Observation of the $Z = N + 1$ Nuclei $^{77}_{39}$Y, $^{79}_{40}$Zr, and $^{83}_{42}$Mo

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The very neutron deficient $Z = N + 1$ nuclei $^{77}_{39}$Y, $^{79}_{40}$Zr, and $^{83}_{42}$Mo have been observed for the first time following the fragmentation of a ^{92}Mo beam. In contrast, no evidence was found for the existence of $^{81}_{41}$Nb and $^{85}_{43}$Tc. The observation of $^{77}_{39}$Y is of particular interest in light of the instability of the odd-proton, $Z = N + 1$ systems, $^{69}_{35}$Br, $^{73}_{37}$Rb, $^{81}_{41}$Nb, and $^{85}_{43}$Tc, and may be explained as a consequence of the shape polarizing effect of the highly deformed, prolate $Z = N = 38$ core. The experimental results are discussed within the framework of the shell-correction model, which together with proton-decay calculations allow an estimate of the proton separation energies of these highly exotic systems to be calculated. [S0031-9007(98)08214-3]

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Nuclei with nearly equal proton and neutron numbers in the $A \sim 80$ region are of fundamental interest for two distinct reasons. First, the nuclear structure properties of these nuclei are strongly determined by deformed shell gaps in the nuclear single particle potential [1], which causes dramatic changes of shape with the addition or removal of one or two nucleons [2,3]. In particular, the nucleon numbers 36 and 38 have been identified with highly deformed oblate [4] and prolate [2,5] shell gaps, respectively. Second, these systems lie in the vicinity of the proton drip line [6–12], the precise position of which is a vital element in determining the path of the postulated astrophysical rapid proton (rp) process of nucleosynthesis [13]. The single particle spectrum of orbitals which lie close to the proton and neutron Fermi surfaces varies considerably with deformation, and this nuclear structure aspect can have a subtle, but important effect on the binding energies of odd-proton nuclei and the position of the proton drip line [14,15]. Futhermore, protons occupying high-l orbitals, which in this region come primarily from the unnatural parity $g_{9/2}$ intruder subshell, would experience an increased centrifugal barrier as compared to those originating from the lower angular momentum, negative parity $p_{1/2}$, $p_{3/2}$, and $f_{5/2}$ orbitals.

Discrepancies in the predictions of mass models [14,15] regarding the proton stability of odd-Z, $T_z = -\frac{1}{2}$ nuclei and their bearing on the path or termination of the rp process [13] have prompted searches for the existence and studies of the decay properties of the $Z = N + 1$ systems $^{65}_{33}$As [6,16,17], $^{69}_{35}$Br [6,10,12,16,17], $^{73}_{37}$Rb [6,10,18,19], and $^{77}_{39}$Y [16,20]. Whereas the nucleus $^{65}_{33}$As has been observed and its basic decay properties studied [6,8], the heavier odd-Z, $T_z = -\frac{1}{2}$ nuclei were not observed in fragmentation reactions [6,10,16,18–20]. However, there is evidence that, as the $T_z = -\frac{1}{2}$, odd-Z nuclei become more spherical with increasing Z—due to the increasing influence of the $N = Z = 50$ doubly magic core—the population of higher-l orbitals may increase the binding and the centrifugal barrier for the odd proton. Indeed, Rykaczewski *et al.* [11] have observed $^{89}_{45}$Rh, which constitutes the heaviest odd-Z, $T_z = -\frac{1}{2}$ nucleus identified to date.

In the present work, evidence for the particle stability of three isotopes with $Z = N + 1$, namely, $^{77}_{39}$Y, $^{79}_{40}$Zr, and $^{83}_{42}$Mo, together with upper limits for the lifetimes of $^{81}_{41}$Nb and $^{85}_{43}$Tc are presented. The nuclei were produced in the fragmentation of a ^{92}Mo^{37+} beam of 60 MeV/nucleon provided by the GANIL facility. The primary beam, of typical intensity 100 enA, was incident on a selection of natural nickel targets of thicknesses between 50 mg/cm^2 and 100 mg/ cm^2. The reaction products were collected and separated using the LISE3 spectrometer [21]. At the final focus of the spectrometer, the fragments were stopped in a four-element silicon detector telescope, the first element of which was 300 μm thick and acted as an energy-loss (ΔE) detector. The remaining three silicon detectors, each of thickness 150 μm, were used to provide redundant energy-loss measurements and to obtain the total kinetic energy of the fragments. A time-of-flight (TOF) measurement together with the energy-loss and total-energy measurement was used to obtain an unambiguous identification in Z, N, and Q for each fragment. An array of seven high-purity germanium detectors of 70% relative efficiency was packed in close geometry around the silicon stack to measure γ decays from isomeric states in the fragments. Decays from previously reported isomers in ^{69}Se, ^{71}Se, ^{73}Kr, and ^{76}Rb were identified and used to provide a validation of the experimental method and a reference point for the particle identification spectra.

Figure 1a shows a two-dimensional spectrum of the atomic number Z determined from the energy loss in the ΔE detectors versus the mass-to-charge ratio determined from the fragment TOF. The projections of the $T_z = 0$ and $-\frac{1}{2}$ species onto the Z axis are presented in Figs. 1b and 1c and clearly show the presence of the even-Z, $Z = N + 1$ nuclei, $^{75}_{38}$Sr, $^{79}_{40}$Zr, and $^{83}_{42}$Mo in our spectra. Evidence for the existence of ^{75}Sr has been previously reported [6]. Tentative evidence for the existence of $^{79}_{40}$Zr has been presented previously by Yennello *et al.* [7]. This isotope is clearly present in the spectrum of Fig. 1c. Both $^{79}_{40}$Zr and $^{83}_{42}$Mo are predicted by the mass evaluation of Audi and Wapstra [15] to be proton bound, with proton separation energies of approximately 1.9 and 1.2 MeV, respectively.

For even-Z nuclei, the pairing between the protons provides extra binding and these nuclei are expected to extend further beyond the $N = Z$ line than odd-Z nuclei. Thus, in common with previous studies [6,10,12], the current data show no evidence for $^{73}_{37}$Rb. Moreover, as demonstrated in Fig. 1c, we found no evidence for the odd-proton nuclei $^{81}_{41}$Nb and $^{85}_{43}$Tc, indicating that the lifetimes of these nuclei are short compared to the time of flight through the spectrometer. Assuming the observation limit of one count and considering the yields expected relative to the neighboring isotopes, we derived upper limits of 80 and 100 ns for the half-lives of ^{81}Nb and ^{85}Tc, respectively. In the region expected for $^{77}_{39}$Y, Fig. 1c clearly shows a peak indicating that the half-life of this isotope is longer than 0.5 μs, the flight time through the LISE3 spectrometer.

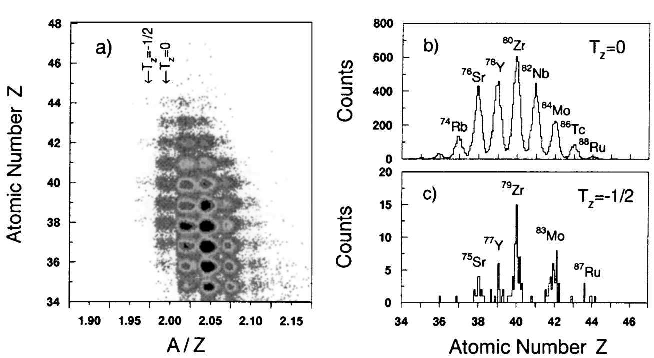

FIG. 1. Two-dimensional atomic number Z versus mass-to-charge ratio A/Z particle identification plot showing the previously unobserved $T_z = -\frac{1}{2}$ nuclei $^{77}_{39}$Y, $^{79}_{40}$Zr, and $^{83}_{42}$Mo as well as the absence of $^{81}_{41}$Nb and $^{85}_{43}$Tc (a). The right-hand side shows projections of the particle identification plot onto the Z axis for the $T_z = 0$ (b) and the $T_z = -\frac{1}{2}$ (c) nuclei.

Qualitatively, this observation is consistent with the proton separation energies predicted by Audi and Wapstra [15] (see Table I), which suggest that ^{77}Y is the most bound of the odd-Z, $T_z = -\frac{1}{2}$ nuclei in this region. However, for the $T_z = -\frac{1}{2}$ nuclei addressed in the current work the uncertainties in the predicted proton separation energies lead to variations in the expected proton-decay half-lives of many orders of magnitude. Additional uncertainties in the estimation of the proton-decay probability are related to the unknown spin and parity of the proton emitter. The ground state configuration of the decaying nucleus determines the orbital angular momentum of the emitted proton and hence the height of the centrifugal barrier which the proton has to tunnel through. Moreover, the influence of the nuclear deformation has to be taken into account [22].

To describe the ground state configurations of the odd-proton, $T_z = -\frac{1}{2}$ nuclei, we have calculated the potential-energy surface as a sum of the macroscopic mass formula of Möller and Nix [23] and the Strutinsky-type microscopic correction. The latter was calculated using the deformed Woods-Saxon potential [24] with the parameters given by Nazarewicz *et al.* [1] and a pairing interaction strength from Ref. [25]. The equilibrium deformation for the blocked proton orbitals was obtained through the minimization of the nuclear potential energy in the (β_2, β_4) plane. Figure 2 shows the proposed ground state configuration and the low-lying excited states of the $T_z = -\frac{1}{2}$ nuclei from ^{69}Br to ^{89}Rh resulting from these calculations. Table I gives the predicted equilibrium deformations for the most probable ground state configurations.

When investigating the single particle levels which reside in the vicinity of the proton Fermi surface in specific $T_z = -\frac{1}{2}$ nuclei, it is instructive to compare the spectra of low-lying states of these odd-Z nuclei with those of the odd-N, $T_z = +\frac{1}{2}$ mirror systems, namely, $^{69}_{34}$Se, $^{73}_{36}$Kr, and $^{77}_{38}$Sr. Assuming the Coulomb displacement energy is small enough in order not to alter the level ordering, the unpaired protons and neutrons in the mirror systems will occupy identical orbitals and thus one might expect the same ground state configuration for each $T_z = \pm\frac{1}{2}$ pair.

Studies of ^{69}Se [26–28] suggest an oblate nucleus with a negative-parity ground state and a $I^\pi = \frac{1}{2}^-$ assignment strongly favored. For ^{69}Br, our calculations predict a $\frac{9}{2}^+$, oblate ground state, with the first $\frac{1}{2}^-$ oblate state appearing at an excitation energy of 280 keV.

TABLE I. Results of the microscopic-macroscopic calculations for the $T_z = -\frac{1}{2}$ nuclei from $^{69}_{35}$Br to $^{89}_{45}$Rh giving the β_2 equilibrium deformation values and the odd-proton configuration of the lowest states, labeled by the deformed asymptotic or spherical quantum numbers. $c_{l_p j_p}$ are the spherical components of the odd-proton wave function contributing to the proton-decay rate. S_p^{cal} values are the limits of proton separation energies derived from the experimental bounds of the half-lives $T_{1/2}^{\text{exp}}$. The right-hand side of the table gives proton separation energies S_p calculated from mass extrapolations [15].

	β_2	Level	$c_{j_p l_p}^2$	$T_{1/2}^{\text{exp}}$ (ns)	S_p^{cal} (keV)	S_p^{extrap} (keV)
$^{69}_{35}$Br	−0.25	$\frac{9}{2}^+$[404]	0.94	<24	<−730	−450 ± 100[a]
	−0.25	$\frac{1}{2}^-$[321]	0.36		<−500	
$^{73}_{37}$Rb	0.42	$\frac{3}{2}^-$[312]	0.09	<30	<−570	−590 ± 400
$^{77}_{39}$Y	0.43	$\frac{5}{2}^+$[422]	0.06	>500	>−610	−170 ± 420
$^{81}_{41}$Nb	0.44	$\frac{1}{2}^+$[431]	0.17	<80	<−610	−630 ± 500
	0.41	$\frac{3}{2}^-$[301]	0.60		<−600	
$^{85}_{43}$Tc	−0.25	$\frac{5}{2}^+$[422]	0.15	<100	<−740	−960 ± 640
	−0.02	$g_{9/2}$	1.0	<100	<−900	
$^{89}_{45}$Rh	0.01	$g_{9/2}$	1.0	>500	>−860	−1060 ± 710[b]

[a] $S_p = (-660 \pm 305)$ keV from the calculated Coulomb shift between ^{69}Br and ^{69}Sr [41].
[b] $S_p = -640$ keV from the recent shell model calculations of Herndl and Brown [42].

The ground state of ^{73}Kr has a negative parity with the accepted assignment of $\frac{3}{2}^-$ stemming from β-decay studies [29–33]. The same spin and parity for the ground state of ^{73}Rb are predicted by our calculations.

The ground state of ^{77}Sr has been deduced to be of positive parity, with $I^\pi = \frac{5}{2}^+$ from both β^+-decay studies [34,35] and the measured magnetic moment [36]. The parity of the ground state of ^{77}Sr has been used to support the argument of a large prolate deformation, $\beta_2 \sim 0.45$, for the $N = Z = 38$ core, ^{76}Sr [36], with the valence neutron occupying the $\frac{5}{2}^+$[422] Nilsson state from the $g_{9/2}$ orbital. For the mirror nucleus ^{77}Y, our calculations predict a quadrupole deformation of $\beta_2 = 0.43$ with the odd-proton occupying the $\frac{5}{2}^+$[422] Nilsson state. The recent observation of a 5^+ state in ^{78}Y [37] supports our assignment of this orbital being the one closest to the ^{76}Sr core and thus the ground state configuration of ^{77}Y. The striking effect of the $N = Z = 38$ deformed shell gap is highlighted in the calculations by the fact that no other orbitals are predicted to lie within 900 keV of the ground state configuration.

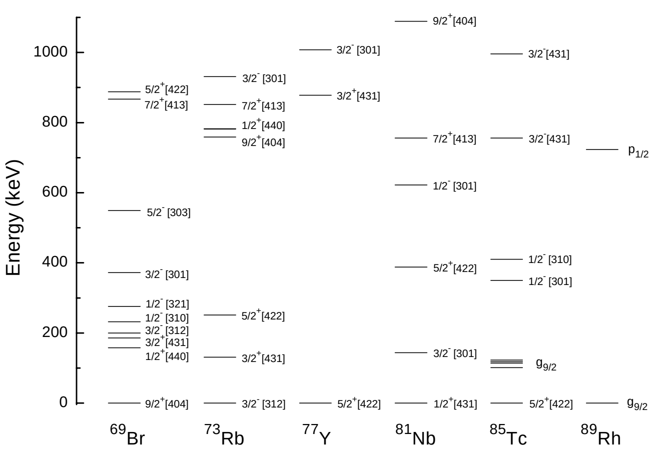

FIG. 2. The proposed ground state configurations and the low-lying excited states of the $T_z = -\frac{1}{2}$ nuclei from ^{69}Br to ^{89}Rh resulting from the microscopic-macroscopic calculations. States are labeled by the deformed asymptotic or spherical quantum numbers.

Nothing is currently known experimentally on the ground state spins of ^{81}Zr and ^{85}Mo, the mirror nuclei of ^{81}Nb and ^{85}Tc. Our calculations predict that in ^{81}Nb the odd proton occupies the $\frac{1}{2}^+$[431] deformed state originating from the $d_{5/2}$ orbital. For the ground state of ^{85}Tc, our calculations predict a $\frac{5}{2}^+$[422] oblate configuration. The increasing influence of the $N = Z = 50$ shell closure induces the spherical shape of ^{89}Rh with the odd proton predicted to occupy the $g_{9/2}$ orbital.

The probability of proton emission from the spherical nucleus can be estimated as a product of the frequency with which the proton attempts to tunnel through the potential barrier and a transmission coefficient calculated by using the WKB approximation [38]. The nuclear structure effects, with the exception of the change of angular momentum, are not included in this type of calculation and are introduced by the spectroscopic factor S which accounts for many-particle effects. These are neglected in our further discussion (i.e., $S = 1$).

According to the prescription of Bugrov and Kadmensky [39], for deformed nuclei the proton-decay amplitude may be obtained as a sum of matrix elements of the deformed nuclear optical potential and the nonspherical part of the Coulomb interaction between the proton and the daughter nucleus weighted by the angular momentum algebra factors and the expansion coefficients $c_{l,j}$ of the initial proton wave function in a spherical basis. In our simplified estimation of the proton-decay probability, we neglect the influence of the deformation on the transmission coefficients and calculate the proton-decay half-life as the ratio of $T_{1/2}^{\rm WKB}(l_p, j_p)/c_{l_p j_p}^2$, where $T_{1/2}^{\rm WKB}(l_p, j_p)$ is the proton-decay half-life calculated within the WKB approximation for spherical nuclei decaying by the emission of a proton with an orbital angular momentum l_p and a total spin j_p. The coefficient c_{l_p,j_p} determines the probability that the proton in the nucleus has the respective orbital and total angular momentum quantum numbers.

Similar to spherical nuclei, the most important input for the calculations of the proton-decay probability is the decay Q value and the orbital angular momentum l_p of the emitted proton. Since for all the cases focused on in the present work, the proton-decay energy has not been determined experimentally, we treat it as a parameter in the $T_{1/2}^{\rm WKB}$ calculations and adjust its value to reproduce the experimental half-life limit. The limits of proton separation energies resulting from such a procedure are given in Table I.

An alternative theoretical approach was considered using relativistic mean-field (RMF) calculations [40] which couple an odd proton to the even-even, $N = Z$ core nuclei from ${}^{68}_{34}$Se to ${}^{88}_{44}$Ru. The single particle spectrum in the vicinity of the Fermi surface is then calculated for the lowest-energy deformed configuration. The residual pairing in the RMF approach is treated in the usual BCS approximation. The results of these calculations were in general agreement with the microscopic-macroscopic predictions for all the $T_z = -\frac{1}{2}$ systems, with both positive parity ground state and low density of states close to the Fermi surface for ^{77}Y being reproduced.

In summary, the fragmentation of a 60 MeV/nucleon ^{92}Mo beam has allowed us to identify the $T_z = -\frac{1}{2}$ nuclei ${}^{77}_{39}$Y, ${}^{79}_{40}$Zr, and ${}^{83}_{42}$Mo, the lightest isotopes of each of these elements reported to date. No evidence was found for ${}^{81}_{41}$Nb and ${}^{85}_{43}$Tc, suggesting that these nuclei are proton unbound. Limits of the proton separation energies derived from the experimental half-life limits allowed us to set constraints on the range of the S_p values predicted by the mass extrapolations [15].

The observation of ${}^{77}_{39}$Y may be interpreted as evidence for the shape polarizing effect of the $N = Z = 38$ prolate shell gap, as predicted by the macroscopic-microscopic calculations. This is highlighted in our calculations by the sparse level density at low excitation energy in ^{77}Y.

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