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National Superconducting Cyclotron Laboratory

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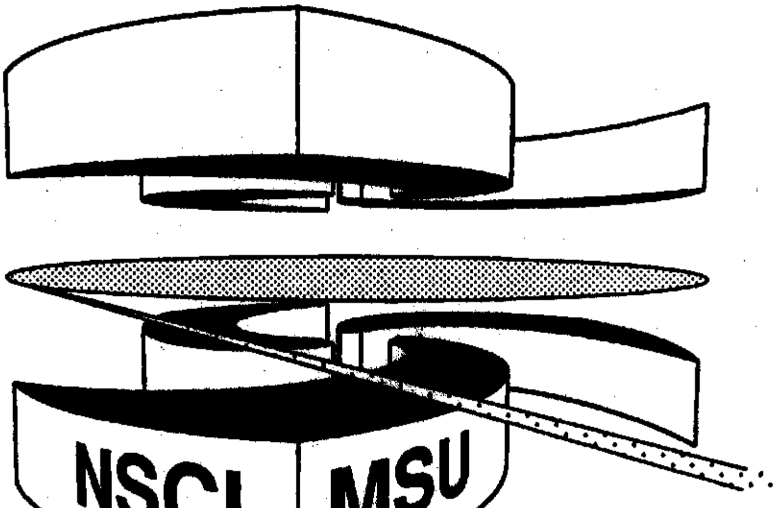

MSUCL-931

MAY 1994

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(July 27, 1994)

Abstract

Nine new very neutron-deficient isotopes of Ag, Pd, Rh, and Ru have been identified among the reaction products of an E/A=60 MeV ^{106}Cd beam using the A1200 projectile fragment separator at the National Superconducting Cyclotron Laboratory. One of these isotopes, ^{94}Ag, is the heaviest observed N=Z nucleus so far. The resulting mass spectra are presented and the astrophysical implications of the stability towards proton emission of one of the new isotopes, ^{95}Ag, are discussed.

21.10.Dr, 25.70.Np, 27.50+e, 95.30.Cq

The properties of proton-rich nuclei in the mass A = 90 range are of great interest to astrophysicists who model the rapid hydrogen burning process in very hot, dense stellar environments. However, little is known about many of the key nuclei that lie along the proton drip-line, and their masses, lifetimes, and decay modes must therefore be estimated in order to include them in the calculation of the rp-process synthesis path. The uncertainties in the predicted ground state properties, together with a lack of knowledge about excited levels, which might serve as final states in beta-decay processes, are enough to produce large uncertainties in the resulting astrophysical calculations. In addition to this astrophysical interest, another motivation for the experimental interest in this mass region lies in the importance to map the exact location of the proton drip-line. The latter provides a crucial test of mass models and a means to determine how well a particular model can be used to extrapolate away from the valley of stability. The goal of the present work was to produce and identify new nuclei near the proton drip-line in the A = 80–100 region up to $Z \approx 48$, including the astrophysically very interesting silver isotope ^{95}Ag. There exists a preliminary report of the observation of this isotope at an on-line mass separator [1].

An $E/A = 60$ MeV beam of the rare isotope ^{106}Cd was focused onto a 44.4 mg/cm^2 natural Ni target with a 9.4 mg/cm^2 ^{9}Be backing at the target position of the A1200. The 9.4 mg/cm^2 ^{9}Be backing was used to increase the fraction of reaction products leaving the target in their fully stripped charge state. The reaction products were separated and identified using the A1200 fragment separator [2]. The separator was run in its symmetric medium acceptance mode with a fragment angular acceptance of $\Delta\varphi$=30 mrad, $\Delta\theta$=34 mrad, and a full momentum acceptance $\Delta p/p = \pm 1.5\%$, centered around 0°. The experimental method employed closely follows that of Bazin *et al.* [3], Mohar *et al.* [4], and Yennello *et al.* [5].

Information from two position-sensitive parallel-plate avalanche counters (PPACs) placed at the second dispersive image of the A1200 separator together with NMR measurements of the dipole fields of the separator were used to determine the magnetic rigidity of the product nuclei. Thin plastic scintillators at the first dispersive image and at the final focus were used to measure the time of flight (TOF) through the device and, hence, the velocity of the reaction products. A four element silicon telescope (ΔE_1, ΔE_2, E_1, E_2) placed at the focal plane of the A1200 provided two independent energy loss measurements as well as the total kinetic energy of the particles.

The detection system was calibrated by using both the primary beam and a number of reaction products. The two energy-loss measurements allowed redundant determination of the atomic number Z of each ion by comparison of its position to that of the primary beam in the ΔE versus E_{total} coordinate space. A measurement of the charge state distribution of ^{106}Cd after the production target showed that $\approx$40% of the reaction products were fully stripped. The charge state Q of each ion was calculated by an appropriate combination of its magnetic rigidity, total kinetic energy, and velocity [3–5]. Consistency of the calculations was ensured by a comparison of the calculated Z with the calculated Q of the ions. Only fully stripped fragments, as selected by a narrow gate on Q=Z fragments, were used for the identification process. Histograms of ΔE versus TOF were prepared in which fragments with a given value of (N-Z) form "columns". For each column separately, the slope of the TOF as a function of 1/Z for the individual nuclides was calculated. For a given column, the ratio between its slope and the the average difference in slopes between adjacent columns is equal to the (N-Z) of that column, thus allowing an unambiguous determination of the mass number A of the fragments. The resultant average resolution of the mass and proton number calculations were $\Delta A/A=0.007$ and $\Delta Z/Z=0.014$.

The mass spectra shown in Figure 1 were obtained by setting narrow gates on the calculated Q and Z parameters as well as requiring reasonable particle trajectories (as determined by the PPAC position spectra). As can be seen in this Figure, the mass resolution is sufficient to clearly separate different isotopes. A number of new nuclides were identified including ^{88}Ru, ^{90,91,92,93}Rh, 92, 93Pd, and ^{94,95}Ag. In addition, a few events corresponding to ^{77}Y, ^{79}Zr, ^{81}Nb, ^{85}Tc, ^{87}Ru, ^{91}Pd, and ^{93}Ag are also observed. Although these events all satisfy the stringent gating requirements mentioned above, we do not wish to state that such few events constitute proof that these nuclei were identified for the first time in this experiment, as they might be the result of "contamination" from neighboring peaks in the Z and Q spectra. The average width of the Z gates used was 30% of the peak spacing. The data shown represent approximately 19 hours of data collection at a single setting of the A1200 separator chosen to optimize the detection of very neutron-deficient reaction products. The beam current during this period was ≈ 0.2 pnA. The observation of an isotope in this experiment implies that the ion has a lifetime longer than its flight time through the separator, which is on the order of 150 ns.

Figure 2 shows a section of the chart of the nuclides in the region of interest (proton number $Z = 40$–50, mass $A = 80$–100). In this figure, the drip-line prediction of Jänecke and Masson [6] is indicated by a solid line. Two of the new nuclei, ^{90}Rh and ^{94}Ag, are predicted to be the last proton stable isotopes of their respective elements. ^{94}Ag is the heaviest N=Z nucleus observed so far, three steps away from the doubly magic nucleus ^{100}Sn.

The result for ^{95}Ag is of special astrophysical interest, since this isotope has recently been singled out as being particularly important in the nucleosynthesis of ^{92}Mo and ^{94}Mo [7]. These two molybdenum nuclei are unique among the "p-process" nuclides (nuclei which are blocked from production by the usual neutron capture processes) in that their isotopic abundances are relatively large, and their synthesis has remained a puzzle. In reference [7] it was shown that synthesis of the neutron deficient molybdenum isotopes could proceed via a series of rapid proton captures on preexisting material. To insure that both ^{92}Mo and ^{94}Mo be produced in the proper ratio, this model requires that ^{95}Ag be bound towards proton emission. The identification of ^{95}Ag in the present work therefore supports the synthesis model of Hencheck *et al.* [7]. (It should be noted that of the 11 mass models in the compilation by Haustein [8], only the model of Masson and Jänecke [9] predicts ^{95}Ag to be proton unstable.)

The present work can also be viewed as a first step towards expanding the knowledge about nuclei at or close to the proton drip-line in this mass region. Before more detailed studies of masses, half-lives, and nuclear structure can be planned and carried out, the production rates of these nuclei must be measured. A comparison with the results of Winger *et al.* [10] indicates that beta-decay half-lives can be measured for nuclides up to and including isotopes with *peak heights* (in Figure 1) of 10 or more. Similarly, the study of Orr *et al.* [11] shows that the masses of nuclides with peak heights about 100 can be measured to within 1 MeV using time-of-flight methods. Nuclear structure measurements, including beta-delayed proton and gamma emission studies, can be expected to require rates yet one order of magnitude higher.

We would like to thank T. Antaya, D. Cole, and the ion source group at NSCL for providing the unusual cadmium beam that made this work possible. This work was supported in part by NSF grants PHY 92-21669 and PHY 92-14992, and by an Oak Ridge Junior Faculty Enhancement Award.

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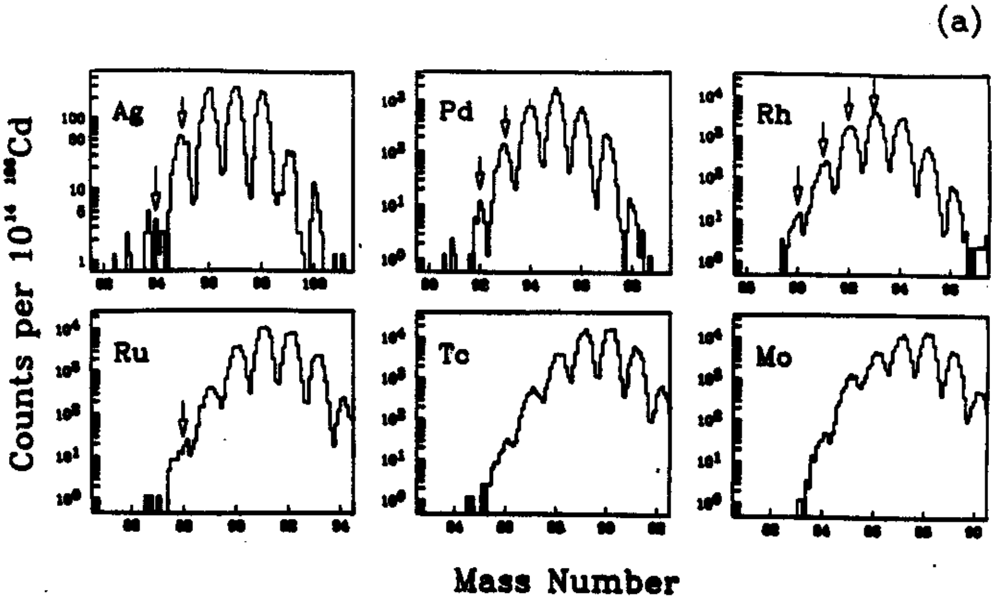
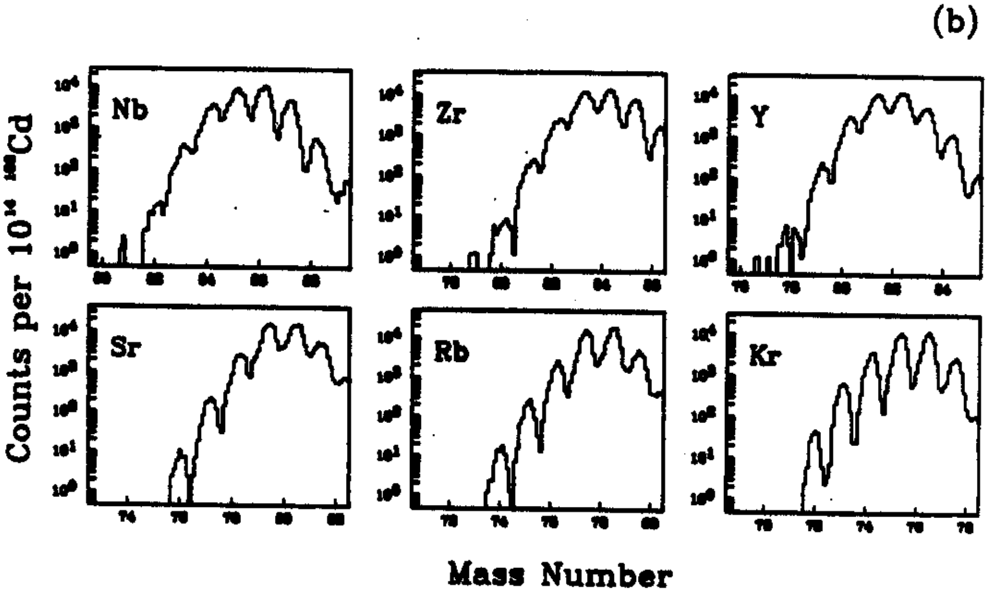
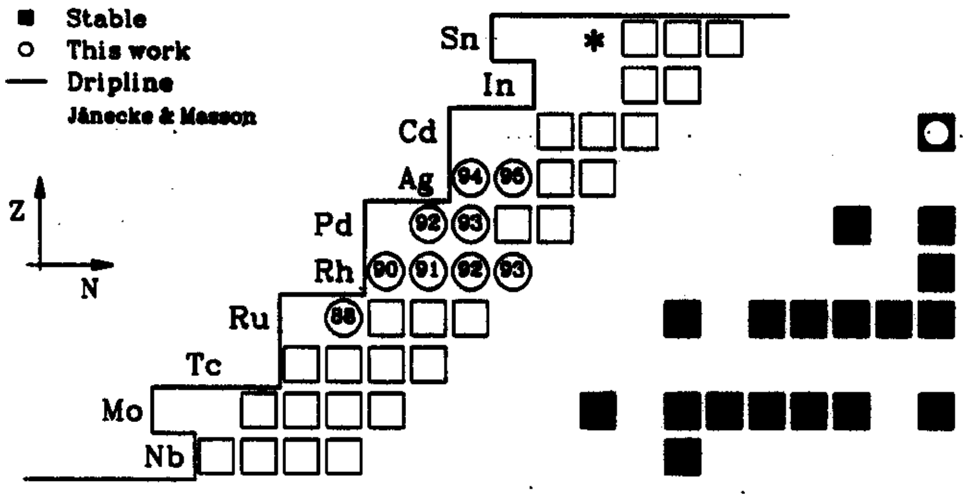
FIGURES

FIG. 1. (a) Mass spectra for Z=42–47 (molybdenum through silver) and (b) mass spectra for Z=36–41 (krypton through niobium). The data was obtained from a single setting of the A1200 separator, selected to optimize the detection of very neutron-deficient nuclei such as ^{94,95}Ag. The number of counts have been normalized to 10^{14} ^{106}Cd primary beam particles incident on the production target. Nuclei identified for the first time in this study are indicated by arrows.

FIG. 2. Section of the chart of the nuclides in the region of interest. Stable nuclei are indicated by black squares, and the projectile ^{106}Cd is specially noted. Open squares indicate previously known nuclei, and those identified in the present work are circled. The doubly magic nucleus ^{100}Sn is indicated by an asterisk. Nuclei to the left of the solid line are predicted to be proton unstable by the mass model of Jänecke and Masson [6].


(a)
Ag
Pd
Rh
Ru
Tc
Mo
Counts per 10¹⁴ ¹⁰⁶Cd
Mass Number


(b)
Nb
Zr
Y
Sr
Rb
Kr
Counts per 10¹⁴ ¹⁰⁶Cd
Mass Number


■ Stable
○ This work
— Dripline
Jänecke & Masson
Z
N
Sn
*
In
Cd
Ag
94
96
Pd
92
93
Rh
90
91
92
93
Ru
88
Tc
Mo
Nb