Radioactive ion beam facilities at INFN LNS

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Abstract. Radioactive ion beams are produced at INFN - Laboratori Nazionali del Sud (LNS) by means of the two operating accelerators, the Tandem and the Superconducting Cyclotron (CS), originally designed to accelerate stable beams. Both the ISOL (Isotope Separation On Line) and the IFF (In-Flight Fragmentation) methods are exploited to produce RIBs in two different ways at different energies: in the first case, the Cyclotron is the primary accelerator and the Tandem accelerates the secondary beams, while in the second case radioactive fragments are produced by the Cyclotron beam in a thin target with energies comparable to the primary beam energy. The ISOL facility is named EXCYT (Exotics at the Cyclotron and Tandem) and was commissioned in 2006, when the first radioactive beam ($^8$Li) has been produced. The IFF installation is named FRIBs (in Flight Radioactive Ion Beams), and it has started to produce radioactive beams in 2001, placing a thin target in the extraction beam line of the Cyclotron. The development of both facilities to produce and accelerate radioactive ion beams at LNS, is briefly described, with some details on the future prospects that are presently under consideration or realization.

1. Introduction

Low and intermediate energy radioactive beams far from the valley of beta stability, offer new opportunities in nuclear physics and nuclear astrophysics research, allowing a deeper exploration of nuclear structure and reaction mechanisms. Furthermore, using radioactive ion beams in nuclear reactions, it is possible to obtain compound nuclei with N/Z values very interesting for studying the behaviour of super heavy elements (at beam energies near the coulomb barrier) or rather the influence of the isospin degree of freedom in the dynamics of nuclear collision (at intermediate energies) [1,2].

At LNS – INFN Catania we have developed two complementary facilities for RIBs production, exploiting the techniques known as ISOL and In-Flight Fragmentation. The former, called EXCYT, allows to produce radioactive beams with energy up to 7 AMeV; the latter, called FRIBs, produces beams with energy up to 60 AMeV.

Within EXCYT a primary ion beam is accelerated by a Superconducting Cyclotron, (CS, K=800, Energy range 8 - 80 AMeV, $P_{\text{max}}=500$W) and it is stopped inside a thick carbon target, that is the core of the target-ion-source (TIS) complex. The radioactive isotopes, produced as fragments of nuclear reactions, are extracted by means of a high voltage (some tens of kV) and then selected in mass by means of a two-stage high resolving mass separator [3]. The beam, whose energy along such a separator can range between 10 keV and 300 keV, is finally transported to the injection stage of a Tandem Van De Graaf ($V_{\text{max}}=15$ MV), figure 1, for the post-acceleration.

The radioactive beams produced by means of the FRIBs facility exploit the primary beam accelerated by the CS, that reacts within a thin target placed in the extraction beam line, before a beam
line composed by a couple of magnetic dipoles. The nuclear fragments with a kinetic energy comparable to the primary beam are selected in magnetic rigidity (p/q) by setting the suitable magnetic field in the dipoles, as given by the LISE code, in order to select the nuclei of interest within an acceptance in momentum of \( \pm 1\% \), [4].

In comparison to EXCYT, the FRIBs beams are not composed by just one nuclear species: in fact they consist of a nuclear admixture that depends on the setting and on the acceptance of the magnetic dipoles. Such a beam is then transported to the experimental apparatus where the particles interact with the final target, thus producing reactions with several projectiles at the same beam time session. Such a technique requires therefore an efficient system of tagging detectors, in order to identify event by event the projectile producing the nuclear reaction, with very high rates (at least \( 10^5 \) Hz) without changing the performances of the system.

2. The EXCYT facility.

The production yield of the radioactive nuclear beam (RNB) depends on many factors, such as the primary beam parameters (element, energy and intensity), the target ion-source properties (nuclear cross-sections, diffusion and effusion mechanism, etc), the charge exchange efficiency, the transport efficiency and the acceleration efficiency. The beam we have produced and post-accelerated, as approved by the LNS Scientific Committee, is \(^{8}\)Li. Taking into account the CS operational diagram, the production of the radioactive ions has been performed by injecting a \(^{13}\)C\(^{4+}\) primary beam of 45 AMeV on a graphite target, with a beam power up to 150 W (\( \sim 1 \) mA). The selection of the target material has been done following the criteria of high porosity, small grain size, high thermal conductivity, high chemical purity, high melting point and low vapour pressure. The chosen UTR146 graphite has been selected, since it is the best target material for such a purpose [5]. The recoils, produced and diffused on the target surface, effuse through the transfer tube to the Tungsten positive surface ionizer and then extracted by an acceleration voltage up to 50 kV. The charge of the exiting ions is +1 and it must be converted to -1 by means of the charge exchange cell (CEC), in order to be accelerated by the Tandem. The beam transport has been followed by means of several diagnostic devices, densely distributed along the whole beam pipe, that allow to visualize the beam profile, to measure the RIB intensity and to identify the radionuclide by means of beta and gamma spectroscopy, figure 2 [6]. The measured transport efficiency through the two stages of the isobaric mass separation is close to 100%, whereas the acceleration transmission at the Tandem is of the order of 50%, a value that is lower than for Li stable beams produced with their current source.

The maximum intensity of \(^{8}\)Li that up to now has been reached on the final target of the experiment, is \( 5 \times 10^4 \) pps. With the same positive ion source, also other elements can be produced, in particular \(^{7}\)Li and \(^{21}\)Na. Different activities are under way in order to achieve a higher intensity of \(^{8}\)Li , reasonably corresponding to \( 5 \times 10^5 \) pps. In order to obtain such a result, it is necessary to increase the primary beam intensity (possibly by a factor three) from the Superconducting Cyclotron, to gain efficiency by the CEC (up to now the main bottleneck) from the measured value of 2.8% to the expected one of 4%, and to increase the transmission through the Tandem. In our current planning a lot of efforts are focused on the optimisation of the TIS assembly and to improve the beam injection into the Tandem, by installing a new quadruplet. The TIS system is presently affected by a number of technological problems related to the current flow of the heater, which encounters many discontinuities due to bad electrical contacts. A new design of the system is planned to be accomplished in the next future.

Not less important than the upgrading of the facility, many efforts have recently been put on safety and reliability issues. In particular, the front-end of the source has been completely renovated, and as a consequence the robot is now able to perform all the remote handling manipulations for which it was realized.

Finally, in order to start developing a new radioactive beam, the installation of a different source type, able to ionise a big number of ion species, is planned in the near future: at the moment a possible choice might be \(^{15}\)O.
Figure 1. The layout of INFN-LNS with the Excyt facility for the production of radioactive beams with the ISOL technique (left). The new target geometry adopted recently (right).

Figure 2. A diagnostic device based on a PSSD (Position Sensitive Silicon Detector), used for very low intensity beam imaging. The picture on the right corresponds to a transversal profile of a radioactive beam.

3. FRIBs.
Fragmentation beams have been produced at LNS for many years. Several production experiments have been performed, in order to produce proton and neutron rich light nuclei, whose identification has been performed by using tagging detectors, suitably developed for the experiments that have exploited such beams, such as the HODO and the CHIMERA detectors. The first experiment performed with a $^{18}$Ne beam by the Prof. Raciti team, has allowed to highlight the two proton decay [7].

By exploiting the LISE code, in which the beam line properties have been included, the magnetic separator is set in order to select the fragments of interest produced by the interaction of the primary
beam with the production target. The particles composing the beam can be tagged one by one, in order to identify them before they react with the final target [8]. Therefore in the data acquired during the experiments, the events related to a particular class of projectiles can be thus selected, allowing to study different reactions in the same beam time. To this aim it is necessary to have a good isotopic resolution for the selected fragments by means of 2D plots $\Delta E$/TOF, choosing suitable detectors for such a purpose, that are able to work at very high rates, at least $10^5$ Hz, for all the time of the measurements, without any deterioration of their performances. Besides, since the beam obtained by fragmentation is poorly focused, its trajectory should be reconstructed, by using position sensitive detectors. The beam tagging devices should therefore identify the fragments, measure their energy and their trajectory (if possible), and also they should perturb as less as possible the secondary beams. Besides, the reactions that occur in the tagging detector should not reach the detectors or should be simply discriminated by the reactions on target.

Taking for instance the CHIMERA tagging system, it consists of a large area microchannel plate (MCP) used as start detector for time of flight (TOF) measurements and a double side silicon strip detector (DSSSD), consisting of 16*16 strips providing the stop signal for TOF measurement, energy loss ($\Delta E$) and position of the impinging beam. For the test of beam production, several primary beams have been used. The last beams are $^{13}\text{C}$, $^{18}\text{O}$ and $^{16}\text{O}$, with an energy of 55 AMeV. The first two beams were used to produce neutron rich nuclei, while the $^{16}\text{O}$ was used for the production of nuclei on the proton rich side. One of the secondary beam used in last experiment with CHIMERA, consisted to set the acceptance window of the separator in the region of $^{11}\text{Be}$, with the help of LISE code that has established the most suited primary beam to be $^{13}\text{C}$ accelerated at 55AMeV, interacting on a 1.5mm $^9\text{Be}$ target. With such a combination of primary beam and target, a quite intense $^{11}\text{Be}$ has been produced (of the order of $10^6$ pps with a 100 W of $^{13}\text{C}^{5+}$ beam), with a high purity (around 50% of the produced beam was $^{11}\text{Be}$). The measured identification scatter plot ($\Delta E$-TOF) is reported in figure 3 (left). The same isotopic region can be produced by using 55 AMeV $^{18}\text{O}^{7+}$, also if with lower intensity ($10^3$ pps with 100 W) and with much more contaminants. However most of the contaminants produced with $^{18}\text{O}$ are quite useful neutron rich beams. Therefore also this choice is good for some experiments. In figure 3 (right) the $\Delta E$-TOF identification plots obtained with $^{18}\text{O}$ as primary beam is shown.

**Figure 3.** Identification scatter plot for the fragmentation beams obtained using a primary beam of $^{13}\text{C}$ 55 MeV/A on a 1.5mm $^9\text{Be}$ target (left). Identification scatter plot for the fragmentation beams obtained using a primary beam of $^{18}\text{O}$ 55 MeV/A on a 1.5mm $^9\text{Be}$ target (right).
The 55 AMeV $^{16}$O beam was used as a primary beam in order to investigate the production of proton rich nuclei. The main aim was to observe the production yield for nuclei in the region of $^{13}$O. In order to prepare a pilot beam for the beam line setting, a 2.1 mm Al degrader has been used. $^{15,14}$O beams are produced with reasonable rate, whereas a large yield has been measured for $^{17}$F, which confirms the presence of proton pickup reactions from the $^9$Be target.

In figure 4 one of the identification scatter plot obtained with $^{16}$O beam on a 2.5 mm thick $^9$Be target is shown.

In this case a DSSSD detector 70µm thick has been used for the $\Delta E$ measurement, whose performances are worse than with the 140µm DSSSD detector used for the $^{13}$C and $^{18}$O primary beams. Such a trouble is due to a non-uniformity of the 70 µm thick detector. A correction that takes it into account is necessary, in order to overcome this problem.

An increase of the beam transmission is expected to come from the new beam monitoring system developed for the transport along the CHIMERA and MAGNEX beam line, that has recently been installed and will be used for the next beam run [9].

Moreover, a significant upgrade of the FRIBs line from the Cyclotron exit to the beam distribution point will be realized at the end of 2010. A new magnetic configuration has been designed that will increace the transverse and momentum acceptance of the existing line after the production target.

As a consequence of this upgrading, an enhancement factor of 10-20 is expected in the experimental halls making use of FRIBs beams, i.e. the CHIMERA and the 20° beam lines. Radioactive beams far from the stability valley, already produced in the present configuration with a poor intensity, like $^{14}$Be, $^9$B, $^9$He, will benefit from the above described upgrading and it will be possible to use them for experiments.
Table 1. Characteristics of the produced fragmentation beams. Intensity is normalized to a primary beam of 100 Watt.

| Primary beam (55 MeV/A) | ⁹Be production target thickness (mm) | Secondary beam and energy | Intensity (kHz) | Abundance |
|-------------------------|-------------------------------------|---------------------------|----------------|-----------|
| ¹³C                     | 1.5                                 | ¹⁰Be - 48 MeV/A           | 10             | 50%       |
| ¹³C                     | 1.5                                 | ¹²B - 47 MeV/A           | 160            | 80%       |
| ¹⁶O                     | 1.5                                 | ¹⁸O - 31 MeV/A           | 5              | 10%       |
| ¹⁶O                     | 1.5                                 | ¹⁸O - 36 MeV/A           | 0.7            | 1.5%      |
| ¹⁶O                     | 2.5                                 | ¹⁷F - 24 MeV/A           | 10             | 20%       |
| ¹⁸O                     | 1.5                                 | ¹⁰C - 49.9 MeV/A         | 9              | 30%       |
| ¹⁸O                     | 1.5                                 | ¹³B - 52 MeV/A           | 4.5            | 15%       |
| ¹⁸O                     | 1.5                                 | ¹⁰Be - 48 MeV/A          | 3              | 10%       |
| ¹⁸O                     | 1.5                                 | ⁸Li - 51 MeV/A           | 3              | 10%       |

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