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Level structure of ^{99}Rh at high spins

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Abstract. High spins states in ^{99}Rh were populated via the ^{66}Zn(^{37}Cl, 2p2n)^{99}Rh reaction at an incident beam energy of 130 MeV. Seventeen new transitions have been observed in the present study and the level scheme has now been extended up to a spin of $J \sim 25\hbar$ and an excitation energy of about $E_x \sim 10$ MeV. The observation of a positive parity E2 cascade based on the $9/2^+$ isomeric level is suggestive of collective behaviour in this nucleus up to high spins. Spherical shell model (within restricted model space) and Cranked shell model calculations were performed to obtain an insight into the observed level structure. The new collective band observed up to a spin of $J \sim 25\hbar$ is suggested to be based on $(\pi\, g^3_{9/2})\otimes(\nu\, g^2_{7/2})$ quasi-particle excitations.

PACS. 21.10.Re Collective levels – 21.60.Cs Shell model – 23.20.Lv Gamma transitions and level energies – 27.60.+j $90 \leq A \leq 149$

1 Introduction

Single particle configurations dominate the level structure of nuclei Mo, Tc, Ru, Rh with $N \leq 51$ even at high angular momenta (J $\sim 20\hbar, E_x \sim 12$ MeV) [1,2], while nuclei with N≥56 exhibit collective degrees of freedom [3,4]. Moreover the transitional nuclei in this mass region are predicted to be γ-soft with modest deformation ($\epsilon_2 \sim$0.15) [5,6]. In recent studies [6–8] collective bands have also been observed up to high spins in nuclei having only ten or eleven active nucleons outside the doubly magic ^{100}Sn core. It is further seen that not only neutron (from N=5 shell) but also proton $g_{9/2}$ excitations are important in understanding the observed collective band structures up to high spins. At the time of the writing of this paper, terminating high spin bands were reported in the nucleus ^{101}Rh [9].

The present work was intended to look for any development of collective bands at high spins in the ^{99}Rh nucleus which has only four active neutrons outside the N=50 magic shell closer and an half-filled $\pi(g_{9/2})$ orbital; that is, only nine active nucleons outside the doubly magic ^{100}Sn core. The last work reported on the high spin study of ^{99}Rh was by Ravikumar et al [10] and is discussed in the sections below. In a recent investigation of high spin states in ^{98}Rh [11] a deformed band was reported, however, no such band was observed by Ghugre and co-workers in a contemporary investigation of high spin states in ^{97,98}Rh as reported in [12].

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2 Experimental Details

High spins states in ^{99}Rh were populated using the ^{66}Zn(^{37}Cl, 2p2n)^{99}Rh reaction at an incident beam energy of 130 MeV. The ^{37}Cl beam was provided by the 15 UD Pelletron Accelerator at the Nuclear Science Centre (NSC), New Delhi. The isotopically enriched (99%) ^{66}Zn target had a thickness of about 1.2 mg/cm^2 on a Pb backing of about 20 mg/cm^2. The use of neutron rich target-projectile combination helped us populate this nucleus with considerable cross-section. $\gamma-\gamma$ coincidences were measured, using the Gamma Detector Array (GDA), at NSC. At the time of the experiment the GDA consisted of 8 Compton Suppressed HPGe (CSGe) detectors, and a 14 element BGO multiplicity filter. The CSGe detectors were mounted in two groups of four each making an angle of 98^o and 144^o with the beam direction. The distance between the target and the HPGe detectors was about 18 cms. Since the multiplicity filter covered only about 35% of the total solid angle this information was not used in the present analysis. About 80 million two or higher fold $\gamma-\gamma$ coincidences were recorded. The most dominant channel formed was the 2p2n channel. The other significant channel was the p2n channel populating ^{100}Pd which is the subject of a separate investigation [13]. The multiparameter data was sorted offline into the conventional 4k x 4k, $E_\gamma - E_\gamma$ matrix, after the pulse heights in all the detectors were software gain matched. A separate 4k x 4k matrix was formed to determine the Directional Correlation (DCO) ratios, for spin parity assignments. Further details of the data analysis techniques and the experimental set-up can be found in [1].

3 Results

A representative coincidence spectrum is shown in Fig. 1. We have observed several new transitions belonging to this nucleus. These have been placed in the level scheme using the observed coincidence relation and the intensity arguments. The multipolarities of the observed transitions has been assigned using the DCO technique. The DCO ratio was defined as

$$R_{DCO} = \frac{I_{\gamma_1}\ at\ 98°,\ gated\ with\ \gamma_2\ at\ 144°}{I_{\gamma_1}\ at\ 144°,\ gated\ with\ \gamma_2\ at\ 98°}$$

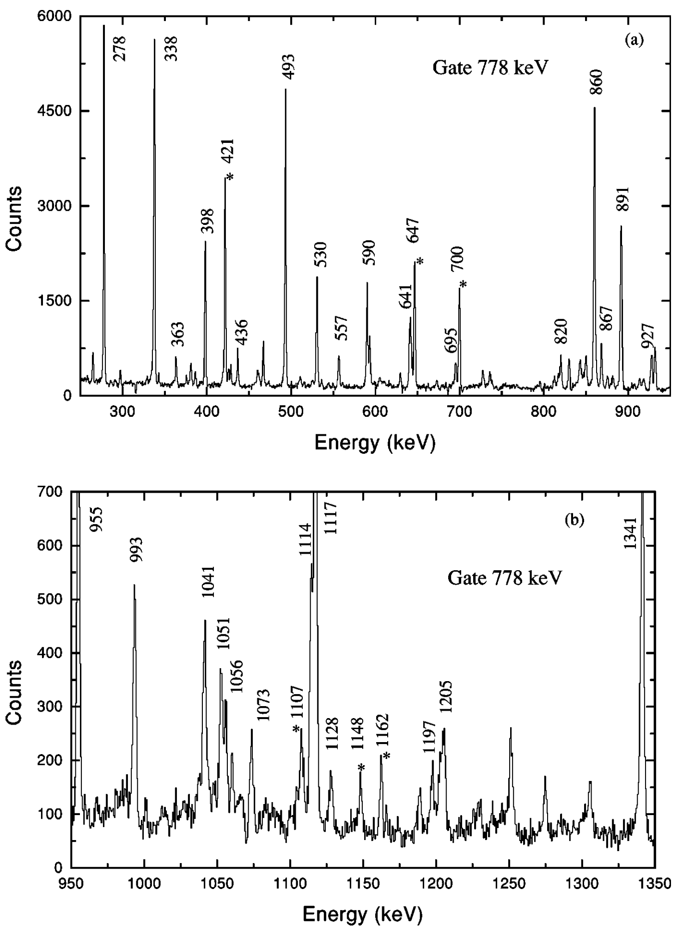

Fig. 1. Representative coincidence spectrum for ^{99}Rh with gate on 778 keV ($13/2^+ \rightarrow 9/2^+$) transition. (a) From 0 to 950 keV (b) From 950 to 1350 keV All the transitions energies are marked within ± 1 keV. The transitions marked with an asterisk are possible contamination from ^{97}Ru in this gate. The spectrum shown has not been corrected for efficiencies of the Ge detectors

with this definition of R_{DCO}, for a quadrupole transition, when the gating transition is a known quadrupole, the ratio is expected to lie between 0.8 and 1.2. A stretched dipole is expected to have R_{DCO} between 0.4 and 0.6, while a value between 0.6 and 0.8 implied a mixed transition. These limits were obtained from fitting to values for transitions of known multipolarity. Pure non-stretched dipole ($L = 1, \Delta J = 0$) transitions are also expected to have R_{DCO} values close to unity. The resultant level scheme is shown in Fig. 3. Tentative spins and/or parities assignments are indicated within parentheses. The γ ray energies, the initial energy level, relative intensities (with the intensity of 777.8 keV transition assumed to be 100 %), DCO ratios and the corresponding spin, parity assignments for the observed transitions is summarized in Table 1. The most interesting observation was the presence of six new transitions, belonging to the positive parity band having energies of 1041, 1051, 1205, 1073, 1128 and 1197 keV (see Fig. 1(b)). These have been placed above the 3586 keV level, and are E2 in character. Thus the positive parity sequence has been extended up to a spin of $J = 49/2^+$, and an excitation energy of about 10.2 MeV. This E2 cascade resembled a rotation-like band, and could indicate the onset of collectivity up to high spins in this mass region. The fragmentation of intensity in two main branches above the 2593 keV level agrees well with the earlier study by Ravikumar and co-workers [10]; while about 29% of total intensity is accounted by the band based on 3710 keV only 9% is that due to the band described above.

The negative parity sequence has been extended up to an excitation energy of 5.7 MeV due to the observation of the 163, 277, 321, 421, 434, 627 and 985 keV γ-rays. The spin assignment of the top two levels in this band is tentative while we have not been able to assign any spin or parity to the topmost level due to very weak intensity of 627 keV transition. As shown in the level scheme the 3710 keV level is also found to decay to the negative parity band through the 163, 434 and 277, 321 keV γ-ray pairs. The intensity of these γ-rays is quite weak, to allow us to determine their multipolarities, and hence the spin and parity of the intermediate levels could not be assigned. Figure 2 shows a section of the sum gate of 278,337,530 and 590 keV transitions; members of the negative parity band and those of the band based on 3710 keV level are indicated. This decay of the 3710 keV level to the negative parity band was not observed in the earlier study [10]. Our DCO analysis indicates that the 1117 keV transition dexciting from 3710 keV level to 2593 keV level is a $\Delta J = 1$ transition. However we are unable ascertain the electric or magnetic character of this transition. In the recently reported study [9] of ^{101}Rh similar band systems are observed up to moderate spins. The band based on 3529 keV level is determined to have a band head spin of $23/2^-$ by Timar et al by linear polarization measurement of the 750 keV transition which de-excites the 3529 keV level to the positive parity band based on $9/2^+$ isomeric state. Further they have also found this band to decay to the negative parity ground state band based on $1/2^-$. We, however, in view the arguments presented in [10] we feel

Table 1. Transition energy (E_γ), initial energy level (E_x), relative intensity (I_γ), DCO ratios (R_{DCO}) and, initial and final spins for the transitions assigned to ^{99}Rh

E_γ [a] (keV)	E_x (keV)	I_γ [b]	R_{DCO} [c]	$J_i \rightarrow J_f$
162.9	3710	5(25) [d]		$23/2 \rightarrow$
276.5	3710	3(25) [d]		$23/2 \rightarrow$
277.6	3988	29(1)	0.6(3)	$25/2 \rightarrow 23/2$
321.0	3434	7(20) [d]		$\rightarrow 21/2^-$
337.3	5193	35(1) [e]	0.52(3)	$31/2 \rightarrow 29/2$
337.5	4325	35(1) [e]	0.52(3)	$27/2 \rightarrow 25/2$
363.0	5682	3(9)	0.46(16)	$33/2^{(+)} \rightarrow 31/2^+$
397.8	2593	16(2)	0.64(5)	$21/2^+ \rightarrow 19/2^+$
420.6	4131	8(18) [d]	0.70(35) [f]	$(25/2) \rightarrow 23/2$
427.1	427	13(2)	1.07(13) [f]	$5/2^- \rightarrow 1/2^-$
428.4	6111	2(12)	0.35(37)	$35/2^{(+)} \rightarrow 33/2^{(+)}$
434.0	3547	5(15) [d]		$\rightarrow 21/2^-$
436.4	3586	4(9)	0.59(13)	$25/2^+ \rightarrow 23/2^+$
493.0	2195	40(1)	0.59(3)	$19/2^+ \rightarrow 17/2^+$
530.4	4856	17(2)	0.54(6)	$29/2 \rightarrow 27/2$
552.0	979	7(4)	1.08(11) [f]	$9/2^- \rightarrow 5/2^-$
556.6	3150	5(7)	0.69(14)	$23/2^+ \rightarrow 21/2^+$
590.0	5783	16(2)	0.65(6)	$33/2 \rightarrow 31/2$
627.2	5743	5(30) [d]		$\rightarrow (27/2)$
640.6	2300	7(4)	0.95(11) [f]	$17/2^- \rightarrow 13/2^-$
680.5	1660	7(4)	0.97(11) [f]	$13/2^- \rightarrow 9/2^-$
695.1	3710	6(2)	0.77(13)	$23/2 \rightarrow 21/2$
777.8	842	100(1)	0.97(5)	$13/2^+ \rightarrow 9/2^+$
812.6	3113	3(13)	1.00(35)	$21/2^- \rightarrow 17/2^-$
816.8	1660	4(13)	0.82(47)	$13/2^- \rightarrow 13/2^+$
819.9	3015	8(6)	0.59(24)	$21/2 \rightarrow 19/2^+$
859.8	1702	71(1)	1.03(3)	$17/2^+ \rightarrow 13/2^+$
868.1	4856	10(5)	0.90(13)	$29/2 \rightarrow 25/2$
891.2	2593	46(2) [e]	0.95(4)	$21/2^+ \rightarrow 17/2^+$
891.8	8016	46(2) [e]	0.50(11) [g]	$41/2 \rightarrow 37/2$
927.5	5783	10(4)	1.03(18)	$33/2 \rightarrow 29/2$
954.6	3150	16(3)	1.03(8)	$23/2^+ \rightarrow 19/2^+$
985.0	5116	7(20) [d]	0.40(35) [f]	$(27/2) \rightarrow (25/2)$
993.2	3586	9(5)	1.11(10)	$25/2^+ \rightarrow 21/2^+$
1041.1	4627	7(11)	0.89(12) [h]	$29/2^+ \rightarrow 25/2^+$
1051.5	5679	5(7)	1.18(16) [h]	$33/2^+ \rightarrow 29/2^+$
1055.7	5319	5(10)	0.81(14)	$31/2^+ \rightarrow 27/2^+$
1073.1	7957	3(4)	1.02(14) [h]	$41/2^+ \rightarrow 37/2^+$
1114.2	4264	9(4)	1.07(14)	$27/2^+ \rightarrow 23/2^+$
1117.4	3710	24(2)	0.50(8)	$23/2 \rightarrow 21/2^+$
1127.9	9085	2(11)	0.93(20) [h]	$45/2^+ \rightarrow 41/2^+$
1197.3	10282	2(9)	0.75(35) [h]	$49/2^+ \rightarrow 45/2^+$
1205.1	6884	4(6)	1.10(24) [h]	$37/2^+ \rightarrow 33/2^+$
1341.1	7124	19(3)	0.97(8)	$37/2 \rightarrow 33/2$

[a] γ-ray energies are accurate to ± 0.2 keV for the strong transitions ($I_\gamma > 10$) rising to ± 0.5 keV for the weaker transitions
[b] Intensities are relative to the intensity of 778 keV transition; the numbers in the bracket are the percentage errors, e.g., 5(10) means 5 ± 0.5
[c] A blank is left for those transitions for which the R_{DCO} could not be computed; the numbers in the bracket are the percentage errors, e.g., 0.50(10) means 0.50 ± 0.05
[d] Intensities are relative to the intensity of 427 keV transition.
[e] Doublet γ ray transition, total intensity only.
[f] From the summed DCO spectra of 427 and 552 keV gates.
[g] From the DCO spectrum of 493 keV gate, which is a dipole.
[h] From the summed spectra of 778 and 860 keV gates.

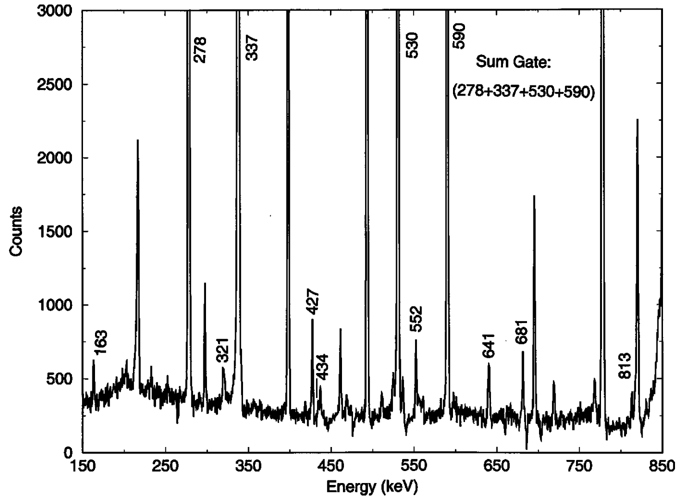

Fig. 2. Sum Gate of 278,337,530 and 590 keV transitions. Members of the negative parity band and those of the band based on the 3710 keV level are indicated. The spectrum shown has not been corrected for efficiencies of the Ge detectors

that linear polarization measurement of 1117 keV is necessary and thus no parity is assigned to the band based on the 3710 keV level.

For the cascade based on the 3.7 MeV level our placement of the γ-rays is consistent with that of Ravikumar and co-workers [10]. But there are certain discrepancies in the spin assignments for the top 4 levels in this cascade. From our analysis we find that 278, 337 keV doublet the 530 and 590 keV transitions to be dipoles, while 868, 927 1341 and 892 keV transitions to be quadrupoles. The quadrupole nature of the 927 (E_x = 5783 keV) and 892 keV (E_x = 8016 keV) transitions was confirmed by gating on the 493 keV ($19/2^+ \rightarrow 17/2^+$) transition. In this gated spectrum, the contribution from the 891 keV ($21/2^+ \rightarrow 17/2^+$) transition is avoided. Thus the 5193 keV level has been assigned a spin of 31/2 (this level was given a double assignment of $J = 29/2, 31/2$ by the earlier workers [10]). Further, the 5783 keV, 7124 keV and 8016 keV levels are assigned a spin of 33/2, 37/2 and 41/2 respectively instead of 31/2,35/2 and 37/2 assignments given earlier.

We have observed two γ-rays having energies 363 and 428 keV, belonging to the sequence based on the 2195 keV level. Our DCO analysis indicates that these inband transitions are $\Delta J = 1$ transitions, and hence are assigned an M1 character.

The observation of seventeen new γ-rays and the modifications in the spin assignments proposed for the levels in the band based on 3.7 MeV has substantially changed the high spin level structure of ^{99}Rh.

4 Discussion and model comparisons

4.1 Shell model

The positive parity yrast sequence up to a spin of J=$17/2^+$ had been described by D. Bucurescu et al [14] within the

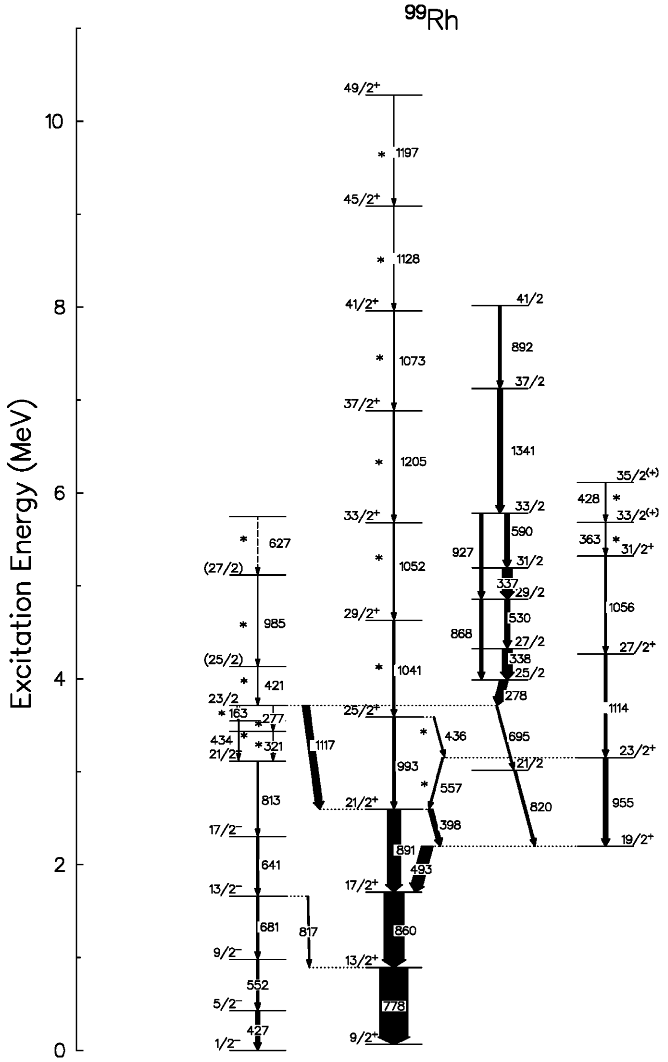

Fig. 3. Level scheme for ^{99}Rh showing excitation and gamma transition energies (rounded off, in keV). Transitions observed for the first time are marked with an asterisk. The width of the arrows are approximately proportional to the relative intensities of the observed transitions. The spin and parity assignments given in parentheses are tentative

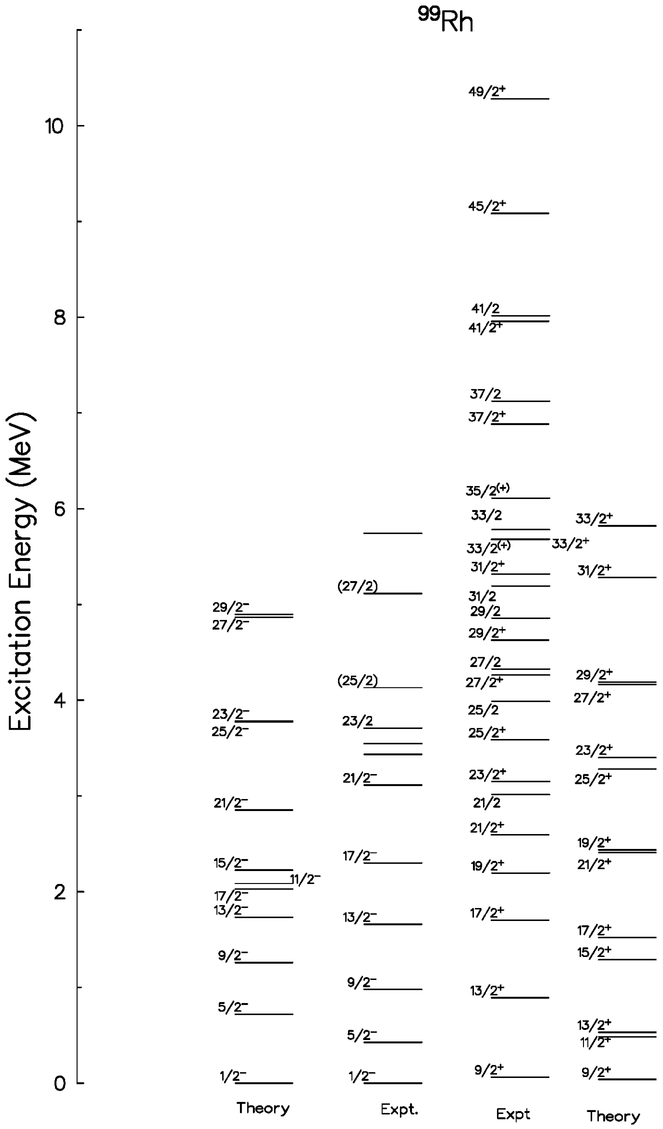

Fig. 4. Comparison of the observed and calculated excitation energies in ^{99}Rh and shell model calculations with ^{88}Sr as the inert core and the $\pi(p_{1/2}, g_{9/2}), \nu(d_{5/2}, s_{1/2})$ model space

framework of interacting boson fermion model (IBFA). However the success of the shell model in interpreting the observed level sequences in ^{97,98}Rh and other neighbouring nuclei in this mass region [1,2,12,15] in recent studies prompted us to perform the shell model calculations for ^{99}Rh, as a starting point. Shell model calculations were performed using the code OXBASH [16]. The model space used in these calculations encompassed the $\pi(p_{1/2}, g_{9/2}), \nu(d_{5/2}, s_{1/2})$ orbitals outside ^{88}Sr as the inert core. The two body matrix elements were taken from the work of Gloeckner [17]. The maximum angular momentum within this restricted space is $J \approx 15\hbar$. The level energies of the sequence based on the $J = 9/2^+$ level have been normalized to the experimental excitation energy of the $J = 9/2^+$ level. The comparison between the experimental excitation energies and the shell model predictions is shown in Fig. 4. As seen from the figure the agreement between the two is reasonable. A point worth mentioning is that in these preliminary calculations, we have not included the $\nu(g_{7/2}, h_{11/2})$ orbitals which are expected to contribute to the higher angular momentum states. Calculations involving these orbitals, are not feasible currently due to the large dimensionality of the matrices involved. However these (restricted basis) calculations help us to have a qualitative understanding for the observed level structure up to moderate spins ($J = 31/2^+, 21/2^-$). The level structure up to such moderate spins can thus be thought to exhibit single particle behaviour.

Determination of the parity for the band based on 3.7 MeV level is crucial to determine the underlying configurations on which this band is based. The polarization measurement for the 1117 keV transition, on which the band head of the strong $\Delta J = 1$ sequences is based has been undertaken in a separate contemporary investigation.

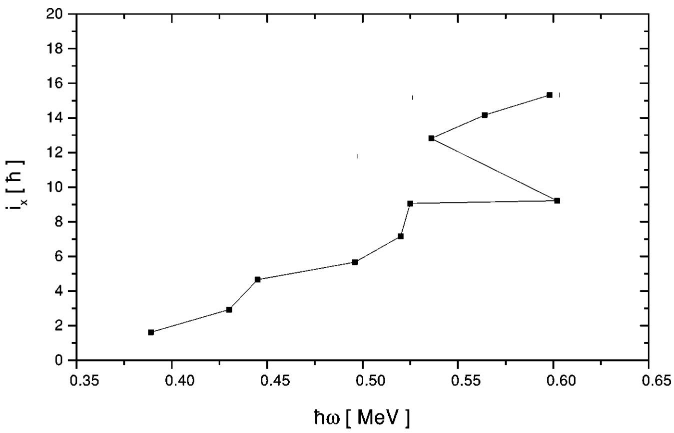

Fig. 5. Plot of aligned angular momentum (i_x) for the positive parity band based on the $9/2^+$ isomeric level in ^{99}Rh vs $\hbar\omega$. For reference the Harris parameters were chosen as $J_o = 8.9\hbar^2\text{MeV}^{-1}$ and J_1=15.7$\hbar^4$Mev^{-3}

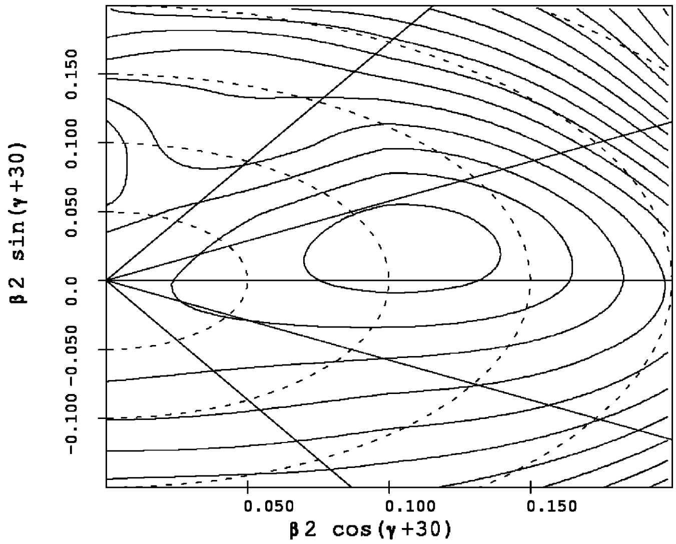

Fig. 6. TRS plot for ^{99}Rh at $\hbar\omega$=0.4 MeV for one quasi-proton in +ve parity, +ve signature. Contour lines are in 250 keV increments

4.2 Crank shell model

To understand the continuation of the E2 sequence for the positive parity yrast band based on the $9/2^+$ isomeric state to J=$49/2^+$, we have tried to look it in terms of the crank shell model (CSM). Fig. 5 illustrates the alignments for this band as a function of rotational frequency. This plot depicts a gradual alignment process up to the rotational frequency of $\hbar\omega \sim 0.53$ MeV with a notable upbend (gain in alignment $\sim$ 3.5 $\hbar$) at $\hbar\omega \sim 0.5$ MeV. While a sharp backbend is observed at the crossing frequency of $\hbar\omega \sim 0.57$ MeV with further gain in alignment of about 6$\hbar$. Thus from frequency $\hbar\omega \sim 0.5$ MeV to $\hbar\omega \sim 0.60$ MeV the total gain in alignment is $\sim 9.5\hbar$. The crank shell model calculations was performed using Woods-Saxon potential with monopole pairing [18]. Figure 5 shows the result of Total Routhian Surface (TRS) calculation at $\hbar\omega$=0.4MeV. The minimum is predicted at quadrupole deformation parameter β_2=0.11, triaxiality parameter $\gamma \sim -15^0$ and hexadecapole deformation parameter β_4=0.019. At these values of the deformation parameters the single-particle routhians were calculated as a function of rotational frequency and is shown in Fig. 7. The pairing gap parameter 'Δ' and the Fermi level 'λ' for the protons and neutrons was determined from the BCS gap equations.

The predicted ab (definitions of the labels are given in the caption for Fig. 7) crossing for the protons at $\hbar\omega$ ~0.37 MeV is blocked in the present case due to the odd proton. As can be seen from the figure the second proton, bc crossing and the first neutron, ab crossing are predicted to be closely competing. However the neutron ab (dominant Nilsson configuration predicted is $1/2^+$[420] of $g_{7/2}$ parentage) quasi-particle routhians are predicted to be strongly interacting at $\hbar\omega$ ~0.46 MeV ; further the predicted gain in alignment is about 3$\hbar$. The bc crossing for the protons is predicted at $\hbar\omega$ ~0.50 MeV (the dominant Nilsson configuration predicted is $3/2^+$[431] of $g_{9/2}$ parentage). The gain in alignment due to this crossing is predicted to be about 6$\hbar$. Compared with the observed upbend at $\hbar\omega$ ~0.50 MeV and the backbend at $\hbar\omega$ ~0.57 MeV in the experimental alignment plot, the crossing frequencies are underpredicted, however the predicted gain in alignments are in good agreement with the observation; moreover there is a qualitative agreement in the predicted interaction strengths. As we know that the crossing frequency is a sensitive function of the pairing gap parameter, reasonable adjustment to the pairing gap parameters can delay the crossing frequencies. We thus, attribute the upbend at $\hbar\omega$ ~0.5 MeV due to the alignment of $g_{7/2}$ neutrons and the backbend at $\hbar\omega$ ~0.57 MeV due to that of the $g_{9/2}$ protons. The alignment plot hence, could reasonably be described as 3 quasi-proton [abc] ($g^3_{9/2}$) and 2 quasi-neutron [ab] ($g^2_{7/2}$) excitations for higher rotational frequencies.

The $\nu h^2_{11/2}$ alignment (the ef crossing) reported for some neighbouring nuclei is predicted to be beyond $\hbar\omega$ ~0.6 MeV for this nucleus. This may be due to the fact that at very low deformation ($\beta_2 \sim 0.1$) the Fermi level is far away from the $\nu h_{11/2}$ orbital in this nucleus. The band is hence, suggested to be based on $(\pi\, g^3_{9/2})\otimes(\nu\, g^2_{7/2})$ quasi-particle excitations at high spins. In the recently reported studies on the terminating bands in ^{101}Rh and ^{102}Pd the interpretation of low and intermediate spins was not discussed. Detailed microscopic calculations of all these nuclei is desirable for complete understanding of structural changes in the nuclei in this mass region from low spin to very high spins.

5 Conclusions

Seventeen new transitions belonging to ^{99}Rh have been observed and placed in the level scheme, thus extending the level scheme to a spin of $J = 49/2\hbar$ and an excitation energy of 10.2 MeV. The observation of a cascade of E2

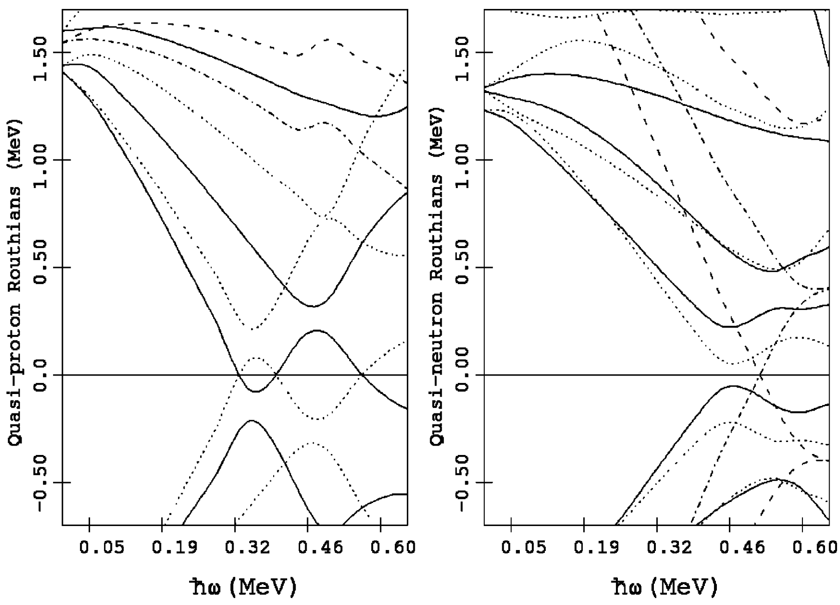

Fig. 7. Plot of quasi-particle routhians against the rotational frequency ($\hbar\omega$) for protons and the neutrons at deformation parameters β_2=0.11,$\gamma = -15°$ and β_4=0.019. The positive parity states are referred as a,b,c,d counted from the Fermi surface with a,c of +1/2 signature (solid line) and b,d of -1/2 signature (dots). The negative parity states are referred as e of +ve signature (dot-dash), f of -ve signature (dashes) in the text

transitions in the yrast band based on $9/2^+$ isomeric state signifies the collective behaviour in this nucleus up to high spins. The results of crank shell model calculations seem to provide good insight for the observed alignments for the band based on the $9/2^+$ isomeric state. The band is suggested to be based on $(\pi\, g^3_{9/2})\otimes(\nu\, g^2_{7/2})$ quasi-particle excitations.

The restricted shell model calculations have provided reasonable understanding of observed level structure up to moderate spins ($J = 31/2^+, 21/2^-$). However, for complete understanding of the high spin states within the shell model frame work large basis shell model calculations are necessary.

Additional spectroscopic data (such as lifetime, polarization and g-factor measurements) and detailed microscopic calculations will be helpful in providing better insight into the complete structure of this nucleus up to high spins.

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