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Decay of 39-day ^{103}Ru and 17-day ^{103}Pd to the levels of ^{103}Rh[†]

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The levels in ^{103}Rh have been studied by following the γ rays and x rays emitted in the decay of 39.35-day ^{103}Ru and 17.5-day ^{103}Pd. Several new γ rays have been detected with an anti-Compton spectrometer which allow the assignment of a new level and improved spin assignments. Conversion coefficients for most transitions following the decay of ^{103}Ru have been calculated using the γ-ray intensity values of this work and literature values for the relative intensities of conversion electrons. The conversion coefficient for the 53-keV transition was also determined via the x-ray to γ-ray coincidence method corrected for the 557γ-53γ angular correlation. The weighted average of both measurements yields the recommended value of $\alpha_K(53) = 1.95 \pm 0.13$ which corresponds to an $M1 + (2.1 \pm 2.0)\%$ $E2$ transition. $B(M1)$ and $B(E2)$ values of (0.040 ± 0.001) and (213 ± 76) Weisskopf units, respectively, have been obtained for the 53-keV transition.

[RADIOACTIVITY ^{103}Ru [from ^{102}Ru(n,γ)], ^{103}Pd [from ^{102}Pd(n,γ)]; measured E_γ, I_γ, I_x, x-γ; deduced ^{103}Rh levels, log*ft*, J, π, ICC, δ, $B(E2)$, and $B(M1)$ values. Enriched targets, Ge(Li) and Si(Li) detector, anti-Compton spectrometer.]

I. INTRODUCTION

The low-lying states of ^{103}Rh have been studied by many investigators, from ^{103}Pd and ^{103}Ru, decay,[1-23] and via Coulomb excitation and nuclear-reaction spectroscopy.[23] The major features of the ^{103}Ru and ^{103}Pd decay to levels in ^{103}Rh have been established by the work of Zoller, Macias, Perkal, and Walters.[12] The ^{103}Ru level spin assignments of Zoller *et al.*[12] were subsequently verified by Avignone and Frey.[18] Pettersson, Antman, and Grunditz,[14] in high-resolution internal-conversion measurements of ^{103}Ru decay, saw a doublet in the conversion-electron spectrum at 610 keV which indicated that the previously known level in ^{103}Rh at 650 keV was actually two levels with energies of 650.1 and 651.4 keV.

The K-shell conversion coefficient[5,6,11,14,18] and the L-subshell ratio[7,14] reported for the 53-keV $(\frac{9}{2}^+ \to \frac{7}{2}^+)$ transition suggest an $M1$ multipole character with little $E2$ admixture; however, there is considerable uncertainty as to the extent of the deduced $E2$ admixture. Potnis *et al.*,[6] Pettersson, Antman, and Grunditz,[14] and Sud, Arora, and Trehan[11] have reported $\leq 1\%$ $E2$ admixture. Mukerji, McNelis, and Kane[5] reported a value of $\alpha_K(53) = 2.74 \pm 0.18$ which corresponds[24] to $13 \pm 2\%$ $E2$ admixture. Furthermore, Avignone and Frey[18] recently reported a value $\alpha_K(53) = 2.47 \pm 0.14$ which corresponds to $9.6 \pm 2.2\%$ $E2$ admixture; but the same authors reported a multipole mixing ratio $\delta(53) = -0.13 \pm 0.03$ from γ-γ angular correlation measurements which gives an inconsistent $1.7 \pm 0.8\%$ $E2$ admixture. The $E2$ admixture to this transition is of some interest because it reflects[25,26] the phonon coupled amplitude in the $\frac{7}{2}^+$ state which is reached from the $\frac{9}{2}^+$ state at 93 keV.

In this work an anti-Compton spectrometer was employed to study the γ rays following the decay of ^{103}Ru and ^{103}Pd in an attempt to identify a low intensity γ-ray doublet at 610 keV corresponding to the doublet seen in the conversion-electron spectrum. It was hoped that such information would give further evidence for the new level at 652 keV and allow spin and parity assignments for this level.

We have also performed a careful measurement of the K-shell conversion coefficient for the 53-keV transition in ^{103}Rh employing the x-ray peak to γ-peak coincidence method using high resolution Ge(Li) and Si(Li) detectors.

II. EXPERIMENTAL PROCEDURES

A. Source preparation

The ^{103}Ru and ^{103}Pd activities were produced in thermal-neutron irradiations of elemental ruthenium powder enriched to 99% in mass 102 and palladium enriched to 93% in mass 102, respectively. Sources of ^{103}Ru for γ-ray spectra were purified radiochemically following the method of Meadows and Matlack[27] and then were deposited on a thin aluminum backing and covered with Mylar. The sources for the x-ray γ-ray coincidence measurements were prepared by depositing carrier-free ^{103}Ru on 0.05-mm thick Mylar film.

The ^{103}Pd source was purified radiochemically following the technique of Prindle[28] and was then electroplated on platinum foil.

B. γ-ray spectra

γ-ray spectra of ^{103}Ru and ^{103}Pd were studied using 20- and 40-cm^3 Ge(Li) detectors both having energy resolution of ≤ 2.2 keV [full width at half maximum (FWHM)] for 1332-keV γ rays. Low-energy photon spectra were studied using a planar 0.5-cm^3 Ge(Li) crystal with FWHM of 600 eV for 122-keV photons. Anti-Compton γ-ray spectra were obtained on the LLL anti-Compton spectrometer using an 8-cm^3 Ge(Li) diode and an NaI(Tl) annulus which had a photopeak-to-Compton ratio of 200 : 1 for the 1332-keV line of ^{60}Co. This spectrometer and its calibration have been described elsewhere.[29] Spectra were stored in a 4096-channel pulse-height analyzer. γ-ray energies and intensities, determined from spectra recorded simultaneously with several standard sources, were analyzed with the aid of the computer code GAMANAL.[30]

C. x-ray–γ-ray coincidence spectra

The K-shell conversion coefficient for the 53-keV transition in ^{103}Rh was obtained as

$$\alpha_K = N_{Kx}/(N_\gamma \omega_K), \tag{1}$$

where N_{Kx} and N_γ are the number of K x rays and 53-keV γ rays observed in coincidence with the 557-kev γ ray following decay of 40-day ^{103}Ru, and ω_K is the K-shell fluorescence yield for Rh. In these experiments a 500-cm^2 × 4-mm Si(Li) x-ray detector with a 0.13-mm beryllium window was used to record the x rays and the 53-keV γ ray, while a 45-cm^3 coaxial Ge(Li) detector was used to detect the 557-keV γ ray. Standard coincidence electronics with a resolving time of ~100 nsec were employed in these measurements. A narrow window of ~10 keV was selected on the 557-keV γ ray and the coincident spectra were recorded with the Si(Li) detector employing a 1024-channel pulse-height analyzer.

Coincidence spectra, recorded at 180°, 135°, and 90°, were corrected for the effect of random coincidence events. A relative efficiency curve of the Si(Li) detector, constructed using ^{241}Am, ^{109}Cd, ^{133}Ba, and ^{57}Co, was used to determine the relative intensities of the K x rays and 53-keV γ ray.

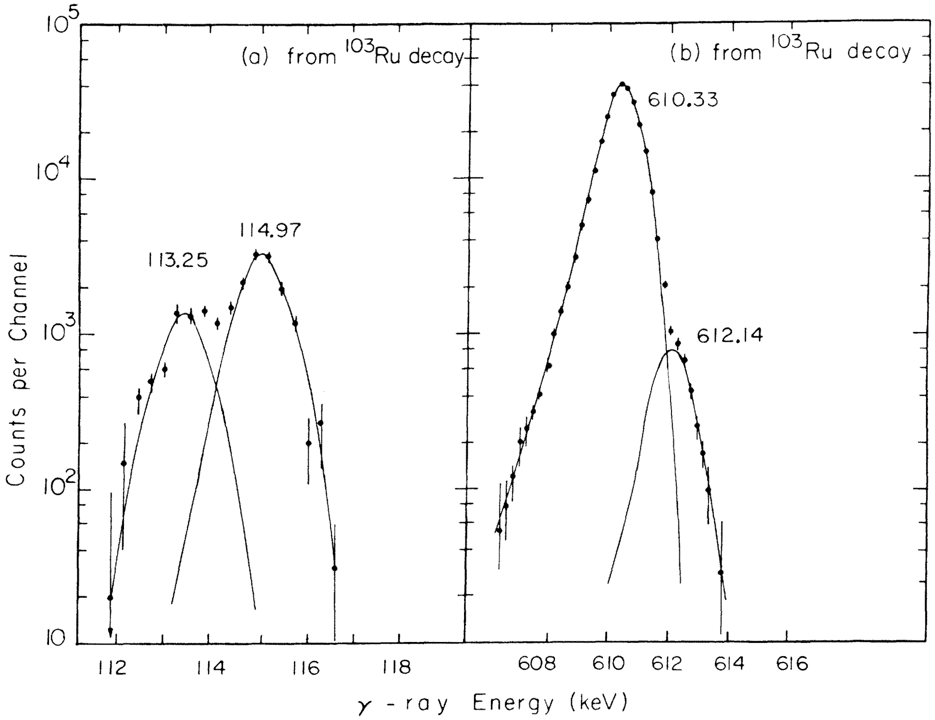

FIG. 1. Details of an anti-Compton γ-ray spectrum following the decay of ^{103}Ru showing doublets at 113-114 and 610-611 keV.

TABLE I. Energies and intensities of γ rays following 40-day ^{103}Ru decay. Upper limits on the intensities of the following unseen transitions were determined from the Compton suppressed spectra:

E_γ	Limit I_γ	Transition
179.24	≤0.003	537 → 357
354.93	≤0.008	650 → 295
536.84	≤0.0009	537 → g.s.

E_γ (ΔE_γ)	I_γ (ΔI_γ) (relative to 497 = 1000) [a]	Transition
39.73 (5)	0.79 (2)	40 → g.s.
42.63 (4)	0.012 (2)	650 → 607
53.29 (1)	4.2 (2)	93 → 40
113.25 (7)	0.040 (8)	650 → 537
114.97 (2)	0.089 (8)	652 → 537
241.88 (5)	0.165 (17)	537 → 295
292.7 (2)	0.03 (3)	650 → 357
294.98 (2)	2.80 (9)	295 → g.s.
317.77 (22)	0.06 (1)	357 → 40
357.39 (14)	0.10 (3)	357 → g.s.
443.80 (2)	3.6 (1)	537 → 93
497.08 (2)	1000 (30)	537 → 40
514.60 (15)	0.054 (15)	607 → 93
557.04 (2)	9.3 (3)	650 → 93
567.87 (13)	0.018 (8)	607 → 40
610.33 (2)	63 (2)	650 → 40
612.02 (3)	0.89 (10)	652 → 40
651.80 (36)	0.0019 (8)	652 → g.s.

[a] To convert to absolute intensities (γ per 10^3 decays) use the following: I_γ(absolute) = I_γ(relative) × (0.864 ± 0.035).

III. EXPERIMENTAL RESULTS

Details from an anti-Compton γ-ray spectrum of ^{103}Ru in Fig. 1 show the separation of doublets at 113-114 keV and 610-611 keV. The peak shapes for these doublets were analyzed by the computer code GAMANAL.[30] The energy and intensity of the γ rays from ^{103}Ru and ^{103}Pd decay as determined in this work are listed in Tables I and II, respectively. Table III lists ^{103}Ru internal conversion coefficients and γ-ray multipolarities using the improved γ-ray intensities of this work and the conversion electron intensities of Pettersson *et al.*[14]

A detailed discussion of the construction of the basic decay schemes of ^{103}Ru and ^{103}Pd has been given by Zoller *et al.*[12] and subsequently verified by others.[14,18] Therefore the following discussion is confined to additions and refinements. The complete decay schemes of ^{103}Ru and ^{103}Pd are shown in Fig. 2. The log*ft* values were calculated using the tables in Ref. 31. No new transitions are reported here in ^{103}Pd decay; however, more accurate intensity values are given.

TABLE II. Energies and intensities of γ rays following 17-day ^{103}Pd decay. Upper limits on the intensities of the following unseen transitions were determined from the anti-Compton spectra:

E_γ	Limit I_γ	Transition
255.26	≤ 0.001	294 → 40
264.42	≤ 0.002	357 → 93

E_γ (ΔE_γ)	I_γ (ΔI_γ) (relative to 40 keV = 1000) [a]	Transition
20.151	Total *K* x ray	*K*α
22.695	= 1.079 × 10^6	*K*β_1
23.143		*K*β_2
39.73 (2)	1000	40 → g.s.
53.29 (1)	0.38 (30)	93 → 40
62.41 (3)	15.2 (5)	357 → 295
241.88 (5)	0.007 (7)	537 → 295
294.98 (15)	41 (1)	295 → g.s.
317.72 (5)	0.22 (1)	357 → 40
357.45 (8)	323 (10)	357 → g.s.
443.79 (5)	0.22 (1)	536 → 93
497.08 (2)	58 (2)	536 → 40

[a] To convert to absolute intensities (γ per 10^6 decays) use the following: I_γ(absolute) = I_γ(relative) × (0.74 ± 0.05). Note that using the method of Grunditz (Ref. 10) the conversion to absolute intensities is: I_γ(absolute) = I_γ(relative) × (0.68 ± 0.07).

Two new γ rays following ^{103}Ru decay observed in the anti-Compton spectrum at 567.87 and 514.60 keV are evidence of a new level in ^{103}Ru at 607.7 keV. Previously unreported γ at 651.80 and 42.63 keV and two γ-ray doublets at 612.02-610.33 keV and 114.97-113.25 keV verify the presence of two levels at 651.8 and 650.1 keV. The existance

TABLE III. ^{103}Rh internal conversion coefficients from ^{103}Ru decay. Calculated using γ-ray intensities from this work and electron intensities from Ref. 1.

Transition (keV)	α_i^{exp}	*i*
39.73	137 ± 19	*K*
	1014 ± 11	*L*
53.29	1.74 ± 0.17	*K*
	0.18 ± 0.02	*L*
114.97	0.27 ± 0.07	*K*
241.88	(1.1 ± 0.3) × 10^{-2}	*K*
294.98	(1.8 ± 0.2) × 10^{-2}	*K*
357.39	(1.9 ± 1.1) × 10^{-2}	*K*
443.80	(6.9 ± 0.7) × 10^{-3}	*K*
497.08	(4.6 ± 0.1) × 10^{-3}	*K*
	(5.5 ± 0.3) × 10^{-4}	*L*
557.04	(3.3 ± 0.5) × 10^{-3}	*K*
	(3.8 ± 0.8) × 10^{-4}	*L*
610.33	(2.5 ± 0.2) × 10^{-3}	*K*
612.02	(5.6 ± 3.4) × 10^{-3}	*K*

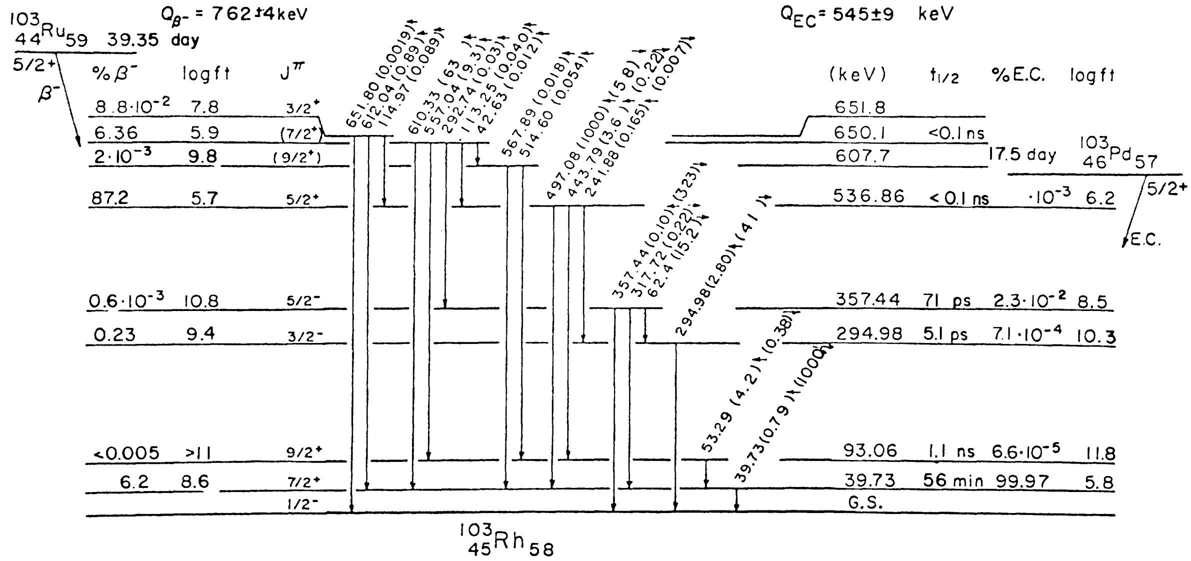

FIG. 2. Decay scheme of 40-day ^{103}Ru and 18-day ^{103}Pd to the levels of ^{103}Rh.

of two levels at ~650 keV was originally proposed by Pettersson *et al.*[14] from conversion electron measurements. Also, we observe a 317.77-keV γ ray which we do not place in the decay scheme.

The K-shell conversion coefficient of the 53-keV transition was calculated from Eq. (1). The K-shell fluorescence yield used is $\alpha_K = 0.807 \pm 0.031$, the recommended empirical value of Bambynek *et al.*[32] The conversion coefficient $\alpha_K(53)$, was calculated to be 2.17 ± 0.05, 2.08 ± 0.04, and 1.91 ± 0.04 at angles of 180°, 135°, and 90°, respectively, yielding a mean or isotropic value of $\alpha_K(53) = 2.02 \pm 0.10$. An additional $\alpha_K(53)$ value obtained from this work from the ratio $I_e(53)/I_\gamma(53)$ is 1.74 ± 0.17 as given in Table III. Taking the weighted average of these two measurements we recommend a value of $\alpha_K(53) = 1.95 \pm 0.13$. This corresponds to a multipolarity of $M1 + (2.1 \pm 2.0)\%$ $E2$ for the 53-keV transition. This recommended value of $\alpha_K(53)$ agrees well with the value of 1.90 ± 0.06 reported by Sud *et al.*[11] but does not agree with the other previously reported values.[5,6,18]

All but one of the earlier experimental determinations of the K-shell conversion coefficient of the 53-keV transition by the γ-ray–x-ray coincidence method[5,6,11] have involved a NaI(Tl) detector for detection of the x rays and 53-keV γ ray. The iodine escape peak of the 53-keV γ ray lies under the Rh x-ray peak; therefore both peak intensities must be corrected for this effect which is dependent upon the particular NaI(Tl) detector employed. It is possible that this may not have been corrected properly in the earlier work. This problem was avoided in this work by using an Si(Li) detector.

The disagreement between this work and the $\alpha_K(53)$ value reported by Avignone *et al.*[18] as well as the earlier papers[5,6,11] is at least partly due to the fact that 557-53-keV γ-γ angular correlation effects were not taken into account by them. In addition, no mention was made in previous papers about correcting for random coincidence events. Previous papers have not explicitly stated the value of ω_K used; however it is likely that a number[33] which is 97% of the currently recommended semiempirical value was used.

$B(M1)$ and $B(E2)$ values of (0.040 ± 0.001) and (213 ± 76) Weisskopf units (W.u.), respectively, have been obtained for the 53-keV transition from the mixing ratio obtained in this work and the lifetime reported in Ref. 23.

Spin and parity assignment for ^{103}Rh levels were made as shown in Fig. 2 using the results of this and previous work. The 607.7-keV level is tentatively assigned a spin and parity of $\frac{9}{2}^+$. The limit of 11 for the logft value and the γ-ray transitions from this level to $\frac{9}{2}^+$ and $\frac{7}{2}^+$ levels indicate that this may have a spin and parity of $\frac{7}{2}^-$, $\frac{9}{2}^-$, or $\frac{9}{2}^+$. However, $\frac{9}{2}^+$ is preferred since Sie *et al.*[34] do not observe any $\frac{7}{2}^-$ or $\frac{9}{2}^-$ level at this energy in their Coulomb excitation experiments but do observe a $\frac{7}{2}^-$ level at 847.7 keV. We have assigned spin and parity of $\frac{3}{2}^+$ to the 651.8-keV level on the basis of an $M1$ transition of 114.7 keV from this level to a $\frac{5}{2}^+$ level and γ-ray transitions from this level to the $\frac{1}{2}^-$ ground state and to a $\frac{7}{2}^+$ level.

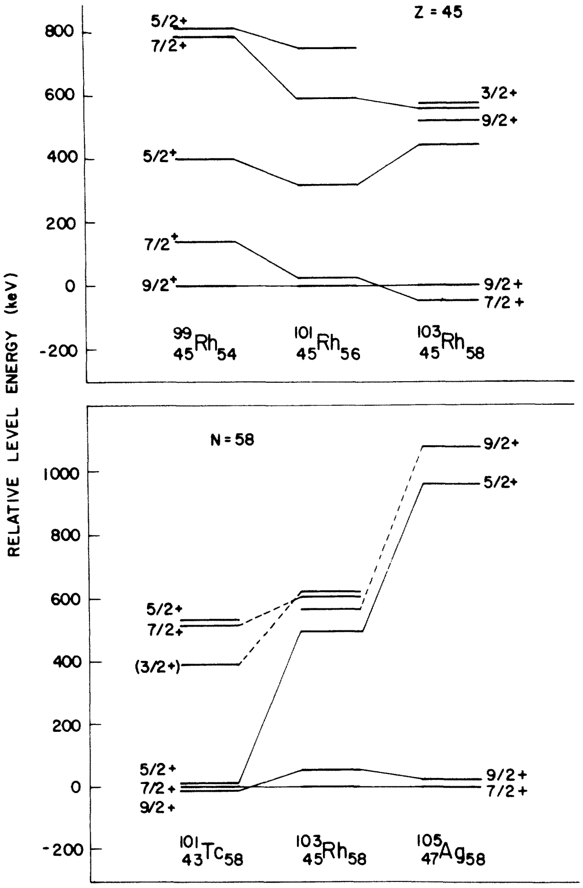

FIG. 3. Comparison of experimental energy levels of even parity levels in odd-mass $Z = 45$ (Rh) nuclei and odd-mass $N = 58$ isotones.

IV. DISCUSSION

A systematic comparison of positive parity levels of ^{103}Rh and neighboring $Z = 45$ and $N = 58$ nuclei is shown in Fig. 3. In the $N = 58$ nuclei the energies of the low-lying $\frac{7}{2}^+$ and $\frac{9}{2}^+$ levels remain nearly constant while the $\frac{5}{2}^+$ level rises sharply from Tc ($Z = 43$) to Rh ($Z = 45$).

Several models have been used in an attempt to describe these nuclei. The pairing plus quadrupole calculations of Kisslinger and Sorenson[25] were not able to duplicate the features of the positive parity levels. A later suggestion by Kisslinger[35] did account for the $J - 1$ level, in this case $\frac{7}{2}^+$, as an intruder state.[36] Recently Kuriyama and coworkers have used a dressed n-quasiparticle formalism in an attempt to calculate the energy of these and other positive parity levels and their properties. They were successful in predicting the position of the $\frac{7}{2}^+$ as well as the $\frac{5}{2}^+$ level. They predict a $B(E2)$ value of $21 \times 10^{-50}\, e^2\,\mathrm{cm}^4$ for the $\frac{9}{2}^+ \rightarrow \frac{7}{2}^+$ (53 keV) transition compared to the experimental value of $(64 \pm 22) \times 10^{-50}\, e^2\,\mathrm{cm}^4$. However their calculations do not predict a low-lying $\frac{3}{2}^+$ level which we observed in ^{103}Rh. Also the $\frac{9}{2}^+$ level is predicted at 1.5 MeV while we identify a level with tentative J^π assignment of $\frac{9}{2}^+$ at 607 keV. They give no prediction of the energy of a second $\frac{7}{2}^+$ level.

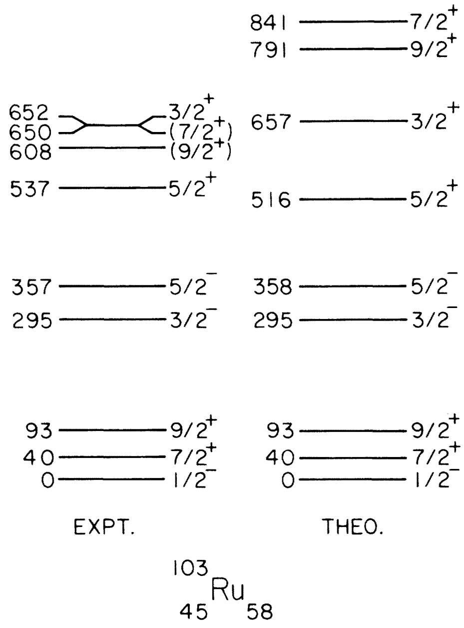

FIG. 4. Comparison of experimental energy levels of ^{103}Rh as determined in this work and the theoretical predictions of Bargholtz (Ref. 37).

Bargholtz has carried out unified model calculations in intermediate coupling of the low-energy spectra of ^{103}Rh.[37] These calculations give remarkable agreement with experimental level energies for both positive and negative parity states as shown in Fig. 4. However, this agreement is in part due to the fact that the parameters of the model are determined by a fit to experimental energies and electromagnetic moments of states in ^{103}Rh.

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