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Levels in doubly odd ^{138}Pr

G. Gangopadhyay[1,a], Samit Bhowal[2], R.K. Bhowmik[3], U. Datta Pramanik[4], P. Ghosh[5], A. Goswami[4], C. Petrache[6], A. Mukherjee[4], S. Muralithar[3], Rajarshi Raut[4], M. Saha Sarkar[4], A.K. Singh[7], R.P. Singh[3], and S. Bhattacharya[4]

[1] Department of Physics, University College of Science, University of Calcutta, Kolkata - 700009, India
[2] Department of Physics, Surendranath Evening College, 24/2 M.G. Road, Kolkata - 700009, India
[3] Nuclear Science Centre, New Delhi - 110067, India
[4] Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata - 700064, India
[5] Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata - 700064, India
[6] Dipartimento di Fisica and INFN, Sezione di Perugia, Università di Camerino, Via Madonna delle Carceri 9, I-62032 Camerino (PG), Italy
[7] Department of Physics, Indian Institute of Technology, Kharagpur - 721302, India

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Abstract. The band structures of the doubly odd ^{138}Pr nucleus have been investigated using the ^{128}Te(^{14}N, 4n)^{138}Pr reaction at a beam energy of 55–65 MeV. Altogether six distinct structures have been established, of which the lower part of the yrast band and two side bands were known from earlier works. The observed level properties of the members of the yrast band have been compared with theoretical calculations performed within the Particle Rotor Model (PRM) with axially symmetric core. The experimental branching ratios and $B(M1)/B(E2)$ values when compared with the theoretical results of the PRM, suggest an oblate core.

PACS. 21.10.Re Collective levels – 23.20.-g Electromagnetic transitions – 21.60.Ev Collective models – 27.60.+j $90 \leq A \leq 149$

1 Introduction

The light rare-earth odd-odd nuclei have drawn considerable attention due to the fact that they permit investigation on the interplay between collective rotation and single-particle motion of the two non-identical particles. Depending on the configurations of the valence quasiparticles, rich and varied structural characteristics have been predicted and confirmed in a number of nuclei. These, in turn, have provided interesting information on the evolution of nuclear shapes, shape coexistence, nonaxial deformation, changing role of parity and Coriolis force etc. with rotational frequency.

In this paper we present the results of our investigation of in-beam γ-ray spectroscopy of ^{138}Pr, carried out using ^{128}Te(^{14}N, 4n) reaction. Prior to this work, the same reaction, was used by Rizzutto *et al.* [1] to study the level properties of this nucleus. In their work a four-HPGe-detector setup along with a $4'' \times 4''$ NaI(Tl) filter for low multiplicity was employed and only a limited identification of the positive-parity yrast band, based on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration and spin-value up to $I = 13$, was made. Three other side bands were reported, of which one (negative-parity band # 3 in ref. [1]) was proposed to be a doubly decoupled band with oblate deformation arising from the $\pi[431]\frac{1}{2}^+ \otimes \nu h_{11/2}$ configuration. However, the placement of a number of transitions and the author's description were not unambiguous [2].

In this paper we will be concerned with the high-spin states in ^{138}Pr. However, for the sake of completeness, it may be pointed out that the low-spin states in this nucleus had been studied from the decay of ^{138}Nd and the results can be found in the compilation of Nuclear Data Sheets [2]. The ground state is a 1^+ state having a half-life of 1.45 min and the low-energy part of the level scheme mainly consists of states with spins less than 2. The first isomeric state ($T_{1/2} = 2.12$ h) with $I^\pi = 7^-$ is at 364 keV.

Only a few theoretical calculations had been carried out to understand the level properties of ^{138}Pr. A detailed theoretical study of the level properties of the high-spin positive-parity states (yrast band) in ^{132,134,136,138}Pr was first done by Datta Pramanik *et al.* [3], in a systematic way, within the framework of the Particle Rotor Model (PRM), wherein two quasiparticles (a proton and a neutron) are coupled to an axially symmetric rotor core

[a] e-mail: gautam@cucc.ernet.in

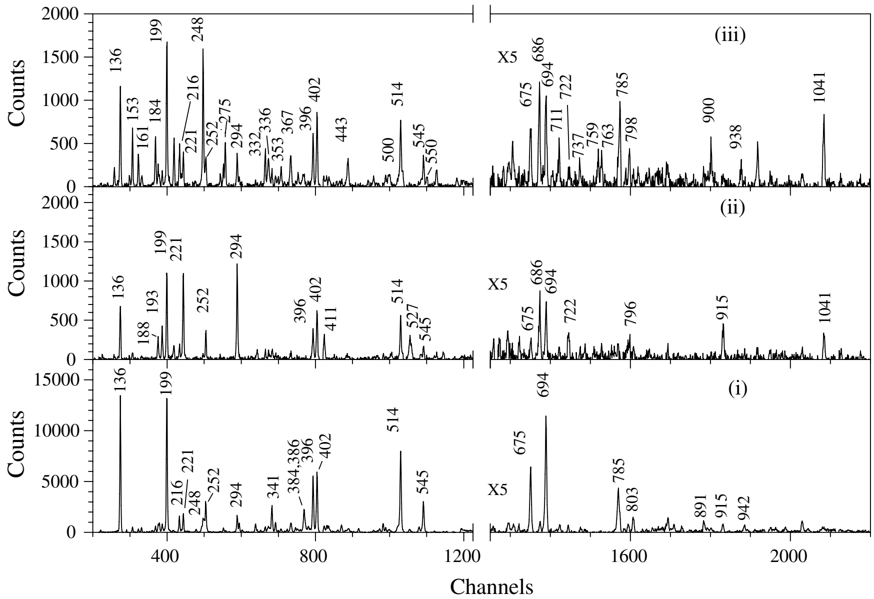

Fig. 1. Selected γ-γ coincidence spectra for the bands of ^{138}Pr, obtained by setting gates on the transitions: i) 396 and 402 keV for band I, ii) 411 and 527 keV for band III and iii) 366 and 443 keV for band IV. The transitions of interest are labelled by their energies in keV.

through Coriolis interaction. These calculations were performed with the full basis states comprising of six Nilsson neutron states and six Nilsson proton states arising from $1h_{11/2}$ orbital. The μ, κ parameters of the deformed oscillator potential were the standard values used in these mass region for $N = 5$ shell. The pairing gap (Δ_p, Δ_n) and the Fermi levels (λ_p, λ_n) were deduced by solving the inverse gap equation. The quadrupole deformation parameter (δ) for each nucleus was obtained from the experimental β_2 values of the neighbouring core. The VMI parameter needed for the calculation of the energy spectra was varied to get a better fit to the band energies. The $M1$ transition probabilities were calculated by using $g_R = Z/A$, $(g_l)_p = 1.0$, $(g_l)_n = 0.0$, $(g_s)_p = 5.585$, $(g_s)_n = -3.826$. The intrinsic quadrupole moments (Q_0), in general, were calculated from the respective experimental $B(E2; 2_1{}^+ \to 0_1{}^+)$ values of the core. However, in the case of ^{138}Pr, in absence of the relevant data of the core, it was taken as an adjustable parameter. Further details of the model, the calculation and the values of the parameters can be found in refs. [3,4]. In the case of ^{138}Pr, the comparison between the theoretical and the experimental transition probability data, could not be carried out due to the nonavailability of the relevant experimental data (branching ratio and $B(E2)/B(M1)$ values) at that time from the work of Rizzutto *et al.* [1]. However, for the other nuclei studied, the theoretical values of the branching ratios and $B(E2)/B(M1)$ values from the PRM calculation [3], were found to be quite sensitive to the choice of the shape of the nucleus. The prime motivations behind the present work were, therefore, to i) study in a more extensive way the level scheme of ^{138}Pr with a larger array of HPGe detectors and ii) determine the relevant transition probability data through the measurement of the intensities of the γ-rays depopulating various states, for a meaningful comparison with the theoretical work [3]. In addition this experiment was also aimed at identifying bands originating from configurations other than that based on $\pi h_{11/2} \otimes \nu h_{11/2}$. It may be noted that a number of such bands had been established in different nuclei in this mass region by recent experimental investigations [5–9].

2 Experimental methods and results

The level properties of ^{138}Pr were studied using the reaction ^{128}Te(^{14}N, 4n)^{138}Pr at a beam energy of 55–65 MeV obtained from the 15UD Pelletron Accelerator at the Nuclear Science Centre (NSC), New Delhi. The target ($\sim 800\ \mu$g/cm^2) was prepared by the vacuum evaporation of enriched ^{128}Te (99.99% purity) powder onto a thin gold foil. The resulting nuclei were investigated with standard in-beam γ-spectroscopy techniques which involved studies of excitation functions, γ-γ coincidence and DCO ratios. A multi-detector array consisting of eight Compton-suppressed HPGe detectors along with fourteen BGO detectors serving as a multiplicity filter was used for these purposes. The excitation function studies indicated that the (^{14}N, 4n) channel, leading to ^{138}Pr, was maximally populated at a beam energy of 57.5–60 MeV and this was found to be in close agreement with the predictions of the CASCADE code. For the subsequent part of the experiment the beam energy was fixed at 60 MeV.

The details of the experimental setup and data acquisition system can be found in refs. [7,10]. A total of 30 million events corresponding to two- or higher-fold coincidences in HPGe was recorded in the list mode. Each coincidence event was qualified with the condition that at

Table 1. Energies (E_γ), intensities (I_γ) and assignments of the γ-rays of ^{138}Pr populated in the present work. Here, N_G indicates the nature of the gating transition, *i.e.* Dipole (D) or Quadrupole (Q) which has been used to measure the DCO of the γ-rays.

E_γ (keV)	I_γ	DCO	N_G	Assignment $I_i^\pi \to I_f^\pi$	Assignment Structure
136.4	334(10)	0.81(5)	D	$9^+ \to 8^+$	I→I
152.9	29(1)	1.32(15)	D	$15^- \to 14^-$	V→V
160.8	10(0.3)			$18 \to 17$	IV →IV
165.4	19(1)			$11^+ \to 10^-$	V →V
183.9	11(1)			$18 \to 17$	IV →IV
187.7	53(2)	0.90(16)	D	$12^+ \to 11^+$	II →II
189.3	24(1)			$13^+ \to 12^+$	VI →VI
193.3	23(1)			$15 \to 14$	III→III
199.1	1000	1.42(4)	D	$8^- \to 7^-$	
216.1	42(1)	1.22(16)	D	$13^+ \to 12^+$	VI →VI
216.4	119(4)	0.90(10)	D	$9^+ \to 8^-$	V→V
221.4	64(2)	1.00(14)	D	$16 \to 15$	III→III
248.1	52(2)	1.13(15)	D	$19 \to 18$	IV→IV
251.6	62(3)	1.02(14)	D	$9^- \to 8^-$	V →V
251.6	133(4)	0.98(10)	D	$13^+ \to 12^+$	II→II
271.4	40(2)	0.83(16)	Q	$11^+ \to 9^-$	V →V
275.4	11(1)			$15 \to 14$	IV→IV
294.0	73(2)	1.16(11)	D	$17 \to 16$	III→III
304.5				$17^+ \to 16^+$	II →II
318.8	34(1)	1.05(16)	D	$13^+ \to 12^+$	VI→VI
331.8	240(2)	0.90(7)	D	$8^- \to 7^-$	V→V
335.8	25(1)	1.33(20)	D	$16 \to 15$	IV→IV
340.8	146(5)	0.98(10)	D	$14^+ \to 13^+$	II→II
345.7	41(1)	0.86(16)	D	$13^+ \to 12^+$	I→I
349.0	60(2)	0.43(12)	Q	$9^- \to 8^-$	V→V
353.1	60(1)	1.25(13)	D	$17 \to 16$	IV→IV
357.7	27(2)			$10^- \to 8^-$	V→V
366.1	41(1)	1.04(17)	D	$20 \to 19$	IV→IV
367.1	39(1)	0.49(17)	Q	$16^- \to 15^-$	V →V
376.1	6(1)			$17 \to 16$	IV→IV
378.6	20(1)			$8^- \to 8^-$	V→V
384.0	133(4)	0.97(8)	D	$15^+ \to 14^+$	II→II
385.8	42(1)	0.86(18)	D	$16^+ \to 15^+$	II→II
388.8	21(1)			$14^+ \to 13^+$	VI→VI
396.2	389(12)	1.03(5)	D	$11^+ \to 10^+$	I→I
401.6	500(15)	0.98(5)	D	$10^+ \to 9^+$	I→I
411.2	43(2)	1.05(18)	D	$18 \to 17$	III→III
412.9	7(1)			$15 \to 15^-$	III→V
415.5	34(1)			$14^+ \to 13^+$	VI→VI
443.4	25(1)	1.05(20)	D	$21 \to 20$	IV→IV
457.7	33(1)	0.99(19)	D	$17^+ \to 16^+$	II→II
485.9	19(1)			$14^+ \to 13^+$	II→I
490.8	43(1)	1.06(19)	D	$13^+ \to 12^+$	II→I
494.3	20(1)			$14^- \to 13^+$	V→I
499.6	16(1)			$18 \to 17$	IV→III
514.3	748(23)	1.06(5)	D	$8^+ \to 7^-$	
526.7	28(1)	0.95(18)	D	$19 \to 18$	III→III
539.1	49(2)	1.12(15)	D	$16^+ \to 15^+$	II→II
545.0	199(6)	0.96(7)	D	$12^+ \to 11^+$	I→I
550.6	4(1)			$22 \to 21$	IV→IV
571.5	6(1)			$19 \to 18$	III→III
580.0				$13^+ \to 11^+$	VI→VI
597.0	40(2)	1.12(15)	D	$11^+ \to 11^+$	II→I
674.9	95(3)	1.01(10)	D	$12^+ \to 11^+$	VI→I
685.6	161(5)	0.94(8)	Q	$11^+ \to 9^+$	V→V
685.7	9(1)			$20 \to 19$	III→III
694.1	400(2)	0.98(5)	D	$8^+ \to 7$	
710.5	56(5)	0.47(14)	Q	$8^- \to 7^-$	V→V
722.3	13(1)			$14 \to 13^+$	III→II
723.3	36(2)			$10^+ \to 9^+$	VI→I
724.8				$15^+ \to 13^+$	II→II
736.5	41(2)			$10^- \to 8^-$	V→V
759.1	29(1)	0.45(17)	Q	$14^- \to 13^+$	V→V
763.1	97(4)			$9^- \to 8^-$	V→V
782.6	15(1)			$14 \to 13^+$	IV→II
784.5	91(3)	0.97(13)	D	$12^+ \to 11^+$	II→II
795.8	12(1)			$16 \to 14^+$	III→II
798.0	130(3)	2.00(10)	D	$11^+ \to 9^+$	I→I
803.2	46(2)			$11^+ \to 10^+$	VI→I
859.0	29(2)			$10^+ \to 8^+$	VI→I
864.3	11(1)			$13^+ \to 11^+$	VI→I
868.0	30(2)	1.22(19)	Q	$15^+ \to 13^+$	V→V
891.0	8(1)			$13^+ \to 11^+$	I→I
900.4	9(1)			$17 \to 16^+$	IV→V
915.2	20(1)			$15 \to 13^+$	III→II
938.1	13(1)			$14^+ \to 12^+$	I→I
942.0	22(1)			$12^+ \to 10^+$	I→I
973.8				$14 \to 12^+$	III→II
982.7				$19 \to 17$	III→III
993.3	26(1)	0.81(20)	D	$11^+ \to 10^+$	II→I
1041.1	166(5)	1.16(7)	Q	$13^+ \to 11^+$	II→II
1177.3	12(1)			$14^+ \to 12^+$	I→I
1181.0	3(1)			$12^+ \to 10^+$	II→I
1212.1				$20 \to 18$	III→III
1213.1	29(2)			$14 \to 12^+$	III→I
1273.4	12(1)			$14 \to 12^+$	IV→I
1395.2	14(1)			$11^+ \to 9^+$	II→I

least two BGO detectors of the multiplicity filter should fire. The pulse height of each detector was gain-matched to 0.5 keV/channel and the γ-γ coincidence data were sorted out into a 4096 × 4096 total E_γ-E_γ matrix. Energy spectra gated by the γ-rays of interest were generated from the matrix. Figure 1 shows the coincidence spectra with gates on a few γ-rays of importance. The multipolarities of the observed γ-rays were determined through the directional correlation (DCO) ratios. For this purpose a separate 4096 × 4096 matrix was generated from the events recorded at 99° along one axis and those recorded at 153° along the other axis. The DCO ratios determined as

$$R_{\rm DCO} = \frac{I(\gamma_1 \text{ at } 153^\circ \text{ with } \gamma_2 \text{ at } 99^\circ)}{I(\gamma_1 \text{ at } 99^\circ \text{ with } \gamma_2 \text{ at } 153^\circ)} \quad (1)$$

(γ_1 is the γ-ray of interest, obtained in coincidence with γ_2) were compared with the theoretical DCO ratios for the assignment of spin. A width of $\sigma = 0.3J$ (J is the

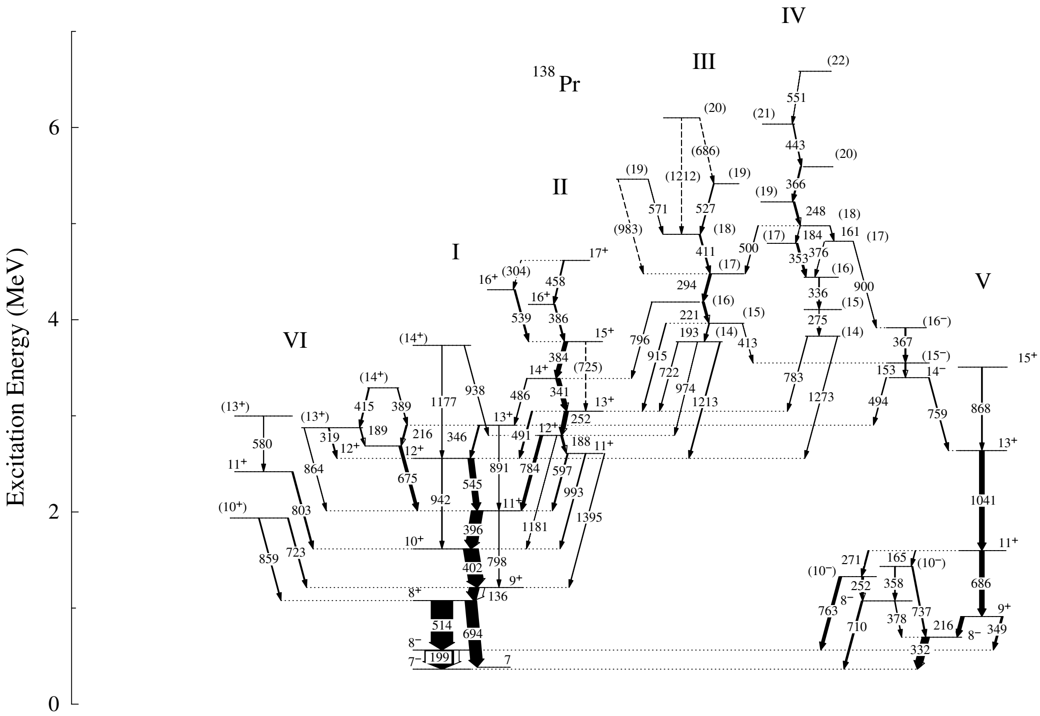

Fig. 2. The proposed level scheme of ^{138}Pr deduced from the present work. The transitions which can only be tentatively placed are indicated by dashed lines.

level spin) was used for the presumed Gaussian distribution of the magnetic substate population. Gates on stretched $E2$ transitions yield R_{DCO} values close to unity for quadrupole γ-rays or $\Delta J = 0$ nonstretched pure dipole transitions and values ranging from 0 to 2, depending on the $E2/M1$ multipole mixing ratios (δ) for $\Delta J = 1$ transitions. However, the usual way of setting the gates on stretched $E2$ transitions was not feasible in most of the cases. Gates set in several cases on strong $\Delta J = 1$ predominantly dipole transition yield $R_{\text{DCO}} = 1$ for $\Delta J = 1$ transitions with small δ and values close to 0.5 for stretched $E2$ γ-rays. In general, the DCO ratios were determined by gating on transitions in the band sequence preceding or following the transition of interest. Whenever possible, different gating transitions have been used and the consistency of assignments has been checked. In table 1 we report only one of the obtained DCO ratios for each transition and also specify the type of gating. It may be noted that in a few cases the experimental DCO ratios are deviating from the theoretical estimates. This is primarily because of the poor statistics in the DCO gates. In those cases one may question the validity of the assignment. However, it should be stressed that the presence (and intensities) of these γ-rays in the multiple gates or in the summed gated spectra of the same band confirmed that they belong to the relevant bands and the assignemnts made therein satisfy the earlier information and the internal consistency of the level scheme in addition to the DCO values.

The level scheme of ^{138}Pr has been constructed from the γ-γ coincidence data, the γ-ray intensities and the multipolarities of the γ-rays. A total of 87 transitions of which 53 are newly observed, has been placed in the level scheme shown in fig. 2. Six distinct band/structure configurations including the positive-parity yrast structure have been established. The energies, relative intensities and the DCO ratios of the γ-rays and the assigned spin-parities of the relevant levels of ^{138}Pr are given in table 1. The proposed energy and spin-parity values of different levels in the constructed scheme are shown in table 2. We assumed that in general the spin increases with excitation energy. We will now discuss the salient features of the experimental results.

Band I, which comprises the low-lying yrast levels of ^{138}Pr (band 1 in ref. [1]), is built on the state at 1078 keV with $I^{\pi} = 8^{+}$, following the systematics of the odd-odd yrast band head excitation energy in this mass region. The data of the present work confirms the basic structure of the yrast band as proposed by Rizzutto *et al.* [1]. Two new transitions, *viz* 938 and 1177 keV, are also found to feed the 12^{+} levels at 2796 and 2557 keV excitation from a newly proposed level with $I^{\pi} = (14^{+})$ at 3733 keV.

Band II in our scheme is band 2 of ref. [1]. Our results are in agreement with those of Rizzutto *et al.* but we have also observed the following new transitions depopulating band II: 486, 891, 1181 and 1395 keV. A weak 304 keV transition is proposed between the $I^{\pi} = 17^{+}$ and 16^{+} state at 4617 and 4312 keV excitation energy, respectively, in band II and a weak 725 keV crossover transition between $I^{\pi} = 15^{+}$ and 13^{+}. Furthermore, it has been possible to observe several new connecting transitions between bands I and II.

Table 2. Energy (E) and the spin-parity (J^{π}) values of the different levels in the proposed level scheme.

E (keV)	J^{π}	E (keV)	J^{π}
364.0	7^-	Structure IV	
384.1	7	3829.2	(14)
562.8	8^-	4105.7	(15)
Structure I		4441.9	(16)
1078.1	8^+	4794.4	(17)
1214.0	9^+	4816.8	(17)
1615.6	10^+	4977.8	(18)
2011.8	11^+	5225.5	(19)
2557.2	12^+	5591.9	(20)
2902.4	13^+	6035.1	(21)
3733.0	(14^+)	6585.1	(22)
Structure II		Structure V	
2608.6	11^+	696.4	8^-
2796.1	12^+	912.0	9^+
3047.8	13^+	1074.7	8^-
3388.5	14^+	1326.7	(10^-)
3772.5	15^+	1433.0	(10^-)
3772.5	15^+	1433.0	(10^-)
4159.0	16^+	1597.7	11^+
4312.2	16^+	2638.7	13^+
4616.7	17^+	3397.6	14^-
Structure III		3507.0	15^+
3770.4	(14)	3549.9	(15^-)
3963.0	(15)	3916.6	(16^-)
4184.1	(16)	Structure VI	
4478.0	(17)	1937.3	(10^+)
4889.0	(18)	2418.3	11^+
5415.3	(19)	2686.6	12^+
5461.5	(19)	2876.0	(13^+)
6101.0	(20)	2998.3	(13^+)
		3291.0	(14^+)

In their work Rizzutto *et al.* suggested a tentative spin-parity of the levels up to $I^{\pi} = (13^+)$ for the yrast band. On the basis of our DCO data and observation of a number of linking transitions we are not only supporting the spin-parity assignments for band I, as suggested by them but also proposing a set of new spin-parities for the states of band II.

The transitions, *viz* 221, 294, 411 and 527 keV, in band III were also observed by Rizzutto *et al.* [1]. But we propose a new placement for this sequence of transitions, at a relatively higher excitation, than that suggested by the earlier work. This is on the basis of a number of new transitions (*viz* 722, 796, 915, 974, 1213 keV) which have been found to connect this band with bands I and II. In addition, a few new transitions belonging to this band (*viz* 193, 686, 1212 keV) have also been observed. No spin-parities were suggested by Rizzutto *et al.* In the present case also, due to the absence of the DCO ratio for these connecting transitions, we are not able to assign a definite parity for the states of this band. The assignment of a tentative spin of 14 for the band head is solely based on the argument that the spin should increase relative to the fed state.

Band IV is entirely a new sequence of transitions reported for the first time in this work. The present results also suggest that this band mainly consists of dipole transitions, similar to those of band III. But unlike band III, it is not so strongly connected to bands I and II, though definite indications of the linking transitions have been found in the gated spectra. This structure is also found to be connected with band III. The argument for assigning a tentative spin (14) for the band head is similar to that given for band III. The other spin assignments are also consistent with the nature of the transitions, as suggested by the DCO ratios.

Band V is the side band (band 3 in ref. [1]) which was originally proposed by Rizzutto *et al.* [1] to be a negative-parity band, though we are proposing a number of changes which are as follows:
i) Taking into consideration the dipole character of the 332, 216 transitions and the quadrupole nature of the 686, 1041 and 868 keV transitions, as obtained through our DCO ratio measurements, the parities of the states at 696, 912, 1598, 2639 and 3507 keV are proposed to be 8^-, 9^+, 11^+, 13^+ and 15^+, respectively. This assignment is well corroborated by the analysis of the recent data on ^{139}Nd from the Euroball and GASP experiment [9]. These authors have identified a similar sequence ($5/2^+$, $7/2^-$, $11/2^-$, $15/2^-$ and $19/2^-$) in that nucleus. ii) We also suggest a change in the placement for the 153 and 367 keV transitions, on the basis of our coincidence data. These γ-rays are now proposed to belong to a negative-parity sequence of two states. The 13^+ state at 2639 keV is linked to the lowest of these negative-parity states at 3398 keV through a 759 keV transition. The suggested spin-parities of the levels at 3398, 3550 and 3917 keV are on the basis of the multipolarities of the linking transition (759 keV) and the rest of the transitions (153 and 367 keV) within this part of the level scheme. The negative-parity structure is also found to be connected through a 900 keV transition to a newly proposed $I^{\pi} = (17)$ state at 4817 keV excitation. The above-mentioned state, in turn, is connected to band IV through the 161 keV (from $I^{\pi} = 18$ state at 4978 keV) transition and also decays through a number of transitions (376, 336, 275, 783, 1273 and 494 keV) to bands I and II. The present work also significantly modifies the lower portion of the structure wherein a number of new levels are being proposed on the basis of the observation of several new transitions. This has, however, made the lower portion of the structure quite complicated. These linking transitions suggest the additional decay path of band V to the 7^- and 8^- states at 364 ($T_{1/2} = 2.1$ h) and 563 keV, respectively.

A part of the structure VI was reported by Rizzutto *et al.* [1]. However, a few new transitions within the states of these structure and lower-lying levels have also been observed in the present work.

3 Discussion

As far as the configuration of the lowest observed state in our experiment and the yrast bands (bands I and II)

Table 3. Calculated and experimental branching ratios of the $\pi h_{11/2} \otimes \nu h_{11/2}$ yrast band in ^{138}Pr.

I_i^π	I_f^π	Branching ratio			$B(M1)/B(E2)$ in ${\mu_n}^2/(eb)^2$		
		Expt.[(a)]	Theory		Expt.	Theory	
			I[(b)]	II[(c)]		I[(b)]	II[(c)]
11^+	10^+	74.3	43.3	94.0	10.4(3)	2.7	54.5
	9^+	25.7	56.7	6.0			
12^+	11^+	85.8	52.5	92.6	19.8(9)	2.8	37.4
	10^+	14.2	47.5	7.4			
13^+	12^+	79.4	28.7	76.3	36.4(3)	3.4	32.0
	11^+	20.6	71.3	23.7			

([a]) Present work. The branching ratios have been calculated from proper gates.
([b]) Calculation with prolate deformation ref. [3].
([c]) Calculation with oblate deformation ref. [3].

are concerned, the following comments can be made. A $\pi h_{11/2} \otimes \nu d_{3/2}$ configuration can be suggested for the 7^- lowest state, while the 8^- state which decays to the ground state by a weak 199 keV transition has probably the $\pi d_{5/2} \otimes \nu h_{11/2}$ configuration. The yrast band is assumed, following the systematics observed in this mass region, to be based on the $\pi h_{11/2} \otimes \nu h_{11/2}$ configuration with band head $I^\pi = 8^+$, arising from the perpendicular coupling between the valence proton and neutron. The theoretical branching ratios and $B(M1)/B(E2)$ values as calculated using the PRM model [3] have been compared with the present experimental results and are given in table 3. The experimental $B(M1)/B(E2)$ values have been calculated from the measured $I_\gamma(M1)/I_\gamma(E2)$ branching ratios by using the relation

$$\frac{B(M1; I \to I-1)}{B(E2; I \to I-2)} = 0.693 \frac{E_\gamma^5(E2)}{E_\gamma^3(M1)} \frac{I_\gamma(M1)}{I_\gamma(E2)}\,, \quad (2)$$

where the $E2/M1$ mixing ratio for the dipole transition was assumed to be zero. It can be seen from the table 3 that the agreement (for states above 11^+) between the theory and experiment in the case of oblate deformation is quite satisfactory. The relatively strong transitions linking band II to band I suggest a configuration involving the unfavoured signature ($\alpha = +1/2$) of the $\pi h_{11/2}[541]3/2^-$ orbital for band II.

In view of the high spin and excitation energy and systematics of similar structures in the neighbouring odd-odd Pr nuclei [5,7], a 4 qp configuration involving a broken pair of protons and neutrons is suggested for bands III and IV, respectively.

Based on the systematics of low-lying states in ^{137}Sm and ^{139}Gd, which shows the presence of the $\nu f_{7/2}$ orbital at low excitation energy, Petrache *et al.* [9] has proposed the existence of a $7/2^-$ state in ^{139}Nd. The $5/2^+$ state in that nucleus has been assigned a $d_{5/2}g_{7/2}$ configuration. The above-mentioned structure of band V in ^{138}Pr can then be based on the same neutron configuration as in ^{139}Nd coupled to a $h_{11/2}$ proton. In fact, by adding a state with spin-parity of $11/2^-$ to the states in ^{139}Nd, we obtain the above-mentioned level sequence. For the sake of completeness, it may be pointed out that similar doubly decoupled structures were observed by Petrache *et al.* [6] in ^{136}Pr, starting at higher spins, indicating the presence of the orbitals from the above $N = 82$ shell closure near the Fermi surface.

4 Conclusion

The high-spin structure of the doubly odd nucleus ^{138}Pr has been studied. Several new level sequences have been established in this nucleus and the present result is in agreement, to an extent, with the earlier report [1] on the three primary bands. However, it has been possible to find out a number of new in-band and inter-band transitions within these bands. Three additional structures are also being proposed. A comparison of the experimental transitional probabilities of the transitions within the yrast band with the theoretical calculation, favours an oblate structure for this band.

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