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Nuclear orientation of ^{97,103,105}Ru and ^{105}Rh[†]

J. A. Barclay,* S. S. Rosenblum, and W. A. Steyert
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545

K. S. Krane
Department of Physics, Oregon State University, Corvallis, Oregon 97331

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Angular distributions have been measured for γ rays emitted following the decays of ^{97,103,105}Ru and ^{105}Rh oriented in an iron matrix at temperatures down to 4 mK. Magnetic moments of the decaying states were deduced to be $|\mu(^{97}\text{Ru})| = (0.687 \pm 0.027)\mu_N$, $|\mu(^{103}\text{Ru})| = (0.67 \pm 0.11)\mu_N$, $|\mu(^{105}\text{Ru})| < 0.3\mu_N$, and $|\mu(^{105}\text{Rh})| = (4.61 \pm 0.16)\mu_N$. Values for the $E2/M1$ mixing ratios were deduced for numerous γ rays in the daughter nuclei. The spin assignment **of the 442-keV level of ^{105}Pd is deduced to be 7/2.**

NUCLEAR MOMENTS ^{97,103,105}Ru, ^{105}Rh [from Ru (n,γ)]; measured $\gamma(\theta)$ from polarized nuclei; ^{97,103,105}Ru, ^{105}Rh — deduced nuclear magnetic moment μ; ^{97}Tc, ^{103,105}Rh, ^{105}Pd — deduced $E2/M1$ γ-ray multipole mixing ratios δ; ^{105}Pd — deduced spin assignment I.

I. INTRODUCTION

The energy levels of odd-mass nuclei in the mass range $50 < A < 150$ have been described by a variety of models, most of which involve the coupling of a single particle (or hole) in a shell-model state to a core which can be excited by surface vibrations (phonons). The various models are distinguished by the manner in which the particle-core interactions are treated, and by the strength of those interactions. In practice, low-energy spectra of odd-mass "spherical" nuclei show more states than can be accounted for in the independent particle shell model. However, the multiplet structure corresponding to independent core and particle excitations is also seldom seen. This indicates the necessity of considering more complex configurations involving weak coupling of the particles to the core.

Since the energy spectra alone are not sufficient to determine the details of the nuclear wave functions, we must look at other nuclear properties. Among these, the electromagnetic multipole moments (both static and dynamic) play the greatest role in distinguishing among the various descriptions. In order to obtain values for the static magnetic moments and $E2/M1$ γ-ray multipole mixing ratios, we have undertaken a study of the angular distribution of γ radiation emitted following the decays of oriented ^{97,103,105}Ru.

II. DECAY SCHEMES

A. ^{97}Ru

A partial decay scheme of ^{97}Ru to levels of ^{97}Tc is shown in Fig. 1. The branching intensities are taken from the work of Phelps and Sarantites,[1] who also determined the multipolarity of the 216-keV γ ray to be $M1 + (10 \pm 4)\%$ $E2$, based on the measured K-conversion coefficient. The anisotropy of the 569-216-keV angular correlation was reported in preliminary form by Bord and Jha,[2] and has been recently remeasured by Krane and Shobaki.[3]

B. ^{103}Ru

The decay of ^{103}Ru to ^{103}Rh is illustrated in Fig. 2. Various investigations of the decay have been summarized in the Nuclear Data Sheets.[4] Angular correlations of the 444- and 557-keV γ rays in coincidence with the 53-keV γ ray have been measured previously, with conflicting results.[4] Unfortunately neither the 444-keV nor the 557-keV radiations were sufficiently intense to be observed in the present work, and thus we are unable to resolve these conflicts. We have observed the 497- and 610-keV transitions, the multipolarities of which have not been determined previously with precision. The β-γ correlation involving the 497-keV transition has been measured previously[5]; the results cannot be analyzed unambiguously to yield the 497-keV mixing ratio owing to the uncertainty in the Fermi-to-Gamow-Teller mixing ratio of the β decay.

C. ^{105}Ru

The decay of ^{105}Ru to levels of ^{105}Rh is illustrated in Fig. 3. There are uncertainties in the ^{105}Rh level scheme, especially with regard to the γ-ray multipolarities, owing to the lack of agreement

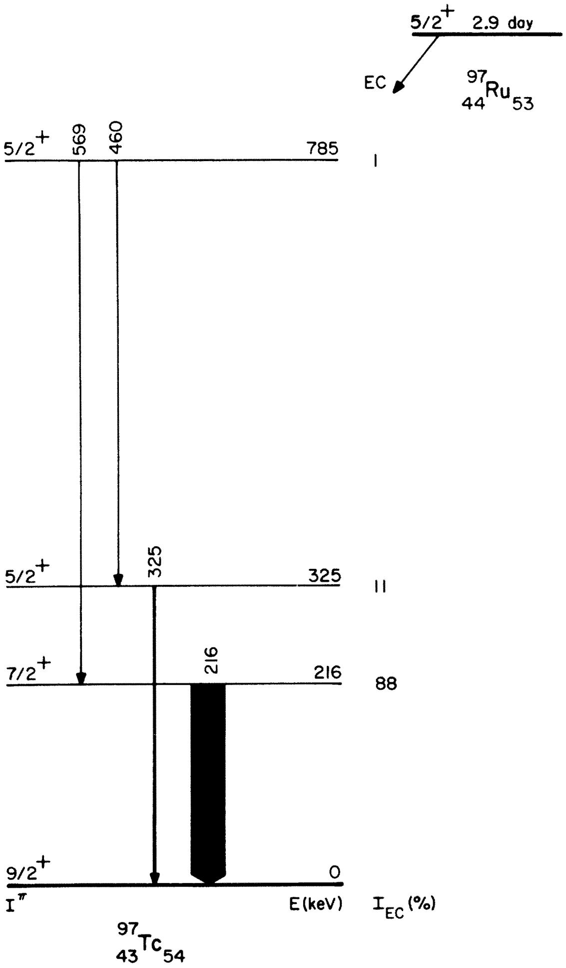

FIG. 1. Partial decay scheme of ^{97}Ru to ^{97}Tc.

among the angular correlation data.[3,6] Unfortunately, the present investigation was not able to observe with sufficient precision any of the γ rays in question. The ground state of ^{105}Rh undergoes β decay to levels of ^{105}Pd with a half-life of 35 hours (Fig. 4). The γ-ray multipolarities of ^{105}Pd have been studied in the ^{105}Ag decay by internal conversion[7] and by angular correlations.[8]

III. EXPERIMENTAL DETAILS

The Ru nuclei were oriented at low temperatures in an iron matrix. A dilute alloy of Ru*Fe* was prepared by melting 99.99% pure Fe with Ru metal to form an alloy of 0.2 at.%. The resulting alloy was rolled to a thickness of 0.10 mm from which a disk of diameter 6 mm was cut. This disk was annealed at 800 °C in H_2 for 45 min and in vacuum for 15 min. The sample was then activated with thermal neutrons at the Los Alamos Omega West reactor and soldered with pure indium to the cold finger of the low temperature apparatus. For determination of the sample temperature, foils of ^{60}Co*Fe* and ^{125}Sb*Ni* were soldered to the cold finger along with the sample.

The low temperatures necessary to polarize the sample nuclei were achieved using a ^{3}He-^{4}He dilution refrigerator coupled to a cerium magnesium nitrate demagnetization stage. Further details of the low temperature apparatus have been given previously.[9] Polarizing fields of up to 0.3 T were applied to polarize the Fe; two mutually perpendicular pairs of Helmholtz coils were used to establish two orthogonal axes of polarization. Previous experiments have suggested that 0.3-T fields are sufficient to saturate Sb*Ni* foils, as well as impurities in Fe.

The γ rays were observed using two Ge(Li) detectors, each aligned with the field direction of one of the Helmholtz pairs. The γ-ray counting rates were determined by integrating the accumulated γ-ray spectra for each peak above an assumed linear background. The intensities so determined were normalized by the isotropic "warm" counting rates and then analyzed according to the relationship

$$W(\theta)=1+\sum_{k=2,4} Q_k B_k U_k A_k P_k(\cos\theta)\,, \qquad (1)$$

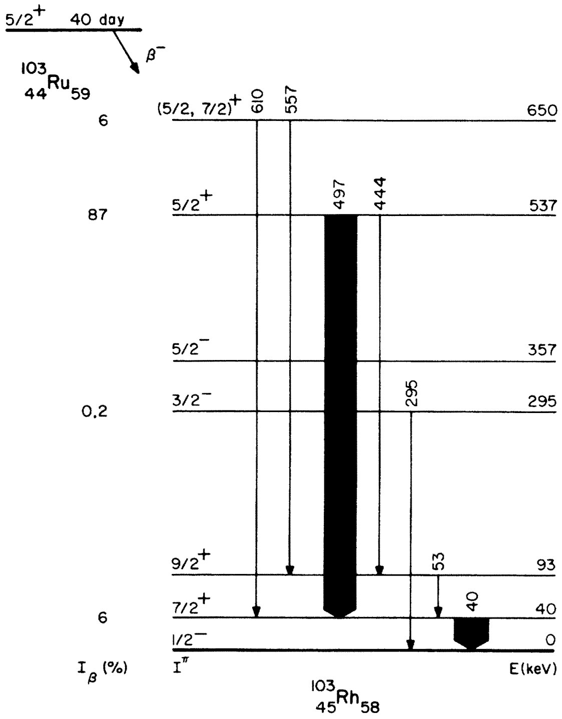

FIG. 2. Partial decay scheme of ^{103}Ru to ^{103}Rh.

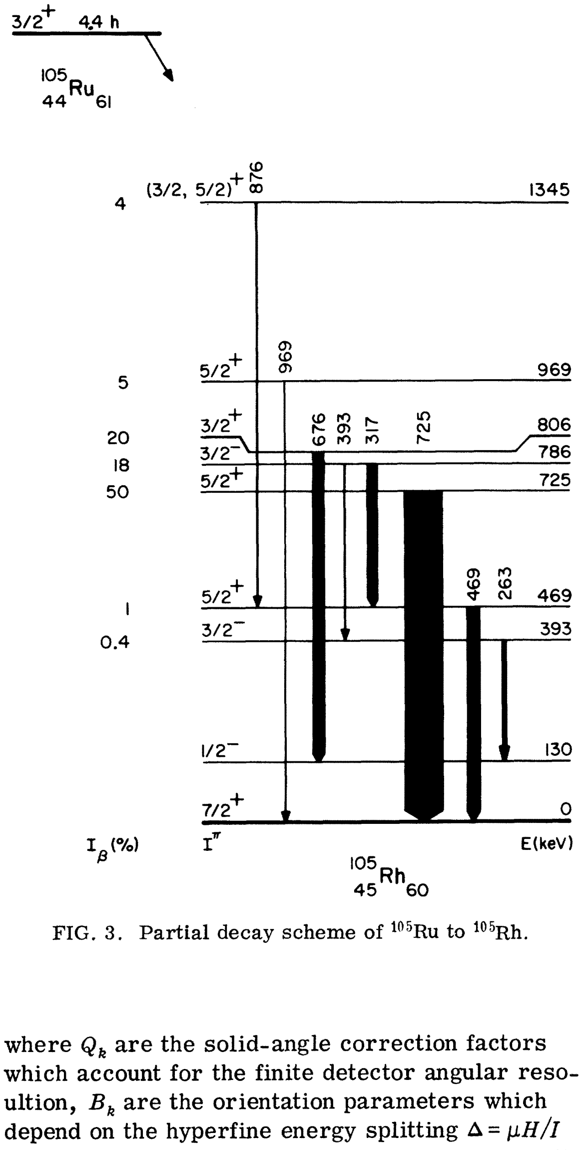

FIG. 3. Partial decay scheme of ^{105}Ru to ^{105}Rh.

where Q_k are the solid-angle correction factors which account for the finite detector angular resolution, B_k are the orientation parameters which depend on the hyperfine energy splitting $\Delta = \mu H/I$ (μ is the nuclear magnetic dipole moment, H is the effective magnetic field, I is the spin of parent state), U_k are the deorientation coefficients which correct for effects of unobserved intermediate radiations, and the A_k are the angular distribution parameters which depend on the γ-ray multipole mixing ratio (defined using emission matrix elements according to the phase convention of Steffen^{10}).

IV. RESULTS

The anisotropies of the γ rays emitted in the ^{97,103,105}Ru and ^{105}Rh decays were determined from a number of measurements taken at a range of temperatures between 4 and 25 mK. A typical set of anisotropies, taken at 5.5 mK, is shown in Table I. The individual results averaged over the temperature range will be discussed below.

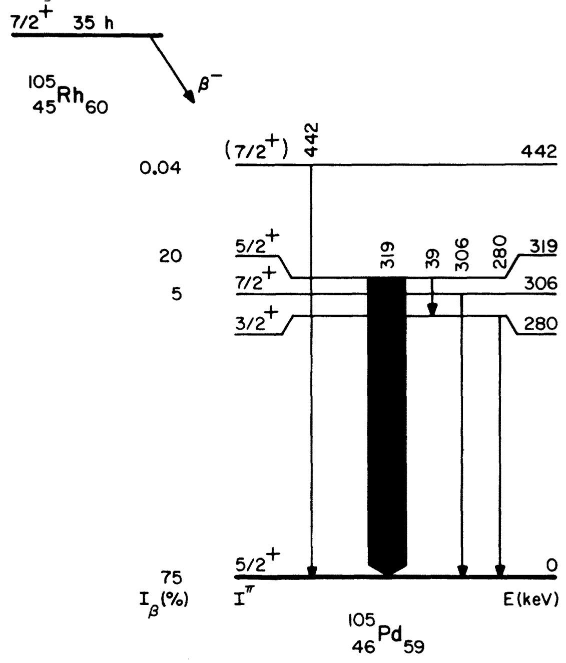

FIG. 4. Partial decay scheme of ^{105}Rh to ^{105}Pd.

A. ^{97}Ru

The pure $E2$ 325-keV transitions can be used to determine the alignment of the ^{97}Ru, assuming the $\frac{5}{2}^+$-$\frac{5}{2}^+$ electron capture decay to be a pure Gamow-Teller type of decay. From averaging data obtained between 5 and 9 mK, we deduce

$$\Delta(^{97}\mathrm{Ru}) = 5.02 \pm 0.17 \text{ mK}.$$

Taking the value of the hyperfine field of Ru in Fe

TABLE I. γ-ray anisotropies following the decays of oriented ^{97,103,105}Ru(T = 5.5 mK).

Parent isotope	E_γ (keV)	$B_2U_2A_2$ (units of 10^{-3})
^{97}Ru	216	306(3)
	325	−81(8)
	569	198(91)
^{103}Ru	497	−20(1)
	610	18(13)
^{105}Ru	676	−3(22)
	725	−4(9)
^{105}Rh	280	147(82)
	306	276(4)
	319	−687(1)
	442 [a]	390(100)

[a] Includes (65 ± 5)% contribution of 444-keV transition from ^{103}Ru.

(Ref. 11) to be −50 ± 1 T we obtain

$$|\mu(^{97}\mathrm{Ru})| = (0.687 \pm 0.027)\mu_N .$$

(A Fermi component of intensity 5% in the decay to the 325-keV level would result in a deduced moment within the quoted uncertainty of the above value.)

The 216- and 679-keV transitions can be analyzed by comparison of their anisotropies with that of the 325-keV transition over the same temperature range (5 to 9 mK), yielding

$$A_2(216) = 0.536 \pm 0.018 ,$$

$$A_2(579) = 0.304 \pm 0.071 .$$

For the 216-keV transition, the measured A_2 yields $E2/M1$ mixing ratios of $+0.27 \pm 0.02$ or $+6.2 \pm 0.5$. The K-conversion coefficient[1] of the 216-keV transition yields $|\delta| = 0.33 \pm 0.08$, in agreement with the former value. For the 569-keV transition, the measured A_2 yields mixing ratios of $+0.12 \pm 0.05$ or $|\delta| > 16$. The angular correlation data[3] are in agreement only with the smaller of these values.

The deduced mixing ratios are summarized in Table II.

B. ^{103}Ru

Neither the 497- nor the 610-keV γ rays showed sizable anisotropies. This could result from a small value for the ^{103}Ru magnetic moment, or else from mixing ratio values which cause small A_2's for both of these $E2+M1$ transitions. From the L-subshell conversion ratios of the 497-keV transition, Pettersson, Antman, and Grunditz[12] deduced a value of $|\delta(497)| = 0.27 \pm 0.17$; for $\delta < 0$, this gives $A_2(497) = -(0.20^{+0.15}_{-0.20})$, which would be consistent with the small, negative values of the anisotropy observed in the present work. The β-γ circular polarization correlation was measured by Behrens and Zernial,[5] with the resulting asymmetry $A = -0.107 \pm 0.011$. The 497-keV mixing ratio cannot be calculated from this result, owing to the uncertainty in the Fermi-to-Gamow-Teller mixing ratio, y, for the β decay. Under the reasonable assumption that the Fermi component is vanishingly small ($|y| < 0.04$),[5] we compute $\delta(497) = -0.12 \pm 0.08$, which would correspond to $A_2 = -0.03 \pm 0.10$. Thus both the conversion coefficient and β-γ correlation are consistent with a small A_2 value.

TABLE II. Deduced $E2/M1$ mixing ratios.

Nucleus	E_γ (keV)	$\delta(E2/M1)$
^{97}Tc	216	$+0.27 \pm 0.02$
	569	$+0.12 \pm 0.05$
^{103}Rh	497	-0.125 ± 0.010
	610	-0.07 ± 0.02 [a] or -4.7 ± 0.6 [a] -0.55 ± 0.05 [b] or $+4.2 \pm 0.07$ [b]
^{105}Rh	725	-0.12 ± 0.05
^{105}Pd	280	$+0.07 \pm 0.07$
	306	$+0.055 \pm 0.002$
	319	$+0.091 \pm 0.013$
	331	-0.077 ± 0.010 [c]
	442	$-(0.8^{+0.7}_{-0.4})$

[a] If $I^\pi = \frac{5}{2}^+$ for the 650-keV level.

[b] If $I^\pi = \frac{7}{2}^+$ for the 650-keV level.

[c] Based on angular correlation data given by Behar and Grabonski (Ref. 8).

An estimate of the ^{103}Ru moment can be obtained from the temperature dependence of the 497-keV anisotropy. From the ratio of the 4- and 8-mK anisotropies we obtain

$$\Delta = 4.9 \pm 0.8 \text{ mK}$$

from which we compute

$$|\mu(^{103}\mathrm{Ru})| = (0.67 \pm 0.11)\mu_N .$$

The $E2/M1$ mixing ratios can be determined from the γ-ray anisotropies to be

$$\delta(497) = -0.125 \pm 0.010$$

and, depending on the spin assignment of the 650-keV level,

$$\delta(610) = -0.07 \pm 0.02 \quad \text{or} \quad -4.7 \pm 0.6 \quad \text{for } I^\pi(650) = \tfrac{5}{2}^+ ,$$

$$\delta(610) = -0.55 \pm 0.05 \quad \text{or} \quad +4.2 \pm 0.07 \quad \text{for } I^\pi(650) = \tfrac{7}{2}^+ .$$

At present there is not sufficient information available to distinguish between these possibilities.

C. ^{105}Ru

In this case, the anisotropies are vanishingly small. However, here we believe the small parent state magnetic moment to be the cause. Based on an analysis of the 676-keV transition, which we take to be pure $E1$, we conclude $B_2 < 0.20$ at 5 mK, and thus

$$|\mu(^{105}\mathrm{Ru})| < 0.3\mu_N .$$

This result is not inconsistent with the results for the magnetic moments of low-lying $\frac{3}{2}^+$ states in ^{99}Ru and ^{101}Ru($\mu \approx -0.3\mu_N$).[13] Assuming the ^{105}Ru moment to be nearly identical to those of the nearby nuclei, our result for the 725-keV transition yields

$$\delta(725) = -0.12 \pm 0.05 .$$

D. ^{105}Rh

The anisotropies of the 306- and 319-keV radiations showed the effect of saturation at the low temperatures attained in the present study. From the saturated anisotropies, the relevant γ-ray information can be deduced. For the 319-keV transition we obtain

$$A_2(319) = -0.514 \pm 0.011\,,$$

corresponding to $\delta = +0.091 \pm 0.013$ or $\delta = +1.35 \pm 0.03$. The lack of an observable P_4 term at saturation suggests a preference for the former value; the $M1$ multipolarity deduced from the observed conversion coefficient supports this choice.

For the 306-keV transition, we obtain

$$A_2(306) = 0.223 \pm 0.004\,,$$

assuming the β decay to the 306-keV level to be primarily Gamow-Teller type (<5% Fermi). This A_2 yields $\delta = +0.055 \pm 0.002$ or -6.3 ± 0.1, and again both the lack of a P_4 term and the measured conversion coefficient support the choice of the smaller value of δ.

An identical analysis in the case of the 280-keV transition yields

$$A_2(280) = 0.180 \pm 0.080\,,$$

from which we obtain

$$\delta = +0.07 \pm 0.07\,.$$

Based on a comparison of the saturated anisotropies with those in the 20–25-mK range, the hyperfine splitting of the ^{105}Rh ground state can be deduced, and we obtain

$$\Delta(^{105}\mathrm{Rh}) = 26.9 \pm 0.9 \text{ mK}\,.$$

Using the measured hyperfine field of Rh in Fe (Ref. 11) of $H = 56.0 \pm 0.1$ T, we deduce for the magnetic moment of ^{105}Rh.

$$|\mu(^{105}\mathrm{Rh})| = (4.61 \pm 0.16)\mu_N\,.$$

The anisotropy of the 442-keV transition can be deduced from the measured anisotropy of the combined (442 + 444)-keV peak to be

$$U_2A_2(442) = 0.95 \pm 0.20\,,$$

assuming that the contribution to the intensity from the 444-keV transition of ^{103}Ru is (65 ± 5)%, based on the measured intensities of the 497- and 319-keV transitions and on the branching ratios.[4,6] This result is not consistent with a $\frac{5}{2}^+$ spin assignment for the 442-keV level of ^{105}Pd, for which the maximum possible value of A_2 is 0.48. For a $\frac{7}{2}^+$ assignment, the A_2 value yields

$$\delta(442) = -(0.8^{+0.7}_{-0.4}).$$

V. DISCUSSION

The magnetic moments of the odd-mass Ru nuclei are summarized in Table III. The present results are in agreement with the systematics of the moments of both $\frac{5}{2}^+$ and $\frac{3}{2}^+$ levels. The $\frac{5}{2}^+$ levels can be associated with the $d_{5/2}$ neutron configuration, for which the Schmidt moment is $-1.9\mu_N$. Deviations from this value can be ascribed to numerous causes, particularly to configurations involving the $g_{7/2}$ state, which lies only 300 keV above the $d_{5/2}$ state. In fact, the substantial deviations from the single-particle moments are not at all surprising, especially in this mass region; what is most surprising is the apparent constancy of the moments as six neutrons are added to the $d_{5/2}$ and $g_{7/2}$ shells. It should be emphasized that the $\frac{3}{2}^+$ state results from a coupling of $d_{5/2}$ and $g_{7/2}$ neutrons, the details of which may change substantially with changes in neutron number. The value of the magnetic moment would be rather sensitive to the nature of the coupling, and thus it is possible that the ^{105}Ru moment may differ substantially from the corresponding values in ^{99}Ru and ^{101}Ru; our deduced value of $\delta(725)$ would be correspondingly affected.

The value we measure for the magnetic moment of ^{105}Rh is in agreement with the more precise value reported by Wese *et al.*,[14] $\mu(^{105}\mathrm{Rh}) = (+4.428 \pm 0.013)\mu_N$, using the technique of nuclear magnetic resonance on oriented nuclei. This agreement can also be considered as a substantiation of the spin assignment for this nucleus.

The 280-keV mixing ratio is in agreement with the value $\delta = +0.132 \pm 0.008$, reported by Behar and Grabowski[8] based on their γ-γ angular correlation measurements. However, our value for $\delta(319)$ differs from their value $-(0.110^{+0.024}_{-0.061})$. Behar and Grabowski derived this result from the 331-319-keV angular correlation by assuming the 331-keV transition to be pure $M1$. If we use the present

TABLE III. Magnetic moments of odd-mass Ru nuclei.

Nucleus	Energy level E (keV)	I^π	Magnetic mount (μ_N)
^{97}Ru	0	$\frac{5}{2}^+$	(−)0.687 ± 0.027 [a]
^{99}Ru	0	$\frac{5}{2}^+$	−0.623 ± 0.019 [b]
^{101}Ru	0	$\frac{5}{2}^+$	−0.698 ± 0.024 [b]
^{103}Ru	0	$\frac{5}{2}^+$	(−)0.67 ± 0.11 [a]
^{99}Ru	90	$\frac{3}{2}^+$	−0.284 ± 0.006 [b]
^{101}Ru	127	$\frac{3}{2}^+$	−0.311 ± 0.026 [b]
^{105}Ru	0	$\frac{3}{2}^+$	$\lvert\mu\rvert < 0.3$ [a]

[a] Present work.

[b] Values taken from Ref. 13.

value of δ(319) together with the measured 331-319 angular correlation, the value of δ(331) given in Table II is derived. This value is consistent with the multipolarity determined by Kawakami and Hisataki from interval conversion data.[7]

The $\frac{7}{2}^+$ spin assignment deduced above for the 442-keV level of ^{105}Pd is consistent with ^{105}Ag decay studies.[7,8] The deduced value of the mixing ratio of the 442-keV transition can be compared with that deduced from direct measurements of the transition probabilities. The 442-keV level has been observed to be strongly Coulomb excited,[15,16] with $B(E2)\uparrow = 0.18 \pm 0.01$ e^2b^2. The half-life of the 442-keV level has been measured to be 3.8 ps.[16] The $B(E2)\uparrow$ value yields a value for the partial $E2$ decay probability which, when compared with the total decay probability, gives a measure of the intensity of the $E2$ component. The remaining intensity must be due to the $M1$ multipole. Such an analysis yields $|\delta(442)| = 0.47 \pm 0.05$, where the error limit includes a contribution resulting from the uncertainty in the spin assignment of the 442-keV level. This result for δ is consistent with our value deduced above.

A direct comparison of the measured γ-ray mixing ratios with theoretical predictions requires a detailed calculation of the nature of the excited states. However, estimates can be made of the magnitudes expected for transitions between levels representing various possible states of the weak coupling between the particle and the phonon-excited core. One representation of the formalism necessary for such an analysis was given by de Shalit.[17] The model can be applied by using parameters for the $M1$ and $E2$ moments characteristic of the appropriate single-particle or collective states (derived from the neighboring even-even nuclei). Such an analysis indicates[3] that, depending on the value of the mixing parameter describing the weak coupling, typical values for the magnitude of δ lie in the range of 0.1–0.2 for transitions corresponding to the deexcitation of the core. It is thus expected that the $E2$ collective core excitation does not give rise to substantial $E2$ components; this expectation is consistent with the values of δ observed in the present work.

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*On leave from Department of Physics, Monash University, Clayton, Victoria, Australia.

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