RIB Production at LNL: the EXOTIC Facility

Marco Mazzocco
Dipartimento di Fisica e Astronomia, Università di Padova, via F. Marzolo 8, I-35131 Padova, Italy
INFN-Sezione di Padova, via F. Marzolo 8, I-35131 Padova, Italy
E-mail: marco.mazzocco@pd.infn.it

Abstract. Nuclear reactions involving radioactive isotopes are extremely relevant in several astrophysical scenarios, from the Big-Bang Nucleosynthesis to Supernovae explosions. In this contribution the production of Radioactive Ion Beams (RIBs) by means of the in-flight technique is reviewed. In particular, the use of direct reactions in inverse kinematics for the production of light weakly-bound RIBs by means of the facility EXOTIC at INFN-LNL (Italy) will be described in detail.

1. Introduction

Radioactive nuclei are involved in several processes of astrophysical interest, ranging from nuclear reactions occurred in the early universe to reaction mechanisms still taking place in stars or in cosmic explosions [1]. Beams of radioactive isotopes provide us the possibility of investigating these processes on Earth. Unfortunately, due to the present-day limited intensity of Radioactive Ion Beams (RIBs), these studies still suffer, in most cases, of low statistical accuracy.

Considerable effort has been currently put by the worldwide Nuclear Physics community for the construction of second generation RIB factories. There exist two main techniques for the production of RIBs: the In-Flight (IF) method and the Isotope Separation On Line (ISOL). In a very schematic description, the IF approach uses heavy ion beams impinging on thin targets. The reaction products retain most of the projectile initial velocity and are in-flight selected by proper combinations of electromagnetic fields before being delivered to the experimental areas. In the other side, the ISOL technique employes either light or heavy ion beams impinging on thick targets kept at high temperature. The reaction products are thus created in a sort of ion source. Then they thermally diffuse out of it, they are mass selected and finally post-accelerated before being delivered to the experimental halls. Both methods have advantages and drawbacks. For instance, IF beams usually require rather faster separation times (in the order of a few $\mu$s), but have poor optical properties, i.e. large emittance. On the contrary, ISOL beams need longer selection times (in the range between a few ms to a second), but the outcoming beams have very good optical properties.

In this contribution, we will initially review the characteristics of the IF production methods (Sec. 2), then we will describe in detail the RIB production by means of direct reactions in inverse kinematics (Sec. 3). As an application, we will present the RIBs produced so far by the facility EXOTIC [2] at INFN-LNL (Italy) (Sec. 4). Some concluding perspectives will finally be given in Sect. 5.
2. In-Flight production method

The main positive aspect of the IF methods is the use of (relatively) thin production targets (up to a few mg/cm$^2$). In this way, the reaction products retain a large fraction of the initial projectile velocity and, due to linear momentum conservation, they have a kinematic (forward) focusing at small angles around the beam direction. A fragment separator can thus be located exactly along the primary beam axis. The selection of the RIB of interest is performed by means of a proper combination of electromagnetic fields and atomic interaction and is generally a process quick (the transit time through a spectrometer is at maximum of the order of a few µs) and independent from the chemical properties of the radioisotopes under production. Moreover, IF RIBs usually do not require the design of post accelerators and consequently IF facilities result to be somewhat less costly than ISOL-based laboratories. However, IF RIBs typically have poor optical quality, in terms of longitudinal and transverse emittance and beam spot on target.

There exist three main IF production techniques: (i) projectile fragmentation, (ii) projectile fission and (iii) direct processes in inverse kinematics. To be effective the first two processes require a projectile energy of a few tens MeV/u and thus a cyclotron, if not a synchrotron, is needed as driver accelerator. The last method is less demanding in terms of beam energy, since it employs direct processes, whose cross sections reach the range of hundreds or thousands mb already at a bombarding energy of a few MeV/u. In this case, even old machines like electrostatic tandem accelerators can be used as primary driver.

3. Direct reactions in inverse kinematics

This IF method employs inverse kinematics reactions (i.e. heavy ion beams of light targets), such as inverse (p,n), (d,n), (d,p) or ($^3$He,n) processes, preferably with negative Q-values. The large linear momentum carried by the heavy projectile implies that the reaction products are emitted in rather narrow cones around the primary beam direction.

In a standard two-body nuclear reaction in inverse kinematics:

\[ p + t \rightarrow p_{like} + t_{like} \]  

where \( p \), \( t \), \( p_{like} \) and \( t_{like} \) are the projectile, target, projectile-like and target-like fragment, respectively, the maximum opening (\( \theta_{max} \)) of the emission cone for projectile-like particles is given by the formula:

\[ \theta_{max} = \arccos \sqrt{\frac{(M_{t_{like}} + M_{p_{like}})(M_{t_{like}}Q_{value} + (M_{t_{like}} - M_p)E_{beam})}{M_pM_{p_{like}}E_{beam}}} \]  

being \( M_p \), \( M_t \), \( M_{p_{like}} \) and \( M_{t_{like}} \) the projectile, target, projectile-like and target-like masses, respectively, \( E_{beam} \) the beam energy (in the laboratory reference frame) and \( Q_{value} = M_p + M_t - (M_{p_{like}} + M_{t_{like}}) \).

The preferred target materials would be hydrogen or helium isotopes. Unfortunately, the are no He-compounds, while H-rich compounds cannot withstand the thermal stress induced by a high intensity primary beam. To circumvent these problems, the use of gas targets, often cooled down to liquid nitrogen temperatures, with metallic windows is generally undertaken.

In the following subsections, we will describe in detail the dependence on beam energy, reaction \( Q_{value} \) and projectile mass \( M_p \) of the maximum emission angles for projectile-like fragments produced in (p,n), (d,p), (d,n) and ($^3$He,n) reactions.

3.1. (p,n) reactions

Figs. 1 and 2 show that the maximum opening of the emission cones for projectile-like fragments produced in (p,n) charge-exchange reactions decreases as the projectile mass increases. This
Figure 1. Maximum emission angles ($\theta_{\text{max}}$) for projectile-like fragments produced in (p,n) reactions as a function of the projectile mass ($M_p$). Different lines correspond to reaction $Q$ values ($Q$) in the energy range from -2 to +2 MeV. The beam energy ($E_{\text{beam}}$) was arbitrarily set to 100 MeV.

Figure 2. Same as Fig. 1. Different lines correspond to beam energies ($E_{\text{beam}}$) ranging from 25 to 85 MeV. The reaction $Q$ values ($Q$) was arbitrarily set to -2 MeV.

feature is clearly related to larger linear momentum carried by heavier projectiles. We also notice that the emission cones get significantly narrower for negative $Q$ values (Fig. 1) and for smaller primary beam energies (Fig. 2). In particular, we can observe in Fig. 2 that when the beam energy is equal to 25 and 40 MeV, the opening of the emission cones vanishes for projectile mass larger than 12 and 19, respectively. The plotted curves were indeed calculated for an hypothetical reaction with a $Q$ value of -2 MeV and, in the laboratory frame, there is a threshold energy, given by the formula:

$$E_{\text{beam, min}} = -Q \frac{M_p + M_t}{M_t}$$

for a negative $Q$ value reaction to occur.

3.2. (d,p) and (d,n) reactions

Figs. 3 and 4 display the maximum emission angles for projectile-like fragments produced either in (d,p) or (d,n) reactions. In these cases, either a loosely-bound neutron or proton is transferred from the deuterium target to the projectile, generating a n-rich or a p-rich RIB, respectively. The increased target mass implies that the openings of the emission cones are somewhat larger with respect to RIBs produced via (p,n) reactions.

3.3. ($^3$He,n) reactions

We finally considered ($^3$He,n) reactions, where two protons are transferred from the gas target to the projectile. These reactions allow producing p-rich RIBs two mass units apart from the valley of $\beta$-stability. In this case the maximum emission angle can reach values as large as $\theta_{\text{max}} = 13^\circ$, as for the production of a $^8$B secondary by means of the reaction $^6Li + ^3He \rightarrow ^8B + n$ ($Q_{\text{value}} = -1.97$ MeV).
3.4. Reaction $Q_{\text{value}}$

Fig. 7 summarizes the reaction $Q_{\text{values}}$ for RIBs which can be produced in two-body processes in inverse kinematics induced on a hydrogen, deuterium and $^3$He gas targets. The data are plotted as a function of the primary beam mass. $^9$Be, $^{20-22}$Ne and $^{36,38,40}$Ar beams, which cannot be delivered by the LNL-XTU tandem accelerator, were excluded from the graph. We can observe that all (p,n) charge exchange reactions have negative $Q_{\text{values}}$. Generally speaking, this a quite favorable circumstance, since the RIB particles are emitted much closer to the beam axis and ion-optical elements (e.g. quadrupoles and dipoles) with smaller openings could be employed without compromising too much the transmission of the fragment separator. However, we should keep in mind, that the trick of using inverse kinematics reactions for the RIB IF production is
Figure 7. Reaction $Q_{\text{values}}$ for RIBs which can be produced by means of (p,n), (d,n), (d,p) and ($^3$He,n) reactions. The data were plotted as a function of the projectile mass. Beams, such as $^9$Be, $^{20-22}$Ne and $^{36,38,40}$Ar, which cannot be delivered by the LNL-XTU tandem accelerator were not included in the figure.

not really effective when the reaction $Q_{\text{value}}$ is much smaller than -5 MeV and for RIB masses heavier than 25 amu, as the minimum energy required for the production reaction to occur in the laboratory frame may easily exceed the capabilities of an electrostatic accelerator, such as the LNL 15 MV tandem.

In addition, we notice that (d,p) reactions usually have positive $Q_{\text{values}}$ (the only notable exemption is the reaction $^7$Li + d employed for the production of a $^8$Li RIB), whereas several (d,n) reactions might be good candidates for the production of p-rich RIBs. Finally, a few ($^3$He,n) reactions have negative $Q_{\text{values}}$, especially for light projectiles masses, and can be possibly employed for the production, for instance, of $^8$B, $^{14}$O and $^{18}$Ne RIBs.

4. RIB production at EXOTIC
The facility EXOTIC [2] was commissioned at INFN-LNL in the years 2003-2004 and was upgraded in 2012 [3]. The production target consists of a 5-cm long gas cell doubly-walled with 2.2-$\mu$m thick havar windows. The target station can operated either at room temperature or can be cooled down to liquid nitrogen temperature ($\approx 90$ K). The standard operating gas pressure is 1 bar and the windows were tested up to 1.4 bar. The ion optical lay-out is made up by eight elements: a first quadrupole triplet (Q1-Q3), a 30°-dipole magnet (DM), a 1-m long Wien (velocity) filter (WF) and a second quadrupole triplet (Q4-Q6). The entire facility is about 8.4 m long.

The secondary beam selection is performed in two stages. At first, the DM selects particles
with the same (within the acceptance of the magnet) magnetic rigidity, \( B\rho = \frac{mv}{q} \), being \( B \) the magnetic field of the DM, \( \rho \) the radius of curvature and \( m, v \) and \( q \) the particle mass, velocity and charge, respectively. According to the basic laws of electromagnetism, different ion species characterized by the same magnetic rigidity have the following kinetic energies, \( E \), and velocities, \( v \):

\[
E = \frac{q^2}{2m} (B\rho)^2 \quad (4)
\]

\[
v = \frac{q}{m} (B\rho) \quad (5)
\]

We can immediately observe that the kinetic energy depends quadratically on the magnetic rigidity, whereas the velocity scales linearly with \( B\rho \). As an example, Figs. 8 and 9 illustrate the behavior of the energy and velocity, respectively, as a function of the magnetic rigidity in \(^{17}\text{F} \) RIB production by means of a \((p,n)\) reaction. We considered in the figure non only the \(^{17}\text{F}^{9+} \) secondary beam, but also four different charge states of the scattered beam, i.e. \(^{17}\text{O}^{8+,7+,6+,5+} \), and three charge states of a possible contaminant beam, i.e. \(^{16}\text{O}^{8+,7+,6+} \).

**Figure 8.** \(^{17}\text{F} \) RIB production: kinetic energy as a function of the magnetic rigidity for the following beams: \(^{17}\text{F}^{9+} \) (black curve), \(^{17}\text{O}^{8+,7+,6+,5+} \) (red curves) and \(^{16}\text{O}^{8+,7+,6+} \) (blue curves).

**Figure 9.** \(^{17}\text{F} \) RIB production: velocity as a function of the magnetic rigidity for the following beams: \(^{17}\text{F}^{9+} \) (black line), \(^{17}\text{O}^{8+,7+,6+,5+} \) (red lines) and \(^{16}\text{O}^{8+,7+,6+} \) (blue lines).

Fig. 8 shows that the parabolas describing the energies of the different ion species can essentially be grouped according to the particle charge state. The most energetic beam is the only one with charge state 9+ (i.e. \(^{17}\text{F}^{9+} \)), then we have beams with charge state 8+ (\(^{17}\text{O}^{8+} \), \(^{16}\text{O}^{8+} \) and, not shown, \(^{17}\text{F}^{8+} \) ) with smaller energies, then 7+, 6+ and so on. We can also identify a fine structure within these groups, since lighter masses, according to Eq. 4, have higher kinetic energies.

The selection provided only by the DM would produce a cocktail beam with the desired RIB together with several different charge states of the scattered beam and, possibly, some other contaminant beams. A typical example of such a circumstance is given in the upper panel of Fig. 2 in Ref. [4], where one clearly sees a small bump related to the \(^{17}\text{F}^{9+} \) RIB, a huge peak due to the \(^{17}\text{O}^{8+} \) scattered beam and then the other \(^{17}\text{O} \) charge states with decreasing intensity.
For this reason, the facility was additionally equipped with a 1-m long WF. In this region we have the superposition of a magnetic field and a perpendicular electrostatic field, $E$, in such a way that the Lorentz force ($\vec{F}_L = q\vec{v} \times \vec{B}$) would be opposite to the electrostatic force ($\vec{F}_E = q\vec{E}$). During an experiment, a proper tuning of both electric and magnetic field of the WF ensures an overall suppression of all contaminant beams and helps achieving a nearly 100-% purity for RIBs produced by means of (p,n) and (d,p) reactions. Some examples are provided by the lower panel of Fig. 2 in Ref. [4] and by Fig. 1 in Ref. [5] for the $^{17}$F and $^7$Be secondary beam production, respectively. Similar scenarios were also observed for the production of $^{15}$O and $^{10,11}$C radioactive beams. In all these cases beam purities as good as 99 % were achieved.

Figure 10. $^8$B RIB production: kinetic energy as a function of the magnetic rigidity for the following beams: $^8$B$^{5+}$ (black curve), $^7$Be$^{4+}$ (red curve), $^7$Li$^{3+}$ (green curve), $^6$Li$^{3+,2+}$ (red curves), $^4$He$^{2+}$ (pink curve) and $^3$He$^{2+}$ (yellow curve).

Figure 11. $^8$B RIB production: kinetic energy as a function of the magnetic rigidity for the following beams: $^8$B$^{5+}$ (black line), $^7$Be$^{4+}$ (red line), $^7$Li$^{3+}$ (green line), $^6$Li$^{3+,2+}$ (red lines), $^4$He$^{2+}$ (pink line) and $^3$He$^{2+}$ (yellow line).

Definitely more puzzling is the production of a $^8$B RIB. In fact, besides the fact that the $^8$B$^{5+}$ RIB is by far the most energetic beam (see Fig. 10) which can be produced by means of the reaction $^6$Li + $^3$He, its velocity is exactly in between those of the $^7$Be$^{4+}$ contaminant beam and of fully stripped $^3$He ions recoiling out from the gas target. In this case, depending on the fine tuning of the WF, one can let either more $^3$He$^{2+}$ or more $^7$Be$^{4+}$ pass through the facility and reach the secondary target. The use of high transparency tracking detectors upstream the final focal plane of the facility may help disentangling the cocktail beam, since the particle velocity is selectively perturbed by the atomic interaction with the detector foils according to the atomic number of the ion species. Fig. 1 of Ref. [6] shows the actual situation occurred during an experiment aimed at measuring the fusion cross section for the system $^8$B + $^{28}$Si at Coulomb barrier energies. Depending on the beam energy and WF tuning, secondary beam purities in the range 30-43% were achieved.

In summary, the facility EXOTIC has already delivered seven RIBs in the energy range 1.5-6 MeV/u: $^7$Be, $^6$Li, $^{11}$C, $^{17}$F (with intensities larger than $10^5$ pps), $^{15}$O (intensity greater than $10^4$ pps), $^{10}$C and $^8$B (intensities around $10^3$ pps).

For the sake of completeness, we underline that there exist other five facilities in the world which produce and deliver RIBs in a similar manner: CRIB (Japan) [7, 8], MARS (USA) [9], TWIN Sol (USA) [10], ANL (USA) [11] and RIBRAS (Brazil) [12].
5. Perspectives

The facility EXOTIC has been operational for more than a decade for the production of RIBs by means of the IF technique. A first experiment of astrophysical interest has been recently performed [13]. The goal of this experiment was the measurement of the cross section for the reaction $^7\text{Be} + n \rightarrow \alpha + \alpha$ in the energy range up to $E_{cm} = 1$ MeV by means of the Trojan Horse Method [14] and the surrogate reaction $^7\text{Be} + ^2\text{H} \rightarrow \alpha + \alpha + \text{p}$. This study is particularly relevant for the cosmological $^7\text{Li}$ problem [15], since this process represents about 2.5% of the $^7\text{Be}$ destruction rate in the standard Big-Bang Nucleosynthesis model. The experiment was performed in November 2015 and a remarkable secondary beam intensity of $1.3 \times 10^6$ pps was achieved throughout the 13 days of beam time. The data analysis has just started.

Acknowledgements

This work was partially supported by the Italian Minister for Education, University and Research (MIUR) within the project RBFR08P1W2_001 (FIRB 2008).

References

[1] Smith M S and Rehm K E 2001 Ann. Rev. Nucl. Part. Sci. 51 91.
[2] Farinon F et al. 2008 Nucl. Instrum. Meth. B 266 4097.
[3] Mazzocco M et al. 2013 Nucl. Instrum. Meth. B 317 223.
[4] Mazzocco M et al. 2010 Phys. Rev. C 82 054604.
[5] Mazzocco M et al. 2015 Phys. Rev. C 92 024615.
[6] Pakou A et al. 2013 Phys. Rev. C 87 014619.
[7] Yanagisawa Y et al. 2005 Nucl. Instrum. Meth. A 539 74.
[8] Yamaguchi H et al. 2008 Nucl. Instrum. Meth. A 589 150.
[9] Tribble R E et al. 1989 Nucl. Instrum. Meth. A 289 441.
[10] Becchetti F D et al. 2003 Nucl. Instrum. Meth. A 505 377.
[11] Harss B et al. 2000 Rev. Sci. Instrum. 71 380.
[12] Lichtenhaler R et al. 2005 Eur. Phys. J. A 25 s733.
[13] Lamia L et al. 2015 Proposal INFN-LNL 15.13.
[14] Tribble R E et al. 2014 Rep. Prog. Phys. 77 106901.
[15] Broggini C et al. 2012 Jour. Cosm. Astrop. Phys. 6 30.