Decay of Rh^{101m} and Rh^{101g}†

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The decay of sources containing Rh^{101m} (4.43 day) and Rh^{101g} (3.3 yr) has been investigated using beta- and gamma-ray spectroscopic methods. Conversion-electron data for Rh^{101m} electron-capture decay have been obtained to complement the gamma-ray data appearing in the literature. The observed transition energies 21.58, 127.24, 179.42, 183.9, 233.4, 237.7, 306.67, and 544.9 keV are consistent with a decay scheme including excited levels in Ru^{101} at 127.2, 306.7, 311.2, (523), and 544.5 keV. The decay of Rh^{101g} is accompanied by transitions with energies 127.24, 198.4, 295.3, 325.2, and 421.8 keV; and coincidence data require that levels in Ru^{101} at 127.2, 325.4, and 422.1 keV be populated. The problem of spin assignments for the levels in Ru^{101} is discussed.

INTRODUCTION

THE two isomers Rh^{101m} (4.43 day) and Rh^{101g} (3.3 yr) have been conclusively identified as $\frac{9}{2}+$ and $\frac{1}{2}-$ states, respectively.[1] The $\frac{9}{2}+$ Rh^{101m} decays partially (10%) via a 157.32-keV $M4$ isomeric transition to Rh^{101g} and partially (90%) via electron capture to states in Ru^{101}. Previous workers[2] have reported that the decays of these isomers populated two essentially different sets of levels in Ru^{101}. Recent precision gamma-ray work by O'Kelley[3] has revealed further details of the decay of Rh^{101m}. O'Kelley has found complementary and consistent information concerning Rh^{101} levels from the decay of Tc^{101} and Rh^{101m}. The present paper gives some conversion-electron data which are consistent with the conclusions of the gamma-ray work. In addition, the decay of Rh^{101g} has been investigated with gamma-ray and conversion-electron spectroscopic techniques. McCarthy's observation[4] of a 25-μsec isomer in Ru^{101} is consistent with the present work if an $\frac{11}{2}-$ state occurs at 523 keV.

The sources of Rh^{101m} for this investigation were separated from Pd^{101} samples following the $Rh^{103}(p,3n)Pd^{101}$ reaction using 42-MeV protons at the Nevis Synchrocyclotron, Columbia University. The procedures for target dissolution and source preparation have been reported elsewhere.[1] After 5 months, the radiations attributed to Rh^{101m} were no longer detectable, and the same sources were then used for the study of Rh^{101g}. Platinum K x rays were always observed with one of the sources, because it was electroplated on a platinum wire backing.

DECAY OF Rh^{101m}

The scintillation spectrum[5] of Rh^{101m} shows gamma rays of 307 and 545 keV with relative intensities of 100 and 5, respectively. Conversion-electron spectra obtained with permanent-magnet spectrographs and an "orange" beta-ray spectrometer showed the existence of a weak 127-keV transition having a 5-day half-life. The numerical equality of the energy value for this transition and for the 127-keV transition excited in Rh^{101g} decay incicates that the same 127-keV level in Ru^{101} is populated in the decay of both Rh^{101m} and Rh^{101g}. Connors[6] has determined that this transition is $M1+E2$, with $0.018<\delta^2<0.028$. Conversion electrons of the 307- and 545-keV transitions have been found in spectra taken with both types of electron spectrometers. Several weaker transitions have been observed only with the permanent-magnet spectrographs. The transitions accompanying Rh^{101m} decay are summarized in Table I. The 157.32-keV $M4$ isomeric transition is not included.

Coincidences were sought between K conversion electrons of the 307-keV transition and gamma rays. Only photons of approximately 230 keV were found in coincidence, with low abundance. Thus we have es-

TABLE I. Transitions in the decay of Rh^{101m}.

Transition energy (keV) Ge(Li) detector	Magnetic spectrograph	Transition intensity[a]
	21.58±0.02	<2[b]
	127.24±0.04	1.4[c]
	179.42±0.05	1.4[d]
	183.9 ±0.1	
	233.4 ±0.1 }	
	237.7 ±0.1 }	≲2
306.9±0.3	306.67±0.02	100
544.7±0.5	544.9 ±0.1	6

[a] Normalized to the 307-keV transition.
[b] Estimated from intensity of L conversion lines relative to K127 line on photographic plates.
[c] Calculated from conversion-electron data.
[d] Required for consistency with intensity of 127-keV transition.

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[2] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences-National Research Council. Washington 25, D. C., 1961), NRC 61-2-26.
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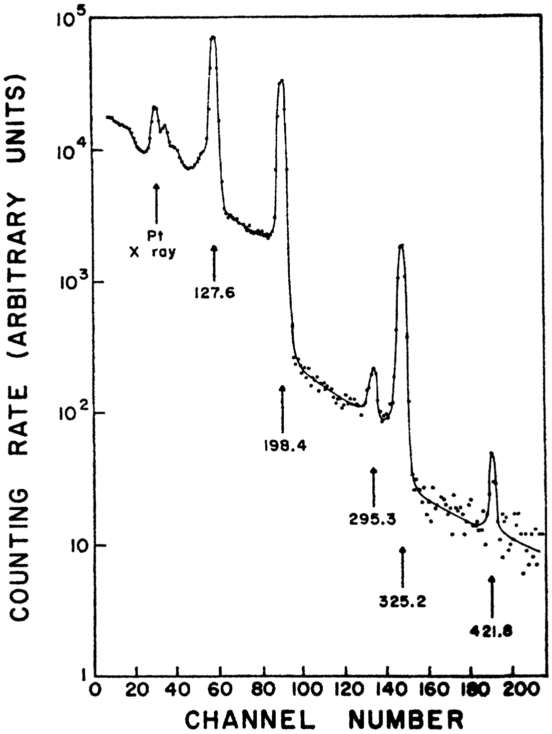

FIG. 1. Gamma-ray spectrum of a Rh^{101g} source taken with a Ge(Li) detector. The platinum x ray arises from excitation of the platinum source backing by gamma radiation from the source. The energies given are average values from the results of several spectra.

tablished a level at 306.7 keV fed by about 93% of the electron-capture decays of Rh^{101m} and depopulated primarily by the 307-keV transition. Numerical energy agreement suggests that a parallel mode of de-excitation is provided by a 179.4–127.2-keV cascade. A level at 544.4 keV is depopulated primarily by a 545-keV transition, but also by a 237.7–306.7-keV cascade. The 233.4- and 183.9-keV transitions depopulate the 544.5-keV level via a new level at 311.2 keV. Alternatively, it would also be possible to have a level at 361.6 keV by inverting the 183.9–233.4-keV cascade. O'Kelley[3] has inferred the existence of a 311.2-keV level in Ru^{101} from his coincidence measurements in the decay of Tc^{101} (ground-state spin $\frac{9}{2}+$). We find no evidence for the plethora of transitions which have recently been attributed to Rh^{101m} decay by Anton'eva *et al.*[7] It is not stated in Ref. 7 whether all the purported transitions had been followed to verify that they exhibited a 4.5-day half-life.

The electron-capture decay of $\frac{9}{2}+$ Rh^{101m} is strikingly similar to the beta decay of $\frac{9}{2}+$ Tc^{101}. For example, Tc^{101} decays 90.0% to the 307-keV level and 6.8% to the 545-keV level,[8] while Rh^{101m} decays $(84\pm2)\%$ to the 307-keV level and $(6\pm2)\%$ to the 545-keV level, with the remaining $(10\pm2)\%$ of the decays accounted for by the 157.32-keV isomeric transition. The work of O'Kelley *et al.*[8] provides log *ft* values of 4.7 and 5.7 for the decay of Tc^{101} to the 307- and 545-keV levels, respectively. We have made the assumption that these approximate log *ft* values are also appropriate for the population of these same levels by the electron-capture decay of Rh^{101m}. If this hypothesis is valid, then from beta-decay monographs[9] one can obtain a value (550 ± 100) keV for the Rh^{101}–Ru^{101} ground-state mass difference, remembering that Rh^{101m} lies 157 keV above the Rh^{101} ground state.[1]

DECAY OF Rh^{101g}

The decay of the long-lived Rh^{101g} has been reported[2] to populate a 324-keV level in Ru^{101}, with subsequent de-excitation via a 324-keV gamma ray and a 198–127-keV cascade. Measurements were begun on a source of Rh^{101} after the 307- and 545-keV gamma rays characteristic of Rh^{101m} had completely disappeared from spectra obtained with a Ge(Li) detector. A gamma-ray spectrum taken with a NaI(Tl) detector revealed a weak 420-keV gamma ray. With a Ge(Li) detector, a weak 295-keV gamma ray was also resolved, as shown in the gamma-ray spectrum, Fig. 1. Intensities were calculated by correcting the photopeak intensities for the detection efficiency, which had been measured with a set of calibrated standard sources. The transition intensities, adjusted for internal conversion, are listed in Table II.

Conversion electrons from the 127- and 198-keV transitions were observed with the beta-ray spectrometer. For these measurements, two photomultiplier tubes were coupled to the plastic scintillation crystal upon which the electrons were brought to focus. By demanding a coincidence between the two photomultiplier outputs, the background arising from electronic noise was eliminated. Church[10] has reported a similar coincidence detection system. Because of the low source strength available, it was not possible to

TABLE II. Transitions in the decay of Rh^{101g}.

Transition energy (keV)		
Ge(Li) detector	Magnetic spectrograph	Transition intensity[a]
127.6±0.5	127.24±0.04	117
198.4±0.8		100
295.3±0.7		1.3
325.2±0.9		15
421.8±1.7		0.3

[a] Normalized to the 198-keV transition. The relative intensities are probably correct within 15%.

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observe electrons from the 325-keV transition. The relative K conversion line intensities for the 127- and 198-keV transitions were found to be 100 and 40, respectively.

A gamma-ray spectrum gated by K conversion electrons of the 127-keV transition was recorded with a 3-in. NaI(Tl) detector. This coincidence spectrum is presented in Fig. 2, together with a singles spectrum for comparison. Cascade sequences of 295–127 and 198–127 keV were clearly demonstrated. Thus in addition to the previously known levels at 127.2 and 325 keV, a new level at 422 keV has now been established from the decay of Rh^{101g}.

The angular correlation of the gamma rays in coincidence with 127-keV gamma rays has been measured using two NaI(Tl) detectors. The results are $A_2 = 0.135 \pm 0.010$ and $A_2 = -0.25 \pm 0.13$ for the 198–127 and 295–127 cascades, respectively. In both cases, A_4 is experimentally zero, confiriming that $I \leq \frac{3}{2}$ for the 127-keV level. These data have been corrected for the finite solid angle subtended by the detectors. The source used had been electroplated on a platinum wire backing.

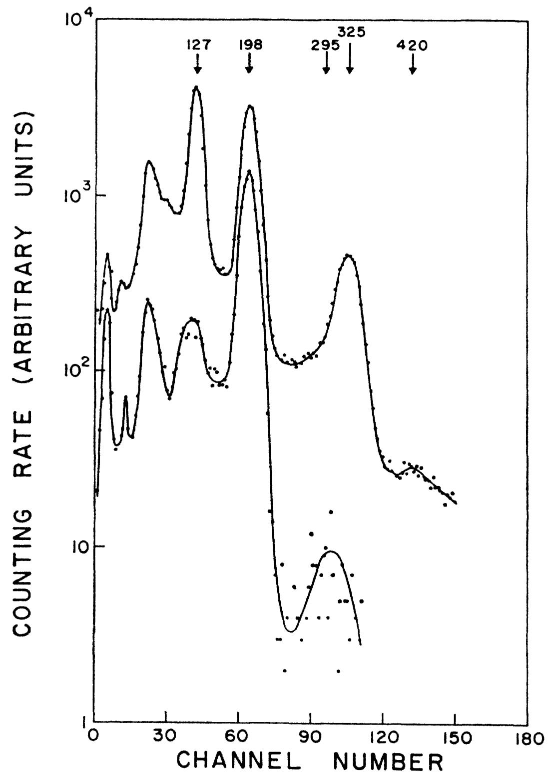

FIG. 2. Coincidence spectrum (lower curve) showing gamma rays at 198 and 295 keV in coincidence with K conversion electrons of the 127-keV transition. The peaks below channel 60 are due to Ru x rays, Pt x rays, backscattering, and Compton effects. Random coincidence events have been subtracted. For comparison, a singles spectrum (upper curve) taken with the same detector and the same counting geometry is given.

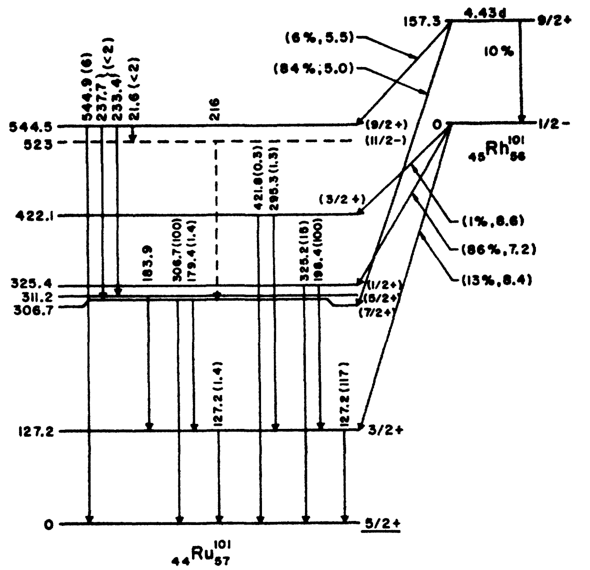

FIG. 3. Level scheme for Ru^{101} showing the decay of Rh^{101m} and Rh^{101g}. Transitions seen following Rh^{101m} decay are shown at the left of the figure, and the intensities in parentheses with each transition energy have been normalized to give the 306.7-keV transition an intensity of 100. Transitions seen following Rh^{101g} decay are shown at the right of the figure, and the intensities are relative to the 198.4-keV transition. The 127.2-keV transition occurs in both decays and appears twice in the diagram for clarity.

No estimate has been made for possible attenuation of the correlation pattern.[11]

A sample of Rh^{101g} has been counted frequently for a period of 7 months in a proportional counter which was standardized daily with a standard U^{238} source. During this period the decay curve has shown only a single component with a half-life of 3.3 ± 0.3 yrs, in agreement with previous estimates of approximately 5 yrs.[2]

PROPOSED DECAY SCHEME

The decays of the species Rh^{101m} and Rh^{101g} are summarized in Fig. 3. The log ft values for Rh^{101m} were assumed, not measured, as explained above. For Rh^{101g} decay, the log ft values have been derived from transition intensities using the Rh^{101}–Ru^{101} mass difference deduced earlier.

Spins and parities are well established for the 0-, 127.2-, and 306.7-keV levels in Ru^{101} from previous work. For the 544.5-keV level, beta-decay selection rules require $\frac{7}{2}+$, $\frac{9}{2}+$, or $11/2+$, but $11/2+$ is excluded by the existence of the 545-keV gamma ray. Of the remaining choices, we prefer $\frac{9}{2}+$ because such an assignment makes possible the inclusion of the 21.6-keV transition, although this is not a strong argument. For the 311.2-keV level, one must have $I \leq \frac{5}{2}$, since there is no direct population from Rh^{101m} or Tc^{101}. Neither 311-

[11] P. Connors and A. Schwarzschild, in a private communication, state that an angular correlation $A_2 = 0.22 \pm 0.02$ has been obtained by them for the 198–127-keV cascade, using a liquid source.

nor 184-keV gamma rays were observed in the decay of Rh^{101g}. If the decay branch to this level is placed at $<1\%$, then it follows that log $ft>9$. A $\frac{5}{2}+$ assignment for the 311.2-keV level is consistent with all the available data.

The log ft values for the three branches in the decay of Rh^{101g} are typical for first-forbidden beta decay in this mass region, indicating $\Delta J=0$, 1, 2 and a parity change. The conversion-electron data suggest that the 198-keV transition is primarily $M1$. Single-particle transition probabilities lead to a preference for a $\frac{1}{2}+$ assignment to the 325.4-keV level, since the 325.4-keV transition would be expected to dominate over the 198-keV transition if both were $M1$. This assignment is consistent with the angular-correlation data if the 198-keV transition is almost pure $M1$. Since O'Kelley[3] has observed a gamma transition from a $\frac{7}{2}+$ or $\frac{9}{2}+$ state to the 422-keV level, then $\frac{1}{2}+$ would not be likely for the 422-keV level. Furthermore since a $\frac{5}{2}+$ assignment would be only marginally consistent with our angular correlation data, we prefer $\frac{3}{2}+$ for the 422-keV level.

McCarthy[4] has observed two gamma rays at 220 and 318 keV decaying with a 25-μsec half-life following (d,p) reactions on natural ruthenium metal. Previously, gamma rays had been reported[12] at 217 and 307 keV with an 18-μsec half-life following (γ,n) reactions on ruthenium metal. Although these two gamma rays are reported in approximately equal abundance, no strong 216-keV gamma ray was observed in the present work. We conclude that the isomeric state in Ru^{101} possibly occurs at 523 keV, depopulated by a 216–307-keV cascade and that the most probable assignment for this isomeric state is $11/2-$. We note that the 21.6-keV transition, for which we have observed L and M conversion electrons, might be accommodated in the level scheme between the 544.5-keV level and the hypothetical isomeric level at 523 keV.

DISCUSSION

The existence of three closely spaced levels near 300 keV could be interpreted as evidence for three members of the quintuplet expected from the core-excitation picture of de-Shalit.[13] If the spin assignments made here are correct, one would choose the 544.5-keV level as the $\frac{9}{2}+$ member. The probable existence of two $\frac{3}{2}+$ levels at 127.2 and 422.1 keV poses a severe problem for the core-excitation interpretation, since only one level of each spin is predicted. The 127.2-keV level has been Coulomb-excited with both alpha particles[14] and neon ions,[15] and Connors[6] has found that the $E2$ portion of the 127-keV transition shows an enhancement of about 18 over the single-particle estimate. Perhaps these two levels share the character of the core-excitation component and also some single-particle character. If the correlations suggested here are correct, then the center of gravity of the multiplet lies between 371 and 404 keV, depending on what choice is made for the $\frac{3}{2}+$ member. For comparison, the first $2+$ states in Ru^{100} and Ru^{102} occur at 538 and 475 keV, respectively.

Since the low-lying states in even-even nuclei have been so successfully identified with collective behavior, it would be surprising if similar collective effects were absent in odd-A nuclei in the same mass region. Unless the ground-state spin is $\frac{1}{2}$ or $\frac{3}{2}$, the expected core-excitation multiplet spans four units of angular momentum. Radioactivity studies alone rarely give complete data in such cases, except when the parent species has an isomeric state which decays partially via beta processes. Even in the present case, it has not been possible to make completely unambiguous spin assignments. The Coulomb-excitation process is capable of exciting all members of these presumed core-excitation multiplets. We suggest that the use of Ge(Li) detectors in such experiments could produce additional data concerning the Ru^{101} nuclear levels.

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