Band structure in ^{95}Ru

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The ^{95}Ru nucleus has been studied through the ^{94}Mo(α,3n)^{95}Ru reaction. A level scheme has been proposed from γ-γ coincidence data and spin assignments are made on the basis of the results of angular distribution measurements. A rotation-particle coupling calculation has been performed and the proposed level scheme is discussed in the light of its predictions. The results obtained in the present work are also compared to those of previous investigations on this nucleus.

I. INTRODUCTION

Level properties of the odd-A Ru isotopes for $A \geq 99$ have been studied[1–4] both experimentally and in the framework of different nuclear models. Similar studies cannot be fruitfully extended to the low-mass neutron-deficient odd-A Ru isotopes due to paucity of experimental data. Of these, the level structures of ^{93,95,97}Ru have been studied mainly through (α,xn) and (^{6,7}Li,$xpyn$) reactions.[5–9] Since the number of neutrons in these isotopes (N=49,51,53) is very near to the N=50 closed shell, one should not expect the presence of appreciable collectivity in their low-lying excitations. However, the experimental spectra in these isotopes exhibit an interesting feature. They show a (ΔI=2) decoupled bandlike structure based on the $1g_{9/2}$ or $d_{5/2}$ shell-model orbital, in the sense that the excitation energies are very close to those of the yrast band in the neighboring even ($A-1$) core. However, only a few members ($J^\pi \leq \frac{21}{2}^+$) of this "decoupled" band have been identified so far in ^{93,95}Ru. The situation is somewhat better in ^{97}Ru. More detailed investigation of these neutron-deficient isotopes would be useful to explore the real nature of this observed decoupled bandlike structure. In addition, these isotopes are good candidates for exploring the possible coexistence of the strong collectivity often associated with intruder hole states from across the N=50 closed shell. Nuclei in the vicinity of other closed shells have been found to exhibit such characteristics for intruder states, e.g., systematic ΔI=1 bands have been observed, built on the $1g_{9/2}$ proton hole states, in Sb, I, and Cs nuclei.[10–13]

In the present work, we report the results of a study on the band structure of ^{95}Ru investigated through the ^{94}Mo(α,3n) reaction. High-spin states of ^{95}Ru have been previously studied through ^{92}Mo(α,n) and ^{92}Mo(^{6}Li,$p2n$) reactions[6,8] at comparatively low bombarding energy ($E \simeq$23–30 MeV). Investigation of the ^{95}Ru level structure through (α,3n) reaction at $E_\alpha \approx$40 MeV (cross section is expected to reach its maximum near this energy according to ALICE code) has been undertaken with a view to (1) extend the known band structure in this isotope to a higher-spin state, (2) locate other sidebands, and (3) explore the possibility of the existence of a ΔI=1 band based on the $1g_{9/2}$ intruder hole state.

II. EXPERIMENTAL PROCEDURE

The α beam obtained from the Variable Energy Cyclotron Centre (VECC), Calcutta, was incident on a self-supporting isotopically enriched ^{94}Mo target (94.6%) with thickness ~5 mg/cm^2. A very good yield was obtained for E_α=40 MeV. The yield could not be improved significantly by changing the energy to a somewhat higher or lower value, so the final measurements were done using this bombarding energy.

The deexcitation γ rays were detected with coaxial HPGe detectors (~20% efficiency) having energy resolution of 2.1–2.3 keV full width at half maximum (FWHM) at 1.33 MeV. γ singles, γ-γ coincidence with two HPGe detectors, and rf gated γ-spectra measurements were carried out to identify the γ-ray cascades in the various residual nuclei. Coincidence data were recorded on magtapes in LIST MODE and an event-by-event analysis was done subsequently to establish the coincidence relationship between different gamma rays. Information on γ-ray multipolarities was obtained from γ-ray angular distribution measurements, recorded in singles mode at six angles between 90° and 140° to the beam direction. The detector was placed at a distance of 20 cm from the target resulting in an angular resolution of ~1°. The extracted photopeak intensities normalized to the intensity of the most intense on-line γ ray recorded at 90° to the beam direction, were fitted to the distribution function

$$W(\theta)=A_0[1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)] .$$

For each transition, a $\chi^2(\sigma,\delta)$ analysis was carried out to assign spin values to the excited levels and multipole mixing ratios (δ) of the γ transitions using the computer program THDST.[14] The fitted value of σ, i.e., the width of the assumed Gaussian distribution for the substate population of the excited levels, shows a rather high degree of alignment (low m-state population), normally observed in this type of experiment.

III. EXPERIMENTAL RESULTS

A total gated γ-ray spectrum is shown in Fig. 1. Prominent γ-ray lines assigned to ^{95}Ru are indicated in the figure. The energies of several γ transitions and their relative intensities determined from the singles γ-ray spectrum, (not shown) recorded at 125° to the beam direction are given in Table I along with the earlier results.[7] A comparison of the relative intensities of relevant γ rays shows that the high-spin yrast states in ^{95}Ru are more strongly populated in the present work than in the reaction ^{92}Mo(^{6}Li,$p2n$) reported earlier.[8] Typical gated energy spectra with energy windows at 255 keV (doublet), 678, and 1352 keV are shown in Fig. 1. The sum of the γ spectra in coincidence with four cascading transitions 255 (doublet), 678, and 1352 keV is also shown. Based mainly on the γ-γ coincidence and the angular distribution data obtained in the present work (Fig. 2), a level scheme for ^{95}Ru has been constructed (Fig. 3). The coincidence relationships for the gamma transitions in ^{95}Ru, obtained in the present work are somewhat different from that expected from the level scheme proposed by Chowdhury et al.[8] For example, the 207- and 313-keV gamma rays, according to the level scheme proposed by them, should not have any coincidence relationship with the 255-keV yrast transition, contrary to what has been observed in the present work (Figs. 1 and 3). A 363-keV gamma transition, not reported earlier, is also observed to be in coincidence with the yrast transitions 255, 678, and 1352 keV. In addition, several new gamma rays, such as 110 (most probably there are more than one transition in this energy region), 239, 291, and 298 keV have been observed in the present work, both in the singles and in the coincidence spectra gated by the 255-keV transition. As no γ-γ coincidence spectrum for ^{95}Ru is shown by Chowdhury et al.,[8] detailed comparison with their results cannot be made.

In the proposed level scheme (Fig. 3), the 1292-keV transition has been placed above both the 255-keV transitions, whereas in the previous work by Chowdhury et al., the same has been shown to connect the 2285-keV ($\frac{17}{2}^+$) level with a higher level at 3577 keV having spin

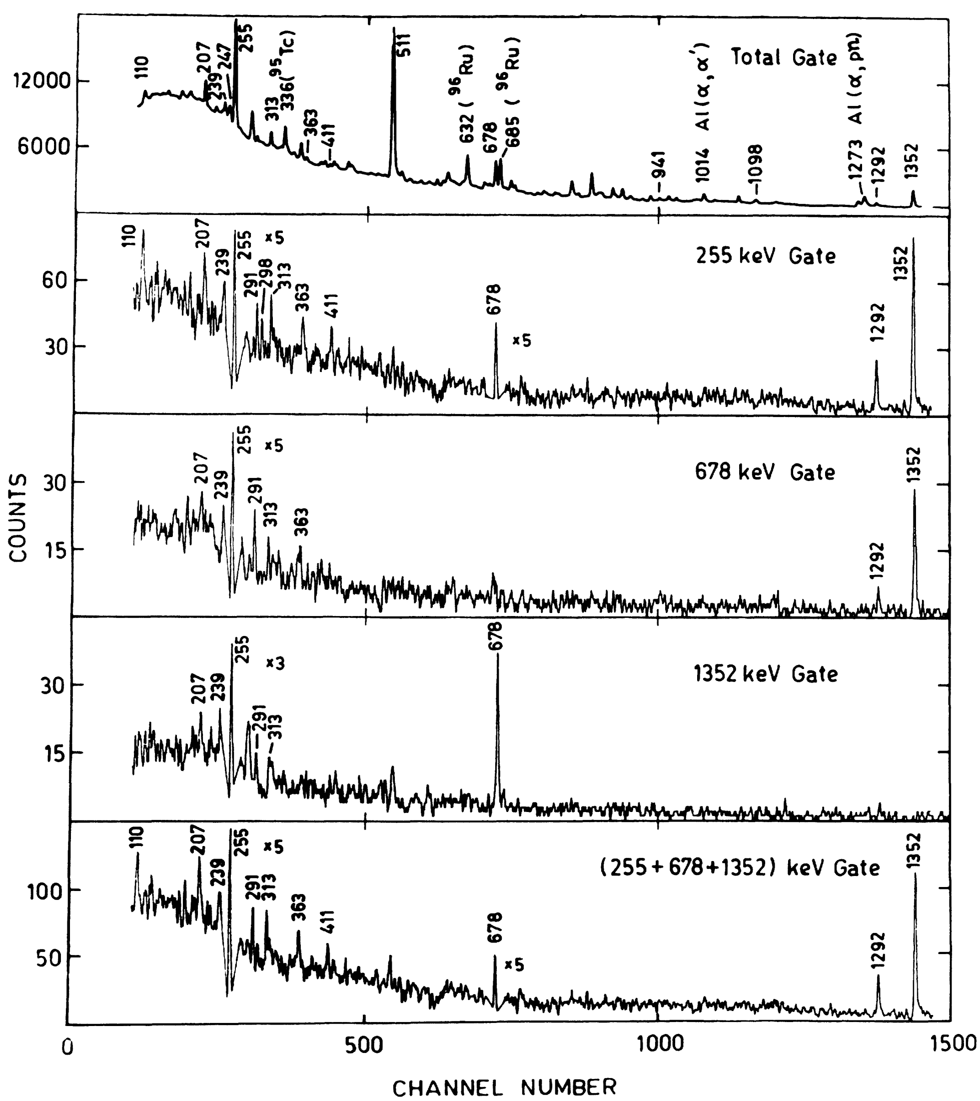

FIG. 1. Typical γ-γ coincidence spectra.

TABLE I. Relative intensities and angular distribution coefficients in ^{95}Ru.

	I_γ		A_2		A_4		
E_γ (keV)	Present work	Previous work[a]	Present work	Previous work[a]	Present work	Previous work[a]	$I_i \to I_f$
207	11	4	-0.36 ± 0.07	-0.26 ± 0.03	-0.10 ± 0.09	-0.07 ± 0.04	$\frac{23}{2}^+ \to \frac{21}{2}^+$
255	108	59	$+0.31\pm0.06$	$+0.31\pm0.01$	-0.06 ± 0.06	-0.11 ± 0.02	$\frac{17}{2}^+ \to \frac{13}{2}^+$
							$\frac{21}{2}^+ \to \frac{17}{2}^+$
313	12	5	-0.31 ± 0.08	-0.21 ± 0.05	-0.07 ± 0.11	-0.06 ± 0.06	$\frac{21}{2}^+ \to \frac{19}{2}^+$
363	21		-0.29 ± 0.03				$\frac{19}{2}^+ \to \frac{17}{2}^+$
411	3	3	-0.30 ± 0.06	-0.26 ± 0.06			$\frac{9}{2}^+ \to \frac{7}{2}^+$
678	63	62	$+0.23\pm0.03$	$+0.28\pm0.05$		-0.04 ± 0.06	$\frac{13}{2}^+ \to \frac{9}{2}^+$
941	13	26					$\frac{7}{2}^+ \to \frac{5}{2}^+$
1292	16	12	$+0.22\pm0.06$	$+0.27\pm0.05$			$\frac{25}{2}^+ \to \frac{21}{2}^+$
1352	100	100	$+0.29\pm0.06$	$+0.32\pm0.02$	$+0.11\pm0.07$	-0.08 ± 0.02	$\frac{9}{2}^+ \to \frac{5}{2}^+$

[a]Reference 8.

parity $\frac{19}{2}^-$. On the basis of the A_2 value deduced in the present as well as in the earlier work (Table I) both the $E2$ and $E1$ character of the 1292-keV gamma transition seems to be reasonable (Fig. 4). However, if the transition is $E1$, as suggested by Chowdhury *et al.*,[8] it will have about 20% $M2$ admixture. If this transition deexcites to the 2285-keV level, the relative intensities of the 255-, 678-, and 1352-keV transitions observed in coincidence with the 1292-keV transition should be equal, whereas, according to the present assignment, the same should come out to be of the order of 2:1:1. The experimental values obtained in the present work are 1.6:1:1. Because of poor statistics (resulting from the rather small value of the relative intensity of the 1292-keV transition) the choice becomes somewhat difficult. However, a comparison of the excitation energies of the yrast states in ^{95}Ru with those in ^{94}Ru [Figs. 5(a) and (b)] lends strong support to the assignment shown in Fig. 3. This point

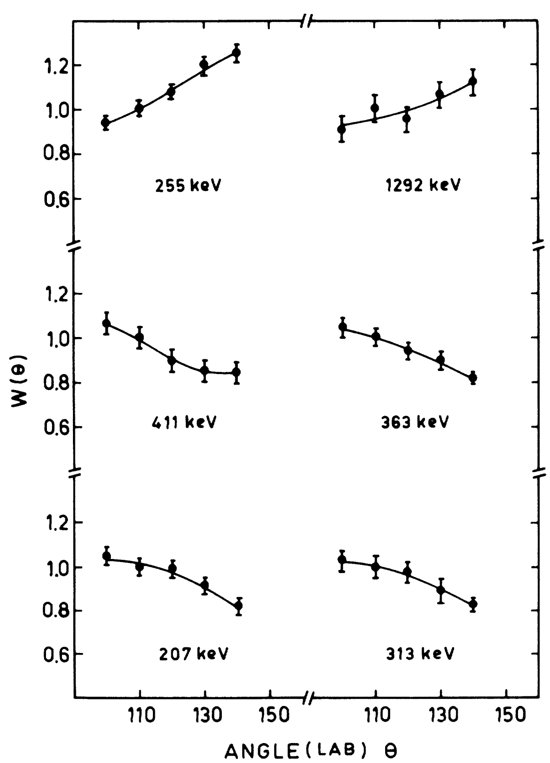

FIG. 2. Least-squares fits to the angular distribution data for several γ-ray transitions.

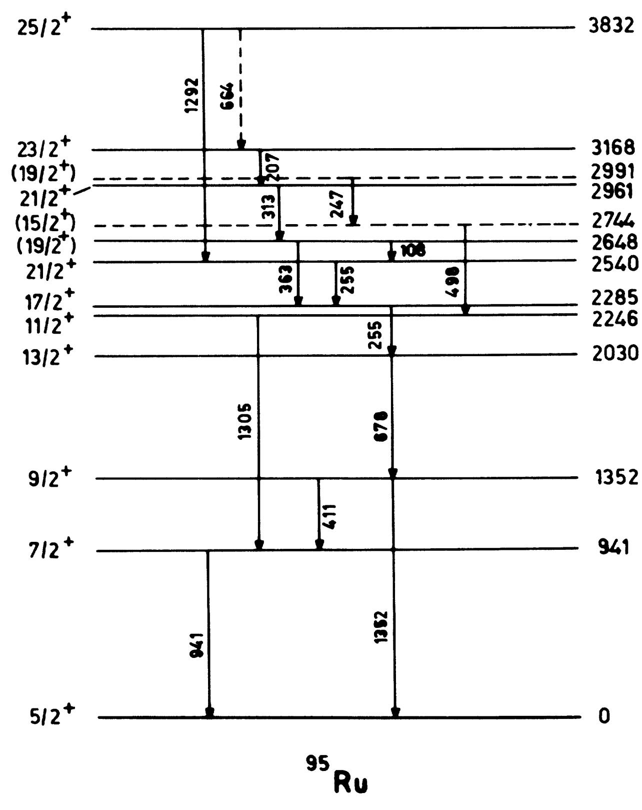

FIG. 3. Proposed level scheme of ^{95}Ru.

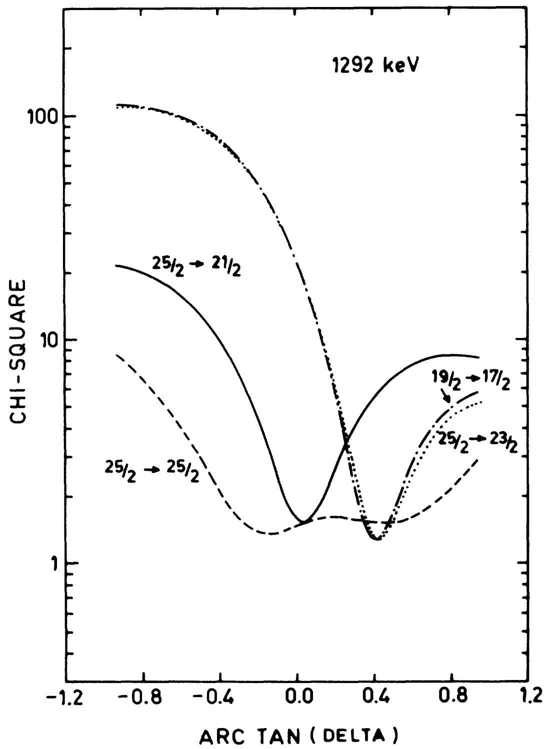

FIG. 4. The $\chi^2(\sigma,\delta)$ analysis of the angular distribution data for the 1292-keV transition. Total χ^2 values are plotted against different values of mixing ratio (δ). The width of the assumed Gaussian distribution for substate population, $\sigma/J=0.45$.

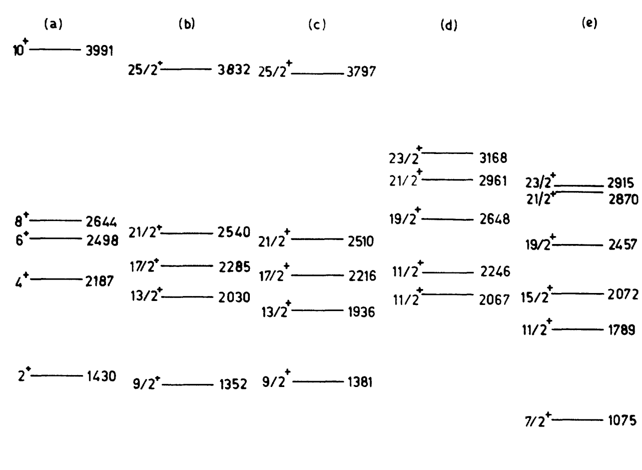

FIG. 5. Comparison of (a) experimental (Ref. 15) yrast band in ^{94}Ru, (b) favored members of the experimental yrast band in ^{95}Ru, (c) relevant portion of the theoretical spectrum in ^{95}Ru, calculated in a rotation-particle model, (d) other members of the experimental yrast band in ^{95}Ru, (e) relevant portion of the theoretical spectrum in ^{95}Ru.

will be discussed in detail in the following section.

The 207-, 313-, and 363-keV gamma rays have been observed to be in coincidence with the known yrast transitions (Fig. 1). The A_2 coefficients deduced from their angular distribution patterns (Fig. 2 and Table I) indicate a predominantly $M1$ character for all of them. These observations and their relative intensities indicate that these γ rays are emitted in cascade and they connect excited states belonging to the same band. Three additional levels at 2648 ($\frac{19}{2}^+$), 2961 ($\frac{21}{2}^+$), and 3168 ($\frac{23}{2}^+$) are proposed to accommodate these gamma transitions and their observed decay properties. The 664-keV gamma transition connecting the 3832- ($\frac{25}{2}^+$) and 3168- ($\frac{23}{2}^+$) keV levels has also been observed in the singles spectrum. The occurrence of the 255-keV transition, in pair, poses some problem in assigning correct energies and spins to these levels. Although based on our data, we consider the proposed deexcitation scheme more reasonable but the other possibility, i.e., these transitions feeding the 2540-keV ($\frac{21}{2}^+$) level instead of the 2285-keV ($\frac{17}{2}^+$) level cannot be ruled out altogether.

Almost all other transitions observed earlier[8] in ^{95}Ru, i.e., the 247-, 281-, 283-, 411-, 894-, 941-, 1098-, and 1305-keV gamma rays, have also been confirmed in the present work. Several excited levels were proposed in the earlier work,[8] based on these deexciting γ rays. All these levels are not shown in Fig. 3. Only those levels whose existence could be independently confirmed in the present work are shown.

IV. ROTATION-PARTICLE COUPLING CALCULATION

The nucleus ^{95}Ru has only one neutron outside the $N=50$ neutron shell, so any appreciable collectivity in the low-energy excitation is not expected. However, it is interesting to note that the excitation energies of the $\Delta I=2$ yrast states closely resemble those[15] of the neighboring even nucleus ^{94}Ru [Figs. 5(a) and (b)]; i.e., the yrast band bears a very close similarity with the observed "decoupled" bandlike structure in the weakly deformed and transitional nuclei arising from strong Coriolis interaction. This has prompted us to make a rotation-particle coupling (RPC) calculation of the level spectrum of ^{95}Ru. The excitation energies of the yrast band in ^{94}Ru do not have any similarity with those expected either in a well-deformed rotational nucleus or a weakly deformed one. So we have chosen a version of the RPC in which[16] the core energies can be directly fed as input parameters, instead of using any energy–angular momentum relation appropriate for a rotating nucleus. There are several parameters in the calculation; of these, the single-particle parameters μ (0.507) and k (0.064) are taken from the prescription of Nilsson et al.[17] The deformation β is taken to be equal to that for ^{94}Mo ($\simeq 0.10$) estimated from the $B(E2)$ data[18] because the neutron-deficient Ru and Mo isotopes with the same neutron number show nearly identical β values. The pairing gap Δ is calculated from the expression $\Delta=12/A^{1/2}$ MeV and the Fermi level was chosen very near to the $\frac{5}{2}^+[402]$ Nilsson orbital. Full strength of the theoretical Coriolis interaction is used. In

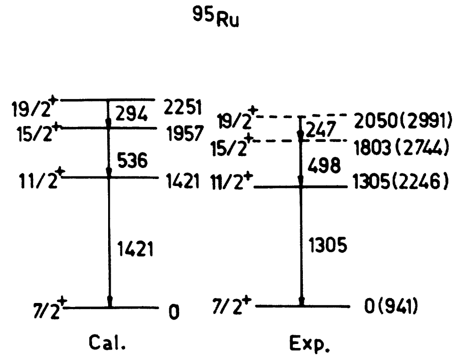

FIG. 6. Proposed band based on the $g_{7/2}$ orbital.

essence, no adjustable parameter is used in the calculation. Results of the calculation are shown in Fig. 5. It is very interesting to note that such a simple calculation reproduces the excitation energies of the observed "favored" members of the band as well as for some of the "unfavored" members. From the calculated wave functions it is seen that the states having spin parity $J^{\pi} \leq \frac{17}{2}^{+}$ are based predominantly on the $\frac{5}{2}^{+}$[402] Nilsson orbital arising from the $d_{5/2}$ state, whereas the higher-spin states have a more mixed character involving in addition the $\frac{5}{2}^{+}$[413] and the $\frac{7}{2}^{+}$[404] orbitals (of $g_{7/2}$ parentage) as well. The spin states based primarily on the last two orbitals are shown separately in Fig. 6. A comparative study of the yrast band in the ^{94}Ru, proposed level scheme of ^{95}Ru and the results of the RPC calculation [Figs. 5(a)–(e)] not only justify our placement of the 1292-keV transition, but also the proposed levels at 2648, 2961, and 3168 keV. On the basis of the calculated energies of the favored band based on the $\frac{7}{2}^{+}$ state arising from the $g_{7/2}$ orbital (Fig. 6), the placement of the 1305-keV gamma transition between the 941-keV ($\frac{7}{2}^{+}$) and the 2246-keV ($\frac{11}{2}^{+}$) levels by Chowdhury *et al.*[8] appears to be reasonable. However, the calculation suggests that the 247-keV transition should deexcite to a $\frac{15}{2}^{+}$ level near 2750-keV excitation energy (Fig. 6), rather than to the 2246 keV ($\frac{11}{2}^{+}$) level proposed in the earlier work. In that case one should expect a gamma transition with $E_{\gamma} \simeq 500$ keV, in cascade with the 941-, 1305-, and 247-keV transitions. In the singles spectrum, there are two gamma transitions (488 and 498 keV) near this value and their relative intensities are consistent with this placement. Also in the coincidence spectrum gated by the 941-keV gamma ray, there is an indication of the presence of a transition near 500 keV. So, the existence of a level at 2744 keV ($\frac{15}{2}^{+}$) deexciting by stretched $E2$ transition to the $\frac{11}{2}^{+}$ state at 2246 keV is proposed (Fig. 6). However, due to poor feeding of the levels based on the 941-keV ($\frac{7}{2}^{+}$) state in the present experiment, coincidence data with good statistics could not be obtained for these cascade transitions. So this assignment is rather tentative in nature.

V. CONCLUSION

The present work extends experimental information on the yrast band in ^{95}Ru up to an excitation energy of 3832 keV with $I^{\pi}=\frac{25}{2}^{+}$. Several new levels belonging to the yrast and the side bands are proposed, based on the present reaction data and results of a rotation-particle-model calculation. In addition, most of the transitions assigned to ^{95}Ru by Chowdhury *et al.*[8] have also been confirmed. No evidence has been found on the existence of a collective band based on the intruder $1g_{9/2}$ hole state.

It is interesting to note that even in a nucleus situated so near to the $N=50$ closed shell, and exhibiting no regularity in the energy–angular momentum relationship in its excitation spectrum, the results of a rotation-particle coupling calculation can be so useful in systematizing experimental data. Since the excitation spectrum in ^{95}Ru closely follows that of ^{94}Ru, only a proper understanding of the structure of the yrast band in ^{94}Ru can reveal the real nature of the excitation mechanism in ^{95}Ru. For the same reason it appears that the next high spin members of the favored band, i.e., the $\frac{29}{2}^{+}$ and $\frac{33}{2}^{+}$ states in ^{95}Ru, should lie near excitation energies of the 12^{+} and the 14^{+} states, respectively, in ^{94}Ru, i.e., around 5–6 MeV. The relative intensities of the gamma rays listed in Table I show that the high-spin yrast states in ^{95}Ru are more strongly populated in the present work in comparison with the reaction ^{92}Mo(^{6}Li,$p2n$) reported earlier. However, a sharp decrease of the relative intensity of the 1292-keV gamma ray in comparison to its succeeding transitions indicates that high-spin states near 5-MeV excitation energy are not expected to be significantly populated in the $(\alpha,3n)$ reaction. High-energy and heavier mass projectiles would be better suited to explore the higher-spin region of the yrast band.

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