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Radioactive ion-beam projects based on the two-accelerator or ISOL principle

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Today, two basically different methods have been developed for production of accelerated radioactive ion beams (RIB). The fragmentation of intense heavy-ion beams, in which the forward momentum imparted to the primary beam fragments is preserved and exploited for mass separation, study and further reactions, is the preferred technique at present. The second method, which is the subject of this review, makes use of spallation, fission and fragmentation reactions in thick targets driven by light particles from a first accelerator or a nuclear reactor. The radioactivity produced is brought to rest in the target and then has to be separated and transformed into an ion beam in order to be post-accelerated in a second machine. This method has in the past 30 years been used successfully at many on-line mass separators to produce low-energy radioactive ion beams. Techniques for the transfer of the nuclear reaction products into an ion beam have been optimized with respect to the individual physical and chemical properties of 70% of the chemical elements. Several new ideas in efficiently matching such an on-line mass separator as injector to a heavy-ion accelerator are currently being developed so that this method holds much promise for the future, in particular when it comes to selecting the intensity and energy choice of the secondary beams. This paper is devoted to a systematic description and discussion of this two-accelerator type of RIB facility, of which many are currently in various phases of construction and planning.

Keywords: ion beam; radioactivity; spallation; fragmentation; fission; accelerator

1. Introduction

Nuclear reaction studies as they were undertaken at the many heavy-ion accelerators were limited in the past to the use of stable projectiles with their naturally restrained N/Z ratios. However, the most interesting nuclear reactions occurring in the cosmos were mainly those involving the far more numerous unstable nuclei. Since secondary-produced unstable projectiles have become available in the laboratory, the field of physics which exploits reactions with such energetic beams of radioactive nuclei has in recent years experienced a remarkable growth. This is mainly due to considerable progress in the production of these secondary beams by means of the projectile-fragmentation method. This method makes use of the large investments which went into accelerators and ion sources for heavy ions worldwide at facilities like GANIL, GSI, MSU and RIKEN. It is a fairly universal method which produces beams of the most exotic nuclei from all regions of the nuclear chart independent of their chemical properties, without delay, and of relatively high energy varying from 10 to 100 MeV u^{-1}. These beams seem to be best suited for elaborate storage-ring or ion-trapping experiments. Recent reviews of these facilities are found in Sherill

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(1991) and Geissel *et al*. (1995). A strong physics case has been made for studies with radioactive beams, which opens up the possibility of new physics experiments in many fields. This case has already been very well presented in the various proposals for RIB facilities to be cited below, and has been well discussed in numerous reports (Tanihata 1989; Sawicki *et al*. 1991; Bruandet *et al*. 1992; Boyd 1994; Mueller 1993; Siemssen 1993) and in the *Proceedings of the Radioactive Nuclear Beams* conference series (Myers *et al*. 1990; Delbar 1991; Morissey 1993; Kubono *et al*. 1997*a*). It emerges from these reports that there is a strong need for more intense beams at lower energies (1–10 MeV u^{-1}) than are currently available from fragment separators. These not only would allow nuclear structure and reactions with radioactive projectiles near the Coulomb barrier to be studied, but would also lead to strong new impulses in more interdisciplinary fields such as astrophysics and materials science. For experiments with these requirements, it has been demonstrated that the isotope separator on-line principle (ISOL) is a particularly powerful technique which provides potentially the largest primary production rates of nuclei far from stability. In this two-accelerator principle, the nuclear reaction products formed by the beam of a primary accelerator or nuclear reactor are brought to rest in a thick target. They are separated and transported from the target by thermal diffusion and desorption processes to an ion source where they are transformed into an ion beam which can be accelerated in a second specialized accelerator. Users of this historically first method for RIB generation have, in 30 years of production and study of low-energy RIB, developed methods which allow the stopped nuclear reaction products to be selectively and efficiently transformed into an ion beam. These are new radiochemical methods which take advantage of both the physical and chemical properties of the individual elements and they have been developed for the majority of the elements. For many, very efficient procedures have been developed which convert them into isobarically pure, singly charged ion beams of excellent beam quality (small emittance); but there remain a few elements for which techniques still need to be developed or improved. During this period of RIB developments, the idea of further accelerating these new beams was regularly taken up in Europe (Bondorf 1967; Hansen 1977), but at the time, neither the physics nor the experimental techniques were ready to exploit the possibilities of nuclear reactions with energetic RIBs. The nuclear astrophysics aspects discussed at the Parksville conference (Buchmann & D'Auria 1985), the start of on-line solid-state physics (Weyer 1981), and the successes of the fragment separators gave RIB physics new momentum, leading to the collection of ideas in the field found in The Isospin Laboratory report (Sawicki *et al*. 1991), which describes an ultimate North American two-accelerator RIB facility.

It was in 1991 that the feasibility of ISOL RIB generation was first experimentally demonstrated by the Louvain-la-Neuve group (Loiselet *et al*. 1993), which, like all the other facilities to be discussed here, still capitalizes on existing infrastructure by using projectiles from more or less suitable but existing driver machines or post-accelerators constructed for other purposes. It was noted five years ago in the report of the NuPECC study group on European RIB facilities (Siemssen 1993) that the conversion of the products into high-charge-state ions was the major subject of development still needed before the two-accelerator method would be really viable. However, the ion-beam time structure and maximum usable driver-beam intensity, determined by the power it deposits in the target, were also matters of concern. In

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the last few years there has been striking progress in these and the other main areas of ISOL-RIB production, listed below.

1. Ion-beam storage and bunching;
2. EBIS and ECR charge-state breeding techniques;
3. ECR ion sources for on-line production of multicharged RIB;
4. thick-target power-density calculations and tests;
5. resonant laser ion sources;
6. ion-source emittance;
7. new target materials;
8. nuclear reaction cross-sections;
9. improved beams and availability of further elements;
10. driver-beam enhanced release and bunched ion-beams;
11. high-resolution isobaric mass-separation.

These developments have removed the last technical obstacles and the ISOL is now ready to take over as a most efficient injector to high intensity RIB accelerators. At present, the following 12 projects are at the operating, construction or planning phase: ARENAS Louvain-la-Neuve (Loiselet *et al.* 1993), ATLAS Argonne, EXCYT Catania (Ciavola *et al.* 1997), REX-ISOLDE Geneva (Habs *et al.* 1997), SIRIUS, RAL Chilton (Bennett *et al.* 1997), GANIL-PLUS Caen (Anne *et al.* 1993), PIAFE Grenoble (Pinston 1997), ISAC-TRIUMF Vancouver (Bricault *et al.* 1997), HRIBF Oak Ridge (Olsen *et al.* 1991), Munich (Thirolf *et al.* 1997), INS Tokyo (Kubono *et al.* 1997*b*) and IsoSpin Laboratory USA (Sawicki *et al.* 1991).

The discussions in this paper are organized around each of the parameters given in equation (1.1), which determine the radioactive beam intensity that may be obtained from a post-accelerator,

$$I = \sigma \Phi N \varepsilon_1 \varepsilon_2 \varepsilon_3 \varepsilon_4, \tag{1.1}$$

where σ is the formation cross-section for the nuclear reactions of interest, Φ the primary-beam intensity, N the usable target thickness, ε_1 the product release and transfer efficiency, ε_2 the ion-source efficiency, ε_3 the delay transfer efficiency due to radioactive decay losses, and ε_4 the post-acceleration efficiency.

In order to provide some of the general background information needed to become acquainted with the subject, in the next section I will introduce the crucial on-line mass-separator technique and discuss recent developments which facilitate its use as injector for the future RIB projects so that existing heavy-ion accelerating techniques can be used efficiently. In § 3 the primary beams from the driver machines are discussed with respect to the production and separation of the radioactivity. The various acceleration methods available are evaluated in § 4. Section 5 presents and comments on the different RIB facilities which are at operating, construction or planning stage.

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2. The isotope separator on-line and recent developments

Shortly after the discovery of artificially produced radioactivity in nuclear reactions, the mass-separator principle was used for its study (Yamagushi 1941). Later, in a pioneering experiment in Copenhagen, Kofoed-Hansen & Nielsen (1951) demonstrated that continuous RIBs could be produced by means of an isotope separator on-line (ISOL) to an accelerator: the method which has become the two-accelerator principle for RIB generation. In the following years, these facilities went through a very fruitful phase of physics experiments in which both beams, and new experimental techniques which elegantly exploit the fact that the radioactivity is delivered as a continuous low-energy (*ca.* 60 keV) beam of isobaric pure nuclei, were developed. As the result of a fruitful symbiosis (between those who produce the beams and those who use them), many of the techniques originally used in the experiments have now been successfully introduced as new accelerator techniques for beam production. Already at that time the many mass-separator experiments on-line to various primary accelerators and reactors gave a clear picture of the best-suited primary projectiles for RIB production in a given region, as can be traced through the proceedings of the EMIS conference series (EMIS 1981, 1987, 1992, 1997) and Siemssen (1993). The unique location of mass separators on-line to the powerful machines of CERN, where beams of p, ^{3}He and ^{12}C of energy ranging from 600 MeV to 18 GeV were available, has demonstrated the strength of this approach. The intense low-energy beams derived from targets with useful thicknesses of 10–500 g cm^{-2} have within the ISOLDE collaboration given rise to the development of a wealth of inexpensive techniques for producing RIBs. However, research and development projects now under way at heavy-ion accelerators and reactors suggest that similar or better intensities in certain regions may be obtained there. The essential point here is that the nuclei of interest are formed in very complex nuclear reactions with many exit channels. Only the selectivity obtained by mass separation combined with efficient chemical separation in the target and ion-source unit can produce isotopic beams of sufficient intensity and purity.

In figure 1 the major ingredients of an ISOL-RIB facility are shown. It consists of four closely matched parts: the nuclear target, the transfer line, the ion source, the mass-separator injector system and the post-accelerator. Of these, the first three, which often are integrated in a target and ion-source unit, play the crucial role.

(*a*) *The target and ion-source unit and its characteristic parameters*

The radioactive nuclei formed in the thick target are brought to rest and then have to be separated from the bulk and converted into an ion beam. This operation can be broken down into three distinct processes: (ε_1) high-temperature thermal 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. It was quickly realized that these three efficiencies often play a more important role in determining the resulting secondary-beam intensities than the usual three factors $\sigma\Phi N$ which determine only the production rate in the target. In fact, the efficiencies that can be obtained for a given product element strongly depend on the properties of the refractory target materials, the primary beam and its time structure, and the type of ion sources which could be adapted to the environment of a particular driver beam. The basic parameters that determine the efficiencies of these

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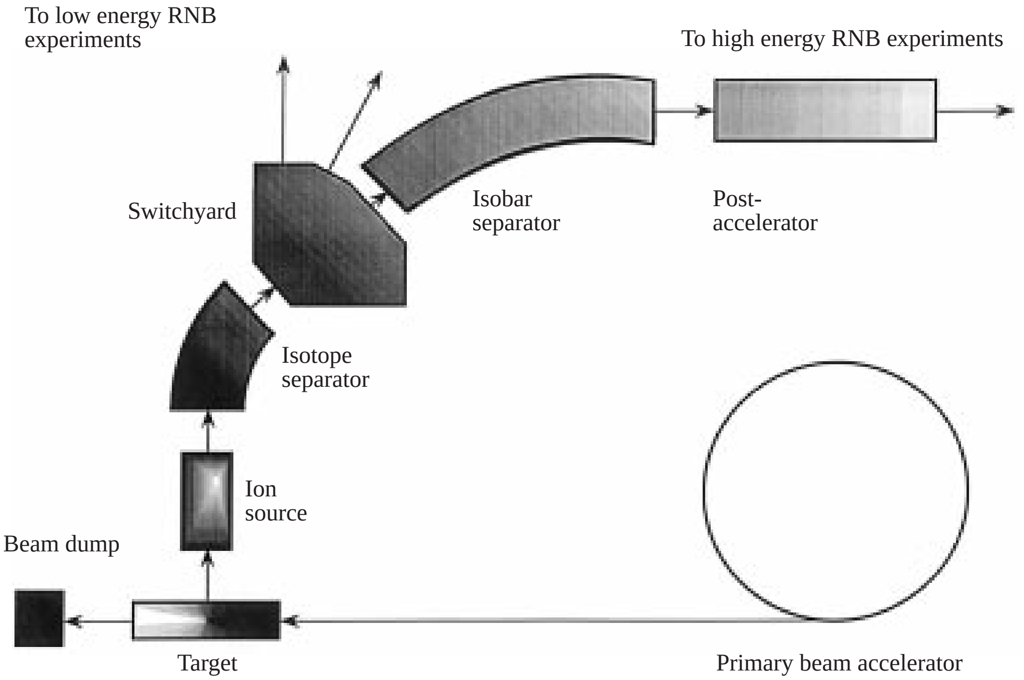

Figure 1. Schematic drawing of an ISOL-type RIB facility.

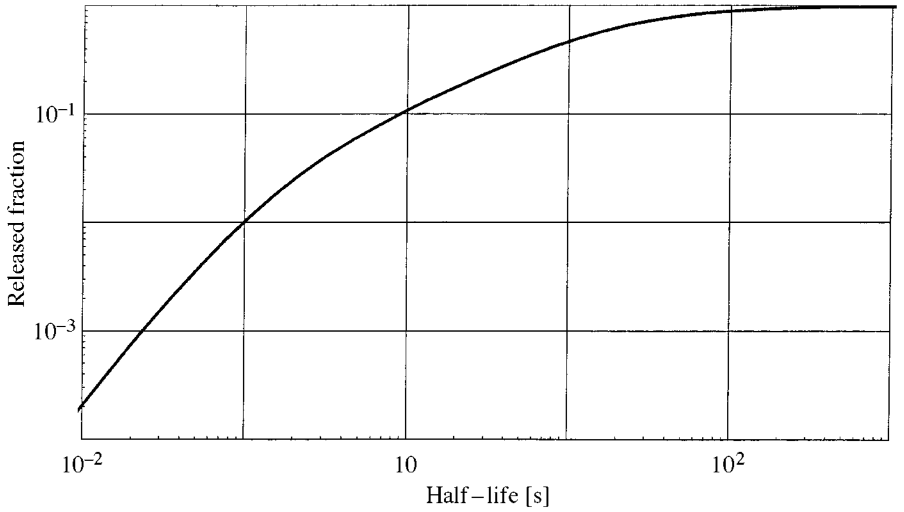

Figure 2. The half-life dependence of the release yield caused by the decay losses in the target and ion source.

new radiochemical separation methods, which for a given product element take place in the target and ion-source unit, are the temperature, diffusion constant, desorption enthalpy, and ionization potential (Ravn 1979). Although for the choice of the target material and construction materials it is essential to know these parameters, it is rarely possible to calculate the parameters ε_1, ε_2 and ε_3 with sufficient precision for

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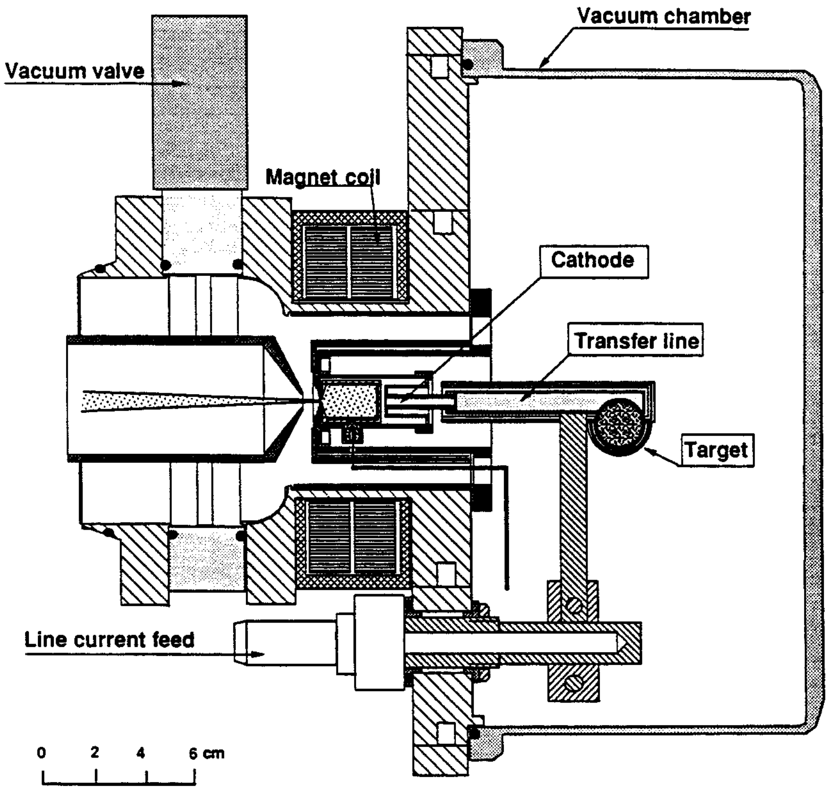

Figure 3. A typical target and ion-source unit, where the target container is connected to an ion source via a transfer tube.

a given nuclide. The efficiencies ε_1 and ε_2 can be determined off-line or on-line with various methods to a good precision. The determination of ε_3 which is a function of half-life can only be done by an on-line determination of the delay function, i.e. the probability that an atom formed at time 0 is extracted from the ion source at time T (Lettry *et al.* 1997*a*). Depending on the element, values for ε_1 and ε_2 in the range 10–90% are not unusual and the typical half-life dependence of ε_3 is shown in figure 2. Another important parameter is the lifetime of the target and ion-source unit. The current techniques allow operation of these units for periods from a few days up to several months before they have to be replaced. During this period sintering, migration or chemical dissociation of the target material, in conjunction with the deleterious effects of the driver beam on the surrounding mechanical structures, eventually causes a failure. For this reason much effort has been put into finding the most economical ways to produce such consumable units. This has, with few exceptions, led to the choice of a relatively simple and inexpensive ion-source technique of which an example is shown in figure 3 (Ravn & Allardyce 1989). It produces singly charged, continuous ion-beams with high efficiency and emittances of typically $\varepsilon \approx 30\pi$ mm mrad. In this respect also, the resonant laser ion sources now coming into general use are also particularly interesting. Obviously, for the use of an ISOL as injector for a heavy-ion accelerator, the conversion of the reaction products into a higher-charge state, possibly bunched beam, at present receives much attention.

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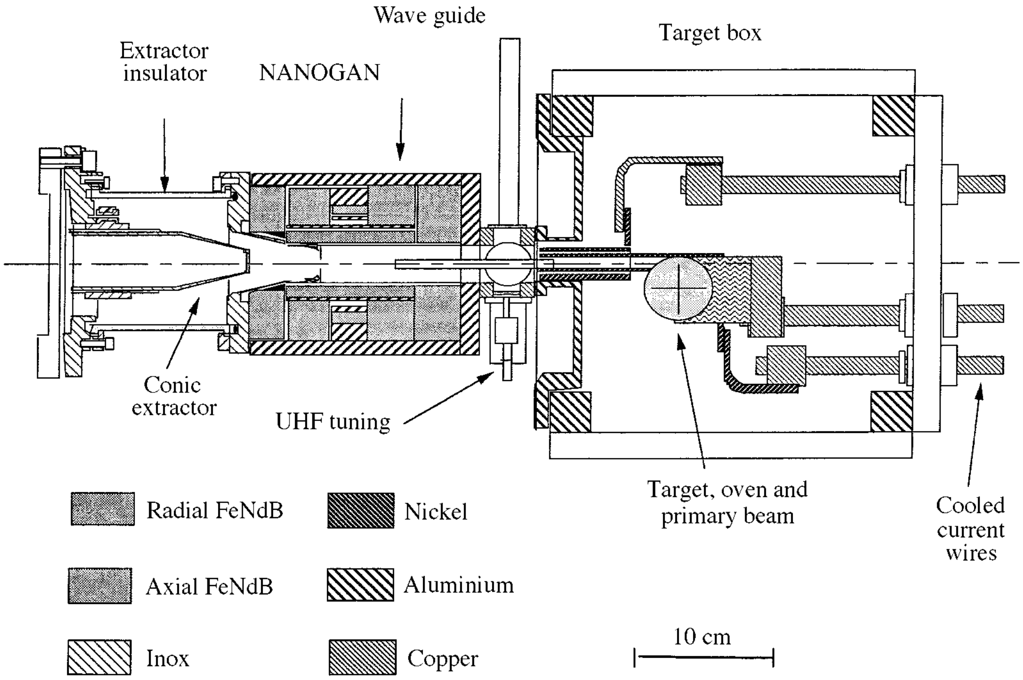

Figure 4. The Spiral ECR ion-source target combination

Three routes are generally followed here: pre-acceleration and stripping (which also allow negative ions to be produced for acceleration in a tandem), direct coupling of an ECR ion source to the target, and charge breeding of the mass-separated beam of singly charged ions in an EBIS or ECR secondary ion source.

(i) *ECR ion sources for on-line multi-charged ion production*

An obvious choice for generating high-ionic-charge states is to do so directly adjacent to the target by coupling to an ECR ion source (ECRIS), and in this way eliminate the need for gas, foil, electron beam or plasma stripping. In general these sources have been successfully developed for high-intensity, stable beam generation rather than for high efficiency and short delay time as required for RIB generation. In order for this technique to compete with the existing singly charged ion-source technique a number of questions have to be answered. Its efficiency and delay for production of multi-charged ions must be higher than the product of those of the singly charged sources and the efficiency of the charge multiplying technique employed downstream. In addition, the cost and inconvenience of employing such an elaborate technique in the high-radiation environment of the target must be carefully evaluated. Because of 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 figure 4, which shows the SPIRAL ion source (Villari 1997). Recent developments confirm the strength of this route for multi-charged RIBs as well, but only for nitrogen (Loiselet *et al.* 1993) and the light rare gases (Villari 1997). Judged from the stable metal consumption of accelerator ECR sources, multi-charge ionization

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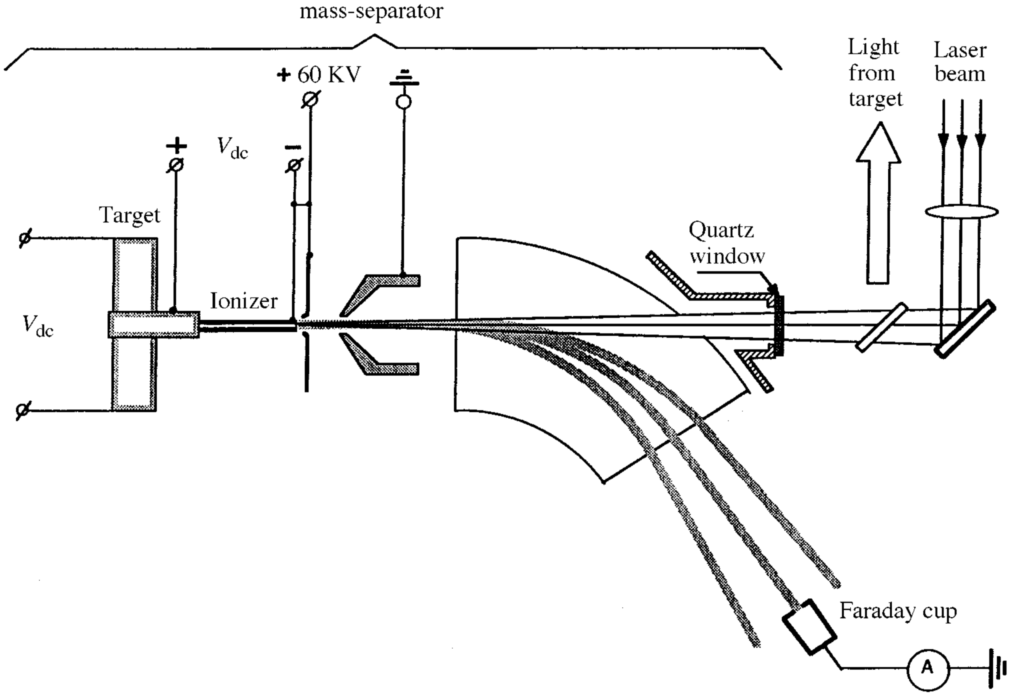

Figure 5. The principle of the ISOLDE laser ion source.

efficiencies of moderately volatile elements such as Ca in a given high-charge state seem to be of the order of 1%. However, it remains to be shown that this 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 them remain there for a very long time. At present, there is little experience in the production of multi-charged radioactive metal ions. It should also be noted that the ECR ion sources generally give transverse emittances 10 times higher than conventional 1^+ ISOL sources.

(ii) *Element-selective, multistep, resonant, laser ion sources*

The principle of stepwise, resonant, laser ionization has in recent years been developed at GSI (Kirchner 1993), ISOLDE (Mishin *et al.* 1993), Gatchina (Barzakh *et al.* 1997), Leuven, (Vermeeren *et al.* 1990), Mainz (Brumm *et al.* 1990), Orsay (Le-Blanc *et al.* 1989) and Takasaki (Koizumi *et al.* 1997). The simplicity of the laser-ionization cavity adjacent to the target makes this ion source particularly interesting for the hostile environment near an on-line target. In addition its speed, efficiency and selectivity match or exceed those of most other ion sources. As shown in figure 5, up to three laser-generated light beams of different wavelengths are sent into a cavity very similar to that of a standard ISOLDE tubular surface-ionization ion source (Sundell & Ravn 1992). The laser interaction with the products flowing through this cavity allows in principle an extremely high element-selective ionization. In practice, suppression of any isobaric surface-ionizable element by more than two orders of magnitude has been difficult to achieve because of the high temperature needed in

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the cavity in order to keep the element of interest in the gas phase. Since the laser ions are currently bunched with 10 kHz, the most often used laser frequency, the selectivity can be considerably improved by shortening the laser ion pulse and gating the separator on it. On the other hand, the theoretically obtainable efficiency is as high as 30%, determined by the frequency and intensity of the available laser light. The experimentally determined efficiencies are typically 10–20% and often exceed those obtained with plasma discharge ion sources. In addition the absence of anode insulators in this source allows operation at a higher temperature which results in shorter delays and less stable beam contamination. In addition, this ion-source principle holds much potential for further development. It is currently being developed for shorter laser ion pulses, further elements, enhancement of the bunching by means of laser ablation of condensed material (Sebastian *et al*. 1997) and reduction of the thermo-ionized current (Beznosjuck *et al*. 1997). The ionization efficiency is obviously determined by the existence of an efficient excitation scheme for which the light can be produced by means of traditional dye lasers pumped by 10 kHz copper-vapour lasers. To this rather elaborate method also the frequency tripling in nonlinear systems has now successfully been used in order to ionize efficiently atoms of elements with high-lying first excited levels like Be, Zn, Cu and Cd (Lettry *et al*. 1998), that require ultraviolet light. Recently, Mn (Fedoseyev *et al*. 1997), Ag (Jading *et al*. 1997) and Ni (Jokinen *et al*. 1997) have been added to the list of elements shown in figure 6 which can be efficiently laser ionized by means of present techniques. The development seems not to stop here. As a function of the availability of Nd:YAG lasers with a high repetition rate, which can pump tunable solid state lasers or optical parametric oscillators, the efficiency, simplicity and range of elements may be further increased (Van Duppen 1997).

(*b*) *The magnetic-analysis stage and ion-source emittance*

As discussed in Ravn & Allardyce (1989), the properties of the three different types of analysing magnets generally used in on-line mass separators play an important role in the purity of the beams to be post-accelerated. They not only perform the isotopic separation, but could, if needed, via higher resolving power, further enhance the chemical selectivity of the system by means of isobaric mass separation. In particular, the elimination of the often abundant stable-beam contaminants (such as atomic, molecular and multi-charged beams) may be needed at this stage depending on the mass resolving power of the following post-accelerator system. Whereas most on-line mass separator facilities successfully used so-called low-current mass separators which allow beams with intensities of $I < 100\,\mu\mathrm{A}$ to be separated with a resolving power (FWHM) of $M/\Delta M = 2000$, new developments show that the on-line use of high-current machines whose resolving power may be pushed towards $R = 30\,000$ is an interesting possibility. Several such systems are planned and have been built (Przewloka *et al*. 1992; Olsen *et al*. 1991; Wada *et al*. 1997). At ISOLDE the high-resolution mass separator (HRS) with a double magnetic-analysis stage and higher-order image aberration is in routine operation on-line (Pr92). In its test version at ISOLDE-3 it was, in conjunction with a surface-ionization source of slit extraction geometry at full aperture pushed to a resolving power of 11 000, which allowed separation of the ^{37}(K–Ca) doublet. It was clearly realized that to bring this machine towards its calculated limit of $R = 30\,000$ would, in addition to a stabiliza-

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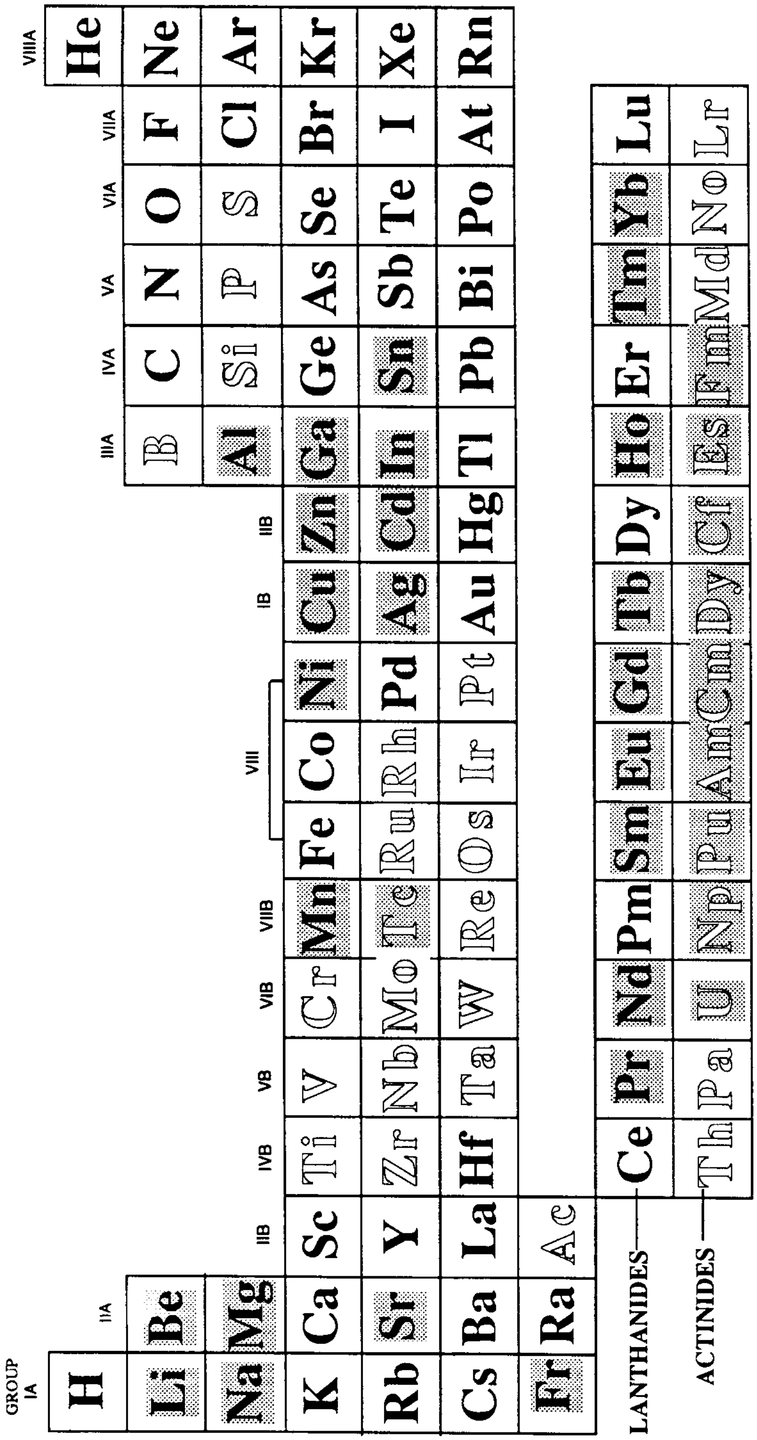

Figure 6. Periodic table of the chemical elements which shows those for which laser ionization techniques have been developed.

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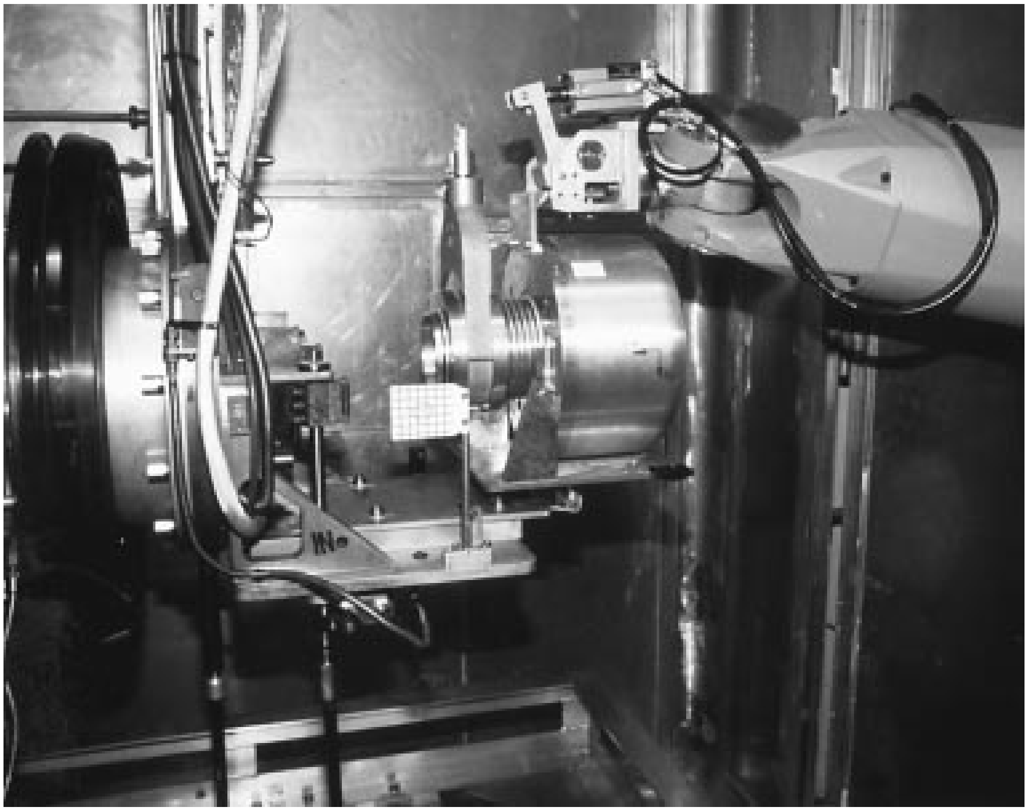

Figure 7. The preprogrammed industrial robot used for target handling at ISOLDE.

tion of all electrical and magnetic fields to a high precision, require the installation of much more elaborate beam observation equipment than traditionally used. In particular, attention has to paid to the acceleration voltage which, due to the ionization in the air surrounding the target region, is subjected to a current load that may make it difficult to maintain the ion energy-stability required to achieve high resolution. In addition, a systematic study of the emittance of the various ion sources has been started, since it is clear that not all have minimum emittance for the same working parameters that give maximum ionization efficiency.

Another important parameter of the magnetic analysis stage is the range of masses it permits simultaneously to bring to the focal plane. The typical value the currently used magnets allow is only ±10–15% of the central mass. This restricts the useful number of beams which the switchyard (Ravn & Allardyce 1989) may eject simultaneously to the experiments. The nuclear reactions as well as the target and ion sources produce often a much wider range of interesting masses. A facility with a broad-range magnet would permit a much more efficient exploitation of the targets when masses far apart may be ejected simultaneously.

(c) *Radioactivity handling and maximum driver-beam intensities*

Another aspect of high-intensity ISOL-RIB production which has to be carefully considered from the start of any project is the handling of the target and ion-source

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units and their adjacent structures, since they contain large amounts of radioactivity and have to be regularly replaced. Despite the fact that the on-line target opposite a reactor fuel element is constructed to liberate efficiently its reaction products, the standard radioactive handling techniques have successfully been used to deal with them. This aspect is particularly well studied for high-energy and intensity proton-driven facilities where typical dose rates in the target region of 60 krad h^{-1} can be encountered 48 h after the end of irradiation (Domingo *et al*. 1981). Two fundamentally different principles of replacing the targets are used at present. At ISOLDE and Oak Ridge the target units sealed by means of a vacuum valve like the one shown in figure 2 are taken care of by means of a preprogrammed industrial robot as shown in figure 7 from (Bjørnstad *et al*. 1987). This procedure has the advantage that the fully off-line tested, temperature-calibrated and completely outgassed units can be transported in an ordinary beam tunnel area under vacuum or inert gas between the hot laboratory and the separator front-end, where they only need a minimum start-up time before they are operational. At CERN, this system has been used successfully for targets in the kilogram mass range in a 1 GeV proton beam of intensities up to 4 μA. With minor modifications of the target unit this method may be used for intensities up to five times this value. From then on it seems necessary also to enable remote replacement of parts of the front end and its extraction electrode. This is planned to be done by converting the target area into a fully fledged hot cell into which the target unit and part of the front end are loaded (down) from the top as seen in figure 8 (from the RIST separator constructed at RAL (Bennett *et al*. 1993)).

With such a system the upper limit of driver-beam intensity is now no longer determined by the handling technique, but by the heat transfer from the target. Early computer calculations (Eaton & Ravn 1987; Talbert *et al*. 1992) indicated that conventional ISOL targets may withstand a beam power of *ca*. 40 kW, which corresponds to a 600 MeV proton-beam current of 200 μA. Present and much more refined calculations and off-line tests with an electrically heated and radiation cooled Ta-target at RAL (Bennett *et al*. 1997) show that the *ca*. 30 kW expected to be deposited in the target by a 100 μA, 800 MeV proton beam is the limit of current technology. Similar considerations for a ^{235}U target immersed in thermal neutrons at ILL (Pinston 1997) indicate that the present upper limit is around 3×10^{13} n cm^{-2}.

Owing to the higher $\mathrm{d}E/\mathrm{d}x$ of heavy ions and low-energy light particles, the power densities in targets for these particles are the highest. Currently, this limits the total accepted power to 6 kW. This has been demonstrated for a graphite target irradiated with 200 μA, 20 MeV protons at Louvain-la-Neuve (Loiselet *et al*. 1993). Calculations and on-line tests with 30 MeV protons of 6 kW deposited power, a 200 μA, 95 MeV u^{-1} ^{20}Ne beam and a 35 particle nA, 73 MeV u^{-1} ^{78}Kr beam show that the graphite target for the SPIRAL project would withstand 6 kW power deposition, provided that the driver beam was continuously rotated (Puteaux *et al*. 1997).

(*d*) *Ion-beam storage and bunching*

Depending on the delays in the target and ion sources, the radioactive ion beam may be bunched with the repetition rate of the primary accelerator and a pulse width which often degenerates into an almost DC beam (Lettry *et al*. 1997*a*). In order efficiently to match modern acceleration techniques, it is advantageous to compress

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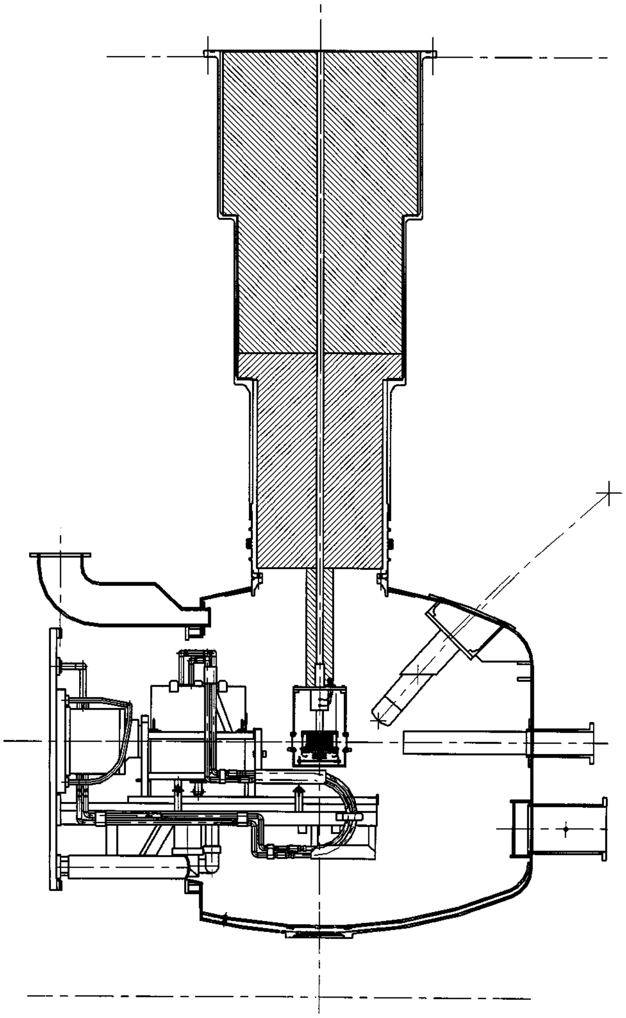

Figure 8. The RIST target and ion-source assembly for top loading into the target shielding.

the ions in short pulses. Several techniques have been developed for this. For the alkali elements, the outlet of the surface ionizer used for their ionization may be equipped with a negative-biased buncher electrode, which when switched to positive enables storage of the ions until it is switched back to negative. At the maximum repetition rate of 50 Hz, this technique allows a duty cycle of *ca.* 10% for Na and K (Touchard *et al.* 1981; Shirakabe *et al.* 1993; Mishin *et al.* 1993). A similar gating technique has also been developed for an ECR ion source, giving a duty cycle of 52% at a repetition rate of 1 kHz (Jeong *et al.* 1997). The application of the laser-induced ablation technique followed by laser ionization may extend this technique to application for a wider range of elements.

A more general and very promising approach found in the layout of REX-ISOLDE shown in figure 9 is the use of a Penning-trap system for the accumulation and bunching of DC beams (Habs *et al.* 1997). Derived from the mass measurement experiments (Beck *et al.* 1997; Bollen 1997) this technique consists of injecting the

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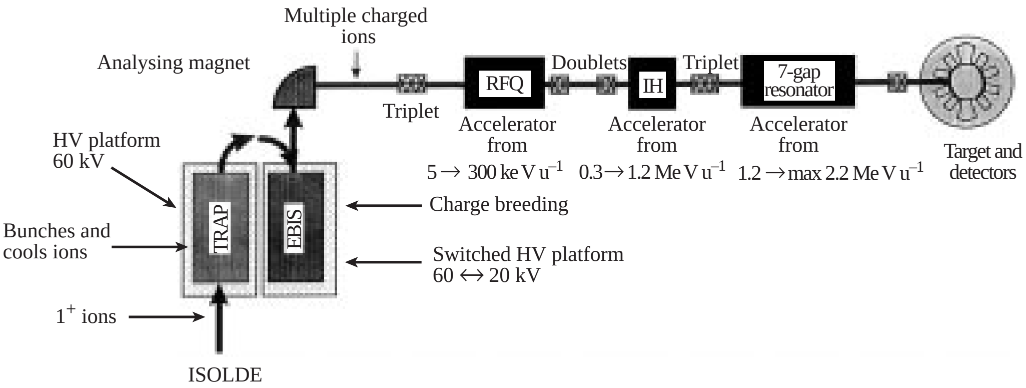

Figure 9. Layout of the new ISOLDE concept for trap bunching and EBIS charge amplification.

ions into the trap where they are stopped by collision with the atoms of a buffer gas. After accumulation they are extracted in pulses with a typical emittance reduction of an order of magnitude to $\varepsilon \sim 3\pi$ mm mrad and an efficiency of 10%. Compared to the previously proposed Paul-trap buncher (Moore 1992), a Penning-trap buncher has the following advantages: simple and effective filling of the trap, high bunch intensities (10^7–10^8 atoms per bunch) and better cooling properties.

Extrapolations to a larger dedicated buncher trap indicate that accumulation efficiencies of 100% can be achieved. In addition, it has been shown that application of the sideband cooling technique allows higher-charged contaminants to be removed efficiently whereas its powerful isobaric mass-separation capability may be obtained at the expense of efficiency.

(*e*) *Charge amplification techniques*

(i) *Beam stripping*

In order to achieve an economical and efficient post-acceleration of the singly charged ions delivered from the mass separator, the mass-to-charge ratio of the ions must be increased. The traditional way to achieve this, frequently proposed in the new projects, is a suitable pre-acceleration to about 200 keV u^{-1} followed by stripping off electrons by passage through a foil or a gas (which is often repeated). This method has the advantage of being very simple and cost effective, but introduces transverse emittance growth. The singly charged beam is now split up in a distribution of higher-charge states, of which only one will be accelerated. The same process is also used to convert positive into negative ions by charge exchange if a tandem accelerator is the final stage. These well-known processes have an efficiency which is mass dependent and of the order of 10–50%, where especially the charge exchange is most delicate and may reduce the beam intensities below those originally foreseen.

(ii) *EBIS charge breeding*

When the post-acceleration scheme requires injection of higher-charge states, a new scheme is proposed (Haas *et al.* 1990; Becker *et al.* 1992), which is particularly well suited to the production of radioactive ion beams. Such beams are, at present,

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characterized by low intensities. The new scheme takes advantage of the electron-beam ion source (EBIS) developments. By modifying this efficient high-charge-state ion source from its usual gas injection to accept singly charged ion injection, a very efficient charge-state multiplier has been produced. By solving the delicate optical beam problems around the injection into this electron beam trap, two groups (Beebe *et al*. 1994; Visentin *et al*. 1995) have demonstrated that 40–50% of the injected bunches of 10^9 singly charged ions are ejected with a narrow charge-state distribution containing 10–50% of the most abundant charge state. Since these devices have reached a high level of reliability and give beams of excellent optical quality independent of the chemical properties of the elements, a dedicated version is currently under construction for the REX-ISOLDE accelerator and is shown in figure 9 (Habs *et al*. 1997).

(iii) *ECR direct high-charge-state ionization or charge breeding*

Like the EBIS, the ECRIS may also be used as a charge-state amplifier by capturing a beam of singly charged ions in its plasma. Tests of stripping singly charged Rb ions in an ECRIS have been performed at ISN-PIAFE (Tamburella 1996). Here, the critical point is the injection of the singly charged ions into the ECR plasma, where the acceptance window allows only 1 V energy spread. By retarding the ions to less than 20 V, an efficiency of 2% was achieved in converting Rb^{+} to Rb^{9+}. Compared to the EBIS charge-breeding technique, the ECRIS technique may be developed for use at higher intensities, but will keep its larger charge-state distribution and dependence on the chemical properties of the elements.

3. Primary beams and nuclear reactions

The radioactive nuclei to be post-accelerated may be produced by a variety of bombarding particles, ranging from thermal neutrons to high-energy heavy ions. From the many on-line mass separators that are or have been in operation the situation is quite well understood. Each of them have their particular advantages, such as production cross-sections, currently available intensities, range of radioactive species that they allow to be produced, and last but not least, the practical constraints on the liberty of choice of techniques, which may be used in conjunction with a given driver particle, which determines the ε in equation (1.1). In order to be able to compare the relative merits of the different driver beams, the reader is referred to the report (Ravn *et al*. 1994) of a working group within NuPECC. Here, some projected beam intensities are given on the basis of measured ε at ISOLDE and other ISOL facilities, which the working group agreed could be achieved elsewhere in an intensive development programme, which has started in several laboratories. Below only the essential features and recent developments for various driver beams are given.

The question as to what is the ‘ideal’ driver should only be answered once the region of nuclei needed for the physics one wants to do is known.

(*a*) *Neutrons*

The highest formation cross-sections are found in the thermal fission of ^{238}U, as shown in the example of figure 10. The high production rates of neutron-rich nuclei

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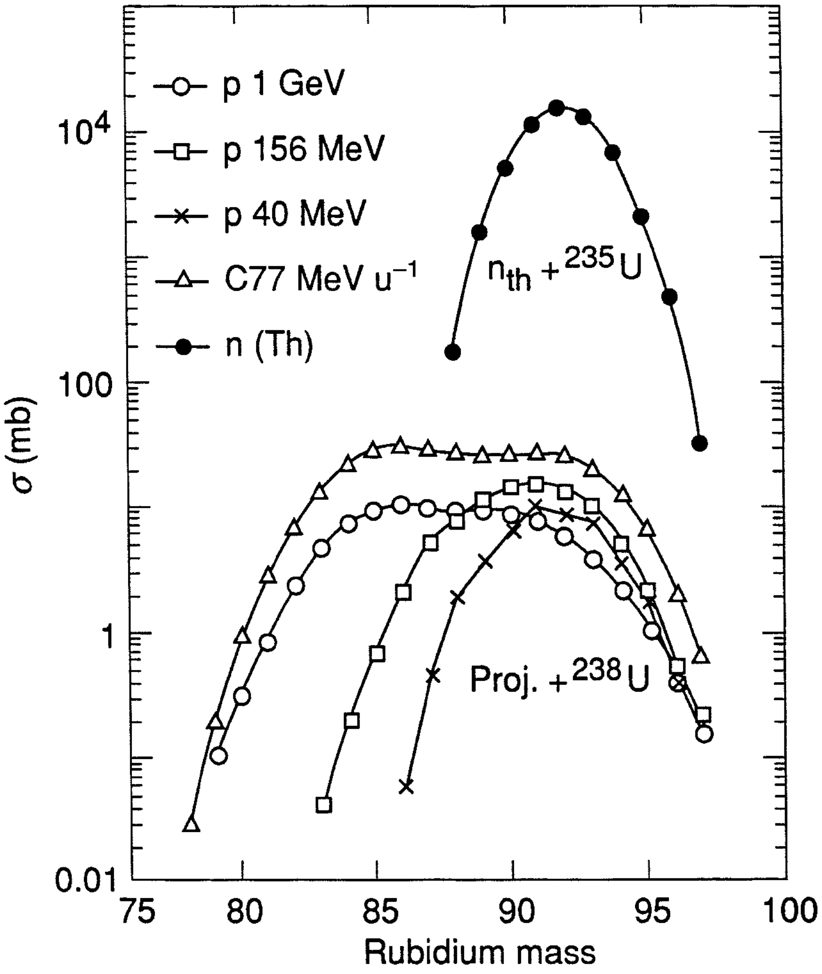

Figure 10. Cross-sections for production of rubidium isotopes by various nuclear reactions.

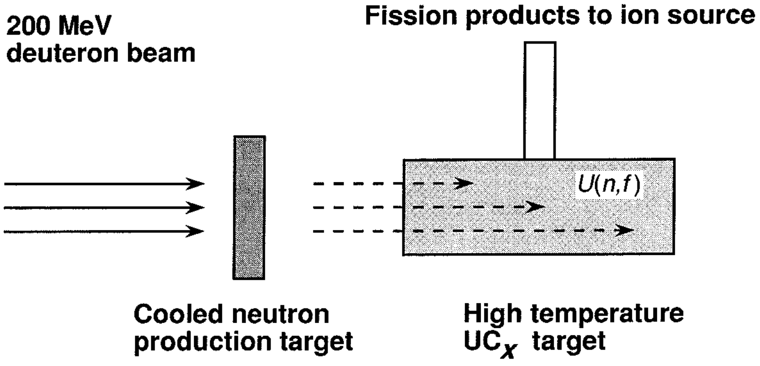

Figure 11. Schematic representation for producing fission fragments by bombarding a high-temperature uranium carbide target with an intense neutron beam formed by stopping a deuteron beam in a well-cooled conversion target.

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that may be obtained in the fission-product mass region of $80 < A < 140$ have for many years been exploited by several on-line mass separators (Ravn & Allardyce 1989). By locating their target next to the core of the reactor, the Studswik group is currently using the highest neutron fluxes of 10^{11} cm^2 s^{-1} (Fogelberg *et al*. 1992). Owing to the restrictions in terms of space, access and other technical reasons they have not been able to use the most efficient ion-source techniques: they work with a long-lived but dual-mode ion source, which has an efficiency a factor of 3–100 lower than today's standard. Neutron fluxes of less than 10^{15} cm^2 s^{-1} are available at reactors elsewhere and have been proposed for the new projects PIAFE Grenoble (Pinston 1997) and Munich (Thirolf *et al*. 1997). These projects may retain the advantage of the very high fission cross-sections only if the most efficient ion-source techniques and other infrastructures like absorbers for compensation of target burn-up are developed also for in-core use. Another interesting concept to obtain high neutron fluxes without using a critical assembly and its hostile environment is proposed by the Argonne group. Their concept is to generate an intense 100 MeV neutron beam by stripping a 200 MeV, 0.5 μA (100 kW) deuteron beam in a well-cooled low-Z target and to let it impinge on a 25 cm long uranium target, as shown in figure 11. The total power of 20 kW developed in the target, which comes essentially from the fission fragments, places neutrons as the particle which deposits lowest power densities. Although the fission and spallation cross-sections of this beam are largely unknown, calculations and recent tests of this concept at the SATURNE National Laboratory (E. Cottereau, personal communication) indicate that production rates obtained with a high-temperature, ISOLDE-type uranium carbide target are comparable with those that can be obtained from a 1 g ^{238}U target in a thermal neutron flux of 10^{14} cm^2 s^{-1}, as indicated by the LAHET calculations (Nolen 1993).

(*b*) *Low-energy protons*

Protons in the energy range $E_{\mathrm{p}} < 60$ MeV are today typically used for medical isotope production. At Louvain-la-Neuve, the medical cyclotron developed in-house ($E_{\mathrm{p}} = 30$ MeV), at HRIBF Oak Ridge the ORIC ($E_{\mathrm{p}} < 60$ MeV), and at INS the $K = 68$ cyclotron ($E_{\mathrm{p}} = 45$ MeV) were used as driver accelerators with beam intensities of up to 500 μA. The low energy opens only a few channels, like (p,xn) reactions, which on the one hand gives high yields near stability, but on the other constrains the range of elements that can be produced owing to the limited choice of refractory target materials. Because of the selectivity of the reactions, the production of unwanted species can be kept low so that radioactive handling problems are largely absent. This situation will change once these facilities exploit the possibility of using uranium-carbide targets for production beams of fission fragments.

(*c*) *High-energy protons*

Particularly high beam intensities have been obtained when the on-line mass separator is combined with an intense proton beam of energy in the range from 500 MeV 18 GeV. Owing to the thick targets (1–500 g cm^{-2}) that may be used, primary-beam conversion rates into secondary radioactive beams of up to $R = 5\times10^{-2}$ are achieved. The three high-energy proton reactions (spallation, fission, and target fragmentation) allow all nuclei to be produced with $Z < 92$. The resulting mass–yield curves given

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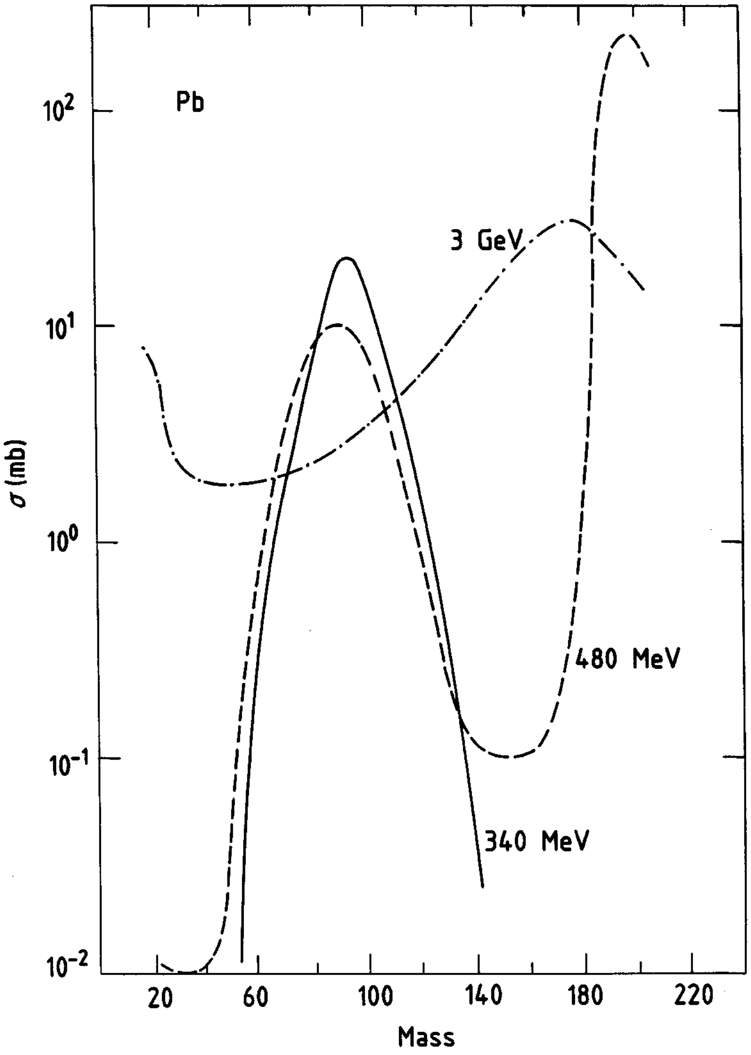

Figure 12. Mass–yield curve for reactions of protons with various energies on Pb and Bi targets.

in figure 12 for different bombarding energies for the reaction of protons on a heavy target illustrate the potentially large range of RIBs that may be produced with such a driver beam. The independent formation cross-sections for these reactions can be calculated by the formulae of Rudstam (1966), Silberberg & Tsao (1973*a*), and Sümmerer (1992). Since these calculations have relatively large uncertainties, recently experimentally determined cross-sections (Schiekel *et al.* 1996) have been added to the existing ones found in the compilation of Silberberg & Tsao (1973*b*) and used for a critical comparison of the various models (Michel & Nagel 1997).

The relatively low power density in the target together with the broad range of nuclear reactions has allowed a very free choice of target materials and has put very few restrictions on the target and ion-source techniques that may be adopted. It should also be noted that the price for this versatility is the handling of large amounts

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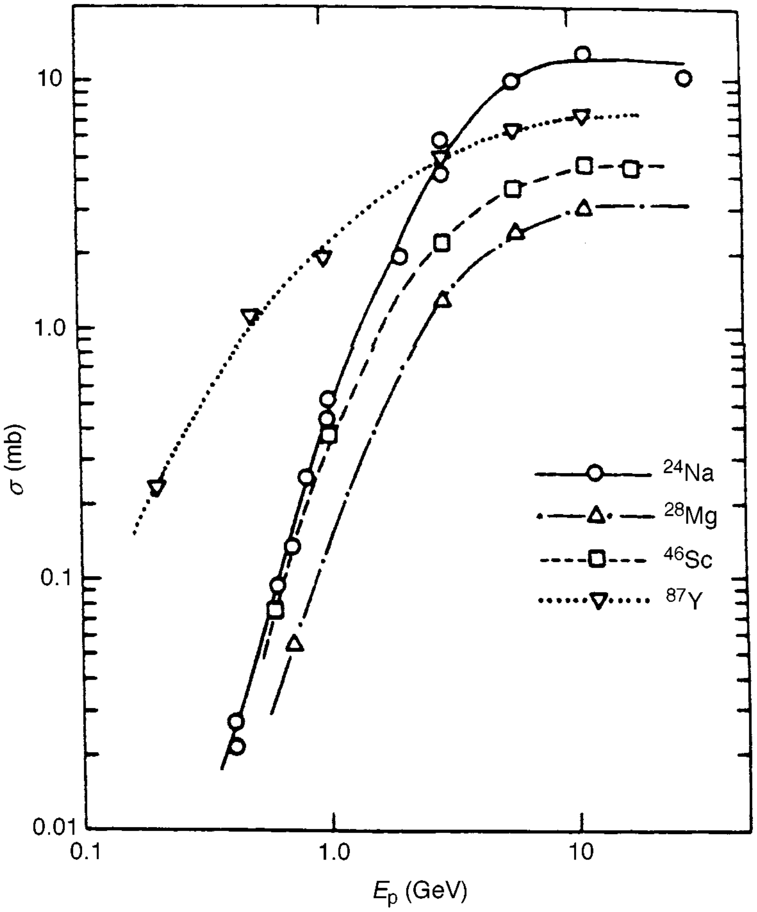

Figure 13. Experimentally measured excitation function for the fragmentation of gold leading to some typically light products.

of radioactivity. At present, two RIB facilities that use high-energy protons are under construction: REX-ISOLDE (1–1.4 GeV) and ISAC-TRIUMF (500 MeV). Both also have experience with low-energy on-line mass separators, and ISOLDE in particular has made major contributions to the large capital of target and ion-source techniques that exists for use with proton beams. The availability of very high proton beam intensities at existing spallation neutron sources, meson factories, proposed energy amplifiers, and the proposed new CERN LHC injector, makes them very attractive locations for future RIB facilities, such as ISOLAB, using beam currents of less than 100 μA in a parasitic mode. As preparation for such a facility, SIRIUS at the Rutherford Appleton Laboratory has constructed a set-up for testing an ISOLDE-type target in an 800 MeV, 100 μA proton beam.

It is therefore no surprise that major projects like ISOLAB, which do not need to capitalize on existing driver accelerators or nuclear reactors but have a real choice, have opted for high-energy protons since they give the largest variety of beams and rely on known techniques. It should be noted that for production of nuclei in certain regions of the nuclidic chart, high intensity is not always the best route. As seen from

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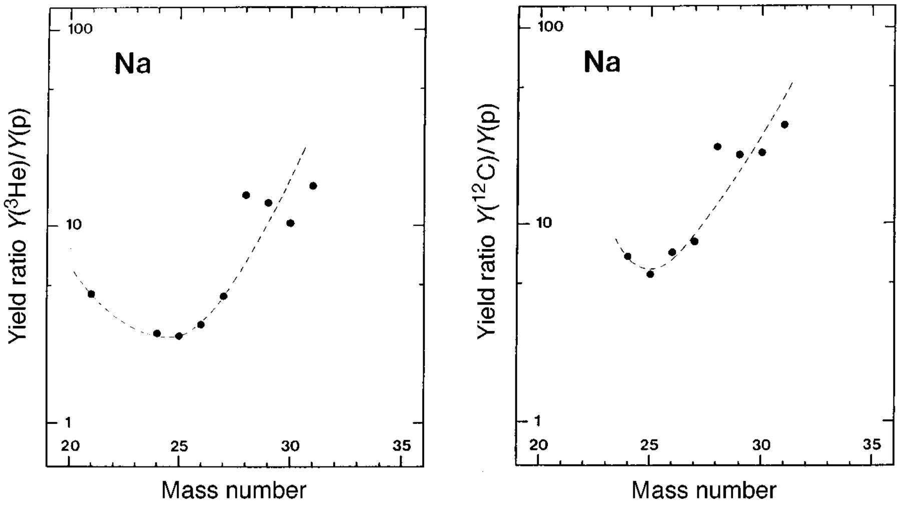

Figure 14. Ratios of sodium beam yields obtained by fragmentation of uranium by means of 86 MeV ^{3}He and ^{12}C over fragmentation of uranium by means of 600 MeV protons.

the excitation curves in figure 13, for deep spallation or fragmentation reactions, a two-fold energy increase around 1 GeV gives a five-fold increase in production rate. The saturation cross-section for more exotic species may well first be reached beyond 5 GeV.

(*d*) *Heavy ions*

As a result of the recent development of ECR ion sources and accelerators, the intensities of heavy-ion (HI) beams with energies of 30–100 MeV u^{-1} have been greatly increased, so that they may offer an interesting alternative to high-energy protons. In particular, the somewhat longer-range light ions ^{3}He and ^{12}C show a cross-section advantage for deep spallation and target fragmentation reactions (Bjørnstad *et al*. 1981*a*, *b*), as seen in figure 14. Here it is seen that the ISOLDE beam-intensity ratio of sodium beams formed in 600 MeV proton and 86 MeV u^{-1} ^{3}He 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. Using protons, a similar increase may be obtained by raising the energy to 1–2 GeV. The higher excitation energy, which the slow, heavy particle can deposit in the target nuclei as compared to protons, gives an increase in cross-section for the reactions shown in figure 12 of 1–10 times that of the 3 GeV proton curve. The highest values are expected from the short-range heaviest ions. As the HI mass rises, the useful target thickness rapidly drops to 4 g cm^{-2} compared with 500 g cm^{-2} for 1 GeV protons. For these it becomes attractive to stop the projectile fragments in a thick refractory target, which can be chosen such that the release properties for a given element are optimized. The typical cross-sections for this reaction are comparable to those for high-energy proton fragmentation of heavy targets as seen in figure 15. The more elaborate targets, which can handle the very high power densities deposited by the HI, have at present allowed this technique to be developed for elements which are released from graphite. In concluding this section, however, it should be noted that the cross-sections alone are insufficient to

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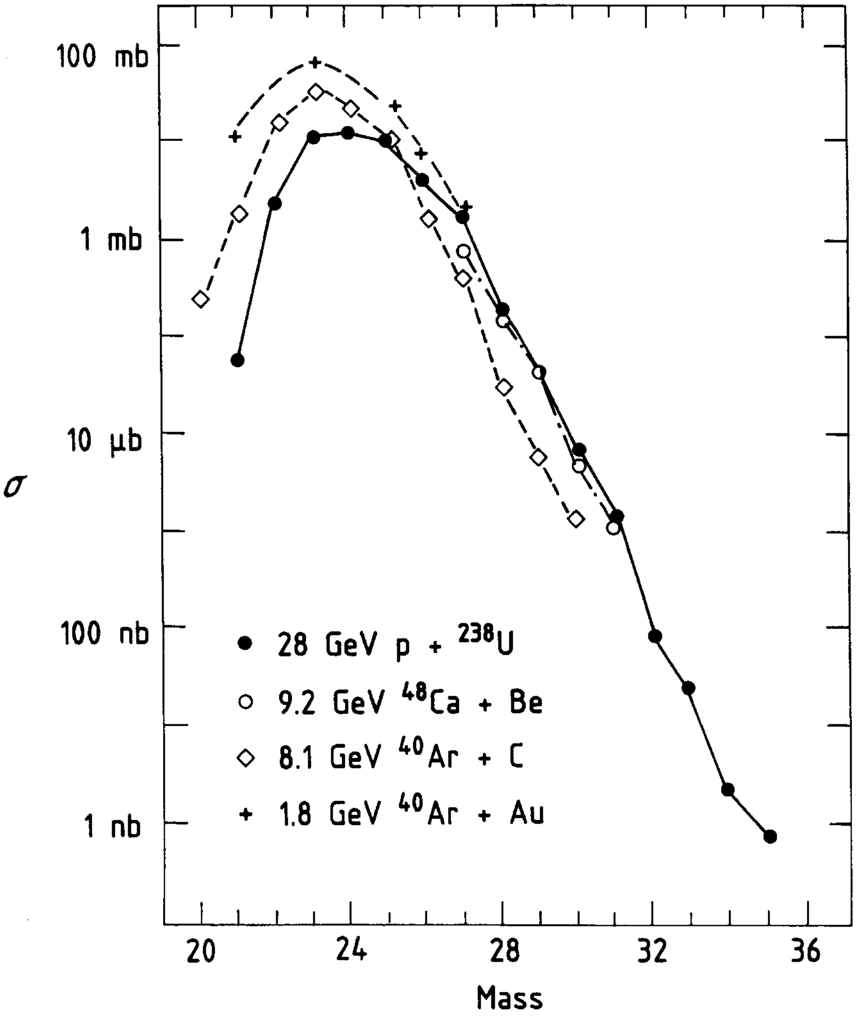

Figure 15. Cross-sections for production of Na-isotopes with various fragmentation reactions.

decide on the best suited reaction for production of RIB, since the other factors of equation (1.1) may change the picture given in this section dramatically.

4. Acceleration methods

(*a*) *Driver machines*

At present, we are at the stage of using the existing driver machines for the start-up of the field. As the energy and intensity requirements can be honoured, the time structure of the beam is the only important choice left to be made. This applies mainly to proton machines, since existing HI accelerator techniques and reactors have beam-time structures close to the optimum for an RIB facility. For the choice of proton driver beams, it has to be carefully evaluated whether a low-repetition-rate synchrotron beam or a faster cycling linac or cyclotron beam is most advantageous.

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In the first case, the deleterious effects on target lifetime caused by the shock wave induced by the intense short proton pulse and the associated instability in accelerating voltage (Kugler *et al*. 1992) are offset by the advantage of allowing a low-frequency bunched release combined with a delay-time enhancement as observed by ISOLDE (Evensen *et al*. 1997; Lettry *et al*. 1997*b*) at the CERN PS-BOOSTER. On the other hand, lifetime or maximum proton-beam intensity may be increased if the more continuous-wave (CW) beams are chosen, which do not display these effects on the target.

(*b*) *Post-accelerators*

For this part of the facilities we envisage a very active development of accelerators dedicated to RIB acceleration alongside the reuse of existing machines. All three well-known accelerator techniques (Tandem Van de Graaffs, cyclotrons and LINACs) have advantages, which will be outlined below.

(i) *Tandem Van de Graaffs*

The reuse of a tandem as post-accelerator is an attractive idea since it gives the highest beam quality and continuous energy variation. This scheme requires injection of negative ions, which limits its use to those elements for which efficient production techniques exist. The very high terminal voltages required to accelerate heavy elements point at a multi-stage post-acceleration.

(ii) *LINACs*

The efficient use of the standard HI acceleration technique by means of LINACs depends critically on the successful use of the techniques to bunch and generate high-ionic-charge states discussed in the previous sections. The new developments in this field are therefore promising for the use of the standard scheme of an RFQ followed by a LINAC, rather than requiring more elaborate CW-RFQ and LINACs, which with singly charged ions are limited to the mass region below 80. Since the transmission and beam quality are very high and energy variability is assured, LINAC techniques are at present the preferred choice.

(iii) *Cyclotrons*

Cyclotrons can combine the functions of mass separation and acceleration and are an alternative to LINACS, which have the same requirements in terms of the availability of multiply charged ions. Although cyclotrons generally have a low transmission and beam quality, much development effort is currently devoted to this solution.

5. Radioactive ion beam projects

There follows a short discussion on the various RIB projects and their latest developments, listed according to driver-beam types.

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(a) ARENAS^3, Louvain-la-Neuve

For some years this has been the only two-accelerator facility in full operation (Loiselet *et al*. 1993). It relies on an intense low-energy proton driver accelerator CYCLONE 30 (30 MeV, 500 μA), a modern, compact and power-efficient type developed for medical radio-isotope production. The gaseous species released from the target are transferred via a room-temperature line to an ECR ion source, which produces a Q/A of 1/7.5 before injection into the existing $K = 110$ MeV CYCLONE post-accelerating cyclotron with 6% transmission. It has yielded beams of ^{6}He, ^{11}C, ^{13}N, ^{19}Ne and ^{35}Ar with energy variable in the region 0.2–0.8 MeV u^{-1}. This facility, specialized for the production of low- and medium-energy light ions close to stability, will in 1998 bring a new high transmission (25%) post-accelerator, the CYCLONE 44, into use. This cyclotron, specially developed for RIB, will raise the intensity of their RIBs by an order of magnitude to about 10^{10} ions s^{-1}, further improve the isobaric separation, and allow the CYCLONE also to be used as a primary accelerator.

(b) INS, Tokyo

This facility is a pilot plant and research and development project (Kubono *et al*. 1997*b*) for a Japanese 'IsoSpin' laboratory planned for the 10 μA, 3 GeV proton-driven E-Arena of the Japanese Hadron Project (Wollnik *et al*. 1990). The concept currently under test at INS in Tokyo makes use of protons and light-ion beams from the $K = 68$ MeV cyclotron (40 MeV protons, 10 μA) as driver beams. By means of a variety of ion-source techniques, bunched singly charged ions from the high-resolution mass separator ($M/\Delta M = 9000$) are injected into a split coaxial RFQ stripper-IH-LINAC, which allows the energy to be varied from 0.2 to 1 MeV u^{-1}. In 1997 the machine was moved to the E-Arena of the KEK proton synchrotron in Tsukuba.

(c) HRIBF-ORNL, Oak Ridge

In 1996 the second ISOL-type RIB facility (Olsen *et al*. 1991) accelerated its first beam of 140 MeV ^{70}As produced in a ^{70}Ge(p,n) reaction with 42 MeV protons from the ORIC cyclotron (60 MeV, 30 μA protons). The negatively charged ion beam was injected into their 25 MV tandem accelerator from a high-resolution mass separator ($M/\Delta M = 30\,000$) and a charge-exchange cell, both located on a 300 kV platform. An intensive target and ion-source development programme aims at developing beams close to stability from ^{17}F to ^{80}Br.

(d) IsoSpin Laboratory, USA

This project is a declaration of interest drafted by a group of physicists proposing a major RIB facility for North America (Sawicki *et al*. 1991). The conceptual design is based on the 1990 state-of-the-art target and ion sources, and high charge formation, and uses a high-energy proton or helion driver accelerator. The remaining accelerator part is left open for discussion and further research and development efforts. However, it indicates the direction of research and development by defining a benchmark facility which includes an RFQ-LINAC post-accelerator. Until now it has served the purpose of arousing interest in RIB physics and drawing attention to the important

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research and development work needed to solve certain technical problems, as well as to educate a generation of physicists in the crucial target and ion-source techniques. This has successfully been achieved, as can be seen from the amount of research and development work started at the other North American projects discussed in this paper, and from the permission from the Department of Energy (DOE) to proceed towards the development of an advanced ISOL concept and its scientific and technical basis, in view of a proposal in 1999.

(*e*) *REX-ISOLDE, Geneva*

The REX-ISOLDE programme for RIB production at CERN (Habs *et al.* 1997) is the natural extension of the ISOLDE facility. This collaboration has chosen its own new concept for post-acceleration of its inventory of more than 600 (Ravn 1986) radioactive ion beams of low energy but of intensities of up to 10^{11} atoms s^{-1}. The project relies on the long experience gathered at the world's largest laboratory for production and study of low-energy radioactive nuclei from all regions of the nuclidic chart produced by means of the 2 μA, 1 GeV proton beam from the PS-BOOSTER synchrotron. The singly charged ions from either one of the two on-line mass separators ($M/\Delta M = 2000$ and $M/\Delta M = 30\,000$) will be continuously injected into a Penning trap. After accumulation for about 20 ms, bunches will be transferred to an electron beam ion-source EBIS. Here the charge-to-mass ratio is amplified to larger than 1/4.5 in about 10–20 ms. It should be noted that the other bunching schemes discussed above are also foreseen. After acceleration in a specially constructed RFQ to 0.5 MeV u^{-1}, a linear accelerator based on an inter-digital H-structure and three 7-gap resonators takes over, as shown in the layout in figure 9. This first stage of post-acceleration will make available beams of variable energy between 0.8 MeV u^{-1} and 2.0 MeV u^{-1}.

At present, the Penning trap is being commissioned at CERN; the EBIS and LINAC which are under construction in the collaboration laboratories will soon be installed in order to allow their physics use in 1998.

In the near future the ISOLDE proton-beam line will be upgraded also to handle the 1.4 GeV energy needed by the PS for LHC injection. This should lead to a production-rate increase of up to one order of magnitude for rare fragmentation products. After demonstration of the viability of this pilot experiment, the current plans to increase the energy to 6 MeV u^{-1} may then be achieved without technical problems. Such an extension may coincide with approval of the proposed 2 GeV proton LINAC for the CERN PS (Garoby & Vretenar 1996). This high-intensity injector needed for the LHC, which is based on the recommissioned LEP RF system, could in a parasitic mode easily deliver an ideal sub-100 μA beam to ISOLDE.

(*f*) *ISAC-TRIUMF, Vancouver*

In 1984 it was proposed to use the 100 μA, 500 MeV protons from the TRIUMF H cyclotron for an RIB facility. After 10 years of experience with the TISOL on-line mass separator, the building of the new RIB facility based on this experience has now started (Bricault *et al.* 1997), and it is planned to have the first accelerated beams available in 2000. The singly charged ion-beam with $A < 30$ delivered from the high-resolution mass separator ($M/\Delta M = 10\,000$) will be accelerated up to 1.5 MeV u^{-1}

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in a two-stage LINAC, consisting of a 35 MHz RFQ and a post-stripper drift-tube LINAC. In order to preserve intensity CW, operation of the RFQ is required. After the stripping, rebunching and matching section, the beam is accelerated to its final energy in a room-temperature IH drift-tube LINAC, also operated in CW mode. Its five independently phased IH tanks allow energy variation down to 0.15 MeV u^{-1}.

(*g*) *SIRIUS-RAL, Chilton*

An on-line mass separator for a radioactive ion-source test (RIST) has been made ready for testing a target and ion source driven by a sub-100 μA proton beam diverted from the 800 MeV synchrotron, which currently serves the pulsed neutron spallation source ISIS at the Rutherford Appleton Laboratory (Bennett *et al*. 1997). The test is part of the preparation of a proposal for an RIB facility named SIRIUS at RAL. This facility plans to develop and use ISOLDE-type singly charged target and ion-source techniques for higher proton beam intensities than those available at ISOLDE.

The RFQ LINAC post-acceleration scheme chosen for this project obtains the needed high-charge states by stripping twice. For this purpose, the target and ion source are kept at a 300 kV potential so that the singly charged ions can be efficiently stripped in front of the RFQ. The following LINAC raises the energy after a second stripping to 10 MeV u^{-1}.

(*h*) *SPIRAL-GANIL, Caen*

The RIB facility SPIRAL on-line to the GANIL accelerator complex is scheduled to be operational in late 1998 (Anne *et al*. 1993). High-intensity ^{2}H–^{40}Ar beams of 2×10^{13} particles per second at 96 MeV u^{-1} from the two coupled $K = 380$ cyclotrons will serve as driver beams, although ions from Ar to U of about 10^{10} particles per second are also available. The products released from the target are given high-charge states in an ECR ion source directly connected to the target. After mass separation in a moderate resolution magnet ($M/\Delta M = 4000$), the ions are post-accelerated in a $K = 265$ compact cyclotron, which has a mass-resolving power of $M/\Delta M = 50\,000$. The energy is variable from 2 to 25 MeV u^{-1}, and the transmission is 30–60% depending on the energy of the accelerated beam. Although the available driver beams allow almost all reaction types, the project is currently focused on projectile fragmentation products of the rare gases He to Kr. For these, a graphite target and ECR ion-source techniques have been developed, which support the 6 kW power deposited by the full-intensity beam.

(*i*) *EXCYT-LNS, Catania*

Driver beams of HI, very similar in energy and mass to those available at GANIL, will be extracted from a $K = 800$ superconducting cyclotron with an intensity of 1 pμA (Ciavola *et al*. 1997). From here on, the project is very similar to the HRIBF scheme. It uses a 15 MV tandem accelerator as post-accelerator, which requires that the target and ion source, high-resolution separator ($M/\Delta M = 20\,000$) and charge-exchange cell are located on a 300 kV platform. This should allow for accelerated secondary beams with $A < 80$ of 0.2–8 MeV u^{-1} energy, of which those with $A < 40$ will be above the Coulomb barrier. The project was financed in 1996, and is planned

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to be operational around 1999. For the longer-term future, a new 200 MeV proton driver is currently under consideration.

(*j*) *ATLAS-ANL, Argonne*

At Argonne National Laboratory, a cost-effective concept for an RIB facility based on the ATLAS accelerator is proposed. As driver accelerator they have chosen an RFQ, and a superconducting LINAC as injector for the ATLAS 210 MV conventional drift-tube LINAC, which raises the energy into the range 6–15 MeV u^{-1}. It can deliver a range of light ions (^{1}H to ^{36}Ar) of 100 MeV u^{-1} with a beam power of 100 kW. Singly charged ions are produced by means of the well-proven ISOL-target and ion-source techniques. In order to match the DC mass-separator beam to the superconducting LINAC, its first section will have to be a normal RFQ operating on a 300 kV platform in CW mode. High-charge states are obtained with typically an 8% overall efficiency by stripping after the RFQ and the first LINAC. An active development programme has been started at ANL on all aspects of the RIB generation. Emphasis seems to be put on targets for very high driver-beam intensities by reducing the power density in the target through conversion of deuterons into neutrons, as discussed in § 3 *a*. While this scheme seems to be very promising for production of fission fragments, the energy of the light particles available for producing a broad range of deep spallation and target fragmentation products is far from optimum (see figure 12). If approved, the target date for completion of the installations is 2001.

(*k*) *PIAFE-ILL, Grenoble*

The PIAFE programme at Grenoble intends to use the high-neutron flux of the ILL reactor to induce fission reactions in a ^{235}U target and ion-source combination located in a neutron flux of 3×10^{13} n cm^{-2} near to the core (Pinston 1997). The singly charged fission products are accelerated out of the reactor shielding with a 30 keV acceleration voltage, where, after a double magnetic-analysis stage in a first phase, they will be used for the low-energy physics programme and research and development on target and ion-source techniques adapted to the restricted space and to the strict reactor safety requirements. While this first stage has been approved and off-line development has started, the second phase will be elaborated in detail according to the results of the first phase and developments in the collaborating laboratories.

(*l*) *Munich*

The outcome of the operation of the first stage of PIAFE will be of prime importance for the newly proposed project at Munich based on the ultra-high-neutron flux in the reactor FRM-II and under construction since 1996 (Thirolf *et al.* 1997). The following post-accelerator will be modelled on the REX-ISOLDE concept, in which the Munich group is already a most active collaboration partner.

6. Summary and outlook

From this overview of RIB facilities based on the ISOL principle, it can be seen that the projects currently in operation or under construction are of a first generation

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which capitalizes, to a greater or lesser degree, on existing accelerators. Together with the already available ISOL technique, they will produce accelerated beams of up to nanoampere intensities. It is shown that the beam intensities that may be obtained at RIB facilities depend not only on primary-beam intensity and energy, formation cross-section and target thickness, but also rather strongly on the efficiency with which the products can be extracted from the target, transformed into an ion beam and further accelerated, and on the extent to which the best of these techniques can be adapted to the environment of a given driver particle and post-accelerator.

The recent worldwide intensification of the (further) development and improvement of the techniques for RIB production discussed above is at the time of writing progressing very rapidly, and has provided successful solutions and suggestions to a number of questions still unanswered a few years ago.

The plans for the second generation RIB laboratories will depend very strongly on where this research and development is invested and will determine whether one such facility capable of producing almost all masses can be envisaged, or if several complementary facilities where all parameters are optimized for the production of only a particular region of nuclei is more attractive.

In any case, these facilities will allow new and challenging experiments on exotic nuclei close to the limits of stability and give new impetus to many other fields of physics which use nuclear methods.

References

Anne, R. (and 19 others) 1993 In *Proc. 3rd Int. Conf. Radioactive Nuclear Beams, MI, USA, 1993* (ed. D. J. Morissey), p. 39. Gif-sur-Yvette: Editions Frontières.

Barzakh, A. E., Denisov, V. P., Fedorov, D. V., Orlov, S. Yu. & Seliverstov, M. D. 1997 *Nucl. Instrum. Meth.* B **126**, 85.

Beck, D., Ames, F., Audi, G., Bollen, G., Kluge, H.-J., Kohl, A., König, M., Lunney, D., Raimbault-Hartmann, H., Schwarz, S. & Szerypo, J. 1997 *Nucl. Instrum. Meth.* B **126**, 374.

Becker, R., Kleinod, M., Goethe, J. W., Donets, E. D. & Pikin, A. 1992 In *Proc. 3rd European Particle Accelerator Conf. (EPAC-92)* (ed. H. Heineke, H. Homeyer & Ch. Petit-Jean-Genaz), p. 59. Gif-sur-Yvette: Editions Frontières.

Beebe, E., Liljeby, L., Pirkin, A., Donets, E. D., Habs, D., Janko, K., Tengblad, O. & van Duppen, P. 1994 *Nucl. Instrum. Meth.* B **93**, 378.

Bennett, J. R. J., Broom, T. A., Densham, C. J., Gardner, I. S. K., Aitken, T., Price, H. G., Warner, D. D., Gelletly, W. & Chapman, R. 1993 In *Proc. 3rd Int. Conf. on Radioactive Nuclear Beams, MI, USA, 1993* (ed. D. J. Morissey), p. 49. Gif-sur-Yvette: Editions Frontières.

Bennett, J. R. J., Densham, C. J., Drumm, P. V., Evans, W. R., Holding, M., Murdoch, G. R. & Panteleev, V. 1997 *Nucl. Instrum. Meth.* B **126**, 117.

Beznosjuck, V. I., Fedorov, D. V., Orlov, S. Yu., Seliverstov, M. D. & Tikhonov, V. I. 1997 *Nucl. Instrum. Meth.* B **126**, 92.

Bjørnstad, T., Gustafsson, H.-A., Jonson, B., Jonsson, O. C., Lindfors, V., Mattsson, S., Poskanzer, A. M., Ravn H. L. & Schardt, D. 1981*a* *Z. Phys. Atoms and Nuclei* A **303**, 227.

Bjørnstad, T. Carraz, L. C., Gustafsson, H.-A., Heinemeyer, J., Jonson, B., Jonsson, O. C., Lindfors, V., Mattsson, S., Poskanzer, A. M. & Ravn, H. L. 1981*b* *Nucl. Instrum. Meth.* **186**, 391.

Bjørnstad, T., Hagebø, E., Hoff, P., Jonsson, O. C., Kugler, E., Ravn, H. L., Sundell, S. & Vosicki, B. 1987 *Nucl. Instrum. Meth.* B **26**, 174.

Downloaded from rsta.royalsocietypublishing.org

Bollen, G. 1997 *Nucl. Phys.* A **616**, 457c.

Bondorf, J. 1967 In *Proc. Int. Symp. on Why and How Should We Investigate Nuclides Far Off the Stability Line, Lysekil 1966* (ed. W. Forsling, C. J. Herrlander & H. Ryde) and *Ark. Fys.* **36**, 681.

Boyd, R. N. 1994 *Int. J. Mod. Phys.* E (March 1994, supp.), 249.

Bricault, P. G., Dombsky, M., Schmor, P. W. & Stanford, G. 1997 *Nucl. Instrum. Meth.* B **126**, 231.

Bruandet, J., Fernandez, B. & Bex, M. (eds) 1992 *Proc. Int. Workshop on the Physics and Technology of Secondary Nuclear Beams, Dourdan, France 1992.* Gif-sur-Yvette: Editions Frontières.

Brumm, Th., Jäger, K., Kluge, H.-J., Suri, B. M., Rimke, H., Trautmann, N. & Kirchner, R. 1990 *Appl. Phys.* B **51**, 200.

Buchmann, L. & D'Auria, J. M. (eds) 1985 *Proc. Accelerated Radioactive Beams Workshop, Parksville, British Columbia, Canada, 1985*, Tri-85-1.

Ciavola, G. (and 13 others) 1997 *Nucl. Instrum. Meth.* B **126**, 258.

Delbar, Th. (ed.) 1991 *Proc. 2nd Int. Conf. on Radioactive Nuclear Beams, Louvain-La-Neuve, Belgium 1991.* Bristol: Adam Hilger.

Domingo, J., Hansen, P. G., Jonson, B., Kugler, E., Ravn, H. L., Sundell, S. & Tschalär, C. 1981 *Nucl. Instrum. Meth.* **186**, 79.

Eaton, T. & Ravn, H. L. 1987 *Nucl. Instrum. Meth.* B **26**, 190.

EMIS 1981 *Proc. Int. Conf. on Electromagnetic Isotope Separators and Techniques Related to their Application* (ed. H. L. Ravn, E. Kugler & S. Sundell). *Nucl. Instrum. Meth.* **186**.

EMIS 1987 *Proc. Int. Conf. on Electromagnetic Isotope Separators and Techniques Related to their Application* (ed. W. L. Talbert). *Nucl. Instrum. Meth.* B **26**.

EMIS 1992 *Proc. Int. Conf. on Electromagnetic Isotope Separators and Techniques Related to their Application* (ed. M. Fujioka, T. Shinozuka & Y. Kawase). *Nucl. Instrum. Meth.* B **70**.

EMIS 1997 *Proc. Int. Conf. on Electromagnetic Isotope Separators and Techniques Related to their Application* (ed. G. Münzenberg, H. Geissel & C. Scheidenberger). *Nucl. Instrum. Meth.* B **126**.

Evensen, A. H. E., Catherall, R., Drumm, P., van Duppen, P., Jonsson, O. C., Kugler, E., Lettry, J., Tengblad, O., Tikhonov, V. & Ravn, H. L. 1997 *Nucl. Instrum. Meth.* B **126**, 160.

Fedoseyev, V. N., Bätzner, K., Catherall, R., Evensen, A. H. M., Forkel-Wirth, D., Jonsson, O. C., Kugler, E., Lettry, J., Mishin, V. I., Ravn, H. L. & Weyer, G. 1997 *Nucl. Instrum. Meth.* B **126**, 95.

Fogelberg, B., Hellström, M., Jacobsson, L., Jerrestam, D., Spanier, L. & Rudstam, G. 1992 *Nucl. Instrum. Meth.* B **70**, 137.

Garoby, R. & Vretenar, M. 1996 CERN/PS/RF/Note 96-27, 25 October 1996.

Geissel, H., Münzenberg, G. & Riisager, K. 1995 *A. Rev. Nucl. Part. Sci.* **45**, 163.

Haas, H., Ravn, H. L., Schempp, A., Allardyce, B. W., Jonson, B. & Rolfs, C. 1990 In *Proc. 1st Int. Conf. on Radioactive Nuclear Beams, Berkeley, USA, 1990* (ed. W. D. Myers, J. M. Nitschke & E. B. Norman), p. 59. Singapore: World Scientific.

Habs, D., Kester, O., Bollen, G., Liljeby, L., Rensfeld, K. G., Schwalm, D., von Hahn, R. & Walter, G. 1997 *Nucl. Instrum. Meth.* B **126**, 218.

Hansen, P. G. 1977 Far unstable nuclei and radioactive ion-beams. *CERN Workshop on Intermediate Energy Physics, Sept. 1977*, PS-CDI/77-43.

Jading, Y. (and 16 others) 1997 *Nucl. Instrum. Meth.* B **126**, 76.

Jeong, S. C., Oyaizu, M., Kawakami, H., Shirakabe, Y. & Nomura, T. 1997 *Nucl. Instrum. Meth.* B **126**, 45.

Jokinen, A. (and 14 others) 1997 *Nucl. Instrum. Meth.* B **126**, 95.

Kirchner, R. 1993 GSI Nachricten 05-93, 2.

Downloaded from rsta.royalsocietypublishing.org

Kofoed-Hansen, O. & Nielsen, K. O. 1951 *K. Danske Vidensk. Selsk. Mat.-Fys. Medd.* **26**(7).

Koizumi, M., Osa, A., Sekine, T. & Kubota, M. 1997 *Nucl. Instrum. Meth.* B **126**, 100.

Kubono, S., Kobayashi, T. & Tanihata, I. (eds) 1997*a* In *Proc. 4th Int. Conf. on Radioactive Nuclear Beams, June 4–7, 1996 Omiya, Japan* and *Nucl. Phys.* A **616**, 1c.

Kubono, S. (and 26 others) 1997*b* *Nucl. Phys.* A **616**, 11c.

Kugler, E., Fiander, D., Jonson, B., Haas, H., Przewloka, A., Ravn, H. L., Simon, D. J. & Zimmer, K. 1992 *Nucl. Instrum. Meth.* B **70**, 41.

Le-Blanc, F. (and 13 others) 1989 *Nucl. Instrum. Meth.* B **72**, 111.

Lettry, J., Catherall, R., Drumm, P., Van Duppen, P., Evensen, A. H. E., Focker, G. J., Jokinen, A., Jonsson, O. C., Kugler, E. & Ravn, H. L. 1997*a* *Nucl. Instrum. Meth.* B **126**, 130.

Lettry, J. (and 13 others) 1997*b* *Nucl. Instrum. Meth.* B **126**, 170.

Lettry, J. (and 12 others) 1998 Recent developments of the ISOLDE laser ion-source. In *Proc. 7th Int. Conf. on Ion Sources, September 1997, Taormina, Italy* (ed. G. Ciavola & S. Gammino). *Rev. Sci. Instr.* **69**, 761.

Loiselet, M. (and 16 others) 1993 In *Proc. 3rd Int. Conf. on Radioactive Nuclear Beams, MI, USA, 1993* (ed. D. J. Morissey), 1993, p. 179. Gif-sur-Yvette: Editions Frontières.

Michel, R. & Nagel, P. 1997 NSC/DOC(97)-1, Nuclear Energy Agency/P&T No. 14. OECD, 1997.

Mishin, V. I., Fedoseyev, V. N., Kluge, H.-J., Letokhov, V. S., Ravn, H. L., Scheerer, F., Shirakabe, Y., Sundell, S. & Tengblad, O. 1993 *Nucl. Instrum. Meth.* B **73**, 550.

Moore, R. B. 1992 *J. Mod. Opt.* **39**, 361.

Morissey, D. J. (ed.) 1993 *Proc. 3rd Int. Conf. on Radioactive Nuclear Beams, MI, USA, 1993.* Gif-sur-Yvette: Editions Frontières.

Mueller, A. 1993 In *Proc. 3rd Int. Conf. on Radioactive Nuclear Beams, MI, USA, 1993* (ed. D. J. Morissey), p. 1. Gif-sur-Yvette: Editions Frontières.

Myers, W. D., Nitschke, J. M. & Norman, E. B. (eds) 1990 *Proc. 1st Int. Conf. on Radioactive Nuclear Beams, Berkeley, USA, 1990.* Singapore: World Scientific.

Nolen Jr, J. A. 1993 In *Proc. 3rd Int. Conf. on Radioactive Nuclear Beams, MI, USA, 1993* (ed. D. J. Morissey), p. 111. Gif-sur-Yvette: Editions Frontières.

Olsen, D. K. (and 15 others) 1991 In *Proc. 2nd Int. Conf. on Radioactive Nuclear Beams, Louvain-La-Neuve, Belgium, 1991* (ed. Th. Delbar), p. 131. Bristol: Adam Hilger.

Pinston, J. A. 1997 *Nucl. Instrum. Meth.* B **126**, 22.

Przewloka, M., Antel, M., Berndt, R., Geisse, Ch., Haas, H., Ravn, H. L. & Wollnik, H. 1992 *Nucl. Instrum. Meth.* B **70**, 451.

Puteaux, J. C. (and 24 others) 1997 *Nucl. Instrum. Meth.* B **126**, 22.

Ravn, H. L. 1979 *Phys. Rep.* **54**, 201.

Ravn, H. L. 1986 In *ISOLDE User's Guide* (ed. H.-J. Kluge), CERN 86-05.

Ravn, H. L. & Allardyce, B. 1989 *Treatise on heavy-ion science* (ed. D. Allan Bromley), vol. 8, p. 363. New York: Plenum Press.

Ravn, H. L. (and 10 others) 1994 *Nucl. Instrum. Meth.* B **88**, 441.

Rudstam, G. 1966 *Z. Naturforsch.* A **21**, 1027.

Sawicki, J. A., Gregorich, K. E., Buchmann, L., Mathews, G. J., Orozco, L., Sprouse, G. D., Hass, M. & Wouters, J. M. 1991 LALP 91-51.

Schiekel, Th. (and 12 others) 1996 *Nucl. Instrum. Meth.* B **114**, 91.

Sebastian, V., Budimann, T. & Huber, G. 1997 *Nucl. Instrum. Meth.* B **126**, 73.

Sherill, B. M. 1991 In *Proc. 2nd Int. Conf. on Radioactive Nuclear Beams, Louvain-La-Neuve, Belgium 1991* (ed. Th. Delbar), p. 2. Bristol: Adam Hilger.

Shirakabe, Y., Ikeda, N., Okkawa, S., Nomura, T. & Shinozuka, T. 1993 *Nucl. Instrum. Meth.* A **337**, 11.

Downloaded from rsta.royalsocietypublishing.org

Siemssen, R. H. 1993 *Report on the ISOL-type Europeean Radioactive Beam Facilities by the NuPECC Study Group NuPECC Report, May 1993*.

Silberberg, R. & Tsao, C. H. 1973*a* *Astrophys. J. Suppl.* **25**, 315.

Silberberg, R. & Tsao, C. H. 1973*b* *NRL Report*, 7593.

Sümmerer, K. 1992 In *Proc. Int. Workshop on the Physics and Technology of Secondary Nuclear Beams, Dourdan, France 1992* (ed. J. Bruandet, B. Fernandez & M. Bex), p. 273. Gif-sur-Yvette: Editions Frontières.

Sundell, S. & Ravn, H. L. 1992 *Nucl. Instrum. Meth.* B **70**, 160.

Talbert, W. L., Hsu, H.-H. & Prenger, F. C. 1992 *Nucl. Instrum. Meth.* B **70**, 175.

Tamburella, C. 1996 Production d'états de charge élevés pour des ions radioactifs. Thesis, ISN Grenoble, France.

Tanihata, I. 1989 *Treatise on heavy-ion science* (ed. D. Allan Bromley), vol. 8, p. 443. New York: Plenum Press.

Thirolf, P. (and 12 others) 1997 *Nucl. Instrum. Meth.* B **126**, 242.

Touchard, F., Biederman, J., de Saint Simon, M., Thibault, C., Huber, G., Epherre, M. & Klapisch, R. 1981 *Nucl. Instrum. Meth.* **186**, 329.

Van Duppen, P. 1997 *Nucl. Instrum. Meth.* B **126**, 66.

Vermeeren, L., Bijnens, N., Huyse, M., Kudryavtsev, Y. A., van Duppen, P., Wauters, J., Qamhieh, Z. N., Thoen, P., Vandeweert, E. & Silverans, R. E. 1990 *Phys. Rev. Lett.* **73**, 1935.

Villari, A. C. C. 1997 *Nucl. Instrum. Meth.* B **126**, 35.

Visentin, B., van Duppen, P., Leroy, P. A., Harrault, F. & Gobin, R. 1995 *Nucl. Instrum. Meth.*, 275.

Wada, M., Katayama, I., Tanaka, J., Strasser, P., Yahata, K., Tomizawa, Y., Nomura, T., Fujioka, M. & Wollnik, H. 1997 *Nucl. Instrum. Meth.* B **126**, 25.

Weyer, G. 1981 *Nucl. Instrum. Meth.* **186**, 201.

Wollnik, H., Meuser, S., Fujioka, M., Shinozuka, T., Nomura, T. & Kawakami, H. 1990 In *Proc. 1st Int. Conf. on Radioactive Nuclear Beams, Berkeley, USA, 1990* (ed. W. D. Myers, J. M. Nitschke & E. B. Norman), p. 603. Singapore: World Scientific.

Yamagushi, S. 1941 *Proc. Phys. Math. Soc. Japan* **23**, 264.