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Characterization of isomers of the nucleus ^{154}Pm

P C SOOD* and R K SHELINE

Florida State University, Tallahassee, FL 32306-3016, USA

* Permanent address: Department of Physics, Banaras Hindu University, Varanasi 221 005, India

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Abstract. Consideration of the expected two-quasiparticle structures and their estimated band head energies, and the selection rules for beta transition rates for the ^{154}Nd → ^{154}Pm → ^{154}Sm decays are used to deduce the configurations for the isomers and the low-spin structures in the neutron rich doubly odd nucleus $^{154}_{61}$Pm$_{93}$. The 2·68 m high spin isomer and the 1·73 m low spin isomer are respectively assigned the spin-parity 4^+ and 1^+ with the configuration $\{p{:}5/2^-[532\uparrow] + n{:}3/2^-[521\uparrow]\}$ with the 2·68 m isomer lying lower in energy, and thus forming the ^{154}Pm ground state. Two-quasiparticle character of the beta-connected states in ^{154}Nd decay and ^{154}Pm decay is discussed.

Keywords. Doubly-odd deformed nucleus ^{154}Pm; isomer configurations from $2qp$ structures and beta selection rules: ground state and beta-connected low-spin levels characterization.

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1. Introduction

The neutron rich doubly odd nucleus $^{154}_{61}$Pm$_{93}$ was first identified over 30 years ago (Wille and Fink 1958). However until 1985 it was possible to study its production only by neutron irradiation of highly enriched ^{154}Sm samples and its subsequent β^- decay to various levels in ^{154}Sm. The measured activities had identified two isomers with 1·73 m and 2·68 m half lives (Helmer 1987). Spin-parity assignments for the isomers were proposed (D'Auria *et al* 1971; Tannila and Kantele 1972; Preiss and Labrecque 1973; Yamamoto *et al* 1974) based on their decay properties and the systematics of Nilsson orbitals for the region. However, since no direct information on the single particle placements in the $(A-1)$ isotone or isotope was available at the time, the configuration, and hence the spin-parity, assignments were mostly speculative and often mutually contradictory. Recently it has become possible to identify the nucleus ^{154}Nd as a fission product and to study its decay (Karlewski *et al* 1985; Greenwood *et al* 1986) to low spin levels in ^{154}Pm. These studies have resulted in a level scheme (Helmer 1987) based on the 1·73 m ^{154}Pm isomer with $I^\pi = 1^+$ assignment to the two levels at 151·7 keV and 850·2 keV and a deduced spin of 0 or 1 for the isomer with no indication of its parity. The suggested spin of the 2·68 m isomer is 3 or 4, again with undefined parity. No isomeric transition has been observed between the two isomers, and presently it is not at all clear which of the two isomers actually lies lower in energy and thus forms the ground state.

In this paper we seek the spin-parity and configuration assignments to the two isomers and a few of the low spin levels in ^{154}Pm and also discuss the relative placement of two isomers based on the following considerations. Much better information is presently available (Lee 1982, 1990) on the single particle proton energies from the spectrum of the $(A-1)$ isotope and $(A+1)$ isotone, although nothing is still known on the level structure of the $(A-1)$ isotone. The results of the recent ^{154}Nd beta decay taken together with the earlier data from the decay of the ^{154}Pm isomers give us the basis for some definitive conclusions through application of the 'strong' rule (Bunker and Reich 1971) relating the asymptotic quantum numbers for allowed unhindered (au) transitions to the observed log *ft* values. In a comprehensive recent survey we (Sood and Sheline 1989) have clearly established the applicability of the 'strong' rule for even mass decays as well. We extend this rule to incorporate the additional fast decay mode pointed out by Fujita *et al* (1970). Further, subsequent to the definition of angular momentum coupling rules (Gallagher and Moszkowski 1958; hereafter abbreviated GM) for two-quasiparticle (2*qp*) doublets in the doubly odd deformed nuclei, and the calculation (Neiburg *et al* 1972; Boisson *et al* 1976; Elmore and Alford 1976) of their splitting energies, Sood and Singh (1982) had developed a formalism for evaluation of the 2*qp* band head energies in the doubly odd nuclei. This approach has since been extended (Sood *et al* 1989) for the 2*qp* states in even–even nuclei in an effort to improve on the zeroeth order estimates (Walker *et al* 1977) in the latter case. This formulation has proven to be very successful for the characterization (spin-parity and configuration assignments) and the relative placement of multiple isomers in the doubly odd nuclei both of the rare earth and the actinide regions, and also for a satisfactory description and prediction of the detailed 2*qp* spectra of these nuclei (Sood and collaborators 1982–88). Significant success has also been achieved in correctly describing the odd-even shifts (Newby 1962; Boisson *et al* 1976; Sood and Ray 1986; Frisk 1988) for the $K=0$ 2*qp* bands in these nuclei.

In §2 we briefly discuss the selection rules for fast allowed beta transitions and outline the 2*qp* band head energy calculations. Section 3 includes the presentation and discussion of our results on the ^{154}Pm isomers and low spin levels.

2. Basic considerations

2.1 *Fast beta transitions*

Alaga (1957) selection rules for beta decays have been extensively examined (Mottelson and Nilsson 1959; Bunker and Reich 1971; Meijer 1976) for odd-mass nuclei of the rare earth region. These investigations concluded that the allowed transitions ($\Delta I = 0, 1; \Delta\pi$ *no*) obeying the asymptotic quantum number $\Omega^{\pi}[Nn_3\Lambda\Sigma]$ selection rule

$$\Delta\Omega = I \quad \Delta N = 0 \quad \Delta n_3 = 0 \quad \Delta\Lambda = 0, \tag{1}$$

and referred to as the allowed unhindered (au) transitions, form a distinct category with $\log ft \leqslant 5{\cdot}2$. This consideration provides a useful strong rule for configuration assignments to the beta-connected states in odd-mass nuclei of the rare earth region, in view of the observation (Bunker and Reich 1971) that the orbital pairs, namely [523] and [514], involved in these 'au' transitions appear in non-overlapping mass ranges in this region. Extension of the Alaga selection rules for the even-mass decays was first investigated by Gallagher (1960) who concluded that the additional nucleon in the even-mass nuclei does not appreciably alter the transition rate of the particle undergoing decay. In a recent exhaustive survey (Sood and Sheline 1989) we have identified 122 cases of allowed beta-decays with $\log ft \leqslant 5{\cdot}2$ in the $149 \leqslant A \leqslant 190$ mass region, including both the odd-A and the even-A nuclei. All the known 'au' transitions in the deformed nuclei have the following underlying spin-flip transformation in terms of the asymptotic quantum numbers $[Nn_3\Lambda\Sigma]$

$$p{:}[5(5-\Lambda)\Lambda\uparrow] \rightleftharpoons n{:}[5(5-\Lambda)\Lambda\downarrow], \quad \Lambda = 2\text{–}5 \tag{2}$$

with the 'spectator' nucleon configuration remaining unchanged in all the even-mass decays.

In addition to the 'au' spin-flip transitions discussed above, Fujita *et al* (1970) suggested another class of 'fast' allowed transitions obeying the selection rule

$$\Delta N = 0 \quad \Delta n_3 = \Delta\Lambda = \pm 1, \tag{3}$$

for which the $\log ft$ values overlap the 'au' range. In particular, their calculations suggested that the transition

$$p{:}5/2^-[532\uparrow] \rightleftharpoons n{:}5/2^-[523\downarrow] \tag{4}$$

may have $\log ft \approx 5{\cdot}0$. We combine eqs (1–4) into the following selection rule for the fast allowed beta transitions

$$\Omega_p^-[5(5-\Lambda)\Lambda\uparrow]_p \rightleftharpoons \Omega_n^-[5(5-\Lambda)\Lambda\downarrow]_n \tag{5}$$

with

$$\Delta\Omega = 1 \quad \text{and} \quad \Delta\Lambda = 0, \tag{5a}$$

or

$$\Delta\Omega = 0 \quad \text{and} \quad \Delta\Lambda = 1. \tag{5b}$$

where (5a) and (5b) are the same as (1) and (3) respectively.

2.2 *Two-particle band head energies*

In the superposition picture each (Ω_1, Ω_2) combination gives rise to a doublet for the two-quasiparticle ($2qp$) configuration with the band numbers

$$K^{\pm} = |\Omega_1 \pm \Omega_2| \tag{6}$$

whose relative ordering is governed by the spin–spin coupling. According to the GM rule the spins-parallel (triplet K_T) state lies lower in energy than the spins-antiparallel (singlet K_S) state for the unlike nucleon pair (np) in the doubly odd nuclei. For the like nucleon pair (pp or nn) in the even–even nuclei, the K_S state lies lower in energy than the K_T state (Gallagher 1962). The $2qp$ band head energies are then evaluated (ignoring configuration mixing) by adding the zero point rotational energy correction and the residual interaction energy contribution to the summed single particle energies

$$E_K(\Omega_1, \Omega_2) = E_1(\Omega_1) + E_2(\Omega_2) + E_{\text{rot}} + E_{\text{int}}. \tag{7}$$

The rotational energy correction is approximated by the expression

$$E_{\text{rot}} \approx (\hbar^2/2\mathfrak{I})[K - (\Omega_1 + \Omega_2)]. \tag{8}$$

For the even–even nuclei, the zeroeth order estimate of the $2qp$ energies may be obtained using the expression (Walker *et al* 1977)

$$E^0(\Omega_1,\Omega_2)=[(\varepsilon_1-\lambda)^2+\Delta^2]^{1/2}+[(\varepsilon_2-\lambda)^2+\Delta^2]^{1/2} \tag{9}$$

where ε is the single particle energy, λ the Fermi energy, and Δ half the pairing energy. For the residual interaction energy calculations (Sood and Singh 1982) we assume a zero range interaction including an explicit $\bar{\sigma}_1\cdot\bar{\sigma}_2$ spin-dependence with W and αW as the strength parameters respectively of the spin-independent (Wigner) and the spin-dependent terms in the interaction. The band head energy for the odd–odd nuclei is calculated (Sood and Singh 1982) using the expression

$$\begin{aligned} E_K(Z,A,\Omega_p,\Omega_n) &= E_p(Z,A-1,\Omega_p)+E_n(Z-1,A-1,\Omega_n) \\ &\quad +\hbar^2/2\mathfrak{I}[K-(\Omega_p+\Omega_n)] \\ &\quad +(1-\alpha)\,WA_0(K)\pm\alpha\,WA_\sigma(K)+(-)^I B\delta_{K,0} \end{aligned} \tag{10}$$

where A_0 and A_σ are respectively the matrix elements of the spin-independent and the spin-dependent terms of the residual interaction evaluated using the appropriate product type Nilsson wave functions and the last term is the Newby (1962) odd-even shift for the $K=0$ bands. The coefficient B may be evaluated empirically (we adopt the sign convention of Elmore and Alford 1976), or theoretically (Boisson *et al* 1976; Sood and Ray 1986; Frisk 1988). For this interaction, the doublet splitting for the $K\neq 0$ bands is obtained as

$$E_{GM}(\text{odd–odd})=2\alpha W|A_\sigma|, \tag{11}$$

$$E_G(\text{even–even})=(1-4\alpha)\,W|A_\sigma|. \tag{12}$$

The information on the two-particle structures in the even–even nuclei is presently too scarce (Sood *et al* 1989, 1990) to permit a reliable evaluation of the interaction parameters and a quantitative prediction of the $2qp$ band head energies for such nuclei.

3. Results and discussion

3.1 *Expected two-quasiparticle bands*

Two-particle structures in the even-mass nuclei are constructed from the single particle orbitals observed in the experimental spectra of the neighboring isotopic (for protons) and isotonic (for neutrons) odd-mass nuclei. The observed excitation energies, taken from the latest nuclear data sheets, for the known single particle configurations up to 1 MeV, are shown for the $Z=61$ isotopes (on the left) and the $N=93$ isotones (on the right) in figure 1. No information is presently available (Lee 1990) on the intrinsic excitations in the $(A-1)$ isotone $^{153}_{60}Nd_{93}$.

The two-quasiparticle bands expected in the doubly odd nucleus $^{154}_{61}Pm_{93}$, based on the single particle orbitals shown in figure 1, are listed in table 1 for the summed single particle energies $(E_p+E_n)\leqslant 700$ keV from the $(A-1)$ isotope and the $(A+1)$ isotone; this table also includes the $2qp$ bands arising from the coupling of the higher neutron orbitals (up to 900 keV excitation in ^{155}Sm) with the ground state proton configuration. We now critically examine the configuration assignments suggested earlier for the two isomers in the light of the above information.

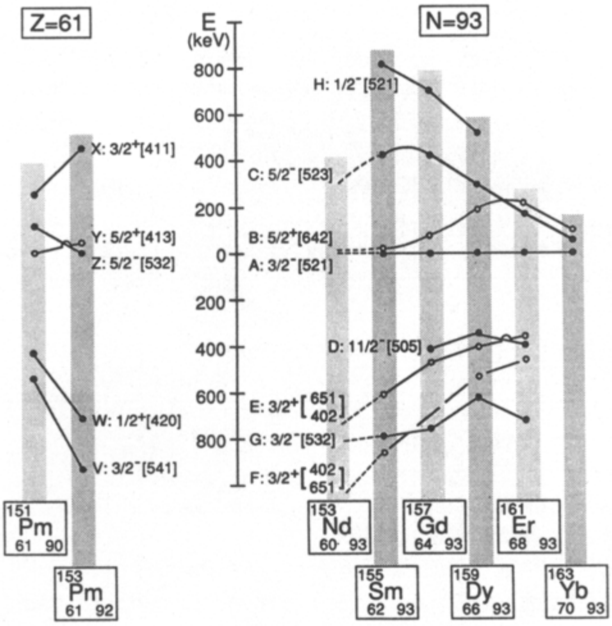

Figure 1. Experimental single-particle excitation energies for the $Z = 61$ proton (on the left) and the $N = 93$ neutron (on the right) nuclei; the data are taken from the latest Nuclear Data Sheets. The alphabetic notation, *ABC*... for the neutrons and *ZYX*... for the protons, relevant to the two-quasiparticle structures in $^{154}_{61}Pm_{93}$, is indicated for the individual orbitals labelled by the asymptotic quantum numbers $\Omega^{\pi}[Nn_3\Lambda]$. The extrapolated location of the neutron orbitals in the $(A-1)$ isotone ^{153}Nd is indicated.

Table 1. Two quasiparticle (2*qp*) band structures $K_{ij}^{\pm} = |\Omega(p_i) \pm \Omega(n_j)|$ expected in ^{154}Pm are tabulated. The excitation energies of the single particle states p_i and n_j in the neighboring odd-mass nuclei are shown in figure 1. The spins-parallel band number K_T is listed first, followed by the spins-antiparallel band number K_S, in accordance with the Gallagher-Moszkowski (GM) rule.

p_i	Z: 5/2⁻[532↑]		Y: 5/2⁺[413↓]		X: 3/2⁺[411↑]	
n_j	K_T	K_S	K_T	K_S	K_T	K_S
A: 3/2⁻[521↑]	4⁺	1⁺	1⁻	4⁻	3⁻	0⁻
B: 5/2⁺[642↑]	5⁻	0⁻	0⁺	5⁺	4⁺	1⁺
C: 5/2⁻[523↓]	0⁺	5⁺	5⁻	0⁻		
E: 3/2⁺[402↓]	1⁻	4⁻	4⁺	1⁺		
Admixed						
F: 3/2⁺[651↑]	4⁻	1⁻				
G: 3/2⁻[532↓]	1⁺	4⁺				
H: 1/2⁻[521↓]	2⁻	3⁺				

3.2 *Results from earlier studies*

D'Auria *et al* (1971) had suggested a coupling of the $3/2^+[651]$, $3/2^+[402]$, or $3/2^-[521]$ neutron orbitals with the $3/2^-[541]$ proton orbital to propose $(3^{\pm},0^{\pm})$ assignment for the ^{154}Pm isomers. The $3/2^-[541]$ proton hole orbital is presently known (Burke *et al* 1978; Lee 1990; and our figure 1) to lie at 935 keV excitation in the ^{153}Pm isotope. Also both the $3/2^+$ neutron orbitals, as seen in figure 1, lie above 600 keV excitation in the $(A+1)$ isotone and are extrapolated to occur at still higher energy in the $(A-1)$ isotone. Considering this updated experimental situation of the involved neutron and proton single particle excitation energies, we conclude that neither the $(3^+,0^+)$ nor the $(3^-,0^-)$ assignment arising from these orbitals can correspond to the ^{154}Pm low-lying (<200 keV) isomers.

Tannila and Kantele (1972) identified the 2·68 m isomer with the $K^\pi=5^-$ and the 1·73 *m* isomer with the $K^\pi=0^-$ states of the 2*qp* configuration (p:$5/2^-[532\uparrow]\pm n$:$5/2^+[642\uparrow]$), and used their Q_{β^-} measurements to place the 5^- isomer (210 ± 70) keV above the 0^- isomer thus suggesting a violation of the GM rule. Their conclusions have been found (Helmer 1987) untenable in view of the more careful Q_β measurements. Theoretically also, no violation of the GM rule is possible for the indicated 2*qp* configuration on the following grounds. While examining the criteria for the violation of the GM rule, it was concluded (Sood 1986) that such a violation can occur if, and only if, $K_S=K^-$ and the following condition is satisfied:

$$E_{\rm rot} > E_{\rm GM}, \tag{13}$$

with the energy expressions given in eqs (8) and (11). Using the global interaction parameters $\alpha W=(1\cdot0\pm0\cdot3)$ MeV with the data given in table 1, we obtain the following limiting values for this 2*qp* configuration

$$E_{\rm rot}\approx(50\pm20)\,{\rm keV};\quad E_{\rm GM}\approx(175\pm40)\,{\rm keV}. \tag{14}$$

Since $E_{\rm GM}$ in this case is at least an order of magnitude larger than $E_{\rm rot}$, condition (13) cannot be satisfied and accordingly no violation of GM rule is possible in this case. Further, the observed (Helmer 1987) decay of the 2·68 isomer to the 1440 keV 2^+ level in ^{154}Sm with $\log ft=6\cdot9$ (indicating an allowed hindered or first forbidden transition) definitely rules out $I^\pi=5^-$ assignment to the parent isomer.

Preiss and Labrecque (1973) deduced the spin-parities of the isomers to be 1^+ and 4^+, said to have been determined by coupling of the $5/2^+[413]$ proton and the $3/2^+[521]$ neutron orbitals. However, an error is evident in their presentation. The [521] neutron orbital has negative parity and hence the suggested coupling can yield only 1^- and 4^- spins for the isomers which is inconsistent with all their subsequent discussion. On the other hand, if the neutron spin is $3/2^+$ from either the [402] or the [651] orbital to be consistent with the deduced 1^+ and 4^+ isomer spins, we see from our figure 1 that the resultant 2*qp* states from these couplings are expected to lie certainly above 500 keV excitation in ^{154}Pm; several other 2*qp* configurations (see our figure 1 and table 1), lie lower in energy, becoming more likely candidates for the isomers.

Yamamoto *et al* (1974) presented the results of their careful study with a well-reasoned discussion of the daughter states in ^{154}Sm; however, they left open the question of the spin-parity assignments to the parent ^{154}Pm isomers.

3.3 *Configurations of beta-connected states*

The only means, presently available, for studying the excited states in ^{154}Pm is through their population in β^- decay (Karlewski *et al* 1985; Greenwood *et al* 1986) of the ^{154}Nd 0^+ ground state, shown on the left in our figure 2. Beta intensities and $\log ft$ values are presently deduced (Helmer 1987) for only three beta branches from this decay. Two of the daughter states at 850·2 keV and 151·7 keV are fed with $\log ft < 5{\cdot}0$ and, on this basis, have been assigned $I^\pi = (1^+)$. No beta branch to the lowest level, identified as the 1·73 m isomer and assigned $I = (0, 1)$, has been indicated nor there are any multipolarity assignments for the gamma rays feeding this isomer. However beta transition rates ($\log ft$ values) from the decay of this low spin isomer, and also of the relatively higher spin 2·68 m isomer, to several levels in ^{154}Sm are known. Thus, at the present stage of our knowledge, primary guidance for configuration assignments to the ^{154}Pm isomers and excited levels has to come from the application of selection rules connecting asymptotic quantum numbers and beta-transition rates.

3.3.1 *Beta decays of ^{154}Nd*: According to the 'strong' rule, given in eq. (5), spin-flip beta transitions with $\log ft < 5{\cdot}0$ connect the orbitals with the neutron in the $\Omega = \Lambda - 1/2$ and the proton in the $\Omega = \Lambda + 1/2$ states. In the $N = 94$ nucleus under considerations, the $3/2[532\downarrow]$ neutron orbital is already filled while the $5/2[523\downarrow]$ neutron orbital lies close to the Fermi surface with a fair occupation probability. On the other hand for $Z = 60$, the $5/2[532\uparrow]$ proton orbital lies above the Fermi surface. Thus the fact beta decays of ^{154}Nd should proceed through the following transitions:

$$^{154}_{60}\mathrm{Nd}_{94}{:}\,0^+\{3/2^-[532\downarrow]^2_n\} \rightarrow {}^{154}_{61}\mathrm{Pm}_{93}\,1^+\,1\{5/2^-[532\uparrow]_p 3/2^-[532\downarrow]_n\}; \tag{15}$$

$$0^+\{5/2^-[523\downarrow]^2_n\} \rightarrow 1^+\,0\{5/2^-[532\uparrow]_p 5/2^-[523\downarrow]_n\}. \tag{16}$$

The transition in (16) proceeds to the 1^+ rotational state of $K^\pi = 0^+$ band, since the $0^+ \rightarrow 0^+$ beta transition is iso-spin forbidden. Consideration of the $2qp$ band head energies of these configurations, discussed in a later subsection, lead to the identification of higher lying 1^+ at 850·2 keV with the configuration ZG of eq. (15) as its major $2qp$ component, and the lower lying 1^+ at 151·7 keV with the configuration ZC of eq. (16) as its major $2qp$ component.

3.3.2 *Beta decays of the 1·73 m ^{154}Pm isomer*: Experimental information on $\log ft$ values from the β^- decay of this isomer to various levels in ^{154}Sm is shown in figure 2 and is discussed in the following for deducing the configuration assignment of the parent state in the context of its having spin value 0 or 1 (Helmer 1987).

Observation of a significant beta branch to the 1099·6 keV 0^+ level in ^{154}Sm with $\log ft = 6{\cdot}8$ rules out 0^+ assignment to the parent state in consideration of the isospin-forbiddenness. Further the observation of a beta branch to the 1178·2 keV 2^+ level in ^{154}Sm with $\log ft = 6{\cdot}9$ rules out a 0^- assignment.

The $1^\pm$ assignments arise from coupling the $3/2^-[521]$ neutron orbital with the $5/2^-[532]$ or $5/2^+[413]$ proton orbital. Nearly 60% of the β-decay from the 1·73 m ^{154}Pm isomer populates only two levels in ^{154}Sm at 2140·9 keV (35% with $\log ft = 5{\cdot}2$) and 2069·8 keV (24% with $\log ft = 5{\cdot}4$). Yamamoto *et al* (1974) examined this decay to deduce $K = 0$ for the 2140·9 keV level and $K = 1$ for the 2069·8 keV level. The observed $\log ft$ values, taken together with the above conclusions and the extended 'strong' rule of eq. (5), suggest the following fast transitions in the 1·73 m ^{154}Pm isomer decay:

$$^{154}_{61}\mathrm{Pm}_{93}: 1^+\{5/2^-[532\uparrow]_p 3/2^-[521\uparrow]_n 3/2^-[532\downarrow]_n^2\}$$
$$\rightarrow {}^{154}_{62}\mathrm{Sm}_{92}: 2141\,\mathrm{keV}\, 0^+\{5/2^-[532\uparrow]_p^2 3/2^-[521\uparrow]_n 3/2^-[532\downarrow]_n\}, \quad (17)$$
$$^{154}_{61}\mathrm{Pm}_{93}: 1^+\{5/2^-[532\uparrow]_p 3/2^-[521\uparrow]_n 5/2^-[523\downarrow]_n^2\}$$
$$\rightarrow {}^{154}_{62}\mathrm{Sm}_{92}: 2070\,\mathrm{keV}\, 1^+\{5/2^-[532\uparrow]_p^2 3/2^-[521\uparrow]_n 5/2^-[523\downarrow]_n\}. \quad (18)$$

It is noticed that the underlying transitions in eqs (15–16) and eqs (17–18) are the same. Somewhat higher log *ft* values in the latter decays are consistent with the well-known fact that the 2*qp* strengths in even–even nuclei are distributed over a number of same K^π states (Sood and Sheline 1990).

In addition to the fast decays discussed above, beta branches are seen (figure 2) to feed four other levels with known spin-parity with comparable log *ft* values characteristic of allowed hindered (ah) or first forbidden transitions. Soloviev and collaborators (Grigoriev and Soloviev 1974) have discussed in detail the microscopic decomposition of low spin levels of deformed even–even nuclei. They deduce the following 2*qp*

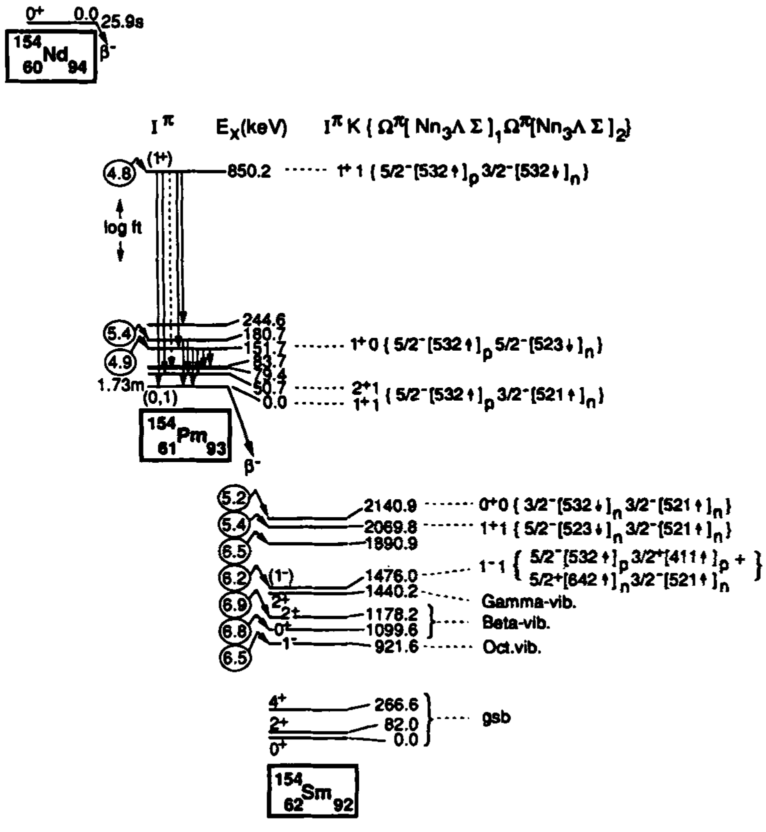

Figure 2. Experimental data for the ^{154}Nd → ^{154}Pm (1·73 m isomer) → ^{154}Sm beta decay chain including the log *ft* values, the spin-parity and level energies (from the Nuclear Data Sheets[8]) and the assigned $I^\pi K$ with the 2*qp* configuration deduced in the present study.

components in the levels of our interest in ^{154}Sm:

$$922\,\text{keV}\ 1^-: p[532\uparrow]p[413\downarrow]\text{--}30\%;$$
$$1100\,\text{keV}\ 0^+: p[532\uparrow]p[532\uparrow]\text{--}39\%;$$
$$1178\,\text{keV}\ 2^+0: \text{same intrinsic structure as } 1100\,\text{keV}\ 0^+ \text{ bandhead};$$
$$1476\,\text{keV}\ 1^-: p[532\uparrow]p[411\uparrow]\text{--}47\%. \tag{19}$$

The observed beta transitions proceeding at comparable rate to each of these four states require that the 'spectator' nucleon configuration, which remains unaltered in all even mass decays, is the one that is common to all these daughter states in ^{154}Sm and the parent state in ^{154}Pm. Accordingly, the $5/2^-[532\uparrow]_p$ orbital is unambiguously a constituent of the parent state, which, for $I = 1$, leads to the unique $1^+\{p[532\uparrow]:n[521\uparrow]\}$ assignment for the 1·73 m ^{154}Pm isomer.

3.3.3 *Configuration of the 2·68 m isomer*: The experimental information (D'Auria *et al* 1971; Yamamoto *et al* 1974) available from the β^- decay of this isomer to various levels of ^{154}Sm is shown in figure 3. In addition, nuclear data sheets (Helmer 1987) include beta branches to the 2^+ and 4^+ levels of the ground band with $\log ft \sim 7$, which are not mentioned by any of the experimentalists. No isomeric transition between the two isomers in ^{154}Pm is observed in any experiment. These considerations restrict the spin of the 2·68 m isomer to $I = (3, 4)$, with its parity undecided. The $I = 3$ assignment is unlikely with the $I^\pi = 1^+$ assignment for the 1·73 m isomer and the non-observance of any inter-connecting isomeric transition. Also an examination of the possible intrinsic $2qp$ bands, as shown in table 1, reveals that the lowest $K = 3$ bandhead corresponding to the 3^- AX configuration is expected at ~ 400 keV excitation while the only other $K = 3$ $2qp$ state seen in table 1 corresponds to the 3^+ ZH configuration and is expected at $\gtrsim 800$ keV (see figure 1). Further the information in table 1 taken together with figure 1 suggests 4^+ AZ $2qp$ configuration as the lowest level with $I = 3, 4$.

The $4^+\{p{:}5/2^-[532\uparrow]\ n{:}3/2^-[521\uparrow]\}$ assignment for the 2·68 m isomer corresponds to the two ^{154}Pm isomers forming a GM doublet. Accordingly one should expect fast beta transitions from the 2·68 m isomer decay, similar to the ones in eqs (17–18), involving $[5(5-\Lambda)\Lambda]$ orbitals transformations. Using the notation of figure 1, the 2070 keV 1^+(AC) $2qp$ state and the 2141 keV 0^+(AG) $2qp$ state in ^{154}Sm should form doublets with the lower lying ($\Delta E \approx 100$–500 keV) 4^+(AC) and 3^+(AG) levels fed with small $\log ft$ values from the 2·68 m isomer decay. However, as already noted, the excited states in even–even deformed nuclei are generally admixtures of several intrinsic configurations. Nesterenko *et al* (1986) have investigated the intrinsic structures of the low lying $K^\pi = 3^+$ and 4^+ states in rare earth nuclei over the mass range $A = 158$–188 indicating the admixed $2qp$ configurations of these states. Experimentally (Helmer 1987) we find 5 levels with possible $I^\pi = 3^+$ and 8 levels with possible $I^\pi = 4^+$ between 1–2 MeV excitation in the ^{154}Sm spectrum. Several of these levels, as seen in figure 3, are populated with $\log ft < 7{\cdot}0$ in the 2·68 m ^{154}Pm isomer decay, indicating the distributed strength among these levels of the $2qp$ configurations under discussion. The highest intensity beta branch in figure 3 feeds the 1987 keV level of unassigned spin and parity with $\log ft \approx 5{\cdot}5$. Considering the fragmented strengths and the pairing occupation probabilities, this low $\log ft$ value indicates the

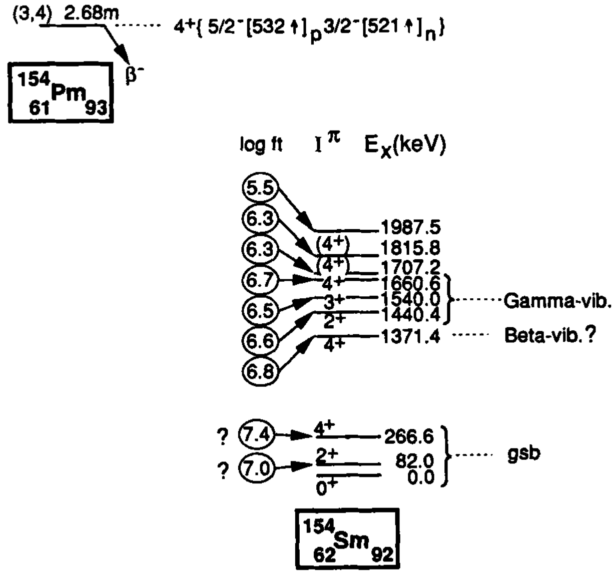

Figure 3. Experimental data for the ^{154}Pm (2·68 m isomer) ^{154}Sm beta decay, including the log *ft* values, level energies and spin-parity values for higher levels from Yamamoto *et al* (1974). Nuclear Data Sheets (Helmer 1987) include beta-feeding to the 2^+ and 4^+ ground band levels (indicated here by a question mark and not deduced in any earlier experimental paper), consequently resulting in higher log *ft* values for beta branches to upper levels. The 2*qp* configuration shown for the ^{154}Pm isomer is deduced in the present study.

presence of $[5(5-\Lambda)\Lambda]$ orbital constituent in both the parent isomer and the daughter state, i.e. this log *ft* value points to the 4^+(AZ) configuration (see figure 1 for alphabetic notation) for the parent 2.68 m ^{154}Pm isomer and the 3^+(AG) or 4^+(AC) 2*qp* configuration as a component of the 1987 keV level as well in ^{154}Sm.

3.4 *Two-quasiparticle band head energies*

In the absence of experimental information on the location of the 1*qp* neutron orbitals in the (A − 1) isotone and on the same 2*qp* configurations in nearby odd–odd nuclei (input data to evaluate the configuration dependent residual interaction parameters), detailed quantitative prediction of the complete 2*qp* spectrum of ^{154}Pm is not being presently attempted. We present here only the results of the bandhead energy calculations related to the characterization and relative placement of the two isomers and configuration assignments to the two $I^\pi = 1^+$ levels at 151·7 keV and 850·2 keV in ^{154}Pm using extrapolated 1*qp* energies and average values of the interaction parameters. Global fits of the observed GM doublet splitting energies yielded (Boisson *et al* 1976; Elmore and Alford 1976) the value $\alpha W \approx 0{\cdot}87$ MeV for the zero-range residual interaction parameter for nuclei of the rare earth region. In the special case of the GM doublet with the 2*qp* configuration having the same $[Nn_3\Lambda]$ asymptotic quantum numbers for the neutron and the proton orbitals, e.g. [523] orbital pair for the ground state GM doublet in ^{164}Ho, the value $\alpha W \approx 0{\cdot}5$ MeV is deduced from the experimental data. Our detailed studies of the 2*qp* bandhead energies yield $\alpha \approx 0{\cdot}25$ for the nuclei of this region. We use these interaction parameters and the calculated interaction matrix elements A_0 and A_σ for the deformation parameter $\delta = 0{\cdot}24$ with the moment of inertia parameter $(\hbar^2/2\mathfrak{J}) \approx 10$ keV in (10) and single particle energies from figure 1 to obtain the $2qp$ bandhead energies. For the $K^\pi = 0^+$ (ZC) band, positions of the 0^+ and 1^+ levels are predicted using the calculated (Sood and Ray 1986) odd-even shift parameter B. Our bandhead energy calculations support the 1^+0(ZC) configuration assignment to the 152 keV 1^+ experimental level and 1^+(ZG) assignment to the 850 keV 1^+ level, both with respect to the 1^+(ZA) 1·7 m isomer bandhead. The results of our calculations for the lowest GM pair are discussed in the following.

3.4.1 *Relative placement of the isomers*: Absence of any observed isomeric transition between the two isomers and the ± 200 keV uncertainty in the beta energies from the decay of the two isomers do not presently permit a determination of the separation energy of the two isomers or even their relative ordering on the experimental grounds. Our $2qp$ bandhead energy calculations predict the $(4^+, 1^+)$ AZ bands as the lowest structures, leading to their characterisation as a GM pair with the spins-parallel member $K^\pi = 4^+$ placed lower in energy. We calculate their separation

$$\Delta E[1^+ \to 4^+] = (20 \pm 12)\,\text{keV}. \tag{20}$$

Several $(4^+, 1^+)$ doublets have been experimentally observed (Rotter *et al* 1984; Balodis *et al* 1987) in the isobaric doubly odd nucleus ^{154}Eu. These investigators pointed out that levels having the proton orbit [532↑], under discussion here, "could not be observed in the (d, p) reactions if there is no admixture of [413↓] configuration." The two $(4^+, 1^+)$ pairs, deduced having this admixture, were placed (Rotter *et al* 1984; Balodis *et al* 1987) at [101 keV 4^+; 135 keV 1^+] and (327 keV 4^+; 403 keV 1^+] in the experimental ^{154}Eu spectrum. Residual interaction energy calculations (Guseva *et al* 1987) concluded very extensive fragmentation, making it difficult to determine the main $2qp$ component in each state; these calculations obtained [157 keV 4^+; 166 keV 1^+] as the energies for the AZ $(4^+, 1^+)$ doublet members in ^{154}Eu with their doublet splitting in agreement with our results for this configuration in eq. (20).

On the basis of the beta transition rates, the calculated $2qp$ spectrum for ^{154}Pm, and the experimental data for ^{154}Eu, we conclude that the 4^+(AZ) 2·68 m isomer is the ground state of ^{154}Pm with the 1^+(AZ) 1·73 m isomer lying (20 ± 12) keV above it.

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