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HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS (HEP & NP)

ECRIS Charge Breeding at ISAC*

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Abstract. An ECR ion source for charge breeding of radioactive ions from the ISAC facility at TRIUMF has been set up at a test stand. It has been operated with different ion sources for the injection of singly charged ions and the efficiency, breeding time and emittance have been determined for several elements. A maximum efficiency of more than 6% for the breeding of Kr^{12+} has been achieved so far. Additionally the charge exchange of Rb and Cs ions in the range of 10+ to 23+ with residual gas molecules in the transport beam lines has been investigated. The absolute values for the cross sections at 10 -15 q keV agree with predictions extrapolated from lower charge states but the strong dependence on the ionization energy of the gas molecules could not be verified.

Key words ECRIS, charge breeding, radioactive ions, charge exchange

1 Introduction

The acceleration of rare isotopes produced at ISOL facilities usually requires charge breeding to meet the A/q acceptance of accelerators. Charge breeding with an ECR ion source has been proposed and developed by the Grenoble group several years ago [1] and it has been tested at several ISOL facilities until now. The advantage of an ECR ion source compared to an EBIS for example [2] is its possibility of running in a continuous beam mode and its practically non existing intensity limitation. As the production of the isotopes of interest is always limited to small amounts the most important operation parameter is the total efficiency. This includes the efficiency to reach the desired charge state, the transport of the highly charged ions and the acceptance and transmission of the accelerator. Charge breeding efficiencies up to about 10% for a single high charge state have been reported so far [3,4]. It varies due to the different ECR source types used and the incoming beam parameters. For volatile elements it is usually higher than for non volatile ones. In case of radioactive isotopes the charge breeding time also limits the efficiency if it is comparable or longer than the half life. The transport and acceleration efficiency depends mainly on the emittance of the highly charged ion beam. In case of a long beam transport charge exchange with residual gas in the beam line reduces the transmission efficiency. At ISAC the beam transport from the charge breeder to the accelerator is about 25 m. Therefore, charge exchange has been studied in more detail in order to get estimations for the vacuum necessary in this line.

2 Charge exchange of highly charged ions with residual gas

If a highly charged ion passes through a gas filled volume it will experience charge exchange. Up to several 10 q keV/u the process with the highest probability is the capture of one electron from the gas atoms or molecules and thus the decrease of the charge by one unit. Two or more electron captures during one collision or the stripping of additional electrons are very unlikely for low energy ion beams. The cross section of this process mainly depends on the velocity of the ions. It is at maximum at low velocities. Experimental values exist mainly for high energy (≥MeV) or at low energies (≤10 q keV). At ISAC the velocity corresponds to an energy around 2 keV/u. (15 q keV for A=150 and q=20). In the low energy range most experimental data are limited up to a charge state of about 10. Empirical formulas have been fitted to the data to correlate the cross section to the ionization energy I of the gas and the charge state q [5,6,7]. The latest one by T. Kusakabe et al. [7] includes molecular

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gases. With I in eV it gives the total charge exchange cros section

$$\sigma_t = \left(1.56 \pm 0.72\right) \cdot 10^{-13} \cdot q^{(0.825 \pm 0.049)} \cdot I^{-(1.75 \pm 0.16)}\ \text{cm}^2 \qquad (1)$$

The extrapolation to higher charge states from simple theories like the over barrier model [8] leads to a linear dependence on q and inverse square dependence on I.

3 Experimental

At the ISAC facility at TRIUMF radioactive nuclei are produced by bombarding solid targets with an intense high energy proton beam. From the heated target they can diffuse out into an ion source, be ionized, accelerated up to 60 keV and mass separated. This ion beam can be injected into a LINAC. The first part of the LINAC consists of an RFQ accelerator, which can accept ions up to A/q=30 at a velocity of 2 keV/u. It is followed by a stripper foil to reach A/q≤7 which allows the further acceleration in a room temperature drift tube structure and finally with superconducting cavities. In its final stage acceleration up to 16 MeV/u will be possible [9]. If ions with masses higher than 30 have to be accelerated higher charge states will be necessary. A/q ≤ 7 is preferable to avoid further losses from stripping.

Charge breeding will take place directly after the mass separation. A 14 GHz ECR PHOENIX from PANTECHNIK will be used. It has been set up at a test bench. There its performance can be studied with the injection of singly charged ions from typical ion sources as they are used at ISAC. The extracted beam can be analyzed with a combination of a magnetic sector followed by an electrostatic bender. This ensures a good mass resolution and the discrimination against scattered or charge exchanged ions. The setup has been described in an earlier publication [10].

The single electrode extraction of the original source design has been changed to a two stage acceleration scheme with additional Einzel lens focusing. This allows a better adaptation of the ion velocity to the acceptance of the accelerator.

4 Measurements and Results

Two different ion sources for the production of the ingoing singly charged ions have been used; an ECR ion source for the noble gas ions Ar, Kr, and Xe and a surface ion source for alkaline ions K, Rb and Cs. The efficiency has been determined by comparing the 1+ beam current on a Faraday cup in front of the charge breeder to the n+ current after mass separation. In order to minimize the intensity of ions produced from the residual gas in the source it has been run with a low flow of He for support gas. The source has been operated at a microwave power between 300 W and 500 W. Charge breeding efficiencies of noble gas ions have been published previously [10]. In the maximum of the charge state distribution the efficiency is about 6% for Kr. In case of the alkaline ions it is at about 3%. The lower efficiency for the alkalies reflects the fact that those elements are not volatile and once they hit the wall of the plasma chamber they are lost for further ionization. The results reached so far are summarized in table 1.

Table 1 list of all elements tested so far with the charge state of maximum efficiency and the rise time to 90% of the signal for this charge state.

Element	mass (amu)	charge state	efficiency (%)	rise time to 90% level (ms)
Ar	40	8	5.5	102
Kr	84	12	6.3	401
Xe	129	17	4.8	465
K	39	9	2.1	
Rb	85/87	13	3	230
Cs	133	18	2.7	300

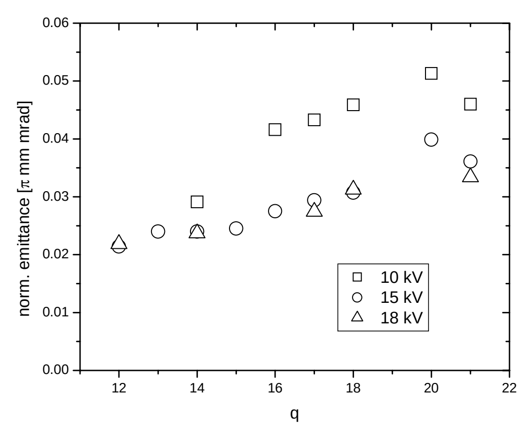

Figure 1 normalized emittance of highly charged Cs beams at several extraction voltages.

With the new two step acceleration system the horizontal emittance of the extracted highly charged ion beam has been measured after the mass separation. At 15 kV total extraction voltage the area of an ellipse containing 90% of the beam intensity is between 15 and 20 π mm mrad for highly charged Cs ions. This is

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well below the acceptance of the transport beam lines and the ISAC accelerator. Figure 1 shows the dependence of the normalized emittance for Cs ions on the charge state and the extraction voltage. The higher values at 10 kV are most probably caused by space charge before mass separation, whereas, the increase with charge state is additionally a result of the extraction out of the magnetic field of the source.

The charge breeding time has been determined by varying the incoming beam with a pulsed steering voltage and measuring the onset of the n+ beam as function of time with respect to this pulse. The time to reach 90% of the beam intensity for the charge state with maximum efficiency is also given in table 1. Figure 2 shows a comparison between the breeding times of highly charged ions of Cs and Xe. The difference can be explained again by their different behavior when deposited on the plasma chamber wall. In case of Rb the rise time is mainly determined by the production time and the confinement in the plasma, whereas for Kr sticking times at the wall can prolong the time to reach equilibrium.

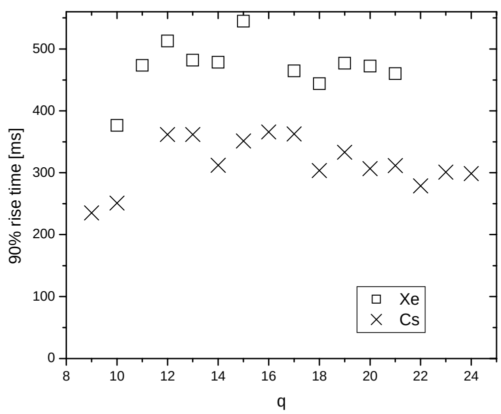

Figure 2 time to reach 90% of the signal after pulsed injection of singly charged ions

The data show only a small dependence on the charge state and in case of the higher charge states the breeding time seems not to depend any longer on it. A reason can be the limited confinement time of the ions in the plasma. Additionally, it may indicate that in contradiction to the theory of a stepwise increase in the charge state other processes like the stripping of several electrons at the same time or Auger effects may be relevant for the formation of high charge states. A similar effect has been reported by S.C. Jeong et al. [4] for the breeding time of Xe in an 18 GHz ECR source. Further detailed measurements and comparison with simulations will be necessary to confirm and explain this behavior.

For the measurement of charge exchange processes in the transport beam lines, charge bred Rb and Cs ions at 10 or 15 q keV have been used. The current has been measured directly after the magnetic separation and again after the electrostatic deflectors. Oxygen (I=12.07 eV) or Nitrogen (I=15.58 eV) gas has been let into this area and the pressure has been measured at 2 locations. The two gases have been chosen as they represent the range in ionization energies for other gases present in the residual gas. If charge exchange occurs within this area the resulting ions will change their E/q value and will be deflected out of the beam path by the electrostatic deflectors. Comparing the two measured current values the transmission has been determined as function of the pressure between $2\cdot10^{-5}$ Pa and $1\cdot10^{-3}$ Pa. In order to discriminate against background ions with the same A/Q value the current with no injected Rb or Cs has been subtracted in both cases. As an example figure 3 shows the transmission as function of the average N_2 pressure for several charge states of Cs. An exponential decay has been fitted to the data. The error bars in the figure are estimated from the accuracy of the current measurements and from fluctuations for repeated measurements. The total cross sections for the charge exchange can be obtained from the fitted decay constant.

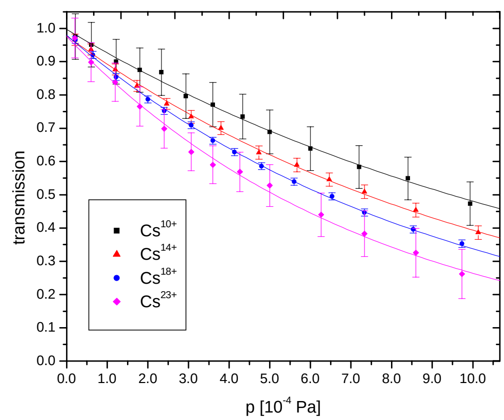

Figure 3 Transmission of Cs^{10+}, Cs^{14+},Cs^{18+} and Cs^{23+} as function of N_2 pressure, together with fitted curves

Figure 4 shows the result for the different charge state, gas and voltage combinations measured together with predictions of equation 1. The displayed errors in the cross sections only reflect the statistical errors from the fitting procedure and the averaging process.

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Systematic errors will affect all values in the same way and shift them up or down. They mainly result from the uncertainty in the pressure measurement and the determination of the interaction path length and can be estimated to a total systematic error of about 30 %.

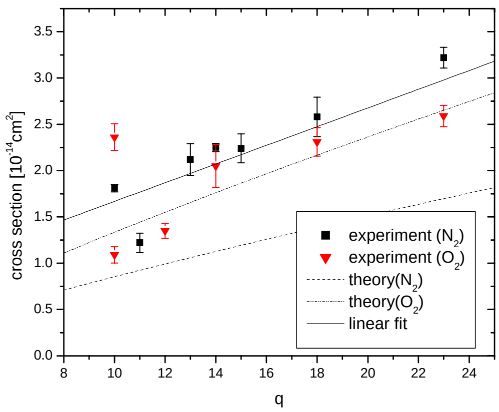

Figure 4 Experimental cross sections for the charge exchange of Rb and Cs ions in N_2 and O_2 gas together with the expectation from equation 1 and a linear fit. The error bars only represent statistical errors.

The strong dependence on the ionization energy of the gas molecules as is predicted by equation 1 can not be seen in our measurements but the results are within the error band of the expectation. A reason for the discrepancy can be the relatively high energy and charge state of the ions compared to most measurements done so far. The dependence on the charge state seems to be linear within the range of investigation. Therefore a linear fit has been made. With this the cross section can be expressed as.

$$\sigma = \left(6.58 \cdot 10^{-15} + 1.01 \cdot 10^{-15} q\right) cm^2 \qquad (2)$$

The error will be again dominated by a systematic error of about 30%. The fit result is included in figure 4. It shows a better agreement for high charge states than for those below 13. In the case of low charged ions shell effects in both the ion and the gas and the possibility of the ions being in a metastable state are expected to have a greater influence.

5 Conclusion and outlook

The measurements at the ion source teststand at TRIUMF have shown that the PHOENIX ECR source can be used as charge breeder for ions from typical on-line ion sources for ISAC. The efficiencies reached so far are up to 6% for noble gases and 3% for alkalies with breeding times up to 460 ms. The breeding time is not sufficiently short for the shortest lived radioactive isotopes but it is comparable to the release time from the target ion source system. Thus, in most cases no significant additional losses due to the radioactive decay are to be expected. The required A/q ≤ 7 where additional stripping can be avoided can be reached up to about Cs.

Extrapolation of equation 2 to a charge state of 30, which will be necessary for the heaviest isotopes at ISAC, leads to a cross section of $(3.7\pm1.1)\cdot10^{-14}$ cm^2. If 20% of beam loss can be accepted for a 25 m beam line this would require an average pressure of $1\cdot10^{-5}$ Pa, which is within the possible reach for such an installation.

Further increases of the efficiency may be possible by changing the deceleration system for the injected ions. Presently the ions are decelerated in one step just before entering the ECR plasma. As has been shown in simulations by Banerjee et al. [11] and in first results by Jeong et al. [12] a smoother deceleration in several steps can increase the capture efficiency and will reduce the extraction of highly charged ions in backwards direction. It is planned to test such a system first at the teststand before moving on-line for the charge breeding of radioactive ions.

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