Decay of $Rh^{102} \rightarrow Ru^{102}$

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The singles and coincident spectra of the gamma rays from the decay of Rh^{102}, which was produced by the (p,n) reaction on ruthenium containing 97.2% Ru^{102}, have been measured with scintillation spectrometers. The energies (in kev) of the gamma rays are: 415±4, 475±5, 630±6, 695±7, 745±8, 765±8, 1050±10, 1105±8, 1110±11, 1365±10, 1565±13, 1795±15, 2040±14, and 511 (annihilation gamma rays). Spins of the levels in Ru^{102} which are consistent with the directional angular correlations of gamma-ray cascades are: 475(2+), 1105(2+ and 4+, doublet), 1525(3), 1840(0+), 1870(3, 4, 5, or 6), 2040(2+), 2220(3), and 2270(?). A value of $E2/M1 \geqslant 225$ for the 630-kev transition $(2+ \rightarrow 2+)$ was deduced from the composite correlation of the 630–475 kev cascades. The branching ratio of cascade to crossover transitions from the decay of the second 2+ state is 1.5±0.3. The intensity of the annihilation gamma rays decays with a half-life of 205±10 days. Gamma-ray spectra have been measured as a function of time for 920 days and a change in the relative population of the states is observed. From this we infer the existence of a long-lived isomeric state in Rh^{102}.

I. INTRODUCTION

Rh^{102} is known to decay by β^- emission to the ground state of Pd^{102} and by β^+ emission and orbital electron capture to the ground state and excited states of Ru^{102}.[1] The (210±10)-day half-life for this activity has been observed by several groups of workers.[2–4] Hisatake and Kurbatov[5] from their investigation of the decay of Rh^{102} have proposed energy levels in Ru^{102} at 0.475, 1.106, 1.565, 1.875, and 2.255 Mev. The state at 1.106 Mev probably corresponds to the second 2+ state at (1100±9) kev observed in Coulomb excitation.[6] The number of crossover decays from the second 2+ state was not measured in the Coulomb excitation experiments. A knowledge of the ratio of cascade to crossover transitions from the second 2+ state is needed to determine the $B(E2)$'s for the cascade and the cross-over transitions. This ratio must be determined by another experiment such as radioactive decay measurements. The interpretation of the decay scheme by Hisatake and Kurbatov gives a value of cascade/crossover ~100 for the decay of the second 2+ state. This value appears to be unreasonably large compared with branching ratio values of 1.5 to 4 from the decay of second 2+ states of other even-even medium weight nuclei. Because of this unsatisfactory situation, we have re-examined the decay of Rh^{102}.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Rh^{102} was produced with the 22-Mev proton cyclotron at ORNL by the (p,n) reaction on a 50-mg sample of ruthenium containing 97.2% Ru^{102}. The beam energy was degraded to enhance the yield of Rh^{102} relative to Rh^{101} from the $Ru^{102}(p,2n)Rh^{101}$ reaction. Sources of Rh^{102} were prepared by a chemical separation of the rhodium from the ruthenium.

The gamma rays from the decay of Rh^{102} were detected with a 3×3 in. NaI scintillation spectrometer. Pulse-height spectra were measured with a 120-channel analyzer of Bell-Kelley design[7] and with a RCL 256-channel analyzer. For the coincident spectra and the angular correlation measurements, two 3×3 in. NaI scintillation spectrometers were used with a fast-slow coincident circuit having a resolving time, 2τ, of either 0.12 or 0.06 μsec.

A. Gamma-Ray Spectra

The singles gamma-ray spectrum of Rh^{102}, which was taken 255 days after preparation of the source, is shown in Figs. 1 and 2. The low-energy portion of the spectrum

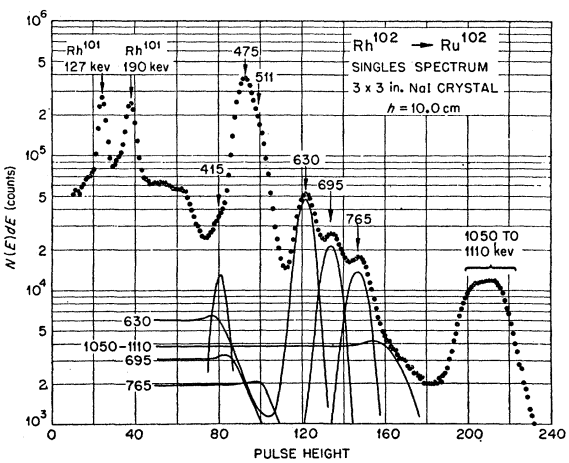

FIG. 1. Pulse-height spectrum of the gamma rays (low energy) from Rh^{102}.

[1] See, for instance, *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).
[2] N. Hole, Arkiv. Mat. Astron. Fysik **34B**, No. 5 (1947).
[3] D. B. Kochendorfer and D. J. Farmer, Phys. Rev. **96**, 855 (1954).
[4] K. Hisatake, J. T. Jones, and J. D. Kurbatov, Bull. Am. Phys. Soc. **1**, No. 5, 271 (1956).
[5] K. Hisatake and J. D. Kurbatov, Bull. Am. Phys. Soc. **3**, 315 (1958).
[6] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. **2**, 267 (1957) and Phys. Rev. **121**, 209 (1961).
[7] P. R. Bell and G. G. Kelley, Oak Ridge National Laboratory Report ORNL-1620, 1953 (unpublished); and Oak Ridge National Laboratory Report ORNL-1975, 1955 (unpublished).

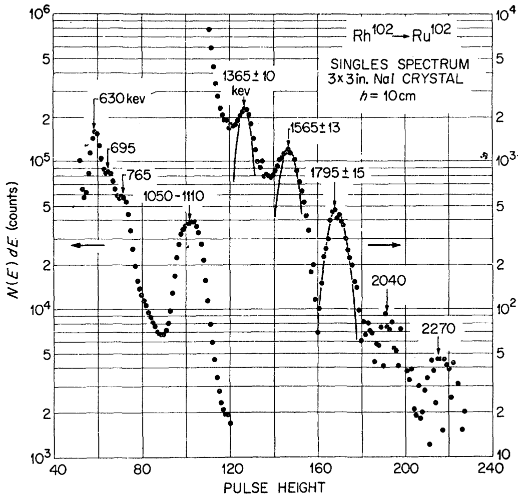

FIG. 2. Pulse-height spectrum of the gamma rays (high energy) from Rh^{102}.

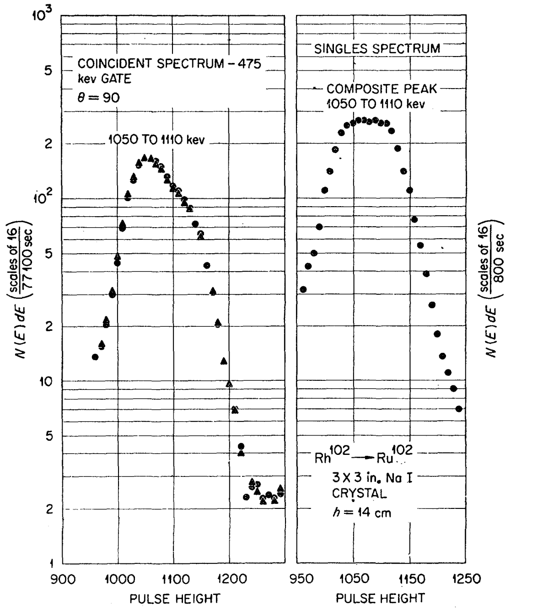

FIG. 3. Pulse-height spectrum of the gamma rays from Rh^{102} with a 50-kev gate at 475 kev.

in Fig. 1 was decomposed into 5 gamma rays plus a composite peak at 1050 to 1110 kev. The gamma rays of 127 and 190 kev are probably due to the decay of Rh^{101} ($\sim$5 year) because a spectrum of the gamma rays from a Rh sample taken 10 days after preparation of the source contained an intense gamma ray of 304 kev. This gamma ray is attributed to Rh^{101} (4.7-day isomeric state). Evidence for the 415-kev gamma ray is brought out more clearly by some of the coincident spectra measurements. The high-energy portion of the spectrum in Fig. 2 was decomposed into gamma rays of 1365±10, 1565±13, 1795±15, and 2040±14 kev and possibly one of 2270 kev. A gamma ray of 2270 kev does fit into the decay scheme to be discussed in Sec. III. Gamma rays from K^{40} (1.46 Mev) and ThC″ (2.615 Mev) in the background spectrum served as convenient standards for energy calibration of the spectrum in Fig. 2. The results from an analysis of this singles spectrum are given in Table I. Corrections for sum peaks from cascade gamma rays have been applied to the intensities given in Table I. The intensity of the annihilation radiation was obtained from measurements of the coincident spectrum of the annihilation gamma rays from the Rh^{102} source and a Na^{22} source.

TABLE I. Relative intensities of gamma rays from Rh^{102}.

E_γ (kev)	Relative intensity
415±5	2.6 ±0.3
475±5	100
630±6	17.4 ±1
695±7	9.5 ±0.6
765±8	6.9 ±0.4
1050−1110	18.0 ±1.1
1365±10	0.67±0.07
1565±10	0.27±0.04
1795±13	0.07±0.02
2040±14	0.06±0.02
511	31.6 ±1.9

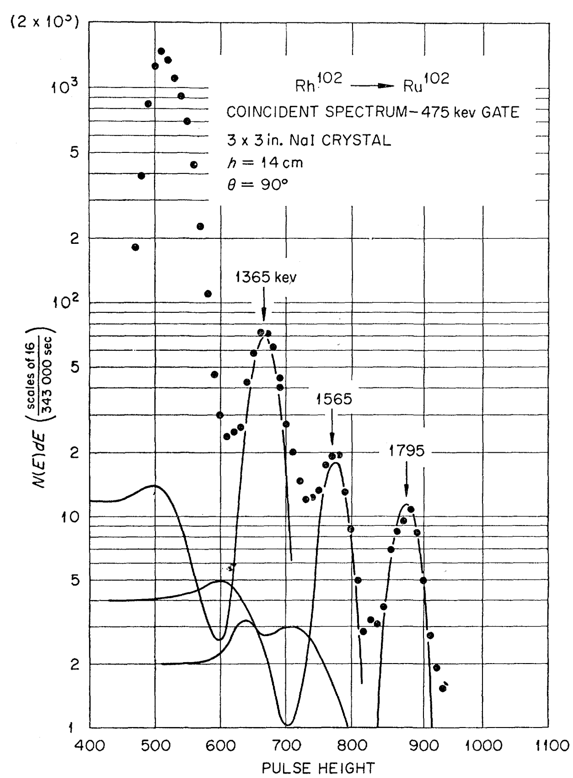

FIG. 4. Pulse-height spectrum of the gamma rays (high energy) from Rh^{102} with a 50-kev gate at 475 kev.

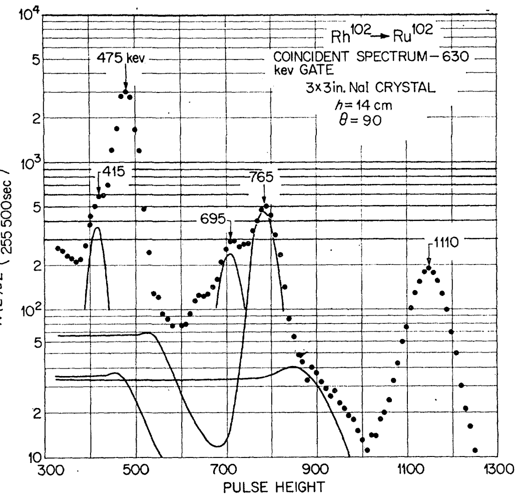

FIG. 5. Pulse-height spectrum of the gamma rays from Rh^{102} with a 50-kev gate at 630 kev.

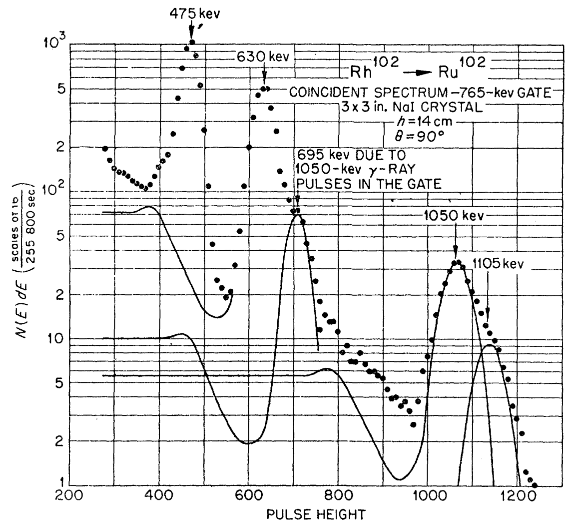

FIG. 7. Pulse-height spectrum of the gamma rays from Rh^{102} with a 50-kev gate at 765 kev.

B. Gamma-Gamma Angular Correlations

The directional angular correlations of several gamma-ray cascades were measured with single-channel gate positions as follows: gates 50 kev wide at 475, 630, 765, and 1050 kev, a gate 30 kev wide at 695 kev, and a gate 160 kev wide positioned about the composite peak at 1050 to 1110 kev. Representative coincident spectra taken at $\theta=90°$ are shown in Figs. 3–9. The distance between the source and each detector was 14 cm.

Many corrections must be applied to obtain the intensities from the angular correlation measurements because there are pulses from other gamma rays and from coincident sums of gamma rays in cascade in the gating window. For example, the following corrections were made to obtain the intensities of the 475-kev gamma ray in the 475–630 kev angular correlation measurements: removal of the Compton distributions of the 1110-, 765-, and 695-kev gamma rays under the 475-kev peak in the coincident spectrum and removal of counts in the 475-kev peak due to pulses from the 695-, 1050-, and 1110-kev gamma rays in the gating window. The positron group, leaving Ru^{102} in the first excited state at 475 kev, was also troublesome in several of the angular correlation measurements at $\theta=0°$ and 10°. A coincident-sum pulse from one of the annihilation gamma rays and the 475-kev gamma ray, which fell

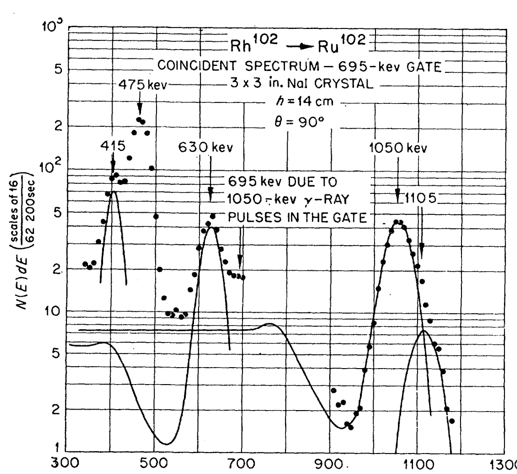

FIG. 6. Pulse-height spectrum of the gamma rays from Rh^{102} with a 30-kev gate at 695 kev.

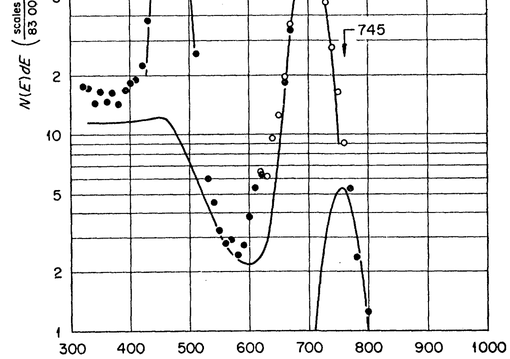

FIG. 8. Pulse-height spectrum of the gamma rays from Rh^{102} with a 50-kev gate at 1050 kev.

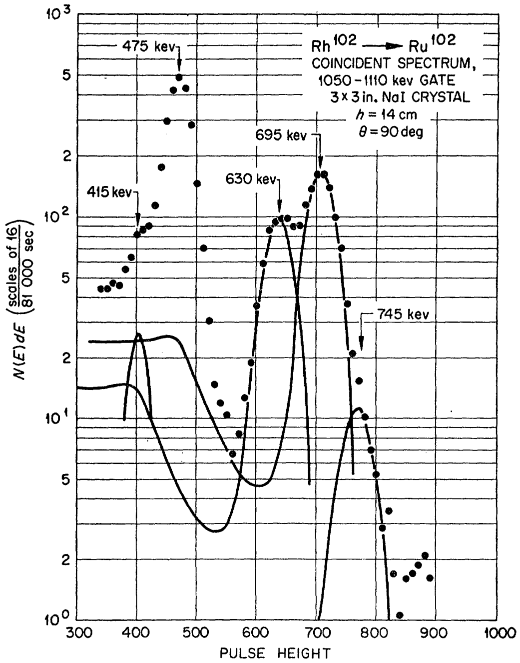

FIG. 9. Pulse-height spectrum of the gamma rays (low energy) from Rh^{102} with a 160-kev gate at 1050–1110 kev.

within the single channel gate, gave rise to 511-kev pulses in the coincident spectrum. As a result, the intensity of the 475-kev gamma ray was obtained from a composite peak in the coincident spectrum for $\theta=0°$ and 10°.

After each correction was applied to the intensities in the angular correlation measurements, a least-squares analysis of the data in terms of a series of Legendre polynomials,

$$W(\theta)=A_0'+A_2'P_2(\cos\theta)+A_4'P_4(\cos\theta),$$

was carried out on an IBM-704. In this way the change in the coefficients A_ν could be traced as each correction was applied to the data. In Table II are listed the angular distribution coefficients which have been corrected for finite angular resolution.[8] An entry for a cascade with two sets of coefficients A_ν corresponds in one case with the gate including the first gamma ray and in the other case with the gate including the second gamma ray.

The coincident spectra were also analyzed to obtain the absolute intensities of the gamma rays. These intensities are given in Table III, together with the intensities obtained from the singles spectrum. Corrections have been made for coincidences which result from pulses of other gamma rays and from coincident sums of gamma-ray cascades in the gating window. This explains why no intensities are included in Table III for some of the peaks which appear in the coincident spectra. The coincident spectrum below 900 kev was not recorded with a 50-kev gate at 475 kev. For this reason no entries appear for the intensities of the 415-, 630-,

TABLE II. Angular distribution coefficients of the terms in the correlation function expressed in Legendre polynomials.

Cascade (E_γ in kev)	A_2	A_4	Decay sequence	δ_1	δ_2
1365–475	0.29 ±0.04	1.00 ±0.13	0(Q)2(E2)0		
1565–475	−(0.20 ±0.02)	0.30 ±0.03	2(D,Q)2(E2)0	2.8±0.2	
1050} 1110}–475	−(0.26 ±0.03)	−(0.003±0.05)	3(D,Q)2(E2)0 3(D,Q)4(Q)2(E2)0	2.6×10^{-1} $-(2.4\times10^{-1})$	
630–475[a]	0.043±0.005	0.146±0.010	{4(Q)2(E2)0 {2(M1,E2)2(E2)0	 ≧15	
765–630	0.113±0.011 0.107±0.010	0.007±0.017 −(0.010±0.018)	{3(D,Q)4(Q)2 {4(D,Q)4(Q)2 {5(D,Q)4(Q)2 {6(Q)4(Q)2	$(3.1\pm0.2)\times10^{-1}$ $-(2.4\pm0.4)\times10^{-1}$ $-(3.0\pm0.4)\times10^{-1}$	
765–475	0.08 ±0.02 0.14 ±0.03	0.02 ±0.03 0.02 ±0.04	{3(D,Q)4(Q)2(E2)0 {4(D,Q)4(Q)2(E2)0 {5(D,Q)4(Q)2(E2)0 {6(Q)4(Q)2(E2)0	$(3.1\pm0.2)\times10^{-1}$ $-(2.4\pm0.4)\times10^{-1}$ $-(3.4\pm0.4)\times10^{-1}$	
1050–475	−(0.274±0.015)	0.019±0.024	3(D,Q)2(E2)0	$(2.6\pm0.15)\times10^{-1}$	
695–1050	−(0.048±0.010)	−(0.003±0.02)	3(D,Q)3(D,Q)2	{$-(3.8\pm0.2)\times10^{-1}$ { or { 3.4±0.2	$-(2.6\times10^{-1})$
1110–630	−(0.32 ±0.02)	−(0.03 ±0.03)	3(D,Q)4(Q)2	$-(2.4\pm0.4)\times10^{-1}$	
1795–475	−(0.17 ±0.03)	0.03 ±0.05			

[a] It is not possible to fit this angular correlation with a single cascade originating from a state at 1105 kev.

[8] M. E. Rose, Phys. Rev. 91, 610 (1953).

695-, and 765-kev gamma rays under column 3 of Table III. However, it is clear from the other entries in this table that the 475-kev gamma ray is in coincidence with the 415-, 630-, 695-, and 765-kev gamma rays.

III. DISCUSSION

An energy level diagram, which is compatible with most of the results tabulated in Tables II and III, is given in Fig. 10. The number in parentheses accompanying the energy of the transition is the relative intensity of the gamma ray. The first and second 2+ states at 475 and 1105 kev have been observed in Coulomb excitation.[6]

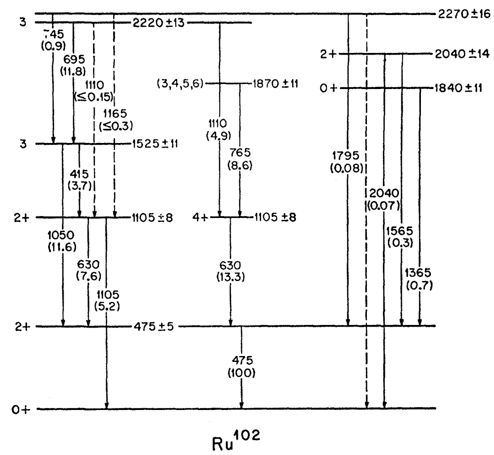

FIG. 10. Transitions and energy levels in Ru ^{102} which occur in the decay Rh^{102}. Energies of the transitions are in kev. The relative intensities of the gamma rays in parentheses accompanying the energies of the transitions correspond to measurements taken 378 days after preparation of the source of Rh^{102}.

A. Evidence for 4+ State at 1105 kev

Both the singles and coincident spectra show that the peak at 1050 to 1110 kev is a complex of gamma rays. There are strong coincident rates between gamma rays in this peak and both the 475- and 630-kev gamma rays. This indicates that a 1100-kev gamma ray exists above the second 2+ state at 1105 kev. (One might argue that perhaps 475- and 630-kev gamma rays exist above the second 2+ state and that these could account for the observed coincidences. However, if this were the case, then 475–475 kev and 630–630 kev coincidences would have been observed.) It is found that there are essentially no coincidences between 1100-kev gamma rays and other 1100-kev gamma rays (see column headed 1050–1110 kev gate). This indicates that there is no crossover decay of a state at 1100 kev. On the other hand, there are strong coincident rates between the gamma ray of 695 kev and gamma rays of 475, 630, and 1105 kev. The possibility that all four γ-rays are in cascade is ruled out by the available decay energy. One is therefore forced to the conclusion that there must be two states at 1105 kev; one a 2+ state with crossover decay and one a 0+ or 4+ state with no crossover decay. It is conceivable that there is a triplet of states of the type 0+, 2+, and 4+ at 1105 kev. However, the observed angular correlation of the 630–475 kev cascade (see below) gives strong evidence for population of a 4+ state, but indicates little, if any, population of a 0+ state.

The coincident measurements show that the 765-kev transition terminates on the 4+ state at 1105 kev. The coincident spectrum shown in Fig. 7 indicates a very small intensity for 1105-kev gamma rays. The observed intensities for the 1050- and 1105-kev peaks are attributed to pulses of the 695- and 745-kev gamma rays which are in the 765-kev gate. The intensities of the 1050- and 1105-kev gamma rays under the column

TABLE III. Intensities of the gamma rays from Rh^{102} in the singles and coincident spectra taken 378 days after preparation of the source.

		Gating gamma ray					
E_γ (kev)	Singles (10^3 γ's/sec)	475 (10^3 γ's/sec)	630 (10^3 γ's/sec)	695 (10^3 γ's/sec)	765 (10^3 γ's/sec)	1050 (10^3 γ's/sec)	1050–1110 (10^3 γ's/sec)
415±5	3.4 ±1.0		2.3±0.5	3.2 ±0.5			0.7 ±0.4
475±5	90 ±5		21.1±2.0	10.5 ±1.2	8.7 ±0.9	10.4±1.5	14.7 ±1.5
630±6	18.0 ±1.1			2.26±0.30	7.7 ±0.8		4.6 ±0.5
695±7	10.6 ±0.7		2.5±0.3			9.1±1.4	10.2 ±1.0
745±8						0.7±0.2	0.8 ±0.2
765±8	7.8 ±0.6		7.5±0.8				
1050±10				8.5 ±0.9	0.8 ±0.1 [a]		<0.02
1105±8				1.57±0.20	0.29±0.06 [a]		0.05±0.02
1110±11			4.4±0.4				0.05±0.02
1165±15							0.3 ±0.1
1050−1110	19.3 ±1.2	14.6 ±1.5					
1365±10	0.72±0.10	0.62±0.10					
1565±13	0.29±0.04	0.22±0.05					
1795±15	0.07±0.02	0.06±0.02					
2040±14	0.06±0.02						

[a] The intensities of these gamma rays result from coincidences with pulses of the 745-kev gamma rays which occur within the 765-kev gate.

TABLE IV. Analysis of the angular correlation data.

Initial state position (kev)	Cascade (E_γ in kev)	Decay sequence	A_2	A_4	δ_1
1525	1050–475		$-(0.274\pm0.015)$	0.019 ± 0.024	
		$0(Q)2(Q)0$	0.3571	1.143	
		$1(D,Q)2(Q)0$	−0.274	−0.001	$-(2.1\times10^{-2})$
		$2(D,Q)2(Q)0$	−0.274	0.158	$-(9.7\times10^{-1})$
		$2(D,Q)2(Q)0$	−0.274	0.288	−2.75
		$3(D,Q)2(Q)0$	−0.274	−0.005	2.6×10^{-1}
		$3(D,Q)2(Q)0$	−0.274	−0.081	1.2×10
		$4(Q)2(Q)0$	0.102	0.009	
2220	1110–630		$-(0.32\ \pm0.02)$	$-(0.03\ \pm0.03)$	
		$5(D,Q)4(Q)2$	−0.32	−0.01	4.2×10^{-1}
		$5(D,Q)4(Q)2$	−0.32	−0.05	3.1
		$4(D,Q)4(Q)2$	$A_2\geqslant-0.18$	(for all δ_1)	
		$3(D,Q)4(Q)2$	−0.32	−0.01	$-(2.4\times10^{-1})$
		$2(Q)4(Q)2$	0.200	0.093	
1870	765–630		0.113 ± 0.011	0.007 ± 0.017	
			0.107 ± 0.010	$-(0.010\pm0.018)$	
		$6(Q)4(Q)2$	0.102	0.009	
		$5(D,Q)4(Q)2$	0.110	−0.005	$-(3.0\times10^{-1})$
		$4(D,Q)4(Q)2$	0.110	0.008	$-(2.4\times10^{-1})$
		$3(D,Q)4(Q)2$	0.110	−0.016	3.1×10^{-1}
		$2(Q)4(Q)2$	0.200	0.093	
1105	630–475		0.043 ± 0.005	0.146 ± 0.010	
		$4(Q)2(Q)0$	0.102	0.009	
		$2(D,Q)2(Q)0$	0.468	0.146	0.9
		$2(D,Q)2(Q)0$	−0.260	0.146	−0.9
		$2(D,Q)2(Q)0$	0.043	0.023	−0.27
		$2(D,Q)2(Q)0$	0.043	0.319	6.4

headed 765-kev gate in Table III are the values resulting from the 745-kev gamma ray in the gate.

B. Angular Correlation Results

The results from the 1365–475 and 1565–475 kev angular correlation measurements are consistent with states of spins 0 and 2 at 1840 and 2040 kev, respectively. Spins 1 and 3 for the state at 2040 kev do not fit the data because $A_4\leq 0$ for the decay sequences $1(D,Q)2(Q)0$ and $3(D,Q)2(Q)0$. The mixing ratio of dipole and quadrupole radiation in the $2\rightarrow 2$ transition is $\delta=2.8\pm0.2$, where δ is defined as $(Q/D)^{\frac{1}{2}}$ in the notation of Biedenharn and Rose.[9]

The angular correlation coefficients for the 1050–475 kev cascade are given in Table IV. Also given in Table IV are the theoretical correlation coefficients which occur for different spin values of the 1525-kev level. For spins 1, 2, and 3 the value of the mixing ratio δ is chosen to give the best agreement between the theoretical and experimental coefficients. The experimental coefficients are consistent with the spin sequence $3(D,Q)2(Q)0$ with $\delta=2.6\times10^{-1}$. Although the spin sequence $1(D,Q)2(Q)0$, is consistent with the angular correlation data, it is excluded because the crossover transition of 1525 kev is not observed in the singles spectrum. Spins greater than 4 for the 1525-kev level are not considered because only dipole and quadrupole radiations for the 1050-kev transition are consistent with the fact that the 695–1050 kev gamma rays are in prompt coincidence.

An analysis of the angular correlation data for the 1110–630 kev cascade is given in Table IV. Spin 2 for the intermediate state at 1105 kev is excluded because the intensity of the 1105-kev gamma ray in the coincident spectrum with the gate at 1050 to 1110 kev is only 1% of the 630-kev gamma-ray intensity. The experimental coefficients are in good agreement with the theoretical coefficients for the spin sequences $5(D,Q)4(Q)2$ and $3(D,Q)4(Q)2$. However the assignment of spin 5 to the level at 2220 kev does not fit the results from the angular correlation measurements of the 695–1050-kev cascade which also originates from this level. For instance, the coefficient A_2 for the sequence $5(Q)3(D,Q)2$ is -0.163; whereas, the experimental coefficient A_2 for the 695–1050-kev cascade is $-(0.048\pm0.010)$. The results from the angular correlation data for the 695–1050-kev cascade are also consistent with spin assignments of 2 and 4 for the 2220-kev level. With the assumption that the 1110–630-kev and 695–1050-kev cascades originate from the same state at 2220 kev, the correlation functions for these cascades are compatible only with the assignment of spin 3.

The composite correlation involving the 1050–475 kev and 1110–475 kev cascades was also measured. Within

[9] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. 25, 729 (1953).

experimental error this composite correlation function is equal to the correlation function for the 1050–475 kev cascade which was obtained with a gate at 1050 kev. This means that the coefficients in the correlation function for the 1–3 cascade involving the 1110- and 475-kev gamma rays are $A_2 = -(0.26 \pm 0.03)$ and $A_4 \approx 0$. The 1–3 correlation should be identical with the 1–2 correlation for the decay sequence $3(D,Q)4(Q)2(Q)0$. In view of a possible error in the removal of the effect of the annihilation radiation from the data at 0° in the 1–3 correlation, the results are compatible with this statement.

The results from an analysis of the 765–630 kev angular correlation are consistent with spin assignments 3, 4, 5, or 6 for the state at 1870 kev (see Table IV). The 1–3 correlation involving the 765- and 475-kev gamma rays is also compatible with these spin assignments, i.e., the 1–3 and 1–2 correlation functions should be identical.

It is not possible to fit the 630–475 kev angular correlation with a single cascade originating from a state at 1105 kev. Assuming a 2+, 4+ doublet and using the relative intensities of the 630-kev gamma rays given in Fig. 10, a value of $E2/M1 \geqslant 225$ for the 630-kev $2+ \to 2+$ transition is obtained. The sign of δ is probably positive.

The observed value for A_4 of $+0.146$ allows a limit to be placed on the amount of population of a possible 0+ state at 1105 kev. The A_4 coefficient for a $0 \to 2 \to 0$ correlation is quite large ($+1.143$). The comparison of the observed A_4 to that for a $0 \to 2 \to 0$ correlation indicates that the population of 0+ state can be no more than 7% of the population of the 4+ state.

A summary of the decay sequences, which fit the angular correlation data, is given in column 4 of Table II. In a triple cascade with the intermediate radiation mixed, it is not possible to define δ so that the intermediate state j always occurs in the same position in the reduced matrix element[10] for the two double cascades, e.g., the mixed transition is first transition in the 1050–475 kev cascade and the same mixed transition is the second transition in the 695–1050 kev cascade. However, if the convention of reference 9 is followed, then $\delta_1 = -\delta_2$. Although the angular correlation of the 1795–475 kev cascade was measured, no attempt was made to analyze the data because several coincident sum peaks contributed appreciably to the intensities.

C. Branching Ratio of Second 2+ State

The branching ratio of cascade to crossover transitions from the decay of the second 2+ state at 1105 kev is 1.5 ± 0.3. This was obtained from the gamma-ray intensities with the gate at 695 kev. This value is in line with observed branching ratios from the decay of the second 2+ states in other even-even nuclei of medium weight. This branching ratio is also consistent with the "singles" intensities of the 630- and 1105-kev gamma rays in Table III. For instance, the difference between the "singles" intensity for the composite peak at 1050–1110 kev and the intensity with the gate at 475 kev is 4.7×10^3 γ's/sec of 1105 kev. Of this intensity, two-thirds results from direct β decay to the second 2+ state at 1105 kev. The summed intensity of the 630-kev gamma rays from direct β decay to the second 2+ state (4.6×10^3 γ's/sec) and from gamma-ray decay to the 4+ and second 2+ states with gates at 695, 765, and 1110 kev is 19.2×10^3 γ's/sec. This value is in good agreement with the "singles" intensity for the 630-kev gamma rays.

D. Long-Lived Isomer in Rh^{102}

After completion of most of the measurements, we noticed that several of the gamma rays were not decaying with the generally accepted half-life of 210 days for Rh^{102}. An examination of the relative intensities in Tables I and III supports this point. The relative intensities of the gamma rays as a function of time are shown in Table V. The intensity of the annihilation radiation, which was obtained from measurements of the coincident spectrum of the annihilation gamma rays from the Rh^{102} source and a Na^{22} source, was measured at 6, 19, and 30 months after preparation of the source. The intensity of the β^+ groups is decaying with a half-life of 205 ± 10 days. This is in agreement with the half-life observed by several groups of workers.[2–4] Relative intensities of the gamma rays are given in Table V because the first 3 entries are from measurements with sources of Rh^{102} of different strengths. A change in the relative population of the states in Ru^{102} is observed. From this we infer the existence of a long-lived isomeric state in Rh^{102}.

From the measurements taken 920 days after preparation of the Rh^{102} source we noticed the following changes

TABLE V. Relative intensities of the gamma rays from Rh^{102} as a function of time.

E_γ (kev) \ Decay time (days)	150	203	255	378	582	920
475–511	131.6	131.6	131.6	131.6	127	119
475	100	100	100	100	100	100
630	16.1	17.3	17.4	20.1	24.4	42.9
695	8.7	9.5	9.5	11.8	21.9	30.7
765	6.2	7.0	6.9	8.7	14.5	22.8
1050–1110	14.2	17.3	18.0	21.5	26.4	39.9

[10] M. E. Rose, Oak Ridge National Laboratory Report ORNL-2516, 1958 (unpublished).

TABLE VI. Log(ft) values for the β-decay groups from Rh^{102} (210 days).

Final state	Type of decay	Intensity (%)	log(ft)	log[$ft(W_0^2-1)$]
Ground state	β^-	19.7	9.54	10.5
Ground state	β^+	7.8	9.03	10.1
Ground state	ϵ capture	13.9	8.9	
475(2+)	β^+	3.9	8.4	
475(2+)	ϵ capture	45.2	8.2	
1105(2+)	ϵ capture	6.3	8.7	
1525(3)	ϵ capture	2.0	8.8	
1840(0+)	ϵ capture	0.6	8.8	
2040(2+)	ϵ capture	0.25	8.6	

in the singles spectrum of the gamma rays. In addition to the 127- and 190-kev gamma rays from the decay of Rh^{101}, a gamma ray of 320 kev stands out clearly above the Compton distributions of the higher energy gamma rays. This gamma ray is interpreted as the crossover transition of the 127–190 kev cascade in Ru^{101}. The 415-kev gamma ray is prominent in the singles spectrum. The high energy portion of the composite peak at 1050–1110 kev is decaying more rapidly than the low energy portion. This is in agreement with the observation of direct β-decay by Rh^{102} (210 day) to the 2+ state at 1105 kev. The 1365-kev gamma ray from the decay of the 0+ state at 1840 kev does not stand out clearly in the singles spectrum. Direct β decay by Rh^{102} (210 day) to the 0+ state at 1840 kev would account for this observation. The 1565- and 1795-kev gamma rays are still present in the spectrum.

E. Log(ft) Values

The relative intensities of the gamma rays in parentheses accompanying the energies of the transitions in Fig. 10 correspond to measurements taken 378 days after preparation of the source of Rh^{102}. From a knowledge of the intensities of the transitions into and out of each state in Ru^{102}, it is possible to obtain the relative intensities of the β-decay groups from Rh^{102} (210 days). Values of the intensities and comparative half-lives for the β-decay groups of Rh^{102} are given in Table VI. The β-decay groups to the states at 1870, 2220, and 2270 kev in Ru^{102} are omitted because these states are probably populated by β decay from the long-lived isomeric state of Rh^{102}. The same statement may be true of the 1525-kev state. In any case the omission of this group would not change appreciably the log(ft) values in Table VI. The relative intensity of the β^- decay group was taken from measurements of other workers[1] ($\beta^+/\beta^-=0.6$). The relative intensities of the β^+ groups to the ground and 475-kev states in Ru^{102} were taken from the work of Hisatake and Kurbatov.[5] To obtain the intensity of ϵ capture to the ground state of Ru^{102}, we used the ratio (f_K/f_+) for allowed transitions from computations by Feenberg and Trigg[11] and by Zweifel.[12] The ratio of L_1 to K capture was taken from calculations by Rose and Jackson.[13] The log(ft) values for the ground-state groups to Pd^{102} and Ru^{102} are characteristic of first-forbidden unique transitions ($\Delta I=2$, yes). On the other hand, the comparative half-lives for the first-forbidden nonunique transitions (based on a 2- assignment to Rh^{102}) are rather large. The K/β^+ ratio for unique first-forbidden transitions has been shown to be close to the value for allowed transitions multiplied by the factor $2(W_0+1)/(W_0-1)$, where W_0 is the maximum positron energy, in units of m_0c^2, including the rest mass.[14] The inclusion of this factor for the ground-state group increases the log(ft) values by 1.5%–2% in Table VI except for the ϵ-capture group to the ground state. The log(ft) for this group is decreased by 5%. An alternative assignment to Rh^{102} would be 1− with abnormally large log(ft) values for all the β-decay groups from Rh^{102}. The relative parities of the states in Ru^{102} are based on a negative parity assignment to Rh^{102}.

F. Comparison with Nuclear Models

Several modifications of the phonon model and alternative interpretations have been suggested in recent years to account for the low-lying levels in even-even nuclei. A comparison of the predictions of these models with the observed levels in Ru^{102} is given in Fig. 11. To determine the parameters in these models one needs, in addition to the energy of the first 2+ state, the energy and spin of one or more additional levels. These additional levels which fix the parameters are indicated by dashed lines in Fig. 11. Scharff-Goldhaber and Weneser[15] considered the weak coupling of the configuration $(f_{7/2})^4$ with $J=0$ to the phonon states. Raz[16] extended this approach by coupling $(f_{7/2})^2$ states with $J=0$, 2, 4, and 6 to the phonon states. The energy level spectrum for an energy ratio of 2.32 for the two 2+ states is shown in Fig. 11. For a definition of the parameters the reader is referred to the original papers.

Wilets and Jean[17] have given a collective approach of the surface oscillations in the "adiabatic" approximation. The level spectrum for a displaced harmonic oscillator (γ unstable) is shown in Fig. 11. The $I=2+$ and 4+ states are degenerate.

Davydov and Filippov[18] have considered in some detail the level spectrum for an asymmetric rotor in the "adiabatic" approximation (fixed β and γ). They introduced a restriction on the moments of inertia given by

[11] E. Feenberg and G. Trigg, Revs. Modern Phys. **22**, 399 (1950).
[12] P. F. Zweifel, Phys. Rev. **107**, 329 (1957).
[13] M. E. Rose and J. L. Jackson, Phys. Rev. **76**, 1540 (1949).
[14] J. Konijn, B. van Nooijen, A. L. Hagedorn, and A. H. Wapstra, Nuclear Phys. **9**, 296 (1958).
[15] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[16] B. James Raz, Phys. Rev. **114**, 1116 (1959).
[17] G. Wilets and M. Jean, Phys. Rev. **102**, 788 (1956).
[18] A. S. Davydov and G. F. Filippov, Nuclear Phys. **8**, 237 (1958).

the hydrodynamical model. More recently, Davydov and Chaban[19] have relaxed the "adiabatic" approximation for the asymmetric rotor by taking into account the coupling between rotational and β-vibrational motions. The nucleus is rigid with respect to a change of the equilibrium value of the parameter γ which determines the deviation of the nuclear shape from axial symmetry. The nonadiabaticity parameter μ is proportional to the ratio of the root-mean-square of the zero-point vibration amplitude in the ground state to the deformation β_0. The inclusion of the rotation-vibration interaction changes appreciably the level spectrum of the Davydov-Filippov model. In Fig. 11 the parameters γ and μ were adjusted to reproduce the two 2+ and the 4+ states in Ru^{102}. The predicted positions for the 3+, 4+, and 6+ states are in fair agreement with those observed in Ru^{102}. The predicted 0+ state is, however, too low in energy to fit the 0+ state in Ru^{102}. Alternatively, one can use the two 2+ and the 0+ states in Ru^{102} to adjust γ and μ. In this case the predicted positions of the 4+ state lies slightly above the second 2+ state. The predicted positions for the 3+, 6+, and second 4+ states are still in fair agreement with those observed in Ru^{102}. Either choice of parameters reproduces a good portion of the level spectrum in Ru^{102}. However, in both cases the parameter μ is very large. This means that the zero-point amplitude of the β vibration is comparable with the deformation. For large μ the model of Davydov-Chaban should probably be modified to include some γ instability (γ vibrations).

Finally, Mallmann[20] has considered the level spectrum

[19] A. S. Davydov and A. A. Chaban, Nuclear Phys. **20**, 499 (1960). A. A. Chaban, Soviet Physics—JETP **11**, 1174 (1960) and J. Exptl. Theoret. Phys. (USSR) **38**, 1630 (1960). For extensive numerical results see P. P. Day, E. D. Klema, and C. A. Mallmann, Argonne National Laboratory Report ANL-6220, 1960 (unpublished).

[20] C. A. Mallmann (submitted for publication in Nuclear Phys.).

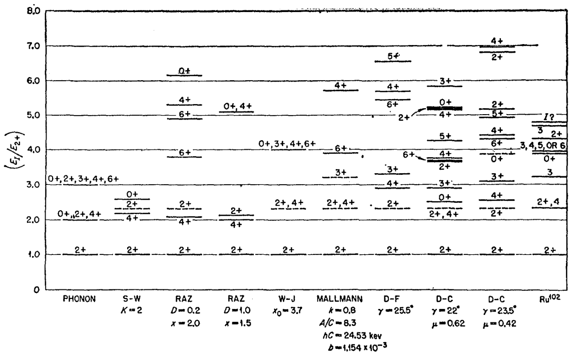

FIG. 11. Comparison of the level spectrum in Ru^{102} with the predictions by various nuclear models which have been suggested to account for the low-lying levels in even-even nuclei.

from an asymmetric rotor with no restrictions on the moments of inertia. The rotation-vibration interaction is introduced as a small perturbation to the general asymmetric rotor. The spin and energy of four levels are, however, required to adjust the parameters. As a result only the prediction for the position of the spin 6 state may be compared with the possible spin 6 state in Ru^{102}.

Note added in proof. Evidence for a 2+ and 4+ doublet at 1105 kev in Ru^{102} has been obtained from Coulomb excitation by Eccleshall, Adams, and Yates at Aldermaston (private communication).

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Note added in proof. After the completion of this work we received a preprint of work by K. Hisatake (submitted to J. Phys. Soc. Japan) on a new investigation of the decay scheme of Rh^{102}. His results are similar to ours although he does not find strong evidence for the 4+ state at 1105 kev.