Angular correlation measurements in the decay of ^{105}Ru

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Gamma-ray angular correlations have been measured for the 316-469, 413-263, 393-263, and 875-469 keV cascades in ^{105}Rh following the decay of ^{105}Ru. Spin-parity assignments in ^{105}Rh are established as $3/2^+$ for the 469-keV level and $5/2^-$ for the 786-keV level, and the present data are consistent with $3/2^+$ assignments for both the 806- and 1345-keV levels. Based on these assignments we find the $E2/M1$ mixing ratios to be $\delta(263) = -0.27 \pm 0.04$, $\delta(393) = -0.30 \pm 0.02$, and $\delta(875) = +1.3^{+0.6}_{-0.4}$.

[RADIOACTIVITY ^{105}Ru [from ^{104}Ru(n,γ)]; measured $\gamma\gamma(\theta)$; deduced ^{105}Rh spin assignments I^π for 469-, 786-, 806-, and 1345-keV levels; deduced ^{105}Rh γ-ray mixing ratios $\delta(263)$, $\delta(393)$, $\delta(875)$.]

I. INTRODUCTION

The level scheme of ^{105}Rh, populated in the decay of ^{105}Ru, has been the subject of a number of studies using various techniques, including γ-ray[1] and conversion electron[2] spectroscopy, (^{3}He, d) and (p,α) reactions,[3] and γ-ray angular correlations.[4-6] It has not yet been possible to propose spin assignments which are consistent with all of these studies. The situation has been summarized recently in the compilation of information on the ^{105}Rh level scheme of the Nuclear Data Sheets.[7] In order to attempt to corroborate the previous information, we have remeasured a number of the angular correlations of γ-ray cascades in the ^{105}Ru decay; the results of these measurements are contained in the present report. In order to remove ambiguities in some of the previous angular correlation studies, which were done with scintillation counters, we have used a two-Ge(Li)-detector apparatus.

During the progress of this work, the results of two additional investigations of the ^{105}Ru γ-γ correlations, also using Ge(Li) detectors, were published.[8,9] Although the results of these two studies were similar to one another, their conclusions regarding the decay scheme differed. These differences are discussed in the present work.

II. ^{105}Ru DECAY SCHEME

A complete discussion of the ^{105}Rh level scheme is given in Ref. 7, and a comprehensive study of the ^{105}Ru decay is given in Ref. 1. In Fig. 1 we show only that portion of the ^{105}Ru decay scheme relevant to the present work. The spins and parities of the ground and first excited states are reasonably established, and the $\frac{3}{2}^-$ assignment of the 392-keV level is consistent with both the decay and reaction data. The assignment of the 469-keV level is less certain. The β decay from the ^{105}Ru $\frac{3}{2}^+$ ground state limits the possible assignments to $\frac{1}{2}^\pm$, $\frac{3}{2}^\pm$, $\frac{5}{2}^\pm$, and the intense 469-keV transition to the ^{105}Rh ground state eliminates the $\frac{1}{2}^\pm$ and $\frac{3}{2}^-$ possibilities. No information on the level is available from the reaction studies. The $\frac{5}{2}^+$ possibility was eliminated by Aras and Walters based on their observation of a weak (0.1% of the 469-keV intensity) transition to the $\frac{1}{2}^-$ level at 130 keV; however, the extremely low intensity of the observed transition (just above the threshold of detectability) and its less than good energy agreement ($E_\gamma = 339.4 \pm 0.2$ keV, while $\Delta E = 339.8 \pm 0.1$ keV) suggest the necessity of angular correlation data to confirm the resulting $\frac{3}{2}^+$ assignment. [The previous angular correlation data of Begzhanov[6] for the 875-469 cascade are in fact not consistent with a $\frac{3}{2}^+$ assignment for this level; as this previous result was obtained with NaI detectors, and since this correlation is significant in confirming or rejecting the 469-keV spin assignment, a remeasurement using Ge(Li) detectors served in part as motivation for the present work.]

The 786-keV level is likewise populated in the ^{105}Ru β decay and thus spin-parity assignments of $\frac{1}{2}^\pm$, $\frac{3}{2}^\pm$, or $\frac{5}{2}^\pm$ are possible. A strong decay to the 130-keV $\frac{1}{2}^-$ level eliminates the $\frac{5}{2}^+$ possibility, and population from the $\frac{5}{2}^+$ 969-keV level eliminates $\frac{1}{2}^-$. The available data do not permit an unique choice among the remaining possibilities. The (p,α) data[3] suggest a $\frac{3}{2}^-$ assignment, while the (^{3}He, d) data[3] indicate l transfers of 2 or 3, suggesting $\frac{3}{2}^+$, $\frac{5}{2}^\pm$, or $\frac{7}{2}^-$. The reported conversion coefficients[2] are erratic and cannot be used to confirm any of these assignments. The previous angular correlation data of Schneider *et al.*[8] favor a $\frac{1}{2}^+$ (or possibly $\frac{5}{2}^-$) assignment,

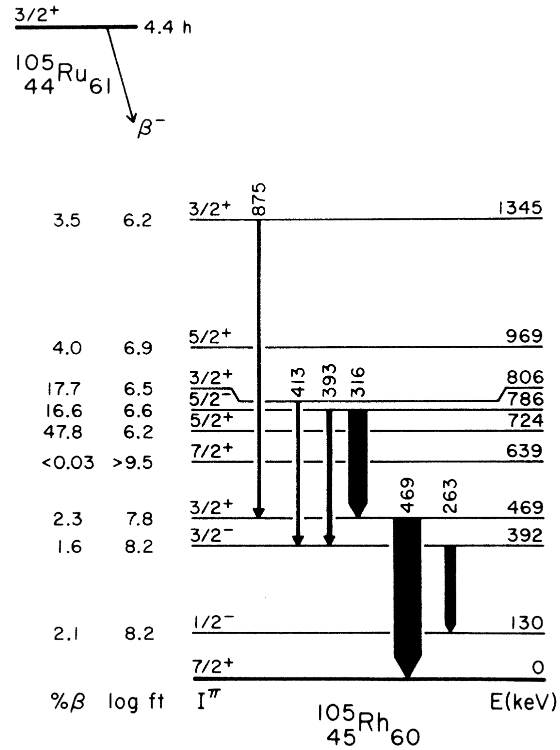

FIG. 1. Partial decay scheme of ^{105}Ru to levels of ^{105}Rh.

while the data of Güven, Kardon, and Seyfarth[9] support a $\frac{3}{2}^-$ or $\frac{5}{2}^-$ assignment.

The 806-keV level is strongly populated in the ^{105}Ru β decay; the transition to the ground state eliminates the $\frac{1}{2}^\pm$ assignments, and the strong branch to the 130-keV $\frac{1}{2}^-$ level eliminates $\frac{5}{2}^+$. The (^{3}He, d) data[3] favor $l=2$ transfer to this level, suggesting spin $\frac{3}{2}^+$ or $\frac{5}{2}^+$. The resulting $\frac{3}{2}^+$ choice is consistent with previous angular correlation data.[8,9]

The 1345-keV level is populated by the ^{105}Ru β decay with a logft of 6.2, suggesting an allowed decay with consequent assignment of $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$. The decay to the 130-keV $\frac{1}{2}^-$ level eliminates $\frac{5}{2}^+$, and Aras and Walters argue for the elimination of the $\frac{1}{2}^+$ possibility based on the observation of an extremely weak transition which is assigned as depopulating the 1345-keV level to a $\frac{7}{2}^+$ level at 639 keV; however, the relatively large uncertainties in the intensity and energy of this transition suggest that independent evidence in support of the spin assignment would be desirable.

III. EXPERIMENTAL DETAILS

The γ-γ angular correlations were performed with both Ge(Li)-Ge(Li) and Ge(Li)-NaI(Tl) detector combinations using a system capable of simultaneously analyzing four independent cascades.[10] The higher-efficiency 7.6-cm × 7.6-cm NaI detector was used in place of one of the 30-cm^3 Ge(Li) detectors to obtain better statistics on the weak 876-469 keV cascade, since there is little chance of disturbance from unresolved competing cascades in that case. Each cascade was measured in two configurations simultaneously; γ_1 was accepted in detector A with γ_2 in detector B, and also γ_2 in detector A with γ_1 in detector B. In addition, windows set on either side of the peaks studied showed that corrections for Compton-background events were negligible.

Samples were prepared by irradiating ^{104}Ru in a thermal flux of 3×10^{12} neutrons/cm^2 sec at the reactor of the Oregon State University Radiation Center. Two samples, one of approximately 2 mg and the other of approximately 8 mg, were irradiated simultaneously, so that the respective activities were approximately 50 and 200 μCi. The weaker sample was used for approximately two half-lives, and then the stronger one was used. The samples were packaged in heat-sealed 2-mm diam polyethelene tubes so that they could be easily reirradiated; the data for the present work were derived from 10 irradiations of the 2 samples.

Coincidence data were accumulated at up to nine angles between 90° and 270°, and the normalized (by the single rates) coincidence counting rates were fitted to the function

$$W(\theta)=1+A'_{22}P_2(\cos\theta)+A'_{44}P_4(\cos\theta)\ . \tag{1}$$

The experimental coefficients were corrected for the finite solid angles subtended by the detectors,[11,12] and then analyzed for the spin assignments and γ-ray multipole mixing ratios using the phase convention of Steffen,[10] in which

$$A_{kk}=A'_{kk}/Q_{kk} \tag{2}$$

$$=B_k(\gamma_1)A_k(\gamma_2)\ , \tag{3}$$

where B_k are orientation coefficients describing the first radiation, and A_k are angular distribution coefficients describing the second radiation; Q_{kk} are the solid-angle correction factors.

The 469-keV level is reasonably short lived ($t_{1/2}<0.4$ nsec[7]); the lifetime of the 393-keV level has not been measured, but comparisons[13] with neighboring nuclei ^{103}Rh and ^{107}Ag show similar $\frac{3}{2}^-$ levels with half-lives of a few psec. We may then assume that, owing to the short lifetimes, corrections for external perturbations are negligible.

IV. RESULTS AND ANALYSIS

The results of the present measurement for the four cascades studied are listed and compared

TABLE I. Angular correlation coefficients in the decay of ^{105}Ru.

Cascade (keV)	A_{22} [a]	A_{44} [a]	A_{22} ($A_{44} \equiv 0$) [a]	Ref.
316-469	0.035(5)	-0.017(4)		4
			-0.012(10)	5
	0.081(8)	0.003(10)		6
			-0.030(20)	8
	-0.020(10)	-0.030(30)	-0.030(10)	9
	-0.026(5)	-0.002(6)	-0.027(5)	Present, Ge(Li)-NaI
	-0.018(4)	0.001(5)	-0.019(4)	Present, Ge(Li)-Ge(Li)
393-263			0.420(30)	8
			0.420(20)	9
	0.386(14)	0.003(17)	0.386(14)	Present, Ge(Li)-Ge(Li)
413-263			-0.310(30)	8
			-0.370(20)	9
	-0.348(16)	0.012(19)	-0.343(15)	Present, Ge(Li)-Ge(Li)
875-469	-0.171(12)	0.014(11)		6
	-0.090(10)	0.022(17)	-0.084(9)	Present, Ge(Li)-NaI
	-0.080(14)	0.009(22)	-0.079(13)	Present, Ge(Li)-Ge(Li)

[a] Uncertainties in last digit(s) are indicated in parentheses.

with previous work in Table I. Agreement with previous work using Ge(Li) detectors is good. The present results, however, disagree with the previous work of Begzhanov.[6] In particular, the earlier work of Begzhanov for the 875-469 keV cascade was not consistent with a $\frac{3}{2}^+$ assignment for the 469-keV level, and thus led to a $\frac{5}{2}^+$ assignment. As we will show below, the present results lead to the opposite conclusion.

In the analysis, we will make two assumptions based on the conversion coefficients measured by Schreiber and Johns.[2] Both the K- and L- conversion coefficients suggest that the 469-keV transition is of $M1$ and/or $E2$ multipolarity, and hence the 469-keV level is assigned as $\frac{3}{2}^+$ or $\frac{5}{2}^+$. The K-conversion coefficient of the 316-keV transition does not yield a consistent solution for the multipolarity, although the L-conversion coefficient suggests $E1$ multipolarity. This indicates negative parity for the 786-keV level, and we will assume the possible assignments to be $\frac{3}{2}^-$ or $\frac{5}{2}^-$ with an $E1$ multipolarity for the 316-keV transition.

If the 469-keV level were assigned $\frac{3}{2}^+$, the expected angular correlation coefficient would be $A_{22}=+0.057$ if the 786 level were $\frac{3}{2}^-$ and the cascade were $\frac{3}{2}^-(E1)\frac{3}{2}^+(E2)\frac{7}{2}^+$, or else $A_{22}=-0.014$ for $I^\pi(786)=\frac{5}{2}^-$ if the cascade were $\frac{5}{2}^-(E1)\frac{3}{2}^+(E2)\frac{7}{2}^+$. Only the latter value is consistent with the measured A_{22}. If the 469-keV level were assigned as $\frac{5}{2}^+$, the 469-keV transition would be of mixed $M1$ and $E2$ multipolarity. Since the 469-keV transition is common to the 875-469 and 316-469 keV cascades, we can write

$$\frac{A_{22}(875\text{-}469)}{A_{22}(316\text{-}469)}=\frac{B_2(875)A_2(469)}{B_2(316)A_2(469)},$$

so that

$$B_2(875)=B_2(316)\frac{A_{22}(875\text{-}469)}{A_{22}(316\text{-}469)}$$

$$=+3.78\pm0.60\,B_2(316)\ .$$

If $I^\pi(786)=\frac{5}{2}^-$, $B_2(316)=-0.428$ and hence, $B_2(875)=-1.62\pm0.25$; if $I^\pi(786)=\frac{3}{2}^-$, $B_2(316)=+0.374$ and $B_2(875)=+1.41\pm0.22$. In both cases the resultant $B_2(875)$ exceeds the extreme values permitted by the spin assignments [-0.89 for $I^\pi(786)=\frac{5}{2}^-$ and $+0.48$ for $I^\pi(786)=\frac{3}{2}^-$]. Thus the present data do not support $I^\pi(469)=\frac{5}{2}^+$, and we conclude that $I^\pi(469)=\frac{3}{2}^+$, in agreement with the conclusion of Aras and Walters[1] based on the branching intensities. The corresponding deduced value of $I^\pi(786)$ is $\frac{5}{2}^-$.

The 806-keV spin assignment may be taken to be $\frac{3}{2}^+$, which is consistent with both decay and reaction data. The 413-263 keV cascade is thus $\frac{3}{2}^+(E1)\frac{3}{2}^-(M1+E2)\frac{1}{2}^-$, and the correlation coefficient $A_{22}=-0.343\pm0.015$ yields an $E2/M1$ mixing ratio of

$$\delta(263)=-0.27\pm0.04 \text{ or } -1.0\pm0.1\ .$$

The K-conversion coefficient of the 263-keV transition[2,7] does not permit a choice between these two values; however, comparison with the mixing ratios of the analogous $\frac{3}{2}^-$ - $\frac{1}{2}^-$ transitions in neighboring nuclei,[14] in particular isotopic ^{103}Rh [$\delta(295)=-0.15\pm0.01$][15] and isotonic ^{107}Ag [$\delta(325)$

$= -0.189 \pm 0.014$],[16] suggests that the smaller value be chosen.

Assuming the $\frac{5}{2}^-$ assignment for the 786-keV level, the 393-263 keV correlation may be analyzed, assuming the cascade to be $\frac{5}{2}^-(M1+E2)\frac{3}{2}^-(M1+E2)\frac{1}{2}^-$; using the above value of $\delta(263)$ and the measured $A_{22}(393\text{-}263) = 0.386 \pm 0.014$, we obtain the $E2/M1$ multipole mixing ratio of the 393-keV transition

$$\delta(393) = -0.30 \pm 0.02 \text{ or } -(13^{+6}_{-3}) .$$

Once again the measured K-conversion coefficient of the 393-keV transition does not permit a choice between these values, but comparisons[14] with similar transitions in neighboring ^{103}Rh [$\delta(586) = -0.27 \pm 0.02$][15] and ^{107}Ag [$\delta(625) = -0.28 \pm 0.03$][16] support the choice of the smaller value.

The present results for the 875-469 keV correlation do not permit a unique spin assignment to be deduced for the 1345-keV level. Assuming a cascade $I^+(M1+E2)\frac{3}{2}^+(E2)\frac{7}{2}^+$ our results are consistent with $I=\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$, with the appropriate choice of the 875-keV $E2/M1$ mixing ratio:

$$I=\tfrac{1}{2}: \quad \delta(875) = +0.07 \pm 0.03 \text{ or } +1.5 \pm 0.1 ;$$

$$I=\tfrac{3}{2}: \quad \delta(875) = +1.3^{+0.6}_{-0.4} ;$$

$$I=\tfrac{5}{2}: \quad \delta(875) = -0.48 \pm 0.07 \text{ or } -(4.2^{+1.4}_{-0.9}) .$$

As discussed above, the γ-ray spectroscopic data[1] indicate a $\frac{3}{2}$ assignment, and our data are not inconsistent with this assignment.

V. DISCUSSION AND CONCLUSIONS

We have confirmed the spin-parity assignment of $\frac{3}{2}^+$ for the 469-keV level of ^{105}Rh, and we support a similar assignment for the 1345-keV level; the 786-keV level is best described by a $\frac{5}{2}^-$ assignment. The values deduced in this work for the spin assignments and γ-ray mixing ratios are somewhat dependent on the internal conversion coefficients of the ^{105}Rh γ rays measured in previous work. Since these conversion coefficients have been shown to be an inconsistent set, it would be desirable to have an independent remeasurement, especially of the 263-, 316-, and 393-keV conversion coefficients, to remove any remaining ambiguities.

The levels of the nuclei in this mass region seem to defy any consistent theoretical interpretation. Previous studies of the electromagnetic transitions in ^{103}Rh and ^{107}Ag[15,16] have yielded experimental confirmation of an interpretation of the low-lying excited states in terms of the weak coupling of a single particle to a vibrating core.[17] On the other hand, recent studies of the odd-A Pd isotopes[18] have suggested that even some of the very low-lying levels can be interpreted[19] in terms of rotational levels of a deformed core within the framework of the Nilsson model. It is hoped that additional results regarding the spin assignments and γ-ray multipole mixing ratios, such as those of the present work, can be useful in distinguishing between such apparently exclusive interpretations.

Note Added: In a recent study of the states of ^{105}Rh populated in the ^{103}Rh(t,p) reaction,[20] no evidence was seen for population of the 786-keV level, even though other low-lying $\frac{3}{2}^-$ and $\frac{5}{2}^-$ levels known from decay studies were populated. This suggests the possibility of even parity for this level, with corresponding $E1$ multipolarity for the 393-keV transition and $M1+E2$ multipolarity for the 316-keV transition, and would be consistent with the arguments advanced by Schneider *et al.*[8] in support of a $\frac{1}{2}^+$ assignment. The present results are not inconsistent with this assignment; assuming the 393-keV transition to be a $\frac{1}{2}^+ \to \frac{3}{2}^-$ pure $E1$ transition, the ratio of the A_{22}'s of the 393-263 and 413-263 cascades is -1.11 ± 0.07 based on our results, compared with the expected value of -1.25. No other even-parity assignment with a pure-$E1$ 393-keV transition is consistent with the angular correlation results. A $\frac{1}{2}^+$ assignment would result in mixed $M1+E2$ multipolarity for the 316-keV transition with $\delta = -0.20 \pm 0.01$ or $+3.0 \pm 0.1$. As stated above, remeasurement of the 316- and 393-keV conversion coefficients would resolve the ambiguity of this spin and parity. The (t,p) data also show a level at 1351 keV ($\pm$10–15 keV) assigned as $\frac{3}{2}^-$ or $\frac{5}{2}^-$; however, the small logft value of the β decay populating the 1345-keV level suggests an allowed decay and thus even parity, making it unlikely that these levels are identical. (The large quadrupole-dipole mixing of the 875-keV transition likewise supports the assignment of even parity.) We are grateful to W. B. Walters for bringing this paper to our attention.

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