THE ECR ION SOURCE AT THE TRIUMF
ISOTOPE SEPARATOR, TISOL

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ABSTRACT

The installation at the isotope separator TISOL of a single staged ECR (Electron Cyclotron Resonance) ion source has been completed. The source can now routinely deliver radioactive species extracted from the production target when bombarded by 500 MeV protons. Among the radioactive species detected so far are isotopes of He, C, N, O, Ne, Cl, Ar, Kr, and Xe including multiple charged states and with yields exceeding in some cases those of the ISOLDE facility at CERN. The effect of varying parameters on the operation of the source are discussed.

1. INTRODUCTION

Single stage ECR (Electron Cyclotron Resonance) ion sources have shown high efficiencies in ionizing gaseous species in the single charge stage[1] and as well have demonstrated long running times without any source maintenance being necessary. For this reason it was decided to couple a single stage ECR to the TISOL isotope separator at TRIUMF[2]. TISOL, a prototype operation of a planned

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radioactive beams facility[3], and the ECR ion source itself (ECRIS) have been described generally in previous publications[2,4,5]. This paper will give a detailed description of the target and ion source system and the operation of the source.

2. SOURCE OVERVIEW

A recent elevation view of the entire TISOL facility is shown in ref. [2]. Fig. 1 displays a side view of the ion transport system from target to the mass analyser while a detailed plan view of the ion source and target chamber is shown in fig. 2.

2.1 The Ion Source

The source is closely related to the one described in ref. [1], i.e. having two quartz tube liners as vacuum insulation and the plasma tube with radial insertion of the RF power. The use of an iron yoke allows for the production of the axial magnetic field with a lower solenoid current and a more compact source. The mirror ratio of 1.3 is produced by an iron ring at the middle of the source. A hexapole of samarium cobalt magnets (surface field 0.52 T) provides the radial electron confinement.

The RF power level available compared to previous descriptions of the source[2,4] is increased by the use of a 3 Kw, 6 GHz klystron powered amplifier on loan from Teleglobe Canada. The change in RF frequency from 10 GHz, used previously, to 6 GHz brought no obvious change in source performance.

The extraction electrode has a Pierce geometry with a 3 mm dia. hole in the centre. The inner quartz tube liner has a 2 mm outlet in a closely fitted stainless steel cap forming the opposite side of the extraction system (fig. 2). The extraction electrode is remotely movable for about 5 cm along the beam axis.

The extraction chamber of the ECRIS is now pumped by a 200 l/sec turbo-molecular pump. Typical pressures achieved in the extraction electrode region are to the order of 3×10^{-6} Torr or lower.

The gas injection end of the ECRIS has been changed from previous constructions. A threaded coupling piece can now be removed from the back and the inner quartz tube easily extracted through the target chamber avoiding the need for complete disassembly in case of repair. This coupling piece now connects directly to the target assembly removing a previous plastic insulator which caused problems due to the high heat levels of the target. In addition, because of HV sparking problems, the plastic insulating flange at the gas feed end of the source has been modified. These sparking problems were caused by indirect heating of the insulating flanges due to the increased RF power levels currently available. For this reason a more extensive cooling of the inner parts of the source has become necessary. To accomplish this the airflow through the cavity has been increased, and in addition, it was necessary to install a closed freon cooling circuit including a heat exchanger to the radioactive cooling water system at TRIUMF.

2.2 The Target Chamber

The inner quartz tube of the ECRIS couples to the target assembly which is a quickly removable unit connected to the back plate of the target vacuum chamber. This assembly (fig. 2) consists of graphite target oven, a transfer line to the ECR source, a heat shield/cooled sink, and the necessary feed-throughs and connections. The target assembly is on high tension (20kV) being insulated by a nylon plastic flange from the rest of the vacuum chamber.

The graphite target oven is a 7.5 cm long graphite cylinder heated by resistive heating (up to 500A). The current feed-throughs are water cooled copper.

Inside the oven is the target crucible, a graphite cylinder (5.5 cm in length) supported on boron nitride insulators which holds the target material. The walls of the crucible are perforated to allow gaseous products to escape. The oven is connected to the tantalum transfer line by a graphite chimney. The target crucible is indirectly heated to temperatures ranging up to 2200°C. The target is surrounded by a tantalum heat shield to achieve the higher temperatures. The target is bombarded by 500 MeV protons with currents up to 500 nA (presently limited to this intensity by target handling considerations). Radioisotopes produced by the proton beam are selectively released by the target matrix and diffuse to the ECR chamber to be ionized.

The transfer line is a 25 cm long, 5 mm diameter tantalum tube held in place by the water cooled heat shield, the target chimney, and the coupling to the target plate. The transfer line has graphite inserts to reduce wall capture of reactive species. The heat shield cools the transfer line and provides a cold spot so that only gaseous species can reach and enter the plasma tube.

The outside gas feed system consists of several test calibrated leaks on high tension close to the source as well as the gas feed line operating from the TISOL Faraday cage above the shielding blocks. This line can be used to introduce carrier gas and other gas species into the source/target assembly.

The heat shield is a water cooled, copper block clamping the transfer line and mechanically stabilized by an additional steel heat shield. It has two functions: to provide cooling to the transfer line, and to shield the high tension insulation of the source from the heat emanating from the target oven.

The target assembly is contained in a water cooled vacuum chamber which is at ground potential. The 6-port chamber is double walled to allow for water cooling. Two ports are used to hold the target assembly and connect to the

ECRIS, two ports are used to connect to the proton beamline, and the final two are used as a vacuum port to the pumping station (cryopump) and to mount a hot filament ion gauge.

3. TEST RESULTS

3.1 Off-line Results

The target assembly can be removed and replaced by a flange containing a gas feed line coupling directly to the ECRIS. Many results reported in this section are derived this way without use of the proton beam.

Optimization of some of the source operating parameters was carried out; magnetic field, RF power, and extraction electrode position were the main parameters tested. Figure 3a-d displays results for the effects of: a) the ECR magnet solenoid current on the $^{20}\text{Ne}^+$ yield, b) the ECR magnet solenoid current on the amount of RF power reflected (using 400 W forward power), c) the extraction electrode separation from the actual source outlet on the total current (on the first Faraday cup) extracted from the source, d) the extraction voltage on the total output current.

An automatic mass scan capacity has been installed at TISOL. A TRIUMF control system μVax computer drives, via a CAMAC crate, the analysing magnet of TISOL as well as simultaneously reading both the analysing magnet's field and the extracted current at a Faraday cup at the collection station. Figure 4 displays such a mass scan with the Neon and $^{15}\text{N}_2$ leaks open.

The automatic mass scan allows a glimpse into the inner workings of the ECR plasma and shows the effect of changing parameters on all species being ionized by the source. Differences between mass scans demonstrate the effect of varying source parameters. The solenoid current can be used as a good example of this.

It has been observed that for different values of ECR magnet current, yields of different species are optimized, and that after changing a source parameter, the magnetic field should be adjusted to maximize the yield of the species of interest. There are many reasons why this could occur. By changing the magnetic field and hence the position of the ECR zone one adjusts the shape and density of the plasma as well as moving its position with respect to the extraction electrode. Additionally, the coupling with the RF field seems to depend on the ECR magnet setting as seen in fig. 3b. It would seem that this situation results in a group of possibly competitive, simultaneous interactions. In the case of lowering the magnetic field a less dense plasma might well result in a lower overall maximum charge state for the species in it, while a shorter path to the plasma electrode should result in less charge exchange with the background gas therefore, the ionization efficiency should remain the same or drop slightly. Unfortunately, with the plasma closer to the inner quartz tube more rest gases adsorbed in the quartz may be released due to the increased thermal heating by the plasma resulting in a greater charge exchange rate, thus decreasing the yield of the species of interest and increasing the background lines in the spectra.

Another use of the mass scan is for monitoring a target while it is being conditioned. The material effusing from the target can be observed and this will indicate whether the target should release a specific isotope of interest and what form it may take.

Neon ionization efficiencies of up to 30%, nitrogen-15 efficiencies of 14% and argon efficiencies of 24% for the 1+charge state have been observed. The extraction vacuum and hence the source vacuum is the critical parameter for high efficiencies. An extraction chamber vacuum of $\leq 3 \times 10^{-6}$ Torr seems to be optimal. With a support gas flow in excess of the equivalent of 50 particle- μA , the

ionization efficiency seems to be reduced, thus no major efficiency improvements were observed with increased support gas flow.

3.2 Molecular and Charge State Distributions

The yields for higher charge states as well as molecular side bands have been investigated due to their importance in the acceleration of radioactive beams.

Radioactive isotopes have been found in such molecular forms as H^3Cl^+ , $^{10}\text{CO}^+$, C^{15}N^+ , $^{15}\text{N}^{14}\text{N}^+$, and $^{15}\text{NO}^+$ with many more molecular species for carbon and nitrogen also observed. Stable beams have N_2^+ , O_2^+ , OH^+ , H_2O^+ molecular bands among others. For most cases investigated the ratio of yield in a side band to that in the elemental form fluctuated strongly with source conditions, for example, for $\gamma(^{15}\text{N}^{14}\text{N}^+)/\gamma(^{15}\text{N}^+)$ the ratio varied between 0.3 and 10.

The yield of $^{20}\text{Ne}^{2+}$ was generally a factor of 10 lower than the $^{20}\text{Ne}^+$ yield while higher charge states became more efficiently produced for heavier noble gases due mainly to their lower ionization potential, for example, $^{40}\text{Ar}^+ 24\%$, $^{40}\text{Ar}^{2+} 11\%$, and $\text{Ar}^{3+} 2\%$. In figure 5 the observed current for the first three charge states of Argon are shown as a function of the net RF power (defined as Forward less Reflected as measured at the amplifier). In figure 6 the on-line yield for multiply charged radioactive isotopes of Neon, Krypton, and Xenon is shown. Clearly, with reductions of only from 2 to 10 for charge states from 1^+ to 3^+ heavier noble gas ions may be accelerated multiply charged on any future radioactive beams facility.

3.3 Radioactive Isotope Production

A plethora of radioactive isotopes produced in different production targets and ionized in the ECR ion source have been found after mass analysis at the TISOL detector station and a summary of observed low Z isotopes is presented in

Table 1.

Half lives of isotopes down to 122 ms (^6He) and 104 ms (^{17}Ne) have been observed indicating short transit times of the radioactive ions through the ECRIS. Molecular side bands have proven to be quite important for obtaining high radioisotope yields. For some isotopes the yields are higher than those obtained at ISOLDE[7] as expected from the high ionization efficiency of ECRIS for certain elements. In this comparison an attempt was made to compare targets of similar Z where possible; target thicknesses were normalized. Data for Cl, Ar, Kr, and Xe are not shown since these were not studied systematically. The yields for Kr and Xe are comparable to results elsewhere, but ECRIS produces multiple charge distributions (Fig. 6).

Up to this time most studies carried out at TISOL have been designed to test the feasibility of using a target for the production of a specific isotope of interest, however, now some of the emphasis is starting to change to optimization of the target and source parameters for actual experimental studies. An example of this is shown in fig. 7 which shows the yield of both ^{23}Ne and ^{22}Ne with net RF power. The dependence for ^{23}Ne ($T_4 = 0.61$ s) shows a marked difference from that exhibited for the stable ^{22}Ne . The peak could result from the onset of higher charge state formation, which is not observed as clearly in the ^{22}Ne study due to background effects, i.e., current at A=22 not due to ^{22}Ne ; the half-life of ^{23}Ne is not believed to play a role.

3.4 ^{15}N Production

The most ambitious experiment proposed so far for the TISOL facility is the determination of the β decay spectrum of ^{15}N ($T_4 = s$) which has major implications for the determination of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ cross section in astrophysical scenarios[6]. This measurement requires a yield of about 10^7 atoms $\cdot s^{-1}$ of ^{15}N .

Off line tests have been done using a ^{15}N leak to study optimal source parameters for ionization of nitrogen. The results of some of these tests can be seen in figure 8 where the effect of net RF power is shown for various different side bands of ^{15}N . The increase of $^{15}\text{N}^+$ at a net RF power 250 W seems to correlate with the leveling off or decrease in the observed molecular currents.

Several possible target materials have been tested in a number of runs (see table 2). The greatest difficulty as revealed in these runs seems to be the release and transfer of ^{16}N , probably as a gaseous molecule (probably N_2 or NO) into the source. At present the material Zeolite 13X ($\text{NaAlSi}_3\text{O}_8$) known to release nitrogen gas at temperatures around 300°C , has exhibited the most promising results. The material was initially conditioned for several hours at 300°C . It did not require additional heating other than beam heating after this point. Additionally, the target provided a more stable, steady yield and was better able to recover from changes to target conditions such as gas flow and temperature changes than previous targets. Also, since the target material is relatively inexpensive, very thick targets can be easily used.

During these runs data was collected on the effect of RF power on the ^{16}N yield which are displayed in figures 9a,b. It is interesting to note how closely linked the stable current at A-16 is to the yield of ^{16}N (Fig. 9a). A similar correlation is noted in figure 9b between the ^{16}N yield (as $^{16}\text{NO}^+$) and A-32 stable current. Since these stable currents arise from the presence of ^{16}O as an atom and molecule, this could indicate some correlation between the ^{16}N release and transport mechanism from the zeolite target into the source and the amount of O_2 trapped in the zeolite. It should be noted that the nitrogen species entering the ECRIS is not necessarily the species extracted from ECRIS.

It was also interesting to note that the addition of a Nitrogen carrier gas

into the system did not increase the yield significantly but it did push more ^{16}N into the observed A-30 band. Zeolite was also the only target which revealed the presence of $^{16}\text{N}_2^+$ with a yield of 2.1×10^3 nuclei/s/ μA which does not scale with what would be expected from off line studies.

4. CONCLUSION

An ECR ion source coupled to the thick target isotope separator (TISOL) has proven to be an effective means to produce radioactive ion beams. The facility is now ready for production mode to service an experimental program. Molecular side-bands proved to be quite important in providing high yields of a number of radioisotopes. The use of multiple charge ions in any future acceleration of radioactive beams now seems quite feasible with the present source, depending upon the required intensities, for elements with low ionization potentials.

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6. REFERENCES

- [1] V. Bechtold and S.A. Sheikh, Proceedings of the Accelerated Radioactive Beams Workshop, Parksville, Canada (1975); TRI-85-1, p.110.
- [2] M. Dombbsky, J.M. D'Auria, L. Buchmann, H. Sprenger, J. Vincent, P. McNeely, and G. Roy, Nucl. Instr. and Meth. A295 (1990), 291.

- [3] L. Buchmann, J.M. D'Auria, J.D. King, G. Mackenzie, H. Schneider, R.B. Moore, and C. Rolfs, Nucl. Instr. and Meth. B26 (1987), 151.
- [4] P. McNeely, G. Roy, J. Soukup, J.M. D'Auria, L. Buchmann, M. McDonald, P.W. Schmor, and H. Sprenger, J. Phys., 50 (1989), C1 807.
- [5] P. McNeely, G. Roy, J. Soukup, J.M. D'Auria, L. Buchmann, M. McDonald, P.W. Schmor, H. Sprenger and J. Vincent, Rev. Sci. Instr. 61 (1990), 273.
- [6] L. Buchmann, spokesman, The $\beta\alpha$ Decay of ^{16}N , Proposal to the TRIUMF Experimental Evaluation Committee, Exp. 589 (1989), unpublished.
- [7] ISOLDE Users Guide, CERN 86-05 (1986 and updates).

TABLE 1

Isotope	Yield* [particle $\cdot\text{s}^{-1}\cdot\mu\text{A}^{-1}$]	Target [g $\cdot\text{cm}^{-2}$]	[Y/Y _i] [†]
^6He	3.7×10^5 3.4×10^5 2.1×10^4	AlN (7.5) MgO (6.2) UO ₂ (2.3)	4.1 (Thc) 4.2 (Thc) 2.7 (Uc)
^{10}C	2.6×10^6 3.8×10^5 1.7×10^5	Zeolite** (4.4) MgO (6.2) CaO (4.3)	192 (CaO) 10.2 (MgO) 12.3 (CaO)
^{13}C	2.6×10^4 2.6×10^4 9.1×10^3	MgO (6.4) Mg ¹⁸⁰ (1 g total) Zeolite (4.4)	15.9 (MgO) 102 (MgO) 8 (MgO)
^{16}N	(See table 2)		
^{17}N	4.4×10^4 2.9×10^4 1.5×10^4	MgO (6.4) Zeolite (4.4) Mg ¹⁸⁰ (1 g total)	.4 (CaO) .4 (CaO) 1.0 (CaO)
^{18}N	7.2×10^2	Zeolite (4.4)	NA
^{19}O	8.5×10^4	Zeolite (4.4 g)	NA
^{19}O	1.0×10^3 4.6×10^2	SiC (8.1) UO ₂ /C (2.3)	NA NA
^{17}Ne	1.6×10^5 5.0×10^2	MgO (6.4) AlN (7.5)	16.7 (MgO) .04 (MgO)
^{18}Ne	3.3×10^6 3.0×10^5	Zeolite (4.4) Mg ¹⁸⁰ (1 g total)	.65 (MgO) .3 (MgO)
^{19}Ne	9.5×10^5	AlN (7.5)	.01 (MgO)
^{23}Ne	1.7×10^7 1.4×10^7 2.8×10^6	MgO (6.2) MgO (8.7) AlN (7.5)	1.6 (MgO) .9 (MgO) .2 (MgO)
^{24}Ne	3.0×10^5 2.3×10^5 2.1×10^5	MgO (6.2) UO ₂ /C (2.3) Ti (7.1)	.09 (MgO) 98 (Thc) .05 (MgO)
^{25}Ne	2.4×10^4 2.3×10^4	Ti (7.1) UO ₂ (2.3)	7.9 (CaO) 8.1 (Thc)
^{26}Ne	yes	UO ₂ (2.3)	NA

* Only highest yields shown, but not optimized in all cases.

† Ratio of best yield at ISOL to yield from ISOLDE (ref. 7) normalized to target thickness.

** Zeolite, 13 x = (NaAlSi₄O₁₀)

*** Species also observed in lower yields at other mass positions.

NA = no reported ISOLDE yield

TABLE 2

Highest Yields of ^{16}N for Various Production Targets*

Target	Thickness (g/cm ²)	A-16	Yield of ^{16}N (particles/s/ μ) A-30	A-32
AlN (powder)	7.5	1.8×10^3	3.9×10^3	2.9×10^3
CaO (powder)	7.0	2.3×10^2	1.2×10^4	3.2×10^3
CaO (chunks)	4.5	-	2.3×10^3	6.8×10^3
Mg ¹⁸⁰ (powder)	(lg total)	4.5×10^4	3.4×10^4	1.7×10^4
MgO (powder)	(1.8g total)	8.1×10^3	1.3×10^4	2.3×10^3
MgO (chunks)	6.4	9.5×10^4	3.8×10^4	1.4×10^4
MgO (pellets)	(8.7)	1.6×10^4	2.6×10^4	-
Zeolite (NaAlSiO ₄)	4.4	3.8×10^5	2.0×10^5	4.7×10^5

* In some cases ^{16}N also found at other mass positions but in lower yields.

FIGURES

- Figure 1: Side view of the ECR-target system as installed at TISOL including beam transport elements and supporting systems, up to the analysing magnet.
- Figure 2: Top view of the ECR Ion Source and target system as installed at the TISOL facility at TRIUMF, showing recent changes to both.
- Figure 3: Optimization of the ECR parameters; a) ^{20}Ne yield as a function of the ECRIS solenoid current; b) the reflected rf power of the solenoid current as a function of ECRIS solenoid current with a fixed forward power of 400W; c) the total source output current of the extraction as a function of extraction electrode separation from the outlet; d) the variation of total output current on extraction voltage.
- Figure 4: Automated mass scan for an on-line run with neon and $^{15}\text{N}_2$ leaks open.
- Figure 5: The dependence of the argon yields for the 1^+ to 3^+ charge states on the RF Net power, (the difference between the forward and reflected power as measured at the RF amplifier).
- Figure 6: Yields for the radioactive isotopes of ^{125}Xe , ^{125}Xe , ^{125}Xe , ^{125}Xe , and ^{23}Ne up to a charge state of 8^+ extracted from either a LaC_2 or a UO_2 target.
- Figure 7: Shown here are the observed counts for counting intervals of 120 seconds for the decay of ^{25}Ne and the observed current of $^{25}\text{Ne}^+$ as a function of net RF power.
- Figure 8: The current for $^{15}\text{N}^+$ various molecular sidebands of ^{15}N as compared to the net RF power.
- Figure 9a: The sum of the counts in the photopeak, single escape peak and the double escape peak of ^{16}N compared to the net RF power; also displayed is the A-16 stable beam current for the same net power level.
- Figure 9b: The sum of the counts in the photopeak, single escape peak and the double escape peak of ^{16}N (as NO^+ , A-32) compared to the net RF power; also displayed is the A-32 stable beam current for the same net power level.

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