Towards electron scattering on unstable, exotic nuclei.

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Since the pioneering work of R. Hofstadter distinguished by the nobel prize in 1961 [Hof61], decades of experimentation [Fro87] have demonstrated that electron scattering is one of the best probes, if not the best, to study the structure of hadronic systems such as nuclei and nucleons. Up to now, its use on short-lived radioactive nuclei remains however out of reach, hampering a more precise characterization of nuclear shell evolution and associated emerging quantum phenomena. The spatial resolution offered by electron of several hundreds of MeV would allow to go from extracting integrated quantities (mean square radii, electromagnetic transition probabilities) to spatially-dependent distributions (radial charge density, charge transition density, magnetic current distributions). Naturally this additional spatial sensitivity would be particularly powerful to discover or to deepen considerably our understanding of halo nuclei [3], neutron skins [Roc11], bubble nuclei [Mut17] or more generally to map shell and shape evolution [Sor08, Hey11], all consequences of modifications of the nuclear force far from stability. Actually, several state-of-the-art theoretical models (e.g., ab-initio [Dug17], beyond mean-field [Yao15]) have been already used or extended to calculate charge/transition densities and plead for experiments of electron scattering on radioactive nuclei to test their predictions.

Additionally, using an electromagnetic interaction precisely described by quantum electrodynamics (QED) lead to a better control of the reaction mechanism up to now limiting our interpretation of reaction cross sections in general. Better controlled uncertainties, limited re-scattering effects, reduced model dependance and final state interactions are for instance crucial to study short and long-range correlations [Bar09] between nucleons in exotic nuclei absent by construction in most of mean-field approaches frequently used.

A facility to perform electron-RI (Radioactive Ion) collisions represents thus a perspective for fundamental nuclear physics that would lead to a major leap in our understanding of atomic nuclei necessary to build a unified picture of this system. First of all, the targeted optimal luminosity for such an ambitious facility is defined by the need to be able to study most of the relevant scattering process including elastic, inelastic, quasi-free to extract all observables of interest. The luminosities required to do so are described in Table 1. Due to the Z^2 dependence of the Mott cross section, studying low Z nuclei requires higher luminosities. The most constraining process is the quasi-free (e,e'p) scattering because it allows to study the full spectral strength of a given nuclei and nucleon-nucleon correlations (short and long-range mentioned previously). A targeted luminosity of 10^{29} $cm^{-2}.s^{-1}$ is thus considered to reach an entirely new range of research.

Worldwide, two major techniques for such a facility were explored up to now :

- The SCRIT (Self-Contained Radioactive Ion Target) concept [Sud05] at RIKEN (Japan) in which a beam of electrons scatters off ions stored longitudinally by a trap and radially by the circulation of the electron beam in a ring.
- The ELISE electron-ion collider concept [Ant11], part of the FAIR project in GSI (Germany) is based on two intersecting rings : a storage ring (NESR) to collect and cool radioactive ions produced by in-flight fragmentation to primary beam quality and an electron ring (EAR) to reach energies between 0.2-0.5 GeV.

These two options with their respective advantages and limitations are discussed in details in a review article [Sud17]. SCRIT reached a proof of concept measurement in 2017 on stable ^{132}Xe with a luminosity of 10^{27} $cm^{-2}.s^{-1}$ [Tsu17] but not yet for a radioactive isotope and is limited by construction to 10^{28} $cm^{-2}.s^{-1}$ for only a few long-lived medium mass nuclei. ELISE on the other hand was designed to reach 10^{28} $cm^{-2}.s^{-1}$ for a larger variety of isotopes but is now out of the funded part of FAIR due to cost limitations. The current situation is such that there is no large-scale electron-ion collider existing or funded in the Nuclear Physics community despite a strong scientific interest highlighted in the NuPECC 2017 long range plan [Nup17].

In light of this context, several initiatives emerged recently in France to define the contours of an optimal e-RI facility and to start building a national development strategy on the subject for the coming decades.

Since GANIL offers the production of DC radioactive beams at low energy, it fits with well with the SCRIT technique. In the framework of the redefinition of GANIL long-range plan in 2015 a first study was thus performed by CEA-Saclay/IRFU to sketch possible designs of an e-RI collider inspired by the SCRIT concept but reaching the 10^{29} $cm^{-2}.s^{-1}$ luminosity target, 100 times higher than the only achieved measurement up to now with SCRIT. The use of an energy recovery linac (ERL) as a basis for this collider was identified as a solution reaching this goal without fundamental showstopper. It has similar advantages to conventional linac but allows increasing the average intensity of the electron beam. However, being a relatively new technology, the ERL solution targeting a 100 mA electron beam intensity up to 650 MeV and 10^6 trapped ions in the target is obviously challenging and requires a progressive R&D program. In this respect a demonstrator machine would allow to study and develop the key technologies needed: the electron source, energy recovering, beam break-up instabilities, the SCRIT ion trapping, detection, etc.

In parallel for high-energy physics, a conceptual design was elaborated and submitted in 2017 for a Powerful Energy Recovery Linac Experiment (PERLE) facility [Per18] derived from the design of the Large Hadron electron Collider (LHeC), an electron beam upgrade under study for the LHC, for which it would be the key demonstrator. It aims at investigating multi-turn, high current and high energy regime of ERLs, in direct line with the requirement for developping a e-RI collider for nuclear physics studies. LAL and IPN Orsay are among the main contributors of this intiative and a possible location is the Orsay campus. Such an ERL could be coupled with a photo-fission source similar in design to ALTO to produce medium-mass radioactive nuclei to inject in a SCRIT-like trap.

In the coming years, it is thus crucial to grab this unique opportunity to build such an ERL-based demonstrator for collisions between electrons and radioactive ions in synergy between different physics communities. This would represent at least a 10-15 years development and a first physics program to tackle mainly elastic/inelastic scattering, the least difficult in terms of luminosities but already unique without direct competitors due to the novelty of the probe. This step is an essential building block for an ideal e-RI collider that could represent the long-term future of GANIL-SPIRAL2 to reach optimal luminosity, study all kinds of scattering processes and benefit from the variety of radioactive species it will produce. Finally, note that an ERL also allows to produce intense synchrotron light sources opening such a facility to a variety of other applications (material science, biomedical studies, etc.).

Reaction	**Deduced quantity**	**Target Nuclei**	**Luminosity [$cm^{-2}s^{-1}$]**
Elastic scattering at small q	r.m.s. charge radii	Light Medium	10^{24}
First minimum in elastic form factor	Density distribution with 2 parameters	Light Medium Heavy	10^{28} 10^{26} 10^{24}
Second minimum in elastic form factor	Density distribution with 3 parameters	Medium Heavy	10^{29} 10^{26}
Inelastic scattering Pygmy/Giant resonances	Position, width, strength, decays	Medium Heavy	10^{28} 10^{28}
Quasi-free scattering	SF, spectral strength	Light	10^{29}

Table 4: Required luminosities for different electron scattering studies, adapted from [10]

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