Secondary-beam production: protons versus heavy ions

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Abstract. The construction of two new-generation complementary RIB facilities in Europe, one based on the in-flight fragmentation or fission (IFF) method (FAIR) and the other on the isotope separation on-line (ISOL) method (EURISOL) is expected in the next 10-15 years. The reaction mechanisms, responsible for the production of the secondary nuclei, along with the technical constrains, have to be considered for the designs of the facilities. In this work, we study which reaction mechanisms can be exploited at best for the production of the secondary beams in the two facilities.

PACS. 25.40.Sc, 25.75.-q

Following NuPECC's recommendations [1], the construction of two new-generation complementary RIB facilities in Europe is foreseen. The next-generation IFF facility in Europe will be realised at FAIR [2], Darmstadt, Germany. The major next-generation ISOL facility will be realised at the EURISOL [3] (location not yet known). At FAIR, the primary beams will consist of ions: all stable nuclei from hydrogen till uranium will be accelerated up to energy of 1.5 GeV per nucleon. At EURISOL, the baseline driver beam consists of 1 GeV protons, but it is under discussion, and it is a topic of the present work, whether an extension to light-ion beams would be convenient.

In both facilities, the energy of the primary beam is in the GeV region. Spallation, fragmentation and fission are the dominant reaction mechanisms, responsible for the formation of secondary nuclei. In order to investigate quantitatively how and which reaction mechanism would reflect on the final production yields, a solid know-how on the physics of spallation, fragmentation and fission reactions is essential. Since about 10 years, these reactions are experimentally investigated in a systematic way at the FRagment Separator (FRS), GSI, Darmstadt. The experiments, performed in inverse kinematics, gave precise measured values of cross-sections and velocity spectra of all secondary nuclei produced from ^{238}U, ^{208}Pb, ^{197}Au, ^{124,136}Xe, ^{124}Sn and ^{56}Fe beams on several targets (from hydrogen to lead) at energies in the range 200-1500 A MeV. Most of the experimental data are published and accessible (see [4] and references therein). Parallel to the experimental campaign, an intensive study aimed to have a better understanding and modelling of the nuclear reactions was carried along. The study resulted in a computational code, named ABRABLA [5].

In the present work, thanks to the acquired experience and exploiting the computation tool ABRABLA, we studied which reaction mechanisms can be exploited at best for the production of the secondary beams in the FAIR and EURISOL facilities.

1 Maximisation of RIB intensities at FAIR

The FAIR project has a broad scientific scope allowing forefront research in several different disciplines of physics, like hadron physics, physics of hadronic matter, plasma physics, atomic physics, applied sciences, and, above all, nuclear structure physics and astrophysics. Research in the latter fields will be possible by the generation of intense, high-quality secondary beams, produced via in-flight fragmentation and in-flight fission and selected and separated through an innovative magnetic spectrometer (Super-FRS). Compared to the present GSI facility, up to a factor of 10,000 in secondary radioactive beam intensities is the technical goal.

The maximisation of the secondary-beam intensities is a relatively simple task, the technical constrains being already fixed. They concern the accelerator complex and therefore the primary beam characteristics (e.g. the intensity), the production target material (limited to carbon), and the Super-FRS characteristics (e.g. the acceptance). Under these conditions, the reaction mechanism is the main determinant of the production rates.

In this work, the secondary-beams intensities were estimated by (i) using always carbon as production-target material, (ii) choosing the optimum target thickness and primary-beam energy according to the criteria reported in ref. [6], (iii) considering all primordial nuclides up to ^{238}U as primary beams, (iv) assuming primary beam-intensities to range from $1\cdot10^{12}$/s for ^{238}U to $3\cdot10^{12}$/s for ^{20}Ne. The semi-empirical code EPAX [7] was used for calculating fragmentation cross sections of all primordial nuclides up to ^{209}Bi used as primary beams. The production of projectile fragments and fission residues from the fissile projectile ^{238}U was calculated with the ABRABLA code. Under the above assumptions, fragmentation-fission reactions and fragmentation-evaporation reactions were calculated with different beam types, target-thicknesses and beam-energies: the best combination for each nuclide is chosen to get the production rate of the given nuclide. See [6, 8] for details. Results are presented in form of a chart of the nuclides in fig. 1. Rates much higher than those actually achievable at GSI are expected for most of the presently known isotopes. Moreover, a large number of nuclides beyond the present limits will become accessible. The most important progress can be expected in the neutron-rich region above the fission fragments, where the N=126 and Z=82 shells can be followed over long chains of isotones and isotopes, respectively.

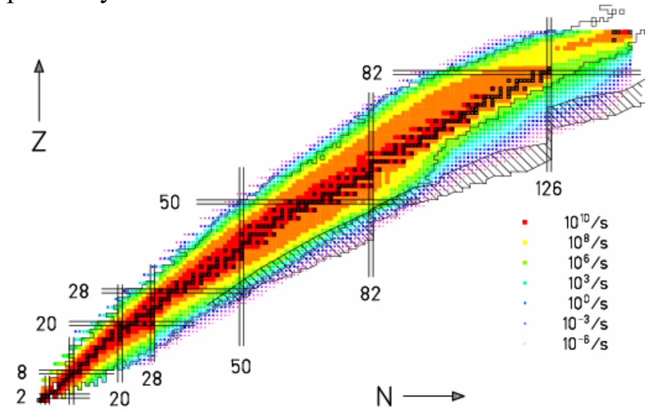

Fig. 1. Predicted productions rates of future RIBs at FAIR. Primordial nuclei, closed shells, limits of known nuclei and the area of predicted r-process path are indicated in black.

2 Maximisation of RIB intensities at EURISOL

The EURISOL project aims at the next-generation European ISOL facility. EURISOL will extend and amplify the work presently being carried out at the first generation RIB facilities, in Europe and all over the world, in the fields of nuclear physics, astrophysics and fundamental interactions.

The project is still in its design phase, so the technical characteristics are not yet completely fixed. Contrary to the case of FAIR, here the technical constrains are strongly relevant to evaluate the secondary-beam intensities. The target type plays a dominant role, affecting strongly the final efficiency, but the choice of the primary beam is also of great importance because it decides on the nuclear reaction involved in the production. Based on the experience gained at ISOLDE, CERN, and in other ISOL facilities, it was chosen to have a primary beam of 1 GeV protons of high intensity (delivering up to about 4 MW power).

In the present contribution we report on a dedicated study aimed to outline which extended capabilities of the driver accelerator would provide substantial benefits in specific cases. This study was carried out in the frame of “task 11, subtask 1”of EURISOL Design Study [9]. Out of this study, three cases are summarised here (sections 2.2, 2.3, and 2.4) and compares with the baseline proton option (section 2.1).

2.1 Yields from the baseline proton-beam

In the baseline design of the EURISOL project, the proton beam will impinge either directly on the production target (direct-target option) or in a high-power (HP) target (converter-target option), where the escaping secondary neutrons will induce fission on a uranium or thorium target placed around the converter.

In the direct-target option, spallation-evaporation and spallation-fission are the dominant reaction mechanisms. Thanks to the campaign of experiments performed at GSI [4], there is a good knowledge on these nuclear reactions. A good overview is offered in fig. 2, where measured and calculated production cross-sections for the reaction p+^{238}U at 1 GeV are presented. The overview reveals that spallation-evaporation produces nuclides reaching from the projectile to about 10 to 15 elements below (a few of them are neutron-rich, most of them are neutron-deficient), while spallation-fission (from Th, U) produces neutron-rich nuclides below Z=65. Although these characteristics were already known before, a good quantitative and systematic knowledge is essential for the estimate of the production rates. In fig. 2, the result of the ABRABLA calculation demonstrates the reliability of our nuclear-reaction code. The excellent predictive power of the code sets the validity of the present work.

In the direct-target option, the fission distribution is very wide, but it is more shifted towards the neutron-deficient side with respect to a typical low-energy fission distribution. Low energy-fission can be exploited in the converter-target option, where the secondary neutrons introduce in the primary nuclei excitation energy of few MeV above the fission barrier. Here, it is of interest to produce a limited number of very neutron-rich isotopes of elements in the Z range 30-60.

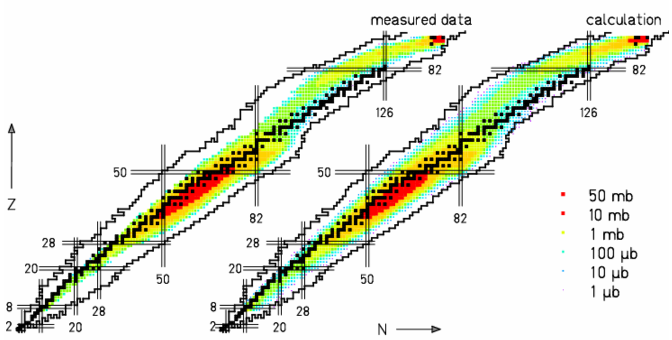

Fig. 2. Measured and calculated production cross sections of all nuclides produced by a 1 GeV proton beam in a thin ^{238}U target.

2.2 Extension to a deuteron beam

In the lower panel of fig. 3, we show the production occurring in the production target of natural uranium, foreseen in the converter-target scenario. The rather low excitation energy introduced by the evaporative neutrons escaping from the converter, whose average energy is 2 MeV, leads mostly to asymmetric fission. The production distributes around Xe and Sr, while nuclides between Z=42 and Z=48 (due to symmetric fission) are weekly produced.

A wider low-energy fission distribution is achievable employing neutrons of higher energy. They can be generated in stripping reaction of deuterons passing through a target material, where the stripped neutrons proceed in forward direction and carry along about half the energy of the impinging deuterons. For this reason, it was thought to be convenient to use a deuteron beam on a converter target. In the upper panel of fig. 3, we show the production occurring in a uranium target irradiated with the neutrons escaping a thick Be target irradiated with a 50 MeV deuteron beam. Compared to the previous case, here the gap between Z=42 and Z=48 is filled up and the tails of the distribution extend slightly further outside the Z range 30-60. On the other hand, the overall production is slightly shifted towards less neutron-rich isotopes, but this effect is not strongly pronounced.

Please note that in fig. 3 the yields are expressed in percent and give information only about the physics of the two reactions. In order to have quantitative prediction for the production rates, one would need to know the fission rates and other input information as the overall ISOL efficiencies for specific elements.

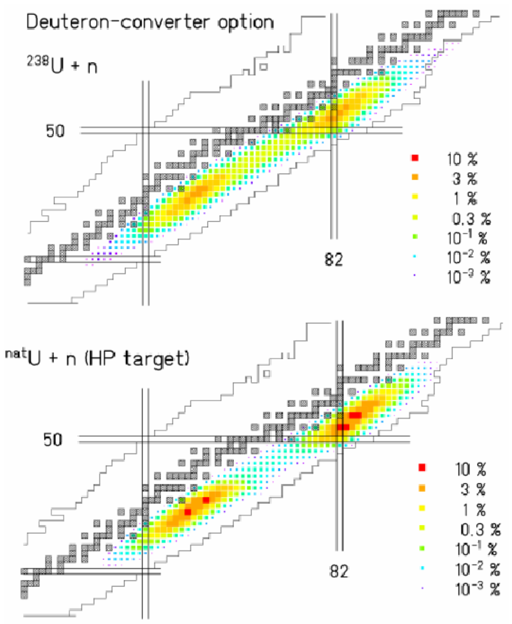

Fig. 3. In-target nuclide yields for the fission of uranium bombarded with neutrons emitted from: a thick Be target irradiated with a 50 MeV deuteron beam (upper figure), and the EURISOL high-power converter target irradiated with 1 GeV protons (lower figure).

2.3 Extension to a ^{3}He beam

In fig. 4, the nuclide distributions of residues produced in the reactions of ^{208}Pb+p and ^{208}Pb+d at different energies are presented. As for the case of ^{238}U+p, the reactions produce spallation-evaporation and spallation-fission products. The fission fragments are not of interest here because their distribution is limited to a region close to the stable nuclides. One can observe that the spallation-evaporation distribution extends to lighter masses as the centre-of-mass energy of the system increases. At the same time, also the production of light nuclei (the so called 'intermediate-mass fragments', IMF) extends to higher masses as the energy increases (this fact is not visible in fig. 4 because IMF were not measured in those experiments). These tendencies can be exploited to increase the production rates in two cases.

The first case concerns those nuclides which are produced at best via spallation-evaporation. In these cases, the best choice is to use a target slighter heavier than the desired nuclide (see section 2.1). However, often the most profitable target is not available technically [10], and one is forced to use a target 10 or up to 20 atomic units heavier. For instance, to produce neodymium (Z=60) isotopes, the best choice is to use a samarium target (Z=62). If one is forced to use Hf (Z=72) or Pb (Z=82) the production drops by 1 and 2 orders of magnitude respectively (see fig. 5). This reduction can be partially compensated by increasing the beam energy. For instance, the use of a 2 GeV deuteron beam would rise up one order of magnitude in the production rate. Since a 2 GeV deuteron beam is not easily achievable technically, one can use a 2 GeV ^{3}He beam, which is expected to produce a similar effect.

The second case is summarised in fig. 6. As previously said, the production of IMF increases by increasing the beam energy. A calculation performed with the intra-nuclear cascade code INCL4 [11] coupled with the evaporative code ABLA (taken from ABRABLA) shows that an even higher production would be achieved by using a 2 GeV ^{3}He beam.

In conclusion, the possibility to accelerate a 2 GeV ^{3}He primary beam would be helpful in many cases.

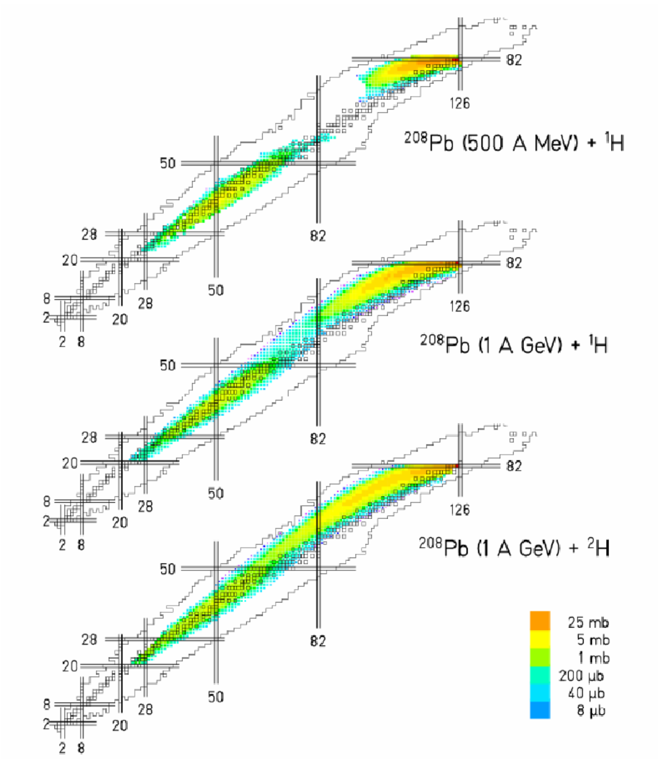

Fig. 4. Nuclide distributions of residues produced in the spallation of ^{208}Pb with 500 MeV protons, 1 GeV protons and 2 GeV deuterons. The cross sections were measured at GSI [4]. Elements below Z≅20 were not measured.

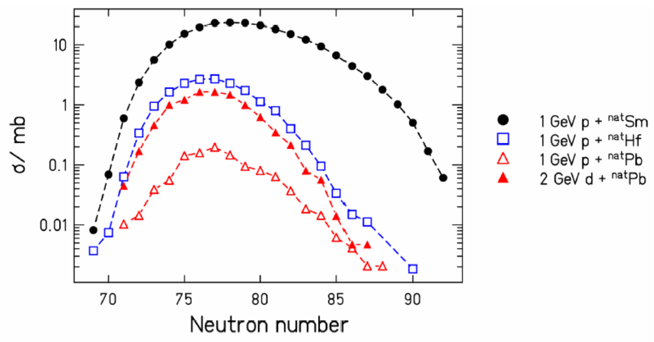

Fig. 5. Calculated production cross sections of neodymium (Z=60) isotopes by 1 GeV protons and 2 GeV deuterons on several targets. Calculations were performed with ABRABLA [5].

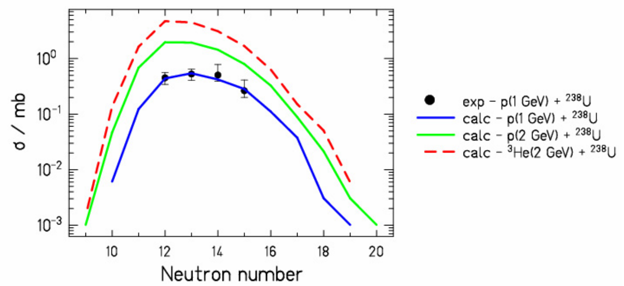

Fig. 6. Calculated production cross sections of sodium (Z=11) isotopes several primary beams on a ^{238}U target. Calculations were performed with INCL4+ABLA [5,11].

2.4 Extension to beams of heavier ions

The last point open to discussion is if it would be convenient to extend the primary beam to heavy ions.

This is a question with no easy answer, because the final production rates depend strongly both on the accelerator characteristics (resulting on the intensity, energy, and *A/q* of the accelerated ions) and on the target technology. Here we limit to two studies, related to two different reaction mechanisms: fragmentation and deep-inelastic transfer.

The Target-and-Ion-Source group of EURISOL performed an elaborate study [12] to estimate the attainable secondary-beam intensities by fragmentation of heavy ions. The estimation was performed assuming a multi-beam driver delivering any heavy-ion beam with *A/q* = 6 or 3 at 166.5 or 333 A MeV, respectively, impinging on a complex converter-catcher target system. The study showed that, compared to the final intensities expected using a 100 μA beam of 1 GeV protons, a higher production of light neutron-deficient nuclides is achievable via fragmentation. However, it must be said that some assumptions (e.g. the overall ISOL efficiencies) used for the above evaluation are not yet experimentally verified. In addition, the gain factors obtained in the above study should be adapted to the primary-beam intensities and energies feasible for the EURISOL driver accelerator.

A second study concerns the possibility to exploit peripheral nucleus-nucleus collisions in the Fermi-energy domain. These collisions can be well described theoretically using the model of deep-inelastic transfer DIT [13] in combination with a deexcitation model.

In the present work, we performed a comparison of the RIB intensities of nuclides around ^{78}Ni produced either in the reactions ^{86}Kr+^{64}Ni, ^{82}Se+^{64}Ni at 25 *A* MeV [14] or in the reaction of 1 GeV protons with ^{238}U, using a beam intensity of 1 pμA and 100 pμA respectively. The result indicates that benefits are found by the use of heavy ions for the production of extremely neutron-rich nuclei, while for the rest of the production a proton-beam is better suited. However, this result depends strongly on the reliability of the code at the tails of the isotopic distributions, which could not be checked experimentally up to now.

3 Conclusions

The knowledge on reaction mechanisms was exploited to investigate the production of RIBs both for an IFF facility (FAIR) and for an ISOL facility (EURISOL).

Under the fixed technical constrains given at FAIR, the intensities of the future RIBs at FAIR were estimated nuclide by nuclide exploiting the most suited reaction mechanism and target-beam combination.

On the basis of the 1 GeV proton driver beam planned at EURISOL, different reaction mechanisms were studied to explore which extended capabilities of the driver accelerator would provide substantial benefits in specific cases. The study showed that: 1) a deuteron beam of some tens of MeV would yield wider nuclide distribution of fission products compared to the 1 GeV proton converter option; 2) a 2 GeV ^{3}He beam would: (i) fill gaps in the masses far below available targets; (ii) enhance the production of neutron-rich IMFs; 3) heavy-ion beams would provide: (i) higher production of light neutron-deficient nuclides via fragmentation, (ii) higher production of light neutron-rich nuclides via deep-inelastic-transfer reaction.

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