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Nuclear Levels of ^{101}Ru Populated in the Decay of ^{101}Rh Isomers*

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The decay properties of 4.3-day ^{101}Rh^m and 3.0-yr ^{101}Rh^g have been investigated with the aid of a *p-i-n*, lithium-drifted germanium gamma-ray detector and with a NaI(Tl) gamma-gamma coincidence spectrometer. Energies (and transition intensities) of the gamma rays from the decay of ^{101}Rh^m are 127.0±0.3 (1.2), 180.1±0.4 (0.9), 184.4±0.5 (0.3), 233.4±0.5 (0.4), 238.1±0.4 (0.5), 306.8±0.3 (100), 311±1 (0.1), 331.9 ±0.4 (0.06), 418±1 (0.01), and 545.2±0.5 (5.6) keV, and coincidence data require these transitions to be fitted into a level scheme in ^{101}Ru with energies at 127.0±0.3, 306.8±0.3, 311.0±0.5, 545.2±0.5, and 639±1 keV. Gamma-ray energies (and transition intensities) observed in the decay of ^{101}Rh^g are 127.0±0.3 (105), 198.4±0.4 (100), 295.4±0.4 (0.9), 325.4±0.3 (21), and 422.4±0.6 (0.6) keV, which are consistent with excited states of ^{101}Ru at 127.0±0.3, 325.4±0.3, and 422.4±0.6 keV. Possible spin assignments for the excited levels in ^{101}Ru are discussed. The half-life of ^{101}Rh^m was remeasured as 4.34±0.01 days.

I. INTRODUCTION

DESPITE a rapid multiplication of available data on nuclear energy levels during the past few years, detailed information on odd-A nuclei is generally less available than for even-A nuclei. This situation may be due, in part, to the complexity often encountered in the decay schemes of odd-A nuclei. The nuclei in the vicinity of $A=101$ lie in an especially interesting region between the closed shells at 50 neutrons and 50 protons. Although theoretical interpretations of the properties of energy levels in this region have not been very successful, it is hoped that more experimental data will stimulate further theoretical work.

The nucleus ^{101}Ru is a promising case for study, since its energy levels may be excited either by beta decay of 14.0-min ^{101}Tc, or by electron capture decay of 4.3-day ^{101}Rh^m and 3-yr ^{101}Rh^g. At the outset of our work on ^{101}Rh^m and ^{101}Rh^g to be reported here, the published information[1] on the decay of ^{101}Tc, ^{101}Rh^m, and ^{101}Rh^g suggested that these nuclei decayed to sets of levels in stable ^{101}Ru which had little in common with one another. However, it was generally accepted that ^{101}Tc, ^{101}Rh^m, and ^{101}Rh^g had spins and parities of $\frac{9}{2}^+$, $\frac{9}{2}^+$, and $\frac{1}{2}^-$, respectively. The assignments for ^{101}Rh^m and ^{101}Rh^g were recently confirmed by Evans, Kashy, Naumann, and Petry.[2]

To resolve the numerous ambiguities arising from an analysis of the reported data on energy levels of ^{101}Ru, it was apparent that high-resolution spectrometry was required to search for gamma rays very closely spaced in energy and that coincidence spectrometry was needed to determine the placement of gamma transitions in the ^{101}Ru level scheme. Our investigation employed a lithium-drifted germanium [Ge(Li)] detector for high-resolution gamma-ray spectrometry. Gamma-gamma coincidence spectrometry was achieved by using two NaI(Tl) detectors connected to a two-parameter pulse-height analyzer. Many of the features seen in our study were also seen in a recent investigation of the ^{101}Rh isomers by Evans and Naumann,[3] who employed gamma-ray and internal conversion electron spectroscopy.

While the present study of the ^{101}Rh isomers was being carried out, the early data[4] obtained at this Laboratory on the decay scheme of ^{101}Tc were also being enhanced by new measurements.[5,6] These new results on ^{101}Tc have given useful collateral information bearing on some of the low-lying energy levels of ^{101}Ru seen in decay of ^{101}Rh, and, in addition, have added considerably to our knowledge of the excited states of ^{101}Ru at energies in excess of 1 MeV. These results on the ^{101}Tc decay will be the subject of a later communication.

II. EXPERIMENTAL METHODS

A. Source Preparation

The sources of ^{101}Rh^m+^{101}Rh^g were produced in the Oak Ridge Isochronous Cyclotron (ORIC) by the reaction ^{99}Tc(α,2n)^{101}Rh. The targets typically were 40 mg of ^{99}Tc metal in a holder of 2 cm^2 area. The irradiations were performed with 22-MeV alpha particles for 6 μA h. The beam energy was chosen with the aid of a Monte Carlo calculation using a computer

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[1] *Nuclear Data Sheets*, compiled by K. Way *et al.* (National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 61-2-26 through 61-2-34, and Recent References through July, 1963).

[2] J. S. Evans, E. Kashy, R. A. Naumann, and R. F. Petry, Phys. Rev. **138**, B9 (1965).

[3] J. S. Evans and R. A. Naumann, Phys. Rev. **140**, B559 (1965).

[4] G. D. O'Kelley, Q. V. Larson, and G. E. Boyd, Bull. Am. Phys. Soc. 2, 24 (1957).

[5] N. K. Aras, G. G. Chilosi, and G. D. O'Kelley, in Symposium on Low-Energy Nuclear Chemistry, 149th National Meeting of the American Chemical Society, Detroit, 1965 (unpublished).

[6] N. K. Aras, G. D. O'Kelley and G. G. Chilosi, Oak Ridge National Laboratory Report No. ORNL-3832, 1965 (unpublished).

program written by Rogers.[7] This program permitted an evaluation of the competition between excitation functions for (α,n), $(\alpha,2n)$, and $(\alpha,3n)$ reactions.

The irradiated ^{99}Tc metal was dissolved in HNO_3, and Rh carrier was added. Chemical purification of the Rh was accomplished through precipitation of $K_3Rh(NO_2)_6$ with KNO_2.

Two days after irradiation and subsequent chemical purification, a typical ^{101}Rh source was examined for impurities with the aid of a Ge(Li) gamma-ray spectrometer. The only significant impurity was 206-day ^{102}Rh, whose disintegration rate at the time was only about 1.4×10^{-3} that of ^{101}Rh^m. A small amount of 21-h ^{100}Rh was also present, but because of its relatively shorter half-life and the nature of its gamma-ray spectrum, it created no serious interference.

B. Instrumentation and Data Processing

The *p-i-n*, Ge(Li) semiconductor gamma-ray detector[8] used in the present investigation had a depletion depth of 3 mm and surface area of 2 cm^2. The lithium-drifted disk was mounted inside an evacuated can of thin-walled aluminum with a copper lid. Electrical connections to the device were supplied via a miniature coaxial fitting in the lid, which in turn mated with a fitting on the end of an evacuated, low-capacitance, coaxial line from the preamplifier.[8] Input capacitance to the preamplifier introduced by this arrangement was about 12 pF. The detector was immersed in a Dewar flask containing a 2-day supply of liquid nitrogen.

The electronic system for the Ge(Li) detector consisted of a Tennelec model 100C preamplifier and a Tennelec model TC-200 main amplifier operated in the single differentiation mode. Integral rates through the amplifier were kept below 5000 pulses/sec for best energy resolution. Pulse-height analysis was accomplished by using the multiparameter analyzer described below as a single parameter analyzer for storing up to 20 ungated spectra of 1000 channels each.

The energy resolution obtained with the Ge(Li) detector system was 3.5–5.5 keV in the energy range with which this investigation was concerned.

Gamma-gamma coincidence studies were carried out with the aid of a Victoreen model MP-204 RT multiparameter pulse-height analyzer.[9] Signals from two 3-in.×3-in.-NaI(Tl) scintillation detectors were amplified and fed to two analog-to-digital converters (ADC) denoted X and Y. The X ADC digitized the incoming pulse amplitude over a span of 200 channels, while the Y ADC digitized over a span of 100 channels. Each time an event occurred in both the X and Y detectors within the coincidence resolving time 2τ of 74 nsec, the X and Y addresses generated by the two ADC units caused the event to be registered in a unique location within the 20 000 word, ferrite-core memory matrix. In the present investigation, it was useful to consider the Y address as determining the coincidence gating energy, by analogy with more traditional coincidence experiments in which a single-channel analyzer is used to select the gating energy. Thus, for each Y address, there is an associated 200-channel coincidence spectrum in X. The analyzer system was programmed to accumulate single-crystal spectra from the X and Y detectors in memory planes provided for the purpose, on a time-sharing basis with the storage of coincidence spectra in the matrix.

Data from the multiparameter analyzer were read out onto magnetic tape, which was processed on a Control Data Corporation 1604-A computer. A number of very useful manipulations could be carried out on the computer: Plots of a set of consecutive Y planes could be generated to study subtle changes in the shape of the coincidence spectra. If desired, several Y planes might be summed together to yield one coincidence spectrum with improved statistics. All of the spectra were corrected for significant backgrounds. The single-crystal spectra from the X and Y detectors were corrected for environmental backgrounds, and all coincidence spectra were corrected for random coincidences. The random coincidence spectra were computed from singles rates and the measured coincidence resolving time 2τ, and also were directly measured by inserting additional delay in one coincidence channel to put the X and Y fast-coincidence gates out of time. Both random coincidence determinations agreed within counting statistics.

III. RESULTS

A. 4.3-Day ^{101}Rh^m

The half-life of ^{101}Rh^m was determined by observing the decay of a small source on an end-window, flow-type proportional counter. An analysis of the counting data accumulated over a period of 61 days was achieved with a computer least-squares fitting program. The half-life thus obtained was 4.34±0.01 days.

A typical gamma-ray spectrum of ^{101}Rh^m recorded with the Ge(Li) detector is shown in Fig. 1. Two very intense gamma rays are seen at 306.8 and 545.2 keV. In this illustration as in the others to follow, the energies shown are the energies measured in the particular experiments. Preferred energies, which take into account all of the experiments, will be found in Table I. A number of low-intensity peaks are super-

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[7] P. C. Rogers, Ph.D. thesis, Massachusetts Institute of Technology, 1962 (unpublished).

[8] The *p-i-n*, Ge(Li) gamma-ray detector was fabricated by R. J. Fox, Instrumentation and Controls Division, Oak Ridge National Laboratory. Details on the use of these detectors can be found in R. J. Fox, I. R. Williams, and K. S. Toth, Nucl. Instr. Methods **35**, 331 (1965).

[9] The general aspects of this analyzer design and its application to the present problem has been described elsewhere; e.g., see G. D. O'Kelley, D. A. Bromley, and C. D. Goodman, *Proceedings of the Conference on Utilization of Multiparameter Analyzers in Nuclear Physics*, edited by L. J. Lidofsky (Office of Technical Services, Department of Commerce, Washington, D. C., 1962), Report No. CU (PNPL)-227 (1962), pp. 49–59.

imposed upon the combined Compton electron and scattering distributions of the 306.8- and 545.2-keV gamma rays. A clearly resolved component is seen at an indicated energy of 127.0 keV. By use of gamma-ray standards to aid in constructing the response due to the 306.8-keV gamma ray, it was possible to resolve a weak line at 157 keV, which is readily identified as the highly converted $M4$ isomeric transition[2] of ^{101}Rh^m.

Of the three remaining low-intensity peaks below 306.8 keV, the one at 198 keV is a prominent feature of the ^{101}Rh^g spectrum and will be discussed later. Analysis of the other two peaks showed that they were too broad to be single gamma rays. At the bottom of Fig. 1 we show portions of the ^{101}Rh^m spectrum taken at expanded amplifier gain; for each peak we show the gross spectrum with the smooth background drawn in, and beneath each one the net peak has been decomposed by using the line width as determined with standards. These double peaks are shown resolved into components of 180.1 and 184.4 keV, and 233.4 and 238.1 keV. The region between the 306.8- and 545.2-keV peaks is slightly distorted by contributions from ^{100}Rh, which decayed away rapidly, and from ^{102}Rh.

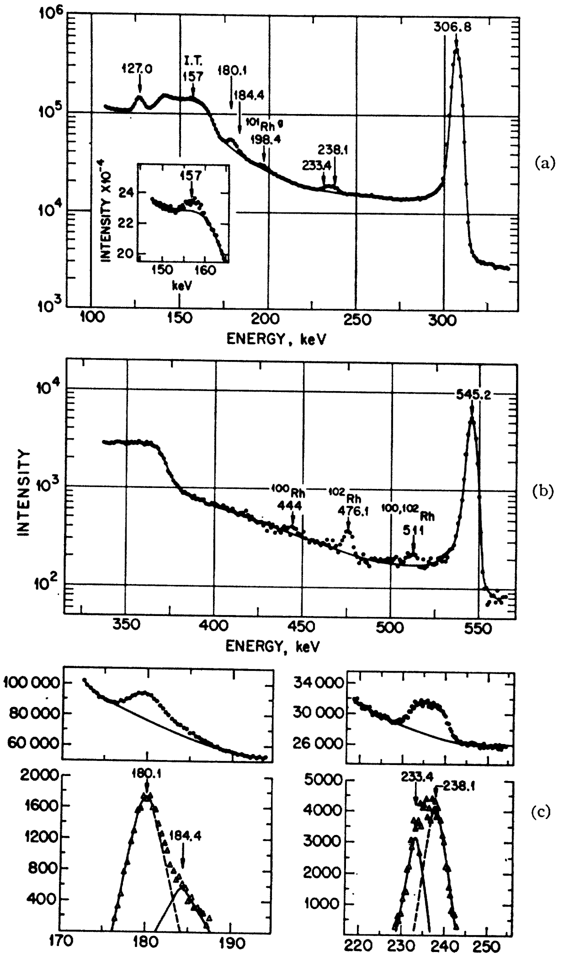

FIG. 1. Gamma-ray spectrum of ^{101}Rh^m recorded with a Ge(Li) detector of 3-mm depletion thickness and 2 cm^2 area. (a): Low-energy part of the spectrum. The inset shows an analysis of the spectrum in the vicinity of the 157-keV isomeric transition, plotted on a linear scale. (b): High-energy region of the spectrum. Impurity peaks were identified by energy and by half-life. (c): Analysis of the low-energy spectrum in the regions of 180 and 235 keV, recorded at expanded amplifier gain and plotted on a linear scale.

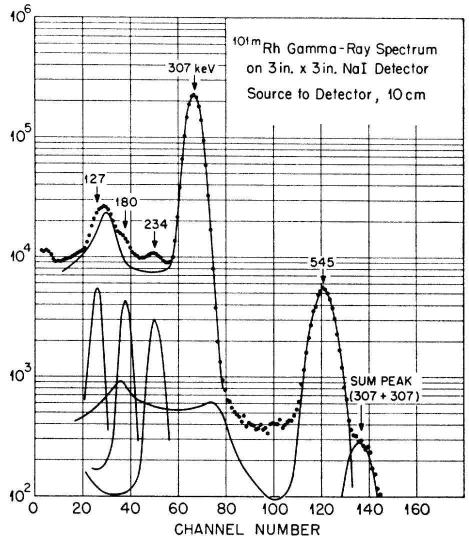

FIG. 2. Single-crystal gamma-ray spectrum of ^{101}Rh^m on a 3-in. ×3-in. NaI(Tl) detector.

The gamma-ray spectrum of ^{101}Rh^m taken with a 3-in.×3-in. NaI(Tl) detector at a source-to-detector distance of 10 cm is shown in Fig. 2. The spectrum shown is one of the 200-channel X detector singles spectra recorded during a coincidence experiment; since the ungated (i.e., the singles) rates were very high, the random sum peak at 307+307 keV is quite pronounced. The X amplifier gain corresponded to about 4.5 keV/channel. The Y singles spectra for the coincidence experiments were very similar in shape to the X singles spectra, except the Y gain was equivalent to about 9 keV/channel, as there were only 100 channels in Y (see IIB., above).

Because the resolution of a NaI(Tl) detector is inherently so poor at the low energies encountered in this investigation, it is impossible to resolve the complex structure in the vicinity of 180 and 234 keV in the singles spectra alone. However, much useful information was obtained from the multiparameter coincidence experiments by choosing the appropriate Y energies for gating. Further, careful analyses of NaI(Tl) singles spectra were used to obtain precise relative intensities of the prominent gamma peaks; intensities of the individual gamma rays which contributed to the peaks at ~180 and ~234 keV were obtained by sharing the singles intensities among the components according to their respective heights in the Ge(Li) spectra.

All of the data on the energies and intensities determined in single-detector Ge(Li) and NaI(Tl) measure-

TABLE I. Summary of 4.4-day $^{101}Rh^m$ gamma-ray data.

E_γ[a] (keV) Scint.	E_γ[a] (keV) Ge(Li)	Relative transition intensity[b]	Concidence quotient with gamma rays of energy (keV) 127	184	234	307	418
127	127.0±0.3	1.2[c]		0.75	0.21		
180	180.1±0.4 184.4±0.5	0.9[d] 0.3[d]	0.56		0.21		
234	233.4±0.5 238.1±0.4	0.4[d] 0.5[d]	0.14	0.18	···	0.002	
307	306.8±0.3	100	···		0.5		
332	331.9±0.4[e]	0.06[f]	0.06				
418[g]	····	0.01[f]	0.01				
545	545.2±0.5	5.6					

[a] These are the best energy values as deduced from all experiments of a given type.
[b] Relative to intensity of 307-keV transition as 100 units. Except where otherwise noted, the intensities were determined from analysis of NaI(Tl) scintillation spectrum.
[c] Corrected for internal conversion to yield transition intensity.
[d] Intensities of individual components within the complex peaks at 180 and 234 keV were obtained from relative intensities determined with the NaI(Tl) spectrometer, sharing the intensities among the components on the basis of their peak heights in the Ge(Li) spectra.
[e] Not directly observed in Ge(Li) singles spectrum. Energy quoted was determined[5,6] in the decay of ^{101}Tc.
[f] Intensities determined only from gamma-gamma coincidence data.
[g] The 418-keV gamma ray is observed only in coincidence with 127 keV.

ments are summarized in the first three columns of Table I.

In Fig. 3(a) we show the coincidence spectrum seen in the X detector when the Y energy was selected to include the 127-keV peak. Although coincidence peaks appear at 180, 234, 307, and 418 keV, the peak at 307 keV was shown to arise entirely from coincidences with Compton electron events from the 234-keV gamma ray. When the Y energy is selected to include most of the complex peak centered at about 181 keV, the coincidence spectrum of Fig. 3(b) is obtained. In agreement with Fig. 3(a), a strong coincidence peak appears at 127 keV. A peak at about 234 keV is also seen, but once again the peak at 307 keV is due to strong coincidences with the Compton electron distribution of the 234-keV gamma ray.

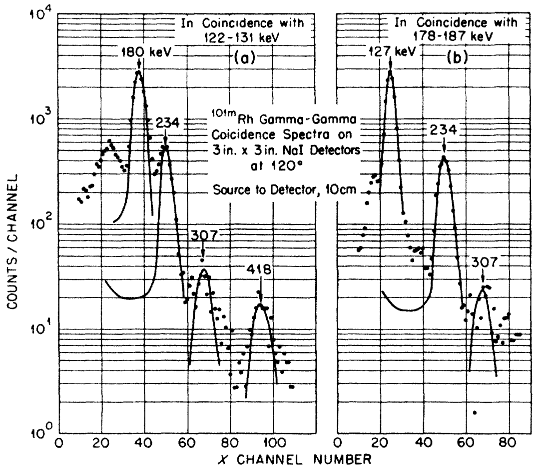

FIG. 3. Gamma-gamma coincidence spectra of $^{101}Rh^m$ taken with the two-parameter analyzer. Coincidence spectra in the X detector when the Y energy interval are (a) 122-131 keV, and (b) 178-187 keV.

"Coincidence quotients" q for the gamma rays in Fig. 3 are given in Table I. The "coincidence quotient" is defined as the ratio of the number of coincident gamma rays of interest to the number of "gating" events [i.e., the number of Y singles events for the Y channel(s) selected]. Complete details on the method of calculation and interpretation of the q values are published elsewhere.[10,11] It should be stressed that, because of the complex nature of the peaks at 180 and 234 keV, the q values in Table I are qualitative where these transitions are involved. When the Y address was moved consecutively across the 180-keV peak, not only did the coincidence intensity q for the 234-keV peak change, but its peak position shifted in a way that suggested strongly the existence of 234–184- and 238–180-keV cascades.

The spectrum in coincidence with 307-keV gamma rays shown in Fig. 4(a) reveals peaks at 235 and 332 keV. From the discussion of the previous figure, the existence of 235–307-keV coincidences is not surprising. The peak at 332 keV occurs too high in channel number to be confused with the known location of the 307-keV peak.

In Fig. 4(b) the existence of a gamma-ray cascade of 332-307 keV is seen more clearly. Here, the energy gate is approximately centered 332 keV, and a well-resolved coincidence peak is observed at 307 keV. There is no other evidence in any of our studies to support the existence of 235–332-keV coincidences. However, in work on the decay of ^{101}Tc, evidence was found[5,6] for transitions in ^{101}Ru at both 331.9 and 311.0 keV. A careful analysis of the Y singles spectrum, including the expected intensity and response function for a 311-keV

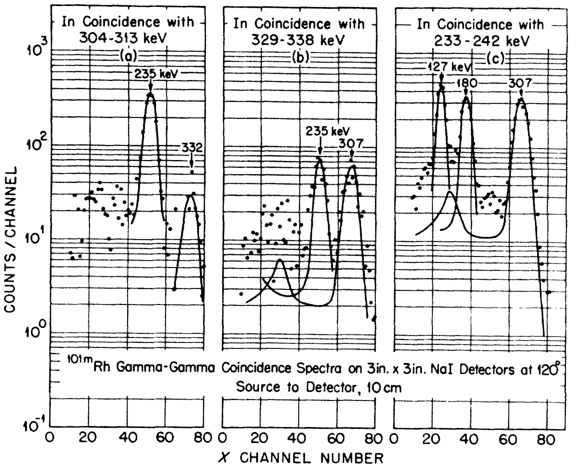

FIG. 4. Gamma-gamma coincidence spectra of $^{101}Rh^m$ taken with the two-parameter analyzer. Coincidence spectra are shown for the X detector when the Y energy was centered on: (a) 306 keV, (b) 332 keV, and (c) 236 keV.

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[10] N. R. Johnson, E. Eichler, G. D. O'Kelley, J. W. Chase, and J. T. Wasson, Phys. Rev. 122, 1546 (1961).

[11] E. Eichler, G. D. O'Kelley, R. L. Robinson, J. A. Marinsky, and N. R. Johnson, Nucl. Phys. 35, 625 (1962).

gamma-ray peak, demonstrated that the 235-keV peak could be accounted for by coincidences with a portion of the 311-keV peak falling within the Y plane at 329-339 keV.

The complex peak at about 234 keV was used to gate the coincidence spectrum shown in Fig. 4(c). The selected Y energy band favors the 238-keV component, and the q values for the coincident peaks change as the Y energy is moved across the 234-keV region. As was the case for q values associated with ~180-keV gate pulses, the q values for this situation are rather qualitative. The changes in spectrum shape are also consistent with cascades at 234-184 and 238-180 keV.

No significant events were found in coincidence with the 545-keV gamma ray, which verifies its assignment as a ground-state transition from the level at 545 keV.

B. 3-Year $^{101}\mathrm{Rh}^{g}$

Measurements were made on the $^{101}\mathrm{Rh}^{g}$ remaining after decay of the short-lived $^{101}\mathrm{Rh}^{m}$. No attempt was made by us to determine the half-life of long-lived $^{101}\mathrm{Rh}^{g}$. Early in our investigation we adopted a new value for the $^{101}\mathrm{Rh}^{g}$ half-life reported by Hisatake, Matsuo, and Kawakami,[12] who measured the decay rate for several prominent $^{101}\mathrm{Rh}^{g}$ internal conversion lines in a beta-ray spectrometer, and found a half-life of 3.0±0.4 yr. This is in agreement with the recent measurement by Evans and Naumann,[3] who used the decay in a beta proportional counter to determine the $^{101}\mathrm{Rh}^{g}$ half-life as 3.3±0.3 yr.

A spectrum of $^{101}\mathrm{Rh}^{g}$ recorded on the Ge(Li) gamma-ray spectrometer showed prominent peaks at 127.0±0.3, 198.4±0.4, and 325.4±0.3 keV. A very weak line at 295.4±0.4 was also resolved from background.

The same scintillation spectrometers and multiparameter analyzer described above were used for a study of gamma-gamma coincidence spectra in the decay of $^{101}\mathrm{Rh}^{g}$. One of the most useful results is given in Fig. 5. Two significant coincidence peaks are seen at 198 and 295 keV. The q value for the 295–127-keV coincidences is our best measure of the relative intensity for the 295-keV transition. The 198–127-keV cascade is well-known from the literature.[1,3,13] When spectra in coincidence with 198-keV were examined, only the 127-keV gamma ray appeared. No other gamma-gamma coincidences were seen which could be attributed to $^{101}\mathrm{Rh}^{g}$.

The relative intensities of the principal lines at 127.0, 198.4 and 325.4 keV were obtained from decomposition of a spectrum taken with a 3-in.×3-in. NaI(Tl) spectrometer and a source-to-detector distance of 10 cm. The intensity of the 295-4-keV gamma ray was determined relative to that of the 325.4-keV peak in the Ge(Li) detector spectrum. The intensity of the 295.4-keV gamma ray was also determined from the 295–127-keV coincidence data. Unfortunately, the 422.4±0.6-keV gamma-ray could not be seen directly with the sources available, because of a substantial contribution from the 418.2-keV gamma ray[14] of ^{102}Rh. In our investigation of ^{101}Tc we observed the coincidences between the 127- and 295-keV gamma rays, the crossover transition which de-excites the level in ^{101}Ru at 422.4±0.6 keV, and determined the relative intensities of the 295- and 422-keV transitions.[5,6] We have used this information to assign the energy and intensity of the 422-keV transition in the decay of $^{101}\mathrm{Rh}^{g}$. The gamma-ray data from the decay of $^{101}\mathrm{Rh}^{g}$ are summarized in Table II.

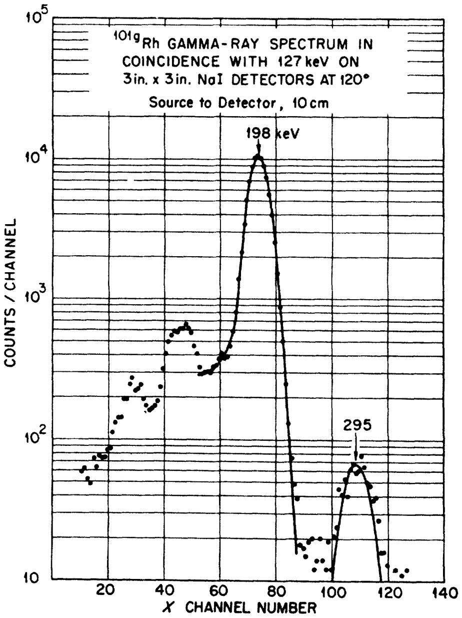

FIG. 5. $^{101}\mathrm{Rh}^{g}$ gamma-ray spectrum in coincidence with the 127-keV gamma ray. The energy interval in the Y detector was 124-131 keV.

TABLE II. Energies and relative intensities of gamma rays determined in the decay of $^{101}\mathrm{Rh}^{g}$.

	Relative intensities	
E_γ[a](keV)	Unconverted gamma rays[b]	Transitions between levels[c]
127.0±0.3	95	105
198.4±0.4	100	100
295.4±0.4	0.9	0.9
325.4±0.3	22	21
(422.4±0.6)[d]	(0.6)[e]	(0.6)[e]

[a] Best energy values from several experiments.
[b] Relative to intensity of unconverted 198.4-keV gamma ray as 100 units. Unless otherwise noted, intensities were determined from an analysis of a NaI(Tl) scintillation spectrum.
[c] Corrected for internal conversion and renormalized to the intensity of the 198.4-keV transition as 100 units.
[d] Not observed directly; see text.
[e] Intensity calculated from intensity of 295.4-keV transition and the known intensity ratio I_{295}/I_{422} in the decay of ^{101}Tc. See text.

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[12] K. Hisatake, S. Matsuo, and H. Kawakami, J. Phys. Soc. Japan **20**, 1107 (1965).

[13] G. Chilosi, K. E. G. Lobner, R. Moro, P. R. Speranza, and G. B. Vingiani (unpublished).

[14] R. L. Robinson, P. H. Stelson, F. K. McGowan, J. L. C. Ford, Jr., and W. T. Milner, Oak Ridge National Laboratory Report No. ORNL-3778, 1964 (unpublished); Nucl. Phys. **74**, 281 (1965).

IV. DECAY SCHEME

A decay scheme consistent with the above experimental obsrvations is given in Fig. 6. The ^{101}Rh-^{101}Ru ground-state mass difference, $Q_{\mathrm{EC}}=0.7$ MeV, was taken from beta-decay systematics of the Way-Wood type.[1] The comparative half-lives for the electron capture transitions in ^{101}Rh^m obtained by use of this energy scale are in rather close agreement with comparative half-lives[5,6] for beta-ray transitions to the same states in ^{101}Ru from the $\frac{9}{2}^+$ ground state of ^{101}Tc. Thus, we conclude that, although the values of log *ft* are not very sensitive to energy, the value used for Q_{EC} in Fig. 6 is sufficiently accurate.

Elementary considerations suggest that the levels of ^{101}Ru studied in this investigation may be assigned positive parity. The shell-model orbitals which are most likely to play a role in the composition of excited states of ^{101}Ru below 1 MeV all have even l values; hence, any neutron configurations composed of these orbitals would have positive parity. The energy required[15] to break a pair of $g_{9/2}$ protons to make one proton available to the $p_{1/2}$ shell is at least 2.2 MeV, which is too high to be of concern in the present level scheme. However, it may be noted that Kisslinger and Sorensen[16] were able to calculate a very low energy (~0.5 MeV) for an $\frac{11}{2}^-$ state in ^{101}Ru. It is difficult to evaluate this result, since the same calculation incorrectly predicts a $\frac{3}{2}^+$ ground state, and the first $\frac{5}{2}^+$ state—presumably the ground state seen here—lies at about 0.5 MeV. In summary, it appears that we may reasonably expect all or nearly all of the states in Fig. 6 to possess even parity.

The principal evidence for the new level at 311.0 keV is the observation of strong coincidences between the 127–184-keV and 184–234-keV gamma rays. Energy relations and intensity balances require a level at 311.0 keV. It will be recalled that high-resolution gamma-ray spectrometry disclosed two pairs of closely-spaced gamma rays at 180 and 184, and at 234 and 238 keV. The gamma-gamma coincidence results also demonstrated that the 306.8-keV state was involved in a gamma-ray cascade of 238–180-127 keV, which is parallel to, but distinctively different from, the cascade concerned with the 311.0-keV level.

Qualitative indications for the existence of a weak 311-keV crossover gamma ray were discussed above, in connection with the gamma-ray spectrum measured in coincidence with 332-keV. The intensity assigned in Fig. 6 to the 311-keV transition is based on the ratio between the intensities of the 311- and 184-keV gamma rays which we determined[5] in the decay of ^{101}Tc.

The existence of a strong gamma-ray transition between the 311.0-keV level and the $\frac{3}{2}^+$ level at 127.0 keV argues against a spin$>\frac{7}{2}$ for the 311.0-keV level. Analysis of our gamma-ray data permits us to set the following upper limits on the intensity of electron-capture decays to the 311-keV level: From the $\frac{9}{2}^+$ level of ^{101}Rh^m, $<0.05\%$ electron capture (log $ft>9$) to the 311-keV level, and from the $\frac{1}{2}^-$ level of ^{101}Rh^g, $<0.7\%$ (log $ft>9.7$). The high minimum value of log *ft* for decay from ^{101}Rh^m implies that the spin of the 311.0-keV state cannot be higher than $\frac{5}{2}^+$. Since the decay of ^{101}Rh^g strongly excites levels of $\frac{1}{2}^+$ and $\frac{3}{2}^+$, the high log *ft* set from the limit on decay from ^{101}Rh^g militates against either $\frac{1}{2}^+$ or $\frac{3}{2}^+$ for the level at 311.0 keV. Thus, we conclude that the 311.0-keV state has spin and parity $\frac{5}{2}^+$.

The state at 325.4 keV is only excited in the decay of $\frac{1}{2}^-$ ^{101}Rh^g, and for this reason is expected to possess a low spin. The value of log $ft=7.5$ is consistent with comparative half-lives for first-forbidden electron capture decays in the same general mass region as ^{101}Rh. The spin of the 325.4-keV level may be either $\frac{1}{2}$ or $\frac{3}{2}$ on the basis of electron-capture probability alone. Gamma-gamma angular correlation and internal conversion electron data[3,13,17,18] have established that the 198-keV gamma transition is predominantly $M1$. If the 325.4-keV gamma transition exhibited a strong $M1$ character also, then its intensity would be much higher than that of the 198-keV transition. The low relative intensity of the 325.4-keV gamma ray strongly supports the assignment of $\frac{1}{2}^+$ for the state at 325.4 keV, although $\frac{3}{2}^+$ cannot be excluded.

Because the 422.4-keV level in ^{101}Ru is excited via the electron capture decay of ^{101}Rh^g, the level must have a spin $\leq\frac{3}{2}$. This suggestion is consistent with our study[5] of the ^{101}Tc decay. No beta decay from the $\frac{9}{2}^+$ ground state of ^{101}Tc to the 422.4-keV state was observed; this evidence suggests that the spin of the 422.4-keV state in ^{101}Ru is less than $\frac{5}{2}$. Further, the decay of ^{101}Tc populates a level of $\frac{7}{2}^+$ at 939.1 keV in ^{101}Ru, which decays to the 422.4-keV state, among others. Since intensity agruments would preclude a $\frac{7}{2}^+-\frac{1}{2}^+$ gamma-ray transition, we prefer spin and parity $\frac{3}{2}^+$ for the state at 422.4 keV. Such an assignment is consistent with the log *ft* for electron capture decay to this level and with the branching ratio of the 295-and 422-keV gamma rays.

To assign the spin of the level at 545.2 keV, it is convenient to bear in mind that this level is populated through decay from the $\frac{9}{2}^+$ states of ^{101}Tc and ^{101}Rh^m. Comparative half-lives for both decays correspond to values expected for allowed beta decay; therefore, for the 545.2-keV state $\frac{7}{2}\leq I\leq\frac{11}{2}$. Gamma-ray transitions are observed between the 545.2-keV level and other excited levels with spins and parities $\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{7}{2}^+$. This gamma-ray information rules out the possibilities $\frac{9}{2}^+$, $\frac{11}{2}^+$, and leaves as the preferred assignment $\frac{7}{2}^+$ for the 545.2-keV state.

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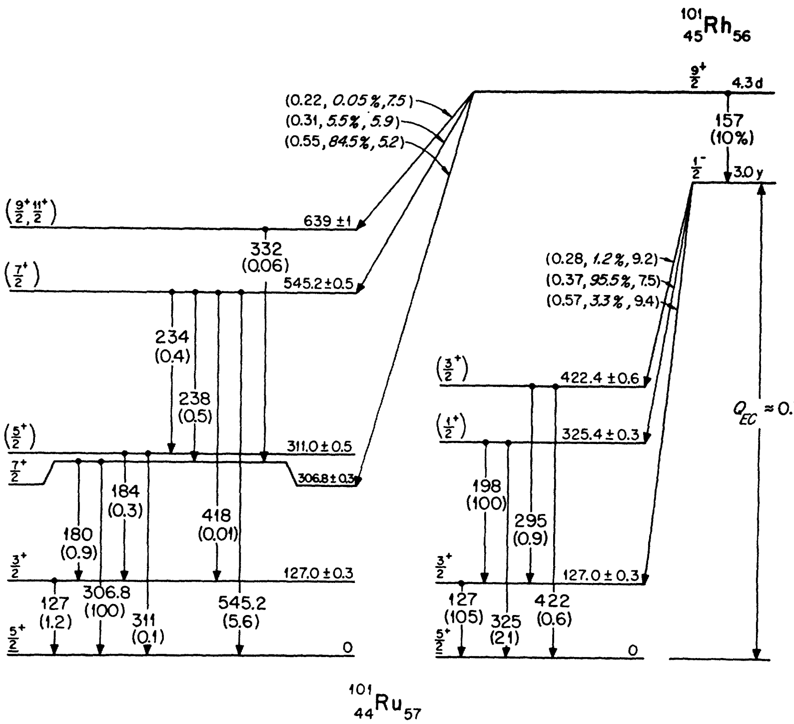
[15] M. G. Mayer, Phys. Rev. **78**, 22 (1950). The energy to break a pair $=(C/A)(2j+1)$; C was taken as 23 MeV, as favored by current nuclear data.

[16] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).

[17] P. Connors and A. Schwarzschild (private communication).

[18] G. T. Wood, S. Koicki, and A. Koicki, Bull. Am. Phys. Soc. (to be published).

FIG. 6. Decay schemes proposed for ^{101}Rh^{m} and ^{101}Rh^{g}. The pair of numbers with each gamma ray gives the gamma-ray energy in keV and in parentheses the relative transition intensity corrected for internal conversion where necessary. The trio of numbers for each electron capture transition gives the transition energy in MeV, the branching in percent, and log *ft* value.



The state of highest excitation energy seen in this work is the state at 639 keV. This state is populated in the decay of both ^{101}Tc and ^{101}Rh^{m}; hence, the spin possibilities lie between $\frac{7}{2}^{+}$ and $\frac{11}{2}^{+}$. Our present data indicate that the 639-keV state does not decay either to the $\frac{5}{2}^{+}$ level at 311.0 keV or to the ground state, but our sensitivity for detecting such transitions is low and they might have been missed. Since gamma decay is observed to proceed to the $\frac{7}{2}^{+}$ level at 306.8 keV, we have assigned either $\frac{9}{2}^{+}$ or $\frac{11}{2}^{+}$ to the 639-keV state.

V. DISCUSSION

As mentioned earlier, the ground-state spin of ^{101}Ru has been measured as $\frac{5}{2}$. It is relevant to any discussion of excited states first to examine the properties of the ground state of ^{101}Ru.

A number of ground-state spins have been measured[19] for odd-mass nuclei near ^{101}Ru. Most nuclei with odd neutrons from 51 to 61 have ground-state spins $\frac{5}{2}^{+}$. In many cases the spin measurements also permit a determination of the magnetic dipole moment,[19] from which an unambiguous assignment of the ground-state parity can be made. For example, both $_{42}{}^{97}$Mo$_{55}$ and $_{44}{}^{99}$Ru$_{55}$ have measured spins of $\frac{5}{2}$ and magnetic dipole moments consistent with even parity. These results for 55 neutrons imply a neutron configuration $(d_{5/2})^5$ beyond the 50-neutron closed shell. In striking similarity to $_{44}{}^{99}$Ru$_{55}$, the measured spin and magnetic dipole moment of $_{44}{}^{101}$Ru$_{57}$ are $\frac{5}{2}$ and -0.69 nm, respectively.[19] The filling order for 51-61 neutrons, as deduced from all available spins, magnetic moments, and electric quadrupole moments, suggests[20] a neutron configuration $(g_{7/2})^2(d_{5/2})^5$ for ^{101}Ru. However, the data are not sufficient to distinguish between this expected configuration and the configurations $(g_{7/2})^4$ $(d_{5/2})^3$ and $(g_{7/2})^6(d_{5/2})^1$.

It would be interesting to attempt an interpretation of the excited states of ^{101}Ru in terms of current nuclear models. Unfortunately, there is no nuclear model which can account for all of the energy levels in odd-A nuclei near $A=100$. Since the neutron and proton numbers of ^{101}Ru lie so far from their respective closed shells, a complete shell-model calculation of the excited states would be very difficult. To obtain insight into the nature of some of the excited levels, we must apply simpler, though necessarily less detailed, treatments.

One interpretation of some of the levels in ^{101}Ru can be obtained through coupling the $\frac{5}{2}^{+}$ ground state to the 2^{+} core of the adjacent even-even nucleus.[21] The transition which de-excites the $\frac{3}{2}^{+}$ level at 127.0 keV is predominantly[3,13,17,18] $M1$. The value of $B(E2)$ for decay via the 127.0-keV transition is ~0.05, which is much less than the $B(E2)$ values for decay of the first 2^{+} states in the neighboring even-even nuclei (0.57 in ^{100} Ru and 0.73 in ^{102} Ru). This evidence supports the view that the 127.0-keV level should be excluded[21] from the core-excitation multiplet. It seems likely that the

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[19] G. H. Fuller and V. W. Cohen, in *Nuclear Data Sheets*, compiled by K. Way *et al.* (National Academy of Sciences—National Research Council, Washington, D. C.), Appendix 1.

[20] M. G. Mayer and J. H. D. Jensen, in *Alpha-, Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Vol. I, Chap. IXA, Table 2.

[21] A. de-Shalit, Phys. Rev. **122**, 1530 (1961).

TABLE III. Assignments of levels in ^{101}Ru based on the Nilsson model.

K	$I^{\pi}[Nn_z\Lambda]$	E(keV)	$\hbar^2/2\mathscr{I}$ (keV)
$\frac{5}{2}$	$\frac{5}{2}^+[402]$	0	
$\frac{5}{2}$	$\frac{7}{2}^+[402]$	306.8	43.8
$\frac{5}{2}$	$\frac{9}{2}^+[402]$	639 or 719[a]	
$\frac{3}{2}$	$\frac{3}{2}^+[411]$	127.0	36.8
$\frac{3}{2}$	$\frac{5}{2}^+[411]$	311.0	
$\frac{1}{2}$	$\frac{1}{2}^+[420]$	325.4	...
$\frac{1}{2}$	$\frac{3}{2}^+[420]$	422.4	
$\frac{7}{2}$	$\frac{7}{2}^+[404]$	545.2	45.4
$\frac{7}{2}$	$\frac{9}{2}^+[404]$	953.4[a]	

[a] Observed only in the decay of ^{101}Tc (see Refs. 5,6).

127.0-keV state has pronounced shell-model character. The selectivity of the beta-decay process and the intense beta decay from the $\frac{9}{2}^+$ level of ^{101}Rh^m to the 306.8-keV level in ^{101}Ru suggest that this beta transition occurs between two states of related, shell-model character. On the assumption that the remaining excited states of energy in keV and (spin and parity) 325.4($\frac{1}{2}^+$), 422.4($\frac{3}{2}^+$), 311.0($\frac{5}{2}^+$), 545.2($\frac{7}{2}^+$) and 639($\frac{9}{2}^+$) comprise the expected band of 5 levels due to core excitation, we computed the center of gravity of these levels by weighting each energy according to $(2I+1)$. The center of gravity so obtained is 498 keV, in good agreement with the average energy of the first 2^+ states in ^{100}Ru and ^{102}Ru, which are 538 and 475 keV, respectively.

Since the value of log *ft* for the electron-capture transition to the 306.8-keV level is 5.2, and that for the transition to the 545.2-keV level is 5.9, it may not be valid to exclude the 306.8-keV level from the core-excitation multiplet. As a test of our choice of levels, we computed the center of gravity as before, except the energy of the $\frac{7}{2}^+$ state was taken as 306.8 keV. The center of gravity so obtained was 333 keV, which is not considered in agreement with the expected value of $\sim$500 keV. Thus, we feel that both the levels at 127.0 and 306.8 keV can be excluded from the core multiplet. The good experimental agreement between the center of gravity calculated when the energy of the $\frac{7}{2}^+$ state was taken as 545.2 keV and the expected energy suggests that the core-excitation interpretation may have some validity in ^{101}Ru.

The core excitation concept is included within the model of Kisslinger and Sorensen,[16] whose treatment makes use of pairing plus a long-range force. However, this model yields an energy-level diagram for ^{101}Ru which is in rather poor agreement with the experimental data. As noted above in Sec. IV, the model of Kisslinger and Sorensen even fails to predict a spin of $\frac{5}{2}$ for the ground state. In view of this disagreement, it appears that the ^{101}Ru nucleus is too far removed from the closed shells for this model to be applied.

All concepts so far discussed represent attempts to interpret in a relatively simple way the complex interactions between nucleons beyond closed shells. Another method of expressing the consequences of this complexity was developed by Nilsson,[22–24] who investigated the effect of an axially symmetric deformation on shell-model states. The pattern of energy levels according to this picture would take the form of a set of intrinsic states, with a rotational band superimposed on each.

The ground state of ^{101}Ru may be assigned[22] to the Nilsson state $\frac{5}{2}^+[402]$. On the basis of reduced electromagnetic transition probabilities and the asymptotic selection rules[24] appropriate to beta and gamma transitions, the excited states of ^{101}Ru were assigned to four rotational bands as shown in Table III. The values of the inertial parameter $\hbar^2/2\mathscr{I}$ calculated from the energy spacings between the first two members of the $K=\frac{3}{2}$, $K=\frac{5}{2}$, and $K=\frac{7}{2}$ bands are larger than those observed in regions of large prolate deformation. Since the deformation assumed for ^{101}Ru was rather small ($\delta \leq 0.05$), the values of the inertial parameters are expected to approach more nearly those of a rigid rotator. Although the evidence for the applicability of the deformed-shell model of Nilsson to ^{101}Ru is tentative, it is heartening that eight excited states of ^{101}Ru can be accommodated by the model in a reasonable way.

Further interpretation of the levels of ^{101}Ru in terms of the models just discussed requires information on gamma-ray transition probabilities. Because some of the data needed for such an evaluation have been determined in the decay of ^{101}Tc, we shall comment later on these aspects in a communication concerned specifically with the decay properties of ^{101}Tc.

In terms of a fit to the energies of excited levels in ^{101}Ru, both the core-excitation model and the deformed shell model yield satisfactory agreement, but the deformed shell model offers the possibility of a somewhat more complete description. It should be stressed that both models are relatively far from the experimental situation, and so may be considered as extreme points of view. Although both cannot be correct, the partial success of each treatment does suggest that both have some merit and that probably in the case of ^{101}Ru we are witnessing the competition between single-particle and collective effects in the same nucleus.

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[22] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **29**, No. 16 (1955); 2nd ed., 1960. The energy levels as a function of deformation in Fig. 5 were used for making the assignments in the present work, since the $d_{5/2}$ orbital falls below $g_{7/2}$, which gives states at small deformations which more nearly reflect the experimental order observed for odd-neutron orbitals in the region of $A=101$.

[23] B. R. Mottelson and S. G. Nilsson, Phys. Rev. **99**, 1615 (1955).

[24] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter **1**, No. 8 (1959).