Targets used in the Production of Radioactive Ion Beams at the HRIBF

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Radioactive ion beams are produced at the Holifield Radioactive Ion Beam Facility using the ISOL (Isotope Separation On-Line) technique where the atoms are produced in a thick target, transported to an ion source, ionized, and extracted from the ion source to form an ion beam. These radioactive ion beams are then accelerated to energies of a few MeV per nucleon and delivered to experimental stations for use in nuclear physics and nuclear astrophysics experiments. At the heart of this facility is the RIB production target, where the radioactive nuclei are produced using beams of light ions (p, d, ^{3}He, α) to induce nuclear reactions in the target nuclei. Several target materials have been developed and used successfully, including Al_2O_3, HfO_2, SiC, CeS, liquid Ge, liquid Ni, and a low-density matrix of uranium carbide. The details of these targets and some of the target developments that led to the delivery of high-quality radioactive ion beams are discussed in this paper.

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At the heart of an ISOL-based radioactive ion beam (RIB) facility is the production target. An accelerated ion beam irradiates the thick production target and radioactive atoms are produced via nuclear reactions that occur as the beam loses energy in the target. The radioactive atoms then diffuse out of the target and are transported to an ion source where either positively-charged or negatively-charged ions are formed. To minimize loss of ions through radioactive decay, the lifetime of the atoms should be long when compared to the time required to diffuse out of the target. The diffusion rate increases rapidly with increasing temperature, so target temperatures are kept as high as possible, often in excess of 2000 C. This high temperature results from the power that is deposited in the target by the production beam or from an external heater. These criteria for the performance of the target place stringent restrictions on the nature of the target material. The targets must be stable with respect to high temperatures, they must be chemically compatible with the target holder, and the radioactive atoms must be able to quickly diffuse out of the target. This paper will present a short overview of the facility and discuss a number of different target materials that have been used successfully to produce radioactive ion beams for experiments at the Holifield Radioactive Ion Beam Facility (HRIBF).

Facility Overview

The HRIBF, at the Oak Ridge National Laboratory, utilizes the ISOL technique to produce ion beams of short-lived radioactive nuclei. The radioactive atoms diffuse out of the target matrix, are transported to an ion source, ionized, extracted at 40 keV, and then separated by mass. These low energy beams are then injected into a second accelerator

and accelerated to energies of a few MeV per nucleon and delivered to targets for nuclear physics experiments. A schematic of the layout of the facility is shown in Figure 1.

The driver accelerator for the facility is the Oak Ridge Isochronous Cyclotron (ORIC), which was first commissioned in 1962. The ORIC [1] is a multi-species, variable energy cyclotron (K=105) and in the present configuration has delivered beams of protons at 42 MeV, deuterons at 44 MeV, and alphas at 85 MeV to the RIB production target. The maximum production beam intensity has been limited by the ability of the RIB production target to dissipate the deposited power.

The post-accelerator at the HRIBF is a folded-geometry 25-MV tandem electrostatic accelerator [2,3] that has been in routine operation since 1982 and has provided more than 75 different stable ion beams for research. The tandem has operated with terminal potentials up to 25.5 MV (highest in the world), and as low as 1 MV with excellent reliability. Negative ions, injected into the tandem, are stripped in the terminal and the positive ions are then accelerated down the high-energy side of the tandem. For light nuclei (A<80), single-stripping allows for acceleration up to at least 5 MeV per nucleon, but for heavy ions (A>80), a second stripping about a third of the way down the high energy side is required to achieve this energy.

The two accelerators are linked by the RIB Injector that is comprised of the ISOL production target, the ion source, a beam extraction system, and initial mass separation on a high voltage platform followed by a transport line that contains the high-resolution mass separator with a mass resolving power of one part in 20,000. Two different types of ion sources have been used to produce the radioactive beams for experiments; a negative ion source [4] for the production of fluorine beams and a general purpose, high efficiency

electron beam plasma (EBP) ion source [5] yielding positive ions. Since the post accelerator requires negative ion injection, a Cs-vapor charge exchange cell follows the positive ion source. This negative ion beam is then accelerated off the RIB Injector platform at 200 keV and delivered to the tandem accelerator.

RIB Production Targets

RIB production targets that produce high-quality radioactive ion beams have several features in common. The thickness of the production target is chosen to maximize the production rate of the desired radioactive nuclei and often the targets are thick enough to stop the incident light-ion beam from the driver accelerator. At the HRIBF, the target thickness generally ranges from 0.4 cm for liquid metal targets up to 8 cm for low-density, fibrous target matrices. Even though the targets operate in a harsh thermal and radiological environment, they must have useful lifetimes of at least a few weeks. The beam power deposited in the target causes the target temperature to increase and the target lifetime is determined by the rate at which the target either sinters or evaporates at this temperature. At the maximum operating temperature the vapor pressure of the target material must be low enough for the ion source to operate efficiently. This pressure limit varies from one type of ion source to another, but is generally between 10^{-5} and 10^{-3} Torr. As a consequence of the limiting target temperatures and vapor pressures, the intensity of the production beam has been limited to 10 μA or less in the targets that are presently in use.

Another characteristic of useful RIB production targets is the ability to release the desired radioactive atom at a rate that is fast, or comparable, to the radioactive decay rate.

The processes that contribute to the release (diffusion, adsorption, effusion) are all strongly temperature dependent, so the targets are operated at the highest temperature possible. However, high operating temperatures alone are often not sufficient. Short diffusion paths (thin fibers, powders, etc.) are generally needed to minimize the losses due to radioactive decay during the time required to diffuse out of the target material. Another important aspect of most production targets is the open structure, which allows the radioactive atoms to effuse quickly through the target matrix and into the ion source. While these physical properties of the target are important, the chemical nature of the target must also be considered. Chemical interactions with the target holder at high temperature can render a target useless for RIB production. Also the chemistry between the target material and the desired radioactive beam will ultimately determine the release efficiency that may be achieved.

Targets for Proton-Rich Beams

Radioactive nuclei on the neutron-deficient side of the stable isotopes are produced using light ion induced nuclear reactions on the target nuclei. Since the energy of the incident particles are relatively low (42 MeV protons, 44 MeV deuterons, and 85 MeV alphas), the reaction products that can be produced are limited to nuclei that are close in mass and charge to the target nuclei. The result is that, in most cases, the development of a new radioactive beam requires the development of a new target. Several target materials have been developed and used successfully at the HRIBF, including Al_2O_3, HfO_2, SiC, CeS, liquid Ge, and liquid Ni. The target materials and the beams extracted from these targets are described in the next few paragraphs.

Most of the RIB experiments that have been completed with proton-rich beams have utilized ^{17}F and ^{18}F beams. The fluorine atoms are produced in a fibrous hafnium oxide (HfO_2) target using the $^{16}O(d,n)^{17}F$ and $^{16}O(\alpha,pn)^{18}F$ reactions with 44 MeV deuterons and 85 MeV alphas, respectively. The ^{17}F production cross-section is peaked at about 3.5 MeV and the cross-section is quite small above 20 MeV [6]. The ^{17}F production rate is $9x10^{-4}$ per incident deuteron and the maximum deuteron beam current that the target can presently handle is 3 μA, resulting in a ^{17}F production rate of about $2x10^{10}$ per second. The highest ^{17}F beam intensity that has been delivered to an experiment is 10^7 ions per second, which means that the overall efficiency of the system from production to delivery of an accelerated beam onto an experimental target is about 0.05%. This overall efficiency is the product of several processes, including, diffusion out of the target material, effusion to the ion source, ionization of the fluorine atoms, transport to the post-accelerator, electron stripping for acceleration to a few MeV per nucleon in the tandem, and transport of the ion beam to the experiment.

The hafnium oxide target is made of thin fibers (5 μm diameter) that have been woven into a cloth material [7] from which strips (1 cm wide) are cut and rolled into cylinders with diameters of 1.5 cm, as shown in the photograph in the top portion of Figure 2. The hafnium oxide rolls are wrapped in an aluminum oxide sheath and inserted into the tantalum target holder that is connected to the ion source via a heated tantalum tube. The density of the target material is 1.15 g/cm^3 and the maximum operating temperature is about 2300 C. The target is heated by the incident production beam and by an external heater that ensures that there are no cold spots where fluorine atoms may collect by sticking to the surfaces of the target or target holder. The aluminum oxide

sheath is present to provide a vapor of aluminum because it was discovered early in the development of this beam that the fluorine was transported from the target to the ion source primarily in the form of the AlF molecule. An additional layer of hafnium oxide cloth (see Fig. 2) is placed around the alumina sheath since tantalum will catalyze the dissociation of alumina at lower temperatures (~1650 C). Fluorine atoms are quite reactive and will readily stick to most surfaces, even at high temperatures, so the transport of fluorine atoms to the ion source is slow when compared to its radioactive decay rate. Fortunately, the AlF molecules seem to be relatively inert and robust, so they not only survive in the high-temperature environment of the target, but they also move relatively quickly to the ion source where the molecule is dissociated and negative fluorine ions are produced in a Cs-sputter type ion source [4].

The range of a 44 MeV deuteron in this target material is only 1.6 cm and the average power density is 39 W/g, while the range of an 85 MeV alpha particle is 0.8 cm with an average power density of 75 W/g. The target thickness (4 cm) is greater than the range of the production beam because inspections of the target after irradiation have shown that significant target damage occurs all along the beam path, not just at the end of the range where the power density is the highest. The extent of the damage increases with time, but the useful lifetime of this target has been demonstrated to be at least eight to ten weeks of irradiation.

Liquid metal targets offer some advantages since diffusion rates are often several orders of magnitude faster in liquids than in solids at a given temperature. In addition, in some circumstances, convection currents in the liquid target can enhance the release of the radioactive nuclei from the target by bringing the atoms closer to the surface, thus

reducing the time required to diffuse out of the target. Another advantage is that liquid metals are generally good thermal conductors as opposed to the fibrous insulating material that make good solid targets. This allows for higher production beam currents on target since the power can be dissipated more quickly. On the other hand, making thin liquid targets is usually more challenging than designing thin solid materials. Liquid targets are often more corrosive than the solid targets we use, so the choice of material for the target holder and the ion source is more important. Even though diffusion rates in liquids are relatively fast, thin liquid targets are desirable to increase the release efficiency for short-lived isotopes. Making thin liquid layers in an open geometry requires that the target material will wet the supporting substrate without interacting so strongly as to destroy the substrate. The vapor pressures of liquids are usually relatively large so at higher target temperatures the ion source efficiency starts to be affected by the high pressures and the overall efficiency for the RIB of interest is decreased. As the liquid surface-to-volume ratio increases (as it will when thin targets are used) the rate of evaporation of the target material will increase, so the target temperature must be limited or the vapors must be trapped before they reach the ion source. In the present configuration the thin liquid targets must be held in a vertical orientation which makes the problem more difficult. In a second RIB production platform that has been proposed we will have the capability to use thin liquid targets that are oriented horizontally since the production beam will irradiate the target from above at some small angle (probably about 15°) with respect to the horizontal axis.

We have used two different liquid metal targets for the production of radioactive nuclei. Liquid germanium was used to deliver radioactive beams of arsenic and gallium

to experiments [5]. The target was about 4 mm thick (10 mm diameter) and the radioactive atoms are produced via proton-induced nuclear reactions using 42 MeV protons. Measurements at the low-intensity On-Line Test Facility (OLTF) and on the RIB Injector indicate that the maximum operating temperature of this target in the present configuration is about 1500 C, corresponding to about 5 μA of 42 MeV protons on target. The ^{69}As beam current on the experimental target was $2x10^6$ particles per second with a beam energy of 2.5 MeV/nucleon. At the same beam energy, the ^{67}Ga beam current on target was $2x10^5$ particles per second. To increase the yield of these beams, we have attempted to make thin liquid Ge targets suspended on various support matrices and to make a target design where the Ge vapors are trapped by condensation on a cooler surface and then recirculated back into the target holder. These attempts have thus far been unsuccessful due to the high reactivity of the liquid Ge with the support materials that have been used (molybdenum, tantalum, tungsten). Graphite has also been used but the surface tension of the Ge is greater than the adhesion to the graphite so the Ge ends up in droplets that increase in size with time until the entire target coalesces into a single drop.

A liquid nickel target was used to produce beams of radioactive isotopes of copper and the efficiencies were measured at the OLTF. The yields were in the range of 10^5 particles per second per microampere of incident proton beam, but the lifetime of the source was very short (~1 day) because the Ni vapors interacted strongly with the tantalum source parts and caused a catastrophic failure. The interaction of nickel with carbon is much more favorable so the next attempt to produce beams of radioactive copper isotopes will be made using a transfer line and source body made of graphite.

The production of beams of radioactive aluminum isotopes on the proton-rich side of stability was recently accomplished using proton-induced and deuteron-induced reactions in a silicon carbide target. The production beam energy was 40 MeV and the radioactive aluminum nuclei were produced in the following reactions; $^{28}Si(p,\alpha)^{25}Al$, $^{28}Si(d,\alpha n)^{25}Al$, $^{28}Si(p,2pn)^{26}Al$, and $^{28}Si(d,\alpha)^{26}Al$. Two different types of SiC target materials have been tested and the yields in both cases were about the same, namely, about 10^4 ions per second per microampere for ^{25}Al and about 2000 ions per second per microampere for the short-lived isomer of ^{26}Al. The deuteron-induced reactions resulted in higher yields in both cases, about 30% higher for ^{25}Al and about a factor of two for ^{26}Al. The radioactive aluminum isotopes were observed both as aluminum ions and as molecular ions. The yield of the molecular ion beam, AlF^+, was comparable to the yield of the Al^+ beam and the molecular beam yield was enhanced when a small amount of SF_6 gas was added to the target during the test.

The production targets that have been tested are a SiC fiber target of 15 μm diameter fibers woven into a cloth material with an overall target density of 0.56 g/cm^3 and a SiC powder target consisting of 1 μm diameter particles that packed to a target density of 1.1 g/cm^3. The maximum operating temperature of SiC is 1650 C at which point the molecule dissociates. Early tests showed that SiC does not sinter, so the short diffusion paths in the powder target will be maintained up to the operating temperatures. At temperatures greater than 1650 C the silicon atoms will interact strongly with the tantalum in the source and will cause failure in a few hours at 1800 C. The next target geometry that is ready for testing is built on a low-density, high-porosity graphite matrix that has been used successfully for our uranium carbide targets [8]. The SiC powder was

suspended in a binder to form a 'paint' that was coated onto the fibers of the graphite matrix. This was then heated to 850 C for one hour to drive off the binder leaving a layer of SiC that is about 2 μm thick. This target has the advantage of short diffusion paths and an open structure which should allow for fast effusion through the target to the ion source.

Another target material that has produced beams of radioactive ions on the proton-rich side of the stable isotopes is cerium sulfide. Radioactive isotopes of chlorine were produced in a cerium sulfide target that consists of a thin layer of CeS material (about 4 μm) deposited onto a tungsten-coated graphite matrix. The graphite matrix is the same material that is used for the uranium carbide targets and the tungsten coating is needed to prevent a reduction of the CeS target material by the carbon in the support matrix. The maximum operating temperature of CeS is 1900 C and after several days of operation at this limiting temperature there were no observed changes in the target material or in the support matrix. Atoms of ^{33}Cl (half-life is 2.5 seconds) and ^{34}Cl (half-life is 32.2 minutes) were produced in the target using both proton-induced and deuteron-induced reactions on the sulfur atoms. No beams of ^{33}Cl were observed in the initial test, but ^{34}Cl was observed both as positively-charged atomic ions and as molecular ions, aluminum chloride, in the range of 10^4 ions per second per microampere of production beam current. The observation of $AlCl^+$ ions is similar to the situation with fluorine beams where it was determined that the fluorine atoms were transported from the target to the ion source as the AlF molecule. Given the results of these initial tests, we believe that the yield of ^{34}Cl can be significantly increased by adding more aluminum vapor to the target environment and by making the CeS target using a material that is enriched in

the ^{34}S isotope. In addition, the negative-ion source that was developed for the fluorine beams [4] will be tested and should work quite well for chlorine beams, thus eliminating the need to convert the AlCl+ ions to negative chlorine ions and the losses that are incumbent in this process.

Radioactive isotopes of silicon, ^{26}Si (half-life is 2.2 seconds) and ^{27}Si (half-life is 4.1 seconds), are produced in proton-induced reactions on ^{27}Al atoms. The target is a low-density, fibrous material of aluminum oxide with fiber diameters of about 6 μm and a density of 0.15 g/cm^3. The thin fibers allow for quick diffusion of the isotopes produced in the target and the open structure results in very short effusion times. This material can be operated at temperatures up to 1900 C, but the initial tests were made at 1750 C because the alumina was in contact with the tantalum target holder, which catalyzes the dissociation of the aluminum oxide molecule at a lower temperature. Most of the radioactive silicon atoms were observed as sulfide molecular ions, which is not too surprising since elements in the same chemical family, Ge and Sn, have been observed to form sulfide molecular ions with high efficiencies in this type of ion source. The measured beam intensity of ^{27}Si was 2000 ions per second per microampere of production beam current and no ^{26}Si ions were observed. The addition of higher concentrations of sulfur atoms in the target to act as a carrier for the silicon atoms, should result in higher yields from the ion source. In addition, if the alumina fibers are well insulated from the tantalum in the target holder and ion source, the operating temperature can be increased, resulting in faster diffusion rates and in higher yields.

A number of recent calculations and experiments with ^{7}Be beams [9,10] are evidence of the presently high level of interest in the physics that can be addressed with

high quality beams of this isotope. The half-life of ^{7}Be is relatively long (53.3 days), so we determined that the best way to make beams of this isotope is to produce the ^{7}Be atoms in a lithium pellet using a (p,n) reaction, separate the beryllium from the lithium using chemical methods, make a sputter target, and produce the beams using a Cs-sputter type ion source. About 10^{16} atoms of ^{7}Be were produced at the Triangle University Nuclear Laboratory in Durham, NC using 8 MeV protons irradiating a lithium pellet. The lithium pellet, containing beryllium, was dissolved and the two elements were separated using an ion exchange column and the difference in solubility of the oxides as a function of solution acidity. The remaining ^{7}Be (~80%), in the form of BeO, was distributed amongst six sputter targets and pressed together with copper powder to form a conductive pellet. These sputter targets will now be inserted for testing into a Cs-sputter type ion source, which is very similar in design to the ion source that is routinely used to inject negative ions of stable isotopes into the tandem. The questions that remain are the sputter rate of the targets, the homogeneity of the ^{7}Be throughout the sputter target, and the ion source efficiency since minor modifications have been made to 'spread out' the Cs sputter pattern on the target.

Uranium Carbide Targets for Neutron-Rich Beams

On the neutron-rich side of the chart of nuclides, the radioactive nuclei are produced as fission fragments in a uranium carbide target, allowing a large number of beams to be extracted from a single target material. This target consists of a thin layer of uranium carbide that is deposited onto the fibers of a rigid, low-density, high-porosity carbon matrix. Figure 3 shows scanning electron micrographs (SEMs) of the carbon

matrix before the coating process and after the uranium carbide coating has been applied. Also shown in Figure 3 is a photograph of the target holder into which the uranium carbide pellets have been placed. The production beam axis is along the long axis of the target holder and the radioactive beams are extracted perpendicular to this and transported to the ion source through a heated tantalum tube operated at about 1800 C.

The uranium carbide (UC) targets are quite durable with the capability to function efficiently for more than 50 days at temperatures in excess of 2100 C. The production beam from our driver accelerator is 42 MeV protons with a current of 10 μA into the target, resulting in about $4x10^{11}$ fissions per second. While the power deposited in the target is modest, 420 W, the average power density is quite high at 97 W/g. The density of these UC targets varies slightly from batch to batch, but the average density is 1.2 g/cm^3 with an overall atomic ratio of carbon to uranium of about three to one. The target thickness is 2.1 g/cm^2 with about 4 g of uranium in the target.

The graphite substrate is a reticulated vitreous carbon (RVC) matrix [8] with a density of 0.06 g/cm^3 and the fiber diameter is about 60 μm. The UC coating on the carbon fibers is homogeneous throughout the RVC matrix with an average coating thickness of about 10 μm. Some larger clusters of UC are also visible throughout the matrix (see Fig. 3). At the present, the UC coatings are applied in the Metals and Ceramics Division at ORNL using a procedure that involves wet chemistry and a series of heating steps [11]. Pellets of the RVC matrix are dipped into a uranyl nitrate solution and then heated to 300 C to convert the uranyl nitrate to uranium oxide. This step is repeated several times until the desired mass of uranium is achieved. Then the pellet is fired to more than 1800 C to convert the oxide into uranium carbide. It is important that

all the uranium oxide is converted before the target is placed into use because excessive vapors of oxygen can cause premature failure in the tantalum parts of the ion source. During the conversion process from the oxide to the carbide, the uranium may interact with the support matrix and cause the pellet to shrink or become very brittle. To prevent this, a suspension of fine carbon powder is added during this conversion step and the dimensions of the UC/RVC pellets are often the same as the original RVC pellet.

Radioactive Beam Development

The present goal of beam development at the HRIBF is not only to develop new beams for the research community, but also to improve the quality of the beams that are presently available. This involves increasing the intensity of the beams delivered to the target and developing techniques to ensure that the delivered radioactive beams have as little isobaric contamination as possible. Target development is necessary to achieve each of these goals. One way to increase the intensity of the delivered radioactive ion beam is to increase the production rate in the target, which means that the target must be designed to withstand higher production beam currents without being destroyed. In general, this means that either the target is modified to allow for faster dissipation of the heat generated in the target, or the target is made larger and the production beam is spread out across the target, thus reducing the power density in the target. Other ways to increase RIB intensity include target modifications (faster release of short-lived nuclei), faster transport mechanisms between the target and ion source, and ion source development to achieve higher ionization efficiencies and lower beam emittance, resulting in better transmission to the experiment. Since negative ions are required for

injection into the post-accelerator, optimization of the charge exchange mechanism can result in higher beam intensities. This may involve changing the beam energy, adjusting the charge exchange cell thickness and medium, or employing a two-step procedure where the ions are neutralized in one cell and then negative ions are formed in a second cell that contains a different vapor.

The purity of the radioactive ion beam is also very important in determining which experiments can be performed. Often, radioactive beams that are produced using the ISOL technique are contaminated with nuclei from the target and from reaction products created by the incident light-ion beam. Most of the contaminant nuclei can be eliminated from the beam using magnetic mass separation but in many cases the resolution of the mass separator is not sufficient to separate isobars having mass differences of less than one part in 15,000. In some unique cases for relatively light ions where the contaminant has fewer protons than the ions of interest, the radioactive beam can be purified by stripping all electrons from the atom after the post-accelerator and selecting the higher charge state in the next magnet before delivering the beam to the experiment. This has worked well for high energy beams of ^{17}F and ^{18}F that are strongly contaminated with oxygen ions from the target.

Ion source selectivity also plays a very important role in the delivery of pure radioactive beams. An example of how this has been used at the HRIBF takes advantage of the fact that negative ions are required for injection into the post-accelerator. Neutron-rich isotopes of bromine and iodine are produced via proton-induced fission in a uranium carbide target. Positive-ion beams of these elements are strongly mixed with isotopes from neighboring elements and the charge exchange efficiencies for Br and I in our

standard Cs-vapor cell are quite low (<1%) and actually lower than for the neighboring elements. Negative ions of Br and I can be made with high efficiency (~15% for Br) directly in an ion source that utilizes surface ionization from a hot LaB_6 surface [12] and the ionization efficiency for neighboring elements is negligible. The extracted beams are pure and the delivered beam intensity from this ion source is about 20 times higher than the best intensities achieved with our standard EBP ion source followed by a Cs-vapor charge exchange cell.

The RIB production targets and the environment in the target region can be tailored to produce beams with high purity. Examples of parameters that can be optimized for specific beams include the target temperature, the target holder material to take advantage of differences in chemical properties, and the addition of vapors to allow for molecular formation and transport to the ion source. The target temperature affects at least two processes that determine the target release efficiency, diffusion out of the target material and effusion through the target matrix and into the ion source. This is especially true for short-lived radioactive nuclei. The effusion times are very element dependent, so changing the target temperature often changes the composition of the extracted beam when more than one species is present. In the case of radioactive silver beams, the purity was enhanced when the target temperature was lowered since the main contaminants, cadmium and indium, were significantly reduced while the silver yield remained unchanged. This technique is also useful when the beam of interest has a relatively long half-life and the half-lives of the contaminants are much shorter.

Sometimes the release efficiency of a particular radioactive isotope can be significantly increased by adding a chemical carrier that combines with the radioactive

atoms of interest to form molecules that are more easily transported to the ion source [13]. At the HRIBF, we recently found that this technique can also be used to purify beams of germanium and tin. When sulfur atoms are added to the target, the sulfide molecules of tin and germanium are extracted with much higher efficiency than observed for the neighboring elements [14,15]. In the mass-132 beam that is extracted from the EBP ion source, ^{132}Sn is 1% of the total beam intensity. When ^{132}Sn is extracted from the ion source as a sulfide molecule, the beam consists of about 96% Sn and 2% each of Sb and Te. This sulfide-molecule technique has been used to deliver highly purified radioactive beams of tin isotopes from ^{128}Sn to ^{134}Sn and germanium isotopes from ^{78}Ge to ^{84}Ge.

The target for the production of ^{7}Be beam that was mentioned earlier is an example of a target preparation technique that was used to reduce the level of the contamination in the desired beam. The ^{7}Be was produced in a lithium target that is comprised of 92.5% ^{7}Li (natural abundance). If the beryllium were not chemically separated from the lithium, the amount of beryllium in the extracted beam would be negligible. Tests will be made soon to determine the extent of the chemical separation and the process will be refined, if necessary, to allow pure beams of ^{7}Be to be delivered to experiments.

Summary

Over the last few years a large number of radioactive ion beams have been produced at the HRIBF and delivered to experiments [16]. To accomplish this, it was necessary to develop several different production targets that were optimized for the

high-intensity, low-energy, light-ion beams that are available from the driver accelerator. A vigorous target research program is vital to the success of an ISOL-based RIB facility. The authors wish to acknowledge the efforts of the entire HRIBF staff in the design, construction and maintenance of this accelerator facility which makes the development and use of these ISOL-type targets possible. The preparation of the ^{7}Be targets was initiated and conducted by Jeff Blackmon at ORNL, in consultation with Uwe Greife at the Colorado School of Mines. Research at the Oak Ridge National Laboratory is supported by the U.S. Department of Energy under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

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Figure Captions

Figure 1. A schematic layout (not to scale) of the Holifield Radioactive Ion Beam Facility showing the RIB production target and the relative positions of the driver accelerator, RIB production platform, and the post-accelerator.

Figure 2. The RIB production target for ^{17}F and ^{18}F. The top panel is a photograph of two HfO_2 rolls, the Al_2O_3 sheath, and the tantalum target holder. The lower panel is a drawing of the target showing the four hafnia rolls, the surrounding alumina sheath, the beam direction, and a piece of the tantalum transfer line that connects the target to the ion source.

Figure 3. The uranium carbide target for the production of neutron-rich radioactive beams. The top panels show micrographs of the graphite matrix before and after the UC coating has been applied. The lower portion is a photograph of the UC targets in a graphite holder that is inserted into a tantalum target holder. The photograph also shows the transfer line that connects the target to the ion source.

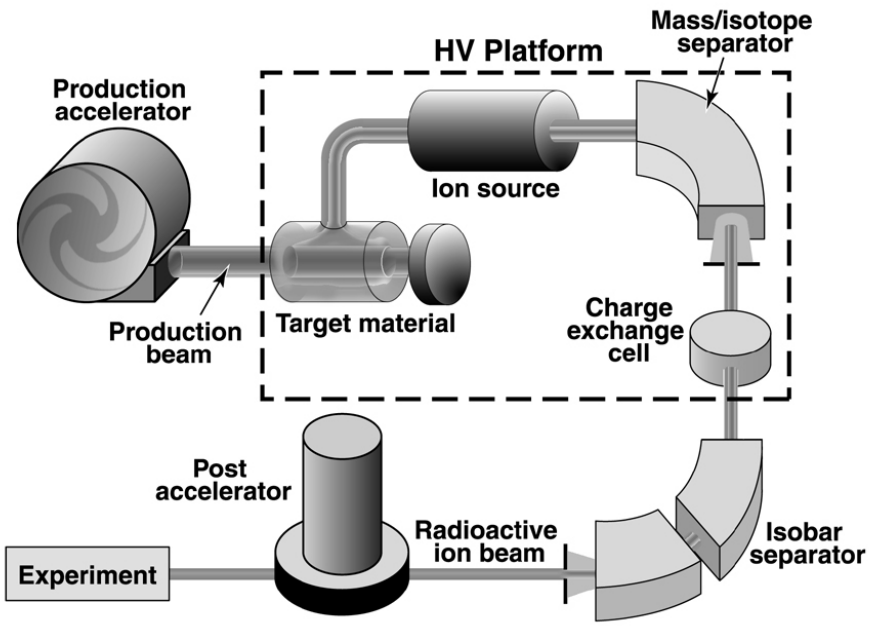
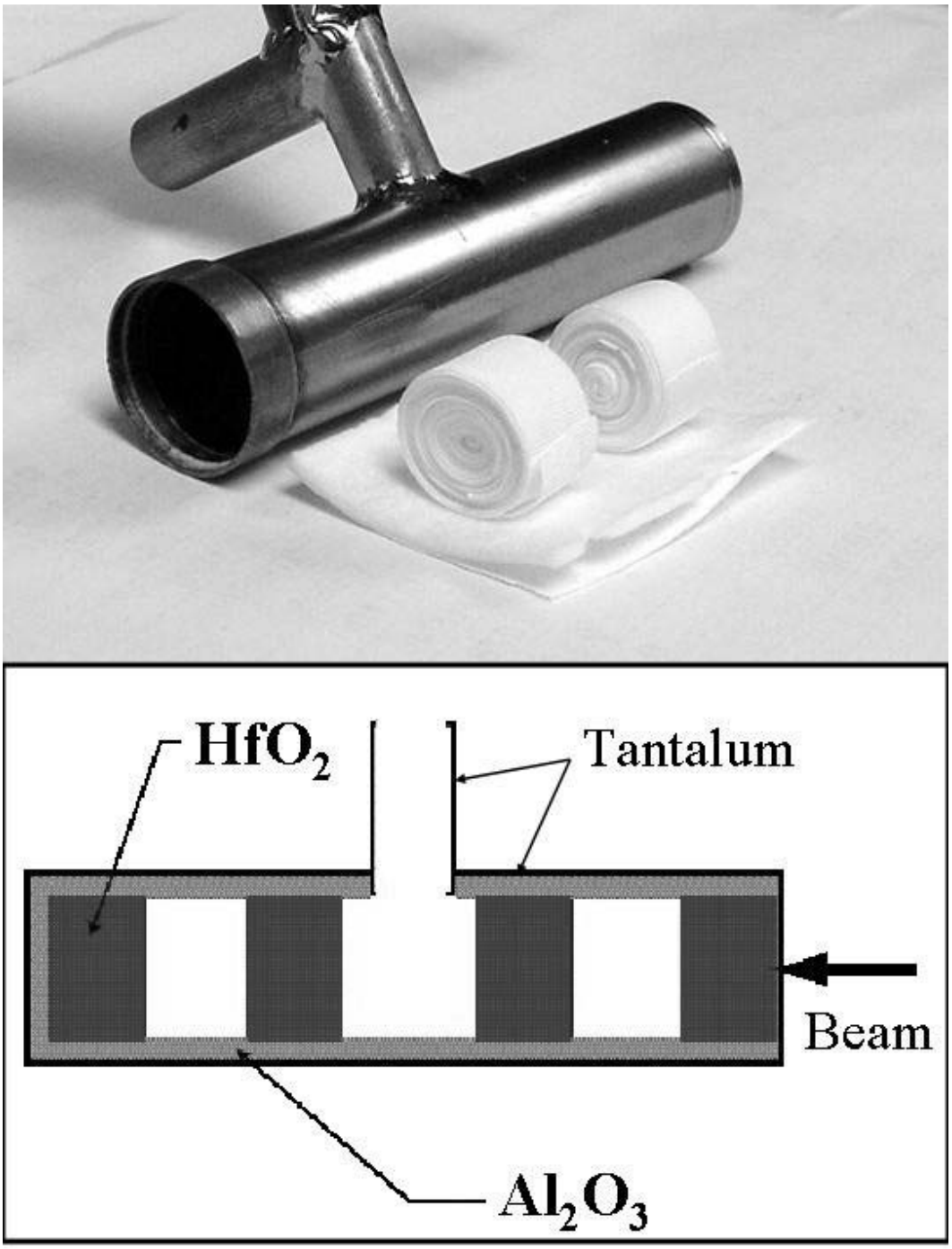


Figure 1. A schematic layout (not to scale) of the Holifield Radioactive Ion Beam Facility showing the RIB production target and the relative positions of the driver accelerator, RIB production platform, and the post-accelerator.



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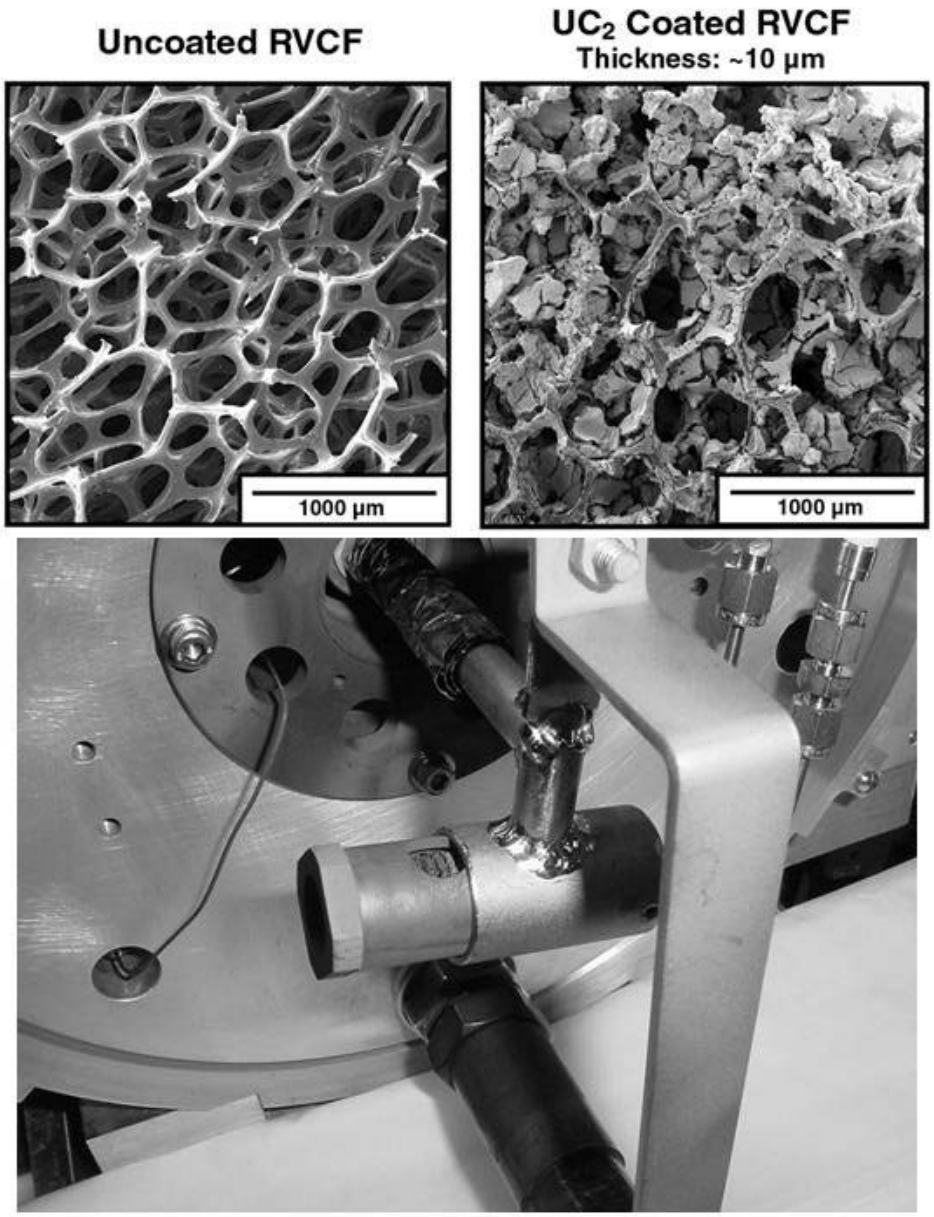

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