Acceleration and identification of charge-bred ^{85}Rb ions

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The re-acceleration of charge bred, radioactive isotope beams from the TAMU light-ion guide and charge breeding electron-cyclotron resonance ion source (CB-ECR) for the T-REX project [1] presents several challenges. When beams of stable isotopes are accelerated though the K500 cyclotron, typically their intensities are of the order of 10^7 particles/sec (about 10 pA) or greater. Thus, the stable beams can be measured with a beam probe in the cyclotron and Faraday cups outside the cyclotron for tuning purposes. However, the charge bred, radioactive isotope beams are expected to have much weaker intensities than the stable beams. Even in the best cases when 10^6 particles/sec could be available for re-acceleration, these intensities are too low to be observed in the same way as the stable beams. Also, due to the high electric and magnetic fields present inside the K500 cyclotron, it is difficult to mount a particle detector, such as a photomultiplier tube and plastic scintillator (PMT-Scint), inside the cyclotron to tune the radioactive beams.

Fortunately, one of the advantages of charge breeding the radioactive ions in the CB-ECR is that several different charge states will be produced for re-acceleration through the K500. At the same time, since the plasma of the CB-ECR is supported by gases of stable isotopes such as oxygen, nitrogen or carbon, the CB-ECR also simultaneously produces stable beams at much higher intensities. By selecting charge states of the radioactive ions that have similar charge-to-mass (Q/M) ratios to the Q/M ratios of the stable beams, the more intense stable beam can be used as a "pilot beam" to guide the tune of the radioactive beam through the K500 cyclotron and ultimately to an experimental setup. After the pilot beam is tuned, if the difference in Q/M ratio between the pilot beam and the radioactive beam of interest is large enough, a slight change in the K500 radio-frequency on the order of 10-100 kHz is all is needed to accelerate and select the radioactive ions instead of the pilot beam. Ideally, once this single parameter is changed, the radioactive beam is tuned and ready to be further optimized with particle detectors in the beamline outside of the K500 cyclotron and finally transported to the experiments.

To practice this pilot beam tuning technique, a test experiment was conducted in February 2016 to accelerate $^{85}Rb^{16+}$ ions produced from a 1^+ ion gun and charge-bred by the CB-ECR. Although $^{85}Rb^{15+}$ and $^{85}Rb^{17+}$ ions from the CB-ECR were accelerated through the K500 in 2013 [2], the ^{85}Rb ions in that case were not measured after the cyclotron with particle detectors to verify their identity. Further, the $^{85}Rb^{16+}$ ions have a similar Q/M ratio to $^{16}O^{3+}$ (Q/M $^{16}O^{3+}$ = 0.1876 versus Q/M $^{85}Rb^{16+}$ = 0.1885). While the $^{16}O^{3+}$ beam is indistinguishable from the $^{85}Rb^{16+}$ ions produced in the CB-ECR before acceleration, they are easily separated during acceleration by the K500 cyclotron. Due to their difference in Q/M ratio, it was calculated that a change of 56 kHz in the K500 radio-frequency for 14 MeV/u would change the accelerated beam from the $^{16}O^{3+}$ to the $^{85}Rb^{16+}$ without changing any other parameters. Once the 56 kHz radio-frequency change was made, the change from $^{16}O^{3+}$ to $^{85}Rb^{16+}$ could be verified by measurements after the K500 cyclotron with the MARS spectrometer [3] and silicon detectors.

The experiment was conducted as follows. A stable beam of $^{84}Kr^{16+}$ at 14 MeV/u was produced by the ECR1 ion source and tuned through the K500 cyclotron to the MARS spectrometer. The $^{84}Kr^{16+}$ beam impinged on a thin, 6.4 μm aluminum foil to strip off the electrons and produce ^{84}Kr ions in several different charge-states ranging from fully-stripped 36+ ions down to 29+ ions. The ^{84}Kr could be identified by the different magnetic rigidities of its charge-states as predicted by the LISE++ program model of the MARS spectrometer [4, 5] and by its energy deposit in a silicon detector telescope mounted at the focal plane of MARS. In this way, the ^{84}Kr beam was used to calibrate the silicon detector telescope and verify the predictions of the LISE++ spectrometer model. The measurement of the $^{84}Kr^{31+}$ charge state in the silicon detector telescope is shown in Fig. 1. By comparing the energy deposited in the telescope for ^{84}Kr charge states 31+ through 36+, the energy of the ^{84}Kr was measured to be 1110 ± 5 MeV, slightly lower than 14 MeV/u because of the energy loss of the beam in the aluminum stripper foil, but in agreement with the predictions of the LISE++ model.

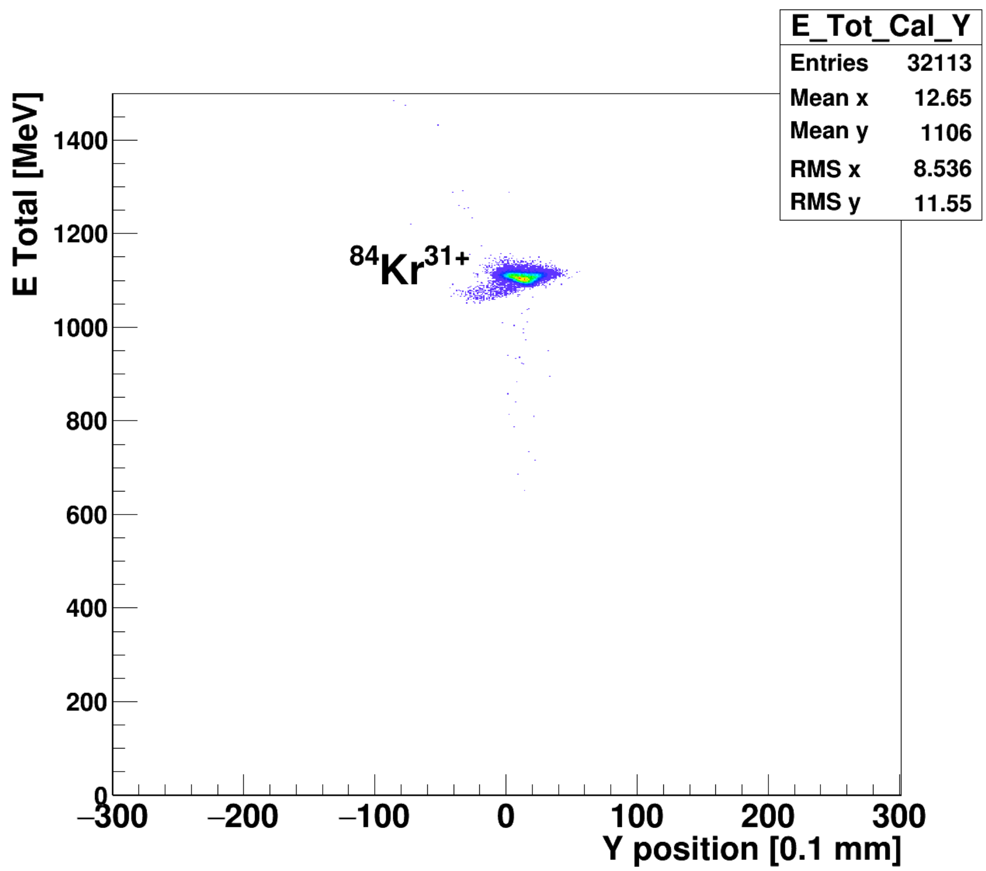

FIG. 1. $^{84}Kr^{31+}$ ion measured at the MARS focal plane with the silicon detector telescope for detector calibration.

Once the MARS silicon detector telescope was calibrated, the $^{85}Rb^{16+}$ was tuned as follows. First, $^{16}O^{3+}$ at 14 MeV/u produced by ECR1 was tuned through the K500 cyclotron to a beam viewer slightly upstream of the aluminum stripper foil at the entrance of the MARS spectrometer. Then the cyclotron injection line was changed to accept the $^{16}O^{3+}$ beam instead from the CB-ECR and $^{16}O^{3+}$ was still measured on the Faraday cup after the K500 cyclotron and observed on the beam viewer at the entrance of MARS. After turning on the Rb 1+ ion gun, the K500 cyclotron radio-frequency was increased by 56 kHz. Immediately, a weak beam spot of $^{85}Rb^{16+}$ was observed in almost the same position on the beam viewer at the entrance of MARS that the $^{16}O^{3+}$ had been seen previously. After some slight optimization of the cyclotron tune, about 50 pA of $^{85}Rb^{16+}$ were obtained.

Next, the beam viewer was removed and the $^{85}Rb^{16+}$ was impinged on the aluminum stripper foil at the entrance of MARS, as was done previously with the ^{84}Kr beam. By changing the magnetic rigidity of MARS, charge states 37+ through 33+ were observed using the silicon detector telescope. The measurement of the $^{85}Rb^{33+}$ charge state in the silicon detector telescope is shown in Fig. 2. The energy of the ^{85}Rb was measured to be 1127 ± 5 MeV, again in agreement with the prediction of LISE++ taking into account the energy losses in the aluminum stripper foil and the slight change in the initial $^{85}Rb^{16+}$ energy because of the cyclotron radio-frequency increase.

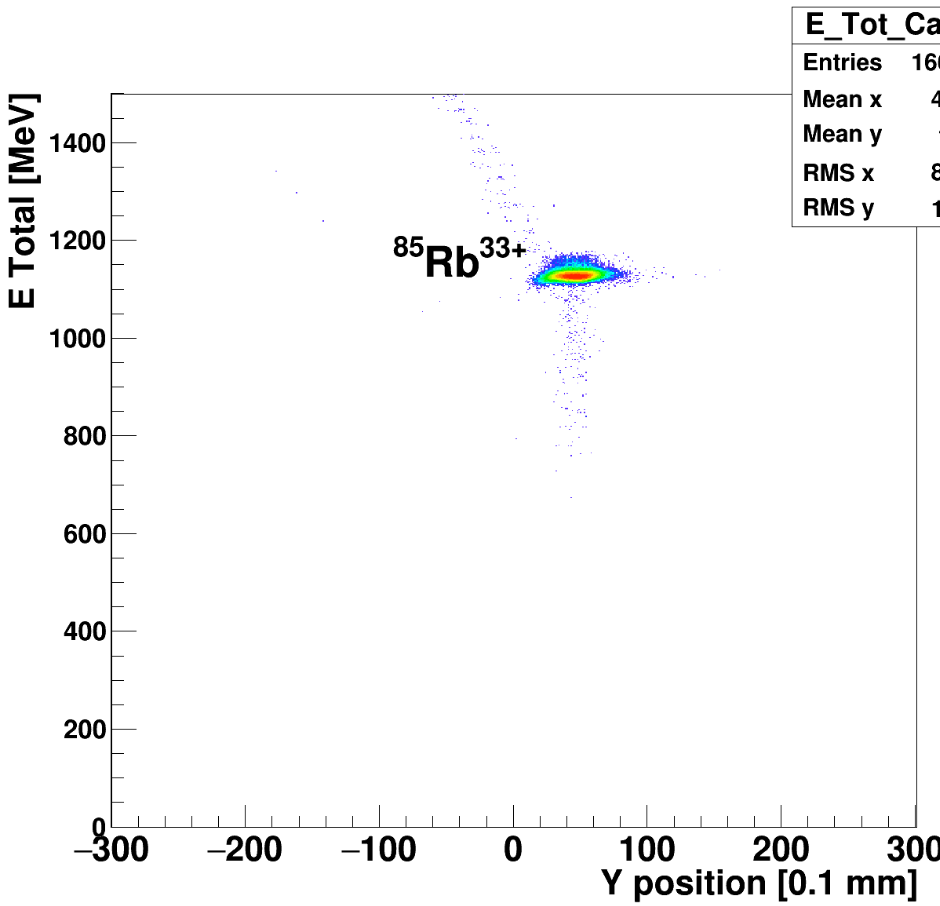

FIG. 2. $^{85}Rb^{33+}$ ions measured at the MARS focal plane with the silicon detector telescope.

As a final test of the pilot beam technique, a test was done to observe the "width" of the $^{16}O^{3+}$ beam at 14 MeV/u with respect to the cyclotron radio-frequency. While observing the $^{16}O^{3+}$ beam, stripped to $^{16}O^{8+}$, with a PMT-Scint detector at the MARS focal plane, the cyclotron frequency was varied in steps of 1 kHz to see when the ^{16}O beam completely disappeared on the detectors. This test was important because if the radioactive beam Q/M ratio was too close to the pilot beam, perhaps the cyclotron would not be able to completely separate the two beams. To completely remove the ^{16}O beam from the detector at the MARS focal plane, a radio-frequency shift greater than 12 kHz was needed. Since the frequency shift for $^{85}Rb^{16+}$ at 14 MeV/u was 56 kHz, the $^{85}Rb^{16+}$ was indeed fully separated from the $^{16}O^{3+}$ during acceleration by the K500 cyclotron. However, it appeared that ions with Q/M ratio differences of less than about 0.0002, corresponding to a frequency shift of about 12 kHz for 14 MeV/u, cannot be separated by the K500 cyclotron. This result is in agreement with previous observations with other stable beams, such as $^{20}Ne^{4+}$ and $^{40}Ar^{8+}$, which have nearly equal Q/M ratios and can not be cleanly separated when both are injected into the cyclotron. In the cases where this occurs, other methods such as a stripper foil after the cyclotron can be used to remove the pilot beam and select the radioactive ions

In summary, charge-bred $^{85}Rb^{16+}$ ions from 1+ ion gun source and the CB-ECR have been tuned through the K500 cyclotron by first tuning an $^{16}O^{3+}$ pilot beam at 14 MeV/u and then increasing the radio-frequency of the cyclotron 56 kHz to select instead the $^{85}Rb^{16+}$ ions at 14 MeV/u. The $^{85}Rb^{16+}$ ions were cleanly separated from the $^{16}O^{3+}$ beam. The $^{85}Rb^{16+}$ was transported to the MARS spectrometer and stripped by a thin aluminum stripper foil. Five separate charge states were measured and their predicted energy was verified by a silicon detector telescope.

In the coming year, it is expected that charge-bred, radioactive ^{64}Ga ions produced by the $^{64}Zn(p,n)$ reaction and transported by the light-ion guide will be available for re-acceleration by the K500 cyclotron. Since the $^{64}Ga^{12+}$ Q/M ratio is 0.18771, nearly the same Q/M ratio as $^{16}O^{3+}$, a similar technique as was used for the $^{85}Rb^{16+}$ could be employed to tune a $^{64}Ga^{12+}$ radioactive ion beam and identify it at the MARS spectrometer. It is also expected that elastically scattered $^{64}Zn^{12+}$ ions, Q/M ratio = 0.18773, from the production target will also be present.

[1] R.E. Tribble *et al.*, Eur. Phys. J. Spec. Top. **150**, 225 (2007).

[2] H.L. Clark *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2012-2013), p. IV-8; http://cyclotron.tamu.edu/2013 Progress Report/index.html.

[3] R.E. Tribble, R.H. Burch, and C.A. Gagliardi, Nucl. Instrum. Methods Phys. Res. **A285**, 441 (1989).

[4] O.B. Tarasov and D. Bazin, Nucl. Instrum. Methods Phys. Res. **B266**, 4657 (2008).

[5] B.T. Roeder and O.B. Tarasov, *Progress in Research*, Cyclotron Institute, Texas A&M University (2013-2014), p. IV-40; http://cyclotron.tamu.edu/2014 Progress Report/index.html.