products of the two-proton radioactivity of very neutron deficient nuclei located between Z=28 and Z=50 at the FRS or the Super-FRS. The GSI/FAIR facility with its high energy and high intensity beams offers unique opportunities to produce and study possible new candidates for this very exotic decay.
The g-spec project will explore the single-particle structure of isomeric states located near $^{100\text{-}132}$Sn and ^{208}Pb via the measurement of nuclear magnetic moments with a new set-up located at the Low Energy Branch. Magnetic moments of very exotic nuclei will be measured for the first time thanks to the highly-improved beam quality and intensity, and the much better experimental conditions at GSI/FAIR.
High-precision probabilities for fission, γ and neutron-emission of nuclei located close to ^{238}U will be simultaneously measured at the CRYRING storage ring. These data will provide new insight into the

de-excitation process of heavy nuclei and enable much more accurate predictions of neutron cross sections of short-lived nuclei. These studies can only be performed at GSI/FAIR, which is the only facility worldwide that operates two inter-connected heavy-ion storage rings: CRYRNG@ESR. The SOFIA set-up will provide for the first time high-precision fission-fragment isotopic yields of very neutron-deficient and neutron-rich fissioning nuclei, allowing for a stringent test of fission models. Such an experiment is only possible at GSI/FAIR, the sole facility worldwide where relativistic uranium beams are available. The project at CRYRING and SOFIA provide complementary information on the dynamics of nuclear fission. The first one is sensitive to the evolution of the fissioning system from the ground state to the fission barrier, whereas the second is sensitive to the descent from the fission barrier to scission.
Finally, the structure of super-heavy nuclei close to Z=102 will be studied by means of high-precision laser spectroscopy, allowing for a deeper understanding of the shell effects that are responsible for the existence of the heaviest nuclei. The proposed experiments are presently only feasible by combining laser spectroscopy in a gas jet with the velocity filter SHIP at GSI/FAIR. In the future, the same type of experiments will continue at S^3 in SPIRAL2/GANIL.

Total requested resources:

Type of budget	2020	2021	2022	2023	2024	Total
Equipment	**695 k€**	**1245 k€**	**310 k€**	**30 k€**	**40 k€**	**2320 k€**
Travel+running costs	**51.5 k€**	**43.5 k€**	**46.5 k€**	**72.5 k€**	**60.5 k€**	**274.5 k€**
Personnel (PhD +Posdocs)	**115 k€**	**155 k€**	**285 k€**	**170 k€**	**120 k€**	**845 k€**
Total	**861.5 k€**	**1443.5 k€**	**641.5 k€**	**272.5 k€**	**220.5 k€**	**3439.5 k€**

Total available human resources:

	2020 etp	2021 etp	2022 etp	2023 etp	2024 etp	Total etp
PhD	**1.4**	**1.3**	**1**			**3.7**
Postdoc (Marie Curie fellow)	**1**	**0.6**				**1.6**
Permanent researchers (IN2P3 and University)	**6.5**	**6.05**	**6.35**	**7.6**	**6.5**	**33**
Permanent Engineers (IN2P3)	**3.8**	**2.2**	**5.3**	**1.6**	**0.8**	**13.7**
Total ETP	**12.7**	**10.15**	**12.65**	**9.2**	**7.3**	**52**

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