FIRST ON-LINE RESULTS FOR As AND F BEAMS FROM HRIBF TARGET / ION SOURCES

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The first on-line tests of the ion sources to provide radioactive ion beams of $^{69,70}\text{As}$ and $^{17,18}\text{F}$ for the Holifield Radioactive Ion Beam Facility (HRIBF) have been performed using the UNISOR facility at HRIBF. The target/ion source is an electron beam plasma (EBP) source similar to the ISOLDE design. The measured efficiencies for ^{69}As and ^{70}As were $0.5 \pm 0.2\%$ and $0.8 \pm 0.3\%$, respectively. The arsenic hold-up time in the tested target/ion source was 3.6 ± 0.3 hours as measured with ^{72}As at a target temperature of 1300°C . The measured efficiencies for ^{17}F and ^{18}F were $0.0052 \pm 0.0008\%$ and $0.06 \pm 0.02\%$, respectively. The source hold-up time for fluorine was measured with Al^{18}F since 88% of the observed radioactive fluorine was found in this molecule. The Al^{18}F hold-up time was 16.4 ± 0.8 minutes at a target temperature of 1470°C .

INTRODUCTION

The recently completed Holifield Radioactive Ion Beam Facility (HRIBF) is designed to provide energetic radioactive ion beams for nuclear physics and nuclear astrophysics research. To produce these beams, light ions from the K=100 Oak Ridge Isochronous Cyclotron (ORIC) will impact a thick target in the ion source of an isotope separator. The extracted radioactive ions, after mass analysis and charge exchange, are injected into the 25 MV tandem accelerator. One of the most challenging aspects of this project is the performance of the target/ion source of the isotope separator. This paper presents results of on-line tests of the initial version of the ion source used to produce arsenic beams. Also, preliminary results for fluorine beams from a similar source are described.

EXPERIMENTAL RESULTS

The UNISOR (1) separator on-line to the Holifield tandem accelerator provides a unique capability (2) to investigate target/ion source performance. Proton and deuteron beams of energy up to 40 MeV are used to produce the desired radioisotopes directly in the target/ion source under investigation. The mass separated ions are counted using traditional on-line nuclear spectroscopy techniques with a moving tape system, γ -ray detector and spectrum multiscaling techniques. Alternatively, in experiments prior to those reported here, heavy ion implantation experiments

similar to those of Kirchner (3) were used to measure release times and efficiencies of various beam/target combinations (2) in preparation for designing and constructing the target/ion source used here.

Target/Ion Source

The target/ion source used in these studies is a modified version of the general design (4) for the HRIBF facility which is similar to the CERN/ISOLDE design (5). Figure 1 shows the electron beam plasma ion source as used in these experiments. The following modifications were made specifically for a liquid germanium target which will be used to produce radioactive arsenic ion beams. Since the vapor pressure of germanium is 10^{-4} torr at 1100°C , it was expected that this would be the maximum operating temperature for the target. With this in mind, the design of the target heater was simplified to a single-pass current path, with an attached heat shield. The cathode current connection was moved from midway along the cathode transfer tube to the rear-most point. This ensures that the transfer line will be at the highest possible temperature which will help to reduce the sticking time (6) of arsenic on the tantalum surfaces. Several layers of 0.025 mm thick tantalum around the transfer line provide additional heat shielding. A carbon target holder, with a 1 mm thick entrance window, is used since tantalum reacts strongly with germanium. The germanium target, designed to stop 40 MeV protons, is 4 mm thick by 9 mm diameter.

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FIGURE 1. Axial cut of the HRIBF liquid germanium target/ion source. Part numbers and construction material are indicated: 1. cathode current lead (Ta), 2. gas (Xe) transfer line (Ta), 3. transfer line (Ta), 4. head flange (C), 5. outer tube (C), 6. heat shields (Mo or Ta), 7. cathode support nut (Mo), 8. anode support tube (Ta), 9. cathode (Ta), 10. anode tube (Ta), 11. end flange (Mo), 12. anode heat shields (Mo), 13. anode support assembly (Ta, BeO, Mo), 14. anode wire (Mo), 15. target holder (C for Ge, Ta for Al_2O_3), 16. target heater (Ta), 17. heater heat shield (Ta).

Several copies of this target/ion source have been constructed and tested off-line to determine typical operating parameters. The single current pass target heater has operated reliably over a wide range of target temperatures starting at 900°C , with no heater current, up to 1570°C with a heater current of 480 A. Moving the cathode connection to the rear of the transfer tube enables the entire line to be operated at temperatures in excess of 1700°C , as measured at the coldest point next to the cathode current connection, with a current of about 350 A. The other operational parameter which is important for the germanium target is the target temperature without any heater current. This temperature is approximately 900°C with cathode and anode at operational conditions. Typical ion source efficiency for Xe is 10-15% with the cathode current of 350 A and anode current of 200 mA at 150 volts. For on-line experiments the Xe gas inlet is restricted to 0.3 mm in order to reduce the flow of reaction products into the gas line. With this arrangement the on-line Xe efficiency is reduced to 3%.

On-Line Arsenic Experiments

The performance of the ion source for the production of arsenic beams was tested using (p,n) and (p,2n) reactions on a natural 99.999% pure germanium target mounted in the ion source. The extracted arsenic ions were deposited onto the tape transport system for 10 minutes and then moved to the detector station and the activity of the sample was counted for 8 minutes. The count rates shown in Fig. 2 are net counts in the

FIGURE 2. Release of ^{69}As and ^{70}As . The net count rate of a characteristic γ -ray from each isotope is plotted. No corrections for detector efficiency or branching ratios have been made. These data were taken at the two indicated target temperatures.

respective transitions. The data are used to determine the absolute efficiency for the target/ion source. These data also clearly show a hold-up time in the target/ion source and an improvement in yield as the target temperature is increased. Using these yield curves and calculated production rates (7), the efficiency of the target/ion source at 1270°C was $0.8 \pm 0.3\%$ for ^{70}As and $0.5 \pm 0.2\%$ for ^{69}As .

Since the growth curves seem to be dominated by the half-life of the respective isotopes, the hold-up time as implied from Fig. 2 must be longer than the half-life of either ^{69}As or ^{70}As . In order to measure the hold-up time in the target/ion source it was necessary to use an arsenic isotope with a longer half-life. After proton irradiation for several hours enough ^{72}As ($t_{1/2} = 26.0\text{ h}$)

FIGURE 3. Release of ^{72}As after proton bombardment is stopped. The net count rate for the 834 keV γ -ray from ^{72}As is plotted versus the time with the solid line being an exponential fit to the data. The dashed line represents the half-life of ^{72}As .

FIGURE 4. The normalized yield of ^{69}As and ^{70}As as a function of the inverse target temperature. The lines are exponential fits to the data. The counts are corrected for detector efficiency and branching ratio and are normalized to a proton beam intensity of 1 μA on a ^{70}Ge target.

activity is built up in the target to enable such a measurement. The proton beam is stopped and the yield of ions released from the source is monitored as a function of time. This is shown in Fig. 3 for ^{72}As . Since the radioactive half-life in this case is much longer than the apparent hold-up time, we say that the hold-up time is 3.6 ± 0.3 hours at 1300°C .

Target temperature is an important parameter for any target/ion source. Figure 4 shows the equilibrium yield for ^{69}As and ^{70}As as a function of the inverse of the target temperature. The data show an exponential increase in the yield with increasing temperature and indicate that the target can be operated at much higher temperatures. The ion source efficiency was constant over the range of the data shown. The data in Fig. 4 are corrected for radioactive decay, detector efficiency and branching ratio and are normalized to 1 μA of protons on an enriched ^{70}Ge target.

Off-Line Fluorine Release Measurements

For some time refractory oxides have been explored as a promising category of target materials for production of radioactive fluorine beams. The most encouraging results so far have been obtained with fibrous Al_2O_3 . The material (8) consists of 3 μm fibers of Al_2O_3 with a SiO_2 binder (2% by weight) and a density of 0.12 g/cm^3 . This Al_2O_3 was tested in an activation and off-line release measurement to determine the fluorine release efficiency. The material was irradiated with a low-intensity proton beam, which produced radioactive fluorine from the $^{16}\text{O}(\text{d},\text{n})^{17}\text{F}$ and $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ reactions. The activity in the target was measured with a high-purity germanium detector to determine the quantity of ^{18}F in the target. The Al_2O_3 target was then heated in a vacuum oven, and the

FIGURE 5. Activation and release measurement on fibrous Al_2O_3 . The filled circles were measured prior to heating, and the open circles measured after heating. The heavy line is the temperature of the target during heating. The thin solid lines show the expected activity for 110m half-life. The dashed line is an exponential fit to the data after heating which gives a half-life of 3.6 h.

^{18}F activity was measured again to determine the fractional release. Activation and release measurements performed with Al_2O_3 in a crystalline form ($\rho=3.7 \text{ g/cm}^3$) showed no significant release. However, measurements performed with the fibrous Al_2O_3 showed near complete release for temperatures greater than 1400°C . The only radiation emitted by the decay of ^{18}F is a 511-keV gamma ray, so the number of 511-keV gamma rays was measured as a function of time to determine the half-life of the activity.

The results of one measurement in which the fibrous Al_2O_3 was heated to a maximum temperature of 1700°C is shown in Fig. 5. The activity measured before heating is in agreement with the known 110 minute half-life of ^{18}F . Following heating in the vacuum oven, only a few percent of the expected activity was observed to remain in the target material. Furthermore, the half-life of the remaining activity was found to be 3.6 h. This activity is not from the decay of ^{18}F , but probably from the decay of an isotope produced by reactions on a contaminant in the Al_2O_3 . We conclude that greater than 95% of the ^{18}F is released after heating to 1700°C . Subsequent tests showed similar results with releases in excess of 80% for targets heated to $T > 1400^\circ\text{C}$. For targets heated to $T < 1200^\circ\text{C}$, no significant release was measured.

On-Line Fluorine Experiments

The performance of a similar ion source for the production of $^{17,18}\text{F}$ was also tested. The only changes in the target/ion source from that described above are in the target holder and target material. The target material was the Al_2O_3 fibers and the target holder was

FIGURE 6. Release of Al^{18}F after proton bombardment is stopped. The net count rate for the annihilation radiation is plotted versus the time with the solid line being an exponential fit to the data. The dashed line represents the half-life of ^{18}F .

made of tantalum and welded to the transfer tube. The reactions used were $^{16}\text{O}(\text{d},\text{n})^{17}\text{F}$ ($t_{1/2} = 64.5$ s) and $^{18}\text{O}(\text{p},\text{n})^{18}\text{F}$ ($t_{1/2} = 110$ m). Because of the extreme reactivity of atomic fluorine, the fluorine isotopes are transported in molecular form with 88% of the observed radioactive fluorine found in mass 44 (45) corresponding to Al^{17}F (Al^{18}F). This is based on measurements of emitted γ -rays at other masses which could correspond to the following molecules (% yield): $\text{F}(3)$, $\text{HF}(2)$ and $\text{SiF}(7)$. In addition, the following masses (molecules) were checked and negligible amounts of radioactive fluorine were observed: $28(\text{BeF})$, $42(\text{NaF})$, $47(\text{BeF}_2)$, $58(\text{KF})$ and $62(\text{AlOF})$. At a target temperature of 1470°C the efficiency of this source for Al^{17}F $0.0052 \pm 0.0008\%$, and the efficiency for Al^{18}F was $0.06 \pm 0.02\%$. The production rates were calculated from the measured cross sections (9) and tabulated stopping powers (10). The uncertainty in the efficiency is primarily due to the estimated uncertainty in the proton beam current on the target. The hold-up time was also measured at 1470°C using the longer lived ^{18}F isotope. The results of this measurement are shown in Fig. 6. By fitting the activity with an exponential, the hold-up time was determined to be 16.4 ± 0.8 minutes. We are currently exploring the effects of source parameters, such as temperature and surface passivation, on efficiencies and hold-up times.

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