

Acceleration and identification of charge-bred ions from the light-ion guide with MARS

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Last year, charge-bred ^{85}Rb from the charge breeding electron-cyclotron resonance ion source (CB-ECR) was accelerated with the K500 and identified with the MARS spectrometer and associated silicon detectors [1]. This 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 in an attempt to produce the first re-accelerated radioactive beam at the Cyclotron Institute.

The experiment was carried out in a similar way as the ^{85}Rb experiment. To calibrate the detectors at the focal plane of the Momentum Acromat Recoil Separator (MARS) [2], a beam of ^{63}Cu at 14 MeV/u was accelerated with the K500 cyclotron and was transported to the target chamber of MARS. The ^{63}Cu beam impinged on a thin ^{12}C stripper foil that was $103\ \mu\text{g}/\text{cm}^2$ 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 [3]. 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 $64\ \mu\text{m}$ thick, position sensitive strip detector and the E detector was a single pad detector that was $500\ \mu\text{m}$ thick. The type and thicknesses of the detectors were chosen such that the ^{63}Cu , and also the desired ^{64}Zn and ^{64}Ga , 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 23+ through 29+ for ^{63}Cu were measured. An average energy of $880.5 \pm 2\ \text{MeV}$ 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. The result of the tune for the $^{63}\text{Cu}^{29+}$ charge state is shown in Fig. 1. It was also noted that the energy resolution (FWHM) of the ΔE and E detectors were 7 MeV and 8 MeV respectively. This resolution was sufficient for the separation of beam species with mass=64, but different

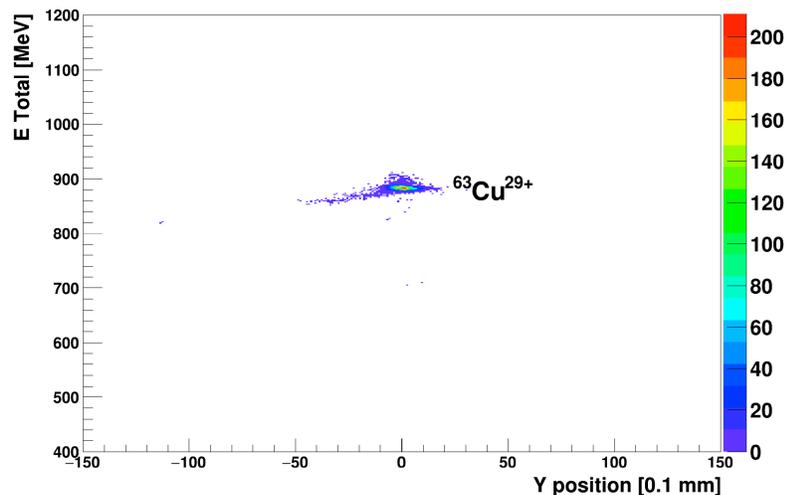


FIG. 1. Total Energy vs. Y-position spectrum obtained for the $^{63}\text{Cu}^{29+}$ calibration beam tune.

charge “Q” as was needed to measure ^{64}Zn and ^{64}Ga simultaneously.

To search for ^{64}Zn and ^{64}Ga ions that had been accelerated by the K500, first a pilot beam of $^{16}\text{O}^{3+}$ at 14 MeV/u was tuned through the K500 cyclotron. The charge-to-mass ratios (Q/M) for $^{16}\text{O}^{3+}$, $^{64}\text{Zn}^{12+}$, $^{64}\text{Ga}^{12+}$ are 0.18756, 0.18773 and 0.18771 respectively. It was calculated for the ^{85}Rb at 14 MeV/u in the previous experiment that a radiofrequency (RF) shift of about 6 kHz corresponded to changing the Q/M ratio accelerated by the K500 by about $\Delta Q/\Delta M \approx 0.0001$. Thus, to shift the frequency for $^{16}\text{O}^{3+}$ to $^{64}\text{Ga}^{12+}$, corresponding to $\Delta Q/\Delta M \approx 0.00015$, a frequency shift of about +8 kHz to +9 kHz was expected. However, it was also noted in the experiment last year that the $^{16}\text{O}^{3+}$ 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, $^{16}\text{O}^{3+}$, $^{64}\text{Zn}^{12+}$ and $^{64}\text{Ga}^{12+}$ 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 ^{64}Zn and ^{64}Ga for the charge states where the Q/M were different would be cleanly separated in rigidity from the ^{16}O pilot beam.

The ^{64}Zn and ^{64}Ga ions were produced by bombarding a thin, enriched ^{64}Zn target with about 5 μA of 15 MeV protons from the K150 cyclotron. The ^{64}Zn ions, produced from proton elastic scattering, and the ^{64}Ga ions, produced from the $^{64}\text{Zn}(p,n)^{64}\text{Ga}$ reaction, were stopped in pure He gas and transported by the Light Ion Guide (LIG) [4] to the CB-ECR. Inside the CB-ECR, the ions were charge-bred in the plasma to $^{64}\text{Zn}^{12+}$ and $^{64}\text{Ga}^{12+}$ ions. Since $^{16}\text{O}^{3+}$ is also extracted from the CB-ECR with the same extraction voltage and magnet settings as the $^{64}\text{Zn}^{12+}$ and $^{64}\text{Ga}^{12+}$ ions, the $^{16}\text{O}^{3+}$ 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 $^{16}\text{O}^{3+}$ beam was tuned to the entrance of MARS, the frequency of the K500 cyclotron was shifted +8 kHz (to optimize for the $^{64}\text{Ga}^{12+}$) to begin the search for the re-accelerated $^{64}\text{Zn}^{12+}$ and $^{64}\text{Ga}^{12+}$.

Prior to sending the $^{16}\text{O}^{3+}$ beam through the K500, a β -decay rate of 20 decays/s was observed with the same magnet settings after the CB-ECR on the silicon detector in the vertical injection line. These β -decays were assumed to arise from the decay of the $^{64}\text{Ga}^{12+}$ ions. Assuming a 1% efficiency for the acceleration of these ions, that would imply that about 0.2 ions/sec would be transported to MARS. Following the charge-stripping models available in LISE++, about 35% of these ions were expected to be in the 29+ charge state following the ^{12}C stripper foil. Taking these efficiencies into account, about one $^{64}\text{Ga}^{29+}$ ion per 14 seconds was expected on the MARS silicon detectors.

MARS was tuned with magnetic rigidity settings optimized to observe the ^{64}Ga and ^{64}Zn in charge states 29+ and 27+. Settings to observe the $^{64}\text{Ga}^{31+}$ were also attempted. The magnetic rigidity of MARS was set with the currents on the magnets as determined by the LISE++ model of MARS [3]. Data were taken separately with the K150 proton beam both on and off.

Since both $^{64}\text{Zn}^{29+}$ and $^{64}\text{Ga}^{29+}$ have the same mass and charge, then they should have the same total energy, 892 MeV, as measured by the silicon detector telescope. However, the energy loss of the two ions in the ΔE detector was different by 19 MeV; 320.6 MeV for ^{64}Zn and 339.8 MeV for ^{64}Ga as calculated by LISE++ [3,5]. In the measurement, a peak corresponding to ^{64}Zn was observed in the ΔE detector spectrum when the K150 proton beam was both on and off. The peak was asymmetric on the high-energy side, leading to background in the region where the ^{64}Ga could be expected. In one experiment run, a shoulder peak with about 100 counts above the background was observed at the energy loss corresponding to ^{64}Ga . Due to the background in the high-energy tail of the ^{64}Zn peak, cleaner

separation of the ^{64}Ga from the ^{64}Zn was not possible in this setup. Assuming a constant background rate, the rate of the ^{64}Ga was about one ion per 30 seconds; about half of what was expected. However, since the background rate in the high-energy tail was about the same as the ^{64}Ga rate with the proton beam on and the shoulder peak was not reproducible, the results were inconclusive. A higher intensity peak with about 680 MeV total energy, consistent with $^{48}\text{Ti}^{22+}$, was also observed. The origin of the ^{48}Ti background is unknown but may be due to the specific aluminum alloy in the CB-ECR plasma chamber. Perhaps the ^{64}Zn that is observed with the K150 proton beam off arises from the same origin. ΔE detector spectra showing measurements of the ^{64}Zn peak with MARS set for the 29+ charge state with the K150 proton beam on and off are shown in Fig. 2.

With MARS set to measure the $^{64}\text{Zn}^{27+}$ and $^{64}\text{Ga}^{27+}$, a peak corresponding to ^{64}Zn was observed

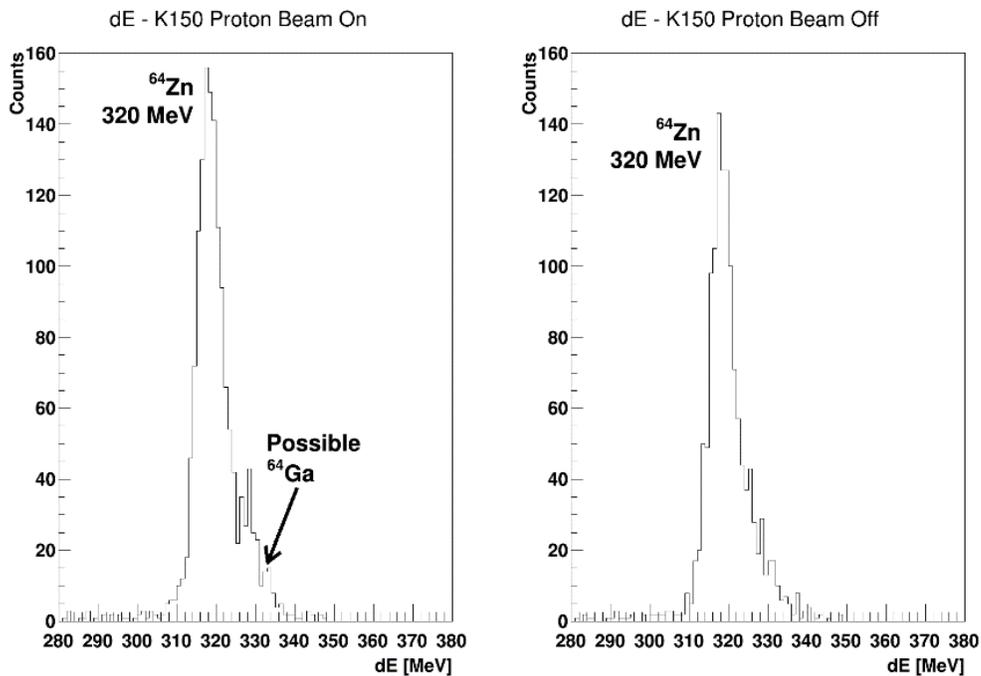


FIG. 2. Spectra showing the ^{64}Zn and possible ^{64}Ga peak for 29+ charge state setting. Clear identification of the ^{64}Ga was not possible. With the K150 proton beam “On”, about 100 counts above background were observed in the region where ^{64}Ga was expected.

again, confirming the identification of the ^{64}Zn . No ^{64}Ga was observed at this setting. However, surprisingly, $^{64}\text{Ni}^{27+}$ was also observed, well separated by 40 MeV from the $^{64}\text{Zn}^{27+}$ in the ΔE detector spectrum. Like the ^{48}Ti , the origin of the ^{64}Ni background is unknown but may be due to contamination in the CB-ECR plasma chamber as before.

A large background from the remnants of the pilot beam was expected with the tunes for the ^{64}Ga 28+ and 24+ charge states, since they are charge-to-mass analogs with the $^{16}\text{O}^{7+}$ and $^{16}\text{O}^{6+}$ respectively. Surprisingly, large background rates of greater than 10 kHz were also observed for when MARS was tuned for the ^{64}Ga 30+ and 26+ charge states. This background was later determined to be from $^{32}\text{S}^{15+}$ and

$^{32}\text{S}^{13+}$, which are charge-to-mass analogs of the ^{64}Ga 30+ and 26+ charge states and are not easily separated with MARS. The source of the ^{32}S background beam is also unknown.

No $^{64}\text{Ga}^{31+}$ was observed even after a measurement of one hour. However, due to the low beam energy, populating the “fully-stripped” charge state of ^{64}Ga was unlikely (~1%) according to the LISE++ charge state models [5].

In future measurements, the following changes are envisioned. First, planned improvements to the LIG and the CBECR will produce a higher rate of ^{64}Ga ions, making them easier to separate from the other background beams. Second, a ΔE detector with better resolution for mass-64 separation will be installed such that ^{64}Ga can be better resolved from the ^{64}Zn that comes with it. Finally, a thick Aluminum degrader/stripper foil about 50.8 microns thick will be used in place of the carbon stripper foil. This thicker foil will separate ^{64}Ga from ^{64}Zn in energy and magnetic rigidity, making it possible to tune them separately to the detector chamber of MARS. The planned measurements will be conducted in the coming year when the improvements to the LIG and CB-ECR have been implemented.

In conclusion, re-acceleration of $^{64}\text{Zn}^{12+}$ and $^{64}\text{Ga}^{12+}$ ions from the LIG and CB-ECR has been attempted. A peak from $^{64}\text{Zn}^{29+}$ ions, obtained after passing the beam through a stripper-foil, was observed confirming that the tune of the K500 cyclotron, the beam-line optics, and MARS was correct. A small shoulder peak, perhaps arising from $^{64}\text{Ga}^{29+}$ ions, was also observed in one experiment run. Beam contamination from higher intensities of ^{48}Ti , ^{64}Ni , and ^{32}S were also present in the re-accelerated beam, independent of if the K150 proton beam was on or off. The possible observation of the ^{64}Ga ions represents the first re-accelerated radioactive ions from the LIG and the CB-ECR. However, further experiments with higher injected ^{64}Ga intensities and higher resolution detector systems should be conducted in order to confirm these results.

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