Reference Number: 103

STATUS OF RADIOACTIVE ION BEAMS AT THE HRIBF

D.W. Stracener*

Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Radioactive ion beams at the Holifield Radioactive Ion Beam Facility are produced using the ISOL technique and are subsequently accelerated up to a few MeV per nucleon for use in nuclear physics experiments. The first radioactive ion beam experiments at the HRIBF were completed at the end of 1998 using ^{17}F beams. Since then other proton-rich ion beams have been developed and a large number of neutron-rich ion beams are now available. The neutron-rich radioactive nuclei are produced via proton-induced fission of uranium in a low-density matrix of uranium carbide. Recently developed radioactive ion beams include ^{25}Al from a silicon carbide target and isobarically pure beams of neutron-rich Ge, Sn, Br, and I isotopes from a uranium carbide target.

PACS: 01.52.tr; 29.25.Ni; 29.25.Rm; 41.75.Cn

Keywords: RIB facility, ISOL production target, accelerated radioactive beams, negative ion source

Corresponding author: Dan Stracener
Address: *Oak* Ridge National Laboratory
P.O. Box 2008, Bldg. 6000, M/S 6368,
Oak Ridge, TN 37831, USA.
Telephone: + 865-576-8766 Fax: + 865-574-1268
E-mail address: stracener@mail.phy.ornl.gov

---

* Spokesman for the HRIBF Staff

Facility Overview

The Holifield Radioactive Ion Beam Facility (HRIBF), at the Oak Ridge National Laboratory, utilizes the ISOL (isotope separation on-line) technique to produce ion beams of short-lived radioactive nuclei. The nuclei of interest are produced by bombarding a thick target with high intensity beams of light ions. The radioactive atoms diffuse out of the target matrix, are transported to an ion source, ionized, extracted at 40 keV, and then mass separated. The HRIBF is unique in that these low energy beams are then injected into a second accelerator and accelerated up 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 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 radioactive ion beam (RIB) production target. The maximum production beam intensity has been limited by the ability of the RIB production target to dissipate the deposited power. Proton and deuteron beams with intensities up to 8×10^{13} pps (alphas up to 2×10^{13} pps) have been delivered to RIB production targets.

The post-accelerator at the HRIBF is a folded-geometry 25-MV tandem electrostatic accelerator 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<100), single-stripping allows for acceleration up to at least 5 MeV per nucleon, but for heavy ions (A>100), a second stripping about a third of the way down the high energy side is required to achieve this energy. The accelerated radioactive ion beams are often comprised of several isobars that are accelerated along with the beam of interest. One technique used to separate isobars of lower mass ions (A<40) is to fully strip the ions after acceleration in the tandem but before the energy-analyzing magnet at the base of the tandem. This technique was used recently to separate ^{17}F ions from the large ^{17}O contamination and allowed a pure ^{17}F beam to be delivered to the experiment.

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 [1] for the production of fluorine beams and a general purpose, high efficiency electron beam plasma (EBP) ion source [2] 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.

An important part of any RIB facility is the experimental equipment since RIB experiments can be quite challenging due to low beam intensities and high β and γ-ray background from the decay of the beam and its daughter nuclei. The HRIBF has a number of versatile and powerful detector systems available that have been optimized for

use with low-intensity beams. There are three major experimental end stations in use at the HRIBF; the Recoil Mass Spectrometer (RMS) [3] used mainly in nuclear structure experiments, the Daresbury Recoil Separator (DRS) [4] used in support of the astrophysics research program, and the Enge Spectrograph [5] that is mostly used in reaction studies. The detector systems that are available for use with these large devices include: CLARION - an array of 11 segmented Clover Ge γ-ray detectors, HYBALL – a 95-element CsI(Tl) charged particle detector, several arrays of silicon strip dE-E detectors, Microchannel Plate (MCP) detectors – for low-intensity beam diagnostics and counting, CARDS – Ge detectors coupled to a moving tape collector, and various ionization chambers. At the DRS a windowless gas target is being developed that will be used to produce a hydrogen target with a thickness of –15mg/cm^2 (10^{19} atoms).

Radioactive Ion Beam Development

The first accelerated radioactive beam (^{69}As) was delivered to an experiment at the HRIBF in June of 1997. Since then a number of radioactive ion beams have been developed and used for nuclear physics experiments as shown in Table 1. Fluorine beams first became available in December 1998 and for the next two years, ^{17}F and ^{18}F were the mainstay of RIB operations [6]. The fluorine is produced in a HfO_2 fiber target using the ^{16}O(d,n)^{17}F, and ^{16}O(α,pn)^{18}F reactions. The microscopic structure of the HfO_2 target is shown in Figure 2. After diffusing out of the hafnium oxide fibers, the fluorine atoms combine with aluminum to form AlF molecules, which then migrate to the ion source where a fluorine beam is formed. The aluminum vapor is supplied from a small

amount of aluminum oxide fibers that are added to the target during installation. The ion source used for this purpose is a unique design optimized for the production of negative fluorine beams [1]. Beginning in the winter of 2000, the first experiments using neutron-rich beams from the fission of uranium were completed [7,8]. The uranium target is made of a thin layer (~10μm) of uranium carbide that is deposited onto the fibers of a rugged, low-density, high-porosity carbon matrix as shown in Figure 2. Both positive-ion and negative-ion sources are used with this target to provide the best quality of neutron-rich beams possible.

At the HRIBF considerable effort is expended to provide new radioactive ion beams for use in nuclear physics experiments. Recently, a silicon carbide target, coupled to an EBP ion source, was used to produce beams of ^{25}Al and ^{26}Al [9]. Two types of targets were used: a SiC fiber (15 μm dia.) target and a SiC powder (1 μm dia.) target. In both cases, the positive ion yields were about 10^4 pps per μA of production beam (40 MeV protons). Additional tests are planned using another target where a thin layer of SiC is deposited onto a low-density carbon matrix, similar to that used in the uranium carbide targets.

There is also a continuous effort to improve the quality of the available radioactive ion beams. The RIB quality is here defined as the intensity of the beam delivered to an experimental end station as well as the homogeneity, or purity, of the beam. Often the proposed experiments **seek** to study processes that have relatively low probabilities, so improved beam quality, along with better detector capabilities, can significantly shorten the amount of time required for a given experiment.

One way to increase the RIB intensity is to increase the production rate of the radioactive nucleus in the ISOL target. At the HRIBF, the light-ion production beam energy is fixed but the beam intensity may be increased. As the intensity increases, the rate of production increases and, generally, the target temperature also increases, which can lead to damage in the target. Design and testing of a larger target holder has begun, which will allow the production beam to be rastered around the target and thus reduce the power density in the target. In addition, more refractory targets (e.g. ThC instead of UC) and ion sources with higher ionization efficiencies are also being considered as means to increase the intensity of radioactive ion beams delivered to experiments.

The other area of research in developing radioactive ion beams of higher quality is the improvement of the beam purity. Beam purity can be enhanced using a variety of techniques including development of ion sources that have high ionization selectivity, using chemical properties to select a particular element, and reducing the emittance of the beam to allow for magnetic isobar separation. If a negative ion beam is required, selective charge exchange schemes may also be used to enhance the yield of one element over another. Examples of how some of these techniques are applied at the HRIBF are discussed in the following paragraphs.

Pure beams of Germanium and Tin isotopes

A large number of fission-fragment ion beams have been extracted from an EBP ion source coupled to a uranium carbide target. The radioactive nuclei are produced via proton-induced fission in the uranium using 42 MeV protons. The extracted beam quality in most cases is quite good and many useful beams can be delivered to experiments.

Unfortunately, some of the more interesting beams are comprised of several isobars that have very small mass differences and thus cannot be separated in the high-resolution magnetic mass separator. For example, the mass-132 beam consists of 87% Te, 12% Sb, and 1% Sn and the Sn isotope is the nucleus of interest. The solution to this problem was recently discovered in an ion source that had a small contamination of sulfur from a previous test. When the Sn isotopes are extracted from the ion source as SnS^+ molecular beams the intensity of the TeS^+ and SbS^+ beams are at least four orders of magnitude lower and below the detection threshold. The ratio of the intensity of the SnS^+ beam to the intensity of the Sn' beam varies as a function of radioactive half-life of the Sn isotope as shown in Figure 3. For relatively short half-lives, the SnS^+/Sn^+ ratio is higher which indicates that the mobility of the SnS molecule in the target and ion source is higher than for the elemental Sn. The SnS^+ beam is converted to a Sn^- beam in a Cs-vapor charge exchange cell with an efficiency of about 40% but this introduces an energy spread of about 400 eV due to the molecular breakup. The measured intensities of the Sn^- beam at a point just before injection into the tandem accelerator indicate that the transmission losses are about 25% greater when the Sn is extracted from the ion source as SnS^+ than when it is extracted as a Sn^+ beam. The intensities of the SnS^+ beams are dependent on the sulfur vapor concentration in the target and the sulfur is now introduced in a controlled manner using a variable leak of H_2S gas into the system.

This technique also works for Ge, which is in the same chemical family as Sn. The negative Ge beam is strongly contaminated with isotopes of Ga, As, and Se when it is extracted from the ion source as a Ge^+ beam but is essentially pure when extracted as a GeS^+ beam. The GeS^+/Ge^+ ratio is about 2 for the short-lived Ge isotopes. It has been

predicted that this technique will also work for silicon beams [10]. Interesting beams of short-lived silicon isotopes (^{26}Si and ^{27}Si) can be produced from ^{27}Al using (p,n) and (p,2n) reactions. We are now investigating the possibility of using an aluminum oxide target coupled to an EBP ion source to see if beams of SiS^+ can be produced.

Pure Beams of Bromine and Iodine Isotopes

From a uranium carbide target and an EBP ion source, beams of bromine and iodine isotopes are extracted but they are mixed with isotopes of the neighboring elements. For example, the mass-88 positive ion beam consists of 7% Br, 33% Kr, and 60% Rb. Even after the Cs-vapor charge exchange cell, this negative ion beam is still a mixture of 26% Br and 74% Rb. Recent tests with an ion source that produces negative ion beams from a hot LaB_6 surface have shown that pure beams of bromine and iodine isotopes can be delivered. This LaB_6 ion source [11] produces a high quality negative ion beam so the need for a charge exchange cell is eliminated. The yield for Br isotopes from this source is about 25 times greater than the yield from the EBP ion source followed by charge exchange. For iodine isotopes, the gain in yield is about a factor of 10 for the LaB_6 ion source over the EBP ion source.

Acknowledgements

The author wishes to acknowledge that this paper is only possible due to the efforts of the entire HRIBF Staff. 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.

References

[1] G.D. Alton, et al., Nucl. Instr. and Meth. B 170 (2000) 515.

[2] H.K. Carter, et al., Nucl. Instr. and Meth. B 126 (1997) 166.

[3] C.J. Gross, et al., Nucl. Instr. and Meth. **A** 450 (2000) 12.

[4] A.N. James, et al., Nucl. Instr. and Meth. A 267 (1988) 144.

[5] J.F. Liang, et al., Nucl. Instr. and Meth. A 435 (1999) 393.

[6] R.F. Welton, Nucl. Phys. A 701 (2002) 452c.

[7] D.W. Stracener, in: J.L. Duggan, I.L. Morgan (Eds.), Proceedings of the Sixteenth Int'l. Conf. on the Application of Accelerators in Research and Industry, CP576, AIP Press, New York, 2000, pp. 257-260.

[8] Tables of available RIB intensities can be found on the HRIBF website at www.phy.ornl.gov/hribf/users/beams/.

[9] In the HRIBF Newsletter, Article RA1, accessible at the following website - www.phy.ornl.gov/hribf/usersgroup/news/fall_01.html.

[10] R. Kirchner, Nucl. Instr. and Meth. B (these proceedings).

[11] H. Zaim, et al., in: J.L. Duggan, I.L. Morgan (Eds.), Proceedings of the Sixteenth Int'l. Conf. on the Application of Accelerators in Research and Industry, CP576, AIP Press, New York, 2000, p. 244.

Table 1: Accelerated Radioactive Beams delivered to physics experiments at the HRIBF.

Radioactive Beam (isotope of interest)	Energy Range (MeV)	Highest Intensity (ions/sec on target)	Purity (%)
^{17}F	10-170	1.0×10^7	33/100
^{18}F	10-25	3.0×10^5	10
^{67}Ga	160	2.5×10^5	>90
^{69}As	160	2.0×10^6	–10
^{78}Ge	175	1.5×10^6	38
^{80}Ge	179	1.8×10^6	10
^{117}Ag	460	1.2×10^6	95
^{118}Ag	455	1.5×10^6	90
^{126}Sn	378	1.0×10^7	50
^{128}Sn	384	2.5×10^6	20
^{132}Te	350-396	5.0×10^6	87
^{134}Te	396-560	2.4×10^6	70
^{136}Te	396	5.0×10^5	50

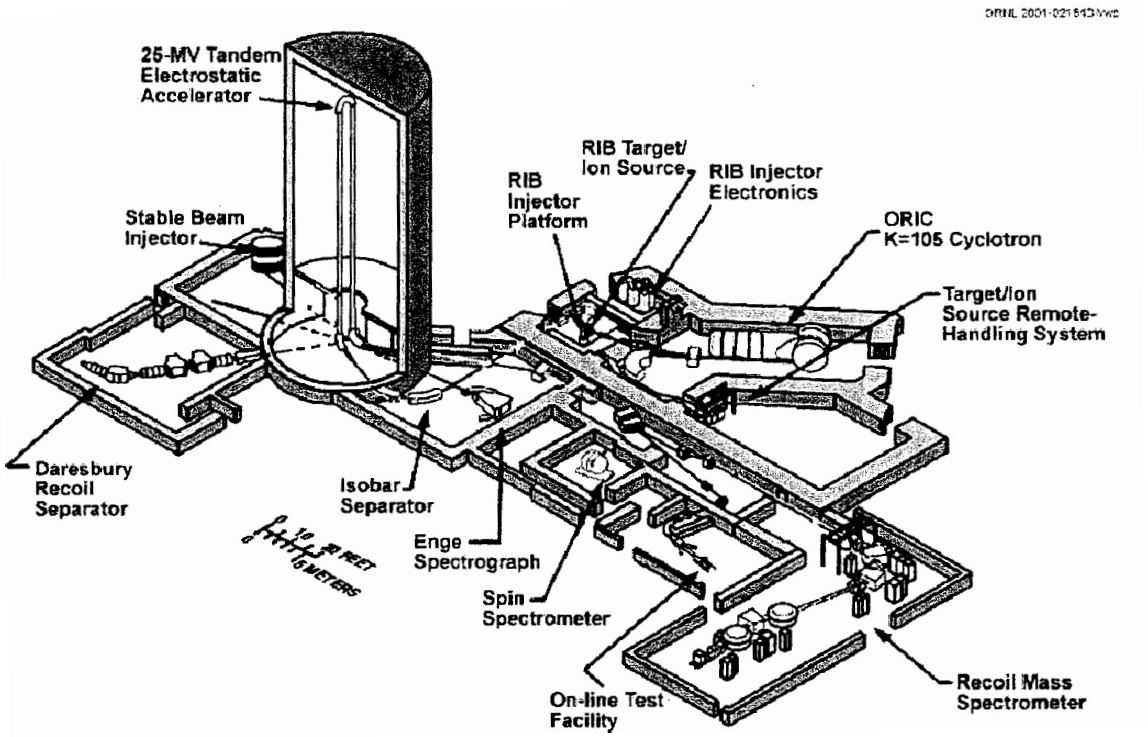

Figure 1: **A** schematic drawing of the Holifield Radioactive Ion Beam Facility showing the two particle accelerators, the RIB production platform, the on-line target and ion source test facility, and the principal experimental equipment.

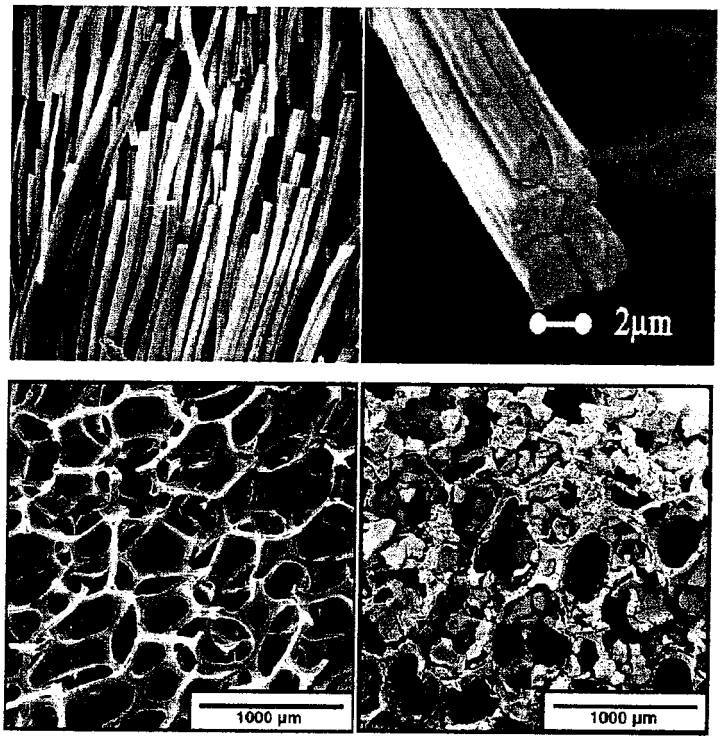

Figure 2: Targets used for RIB production at the HRIBF. The top panels show SEMs of the HfO_2 fibers at two different magnifications. **The** bottom panels show SEMs of the uranium carbide target. The left panel shows the uncoated carbon matrix and the right panel shows the target with the uranium carbide coating.

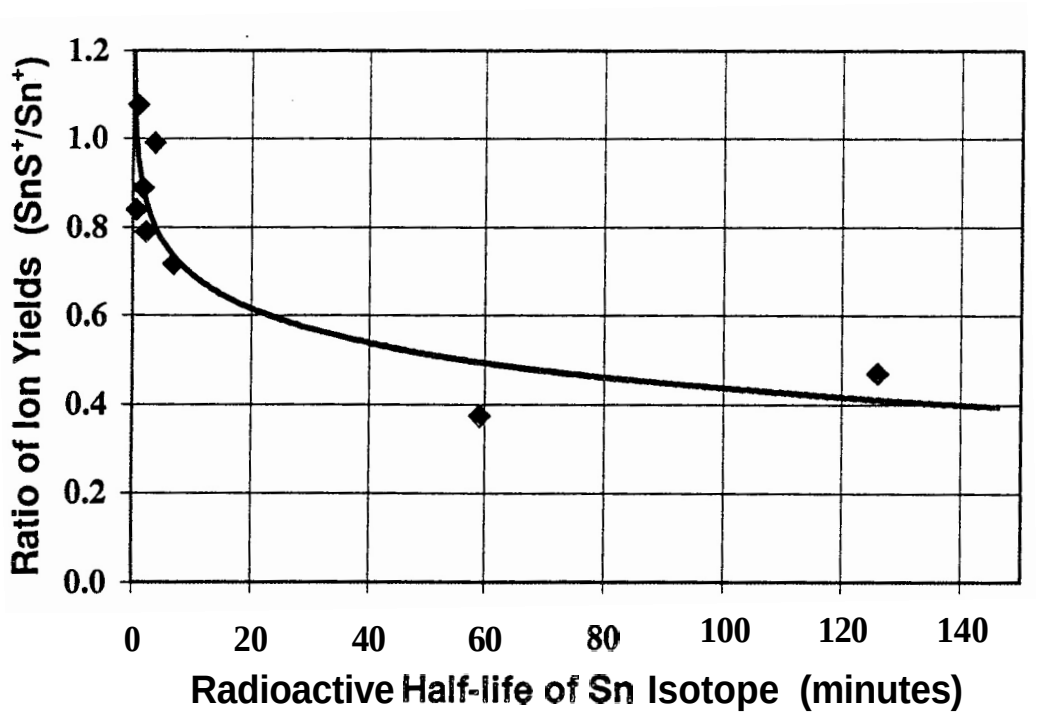

Figure 3: Ratio of beam intensities (SnS^+/Sn^+) from an EBP ion source as a function of radioactive half-life of several tin isotopes. The ratio is larger for Sn isotopes with relatively short half-lives, indicating that SnS molecules have a higher mobility in the target and ion source than the Sn atoms.