PRAMANA
— journal of
physics

© Printed in India

Vol. 43, No. 4,
October 1994
pp. 339–352.

Level structures in the odd-odd nucleus ^{180}Re

ASHOK KUMAR JAIN, PRAKASH C SOOD* and RAYMOND K SHELINE†
Department of Physics, University of Roorkee, Roorkee 247 667, India
*Physics Department, Banaras Hindu University, Varanasi 221 005, India
†Florida State University, Tallahassee, FL 32306, USA

MS received 17 May 1994; revised 4 August 1994

Abstract. Experimental data on energy levels of the odd-odd deformed nucleus ^{180}Re obtained from radioactive-decay and heavy-ion reaction studies are analysed to deduce spin-parity and configuration assignments for the six observed rotational bands based on the selection rules for fast beta transitions, criteria for the relative-energy ordering of the triplet and singlet bandheads, two-particle-plus-rotor model calculations including Coriolis mixing, rotational energy systematics involving staggering features, and considerations of gyromagnetic ratios, signature splittings and rotational band alignments.

Keywords. Doubly odd deformed nucleus; Nilsson configuration assignments; Coriolis coupling calculations; systematics and g-factors.

PACS Nos 21·60; 27·70

1. Introduction

The presently available level scheme [1] of the odd-odd deformed nucleus $^{180}_{75}Re_{105}$ is confusing in that it consists of a number of subsets of disconnected rotational bands, mostly with tentative, and often conflicting, spin-parity and configuration assignments. A decade ago, the only information available on this level scheme came from the electron capture decay [2–5] of the 21·5 min O^+ ground state of ^{180}Os; this decay could populate only low-spin ($I < 2$) states. The proposed level scheme [1] suggests assignments for the four lowest levels [$E_x < 75$ keV] based on the systematics of single particle orbitals in the neighbouring nuclei. During the eighties, two independent heavy-ion fusion evaporation (HI, xn) reaction studies, one by the Brookhaven–Buenos Aires (BB) collaboration [6] and the other by the Jülich–Berlin–Copenhagen (JBC) collaboration [7–10], have yielded extensive transition data which could be grouped into several sets of rotational bands. However, in spite of persistent efforts, no connection with the earlier known low-spin states could be established, nor has it been possible to interconnect the various subsets of rotational bands revealed in the heavy-ion reaction studies. Further, the two recent studies by Kreiner *et al* [6] and Venkova *et al* [10], although identifying three similar band sequences, suggested totally different structures (band quantum numbers, spin-parities, configurations) for each of the identified bands. Even after continued efforts, spread over many years and trying out widely differing combinations of possible quasiparticle (qp) configurations, the JBC collaboration could advance only tentative assignments, often based on plausibility considerations. As explicitly pointed out by them [10], their suggested interpretations occassionally contain certain physically unacceptable

features, e.g. Gallagher-Moszkowski (GM) rule [11] violation and alignment inconsistencies, which cannot be explained within the so-far accepted characteristics of the residual neutron-proton interaction and the observed alignment features of Nilsson orbitals in neighbouring odd-A nuclei respectively.

Faced with this situation, we chose to re-examine the experimental data, guided by two-quasiparticle-plus-rotor model (TQPRM) calculations including Coriolis mixing, to decide between the conflicting assignments and to arrive at physically acceptable characterisations consistent with the deduced experimental features. In § 2, we scan the complete $2qp$ configuration space defined by the observed single-particle excitations in the (A-1) isotone and isotope for the neutrons and protons respectively; previously suggested characterisations of the observed bands within the scheme is also described. The outline of our formulation and the results for the various $2qp$ bandhead energies using the TQPRM are presented in § 3. In the final section, we critically examine the available experimental data and deduced properties for each of the identified bands with $K < 10$ (thus excluding $4qp$ structures from our discussion) to arrive at the $2qp$ configuration for each band, consistent with its known features. In common with the earlier investigations, we do not find it possible to interconnect the three pairs of bands under discussion based on the available experimental results.

2. Intrinsic excitations and observed bands

In the two-particle-rotor formulation for odd-odd deformed nuclei each neutron (in Nilsson orbital Ω_n) and proton (Ω_p) combination gives rise to a pair of bands with band quantum numbers $K_\pm = |\Omega_p \pm \Omega_n|$ with relative energy ordering given by the GM rule. According to this rule for Nilsson model asymptotic quantum numbers $[Nn_3\Lambda\Sigma]$, the spins-parallel triplet state K_T lies lower in energy than the spins-antiparallel singlet state K_S within each GM doublet. In table 1, we list $K^\pi(\Omega_p, \Omega_n)$ values for the $2qp$ intrinsic excitations in $^{180}_{75}Re_{105}$ arising from combining all observed Ω_p orbitals in $^{179}_{75}Re_{104}$ and Ω_n orbitals in $^{179}_{74}W_{105}$. The experimentally determined [12] excitation energies $E(\Omega_i)$ for each single particle orbital in the (A-1) isotope and isotone are also listed respectively in the top row and the first column in our table 1. A zeroth-order estimate of the $2qp$ excitation energy for a specified (Ω_p, Ω_n) configuration may be obtained by simply summing the corresponding $1qp$ energies listed here.

The lowest four levels, placed at 0·0, 20·1, 49·8, and 74·6 keV in ^{180}Re from ^{180}Os electron-capture decay (Refs 4 and 5), have been respectively assigned $I^\pi K$ values $1^-1, 1^+1, 2^-1$, and 2^+1, belonging to the $1^-[p_0n_0]$ and $1^+[p_1n_0]$ bands (henceforth referred to as band 1 and band 2) in the notation (p_i, n_j) of our table 1. These assignments are based on the log ft values for beta decay in the $^{180}Os \rightarrow {}^{180}Re \rightarrow {}^{180}W$ chain, multipolarities (E1, M1) of gamma transitions to the ground state in ^{180}Re, and Nilsson orbital systematics of the region.

Excluding the possible $4qp$ bands with $K \geqslant 10$, the two (HI, xn) reaction studies [6, 10] have three very similar bands for which dissimilar (conflicting) assignments have been suggested by the two groups. For the band with lowest $\Delta I = 1$ transition energies 208·8, 228·4, 246·0, 261·5, ..., keV, (hereafter referred to as band 3 which is band 1 of ref. [10] and band A of ref. [6]) Kreiner *et al* [6] suggested the character $8^+[p_1n_0]$ whereas Venkova *et al* [10] suggested its character as $6^-[p_0n_0]$. The two proposed assignments constitute singlet (K_S) counterparts of the $1^+[p_1n_0]$ and $1^-[p_0n_0]$ bands populated in electron-capture decay. However, no connection with the lower lying low-spin bands could be established, and consequently the bandhead

Table 1. The low-energy two-quasiparticle spectrum of ^{180}Re. The column headings denote the proton orbitals (p_i), their Nilsson quantum numbers $\Omega^{\pi}[Nn_3\Lambda\Sigma]$, and observed excitation energy (in keV) and the decoupling parameter a in the case of a $K = 1/2$ band in the neighbouring (A-1) isotope. Similarly, the rows contain the same information for the neutron orbitals from the (A-1) isotone. The band quantum numbers K are given in the order of $K_T(\Sigma = 1)$ followed by $K_S(\Sigma = 0)$; below each K value is listed its calculated position by using a zero-range residual n–p interaction [16–18]. A deformation $\delta = 0{\cdot}24$ and the interaction parameters $\alpha = 0{\cdot}21$ and W = 4·4 MeV were used in the calculation.

p→	p_0		p_1		p_2	
^{179}Re	$5/2^+[402\uparrow]$		$9/2^-[514\uparrow]$		$1/2^-[541\downarrow]$	
n ^{179}W	0·0 keV		80 keV		118·5; 5·9	
n_0	1^-	6^-	1^+	8^+	4^+	3^+
$7/2^-[514\downarrow]$						
0·0	0	160	35	260	300	340
n_1	2^-	3^-	4^+	5^+	1^+	0^+
$1/2^-[521\downarrow]$					GM inv?	
221·9; 0·82	335	435	490	550	470	400
n_2	7^+	2^+	9^-	0^-	4^-	5^-
$9/2^+[624\uparrow]$						
308·9	450	510	290	350	600	660
n_3	5^-	0^-	7^+	2^+	2^+	3^+
$5/2^-[512\uparrow]$						
430·2	380	425	480	565	750	760
n_4	6^+	1^+	8^-	1^-	1^-	4^-
$7/2^+[633\uparrow]$	GM inv?					
477·3	680	665	585	600	815	855

energy for band 3 remains undefined. The next common band in both the heavy-ion reaction studies has the lowest $\Delta I = 1$ transition energies 134·4, 176·7, 210·0, 237·5,... keV (hereafter referred to as band 4 which is band 4 of ref. 10 and band B of ref. 6). Both investigators connect it to our band 3 with a 78·6-keV $E1$ transition, thus establishing opposite parities for these two bands and also defining the bandhead separation energy. However, Kreiner *et al* [6] suggest its configuration as strongly admixed $\{9^-[p_1n_2]; 8^-[p_1n_4]\}$ involving $i_{13/2}$ neutron orbitals, whereas Venkova *et al* [10] characterize it as $7^+[p_0n_2]$.

The third common band for the two groups has the lowest $\Delta I = 1$ transition energies 92·2, 149·3, 182·5, 220·7,... keV (hereafter referred to as band 5, same as in ref. 10 and band D of ref. 6). Kreiner *et al* [6] describe it as the strongly admixed $\{7^+[p_0n_2]; 6^+[p_0n_4]\}$ band involving $i_{13/2}$ neutron orbitals, whereas Venkova *et al* characterize it as $3^-[p_0n_1]$ singlet band. Another band, identified only by Venkova *et al* [10], but not seen by Kreiner *et al* has the lowest $\Delta I = 1$ transition energies 106·3, 133·2, 159·4, 173·4,... keV (hereafter referred to as band 6, in common with ref. 10). This band has the uncommon feature of turning decoupled at higher spins with no $\Delta I = 1$ observed transitions, and thus splitting into two separate $\Delta I = 2$ sequences. Further there are strong interband transitions linking bands 5 and 6, leading Venkova *et al*

to surmise that these two bands possibly constitute a $\Delta K = 1$ GM doublet (thus one of the odd particles occupies a $\Omega = 1/2$ orbital). Based on this reasoning, they characterize band 6 as the $2^-[p_0 n_1]$ triplet band while pointing out that this proposal violates the GM rule and cannot be explained within the present understanding of the residual neutron-proton interaction. In addition, both investigators list one more band each for which K is not a good quantum number: Kreiner *et al* [6] list it as a $\Delta I = 2$ sequence starting from $I^\pi = 5^+$ whereas Venkova *et al* [10] list it as a signature split band starting at $I^\pi = 7^-$. These stand-alone (not connected to any other identified level in ^{180}Re) bands in the two cases have differing transition energies, and may not even belong to this level scheme. Accordingly we restrict our analysis in the following to a discussion of the six bands with a view to arrive at their credible characterization, consistent with the known experimental features.

3. Formulation and 2QP bandhead energies

We use a two-quasiparticle-plus-rotor Hamiltonian written as [13–15],

$$H = H_{\text{intr}} + H_{\text{rot}} \tag{1}$$

where

$$H_{\text{intr}} = H_{\text{av}} + V_{\text{np}} \tag{2}$$

and

$$H_{\text{rot}} = \hbar^2/2\mathscr{I}(I^2 - I_3^2) + H_{\text{cor}} + H_{\text{ppc}} + H_{\text{irrot}}. \tag{3}$$

In writing (1) we have neglected the pairing and vibrational terms. The intrinsic Hamiltonian H_{intr} consists of an averaged single-particle potential (the Nilsson model in our case) and a residual neutron-proton interaction term. Other terms in the H_{rot} are defined as

$$H_{\text{cor}} = -\hbar^2/2\mathscr{I}(I^+ j^- + I^- j^+), \tag{4a}$$

$$H_{\text{ppc}} = \hbar^2/2\mathscr{I}(j_{\text{p}}^+ j_{\text{n}}^- + j_{\text{p}}^- j_{\text{n}}^+), \tag{4b}$$

$$H_{\text{irrot}} = \hbar^2/2\mathscr{I}[(j_{\text{p}}^2 - j_{\text{pz}}^2) + (j_{\text{n}}^2 - j_{\text{nz}}^2)], \tag{4c}$$

where the different quantities have their usual meaning. The basis eigenfunctions used are the symmetrized product of D^I_{MK} and the intrinsic wave functions $|K\alpha\rangle$,

$$|IMK\alpha\rangle = \sqrt{\frac{2I+1}{16\pi^2(1+\delta_{k0})}}\{D^I_{MK}|K\alpha\rangle + (-1)^{I+K}D^I_{M-K}R_i|K\alpha\rangle\} \tag{5}$$

where $\alpha = \rho_{\text{n}}\rho_{\text{p}}$ represents the odd-neutron and the odd-proton product state. First, we put all the coupling terms in (4) to be zero. Then by using the rest of the Hamiltonian, we calculate the unmixed $2qp$ bandhead energies as [16–18]

$$E_K(p_i n_j) = E(p_i) + E(n_j) + E_{\text{rot}}(K) + E_{\text{res}}(K) \tag{6}$$

where the first two terms represent the single quasi-proton and single quasi-neutron energies for the states in question, usually taken from the neighbouring $(A-1)$ isotone/isotope respectively. The last two terms represent respectively the zero-point rotational energy and the residual neutron-proton interaction energy. The residual n–p interaction energy is obtained from theory by using a zero range spin-dependent

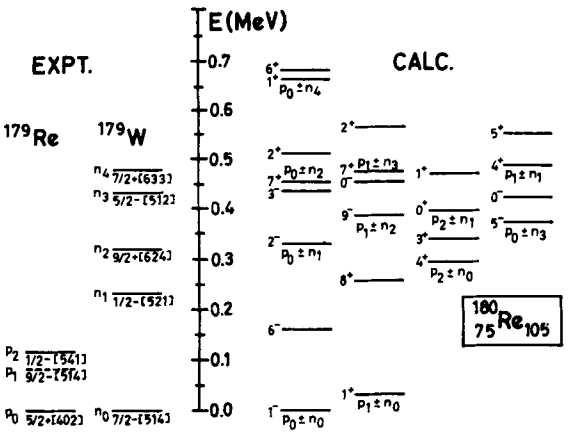

Figure 1. The calculated two-quasiparticle bandhead energies of ^{180}Re before Coriolis mixing are plotted on the right-hand side in the notation of table 1. On the left-hand side are shown the one-quasiparticle energies from the neighbouring odd-A nuclei [12]. Only the lowest three proton configurations and the lowest five neutron configurations are considered.

interaction and Nilsson wave functions. The resulting expression is [16]

$$E_{res}(K) = (1-\alpha)\, WA_0(K) \pm \alpha W A_\sigma(K) + (-1)^I B\delta_{K0} \tag{7}$$

where W is the strength parameter of the Wigner part, αW is the fractional strength of the spin-dependent part in the residual interaction, and A_0 and A_σ are the respective matrix elements. The last term represents the odd-even shift (or Newby shift) contribution in the case of $K = 0$ bands [13, 19, 20]. We use an average value of $\alpha = 0{\cdot}21$, $W = 4{\cdot}4$ MeV, and the calculated excitation energies are listed in table 1 for all the $2qp$ configurations included in our calculation. The matrix elements for the case of the $\{9/2^-[514]_p,\ 7/2^-[514]_n\}$ configuration were attenuated by a factor of 0·5, as is the practice for the cases where all the Nilsson quantum numbers are the same giving an unusually large value of A_0 and A_σ. The resulting $2qp$ excitation spectrum along with the input $1qp$ energies are plotted in figure 1.

The coupling terms of (4) were then switched on and all bands were allowed to mix together. The moment-of-inertia parameters of the bands were taken either from neighbouring odd-odd nuclei where the band is known, or from the expression

$$\mathcal{I}_{o-o} = \mathcal{I}_p + \mathcal{I}_n - \mathcal{I}_{e-e} \tag{8}$$

which uses the moments of inertia of the odd neighbours and the even-even core.

4. Analysis and discussion

Now we discuss the configuration assignments for the three pairs of bands in the light of TQPRM predictions and various properties of respective energy levels observed or deduced directly from the experimental data.

4.1 *Bands populated in beta decay*

As mentioned in § 2, electron capture decay of the ^{180}Os 0^+ parent state populates 1^-(0·0 keV) and 2^-(49·8 keV) levels in ^{180}Re assigned as the lowest members of the

$1^-(p_0n_0)$ band, and also the $1^+(20{\cdot}1\,\text{keV})$ and $2^+(74{\cdot}6\,\text{keV})$ levels of the $1^+(p_1n_0)$ bands. The $^{180}_{76}Os_{104} \rightarrow {}^{180}_{75}Re_{105}$ decay involves breaking a proton pair in the ^{180}Os ground state and placing the transformed neutron in one of the unoccupied neutron orbitals above the N = 104 Fermi surface. The lowest neutron orbital above the N = 104 Fermi surface is $7/2^-[514]$. Thus the beta branches of ^{180}Os decay, feeding the ground and the first excited states of ^{180}Re, correspond to the transformations:

$$^{180}\text{Os}\{0^+\} \rightarrow {}^{180}\text{Re}\{1^-, 0{\cdot}0\,\text{keV}\}:$$

$$0^+\{5/2^+[402]^2_p\} \rightarrow 1^-\{5/2^+[402]_p, 7/2^-[514]_n\} \tag{9}$$

and

$$^{180}\text{Os}\{0^+\} \rightarrow {}^{180}\text{Re}\{1^+, 20{\cdot}1\,\text{keV}\}:$$

$$0^+\{9/2^-[514]^2_p\} \rightarrow 1^+\{9/2^-[514]_p, 7/2^-[514]_n\}. \tag{10}$$

A 'strong' selection rule for the allowed unhindered beta decay in the rare earth region has recently been established by Sood and Sheline [21]; according to this rule, any beta branch with $\log ft \leqslant 5{\cdot}2$ in the $A = 180$ region necessarily involves a $[514]_p \Leftrightarrow [514]_n$ spin-flip transition. The observed [1] $\log ft = 4{\cdot}5$ for the transition in (10) above, confirming the configuration $1^+(p_1n_0)$ for the 20·1-keV based band. Further the observed $\log ft = 4{\cdot}5$ for the ^{180}Re ground-state decay to the 1006·3-keV 2^- level in ^{180}W, which can only correspond to the transformation

$$^{180}\text{Re}, 1^-\{5/2^+[402]_p 7/2^-[514]_n\} \rightarrow {}^{180}\text{W}, 2^-\{5/2^+[402]_p 9/2^-[514]_p\}.$$

The $^{180}\text{Os} \rightarrow {}^{180}$Re decay level scheme also includes six other levels with $E_x = 218$–717 keV. However, no information is given about the intensities of individual beta branches, nor about which of these levels are directly fed. Accordingly it is presently not possible to propose any assignment for these levels. Based on our above discussion, we expect the following other transformations to directly populate ^{180}Re levels in this decay:

$$0^+\{9/2^-[514]^2_p\} \rightarrow 0^-\{9/2^-[514]_p 9/2^+[624]_n\},$$

$$0^+\{1/2^-[541]^2_p\} \rightarrow 1^+0 \text{ and } 1^+1\{1/2^-[541]_p 1/2^-[510]_n\},$$

$$0^+\{5/2^+[402]^2_p\} \rightarrow 2^-\{5/2^+[402]_p 1/2^-[510]_n\}.$$

The ^{180}Os decay needs further careful experiments including β–γ coincidence studies to elucidate this part of the ^{180}Re level scheme.

4.2 *Bands 3 and 4*

The (*HI, xn*) investigators [6, 10] agree that these two bands interconnect through a 78·6-keV *E*1 transition; this indicates opposite parities for the two bands with $\Delta K \leqslant 1$. Excepting this agreement, the groups give conflicting interpretation of data for the two bands. Whereas Kreiner *et al* characterized bands 3 and 4 (their bands A and B) as $8^+(p_1n_0)$ and mixed $\{9^-(p_1n_2); 8^-(p_1n_4)\}$ rotational bands, Venkova *et al* considered averaged mixing ratios and deduced gyromagnetic ratios g_K, along with Nilsson orbital systematics to suggest $6^-(p_0n_0)$ and $7^+(p_0n_2)$ characters for bands 3 (their band 1) and 4 respectively; they sought further confirmation of their assignment by considering rotational spacings and aligned angular momentum patterns. We

re-examine the data and various factors considered by Venkova *et al* in light of TQPRM predictions to arrive at an acceptable assignment for these bands.

First we consider the signature splitting expected for the above alternative assignments.

Signature splitting: The favoured signature is given by $\alpha_f = \{(-1)^{j_p - 1/2} + (-1)^{j_n - 1/2}\}$. The $5/2^+[402]_p$ orbital belongs to $d_{5/2}$ and $7/2^-[514]_n$ has a predominantly $h_{9/2}$ character in the Nilsson model. Therefore it gives the favoured signature $\alpha = 1$, favouring odd spins in the $K = 6^-$ band. Similarly, $9/2^+[624]_n$ belongs to $i_{13/2}$ and therefore $\alpha = 1$ signature would be favoured in $K = 7^+$ band also.

We however assign these bands as $K = 8^+$, $\{9/2^-[514]_p, 7/2^-[514]_n\}$ and $K = 9^-$, $\{9/2^-[514]_p, 9/2^+[624]_n\}$, respectively. According to our assignments $\alpha = 0$ signature would be favoured in both the bands and therefore even spins would lie lower in energy. Experimental data indeed show that even spins are actually favoured in both the bands. Note that changing $K = 6^-$ and 7^+ to $K = 8^+$ and 9^- will not change the favoured spin in the experimental data.

g_K- factors: The g_K factors deduced from the mixing ratios and angular distributions by Venkova *et al* and the Nilsson model estimates are summarized in table 2. The experimental values are $0{\cdot}92 \pm 0{\cdot}13$ for a $K = 6$ assignment and $0{\cdot}69 \pm 0{\cdot}09$ for a $K = 7$ assignment; these may be compared with the Nilsson-model estimates of 0·8 and 0·4 respectively. If we assign the K-values $K = 8$ and 9 to these two bands, the deduced g_K factors are $0{\cdot}75 \pm 0{\cdot}13$ and $0{\cdot}47 \pm 0{\cdot}09$ respectively which are in much better agreement with the Nilsson-model estimates of 0·8 and 0·5 for these two bands.

Systematics from neighbouring nuclei: A comparison of the behaviour of $K = 8$ and 9 bands observed with the same $2qp$ configuration in ^{178}Ta and ^{182}Re has been made with the proposed assignments in ^{180}Re in figure 2. The behaviour of the bands in all cases is very similar. This is a very strong indication in support of our assignments.

Table 2. Average gyromagnetic ratios g_k of bands in ^{180}Re as deduced by Venkova *et al* [10] from mixing ratios and angular distributions for different K values; the numbers in parentheses in columns 3 and 6 are extrapolated values. The entries in columns 4 and 7 are calculated g_k values [10] in the framework of the Nilsson model for the $2qp$ configuration specified in columns 2 and 5 in the notation of our table 1. The first row refers to band 1 of Venkova *et al* [10] which is the same as our band 3. Band 5 in our description has the admixed configuration as listed for the $K^\pi = 4^+$ entry in column 5.

Band No.	Venkova *et al* [10]			Ours		
	$K^\pi(p_i, n_j)$	g_k (expt)	g_k (calc)	$K^\pi(p_i, n_j)$	g_k (expt)	g_k (calc)
3	$6^-(p_0 n_0)$	$0{\cdot}92 \pm 0{\cdot}13$	0·8	$8^+(p_1 n_0)$	$0{\cdot}75 \pm 0{\cdot}13$	0·8
4	$7^+(p_1 n_3)$	$0{\cdot}69 \pm 0{\cdot}09$	0·4	$9^-(p_1 n_2)$	$(0{\cdot}47) \pm 0{\cdot}09$	0·5
5	$3^-(p_0 n_1)$	$1{\cdot}03 \pm 0{\cdot}10$	1·4	$4^+(p_2 n_0)$ $(p_1 n_1)$	$0{\cdot}86 \pm 0{\cdot}09$	0·3 1·4
6	$2^-(p_0 n_1)$	$0{\cdot}08 \pm 0{\cdot}18$	1·3	$3^+(p_2 n_0)$	$(0{\cdot}25) \pm 0{\cdot}18$	0·2

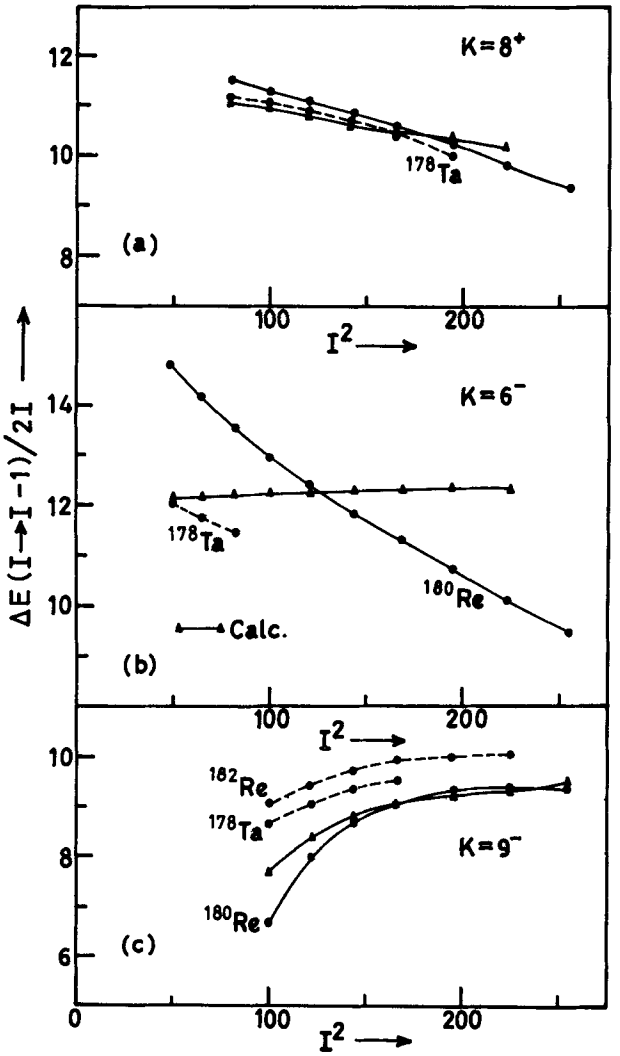

Figure 2. The behaviour of calculated rotational energy levels (shown by triangles joined by a solid line) for $K = 6$, 8 and 9 band assignments in ^{180}Re are compared with the actual data (dots joined by solid line) if the data were assigned these band quantum numbers. The energy difference $\Delta E(I \to I-1)/2I$ vs. the angular momentum square I^2 is plotted. Also shown by dashed lines are the experimental data for these bands in other odd-odd nuclei if available [24]. The experimental behaviour matches the calculated behaviour if the bands 3 and 4 are assigned the band quantum numbers $K = 8$ and 9 respectively.

Also, the compression of experimental energy levels of $K = 8$ and 9 bands is satisfactorily reproduced by the Coriolis mixing calculations as shown in figure 3.

Bandhead separation and GM splitting energy: The $K^\pi = 6^-$ bandhead assigned by Venkova *et al* is shown to feed a level with $I^\pi = 4^-$ or 5^- through a 134·5-keV γ-ray. The only origin of the 4^- or 5^- level is the $K^\pi = 1^-$ ground-state band. The observed separation for this GM pair in ^{176}Lu is 174 keV, whereas the $I^\pi = 4^-$ level of the

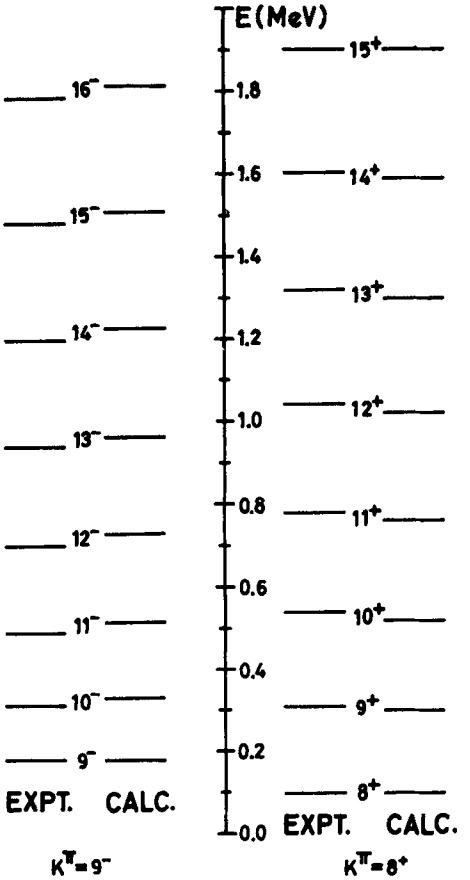

Figure 3. The rotational-energy levels of the $K = 8$ and 9 bands are compared with the calculated energy levels from the two-particle plus rotor model. The observed compression of the level energies is correctly reproduced.

$K^\pi = 1^-$ band is expected at $\geqslant 225$ keV. If we accept this assignment, it would imply an unacceptably large splitting ($\geqslant 360$ keV) of the $(6^- - 1^-)$ GM pair. It is therefore clear that the $K^\pi = 6^-$ assignment is not correct.

Similarly, band 4, assigned as the $K^\pi = 7^+$ band, lies barely 78·6 keV above the 6^- bandhead, whereas the expected separation is $\geqslant 250$ keV. Both the $K^\pi = 8^+$ and 9^- bands are expected to lie much lower and close together and satisfy all the criteria.

Alignment: The arguments in support of their assignments by Venkova *et al* based on alignments are not conclusive and do not exclude the configuration assignments made by us. The proton configuration used by Venkova *et al* is $5/2^+[402]_p$ whereas we replace this by $9/2^-[514]_p$, keeping the neutron configurations the same. We find that the alignment plots of $5/2^+[402]_p$ and $9/2^-[514]_p$ are very similar in their general behaviour as well as the total gain in alignment.

All the criteria/arguments therefore support the $K^\pi = 8^+(p_1 n_0)$ and $K^\pi = 9^-(p_1 n_2)$ assignments made by us.

4.3 *Bands 5 and 6*

Kreiner *et al* [6] identified only band 5 (labelled D by them) and assigned it an $i_{13/2}$ mixed $\{7^+(p_0n_2); 6^+(p_0n_4)\}$ configuration; however they deduced a value $K = 3{\cdot}59$ from the observed rotational spacings and also their calculations yielded $K_{calc} = 3{\cdot}89$ for this band.

On the other hand, Venkova *et al* [10] observed both of these bands and observed interband transitions for a few rotational levels connecting these two bands. The observed features indicated the same parity and $\Delta K = 1$ for these two bands with the higher-K band lying lower in energy, and also pointed to the possibility that the two bands may constitute a GM doublet with either the proton or the neutron occupying an $\Omega = 1/2$ orbital. Following these pointers and guided by the deduced mixing ratios δ and gyromagnetic ratios g_k, they proposed the lowest expected $\Omega = 1/2$ containing $2qp$ configuration (p_0n_1):$\{5/2^+[402]_p \pm 1/2^-[521]_n\}$ for these bands. However, as also discussed by them, this proposal has three serious shortcomings as discussed below.

First, by placing the $K^\pi = 3^-$ singlet band of the GM doublet lower in energy than its $K^\pi = 2^-$ triplet counterpart, the suggested assignment violates the GM rule. While critically examining the criteria for the applicability of the GM rule, Sood [22] had established the 'strong' rule that no violation of the GM rule is possible for cases wherein $K_T = K_< = |\Omega_p - \Omega_n|$, as is the case for this proposal. In view of this strong rule, the above suggested assignment is physically unacceptable. Secondly, their plots of alignment as a function of rotational frequency for the constituent orbitals for the neighbouring odd-A bands and for the bands 5 and 6 in ^{180}Re clearly reveal that the observed alignment variations of both these bands are inconsistent with their having a 5/2[402] proton orbital constituent. This is clearly reflected in the alignment plots (figure 4) of the orbitals under discussion from the neighbouring odd-A nuclei and also the bands 5 and 6 in ^{180}Re. We find that the 5/2[402] proton orbital exhibits a sharp rise at $\hbar\omega \approx 0{\cdot}27$ MeV, which is completely absent in bands 5 and 6. Thirdly the structure of the two bands is seen to differ markedly above the 5th rotational levels. Whereas the mixed dipole-quadrupole transitions are stronger than the stretched $E2$ transitions in band 5, band 6 separates into two stretched $E2$ sequences of different signatures with the $\Delta I = 1$ transitions having intensities too low to be observable. Also the alignment curves of bands 5 and 6 are seen to differ somewhat from each other. These features are inconsistent with their characterization as GM partners having the same configuration.

In view of these serious shortcomings of the proposed assignments for bands 5 and 6, we scanned the available configuration space, as shown in table 1, to look for bands of the same parity with $\Delta K = 1$ wherein the higher K is the triplet band. It is seen that the $K^\pi = 4^+$ (triplet) and $K^\pi = 3^+$ (singlet) bands of the (p_2n_0):$\{1/2[541]_p, 7/2[514]_n\}$ configuration meet these requirements. This choice does not violate the GM rule, nor does it contain the unacceptable (from alignment considerations) 5/2[402] proton orbital. The differing structure patterns for higher spins (above the levels connected by interband transitions) may result from mixing of another configuration in one of the bands. It is seen from table 1, and figure 1, that another $4^+(p_1n_1)$:$\{9/2[514]_p, 1/2[521]_n\}$ triplet band is expected not too far above the $4^+(p_2p_0)$; these two configurations may mix through $\Delta K = 0$ coupling [23], leading to structural differences for band 5 and band 6. Recalling that signature-dependent effects related to large decoupling parameters split the concerned bands into two

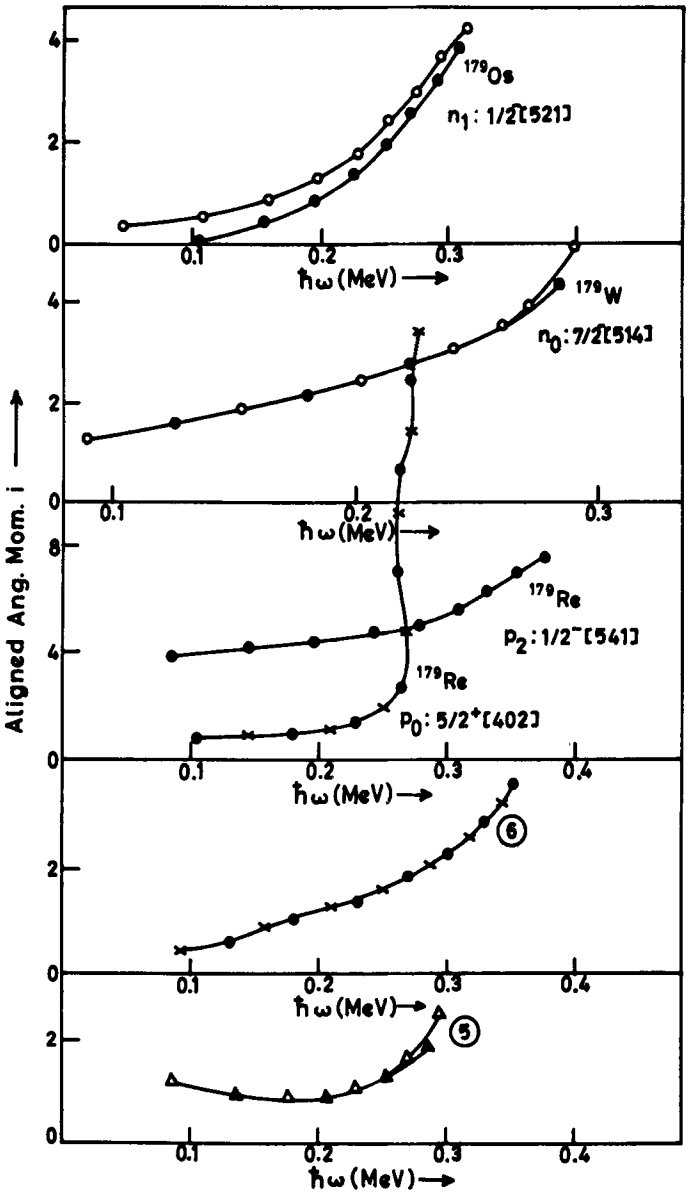

Figure 4. Plots of experimental aligned angular momenta i for the bands 5 and 6 in ^{180}Re and bands in neighbouring odd-A nuclei having configurations invoked to make configuration assignments for bands 5 and 6 as a function of the rotational frequency $\hbar\omega$ (adapted from ref. 10).

$\Delta I = 2$ sequences, we can relate the occurrence of such signature-split $\Delta I = 2$ sequences in band 6 to its $1/2[541]_p$ component which has decoupling parameter $a \approx 6{\cdot}0$. On the other hand, admixture of the $4^+(p_1 n_1)$ configuration with $1/2[521]_n$ component and decoupling parameter $a \approx 1{\cdot}0$ in band 5 results in the appearance of mixed dipole-quadrupole transitions in this band. Further support for these admixtures in band 5 comes from consideration of the gyromagnetic ratios g_k as listed in our table 2, we find that band 5 if assigned $K = 4$ has an experimental value in agreement with the

calculated Nilsson model value provided the $K^\pi = 4^+(p_2n_0)$ band has a significant $4^+(p_1n_1)$ component. It is also seen from table 2 that the assignment $2^-(p_0n_1)$ of Venkova *et al* [10] for band 6 is clearly unacceptable on this point; our choice of a $3^+(p_2n_0)$ configuration for this band yields satisfactory agreement. Further, as noted by Kreiner *et al* [6], the observed rotational level energies in band 5 yield $K \approx 4$ supporting our assignment.

Thus a consideration of all of these experimental and theoretical features, e.g. rotational level spacings, their alignments, signature splitting, g_k factors, singlet-triplet ordering etc., supports the admixed $4^+[(p_2n_0); (p_1n_1)]$ and $3^+(p_2n_0)$ assignments for bands 5 and 6 respectively. This assignment has no physically unacceptable or experimentally inconsistent features as noticed for the earlier proposed $3^-(p_0n_1)$ and $2^-(p_0n_1)$ assignment for these bands.

5. Summary and conclusions

The experimental data on the energy levels of the odd-odd deformed nucleus ^{180}Re obtained from ^{180}Os ε-decay and from ^{170}Er($14N, 4n\gamma$), ^{176}Yb($^{10}B, 6n\gamma$) and ^{181}Ta($\alpha, 5n\gamma$) reaction studies have been examined to deduce the spin-parities (band quantum numbers K^π) and $2qp$ (Ω_p, Ω_n) configuration assignments for the three pairs of bands with $K < 10$. The earlier suggested, tentative and conflicting, assignments have been critically examined with a view to arrive at acceptable assignments free from the inconsistencies and physically undesirable characteristics of earlier proposals. $2qp$ bandhead-energy calculations for a zero range residual interaction including band mixing have been used for mapping the extended configuration space. Strong rules for the applicability of the GM rule for triplet-singlet ordering, and for configurational relationships in allowed unhindered beta decays, are used as guidelines.

Our analysis confirms the earlier suggested $I^\pi K$ and configuration assignments for the four lowest levels observed in ^{180}Os decay. For the pair of high-spin opposite-parity bands, where the higher lying 73 ± 3 ns bandhead is connected by a 78·6-keV $E1$ transition to the lower lying bandhead, we assign the configuration $9^-\{9/2[514]_p + 9/2[624]_n\}$ and $8^+\{9/2[514]_p + 7/2[514]_n\}$. These assignments are the same as given by Kreiner *et al* [6] who had also suggested additional $i_{13/2}$ mixing in the $K^\pi = 9^-$ band. For the pair of same-parity interconnected (through inter-band transitions) bands numbered 5 and 6 by us and also by Venkova *et al* [10], we assign the admixed configuration $4^+\{1/2[541]_p + 7/2[514]_n\}$ and $4^+\{9/2[514]_p - 1/2[521]_n\}$ for band 5 and $3^+\{1/2[541]_p - 7/2[514]_n\}$ for band 6. These assignments are shown to be consistent with all the features deduced for these bands in heavy-ion reaction studies and are free from the unphysical or undesirable characteristics noticed for the earlier tentative suggestions. In common with the earlier investigations of this level scheme, we also do not find it possible to interconnect these three pairs of bands or to connect the observed excitations with the ground state on the basis of available experimental data.

Acknowledgements

Valuable communications from E Browne, B Singh and R M Lieder are gratefully acknowledged. Useful comments from David Headly are highly appreciated. These investigations were supported by the Department of Atomic Energy, Govt. of India, at the University of Roorkee and Banaras Hindu University, and by the US National

Science Foundation under contract no. PHY-92-07336 with the Florida State University.

References

[1] E Browne 1987 *Nuclear Data Sheets* **52**, 127; private communication 1994
[2] K J Hofstetter and P J Daly, *Phys. Rev.* **152**, 1050 (1966), **159**, 1000 (1967)
[3] P F A Goudsmit, J Konijn and F W N de Boer, *Nucl. Phys.* **A104**, 497 (1967)
[4] B Harmatz and T H Handley, *Nucl. Phys.* **A121**, 481 (1968)
[5] J Konijn, P F A Goudsmit, F W N DeBoer and B J Meijer, *Nucl. Phys.* **A114**, 602 (1968)
[6] A J Kreiner, J Davidson, M Davidson, D Abriola, C Pomar and P Thieberger, *Phys. Rev.* **C36**, 2309 (1987)
[7] Ts Venkova, B Bochev, W Gast, T Kutsarova, R M Lieder, T Morek and G Sletten, *Annual Report* 1983, IKP, KFA Julich, Jul-Spez-255, 57 (1984)
[8] J Schaffler-Krah, Ts Venkova, B Bochev, W Gast, G Hebbinghaus, A Kramer-Flecken, T Kutsarova, R M Lieder, T Morek, G Sletten and W Urban, *Annual Report* 1984, IKP, KFA Julich, Jul-Spez-305, 126 (1985)
[9] Ts Venkova, R M Lieder, T Morek, W Gast, G Hebbinghaus, A Kramer-Flecken, J Schaffler-Krah, W Urban, H Kluge, K H Maier, A Maj and G Sletten, *Annual Report* 1985, IKP, KFA Julich, Jul-Spez-344, 49 (1986)
[10] Ts Venkova, R M Lieder, T Morek, W Gast, G Hebbinghaus, A Kramer-Flecken, J Schaffler-Krah, W Urban, G Sletten, H Kluge and K H Maier, *Nucl. Phys.* **A514**, 87 (1990)
[11] C J Gallagher and S A Moszkowski, *Phys. Rev.* **111**, 1282 (1958)
[12] A K Jain, R K Sheline, P C Sood and K Jain, *Rev. Mod. Phys.* **62**, 393 (1990)
[13] J P Boisson, R Piepenbring and W Ogle, *Phys. Rep.* **C26**, 99 (1976)
[14] A K Jain, J Kvasil, R K Sheline and R W Hoff, *Phys. Lett.* **B209**, 19 (1988)
[15] A K Jain, J Kvasil, R K Sheline and R W Hoff, *Phys. Rev.* **C40** 432 (1989)
[16] P C Sood and R N Singh, *Nucl. Phys.* **A373**, 519 (1982)
[17] P C Sood, R K Sheline and R S Ray, *Phys. Rev.* **C35**, 1922 (1987)
[18] P C Sood, R K Sheline and R W Hoff, *Pramana – J. Phys.* **30**, 93 (1988)
[19] P C Sood and R S Ray, *Pramana – J. Phys.* **27**, 537 (1986)
[20] A Goel, A K Jain, R W Hoff and R K Sheline, *Pramana – J. Phys.* **36**, 105 (1991)
[21] P C Sood and R K Sheline, *At. Data Nucl. Data Tables*, **43**, 259 (1989); P C Sood and R K Sheline *Phys. Scr.* **41**, 25 (1990)
[22] P C Sood, *Radiation effects* **95**, 115 (1986)
[23] H Massman, J O Rasmussen, T E Ward, P E Haustein and F M Bernthal, *Phys. Rev.* **C9**, 2312 (1974)
[24] R K Sheline, D M Headly, P C Sood, A K Jain, R W Hoff, D Nosek, J Kvasil and D G Burke, *At. Data Nucl. Data Tables* (to be submitted)