Identification of New Nuclei near the Proton-Drip Line for $31 \leq Z \leq 38$

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An $E/A = 65$ MeV ^{78}Kr beam has been used to produce six new isotopes near the proton-drip line. The newly commissioned A1200 beam-analysis device was used to observe the astrophysically interesting isotope ^{65}As, as well as ^{61}Ga, ^{62}Ge, ^{63}Ge, ^{69}Br, and ^{75}Sr. Implications of the observation of these nuclei are discussed in terms of the astrophysical *rp* process.

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The ability to study proton-drip-line nuclei in the mass range $50 < A < 100$ is essential for understanding certain astrophysical processes as well as interesting nuclear structure found in this region. In particular, the particle stability of ^{65}As has been of interest in recent years with respect to the duration and termination of the rapid-proton-capture (*rp*) process, introduced by Wallace and Woosley.[1] The properties of ^{65}As have been identified as key in determining the importance of the *rp* process in certain stellar environments.[2-4] The various atomic-mass predictions[5] disagree as to whether the nucleus is bound or whether it may, in fact, be a ground-state proton emitter. A number of studies[6-8] have attempted to identify the ground-state proton decay of ^{65}As and ^{69}Br but have produced no evidence for such activity, and until now there have been no observations of ^{65}As. The observation of the particle stability of ^{65}As alone would at least indicate the possible continuation of the process to higher masses. The same argument can be made for ^{69}Br and ^{73}Rb. There is also a great deal of interest in the collective properties of nuclei in this region. Especially large and unusual deformations are predicted in the $N = Z$ nuclei with masses from 64 to 80 due to the lowering of the $g_{9/2}$ orbits for both protons and neutrons in these nuclei. For example, ^{76}Sr and ^{80}Zr are two nuclei with ground-state deformations among the largest known to exist.[9] Thus a method which can produce these nuclei with reasonable intensities would allow studies of nuclei not accessible in fusion-evaporation reactions.

This Letter describes the results of an experiment to produce and observe new nuclei near the proton-drip line in the mass region $50 < A < 100$. Such observations were made possible for the first time by the combination of a high-energy, rare-isotope beam of ^{78}Kr and the newly commissioned A1200 beam-analysis device at the National Superconducting Cyclotron Laboratory at Michigan State University. Figure 1 shows a schematic layout of the A1200, which consists of a series of fourteen superconducting quadrupoles and four superconducting dipoles. It has an angular acceptance of 0.8 msr, a 3% momentum acceptance, and a maximum rigidity of 5.4 Tm.[10] The method used to produce and identify these isotopes is similar to that used by GANIL for mapping the proton-drip line below $Z = 30$,[11] with the addition of precise rigidity information. An $E/A = 65$ MeV ^{78}Kr beam was produced by the K1200 cyclotron and reacted with an enriched ^{58}Ni target, 94 mg/cm^2 thick, at the object point of the A1200. The reaction products were collected and transported through the A1200 mass separator to a four-element silicon-detector telescope ($\Delta E1$, $\Delta E2$, $E1$, and $E2$) at the achromatic final image point of the device. A position-sensitive parallel-plate avalanche detector placed at an intermediate dispersive focal plane, labeled image No. 2 in the figure, and an NMR measurement of the dipole fields were used to determine the rigidity of the nuclei produced. The rigidity was calibrated by sweeping the primary beam across

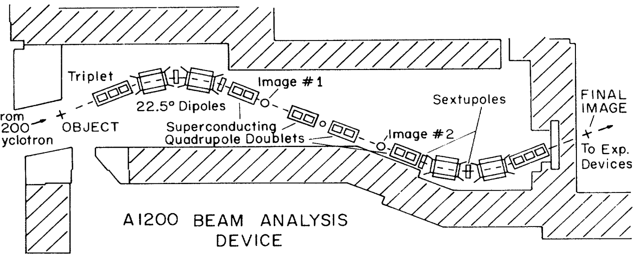

FIG. 1. Schematic layout of the A1200 beam-analysis device.

the dispersive image. The silicon-detector telescope provided two energy-loss measurements and a total-energy measurement which enabled redundant Z determinations from ΔE vs E_{total} spectra. The total-kinetic-energy measurement was also used to determine the Q, or charge, used to calculate the mass from the particle rigidity measurement. A thin plastic-scintillator start detector was placed after the first dipole pair at image No. 1. The time difference between the start-detector signal and the signal produced in the $\Delta E1$ silicon detector over the 14-m flight path was used to determine the velocity of each particle. The measured parameters, rigidity, ΔE, E_{total}, and velocity, were combined to give redundant isotope identification of each detected particle. This analysis is similar to that described by Bazin *et al.*,[12] for the study of neutron-rich isotopes using an $E/A = 44$ MeV ^{86}Kr beam at GANIL.

The detection system was calibrated initially 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 the ΔE versus time-of-flight isotope spectrum that unbound nuclei such as ^{8}Be and ^{16}F were absent. By collecting data at overlapping rigidity settings, a continuous isotope spectrum was obtained which permitted unambiguous identification. Finally, ΔE, E_{total}, time-of-flight, and rigidity information from approximately thirty isotopes were fitted to determine the energy and time calibrations for the device.

The resulting mass spectra for $Z = 30$–38 (zinc through strontium) are shown in Fig. 2. Several new isotopes at or near the proton-drip line are indicated in the mass spectra: ^{61}Ga, ^{62}Ge, ^{63}Ge, ^{65}As, ^{69}Br, and ^{75}Sr. Two events corresponding to ^{60}Ga and one event for ^{70}Kr are also observed; however, it is difficult to conclude from such a small number of events whether these nuclei were in fact identified or whether the events were due to a background process. 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 nuclei are actually proton unbound with partial

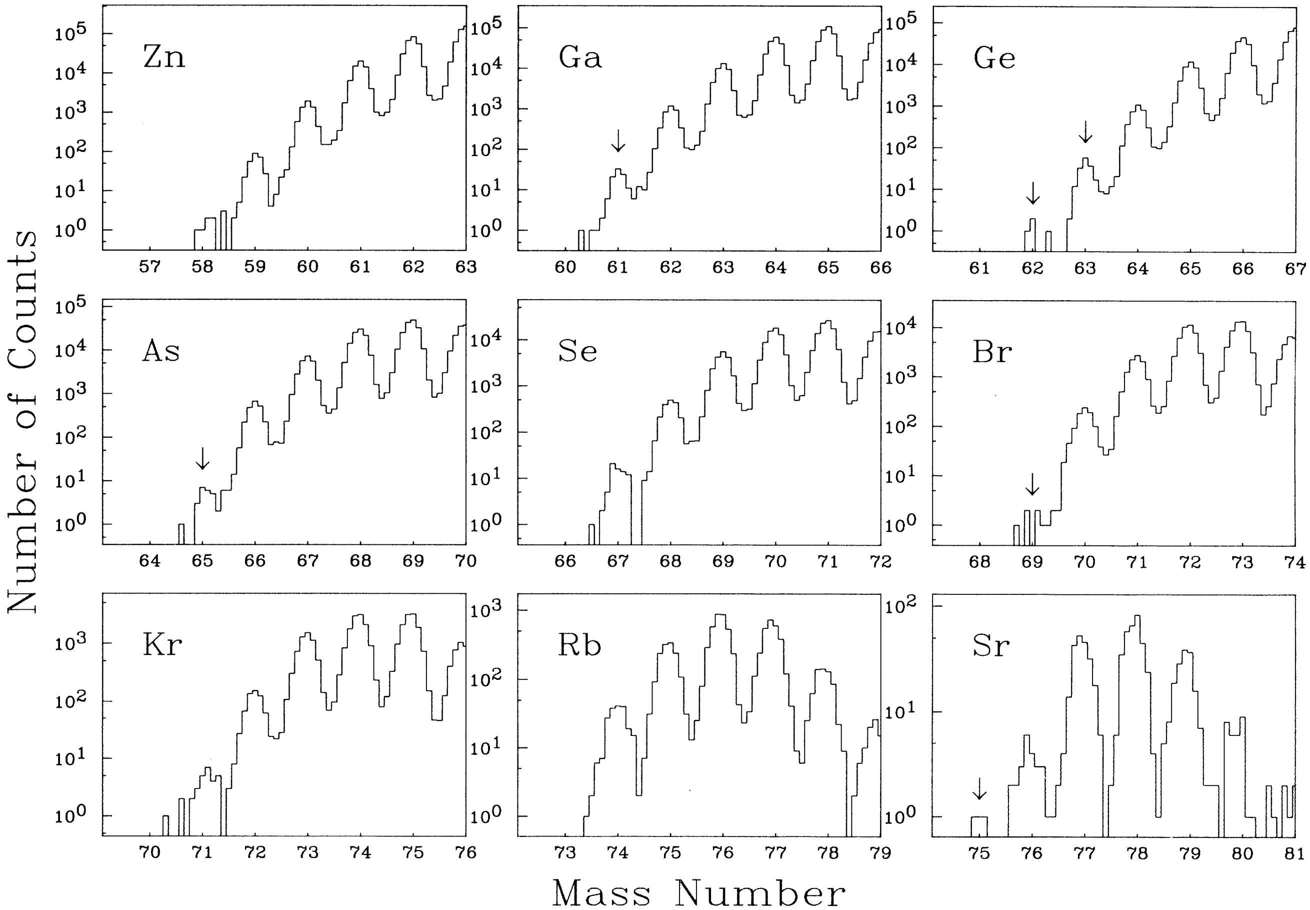

FIG. 2. Mass spectra showing the number of counts in each mass peak for $Z = 30$–38 (zinc through strontium) on a logarithmic scale. The new nuclei are indicated with arrows.

half-lives greater than times of this order. The nonobservation of an isotope in this work implies either that it has a half-life short compared to the flight time or that its production rate was too low to make it observable.

According to the Haustein atomic-mass-prediction compilation,[5] it is likely that the proton-drip line has now been reached for the odd-Z elements arsenic, bromine, and rubidium. An experimental argument for this can be made by integrating the yields of neighboring peaks in the lightest two or three masses of each spectrum in Fig. 2. The number of counts in the peaks decreases by roughly a factor of 20 per isotope as the mass decreases. The counts in the ^{65}As peak and the ^{69}Br peak are lower by more than a factor of 100 from the yields of the adjoining isotopes. One interpretation is that these nuclei are very weakly bound and have no excited states and hence in a statistical process would be weakly populated. A case can be made that ^{74}Rb is the last bound nucleus since there are several hundred counts in its peak, and there is not a single event attributable to ^{73}Rb. This is consistent with the previous results of D'Auria *et al.*[13] at ISOLDE. Therefore, ^{69}Br is most likely the highest observable odd-Z $T_Z = -\frac{1}{2}$ nucleus.

The proton-drip line is shown as a dashed line in Fig. 3 for one of the most reliable mass predictions[14] in this region, and the nuclei identified for the first time in the present experiment are shown as circles. All of these isotopes are important to the *rp* process, which is thought to be an important means of energy generation in high-proton-density, high-temperature environments. Figure 3 also shows the path calculated[15] for a particular case in which proton capture and β^+ decay occur along the proton-dip line beyond the nickel region. The extended *rp*-process calculation was carried out for an astrophysical thermonuclear explosion known as a type-I x-ray burst.[16] In this model, a neutron star accretes matter from a hydrogen-rich companion in a binary-star system. The result is a thermonuclear explosion on the surface of the neutron star at very high temperature and density (approximately 10^9 K, hydrogen densities about 10^6 g/cm^3). Because of the high gravitational field of the neutron star, the nuclei produced in the explosion are held at the surface, and only the radiated energy escapes. Hydrogen and helium burning in the synthesis chain provide the energy necessary to sustain the reaction, and the proton and alpha capture reactions will continue into the nickel region where the alpha capture (*αp* process) ceases due to increasing Coulomb barriers. The proton synthesis is thought to continue up to the mass-100 region via the extended *rp* process if ^{65}As and other drip-line nuclei are sufficiently bound.

The observation of ^{65}As in this experiment indicates the possibility that the process will continue past ^{64}Ge without significantly slowing down. Whether the flow continues depends on the degree of binding of ^{65}As. If the proton binding energy is less than 250 keV or so,[2,4] photodisintegration will destroy most of the ^{65}As nuclei produced before they can be processed to higher mass nuclei (similarly for ^{69}Br). The absence of ^{73}Rb already indicates a slowing of the process at ^{72}Kr. In order to proceed to higher masses, ^{72}Kr must β decay to ^{72}Br so that subsequent proton captures and β decays may continue. But since the half-life of ^{72}Kr is on the order of the time of the thermonuclear explosion, there will be at least a significant slowing of the process at this point. Although the identification of ^{65}As, ^{69}Br, and the ab-

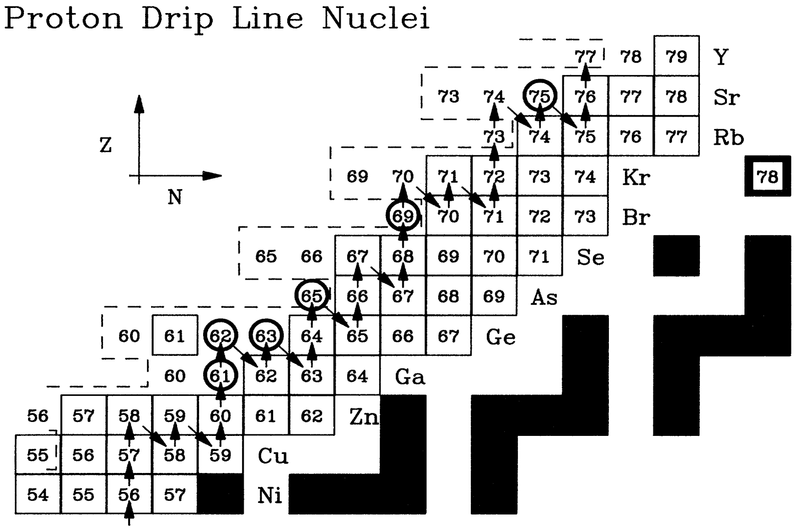

FIG. 3. Section of the chart of the nuclides in the region of interest. Stable nuclei are indicated by filled squares, and the projectile ^{78}Kr is specially noted. Open squares indicate nuclei that have been previously identified, and those circled were identified in the present work. Nuclei to the left of the dashed line are predicted to be unstable by the mass model of Jänecke and Masson (Ref. 14). The arrows indicate a possible flow for the *rp* process as described in the text.

sence of ^{73}Rb are major advancements in understanding the limits of the *rp* process, further information is needed about the half-lives, structures, and decay modes of the newly identified nuclei to calculate the energy evolution of the system and provide a comparison for the various *rp*-process sites that might exist in our Galaxy.[16]

In summary, the proton-drip line has apparently been reached for $Z=33$, 35, and 37, and the heaviest odd-Z $T_Z=-\frac{1}{2}$ nucleus, ^{69}Br, has been identified. Several of the new proton-rich isotopes are important to the astrophysical *rp* process; in particular, ^{65}As and ^{69}Br. Further, the nonobservation of ^{73}Rb indicates a difficulty in the *rp* process continuing to higher mass. Some of the new nuclei may also be important in studying the deformed nuclei that are found in this mass region near the $N=Z$ line. Future work is necessary to determine the half-lives, decay modes, and structures of these nuclei as well as to continue mapping the proton-drip line above $Z=30$.

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