Identification of ^{112}In: First re-accelerated radioactive light-ion guide beam

B.T. Roeder, F. Abegglen, J. Arje, G.J. Kim, A. Saastamoinen, and G. Tabacaru

This year, following the installation of a 2.5m long Sextupole Ion Guide (SPIG) upstream of the CB-ECRIS, the first charge-bred and reaccelerated radioactive beam from the Light Ion Guide project was realized. Leading up to the attempt to re-accelerate the ions through the K500, $^{114}In^{19+}$ from $^{114}Cd(p,n)^{114}In$ with 10 MeV protons from the K150 cyclotron was observed after the CB-ECRIS at a rate of ~1200 decays/sec per μA of proton beam on the LIG target. This represented a large improvement over previous results. However, following the re-acceleration of ^{114}Cd ions last year [1], it was noted that a reaction product with different mass than the production target was needed. ^{112}In is produced from the same ^{114}Cd target with high cross section if the proton beam energy is increased to 28 MeV [2].

The experiment was carried out in a similar way as the previous experiments to measure ^{85}Rb, ^{64}Zn, and ^{114}Cd from the CB-ECR [1,3,4]. To calibrate the detectors at the focal plane of the Momentum Acromat Recoil Separator (MARS) [5], a beam of ^{109}Ag at 14 MeV/u was accelerated with the K500 cyclotron and was transported to the target chamber of MARS. The ^{109}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 [6,7]. 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 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 ^{109}Ag, and also the desired ^{112}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 38+ and 39+ for ^{109}Ag were measured. An average energy of 1502 ± 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. An excellent energy resolution of about 10 MeV FWHM was obtained for the ΔE detector which allowed for the identification of individual elements with the same mass.

To search for ^{112}In ions that had been accelerated by the K500, first a pilot beam of $^{16}O^{3+}$ at 14 MeV/u was tuned through the K500 cyclotron. The charge-to-mass ratios (Q/M) for $^{16}O^{3+}$ and $^{112}In^{21+}$ are 0.18758 and 0.18768 respectively. Taking into account that the percent change in the charge to mass ratio here is +0.053%, to shift the frequency for $^{16}O^{3+}$ to $^{112}In^{21+}$ corresponding to $\Delta Q/\Delta M \approx 0.00010$, a frequency shift of about +6.5 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 both $^{16}O^{3+}$ and $^{112}In^{21+}$ 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 ^{112}In for the charge states where the Q/M were different would be cleanly separated in rigidity from the ^{16}O pilot beam.

The ^{112}In ions were produced by bombarding a thin, enriched ^{114}Cd target with about 2 μA of 28 MeV protons from the K150 cyclotron. The ^{112}In ions, produced from the $^{114}Cd(p,3n)^{112}In$ reaction, were

stopped in pure He gas and transported by the Light Ion Guide (LIG) [6] to the CB-ECR. Inside the CB-ECRIS, the ions were charge-bred in the plasma to $^{112}In^{21+}$ ions. Since $^{16}O^{3+}$ is also extracted from the CB-ECRIS with the same extraction voltage and magnet settings as the $^{112}In^{21+}$ ions, the $^{16}O^{3+}$ was used as a pilot beam to develop the tune from the CB-ECRIS through the K500 cyclotron and eventually to MARS. Then, once the $^{16}O^{3+}$ beam was tuned to the entrance of MARS, the frequency of the K500 cyclotron was shifted +6.5 kHz (to optimize for the $^{112}In^{21+}$) to begin the search for the re-accelerated ions.

MARS was tuned with magnetic rigidity settings optimized to observe the ^{112}In in charge states 34+ though 41+ as predicted by the LISE++ charge stripping models. The magnetic rigidity of MARS was set with the currents on the magnets as determined by the LISE++ model of MARS [7,8]. The ΔE vs. E spectrum obtained with MARS set to measure the $^{114}In^{38+}$ after the stripper foil is shown in Fig. 1. Particles with Mass 112 dominate the spectrum and $^{112}In^{38+}$ is visible in the Mass 112 group. ^{112}Cd and ^{112}Sn, likely originating from CB-ECRIS plasma chamber contamination, were also present. A few other ions with Q/M ≈ 3/16, similar to the $^{16}O^{3+}$ pilot beam, were also observed.

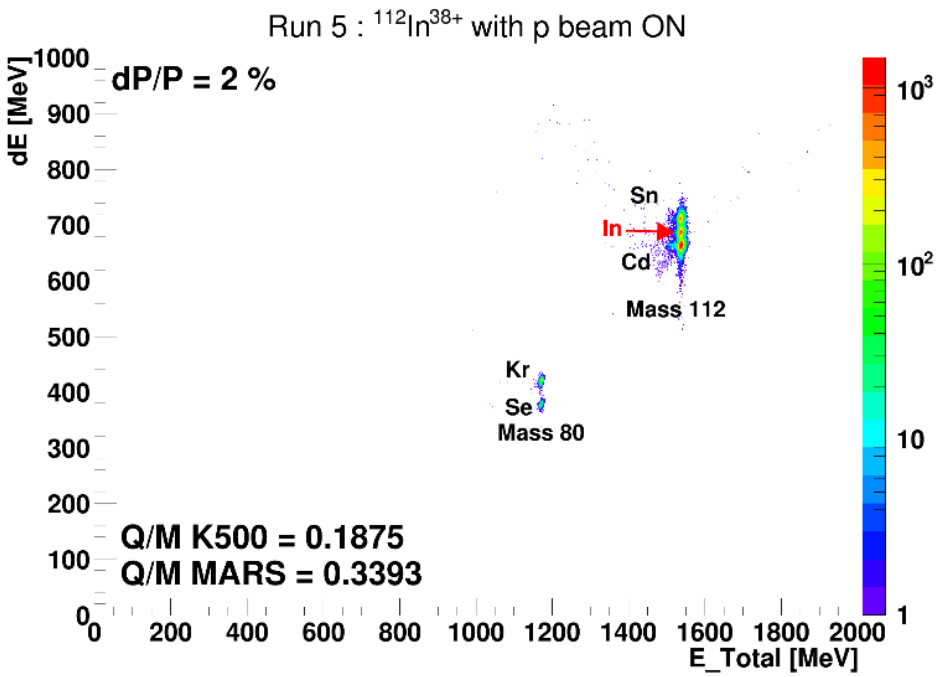

FIG. 1. Energy Loss (ΔE) vs. Total Energy spectrum obtained for the $^{112}In^{38+}$ MARS tune.

Measurements were conducted with the proton beam "on" and "off" the LIG target for 3 minutes each. Some results of these measurements are shown in Fig. 2 for the $^{112}In^{39+}$ setting. The peak corresponding to ^{112}In disappears if the K150 proton beam is stopped while the others remain. A maximum rate of 100 counts/sec for ^{112}In was observed on the MARS silicon detector telescope with MARS tuned for $^{112}In^{39+}$ and 2 μA of proton beam on the LIG target.

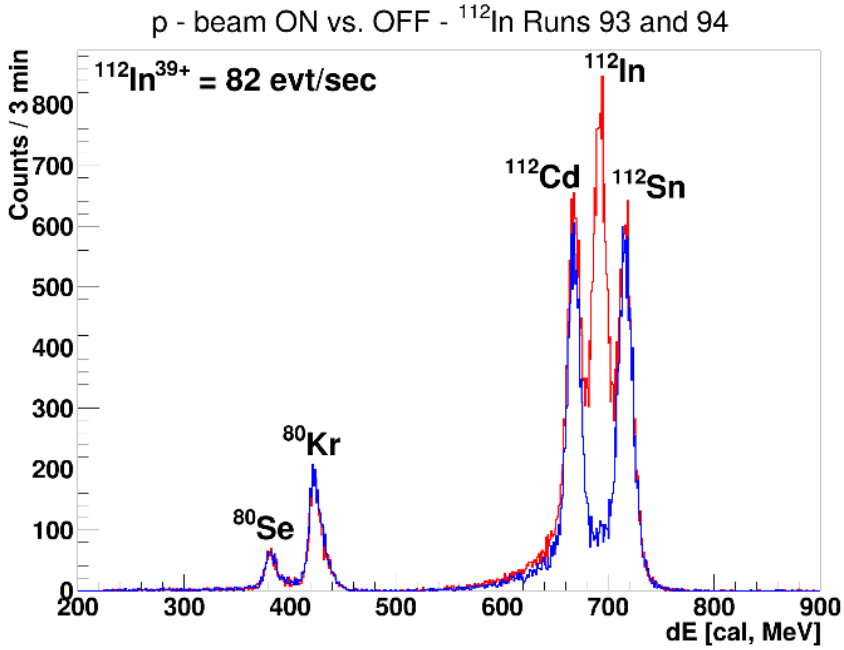

FIG. 2. ΔE Spectra showing the ^{112}In measured at the MARS focal plane for the 39+ charge state settings. The measurements for the proton-beam "off" (shown in blue) and the proton beam "on" (shown in red) were measured for 3 minutes each. The peak corresponding to ^{112}In is clearly visible with the K150 proton beam "On" versus when the proton beam was "Off".

Considering the charge state scan measured at the MARS focal plane, about 30% of the re-accelerated ^{112}In was observed at the MARS focal plane with the $^{112}In^{39+}$ magnet settings. Also, the transmission of the beam through the K500 cyclotron was estimated to be about 10%, based on the measurements of the $^{16}O^{3+}$ pilot beam on faraday cups before and after the cyclotron. Thus, it can be implied about 3.3×10^3 p/s of $^{112}In^{21+}$ was produced before the K500 cyclotron by the LIG+CB-ECRIS with 2 μA of proton beam on the production target.

In conclusion, ^{112}In from the LIG and CB-ECRIS has been re-accelerated by the K500 cyclotron and observed at the MARS focal plane. Peaks $^{112}Cd^{39+}$, $^{112}In^{39+}$ and $^{112}Sn^{39+}$ 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 $^{112}In^{39+}$ 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 ^{112}In ions represents the first confirmed re-accelerated radioactive ions from the LIG and the CB-ECRIS. Following this result, the re-acceleration of lighter ions, such as ^{57}Ni, is planned for coming year.

[1] B.T. Roeder *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2017-2018),p. IV-63; http://cyclotron.tamu.edu/progress-reports/2017-2018/SECTION IV.html.

[2] *TENDL-2017*, https://tendl.web.psi.ch/tendl_2017/tendl2017.html.

[3] B.T. Roeder *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2015-2016), p.IV-16; http://cyclotron.tamu.edu/progress-reports/2015-2016/SECTION IV.html.

[4] B.T. Roeder *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2016-2017), p. IV-17; http://cyclotron.tamu.edu/progress-reports/2016-2017/SECTION IV.html.

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

[6] G. Tabacaru *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2018-2019), p. IV-13; *Cyclotron Institute upgrade project: Section IV: Progress on the Light Ion Guide*, http://cyclotron.tamu.edu/progress-reports/2018-2019/SECTION IV.html.

[7] B.T. Roeder *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2013-2014), p. IV-40; http://cyclotron.tamu.edu/progress-reports/2013-2014/SECTION IV.html.

[8] O.B. Tarasov and D. Bazin, Nucl. Instrum. Methods Phys. Res. B**266**, 4657 (2008).