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BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.*

New nuclei near the proton drip line around $Z = 40$

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A ^{92}Mo beam with an energy of $E/A = 70$ MeV has been used to produce new isotopes near the proton drip line. The Michigan State University National Superconducting Cyclotron Laboratory A1200 fragment separator was used to detect the new isotopes ^{78}Y, ^{82}Nb, ^{85}Mo, ^{86}Tc, and ^{89,90}Ru.

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The heaviest stable nuclei along the $N = Z$ line have recently been the subject of intense study [1–3]. This is due to both the astrophysical significance of the rapid proton capture (rp) process and the unusual structure and shape of the nuclei themselves. The strongest deformation of any nucleus has been shown to be ^{76}Sr ($\beta_2 = 0.45$) [4]. This deformation of nuclei decreases as the shell closure at $Z = 50$ is approached. Previous to this work the heaviest $N = Z$ nucleus was ^{84}Mo, which has a deformation of $\beta_2 = 0.30$ [2]. Progress is being made in the theoretical understanding of the properties of these nuclei with many nuclear models [5]. The results of these calculations are sensitive to the choice of model parameters so that ground-state deformation measurements far from stability provide tests of the model predictions. Furthermore, these different mass models also predict varying limits of stability against proton emission. Therefore, experimentally defining the proton drip line is an important first step toward the determination of the best model parameters. Such experiments also provide production rate measurements of proton-drip-line nuclei so that detailed studies of their properties can be planned.

Here we report the results of an experiment designed to produce and observe new nuclei near the proton drip line in the $A \sim 85$ mass region. These observations were made possible by the combination of a high-energy beam of a rare isotope, ^{92}Mo, and the A1200 fragment analyzer at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University [6]. Figure 1 shows a schematic layout of the A1200, which consists of fourteen superconducting quadrupole and four superconducting dipole magnets. It has an angular acceptance of 4.3 msr, a momentum acceptance of 3%, and a maximum rigidity of 5.4 T m [6]. The experimental method employed in the present experiment closely follows that of Bazin *et al.* [7] and Mohar *et al.* [3].

An $E/A = 70$ MeV ^{92}Mo beam was produced by the K1200 cyclotron and transported to the high-acceptance target position of the A1200, where it interacted with a 97-mg/cm^2-thick enriched ^{58}Ni target with a 3-mg/cm^2 Al backing. The Al backing was used to increase the fraction of reaction products in their fully stripped charge state [8]. The position and angle of the reaction products were measured at both Dispersive Image 2 and the Final Achromatic Image (see Fig. 1) by pairs of parallel plate avalanche counters (PPACs). The transit time through the device was measured by thin plastic scintillators placed at Dispersive Image 1 and the final image. The time difference over the approximately 14-m flight path was used to determine the time of flight (TOF) and thus the velocity of each particle. At the Final Image the reaction products were implanted into a four-element silicon telescope (dE_1, dE_2, E_1, and E_2). This silicon telescope provided two energy-loss measurements before stopping the particle, thus allowing redundant Z determinations. NMR measurements of the dipole fields along with the position information from the PPACs at Image 2 were used to determine the rigidity of each particle.

The detection system was initially calibrated by transporting the primary beam through the device. Further calibration and isotope identification were obtained by setting the A1200 to detect light nuclei and verifying in

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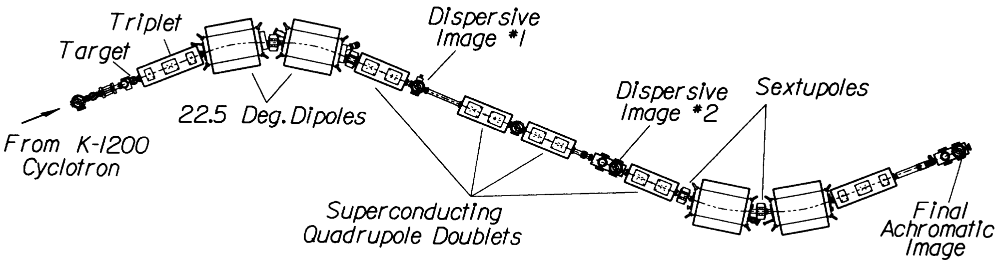

FIG. 1. Schematic layout of the A1200 beam analysis device.

an energy-loss (dE_1 or dE_2) versus TOF histogram that the unbound nucleus ^{8}Be was absent. The magnetic settings of the device were then changed in small steps from the rigidity needed to transport such light nuclei to the rigidity needed to transport the heavier elements of interest. Selection of fragments near the central rigidity of each of these settings resulted in a composite spectrum containing isotopes for Z from 3 to 44. Finally, the measured values of dE, E, TOF, and rigidity from approximately 30 isotopes were fitted to determine smooth functions for the calibrations of the system, which permitted unambiguous identification of all fragments.

All of the transported isotopes could be identified in a dE versus TOF plot for the full 3% momentum acceptance only after both the dE and TOF were compensated for the differing rigidity and path length of each particle. The TOF was compensated for $B\rho/B\rho_0$ (the measured rigidity versus the central rigidity) and the path length l_0/l (central path length versus off-axis path length). Both the ρ and the l were derived from the measured x position at Dispersive Image 2.

These adjustments were used in a dE_c versus TOF_c histogram to assure unambiguous identification throughout the experiment. In order to accumulate the statistics from various magnetic settings of the A1200, the Z of the fragment was first identified and then the mass calculated. The Z of the ion was calculated from the energy loss in each dE detector and the velocity of the particle using

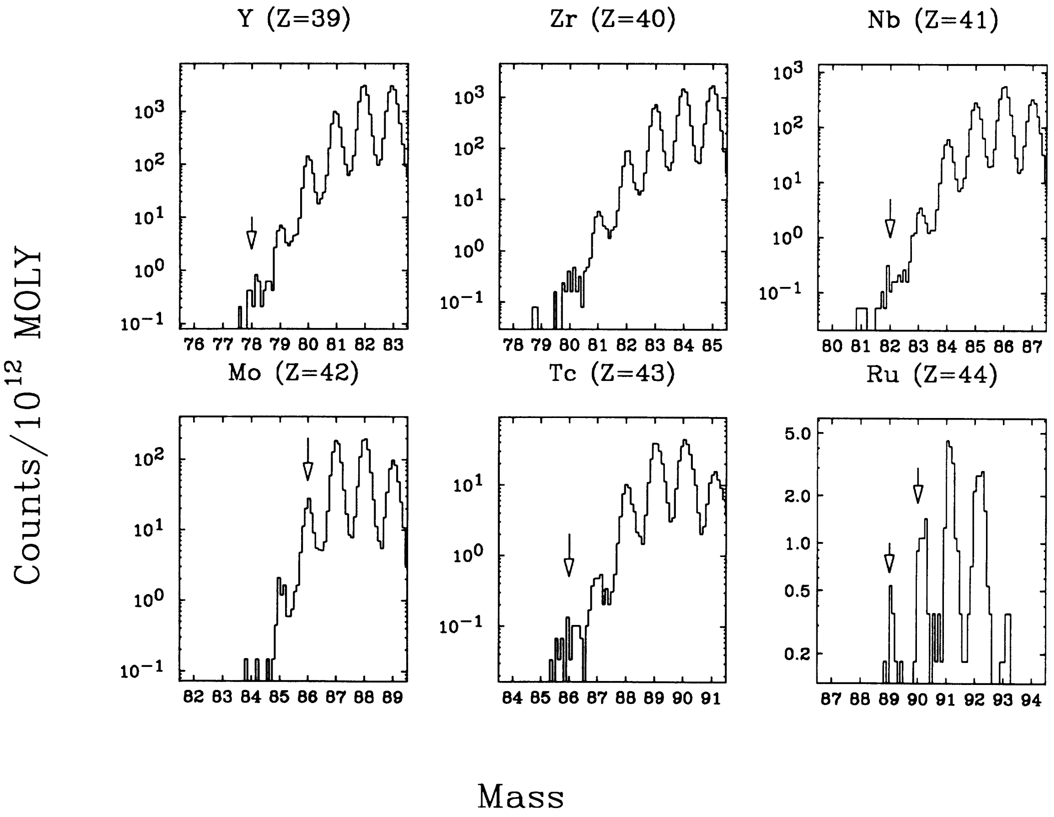

FIG. 2. Mass spectra for $Z=39$–44 (yttrium through ruthenium). Arrows show the nuclei identified for the first time in this study.

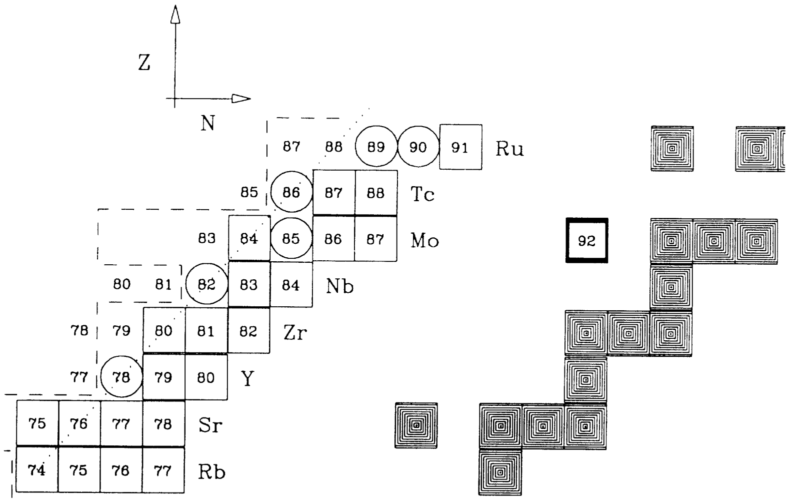

FIG. 3. Section of the chart of the nuclides in the region of interest. Stable nuclei are indicated by shaded squares, and the projectile ^{92}Mo is specially noted. Open squares indicate nuclei that have been previously identified, and those identified in the present work are circled. Nuclei to the left of the dashed line are predicted to be unstable by the mass model of Jänecke and Masson [11]. The dotted line follows nuclei with $N=Z$.

the formula

$$Z \approx [dE(\gamma-1)]^{1/2}\ , \tag{1}$$

which is based on the characteristic energy loss of the particle through the silicon detector. The velocity of the particle was determined from the TOF, corrected for vertical position dependence in the start detector. The calculated Z values were normalized to known charges independently for the two dE detectors. Contours in a plot of Z_1 versus Z_2 with Z resolution sufficient to separate the atomic species provided a redundancy check on Z identification. The charge state Q was assigned to be an integer value taken from the Z identification. The mass of the particle was then calculated from the charge, rigidity, and velocity of the particle and the magnetic setting of the A1200,

$$M=\frac{QB\rho}{\beta\gamma}\ , \tag{2}$$

and normalized to known masses. As can be seen in Fig. 2 the mass resolution is sufficient to clearly separate the isotopes.

The mass spectra for residues with Z from 39 to 44 are shown in Fig. 2 with the new isotopes marked by arrows. Although both ^{84}Mo and ^{86}Mo have been previously observed [2,9], no reference to the identification of ^{85}Mo was found. The other new isotopes observed in this study are ^{78}Y, ^{82}Nb, ^{86}Tc, and ^{89,90}Ru.

The observation of an isotope in the present experiment implies that the ion lives longer than its flight time through the A1200, which is of the order of 150 ns. Therefore, it is possible that some of the observed isotopes are actually proton unbound with half-lives greater than times of this order. The nonobservation of an isotope in this work implies either that it is unbound, that it has half-life short compared to the flight time, or that its production rate was too low to make it observable.

The work of Mohar *et al.* [3] identified the new isotopes of ^{65}As and ^{69}Br as well as confirmed the instability of ^{73}Rb previously reported by the ISOLDE group [10], and suggested that ^{69}Br was the heaviest of the odd Z $T_z=-\frac{1}{2}$ nuclei. In the present work the statistics are not sufficient to test this assertion. Figure 3 shows the nuclei in the vicinity of the $N=Z$ line with proton number $37 \leq Z \leq 44$. The proton drip line as predicted by Jänecke and Masson [11] is shown by the dashed line. Nuclei with $N=Z$ lie along the dotted line; the positions of stable nuclei are shaded and those of previously observed nuclei are boxed. The new nuclei are shown as circles. Three of the new nuclei (^{78}Y, ^{82}Nb, and ^{86}Tc) are predicted to be the last proton stable nuclei for their respective atomic numbers [11]. The stability of these nuclei help define possible rp processes above krypton [12]. Studies of ^{83}Nb [13] suggest that the neutron-deficient niobium isotopes become more deformed as their mass decreases because of the lessening influence of the shell closure at $N=50$. Based on N_nN_p systematics [14], the very neutron-deficient isotopes of yttrium should be some of the most deformed nuclei in this region, and perhaps overall. Now that some of these new nuclei have been identified and can be produced, detailed studies of their structure, shape, and decays can be planned.

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