Level structure of ^{99}Rh and ^{101}Rh via the ^{99}Ru and ^{101}Ru(p,nγ) reactions

G. Kajrys, G. Dufour, S. Pilotte, and S. Monaro
Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Québec, Canada H3C 3J7
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The structure of low lying levels in ^{99}Rh and ^{101}Rh has been investigated with the (p,nγ) reaction employing γ-ray spectroscopy techniques. Many new levels in both nuclei are proposed on the basis of γ-γ coincidence data. Spin assignments for several levels have been determined from excitation function and angular distribution data. The results are compared to previous work and to the available theoretical calculations.

I. INTRODUCTION

In a previous paper[1] we reported on the high spin states in ^{99}Rh and ^{101}Rh populated via the (^{6}Li,3n) reaction. While many new high spin states were observed, we could say little on the weakly excited, low lying, low spin states which have been investigated chiefly through decay studies [^{99}Rh (Ref. 2) and ^{101}Rh (Refs. 3 and 4)] and in the case of ^{101}Rh, via the (p,t) reaction.[5] However, very few firm spin and parity assignments have been made for the many levels detected in those works. A useful summary of the known low lying states in the neutron-rich nuclei ^{99}Rh—^{109}Rh can be found in the work of Flynn *et al.*[6] While a $\frac{3}{2}^-$, $\frac{5}{2}^-$ doublet of levels is a characteristic of the level structure of ^{101}Rh, ^{103}Rh, and ^{105}Rh, only the $\frac{5}{2}^-$ state has been identified in ^{99}Rh. In addition, previous work[1] has thrown some doubt on the $\frac{7}{2}^-$ spin-parity assignment[5] to the 850.4 keV level in ^{101}Rh. The presence or absence of these states is of crucial importance to nuclear structure calculations in this mass region. In this paper we wish to present the results of a (p,nγ) reaction study on ^{99}Rh and ^{101}Rh, restricting ourselves to a discussion on those levels below $\sim$1.5 MeV in excitation energy. The nonselective nature of the p,n reaction mechanism is an ideal tool for the investigation of all low spin states with $J \leq \frac{13}{2}$ and our results help resolve several uncertainties while providing information on many new levels.

II. EXPERIMENTAL DETAILS

Isotopically enriched ($\approx$97%) ^{99}Ru and ^{101}Ru powder was sintered onto thick tantalum backings yielding targets whose thicknesses were estimated at $\approx$20 mg cm^2. The targets were placed in a cylindrical glass target chamber lined with tantalum foil and were bombarded with protons from the Université de Montréal Tandem accelerator. Proton energies ranged between 3.2 and 6.5 MeV. Excitation functions and angular distributions were measured using a 90 cm^3 Ge(Li) detector, with 2.0 keV resolution at 1.33 MeV, placed 15 cm from the target. Gamma-ray spectra, up to 1.75 MeV in energy, were recorded between 3.2 and 4.7 MeV (^{101}Rh) and 4.0 and 6.5 MeV (^{99}Ru) bombarding energy, increasing in 500 keV steps.

A typical spectrum from the ^{99}Ru(p,n)^{99}Rh reaction, taken at 6.0 MeV, is shown in Fig. 1. For the angular distributions, spectra were recorded in 15° intervals between 0° and 90° to the beam direction. A NaI detector placed at −90° to the beam direction, together with the integrated beam current, were used to normalize each spectrum. The angular distributions were performed with 4.2 MeV (^{101}Rh) and 5.5 MeV (^{99}Rh) protons.

The γ-γ coincidence data were obtained at 5.5 MeV bombarding energy for both nuclei, using a second Ge(Li) counter with 2.1 keV resolution at 1.33 MeV. Standard fast discrimination timing techniques were employed to obtain a prompt coincidence timing peak with $\approx$15 ns timing resolution (full-width at half maximum). Coincidences were recorded event by event onto magnetic tape

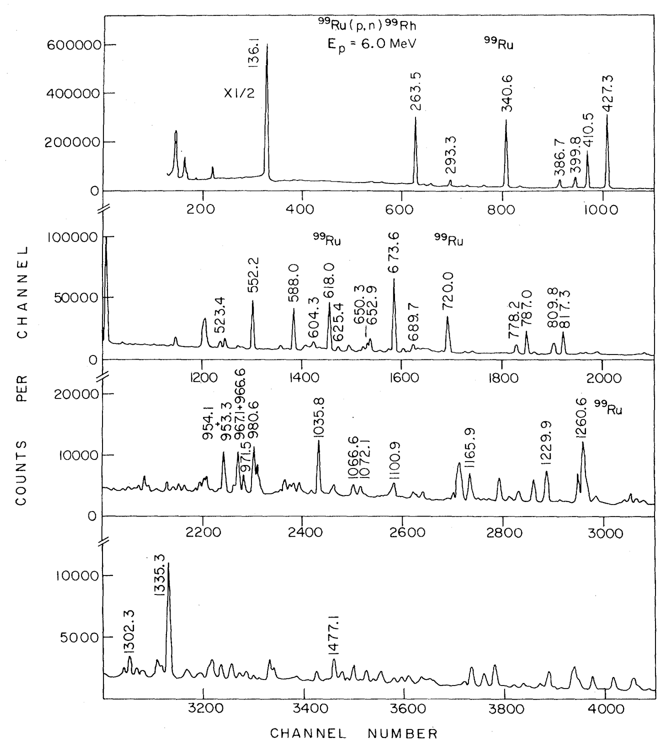

FIG. 1. A typical γ-ray spectrum obtained from the ^{99}Ru(p,n)^{99}Rh reaction at 6.0 MeV bombarding energy. Energies are in keV and labeled peaks belong to ^{99}Rh unless otherwise specified.

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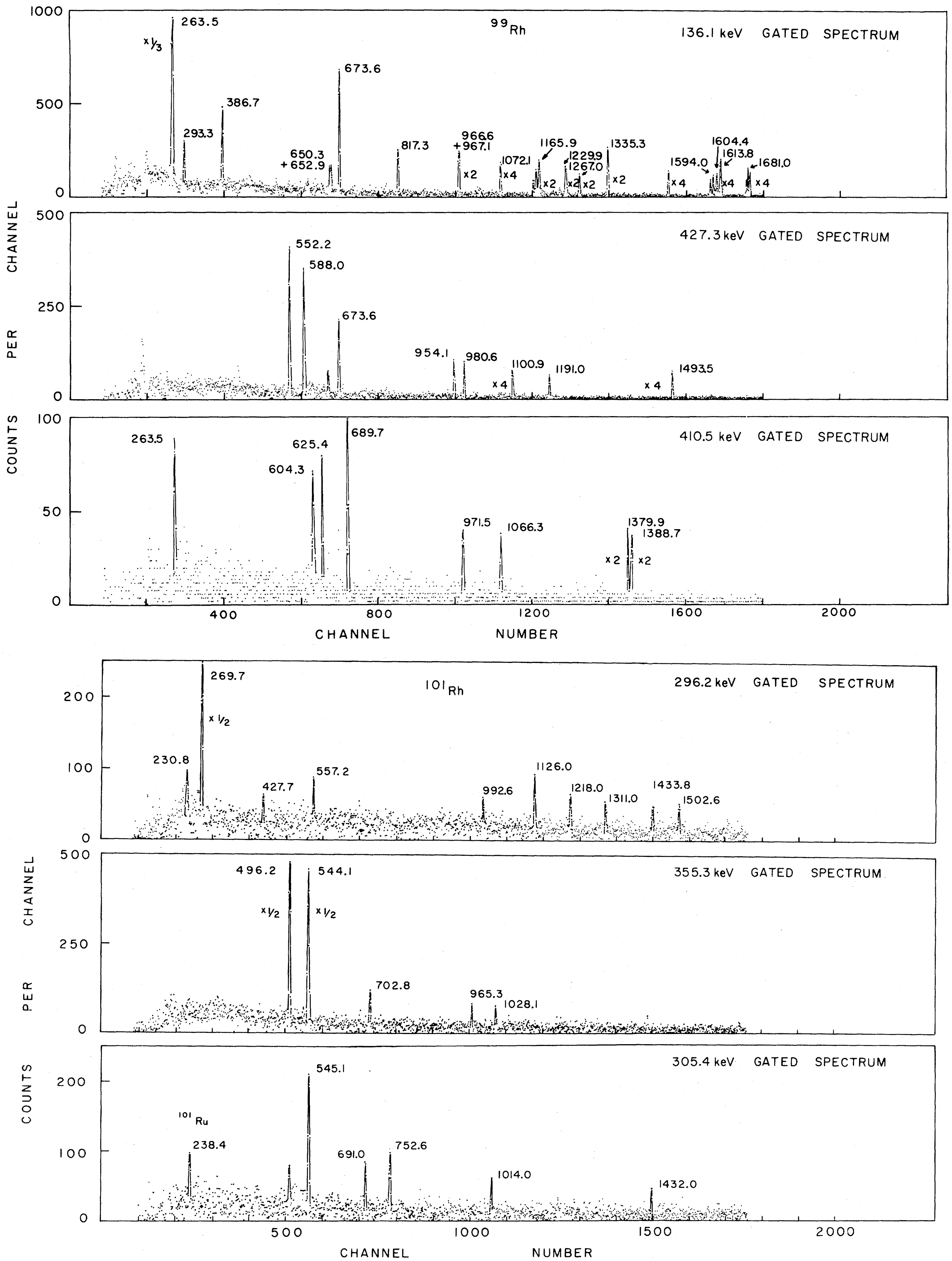

FIG. 2. Some examples of the γ-γ coincidence data obtained for ^{99}Rh and ^{101}Rh. Energies are in keV and the spectra have been corrected for background contributions.

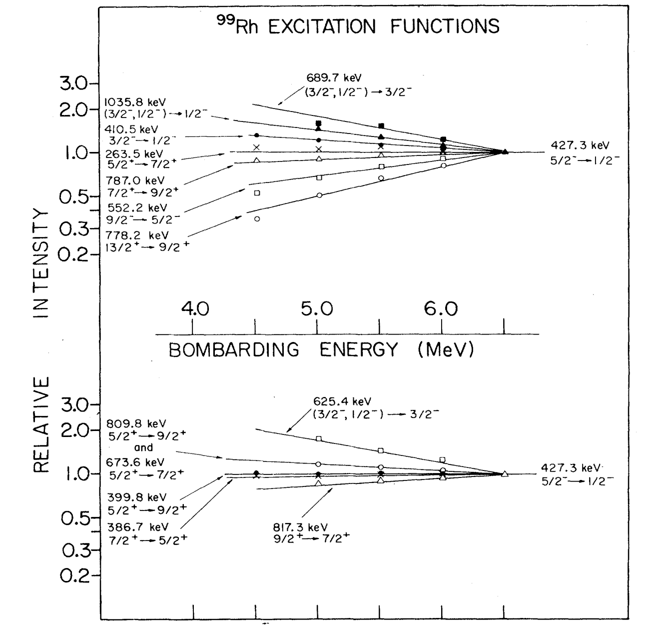

FIG. 3. Relative excitation functions of transitions in ^{99}Rh. The yield of each transition is normalized to that of the $\frac{5}{2}^- \rightarrow \frac{1}{2}^-$, 427.3 keV transition in ^{99}Rh.

for subsequent analysis. This was performed by setting windows on each peak observed in one detector and reconstructing the prompt coincidence spectrum of the other detector. Compton background and random time spectra were then subtracted out to obtain the final gated coincidence spectra, some examples of which are shown in Figs. 2(a) and (b). Using the known[2,3,7] deexcitation properties of low lying levels in ^{99}Rh and ^{101}Rh, the decay schemes were built up using the γ-γ coincidence data and checked for consistency with the excitation function and angular distribution results. Gamma-ray yields were obtained with the peak fitting program SAMPO.[8] In order to estimate the spin of each level, the relative yields of its deexcitation γ rays were plotted as a function of bombarding energy using for normalization purposes the yield of the intense $\frac{5}{2}^- \rightarrow \frac{1}{2}^-$ transition in ^{99}Rh (427.3 keV) and ^{101}Rh (355.3 keV).

A disadvantage of the (p,n) reaction is the small alignment produced in the low spin ($J \le \frac{5}{2}$) γ-emitting states. This leads to almost isotropic angular distributions for many of the transitions detected in this work and no attempt was made to extract mixing ratios from the data. For higher spin levels, where nonisotropic angular distributions were measured, the A_4 coefficients were zero

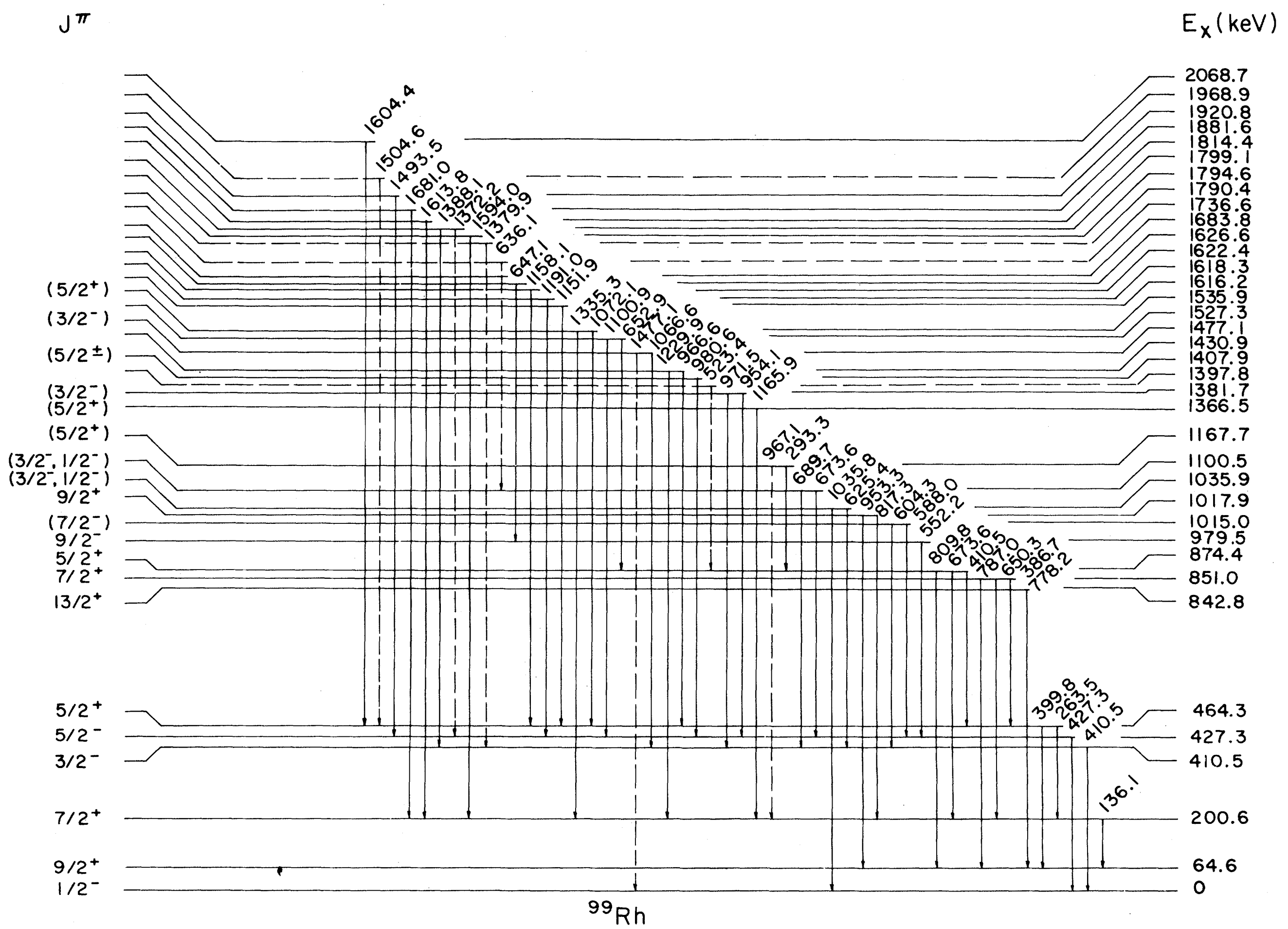

FIG. 4. The decay scheme of ^{99}Rh obtained from this study. Energies are in keV. Dotted levels and transitions are only weakly established. Spins in parentheses are considered probable but not definitely established.

TABLE I. A summary of level energies, γ-ray energies, relative intensities, and angular distribution results obtained in this work for ^{99}Rh.

Excitation energy (keV)	Gamma-ray energy (keV)	Relative intensity (%)	$J_i^\pi \to J_f^\pi$	A_2[e]
200.6	136.1[a]		$\frac{7}{2}^+ \to \frac{9}{2}^+$	
410.5	410.5[b]	45.8±1.5	$\frac{3}{2}^- \to \frac{1}{2}^-$	−0.07±0.04
427.3	427.3	100	$\frac{5}{2}^- \to \frac{1}{2}^-$	f
464.3	263.5	44.3±1.5	$\frac{5}{2}^+ \to \frac{7}{2}^+$	f
	399.8	12.3±0.4	$\to \frac{9}{2}^+$	f
842.8	778.2	5.2±0.3	$\frac{13}{2}^+ \to \frac{9}{2}^+$	0.17±0.07
851.0	386.7	9.4±0.4	$\frac{7}{2}^+ \to \frac{5}{2}^+$	−0.08±0.05[f]
	650.3	4.7±0.3	$\to \frac{7}{2}^+$	
	787.0	14.1±0.6	$\to \frac{9}{2}^+$	−0.13±0.05
874.4	410.5[b]	45.8±1.5	$\frac{5}{2}^+ \to \frac{5}{2}^+$	
	673.6[b]	40.3±1.2	$\to \frac{7}{2}^+$	−0.09±0.03
	809.8	7.8±0.3	$\to \frac{9}{2}^+$	−0.09±0.05
979.5	552.2	16.8±0.5	$\frac{9}{2}^- \to \frac{5}{2}^-$	0.05±0.04
1015.0	588.0	16.3±0.5	$(\frac{7}{2}^-) \to \frac{5}{2}^-$	−0.14±0.04
	604.3	3.0±0.2	$\to \frac{3}{2}^-$	
1017.9	817.3	13.2±0.4	$\frac{9}{2}^+ \to \frac{7}{2}^+$	−0.26±0.04
	953.3[b]	1.2±0.1	$\to \frac{9}{2}^+$	c
1035.9	625.4	2.3±0.1	$(\frac{3}{2}^-, \frac{1}{2}) \to \frac{3}{2}^-$	−0.11±0.08
	1035.8	11.4±0.5	$\to \frac{1}{2}^-$	−0.08±0.04
1100.5	673.6[b]	40.3±1.2	$(\frac{3}{2}^-, \frac{1}{2}^-) \to \frac{5}{2}^-$	
	689.7	4.3±0.2	$\to \frac{3}{2}^-$	−0.10±0.05

TABLE I. (*Continued*).

Excitation energy (keV)	Gamma-ray energy (keV)	Relative intensity (%)	$J_i^\pi \rightarrow J_f^\pi$	A_2[e]
1167.7	293.3[b]	5.5±0.2	$(\frac{5}{2}^+)\rightarrow(\frac{5}{2}^+)$	f
	967.1	7.2±0.4	$\rightarrow\frac{7}{2}^+$	−0.09±0.05
1366.5	1165.9	1.3±0.1	$(\frac{5}{2}^+)\rightarrow\frac{7}{2}^+$	c
	1302.3	2.6±0.2	$\rightarrow\frac{9}{2}^+$	c
1381.7	954.1[b]	1.2±0.1	$(\frac{3}{2}^-)\rightarrow\frac{5}{2}^-$	c
	971.5	3.7±0.2	$\rightarrow\frac{3}{2}^-$	−0.11±0.07
1397.8	523.4[c]		$\rightarrow(\frac{5}{2}^+)$	
1407.9	980.6	8.6±0.4	$(\frac{5}{2}^\pm)\rightarrow\frac{5}{2}^-$	−0.18±0.04
1430.9	966.6[b]	7.2±0.4	$\rightarrow\frac{5}{2}^+$	
	1229.9	7.6±0.4	$\rightarrow\frac{7}{2}^+$	−0.11±0.05
1477.1	1066.6	2.3±0.2	$(\frac{3}{2}^-)\rightarrow\frac{3}{2}^-$	c
	1477.1	3.2±0.2	$\rightarrow\frac{1}{2}^-$	c
1527.3	652.9[d]		$\rightarrow(\frac{5}{2}^+)$	
	1100.9[d]		$\rightarrow\frac{5}{2}^-$	
1535.7	1072.1	1.8±0.2	$(\frac{5}{2}^+)\rightarrow\frac{5}{2}^+$	c
	1335.3[c]		$\rightarrow\frac{7}{2}^+$	

[a]Doublet with Coulomb excitation line in ^{181}Ta.
[b]Doublet in ^{99}Rh. Total intensity only.
[c]Weak transition.
[d]Unresolved doublet.
[e]Within the experimental uncertainties the A_4 coefficients are zero and their values are not given in this table.
[f]Isotropic.

within the experimental error and their values are not given here.

III. RESULTS FOR ^{99}Rh

Some relevant excitation functions and the decay scheme of ^{99}Rh as deduced in this work are shown in Figs. 3 and 4, respectively, while a summary of the level energies, γ-ray energies, and angular distribution results is shown in Table I.

A. The 0.0, 64.6, and 200.6 keV levels

The ground state and the first two excited states in ^{99}Rh are known to have spin-parity values of $\frac{1}{2}^-$, $\frac{9}{2}^+$, and $\frac{7}{2}^+$, respectively.[2,7] We can say little on the 64.6 keV, $\frac{9}{2}^+$ isomeric level ($t_{1/2}$=4.7 h), while the 136.1 keV transition deexciting the $\frac{7}{2}^+$, 200.6 keV level is a doublet with the Coulomb excited 136.3 keV line in ^{181}Ta, used for shielding and beam collimation.

B. The 410.5, 427.3, and 464.3 keV levels

A new level at 410.5 keV is inferred from our data. A 410.3 keV transition already exists[2] in ^{99}Rh, deexciting a level at 874.4 keV. However, from the measured intensities of the other known transitions deexciting the 874.4 keV level,[2] this branch accounts for only $\approx 15\%$ of our measured intensity for the 410.5 keV γ ray. In addition, three pairs of γ rays differing in energy by approximately 17 keV are observed in the γ-ray singles spectra. One member of each pair is in coincidence with the known 427.3 keV transition, with the other member in coincidence with the 410.5 keV γ ray. This strongly suggests new levels at 410.5, 1015.0, 1100.5, and 1381.7 keV. The latter three levels are discussed below. As mentioned in the Introduction, a low lying $\frac{3}{2}^-,\frac{5}{2}^-$ doublet of states is observed in $^{101-105}$Rh and a $\frac{3}{2}^-$ level at 410.5 keV in ^{99}Rh would nicely fit in with the level systematics of these nuclei.

The $\frac{5}{2}^-$ level at 427.3 keV is well established[1] and our data add nothing new. Similarly, our results confirm the level at 464.3 keV and support the $\frac{5}{2}^+$ spin-parity assignment obtained in decay work.[2]

C. The 842.8, 851.0, and 874.4 keV levels

The $\frac{13}{2}^+$ level at 842.8 keV is well established,[1,9,10] decaying solely to the $\frac{9}{2}^+$, 64.6 keV state and our data on the 778.2 keV transition fully support those findings. The level at 851.0 keV is firmly established via the strong 650.3-136.1, 386.7-263.5, and 386.7-399.8 keV coincidences (the 263.5 and 399.8 keV transitions deexcite the $\frac{5}{2}^+$, 464.3 keV level). A transition to the $\frac{9}{2}^+$, 64.6 keV level exists and has been included in the decay scheme. The excitation function of all three transitions favor slightly a $\frac{7}{2}$ spin assignment to this state with probable positive parity from its decay mode. This is compatible with the angular distribution data and is in agreement with the results of decay work.[2]

The level at 874.4 keV has been previously observed[2] and is confirmed here by the strong 136.1-673.6 keV coincidence and the weaker 410.5-263.5 keV coincidence. Both the 410.5 and 673.6 keV transitions are doublets (see the 410.5 and 1100.5 keV levels, respectively). An 809.8 keV transition deexciting to the 64.6 keV level, seen in the singles spectra, has been inferred in decay work[2] and is included in the decay scheme. Its excitation function favors a $\frac{5}{2}$ spin assignment, while the decay mode of the level suggests a positive parity. A $\frac{5}{2}^{(+)}$ assignment is also consistent with the angular distribution of the 809.8 keV transition and is in total agreement with the results of decay work.[2]

D. The 979.5 and 1015.0 keV levels

The $\frac{9}{2}^-$ level at 979.5 keV was established in a (^{6}Li,3nγ) reaction work[1] and our data fully support that assignment. It decays solely via a 552.2 keV transition to the $\frac{5}{2}^-$, 427.3 keV level.

A new level at 1015.0 keV is needed to explain the 410.5-604.3 and 427.3-588.0 keV coincidences. The 604.3 keV γ ray is weak and its yield is difficult to determine accurately since it sits on the shoulder of the Ge(n,n′) distribution. The excitation function of the 588.0 keV transition supports a $\frac{5}{2}$ or $\frac{7}{2}$ spin assignment with the latter favored by the angular distribution results. From the decay mode a negative parity is likely.

E. The 1017.9, 1035.9, 1100.5, and 1167.7 keV levels

The level at 1017.9 keV is firmly established via the strong 817.3-136.1 keV coincidence and has been observed in decay work[2] where, in addition, a 954.0 keV transition to the 64.6 keV level was detected. In this work the 953.3 keV γ ray is a weak doublet whose yield could not be accurately determined. A $\frac{7}{2}$ or $\frac{9}{2}$ spin is suggested for this level from the excitation function of the 817.3 keV transition with the latter value favored by the angular distribution data. This compares with the $\frac{5}{2}^+$ or $\frac{7}{2}^+$ value inferred in decay work.[2]

A new level at 1035.9 keV is needed to explain the 625.4-410.5 keV coincidence. A possible ground state transition exists and has been included in the decay scheme. Both transitions have similar excitation functions favoring a $\frac{3}{2}$ or $\frac{1}{2}$ spin. The slightly nonisotropic angular distributions of both transitions favor a $\frac{3}{2}^-$ spin-parity assignment.

The 410.5-689.7 and 427.3-673.6 keV coincidences firmly establish a new level at 1100.5 keV. The 673.6 keV transition is a doublet (see the 874.4 keV level), while the excitation function of the 689.7 keV transition favors a $\frac{3}{2}$ or a $\frac{1}{2}$ spin assignment. The angular distribution of the 689.7 keV transition slightly favors a $\frac{3}{2}$ spin value.

Our data confirms the level at 1167.4 keV observed in decay work[2] where a $\frac{3}{2}^+,\frac{5}{2}^-$ spin parity was suggested. In our work it is based on the 967.1-136.1 keV coincidence and the presence of the 293.3 keV γ ray in the 809.8 and 673.6 keV gated spectra associated with the 874.4 keV level. The 967.1 keV γ ray is a doublet (see the 1430.9 keV level), while the excitation function of the 293.3 keV transition favors a $\frac{5}{2}$ spin. We have little evidence for the 702.7 keV transition observed in decay work. From the decay mode a $\frac{5}{2}^+$ spin-parity assignment is probable and is not inconsistent with the isotropic angular distribution of the 293.3 keV transition. The level at 1111.2 keV observed in decay work could not be confirmed since we have little evidence for the many transitions reported to deexcite it.[2]

F. The 1366.5, 1381.7, and 1397.8 keV levels

The $(\frac{5}{2}^+,\frac{7}{2}^\pm)$ level at 1366.5 keV observed in decay work[2] is confirmed here by the weak 136.1-1165.9 keV coincidence, and the 1302.2 keV transition to the 64.6 keV level, observed in the singles spectrum, has been included in the decay scheme. The excitation functions of both transitions favor a $\frac{5}{2}$ spin value. No reliable angular distributions could be obtained for these two weak transitions.

A new level at 1381.7 keV is based on the 410.5-971.5 and 427.3-954.1 keV coincidences. The weak 954.1 keV transition is a doublet (see the 1017.9 keV level), while the excitation function of the 971.5 keV transition favors a $\frac{3}{2}$ assignment. A $\frac{3}{2}^-$ spin parity is consistent with the angular distribution data and the decay mode of the 1381.7 keV level.

Our evidence for the 1397.8 keV level is weak and is based on the presence of 809.8 and 673.6 keV lines in the 523.4 keV gated spectrum. The weakness of the 523.4 keV transition precluded any further analysis and this level has been left dotted in the decay scheme.

G. The 1407.9, 1430.9, and 1477.1 keV levels

A new level at 1407.9 keV is based on the 427.3-980.6 keV coincidence. A spin of $\frac{5}{2}$ is consistent with the excitation function and angular distribution data on the 980.6 keV transition.

The 1229.9-136.1 and 966.6-263.5 keV coincidences suggest a new level at 1430.9 keV. The 966.6 keV transition is a doublet (see the 1167.7 keV level), while our data on the 1229.9 keV transition is insufficient to determine the spin of the level.

A new level at 1477.1 keV is based on the weak 1066.6-410.5 keV coincidence. The excitation function of the 1066.6 keV transition favors a $\frac{3}{2}$ spin. A possible ground state transition, with a similar excitation function, also exists and is left dotted in the decay scheme. Both deexcitation γ rays are weak and no reliable angular distribution data were obtained.

H. The 1527.3 and 1535.7 keV levels

We have supporting evidence for levels at 1527.3 and 1535.7 keV which have been observed in decay work.[2] The level at 1527.3 keV is based on the 1100.9-427.3 keV coincidence and the presence of the 652.9 keV line in the 673.6 and 809.8 keV gated spectra associated with the 874.4 keV level. We have no evidence for the 1063.8 keV transition reported in decay work.[2] Both the 1100.9 and 652.9 keV transitions are closely spaced doublets and we can say little about the spin of the 1527.3 keV level. The level at 1535.7 keV is based on the 136.1-1335.3 and 263.6-1072.1 keV coincidences. The 368.0 and 1471.0 keV transitions reported in decay work[2] were not detected, while the possible 684.8 keV transition comes predominantly from ^{99}Ru (685.8 keV). The weakness of the 1335.3 and 1072.1 keV transitions precluded the measurement of the spin of the 1535.9 keV level. Our limited data slightly favors a $\frac{5}{2}$ spin assignment.

I. Levels above 1535.9 keV

From the γ-γ coincidence data we have evidence for many additional low spin states above 1535.9 keV, some of which have been observed in decay work. However, spin assignments are difficult to establish since most of the transitions appear only weakly in the singles spectra. Hence we have included them in the decay scheme but do not discuss them in detail.

IV. RESULTS FOR ^{101}Rh

Some relative excitation functions of particular relevance and the decay scheme of ^{101}Rh as deduced in

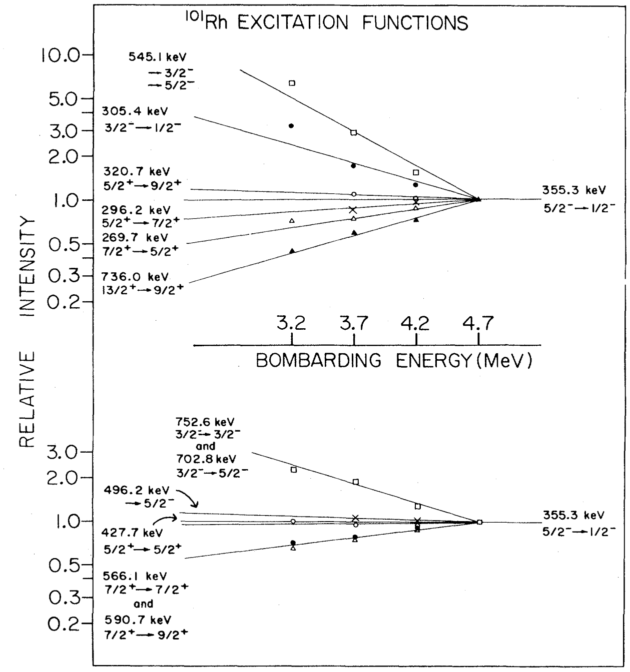

FIG. 5. Relative excitation functions of transitions in ^{101}Rh. The yield of each transition is normalized to that of the $\frac{5}{2}^- \rightarrow \frac{1}{2}^-$, 355.3 keV transition in ^{101}Rh.

this work are shown in Figs. 5 and 6, respectively, while a summary of level energies, relative intensities, and angular distribution results is shown in Table II.

A. The 0.0, 157.3, and 181.8 keV levels

The ground state and the first two excited states in ^{101}Rh are known to have spin-parity values of $\frac{1}{2}^-$, $\frac{9}{2}^+$, and $\frac{7}{2}^+$, respectively.[3,7] Our data add nothing new to these assignments and we do not observe the $\frac{7}{2}^+ \rightarrow \frac{9}{2}^+$, 24.5 keV transition.

B. The 305.4 and 355.43 keV levels

The $\frac{3}{2}^-$, $\frac{5}{2}^-$, doublet of levels at 305.4 and 355.3 keV is well established.[1,3,5] The yield of the 305.4 keV γ ray is difficult to measure accurately due to the buildup of the 306.8 keV line of ^{101}Ru following the decay of the 4.34*d*, 157.3 keV, $\frac{9}{2}^+$ state in ^{101}Rh. Its excitation function supports a $\frac{3}{2}$ spin assignment.

C. The 478.0 and 748.0 keV levels

A level at 478.0 keV has been observed in decay work[3] and a spin parity of $\frac{5}{2}^+$ was assigned. This is consistent with our data on the 296.2 and 320.7 keV transitions deexciting the level to the low lying $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states, respectively.

The presence of the 320.7 and 296.2 keV lines in the 269.7 keV gated spectrum establishes the level at 748.0 keV. In addition, 590.7 and 566.1 keV transitions to the low lying $\frac{9}{2}^+$ and $\frac{7}{2}^+$ states, respectively, together with

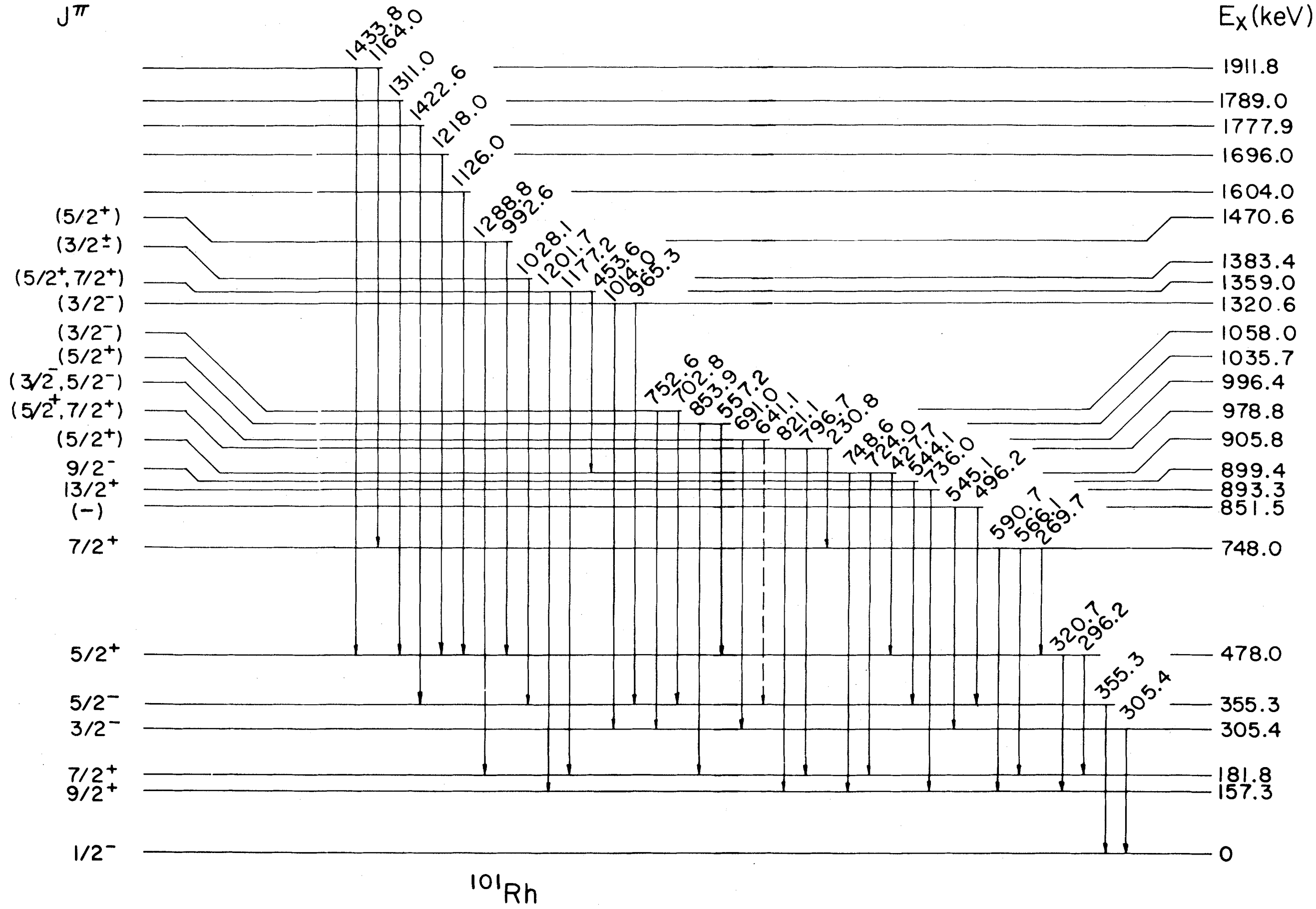

FIG. 6. The decay scheme of ^{101}Rh obtained from this study. Same caption as Fig. 4.

the 269.7 keV transition are observed in the gated spectrum of the 230.8 keV transition deexciting the 978.8 keV level (see below). The excitation functions of all three transitions, Fig. 5, strongly favor the $\frac{7}{2}$ spin assignment obtained in decay work.[3] Positive parity is likely from the decay mode. A $\frac{7}{2}^+$ assignment is not inconsistent with the angular distribution data. No evidence for an $\frac{11}{2}^+$ level at 747.7 keV, reported in (^{6}Li,3nγ) reaction work,[1] was found. However, since also the $\frac{13}{2}^+$, 893.3 keV level is very weakly populated here, it is probable that the $\frac{11}{2}^+$ level at 747.7 keV is too weakly excited to be observed.

D. The 851.5 keV level

A $\frac{7}{2}^-$ level at 851 keV has been detected in a (p,t) reaction study[5] and can probably be identified with the 850.4 keV level observed in (^{6}Li,3nγ) reaction work.[1] Its presence is confirmed here via the strong 545.1-305.4 and 496.2-355.3 keV coincidences. However, the $\frac{7}{2}^-$ spin-parity assignment has to be reviewed in light of the present work. While the excitation function of the 496.2 keV transition favors a $\frac{5}{2}$ spin, that of the 545.1 keV transition strongly favors a $\frac{1}{2}$ or $\frac{3}{2}$ spin value, indicating that the 851.5 keV level is probably a doublet. Previous work[1] on the 496.2 keV transition suggested a $\frac{3}{2}$ spin value, in disagreement with the (p,t) reaction work[5] result, and lent support to a doublet of levels at 851.5 keV, one state with spin $\frac{7}{2}$ and one with spin $\frac{1}{2}$. Since transitions from both components are possible to the $\frac{3}{2}^-$, $\frac{5}{2}^-$ doublet at 305.4 and 355.3 keV, respectively, we cannot assign spin values unambiguously. However, a $\frac{7}{2}^-$, $\frac{1}{2}^-$ doublet of levels at 851.5 keV offers the most consistent explanation of the available data.

E. The 893.3 and 899.4 keV levels

The $\frac{13}{2}^+$ level at 893.3 keV, observed in (^{6}Li,3nγ) reaction work,[1] cannot be verified directly from this work. Our data on the 736.0 keV transition, however, does support the $\frac{13}{2}$ spin assignment obtained in that work.

The 899.4 keV level is based on the strong 544.1-355.3 keV coincidence. Since the 544.1 keV transition is a doublet (see the 851.5 keV level) we can say little about the spin of this level. Previous work[1,5] strongly favors a $\frac{9}{2}^-$ spin-parity value.

F. The 905.8 and 978.8 keV levels

A level at 905.6 keV has been observed in decay work[3] where a $\frac{5}{2}^+$ spin parity was assigned. In our work it is

TABLE II. A summary of level energies, γ-ray energies, relative intensities, and angular distribution results obtained in this work for ^{101}Rh.

Excitation energy (keV)	Gamma-ray energy (keV)	Relative intensity (%)	$J_i^\pi \rightarrow J_f^\pi$	A_2
181.8	24.5		$\frac{7}{2}^+ \rightarrow \frac{9}{2}^+$	
305.4	305.4	61.1±2.0	$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	−0.07±0.03
355.3	355.3	100	$\frac{5}{2}^- \rightarrow \frac{1}{2}^-$	−0.06±0.03
478.0	296.2	76.7±2.0	$\frac{5}{2}^+ \rightarrow \frac{7}{2}^+$	−0.11±0.03
	320.7	2.8±0.1	$\rightarrow \frac{9}{2}^+$	−0.10±0.04
748.0	269.7	9.9±0.2	$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$	−0.10±0.03
	566.1	7.7±0.2	$\rightarrow \frac{7}{2}^+$	−0.08±0.04
	590.7	38.2±0.8	$\rightarrow \frac{9}{2}^+$	−0.08±0.02
851.5	496.2	27.1±0.5	$\frac{7}{2}^-, \frac{1}{2}^- \rightarrow \frac{5}{2}^-$	−0.14±0.02
	545.1[a]	122 ±2.5	$\rightarrow \frac{3}{2}^-$	
893.3	736.0	4.0±0.1	$\frac{13}{2}^+ \rightarrow \frac{9}{2}^+$	0.14±0.02
899.4	544.1[a]	122 ±2.5	$\frac{9}{2}^- \rightarrow \frac{5}{2}^-$	
905.8	427.7	2.1±0.05	$(\frac{5}{2}^+) \rightarrow \frac{5}{2}^+$	−0.09±0.02
	724.0	24.3±0.8	$\rightarrow \frac{7}{2}^+$	−0.10±0.02
	748.6	8.2±0.3	$\rightarrow \frac{9}{2}^+$	−0.16±0.04
978.8	230.8	2.8±0.1	$(\frac{5}{2}^+, \frac{7}{2}^+) \rightarrow \frac{7}{2}^+$	−0.10±0.04
	796.7	9.0±0.3	$\rightarrow \frac{7}{2}^+$	−0.32±0.05
	821.1	3.4±0.1	$\rightarrow \frac{9}{2}^+$	−0.22±0.05
996.4	641.1	b	$(\frac{5}{2}^-, \frac{3}{2}^-) \rightarrow \frac{5}{2}^-$	
	691.0		$\rightarrow \frac{3}{2}^-$	
1035.7	557.2	b	$(\frac{5}{2}^+) \rightarrow \frac{5}{2}^+$	
	853.9	17.9±0.4	$\rightarrow \frac{7}{2}^+$	−0.09±0.03
1058.0	702.8	7.5±0.2	$(\frac{3}{2}^-) \rightarrow \frac{5}{2}^-$	−0.06±0.03
	752.6	5.3±0.2	$\rightarrow \frac{3}{2}^-$	

TABLE II. (*Continued*).

Excitation energy (keV)	Gamma-ray energy (keV)	Relative intensity (%)	$J_i^\pi \rightarrow J_f^\pi$	A_2
1320.6	965.3	6.7±0.2	$(\frac{3}{2}^-) \rightarrow \frac{5}{2}^-$	−0.11±0.04
	1014.0[c]	37.7±1.0	$\rightarrow \frac{3}{2}^-$	
1359.0	453.6[c]	3.0±0.2	$(\frac{7}{2},\frac{5}{2})^+ \rightarrow \frac{5}{2}^+$	
	1177.2	1.9±0.08	$\rightarrow \frac{7}{2}^+$	−0.13±0.06
	1201.7	6.3±0.2	$\rightarrow \frac{9}{2}^+$	−0.11±0.04
1383.4	1028.1	7.4±0.3	$(\frac{3}{2}^\pm) \rightarrow \frac{5}{2}^-$	−0.16±0.05
1470.6	992.6	3.1±0.1	$(\frac{5}{2}^+) \rightarrow \frac{5}{2}^+$	−0.13±0.04
	1288.8	7.5±0.3	$\rightarrow \frac{7}{2}^+$	−0.11±0.04

[a]Doublet in ^{101}Rh. Total intensity only.
[b]Weak transition.
[c]Closely spaced doublet. Total intensity only.

based on the 427.7-296.2 keV coincidence and we include possible transitions to the low-lying $\frac{9}{2}^+$ and $\frac{7}{2}^+$ states which are observed in decay work[1] and in our singles spectrum. A $\frac{5}{2}^+$ spin-parity assignment is consistent with our data on the 427.7 and 724.0 keV transitions, while the excitation function of the 748.6 keV transition does not distinguish between $\frac{5}{2}$ and $\frac{3}{2}$.

We have no evidence for the level at 974.7 keV observed in decay work.[3] A level at 978.8 keV deduced in decay work[3] is confirmed by the presence of the 230.8 keV line in the gated spectra of those transitions that deexcite the 748.0 keV level. Only transitions to the low lying $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states were observed in decay work and these transitions have been included in our decay scheme. A $\frac{7}{2}^+$ or $\frac{5}{2}^+$ spin parity is favored from our excitation function data on all three transitions. This compares with the $\frac{7}{2}^-,\frac{9}{2}^+$ value from decay work. We have no evidence for a $\frac{1}{2}^-$ level at 977 keV reported in pickup reaction work.[5]

G. The 996.4, 1035.5, and 1058.0 keV levels

The level at 996.4 keV is based on the weak 691.0-305.4 keV coincidence. No reliable yield of the 691.0 keV γ ray could be obtained since it lies on the shoulder of the Ge(n,n′) distribution. A possible transition to the $\frac{5}{2}^-$, 355.3 keV level exists and this transition has been dotted in the decay scheme since it is extremely weak. Our limited data suggests a $\frac{3}{2}$ or $\frac{5}{2}$ spin assignment. A $\frac{3}{2}^-$ spin parity was found in a (p,t) reaction study.[5]

The level at 1035.7 keV is based on the weak 296.2-557.2 keV coincidence. An 853.9 keV transition to the $\frac{7}{2}^+$, 181.8 keV level reported in decay work[3] has been included in the decay scheme. A $\frac{5}{2}$ spin assignment is suggested by the excitation function of the 853.9 keV transition.

A level at 1058 keV has been observed in a (p,t) reaction study[5] and in decay work.[3] It is firmly established here from the 305.4-752.6 and 355.3-702.8 keV coincidences. Both transitions have identical excitation functions favoring a $\frac{3}{2}$ spin value. The yield of the 752.6 keV transition is difficult to determine accurately. A $\frac{5}{2}^-$ assignment was obtained in (p,t) reaction work.[5]

H. The 1320.6, 1359.0, and 1383.4 keV levels

Our data confirms levels at 1320.6 and 1359.0 keV, as observed in decay work,[3] while the 1383.4 keV level is new. The 965.3-355.3 and 1014.0-305.4 keV coincidences firmly establish the 1320.6 keV level. The excitation function of the 965.3 keV transition favors a $\frac{3}{2}$ spin assignment. The 1014.0 keV γ ray is a closely spaced doublet. A $\frac{5}{2}^-$ or $\frac{7}{2}^-$ spin parity was inferred in decay work.[3]

Of the many γ rays seen to deexcite the 1359.0 keV level in decay work, only the 453.6, 1177.2, and 1201.7 keV transitions were observed in this study. The 453.6 keV transition is in coincidence with the 724.0 keV line deexciting the 905.8 keV level. A $\frac{7}{2}$ or $\frac{5}{2}$ spin is suggested by the excitation function and angular distribution data on the weak 1177.2 and 1201.7 keV transitions while the 453.6 keV transition is a doublet. The 1383.4 keV level is based on the 1028.1-355.3 keV coincidence. A $\frac{3}{2}$ spin is suggested by the excitation function data.

I. The 1470.6 keV level

Of the ten transitions reported to deexcite the 1470.6 keV level in decay work[3] we have firm evidence for the 1288.8 and 992.6 keV transitions only. The excitation functions of both transitions favor a $\frac{5}{2}$ spin assignment in agreement with previous results.[3]

J. Levels above 1470.6 keV

Five additional levels above 1470.6 keV could be inferred from the γ-γ coincidence data of which the 1696.0, 1789.0, and 1911.8 keV states have been already observed,[3] while the 1604.0 and 1777.9 keV levels are new. Our data is insufficient to establish possible spin assignments for these five levels.

V. CONCLUSION

In this discussion we wish to treat essentially negative parity levels on which a large amount of theoretical work is now available. A summary of the experimental results for the negative parity levels in ^{97}Rh—^{103}Rh is shown in Fig. 7. The data on ^{97}Rh is from a recent study using (^{3}He,pnγ) and (^{2}H,nγ) reactions,[11] while the data on ^{103}Rh is taken from a Coulomb excitation study[12] for levels below 1 MeV and from a (^{6}Li,3nγ) reaction work[13] for high spin levels above 1 MeV. The data on the other odd-mass Rh nuclei is from a recent study performed in this laboratory.[1] While our results favor more a $\frac{3}{2}^-$ spin-parity assignment to the 1058.0 keV level in ^{101}Rh, we cannot completely rule out the $\frac{5}{2}^-$ assignment obtained in a (p,t) reaction study.[5] A striking feature in Fig. 7 is the similarity in structure exhibited by these four nuclei (and also by ^{105}Rh whose results[7] are not shown here). The $\frac{5}{2}^- - \frac{1}{2}^-$ energy gap is some 200 keV below the $2_1^+ - 0_1^+$ energy gap in the adjacent even-even Ru nuclei, while the splitting between the first $\frac{5}{2}^-, \frac{3}{2}^-$ states increases only slowly with increasing neutron number. The $\frac{9}{2}^-, \frac{7}{2}^-$ splitting also remains small, with the $\frac{7}{2}^-$ state appearing above the $\frac{9}{2}^-$ level in ^{97}Rh and ^{99}Rh. Additional work is needed to tie down the second $\frac{5}{2}^-, \frac{3}{2}^-$ doublet in ^{99}Rh and ^{101}Rh and to locate the first $\frac{3}{2}^-$ state in ^{97}Rh.

Much of the present theoretical work on the more neutron-rich transitional nuclei around mass 100 is centered on the interacting boson model[14] (IBM), which appears capable of overcoming some of the difficulties encountered by the vibrational (even-even isotopes) and the weak-coupling (odd-mass isotopes) models. Vervier and Janssens,[15] for example, have obtained very good agreement between the negative parity states observed in ^{103}Rh and calculation[5] where a $j=\frac{1}{2}$ fermion is coupled to a boson core in the SU(5) limit of the IBM. A particular success of the model is the lowering of the $\frac{5}{2}^-, \frac{3}{2}^-$ and $\frac{9}{2}^-, \frac{7}{2}^-$ doublets with respect to the positions of the 2^+ and 4^+ core states in ^{102}Ru. Good agreement is also achieved in ^{99}Rh and ^{101}Rh by similar calculations[16] which also determine higher spin negative parity levels. These results are shown in Fig. 7.

The second $\frac{1}{2}^-$ state in ^{101}Rh is predicted to lie some 10 keV above the first $\frac{7}{2}^-$ state at 928.9 keV and for

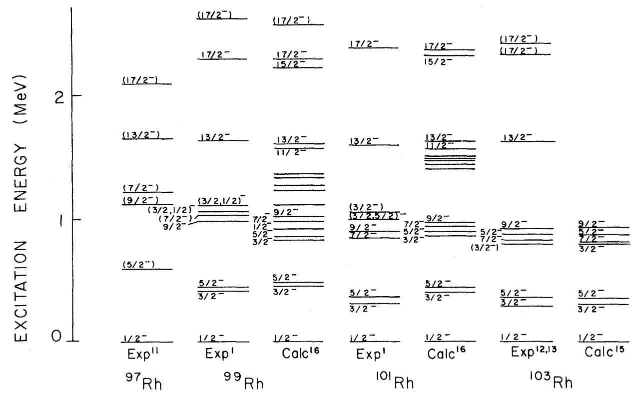

FIG. 7. A comparison of the negative-parity level structure observed in $^{97-103}$Rh with the results of calculations employing the interacting boson model. Level energies in ^{97}Rh have been shifted to line up the $\frac{1}{2}^-$ states in all four nuclei.

reasons of space is not shown in Fig. 7. The five states above the $\frac{9}{2}^-$ state in ^{99}Rh have spins of $\frac{9}{2}^-, \frac{7}{2}^-, \frac{7}{2}^-, \frac{5}{2}^-$, and $\frac{1}{2}^-$, respectively, in order of decreasing energy. The model accounts well for the four levels detected in this work around 1 MeV in excitation energy and is in excellent agreement with the positions of the $\frac{13}{2}^-$ and $\frac{17}{2}^-$ states determined elsewhere.[1]

Little theoretical work has yet been done on the positive parity levels in the odd-mass Rh isotopes. While there are some similarities with the odd-mass Tc isotopes, for which a large body of experimental and theoretical work is available, a direct comparison is not very fruitful since the tendency toward deformation is much less marked in Rh than in Tc (Ref. 6). For example, while there occurs a rapid change in the positions of the lowest $\frac{9}{2}^+, \frac{7}{2}^+$, and $\frac{5}{2}^+$ states in going from ^{99}Tc to ^{103}Tc (Ref. 17) with a complete reversal of the level sequence, only the $\frac{9}{2}^+$ and $\frac{7}{2}^+$ states in Rh behave in a similar fashion and the known $\frac{5}{2}^+$ state remains relatively static. Calculations in the framework of the IBM on ^{97}Rh (Ref. 11) have been performed. Reasonable agreement with experiment is obtained for the level structure only by the inclusion of $2d_{5/2}$ proton configurations which couple strongly to the low-lying $1g_{9/2}$ core coupled states.[11] Given the success of the IBM in describing the odd-mass Tc isotopes[17,18] it would be interesting to perform similar calculations also on the more neutron-rich Rh nuclei.

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