Methods for the production of radioactive ion beams.

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Introduction

Since the discovery of the radioactivity and of its potential applications, the nuclear matter behaviour has continuously been a major issue crucial to power production and more fundamentally to nuclei-synthesis. The first studies were performed with nuclei present on the earth, all being stable or close to the stability. To explore their history, it was necessary to produce artificially their parents, by making existing nuclei collide at sufficient energies to overcome the Coulomb barrier. As absent in our environment, the reaction products are said "exotic", and their exoticism increases with their distance to the stability. Go back further in history requires more exotic nuclei, which are harder to produce due to fewer nuclear reaction cross-sections and due to their shorter half-lives. They are thus more difficult to observe. For statistical reason, the number of reactions must be maximized during the physics experiment. And to limit the duration of the experiment, the number of reactions per unit of time must be large, while limited by the instrumentation and acquisition systems. One can extract from that simple consideration the figure of merit a Radioactive Ion Beam (RIB) method has to satisfy:

- Optimum nuclear reaction cross section. Parameters are the collision energy, the nature of the target and of the projectile nuclei
- Maximum intensity of the impinging ion beam, and target length suited to its range in target matter
- Short response time between the instant exotic nuclei are produced and the instant they are available to avoid losses by radioactive decay
- High efficiency of the method to minimize the losses. (The efficiency of the experimental instrumentation is not considered here, as out of the RIB production system but it is indeed important)
- Purity of the beam, and thus selectivity of the method right from the in-target production

RIB installations can also be evaluated regarding additional criteria, sometimes neglected:

- Availability of the primary beam, related to the reliability of the production system
- Variety of the RIBs, which is strongly connected to the variety of the methods available
- Quality of the RIBs in terms of energy, emittance, stability…
- Energy range of the RIBs, *i.e.* with or without post-acceleration
- Quantity of nuclear waste produced
- Cost of maintenance and operation
- Tuning process

As shown through the world overview of the different installations regularly reported during the international EMIS conference [1], no method fulfils all the above figures of merit.

The regions of the nuclide chart close to the valley of stability are the most accessible. Most of them were studied by previous or still existing installations. Close to the valley, the reaction cross-sections are larger, and several nuclear reactions and techniques can lead to a sufficient production of a given RIB. There is generally several technical solutions. For instance, neutron rich intermediate mass isotopes ($80 < A < 150$) can be produced by spallation reaction of heavy nuclei (CERN/ISOL method, see left side of Figure 1) or by fission of U induced by protons at lower energy (SPES/INFN method, see right side of Figure 1). Nevertheless, these methods have different selectivity and thus downstream instruments are necessary to separate the contaminants, often reducing the global efficiency of the method.

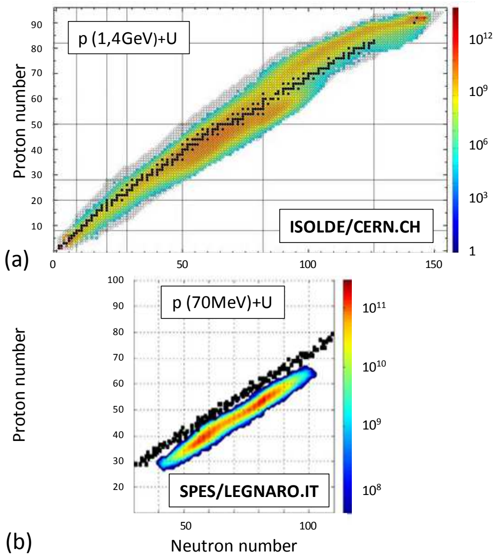

Figure 1: In-target production by U spallation at ISOLDE/CERN (a) and by U fission expected at SPES/INFN (b).

Three regions are poorly covered by the current RIB techniques: light nuclei (A< 60), neutron deficient nuclei and neutron rich heavy nuclei regions. The present challenge and goal of GANIL RIB facilities is to push the limits towards more exotic nuclei, provide new beams in these regions, and increase intensities in regions already covered by other installations.

The most widespread RIB methods are Isotopes Separator On Line (ISOL) and In-Flight techniques, whom principles are presented in Figure 2.

Both methods have been using at GANIL for years. SPIRAL1 (Système de Production d'Ions Radioactifs Accélérés en Ligne) uses the ISOL technique and has been recently upgraded to extend the catalogue of RIBs in the region of "light" isotopes and in a close future in the region of neutron deficient isotopes of intermediate masses. Downstream from the TISS, a cyclotron can post-accelerate the ions up to an energy of 25 MeV/A, depending on their mass to charge ratio, while separating the beams from its contaminants with a mass to charge resolution of 10^{-4}.

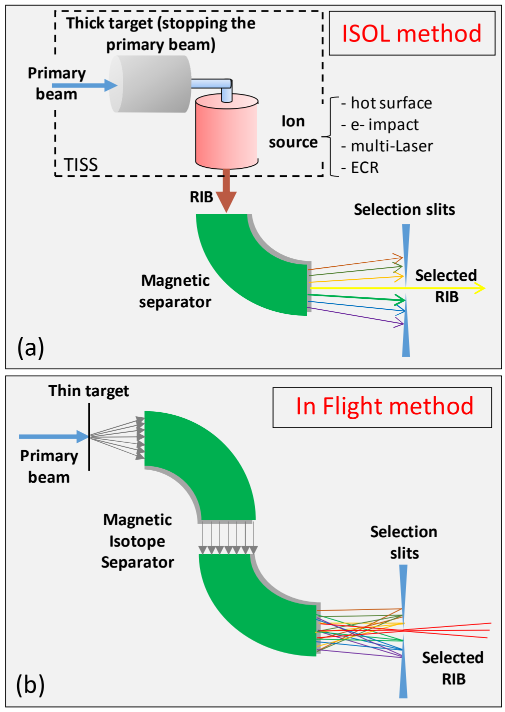

Figure 2: Schematic principles of ISOL (a) and In-Flight (b) methods. TISS is the abbreviation of Target Ion Source System.

After a first In-Flight separator system named SISSI, a new one called S3 is under construction within the framework of the SPIRAL2 facility. According to the intensities of the primary beams delivered by the superconducting LINAC, presently under commissioning, the expected intensities of neutron deficient isotopes will be the largest over a mass range going up to super-heavy elements.

Then, the phase 2 of the SPIRAL2 project could be started to produce RIBs in the neutron rich region obtained by neutron-induced-fission of U and so allows GANIL facilities to cover a large area of the nuclide chart.

The different methods and the current status of GANIL RIBs will be presented.

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[1]: EMIS conference, published in Nuc. Instrum and Method