Radioactive Ion Beams at the HRIBF

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Abstract. The Holifield Radioactive Ion Beam Facility (HRIBF) is now delivering beams of radioactive ions for nuclear physics experiments. The radioactive ions are produced using the Isotope-Separator-On-Line (ISOL) technique and then injected into a 25 MV tandem electrostatic accelerator and accelerated to energies of 0.1 – 10 MeV per nucleon for light nuclei and up to 5 MeV per nucleon for nuclei heavier than 100 amu. In the past year, the facility has provided almost 1200 hours of ^{17}F and ^{18}F beams for research with intensities up to 3×10^6 ions/s on target. Also, the facility has provided beams of neutron-rich radioactive ions using proton-induced fission in a highly permeable uranium carbide target. The first such beam delivered to an experiment was ^{118}Ag with intensities up to 2×10^6 ions/s on target. Details of the techniques used to produce these beams and other beam development projects will be discussed.

INTRODUCTION

The HRIBF, at the Oak Ridge National Laboratory, utilizes the ISOL 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 diagram of the ISOL process as implemented at the HRIBF is shown in Figure 1. Brief descriptions of the driver accelerator, the Radioactive Ion Beam (RIB) Injector, and the post-accelerator systems are given in the next section. Details of the development of ^{17,18}F beams and neutron-rich beams are also presented in this paper.

ACCELERATOR SYSTEMS

The driver accelerator for the facility is the Oak Ridge Isochronous Cyclotron (ORIC), which was first commissioned in 1962. The ORIC is a variable energy cyclotron (k=100) and in the present configuration has delivered high-intensity beams of protons at 42 MeV, deuterons at 49 MeV, and 85 MeV for ^{4}He beams. The maximum beam intensity delivered has been limited by the ability of the RIB production target to dissipate the power deposited in the target. Proton and deuteron beams with intensities up to 12 μA have been delivered to RIB production targets. The reliability of the cyclotron has greatly improved due to a number of improvements made over the last couple of years. These include the replacement of several aging power supplies (one of which was built in 1938), improved extraction efficiency (1), and a change in the design of

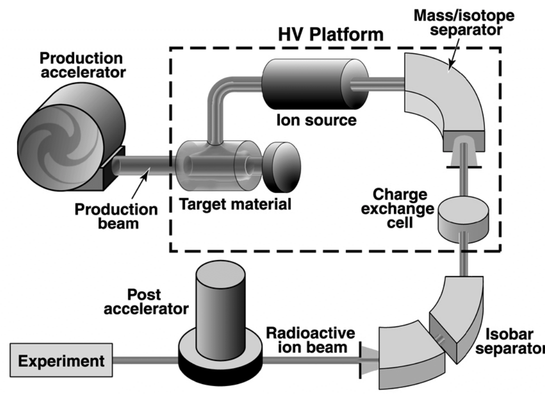

FIGURE 1. Shown are the various elements of the HRIBF for the production and acceleration of RIB's. (not to scale)

the ORIC ion source, which improved the operational lifetime from 300 hours to more than 800 hours.

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Recently, the cyclotron operated nearly continuously for a three-month period.

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 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 is enough to allow for acceleration up to ~5 MeV per nucleon, but for heavy ions (A>100) a second stripping is required to achieve this energy. Double-stripping has successfully been used with radioactive ion beams at intensities of 10^6 ions/second. Often, the radioactive ion beams contain several isobars that are accelerated along with the beam of interest. One technique used to separate isobars of light ions is to fully strip the ions after acceleration in the tandem. This technique was used recently to separate ^{17}F ions from the large ^{17}O contamination.

These two accelerators are linked together by the RIB Injector that is comprised of the production target, the ion source, initial mass separation, and acceleration of negatively charged ions to 200 keV for injection into the tandem. The main component is the target/ion source (TIS) and its enclosure. Two TIS systems have been used in the past year for production of $^{17,18}F$ beams from a hafnium oxide target, and neutron-rich beams from proton-induced fission of uranium. Both of these have been quite successful and have provided beams of sufficient quality, intensity, and duration to facilitate the completion of several experiments as shown in Table 1. The success of these two systems was due to recent improvements and modifications to the RIB Injector. The TIS enclosure has been modified to increase its reliability and lifetime in the high-temperature and high-radiation environment present on the RIB Injector. A new Cs-vapor charge exchange cell has been installed, which gives longer operational lifetimes, better reliability, and better transmission than the previous version. A tape system has been installed after the isobar-separator magnet to allow for analysis of the intensity and purity of the beam. Since several isobars may be present in the beam, target/ion source parameters and beam-tuning parameters will be adjusted to optimize the purity of the beam.

^{17,18}F BEAM DEVELOPMENT

The target/ion source system used to produce the fluorine beams consisted of a Kinetic Ejection Negative Ion Source (2) coupled to a target of hafnium oxide fibers (3). A SEM of these HfO_2 fibers is shown in Figure 2. The radioactive fluorine isotopes were produced in the oxide target via the $^{16}O(d,n)^{17}F$ and the $^{16}O(\alpha,pn)^{18}F$ reactions, using 45 MeV deuterons and 85 MeV α-particles. The intensity of the beam on the production target was limited to less than 3 μA since previous tests with high intensity beams from ORIC had shown that the target rapidly deteriorated at higher beam currents. The low-density (1.15 g/cm^3) hafnia-fiber target consisted of four rolls, each having a diameter of 15 cm and a length, along the beam axis, of 1 cm. The rolls were separated along the beam axis by ~1 cm to allow heat to radiate out to the walls of the target holder. Previous tests had shown that the yield of $^{17}F^-$ was enhanced if a small amount of Al_2O_3 was present in the target holder, so a liner of alumina fiber material was placed around the hafnia cylinders. This TIS and its enclosure operated without failure for 1420 hours (59 days) and was working when it was removed. The target was irradiated for more than 3400 μA-hours with deposited power per unit length of 52 W/g/cm^2. As shown in Table 1, seven experiments (4,5) were recently completed with radioactive fluorine beams.

TABLE 1. Radioactive Ion Beams Delivered to Experiments During the Last Year

RIB Species	Beam Energy (MeV)	Beam Intensity (ions/second)	# of hours beam-on-target	# of Completed Experiments
^{17}F	10 – 68	3×10^6	1060	5
^{18}F	10 – 14	6×10^5	120	2
^{117}Ag	460	1×10^6	72	detector tests
^{118}Ag	500	2×10^6	240	1
^{126}Sn	300	$> 10^5$	4	low-intensity diagnostics tests
^{134}Te	300	1×10^6	8	

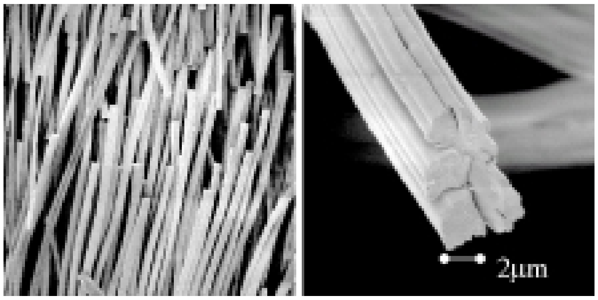

FIGURE 2. These SEM's show the HfO_2 target material used in the production of radioactive fluorine beams.

NEUTRON-RICH BEAMS

At the HRIBF, the focus of the various beam development projects for the last few years has been on proton-rich isotopes of As, Ga, Cu, Ni, and F (1,3,6). After tests of a uranium carbide target at the UNISOR Facility (7) using low-intensity proton beams from the tandem, administrative approval was recently granted to use a fissionable target on the RIB Injector. The ion source used was an Electron-Beam-Plasma Ion Source (EBPIS) (8) and was operated for more than 1200 hours (50 days) without a failure.

The target, supplied by Babcock and Wilcox, McDermott Technologies of Lynchburg, VA, is a low density highly permeable graphite matrix coated with a thin layer of uranium carbide (9). Scanning electron micrographs of the reticulated vitreous carbon (RVC) matrix before and after coating are shown in Figure 3. The fibers of the RVC matrix are ~60 µm thick and the material has a density of 0.06 g/cm^3. After the coating process, the surface layer was analyzed and found to be ~12 µm thick and to contain an atomic ratio of U:C of 1:1.85. The density of the coated matrix was 1.34 g/cm^3 with an overall U:C mass ratio of 6.6:1. The target material was delivered as disks that were 15 mm in diameter and 2 mm thick. Nine of these disks were used for the target on the RIB Injector, which resulted in a uranium target thickness of 2.1 g/cm^2. The target thickness was chosen to allow a 40 MeV proton beam to exit with 15 MeV since the cross-section for proton-induced fission drops off rapidly for proton energies less than 18 MeV. Also, since less power is deposited in the target, the operating temperatures should be lower, resulting in longer operational lifetimes. No significant decrease in yields was observed during a period of 12 days during which there was an average proton beam intensity of 10 µA on target. The average beam power deposited per unit length in this target was 125 W/g/cm^2. Not only did the ion source and the target perform above expectations, but the enclosure also endured the thermally and radiologically harsh environment. More than 5000 µA-hours were logged on this TIS and its enclosure before a vacuum leak began to develop. However, this problem was slow to develop and the system was used for several days after the leak was first noticed.

A survey of positive ion yields from this TIS was made using a tape system and a γ-ray detector that were located just off the RIB Injector Platform. At least 130 isotopes of 20 different elements were observed between ^{78}Ga and ^{144}La. Not all elements in that range were observed since some are quite refractory (e.g. Zr-Rh) and will not be released from the target. Some, observed as positive ions, will not be available as accelerated beams because either they do not form negative ions (e.g. noble gases) or the charge exchange efficiencies are very small. A table of the measured yields can be viewed on-line on the HRIBF Website (10). After the initial survey of yields, several beams were tuned through the tandem and accelerated to experimental stations (see Table 1).

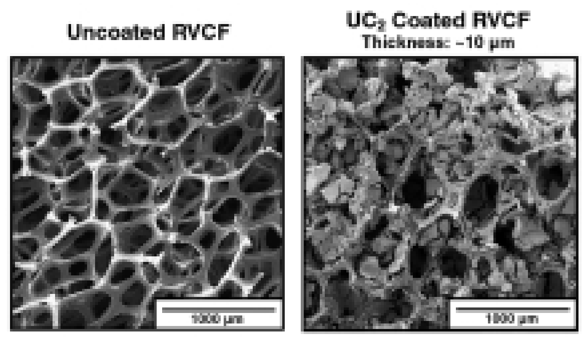

FIGURE 3. SEM's of the graphite matrix used for the uranium carbide targets, before and after coating.

OTHER BEAM DEVELOPMENT

While the main effort of the facility has been focused on the aforementioned development projects, other targets and ion sources are being developed and tested. An ion source for long-lived RIB's has been tested extensively off-line and is ready for installation on the RIB Injector. This source (6), called the batch-mode source, is a multi-sample, Cs-sputter type source that produces negative ions directly. It is similar to the source that has been used for almost 20 years in the stable-ion injector for the tandem with the added feature of a rotating target wheel with up to eight different target positions. The sputter target is initially aligned with the ORIC beamline and the radioactive species of interest is produced in nuclear reactions using intense beams of light ions. This target is then rotated 90° into the sputter region where the negative ions are formed and extracted to form the beam. While this target is being used, the next target is irradiated with the production beam. The frequency at which the target wheel is rotated depends on the half-life of the isotope of interest. This ion source will initially be used on the RIB Injector with four graphite pellets to produce beams of ^{11}C (T_ = 20.3 m) and four CaF_2 pellets to produce beams of ^{18}F (T_ = 110 m). After these runs, nickel pellets will be inserted to produce ^{56}Ni beams.

Interest in neutron-rich isotopes of bromine is strong in the nuclear structure community and the release efficiency of bromine from the uranium carbide target is quite good. The measured positive-ion yields from this target coupled to an EBP ion source are ~10^8 ions/s but the charge exchange efficiency of bromine in a Cs-vapor cell is quite low (~1%). To overcome this limitation, a negative surface ionization source, using a LaB_6 surface, has recently been tested and optimized for the direct production of negative ions of bromine (11). This source has an efficiency for Br (~10%) that is comparable to the efficiency of the EBPIS but with the advantage that the ions are already negatively charged and thus no charge exchange is needed. With the negative surface ionization source, the intensities of bromine beams delivered to experiments should be two orders of magnitude higher. This will soon be tested on-line at the UNISOR Facility (7).

A positive surface ionization source using a hot tantalum or tungsten surface is being developed and tested for use with electropositive elements such as rubidium and strontium. These two elements, in particular, have high production rates in the uranium carbide target and have high release efficiencies. This type of source has been shown to have a very high efficiency (up to 90%) for the Group I elements and good efficiencies for many other elements (12). While the charge exchange efficiency for Rb is low (0.3%), this source should result in at least one order of magnitude improvement in the extracted beam intensities measured from the EBPIS and should deliver beam-on-target intensities of 10^6 ions/s for Rb isotopes with half-lives greater than one second.

Another type of uranium carbide target, built on a carbon matrix with a high thermal conductivity, has been tested recently. Details of this target are given in Ref. 13. Other targets under development include SiC (powder and fibers) for ^{25}Al beams and CeS powder for beams of $^{33,34}Cl$.

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