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Newby shift of $K = 0$ rotational bands in odd–odd rare-earths

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Abstract. A data set of 29 experimentally determined Newby shifts in rare-earth nuclei is examined for the reliability of each values. Using this data set, Newby shifts are obtained which are free from the Coriolis and the particle–particle coupling effects. These new empirical values help resolve the failure of a recently proposed rule for the sign of the Newby shift in the $\{5/2[413]p - 5/2[642]n\}$ configuration of ^{160}Tb and the $\{5/2[402]p - 5/2[512]n\}$ configuration of ^{174}Lu. Also the Newby shifts are significantly modified in two other cases namely the $\{1/2[411]p - 1/2[521]n\}$ configuration in ^{168}Tm and the $\{1/2[541]p - 1/2[521]n\}$ configuration in ^{172}Lu. Only marginal changes are seen in the rest of the cases in the rare-earth nuclei.

Keywords. Newby shift; rare-earth nuclei.

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1. Introduction

An important feature of the rotational bands with $K = |\Omega_p - \Omega_n| = 0$ in odd–odd deformed nuclei is an odd–even shift in rotational energy levels, also known as the Newby shift (Newby 1962; Boisson *et al* 1976). The Newby shift arises from the special nature of the wavefunction for a $K = 0$ band which may be written as

$$|IMK = 0, \alpha\rangle = (2I + 1/32\pi^2) D^I_{MO} \{ |K = 0, \alpha\rangle + (-1)^I R_i |K = 0, \alpha\rangle \} \qquad (1)$$

where R_i is the rotation operator $\exp(-i\pi J_y)$ with eigenvalues $j_\alpha = \pm 1$ and

$$|K = 0, \alpha\rangle = 1/\sqrt{2} \{ |\rho_p \Omega\rangle |\rho_n - \Omega\rangle - j_\alpha |\rho_p - \Omega\rangle |\rho_n \Omega\rangle \}. \qquad (2)$$

The index α denotes the single particle configuration ($\alpha = \rho_n \rho_p$) of the odd neutron and the odd proton and K is the projection of the intrinsic angular momentum on the symmetry axis (Jain *et al* 1989); also, $\Omega_p = \Omega_n = \Omega$. Thus the total wavefunction is nonvanishing when $j_\alpha = +1$, $I = 0, 2, 4, 6 \ldots\ldots$ and $j_\alpha = -1$, $I = 1, 3, 5, 7 \ldots\ldots$ or, $j_\alpha = (-1)^I$. This splits the $K = 0$ band into two sequences; $j_\alpha = +1$ and $j_\alpha = -1$ sequence corresponding to the different intrinsic wavefunction given by expression (2). The residual neutron–proton interaction V_{np} gives rise to a different diagonal contribution for $j_\alpha = \pm 1$ band members causing an odd–even shift given by the diagonal contribution,

$$E_N = (-1)^{I+1} \langle \rho_p \Omega; \rho_n - \Omega | V_{np} | \rho_p - \Omega; \rho_n \Omega \rangle. \qquad (3)$$

This definition of E_N differs from the quantity E_N of Boisson *et al* (1976) by a factor of parity and is opposite in sign to the quantity B of Elmore and Alford (1976).

A complete explanation of the sign and magnitude of the Newby shifts is yet to be found. Many calculations of the Gallhager–Moszokowski (G–M) splitting energies and the Newby shifts by using a phenomenologial neutron–proton interaction have been attempted in the past (Jones *et al* 1971; Pyatov 1976; Elmore and Alford 1976; Boisson *et al* 1976; Sood and Ray 1986). The general result is that the force parameters which fit the G–M splittings best do not reproduce the Newby shifts and vice versa. The central force fitted to reproduce the G–M splittings often gives the wrong sign for the Newby shifts in triplet configurations (neutron and proton single-particle states having opposite spins) whereas a correct sign is obtained in singlet configurations (neutron and proton single-particle states having parallel spins) but the magnitude is large. A tensor force is therefore invoked to calculate the Newby shifts which becomes particularly important in triplet configurations; however, this does not resolve the problem completely.

These observations led Frisk (1988) to propose an empirical rule for the sign of the Newby shifts when the angular momenta of the proton and neutron orbitals (j_p, j_n) are good quantum numbers. According to this rule: the favoured spins in a $K = 0$ band, I_F, are given by the expression $I_F = (j_p + j_n)$ mod 2. The rule seems to work well in 11 of the 15 configurations in the rare-earth region. However, Frisk (1988) suggests that the validity of the rule is questionable if the configuration is of a mixed singlet-triplet character, or if the dominating part of the configuration involves an *s*-shell.

The aims of the present paper are the following: Firstly we examine the experimental evidence supporting the configuration assignments to identify those cases where the existence of the band and the spins and parities of its levels could be determined without influence from systematic behaviour in other nuclides or, from theoretical calculations. In other words, we wish to make band assignments that are completely independent of any but the simplest nuclear models. The second aim of this paper is to treat the configuration mixing due to Coriolis and particle–particle coupling so that the Newby shift obtained contains only the effects of the residual n–p interaction. The theoretical calculations until now have used the empirical values of Newby shifts derived from the simple formula

$$\begin{aligned} E_N = \tfrac{1}{2}(-1)^{I+1}[E_k(I) - E_k(I-1)] + \hbar^2/2\mathscr{I}[(-1)^I \\ \times I - a_p a_n \delta_{\Omega_n, 1/2} \delta_{\Omega_p, 1/2}] \end{aligned} \tag{4}$$

where a_p and a_n are decoupling parameters for proton and neutron configurations, respectively. This expression takes into account the diagonal Coriolis contribution but does not consider the non-diagonal Coriolis mixing and the particle–particle coupling effects which are quite significant particularly for the $K^- = |\Omega_p - \Omega_n|$ bands (Jain *et al* 1989). The decoupling parameters a_p and a_n may also get modified in an odd–odd nucleus. It is therefore important that pure values of the Newby shifts devoid of nondiagonal Coriolis and particle–particle coupling effects be obtained and used in fitting the force parameters. These calculations are also immensely useful in checking the validity of the empirical rule proposed by Frisk (1988) particularly in cases where it is supposedly being violated due to configuration mixing. This excercise enables us to determine quite different values of the Newby shift in at least four cases and resolves the disagreement with the Frisk rule in two cases.

2. Experimental data and determination of Newby shifts

The experimental data (table 1) were examined for (a) the number and type of reactions used to populate band levels, (b) the availability of data on gamma transitions that populate or, depopulate band levels, including experimentally determined multipolarities, (c) gamma–gamma coincidence data, (d) the total number of levels identified as belonging to the band, and (e) the band-head energy because rotational bands are more easily characterized at low excitation energy. The entries in column 3 of table 1 are ranked A, B or C, according to the reliability of their supporting experimental data which are summarized in columns 9 to 12.

Column 4 of table 1 lists the Newby shift calculated from the experimental data by using the expression (4). Column 6 lists the calculated values due to Frisk obtained by fitting the experimental Newby shifts to a six parameters $n-p$ interaction and Y (for yes) in this column indicates that the sign of the experimental value agrees with that predicted by the empirical rule. It may be noted that the rule is violated in many cases indicated by N (for no). In particular, one band each in $^{156-160}$Tb, $^{174-176}$Lu and two bands in ^{154}Eu are found to disobey the empirical Frisk rule. Eight of the 29 entries in table 1 are given the most reliable (A) ranking; 6 different configuration are represented. The identification of this subset produces some possible clarifications where multiple determinations of a matrix element exist. For the data sets of the $\{3/2[411]p-3/2[521]n\}$ and $\{7/2[404]p-7/2[633]n\}$ bands, the A data show less spread than the others; in the former case, it is only the A values that exhibit the same sign as the calculated values (table 1, column 6). The rms deviations listed at the bottom of the table 1 correspond to a comparison of the experimental values (column 4) with the theoretical predictions of Frisk (column 6) and a comparison of the values determined by us (column 5) with those of Frisk. It is observed that restricting the data set to A-ranked values does produce some improvements in the data fit, indicated by the rms deviations. If the redetermined values are used in fitting the force parameters in calculations similar to those of Frisk, a further improvement is expected.

The new empirical values or, the redetermined values given in the column 5 of table 1 are the results of the two-quasi-particle-plus-rotor model (TQPRM) calculations. A complete description of the model as used in the present work was recently presented by Jain *et al* (1989) and a brief outline relevant to this paper is given in the following.

The total Hamiltonian is divided into two parts, the intrinsic and the rotational,

$$H = H_{\text{intr}} + H_{\text{rot}}. \tag{5}$$

The intrinsic Hamiltonian is taken to be the standard Nilsson model Hamiltonian with ε_2 and ε_4 deformations, a short range pairing interaction H_{pair} and a residual neutron–proton interaction V_{np}, so that

$$H_{\text{intr}} = H_{\text{av}} + H_{\text{pair}} + V_{np}. \tag{6}$$

The vibrational part has been neglected in this formulation. For an axially symmetric reflection-symmetric rotor,

$$H_{\text{rot}} = \frac{\hbar^2}{2\mathscr{I}}[(I^2 - I_3^2) - (I^+ j^- + I^- j^+) + (j_p^+ j_n^- + j_p^+ j_n^-) \\ + (j_p^2 - j_{pz}^2) + (j_n^2 - j_{nz}^2)] \tag{7}$$

where the terms have there usual meaning.

Table 1. Newby shifts: Experimental and calculated values due to Frisk and the redetermined values from our calculations along with a summary of experimental data. The data on neighbouring odd-A nuclei used in our calculations were taken from Jain *et al* (1990).

Configuration	Nucl.	*R*[a]	Newby shift[c] (keV) Exp	Our	Fsk[b]	Def[d] ε_2	ε_4	Rot band[e] *E*(*I*)	#lvls		Summary expt. data[f]
1	2	3	4	5	6	7	8	9	10	11	12
5/2[413]*p* − 5/2[642]*n*T	^{154}Eu	B	13	8·7	40 Y	0·22,	−0·03	287(0)	4	GM	ng dp
	^{156}Eu	C	3	3·2	40 Y	0·22,	−0·03	0(0)	2		bd tp
	^{160}Tb	B	−3	8·5	40 N	0·22,	−0·03	222(0)	5	G(M)	ng
5/2[413]*p* − 5/2[523]*n*S	^{154}Eu	C	−8	−8·4	13 N	0·22,	−0·03	415(0)	4	GM	ng arc dp
3/2[411]*p* − 3/2[651]*n*S	^{154}Eu	C	36	37·8	−14 N	0·22,	−0·03	342(0)	3	GM	ng dp
3/2[411]*p* − 3/2[521]*n*S	^{154}Eu	A	8	6·3	29 Y	0·22,	−0·03	279(0)	5	GM	ng arc dp
	^{156}Tb	C	−10	−11·7	29 N	0·22,	−0·02	100(1)	4		hd at
	^{158}Tb	C	−8	−8·0	29 N	0·24,	−0·02	110(0)	5		dt
	^{160}Tb	A	17	18·1	29 Y	0·25,	−0·02	79(0)	5	GM	ng dt
3/2[411]*p* − 3/2[402]*n*T	^{158}Tb	C	32	32·4	31 Y	0·24,	−0·02	420(0)	3		dt
7/2[523]*p* − 7/2[633]*n*S	^{166}Ho	A	32	32·0	31 Y	0·22,	0·01	0(0)	8	GM	ng arc dp ta
7/2[404]*p* − 7/2[633]*n*T	^{166}Ho	C	75	77·7	36 Y	0·27,	0·01	803(0)	6		ta
	^{170}Lu	A	42	45·4	36 Y	0·25,	0·02	0(0)	3	GM	ec
	^{172}Lu	C	56	56·4	36 Y	0·26,	0·03	65(0)	2	GM	ec at hd
	^{174}Lu	A	44	40·0	36 Y	0·26,	0·04	281(0)	8	G	png lng dt at
	^{176}Ta	B	42	43·2	36 Y	0·24,	0·05	100(0)	3	GM	ec
1/2[411]*p* − 1/2[521]*n*S	^{168}Tm	C	28	42·9	30 Y	0·26,	0·02	167(0)	4		dt
	^{170}Tm	A	37	37·9	31 Y	0·27,	0·03	150(0)	6	GM	ng dp ta
	^{172}Tm	B		16·5	31 Y	0·27,	0·04	475(0)	2	GM	bd
	^{170}Lu	B		16·8	31 Y	0·25,	0·02	407(0)	2	GM	ec
1/2[411]*p* − 1/2[400]*n*T	^{168}Tm	C	25	22·3	16 Y	0·26,	0·02	1056(0)	3		dt
1/2[541]*p* − 1/2[521]*n*S	^{172}Lu	C	−92	−68·0	−34 Y	0·26,	0·03	232(0)	4		ec at hd
5/2[402]*p* − 5/2[512]*n*S	^{174}Lu	C	−28	9·5	12 N	0·26,	0·04	522(1)	2		hd dt png lng
7/2[404]*p* − 7/2[514]*n*S	^{176}Lu	A	−69	−68·9	−3 N	0·26,	0·05	127(1)	8	GM	ng dp ta
7/2[523]*p* − 7/2[514]*n*T	^{176}Lu	C	154	155·9	68 Y	0·26,	0·05	1057(0)	6		ta
7/2[404]*p* − 7/2[503]*n*T	^{182}Ta	A	−26	−26·5	−36 Y	0·23,	0·06	558(1)	6	G	ng rc dp
	^{184}Ta	C		−29·1	−35 Y	0·21,	0·06	228(1)	2	G	bd

$9/2[514]p-9/2[505]n$T	^{188}Re	C	54	53·4	70	Y	0·18,	0·05	500(3)	2	G	ng dp
	^{190}Re	C		66·1	70	Y	0·18,	0·05	162(0)	2	G	bd it

rms (all entries): 34·4 29·4; rms (Set A): 25·4 25·5

[a] – Ranking as to reliability of the supporting evidence for the value of the Newby shift where A indicates most reliable.

[b] – A Y(for yes) in this column indicates that the sign of the experimental value agrees with that predicted by Frisk's rule (1988).

[c] – Experimental data are listed in column 4; new empirical values from our calculations are listed in column 5. In column 6, the values predicted by Frisk are given. Calculated Newby shifts due to Frisk (column 6) are compared with the experimental Newby shifts (column 4) and redetermined values from our calculations (column 5) and the respective rms deviations are given at the bottom of the table. For the signs of the Newby terms in this paper, we have adopted the convention that a positive value of E implies that even spins are favoured. Note that this convention sometimes differs from that of other authors, e.g. Boisson *et al* (1976) reverse the sign of E_N, but only for configurations with negative parity. Other authors (Elmore and Alford 1976; Jones *et al* 1971) completely reverse the sign of E_N relative to the convention adopted here.

[d] – The deformation parameters $(\varepsilon_2, \varepsilon_4)$ used in the calculations are listed in columns 7 and 8 and were taken from Elmore and Alford (1976).

[e] – Listed for each rotational band in columns 9–10 are bandhead energy in keV, angular momentum of the lowest energy level in parentheses, and number of levels identified. Tentatively identified levels are not included, but may have been used in calculating the experimental Newby shifts.

[f] – G denotes observation of depopulating gamma rays; M denotes multipolarities from conversion coefficient measurements. Mode of populating band levels: ng = thermal neutron capture; dp, hd, at, tp, dt, ta = single nucleon transfer reactions where p = proton, d = deutron, t = triton, h = 3He, and a = 4He; bd = beta decay; arc = average resonance neutron capture; ec = electron capture decay, png = primary neutron-capture gamma ray; lng = (^{7}Li, n gamma) reaction; rc = resonance neutron capture; it = isomeric transition. The data are taken from:

^{154}Eu (Balodis *et al* 1987), ^{156}Eu, ^{156}Tb (Helmer 1986), ^{158}Tb (Lee 1980), ^{160}Tb (Kern *et al* 1974), ^{166}Ho (Dewberry *et al* 1982; Schilling *et al* 1978; Ignatochkin 1987), ^{168}Tm (Jones and Sheline 1971; Kolata and Maher 1975; Shirley 1988), ^{170}Tm (Dewberry *et al* 1981b), ^{172}Tm (Hansen *et al* 1965), ^{170}Lu (Treherne *et al* 1969), ^{172}Lu (Gongqing 1987), ^{174}Lu (O'Neil and Burke 1972; Bruder *et al* 1987a, b) ^{176}Lu (Hoff *et al* 1985; Dewberry *et al* 1981a), ^{182}Ta (Reich *et al* 1971), ^{184}Ta (Ward *et al* 1973), ^{188}Re (Shera *et al* 1972; Sterba *et al* 1979; Singh and Viggars 1981), ^{190}Re (Haustein *et al* 1976).

An appropriate set of basis eigenfunctions of $H_{av} + H_{pair} + (\hbar^2/2\mathcal{J})(I^2 - I_3^2)$ is chosen. These basis functions have the form

$$|IMK\alpha\rangle = \left\{\frac{2I+1}{16\pi^2(1+\delta_{ko})}\right\}^{1/2} [D^I_{MK}|K\alpha\rangle + (-1)^{I+K} D^I_{M-K} R_i |K\alpha\rangle], \quad (8)$$

where $\alpha \equiv \rho_n \rho_p$ characterizes the configuration of the odd-neutron and the odd-proton. The choice of the set of basis functions is very important as all the states that can couple together and may influence each others behaviour should be included. The matrix of the total Hamiltonian (5) is then constructed and diagonalization carried out for each spin. The Newby shift E_N enters as a parameter along with other parameters such as the quasi-particle energies, the moment of inertia and the single particle matrix elements $\langle j^+ \rangle$. The single particle matrix elements are initially taken from the Nilsson model wavefunctions and some of the important ones are modified during the least square fitting procedure of the band level energies. These calculations can mix any number of bands representing the various two-quasiparticle states that interact strongly. If all the important bands are not known, it becomes necessary to estimate the energies of certain unidentified bands. An estimate of the excitation energies of unidentified bands is obtained by use of a simple semiempirical approach discussed in many papers (Motz *et al* 1967; Sood *et al* 1986; Hoff 1988), and is based on the known properties of given quasiparticle states in neighbouring odd-A nuclei.

Besides rather complete Coriolis mixing calculations possible with this formulation, another outcome of these calculations is the pure value of the Newby shift and also the Gallahager–Moszkowski splitting energy for a given two-quasiparticle configuration since the Coriolis coupling and the particle–particle coupling effects have been properly taken into account; we call these the new empirical values (or, the redetermined Newby shifts) and are presented in column 5 of table 1. It may be noted that any new calculation attempting to fit a set of force parameters to reproduce the Newby shifts must use the values given by us in column 5. This will yield a much better theoretical prediction of the Newby shift.

The newly extracted values of the Newby shifts given in column 5 of table 1 lead to an agreement with the Frisk rule in two cases viz. ^{160}Tb and ^{174}Lu where the rule was seemingly violated. Furthermore the rms deviation of the newly deduced values with the predictions of Frisk is now quite reduced. A detailed analysis and discussion of those and other cases where the rule does not work, is given in the following section.

3. Results and discussion

(i) The $\{5/2[413]p - 5/2[642]n\}$ configuration in ^{160}Tb has an experimental Newby shift $E_N = -3$ keV, whereas the Frisk rule predicts a positive sign for the Newby shift. This apparent contradiction is resolved from the TQPR calculations which predict a Newby shift $E_N = +8{\cdot}5$ keV. The $K = 0$ band under discussion is found to show a strong particle–particle coupling with another $K = 0$, $\{3/2[411]p - 3/2[651]n\}$ band and the sequence of mixing is shown in figure 1. It is interesting to note that both the $K = 0$ bands involved in the mixing have a positive Newby shift, whereas the resultant odd–even effect corresponds to a negative Newby shift (odd–spin members are favoured, see figure 2). This is a result of a strong mixing between the odd-I spin

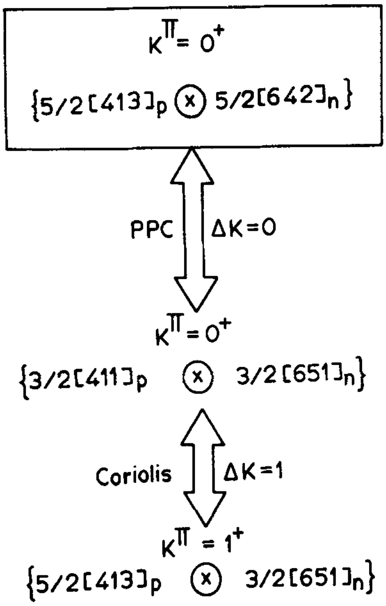

Figure 1. The $K^{\pi} = 0^{+}$, $\{5/2[413]p - 5/2[642]n\}$ band in ^{160}Tb predominantly mixes with the odd-I members of another $K = 0$ band by particle–particle coupling which subsequently couples with a $K = 1$ band by Coriolis coupling.

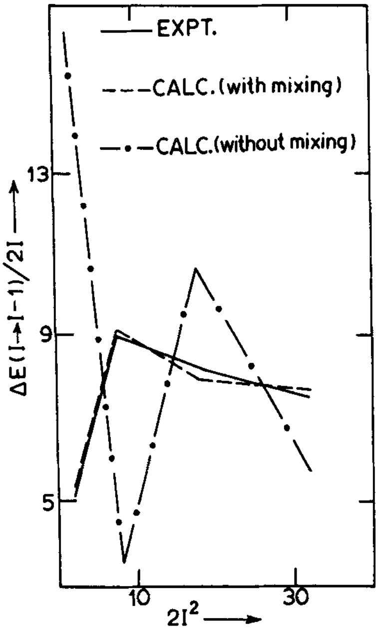

Figure 2. Plot of $\Delta E(I \to I-1)/2I$ vs $2I$ for the $K^{\pi} = 0^{+}$, $\{5/2[413]p - 5/2[642]n\}$ band in ^{160}Tb. Note that the positive Newby shift gives a phase opposite to the experimental data for no mixing. Mixing with the bands shown in figure 1 however reverses the phase of staggering.

members of the two $K = 0$ bands; a 40–50% mixing is seen in the odd-I spin members as compared to a 2–3% mixing in the even-I members. This leads to a reversal in the final phase of staggering.

The $\{5/2[413]p - 5/2[642]n\}$ configuration is also observed in $^{154-156}$Eu; however, the mixing with $K = 0$, $\{3/2[411]p - 3/2[651]n\}$ is seen to be small (10%) and does not affect the resultant Newby shift.

(ii) The $\{5/2[413]p - 5/2[523]n\}$ and $\{3/2[411]p - 3/2[651]n\}$ configurations in ^{154}Eu also disobey the Frisk rule. We find that the band based on the former configuration is a pure band; the latter configuration does exhibit an ~ 10% admixture with the $\{5/2[413]p - 5/2[642]n\}$ configuration but it does not explain the opposite sign of the Newby shift. It may be noted that the moment of inertia parameters in these two bands have an unusually small value of 6·1 and 5·0 respectively; this indicates the presence of other configuration mixing effects.

(iii) The Newby shift of the $\{3/2[411]p - 3/2[521]n\}$ configuration in ^{154}Eu and ^{160}Tb satisfies the Frisk rule; however, the same configuration in ^{156,158}Tb violates the rule. We do not observe any Coriolis and particle–particle mixing in these bands. It was in fact difficult to obtain a good fit of the $K = 0$ bands in ^{156,158}Tb whereas a good fit was easily obtained in ^{154}Eu and ^{160}Tb. It should be pointed out that the rotational bands in ^{156,158}Tb are ranked in 'C' category while they are ranked in the 'A' category in ^{154}Eu and ^{160}Tb.

(iv) The $\{5/2[402]p - 5/2[512]n\}$ configuration in ^{174}Lu also violates the Frisk rule. The data of this band are tentative in nature and fall in category 'C'. The proton transfer reaction (O'Neil and Burke 1972) yielded tentative assignments of 0^- (555 keV), 1^- (521 keV) and 4^- (833 keV?); an additional peak at 621 keV was interpreted as an unresolved 2^- and 3^- doublet. Later work of Bruder *et al* (1987a, b) using $(p, 3n)$ and (Li, $3n$) reactions confirmed the 1^- (521 keV) level; the only other level observed was 621 keV which was tentatively assigned as a 2^- level (Bruder *et al* 1987a) or, a 3^- level (Bruder *et al* 1987b). The experimental value of Newby shift reported in literature is $E_N = -28$ keV and is based on the level energies of 0^- (555 keV), 1^- (521 keV) and 2^- (621 keV).

We find that the $K = 1^-$, $\{7/2[404]p - 5/2[512]n\}$ band in ^{174}Lu exhibits an odd–even shift which seems to arise from a Coriolis coupling with the $K = 0$, $\{5/2[402]p - 5/2[512]n\}$ band. The odd–even shift of the $K = 1$ band can however be explained only if the Newby shift of the $K = 0$ band is taken to be positive. This requires that the assignments of level energies in the $K = 0$ band be 1^- (521 keV) and 3^- (621 keV) and a positive Newby shift $E_N = 9{\cdot}5$ keV which is in agreement with the Frisk rule. The single particle matrix element $\langle 7/2[404] | j^+ | 5/2[402] \rangle p$ is assigned a value of 3·12 as compared to the Nilsson model value of 0·47 (see figure 3). These calculations also predict that the $K = 0$, $I = 0$ level should lie near 484 keV and the $I = 2$ level near 543 keV.

(v) The Newby shift of two other $K = 0$ bands are predicted to be quite different in value although the sign agrees with the Frisk rule; these are the $\{1/2[411]p - 1/2[521]n\}$ configuration in ^{168}Tm and the $\{1/2[541]p - 1/2[521]n\}$ configuration in ^{172}Lu. The experimental values of Newby shifts quoted in the literature are 28 keV and -92 keV while we obtain 43 keV and -68 keV respectively; these differences are mainly due to a direct mixing with the G–M partner band and a modification of the decoupling parameter values. It may be noted that the data for these bands fall in category 'C' and more careful measurements are necessary to obtain precise and reliable data.

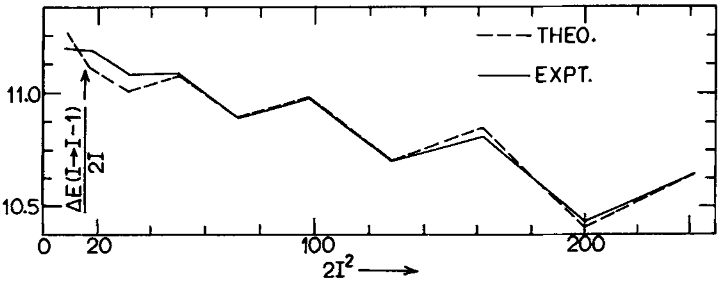

Figure 3. Staggering plot for the $K^\pi = 1^-$, $\{7/2[404]p - 5/2[512]n\}$ band in ^{174}Lu which results in a positive Newby shift for the $K^\pi = 0^-$, $\{5/2[402]p - 5/2[512]n\}$ band in ^{174}Lu.

4. Conclusion

To conclude, we have examined the reliability of the experimental data on $K = 0$ bands in the rare-earth region and redetermined the values of the Newby shift due only to $n - p$ residual interaction by removing the effects of Coriolis and particle-particle coupling. This leads to new empirical values of the Newby shift in both ^{160}Tb and ^{174}Lu; the signs of the new values agree with the Frisk empirical rule. Also, quite different values of Newby shift are obtained in both ^{168}Tm and ^{172}Lu. The Newby shifts in other cases change marginally. This still leaves five cases where the Frisk rule fails; other mixing effects may be important in these cases. Possibly vibrational or, octupole correlations play an important role in these cases.

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References

Balodis M K *et al* 1987 *Nucl. Phys.* **A472** 445
Boisson J P, Pipenbring R and Ogle W 1976 *Phys. Rept.* **C26** 99
Bruder A, Dousse J C, Drissi S, Gasser M, Ionescu V A, Kern J, Perny B, Rast M and Rheme C 1987a *Nucl. Phys.* **A467** 1
Bruder A, Drissi S, Ionescu V A, Kern J and Vorlet J P 1987b *Nucl. Phys.* **A474** 518
Dewberry R A, Sheline R K, Lanier R G and Lasijo R 1982 *Z. Phys.* **A307** 351
Dewberry R A, Sheline R K, Lanier R G, Mann L G and Struble G L 1981a *Phys. Rev.* **C24** 1628
Dewberry R A, Sheline R K, Lanier R G, Struble G L and Mann L G 1981b *Phys. Rev.* **C24** 1643
Elmore D and Alford W P 1976 *Nucl. Phys.* **A273** 1
Frisk H 1988 *Z. Phys.* **A330** 241
Gongqing Wang 1987 *Nucl. Data Sheets* **51** 577
Hansen P G, Nielson H L, Williams E T and Wilsky K 1965 *Nucl. Phys.* **71** 481
Haustein P E, Franz E M, Katcoff S, Morcos N A, Smith Jr H A and Ward T E 1976 *Phys. Rev.* **C14** 645
Helmer R G 1986 *Nucl. Data Sheets (NY)* **49** 383
Hoff R W 1988 *J. Phys.* **G14** 343
Hoff R W, Casten R F, Bergoffen M and Warner D D 1985 *Nucl. Phys.* **A437** 285

Hoff R W, Jain A K, Kvasil J, Sood P C and Sheline R K 1989 *Invited paper at Symposium on Exotic Nuclear Spectroscopy* (American Chemical Society) Miami Beach, FL, Preprint UCRL-101090

Ignatochkin A E 1987 *Nucl. Data Sheets (NY)* **52** 365

Jain A K, Kvasil J, Sheline R K and Hoff R W 1989 *Phys. Rev.* **C40** 434

Jain A K, Sheline R K, Sood P C and Jain Kiran 1990 *Rev. Mod. Phys.* **62** 393

Jones H D, Onishi N, Hess T and Sheline R K 1971 *Phys. Rev.* **C3** 529

Jones H D and Sheline R K 1971 *Ann. Phys.* **63** 28

Kern J *et al* 1974 *Nucl. Phys.* **A221** 333

Kolata J J and Maher J V 1975 *Phys. Rev.* **C8** 285

Lee M A 1980 *Nucl. Data Sheets (NY)* **31** 381

Motz H T *et al* 1967 *Phys. Rev.* **155** 1265

Newby N D 1962 *Phys. Rev.* **125** 2063

O'Neil R A and Burke D G 1972 *Nucl. Phys.* **A195** 207

Pyatov N I, 1976 *Bull. Acad. Sci. USSR Phys. Ser. (English Transl.)* **A273** 1

Reich C W, Helmer R G and Greenwood R C 1971 *Nucl. Phys.* **A168** 487

Schilling K D, Kaubler L, Andrejtscheff W, Muminov T M, Kalinnikov V G, Marupov N Z, May F R and Seidel W 1978 *Nucl. Phys.* **A299** 189

Shera E B, Gruber U, Maier B P K, Koch H R, Schult O W B, Lanier R G, Onishi N and Sheline R K 1972 *Phys. Rev.* **C6** 537

Shirley V S 1988 *Nucl. Data. Sheets (NY)* **53** 223

Singh B and Viggars D A 1981 *Nucl. Data Sheets (NY)* **33** 275

Sood P C, Hoff R W and Sheline R K 1986 *Phys. Rev.* **C33** 2163

Sood P C and Ray R S 1986 *Pramana – J. Phys.* **27** 537

Sterba F, Holan P, Kvasil J, Horakova M and Sheline R K 1979 *Czech. J. Phys.* **B29** 1215

Treherne J, Vanhorenbeeck J and Valentin J 1969 *Nucl. Phys.* **A131** 193

Valentin J and Santoni A 1963 *Nucl. Phys.* **47** 303

Ward T E, Chu Y Y and Cumming J B 1973 *Phys. Rev.* **C8** 340