Excited states of ^{97}Ru and ^{103}Ru

G. Kajrys, J. Dubuc, P. Larivière, S. Pilotte, W. Del Bianco, and S. Monaro
Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Québec, Canada H3C 3J7
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The ^{97}Ru and ^{103}Ru nuclei have been studied via in-beam gamma ray spectroscopy through the ^{94}Mo(α,n)^{97}Ru, ^{94}Mo(^{6}Li,p2n)^{97}Ru, and ^{100}Mo(α,n)^{103}Ru reactions. Partial levels schemes can be proposed from γ-γ coincidence data, whereas excitation function and angular distribution measurements were used to determine the spins of several excited levels. The results are compared to previous work carried out on these nuclei.

I. INTRODUCTION

The nuclei around $A=100$ are interesting since their structure exhibits a large variety of characteristics as Z and N vary. In the even-even nuclei, vibrational and rotational level sequences have been encountered, whereas in several odd-A nuclei positive-parity and negative-parity bands have been identified.[1–20] Even though, the nature of these bands has been explained with a moderate degree of success in particular cases, an adequate and general model description for the odd-A nuclei of this region does not yet exist. Additional experimental information is certainly required to understand the complex nature of these nuclei and this work may be regarded as part of a systematic study of the odd-mass nuclei in this region.[3,5,6,11,14,15,20]

Prior to the present study data on medium and high spin excited states of ^{97}Ru and ^{103}Ru were obtained from ^{94}Mo(α,n), ^{95}Mo(α,2n), and ^{100}Mo(α,n) reaction measurements[1,7,9] and the lifetimes of some of the high-spin states in ^{97}Ru were determined by Bucurescu *et al.*[21] via the ^{88}Sr(^{12}C,3n) reaction. However, during a recent investigation of ^{97}Rh through the ^{94}Mo(^{6}Li,3n) reaction,[15] good data on medium and high-spin states in ^{97}Ru were also obtained by the ^{94}Mo(^{6}Li,p2n) reaction. A preliminary analysis of these data clearly showed that some inconsistencies existed in relation to previous findings on this nucleus. Thus a detailed investigation of the properties of ^{97}Ru was carried out by the ^{94}Mo(α,n) and ^{94}Mo(^{6}Li,p2n) reactions. To complete the work on the odd-mass Ruthenium isotopes[11] the ^{103}Ru was also restudied by the ^{100}Mo(α,n) reaction and several new results will be presented herein.

II. EXPERIMENTAL PROCEDURE

Self-supporting targets of ^{94}Mo and ^{100}Mo (97% enriched and 10 mg/cm^2 thick) were bombarded with the α beam from the University of Montréal EN Tandem accelerator while the ^{6}Li beam extracted from the Chalk River Tandem Van de Graaff facility was used to bombard a ^{94}Mo target. For each of the reactions employed, γ-ray excitation functions, γ-ray angular distributions, and γ-γ coincidences were recorded. Excitation functions were measured in 2-MeV steps between 12- and 18-MeV bombarding energy for the α beam and between 20- and 34-MeV bombarding energy for the ^{6}Li beam. Deexcitation γ rays up to $\sim$1.5 MeV in energy were detected using a 96 cm^3 Ge(Li) detector having a resolution of 2.1 keV at 1.33 MeV and placed at 15 cm from the target at 90° to the beam direction. Figure 1 shows a typical γ-ray singles spectrum produced by the ^{100}Mo(α,n) reaction at 16 MeV while some examples of the relative yields of deexcitation γ rays are shown in Figs. 2 and 3 for ^{97}Ru and ^{103}Ru,

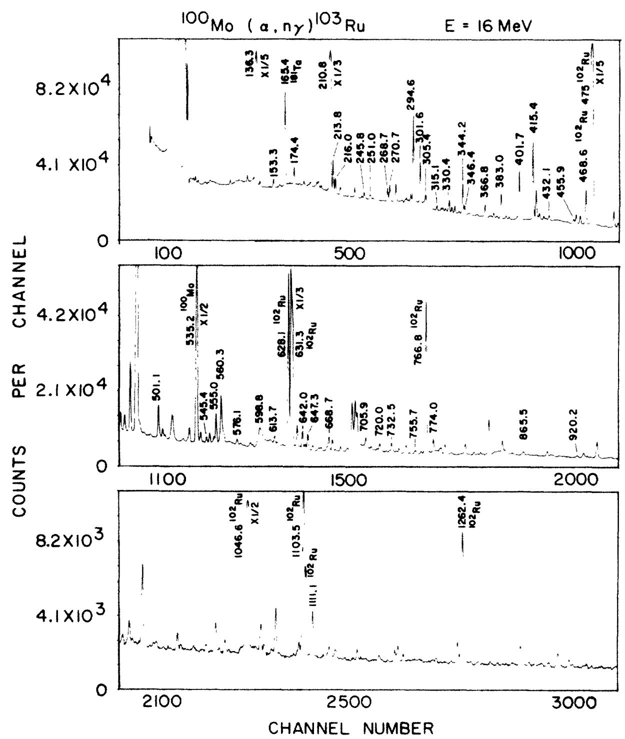

FIG. 1. A typical spectrum from the ^{100}Mo(α,n)^{103}Ru reaction taken at $E_\alpha=16.0$ MeV. Energies are in keV and labeled peaks belong to ^{103}Ru unless otherwise indicated.

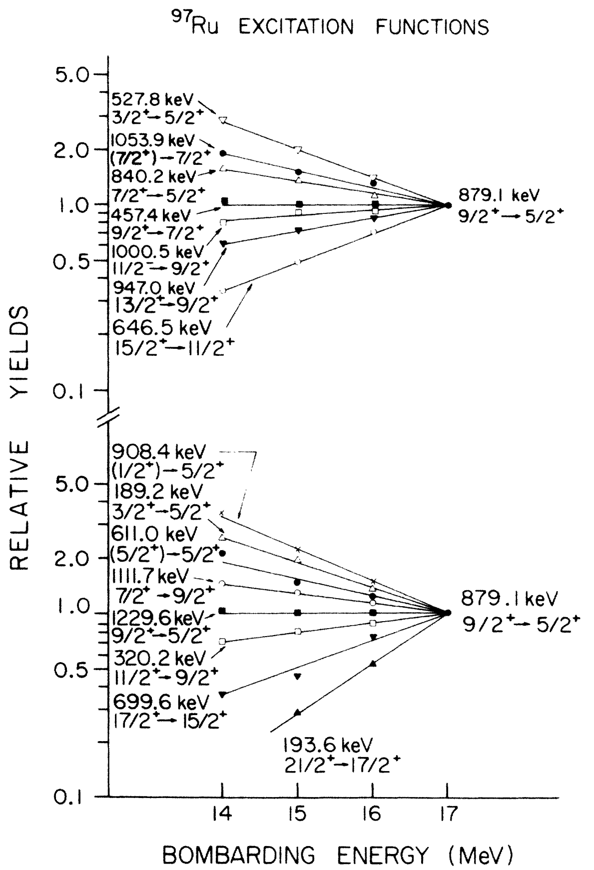

FIG. 2. Relative excitation functions for transitions in ^{97}Ru. The yields are normalized to that of the 879.1 keV ($\frac{9}{2}^+ \rightarrow \frac{5}{2}^+$) transition.

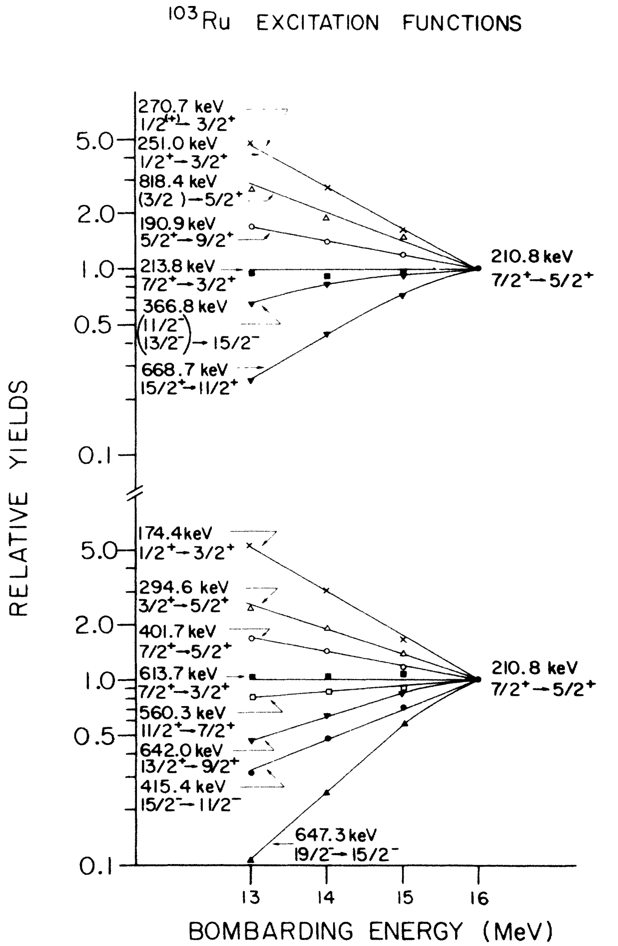

FIG. 3. Relative excitation functions for transitions in ^{103}Ru. The yields are normalized to that of the 210.8 keV ($\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$) transition.

respectively. The γ-γ coincidence measurements were performed using two Ge(Li) detectors (resolution of 2.1 and 2.0 keV at 1.33 MeV, respectively) placed at 90° and −55° to the beam direction. Standard timing techniques were employed and a timing resolution of 15 ns on the prompt coincidence peak was obtained. The coincidence data were event-mode recorded onto magnetic tapes for subsequent playback and analysis. Some typical examples of the γ-γ coincidence spectra are shown in Fig. 4.

Angular distributions were measured using the 96 cm^3 detector positioned successively at 15° intervals between 0° and 90° to the beam direction. A current integrator together with another Ge(Li) detector placed at −90° to the beam direction served as normalization monitors. The angular distribution and excitation function spectra were analyzed using the peak fitting procedure SAMPO.[22] The possible spin values of each level were usually deduced from the relative yield curves of the deexcitation γ rays. These values were then used in a fit to the angular distribution data which yielded, via the lowest reduced χ^2, the most probable value of the spin J and the multipole ratio δ of the deexciting transition. The procedures given by Rose and Brink[23] were employed throughout in the analysis of the angular distribution data.

III. RESULTS

A. The level scheme of ^{97}Ru

The decay scheme as deduced in this work is shown in Fig. 5, while the angular distribution results are presented in Table I.

1. The 0.0-, 189.2-, and 421.7-keV levels

The ground state and first two excited states have spin parities of $\frac{5}{2}^+$, $\frac{3}{2}^+$, and $\frac{7}{2}^+$, respectively, as deduced from previous (d,p) reaction[24,25] and decay work.[26] The ground and second excited state have a $2d_{5/2}$ and $1g_{7/2}$ configuration,[24,25] respectively, as expected from the shell model, while the $\frac{3}{2}^+$ 189.2-keV excited state, which is very weakly excited in (d,p) reaction work,[24,25] has probably a more complex configuration as already observed in other nuclei of this region. Our excitation function data on the 189.2 keV transition clearly supports a $\frac{3}{2}$ spin assignment which is consistent with its isotropic angular

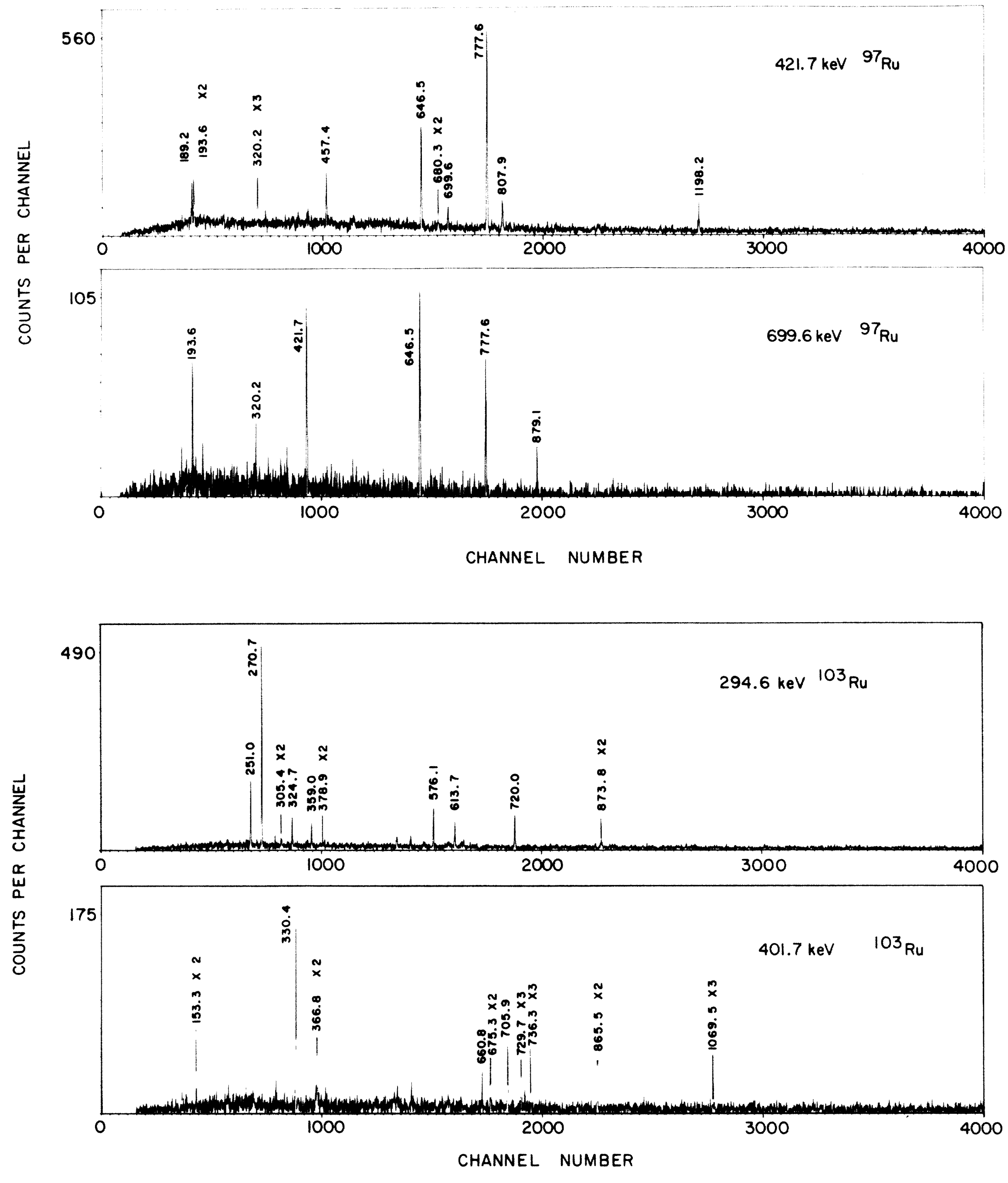

FIG. 4. Some examples of the γ-γ coincidence spectra for the ^{97}Ru and ^{103}Ru nuclei.

distribution. The 421.7-keV γ ray is a doublet (see the 611.0-keV level) and thus its angular distribution and excitation function data are of limited use. The $\frac{7}{2}^+$ assignment is adopted here since all the previous works agree on this value which is also expected from systematic considerations.

2. *The 527.8-, 611.0-, and 771.5-keV levels*

The 527.8-keV level has been observed in (d,p) reaction and decay work[24,26] leading to a spin-parity assignment of $\frac{3}{2}^+$ which is firmly supported by our data on the 338.6- and 527.8-keV transitions. The 611.0- and 771.5-keV states have been observed previously in decay work,[26] where $\frac{1}{2}^{\pm}$ or $\frac{3}{2}^{\pm}$ spin values were suggested while the level at 770 keV has also been observed in (d,p) reaction work where a $\frac{3}{2}^+$ or $\frac{5}{2}^+$ spin was inferred.[24] Very little can be said from our data on the 611.0-keV level since the 421.8-keV transition decaying to the $\frac{3}{2}^+$ 189.2-keV state is the weaker member of a doublet (see the 421.7-keV level) and the 611.0-keV γ ray is weak even though its yield curve would suggest a $\frac{5}{2}$ spin. A $\frac{3}{2}$ or $\frac{5}{2}$ spin value can be inferred from the excitation function of the 582.3 keV transition deexciting the 771.5-keV level to the $\frac{3}{2}^+$ 189.2-

TABLE I. A summary of level energies, γ-ray energies, relative intensities, and angular distribution results obtained in this work for ^{37}Ru.

E_x (keV)	E_γ (keV)	Relative[a] intensity (%)	$J_i^\pi \to J_f^\pi$	A_2[a]	A_4[a]	δ[b]
0.0			$\frac{5}{2}^+$			
189.2	189.2	44.0(20)	$\frac{3}{2}^+ \to \frac{5}{2}^+$	−0.031(34)	0.036(42)	
421.7	421.7[c]	100.0	$\frac{7}{2}^+ \to \frac{5}{2}^+$	−0.202(24)	0.056(32)	
527.8	338.6	2.4(2)	$\frac{3}{2}^+ \to \frac{3}{2}^+$	0.015(36)	0.041(42)	
	527.8	9.2(5)	$\to \frac{5}{2}^+$	−0.093(34)	0.050(40)	
611.0	421.8[c]		$(\frac{5}{2}^+) \to \frac{5}{2}^+$			
	611.0	<1	$\to \frac{5}{2}^+$			
771.5	582.3	6.4(3)	$(\frac{5}{2}^+) \to \frac{3}{2}^+$	−0.119(36)	0.054(50)	
	771.5[c]		$\to \frac{5}{2}^+$			
840.2	418.5	<1	$\frac{7}{2}^+ \to \frac{7}{2}^+$			
	651.0[c]		$\to \frac{3}{2}^+$			
	840.2	32.2(15)	$\to \frac{5}{2}^+$	−0.765(50)	0.152(55)	1.4±0.3
879.1	457.4	6.2(3)	$\frac{9}{2}^+ \to \frac{7}{2}^+$	−0.588(48)	0.077(54)	$1.5^{+0.5}_{-0.4}$
	879.1	63.1(30)	$\to \frac{5}{2}^+$	0.253(32)	−0.059(40)	$E2$
908.4	719.2		$(\frac{1}{2}^+) \to \frac{3}{2}^+$			
	908.4	1.0(2)	$\to \frac{5}{2}^+$	−0.057(78)	0.055(88)	
1184.4	995.2	3.4(2)	$(\frac{3}{2}^+, \frac{5}{2}^+) \to \frac{3}{2}^+$	−0.480(64)	0.062(78)	
	1184.4	4.3(2)	$\to \frac{5}{2}^+$	−0.187(40)	0.077(44)	
1199.3	320.2	7.2(3)	$\frac{11}{2}^+ \to \frac{9}{2}^+$	−0.430(40)	0.085(45)	$2.3^{+0.8}_{-0.5}$
	777.6	41.9(20)	$\to \frac{7}{2}^+$	0.223(50)	−0.020(54)	$E2$
1229.6	350.5	1.9(2)	$\frac{9}{2}^+ \to \frac{9}{2}^+$	0.246(50)	−0.037(62)	
	389.4	4.5(2)	$\to \frac{7}{2}^+$	−0.227(5)	0.066(56)	$M1$
	807.9	8.2(4)	$\to \frac{7}{2}^+$	0.385(38)	0.189(46)	$-3.1^{+4.8}_{-1.3}$
	1229.6	6.3(3)	$\to \frac{5}{2}^+$	0.272(58)	−0.092(72)	$E2$
1376.5	1187.3	2.4(2)	$(\frac{1}{2}^+, \frac{3}{2}^+) \to \frac{3}{2}^+$			
1542.9	663.8	1.8(2)	$(\frac{7}{2}^+) \to \frac{9}{2}^+$			
	702.7[c]		$\to \frac{7}{2}^+$			
	771.4[c]		$\to \frac{5}{2}^+$			
1619.9	740.8	4.1(2)	$\frac{11}{2}^+ \to \frac{9}{2}^+$	−0.865(46)	0.124(56)	1.7±0.2
	779.7		$\to \frac{7}{2}^+$			
	1198.2	6.5(3)	$\to \frac{7}{2}^+$	0.240(38)	−0.008(48)	$E2$
1826.1	947.0	16.5(9)	$\frac{13}{2}^+ \to \frac{9}{2}^+$	0.238(32)	−0.059(40)	$E2$
1845.8	646.5	17.9(9)	$\frac{15}{2}^+ \to \frac{11}{2}^+$	0.287(36)	−0.086(46)	$E2$
1879.6	650.0[c]		$\frac{11}{2}^- \to \frac{9}{2}^+$			
	680.3	3.2(2)	$\to \frac{11}{2}^+$	0.293(44)	0.040(55)	$E1$
	1000.5	7.6(3)	$\to \frac{9}{2}^+$	−0.273(40)	0.040(52)	$E1$
1933.0	1053.9	<1	$(\frac{7}{2}^+) \to \frac{7}{2}^+$			
1990.8	1111.7	1.7(2)	$\frac{7}{2}^+ \to \frac{9}{2}^+$	−0.256(59)	0.210(67)	
2020.3	400.4	2.1(2)	$\frac{13}{2}^+ \to \frac{11}{2}^+$	−0.248(46)	0.042(48)	
	821.0[c]		$\to \frac{11}{2}^+$			
2488.1	662.0		$\to \frac{13}{2}^+$			
2502.3	676.2	1.3(3)	$(\frac{13}{2}^+, \frac{15}{2}^+) \to \frac{13}{2}^+$	0.275(44)	−0.001(66)	
2545.4	699.6	3.5(3)	$\frac{17}{2}^+ \to \frac{15}{2}^+$	−0.550(44)	0.094(52)	$2.0^{+0.6}_{-0.4}$
2553.1	673.5	2.5(2)	$\frac{15}{2}^- \to \frac{11}{2}^-$	0.289(44)	−0.028(51)	$E2$
	727.0	1.5(2)	$\to \frac{13}{2}^+$	−0.360(48)	0.059(54)	$E1$
2596.2	1396.9	0.8(2)	$(\frac{9}{2}) \to \frac{11}{2}^+$	0.253(55)	0.090(65)	
2640.8	814.7	1.4(2)	$\frac{17}{2}^+ \to \frac{13}{2}^+$	0.194(42)	−0.021(50)	$E2$
2649.1	823.0[c]		$\to \frac{13}{2}^+$			

TABLE I. (*Continued*).

E_x (keV)	E_γ (keV)	Relative[a] intensity (%)	$J_i^\pi \rightarrow J_f^\pi$	A_2[a]	A_4[a]	δ[b]
2739.0[d]	193.6		$\frac{21}{2}^+ \rightarrow \frac{17}{2}^+$	0.250(40)	−0.006(40)	$E2$
2743.2[d]	897.4		$\frac{17}{2}^+ \rightarrow \frac{15}{2}^+$	0.351(54)	0.130(65)	$3.8^{+1.4}_{-2.5}$
2759.3[d]	213.8[c]		$\frac{19}{2}^+ \rightarrow \frac{17}{2}^+$			
	913.5		$\rightarrow \frac{15}{2}^+$	0.359(39)	−0.065(48)	$E2$
3620.2[d]	860.9		$\frac{23}{2}^+ \rightarrow \frac{19}{2}^+$	0.280(40)	−0.060(50)	$E2$
	881.2		$\rightarrow \frac{21}{2}^+$	−0.219(35)	0.003(42)	
3668.6[d]	929.6		$\frac{25}{2}^+ \rightarrow \frac{21}{2}^+$	0.290(41)	−0.076(50)	$E2$
4261.4[d]	592.8		$(\frac{27}{2}^+) \rightarrow \frac{25}{2}^+$	−0.295(38)	0.056(46)	
	641.2		$\rightarrow \frac{23}{2}^+$			

[a]Uncertainties in the least significant figures are indicated in parentheses.

[b]Rose and Brink convention (Ref. 23).

[c]Doublet.

[d]The intensities of the γ rays deexciting these levels are not reported since they have been essentially studied via the ^{94}Mo(^{6}Li,p2n) reaction.

keV first excited state. However, a $\Delta J = 1$ is favored from the angular distribution making a $\frac{5}{2}$ spin assignment to the 771.5-keV level more consistent. No information can be extracted from the 771.5-keV transition which appears in coincidence with itself (see level at 1542.9 keV). The parity of this level is probably positive from its decay mode.

3. *The 840.2-, 879.1-, and 908.4-keV levels*

Intense 840.2- and 879.1-keV lines in the single spectrum and coincidence data confirm the existence of these two levels already observed in decay work[26] and in a previous ^{95}Mo(α,2n) reaction study.[9] Spins of $\frac{7}{2}$ and $\frac{9}{2}$ are strongly favored from the excitation and angular distribu-

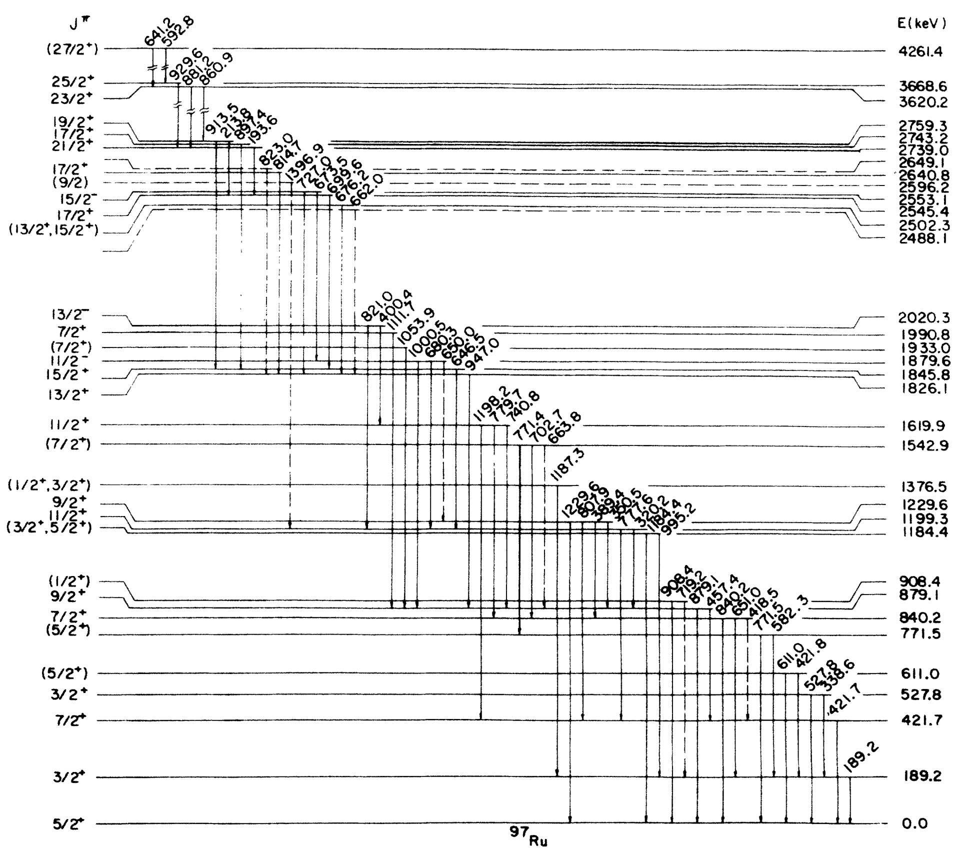

FIG. 5. The decay scheme of ^{97}Ru. Energies are in keV. Dotted transitions and levels are considered probable but not definitely established.

tion data on the 840.2-, 457.4-, and 879.1-keV γ rays. Transitions of 418.5 and 651.0 keV deexcite also the 840.2-keV level, but very little information can be extracted from these γ rays since the former is weak and the latter is a doublet, a large fraction of which comes from the excitation of the first excited state of ^{98}Ru via the ^{95}Mo(α,n) reaction.

The 908.4 keV state was reached by a very strong $l_n=0$ transfer in a (d,p) reaction work[25] suggesting a $\frac{1}{2}^+$ spin-parity assignment which is consistent with our data on this state. Positive parity for the 840.2- and 879.1-keV levels is strongly favored from their excitation and deexcitation modes. We cannot confirm the existence of a $\frac{7}{2}^+$, 810.9-keV level proposed earlier[9] since the 389.4-keV γ ray reported in coincidence with the 421.7-keV transition must be placed elsewhere in the decay scheme of ^{97}Ru (see level at 1229.6 keV).

4. The 1184.4-, 1199.3-, 1229.6-, and 1376.5-keV levels

The 1184.4- and 1376.5-keV levels are low spin states already observed in the $\frac{1}{2}^-$ ^{97}Rh decay.[26] The former level was also reached by an $l_n=2$ transfer in (d,p) reaction work.[24,25] Our data support a $\frac{3}{2}$ (or $\frac{5}{2}$) and a $\frac{1}{2}$ (or $\frac{3}{2}$) spin assignment to the 1184.4- and 1376.5-keV levels, respectively, in agreement with previous results.[24,26] Two intense transitions of 320.2 and 777.6 keV deexcite the 1199.3-keV level. A spin of $\frac{11}{2}$ is strongly supported from the excitation function data which is consistent with the $\Delta J=1$ and $\Delta J=2$ characteristic angular distributions of the 320.2- and 777.6-keV γ rays, respectively. The 1229.6-keV state is evinced via the presence of four deexcitation γ rays at 350.5, 389.4, 807.9, and 1229.6 keV whose excitation functions and angular distributions strongly support a $\frac{9}{2}$ spin assignment. The parity of all these levels is, most probably, positive due to their decay mode.

5. The 1542.9-, 1933.0-, 1990.8-, and 2596.2-keV levels

These are the only low spin levels ($J\leq\frac{9}{2}$) excited in this work above 1.5 MeV. The first three states are also evinced in the $\frac{9}{2}^+$ ^{97}Rh decay[26] and $\frac{7}{2}^+$ or $\frac{9}{2}^+$ spin values have been proposed for the 1933.0- and 1990.8-keV levels. A $\frac{7}{2}$ spin assignment is suggested for both levels from our data, even though a $\frac{5}{2}$ spin value for the 1933.0-keV level cannot be excluded from the excitation function of the 1053.9-keV γ ray deexciting it (see Fig. 2). The 1542.9-keV level is deexcited by the 663.8-, 702.7-, and 771.4-keV transitions. The 702.7 and 771.4 γ rays are doublets (see below for the 702.7-keV transition and the 771.5-keV level) and no information could be extracted from them. However, the excitation function of the other γ ray seem to support a $\frac{7}{2}$ spin assignment to the 1542.9-keV level whose parity is probably positive from its decay mode. It should be mentioned that Hseuh *et al.*[9] did find the 702.7-keV transition in coincidence with an 871.3-947.0 cascade (the 947.0-keV transition deexcite the 1826.1-keV level; see below) establishing the existence of levels at 2697.9 and 3400.6 keV, respectively. However, we have no evidence for these states since our coincidence data both from the ^{94}Mo(α,n) and the ^{94}Mo(Li,p2n) reaction do not support the (947.0-871.3-702.7)-keV cascade. A possible explanation for the (871.3-702.7)-keV coincidence is that it arises from the Coulomb excitation or direct production of ^{94}Mo. Finally, the 2596.2-keV level is based on the (1396.9-777.6)-keV coincidence, the 777.6-keV γ ray deexciting the $\frac{11}{2}^+$ 1199.3-keV level. Our data favor a $\frac{9}{2}$ spin assignment to this level whose parity is uncertain.

6. The 1619.9-, 1826.1-, and 1845.8-keV levels

The 1619.9-keV level is deexcited by three γ rays of 740.8, 779.7, and 1198.2 keV. The first γ ray is seen in coincidence with the 879.1-keV ($\frac{9}{2}^+\rightarrow\frac{5}{2}^+$) transition while the other two are in coincidence with the 840.2 ($\frac{7}{2}^+\rightarrow\frac{5}{2}^+$) and the 421.7 ($\frac{7}{2}^+\rightarrow\frac{5}{2}^+$) keV transitions, respectively. No information can be extracted from the 779.7-keV γ ray since it is masked in the singles spectrum by the more intense 777.6-keV line (see the 1199.3-keV level). However, the excitation functions and the angular distributions of the other two γ rays strongly support a $J^\pi=\frac{11}{2}^+$ for the 1619.9-keV level in agreement with the work of Hseuh *et al.*,[9] who only observed the 1198.2-keV transition.

Very intense lines of 947.0 and 646.5 keV are seen in coincidence with those γ rays which deexcite the 879.1- and 1199.3-keV levels, respectively. From our data, spin parities of $\frac{13}{2}^+$ and $\frac{15}{2}^+$ are proposed for the 1826.1- and 1845.8-keV states, respectively, confirming the results of Hseuh *et al.*,[9] These authors found also strong $E2$ transitions of 773.0 and 882.1 keV in coincidence with each other and with the 947.0-keV γ ray establishing levels at 2599.5 ($\frac{17}{2}^+$) and 3481.7 ($\frac{21}{2}^+$) keV. Since we have no evidence for the 773.0 and 882.1 keV γ rays both in the ^{94}Mo(α,n) and ^{94}Mo(^{6}Li,p2n) reaction, the existence of the 2599.5- and 3481.7-keV states cannot be confirmed.

7. The 2020.3-, 2488.1-, 2502.3-, and 2545.4-keV levels

The first three levels are proposed here for the first time. The 2020.3-keV state is inferred by the (400.4-1198.2)- and (821.0-777.6)-keV coincidences. The 821.0-keV transition is an unresolved doublet in the singles spectrum while our data on the 400.4-keV transition would support a $J^\pi=\frac{13}{2}^+$ spin-parity assignment. The 2488.1-keV level is based exclusively on the (662.0-947.0)-keV coincidence. The weakness of the 662.0-keV γ ray precluded an accurate analysis of its excitation and angular distribution data and no spin value can be given from our work. For the 2502.3-keV level, based on the (676.2-947.0)-keV coincidence, spins of $\frac{13}{2}$ or $\frac{15}{2}$ are suggested by the excitation function data on the 676.2-keV γ ray while its angular distribution favors a $\frac{15}{2}$ value. The 2545.4-keV level is established via the (699.6-646.5)-keV strong coincidence. The data on the 699.6-keV transition strongly support a $\frac{17}{2}^+$ spin parity for this level.

8. The 2640.8- and 2649.1-keV levels

These two levels are proposed via coincidence measurements since the 814.7 and 823.0-keV γ rays are seen in coincidence with the 947.0-keV transition deexciting the 1826.1-keV $\frac{13}{2}^+$ state. The excitation function and the angular distribution of the 814.7-keV transition suggest a spin of $\frac{17}{2}$ for the 2640.8-keV level. No spin value for the 2649.1-keV state can be inferred from the 823.0-keV γ ray since this transition is an unresolved doublet a large fraction of which comes from the deexcitation of the 6^+ to 4^+ level of ^{98}Ru produced through the ^{95}Mo(α,n) reaction. The parity of the 2640.8-keV level is proposed to be positive from the quadrupole nature of the 814.7-keV transition.

9. The 2739.0-, 2743.2-, 2759.3-, 3620.2-, 3668.6-, and 4261.4-keV levels

These high spin levels are essentially established via the ^{94}Mo(^{6}Li,p2n) reaction which due to the higher angular momentum transferred gives data of much better quality than those from the ^{94}Mo(α,n) reaction. A new level at 2743.2 keV is needed to explain the (897.4-646.5)-keV coincidence (the 646.5-keV γ ray deexcites the $\frac{15}{2}^+$ 1845.8-keV level) and the data on the 897.4-keV γ ray support a spin-parity assignment of $\frac{17}{2}^+$ for the 2743.2-keV level. The data on the 2739.0-, 2759.3-, and 3668.6-keV levels suggest spins of $\frac{21}{2}^+$, $\frac{19}{2}^+$, and $\frac{25}{2}^+$, respectively, in agreement with the findings of Hseuh *et al.*[9] The levels at 3620.2 and 4261.4 keV are proposed via coincidence measurements. The yields and the angular distributions of the 860.9- and 881.2-keV transitions strongly support a spin of $\frac{23}{2}^+$ for the 3620.2-keV level while a spin of $\frac{27}{2}$ is inferred from the excitation functions of the 529.8- and 641.2-keV γ rays deexciting the 4261.4-keV state. This spin value is supported by the angular distribution of the 592.8-keV γ ray whereas no similar information can be extracted from the 641.2-keV transition.

10. The 1879.6- and 2553.1-keV levels

These two levels are discussed together since they are believed to be the only negative parity states in ^{97}Ru excited in the present work. The level at 1879.6 keV is firmly established via the (650.0-1229.6)-, (680.3-777.6)-, and (1000.5-879.1)-keV coincidences. Little can be deduced from the composite nature of the 650.0-keV γ ray (see level at 840.2 keV). However, the yields of the 680.3- and 1000.5-keV transitions and their angular distributions strongly support a spin value of $\frac{11}{2}$. Even though the present data are not sufficient to assign with certainty a negative parity to the 1879.6-keV level, we think that an $\frac{11}{2}$ assignment is reasonable for the following reasons. A level at 1884 was reached by an $l_n=5$ transfer in a (d,p) reaction work[25] suggesting a $1h_{11/2}$ configuration. Similar levels have been evinced in ^{103}Ru (this work and Ref. 7), ^{101}Ru, and ^{99}Ru (see Ref. 11) at 238.0, 527.4, and 1069.7 keV, respectively. Thus an $\frac{11}{2}^-$ state at 1879.6 keV would fit very well the systematics of the $h_{11/2}$ states in the Ru nuclei as well as in the $N=53$ isotones.[27]

The level at 2553.1 keV is inferred from the (673.5-1000.5)- and (727.0-947.0)-keV coincidences, the 1000.5- and 947.0-keV transitions deexciting the $\frac{11}{2}^-$ 1879.6- and $\frac{13}{2}^+$ 1826.1-keV levels, respectively. The excitation functions of the 673.5- and 727.0-keV transitions favor a $\frac{15}{2}$ spin assignment which is also supported by the angular distribution results since the 673.5-keV transition has a quadrupole character while the 727.0-keV distribution is well fitted by a $\Delta J=1$ ($\delta \simeq 0$) transition. Clearly the parity of the $\frac{15}{2}$ 2553.1-keV level depends on that of the 1879.6-keV level since if the parity of the latter is negative, as is proposed, the parity of the former must be also negative to be in agreement with the angular distribution results. $\frac{15}{2}^-$ levels have been detected in ^{103}Ru (this work and Ref. 7), ^{101}Ru, and ^{99}Ru (Ref. 11) at 653.4, 958.0, and 1571.7 keV, respectively and the 2553.1-keV state in ^{97}Ru would fit very well the systematics of these negative parity bands which are probably formed via a coupling of the odd neutron in the $h_{11/2}$ orbit with the even-even Ru core. In fact considering the ratio $\Delta E/E_{2+}$, where ΔE is the energy difference between the $\frac{15}{2}^-$ and $\frac{11}{2}^-$ states in the same nucleus and E_{2+} is the energy of the 2^+ first excited state of the adjacent even-even Ru isotope, one obtains the values of 0.87, 0.80, 0.77, and 0.81 for ^{103}Ru, ^{101}Ru, ^{99}Ru, and ^{97}Ru, respectively.

B. The level scheme of ^{103}Ru

The decay scheme as deduced in this work is shown in Fig. 6 while the various results are summarized in Table II.

1. The 0.0-, 3.0-, 136.3-, 174.4-, and 213.8-keV levels

$\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{5}{2}^+$, and $\frac{1}{2}^+$ spin-parity values have been assigned to the ground and the first three excited states in ^{103}Ru via (d,p), (p,d), (d,t), (n,γ), (α,nγ) reaction, and decay studies.[7,28–31] We are not able to make any statement concerning the spins of the ground and first excited states from our work alone, even though the existence of several pairs of γ rays having a 3-keV difference confirms the two levels. The excitation function data on the 133.3-keV γ ray suggests a $\frac{5}{2}$ spin assignment to the 136.3 keV state. No conclusion can be drawn on the much stronger 136.3-keV transition since this is a composite line in the single spectrum. However, in a recent investigation of ^{103}Ru via the (n,γ) reaction, it was found that the 136.3-keV γ ray is an almost pure $M1$ transition[32] ($\delta=0.36$). The excitation function data and the isotropic angular distribution of the 174.4-keV transition clearly support the $\frac{1}{2}^+$ spin assignment to the 174.4-keV level.

From (d,p) and (d,t) reaction studies[28–30] a $\frac{7}{2}^+$ spin-parity assignment to the 213.8-keV level has been inferred. This assignment is strongly supported by the $\Delta J=1$ angular distribution of the 210.8-keV transition and by its excitation function as well as that of the 213.8-keV γ ray. It should be mentioned that the 210-keV line is composite since a 210.1-keV transition has been found to deexcite the 346.4-keV level (see below) via coincidence measurements. However, the intensity of this transition is only

TABLE II. A summary of level energies, γ-ray energies, relative intensities, and angular distribution results obtained in this work for ^{103}Ru.

E_x (keV)	E_γ (keV)	Relative[a] intensity (%)	$J_i^\pi \rightarrow J_f^\pi$	A_2[a]	A_4[a]	δ[b]
0.0			$\frac{3}{2}^+$			
3.0			$\frac{5}{2}^+$			
136.3	133.3		$\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$			
	136.3[c]		$\rightarrow \frac{3}{2}^+$			
174.4	174.4	2.3(2)	$\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$			
213.8	210.8[c]	100	$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$	−0.211(32)	0.026(36)	
	213.8	5.5(3)	$\rightarrow \frac{3}{2}^+$			
238.0	$T_{1/2}=1.7$ ms		$\frac{11}{2}^-$			
297.6	294.6	16.5(6)	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$	−0.213(28)	0.025(33)	*M*1
346.4	210.1[c]	2.5(2)	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$			
	346.4	2.5(2)	$\rightarrow \frac{3}{2}^+$	0.186(40)	−0.021(47)	
404.7	268.7	2.3(2)	$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$	−0.471(43)	0.038(50)	$+1.1^{+0.9}_{-0.4}$
	401.7	11.9(4)	$\rightarrow \frac{5}{2}^+$	−0.638(12)	0.072(19)	$+1.1\pm0.2$
432.1	432.1	2.2(2)	$(\frac{1}{2}^+) \rightarrow \frac{3}{2}^+$			
476.0	301.6[c]		$\rightarrow \frac{1}{2}^+$			
501.1	287.3		$\frac{5}{2}^+ \rightarrow \frac{7}{2}^+$			
	364.8		$\rightarrow \frac{5}{2}^+$			
	501.1	1.9(2)	$\rightarrow \frac{3}{2}^+$	−0.485(49)	0.052(57)	
548.4	251.0	1.0(1)	$\frac{1}{2}^+ \rightarrow \frac{3}{2}^+$	0.010(39)	−0.019(49)	
	374.0		$\rightarrow \frac{1}{2}^+$			
	545.4	1.6(2)	$\rightarrow \frac{5}{2}^+$	−0.060(60)	−0.040(70)	
558.0	153.3	1.0(1)	$\frac{9}{2}^+ \rightarrow \frac{7}{2}^+$	−0.352(32)	−0.015(37)	
	344.2	6.0(3)	$\rightarrow \frac{7}{2}^+$	−0.671(37)	0.063(46)	$+1.0^{+0.5}_{-0.3}$
	421.7	2.5(2)	$\rightarrow \frac{5}{2}^+$	0.207(58)	−0.078(73)	*E*2
	555.0	8.6(5)	$\rightarrow \frac{5}{2}^+$	0.244(34)	−0.075(40)	*E*2
562.9	388.5	1.1(1)	$\rightarrow \frac{1}{2}^+$			
568.3	270.7	3.5(3)	$\frac{1}{2}^{(+)} \rightarrow \frac{3}{2}^+$	−0.014(38)	0.031(46)	
592.2	245.8		$\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$			
	378.4[c]	<1	$\rightarrow \frac{7}{2}^+$	−0.244(74)	0.020(89)	
	455.9	2.1(2)	$\rightarrow \frac{5}{2}^+$	0.206(27)	−0.018(37)	
622.3	324.7	1.0(1)	$(\frac{3}{2}^+,\frac{5}{2}^+) \rightarrow \frac{3}{2}^+$	0.025(39)	0.006(45)	
653.4	415.4	31.8(18)	$\frac{15}{2}^- \rightarrow \frac{11}{2}^-$	0.244(45)	−0.090(27)	*E*2
661.5	315.1	<1	$(\frac{3}{2},\frac{5}{2}) \rightarrow \frac{3}{2}^+$			
	487.1	<1	$\rightarrow \frac{1}{2}^+$			
	658.5		$\rightarrow \frac{5}{2}^+$			
	661.5[c]		$\rightarrow \frac{3}{2}^+$			
697.7	483.9		$(\frac{7}{2}^+) \rightarrow \frac{7}{2}^+$			
	561.4		$\rightarrow \frac{5}{2}^+$			
735.1	330.4	2.6(2)	$\frac{5}{2}^+ \rightarrow \frac{7}{2}^+$	−0.591(44)	0.035(50)	$+0.6^{+0.7}_{-0.6}$
	521.3[c]	<1	$\rightarrow \frac{7}{2}^+$			
	598.8		$\rightarrow \frac{5}{2}^+$			
	732.5	4.2(3)	$\rightarrow \frac{5}{2}^+$	0.190(34)	−0.023(40)	
748.9	190.9	<1	$\frac{5}{2}^+ \rightarrow \frac{9}{2}^+$	0.157(46)	−0.016(51)	*E*2
774.0	216.0	1.9(2)	$\frac{11}{2}^+ \rightarrow \frac{9}{2}^+$	−0.483(42)	0.046(47)	
	560.3	15.7(8)	$\rightarrow \frac{7}{2}^+$	0.224(25)	−0.075(29)	*E*2
873.7	305.4	<1	$(\frac{3}{2}^+,\frac{5}{2}^+) \rightarrow \frac{1}{2}^+$	0.103(37)	−0.044(50)	
	576.1	1.7(2)	$\rightarrow \frac{3}{2}^+$	0.200(41)	−0.011(62)	
911.4	565.0		$\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$			

TABLE II. (*Continued*).

E_x (keV)	E_γ (keV)	Relative[a] intensity (%)	$J_i^\pi \rightarrow J_f^\pi$	A_2[a]	A_4[a]	δ[b]
	613.7	2.9(3)	$\rightarrow \frac{3}{2}^+$	0.226(26)	−0.015(31)	E2
	775.1[c]		$\rightarrow \frac{5}{2}^+$			
927.3	359.0	<1	$(\frac{1}{2}^+,\frac{3}{2}^+) \rightarrow \frac{1}{2}^+$			
	378.9[c]		$\rightarrow \frac{1}{2}^+$			
931.4	383.0	<1	$(\frac{3}{2},\frac{5}{2}) \rightarrow \frac{1}{2}^+$	−0.013(39)	−0.024(46)	
954.7	818.4	<1	$(\frac{3}{2}) \rightarrow \frac{5}{2}^+$	−0.210(45)	−0.045(60)	
988.9	487.8	<1	$\rightarrow \frac{5}{2}^+$			
	775.0[c]		$\rightarrow \frac{7}{2}^+$			
1017.6	720.0[c]		$(\frac{5}{2},\frac{7}{2}) \rightarrow \frac{3}{2}^+$			
1020.2	366.8	3.6(3)	$(\frac{11}{2}^-,\frac{13}{2}^-) \rightarrow \frac{15}{2}^-$	−0.030(40)	0.015(50)	
1065.5	660.8[c]		$\rightarrow \frac{7}{2}^+$			
1080.0	675.3	<1	$\rightarrow \frac{7}{2}^+$			
1110.6	552.7	1.1(1)	$\frac{11}{2}^+ \rightarrow \frac{9}{2}^+$	−0.243(38)	−0.094(43)	
	705.9	4.1(3)	$\rightarrow \frac{7}{2}^+$	0.260(36)	−0.113(46)	E2
1134.0	729.3	<1	$\rightarrow \frac{7}{2}^+$			
	920.2	<1	$\rightarrow \frac{7}{2}^+$			
1141.0	736.3	<1	$(\frac{3}{2},\frac{5}{2}) \rightarrow \frac{7}{2}^+$			
1171.4	623.0		$(\frac{1}{2},\frac{3}{2}) \rightarrow \frac{1}{2}^+$			
	873.8		$\rightarrow \frac{3}{2}^+$			
1200.0	426.0	<1	$\frac{13}{2}^+ \rightarrow \frac{11}{2}^+$	−0.650(230)	0.290(240)	$3.0^{+1.5}_{-3.0}$
	642.0	6.4(4)	$\rightarrow \frac{9}{2}^+$	0.248(37)	−0.092(48)	E2
1270.2	865.5		$\rightarrow \frac{7}{2}^+$			
1288.3	720.0[c]		$\rightarrow \frac{1}{2}^+$	0.205(54)	0.007(59)	
1300.7	647.3	6.5(4)	$\frac{19}{2}^- \rightarrow \frac{15}{2}^-$	0.264(35)	−0.116(40)	E2
1313.7	539.7	2.9(3)	$\frac{11}{2}^+ \rightarrow \frac{11}{2}^+$	0.168(38)	−0.031(48)	
	755.7	1.1(1)	$\rightarrow \frac{9}{2}^+$	−0.576(44)	0.059(50)	$0.8^{+0.4}_{-0.3}$
1378.5	810.2		$\rightarrow \frac{9}{2}^+$			
1442.7	668.7	6.3(4)	$\frac{15}{2}^+ \rightarrow \frac{11}{2}^+$	0.271(30)	−0.115(40)	E2
1474.2	1069.5		$\rightarrow \frac{7}{2}^+$			
2131.0	688.3	2.4(4)	$\frac{19}{2}^+ \rightarrow \frac{15}{2}^+$	0.395(40)	−0.062(50)	E2

[a]Uncertainties in the least significant figures are indicated in parentheses.
[b]Rose and Brink convention (Ref. 23).
[c]Doublet.

2.5% of that of 210.8 keV and should not affect the data on the latter γ ray. Klamra and Rekstad[7] proposed a level at 287.7-keV via the (151.7-136.3)-keV coincidence and the 287.3-keV γ ray. We cannot support the existence of this level since no 151.7-keV line is present in our singles spectra and the 287.3-keV transition must be placed elsewhere in the decay scheme (see level at 501.1 keV).

2. *The 297.6-keV level*

A level at approximately this energy has already been observed in stripping, (n,γ) and (α,nγ) reaction work.[28–32] The level is based on a strong 294.6-keV transition decaying to the $\frac{5}{2}^+$ 3.0-keV first excited state and on a plethora of γ rays in coincidence with it deexciting higher energy levels (see Fig. 6). Conflicting spin-parity values have been assigned to the 297.6-keV level. For instance, previous (d,t) (Ref. 28) and (d,p) (Ref. 29) reaction works concluded that this state is reached by an $l_n=0$ and an $l_n=1$ (or 3) transfer, respectively. The first result would imply spin $\frac{1}{2}^+$ while the second result would yield a negative parity for this level. Klamra and Rekstad[7] infer a $\frac{7}{2}^-$ spin-parity assignment from their data and more recent (p,d) and (d,p) reaction experiments[30] suggest an $l_n=3$ transfer to this state, even though an $l_n=2$ transfer seems equally plausible from the data. Our excitation function (see Fig. 3) strongly suggest a $\frac{3}{2}$ spin assignment which is compatible with the angular distribution data ($\delta \simeq 0$). A low spin value of $\frac{3}{2}$ would also be in agreement with the γ-γ coincidence data which show that this state is fed by γ rays deexciting higher energy spin $\frac{1}{2}$

levels (see the 548.4- and 568.3-keV levels). It is difficult to infer the parity of the 297.6-keV level from our results alone. From its excitation and deexcitation mode a positive parity is favored which is also in agreement with the fact that $\frac{3}{2}^-$ levels are not expected at such low energy in the Ruthenium nuclei. Clearly further experiments such as polarization measurements, would be helpful to clarify definitely the nature of this state.

3. The 346.4-, 404.7-, 432.1-, and 476.0-keV levels

The 346.4-keV level is inferred by the (210.1-136.3)-keV coincidence. No information can be extracted from the 210.1-keV γ ray since it is the weaker member of a doublet (see the 213.8-keV level). However, the yield of the 346.4-keV ground state transition suggests a spin of $\frac{3}{2}$ which is compatible with its angular distribution and previously obtained results.[28–30] The parity of this level should be positive from its excitation and decay mode.

The (268.7-136.3)-keV coincidence establishes the level at 404.7 keV which is deexcited by a 401.7-keV transition to the $\frac{5}{2}^+$ 3.0 keV state. The yields of the 268.7- and 401.7-keV γ rays suggest a $\frac{5}{2}$ or $\frac{7}{2}$ spin assignment with the latter strongly supported by the angular distribution data. The parity of this state must be positive. A level at approximately 430 keV is well established in reaction work[28–30] as having spin $\frac{1}{2}^+$. Also Klamra and Rekstad[7] suggested the existence of a $\frac{1}{2}^+$ 431.9-keV level. Our data show the presence of a 432.1-keV γ ray in the singles spectra. However, this transition was not found in coincidence with any other γ ray and no information could be extracted from its yield and angular distribution. Thus we prefer to indicate the 432.1-keV level as dotted. The 476.0-keV state is established via the (301.6-174.4)-keV coincidence. However, little can be said on this level since the 301.6-keV γ ray is composite. Klamra and Rekstad[7] have proposed a level at 479.5 keV from the (305.2-174.4)-keV coincidence. Our data do not support the existence of this level since the 305.4-keV transition must be placed elsewhere in the ^{103}Ru decay scheme (see level at 873.7 keV).

4. The 501.1-, 548.4-, 562.9-, and 568.3-keV levels

The 501.1 and 562.9-keV levels are established via the (287.3-210.8)-, (364.8-136.3)-, and (388.5-174.4)-keV weak coincidences. A 501.1-keV ground state transition is placed as deexciting the 501.1-keV level from energy considerations and coincidence data (see the 988.9-keV level). The yield of the 501.1-keV γ ray and its angular distribution suggest a spin of $\frac{5}{2}$ for the 501.1-keV state in agreement with previous reaction work.[28–30] Very little information is obtainable for the 562.9-keV level.

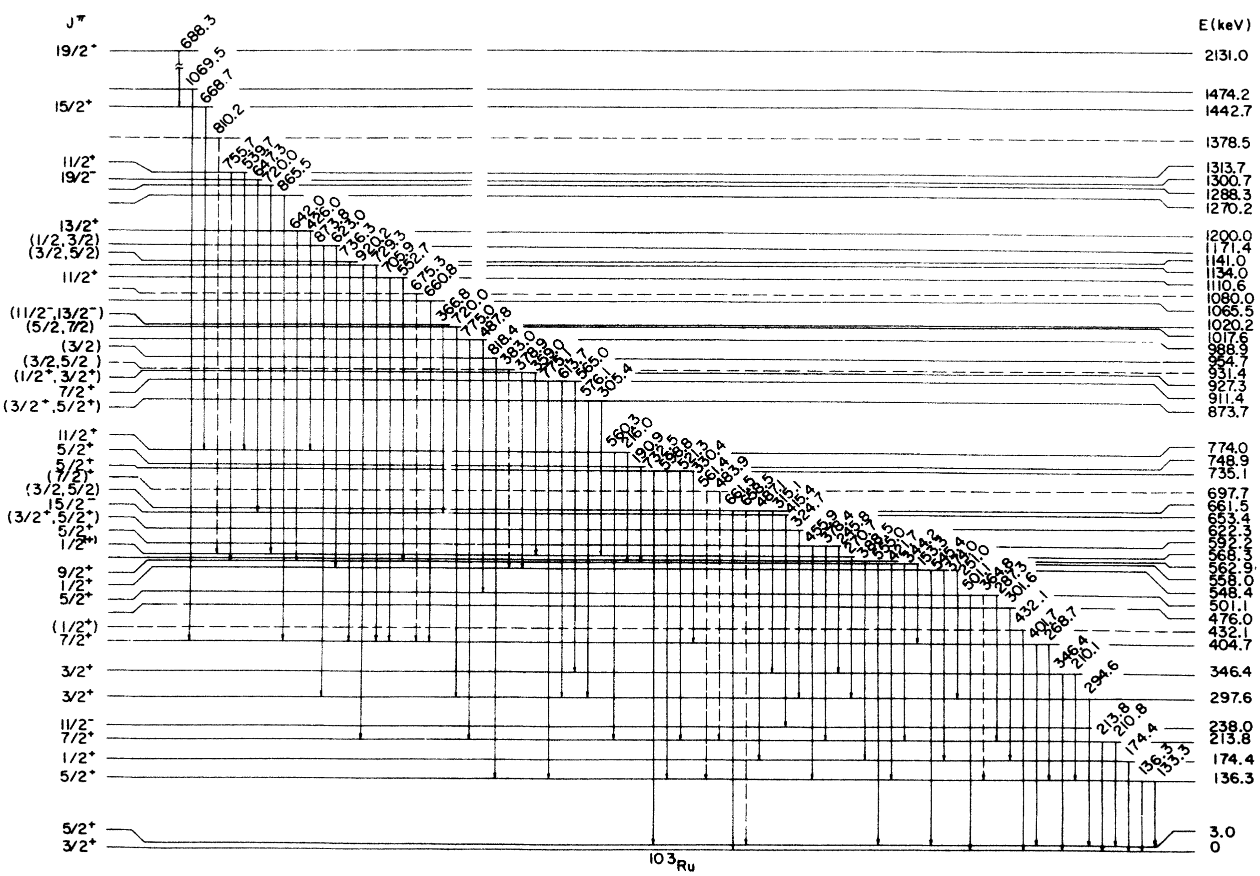

FIG. 6. Same as Fig. 5 but for the decay scheme of ^{103}Ru.

The 548.4 and 568.3-keV levels are important since their spin assignment seems to support the $\frac{3}{2}^{(+)}$ spin value of the 297.6-keV state. Transitions of 251.0, 374.0, and 545.4 keV deexcite the 548.4-keV level. The yields of the 251.0 and 545.4-keV γ rays, their isotropic angular distributions, and the decay mode of the 548.4-keV level strongly suggest a $\frac{1}{2}^{+}$ assignment. The 568.3-keV level is established from the (270.7-294.6)-keV coincidence. The excitation function and angular distribution data on the 270.7-keV γ ray support a spin of $\frac{1}{2}$ for this level. The 548.4- and 568.3-keV states were also detected by Klamra and Rekstad[7] who proposed spin assignments of $\frac{3}{2}$ or $\frac{5}{2}$ for both levels in disagreement with the present results.

5. The 592.2-, 622.3-, 661.5-, and 697.7-keV levels

The 592.2-keV level is established via the (455.9-136.3)-, (378.4-210.8)-, and (245.8-346.4)-keV coincidences. The data on this state clearly support a $J^{\pi}=\frac{5}{2}^{+}$, in agreement with previous studies.[28–30] The (324.7-294.6)-keV coincidence establishes the existence of the 622.3-keV level. The yield and the almost isotropic angular distribution of the 324.7-keV γ ray supports a spin of $\frac{3}{2}$ for the 622.3-keV state even though a $\frac{5}{2}$ value cannot be discarded.

Four transitions at 661.5, 658.5, 487.1, and 315.1 keV deexcite the 661.5-keV level. The last two γ rays are placed via coincidence measurements while the first two γ rays are placed through energy considerations even though the 661.5-keV transition seems composite (see level at 1065.5). The data on this level are limited and seem to suggest a low spin value at $\frac{3}{2}$ or $\frac{5}{2}$ in agreement with previous work.[28–30] The weak (483.9-210.8)- and (561.4-136.3)-keV coincidences establish a level at 697.7 keV about which we can say very little. The $\frac{7}{2}^{+}$ spin assignment is taken from previous reaction work.[28–30]

6. The 735.1-, 748.9-, 873.7-, and 911.4-keV levels

The 735.1-keV level, already detected in a previous (α,n) reaction work[7] where no spin assignment was given, is established in this study via the 330.4-, 521.3-, 598.8-, and 732.5-keV transitions deexciting it. The data on the 521.3- and 598.8-keV γ rays are of little use in assigning the spin of this level since the first transition is a doublet and the 598.8- keV line is strongly mixed with those coming from the (n,n') reaction on the Ge(Li) detector. However, the excellent data on the 330.4- and 732.5-keV γ rays and the decay mode suggest a $J^{\pi}=\frac{5}{2}^{+}$ for the 735.1-keV state. The 748.9-keV level is established by the 190.9-keV transition in coincidence with those γ rays deexciting the $\frac{9}{2}^{+}$ 558.0-keV level (see below). The excitation function and the angular distribution data suggest a $\frac{5}{2}^{+}$ assignment to this level. The 873.7-keV state is deexcited by the 305.4- and 576.1-keV γ rays in coincidence with the 270.7- (568.3-keV level) and the 294.6-keV transitions, respectively. The data on these γ rays support a low spin value of $\frac{3}{2}$, even though $\frac{5}{2}$ cannot be ruled out. The 911.4-keV state is established via the (565.0-346.4)-, (613.7-294.6)-, and (775.1-136.3)-keV coincidences. No reliable information can be obtained from the weak 565.0-keV γ ray or the 775.1-keV transition, which is a doublet (see level at 988.9 keV). However, the excitation function of the 613.7-keV transition strongly favors a $\frac{7}{2}$ spin assignment while its angular distribution is consistent with a $\Delta J=2$ quadrupole type of emission. This result would tend to support a $\frac{3}{2}$ spin assignment to the 297.6-keV level since a $\frac{7}{2}^{-}$ value would require a large $M2/E1$ mixing ratio for the 613.7-keV transition. We cannot confirm the existence of the 737.0- and 768.4-keV levels previously reported.[7]

7. The 927.3-, 931.4-, 954.7-, 988.9-, and 1017.6-keV levels

A 927.3-keV level has been detected in a (n,γ) reaction experiment[31] with several γ rays branches. Of these we see only the 378.9- and 359.0-keV lines, probably for intensity reasons. The 378.9-keV γ ray is a doublet (see level at 592.2 keV) and the excitation function of the 359.0-keV transition suggests a $\frac{1}{2}$ or $\frac{3}{2}$ spin assignment with probable positive parity from decay mode considerations. The 931.4-keV level is established via the (383.0-251.0-294.6)-keV cascade and the (383.0-545.4)-keV coincidence while the 954.7-keV level is established through the (818.4-136.3)-keV coincidence. The yield of the 383.0-keV γ ray suggests a $\frac{5}{2}$ (or $\frac{3}{2}$) spin assignment while its isotropic angular distribution favors $\frac{3}{2}$. A $\frac{3}{2}$ spin assignment to the 954.7-keV level is supported by the data on the 818.4-keV γ ray. Our evidence for the 988.9-keV level comes from the (487.8-287.3)- and (775.0-210.8)-keV coincidence with the 287.3-keV γ ray deexciting the $\frac{5}{2}^{+}$ 501.1-keV level. These transitions are, however, weak and no spin assignment can be obtained from their data. The 1017.6-keV level is established via the (720.0-294.6)-keV coincidence. However, the 720.0-keV γ ray is a doublet with the weaker member deexciting a level at 1288.3 keV. A spin of $\frac{5}{2}$ or $\frac{7}{2}$ is suggested for the 1017.6-keV level from the excitation function of the 720.0-keV transition.

8. The 1065.5-, 1080.0-, 1134.0-, and 1141.0-keV levels

All these weakly excited levels are established via coincidence measurements. However, only for the 1141.0-keV state a spin value of $\frac{3}{2}$ or $\frac{5}{2}$ can be inferred from the yield of the 736.3-keV γ ray decaying to the $\frac{7}{2}^{+}$ 404.7-keV level.

9. The 1171.4-, 1270.2-, 1288.3-, 1378.5-, and 1474.2-keV levels

The 1171.4-keV level is proposed via the (623.0-251.0)-, (623.0-545.4)-, and (873.8-294.6)-keV coincidences. The yield of the 623.0- and 873.8-keV γ rays suggest a spin value of $\frac{1}{2}$ (or $\frac{3}{2}$). We have already mentioned the 1288.3-keV level (see above the 1017.6-keV level). This state as well as the others at 1270.2, 1378.5, and 1474.2 keV are established via weak coincidence measurements and very little can be inferred from the available data.

10. High spin states: Negative parity levels

In the present section negative parity levels with $J \geq \frac{9}{2}$ will be discussed while in the next section positive parity levels ($J \geq \frac{9}{2}$) will be considered.

We have no direct evidence for the $\frac{11}{2}^-$ 238.0-keV level which is known from previous reaction work.[28–30] A very intense 415.4-keV line is observed in the singles spectra and its excitation function as well as its angular distribution strongly suggest that it originates from a $\frac{15}{2}$ level. For these reasons we infer that the 415.4-keV γ ray deexcites a $\frac{15}{2}^-$ level at 653.4 keV. This placement would also be in excellent agreement with the systematics of similar states existing in ^{99}Ru and ^{101}Ru.[11]

From coincidence data it is found that the 653.4-keV level is excited by the relatively intense transitions of 366.8 and 647.3-keV which establish the existence of the 1020.2 and 1300.7-keV levels, respectively. The excitation function of the 366.8-keV γ ray suggests a $\frac{11}{2}$ or $\frac{13}{2}$ spin assignment while its angular distribution favors $\frac{13}{2}$. On the other hand, the yield of the 647.3-keV γ ray strongly suggests a $\frac{19}{2}$ spin assignment to the 1300.7-keV level which is compatible with the $\Delta J=2$ inferred from its angular distribution. The parity of these two levels is clearly considered as negative. The (647.3-415.4)-keV cascade ($\frac{19}{2}^- \rightarrow \frac{15}{2}^- \rightarrow \frac{11}{2}^-$) fits very well the systematics of similar cascades existing in ^{99}Ru, ^{101}Ru (Ref. 11), as well as, probably, in ^{97}Ru (see this work) and is confirmed by a recent ^{7}Li massive transfer reaction work,[33] where negative and positive parity bands have been evinced in several nuclei around $A=100$.

II. High spin states: Positive parity levels

The (421.7-136.3)-, (344.2-210.8)-, and (153.3-401.7)-keV coincidences established a level at 558.0 keV. The 555.0-keV transition is placed as deexciting to the $\frac{5}{2}^+$ 3.0 keV state for it is seen in strong coincidence with the 216.0-keV γ ray which deexcites the 774.0 keV level (see below). The various γ ray yields suggest a $\frac{9}{2}$ spin assignment (even though $\frac{7}{2}$ cannot be discarded) to this state, strongly supported by the angular distribution data. Positive parity can be assigned to the 558.0-keV level from its decay mode. The $\frac{9}{2}^+$ spin-parity assignment is in agreement with recent results obtained in a ^{7}Li massive transfer reaction work.[33] This level was also evinced by Klamra and Rekstad[7] who proposed a $\frac{7}{2}$ or $\frac{9}{2}$ spin value.

The strong (560.3-210.8)-keV coincidence establishes a level at 774.0-keV which is also confirmed by the (216.0-555.0)-keV coincidence (see above the 558.0-keV level) and the (216.0-344.2-210.8)-keV cascade. The angular distribution and excitation function data strongly support an $\frac{11}{2}^+$ spin assignment in agreement with previous results.[7,33] Coincidence data show the existence of a (668.7-688.3)-keV cascade on top of the 774.0-keV level establishing states at 1442.7 and 2131.0 keV, respectively. The yields and angular distributions of the 668.7- and 688.3-keV γ rays clearly suggest $\frac{15}{2}^+$ and $\frac{19}{2}^+$ spin-parity values for the 1442.7- and 2131.0-keV states, respectively, in agreement with previous results.[33]

The 705.9- and 401.7-keV γ rays are in strong coincidence suggesting a level at 1110.6-keV which is confirmed by the (552.7-344.2-210.8)-keV cascade. The yields of the 705.9- and 552.7-keV γ rays favor an $\frac{11}{2}$ spin assignment which is consistent with their angular distributions. The parity of this state should be positive from its decay mode. This level was detected also by Klamra and Rekstad[7] who did not propose any spin value.

Two new levels at 1200.0 and 1313.7 keV are proposed in the present work via coincidence measurements. The 1200.0-keV state is supported by the (426.0-560.3-210.8)- and (642.0-555.0)-keV cascades. The yields of the 426.0- and 642.0-keV γ rays and the decay mode of this level strongly suggest a $\frac{13}{2}^+$ spin-parity assignment which is consistent with the angular distribution data. The excitation functions of the 539.7- and 755.7-keV γ rays which deexcite the 1313.7-keV level are consistent with a $\frac{9}{2}$ or $\frac{11}{2}$ spin value while their angular distributions clearly support an $\frac{11}{2}$ spin assignment. The parity of this level is, most probably, positive from the large quadrupole-dipole mixing ratio of the 755.7-keV transition and the decay mode.

IV. DISCUSSION

During the preparation of this article Chowdhury *et al.*[34] obtained a level scheme of ^{97}Ru by studying the ^{93}Nb(^{7}Li,3n) reaction. Our results are in fair agreement with theirs even though a few discrepancies exist. For instance, we cannot support the ordering of the 717- and 673.5-keV transitions placed above the $\frac{11}{2}^-$ state at 1879.6 keV since our coincidence data strongly suggest that this ordering must be reversed. A further discrepancy is the absence in our decay scheme of the (773-882-155)-keV γ ray cascade in coincidence with the 879.1-keV transition. Those three coincident transitions have been observed[5] in ^{97}Tc and their placement in ^{97}Ru is considered doubtful. We cannot confirm the existence of the 3942 ($\frac{23}{2}$) and 4731 ($\frac{29}{2}^+$) keV levels since in our data the 1203- and 467-keV γ rays deexciting the 3942- and 4731-keV levels, respectively, are absent or too weak to be detected.

In the following we discuss primarily those high- and medium-spin, positive parity states connected by strong transitions. The systematic and structure of the negative parity levels has been well covered by Chowdhury *et al.*[34] and will not be reported here. In Fig. 7 the systematics of possible band structures in the odd-mass $^{97-103}$Ru isotopes is presented, the data on ^{99,101}Ru being taken from Kajrys *et al.*[11] While the band structures observed in ^{99}Ru and ^{101}Ru are quite similar, ^{97}Ru and ^{103}Ru clearly show marked differences. In ^{103}Ru the main cascade (shown to the right of Fig. 7) follow closely a $J(J+1)$ energy level sequence indicative of a deformed rotational nucleus. A similar structure is present[16–20] in the neighboring odd-A Palladium nuclei ($Z=46$, $N \geq 55$), but is not observed in the lighter odd-mass Ru and Pd isotopes showing that the onset of deformation in these nuclei is quite rapid. In ^{103}Ru it is also accompanied by a large increase in the level density. A second cascade, built on the first $\frac{7}{2}^+$ state in ^{99}Ru and ^{101}Ru (shown to the left in Fig. 7) is not strongly populated in ^{103}Ru, but gets progressively stronger with decreasing neutron number, becoming the main band sequence in ^{97}Ru, where the "unfavored" $\frac{9}{2}^+$ and $\frac{13}{2}^+$ states are observed slightly above the favored $\frac{11}{2}^+$ and $\frac{15}{2}^+$ states. Similar levels below the favored

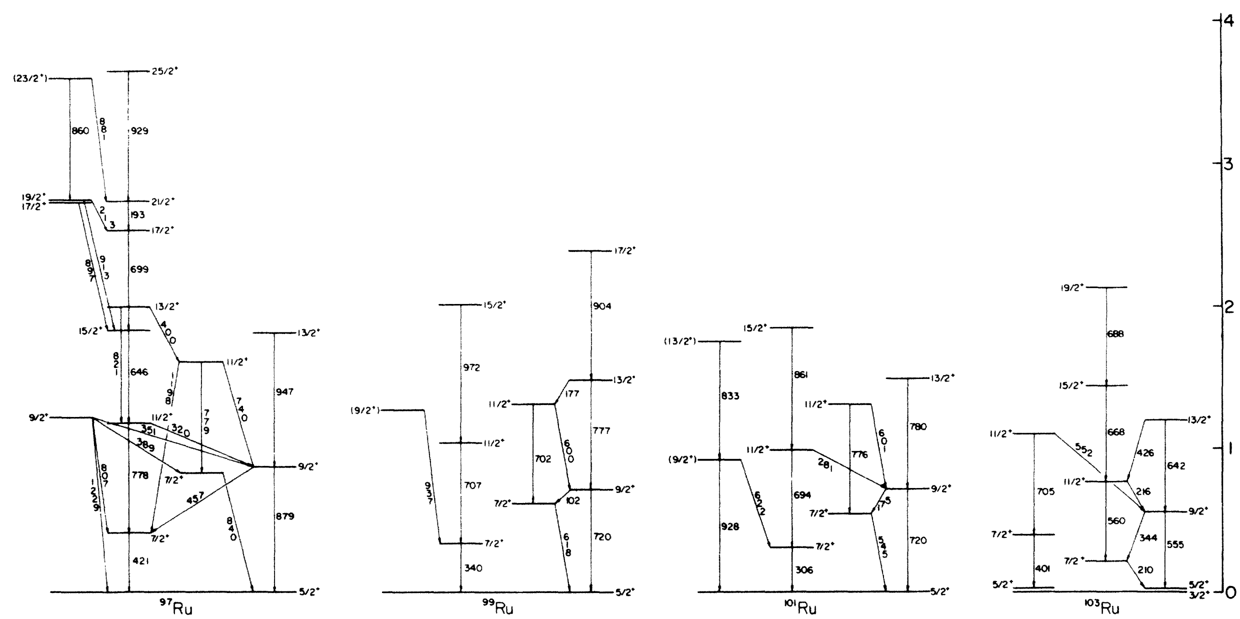

FIG. 7. A comparison of band structures (positive parity states) observed in the odd-mass $^{97-103}$Ru nuclei.

states have been located[11] in ^{101}Ru, while a possible $\frac{9}{2}^+$ state has been detected above the $\frac{11}{2}^+$ level in ^{99}Ru.[11] In addition, a large number of interband transitions are present in ^{97}Ru and become progressively smaller with increasing neutron number. Similar features are also observed in the neighboring Mo ($Z=42$) and Pd ($Z=46$) nuclei[1-3,20] which show marked differences in the level structure as the neutron number approaches the $N=50$ closed shell leaving the predominant and very similar configuration of the $N=53$ isotones[2,20] (^{95}Mo, ^{97}Ru, and ^{99}Pd) as that of a neutron quasiparticle coupled to a vibrating even-even core. This is in keeping with the more spherical nature of the ^{94}Mo, ^{96}Ru, and ^{98}Pd cores ($N=52$) which makes the quasiparticle phonon-coupling model as the more appropriate to explain the structure of these poor-neutron odd-A nuclei.

V. CONCLUSION

The structure of the low and medium spin states in ^{97}Ru and ^{103}Ru shows clearly that these two nuclei define a spherical to deformed transition region in the $Z=44$ isotopes. While confirming existing levels, many more states have been found in the present work which could play an important role in formulating nuclear models. At the same time the existence of several adopted levels has been questioned. Information on transition rates is sorely needed to categorize, in a more quantitative fashion, the type of nuclear excitations involved in these nuclei, where both collective and single-particle degrees of freedom coexist. Only for ^{97}Ru these measurements have been performed.[21] However, the results become somewhat questionable in the light of the present data.

Finally, it would be desirable and very interesting to carry out detailed and systematic calculations on the odd mass Ru isotopes via the interacting boson fermion model.[35] Some calculations have been performed only for the negative parity states of ^{99}Ru (Ref. 10) and ^{101}Ru (Ref. 8) and for the positive parity levels of ^{99}Ru (Ref. 10). The experimental features in these two nuclei are well reproduced by the calculations which seem very promising in explaining the characteristics of nuclei which belong to transitional regions as that at about $A=100$.[36,37]

[1]C. M. Lederer, J. M. Jaklevic, and J. M. Hollander, Nucl. Phys. **A169**, 489 (1971).

[2]L. Mesko, A. Nilsson, S. A. Hjorth, M. Brenner, and O. Holmlund, Nucl. Phys. **A181**, 566 (1972).

[3]J. Dubuc, G. Kajrys, P. Larivière, S. Pilotte, W. Del Bianco, and S. Monaro (to be published).

[4]D. G. Sarantites, Phys. Rev. C **12**, 1176 (1975).

[5]G. Kajrys, M. Irshad, S. Landsberger, R. Lecomte, P. Paradis, and S. Monaro, Phys. Rev. C **26**, 1462 (1982).

[6]G. Kajrys, W. Del Bianco, S. Pilotte, S. Landsberger, and S. Monaro, Phys. Rev. C **31**, 409 (1985).

[7]W. Klamra and J. Rekstad, Nucl. Phys. **A243**, 395 (1975).

[8]M. J. A. de Voigt, J. F. W. Jansen, F. Bruining, and Z. Sujkowski, Nucl. Phys. **A270**, 141 (1976).

[9]M. Brenner, D. Hseuh, W. Klamra, and D. G. Sarantites, Research Institut of Physics, Stockholm, annual report, 1976; D. Hseuh *et al.* (private communication).

[10]E. H. du Marchie Van Voorthuysen, M. J. A. de Voigt, N. Blasi, and J. F. W. Jansen, Nucl. Phys. **A355**, 93 (1981).

[11]G. Kajrys, R. Lecomte, S. Landsberger, and S. Monaro, Phys. Rev. C **28**, 1504 (1983).

[12]G. S. Whisnent, R. H. Castain, F. A. Rickey, and P. C.

Simms, Phys. Rev. Lett. **50**, 724 (1983).
[13]E. Nolte, G. Korschinek, and U. Hein, Z. Phys. A **298**, 191 (1980).
[14]G. Kajrys, M. Irshad, S. Landsberger, R. Lecomte, P. Paradis, and S. Monaro, Phys. Rev. C **26**, 138 (1982).
[15]G. Kajrys, S. Landsberger, and S. Monaro, Phys. Rev. C **28**, 2335 (1983).
[16]P. C. Simms, G. J. Smith, F. A. Rickey, J. A. Grau, J. R. Tesmer, and R. M. Steffen, Phys. Rev. C **9**, 684 (1974).
[17]J. A. Grau, F. A. Rickey, G. J. Smith, P. C. Simms, and J. R. Tesmer, Nucl. Phys. **A229**, 346 (1974).
[18]F. A. Rickey, J. A. Grau, L. E. Samuelson, and P. C. Simms, Phys. Rev. C **15**, 1530 (1977).
[19]P. Fettweis, P. Del Marmol, M. Degreef, P. Duhamel, and J. Vanhorenbeeck, Z. Phys. A **305**, 57 (1982).
[20]P. Larivière, J. Dubuc, G. Kajrys, S. Pilotte, and S. Monaro (to be published).
[21]D. Bucurescu, G. Constantinescu, M. Ivascu, W. Andrejtscheff, B. Bochev, and T. Kutsarova, J. Phys. G **6**, 103 (1980).
[22]J. T. Routti and S. G. Poussin, Nucl. Instrum. **72**, 125 (1969).
[23]H. J. Rose and D. M. Brink, Rev. Mod. Phys. **39**, 306 (1967).
[24]C. L. Hollas, K. A. Aniol, D. W. Gebbie, M. Borsaru, J. Nurzynski, and L. O. Barbopoulos, Nucl. Phys. **A276**, 1 (1977).
[25]L. R. Medsker, L. H. Fry, Jr., and J. L. Yntema, Phys. Rev. C **15**, 649 (1977).
[26]S. Ohya, Nucl. Phys. **A235**, 361 (1974).
[27]*Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978), pp. 377 and 394, and references therein.
[28]R. C. Diehl, B. L. Cohen, R. A. Moyer, and L. H. Goldman, Phys. Rev. C **1**, 2086 (1970).
[29]H. T. Fortune, G. C. Morrison, J. A. Nolen, Jr., and P. Kienle, Phys. Rev. C **3**, 337 (1971).
[30]G. P. A. Berg, M. Demarteau, A. Hardt, W. Hürlimann, S. A. Martin, J. Meissburger, W. Oelert, H. Seyfarth, B. Styczen, M. Köhler, I. Oelrich, and J. Scheerer, Nucl. Phys. **A379**, 93 (1982).
[31]B. Harmatz, Nucl. Data Sheets (N.Y.) **23**, 433 (1979).
[32]H. Seyfarth, K. Schreckenbach, S. Brant, and V. Paar (to be published).
[33]D. R. Haenni, H. Dejbakhsh, R. P. Schmitt, and G. Mouchaty, Cyclotron Institute, Texas A&M University report, pp. 2 and 3 (1982).
[34]P. Chowdhury, B. A. Brown, U. Garg, R. D. McKeown, T. P. Sjoreen, and D. B. Fossan, Phys. Rev. C **32**, 1238 (1985).
[35]A. Arima and F. Iachello, Ann. Phys. (N.Y.) **99**, 253 (1976).
[36]K. Weeks and T. Tamura, Phys. Rev. C **22**, 888 (1980).
[37]J. Stachel, P. Van Isacker, and K. Heyde, Phys. Rev. C **25**, 650 (1982).