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High spin states and band structure in ^{99}Rh and ^{101}Rh

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High spin states in ^{99}Rh and ^{101}Rh have been populated via the ^{96,98}Mo(^{6}Li, $3n$) reaction. Two cascades based on the $\frac{1}{2}^-$ ground state and the $\frac{9}{2}^+$ isomeric state are attributed to each nucleus on the basis of γ-γ coincidence measurements. Excitation functions and angular distribution measurements were used to assign spin values and determine some multipole mixing ratios.

[NUCLEAR REACTIONS ^{96,98}Mo(^{6}Li,$3n$)^{99,101}Rh, $E=18-34$ MeV; measured E_γ, n-γ, γ-γ coincidences, γ-ray angular distributions; ^{99}Rh, ^{101}Rh deduced levels, J^π; enriched targets, Ge(Li) detectors.]

I. INTRODUCTION

The region of nuclei around $A=100$ is very interesting since these nucleides show both quasiparticle and collective modes of excitation. Furthermore, rapid transitions in shape from spherical to deformed are expected in this nuclear region. As part of a systematic study of nuclei in the mass range around $A=100$ (Refs. 1–4) we have investigated high-spin states in ^{99}Rh and ^{101}Rh via the ^{96,98}Mo(^{6}Li,$3n\gamma$) reaction. Most of our knowledge of these two nuclei is limited to the low-spin levels populated in radiative decay[5–7] or as in ^{101}Rh via the ^{103}Rh(p,t) reaction.[8] It is only recently that high-spin positive-parity states have been proposed in ^{99}Rh,[9,10] using heavy ion reactions. However, on the basis of the weak coupling model, which seems to work fairly well in this nuclear region, low-lying negative-parity states are expected to arise from the coupling of the $2p_{1/2}$ proton to the phonon excitations of the corresponding even-even Ru core. Indeed, recently available information on the similar nuclei, ^{97}Tc and ^{99}Tc,[11,12] has shown the presence of cascades based on the $\frac{9}{2}^+$ ground state and the $\frac{1}{2}^-$ first excited isomeric state. Clearly, it would be useful to establish the existence and systematics of such cascade structures also in the Rh isotopes, both as an aid and encouragement to further theoretical studies in this region of nuclei.

II. EXPERIMENTAL PROCEDURES

The ^{6}Li beam from the Chalk River Nuclear Laboratory (CRNL) MP tandem accelerator was used to bombard targets of isotopically enriched ($\sim$97%) ^{96}Mo and ^{98}Mo. The targets were in the form of metallic rolled foils with a thickness of approximately 10 mg/cm^2. In-beam γ-ray singles spectra were obtained with a 72 cm^3 Ge(Li) detector having a resolution of 2.0 keV at 1.33 MeV. The detector was placed 15 cm from the target and at an angle of 90° with respect to the incoming beam. To help identify reaction products, γ-ray spectra in coincidence with neutrons were also recorded and at the end of each irradiation a background spectrum was taken. A 5 cm$\times$17.5 cm NE 213 liquid scintillator, placed at 0° to the beam axis was used for the n-γ coincidence measurements. A typical γ-ray spectrum is shown in Fig. 1. Particular care was taken to identify "unwanted" γ rays coming mainly from the (^{6}Li, αn), (^{6}Li,$2n$) reactions and the beta decay of the parent Rh nucleus to levels in the corresponding Ru isotope.[13] Excitation functions of gamma rays up to 2 MeV in energy were measured in 2 MeV steps between 18 and 34 MeV bombarding energy. From the yields of the 427.1 and 354.8 keV gamma rays deexciting the first $\frac{5}{2}^-$ state in ^{99}Rh and ^{101}Rh, respectively, the peak in the (^{6}Li,$3n$) reaction was estimated to occur at 30 MeV

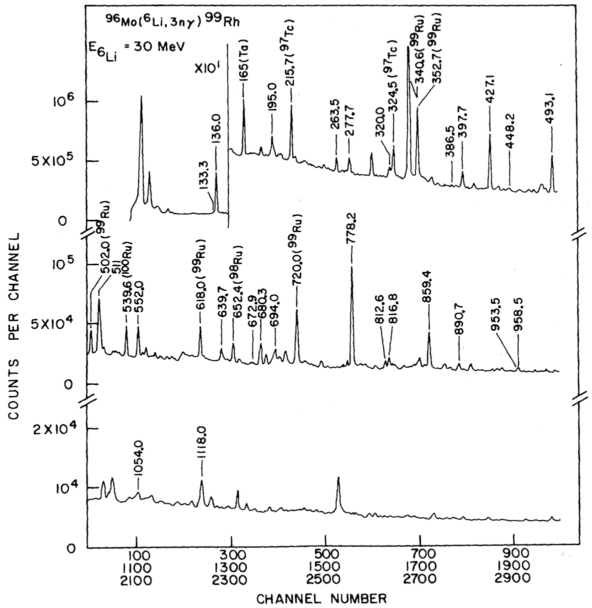

FIG. 1. In beam singles gamma ray spectrum of ^{99}Rh resulting from the ^{96}Mo(^{6}Li,$3n\gamma$) reaction. $E_{\mathrm{Li}}=30$ MeV and $\theta=90°$. Energies are in keV. The labeled photopeaks are assigned to ^{99}Rh unless otherwise indicated.

bombarding energy.

Gamma-ray coincidence and angular distribution measurements were subsequently carried out at $E_{^{6}\mathrm{Li}}=28$ MeV. In the former experiment two Ge(Li) detectors, with active volumes of 96 and 75 cm^3 and having a resolution of 2.1 keV at 1.33 MeV, were used. The two detectors were placed at 55° and 90° to the beam axis and were shielded from one another with a 10 cm lead absorber. Coincidence timing was derived from standard constant-fraction discriminator techniques and a resolving time of 10 ns FWHM on the prompt coincidence peak was obtained. The coincidence events were stored serially on magnetic tapes and a computer sorting procedure was employed off-line to obtain the spectra in coincidence with selected peaks and background gates. Some γ-γ coincidence spectra are shown as an example in Fig. 2. The angular distribution measurements were carried out with the 72 cm^3 Ge(Li) detector placed at 20 cm from the target and the γ ray spectra were recorded at 15° intervals from 90° to 0°, the target being placed at 45° with respect to the incident beam. A 12.5 cm$\times$12.5 cm NaI(Tl) detector, placed at $-90°$ to the beam axis, was used as a monitor to normalize the number of counts at each angle. The total incident charge was also collected for the same purpose. All the gamma ray yields for the excitation functions and angular distributions were determined employing the peak fitting program SAMPO.[14] The basis of the analytical procedure used to obtain information on spins and multipole mixing ratios from transition gamma rays following (HI, xn) reactions is well documented.[15] Limiting values for the excited state spins are established from the gamma ray excitation functions and a χ^2 fit to the angular distribution data carried out for each possible initial spin using two free parameters, the $E2$-$M1$ multipole mixing ratio δ and the Gaussian width σ used to determine the population parameters of the aligned state. The measured angular distributions were fitted to the usual function

$$W(\theta)=A_0[\,1+A_2Q_2P_2(\cos\theta)+A_4Q_4P_4(\cos\theta)]$$

where Q_K are the attenuation coefficients of the gamma-ray counter.[16] Some typical examples of gamma ray angular distributions are presented in Fig. 3.

III. THE LEVEL SCHEMES

A. ^{99}Rh

The results obtained for ^{99}Rh are summarized in Table I and the decay scheme deduced from γ-γ coincidences, gamma ray excitation functions, and angular distribution measurements is shown in Fig. 4. A number of levels which are connected by strong transitions or which have similar characteristics will be discussed together. Other levels will be considered in a successive part of the discussion.

1. Negative parity levels

The ground state and the 427.1, 979.1, 1659.4, and 2299.1 keV states form a sequence connected by strong transitions. The ground state of ^{99}Rh is known to have spin $\frac{1}{2}^-$ and only the lowest excited state at 427.1 keV was observed in the beta decay of ^{99}Pd and spin $\frac{5}{2}^-$ assigned[5] which is consistent with our data on the 427.1 keV transition. The excitation functions and angular distributions of the 552.0, 680.3, and 639.7 keV gamma rays establish spins of $\frac{9}{2}$, $\frac{13}{2}$, and $\frac{17}{2}$ for the levels at 979.1, 1659.4, and 2299.1 keV. Obviously, owing to the very probable nature of these transitions (strong $E2$)

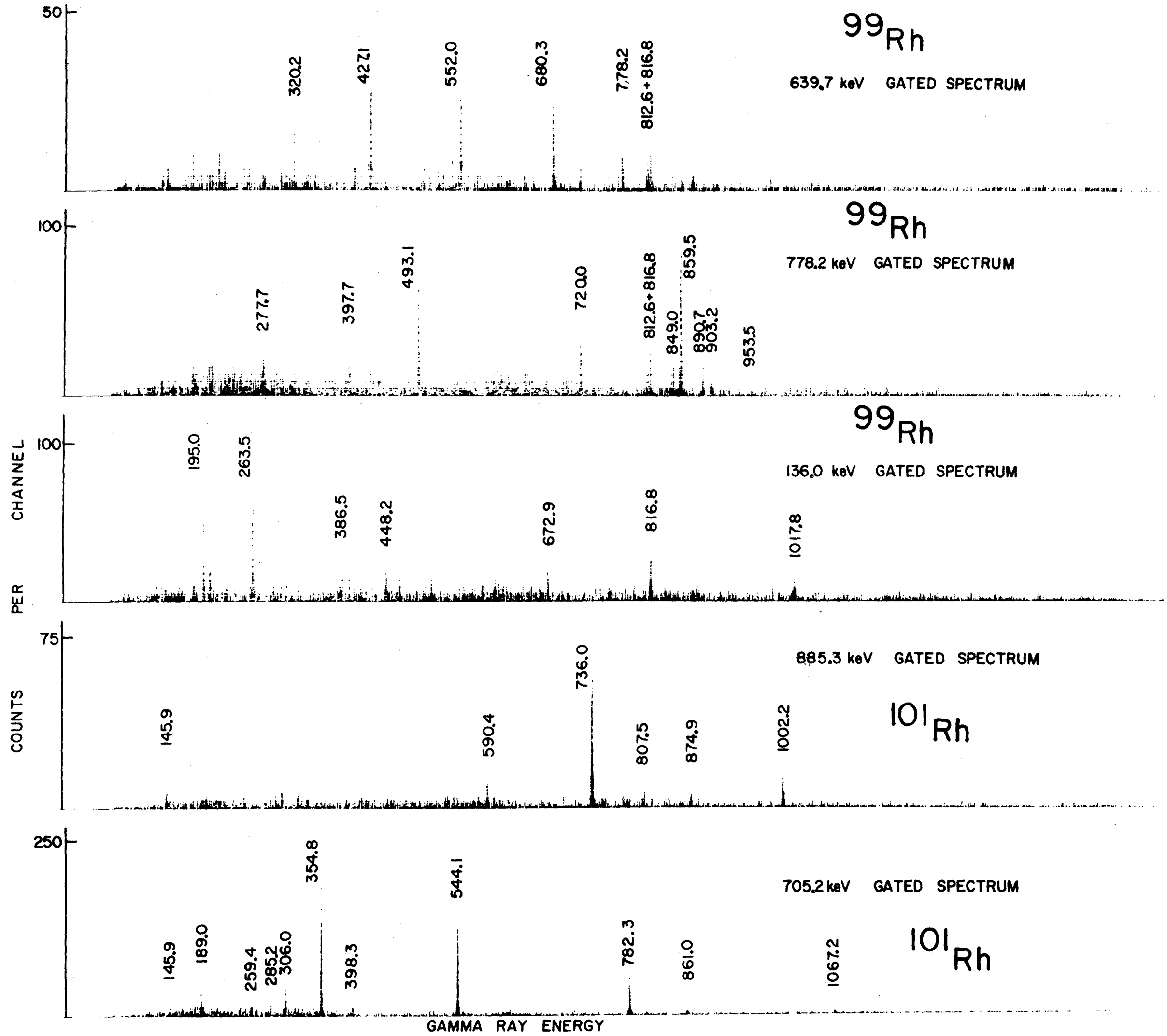

FIG. 2. Selected γ-γ coincidence-gated spectra of transitions in ^{99}Rh and ^{101}Rh. Energies are in keV. The shown spectra are corrected for background and random coincidences.

the parity of these levels must be negative. These spin-parity assignments are also supported by the fact that no crossover transitions are observed in the cascade. This would exclude the possibility that the higher lying state in the cascade has a spin equal to or lower than that of a lower lying level.

Two additional states at 2617.9 and 3111.7 keV are also suggested by the coincidence data. From the excitation function and the angular distribution of the 958.5 keV gamma ray a spin $\frac{17}{2}$ is assigned to the former level. The parity of the 2617.9 keV state is, most probably, negative due to its deexcitation mode. For the weak 320 keV transition, the angular distribution analysis is consistent with this assignment. No reliable information could be obtained for the 3111.7 keV level since the 812.6 keV transition deexciting it is weak and is also strongly mixed with the $6^+ \rightarrow 4^+$ gamma ray from the Coulomb excitation of ^{96}Mo. This level is placed in this section of the discussion only on the somewhat weak argument that it deexcites to a member of the negative parity cascade.

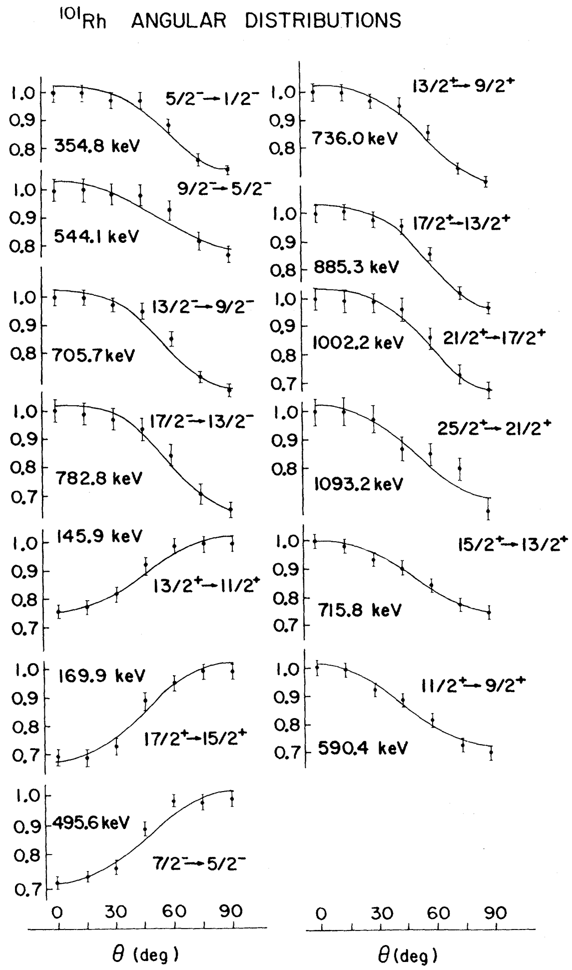

FIG. 3. Typical angular distributions for transitions in ^{101}Rh. The solid curve represents the best fit to the relative yields for the given spin values varying the parameters σ and δ as explained in the text.

2. *Positive parity levels*

As mentioned earlier a high-spin cascade based on the $\frac{9}{2}^+$ isomeric state[18] has been previously suggested[9,10] which is consistent with our data. The 778.2 keV gamma ray is the strongest line in the singles spectrum and forms a yrast cascade together with the 859.4 and 890.7 keV lines. The angular distributions of these gamma rays clearly indicate quadrupole transitions; consequently we assign the following spins: $\frac{13}{2}^+$ (842.8 keV), $\frac{17}{2}^+$ (1702.2 keV), and $\frac{21}{2}^+$ (2592.9 keV). Of course it is impossible to prove by the coincidence technique that this cascade feeds the 64.6 keV isomeric state because of its long lifetime. This placement, however, is supported both by the fact that the 778.2 keV gamma ray is the strongest transition in ^{99}Rh and that it is not observed in the beta decay of ^{99}Pd (Ref. 5) and by more direct evidence which will be discussed in the next section.

Other high-energy levels previously seen[9] and confirmed in this work are those at 2195.3 and 3148.8 keV. A $\frac{19}{2}^+$ spin is assigned to the 2195.3 keV state on the basis of the dipole nature of the 493.1 and 397.7 keV transitions. A $\frac{23}{2}^+$ spin is instead assigned to the 3148.8 keV level since it deexcites via a quadrupole transition to the 2195.3 keV, $\frac{19}{2}^+$ state. Levels at 2930.9, 3207.7, and 4326 keV were also previously detected.[9] The existence of the latter two levels is confirmed in this work via coincidence measurements. However, the placement of the 277.7 keV gamma ray above the 337 keV transition is not supported in the present study since the intensity of the former gamma ray seems larger than that of the latter. Thus the 2930.0 keV level should be replaced by a 2870.6 keV state. No reliable information could be obtained for all these levels since the 277.7 and 337 keV transitions are strongly mixed with other lines from ^{99}Ru and the 1118.0 keV gamma ray is very weak. We have no evidence for the other high-energy states seen by Piel and Scharff-Goldhaber[9] presumably from angular momentum limitations. However, additional levels at 2726.2, 2889.3, and 3780.0 are suggested from γ-γ coincidence data. Unfortunately no spin assignment can be made in this work for the gamma rays deexciting these states are weak or masked by nearby strong lines.

3. *Low-energy levels*

Very few of the low energy and spin states observed in the decay of ^{99}Pd (Ref. 5) were seen in the present investigation. The 263.5, 386.5, and 672.9 keV gamma rays are in coincidence with the known 136.0 keV transition deexciting the $\frac{7}{2}^+$ 200.6 keV level. The 263.5 and 386.5 keV gamma rays are also seen in coincidence with each other. All this establishes the excitation via the ^{96}Mo(^{6}Li,3n) reaction of the previously observed levels at 464.1, 850.6, and 873.5 keV. All the other known transitions deexciting these states[5] which have been observed in the singles spectrum, were placed in the decay scheme of ^{99}Rh (Fig. 4) as reported in Ref. 5. The (136.0−816.8) keV coincidence establishes an already known level at 1017.4 keV.[5] The 816.8 keV coincidence gate bears a particular significance for the ^{99}Rh level structure since it seems to yield some

TABLE I. Summary of level energies, γ-ray energies, relative intensities, J^π values, and angular distribution results for transitions in ^{99}Rh determined in this work. The sign of the mixing ratio follows the convention of Rose and Brink (Ref. 17).

Level energy (keV)	γ-ray energy (keV)	Relative intensity %	$J_i^\pi \rightarrow J_f^\pi$	$A_2^{\rm exp}$	$A_4^{\rm exp}$	$\delta(E2/M1)$
200.6	136.0[a]		$\frac{7}{2}^+ \rightarrow \frac{9}{2}^+$			
427.1	427.1	100	$\frac{5}{2}^- \rightarrow \frac{1}{2}^-$	0.235(0.015)	−0.088(0.019)	$E2$
464.1	263.5	15.2(0.5)	$\frac{5}{2}^+ \rightarrow \frac{7}{2}^+$	0.065(0.016)	−0.040(0.020)	$+0.43^{+0.18}_{-0.21}$
842.8	778.2[b]	304.6(5.0)	$\frac{13}{2}^+ \rightarrow \frac{9}{2}^+$	0.273(0.008)	−0.069(0.010)	$E2$
850.6	386.5[c]	$\lesssim$2.0(0.3)	$(\frac{7}{2}^+) \rightarrow \frac{5}{2}^+$			
873.5	672.9[c]	6.3(0.5)	$(\frac{5}{2}^+) \rightarrow \frac{7}{2}^+$	−0.074(0.026)	−0.008(0.03)	
979.1	552.0	71.4(1.0)	$\frac{9}{2}^- \rightarrow \frac{5}{2}^-$	0.290(0.015)	−0.107(0.020)	$E2$
1017.4	816.8[d]	38.0(2.0)	$\rightarrow \frac{7}{2}^+$			
1659.4	680.3	47.0(2.0)	$\frac{13}{2}^- \rightarrow \frac{9}{2}^-$	0.221(0.015)	−0.093(0.020)	$E2$
	816.8[d]	38.0(2.0)	$\frac{13}{2}^- \rightarrow \frac{13}{2}^+$			
1702.3	859.4	110.5(2.0)	$\frac{17}{2}^+ \rightarrow \frac{13}{2}^+$	0.326(0.007)	−0.129(0.010)	$E2$
2195.3	493.1	41.7(1.0)	$\frac{19}{2}^+ \rightarrow \frac{17}{2}^+$	−0.155(0.016)	−0.024(0.018)	$M1$
2299.1	639.7	27.8(1.0)	$\frac{17}{2}^- \rightarrow \frac{13}{2}^-$	0.304(0.023)	−0.092(0.031)	$E2$
2592.9	890.7	18.8(0.5)	$\frac{21}{2}^+ \rightarrow \frac{17}{2}^+$	0.297(0.015)	−0.169(0.020)	$E2$
	397.7	15.9(0.5)	$\frac{21}{2}^+ \rightarrow \frac{19}{2}^+$	−0.093(0.024)	−0.027(0.026)	$M1$
2617.9	958.5	$\lesssim$4.0(0.3)	$\frac{17}{2}^{(-)} \rightarrow \frac{13}{2}^-$	0.276(0.061)	−0.184(0.076)	$E2$
	320[e]	$\lesssim$10.6(0.5)	$\frac{17}{2}^{(-)} \rightarrow \frac{17}{2}^-$	0.096(0.038)	−0.030(0.045)	
2726.2	133.3[e]	$\lesssim$9.5(0.5)	$\rightarrow \frac{21}{2}^+$			
2870.6	277.7[e]	9.00(0.5)	$\rightarrow \frac{21}{2}^+$			
2889.3	694.0[f]	15.0(1.0)	$\rightarrow \frac{19}{2}^+$			
3111.7	812.6[g]	25.0(1.0)	$\rightarrow \frac{17}{2}^-$			
3148.8	953.5	13.5(1.0)	$\frac{23}{2}^+ \rightarrow \frac{19}{2}^+$	0.266(0.015)	−0.120(0.020)	$E2$
3207.7	$\approx$337[e,h]					
3780.0	1054.0[e]					
4325.7	1118.0[e,f]	18.0(2.0)				

[a]Doublet with 136.0 keV line from ^{181}Ta used for the collimators and the Faraday cage.
[b]Triplet gamma ray line from ^{99}Rh, ^{96}Mo [Coulomb excitation ($2^+ \rightarrow 0^+$)], and ^{99}Ru (1321.6 keV level). Total intensity only.
[c]Too weak for a reliable spin determination but evident from the γ-γ coincidence data.
[d]Doublet in ^{99}Rh. Total intensity only.
[e]Probable placement from γ-γ coincidence data only.
[f]Closely spaced doublet in the spectrum. Total intensity only.
[g]Doublet with $6^+ \rightarrow 4^+$, ^{96}Mo, Coulomb excitation gamma ray. Total intensity only.
[h]Masked by intense 340.7 keV line from ^{99}Ru.

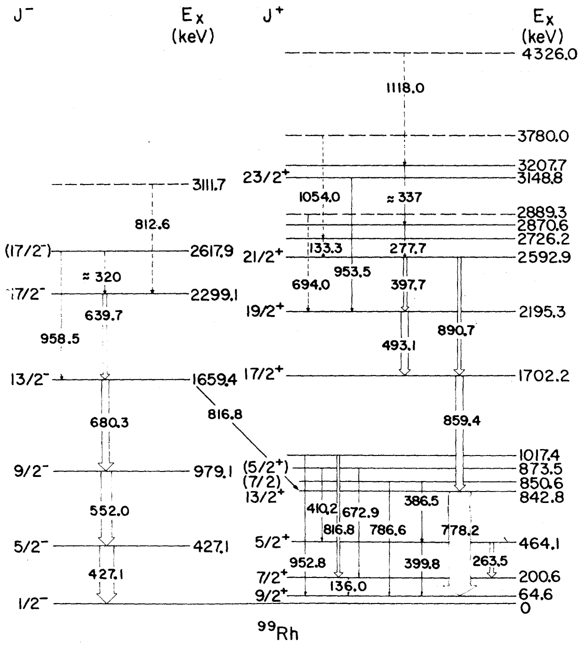

FIG. 4. Level scheme of ^{99}Rh as derived from this study. Energies are in keV and the width of the arrows indicates the relative intensities of the transitions. Dashed lines indicate levels or gamma rays whose position in the level scheme is doubtful. The spins and parities enclosed in parentheses are considered probable but not definitely established.

direct support to the placement of the 778.2 keV gamma ray above the 64.6 keV $\frac{9}{2}^+$ isomeric state. In fact, the 816.8 gated spectrum shows besides the strong 136.0 keV gamma ray, the presence of weaker peaks at 639.7, 778.2, and 958.2 keV. Thus the 816.8 keV gamma ray seems to be a doublet whose weaker member connects the 1659.4 keV level with the level deexcited by the 778.2 keV transition. Indeed if the 778.2 keV gamma ray feeds the 64.6 keV isomeric state a 817 keV transition would fit nicely between the 1659.4 ($\frac{13}{2}^-$) and 842.8 ($\frac{13}{2}^+$) keV levels explaining the above coincidence data. The spin of the 1017.4 keV level could not be determined in this work because of the doublet nature of the 816.8 keV transition and the weakness of the 952.8 keV gamma ray which is known to decay to the 64.4 keV $\frac{9}{2}^+$ isomeric state.[5]

B. ^{101}Rh

The results obtained for ^{101}Rh are summarized in Table II and the decay scheme deduced from γ-γ coincidences, gamma ray excitation functions, and angular distribution measurements is shown in Fig. 5.

1. Negative parity levels.

A cascade based on the 354.8 keV transition to the $\frac{1}{2}^-$ ground state of ^{101}Rh (Refs. 6–8) was observed in the present work. The excitation functions and the quadrupole nature established from the angular distributions of the 354.8, 544.1, 705.2, and 782.2 keV gamma rays assign spins $\frac{5}{2}^-$, $\frac{9}{2}^-$, $\frac{13}{2}^-$, and $\frac{17}{2}^-$ to the 354.8, 898.9, 1604.1, and 2386.3 keV levels, respectively. This confirms the earlier work of Del Vecchio *et al.*[8] who, using the ^{103}Rh(p,t) reaction, assigned $l=2$ and $l=4$ angular momentum transfer to states at 355 and 898 keV, respectively. The existence of a $\frac{7}{2}^-$ level at 1604.3 keV was also suggested in the decay of ^{99}Pd.[7] This state, however, cannot be the same since its deexcitation mode is completely different[7] and our data strongly support a $\frac{13}{2}^-$ spin assignment.

2. The 305.0, 850.4, and 1576.5 keV levels

States at 305 and 850 keV were evinced by Del Vecchio *et al.*[8] who assigned spins $\frac{3}{2}^-$ and $\frac{7}{2}^-$, respectively. These two levels are weakly excited in the present study. The known 305 keV transition decaying to the $\frac{1}{2}^-$ ground state[6,7] is masked by the intense 306.8 keV gamma ray from ^{101}Ru (Ref. 13) and by another 306 keV transition detected in coincidence with all the members of the cascade previously discussed. The level at 850 keV is confirmed in this work via the existence of a 495.6 keV gamma ray decaying to the $\frac{5}{2}^-$ 354.8 keV state. However, the excitation function of the 495.6 keV transition suggests a $\frac{3}{2}^-$ spin assignment more than $\frac{7}{2}^-$.[8]

The existence of a level at 1576.5 keV is suggested from γ-γ coincidence measurements. However, no spin assignment could be made because of the weakness of the 677.6 keV transition decaying to the $\frac{9}{2}^-$ 898.9 keV state.

3. Levels above 2386.3 keV

The γ-γ coincidence data support the existence of several levels above the $\frac{17}{2}^-$ 2386.3 keV state. A level is proposed at 2671.5 keV, deexciting by a

TABLE II. Summary of level energies, γ-ray energies, relative intensities, J^π values, and angular distribution results for transitions in ^{101}Rh determined in this work.

Level energy (keV)	γ-ray energy (keV)	Relative intensity %	$J_i^\pi \rightarrow J_f^\pi$	A_2^{exp}	A_4^{exp}	$\delta(E2/M1)$
305.0	305.0[a]	$\lesssim$14(2)	$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$			
354.8	354.8	75.6(1.0)	$\frac{5}{2}^- \rightarrow \frac{1}{2}^-$	0.250(0.007)	−0.109(0.010)	$E2$
478.1	296.0[b]	10.3(0.5)	$\frac{5}{2}^+ \rightarrow \frac{7}{2}^+$	0.028(0.017)	−0.064(0.021)	$+0.06^{+0.3}_{-0.2}$
747.7	590.4	50.2(1.0)	$\frac{11}{2}^+ \rightarrow \frac{9}{2}^+$	0.255(0.008)	−0.03(0.01)	$-0.68^{+0.12}_{-0.14}$
	270.0[c]	$\lesssim$3.0(0.5)	$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$			
850.4	495.6[d]	8.4(0.5)		−0.225(0.016)	−0.026(0.018)	$M1$
			$\frac{3}{2}^- \rightarrow \frac{5}{2}^-$			
893.3	736.0	100	$\frac{13}{2}^+ \rightarrow \frac{9}{2}^+$	0.298(0.007)	−0.122(0.010)	$E2$
	145.9[e]	17.5(0.8)	$\frac{13}{2}^+ \rightarrow \frac{11}{2}^+$	−0.170(0.016)	−0.035(0.018)	$M1$
898.9	544.1[e]	77.8(3.0)	$\frac{9}{2}^- \rightarrow \frac{5}{2}^-$	0.197(0.015)	−0.104(0.019)	$E2$
977.8	230.1	$\lesssim$2.0(0.5)	$(\frac{9}{2})^+ \rightarrow \frac{11}{2}^+$ or $(\frac{9}{2})^+ \rightarrow \frac{7}{2}^+$			
1576.5	677.6[g]		$\rightarrow \frac{9}{2}^-$			
1604.1	705.2	49.2(1.0)	$\frac{13}{2}^- \rightarrow \frac{9}{2}^-$	0.302(0.007)	−0.126(0.010)	$E2$
1607.3	859.6[f]	≈27.5(2.0)	$\rightarrow \frac{11}{2}^+$			
1609.1	861.1[f]	≈27.5(2.0)	$\frac{15}{2}^+ \rightarrow \frac{11}{2}^+$			
	715.8	19.4(0.8)	$\frac{15}{2}^+ \rightarrow \frac{13}{2}^+$	0.206(0.012)	−0.036(0.015)	$-0.59^{+0.17}_{-0.14}$
1778.6	885.3	50.8(1.0)	$\frac{17}{2}^+ \rightarrow \frac{13}{2}^+$	0.307(0.007)	−0.131(0.010)	$E2$
	169.9	3.1(0.5)	$\frac{17}{2}^+ \rightarrow \frac{15}{2}^+$	−0.246(0.027)	−0.025(0.032)	$M1$
2386.3	782.2	31.1(1.0)	$\frac{17}{2}^- \rightarrow \frac{13}{2}^-$	0.321(0.015)	−0.131(0.020)	$E2$
2586.1	807.5	6.5(0.5)	$\rightarrow \frac{17}{2}^+$			
2653.6	875.0	$\lesssim$5.0(0.5)	$\rightarrow \frac{17}{2}^+$			
2671.5	1067.2	8.4(0.3)	$(\frac{17}{2}^-) \rightarrow \frac{13}{2}^-$	0.173(0.015)	−0.058(0.019)	$E2$
	285.2	2.5(0.2)	$(\frac{17}{2}^-) \rightarrow \frac{17}{2}^-$	0.329(0.040)	−0.072(0.050)	
2780.8	1002.2	16.3(0.8)	$\frac{21}{2}^+ \rightarrow \frac{17}{2}^+$	0.299(0.016)	−0.014(0.02)	$E2$
2784.6	398.3	3.2(0.5)	$\rightarrow \frac{17}{2}^-$			

TABLE II. (*Continued.*)

Level energy (keV)	γ-ray energy (keV)	Relative intensity %	$J_i^\pi \to J_f^\pi$	A_2^{exp}	A_4^{exp}	$\delta(E2/M1)$
2930.9	259.4	4.6(0.5)	$\to (\frac{17}{2}^-)$			
	145.9^e	17.5(0.8)				
	544.6^e	77.8(3.0)	$\to \frac{17}{2}^-$			
3247.3	861.0^f	≈27.5(2.0)	$\to \frac{17}{2}^-$			
3553.3	306^a					
or	or					
3436.3	189	10.7(0.5)				
3744.3	189 or 306	10.7(0.5)				
3874.0	1093.2	2.5(.15)	$\frac{25}{2}^+ \to \frac{21}{2}^+$	0.271(0.040)	−0.076(0.051)	$E2$

^{a}Doublet with intense 306.8 keV line from ^{101}Ru.
^{b}Doublet with 295.0 keV line from ^{101}Ru.
^{c}Very weak transition here indicates a $\frac{7}{2}^+$, $\frac{11}{2}^+$ doublet level at 747.7 keV. See text.
^{d}The excitation function for this transition suggests a spin of $\frac{3}{2}^-$ for this level.
^{e}Doublet γ ray in ^{101}Rh. Total intensity only.
^{f}Unresolved triplet. Total intensity only.
^{g}Very weak transition. Level suggested from γ-γ coincidence data only.

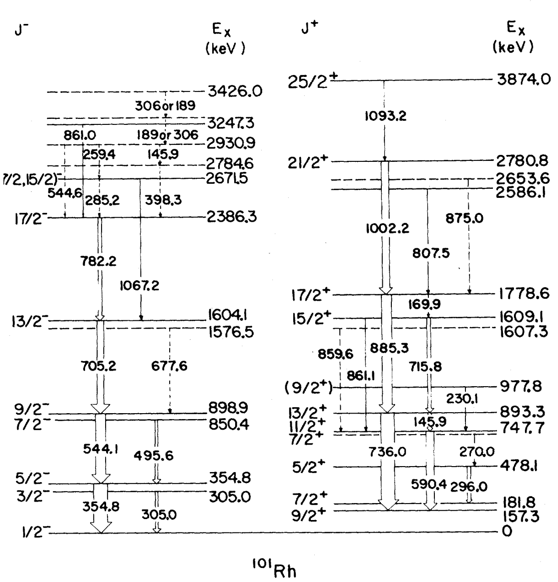

FIG. 5. Level scheme of ^{101}Rh as derived from this study. (See caption of Fig. 4.)

1067.2 keV transition to the $\frac{13}{2}^-$ 1604.1 keV level and by a weak 285.2 keV transition to the $\frac{17}{2}^-$ state at 2386.3 keV. The angular distribution and excitation function of the 1067 keV gamma ray suggest a $\frac{17}{2}$ or $\frac{15}{2}$ spin assignment. Because of the almost pure quadrupole nature of this transition, the parity of the 2671 keV level must be negative. The level order above 2671.5 keV is difficult to determine. However, two pairs of coincident weak gamma rays whose sum add to ~545 keV are observed and have been placed in their most likely positions (see Fig. 5) giving rise to levels at 2784.6 and 2930.9 keV. The existence of the 2930.9 keV state would also allow the placement of a 545 keV transition decaying to the 2386.3 keV level. In fact, the 544.1 ($\frac{9}{2}^- \to \frac{5}{2}^-$) keV gamma ray is seen in coincidence with itself and the weaker member of this doublet fits very well between the 2930.9 and 2386.3 keV levels.

189.0 and 306.0 keV gamma rays, which are in coincidence with all members of the $\frac{1}{2}^-$ ground state cascade, have been placed above the 2930.9 keV level. The 189 keV transition is quite intense and has a high-spin character. In addition, an 861 keV gamma ray was found in coincidence with all members of the $\frac{1}{2}^-$ ground state cascade requiring the existence of a level at 3247.3 keV. No spin could be assigned to this level since the 861 keV gamma ray is strongly admixed with transitions of the same energy (see below).

4. Positive parity levels

A (736.0 — 885.3 — 1002.2 — 1093.2) keV gamma ray cascade was observed in this work and it has been placed on the $\frac{9}{2}^+$ isomeric state of ^{101}Rh.[18] This placement, even though not directly evidenced in this study, seems reasonable considering the fact that the 736.0 keV gamma ray is the most intense line in the singles spectrum and its excitation function supports a high spin value ($\geq \frac{11}{2}$). The possible placement above the $\frac{7}{2}^+$ 181.8 keV state is rejected from systematics considerations (see ^{99}Rh and Refs. 11 and 12) and from the fact that in this case crossover transitions in the cascade could be expected. The excitation functions and the quadrupole nature of all members of this cascade strongly suggest spins of $\frac{13}{2}^+$, $\frac{17}{2}^+$, $\frac{21}{2}^+$, and $\frac{25}{2}^+$ for the levels at 893.3, 1778.6. 2780.8, and 3874.0 keV, respectively.

5. The 747.7 and 1609.1 keV levels

These two levels are established from γ-γ coincidence measurements. The negative A_2 coefficient of the intense 145.9 keV line strongly suggests an $\frac{11}{2}^+$ assignment for the 747.7 keV level. This is also consistent with the angular distribution of the equally intense 590.4 keV gamma ray. A $\frac{7}{2}^+$ level at 747.7 keV has previously been found in the decay of ^{101}Pd (Refs. 6 and 7) deexciting mainly by 590.4 and 270.0 keV transitions with an intensity ratio of 2 to 1. However, in the present work, the 270 keV transition was observed only weakly and the level at 747.7 keV is most likely a $\frac{7}{2}^+$ and $\frac{11}{2}^+$ doublet. A spin assignment of $\frac{15}{2}^+$ is suggested for the 1609.1 keV state, from the angular distribution data of the 169.9 and 715.8 keV gamma rays deexciting the 1778.6 ($\frac{17}{2}^+$) and 1609.1 keV levels, respectively.

6. Additional positive parity levels

The existence of several additional levels was suggested by the γ-γ coincidence data and have been included in Fig. 5. The 807.5, 875.0, and 859.6 keV transitions were seen as unresolved lines in the singles spectra while the 230.1 and 270.0 (see above) keV gamma rays were seen only weakly. Thus good angular distributions and excitation functions could not be obtained for most of these transitions hampering the spin assignment of the levels deexcited (or excited) by them. The $\frac{5}{2}^+$ and $\frac{9}{2}^+$ spins of the 478.1 and 977.8 keV states, respectively, have previously been inferred.[7] Finally, the isotropic distribution of the 296.0 keV gamma ray deexciting the $\frac{5}{2}^+$ level at 478.1 keV disagrees with the large $E2$ mixture found in the decay of ^{101}Pd.[7] Possibly, this is due to the presence of a contaminant 296 keV gamma ray in ^{101}Ru populated by the decay of ^{101}Rh.[13]

IV. CONCLUSION

A spectroscopy study of ^{99}Rh and ^{101}Rh has been made via the ^{96,98}Mo(^{6}Li,3n) reaction to improve the knowledge of the level structure of these two nucleides. The most important finding of the present work is the assessment in both nuclei of yrast cascades, consisting of $E2$ transitions, built on the $\frac{1}{2}^-$ and $\frac{9}{2}^+$ ground and isomeric state, respectively. The finding of the high-spin cascade built on the $\frac{9}{2}^+$ isomeric state of ^{99}Rh definitely confirms its existence as previously inferred.[9,10] The other yrast cascades are reported here for the first time.

It is difficult at this point to give an explanation of the origin and nature of these yrast cascades since no theoretical calculations on the Rh nuclei are available. The positive-parity cascade could possibly be discussed in terms of the rotation-aligned coupling (RCA) model[19,20] as has been done in the case of similar nuclei around the $N=50$ region.[21,22] In this model the odd particle is decoupled from the even-even core by the Coriolis force, producing level spacings in the odd-A nucleus similar to those of the core. As shown in Fig. 6 this is not the case for ^{99}Rh and ^{101}Rh since the levels have significantly higher energies than those in the core. Furthermore, above and below the $\frac{17}{2}^+$ state in ^{99}Rh and ^{101} Rh, respectively, there are excited levels that could be better explained in the framework of a weak coupling picture. The yrast states, however, are more preferentially excited than these levels. Also the negative-parity bands bear a resemblance to decoupled bands expected in the RCA model.[19,20] There is, however, no theoretical reason for expecting such a coupling to occur for a $p_{1/2}$

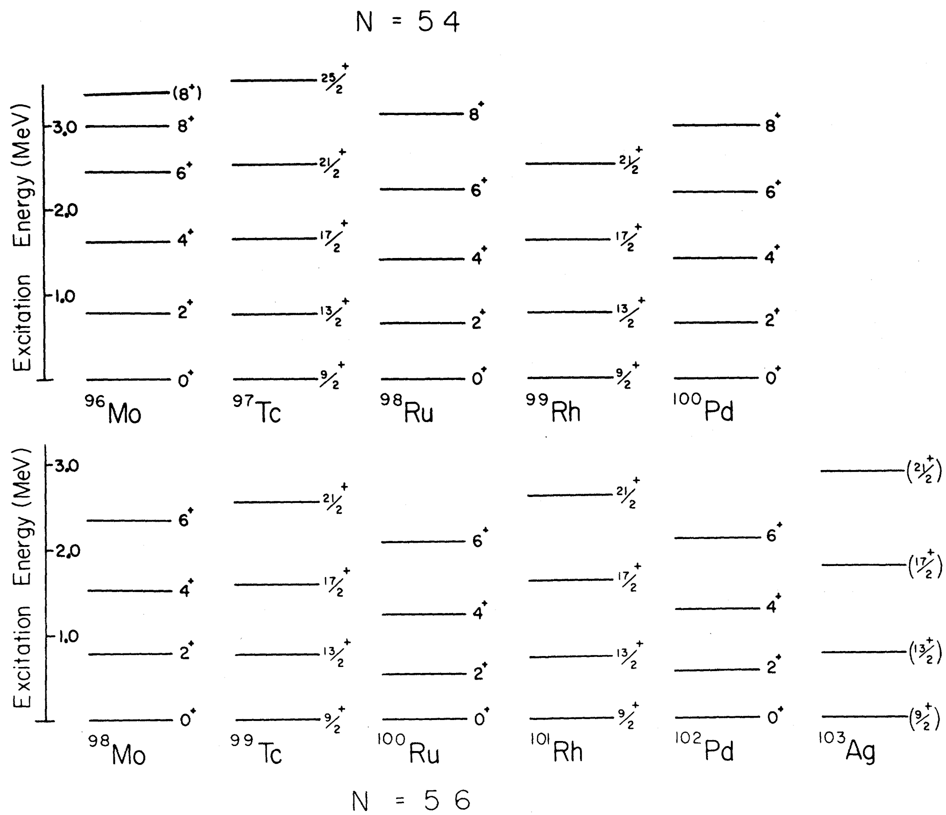

FIG. 6. Comparison of the positive-parity bands in ^{99}Rh and ^{101}Rh with the ground state bands in the neighboring even-even isotopes. Similar bands reported in some Tc nuclei and ^{103}Ag are also shown for completeness. For ease of comparison the energies of the odd-A states in ^{99}Rh, ^{101}Rh, and ^{103}Ag have been shifted so that the $\frac{9}{2}^+$ states line up with 0^+ ground states. See Refs. 22, 11, 12, 23, and 24 for the data on ^{95}Tc, ^{97}Tc, ^{99}Tc, and ^{103}Ag, respectively.

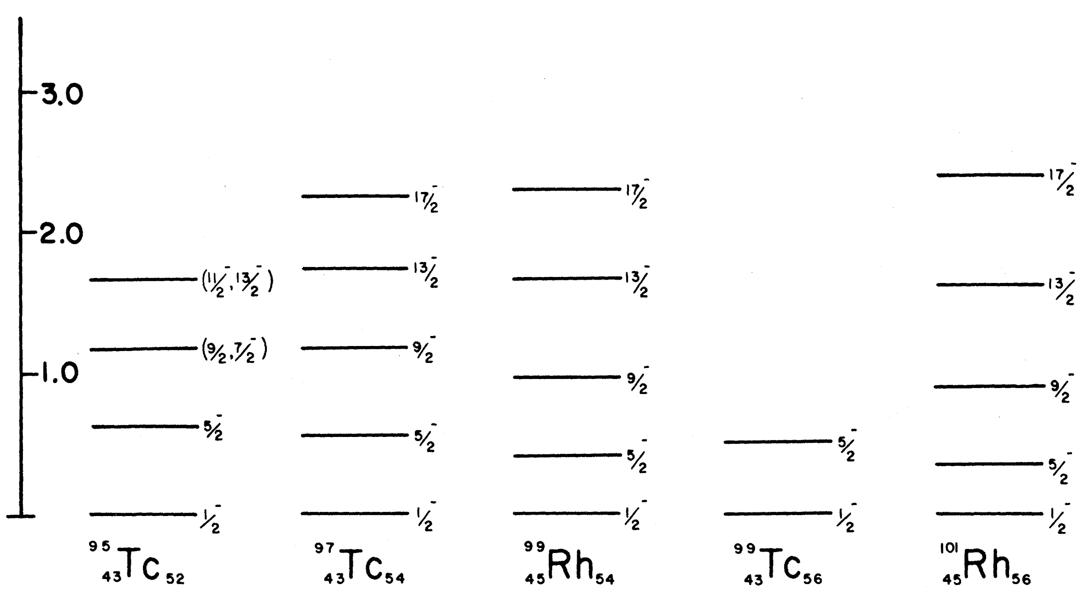

FIG. 7. Comparison of the negative-parity bands in some Tc and Rh nuclei. See Refs. 22, 11, 12, and 13 for the data on ^{95}Tc, ^{97}Tc, and ^{99}Tc, respectively, Very little information is available on ^{99}Tc and none on ^{103}Ag. For ease of comparison the energies of the odd-A states in the Tc nuclei have been shifted so that the $\frac{1}{2}^-$ states line up with those of ^{99}Rh and ^{101}Rh.

particle (or hole) state. It should be remarked that the negative parity band is more strongly excited in ^{101}Rh than in ^{99}Rh whereas the opposite is true for the positive parity band. This trend is even more emphasized in ^{97}Rh and ^{103}Rh as observed in a similar work recently performed in this laboratory on these two nuclei. Similar positive- and negative-parity bands have also been found in ^{95}Tc (Ref. 23) and ^{97}Tc (Refs. 11 and 12) whereas only positive-parity yrast states have been reported in ^{99}Tc (Ref. 24) and also in ^{103}Ag and ^{105}Ag.[25] For the odd-A technetium isotopes some theoretical work is available.[26,27] The positive- and negative-parity bands in the Tc nuclei are suggested as arising essentially from a $(\pi g_{9/2})^3$ and a $(\pi g_{9/2})^4(\pi p_{1/2})^{-1}$ cluster, respectively, coupling to the quadrupole vibrations of the core. These calculations, which are based on the particle-vibrational coupling model of Alaga and Paar,[28] could be extended to the odd-A Rh nucleides as well since the band structure of these nuclei bear an amazing resemblance to that of the Tc nuclei as can be seen in Figs. 6 and 7. However, these calculations fail considerably in explaining the nuclear properties of the odd-A Tc nuclei,[4] and thus their application to the odd-A Rh isotopes does not entail any optimism. Clearly these transitional nuclei which display both collective and single-particle features, require a better experimental knowledge and a more systematical study of their properties. This would be of invaluable help in setting up more reliable theoretical predictions.

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[1]J. Barrette, M. Barrette, R. Haroutunian, G. Lamoureux, S. Monaro, and S. Markiza, Phys. Rev. C 11, 171 (1975).

[2]P. Paradis, G. Lamoureux, R. Lecomte, and S. Monaro, Phys. Rev. C 14, 835 (1976).

[3]S. Landsberger, R. Lecomte, P. Paradis, and S. Monaro, Phys. Rev. C 21, 588 (1980).

[4]S. Landsberger, R. Lecomte, P. Paradis, and S. Monaro, Nucl. Phys. A339, 238 (1980).

[5]M. E. Phelp and D. G. Sarantites, Nucl. Phys. A135, 116 (1969).

[6]M. E. Phelp and D. G. Sarantites, Nucl. Phys. A159, 113 (1970).

[7]B. Nyman, J. Sieniawski, and H. Petterson, Phys. Scr. 5, 13 (1972).

[8]R. M. Del Vecchio, R. A. Naumann, J. R. Duran, H. Hübel, and W. W. Daehnick, Phys. Rev. C 12, 69 (1975).

[9]W. F. Piel, Jr. and G. Schraff-Goldhaber, Phys. Rev. C 15, 287 (1977).

[10]A. H. Lumpkin, L. H. Harwood, L. A. Parks, and J. D. Fox, Phys. Rev. C 17, 376 (1978).

[11]D. Hippe, H. W. Schuh, A. Rademacker, K. O. Zell, P. von Brentano, A. Gelberg, and D. B. Fossan, in *Proceedings of the International Conference on the Structure of Medium-Heavy Nuclei, Rhodes, 1979* (The Institute of Physics, Bristol, 1980), p. 252.

[12]G. Kajrys, R. Lecomte, S. Landsberger, P. Paradis, and S. Monaro, Phys. Rev. C (to be published).

[13]*Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978), pp. 423–444.

[14]J. T. Routti and S. G. Prussin, Nucl. Instrum. Methods 72, 125 (1969).

[15]P. Taras and B. Haas, Nucl. Instrum. Methods 123, 73 (1975).

[16]J. Barrette, G. Lamoureux, and S. Monaro, Nucl. Instrum. Methods 93, 1 (1971).

[17]H. J. Rose and D. M. Brink, Rev. Mod. Phys. 39, 306 (1967).

[18]H. Rubinsztein and M. Gustafsson, Phys. Lett. 58B, 283 (1975).

[19]F. S. Stephens, R. M. Diamond, and S. D. Nilsson, Phys. Lett. 44B, 429 (1973).

[20]F. S. Stephens, Rev. Mod. Phys. 47, 43 (1975).

[21]J. S. Clements, L. R. Medsker, L. H. Fry, Jr., and L. V. Theisen, Phys. Rev. C 21, 1285 (1980), and references therein.

[22]D. Bucurescu, G. Constantinescu, M. Ivascu, N. V. Zamfir, M. Avrigeanu, and D. Cutoin, J. Phys. G. 7, 667 (1981), and references therein.

[23]K. A. Marshall, J. V. Thompson, W. B. Cook, and M. W. Johns, Can. J. Phys. 56, 117 (1978), and references therein.

[24]D. Hippe, private communication.

[25]*Table of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978), pp. 456 and 472.

[26]S. M. Abecasis, O. Civitarese, and F. Krinpotic, Z. Phys. A 278, 309 (1976).

[27]C. Bargholtz and S. Beshai, Z. Phys. A 283, 89 (1977).

[28]G. Alaga and V. Paar, Phys. Lett. 61B, 129 (1976).