Radioactive ion beam development in Berkeley*

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Two radioactive ion beam projects are under development at the 88" Cyclotron, BEARS (**B**erkeley **E**xperiment with **A**ccelerated **R**adioactive **S**pecies) and the ^{14}O experiment. The projects are initially focused on the production of ^{11}C and ^{14}O, but it is planned to expand the program to ^{17}F, ^{18}F, ^{13}N and ^{76}Kr.

For the BEARS project, the radioactivity is produced in form of either CO_2 or N_2O in a small medical 10 MeV proton cyclotron. The activity is then transported through a 300 m long He-jet line to the 88" cyclotron building, injected into the AECR-U ion source and accelerated through the 88" cyclotron to energies between 1 to 30 MeV/ nucleon.

The ^{14}O experiment is a new experiment at the 88" cyclotron to measure the energy-shape of the beta decay spectrum. For this purpose, a target transfer line and a radioactive ion beam test stand has been constructed. The radioactivity is produced in form of CO in a hot carbon target with a 20 MeV ^{3}He from the 88" Cyclotron. The activity diffuses through an 8m long stainless steel line into the 6.4 Ghz ECR ion source IRIS (**I**on source for **R**adioactive **IS**otopes). It is then ionized and accelerated to 30 keV to mass separate the ^{14}O and then implanted into a carbon foil.

In order to optimize the on-line efficiencies of the LBNL ECR ion sources, off-line ionization efficiency studies are carried out for various gases. A summary of the ionization efficiency measurements is presented.

1. Introduction

There are significant efforts worldwide to produce radioactive ion beams (RIB) for science research. The availability of beams of unstable nuclei offers new opportunities for research into nuclear structure and nuclear astrophysics. Until the construction of a new American Isotope Separator On-Line (ISOL) facility is approved and realized, limited RIB capabilities are being provided from various facilities within the United States [1-3]. At the 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory (LBNL) two radioactive ion beam initiatives are under development:

1) BEARS: The **B**erkeley **E**xperiment with **A**ccelerated **R**adioactive **S**pecies [4]
2) ^{14}O experiment [5]

Because of the low production yield for radioactive species, the transport efficiency of each component of the RIB system is essential. In order to optimize the efficiency of the ion source for RIB production, off-line ionization efficiency and ion beam decay time studies were carried out with the AECR-U ion source. These off-line efficiencies are compared with the measured on-line efficiencies for ^{11}C and ^{14}O.

In addition the newest ECR ion source IRIS, (Ion source for Radioactive ISotopes) started operation in April 99 at our radioactive ion beam test stand. The primary goal of this test stand is the on-line production of an intense $^{14}O^{+}$ or $^{14}O^{2+}$ ion beam. Results of the first on-line tests are presented.

2. The BEARS initiative

The BEARS experiment involves coupling of the Biomedical Isotope Facility (BIF) at LBNL [6] with the 88-Inch Cyclotron through a 300-meter transfer line.

The initial studies for BEARS are focused on the production of an ^{11}C as well as a ^{14}O ion beam, but it is planned to expand the program to ^{17}F, ^{18}F, ^{13}N (transfer line) and ^{76}Kr (batch mode).

Until completion of the transfer line construction in June 99, experiments have been done using a batch mode. The activity was produced with either the 88-Inch Cyclotron or the medical cyclotron to test the on-line efficiency of the two ECR ion sources. In the later case, the activity was transported by truck in a special lead-shielded container to the LBNL 88-Inch Cyclotron. It was subsequently separated from the target gas using the cryogenic trapping method (see section 4), then ionized and accelerated. This method of transport is only applicable to relatively long-lived ^{11}C (half-life 21 minutes).

3. AECR-U ionization efficiency for stable gases

A detailed description of the AECR-U ion source (Advanced Electron Cyclotron Resonance-Upgrade) can be found elsewhere [8].

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The ion source is optimized for production of high charge state ions by combining all of the advances in ECR sources made in recent years – two frequency heating, aluminum chamber, bias disk, high magnetic mirror field and radial pumping.

Ionization efficiencies and gas hold-up times for high charge state ions have been measured for various calibrated gas leaks from stable CO, CO_2, O_2, Ar, CHF_3, Kr and Xe. The leak rates of these ranged from a few to tens of pμA (with a quoted uncertainty of ±15%). The gases were axially injected into the source through one of the off-axis wave-guide ports. Helium or oxygen support plasma was used to optimize the ion production. The quoted ionization efficiencies represent the overall system efficiencies (ion source and transport line).

The ionization efficiencies of various high charge state ion beams for noble gases (Ar, Kr and Xe) are summarized in Table 1. Each charge state has been optimized individually. Efficiencies up to about 13% were measured for the Ar^{8+} and Ar^{9+}, 13% for Kr^{19+}, and about 20% for Xe^{20+}. For the higher charge states, the efficiency was 5% for Ar^{14+}, 1.2% for Ar^{16+}, 4% for Xe^{30+} and 2 % for Xe^{31+}. These ionization efficiencies achieved for the high charge states are comparable efficiencies achieved with the 1+/n+ method [9]. Despite the facts, that the source has radial pumping the high ionization efficiencies indicate that a significant fraction of the atoms is ionized in the first path through the AECR-U plasma.

As an illustration, Fig.1 shows how the AECR-U ion source can be optimized for the production of Ar^{9+} and Ar^{11+}. The overall efficiency for Ar (the sum of all charge states) varied from 58% to 66%. Optimization of the AECR-U for Ar^{16+} resulted in the lowest total ionization efficiency of 58%, while the optimization for Ar^{11+} lead to the highest total ionization of 66%. These results indicate that an average total ionization of 60% for argon was achieved with the LBNL AECR-U ion source.

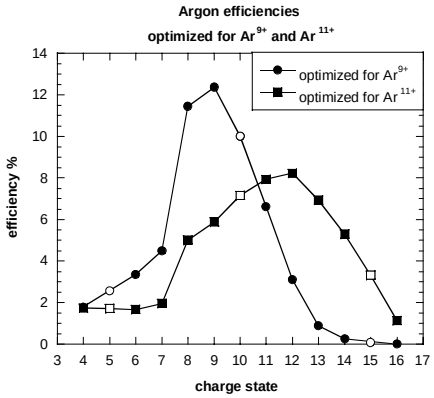

Fig.1 Ionization efficiency distribution for argon spectra optimized on Ar^{9+} and Ar^{11+} with oxygen as support gas. The open symbols indicate the mixed ion species.

Figure 2 shows a comparison of the measured ion beam current decays of Ar^{11+}, Kr^{20+} and Xe^{25+} after the gas flow was shut off. The beam current decay can be described by a mean decay time τ with an exponential fit $A \cdot \exp(-t/\tau)$. The decay times are summarized in Table 1. The higher charge state ion beams seem to have a slightly longer decay time. Nevertheless, within a certain percentage range, the mean decay times seem to be in the same range for all ion beams of a specific element.

As listed in Table 1, the category decay times for Ar, Kr and Xe are in the order of 3.6, 7.7 and

Ar	(%)	τ(sec)	**Kr**	(%)	τ(sec)	**Xe**	(%)	τ(sec)
Ar^{8+}	12.7		Kr^{17+}	12.9[a]		Xe^{20+}	20.4[b]	
Ar^{9+}	12.4	3.6	Kr^{19+}	10.2[a]		Xe^{21+}	13.8[b]	
Ar^{11+}	10.4	3.2	Kr^{19+}	13.7[c]	7.3	Xe^{22+}	14.9[b]	
Ar^{12+}	9	3.6	Kr^{20+}	11.2[a]	7.7	Xe^{23+}	16.0[b]	7.9
Ar^{13+}	6.9	3.6	Kr^{20+}	12.3[c]	7.7	Xe^{25+}	19.0[b]	9.3
Ar^{14+}	5.4	4.4	Kr^{22+}	6.5[a]		Xe^{26+}	17.8[b]	
Ar^{16+}	1.2		Kr^{23+}	6.3[a]		Xe^{27+}	14.0[b]	9.9
			Kr^{25+}	4.2[a]		Xe^{29+}	7.3[b]	
						Xe^{30+}	4.1[b]	
						Xe^{31+}	2.0[b]	

[a] 12 x 12 mm resolving slits, [b] 16 x 16 mm resolving slits, [c] He used as mixing gas

Table 1 Ionization efficiencies and mean beam current decay times of the extracted ion beams for selected charge states of noble gases after the gas flow was shut off.

9.5 seconds, respectively.

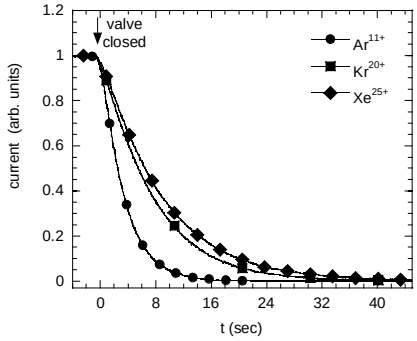

Fig.2 Normalized beam current decay for selected charge states for a few noble gases with the LBNL AECR-U ion source.

For the non-noble gases similar or higher ionization efficiencies were measured for various high charge state ion beams from CO, CO_2, O_2 and CHF_3. Efficiencies of up to 25% were achieved for C^{4+}, 33% for O^{6+} and about 7% for O^{7+}, and 5% for F^{7+}. Table 2 summarizes the measured ionization efficiencies. The non-noble ion beams may react with or stick to the plasma chamber surface made of aluminum. Therefore, the experimental ion beam current decay time is now described by an exponential fit $A\cdot\exp(-t/\tau_{fast})+B\cdot\exp(-t/\tau_{slow})$. The fast component describes the holdup time of the ions in the plasma, the slow component is related to the wall sticking. Since C and O are always present in the ion source, the long time component can not be clearly distinguished from the residual gas signal. Generally, about 70 % of the signal is dropped within τ_{fast}, which is listed in Table 2. The fast components of the current decay time for ion beams produced from non-noble are similar to noble gases. However, there is a difference in the decay time for the same ion produced from different gases, which is likely due to the chemical properties of the these gases.

As an illustration, the ion beam decay times for C^{4+}, produced from CO, CO_2 and CHF_3 are shown in Fig.3. The shortest gas hold up time has been measured for ions produced from CO, which behaves as a noble gas prior to dissociation.

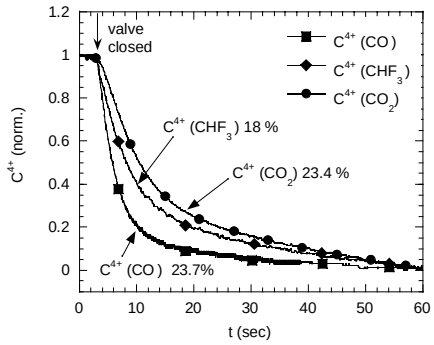

Fig. 3 Normalized current decay for C^{4+} ion beams from CO, CO_2 and CHF_3 calibrated leaks with the AECR-U ion source.

4. AECR-U and LBNL ECR ionization efficiencies for radioactive gases

For the on-line tests, the radioactivity was produced in a nitrogen gas target using 10 MeV protons either produced by the 88-Inch Cyclotron or the Biomedical cyclotron via the reaction ^{14}N (p, ^{4}He) ^{11}C and ^{14}N (p, n) ^{14}O. The ^{14}O is believed to be in the form of N_2O or NO. The ^{11}C activity is predominantly in the form of $^{11}CO_2$, when a trace amount of $^{16}O_2$ is added to the target gas. The activity is swept out of the target with a He-jet and transported in a narrow capillary to a cryogenic trapping system. There the activity is condensed in a liquid nitrogen trap, while the support gas is pumped away. After filling, the trap is warmed up to 195 K. At this temperature, about 90 % of the ^{11}C activity and about 40 % of the ^{14}O activity are released [4]. The radioactive gas is then axially bled into

calibrated leak			**calibrated leak**			**calibrated leak**			**calibrated leak**		
CO	(%)	τ(sec)	CO_2	(%)	τ(sec)	O_2			CHF_3		
O^{5+}	11.5	3.2	O^{5+}	12.5		O^{2+}	3.9		F^{5+}	2.8	
O^{6+}	26.3	3.2	O^{6+}	33	7.1	O^{3+}	8		F^{7+}	4.5*	4.5
O^{7+}	7.5	3.2	O^{7+}	7.44		O^{5+}	11.3		F^{9+}	0.7*	
						O^{6+}	16.0	4.7			
C^{4+}	23.7	2.9	C^{4+}	23.4	5.6	O^{7+}	5.6		C^{4+}	18	4.3
C^{5+}	14.1	2.9	C^{5+}	15.4							

- 8 x 8 mm resolving slits

Table 2 Ionization efficiencies and hold up times for selected charge states of oxygen, carbon and fluorine ions produced by the LBNL AECR-U ion source with CO, CO_2, O_2 and CHF_3 calibrated leaks.

the AECR-U or radially into the LBNL ECR ion source through a needle valve to limit the gas load into the ion source.

Listed in Table 3 is a comparison of the ionization efficiencies measured with the LBNL ECR and the AECR-U ion source. As shown in Table 3 the ionization efficiencies are much higher with the AECR-U than with the LBNL ECR. The main reasons for this are probably the axial feed and the lower conductance of the AECR-U chamber. Furthermore the plasma confinement and hot electron density is much higher in the AECR-U. Therefore, the highest ionization efficiency for carbon with AECR-U is achieved for C^{4+}, while it is C^{1+} with the LBNL ECR.

ION	ECR (%)	AECR-U (%)
$^{11}C^{1+}$	1.1	
$^{11}C^{2+}$	0.7	
$^{11}C^{3+}$	0.4	4
$^{11}C^{4+}$	0.9	11
$^{11}{}_{C}{}^{5+}$	0.1	5
$^{11}C^{6+}$		2
$^{14}O^{3+}$	0.4	
$^{14}O^{4+}$	0.4	
$^{14}O^{5+}$	0.45	
$^{14}O^{6+}$		3.6
$^{14}O^{7+}$		1.2
$^{14}O^{8+}$		0.4

Table 3 On-Line efficiency measured with the ECR and the AECR-U ion sources.

The stated ionization efficiencies for the radioactive gases are lower than for the stable gases, but peak on the same charge state. Since the efficiency was measured by summing up the total activity collected in the Faraday Cup, no direct tuning signal was available to optimize the AECR-U ion source. Furthermore, a fair amount of nitrogen is released with the activity, which is not an ideal mixing gas for the production high charge state carbon ions and increases the neutral pressure more than is optimal.

As in the case of natural CO_2, the ion beam decay time has of a slow and a fast component. The fast component describes the holdup time of the ions in the plasma; the slow component is related to the wall sticking time.

Figure 4 compares the ion current decay time for stable and radioactive carbon. In order to measure the current decay time for ^{11}C without any $^{11}B^{4+}$ contamination coming from the ECR ion source, the $^{11}C^{4+}$ ion beam was fully stripped after extraction from the cyclotron and mass-separated.

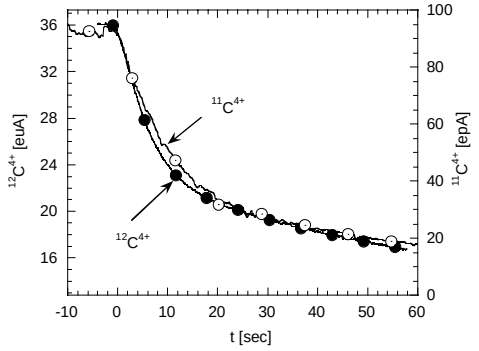

Fig.4 Current decay for a 11C6+ ion beam after extraction from the cyclotron during the first minute of activity release from the cryogenic trap in comparison with the stable 12C4+ ion beam decay.

Unlike for the stable gases, the fully stripped ^{11}C has no background in the ion source. Therefore, the wall-sticking component can be clearly measured. Figure 5 shows the ion beam decay after 12 minutes of continuos release of radioactive $^{11}CO_2$. After the initial fast decay, there is a slow beam current decay of ^{11}C coming off the chamber walls showing a mean decay time of about 6 min.

With the present set-up a maximum beam intensity of $1 \cdot 10^8$ pps at 100 MeV was extracted from the 88-Inch Cyclotron.

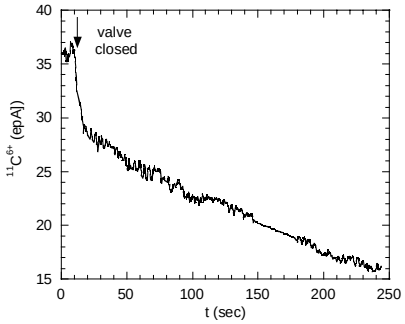

Fig.5 Current decay for a $^{11}C^{6+}$ ion beam after extraction from the cyclotron after 12 minutes of continuos release from the cryogenic trap

5. The ^{14}O experiment

In the ^{14}O experiment, it is planned to measure the shape of the beta-decay spectrum. For this purpose an intense ($2 \cdot 10^6$ pps), low energy ^{14}O ion beam is needed. ^{14}O is produced in the form of CO in a high temperature carbon target using a 20 MeV $^3He^+$ beam from the LBNL 88" Cyclotron via the reaction ^{12}C (^3He,n) ^{14}O. The neutral radioactive CO molecules diffuse through the 8 m long room temperature

stainless steel line from the target chamber into an ion source outside the cyclotron vault. In order to minimize the background radiation for the planned experiment, the ^{14}O atoms must be separated from the other radioactive isotopes produced in the carbon target and implanted into a thin carbon foil. Therefore, we have developed an experimental set-up including the target, a 8 m long stainless steel transfer line, a compact ECR ion source, and a low energy ion beam transport line [7]

6. IRIS-ECR ion source

For the ^{14}O experiment a compact ECR ion source IRIS (**I**on source for **R**adioactive **IS**otopes) has been developed. An existing 2.45 GHz ECR ion source [11] was upgraded for 6.4 GHz microwave operation. The mirror field was improved to reach a maximum field of 0.7 Tesla at the injection and 0.4 Tesla at the extraction. At the plasma chamber-wall the sextupole-field strength reaches 0.32 Tesla.

The microwaves are launched through an off-axis wave-guide terminated at a bias plate in the injection region. The aluminum plasma chamber with a diameter of 13.5 cm and the mirror length of 28.3 cm provide a relatively large plasma volume of 5 liters. The plasma chamber is double-walled to accommodate cooling water. Pumping can be provided through a 9 cm^2 pumping port at the injection side of the ion source. The activity is injected off-axis through another 1cm port.

7. Preliminary on-line results with the IRIS ECR ions source

Figure 6 shows the set-up for the initial on-line test. The activity is produced on a hot carbon target in form of CO and diffuses through a 8 m long transfer line up to the test stand outside the cyclotron vault. In the current setup, the transfer-line is pumped through a turbo molecular pump. The backing side of the turbo is connected to the ion source. The gas load must be limited with a gas inlet valve. Therefore, a fair amount of activity is decaying in the turbo pump backing line before it is released into the ECR ion source.

With this set-up, an overall efficiency of about 0.8% was measured for singly and doubly charged ^{14}O. With $4.5 \cdot 10^7$ pps ^{14}O measured at the backing line, an continuos ion beam of $3 \cdot 10^5$ pps has been achieved at the Faraday cup for O^+ and O^{2+}, with an overall ion beam transport transmission of about 50%.

For one of the next experimental runs, we are planning to replace the pump with a cold trap to freeze out everything but the desired CO. This should minimize the gas load to the ECR ion source and reduce the delay times between the transfer line and the ion source.

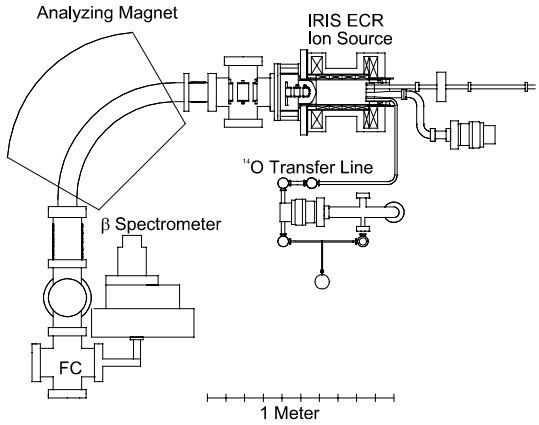

Fig. 6 Schematic of the new exotic ion beam test stand and the ^{14}O experiment.

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