RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 57, NUMBER 2 FEBRUARY 1998

Observation of a deformed band in ^{98}Rh

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(Received 5 November 1997)

The high spin level structure of ^{98}Rh has been extended to a spin of $16\hbar$ and excitation energy of 8.3 MeV through the discrete-line γ-ray spectroscopy. A negative parity rotational band has been observed which exhibits a large signature splitting and a signature inversion at $I=10\hbar$. The particle-rotor model calculations using a β=0.13 and $(\pi g_{9/2}\otimes \nu h_{11/2})$ configuration for the odd proton and neutron give a good description of the above-mentioned characteristics of the band. Thus ^{98}Rh is the nucleus closest to the $N=50$ shell closure which exhibits a deformed band based on the $h_{11/2}$ intruder orbital. [S0556-2813(98)50502-X]

PACS number(s): 21.10.Re, 23.20.−g, 21.60.Ev, 27.60.+j

In recent years the high spin behaviors of nuclei in mass-100 region have been studied extensively in order to investigate the interplay between the single particle and the collective degrees of freedom near the $N=Z=50$ shell closure. The deformed intruder bands based on $\pi h_{11/2}$ orbital have been found even for $Z=51$ [1]. However, for $Z<50$ and $N>50$ nuclei, rotational bands have been observed with six neutrons (or more) outside the $N=50$ shell closure [2,3]. These bands originate due to the occupation of the 1/2[550]$h_{11/2}$ orbital as the neutron Fermi surface lies very close to this orbital even for a small deformation of $\beta\sim0.15$. But in more neutron deficient nuclei, e.g., ^{100}Pd ($N=54$), recent data indicate the absence of $\nu h_{11/2}$ contribution to the yrast band [4]. This is possible if there is no stable deformation in the case of $N=54$; thus moving the Fermi level away from the $\nu h_{11/2}$ orbital or if the deformed neutron configurations have energies far higher than the yrast sequence.

Recently Wyss *et al.* have predicted the existence of deformed neutron configurations with negative parity ($\nu h_{11/2}$) at near yrast energies in ^{96,97,98}Ru from total routhian surface (TRS) calculations (as mentioned in [5]). In these calculations the best case for stable deformation appears to be in ^{97}Ru ($N=53$) which is predicted to have a relatively low lying (less than 300 keV above the yrast configuration) near prolate minimum ($\beta\sim0.13$) based on the $[\nu h_{11/2}\otimes(\pi g_{9/2})^2]$ configuration. In this perspective $N=53$ nuclei seem to be the best candidates to exhibit rotational behavior closest to the $N=50$ shell closure. However existing experimental data on odd mass ^{97}Ru ($Z=44$) [5] and ^{99}Pd ($Z=46$) [6] do not exhibit any nonyrast negative parity band built on the $\nu h_{11/2}$ state.

In the present paper, we investigate the high spin behavior of the odd-odd partner of these $N=53$ nuclei, ^{98}Rh ($Z=45$). This study is expected to reveal whether the presence of an unpaired proton has any extra stability effect on the near-yrast deformed minimum which has been predicted by Wyss *et al.*

In the previous study of ^{98}Rh a cascade of five γ transitions has been assigned to the nucleus by performing γ-γ coincidences with two HPGe detectors and the level scheme was established up to a spin of $10\hbar$ [7]. In the present study the high spin states in ^{98}Rh were populated through the ^{70}Ge(^{32}S,$3pn$) reaction. The 128 MeV ^{32}S beam was obtained from the 14-UD pelletron accelerator at TIFR, Bombay. The target was prepared by evaporating $\sim$800 μg/cm^2 enriched ($\sim$95%) ^{70}Ge on 10 mg/cm^2 gold. A total of 30 million γ-γ coincidences was collected by five Compton suppressed HPGe detectors placed at 22 cm from the target and at 45°, 75°, 165°, 225°, and 285° with respect to the beam direction [8]. Each event was qualified by a twofold trigger (at least) in a 14 element NaI(Tl) multiplicity filter in order to suppress the radioactivity background. The angular distribution data were collected by placing the detectors at 45°, 90°, 165°, 240°, and 330°. For this configuration the target to detector distance was 25 cm. The directional correlation orientation (DCO) ratios of the γ rays were determined from the data obtained with the detectors placed at 75°, 165°, and 285°.

The present level scheme was built up from the coincidence spectra of previously assigned cascade of 841, 725, 994, 980, and 264 keV transitions. Figure 1 shows the gated spectrum with 841 keV γ transition. Both 841 and 725 gates showed the presence of a 1407 keV transition. As will be discussed later, this transition provided the crucial connection to the negative parity levels. The coincidence spectrum with 1407 keV gate, in turn, revealed the presence of a 549 keV γ ray which was assigned to the negative parity band. The 549 keV gate led to the construction of the negative parity band in ^{98}Rh. These gated spectra are also shown in Fig. 1. The relative intensities and the DCO ratios of the γ rays assigned to ^{98}Rh from the present work are given in Table I.

In addition, the angular distribution for 841, 725, 994, and 980 keV γ transitions was measured and were found to agree well with the previously reported values [7]. All these tran-

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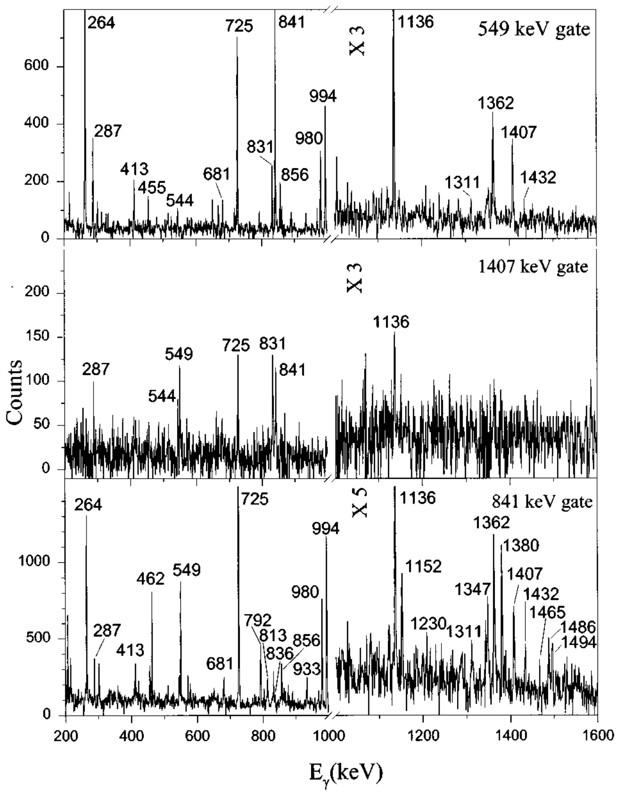

FIG. 1. γ-γ coincidence spectra with 841, 1407, and 549 keV gates in the ^{70}Ge(^{32}S,3$pn\gamma$)^{98}Rh reaction.

sitions had A_2/A_0 values around $+0.30$ and A_4/A_0 values around -0.10 and thus they were identified as stretched $E2$ transitions. The DCO ratio values for 725, 994, and 980 keV γ transitions were found to be within 1.10 ± 0.06 when the gating transition was 841 keV. For all the other γ transitions the DCO ratio values were either around 0.5 ($\Delta I=1$ transition) or around 1.0 ($\Delta I=2$ transition). Only exception was the 264 keV transition for which the DCO ratio value was found to be 0.88(12), but has been assumed to be a $\Delta I=1$ transition in order to be consistent with the overall spin assignment for ^{98}Rh. The present level scheme (shown in Fig. 2) was constructed by taking into account various gating conditions and the multipolarities of the γ transitions.

The 1407 keV γ transition which had been observed in the 841 and 725 keV gated spectra, exhibited a dipole character in the DCO measurements. In the gated spectra this γ ray appeared as a sharp line thus indicating that the lifetime of the state deexcited by the 1407 keV transition was greater than the stopping time of ^{98}Rh in the gold backing ($\sim$1.2 ps). Considering the branching ratio of the γ transitions deexciting the state ($I=7\hbar$), the partial lifetime for the 1407 keV transition was found to be greater than 2 ps. This value is two orders of magnitude higher than the Weisskopf estimate for an $M1$ transition of the same energy. On the other hand this large lifetime could be possible, provided it is an $E1$ transition. Then the observed retardation factor of 0.3×10^{-5} or more is found to be consistent with the systematics of observed $E1$ retardation over the periodic table. This led to the assignment of negative parity to the $I=7\hbar$ level at 2973 keV. For all other cases the usual criterion, increasing spin with increasing excitation energy, has been assumed in building the level scheme of ^{98}Rh. It is interesting to note that another high-energy $E1$ transition of 1494 keV has also been observed (Fig. 1) which connects the 11^- state to the 10^+ yrast state.

TABLE I. Relative intensities and DCO ratios for γ transitions (E_γ) which deexcite the energy levels (E_i) in ^{98}Rh.

E_γ (keV)	E_i (keV)	Relative intensity	R_{DCO}	$I_i^\pi\rightarrow I_f^\pi$
264	3804	22(1)	0.88(12)	$9^-\rightarrow10^+$
287	3804	5(1)	0.40(12)	$9^-\rightarrow8^-$
413	2973	5(1)	0.37(15)	$7^-\rightarrow8^+$
455	5489	12(1)	0.39(10)	$12^-\rightarrow11^-$
462	3022	25(2)	0.45(13)	$9^+\rightarrow8^+$
506	6851	5(1)	0.42(18)	$14^-\rightarrow13^-$
544	3517	10(1)	0.41(16)	$8^-\rightarrow7^-$
549	4353	25(2)	0.38(8)	$10^-\rightarrow9^-$
681	5034	7(1)	0.40(15)	$11^-\rightarrow10^-$
725	1566	92(3)	1.05(11)	$6^+\rightarrow4^+$
792	3814	22(2)	1.03(14)	$11^+\rightarrow9^+$
813	4353	10(1)	0.98(16)	$10^-\rightarrow10^+$
831	3804	13(1)	1.08(18)	$9^-\rightarrow7^-$
836	4353	5(1)		$10^-\rightarrow8^-$
841	841	100		$4^+\rightarrow2^+$
856	6345	17(2)	0.44(11)	$13^-\rightarrow12^-$
933	6127	11(1)	1.10(14)	$15^+\rightarrow13^+$
980	3540	45(2)	1.16(14)	$10^+\rightarrow8^+$
994	2560	74(2)	1.14(12)	$8^+\rightarrow6^+$
1136	5489	31(2)	0.98(16)	$12^-\rightarrow10^-$
1152	6346	11(1)	1.08(15)	$15^+\rightarrow13^+$
1230	5034	2(1)		$11^-\rightarrow9^-$
1311	6345	8(2)		$13^-\rightarrow11^-$
1347	7474	8(2)	1.10(30)	$17^+\rightarrow15^+$
1362	6851	24(3)	0.94(20)	$14^-\rightarrow12^-$
1380	5194	21(3)	1.14(20)	$13^+\rightarrow11^+$
1407	2973	17(2)	0.47(25)	$7^-\rightarrow6^+$
1432	8283	10(2)	0.89(30)	$16^-\rightarrow14^-$
1465	7810	5(1)		$(15^-)\rightarrow13^-$
1486	8960	5(1)		$(19^+)\rightarrow17^+$
1494	5034	11(2)	0.44(30)	$11^-\rightarrow10^+$

It is observed from the level scheme (Fig. 2) that the nonyrast negative parity levels are connected by $E2$ transitions as well as by intermediate $M1$ transitions. The level energy differences $E(I)-E(I-1)$ for these set of levels have been plotted as a function of angular momentum I in Fig. 3(a). It clearly exhibits a signature (α) splitting. At high spins the energy difference for even I values are lower ($\alpha=0$) as compared to the odd I ($\alpha=1$) values. This large signature splitting indicates that the negative parity levels constitute a deformed band where one of the odd particles occupies a low Ω component of a high j orbital. The Nilsson single particle energy level diagram shows that at small deformations the odd proton occupies the $\Omega=5/2$ level of $g_{9/2}$ orbital. If the present band is identified with the deformation minimum having $\beta\sim0.13$ observed in the TRS calculation [5], then the odd neutron occupies a low Ω level of $h_{11/2}$ orbital. This configuration would then be consistent with the observed behavior of the nonyrast negative parity band. In

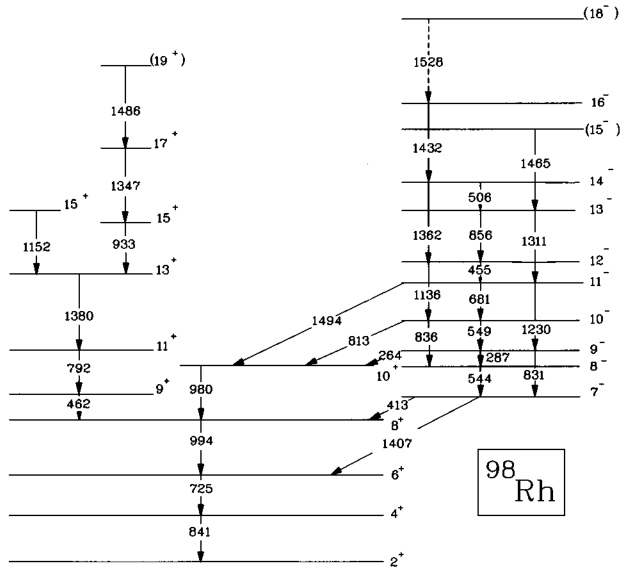

FIG. 2. Partial level scheme of ^{98}Rh. The γ-transition energies are in keV.

subsequent discussions in this paper, the above configuration has been considered and various properties of the negative parity band have been investigated in order to check the validity of this assignment.

In odd-odd nucleus the favored signature is defined as [9]

$$\alpha_f = \tfrac{1}{2}[(-1)^{j_p-1/2} + (-1)^{j_n-1/2}] \quad (1)$$

and for $j_p = 9/2$ and $j_n = 11/2$, $\alpha = 0$ is favored. Thus a normal signature splitting is observed in ^{98}Rh for $I > 10$. For $I < 10$, however, $\alpha = 1$ is favored and an anomalous splitting is observed. Thus at $I = 10\hbar$ a signature inversion [marked with an arrow in Fig. 3(a)] occurs in ^{98}Rh. Similar signature inversion phenomena at low spins have already been observed in several odd-odd nuclei, e.g., ^{156}Tb in the rare earth region [10] and ^{84}Y in mass-80 region [11]. It is also interesting to note that for all these nuclei, the signature inversion was found to occur at a angular momentum equal to $(j_p + j_n)$ or very close to it. In ^{98}Rh also the inversion occurs at the $(j_p + j_n)$ value for the assigned configuration $(\pi g_{9/2} \otimes \nu h_{11/2})$.

In order to obtain quantitative predictions on the observed amplitude of signature splitting and the $B(M1)/B(E2)$ ratios of the transitions in the negative parity band, the particle rotor model (PRM) calculations involving a quasiproton and a quasineutron coupled to an axially symmetric core [12] were performed for ^{98}Rh for a deformation $\beta = 0.13$. A fixed moment of inertia of $(\hbar^2/2\Im = 50$ keV) has been assumed for the core which is about twice the rigid moment of inertia value for ^{98}Rh. The Nilsson parameters $\mu_p = 0.435$, $\kappa_p = 0.064$, $\mu_n = 0.350$, and $\kappa_p = 0.070$ were assumed for this mass range [13]. The Fermi energy (λ) and the pair gap (Δ) for the protons and neutrons have been found by solving the gap equation. The λ and Δ values were found to be $\lambda_p = 45.25$ MeV, $\Delta_p = 1.3$ MeV, $\lambda_n = 48.61$ MeV, $\Delta_n = 1.4$ MeV. With these values the PRM calculations were carried out with the odd proton in $g_{9/2}$ and the odd neutron in $h_{11/2}$ orbitals. The Coriolis attenuation factor for neutron was taken as 0.7. In these calculations the amplitude and the phase of the signature splitting are well reproduced, but the signature inversion was not found. However, the signature inversion phenomenon at low spins was previously examined by Hamamoto in the PRM framework involving single j orbitals for the odd particles [9]. It was found that the signature inversion depends critically on the position of Fermi surfaces of protons and neutrons. In accordance to this observation λ_p was slightly adjusted to 45.05 from 45.25 in the present calculation and the signature inversion was found to occur at $I = 10\hbar$. However, in the case of ^{98}Rh the occurrence of signature inversion does not depend on λ_n which lies about 3 MeV below the $\Omega = 3/2$ level of the $h_{11/2}$ orbital. The results of these calculations are shown in Fig. 3(b). A comparison between Figs. 3(a) and (b) shows that the PRM calculations give a good overall description of all the observed features of the negative parity band of ^{98}Rh. However at low spins the observed amplitude of splitting is not reproduced in the present calculations. This difference might originate from the fact that the low spin states can have substantial contribution from single particle excitations which is not considered in the PRM framework.

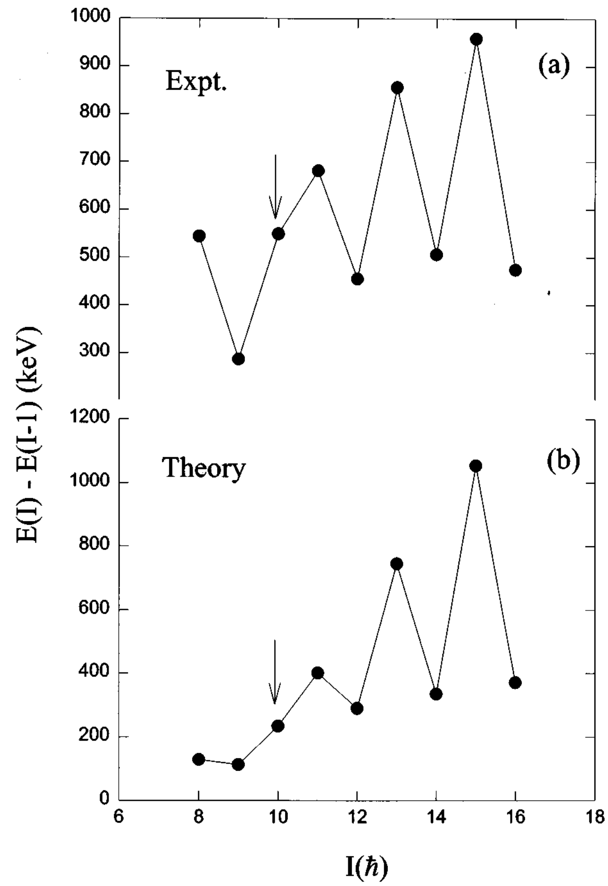

FIG. 3. (a) Observed energy differences $E(I) - E(I-1)$ as a function of angular momentum (I) in ^{98}Rh. The arrow indicates the position of signature inversion. (b) Calculated energy difference as a function of I using PRM with $\beta = 0.13$, $j_p = 9/2$, and $j_n = 11/2$. A Coriolis attenuation factor of 0.7 was used for the odd neutron.

The PRM wave functions were further used to predict the $[B(M1), I \to I-1]$ and $[B(E2), I \to I-2]$ values for the γ transitions of the negative parity band. The calculated

TABLE II. Experimental and calculated $B(M1)/B(E2)$ ratios for transitions in ^{98}Rh.

I^{π}	$[B(M1)/B(E2)]_{\text{expt}}$ $\mu_n^2/e^2\text{b}^2$	$[B(M1)]_{\text{theo}}$ μ_n^2	$[B(E2)]_{\text{theo}}$ $e^2\text{b}^2$	$[B(M1)/B(E2)]_{\text{theo}}$ $\mu_n^2/e^2\text{b}^2$
9^-	4.5 ± 1.2	0.375	0.063	5.95
10^-	8.7 ± 2.1	0.508	0.061	8.33
11^-	22 ± 11	0.098	0.068	1.43
12^-	5.4 ± 0.8	0.512	0.070	7.31
13^-	9.1 ± 2.8	0.056	0.072	0.78
14^-	4.1 ± 1.2	0.495	0.075	6.60

$B(M1)/B(E2)$ ratios were compared with the experimental values assuming that the $(I\rightarrow I-1)$ transitions are pure $M1$. In the calculation of $B(E2)$ values the quadrupole moment (in barns) was estimated from [14]

$$Q_0=0.011ZA^{2/3}\beta \tag{2}$$

and it was found to be 1.4 b. The proton and neutron effective charge was assumed to be 1.5 and 0.5, respectively. In the calculations of the $B(M1)$ values, the spin factors g_s^p and g_s^n were assumed to be 0.6 times the free nucleon values while $g_l^p=1.0$, $g_l^n=0$, and $g_R=Z/A=0.46$ were used. The experimental and calculated values are given in Table II. The observed $B(M1)/B(E2)$ ratio shows a sharp increase up to $I=11\hbar$ and decreases at higher spins thus indicating an enhancement in the collective excitation for $I\geqslant 12\hbar$ in ^{98}Rh. However the theoretical $B(M1)/B(E2)$ ratios using the PRM wave functions show a large staggering which is essentially due to the variation in $B(M1)$ values. This nature of $B(M1)$ staggering is expected from PRM calculations using a symmetric core [9,11]. Thus although the PRM calculations give a good description of the observed signature splitting and inversion, this simple model calculations fail to reproduce the observed $B(M1)/B(E2)$ ratios for the 11^- and 13^- states in ^{98}Rh (Table II).

For the sake of completeness, it is to be mentioned that in the present work another group of positive parity levels were found in ^{98}Rh and they are shown in the left side of the level scheme (see Fig. 2). These high spin states may originate due to the occupation of the three neutrons outside the $N=50$ shell to the $g_{7/2}$ orbital along with the protons in the $g_{9/2}$ orbital. However, to have a more definitive idea about the structure of the high spin positive parity levels, a detailed theoretical calculation is needed.

In conclusion, a strongly coupled negative parity band has been observed in ^{98}Rh. This band exhibits a signature splitting and inversion at $I=10\hbar$. The $B(M1)/B(E2)$ rates also show a signature dependence. Thus ^{98}Rh ($N=53$) is the nucleus closest to the $N=50$ shell closure which exhibits collective behavior in mass-100 region. A PRM calculation with odd proton in the $g_{9/2}$ orbital and odd neutron in $h_{11/2}$ orbital coupled to an axially symmetric core with fixed moment of inertia provides a good description of all the observed features of the band. In this model the Nilsson wave functions at $\beta=0.13$ were used and λ_p was the only parameter whose value was slightly changed from that predicted by the gap equation in order to reproduce the observed signature inversion. Thus we attribute a $(\pi g_{9/2}\otimes \nu h_{11/2})$ configuration to the band which can be identified with the near-yrast deformed minimum found in the TRS calculations for ^{97}Ru.

The authors would like to thank Dr. R. G. Pillay for his help during the experiment. Thanks are also due to D. C. Ephraim for target preparation and the pelletron staff for their support.

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