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Radioactive Ion Beams: Production and Experiments at INFN-LNL

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Abstract. In this contribution the main mechanisms and techniques for the production of Radioactive Ion Beams are reviewed. In particular, the in-flight facility EXOTIC at INFN-LNL will be described and the results of a recent measurement of interest for the cosmological ^{7}Li problem will be presented.

1 Introduction

In the chart of nuclei, the graphical representation of the combinations of protons and neutrons observed either in Nature or in experiments, radioactive nuclei outnumber stable nuclei by more than one order of magnitude [1]. As we move apart from the valley of β-stability, where stable and metastable nuclei are situated, we might encounter new phenomena, such as new decay modes, for instance proton-, neutron- and 2 proton-radioactivity, nuclei with exotic shapes or deformations, and also the well-established nuclear shell closures exhibit an evolution as we move towards the limits of existence on nuclei.

Radioactive nuclei are involved in many astrophysical scenarios, from the quiescent burning stages to the more dramatic supernova explosions. In our Sun, about 1% of the energy production is generated by the CNO cycle, which involves radioactive nuclei, and also the ppII and ppIII chains proceed through the intermediate production of unstable nuclei. In that respect, spectroscopic information on nuclei far from stability are of paramount relevance to calculate the cross sections for the reactions of interest and to predict the paths of the astrophysical processes in different stellar environments.

The study of the properties of the reactions induced by radioactive nuclei is complicated by the fact that, in most cases, these nuclei are short-lived, preventing the possibility of accumulating and safely handling macroscopic quantities useful for manufacturing a standard target or to be used as source material. Therefore, to perform these studies we need at first a (primary) nuclear reaction to occur for the production of the radioactive ion species of interest, which typically are not produced alone, thus we need also an efficient and fast selection technique to purify from the contaminant beams, in some cases even orders of magnitude more intense than the desired Radioactive Ion Beam (RIB). The rapidity of the entire process is another key requirement, since these ions are short-lived, and they will immediately start decaying after their production. Finally, dealing typically with rather small

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cross sections, all different stages for the RIB production must be optimized, from the choice of the most suitable projectile-target combination to the beam energy, from the power dissipation into the target to the design of instruments capable to operate in an environment potentially exposed to high radiation dose.

2 RIB Production Mechanisms

The production mechanisms for RIBs can be schematized into five categories: fragmentation, fission, spallation, fusion and two-body reactions in inverse kinematics.

2.1 Fragmentation

Fragmentation is caused by peripheral reactions leading to the removal of a certain number of nucleons. The production cross sections are nearly constant as a colliding energy of a few tens of MeV/u is exceeded. The advantage of increasing the beam energies, thus investing in the construction of a more powerful accelerator, consists in a smaller angular opening around the primary beam direction for the emission cone of the recoiling RIB under production. Fragmentation is mostly used for the production of proton-rich nuclei; however, it is often used as a powerful method to produce neutron-rich RIBs, especially in the heavier mass region.

2.2 Fission

Fission is a spontaneous decay mode for many transuranic isotopes. This process can also be induced by the energetic collision of fissile material with light nuclei. Due to the overwhelming abundance of neutrons with respect to protons in metastable fissile nuclei, this mechanism produces neutron-rich RIBs, especially in the mass region between A = 70 and A = 160. Due to the systematics of fission reaction, the emission cones for the fission fragments are significantly larger than for fragmentation reaction products. Emission cones with wider angular opening require the design of particle spectrometers with larger angular acceptance to guarantee a better transmission and, in turn, a higher RIB intensity.

2.3 Spallation

Spallation is the interaction of a particle, mostly a single nucleon, at energies between 100 MeV and a few GeV with a target. After the interaction, many nucleons are ablated and the residual nuclei can be very different from the initial target nucleons. This mechanism has rather high cross sections for the production of neutron-deficient RIBs.

2.4 Fusion

Fusion is a process where, after the interaction, projectile and target form a compound nucleus at moderately high excitation energy. The system de-excites by emitting protons, neutrons, alpha particles, and gamma rays giving origin to a plethora of evaporation residues. These nuclei recoil in forward direction with a mean velocity approximately equal to the compound nucleus velocity, which is a fraction significantly smaller than the projectile velocity. Recoil separators exploit this feature to select the residues, however the separation efficiency is strongly limited, since this mechanism occurs essentially in the low energy regime (a few MeV/u) and consequently the residues are produced with broad angle, velocity and charge state distributions. So far, fusion has been employed for spectroscopy studies, for the synthesis of superheavy elements, but not for the production of RIBs.

2.5 Two-body reactions in inverse kinematics

We group into this category inverse (p,n), (d,n) and (^{3}He,n) reactions, preferably with negative Q-value and forward-peaked differential cross sections. Linear momentum conservation ensures that the RIBs are produced with narrow openings (< 10°) around the primary beam direction. Hydrogen and helium are the preferred target material for this mechanism, but there are no helium compounds and hydrogen-rich compounds cannot typically withstand the thermal stress induced by an intense primary beam. Therefore, to circumvent these problems, the use of gas targets with metal windows is routinely undertaken. This production mechanism works particularly nicely for light RIBs (up to A = 30-40) a few mass units away either on the n-rich or p-rich sides of the valley of stability.

3 RIB Production Techniques

Unless the radioactive species of interest is long-lived enough and has the suitable chemical properties to be produced in batch-mode and employed as ion source or target material, there exist two complementary techniques for the RIB production and separation: the in-flight and the Isotope Separation On-Line (ISOL) methods.

3.1 In-Flight

In the in-flight method [2], a heavy-ion beam with energy ranging from a few MeV/u to a few GeV/u impinges on a thin production target. For projectile fragmentation and fission, the preferred target material is beryllium, a monoisotopic element with low atomic number and high melting point. The inverse kinematics and the high bombarding energy guarantee a strong forward focusing at small angles around the primary beam direction of the reaction products.

The RIB selection exploits proper combinations of electromagnetic fields and atomic interaction, occurs in a fast time scale (the time needed to travel through the entire separator, usually less than 1 μs) and is independent from the RI chemical properties. Moreover, the secondary beams retain a large fraction of the initial projectile velocity, thus in-flight facilities usually do not require the construction of a post-accelerator. The use of a thin target is recommended to minimize the energy loss and the angular straggling through the target thickness, which might compromise the performances of the fragment separator in terms of transmission, selection quality and purification of the RIB under production. Possible drawbacks of this technique are associated with the generally poor beam quality, i.e. large longitudinal and transverse emittance and beam-spot on the secondary target. Nevertheless, this method is very fast and universal, RIBs are directly available at high energy and is particularly adapted for the production and identification of new isotopes.

3.2 ISOL

The ISOL [3] technique provides very good quality beams with small emittance and energy spread and with high purity. These positive aspects come at the price of the complexity of the entire facility. In fact, the primary beam impinges on a thick production target. The produced radioactive species diffuse into the target material, kept at high temperature to increase the ion mobility, then effuse into the target container and, after a series of collision with the walls, are finally transferred towards the source to be ionized. All these processes (diffusion, effusion, sticking time on the container walls, extraction, transfer, ionization) are strongly chemistry dependent and require a certain amount of time. Compared to the in-flight method, ISOL is considered to be significantly slower and long development times are needed for each different ion species.

After the ionization, which might already be a rather selective process, especially when laser frequencies are employed, the radioactive ions are ready for a isotopic/isobaric separation, whose resolution depends on the optical design of the magnetic spectrometer. At this stage, the RIB is still at low energy and with a small charge state. To match the beam energy range of interest for "standard" Nuclear Physics experiments, a post-acceleration stage must be implemented in an ISOL facility. To increase the performance of the post-accelerator, the RIB charge state can be raised by means of a charge breeder. At the end of the post-acceleration, the RIBs have practically the same optical properties of stable beams and are particularly adapted for detailed spectroscopic studies.

4 The Facility EXOTIC

EXOTIC [4] is an in-flight facility installed at the Laboratori Nazionali di Legnaro (LNL) of the Istituto Nazionale di Fisica Nucleare (INFN), near Padova (Italy). Light weakly-bound RIBs are produced by means of two-body inverse kinematic reactions induced by heavy-ion beams, accelerated by a 15 MV XTU-Tandem, impinging on a gas target. The commissioning of the facility was performed in 2004 and a substantial upgrade process was subsequently held in 2012 [5]. So far, 8 light RIBs have been delivered in the energy range of a few MeV/u: ^{8}Li, ^{7}Be, ^{8}B, ^{10,11}C, ^{15}O, ^{17}F and ^{18}Ne.

The ion optical design of EXOTIC includes a first quadrupole triplet, a dipole magnet, a Wien filter and a second quadrupole triplet. The double selection in magnetic rigidity and velocity acted by the dipole magnet and the Wien filter, respectively, helped achieving secondary beam purities as good as 99%. Mostly reaction dynamics studies at Coulomb barrier energies and experiments on clustering have been performed. In March 2021 the two reaction chambers at the final focal of EXOTIC were dismounted to permit the installation of the Advanced GAmma-ray Tracking Array (AGATA [6]) and platform with the relative services and we submitted a Technical Design Report and a Letter-of-Intent for investigating the possibility to couple the facilities EXOTIC and AGATA and exploit the unique features guaranteed by the light RIBs delivered and the state-of-the-art performances of AGATA.

5 Recent Experiment

Quite recently, a first experiment [7] of astrophysical interest was performed to study the ^{7}Li cosmological problem. In fact, the ^{7}Li abundance observed in metal-poor stars is a factor of 3 smaller than standard Big-Bang Nucleosynthesis (BBN) theoretical predictions. In the BBN reaction network, ^{7}Li is essentially produced by the electron capture decay of ^{7}Be. In that respect, the investigation of the ^{7}Be destruction mechanisms in the BBN energy range (20-70 keV) might provide a Nuclear Physics solution of the long-standing ^{7}Li cosmological problem [8]. The second most dominant ^{7}Li destruction process, after the ^{7}Be(n,p)^{7}Li, is the reaction ^{7}Be(n,α)^{4}He. The study of this reaction is complicated by the fact that it involves both a radioactive projectile and a radioactive target. We therefore employed the Trojan Horse (indirect) Method (THM) [9] by making use of the surrogate three-body reaction d(^{7}Be,α^{4}He)p.

The ^{7}Be RIB was delivered by the facility EXOTIC at 20.4 MeV with an intensity of 5-8 x 10^{5} pps and impinged on a 400-μg/cm^{2} CD_2 target. The two α-particles were detected in coincidence by means of four telescopes of the EXPADES detector array [10], placed at suitable angles to fulfil the requirements prescribed by the THM for the observation of a quasi-free process, where the (undetected) proton acted as a spectator in the reaction. The trend of cross section extracted for the ^{7}Be(n,α)^{4}He with the THM is in agreement with the recent direct measurement (of the reverse reaction) performed by Kawabata et al. [11] and with the work of Hou and collaborators [12].

In conclusion, the discrepancy between the predicted value for the ^{7}Li abundance and the observed value for low-metallicity stars still remains large, suggesting once again the need of alternative solutions for the cosmological lithium problem. However, we should underline that this study represents one of the first applications of the THM to RIB induced reactions, following the main stream started with the investigation of the reaction ^{18}F(p,α)[13-15]. Nevertheless, ^{7}Be(n,α)^{4}He represents the first attempt to measure via the THM a reaction involving a neutron and a RI, similarly to the study recently carried out for the reaction ^{7}Be(n,p)^{7}Li [16], also of paramount importance for the BBN. These works open the way to the possible future investigation of other neutron induced reactions of astrophysical interest with short-lived radioactive nuclei exploiting the capabilities of the THM.

References

1. https://people.nscl.msu.edu/~thoennes/isotopes/index.html
2. D.J. Morrissey and B.M. Sherill, Lect. Notes Phys. **651**, 113 (2004)
3. P. Van Duppen, Lect. Notes Phys. **700**, 37 (2006)
4. F. Farinon et al., Nucl. Instrum. and Methods B **266**, 4097 (2008)
5. M. Mazzocco et al., Nucl. Instrum. and Methods B **317**, 223 (2013)
6. https://www.agata.org
7. L. Lamia et al., Ap. J. **879**, 23 (2019)
8. C. Broggini et al., Journal of Cosmology and Astroparticle Physics **6**, 030 (2012)
9. R.E. Tribble et al., Reports on Progress in Physics **77**, 106901 (2014)
10. D. Pierroutsakou et al., Nucl. Instrum. and Methods A **834**, 46 (2016)
11. T. Kawabata et al., Phys. Rev. Lett. **118**, 052701 (2017)
12. S.Q. Hou et al., Phys. Rev. C **91**, 055802 (2015)
13. S. Cherubini et al., Phys. Rev. C **92**, 015805 (2015)
14. R.G. Pizzone et al., Eur. Phys. J. A **52**, 24 (2016)
15. M. La Cognata et al., Ap. J. **846**, 65 (2017)
16. S. Hayakawa et al., Ap. J. **915**, L13 (2021)