Proposal for the future of GANIL – in the years 2030s

Nuclear structure from electron-ion collisions

We propose to address fundamental questions on the structure of unstable nuclei with a focus on nucleon density distributions. Densities were investigated using electron-stable target scattering and give rise to a set of data founding our knowledge of the nuclear shape in the valley of stability. Similar detailed and precise information could be obtained for exotic nuclei with an electron-Radioactive Ion (RI) collision machine. These measurements could be done at GANIL. A project proposal on the question of the charge densities of radioactive nuclei will remain pertinent in the next decades. ***This project would make GANIL a world competitive machine with unique observables.*** *It would attract in situ the international e-RI community for common experimental programs. The main challenge is to have the electron machine and the instrumentation designed for the e-RI collisions. The purpose of the current proposal is to outline the objectives of the project and the work tasks to be done in the next years. Applications of an electron accelerator at GANIL are also underlined.*

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Milestones of our knowledge on nuclear densities

Electron scattering has been an optimal probe to build our knowledge on the structure of stable nuclei since the 50s [***Hof53***]**.** Intensive measurements of the scattering observables on these nuclei (with targets of isotopes) were done varying the electron beam energy to extend the range of transfer momenta and have a detailed extraction of the nuclear density distributions [***FroP87, Ae91***]. From 50s till the end of the 90s, the worldwide panorama for these studies was, in the United States, the MIT Bates Laboratory, the SLAC followed by the Jefferson Laboratory (starting, end of 90s, the research on the quasi-elastic electron scattering on nuclei and on the nucleon structure), and, in France, the Saclay Laboratory in the 80-90s. These labs provided most of the nuclear data we have up to now, compiled in the nuclear data tables [***ANDT87***] and used as references to discuss the densities of stable nuclei. To investigate neutron densities, hadronic probes were used complementarily to leptonic ones; mainly using proton scattering of stable nuclei [***DiffCapp***]. At the end of the 80s, the area of radioactive ion beam facilities started. Since it was not possible to make targets of the short-lived isotopes, nuclear structure investigations have been pursued mainly using hadronic probes.

Next-generation nuclear structure studies with electron-RI collisions

The purpose of the present proposal is to revive the physics of electron-ion collisions for radioactive nuclei at GANIL. Via future e-RI experiments, we propose first to investigate directly charge density distributions of these exotic systems in which unique quantum phenomena emerge. To do so, we plan to start an extensive program to measure (e,e) elastic scattering cross sections to extract directly these distributions through a model-independent analysis and compare them to theoretical predictions. Theory-wise, detailed densities are much more demanding than integrated quantities (such as root mean square radii) and encapsulate different correlation effects. As such, they offer an unprecedented test bench for state-of-the-art nuclear structure models. Their availability over a wide range of unstable isotopes would thus systematically provide model-independent constraints very complementary to information from other probes like (p,p) scattering.

This strategy aims primarily at unveiling fundamental features related to the shape of exotic nuclei (e.g. nucleon halo, clustering, shape transitions) all being consequences of the underlying nuclear force and its modification away from stability [***SCMF03***]. Conjectured central depletion in the proton density could also be measured unambiguously for systems like ^{34}Si for which the link between observables and the microscopic details of the nuclear interactions was investigated by a variety of theoretical calculations [***Theo34Si***].
Additionally, the study of neutron skins in neutron-rich isotopes would greatly benefit from the combination of electron and proton scattering data on unstable nuclei having different neutron-proton ratios. As exemplified for ^{208}Pb [***TheoNS11***], this observable helps to shed light on the density dependence of the nuclear symmetry energy of the nuclear equation of state (EoS). Differences in charge radii and densities of proton-rich mirror nuclei will also be directly measurable and helpful to characterize the isospin dependence of the EoS [***ChRms***]. These new constraints would thus contribute to improve our understanding of nuclear matter, a necessary step to model different neutron star systems [***Bau2020***], such as mergers recently identified by the detection of gravitational waves [***GW2017***] and sites of r-process nucleosynthesis [***GoBJ11***].
Progressively, the e-RI project can be widely extended to examine other fundamental questions related to shell/shape evolution by studying different electron scattering channels, or other observables, in general more demanding than elastic scattering in terms of luminosity (*see next section for detailed numbers*). For instance:
- From the (e,e') inelastic scattering cross sections, the charge transition densities can be extracted, which gives a set of observables to characterize precisely the nature of collective configurations involved in nuclear states and their mixing. This would be particularly relevant for the study of shape coexistence or high-energy resonances (giant, pygmy, etc.) [***InelExp***];
- The studies of single-particle strength in exotic nuclei is crucial to quantify its quenching by long and short-range correlations [***TheoLRC09***]; they can be performed via (e,e'p) quasi-free scattering;
- Magnetic form factors can give access to valence nucleon configurations [***Don84***].
Such a facility would thus offers to GANIL bright scientific perspectives for several decades.

It is worth pointing that the main ideas discussed here on the required observables were outlined in the framework of the NuPECC long- range plan (LRP) perspective in 2016-2017 [***LRP2017***]. In this context, it was pointed out that electron beams of 400-800 MeV provide the ideal spatial resolution scale of about 0.5 fm to study charge distributions. Conclusions and recommendation of our community were written as follows*:*
« *Ion-electron colliders represent a crucial innovative perspective in nuclear physics to be pushed forward in the coming decade. They would require the development of intense electron machines to be installed at facilities where a large variety of radioactive ions can be produced* ».
Correspondingly, new theoretical tools will be put in place for electron-nucleus collisions. On the one hand, some of the knowledge acquired in the past on electron collisions with stable nuclei has to be recovered and revised in light of recent advances. On the other hand, newly developed approaches need to be adapted and generalized to the description of new processes and observables. In particular, the interpretation of the quasi-free (e,e'p) scattering processes would benefit largely from a revision of the reaction mechanism to investigate final state interactions, including consistently nuclear short- and long-range-correlation effects mentioned previously [***TheoLRC09***].

Observables and luminosity

The insight one can get into density distributions depends on the accuracy of the measured form factor and the range of momentum transfer covered. This translates into luminosity constraints to access different structure observables. Orders of magnitudes are given in Tab.1 (developed from the one established in the LRP document [***LRP2017***]).

As an example, for elastic scattering:

- Global indicators are accessible first, like root mean square radii and diffuseness, to model densities by simple analytical functions, such as two-parameter Fermi function, as done extensively for stable nuclei reported in nuclear data tables [***ANDT87***]. This can be achieved with luminosity starting from 10^{24} $cm^{-2}.s^{-1}$ for heavy nuclei to 10^{28} $cm^{-2}.s^{-1}$ for lighter ones (lower Z).
- When form factor are measured precisely over an extended momentum transfer, the charge density can be mapped and extracted via a model independent analysis [***Sick74***]. It corresponds to differential cross sections measured up to the second minimum and translates into luminosities in the range 10^{26-29} $cm^{-2}.s^{-1}$, again depending on the element.

From luminosities around 10^{29} $cm^{-2}.s^{-1}$ and higher, the study of other processes mentioned previously can be reached offering unprecedented possibilities as stated in [***LRP2017***] : « *As a long-term goal, such facilities would allow (e,e') inelastic scattering with selectivity to the transferred angular momentum, (e,e'f) electro-fission with detection of fragments, and (e,e'p) quasi free-scattering studies with radioactive ions* ».

Observables **deduced quantities**	**Reactions** *(q: momentum transfer)*	**Type of nucleus**	**Intensity I or** **Luminosity L**
r.m.s. matter radii	**(p,p)** *elastic at small q*	Light to heavy	I : 10^4 10^6 s^{-1}
r.m.s. charge radii	**(e,e)** *elastic at small q*	Light	L: 10^{24} $cm^{-2}s^{-1}$
Charge density distribution with 2 parameters ρ_{ch}	**(e,e)** *First min. in elastic form factor*	Light Medium Heavy	L: 10^{28} 10^{26} $cm^{-2}s^{-1}$ 10^{24}
Charge density distribution with 3 parameters ρ_{ch}	**(e,e)** *2nd min. in elastic form factor*	Medium Heavy	L: 10^{29} $cm^{-2}s^{-1}$ 10^{26}
Energy spectra, width, strength, decays	**(e,e')**	Medium-Heavy	L: 10^{28-29} $cm^{-2}s^{-1}$
Neutron-skin density from ρ_m and ρ_{ch}	**(p,p) and (e,e)** Combined (p,p') and (e,e')		(p,p) I: 10^6 s^{-1}; **(e,e) L : 10^{29-30}** (p,p') I:10^{6-8} s^{-1} ; **(e,e') L ~10^{30}**
Spectral functions, correlations Magnetic form factor → Proton and neutron transition densities *Direct access to neutron-skin*	**(e,e'p)**		10^{30-31} **(e,e'p) L ~10^{30-31}** $cm^{-2}s^{-1}$

Table 1. Observables from e-RI collisions and luminosity

An initial luminosity target of 10^{29} $cm^{-2}.s^{-1}$ is thus considered to reach an entirely new range of research and opening the way for further upgrades. Then, the long-term goal of GANIL would be to extend progressively the applicability of those methods to a broader range of exotic nuclei allowing systematic and model-independent studies leading to the build-up of nuclear data tables away from stability in the years 2040-2050s.

Machines around the world

Since the 2000s, the physics of electron-ion collisions has been part of the main international projects aiming to probe the nuclear structure of exotic nuclei [***eRIB17***]: SCRIT *(Self Confined Radioactive Ion Target)* [***Scrit05***] at RIKEN in Japan, ELISe *(Electron Ion Scattering in a storage ring - eA collider)* [***Elise07***] planned in the second

phase of FAIR in Germany, and since 2017 the Dubna Electron-Radioactive Isotope Collider fAcility (DERICA) within the Acculina2 project [***Dubna18***] in Russia.
When SCRIT was launched in the years 2004-2005, it represented the world's first electron-scattering facility for exotic nuclei [***Scrit04***]. It consists of a dedicated electron storage ring device with circulating electron bunches colliding with trapped ions. The "ion trapping" phenomenon forms a local target which makes electron scattering off short-lived radioactive nuclei possible [***Scrit09***]. First test results were obtained with the stable isotopes ^{132}Xe [***Scrit17***]. Note that the charge density shape was determined with only 10^8 target ions with a luminosity over 10^{27}cm^{-2}s^{-1} which represents up to now the current limit of the SCRIT device. However, the quality of the SCRIT data for ^{132}Xe(e,e) were sufficient to be compared to recent *ab initio* calculations [***Th132Xe***].

The scope of our proposal

In the years 2015-2016, there was a project initiated by the CEA Saclay to think about a possible *Electron-Trapped Ion Collider*, ETIC [***ETIC15***]. While based on the SCRIT ion-trap concept, ETIC aims at reaching much higher luminosities (up to a factor 100 or 1000), around 10^{29}cm^{-2}s^{-1}. This would allow performing experiments on isotopes with much smaller production rates and at the same time more detailed measurements, thus increasing the physics reach in quantity and quality. This project was explained in a workshop organized in 2016 on e-Radioactive Ion Beams (RIB) collisions [***ESNT16***]. How to revisit this project in the context of the present RIB beams, which are or will be available at GANIL, remains to be discussed**.**
The recently developed technique of ***energy recovery linac*** (ERL) was identified as a possible suitable solution to reach a luminosity of 10^{29}cm^{-2}s^{-1}. However, an R&D program (including a demonstrator) has to be done on the ETIC project, based on the ERL concept, to reach the identified performances.
Such an R&D platform was discussed in the context of the PERLE *"Powerful Energy Recovery Linac for Experiments".* This project aims at building a LINAC prototype for the Large Hadron electron Collider (LHeC) with a high current (15mA) and high energy (up to 450 MeV) using a multi(3)-turn energy recovery linac [***PERLE18cdr, EICUG2019***]. The adjunction of an upgraded photo-fission source to this ERL, could represent a technical option to perform the first stage of a R&D project on a SCRIT-like device at lower luminosity. However this would require to organize an expert team on the technical issues (***see below, work plan***).
The physicists of our community, gathered in the present proposal, are willing to develop physics cases for a future dedicated electron-RIB machine at GANIL for the years 2030s, exploiting the radioactive ion beams produced by the existing facility or by the next production scheme of RIBs (*the scenario of the RIB productions is discussed in the other contributions*). The assets of the GANIL facility would be the local expertise existing in ion trap and all the purifying tools available at DESIR, as well as the required cryogenic infrastructures and the INB framework allowing continuous luminosity upgrades.
All the main questions addressed in the field of exotic nuclei have been treated up to now by the most advanced accelerators and will be treated in the future with machines which are significantly ahead in the production of exotic nuclei: nowadays, RIKEN is at the forefront of the production of rare exotic nuclei, and with RIBF which started in 2007, it is a unique machine to delineate the neutron dripline. In 2019, at RIBF "the boundaries of nuclear chart have been updated for the first time in 20 years", with the newly established limit in the Ne isotopic chain, ^{34}Ne being the last bound isotope [***RIBF34Ne***], the previous limit was ^{24}O. The advances obtained by the current machines like RIBF is such that in the international context of the 2035s GANIL, as of today, will not be able to compete in the scientific field of the very neutron-rich exotic nuclei.
With the e-RI project, GANIL would still be in the run for a unique and exciting program: it would open a new era for nuclear physics with long-awaited structure studies of exotic nuclei by electron scattering gradually becoming accessible. Starting the project in 2020 would make GANIL **a world competitive machine with unique observables** in the scientific context of the years 2035, regardless of the evolution of the RIB machines around the world. Moreover this would be a very appealing machine project within the international community, in particular for physicists at GSI, at Dubna and at RIKEN who proposed e-RI programs at their own facilities.

Tentative work plan for the project

It is not the purpose of this document to discuss the production modes of the exotic nuclei. Here we focus on the electron-RIB collision installation, and we underline that the intensities of the radioactive ion beams is not the main issue since we do not plan to deal with the most exotic species close to the driplines, which are typically associated to low intensity beams. Dealing with neutron-rich or deficient nuclei of moderate intensities would give rise to completely new studies of the nuclear shapes, which are not known at present, since only radii have been obtained for some species, mainly by laser spectroscopy technique.
We thus plan to focus on radioactive beams easily produced at intensities at and above 10^6 pps. With these rates, we should be able to measure e-RI cross sections and to extract the nuclear form factors. The beams of interest could be obtained from the present GANIL/SPIRAL1 and the beams foreseen in the S^3 project as well as the ones that could be produced by photofission (*as proposed in a separate contribution).* Since GANIL offers RIBs without post-acceleration, it would be well adapted to a SCRIT-like technique.
The new structure studies opened by e-RI collisions are under discussion to push forward these ideas into physics cases and to organize discussions and network activities between theorists and experimentalists on the measurements of electron-radioactive ion collisions observables.
In the next 5 years, the activities have to be organized following four main paths and problematics related to the e-RIB experiments and their interpretation:
- Determination of the possible measurements of the observables depending on the characteristics of the machine, energy, luminosity;
- Theory for e-RIB experiments, with renewal of the calculations for the e-RI scattering observables,
- Electron and RIB production, **the technical options for the e-RI collisions will be compared**: i) e-RI collider; ii) the storage and fixed target preparation for e-RIB experiments;
- Instrumentation (design of the machine, development of the spectrometers).

Part of the crucial questions related to the technical difficulties are already identified and should be investigated in the primary phases of the project, **with the goal of reaching the 10^{30} luminosity (in a first step in the 2030s).** We underline here a few ones. For both options, the main issues are related to the spatial charge distribution and confinement effects of the charge densities of the RIB and to the ways of reaching optical beam qualities enough to proceed to the collisions in a reduced vertex area. A key point is the ion capture efficiency. The more efficient the capture is, the less intensity we need. The parameters can then be relaxed.
For the option of the SCRIT-like technique, the project should examine in particular how to overcome the problems of the spatial charge effects of the plasma in the ion trapping area. The case of a circular collider, which can work up to 700 MeV, was already explored, and a first draft plan (with beam optical characteristics) was delivered [***ETIC15***]. The main limitation comes from the intra beam scattering (IBS). At low energy (less than 700 MeV), the IBS becomes an issue. It limits the stored intensity and thus the luminosity. A solution was proposed to use harmonic cavities to make RF gymnastics. That is more expensive and requires more studies.
For the electron recirculating linac (ERL), the IBS is not anymore a problem and we can work at lower energy. A first layout has been shown at 530 MeV. A special effort must be performed on the electron source quality.
That is why a proposal of an intermediary step was made, in 2016, with a 140 MeV demonstrator to validate some of the key points of such a machine.
To examine the technical issues of the e-RI project, it is mandatory to constitute a group of physicists and engineers experts of these questions, and to define a work plan between the technical divisions of IRFU and IN2P3 with an international team of experts interested in the physics of the future project. Starting in 2020, the time scale would be: i) one year for a team of two experts pushing forward the studies on both options to define the achievable performances, finally selecting the best option for the physics requirements, ii) 4-5 years for the conceptual design report, ii) construction phase to be ready for the e-RI physics in the years 2035.

Let there be more light. Possible applications under discussion.
An ERL device is the appropriate instrument to produce intense photon backscattering beams resulting from intense laser light collisions with high-energy electron beams. The LHeC demonstrator may deliver a beam of about 220 MeV energy (one cryomodule) or 440 MeV (with 2). Physics applications (if relevant in the scientific context of 2035) would request a different energy regime. For instance the PERLE configuration could produce "a nearly 1 GeV energy electron beam suitable for ep scattering physics, possibly using polarised electrons in weak interaction measurements. Backscattering processes may generate a photon beam of 30 MeV energy which is of interest to reach beyond the so-called giant dipole resonance" [***Perle18cdr***].

This opens a variety of possible applications for therapy and for material science researches.
For therapy purposes, using flash dose deposit and micromesh techniques [***Thmed1***] requires accelerator of high-intensity electrons at energies between 150 and 300 MeV. This was part of the programme intended for the PRAE platform (*PRAE is not considered anymore*) [***Thmed2***].
The GANIL site would be also interesting **for R&D medical studies**, since it is ideally located for the pre-clinical tests on animals (small and large-sized) which are already part of studies done at ARCHADE and CYCERON. The developments of the dedicated instrumentation and areas for the preclinical test studies would represent an interesting aspect of the application of the electron beams at GANIL.
- **Use of the beam dump for radioisotope production**, similar to the photofission performed at ARIEL [***Thmed3***]. This would require a new building, for the (hot) chemical processes needed to extract the radioisotopes. GANIL is an optimum site since it is located near-by the "Francois Baclesse" oncology centre. This would also constitute a complementary installation for the R&D radioisotope room, which is proposed to be associated with the LINAG (*in a separate contribution).*
- **Other applications** may be envisioned and will be discussed, **for solid-state physics and chemistry**, with colleagues from CIMAP and CRISMAT; **for industry**, for instance for micro-satellite irradiation.

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