Acceleration and identification of charge-bred ions from the light-ion guide with MARS: Identification of ^{114}Cd

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During the last two years, experiments have been carried out to accelerate and identify charge-bred ions from the light-ion guide at the Cyclotron Institute as part of the facility upgrade project. In 2016, ^{85}Rb from the charge-breeding electron-cyclotron resonance ion source (CB-ECR) was accelerated with the K500 and identified with the Momentum Acromat Recoil Separator (MARS) [1] and associated silicon detectors [2]. Last year, a follow-up experiment was designed to search for ^{64}Zn and ^{64}Ga ions that had been produced and transported with the Light-Ion Guide (LIG) to the CB-ECR and then re-accelerated with the K500 [3]. While some ^{64}Zn was identified with MARS, it was difficult to determine if the ^{64}Zn come from the LIG because ^{64}Zn was present as part of the background beam from the CB-ECR. ^{64}Ga was not observed unambiguously at MARS either.

This year, following a series of design changes to the injection side of the CB-ECR, a new reaction was attempted to produce the first charge-bred and accelerated beam from the Light Ion Guide project. Using 10 MeV protons from the K150 cyclotron on a thin, enriched target of ^{114}Cd, ^{114}In was produced via the ^{114}C(p,n)^{114}In reaction. This reaction was chosen because of its high cross section, the reasonably short half-life of ^{114}In (71.9 s), and the heavier mass of the ^{114}In relative to the ^{64}Ga which was thought to make it easier to charge-breed. Leading up to the attempt to re-accelerate the ions through the K500, ^{114}In^{19+} was observed after the CB-ECR at a rate of 238 decays/sec per μA of proton beam on the LIG target.

The experiment was carried out in a similar way as the previous experiments to measure ^{85}Rb and ^{64}Zn from the CB-ECR. To calibrate the detectors at the focal plane of MARS, a beam of ^{107}Ag at 11 MeV/u was accelerated with the K500 cyclotron and was transported to the target chamber of MARS. The ^{107}Ag beam impinged on a thin ^{12}C stripper foil that was 47.7 μg/cm^2 thick. The stripper foil removed electrons from the beam such that the resulting charge states of the beam could be tuned through MARS at rigidities calculated with the LISE++ model of MARS [4]. Once each charge state was tuned through MARS, it was measured at the focal plane with detectors consisting of a ΔE-E silicon telescope. The ΔE detector was a 63 μm thick, position sensitive silicon strip detector and the E detector was a single pad detector that was 500 μm thick. The type and thicknesses of the detectors were chosen such that the ^{107}Ag, and also the desired ^{114}Cd and ^{114}In, could be detected and identified using their energy loss in the silicon detectors and their position at the MARS focal plane. During the calibration, charge states 36+ through 39+ for ^{107}Ag were measured. An average energy of 1170 ± 2 MeV was observed by calculating the beam energy based on a prior calibration of the MARS D1 dipole field and comparing the energy deposits in the silicon telescope for each charge state. Due to the relatively high mass and low energy of the desired ^{114}Cd and ^{114}In, it was noted that this detector setup would not be sufficient to separate ^{114}Cd from ^{114}In. However, as any product with mass 114 could be identified versus other atomic masses by measuring their total energy, this setup was sufficient to determine if ions from the LIG were being re-accelerated by the K500.

To search for ^{114}Cd and ^{114}In ions that had been accelerated by the K500, first a pilot beam of $^{12}C^{2+}$ at 11 MeV/u was tuned through the K500 cyclotron. The charge-to-mass ratios (Q/M) for $^{12}C^{2+}$, $^{114}Cd^{19+}$, $^{114}In^{19+}$ are 0.16667, 0.16683 and 016683 respectively. Taking into account that the percent change in the charge to mass ratio here is +0.096%, to shift the frequency for $^{12}C^{2+}$ to $^{114}Cd^{19+}$ and $^{114}In^{19+}$ corresponding to $\Delta Q/\Delta M \approx 0.00016$, a frequency shift of about +9 kHz was expected. However, it was also noted in the ^{85}Rb experiment that the $^{16}O^{3+}$ pilot beam could still be observed as much as 12 kHz away from the optimum frequency. As a result, it was expected that all three beams in this case, $^{12}C^{2+}$, $^{114}Cd^{19+}$ and $^{114}In^{19+}$ would be transported to the MARS target chamber simultaneously despite the slight change in the frequency of the K500 cyclotron. But, after being stripped with the thin carbon stripper foil, the ^{114}Cd and ^{114}In for the charge states where the Q/M were different would be cleanly separated in rigidity from the ^{12}C pilot beam.

The ^{114}Cd and ^{114}In ions were produced by bombarding a thin, enriched ^{114}Cd target with between 1 and 4 μA of 10 MeV protons from the K150 cyclotron for the test run. The ^{114}Cd ions, produced from sputtering and proton elastic scattering, and the ^{114}In ions, produced from the ^{114}Cd(p,n)^{114}In reaction, were stopped in pure He gas and transported by the Light Ion Guide (LIG) [5] to the CB-ECR. Inside the CB-ECR, the ions were charge-bred in the plasma to $^{114}Cd^{19+}$ and $^{114}In^{19+}$ ions. Since $^{12}C^{2+}$ is also extracted from the CB-ECR with the same extraction voltage and magnet settings as the $^{114}Cd^{19+}$ and

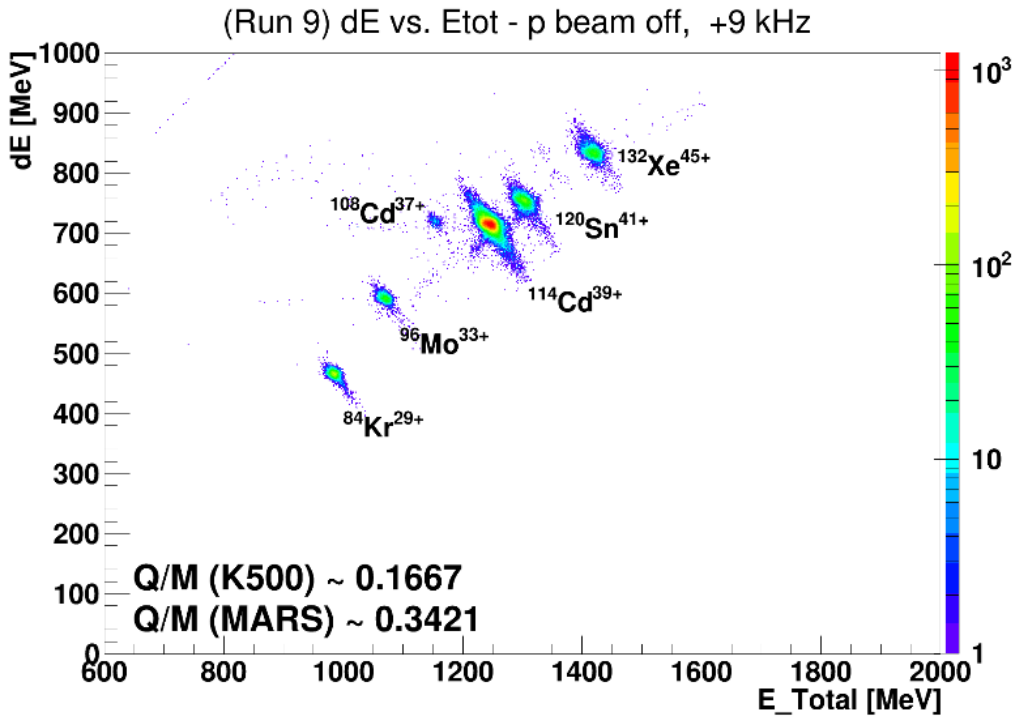

FIG. 1. Energy Loss (ΔE) vs. Total Energy spectrum obtained for the $^{114}Cd^{39+}$ MARS tune.

$^{114}In^{19+}$ ions, the $^{12}C^{2+}$ was used as a pilot beam to develop the tune from the CB-ECR through the K500 cyclotron and eventually to MARS. Then, once the $^{12}C^{2+}$ beam was tuned to the entrance of MARS, the

frequency of the K500 cyclotron was shifted +9 kHz (to optimize for the $^{114}Cd^{19+}$ and $^{114}In^{19+}$) to begin the search for the re-accelerated ions.

MARS was tuned with magnetic rigidity settings optimized to observe the ^{114}Cd and ^{114}In in charge states 37+ though 39+ as predicted by the LISE++ charge-stripping models and the observations of the stripping of the ^{107}Ag beam. The magnetic rigidity of MARS was set with the currents on the magnets as determined by the LISE++ model of MARS [4,6]. The ΔE vs. E spectrum obtained with MARS set to measure the $^{114}Cd^{39+}$ and $^{114}In^{39+}$ after the stripper foil is shown in Fig. 1. Mass 114, mostly ^{114}Cd, was clearly visible and the most intense ion measured. A few other ions with Q/M ≈ 1/6, similar to the $^{12}C^{2+}$ pilot beam, were also observed. The origin of these other ions is unknown, but they should be related with some contamination in the CB-ECR as they were present independent of the proton beam on the LIG target.

Measurements were conducted with the proton beam "on" and "off" the LIG target for 1 minute each. The intensity of the proton beam on the LIG target was also varied from 1 μA to 4 μA. The results of these measurements are shown in Fig. 2 for the $^{114}Cd^{38+}$ and $^{114}Cd^{39+}$ settings. While there was some ^{114}Cd background present when the proton beam was "off", the ^{114}Cd rate increased when the proton

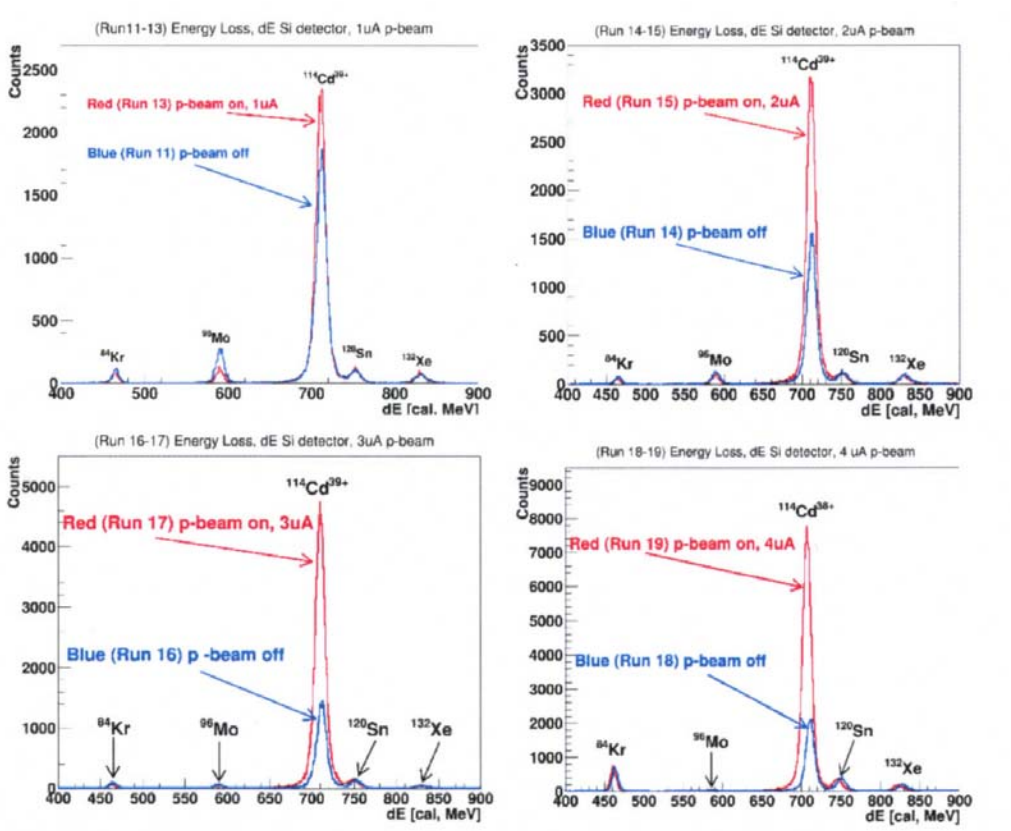

FIG. 2. Spectra showing the ^{114}Cd peak for 39+ and 38+ charge state settings. The measurements for each spectrum were taken for 1 minute. Identification of the ^{114}Cd from the LIG is shown by the red spectrum where the intensity of the ^{114}Cd is clearly increased with the K150 proton beam "On" versus the blue spectrum with the beam "Off".

beam was "on". Accounting for the background, the ^{114}Cd rate at MARS also appeared to increase linearly with the amount of proton beam on target. A maximum rate of 1.4×10^3 counts/sec above the

background was observed on the MARS silicon detector telescope with MARS tuned for $^{114}Cd^{38+}$ and 4 μA of proton beam on the LIG target. It should be noted here that the background rate for ^{114}Cd was around 400 counts/sec with the proton beam "off". ^{114}In was likely also present for the same MARS settings, but could not be observed directly from its energy loss due to its similar mass with the ^{114}Cd and the large intensity of the ^{114}Cd transmitted.

In conclusion, re-acceleration of $^{114}Cd^{19+}$ and $^{114}In^{19+}$ ions from the LIG and CB-ECR has been attempted. Peaks from $^{114}Cd^{38+}$ and $^{114}Cd^{39+}$ ions, obtained after passing the beam through a stripper-foil, were clearly observed confirming that the tune of the K500 cyclotron, the beam-line optics, and MARS was correct. The peak arising from the $^{114}Cd^{39+}$ ions varied in intensity depending on if the K150 proton beam was "on" or "off", if the LIG was "on" or "off", and also the intensity increased linearly if the amount of proton beam on the LIG was increased. The observation of the ^{114}Cd ions represents the first confirmed re-accelerated ions from the LIG and the CB-ECR. Further experiments with higher resolution detector systems and/or the ability to measure β-decay are envisioned to observe the ^{114}In decay that should have been simultaneously present.

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