High-Efficiency Target-Ion Sources for RIB Generation*

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Abstract

A brief review is given of high-efficiency ion sources which have been developed or are under development at ISOL facilities which show particular promise for use at existing, future, or radioactive ion beam (RIB) facilities now under construction. Emphasis will be placed on those sources which have demonstrated high ionization efficiency, species versatility, and operational reliability and which have been carefully designed for safe handling in the high level radioactivity radiation fields incumbent at such facilities. Brief discussions will also be made of the fundamental processes which affect the realizable beam intensities in target-ion sources. Among the sources which will be reviewed will be selected examples of state-of-the-art electron-beam plasma-type ion sources, thermal-ionization, surface-ionization, ECR, and selectively chosen ion source concepts which show promise for radioactive ion beam generation. A few advanced, chemically selective target-ion sources will be described, such as sources based on the use of laser-resonance ionization, which, in principle, offer a more satisfactory solution to isobaric contamination problems than conventional electromagnetic techniques. Particular attention will be given to the sources which have been selected for initial or future use at the Holifield Radioactive Ion Beam Facility now under construction at the Oak Ridge National Laboratory.

1.0 INTRODUCTION

During the past few years, world-wide interest has developed in the use of radioactive ion beams to address questions concerning the structure of the nucleus and on the nucleosynthesis burn cycles which power stellar processes and which are responsible for heavy element formation. Because many of the nuclear reactions important in nuclear, nuclear structure, and astrophysics are inaccessible to experimental study using stable/stable beam/target combinations, they can only be studied with accelerated radioactive ion beams (RIBs). Such beams, therefore, offer unique opportunities to further our knowledge of the nucleus and the energetics of our solar system. As a consequence, world-wide interest has led to the development and proposed development of RIB facilities in Asia, Europe, and North America [see, e.g., the facilities listed in Ref. 1]. Of the several facilities listed in Ref. 1, only the RIB facility at Louvain-la-Neuve is presently operational [2], while the Holifield Radioactive Ion Beam Facility (HRIBF) at the Oak Ridge National Laboratory has been funded and is now under construction [3].

The most universal method for generating RIBs uses the well-known on-line isotope separator (ISOL) technique in which radioactive nuclei are produced in selectively chosen targets by proton, deuteron, helium, heavy ion, or neutron beams. The ISOL technique involves a multi-step process in which the reaction products are thermally diffused from the target, transported to the ionization chamber of the ion source, ionized, and separated according to mass in an ISOL. For RIB research, the ions must then be accelerated to the energy required for the particular experimental study. For nuclear physics, nuclear structure physics, and astrophysics research, beam intensities ranging from \(10^3\) to \(10^12\) particles/s are typically required. The generation rates in the target are set by practical limits on the primary beam intensity in terms of maximum permissible power densities on the target which can be used without compromising the efficiency of the ion source or the physical integrity of the target and the reaction cross sections for producing the species of interest. The radioactive product beam intensity is determined by the rate at which the particular species can be diffused from the target, and the average residence time of the species on surfaces between the target and the ionization volume of the source in relation to the lifetime of the particular radioactive species, the ionization efficiency of the ion source, and losses in beam transport between the ion source and experimental station. The diffusion and surface adsorption/desorption processes are exponentially dependent on temperature, as well as the chemistry and metallurgy between the radioactive species and the target material and materials from which the source are constructed. The upper temperature at which the target-ion source can be operated without deleteriously affecting the ionization efficiency is set by the vapor pressure characteristics of the target material. Because of these factors, a premium is placed on ion sources with demonstrated high efficiencies.


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Our present knowledge of the properties of nuclei far from the region of beta stability can be, in part, attributed to the successful development of reliable, long-lived, and efficient ISOL ion sources with fast release properties. Many ion source developments have been made over the past few decades for ISOL applications, many of which have been recently included in reviews by Ravn [4] and Van Duppen, et al. [5]. For information on the latest developments in on-line mass separators and target-ion sources associated with their use, readers are encouraged to consult the proceedings of the most recent electromagnetic isotope separator (EMIS) conferences [6,7]. In the present paper, the requirement of brevity places limitations on the number and types of sources which can be included; therefore, the review will be restricted to examples of sources which represent state-of-the-art developments of a particular source type which have demonstrated high ionization efficiencies and reliable performances at ISOL facilities. Among the sources which will be included in the review will be efficient universal electron impact ionization-type sources which use hot cathodes or microwave power (ECR) to generate the plasma or the more species-limited sources which use either surface ionization or thermal ionization. A limited number of new sources or new source concepts will also be discussed such as the multi-photon resonance laser ion sources now under development or ISOL versions of negative ion sources based on the plasma sputter principal.

The degree of success of any RIB facility can be measured in terms of the performance, reliability, species versatility, and design attributes of the ion source or ion sources selected for use. In this paper, a limited review will be given of sources which meet the rather stringent criteria imposed for RIB generation. Because of familiarity, more than casual attention will be given to sources which have been designed and selected for initial use or are presently under consideration for use at the HRIBF now under construction at the Oak Ridge National Laboratory [3].

2.0 FUNDAMENTAL PROCESSES WHICH AFFECT RADIOACTIVE ION BEAM INTENSITIES

The principal processes whereby short-lived radioactive species are lost between initial formation and utilization are associated with the hold-up times required by diffusion release from the target, adsorption residence times on surfaces in the source, and ion source efficiencies for forming beams of the particular species. The diffusion and adsorption processes are briefly described below.

2.1 The Diffusion Process

The time and temperature-dependent release of a nuclear reaction product species, embedded in a chemically dissimilar target material, implies the presence of a binary diffusion mechanism which underlies the release process. Whenever there is a concentration gradient of impurity atoms or vacancies in a solid material, the atoms or vacancies will move through the solid until equilibrium is reached. The phenomenological time-dependent relation appropriate for diffusion of a radioactive species with half-life \( \tau_{1/2} = \frac{0.693}{\lambda} \) can be expressed by Fick's second law [8] given by

\[
\frac{\partial n}{\partial t} = D \nabla^2 n - n \lambda
\]

(1)

The diffusion process is driven not only by the concentration gradient, but by the activation energy \( H_A \) required to move the atoms from site to site through the solid. Of course, \( n \) is time dependent whenever the atom is radioactive. The diffusion coefficient is often found to vary with temperature according to

\[
D = D_0 \exp\left(-\frac{H_A}{kT}\right)
\]

(2)

In Eq. 2, \( H_A \) is the barrier height or activation energy which must be supplied to the atom or molecule through lattice vibrations to enable the particle to move from site to site through interstitial or vacancy diffusion processes. The diffusion constant \( D_0 \) is related to the vibrational frequency and lattice parameters of the solid crystal.

2.2 Surface Adsorption

Excessively long time delays in relation to the lifetime of the radioactive species can result in significant losses of beam intensity in an ISOL facility. Following diffusion, the atom of interest must be evaporated from the target surface and diffused into the ionization chamber of the ISOL source. The residence time of a particle on a surface is given by the Frenkel equation

\[
\tau = \tau_0 \exp\left[H_{ad} / kT\right]
\]

(3)

where \( H_{ad} \) is the heat of adsorption or enthalpy, \( k \) is Boltzmann's constant, \( T \) is the absolute temperature, and \( \tau_0 \) is the time required for a single lattice vibration (\( \approx 10^{-13} \) s). The heat of adsorption depends on the chemistry between the adsorbed atom and the surface where the adsorption takes place. The heat of adsorption varies widely depending upon the
adsorbed/adsorbate combination (see, e.g., Ref. 9). Thus, the choice of target materials for high-temperature vapor transport source components is extremely important in order to minimize the residence time of adsorbed atoms on the surfaces between the target and ionization chamber. Chemically inert materials are desirable because they, in principle, can substantially reduce the residence times of adsorbed exotic atoms on the surface during transport from the target to the ionization chamber of the source. In the best case, source components should be fabricated from materials such as iridium or of less expensive iridium-coated materials such as tantalum or tungsten. Rhenium is also attractive; although it is more chemically active than iridium, it is much less active than most other refractory metals and is less expensive than iridium. For example, the residence time for oxygen on hot Ta (2000°C) metal is \(-6 \times 10^8\) s compared to 5.7 \(\mu\)s on Ir at the same temperature. This correlates to a difference in residence time of \(-1 \times 10^{14}\). Clearly, Ir would be the best choice for eliminating losses due to chemical adsorption.

The desorption rate per unit area, \(\frac{dN}{dt}\), of adsorbed atoms in thermal equilibrium with a surface at temperature \(T\) can be expressed according to

\[
\frac{dN}{dt} = S(T)N \omega_{\text{st}} \exp\left[-\frac{H_{\text{ad}}}{kT}\right]
\]

where \(S(T)\) is the temperature-dependent sticking coefficient, \(N\) is the number of atoms adsorbed per unit area, and \(\omega_{\text{st}} = 1/\tau_0\).

2.3 ISOL Target Material Selection

One of the major challenges in any ISOL facility is associated with the requisite fast and selective thermal release of minute amounts of the product radioactive atoms from the ISOL target in the presence of bulk quantities of target material. Satisfactory solutions to this challenging problem can only be reached by careful design of the ISOL source and by careful consideration of the properties of the physical, chemical, and metallurgical properties of the radioactive species in relation to those of the target. While there appears to be no lack of choices for the efficient ionization of elemental or molecular feed materials, the primary problem lies in the availability and proper choice of target materials which are sufficiently refractory so that they can be heated to the elevated temperatures necessary for fast release of the product radioactive species without vaporization or sublimation of the target material itself. The vapor pressures of the unwanted species must be kept at a rate sufficiently low so as to avoid spoiling the rather stringent vacuum levels required for efficient ionization (~\(\times 10^{-3}\) to \(\times 10^{-4}\) Torr [10,11]).

In the ISOL scheme, the primary ion beam intercepts the target which resides either in the source itself or is closely coupled to the ion source by means of a tube. Ideally, the target material should be selected so as to maximize the speed of release of the species of interest at the maximum operational temperature which avoids spoiling the efficiency of the source. More than 68 of the elements in the periodic chart have been produced, released, mass separated, and their products studied at various ISOL facilities. For example, at the CERN-ISOLDE facility, more than 600 radioactive beams representing 66 elements have been provided for research with intensities ranging up to \(10^{12}\) ions/s [12].

The requirement of fast release of short-lived radioactive species from target materials most generally requires high temperature target-ion source operation. In the ideal case, the target material should be refractory while simultaneously exhibiting low vapor pressures (< \(\times 10^{-4}\) Torr) at the elevated operational temperatures of the target-ion source (~\(1300^\circ\mathrm{C}\) to ~\(2000^\circ\mathrm{C}\)) in order to avoid sublimation or vaporization of the target which exceeds those for efficient ionization (see, e.g., Refs. 10 and 11). The choice of target material is further restricted by the requirement that the radioactive material itself not be refractory and that it not form refractory compounds within the target material. The radioactive atoms should, in the ideal case, possess physical and chemical properties almost opposite to those of the target material; that is, they should be easily diffused from the target material either in elemental form or in compound form, and upon exit, be readily desorbed and vaporized from the target surface. These idealized differences in chemical and physical properties which are desirable for fast release of the species of interest are not often practically realizable, particularly, for close lying elements where their physical and chemical properties are often similar. This poses particular challenges for RIB facilities such as the operational RIB facility at Louvain-la-Neuve and the Holifield Radioactive Ion Beam Facility now under design and construction at the Oak Ridge National Laboratory. Fortunately, nature has provided C, B, Cr, Hf, Ir, Mo, Nb, Os, Re, Ru, Ta, V, W, and Zr and several metal borides, carbides, nitrides, oxides, and a few sulfides which meet both the refractory temperature and low vapor pressure requirements for use as target materials. In addition, several intermetallic alloys such as Hf₃Si₂, LaAl₃, Zr₅Ge₃, and Zr₅Si₃ as well as metal aluminates, silicates, titanates and other more complex compounds also meet these criteria and are viable choices for target materials. Obviously, compounds are desirable which contain the highest percentage of the element of interest so as to maximize the production rate of the
radioactive species of interest. Still other factors which complicate the choice of target material must be considered such the production of unwanted, long lived radioactive by-products, must be given consideration.

2.4 Studies of the Release Properties of ISOL Target Materials

Experimental studies are under way at the Oak Ridge National Laboratory which utilize ion implantation techniques to evaluate the release properties of stable isotopes of radioactive elements from refractory targets mounted in the UNISOR [13] version of the FEBIAD ion source [14]. These experiments [15], similar to those conducted at GSI by Kirchner over the past several years [16,17], are designed to measure the time evolution, ionization efficiencies and release efficiencies of implanted elements diffused from refractory target materials which are candidates for forming RIBs at ORNL.

The requirement of fast diffusion from the target not only involves the physical, chemical, and metallurgical properties of the target beam combination, but the target particle size and geometry, as well. Ideally, the target should be finely divided powder which does not sinter or melt at the source operating temperature so that the diffusion time for the particle to reach the surface of the solid is as short as practicable. Figure 1 illustrates the time-dependent behavior of the fractional release of stable and radioactive ion-implanted Cl atoms from a flat Zr5Si3 target as predicted by numerical solution to the one-dimensional form of Fick's second law (Eq. 1). Diffusion constants D were derived from fits to experimental 35Cl time release data [15]. The atoms are assumed to be implanted to a depth of 5 μm in Zr5Si3 in a profile such as predicted by TRIM [18] simulations.

It is anticipated that both flat-plate and spherical-geometry targets will be used at the HIBF and, therefore, the appropriate form of Eq. (1) can be used to estimate release properties of the materials under consideration for use as targets provided that reasonable estimates for D are known. One of the principal objectives of the ion implantation studies is to determine diffusion constants so that such estimates can be made for uniformly distributed radioactive ion beams. Obviously, spherical-geometry particles with dimensions as small as can be practically produced are highly desirable in order to reduce the diffusion times to values commensurate with the requirement of swift release of the decaying product species. Fractional intensity versus time profiles for uniformly distributed 33Cl (τ1/2 = 2.5 s) released from both disk- and spherical-geometry Zr5Si3 targets are displayed in Fig. 2 for disk

![Figure 1](image1.png)

**Figure 1.** Simulation of the time/release profiles for various isotopes of Cl from Zr5Si3 implanted to a depth of 5 μm. Time/release profiles were determined by solution of Eq. 1 for the one-dimensional case. Diffusion constants were determined by fits to experimental data taken from Ref. 15.

![Figure 2](image2.png)

**Figure 2.** Comparisons of the time/release profiles for uniformly distributed 33Cl from disk and spherical geometry Zr5Si3 targets for disk thicknesses/spherical particle sizes of 20 μm and 200 μm, respectively. The time/release profiles were determined by numerically solving the appropriate form of Eq. 1. Diffusion constants were determined by fits to experimental data taken from Ref. 15.

thicknesses/spherical particle sizes of 20 μm and 200 μm, respectively. These release curves clearly show the advantage of spherical-geometry macro-particles over solid disk-geometry targets.
3.0 CANDIDATE ION SOURCES FOR RIB GENERATION

The ISOL technique is complicated by high-temperature physics, chemistry, metallurgy, diffusion, and surface adsorption processes which take place in the target-ion source; all of these processes add to the delay times which result in losses of the short-lived radioactive species of interest. For RIB generation, the source should ideally exhibit the following properties: high efficiency; high temperature operation in order to minimize the diffusion times from the target and short residence times on the surface; low energy spreads; chemical selectivity; flexibility for adaptation to different temperature ranges and modes of operation; target temperature control; long lifetime; and stable electrical and mechanical properties. The source should, as well, be designed for safe and expedient insertion/removal from the ISOL facility to permit changing of the target material and source repairs as required in high radioactivity radiation level fields.

3.1 Electron Beam Plasma Ion Sources

The FEBIAD ion source. The forced electron beam induced arc discharge (FEBIAD) source, developed at GSI by Kirchner [14,19,20], differs from conventional plasma discharge sources in that it does not require a minimum pressure for stable operation (commonly referred to as the Langmuir criterion for stable discharge). The source operates at pressures of more than one order of magnitude lower than the Nielsen plasma discharge source [21] as clearly demonstrated by Kirchner and Roekl [10]. The source is well suited for ISOL applications which involve the use of heavy ions to produce the radioactive species of interest in that it operates stably and efficiently over a pressure range of $1 \times 10^{-5}$ Torr to $2 \times 10^{-4}$ Torr at elevated temperatures. Several versions of the source have been developed at GSI (see, for example, Refs. 14, 19, and 20 for specific details on the respective sources); these sources differ in their materials of construction, ionization chamber volumes and achievable target temperatures, depending on the particular source geometry. Figure 3 compares the ionization efficiencies for Xe as a function of discharge pressure with those for the Nielsen plasma discharge source [21], as reported in Ref. 10. As noted, the efficiency of the FEBIAD source is constant over more than a decade of pressure while the efficiency of the Nielsen source has a very strong onset at the critical pressure above which it immediately begins to fall; this behavior is characteristic of sources which operate at higher discharge pressures. The FEBIAD source [14] is used routinely on the UNISOR facility as the principal ISOL source and is displayed schematically in Fig. 4. The FEBIAD ion source uses an indirectly heated cathode to provide an electron beam for initiating a low pressure discharge from which the ion beam is extracted. The discharge is collimated by an external solenoidal magnetic field. The electron beam from the cathode is accelerated to the positively biased anode structure. A fraction of the beam passes through a grid structure in the entrance end of the cylindrical anode where it produces a low density plasma by ionizing vapor released from the target and reference monitor gas (usually Xe). A small fraction of the electron beam passes through the ion exit aperture and is reflected back through the ionization chamber; these electrons execute harmonic motion along the axis of symmetry. The anode cylinder and target are heated by electron bombardment and radiation from the cathode. The target temperature of

![Figure 3. Ionization efficiency for Xe$^+$ versus pressure inside FEBIAD and modified Neilsen (MNIS) [10] ion sources.](image)

![Figure 4. Schematic drawing of the FEBIAD ion source used on-line at UNISOR [13] in the element/refractory target release experiments [15]. The source is a copy of the source described in Ref. 14.](image)
the UNISOR FEBIAD ion source [14] can be varied somewhat by its position relative to the anode; in the standard position, the measured target temperature (typically 1645 °C) is found to be almost independent of the source discharge parameters required for stable source operation; however, the target temperature is found to increase linearly with power deposited in the target by the heavy ion primary beam [15]. The geometry of the source is not well suited for RIB generation with high energy light primary ions because of the location of the target and the lack of independent control over the target temperature; it is, however, well suited for conventional ISOL applications which employ heavy ions to generate the radioactive species and for studying the time dependent release profile of characteristics of target or catcher materials by using ion implantation; this technique, developed at GSI, has been used extensively during the past few years to determine the time dependent release profiles and ionization efficiencies for many heavy elements implanted into a variety of catcher foils. Reference 17 provides a recent comprehensive summary of this work. From such data, fundamental important information can be extracted concerning the diffusion process; for example, diffusion constants for the particular element/target combination can, in principle, be extracted. This technique offers a powerful means for pre-selecting target materials with good release characteristics in advance of their use for RIB generation. The method has been adopted at the HRIBF for this purpose [15], as discussed in Section 2. The efficiency of the FEBIAD ion source is quite high for slow moving heavy ions; for low mass, fast moving atoms with high ionization potentials, the source is not as impressive. For example, the measured ionization efficiencies for the noble gas elements, as reported in Ref. 17, are, respectively, Ne: 1.5%; Ar: 18%; Kr: 36%; and Xe: 54%. The following equation is found to be useful in approximating the ionization efficiencies η for the noble gases:

\[ \eta_{\text{calc}}(\%) = \frac{4 \times 10^2 \langle \ell \rangle D_0 N_e}{A_o} \left( \frac{\pi M_i}{8kT_e} \right)^{1/2} \]

\[ \times \exp\left(-\frac{4\langle \ell \rangle D_0 N_e}{A_o} \left( \frac{\pi M_i}{8kT_e} \right)^{1/2} \right) \]

\[ \times \exp\left(-\frac{4\langle \ell \rangle D_0 N_e}{A_o} \left( \frac{\pi M_i}{8kT_e} \right)^{1/2} \right) \]

Where \( \langle \ell \rangle \) = average path length for a particle in the plasma; \( D_0 \) = constant (cm²/s); \( A_o \) = emission area of the source; \( k \) = Boltzmann's constant; \( T_e \) = ion temperature; \( T_e \) = electron temperature; \( I_p \) = ionization potential; \( N_e \) = number of electrons in the valence shell of the atom with a given \( I_p \); and \( M_i \) = mass of species. The following values are used for terms in Eq. 5 when estimating ionization efficiencies for the FEBIAD ion source: \( (kTe) = 3 \) eV; \( T_e = 2273^\circ \text{K} \); and \( 4\langle \ell \rangle D_0 / A_o = 5.39 \times 10^3 \) cm/s.

The CERN-ISOLDE Ion Source. The CERN-ISOLDE on-line source is similar in principle to the FEBIAD source. The design features of several versions of the source have recently been described by Sundell and Ravn [22]. The CERN ISOLDE target/ion source has been utilized extensively for the production of short-lived radioactive species and has been cleverly engineered to enable remote installation and removal from the facility as required for safe handling in high-radiation-level fields. Such sources are routinely equipped with standard leak of a noble gas, usually xenon, which is continually fed into the source at a known feed rate to enable real-time determination of the source performance. This information is then used as a gauge for determining the relative ionization efficiency for the species of interest. Since the ionization potentials for the noble gases range from 24.46 eV (He) to 10.7 eV (Rn), the efficiencies at which a particular source can ionize each of these elements can serve as a valuable figure of merit for a particular source type. Electron impact ionization sources of the FEBIAD-CERN-ISOLDE type are quite efficient for low-ionization-potential elements and elements which are heavy and, therefore, move slowly through the ionization volume of the source. However, those sources do not appear to ionize low-mass elements or molecular materials efficiently, particularly those with high ionization potentials. The ionization efficiencies for these sources are close to those measured for the FEBIAD source. For example, the maximum efficiency recorded for Xe is 56% [23].

The high-temperature version of the CERN ISOLDE source [24] has been selected as the first source to be used for the generation of radioactive ion beams at the HRIBF because of its low emittance, relatively high ionization efficiency, and capability for producing a broad range of radioactive species. Of equal importance, the source has been cleverly engineered for remote installation, removal and servicing as required in safe handling of highly radioactive contaminated sources, source components, and ancillary equipment. The source design also permits easy modification to lower temperature versions and conversion from electron impact ionization to either thermal or positive and negative surface ionization sources. The reasons for choosing the CERN ISOLDE source and design features of the source are discussed below.

After careful comparisons of several source types, including the ECR ion source, the high-temperature version of the CERN ISOLDE source was chosen for the first use at HRIBF source because of its very low emittance (4 π mm.mrad MeV1/2), relatively high
ionization efficiency, capability for producing a much broader range of elemental species, and because the source has been cleverly engineered for remote installation, removal and servicing. These features have not yet been incorporated in state-of-the-art ECR sources. The HRIBF version of the CERN-ISOLDE source is described in Ref. 24. A cross-sectional view of the source mounted on the high-voltage platform of the HRIBF facility is shown in Fig. 5.

Figure 5. Cross-sectional view of the HRIBF High-Temperature Target/Ion Source Assembly [24].

The high-temperature target and ionization chamber of the source are shown schematically in Figs. 6 and 7. A collimated ion beam from the ORIC will pass through a thin Re window where it interacts with the refractory target material chosen for the production of the desired radioactive beam. The Ta target material reservoir is lined with Ir or Re metal as is the beam transport tube and internal surfaces of the source. The thickness of the target is chosen so that the projectile has an energy spread within the target medium which approximates that required for optimum radioactive species production. The unreacted beam exits the target through a second Re window, then strikes a cooled C beam stop. This technique reduces the power deposited in the target and thereby simplifies temperature control problems.

The target reservoir is positioned within the inner diameter of a series-connected, resistively heated, three-cylinder, Ta tube. The reservoir can be heated to temperatures exceeding 2100°C by passing a current through the tubular structure. The power required to heat the assembly to 2100°C is estimated to be 5.5 kW (11 V at 500 A). Temperature control will be maintained within ±2°C by use of feedback circuitry driven by a two-color pyrometer to adjust the current through the heater.

The electron emitter cathode is also made of Ta and is resistively heated to thermionic emission temperatures, ~2125°C. The electron beam, typically ≥250 mA, is accelerated through a potential difference of 200-300 V to the perforated anode plate where it passes into the cylindrical cavity of the anode structure and ionizes the gaseous material. Collimation of the electron beam is effected by adjusting the coaxially directed solenoidal magnetic fields so as to optimize the ionization efficiency of the species of interest. The cathode power required to achieve thermionic emission temperature will be ~2 kW (400 A at 5 V).

The total power required to heat the ISOL/target and cathode to the temperatures listed above and to ionize the vaporous material transported from the target to the ionization chamber of the source will be of the order of 7.5 kW to 8.0 kW. Table 1 provides a list of the power supplies required to operate the high-temperature version of the source.

Figure 6. Cross-sectional side view of the HRIBF high-temperature target/ion source showing the target, vapor transport tube, and ionization chamber of the source [24].

Figure 7. Cross-sectional top view of the HRIBF high-temperature target/ion source showing the target, vapor transport tube, and ionization chamber of the source [24].
Table 1. Power supply requirements for the ORRIBF ion source.

<table>
<thead>
<tr>
<th>Power Supply</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>60 kV at 2 mA</td>
</tr>
<tr>
<td>Extraction</td>
<td>30 kV at 2 mA</td>
</tr>
<tr>
<td>Anode</td>
<td>400 V at 1.5 A</td>
</tr>
<tr>
<td>Cathode</td>
<td>6 V at 500 A</td>
</tr>
<tr>
<td>Target</td>
<td>20 V at 1000 A</td>
</tr>
<tr>
<td>Magnet Coils</td>
<td>20 V at 50 A (3 each)</td>
</tr>
</tbody>
</table>

The electron beam generated plasma (EBPG) ion source. The electron beam generated plasma (EBGP) ion source, developed for use at the OASIS facility by Nitschke [25], is shown schematically in Fig. 8. The source has demonstrated high efficiencies and very high temperature operation (~2700°C). The anode of the source is a cylindrical grid, the ends of which are circular plates; in one end of the anode, radioactive atoms are admitted into the ionization chamber of the source through a thin W window or through concentric tubes. The other end of the anode has an aperture through which the ion beam is extracted following ionization. The cylindrical grid is inside a cylindrical cathode closely spaced to the grid. Electrons from the cathode, produced by electron bombardment of the outer surface of the cylindrical cathode, are accelerated radially inward through the grid where they execute harmonic motion about the axis of symmetry of the anode, passing many times through the ionization volume of the source before they are thermalized. The source has demonstrated efficiencies rivaling those recorded for the FEBIAD source. Figure 9 displays the ionization efficiency for Kr as a function of electron bombardment potential. As noted, the efficiency for this species is very close to the maximum values recorded for the FEBIAD ion source. Table 2 compares the efficiencies for a number of elements, as calculated from Eq. 5, with those measured from the EBGP, FEBIAD, and CERN-ISOLDE ion sources. The geometry of the EBGP source makes it very attractive for use in RIB applications; for example, the CERN-ISOLDE ion source which will be used at the HRIBF can readily be equipped with a radially directed cathode-anode structure such as used in the EBPG source. The solenoidal magnetic field customarily used in the CERN-ISOLDE source would not be used for the EBGP mode of operation. The radioactive species would be transported from the target to the ionization volume in an identical way as discussed previously.

3.2 Thermal Ion Sources

At high temperatures, collisions between gas particles may produce ionization provided that their relative energies exceed the first ionization of the atoms or molecules that make up the gas. For the case of a monoatomic gas, a fraction of the total number of gas particles will be in various stages of ionization at thermal equilibrium. Ionization equilibrium is a particular case of chemical equilibrium corresponding to a series of ionization reactions symbolically written as

$$A_0 = A_1 + e; A_1 = A_2 + e;$$

where A0 denotes a neutral atom and A1, A2 denote, respectively, singly and doubly ionized atoms and e is the electron removed in the collision. For such
Table 2. Comparisons of Calculated and Experimentally Measured Ionization Efficiencies η for Electron Beam Plasma Ion Sources. Estimated ionization efficiencies were calculated by using Eq. 5.

<table>
<thead>
<tr>
<th>Z</th>
<th>Element</th>
<th>I_p (eV)</th>
<th>N_s</th>
<th>η_calcd (%)</th>
<th>η_exp (%)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>20Ne</td>
<td>21.56</td>
<td>8</td>
<td>2.0</td>
<td>1.5</td>
<td>19</td>
</tr>
<tr>
<td>18</td>
<td>40Ar</td>
<td>15.76</td>
<td>8</td>
<td>16.6</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>24</td>
<td>54Cr</td>
<td>6.77</td>
<td>1</td>
<td>37.0</td>
<td>&gt;20</td>
<td>19</td>
</tr>
<tr>
<td>26</td>
<td>57Fe</td>
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</tr>
<tr>
<td>32</td>
<td>72Se</td>
<td>7.90</td>
<td>4</td>
<td>65.6</td>
<td>41</td>
<td>19</td>
</tr>
<tr>
<td>36</td>
<td>84Kr</td>
<td>14.00</td>
<td>8</td>
<td>34.1</td>
<td>35</td>
<td>19</td>
</tr>
<tr>
<td>38</td>
<td>84Kr</td>
<td>14.00</td>
<td>8</td>
<td>34.1</td>
<td>36</td>
<td>24</td>
</tr>
<tr>
<td>46</td>
<td>100Pd</td>
<td>8.33</td>
<td>18</td>
<td>86.5</td>
<td>&gt;25</td>
<td>19</td>
</tr>
<tr>
<td>47</td>
<td>107Ag</td>
<td>7.58</td>
<td>1</td>
<td>38.7</td>
<td>47</td>
<td>19</td>
</tr>
<tr>
<td>47</td>
<td>107Ag</td>
<td>7.58</td>
<td>1</td>
<td>38.9</td>
<td>50</td>
<td>19</td>
</tr>
<tr>
<td>50</td>
<td>118Sn</td>
<td>7.34</td>
<td>4</td>
<td>74.0</td>
<td>53</td>
<td>19</td>
</tr>
<tr>
<td>50</td>
<td>124Sn</td>
<td>7.34</td>
<td>4</td>
<td>74.6</td>
<td>54</td>
<td>19</td>
</tr>
<tr>
<td>54</td>
<td>129Xe</td>
<td>12.13</td>
<td>8</td>
<td>54.6</td>
<td>52</td>
<td>19</td>
</tr>
<tr>
<td>54</td>
<td>132Xe</td>
<td>12.13</td>
<td>8</td>
<td>54.6</td>
<td>53</td>
<td>19</td>
</tr>
<tr>
<td>54</td>
<td>132Xe</td>
<td>12.13</td>
<td>8</td>
<td>54.8</td>
<td>56</td>
<td>25</td>
</tr>
<tr>
<td>79</td>
<td>197Au</td>
<td>9.23</td>
<td>1</td>
<td>32.9</td>
<td>50</td>
<td>19</td>
</tr>
<tr>
<td>82</td>
<td>208Pb</td>
<td>7.42</td>
<td>4</td>
<td>78.8</td>
<td>52.8</td>
<td>19</td>
</tr>
<tr>
<td>83</td>
<td>209Bi</td>
<td>7.29</td>
<td>5</td>
<td>12.9</td>
<td>68.3</td>
<td>19</td>
</tr>
</tbody>
</table>

The ionization efficiency for an atom with first ionization potential I_p can be expressed in the following form:

\[
\eta = \left[1 + \frac{90}{2g_0 \left(2\pi \hbar^2/m \right)^{3/2}} \exp\left(\frac{+I_p}{kT}\right)\right]^{-1/2}
\]  

(7)

where \( m \) is the mass of the electron, \( T \) is the temperature, \( I_p \) is the first ionization potential of the atom, \( g_0 \) gives the respective statistical weights of the electron, atom, or ions, and \( \hbar = h/2\pi \), where \( h \) is Planck's constant. For electrons \( g = 2 \) and for atoms or ions \( g = (2L + 1)(2S + 1) \), where \( L \) and \( S \) are the orbital and spin angular momentum quantum numbers of the atom or ion.

This expression determines the degree of ionization as a function of pressure and temperature. The process of thermal ionization is not a practical means of producing ions in the laboratory, but accounts for ionization processes in the stars. However, the temperature need not be exceedingly high for a reasonable degree of ionization for easily ionized elements. Figure 10 illustrates the degree to which atomic hydrogen, mercury, calcium, and cesium are ionized as a function of temperature at \( p = 1 \times 10^{-3} \) and \( 1 \times 10^{-2} \) Torr. The first reported applications of this technique are described in Refs. [27] and [28]. Such sources are relatively efficient for elements with ionization potentials \( I_p \leq -7 \) eV.

The efficiency and thermodynamics of the thermal ion source have been studied by Kirchner using ion implantation techniques as described in Ref. 29. Kirchner concludes that thermal equilibrium is generally not realized in his source. Table 3 compiles ionization efficiencies for a number of elements, including Cs, Sr, Nb, and La, all of the lanthanides, and U, Pu, and Cm of the actinides as measured by use of the thermal ionization source described in Ref. 28. The source can be very efficient as indicated. This mode of ionization clearly is not pure surface ionization as can be seen by comparing the ionization efficiencies for Cs as predicted from simple surface ionization (Fig. 13) and thermal ionization theories (Fig. 10), even after adjusting the temperature to 2727°C for the case of surface ionization. For the adjusted case, the surface ionization theory predicts an ionization efficiency \( \eta = -4\% \) compared to a predicted value of \( \eta = -20\% \) for thermal ionization efficiency. The latter value is closer to the experimentally measured value of \( \eta = 13\% \), reported in Ref. 28 for only one run. The differences in ionization efficiencies between Johnson, Bolson, and Henderson [28] and the measurements of Kirchner [29] must lie in the differences in chemical forms of the species studied. For the case of Ref. 28, compounds were dissociated to form the ion beam; whereas, elemental species were used by Kirchner, Ref. 29, as a natural consequence of the ion implantation technique used in his studies. If, perchance, polar dissociation processes are in play, complementary negative ion beams of the anion species would also be present for use. They would be
especially welcome for use in RIB facilities such as HRIBF which accelerates negative ion beams. Ionization efficiencies versus effective ionization potential are shown in Fig. 11, where \( N = 1 \) corresponds to the surface ionization mode, \( N = 7500 \) corresponds to the thermal equilibrium case, and \( N = 150 \) to the actual non-thermal equilibrium case as measured in Ref. 29. Figure 11 also illustrates the chemical selectivity of this type of source.

A thermal ion source has also been designed for use at the TRISTAN facility [30]. A schematic representation of a thermal source now under design at the HRIBF is shown in Fig. 12. The vapor transport tube, made of W or Ta, will be resistively heated to \( \sim 2100^\circ C \). In addition, the thermal ionization region of the vapor transport tube will be heated to \( \sim 2600^\circ C \) by electron bombardment.

![Figure 12. A thermal ionization source concept for use in ionizing elements with ionization potentials \( \leq 6.5 \text{ eV} \). The source will be complementary to the CERN-ISOLDE electron beam plasma source [24] at the HRIBF.](image)

### 3.3 Surface Ionization Sources

**Positive surface ionization.** For thermodynamic equilibrium processes, the ratio of ions to neutrals that leave an ideal surface can be predicted from Langmuir-Saha surface ionization theory. For atoms or molecules leaving a heated surface, the probability of positive ion formation \( \eta_i \) is given by

\[
\eta_i = \frac{\omega_+}{\omega_0} \left[ \frac{1 - r_+}{1 - r_0} \right] \exp \left( \frac{\phi - l p}{kT} \right)
\]

\[\times \left[ 1 + \frac{\omega_+}{\omega_0} \left( \frac{1 - r_+}{1 - r_0} \right) \exp \left( \frac{\phi - l p}{kT} \right) \right]^{-1}, \tag{8}\]

where \( r_+ \) and \( r_0 \) are the reflection coefficients of the positive and neutral particles at the surface, \( \omega_+ \) and \( \omega_0 \) are statistical weighting factors, \( T \) is the absolute temperature, and \( k \) is Boltzmann's constant. \( \omega_+ \) and \( \omega_0 \) are related to the total spin of the respective species given by

\[
\omega = 2 \sum_i s_i + 1
\]

where \( s_i \) is the spin of the electron. Optimum ionization efficiencies are obtained for high-work-
function materials and low-ionization-potential atomic species. For elements for which \( I_p > \phi \), the process is much less efficient. For example, the work function for clean tungsten is about 4.6 eV and the ionization potential for indium is 5.8 eV. Thus, in this case, the exponential term \((\phi - I_p)\) in the Langmuir-Saha relation is negative and, therefore, the probability of ionization is low. A plot of the efficiency of ionization of a number of elements as a function of the ionization potential \( eV \) for the high-work-function iridium surface is shown in Fig. 13.

![Figure 13](image)

Figure 13. Surface ionization efficiencies of the group IIA, IIA, and IIIA elements as a function of ionization potential \( eV \) as calculated from Eq. 8.

It is seen that the efficiency is relatively high for some atoms, but is low \((10^{-2} \text{ or } 10^{-3})\) for atoms of In, Ca, Al, Ga, and Tl. The incident particles which are not ionized are evaporated as neutral atoms. Surface ionization sources can be highly element selective due to the fact that neighboring elements often have very different ionization potentials or electron affinities.

Equation 8 applies to an idealized situation in which the surface properties are isotropic and there are no surface contaminants. In practice, the variation of \( \phi \) with crystalline orientation in cases where the metal is polycrystalline as well as uniformly or nonuniformly distributed surface contaminants must be considered. All of these effects, in principle, can be taken into account by appropriately summing over the admixtures of existing work functions and statistical weighting factors in the expression.

Positive surface ionization sources. Positive surface ionization sources are quite simple and easy to operate. The principle has been used at CERN-ISOLDE [31] and TSIOL facility [32] to generate ion beams from low-ionization-potential elements. Although they have limited applications in terms of species, the process is highly chemically selective as indicated in Fig. 13. The CERN-ISOLDE source can be easily retrofitted to accommodate the positive surface ionization source mode of operation, as demonstrated at INS to ionize \( ^{38}\text{K} \) [33]. A high-intensity prototype positive/negative surface ionization source, equipped with a spherical geometry ionizer has been successfully tested for the generation of high intensity beams of \( ^{137}\text{Cs}^+ \) [34]. Figure 14 displays a positive surface ionization source which will be used as complementary to the CERN-ISOLDE source at the HRIBF. The ionizer and vapor transport tube will be Ir coated tantalum and heated resistively to \( \sim1100^\circ\text{C} \).

![Figure 14](image)

Figure 14. A positive surface ionization source concept for use in ionizing group IA elements. The source will be complementary to the CERN-ISOLDE electron beam plasma source [24] at the HRIBF.

Negative surface ionization. Analogously for negative surface ionization, the probability for arrival at a position far from the metal in a given state depends on the magnitude of the difference between the electron affinity \( E_A \) and the surface work function \( \phi \) of the atom or molecule, i.e., \( \left( E_A - \phi \right) \). For thermodynamic equilibrium processes, the ratio of ions to neutrals which leave an ideal surface can be predicted from Langmuir-Saha surface ionization theory appropriate for negative ion formation. The form of the Langmuir-Saha equation for the probability of negative ion formation for neutral particles of electron affinity \( E_A \) interacting with a hot metal surface at temperature \( T \) and constant work function \( \phi \) is given by
\[ \eta_i = \frac{\omega_1}{\omega_0} \frac{1-r_1}{1-r_0} e^{(E_A - \phi)/kT} \times \left[ 1 + \frac{\omega_1}{\omega_0} \frac{1-r_1}{1-r_0} e^{(E_A - \phi)/kT} \right]^{-1}, \]

where \( r_1 \) and \( r_0 \) are the reflection coefficients of the particle at the surface and \( \omega_1 \) and \( \omega_0 \) are statistical weighting factors for the negative ion and neutral atom, respectively. \( \omega_1 \) and \( \omega_0 \) are related to the total spin of the respective species given by

\[ \omega = 2 \sum s_i + 1, \]

where \( s_i \) is the spin of the electron. The predicted probabilities for surface ionization of selected atoms or molecules leaving a clean LaB\(_6\) surface maintained at 1372\(^\circ\)K are illustrated in Fig. 15.

---

**Figure 15.** Ionization efficiencies for negative surface ionization of selected high-electron-affinity atoms and molecules from a hot LaB\(_6\) surface as calculated from Eq. 9.

From Eq. 9, it is evident that negative ion yields could be enhanced by lowering the work function \( \phi \) or increasing the surface temperature \( T \) for elements where \( E_A \leq \phi \). The former can be effected by surface adsorption of minute amounts of low-work-function materials such as the group IA and IIA elements. Analogously, the adsorption of minute amounts of highly electronegative atoms or molecules such as oxygen or the halogens can deleteriously affect the negative surface ionization efficiency by raising the work function.

The negative form of surface ionization is also highly chemically selective (see Fig. 15, for example) and, therefore, can be used to great advantage for the generation of high-electron-affinity elements such as the group VIIA (halogens). Unfortunately, there is limited availability of a wide variety of stable, low work materials. LaB\(_6\) is the most frequently used low-work-function surface ionizer, having a work function \( \phi \approx 2.7 \) eV for polycrystalline and \( \phi \approx 2.36 \) eV for single crystalline material.

**Negative surface ionization sources.** An on-line form of the negative surface ionization source has been developed at CERN-ISOLDE, which is equipped with a LaB\(_6\) surface ionizer [35]. The positive/negative surface ionization source described in Ref. 34 has also been used to generate beams of UF\(_6\). The CERN-ISOLDE-type source can easily be retrofitted with a LaB\(_6\) ionizer and used to efficiently ionize high-electron-affinity elements as clearly evidenced by the successful application described in Ref. 35. A prototype spherical-geometry negative-surface source, planned for use at the HRIBF, is displayed in Fig. 16.

---

**Figure 16.** A negative surface ionization source concept for use in ionizing elements with high electron affinities such as the group VIA and VIIIA elements.

### 3.4 ECR Ion Sources

Electrons moving along the field lines of an external magnetic field of flux density \( B \) can be resonantly accelerated by the electric field associated with microwave radiation of the proper frequency which matches the electron-cyclotron resonance condition, \( \omega_{ECR} = \omega_{rf} = \text{Bev/m} \). The region where the ECR condition is met is referred to as the ECR zone. Electrons passing through the ECR zone, which are coincidentally in phase with the electric field, are accelerated by the transfer of electromagnetic energy perpendicular to the direction of the magnetic field; electrons arriving out of phase with the electric field undergo deceleration. On subsequent passes through the ECR zone, electrons gain a net energy and are said to have been stochastically heated; when
the energies exceed the ionization energies of the atoms or molecules in the evacuated cavity, a plasma is formed. Several ion sources, based on the ECR principle, have been developed for ISOL applications including those described in References 36, 37, and 38. A schematic representation of the ISOL ion source utilized on-line at TRIUMF [37] is displayed in Fig. 17. A compact single stage, permanent magnet ECR ion source is now being developed for on-line use at GANIL for potential RIB applications [39].

![Figure 17. Schematic drawing of the TISOL target/ECR ion source (Ref. 37).](image)

The ECR ion source is superior in terms of ionization efficiencies for low mass, high ionization potential elements and in terms of their capabilities for producing multiply charged ion beams. Another principal advantage of the ECR ion source is that it does not rely on a negatively biased hot cathode for generating and sustaining the plasma which limits the lifetimes of conventional electron beam plasma sources due to physical sputtering of the cathode material. The principal disadvantage of the source is that, in its present state of development, the discharge chamber can only be operated at modestly high temperatures which severely limits the number of species that the source can be used to process. The ionization efficiencies for condensable materials will be less than those for more volatile elements. However, due to the high probability for ionization during transit through the ionization volume of the source, there is evidence that the efficiencies for condensable materials may be relatively high, as well. The ECR ion source, however, is particularly well suited for the processing of highly volatile or gaseous materials and usually out performs electron beam plasma sources for low atomic number species. The prototype on-line ECR ion source was first developed at Karlsruhe [36] for ISOL applications; the source has demonstrated efficiencies for C of 10%; for N up to 27%; for O up to 5%, for Ne up to 31% and Xe up to 65%. This source was duplicated at TRIUMF [37] and has recently been used on-line for $^{16}\text{N}$ experiments [40]. Ionization efficiencies of 18% for N, 37% for C and 14 % for Ne and 35% for Ar have been measured with the on-line ECR ion sources at Louvain-la-Neuve [38,41,42]. The ionization efficiencies for the ECR ion source are sensitively dependent on the pressure in the discharge chamber as evidenced by the measurements made at Louvain-la-Neuve and displayed in Fig. 18. These sources are clearly more efficient for low mass, high ionization potential elements than conventional, hot cathode electron beam plasma type sources such as the FEBIAD and CERN-ISOLDE type ion sources. On the other hand, the ionization efficiencies for Xe in this source are close to those recorded at CERN-ISOLDE [23] and GSI [17] for Xe (~54%). These sources are particularly impressive for difficult to ionize elements such as He and Ne. Table 4 compares the performances of electron beam plasma and ECR ion sources for ionizing a few elemental species.

![Figure 18. Ionization efficiencies as a function of ambient pressure in the single-stage ECR source of Ref. 38.](image)

3.5 Plasma Sputter Negative Ion Sources

The adsorption of less than a monolayer of a highly electropositive adsorbate material on the surface of a sample undergoing particle bombardment greatly enhances the probability for secondary negative ion formation [43]. While it is possible that other independent and distinct negative ion formation processes may coexist during sputtering, there is convincing evidence that the mechanism of ion formation during sputtering of a metal surface covered
with a partial layer of a material such as cesium is a form of surface ionization. In the prescription of Nørskov and Lundqvist [44], the probability for negative ion formation during sputtering can be represented by the following simple energy-dependent relation:

$$
\eta_i = \frac{2}{\pi} \phi - \beta^* \sqrt{M_2 \{\phi(\sigma) - E_A + V_I\} / \sqrt{2E_2 \cos \theta}} \quad (10)
$$

In Eq. 10, $\phi$ is the work function of the surface which is a function of the relative adsorbate coverage $\sigma$, $E_A$ is the electron affinity of the ejected particle of mass $M_2$ and energy $E_2$, $V_I$ is the image potential induced in the surface by the escaping ion, $\theta$ is the polar angle of the sputtered ion with respect to the surface normal and $\beta$ is a constant. In Eq. 10, $\sqrt{2E_2 / M_2 \cos \theta} = v_\perp$ is the component of the velocity of the escaping particle perpendicular to the metal surface.

The technique of sputtering a surface covered with a fractional layer of a highly electropositive adsorbate material such as cesium has proved to be a universal method for generating atomic and molecular negative ions beams from most chemically active elements. In addition to being versatile in terms of species, sources based on this concept are simple in design, easy to operate, and generally have long lifetimes. Because of these factors, such sources are utilized extensively in most tandem electrostatic accelerator heavy ion physics research laboratories, as well as for use in a growing number of other applications, including high-energy ion implantation and tandem accelerator mass spectrometry. Positive ion beams, usually formed by either direct surface ionization of a group IA element or in a heavy noble gas (Ar, Kr, or Xe) plasma discharge seeded with alkali metal vapor, are accelerated to energies between a few hundred eV and several keV where they sputter a sample containing the element of interest. The presence of a fractional layer of a highly electropositive adsorbate material is critically important to the enhancement of negative ion formation during the sputtering process. A small fraction of the sputter ejected particles leave the adsorbate covered surface as negative ions and are accelerated through an extraction aperture in the source. Several sources predicated on this principle have been developed, some of which are described in Ref. 45. Sources based on this principle are particularly appealing for applications involving the postacceleration of RIBs with tandem accelerators such as the HRIBF. In particular, sources which use a plasma to sputter the sample [46-49] are especially attractive because this technique assures uniform sputtering and, consequently, good overlap of the bombarding species and the material containing the radioactive ion beam.

Figure 19 displays a schematical representation of a plasma sputter source now under design for use at the HRIBF. The source will be housed in the source vacuum envelope as the CERN-ISOLDE source. Radioactive species from the target will be transported at high temperatures through the vapor transport tube into the plasma discharge chamber where the vapor will be condensed on the cold cathode surface. A Xenon plasma, seeded with cesium from an external oven, will be ignited either by a filament or a rf coil. The final choice of the two means of igniting the

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**Table 4. Comparison of ionization efficiencies $\eta_i$ for various electron beam plasma (EBP) and ECR ion sources.**

<table>
<thead>
<tr>
<th>Z / Element</th>
<th>$\eta_i$ (eV)</th>
<th>$\eta_{EBP}$ (%)</th>
<th>Ref.</th>
<th>$\eta_{ECR}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 $^4$He</td>
<td>24.59</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6 $^{12}$C</td>
<td>11.25</td>
<td>-</td>
<td>10</td>
<td>36</td>
</tr>
<tr>
<td>7 $^{14}$N</td>
<td>14.53</td>
<td>-</td>
<td>20</td>
<td>38</td>
</tr>
<tr>
<td>8 $^{18}$O</td>
<td>13.61</td>
<td>-</td>
<td>55</td>
<td>36</td>
</tr>
<tr>
<td>10 $^{20}$Ne</td>
<td>21.56</td>
<td>1.6</td>
<td>17</td>
<td>52</td>
</tr>
<tr>
<td>18 $^{40}$Ar</td>
<td>15.78</td>
<td>19</td>
<td>17</td>
<td>35</td>
</tr>
<tr>
<td>38 $^{84}$Kr</td>
<td>14.00</td>
<td>35</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>54 Xe</td>
<td>12.13</td>
<td>55</td>
<td>17</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>36</td>
</tr>
</tbody>
</table>

---
plasma will be determined during off-line testing of the source. The radioactive ion beam will be formed by sputter ejection of atoms or molecules from the negative biased spherical geometry sputter probe covered with a partial layer of cesium adsorbate material. The double sheath surrounding the negatively biased sputter probe (spherical radius 30 mm and diameter $\phi = 12.5$ mm), which is maintained at a variable voltage (0–1000 V) relative to the housing, serves as the acceleration gap and lens for focusing the negative-ion beam through the exit aperture (diameter $\phi = 3$ mm). At this point, the ion beam is further accelerated to energies up to 50 keV prior to mass analysis. The efficiencies of several negative ion species have been estimated by Tsuji and Ishikawa [49]. Their results are shown in Table 5.

<table>
<thead>
<tr>
<th>Negative ion</th>
<th>C-</th>
<th>Si-</th>
<th>Cu-</th>
<th>Ge-</th>
<th>Mo-</th>
<th>Ta-</th>
<th>W-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability (%)</td>
<td>18.3</td>
<td>15.6</td>
<td>12.1</td>
<td>13.6</td>
<td>(0.52)</td>
<td>(1.59)</td>
<td>8.07</td>
</tr>
</tbody>
</table>

The emittance of the source is quite good ($\sim 8\pi$ mm.mrad [MeV]$^{1/2}$) as measured by Mori for the compact plasma sputter described in Ref. 48 when operated with mA beams of Cu$^-$. The emittance is much lower than the acceptance of the 25-MV tandem accelerator [50] and, therefore, should be easily transported to the terminal stripper in the machine.

### 3.6 Multi-photon Resonance Ionization Sources

Multi-photon resonance spectroscopy (RIS) has been utilized for a number of years to selectively ionize atoms [51]. The scheme is, in principle, very simple; the difficult challenge is to find the most efficient scheme for ionizing a particular atom. Two or more photons with energies precisely tuned so that the sum of their respective quanta precisely match the energy required to populate a particular excited state are used in step-wise fashion until the electron reaches the ionization continuum. Since the ionization process requires the precise matching of the sum of the photon energies to each of the energy levels of the particular atom, the process is resonant and uniquely species selective; the RIS scheme is, therefore, highly discriminatory against potential contaminants. Thus, RIS offers a means of generating fully ionized, isotopically and isochronically pure RIBs. Approximately 80% of the elements in the periodic chart can be resonantly ionized with the RIS technique with existing lasers. In order to saturate a particular transition, high power photon beams are required at every step of the excitation/ionization process. To achieve the required power levels, the lasers must operate in pulsed mode. Most high power pulsed lasers have low duty factors ($\ll 10^{-3}$). This means that the RIS scheme will only be able to generate low repetition rate, pulsed ion beams. Since most RIB applications require beam-on-target intensities exceeding $1 \times 10^{10}$ particles/s, this characteristic may limit the number of experiments that can be performed with pulsed beams.

Several groups are actively developing RIS laser ion sources for future ISOL applications. The RIS scheme has been applied to resonantly ionize atoms released from an ISOL target and effused through tubular or insulated cavities which are operated at high temperatures to prevent condensation. Two or three tunable dye laser beams are collinearly focused through the cavity with their wave lengths chosen to resonantly ionize the species of interest. This source is handicapped by the fact that some of the atoms are in excited states or may be thermally or surface ionized due to the high temperatures required to prevent condensation on the walls of the cavity. The otherwise chemical selectivity character of the RIS process is, therefore, compromised. Nevertheless, the hot cavity-RIS technique has been used off-line by Andreev, et al. to selectively ionize Sr to efficiencies of 17% [52] and by Ames, et al. to ionize Tc to efficiencies of 13% [53]. These groups both employed Cu vapor lasers which operate at high repetition rates to pump tunable dye lasers. This RIS scheme has been duplicated by Alkhazov, et al. to study the ionization of the rare earth elements Yb, Ho, Tl, and Sm [54].

Mishin, et al. utilized the RIS technique to determine the ionization efficiencies for Sn, Tm, Yb, and Li [55]. Efficiencies up to 15% were recorded for Yb. In these studies, it was found that the initial chemical selectivity factor for Tm, compromised by surface and thermal excitation/ionization processes, could be increased from 10 to 10000 by the proper choice of cavity material and by reducing the cavity temperature; the gain in selectivity was made by suppressing thermal and surface ionization processes. Furthermore, it was found that another factor of 10 could be gained by using gated detection techniques on the bunched beam. The laser ion source utilized for these experimental tests is shown in Fig. 20.

One possible solution to the low duty factor and isobaric contamination problems is to use a cold trap to condense the vapor from the ISOL target and to use laser ablation/vaporization to desorb the condensed material in pulses which are in exact synchronism with RIS pulsed dye laser system to selectively ionize the material. The laser desorption technique has been used to desorption Pt and Au which were ion implanted into samples and to study the Pt-Au isobar contamination problem by using the RIS technique. Ionization efficiencies for this study only reached $5 \times 10^{-3}$ [56]. However, the desorption efficiencies for the process reached 60%.
4.0 Conclusions

The most difficult challenge related to the efficient generation of RIBs using the ISOL technique is associated with target issues and not the ion source itself. The challenge is to select a target material which will withstand the high temperatures required to efficiently, and promptly release the short lived species of interest while preserving the vacuum requirements of the ion source. The speed at which the element is released from the target is directly related to the diffusion properties of the species/target material combination. The ion implantation technique, described in Section 2, offers a cost effective means of selecting the most appropriate material for the particular species of interest. As pointed out by Ravn [4], in general, each element must be considered separately, often requiring dedicated efforts to solve specific problems, in order to generate useful RIBs of the element. Much work remains to be done in the area of target material selection and the development of techniques to enhance the release of elements from a properly chosen target material.

ISOL ion source development continues to be driven by needs for sources with improved chemical selectivity, high duty factors, and more universal species capabilities. Despite the fact that electron beam plasma ion sources have poor chemical selectivity characteristics, they have a decided advantage in that they are closer to being universal than other ISOL sources that have been developed to date. Of the electron beam sources, the CERN-ISOLDE source is very appealing for RIB generation applications because of a number of reasons, including the following: 1) it is competitively efficient; 2) it has demonstrated reliability over many years of operation at CERN-ISOLDE; 3) the target temperature can be controlled independently of the discharge parameters of the source; 4) it can be readily adapted for a wide range of operational temperatures and for other modes of operation; 5) it is readily adaptable to other types of ion sources; 6) it has been engineered for safe removal and installation in the high level radiation fields incumbent at an ISOL facility.

Although ECR ion source development has made considerable progress, this source type still suffers from the fact that no really satisfactory solution to the low wall temperature/condensation problem has been found; as a consequence, the source, in its present state of development, has very limited species capabilities for ISOL applications. However, there is ample incentive to solve this problem because of the obvious advantage of the ECR source over conventional source types in terms of ionization efficiency.

The results from the testing of RIS laser sources has been rather encouraging and it is expected that this technology will rapidly advance in the future. The RIS techniques offers the idealistic prospect of eliminating the need for expensive isotope and isobar electromagnetic separation devices.

Plasma or cesium sputter ion sources offer another possibility for the efficient formation of negative ion beams from high electron affinity elements. Sources, based on this well developed technology, do not suffer from poisoning effects as do direct negative surface ionization sources and are very appealing for use at tandem accelerator based RIB facilities such as the HRIBF.

Thermal and surface ionization sources have reached a certain degree of maturity in their development but still play important roles for the efficient generation of ion beams from specific elements. Surface ionization sources, in particular, offer a high degree of chemical selectivity and are simple and easy to operate.

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[8] See, for example, Diffusion in the Condensed State, J. S. Kirkaldy and D. J. Young (The Institute of Metals, London, 1987), Ch. 1.


[42] M. Gaezels, et al., to be published.


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