ION SOURCES FOR RADIOACTIVE BEAMS

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The ion sources reviewed here, most of them developed for isotope separation on-line (ISOL), are classified according to their ionizing mechanism, utilizing electrons, heat, light, and penetration of matter. Emphasis is put on the beam-optical characteristics ion current density, energy spread, and emittance and on the ISOL-essentials "efficient, fast, and selective", both for the ion source and the complete target/ionsource-system.

1 INTRODUCTION

Ion sources for radioactive beam facilities have essentially the same task as the ones[1,2] developed for isotope separation on-line (ISOL). On a meeting of accelerator specialists it is close at hand to emphazise the demands to an ISOL-source by comparison with the demands to the more familiar accelerator ion sources. Common is the demand for reliability, universality, stability, long lifetime, low emittance and low energy spread. The difference lies in the fact that accelerator sources have to convert (usually unlimited and well-defined) charge materials into intense ion currents, whilst ISOL-sources have to convert the limited number of particles produced in nuclear reactions as *efficiently* as possible into ions, the corresponding ion current hardly ever reaching the μA-range. Since the "charge material" of ISOL-sources is radioactive, i.e. often of very limited lifetime, and composed of many elements, the conversion should proceed in a *fast* and *selective*, i.e. element-specific way - requirements, generally without meaning for an accelerator source. A further difference may be that these three main requirements do not only apply to the ion source proper, but to the system of ion source and its production target.

Of the possible mechanisms leading to ionization, i.e. *electron-bombardment, heat, interaction with light, penetration of matter*, and *high electric fields*, all except the last one have been utilized for ISOL-sources and serve for the subsequent classification.

2 ELECTRON-IMPACT ION SOURCES

Since electron-impact ionization cross-sections do not differ too strongly among neighbouring elements, the sources of this chapter are in principle universal and unselective. Limits of

universality and thus a certain degree of selectivity may, however, arise from the fact some elements are not sufficiently volatile at the operation temperature of the ion source and are lost due to surface adsorption or diffusion into the bulk of the source enclosure.

2.1   Low pressure arc discharge ion sources

These sources typically are composed of a cylindrical anode, sealed by two end-plates (the cathode plate with the filament and the anti-cathode) to a hot and gastight enclosure for the gaseous discharge. Ions are created by fast (30–100 eV) glow electrons from the filament. At and above a threshold pressure of 10^{-3} to 10^{-2}mbar, the primary electron current rises strongly to its saturation value due to formation of the cathode double-layer. This is the drop of practically the full discharge voltage within short distance of the filament, while the rest of the enclosure fills with the practically neutral low pressure arc plasma. The resulting high flux of ionizing particles, often amplified by an external solenoidal field which additionally increases the ion-confining forces of the plasma, makes this class of sources quite efficient (typically 30% for Ar, Kr, or Xe). Depending on whether ion emission is performed axially through a hole in the cathode- or anti-cathode-plate, or radially through a slit in the anode, the design is a *Hollow-cathode*,[3] *Nielsen*[4] or *Bernas-Nier*[5-7] ion source. They all have both low emittance (emittance values given in his review refer to 90-95% of the beam intensity and 30 kV acceleration voltage) and energy spread ($\lesssim 20\pi$ mm mrad,[6] few eV). Due to the pressure threshold (close to which the discharge tends strongly to instabilities) the output current density is quite high ($j_i > 10 mA/cm^2$). The high ion currents, especially for the Bernas-Nier source, are advantageous, if the ion source is coupled to targets emanating great amounts of material,[7] exclude, however, the simple and economic low-intensity mass separator concept due to space charge problems.

2.2   Space-charge compensated electron-bombardment sources

Similar in design to the low pressure arc sources and like those suited for all elements of sufficient volatility at the temperature of the enclosure (up to 2500 K), this class of sources avoids the arc threshold pressure and the associated instabilities by extracting the primary electrons by a grid. The main types, especially developed for ISOL applications, are the *FEBIAD*-source[8] with an axial cathode-grid geometry and the radial-geometry *EBGP*-source.[9] The advantage of the former is its rugged design, the advantage of the latter the non-necessity of a source magnet, its easy conversion into a high-temperature-cavity ionizer (chapter 3.2) and its high ultimate temperature by avoiding electrical insulators within the hot enclosure. Typical for these sources are high and widely pressure-independent ionization efficiencies (20-70% for the elements above neon). Similar in emittance and energy spread to the low pressure arc sources, they have substantially lower output current densities ($j_i < 1 mA/cm^2$) thus being easily compatible with any mass separator concept.

2.3   Electron-cyclotron resonance ion sources

Primarily intended as high-charge-state accelerator source, the *ECR*-source has now also found considerable appreciation as 1^+-ionsource in ISOL. The reason is that the very high

efficiency for gases,[10-12] and especially its capability of dissociating and ionizing efficiently molecular gases of C, N, O, chemical reactivity preventing their handling in high temperature enclosures. Its principle is microwave-driven electron-bombardment ionization, the low-density discharge plasma being confined by a magnetic field configuration of axial mirror plus radial hexapole field. Typical are ion current densities of around 1 mA/cm^2 out of orifices from 3 to 10 mm diameter, however, with quite high emittances of 70 to 150π mm mrad.[13,14] A great advantage is the long lifetime and stable running conditions for gases due to the absence of wearing parts; disadvantageous is the strong decrease of efficiency with increasing pressure. Due to the cold enclosure ECR's can hardly compete in efficiency for less-volatile elements with high-temperature sources. If, however, high ionic charge states from the source are required by certain post-accelerator concepts, even efficiencies of around 1% as reached e.g. for high charge states of Ca are of unrivalled importance, although considerably lower than the 25% reached for Ar^{8+}.[14]

3 THERMIONIC ION SOURCES

The ionization efficiency of thermo-ionizers is strongly dependent on the ionization potential (electron affinity) of the element considered. Differences in these quantities for neighbouring elements may make the ionization process intrincally selective.

3.1 Positive and negative surface ionization sources

Surface ionization occurs when a valence electron of an adsorbed atom has a sufficiently high chance to tunnel into the Fermi-sea represented by the adsorbing material. The ionization probability is given by the Saha-Langmuir equation, i.e. it is high and almost temperature-independent for $W_i < \varphi$ (W_i ionization potential of adsorbed atom, φ work function of surface), and strongly dependent on temperature and ($W_i - \varphi$) for $W_i > \varphi$. Efficient ionization is thus restricted to elements with $W_i < 5.5$ eV, e.g. alkalines and alkaline earths, desorbing from *high*-workfunction surfaces such as W, Re, and Pt.

Analogously efficient negative surface ionization is possible for elements with electron affinities $E_A > \varphi$, e.g. the halogenes. It requires *low*-workfunction surfaces such as LaB_6 or BaO. Since these materials are limited in operation temperature, an ISOL-design should minimize the number of surface collisions,[15] to avoid excessively long hold-up times.

3.2 High-temperature cavity ion sources

These sources are a special class of positive surface ionizers,[16] where the ionization takes place inside a closed (except for the outlet hole) volume[17] with the effect that atoms have a multifold chance of being surface-ionized. At high temperture and low plasma densities the ionization efficiency may exceed the Saha-Langmuir values by orders of magnitude. For high neutral densities the amplification factor may be as high as the mean number of wall collisions.[18] This makes the coupling of relatively volatile targets unproblematic, as long as the vapour is not surface-ionized or only to low degree. In the opposite case, i.e. for high plasma densities, the efficiency may drop drastically, even below the values given by the

Saha-Langmuir-equation. Its high temperature (up to >3000 K) gives access to refractory elements; efficient ionization is, however, restricted to elements with $W_i < 7$ eV, e.g. the lanthanides. Ion currents may be as low as 1 μA/cm^2, energy spread and emittance are very low (< 1 eV, $< 2\pi$ mm mrad).

4   LASER ION SOURCES

Multistep photo-ionization using intense laser light of 2 or 3 (eventually even of only 1[19]) wavelength is of increasing importance both in trace analysis and ISOL.[20-23] Resonant excitation at least in the first step with subsequent transition(s) into the continuum or to auto-ionizing- or Rydberg-states, guarantees intrinsic selectivity of the ionization process which may, however, be limited due to surface ionization of neighbouring elements. Ionization efficiencies of the order of 10% are achieved for favourable excitation schemes, even using low duty-cycle pulsed lasers. Only these have usually sufficient power (either directly or for driving tunable dye-lasers) to saturate the transitions. To overcome the low duty-cycle, the photo-ions have to be effectively prevented from recombination, e.g. by confinement in the potential trough of a hot cavity[21] or in a gas cell,[19] eventually combined with fast ejection geometries. The consequently bunched structure of the ion beam (typically 10 kHz, 10–30 μs) allows for enhanced selectivity by gated detection and may be useful for post acceleration. Emittance and current density are low (comparable to hot cavity ionizers); the energy spread, however, may be some 10 eV, i.e. corresponding to the electrostatic potentials applied for fast ejection of the ion pulses.

5   ION GUIDES

The ion guide technique, developed in Jyväskylä[24] and adopted succesfully also by many other ISOL-groups,[25] utilizes the fact that radioactive nuclei, when recoiling from their production target are highly charged and may be efficiently discharged to charge statue 1$^+$ in a stopping gas as e.g. pure helium. It is thus a universal (but consequently unselective) and very fast "ion source", since there are no delays due to solid state diffusion and surface adsorption. Restrictions of the technique to light-ion induced reactions and to very thin targets, as well as ion losses due to charge exchange wih impurities, wall collisions, or three-body-recombination, however, limit the rates of separated isoptopes to values typically below 10^5/s and thus the applicability for RIB-projects.

6   THE TARGET/ION-SOURCE SYSTEM

So far only the contribution of the ion source to the essentials *efficient, fast*, and *selective* of the target/ionsource-system was considered. The system adds to the losses by incomplete ionization the halflife-dependent losses due to the finite processing time between creation of a reaction product and its release from the system as an ion beam. On the other hand it may enable selectivity in cases, where this is not possible by the ionizing mechanism. Established

techniques are "chemical evaporation", i.e. the on-line-formation of compounds,[26] enabling often both improved separation of wanted elements and suppression of unwanted. A particularly favourable case is the formation of fluorides of Sr and Ba by adding CF_4 permitting practically 100%-efficient and completely exclusive separation as SrF^+ (BaF^+) ions.[27,28]

Other techniques utilize the delays caused by solid-state diffusion in the target material or by surface adsorption at the walls of the system, most effectively by the latter.[26,29] The associated problems and perspectives are best exemplified by looking at the propagation of reaction products through two somewhat idealized ISOLDE-systems.[26,30] Both are supposed to be operated at 2500K and to use thick Ta targets consisting of 100 μm Ta-foils, and of 10 μm Ta-powder, respectively, thus minimizing the surface/volume-ratio of the target material and vice versa. Considered are reaction products of Xe, Yb, and Dy, which have practically the same solid-state diffusion speed in tantalum ($D \approx 5 \times 10^{-9}$ cm^2/s) but very different mean sticking times on tantalum surfaces ($\tau_a \approx 0, 50$ μs, and 500 μs, respectively). Xenon, though not a typical reaction product of Ta targets, is included to illustrate, how volatile elements, not suffering from sizeable wall sticking times, are still delayed in the gaseous phase by molecular flow. Calculations based on References 29 to 31 show in qualitative agreement with experiment[32] that for the foil target the main losses arise from solid state diffusion, and that the halflife-dependence of the release efficiency differs relatively little for the three elements (no selectivity), allowing even for the separation of shortlived Dy-isotope. The "much faster" powder target, on the other hand, gives considerably better yields for the volatile Xe, while Dy (and most other lathanides) are strongly discriminated, thus opening for the most volatile lanthanide element Yb a wide halflife-window for reasonably efficient and selective separation.

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