COMPARISON OF RADIOACTIVE ION-BEAM INTENSITIES PRODUCED BY MEANS OF THICK TARGETS BOMBARDED WITH NEUTRONS, PROTONS AND HEAVY IONS

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ABSTRACT

Target and ion-source techniques which allow rapid separation of thermalized radioactive nuclei from 1–500 g/cm² thick irradiated target material and continuously convert them into a mono-isotopic ion beam have been proven to be a powerful method of radiochemical separation. These techniques combine nuclear reactions with high-temperature chemistry, metallurgy, solid-state diffusion, and ionization phenomena. Developed at the many mass separators on-line to various accelerators or reactors they are today widely used to produce low-energy (10–60 keV) radioactive ion-beams for physics experiments. Since some years they have reached a stage of development that allows the production of high-intensity beams of up to 10¹² ions/s of radioactive isotopes of most elements in the periodic system. Such on-line mass separators seem to be excellent injectors to a second accelerator which accelerates up to 20 MeV/u. This paper discusses the radioactive beam intensities that may be injected into proposed or working European radioactive ion-beam facilities which make use of such injectors. First a short introduction is given to the technique of on-line mass separation. This is followed by a detailed discussion of the three factors that determine the production rates in the target, i.e. reaction cross-sections, primary beam properties, and target thicknesses, and by a discussion of the more decisive factors that control the efficiency with which the radioactive nuclei produced in the target can be transformed into an injection ion-beam of typically 10–60 keV energy. Throughout the discussion the influence of new developments is assessed. Finally, selected examples of realistic beam intensities are given, which are used for intercomparison of the different production methods used by the various European projects.

(IS01)

to be submitted to Nucl. Instrum. & Methods

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1 INTRODUCTION

Interest in the study of nuclei lying far from β -stability has led to the development of new techniques for the production of ion beams of radioactive nuclei. This production is achieved by the bombardment of a target material of sufficient thickness to stop the nuclear-reaction products. The products have to be continuously separated from the bombarding beam and the target in order to convert them into an ion beam. The advanced technological processes which are needed to produce pure beams of radioactive nuclei are strongly dependent on the physical and chemical properties of the individual elements. They take place in the target and ion-source unit, which form the heart of an on-line mass separator facility, and have to be developed specifically for each element or group of elements. Once this is achieved, the method has a number of advantages for the production of high-intensity radioactive ion beams. Today the development of such systems has reached a stage that allows the production of intense low-energy beams of the radioactive isotopes of most elements in the periodic system. This makes them a logical choice as injectors to post-accelerators for production of radioactive ion-beams (RIB).

Particularly high beam intensities have been obtained when the on-line mass separator is combined with intense proton beams of 30 MeV-10 GeV energy. Owing to the thick targets ($1\text{-}500\text{ g/cm}^2$) that may be used, primary beam conversion rates into secondary radioactive beams of up to $R = 5 \times 10^{-2}$ are achieved. However, R&D projects proposed at heavy-ion accelerators and reactors suggest that similar intensities may now be obtained there. Presently the following European projects are operating, under construction or proposed: ARENAS³ Louvain-la-Neuve¹⁾, EXCYT Catania²⁾, ISOLDE-CERN³⁾, RAL³⁾, GANIL-PLUS⁴⁾, and PIAFE⁵⁾. It is the purpose of this paper to compare the radioactive ion-beam intensities that may be obtained at the injector level of these projects which are based on a variety of primary beams. Other relevant information of the primary and secondary accelerators of these projects are given in Table 1.

After a short introduction to the concept of on-line mass separation in Section 2, a discussion follows of each of the parameters given in Eq. (1) which determine the radioactive beam intensity that may be obtained

$$I = \sigma \cdot \Phi \cdot N \cdot \epsilon_1 \cdot \epsilon_2 \cdot \epsilon_3 . \quad (1)$$

In Section 3 the formation cross-sections σ for the nuclear reactions of interest are discussed, followed in Section 4 by a discussion of the primary-beam intensities Φ , target thicknesses N and the resulting power densities. The product release and transfer efficiency ϵ_1 , the ion-source efficiency ϵ_2 , and the delay transfer efficiency ϵ_3 due to radioactive decay losses are described in Sections 5-7 successively. A more extensive overview of recent developments in the field may be found in the proceedings of the last EMIS conference^{6,7)}. Finally, in Section 8, specific examples of calculated and experimentally-determined cross sections and beam intensities are given, which illustrate our comparison of the different production methods.

2 THE ON-LINE MASS SEPARATOR CONCEPT

The concept of isotope separator on-line⁸⁾ (ISOL) is shown in Fig. 1. The thermalized nuclear-reaction products are continuously transferred from the target to the ion source and extracted by a high voltage in order to be mass-analyzed by means of a magnet. The essential point here is that the nuclei of interest are formed in very complex nuclear reactions with many exit channels. Only mass separation combined with chemical separation in the target and ion-source unit can produce isotopic beams of sufficient purity. In Fig. 2 an example of the heart of such a facility, the target and ion-source unit⁹⁾, is shown. The radioactive nuclei formed in the target according to the equation $Y_0 = \sigma \cdot \Phi \cdot N$ are thermalized in the thick target and have now to be transformed into an ion beam. This operation can be broken down into three distinct processes, which each has an efficiency as defined in Section 1: (ϵ_1) diffusion to and release from the target surface and transfer by diffusion through the transfer line from the target to the ion-source, (ϵ_2) ionization, and (ϵ_3) decay during the entire process. The many different ISOL facilities in operation that are finding ever-widening applications in the areas of nuclear and other sciences are reviewed in Ref. 8. The growing interest^{10,11)} in the application of short-lived radioactive ions as projectiles has revived the ideas of post acceleration of the beams available from on-line mass separators. This possibility was in fact already discussed at the 1965 Lysekil Conference on Nuclei far from Stability¹²⁾, which marked the start of the field. Since then the ISOL technology has progressed considerably and reached the stage where its combination with a post-accelerator has become a technical feasibility.

3 NUCLEAR REACTIONS AND CROSS SECTIONS

The particular radioactive nuclei which are to be post-accelerated may be produced by a variety of bombarding particles and nuclear reactions. The three high-energy proton reactions which are most often used to produce the nuclei of interest are spallation, fission, and fragmentation. The resulting mass-yield curves are given in Fig. 3 for different bombarding energies for the reaction of protons on a heavy target¹³⁾. Similar reactions may be induced with relativistic light to heavy ions, which in addition allow the use of projectile fragmentation. The formation cross-sections for a particular product nucleus can be calculated by the formulae of Rudstam¹⁴⁾, Silberberg and Tsao¹⁵⁾, and Sümmerer¹⁶⁾. Since these calculations have relatively large uncertainties, the following discussion is based as far as possible on published experimentally-determined cross-sections. Such values for all three proton induced reactions are found in the compilation of Silberberg and Tsao¹⁷⁾.

Whereas reactions with protons and heavy ions allow us to produce all nuclei of interest, the very high cross sections for thermal neutron induced fission of ^{235}U can only be used to produce neutron-rich isotopes of a limited number of elements. For low energy neutrons or protons ($E < 100$ MeV) reactions like (n, γ) , (p, n) and (p, α) lead to good yields of products near stability. But it is only at $E > 100$ MeV, where the onset of the spallation and target fragmentation takes place, that a wide range of nuclei becomes accessible. The total reaction cross-section not only increases considerably between 200 MeV and 1 GeV in the region of target fragmentation and fission as seen in Fig. 3¹⁸⁾ but the cross-section also rises for deep spallation reactions. A typical example of this is shown in Fig. 5, where the excitation curve for the production of krypton isotopes by spallation of silver¹⁸⁾ shows a weak optimum close to 1 GeV. The gains in cross-section, by increasing the energy from 0.6 to 1 GeV, range from a factor of 2 near stability at mass $A = 84$ to a factor of 5 at mass $A = 78$ and are estimated to be as much a factor of 10 far from stability. For spallation, leading to products close to the target and the line of

stability, the maximum cross-sections are already reached at ~ 200 MeV proton energy as seen on the excitation curve for the production of argon isotopes by spallation of scandium¹⁸⁾ shown in Fig. 6. By raising the proton energy, gains are expected in the cross sections for target fragmentation reactions leading to neutron-rich light nuclei. This is indicated by the excitation function¹⁹⁾ for the production of some light fragments from a gold target shown in Fig. 7.

Due to the recent development of ECR ion sources the intensity of HI beams with energies of 30–100 MeV/u have been greatly increased so that they may become of interest for the production of radioactive ion beams. The higher excitation energy, as compared to protons, which the slow heavy particle can deposit in the target nuclei gives a cross-section increase for the reactions shown in Fig. 3 of 1–10 times that of the 3 GeV proton reaction. The highest values are expected from the short-ranging heaviest ions. The light ions of somewhat longer range ^3He and ^{12}C show a cross-section advantage for deep spallation and target fragmentation reactions, as seen in Fig. 8. Here it is seen that the ISOLDE beam-intensity ratio²⁰⁾ of sodium beams formed in 600 MeV proton and 86 MeV/u ^3He and ^{12}C fragmentation of uranium increases by a factor of 10 near stability, reaching a factor of 50 on the far neutron-rich side.

Figure 9 shows a comparison²¹⁾ of isotopic distributions of rubidium produced by fission of ^{238}U with protons of various energies, 77 MeV/u ^{12}C ions, and thermal neutron fission of ^{235}U . It is seen that the cross-sections for the ^{12}C reaction are 2–5 times higher than for 1 GeV protons, whereas the cross-sections for thermal neutron fission are up to three orders of magnitude larger. Only small gains were observed for close spallation reactions ($\Delta Z = 3$) with the HI¹⁶⁾. A further interesting possibility might be to use the projectile fragmentation in thick targets as a production technique.

It is seen that the highest cross-sections are found in the thermal fission of uranium, followed by the HI reactions which are generally somewhat higher than for the corresponding proton reactions. In concluding this section, however, it should be noted that the cross-sections alone are insufficient to decide on the best suited reaction for production of RIB, since the other factors of Eq. 1 may change the picture given in this section dramatically.

4 PRIMARY BEAM INTENSITIES AND TARGET THICKNESSES

The production rates in the target are determined by the product $\Phi \cdot N$ rather than by the cross-sections alone discussed in the previous section. In Table 2 a collection of important beam and target parameters is given, i.e.: the primary-particle energy loss, the maximum available primary-beam intensity, maximum target thicknesses, and the resulting power deposited in the target. The power density was calculated supposing a beam spot area of 1 cm^2 .

For thermal neutrons the level of technical development at Studsvik²²⁾ presently allows one to use target amounts of the order of 1 g in a flux density of $3 \cdot 10^{11}$ neutrons per $\text{cm}^2 \cdot \text{s}$. An increase of $\Phi \cdot N$ by one order of magnitude seems to be feasible with a moderate R&D effort and will not exceed the total power deposit already handled in connection with other particles. To use the maximum available flux density of 10^{14} neutrons per $\text{cm}^2 \cdot \text{s}$ seems to require a major R&D effort which may be started at the ILL Laboratory in Grenoble⁵⁾.

Protons of 30 MeV are currently used in the pioneering two-accelerator RIB project²³⁾ at Louvain-la-Neuve. The short range of these protons is offset by the available beam intensity of 500 μA . The present technological limit is $\sim 200 \mu\text{A}$, which deposits a total power of 6 kW in the target. In contrast, the long range of $\sim 1 \text{ GeV}$ protons allows at ISOLDE the use of targets of the order of moles per cm^2 ; a target thickness of 110 g/cm^2 of ^{238}U has been chosen for the calculations as being the worst case owing to the additional fission power. A total power of 5 kW (electrical and beam heating from 3 μA of protons) is handled without problems due to the low-power density in such large targets. As a logical consequence of the change at ISOLDE from a 600 MeV driver beam to one of 1 GeV it is now suggested that the target length be doubled to 40 cm. Calculations show²⁴⁾ that for solid refractory targets it is technically possible to use proton-beam intensities of the order of 100 μA , and tests of ISOLDE-like targets at the spallation neutron source of the Rutherford Appleton laboratory²⁵⁾ are in preparation.

For heavy ions the high specific-energy loss limits the target thickness to the level of what can be used by low-energy protons, but owing to their energy the total power and power density are the highest in the field. It should be noted that high power density has both beneficial and deleterious effects on the target. On one hand it may cause a reduction in the release time from the target material as will be discussed in Sections 5 and 7. On the other hand it tends to locally overheat windows and the target material, and to dissociate chemical compounds which may give rise to an unwanted gas load of the ion source. The target and ion-source development programme started at GANIL²⁶⁾ will most certainly address these effects.

5 RELEASE AND TRANSFER OF PRODUCTS FROM THE TARGET

The general problem is one of mass transfer, i.e. typically to separate the 10^{-1} to 10^{12} produced nuclei (per second) from the 10^{23} target atoms and to transfer them to the ion source. The different steps of this process and the losses from various effects are illustrated in Fig. 10. They determine the most important parameters of the system: the release yield and the target to source transport efficiency, which are combined in the factor ϵ_1 of Equation 1. In the following each of these steps is discussed separately and references to further information are given.

5.1 Target material and product release

The separation of the products from the bulk of the target can be done by merely heating a target material with a low vapour pressure to a sufficiently high temperature so that the more volatile nuclei of interest, which are stopped in the target, are released by diffusion and desorption processes. In this way the flow of material can be kept sufficiently low to allow the ion source to perform optimally. A number of such materials have been found and their release properties studied⁷⁾. In the favorable cases the release from the target occurs with an efficiency of 90–100%, there being only small losses in strongly bound sites in the solid targets.

Often an element is poorly released from the target/ion-source system due to a too low diffusion speed or to chemical bonds to the surfaces of the system. By in situ synthesis of a more volatile compound, a technique often referred to as chemical evaporation^{27,28)}, a number of less-volatile elements recently have been successfully extracted. An example of this is illustrated in Fig. 11, which shows the selenium beams

obtained from a ZrO_2 target²⁹⁾ where the volatile CO_2 homologous COSe compound was synthesized on the surface of the target by the addition of O_2 . Similar reactions may be used to release the two other members S and Te of the group VIa elements which are also difficult to separate from a target due to their tendency to form refractory compounds.

A particularly elegant and precise method of studying the release from the target or catcher materials recently has been demonstrated at GSI³⁰⁾ and indicated in Fig.10. They implant a high-energy HI-beam of the element of interest directly into the real target and ion-source system and record the intensity of the fraction of the originally implanted HI which is released and reionized. In this way they obtain not only the release efficiency of the system but also the time distribution function $p(t)$ discussed in section 7 and the ion-source efficiency.

5.2 Target-to-source transfer

The chemical affinity of the desired species to the walls of the target container, the transfer tube, and the ion source determine the losses by adsorption and diffusion. Since these surfaces are often kept at high temperature, the main effect is a delay of a nature analogous to the release of the product from the target materials, also discussed in Section 7. For extreme cases, where the hold-up time on the surfaces is long or the diffusion speed in the tube construction material is very high, losses through the container and tube walls have been shown to be of importance, as well as the losses through unavoidable mechanical leaks. The use of the chemical evaporation technique here may also speed up the transfer and help to keep the products in the gas phase. If a careful choice of construction materials with minimum affinity to the wanted species is made, as discussed in Ref. 7, transfer efficiencies of 80–90% may be obtained.

6 IONIZATION EFFICIENCIES

The widespread use, both in basic research and industry, of heavy-ion beams of stable isotopes has led to a large variety of ion sources for their production. Since the amount of stable input material for these purposes is usually unlimited, only little emphasis has been put on their efficiency. Despite this, most of our inspiration for the development of ISOL sources comes from work in this field, which is reviewed in Ref. 8. There is no universal source that will be best suited for all the elements. Most often the source has to be optimized for each element or group of elements. The alkali, the alkaline earth, and the rare earth elements are efficiently ionized (>50%) by means of surface ionization³¹⁾ or thermal ionization³²⁾ sources, which have the particular advantage of working at temperatures around 2000°C. Also the halogens may be efficiently ionized as negative ions by means of surface ionization³³⁾.

The group of noble gases are conveniently ionized in hot-cathode plasma-discharge sources in yields of 1 to 60%. Most of the remaining elements seem only to be ionizable in useful yields (>1%) by means of plasma-discharge sources kept at high temperature so that atoms which impinge on the walls may be desorbed again. In fact, the efficiency of the ionization process itself is usually very high; it is the often irreversible losses of atoms and ions by condensation on the walls of the sources that determine their efficiency. The major difficulties in maintaining the high temperatures needed (often above 1800°C) are the unavoidable chemical reactions between the anode insulators and the conductive part of the source which will eventually give rise to leaks and an uncontrollable gas pressure

in the source. The hot-cathode plasma-discharge ion-sources have probably reached their limits of development. Only a careful choice of construction materials, with minimum affinity to the products or the chemical reactions, discussed in Section 5, may reduce the losses to the walls and keep the products in the gas phase. An example of this is seen in the production of oxygen beams from a platinum target combined with a graphite ion source³⁴⁾.

New techniques such as laser and ECR ion sources seem at present to be the most promising way of making further progress. At Gatchina and ISOLDE a concept for an on-line laser ion source has been developed^{35,36,37)}. It makes use of stepwise resonant laser ionization in a cavity, as shown in Fig. 12. Up to three laser beams of different frequency are directed through the analyzing magnet to overlap with the flow of reaction products in a hot tubular cavity connected to the target, as shown in detail in Fig. 13. The advantage of this source is high element selectivity. Suppression of neighboring rare-earth elements by a factor of 10^4 has been achieved with ion-source efficiencies of 10–20 %. Since the lasers are pulsed with 10 kHz the ion beam has the same pulse frequency but a pulse width of 25 μ s, as shown in Fig. 14. Resonant laser ionization in a gas cell combines the selective ionization of the laser method with the universal thermalization process in a gas³⁸⁾. This method has recently been tested on-line by the Leuven group³⁹⁾ who selectively ionized the 189 ms ^{55}Ni isotope. Other advantages of this concept are that it is insulator free and employs only an exceedingly simple mechanical construction in the vicinity of the target. On the other hand, the source delivers only singly charged ions.

This is contrary to the ECR ion source, which promises high charge states, pulsed beams, and high efficiency. Due to its rigorous plasma confinement, ionization efficiencies of 10–40% have been demonstrated for singly charged ions of light gaseous elements. These sources are beginning to be used successfully at on-line mass separators. A typical layout is seen in Fig. 15 which shows the TISOL⁴⁰⁾ ion-source together with the ionization efficiencies measured at the Louvain-la-Neuve on-line ECR source^{41,42)}. Similar efficiencies for the light noble gases, but in high charge states, are now reported from GANIL⁴⁾. Judged from the stable metal consumption of accelerator ECR sources, ionization efficiencies of moderately volatile elements such as Ca in a given high charge states seems to be of the order of 1%. However, it remains to be shown that this high efficiency is not obtained at the expense of a very high delay time in the ion source, since the wall temperature of these sources is so low that atoms that reach the walls remain there for a very long time. This obviously is not a problem in operation with stable isotope material which in equilibrium has saturated the inner surfaces of the source.

7 DELAY TRANSFER EFFICIENCIES

The time taken by the processes discussed in the previous sections causes loss by decay of the radioactive products. This loss can be theoretically described in terms of diffusion and desorption processes. A detailed discussion is found in Refs. 8 and 31. So far the fastest systems developed are based on solids in the form of foils, wires, and powders, kept at high temperature. The crucial parameter is a function $p(t)$ which can be measured for the entire system but is often determined by the slowest step in the process. A simple description of this function is the delay half-time i.e. the time it takes for one half of the produced atoms to leave the target. For a powder target characterized by an average grain radius R and a product diffusion constant D , in the case where the delay is

governed by the diffusion in the target grains, the delay time distribution which is the probability $p(t)$ per unit time that an atom produced at time zero crosses the grain boundary at time t is:

$$p(t) = \frac{6D}{R^2} \sum_{n=1}^{\infty} \exp\left[-\frac{n^2\pi^2Dt}{R^2}\right]. \quad (2)$$

Expressions of a similar type describe $p(t)$ if the delay is governed by diffusion in target materials of other shapes, diffusion in the pores of the target material, or diffusion to and in the source. With reasonable assumptions for D and R , good fits to the experimentally observed release data can be obtained. For a product with mean lifetime T_m much shorter than the average delay time, the delay transfer efficiency is given by

$$\epsilon_3 = \frac{3\sqrt{DT_m}}{R}, \quad (3)$$

as shown for Rb isotopes as a function of half-life in Fig. 16. The most powerful method of determining $p(t)$ and hence ϵ_3 is the HI implantation method described in Section 5. Recently a number of systems dominated by the surface desorption process have been investigated by the GSI group³⁰⁾ and successfully related to the enthalpies of desorption, as shown in Fig. 17 for the overall efficiencies of some non-volatile elements.

The rate of chemical reactions giving rise to release from the surfaces were studied for nitrogen by the Louvain-la-Neuve group⁴³⁾, who found that a partial pressure of stable nitrogen had to be present in order to release the strongly surface bound ^{13}N atom as the stable ^{14}N - ^{13}N molecule. This is illustrated in Fig. 18, which shows the intensity of the ISOLDE ^{14}N - ^{16}N beam as a function of $^{14}\text{N}_2$ partial pressure. The corresponding $p(t)$'s for ^{15}N - ^{15}N , ^{15}N and ^{14}N - ^{15}N , ions released from a typical ISOLDE target and ion system⁴⁴⁾ are shown in Fig. 19. It is seen that the delay increases in the order listed above, indicating that they are formed by dissociation including a surface adsorption step of the ^{15}N .

The power deposition and the cascade of nuclear reactions and secondary particles which give rise to a mechanical shock wave in the target are found to strongly enhance the release, i.e. $p(t)$. This makes the targets faster, as indicated by the delays measured by the Orsay group in their CERN-PS experiment, where the protons are delivered in 2.4 μs long bursts every few seconds. They observed⁴⁵⁾ delay half-times of 50 ms. In the first test of the PS-booster ISOLDE⁴⁶⁾ this effect was confirmed by the delay half-time for Ne produced in a MgO target which was reduced from 1 s to 400 ms, as seen in Fig. 20. With such a primary beam structure the ISOL beam is now bunched.

8 BEAM INTENSITIES AT THE EUROPEAN PROJECTS

It is a difficult task to predict in a consistent way the intensities obtainable at the various working and proposed radioactive beam facilities in Europe. In some projects the beams have already been developed with available but not always optimal means. The more or less well known reaction cross-sections and losses discussed above are embedded in the measured beam intensities. In other cases the beam intensities are pure extrapolations based on calculated cross-sections and the introduction of the best available new techniques with more or less optimistic values for the efficiencies discussed above.

The authors have chosen to use as far as possible experimental values from already operating on-line mass separators or only to use conservative extrapolations from those in order to produce the data used in the comparison. Only in a few cases where experimental informations were lacking theoretical values and/or the estimates of the authors were used. However, several of the projects rely on the successful accomplishment of a more or less elaborate technical research and development work the details of which are given below. It should be noted that the discussed intensities are of the positive ion-beams at the exit of the on-line mass separator before injection into the following accelerating structure. They do not include distributions on different charge states, charge exchange or stripping probabilities

8.1 Choice of beams for inter-comparison

As discussed above the efficiencies ϵ_i of Eq. 1 with which the transfer of the reaction products into an ion beam takes place are strongly element dependent and determine the intensity that may be obtained. In fact very efficient techniques have only been developed for about one half of the chemical elements (see Fig. 4). For the remaining elements the situation varies from low intensity but still useful for low-energy on-line studies to elements which have not yet been observed as on-line beams. Since it is not the intention of this work to discuss the isotopes of all elements a selection of nuclides to be used in the comparison was made. A first constraint to the list of elements to be discussed was predominantly to choose them among those for which the experimental technique works best. Secondly, from these elements only those likely to be demanded by the experimental programme were chosen. The choice of nuclide mass has been dictated by typical demands from the experimental programme. The final list is found in Table 3.

8.2 Interesting beams not considered in the comparison

The selection of beams made in section 8.1 unfortunately leaves out a few of the most demanded elements like fluorine, sulphur, silicon, phosphorus, chlorine, calcium and nickel for which no target and ion-source technique that would give beams worth accelerating has yet been developed. On the other hand a number of nuclei which are produced in even higher intensities than the selected ones have been omitted since they are not yet requested by any experiment.

The elements sulphur, silicon and phosphorus belong to the class of elements which are refractory or form predominantly refractory compounds with the usual target and ion-source metals or impurities present in them. Methods for their release and transfer into an ion source have therefore not yet been developed. There is no lack of ideas and techniques on how to develop these beams by suitable selection of target and ion source materials, by chemical evaporation technique, by collection of projectile fragments in a suitable catcher or by gas-jet technique. It requires, however, a dedicated research effort of several man-years like that of the development of the ^{13}N beam at Louvain-la-Neuve⁴⁷⁾ where nitrogen a few years ago belonged to the same class of elements which for similar reasons were not yet developed.

The halogens, fluorine and chlorine have also been extracted on-line^{29,33)}. They need further development in order to overcome the losses caused by the long delays and

the distribution into the many molecular ion beams formed due to the strong chemical bonds these elements form with the ion-source construction materials and the impurities found therein. Their low efficiency for negative surface ionization may have the same cause.

The metals calcium and nickel seem to be somewhat easier cases since beams of Ca have been produced at ISOLDE⁴⁸⁾ and beams of Ni have been studied at GSI⁴⁹⁾. These were not included in the list since it was felt that their intensities were too low and could be improved. In many cases also other isotopes of the listed elements may be of interest. The reader can in most cases deduce the intensities of those by extrapolation of the relevant mass yield curves like the ones shown in Fig. 21.

8.3 Primary beam intensity

The lists of beam intensities for the different projects have been normalized to a primary beam intensity of one particle μA except for the thermal neutron based PIAFE facility for which neutron flux densities of $6.25 \cdot 10^{12}$ and 10^{14} neutrons/s $\cdot\text{cm}^2$ have been considered. It should be noted that an intensity of one particle μA for some primary beams is a high intensity whereas other particles may be available and usable in orders of magnitude higher intensities as will be discussed individually below.

8.4 ARENAS³

Of the beams selected for comparison the ones listed in Table 4 are planned to be produced and post accelerated at ARENAS³. It should be noted that the primary 30 MeV proton beam is available in intensities of up to 500 μA and that post accelerated beams of ^{13}N , ^{19}Ne , and ^{11}C beams are in the commissioning stage since mid 1992. The targets for these nuclei have at present only been tested up to 200 μA at which intensity problems with target overheating occurs. The measured beam intensities have therefore not yet reached the intensities projected by means of the values of ϵ_1 , ϵ_2 and ϵ_3 listed in Table 4. The latter ones are generally agreed to be obtainable under ideal conditions of target and source layout and source gas load and are the same used for all the projects. With some further beam development it is reasonable to expect to reach the projected intensities. A new postaccelerator dedicated to nuclear astrophysics is now in the design phase. The first radioactive beams from this K=33 cyclotron are expected in the beginning of 1997. The 20 μA beams of p, d and α from the k=110 CYCLONE cyclotron can then also be used for the production of the radioactive atoms. As the spallation channel opens up the loss in primary beam intensity can often be compensated by the higher cross-section and the thicker target. The relatively short list of beams reflects the limitation of low energy protons, deuterons and alpha particles for which the reaction cross-sections decrease dramatically further from stability.

8.5 ISOLDE-CERN and RAL-ISOLDE

The intensities of singly charged beams obtained at the old ISOLDE⁵⁰⁾ on-line to the 600 MeV CERN synchrocyclotron together with the rather well documented values for ϵ_1 , ϵ_2 and ϵ_3 serve as basis for the list of beams that may be produced by the ISOLDE and the Rutherford Appleton project but also by extrapolation as basis for a part of the beams that may be produced at GANIL and CATANIA. The intensity of the 1 GeV

protons available for the new PS-BOOSTER based ISOLDE is $3 \cdot 10^{13}$ protons per burst which corresponds to an average current of $2 \mu\text{A}$. At the Rutherford Appleton Laboratory an 800 MeV proton beam current of $100 \mu\text{A}$ could be made available.

In Table 3 columns 1 to 3, the beams chosen for the comparison are listed together with their half-life and production target. Column 5 shows the measured beam intensities at the old ISOLDE with exception of the five beams marked with an asterisk, they are calculated values as the corresponding target technique has not been tested on-line. Listed in column 4 are the production rate in the target calculated on the basis of the formation cross-sections obtained from the Silberberg and Tsao formula and the used target thickness. In principle the ratio of the values in column 5 and 4 should give the overall efficiency, i.e. the product $\epsilon_1 \cdot \epsilon_2 \cdot \epsilon_3$. Since this calculation give somewhat inconsistent results, the projected overall efficiency given in column 6 is the product $\epsilon_1 \cdot \epsilon_2 \cdot \epsilon_3$, where $\epsilon_1 = 0.8$ and the product $\epsilon_1 \cdot \epsilon_2$ and ϵ_3 are listed in column 7 and 8 respectively. The values of ϵ_2 and ϵ_3 are obtained from independent measurements, published values for the best suited ion-sources or the estimate of the authors.

In order to extrapolate to the beam intensities that will be obtained at the new PSB-ISOLDE shown in column 11 the values in column 5 were multiplied by (i): the ratio of the somewhat thicker targets to be used in the future as listed in column 9 over the earlier used target thickness, by (ii): the ratio of the efficiency of the best suited ion source over the measured value of the earlier used source and by (iii): the ratio of the production cross-sections at 1 GeV over the production cross-sections at 600 MeV. The latter values listed in column 10 are the ones obtained by means of the Silberberg and Tsao formula in some cases corrected by the estimate of the authors who has taken newer experimental data into account.

With the exception of the beams marked with an asterisk in Table 3 there are no major R & D problems to be solved to go ahead with the proposed post accelerator at ISOLDE. However, as an important part of the ISOLDE collaboration there is a continuous beam development programme in order to make further beams available and to improve some the other 600 isotopic beams available.

These developments continue along the following lines:

- 1) To exploit the bunched character of the BOOSTER beam in order to reduce the delay losses. It has already been observed that strongly bunched proton beams and heavy ion beams may shorten the delay times. In the first booster ISOLDE experiments the delay half time of Ne release from the MgO target was reduced from 1 s to 0.4 s which indicate that much thicker targets may be used than shown in Table 3 without increasing the delay losses. To the extent this is also observed with the other targets listed, order of magnitude higher beam intensities of the presently delay loss limited beams may be expected.

- 2) To continue the investigation of the release of nuclear reaction products from prospective target materials with or without the chemical evaporation techniques which has made intense beams of the sulphur group element Se available on line. This procedure is presently the most promising method to extend the thick target method to non volatile metals.

- 3) To implement ECR ion source technique in the ISOLDE front ends, in a first stage for efficient single ionization of gaseous elements or compounds as He, N, O, CO, Ne and Ar. For these very high efficiencies have been demonstrated elsewhere and at the

ISOLDE test separator. At a later stage the ECR source may be used for the production of high charge state of both gases and metals.

4) To follow up the successful development of the laser ion-source by installing a permanent laser setup for this purpose only. This would allow one to improve the isobaric mass purity and in some cases to increase the ionization efficiency for singly charged ions.

5) In collaboration with the Rutherford Appleton Laboratory to perform a full scale test of a target developed for 100 μA proton beam-intensity. This test, which is in preparation, will show to what extent the power density calculations are correct in their prediction that most present ISOLDE targets will support proton beam intensities of up to 100 μA .

8.6 GANIL

It has been shown at the CERN SC²⁰⁾ and ISOLDE²¹⁾ that 86 MeV/u ^3He and ^{12}C are very attractive primary beams for production of nuclei far from stability as compared to 600 MeV protons. Although of intensity comparable to the proton beam the ^3He beam did not generally replace the proton beam for reasons of He beam reliability and overheating of the present target design. For the ^{12}C beam it was concluded that the cross-sections were the highest but production break even with protons was not reached due to low ^{12}C beam intensity and short range in the target.

Recent progress on ECR sources combined with an upgrading programme will allow GANIL to increase the intensities from $2 \cdot 10^{12}$ to $5 \cdot 10^{13}$ ions per s (8 particle μA) for the light ions like ^3He to ^{12}C . This revives the idea of using light HI as primary beam for production of RIB. In addition the GANIL group suggests to develop on-line ECR ion-source target combinations for direct production of multicharged ions. The high intensities of HI in the mass region 40 opens up the possibility also to make use of particle fragmentation. By developing target and ion-source systems where the fragments are stopped in a suitable catcher, located in the ion-source, very attractive production rates of light radioactive ions may be obtained as discussed below.

In order to predict the beam intensities that may be achieved at this HI based project it was chosen mainly to extrapolate from the ISOLDE data in Table 3. The final low energy radioactive beam intensities at GANIL, listed in Table 5 column 11, were calculated as follows. For the elements with an asterisk the value is calculated based on the projectile fragmentation cross-section systematics of Sümmerer¹⁶⁾. These calculated production rates in the target listed in column 6 are multiplied with the projected overall efficiency listed in column 7. The efficiencies are taken from the ISOLDE Table 3, where it should be noted that the ion source efficiencies are for singly charged ions only, so that the efficiency for their ECR source for higher charge states is not taken into account. For the remaining elements the beam intensities at PSB ISOLDE Table 3 column 11 were normalized to the GANIL target thickness listed in column 5 and multiplied with a cross-section gain factor which varies from 1.5 to 6 dependent on the type of reaction as seen from Fig. 9.

It should be noted that the listed final GANIL beam intensities are assuming a successful development of some new very promising ideas. A vigorous development

programme has been started at GANIL of combining thick target technique with ECR sources in order to extend the very high efficiencies obtained for multicharged rare gas atoms to less volatile elements or elements which readily forms refractory compounds. Also the deleterious effects of the high power densities on the target materials and the resulting gas load of the ion source will have to be studied before it can be determined how much of the available primary beam-intensity can be used.

8.7 Catania

Since the energy and mass of the primary beams of this HI based project are identical to the ones of GANIL the final low energy beam intensities listed in Table 6 are taken to be the same as listed for GANIL in Table 5. The maximum primary beam is expected to be 1 particle μA . It should be noted that the use of a tandem accelerator as post-accelerator, although ideal with respect to beam quality, introduces an additional efficiency factor for charge exchange to negative ions which is not included in Table 6.

8.8 PIAFE Grenoble

The fact that this project makes use of thermal-neutron fission-products limits the list of beams shown in Table 7 to neutron-rich species. The final beam intensities are obtained by extrapolation from the measured beam intensities at the OSIRIS on-line mass separator at the Studsvik reactor⁵¹⁾. The PIAFE project has several options as to the location of the target with respect to the reactor core inside the reactor shield. In the first half of Table 7 it is assumed that the integrated target and ion-source technique of the OSIRIS group is used in a region where the neutron flux density is $6.25 \cdot 10^{12}$ neutrons/cm²·s. Although the OSIRIS technique has only been tested up to $3 \cdot 10^{11}$ neutrons/cm²·s the authors see no major technical difficulty to use it in a flux density of $6.25 \cdot 10^{12}$ neutrons/cm²·s. This would allow to benefit from the very low decay losses reported for metals by the OSIRIS group. The option to move closer to the reactor core where the flux density reaches $1 \cdot 10^{14}$ neutrons/cm²·s is not excluded but requires some empirical tests and possibly also development work. At present this option can be used for the rare gases, in which case the target and the ion source can be physically separated by a distance of the order of one meter. In order to show the strength of the project with respect to neutron rich Kr and Xe beams the intensities in the second part of Table 7 are calculated for a flux density of $1 \cdot 10^{14}$ neutrons/cm²·s.

In order to achieve the listed intensities the PIAFE group has started an ambitious R&D project which in addition to solve general problems around the operation of a conventional plasma discharge ion source near the core of a high flux reactor also involves the interesting possibility to catch the low energy singly charged ions inside an ECR ion-source, located outside the reactor shield, for production of multicharged ions.

9 CONCLUSION

With the existing ISOL technique we have today a very powerful injector for radioactive beam accelerators and many beams have already been developed that will produce accelerated beams of nanoampere intensities^{23,50)}. It is shown that the beam intensities which may be obtained at RIB facilities not only depend on primary beam

intensity and formation cross-section but depend rather strongly on target thickness and the efficiency with which the products can be transformed into an ion beam. For comparison between various projects, lists with intensities of projectiles relevant to a physics programme have been prepared and discussed.

It is seen that the techniques developed for high-energy protons presently lead the field concerning intensity and the variety of ions, although it has been demonstrated that low-energy protons play a role for a limited number of beams. Cross-section considerations and recent beam developments indicate that thermal neutrons and energetic HI also deserve consideration as primary particles since they have the potential to give equal or higher intensities in some mass regions. In the two latter cases the degree of success will depend on substantial R&D work, which has only recently been started.

A comparison of the three production methods used by the various projects suffers from the fact that only for the protons the essential development has reached the critical stage where experimental intensities of a sufficient level emerge. For the other particles we rely on the projected outcome of the R&D work. A graphic view of the present status is seen in Fig. 21, which shows the routinely obtained rubidium beam intensities at ISOLDE and OSIRIS. Also shown are the intensities that can be obtained with 77 MeV/u ^{12}C , which are calculated from the experimentally known cross-sections, the maximum usable target thickness, and $\epsilon_1 = 0.8$, $\epsilon_2 = 0.95$ and $\epsilon_3 = 0.9$, as measured at ISOLDE. In this medium to heavy mass region the high energy protons are presently found to be the most suitable primary beam. A typical example from the light mass region is given in Fig. 22 where the projected heavy ion particle fragmentation and spallation production of Ar nuclei at GANIL is compared to the measured Ar beam intensities at ISOLDE. It is seen that particle fragmentation production may take the lead once it is developed. The same trend is found for all the other light mass beams discussed as seen in Table 8 which summarizes the final intensities listed in the tables 3 to 7.

It should be noted that while the used 200 μA low energy proton beam and the 1 μA heavy ion beams heats the targets close to the limits of present technology, the neutron and high energy proton intensities used in the tables are orders of magnitude from that limit. The situation described above may therefore change as a function of the R&D work planned by the different projects in the direction of making use of the highest primary beam intensities listed in Table 2.

FIGURE CAPTIONS

Figure 1. The principle of on-line electromagnetic mass separation, which is used to convert the nuclear reaction products formed by bombarding a thick target into an array of mono-isotopic ion beams.

Figure 2. A typical target and ion-source unit, where the target container is connected to an ion source via a transfer tube.

Figure 3. Mass yield curve for bombardment of Pb and Bi with protons of various energies.

Figure 4. Periodic table of the chemical elements which shows those for which the neutron rich isotopes can be produced by thermal neutron fission of ^{235}U .

Figure 5. Experimentally measured excitation function for the spallation of silver ($Z = 47$) leading to krypton isotopes ($Z=36$).

Figure 6. Experimentally measured excitation functions for the spallation of scandium ($Z = 21$) leading to argon isotopes ($Z=18$).

Figure 7. Experimentally measured excitation functions of some typical light products obtained by the fragmentation of gold.

Figure 8. Ratios of sodium beam yields obtained by fragmentation of uranium by means of 86 MeV/u ^3He and ^{12}C over fragmentation of uranium by means of 600 MeV protons.

Figure 9. Cross-sections for production of rubidium isotopes by various nuclear reactions.

Figure 10. Schematic representation of the transfer of the reaction products from the target to the ion source and the possible loss mechanisms. The heavy-ion beam indicates that these effects can be studied in a particularly precise way by means of energetic HI.

Figure 11. Beam intensities of only the most neutron-deficient Se isotopes obtained by irradiating a 6.2 g/cm^2 ZrO_2 target combined with a high-temperature plasma-discharge ion source to which O_2 gas was added. The notations g and m refers to the ground state and the metastable state of the nuclide respectively.

Figure 12. The principle of the ISOLDE laser ion source.

Figure 13. Layout of the ISOLDE target and laser ion-source unit.

Figure 14. Pulse shape of the photoion current of Sn. The dashed line indicates the time of flight through the mass separator. The solid line indicates the next laser pulse.

Figure 15. Layout of the TISOL on-line ECR source and gas yields measured with the Louvain-la-Neuve ECR source.

Figure 16. Decay loss of Rb isotopes as a function of half-life. The insert shows the delay curve from which the $p(t)$ is derived. It is in this case obtained by sampling the radioactive ion beam intensity as a function of time after switching off the proton beam.

Figure 17. Overall efficiencies of Ti, Fe, and Pd as a function of half-life measured by means of the previously implanted stable high-energy HI.

Figure 18 Release of ^{16}N - ^{14}N ions from a graphite platinum target as a function of $^{14}\text{N}_2$ partial pressure in arbitrary units.

Figure 19. Delay time distribution of various nitrogen beams from a graphite ion source.

Figure 20. Delay time distribution $p(t)$ of Ne from the ISOLDE MgO target irradiated with $3 \cdot 10^{13}$, 1 GeV protons in 2.4 μs wide bursts.

Figure 21. Measured production rates of Rb isotopes produced by means of 1 GeV protons and thermal neutrons compared with calculated production rates with 77 MeV/u ^{12}C -ions.

Figure 22. Argon yields measured at the PSB-ISOLDE by bombardment of a 5g/cm^2 CaO target with 1 μA , 1 GeV protons and projected to the use of an ECR ion-source with an efficiency of 40% for singly charged Ar-ions (i.e. a factor of 8 higher than the presently used ion source). The projected Ar yields at GANIL are shown as obtained by fragmentation of a 1 μA , ^{36}Ar beam for the neutron deficient nuclei and 1 μA , ^{12}C spallation of a 1g/cm^2 CaO target for the neutron rich nuclei also using the same ECR ion source.

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PROJECT	PRODUCTION BEAM				TARGET		RADIOACTIVE BEAMS				STATUS
	Driver Accelerator	Particle	Energy MeV	Intensity μ A	Element Z	Thickness μ /cm ²	Post Accelerator	Beam A	Energy MeV/A	Intensity /s	
Louvain La Neuve	K=30 cyclotron	p	30	500	3-17	1	K=110 cyclotron	6-31	0.6-27	5E+08	Operating facility
Louvain la Neuve ARENAS	K=110 cyclotron	p,d,He	80	25 ext 300 int.	3-17	5	K=33 cyclotron	6-31	0.2-0.8	1E+09	Under construction
ISOLDE CERN Geneva	1.0GeV synchrotron	p	1000	3	4-92	3-300	linac	6-30	1	1E+09	ISOL+ Project
GANIL Caen	K=30+380+380 cyclotrons	C-Ar	100MeV/u	8	6-92	3	linac	<220	5-50	1E+09	Project
The Rutherford Appleton Laboratory	800 MeV synchrotron	p	800	100	4-92	3-200	linac or synchrotron	<80	6.5	1E7-1E12	Project
PIAFA ILL Grenoble	High flux reactor	n	thermal	1E14/s cm ²	235	1	K=88+K=160 cyclotrons	78-146	3.8-20	1E3-1E8	Project
INFN-LNS Catania	K=800 Cyclotron	C-Ar	50-80 MeV/u	1	1-16	3	15MV tandem	4-30	5-50	4E+08	Under construction

Table 1

Particle	Energy MeV	Energy loss dE/dx MeV/g*cm2	Target thickness, element g/cm2	Total power for a beam of: 6.25E12 particles/s (1μA) W	Power density W/cm3	Maximum available beam particles/s
Neutrons	thermal	160/fission	1, U-235	160	32	5E+14
Protons	1000	1.2	110, U-238	420	7	6E+14
Protons	30	16.7	0.9, Carbon	30	75	3E+15
12C	1152	200	4, Tin	800	1200	6E+13
36Ar	3456	2351	0.9, Carbon	2100	5250	6E+13

Table 2.

Beam and target data			ISOLDE target characteristic at 600 MeV protons				Extrapolated ISOLDE-PSB target		
Beam	Half life	Target Material	Production rate in target Atoms/s·μA	Experimentally obtained beam intensities Atoms/s·μA	Projected overall efficiency %	Release and delay efficiency %	Ion-source efficiency %	Target thickness g/cm ²	Projected final intensities Atoms/s·μA
8He	122ms	UC	2.3E+6	6.6E+5	2.9E+0	2.9E+1	1.0E+1	110	2.6E+8
8Li	842ms	Ta	1.6E+9	3.9E+8	3.8E+1	4.0E+1	9.5E+1	122	1.1E+9
11Li	9ms	Ta	6.9E+5	3.0E+3	3.0E-1	3.2E-1	9.5E+1	122	1.5E+4
7Be*	53d	C	4.3E+11	3.4E+9	8.0E-1	8.0E+1	1.0E+0	63	1.4E+10
14Be*	5ms	Ta	1.8E+4	5.7E-3	3.2E-5	3.2E-3	1.0E+0	122	2.8E-2
11C	20m	MgO	4.7E+9	6.8E+5	8.0E+0	8.0E+1	1.0E+1	72	9.3E+9
13N	10m	MgO	7.0E+9	9.2E+3	1.6E+1	8.0E+1	2.0E+1	72	7.0E+9
14O	71s	Pt	8.8E+5	2.0E+4	1.2E+1	6.0E+1	2.0E+1	375	2.9E+9
15O	2m	Pt	8.8E+6	3.0E+4	1.3E+1	6.6E+1	2.0E+1	375	4.3E+9
19O	27s	Pt	8.8E+5	1.0E+4	8.2E+0	4.1E+1	2.0E+1	375	1.4E+9
22O	2.3s	Pt	3.2E+4	4.0E+2	3.8E-1	1.9E+0	2.0E+1	20	3.0E+6
17F*	65s	Al	4.8E+9	2.8E+7	5.8E-1	5.8E+1	1.0E+0	108	1.6E+8
19Ne	17s	MgO	1.9E+9	3.0E+7	1.6E+1	8.0E+1	2.0E+1	72	2.3E+10
26Ne	162ms	U	3.2E+6	7.0E+3	1.6E+0	8.0E+0	2.0E+1	55	1.1E+6
20Na*	446ms	Al	2.2E+9	4.9E+8	2.3E+1	2.4E+1	9.5E+1	108	9.8E+8
30Na	53ms	UC	1.5E+5	6.0E+2	3.8E+0	4.0E+0	9.5E+1	55	1.3E+4
26mAl*	6s	Ta	2.5E+7	3.8E+5	1.5E+0	1.5E+1	1.0E+1	122	1.9E+6
30S*	1s	CaCl ₂	1.6E+10	5.0E+2	3.2E-6	3.2E-3	1.0E-1	51	5.0E+2
34Ar	844ms	CaO	7.1E+8	3.8E+6	1.6E+1	4.0E+1	4.0E+1	65	2.3E+8
35Ar	1.8s	CaO	7.1E+9	4.1E+7	2.2E+1	5.6E+1	4.0E+1	65	2.4E+9
72Zn	46h	U	1.7E+8	2.7E+6	8.0E+0	8.0E+1	1.0E+1	110	2.2E+8
78Zn	1.5s	U	1.7E+5	1.4E+4	4.8E-1	4.8E+0	1.0E+1	110	1.1E+6
73Se	7h	ZrO ₂	2.7E+9	3.0E+8	8.0E+0	8.0E+1	1.0E+1	118	8.3E+9
74Kr,	12m	SrO	1.5E+9	4.9E+8	3.2E+1	8.0E+1	4.0E+1	100	1.6E+9
91Kr	8.6s	U	1.6E+9	1.5E+8	2.9E+1	7.2E+1	4.0E+1	110	1.2E+9
94Kr	0.2s	U	2.2E+8	1.4E+6	6.4E+0	1.6E+1	4.0E+1	110	1.1E+7
97Rb	170ms	U	2.5E+7	5.6E+6	1.1E+1	1.2E+1	9.5E+1	55	9.6E+7
111In	2.8d	Sn	6.6E+8	1.0E+9	3.2E+1	8.0E+1	4.0E+1	240	1.8E+10
105Cd	56m	Sn	4.0E+10	3.5E+8	3.2E+1	8.0E+1	4.0E+1	240	8.0E+8
108Sn	10m	TeCl ₄	1.2E+8	5.0E+6	4.0E+1	8.0E+1	5.0E+1	24	2.9E+7
132Sn	40s	U	1.6E+7	1.0E+5	2.4E+0	4.9E+0	5.0E+1	110	3.5E+6
121Cs	2.3m	La	7.4E+9	7.3E+9	7.6E+1	8.0E+1	9.5E+1	280	2.2E+10
144Cs	1s	U	1.3E+9	1.0E+9	3.8E+1	4.0E+1	9.5E+1	110	8.2E+9
142Xe	1.2s	U	5.2E+7	4.2E+6	2.6E+1	4.4E+1	6.0E+1	110	3.3E+7
144Xe	1.2s	U	5.2E+8	8.6E+4	2.6E+1	4.4E+1	6.0E+1	110	7.0E+5

Table 3.

Beam and target data			ARENAS3 target characteristics CYCLONE-30 as primary accelerator				ARENAS3	
Beam	Half life	Target Material	Target thickness g/cm ²	Production rate in target Atoms/ s*μA	Projected overall efficiency %	Release and delay efficiency %	Ion-source efficiency %	Measured accelerated beam intensities Atoms/s*μA
7Be	53d	LiF	0.5	9.4E+9	8.0E-1	8.0E+1	1.0E+0	7.5E+7
11C	20m	BN	0.5	9.4E+9	8.0E+0	8.0E+1	1.0E+1	7.5E+8
13N	10m	C	1	1.0E+10	1.6E+1	8.0E+1	2.0E+1	1.6E+9
15O	2m	LiF	0.5	4.4E+9	1.3E+1	6.6E+1	2.0E+1	5.7E+8
19Ne	17s	LiF	0.7	4.4E+9	1.6E+1	8.0E+1	2.0E+1	7.0E+8
34Ar	844ms	LiCl	1	1.1E+9	1.6E+1	4.0E+1	4.0E+1	1.8E+8
35Ar	1.8s	LiCl	1	3.2E+9	2.2E+1	5.6E+1	4.0E+1	7.0E+8
91Kr	8.6s	UC	0.5	1.5E+8	2.9E+1	7.2E+1	4.0E+1	4.4E+7
ARENAS3 target characteristics								
CYCLONE (k=110) as primary accelerator								
8Li	842ms	C	4.1	1.1E+10	3.8E+1	4.0E+1	9.5E+1	4.2E+9
7Be	53d	C	4.5	2.1E+10	8.0E-1	8.0E+1	1.0E+0	1.7E+8
11C	20m	BN	3	2.2E+10	8.0E+0	8.0E+1	1.0E+1	1.8E+9
13N	10m	C	5.8	1.4E+10	1.6E+1	8.0E+1	2.0E+1	2.2E+9
14O	71s	C	1.5	3.7E+9	1.2E+1	6.0E+1	2.0E+1	4.4E+8
15O	2m	LiF	2.3	1.4E+9	1.3E+1	6.6E+1	2.0E+1	1.8E+8
19Ne	17s	LiF	4.4	9.4E+9	1.6E+1	8.0E+1	2.0E+1	1.5E+9
34Ar	844ms	LiCl	6	2.1E+9	1.6E+1	4.0E+1	4.0E+1	3.4E+8
35Ar	1.8s	LiCl	6	6.2E+9	2.2E+1	5.6E+1	4.0E+1	1.4E+9

Table 4

Beam and target data			GANIL target characteristics					GANIL	
Beam	Half life	Target	Nuclear Reaction and beam energy	Target thickness g/cm ²	Production rate Atoms/s*μA	Projected overall efficiency %	Release and delay efficiency %	Ion-source efficiency %	Projected final intensities Atoms/s*μA
8He*	122ms	MgO	15N 83 MeV/u	2.3	7.6E+7	2.9E+0	2.9E+1	1.0E+1	2.2E+6
8Li*	842ms	C	15N 83 MeV/u	2.1	4.2E+9	3.8E+1	4.0E+1	9.5E+1	1.6E+9
11Li*	9ms	C	18O 76 MeV/u	1.3	2.0E+7	3.0E-1	3.2E-1	9.5E+1	6.1E+4
7Be*	53d	C	12C 96 MeV/u	2.6	1.8E+10	8.0E-1	8.0E+1	1.0E+0	1.4E+8
14Be*	100ms	C	18O 76 MeV/u	0.3	7.0E+6	3.2E-5	3.2E-3	1.0E+0	2.2E+0
11C*	20m	MgO	12C 96 MeV/u	3	1.9E+10	8.0E+0	8.0E+1	1.0E+1	1.5E+9
13N*	10m	C	14N 96 MeV/u	2.3	2.4E+10	1.6E+1	8.0E+1	2.0E+1	3.8E+9
14O*	71s	C	16O 96 MeV/u	2	4.4E+9	1.2E+1	6.0E+1	2.0E+1	5.3E+8
15O*	2m	C	16O 96 MeV/u	2	2.2E+10	1.3E+1	6.6E+1	2.0E+1	2.9E+9
19O*	27s	C	22Ne 79 MeV/u	1.2	4.0E+9	8.2E+0	4.1E+1	2.0E+1	3.3E+8
22O*	2.3s	C	26Mg 81 MeV/u	1.1	1.6E+7	3.8E-1	1.9E+0	2.0E+1	6.1E+4
17F*	65s	MgO	20Ne 96 MeV/u	0.8	1.0E+10	5.8E-1	5.8E+1	1.0E+0	5.8E+7
19Ne*	17s	MgO	20Ne 96 MeV/u	1.8	1.3E+10	1.6E+1	8.0E+1	2.0E+1	2.1E+9
26Ne	162ms	U	12C 96 MeV/u	5	1.9E+7	1.6E+0	8.0E+0	2.0E+1	3.1E+5
20Na*	446ms	C	24Mg 96 MeV/u	1.2	2.5E+9	2.3E+1	2.4E+1	9.5E+1	5.7E+8
30Na	53ms	UC	12C 96 MeV/u	5	9.1E+4	3.8E+0	4.0E+0	9.5E+1	3.5E+3
26mAl	6s	C	27Al 90 MeV/u	1	8.0E+9	1.5E+0	1.5E+1	1.0E+1	1.2E+8
30S*	1s	C	32S 96 MeV/u	0.9	3.6E+9	3.2E-5	3.2E-2	1.0E-1	1.2E+3
34Ar*	844ms	MgO	36Ar 96 MeV/u	0.9	2.5E+9	1.6E+1	4.0E+1	4.0E+1	4.0E+8
35Ar*	1.8s	MgO	36Ar 96 MeV/u	0.9	9.6E+9	2.2E+1	5.6E+1	4.0E+1	2.2E+9
72Zn	46h	U	12C 96 MeV/u	5	3.3E+8	8.0E+0	8.0E+1	1.0E+1	2.7E+7
78Zn	1.5s	U	12C 96 MeV/u	5	3.5E+7	4.8E-1	4.8E+0	1.0E+1	1.7E+5
73Se	7h	ZrO2	12C 96 MeV/u	3	4.0E+9	8.0E+0	8.0E+1	1.0E+1	3.2E+8
74Kr	12m	Nb	12C 96 MeV/u	4	3.1E+8	3.2E+1	8.0E+1	4.0E+1	9.8E+7
91Kr	8.6s	U	12C 96 MeV/u	5	5.8E+8	2.9E+1	7.2E+1	4.0E+1	1.7E+8
94Kr	0.2s	U	12C 96 MeV/u	5	4.9E+7	6.4E+0	1.6E+1	4.0E+1	3.1E+6
97Rb	170ms	U	12C 96 MeV/u	5	4.6E+8	1.1E+1	1.2E+1	9.5E+1	5.3E+7
111In	2.8d	U	12C 96 MeV/u	5	3.6E+9	3.2E+1	8.0E+1	4.0E+1	1.2E+9
105Cd	56m	Sn	12C 96 MeV/u	4	6.2E+7	3.2E+1	8.0E+1	4.0E+1	2.0E+7
108Sn	10m	TeCl	12C 96 MeV/u	3	1.3E+7	4.0E+1	8.0E+1	5.0E+1	5.4E+6
132Sn	40s	U	12C 96 MeV/u	5	2.6E+7	2.4E+0	4.9E+0	5.0E+1	6.3E+5
121Cs	2.3m	La	12C 96 MeV/u	4	8.1E+8	7.6E+1	8.0E+1	9.5E+1	6.2E+8
144Cs	1s	U	12C 96 MeV/u	5	3.9E+9	3.8E+1	4.0E+1	9.5E+1	1.5E+9
142Xe	1.2s	U	12C 96 MeV/u	5	2.3E+7	2.6E+1	4.4E+1	6.0E+1	6.1E+6
144Xe	1.2s	U	12C 96 MeV/u	5	4.8E+5	2.6E+1	4.4E+1	6.0E+1	1.3E+5

Table 5.

Beam and target data			CATANIA target characteristics					CATANIA	
Beam	Half life	Target Material	Nuclear Reaction and beam energy	Target thickness in g/cm2	Production rate Atoms/s* μ A	Projected overall efficiency %	Release and delay efficiency %	Ion-source efficiency %	Projected intensity before charge exchange Atoms/s* μ A
8Li	842ms	C	15N 83 MeV/u	2.1	4.2E+9	3.8E+1	4.0E+1	9.5E+1	1.6E+9
11Li	9ms	C	18O 76 MeV/u	1.3	2.0E+7	3.0E-1	3.2E-1	9.5E+1	6.1E+4
11C	20m	MgO	12C 96 MeV/u	3	1.9E+10	8.0E+0	8.0E+1	1.0E+1	1.5E+9
13N	10m	C	14N 96 MeV/u	2.3	2.4E+10	1.6E+1	8.0E+1	2.0E+1	3.8E+9
14O	71s	C	10O 96 MeV/u	2	4.4E+9	1.2E+1	6.0E+1	2.0E+1	5.3E+8
15O	2m	C	16O 96 MeV/u	2	2.2E+10	1.3E+1	6.6E+1	2.0E+1	2.9E+9
19O	27s	C	22Ne 79 MeV/u	1.2	4.0E+9	8.2E+0	4.1E+1	2.0E+1	3.3E+8
22O	2.3s	C	26Mg 81 MeV/u	1.1	1.6E+7	3.8E-1	1.9E+0	2.0E+1	6.1E+4
17F	65s	MgO	20Ne 96 MeV/u	0.8	1.0E+10	5.8E-1	5.8E+1	1.0E+0	5.8E+7
20Na	446ms	C	24Mg 96 MeV/u	1.2	2.5E+9	2.3E+1	2.4E+1	9.5E+1	5.7E+8
30Na	53ms	UC	12C 96 MeV/u	5	9.1E+4	3.8E+0	4.0E+0	9.5E+1	3.5E+3
30S	1s	C	32S 96 MeV/u	0.9	3.6E+9	3.2E-5	3.2E-2	1.0E-1	1.2E+3

Table 6.

Beam and target data			PIAFE target characteristics					PIAFE
Beam	Half life	Target Material	Target amount g	Production rate in target Atoms/s	Projected overall efficiency %	Release and delay efficiency %	Ion-source efficiency %	Projected beam intensities after 1st ion source
For the metals the target is anticipated to use the OSIRIS target technique in a flux of 6.25E12n/s*cm2								
78Zn	1.5s	U	1	3.8E+8	5.7E-2	4.1E+1	1.4E-1	Atoms/s*6.25E12n
97Rb	170ms	U	1	4.6E+9	5.7E+0	1.9E+1	3.0E+1	2.2E+5
132Sn	40s	U	1	5.4E+10	3.6E-1	9.6E+1	3.7E-1	2.6E+8
144Cs	1s	U	1	3.4E+10	7.4E+0	4.6E+1	1.6E+1	1.9E+8
For the rare gases the target will be separated from the first ion-source, the neutron flux is here 1E14/s*cm2								
91Kr	8.6s	U	1	4.3E+12	2.8E+1	7.8E+1	4.0E+1	Atoms/s*1E14n
94Kr	0.2s	U	1	1.4E+11	4.0E-1	1.4E+1	4.0E+1	1.2E+12
144Xe	1.2s	U	1	1.2E+10	1.2E+1	4.3E+1	6.0E+1	5.6E+8
142Xe	1.2s	U	1	6.6E+11	1.2E+1	4.2E+1	6.0E+1	1.4E+9
								7.9E+10

Table 7.

Beam and target data		ISOLDE	GANIL	CATANIA	ARENAS3		PIAFE
Beam	Half life	Projected final intensities Atoms/s* μ A	Projected final intensities Atoms/s* μ A	Projected final intensities Atoms/s* μ A	k=30 Projected intensities Atoms/s* μ A	k=110 Projected intensities Atoms/s* μ A	Projected final intensities Atoms/s*6.25E12n
8He	122ms	2.6E+8	2.2E+6				
8Li	842ms	1.1E+9	1.6E+9	1.6E+9		4.2E+9	
11Li	9ms	1.5E+4	6.1E+4	6.1E+4			
7Be	53d	1.4E+10	1.4E+8		7.5E+7	1.7E+8	
14Be	5ms	2.8E-2	2.2E+0				
11C	20m	9.3E+9	1.5E+9	1.5E+9	7.5E+8	1.8E+9	
13N	10m	7.0E+9	3.8E+9	3.8E+9	1.6E+9	2.2E+9	
14O	71s	2.9E+9	5.3E+8	5.3E+8		4.4E+8	
15O	2m	4.3E+9	2.9E+9	2.9E+9	5.7E+8	1.8E+8	
19O	27s	1.4E+9	3.3E+8	3.3E+8			
22O	2.3s	3.0E+6	6.1E+4	6.1E+4			
17F	65s	1.6E+8	5.8E+7	5.8E+7			
19Ne	17s	2.3E+10	2.1E+9		7.0E+8	1.5E+9	
26Ne	162ms	1.1E+6	3.1E+5				
20Na	446ms	9.8E+8	5.7E+8	5.7E+8			
30Na	53ms	1.3E+4	3.5E+3	3.5E+3			
26mAl	6s	1.9E+6	1.2E+8				
30S	1s	5.0E+2	1.2E+3	1.2E+3			
34Ar	844ms	2.3E+8	4.0E+8		1.8E+8	3.4E+8	
35Ar	1.8s	2.4E+9	2.2E+9		7.0E+8	1.4E+9	
72Zn	46h	2.2E+8	2.7E+7				
78Zn	1.5s	1.1E+6	1.7E+5				2.2E+5
73Se	7h	8.3E+9	3.2E+8				
74Kr,	12m	1.6E+9	9.8E+7				
91Kr	8.6s	1.2E+9	1.7E+8				
94Kr	0.2s	1.1E+7	3.1E+6		4.4E+7		7.4E+10
97Rb	170ms	9.6E+7	5.3E+7				3.5E+7
111In	2.8d	1.8E+10	1.2E+9				2.6E+8
105Cd	56m	8.0E+8	2.0E+7				
108Sn	10m	2.9E+7	5.4E+6				
132Sn	40s	3.5E+6	6.3E+5				
121Cs	2.3m	2.2E+10	6.2E+8				1.9E+8
144Cs	1s	8.2E+9	1.5E+9				
142Xe	1.2s	3.3E+7	6.1E+6				2.5E+9
144Xe	1.2s	7.0E+5	1.3E+5				4.9E+9
							8.7E+7

Table 8

THICK TARGET CONNECTED
TO AN ION-SOURCE

Fig. 1

TARGET ION SOURCE ASSEMBLY

Fig. 2

Fig. 3

GROUP IA		PERIODIC TABLE OF THE ELEMENTS																VIIA
H																		He
Li	Be											B	C	N	O	F	Ne	
Na	Mg											Al	Si	P	S	Cl	Ar	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
Fr	Ra	Ac																
LANTHANIDES			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
ACTINIDES			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

Elements in bold characters are available as beams at ISOLDE

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

IMPLANTATION OF ENERGETIC HEAVY IONS

Fig. 10

Fig. 11

Fig. 12

Layout of the ISOLDE laser ion source.

Fig. 13

Fig.14

ELECTRON CYCLOTRON RESONANCE (ECR) ION SOURCES

Fig. 15

Fig. 16

Fig. 17

Release of $^{16}\text{N}^{14}\text{N}^+$ from a mixed Platinum-graphite target as function of $^{14}\text{N}_2$ partial pressure.

Fig. 18

Delay time distribution of various Nitrogen
beams in a graphite ion-source

Fig. 19

19-Ne delay in MgO target (#001) at ISOLDE/GPS,
June-92 (with full beam, 3E13 p/pulse)

Fig. 20

Fig. 21

Fig. 22