Eur. Phys. J A **2**, 129–141 (1998)

THE EUROPEAN
PHYSICAL JOURNAL A

A study of ^{223}Ra populated by α-decay

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Received: 17 November 1997 / Revised version: 8 January 1998
Communicated by D. Schwalm

Abstract. The low spin states of ^{223}Ra have been populated via α-decay from ^{227}Th which was itself produced following β^- decay of an ^{227}Ac source. α–γ and $\alpha - e_{K,L,M}$ angular correlation measurements have been analysed using the correct ground state spins of ^{227}Th($= 1/2^+$) and ^{223}Ra($= 3/2^+$) for the first time.

The analysis has allowed unique J^π values to be assigned to almost all levels below 400 keV excitation in ^{223}Ra.

Values of $(g_K - g_R)/Q_0$ have been deduced for several members of the $K = 3/2^\pm$ bands (for the first time in an odd N nucleus in this mass region) allowing estimates of g_K and g_R to be extracted. The values of g_K and g_R are not significantly different for the positive and negative parity band members and tend to support other strong evidence that stable octupole deformation exists in ^{223}Ra at low excitation energies.

PACS. 23.60.+e α decay – 23.20.En Angular distribution and correlation measurements – 21.10.Ky Electromagnetic moments

1 Introduction

Over the past thirty or so years a wealth of experimental data has been accumulated for the nucleus ^{223}Ra, principally from the α-decay of ^{227}Th and from the β^- decay of ^{223}Fr. An evaluation [1] of the available data on ^{227}Th highlighted its complexity by noting that there were 46 α-groups and 240 γ-transitions following the α decay of ^{227}Th with a further 56 γ-ray transitions following the β^- decay of ^{223}Fr. The evaluation of the probable band structure in ^{223}Ra compatible with the then existing data led to a comprehensive set of tentative spin assignments [1] which is contained in compilations [2, 3]. However, attempts to place these tentative assignments on a sound experimental basis by α–γ angular correlations are now known to be flawed since no complete angular correlation analysis prior to the present one has utilised the correct ground state spins of both ^{227}Th and ^{223}Ra. A measurement [4] of the ground state spin of ^{223}Ra showed that it is 3/2 while a recent measurement [5] showed that the ground state spin of ^{227}Th is 1/2. Positive parity is assumed for both states following α-decay systematics [6].

The level structure and assumed J^π values have previously been interpreted in terms of a stable octupole deformed ^{223}Ra nucleus [1, 7]. These studies not only successfully accounted for the parity doublet structure which is a key indicator of octupole correlations but were also able to explain theoretically the similar magnetic dipole moments of the $K = 3/2^\pm$ bandheads. Octupole correlations are expected in those regions of the periodic table where single particle states differing by $\Delta j = \Delta l = 3$ lie close to the Fermi surface. This condition is satisfied in the regions N or Z $\approx 85 - 92$ and N $\approx 131 - 139$ where evidence for octupole correlations is strongest [6, 7, 8]. The observation of strong B(E3)↑ reduced transition probabilities in ^{148}Nd [9] and in ^{226}Ra [10] by means of Coulomb excitation experiments is one of the most direct pieces of evidence that octupole correlations exist in the lanthanide and light actinide regions of the periodic table where N or Z $\approx 88 - 90$. Recent experiments [11] on previously inaccessible even-even Ra and Rn isotopes around A $= 220 - 226$ also provide striking direct evidence that octupole correlations exist in this mass region. However, not all nuclei in these mass regions are amenable to such definitive experiments and indirect evidence, particularly in odd mass nuclei, is usually required to infer that octupole correlations exist.

Since parity is no longer a good quantum number in a reflection asymmetric potential, the low lying single particle states become states of mixed parity in the intrinsic frame, leading to near degenerate states of opposite parity as experimental observables. With increasing excitation energy rotational bands develop based on the opposite parity bandheads where intra band electromagnetic decays usually take the form of enhanced electric dipole transitions [12]. Even though the observation of parity doublets in odd-A nuclei may be a necessary condition it is certainly not sufficient to confirm that octupole correlations exist. In a reflection asymmetric potential the

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[761]$3/2^-$ and [631]$3/2^+$ orbitals in ^{223}Ra are believed to mix [1, 7] giving rise to a "hybridized" wavefunction with approximately equal admixtures leading to approximately equal values of magnetic dipole moments for positive and negative parity bandheads. In the case of ^{223}Ra, the magnetic dipole moments for the $3/2^{\pm}$ bandheads are in good agreement within experimental errors supporting the case for octupole deformation [1, 7].

Similar behaviour is expected for the quantity $(g_K - g_R)/Q_0$. In the case of the odd proton nucleus ^{227}Ac values of $(g_K - g_R)/Q_0$ for the opposite parity $K = 3/2$ bands lie close to the single hybridized value expected for stable octupole deformation [7].

It has been pointed out, however [6, 7] that, in a reflection symmetric potential, single particle orbitals of the same total angular momentum projection on the axial symmetry axis and opposite parity may lie close together. One can therefore generate rotational bands based on single particle orbitals which mimic parity doublet rotational bands. Despite this apparent similarity, opposite parity rotational bands based on separate single particle orbitals should give rise to very different magnetic observables. In particular, the magnetic dipole moments based on the two single particle orbitals should be different as should their intrinsic gyromagnetic ratios g_K [13, 14].

It is clearly important to deduce values of $(g_K - g_R)/Q_0$ for another case and we report here measurements in ^{223}Ra which allow the extraction of values of g_K and g_R. It is then possible to investigate whether they support the other indications of octupole deformation in this nucleus. The relative sign of E2/M1 multipole mixing amplitudes can be obtained from angular correlation experiments of the type described here. Therefore, since the ground state quadrupole moment of ^{223}Ra has been experimentally determined to be positive [2] then the sign of $(g_K - g_R)$ for two of the transitions in the positive parity band is unambiguously determined. Also, because the magnetic dipole moments have been measured for the positive and negative parity bandheads we are able to deduce values of g_K and g_R for the two bands. As the orbital contribution g_ℓ to g_K should be zero to first order for neutrons we are therefore sampling the variation of g_S between the two bands, which should be small in the case of a hybridized wavefunction.

2 Experimental details

An ^{227}Ac source ($T_{1/2} \approx 22$ years) was obtained for the measurements. The nucleus ^{227}Ac β^- decays to ^{227}Th($T_{1/2} \approx 19$ days) which in turn α-decays to ^{223}Ra. The experiments were carried out after secular equilibrium was established. The source consisted of $\approx 10\,\mu$Ci of ^{227}Ac evaporated as a 4 mm diameter spot onto a thick gold backing. The γ-rays were detected with a Be windowed, low energy, hyperpure Ge detector while internal conversion electrons were detected using a 100 mm^2, 3 mm thick, Si(Li) detector. Five silicon PIN diodes with circular collimators (8 mm diameter holes) were used to detect α-particles positioned at 180°, 155°, 135°, 115° and 90° relative to the Ge detector. The Ge, Si(Li) and PIN detectors were positioned 9.0, 5.5 and 3.0 cm. respectively from the source.

Energy calibration of the Ge and Si(Li) detectors was accomplished using ^{152}Eu and ^{133}Ba γ-ray sources and a ^{207}Bi electron source. Since the α-energies involved in the ^{227}Th decay chain are well known, the ^{227}Ac source itself was used for the energy calibration of the PIN diodes. The α-particle energy resolution was typically $\approx$25 keV and the γ-ray energy resolution for transitions less than 250 keV was typically 1 keV. The low energy cut off was $\approx$4 keV. The electron resolution was $\approx$2.5 keV for electron energies of $\approx$150 keV. Using these detectors we have developed a versatile and compact system which allows the simultaneous measurement of α–γ and $\alpha - e_{K,L,M}$ angular correlations. The experimental arrangements have been described in more detail elsewhere [15] where typical spectra are shown.

3 Data analysis

The energy levels, γ-ray transition energies and intensities adopted in the present work are those compiled from several earlier studies [2].

The experimental α–γ angular correlation data were initially fitted using Legendre polynomial coefficients in the usual form

$$W(\theta) = \sum A_k Q_k P_k(\cos\theta)$$

where Q_k are solid angle correction factors. Hence normalised Legendre polynomial coefficients $a_2 = A_2/A_0$ and $a_4 = A_4/A_0$ were calculated. These coefficients a_2 and a_4 are labelled 'experimental' in Table 1 and can be compared with other similar determinations from α–γ angular correlation measurements in ^{223}Ra [e.g. 16], since no spin assumptions are made to obtain these coefficients.

The ground state spin of ^{223}Ra has been measured [4] as $J = 3/2$ while the ground state spin of ^{227}Th has been measured [5] as $J = 1/2$. If we follow systematics [6] and assume positive parity for both of these ground states then α–γ angular correlations analysis becomes particularly simple. Conservation of angular momentum and parity implies that α-transitions from the ground state of ^{227}Th to energy levels in the daughter nucleus can only proceed by a single pure even L transition to positive parity states and by a single pure odd L transition to negative parity states.

Following an earlier notation [17] we can write the α–γ angular correlation yield for the α-decay from a parent (spin 1/2) ground state to an excited state (spin J_1) in the daughter nucleus, followed by γ-decay to a lower excited state (spin J_2) as

$$\begin{aligned} W(\theta) = \sum_k & B_k(J_1) Q_k P_k(\cos\theta) \\ & \times \{R_k(L_{12}, L_{12}, J_1, J_2) + 2\delta R_k(L_{12}, L_{12}+1, J_1, J_2) \\ & \quad + \delta^2 R_k(L_{12}+1, L_{12}+1, J_1, J_2)\}/(1+\delta^2) \end{aligned}$$

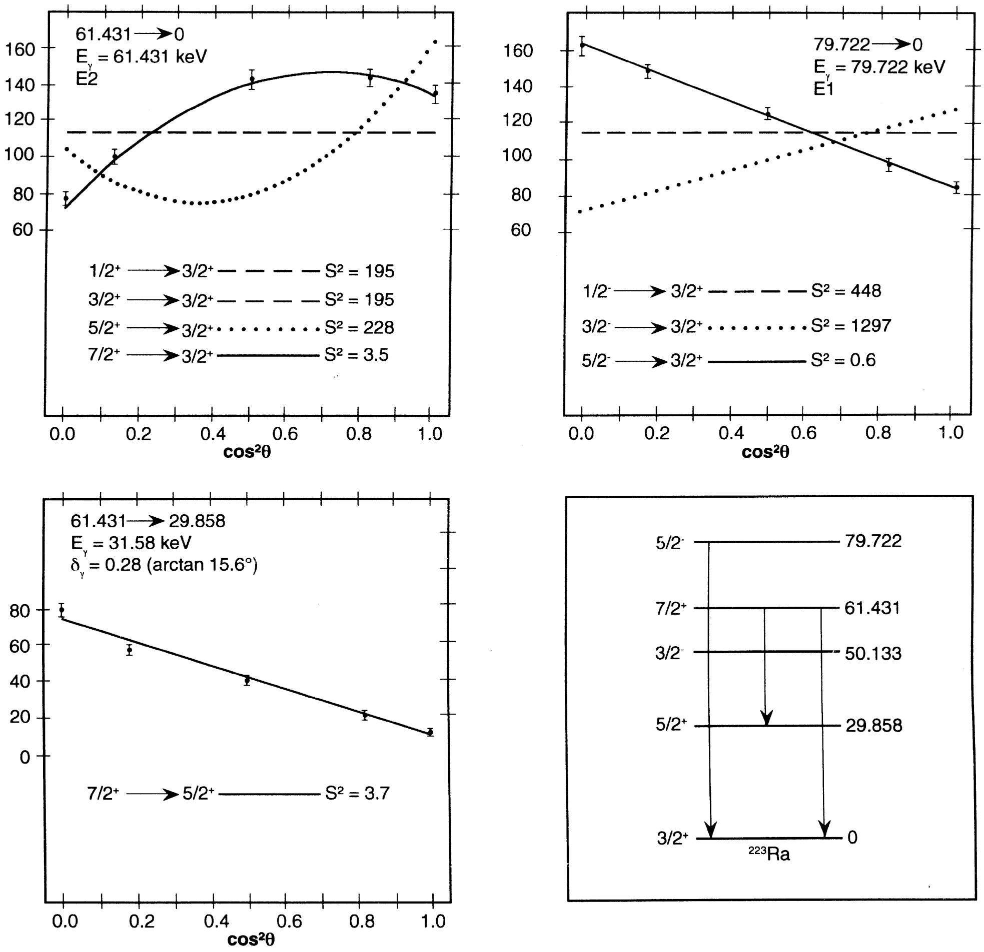

Fig. 1. Fitted (α–γ) angular correlations for the 61.431 keV E2 transition to the ground state, the 31.58 keV transition from the 61.431 keV level to the 29.858 keV level and the E1 transition from the 79.722 keV level to the ground state. The partial γ-ray decay scheme for levels below 100 keV shows only those transitions for which angular correlations have been extracted

where L_{12} and $L_{12}+1$ are the lowest order γ-ray multipoles allowed by J_1 and J_2, δ is the γ-ray multipole mixing ratio, $P_k(\cos\theta)$ are Legendre polynomials and values of R_k coefficients are tabulated [17] for several J_1, J_2.

For an α-decay via a pure L transition we may write $B_k(J_1) = S_k(L, L, J_1, 1/2)$ which are tabulated [17] as population tensors, for several L, J_1.

The theoretical fit to the experimental α–γ angular correlation data $W(\theta)$ for a given J_1, J_2 therefore produces Legendre polynomial coefficients a_2 and a_4 which then depend on the spins hypothesised for J_1 and J_2; such coefficients are labelled 'theoretical' in Table 1. Where multipole mixing ratios have been tabulated as pure E1, M1 or E2 transitions in Nuclear Data Sheets [2] on the basis of internal conversion coefficient measurements we have assumed those values. For mixed multipole transitions (E2/M1) or when theoretical Legendre polynomial coefficients with pure multipoles were more than two standard errors from the 'experimental' Legendre polynomial coefficients (Table 1) then the multipole mixing ratio δ was allowed to vary as a free parameter, the values obtained from the present work being given in Table 1.

Hence, the α–γ theoretical fits obtained have either four degrees of freedom (only the normalisation varied for pure multipole fits) or three degrees of freedom (normalisation and δ). Accordingly best estimates of δ are given at the minimum value of the squares of residuals S^2 versus δ plot i.e. at $S^2_{\rm min}$ while standard errors in δ are obtained using a prescription based on the magnitude of the errors [18]. The 0.1% confidence limit for three degrees of freedom is $S_2 = 16.27$ and for four degrees of freedom it is 18.47.

It should be noted that the sign of δ obtained from the present work may differ from some γ–γ angular correlation analyses. We adhere to a phase consistent sign convention [17] in the present work.

In addition to the many extracted α–γ angular correlations, it proved necessary to extract four point (25°, 45°, 65° and 90°) $\alpha - e_{L,M}$ angular correlations for a 113.159 keV E2 transition. Appropriate theoretical α–γ angular correlation coefficients a_2 and a_4 were scaled by particle parameters b_2 and b_4 for a pure E2 transition [19] to generate $\alpha - e_L$ and $\alpha - e_M$ fits for various spin hypotheses. Once again only the normalisation of theory to experiment is a free parameter.

4 Level analysis from the angular correlations

4.1 The four excited states below 100 keV

The level at 50.133 keV has been assigned $J^\pi = 3/2^-$ from the results of γ–γ angular correlation analysis [2].

Table 1. Experimental a_2 and a_4 Legendre polynomial coefficients corrected for solid angle attenuation together with theoretical Legendre polynomial coefficients for principally pure dipole or quadrupole transitions between initial and final state spins $J_1^\pi \rightarrow J_2^\pi$ in ^{223}Ra. The transitions marked with an asterisk * have mixed multipolarity with mixing ratios evaluated here given in column 7. The 113.159 keV transition marked with double asterisks is a doublet as discussed in the text, the theoretical coefficients in this case are for pure dipole and pure quadrupole transitions

Populated	γ-ray	Experimental		Theoretical		Mix Ratio	
Level (keV)	(keV)	a_2 (Δa_2)	a_4 (Δa_4)	a_2	a_4	δ ($\Delta\delta$)	$J_1^\pi \rightarrow J_2^\pi$
61.43	61.43	0.49(4)	−0.33(5)	0.51	−0.37		$7/2^+ \rightarrow 3/2^+$
	31.58*	−0.88(5)	0.10(6)	−0.86	0.05	0.28(5)	$7/2^+ \rightarrow 5/2^+$
79.72	79.72	−0.40(2)	0.00(3)	−0.40	0		$5/2^- \rightarrow 3/2^+$
123.79	93.93	−0.34(3)	0.01(4)	−0.36	0		$7/2^- \rightarrow 5/2^+$
	62.45	0.44(3)	−0.11(5)	0.48	0	E1	$7/2^- \rightarrow 7/2^+$
130.17	100.27	0.46(8)	−0.27(12)	0.48	−0.29		$9/2^+ \rightarrow 5/2^+$
174.58	94.90	0.38(5)	−0.26(5)	0.48	−0.29		$9/2^- \rightarrow 5/2^-$
	113.159**	−0.18(1)	−0.035(15)	−0.33	0		$9/2^- \rightarrow 7/2^+$
174.62	113.159**	−0.18(1)	−0.035(15)	0.45	−0.24		$11/2^+ \rightarrow 7/2^+$
234.80	234.81*	−0.23(3)	−0.05(4)	−0.26	0	−0.07(2)	$5/2^+ \rightarrow 3/2^+$
	205.03*	0.58(4)	−0.05(6)	0.58	0	−0.12(7)	$5/2^+ \rightarrow 5/2^+$
	184.65	−0.44(8)	−0.06(13)	−0.40	0		$5/2^+ \rightarrow 3/2^-$
247.39	117.20	−0.27(3)	−0.05(4)	−0.32	0		$11/2^- \rightarrow 9/2^+$
280.20	250.35	−0.40(12)	0.19(19)	−0.36	0		$7/2^+ \rightarrow 5/2^+$
	219.00	0.38(19)	0.44(30)	0.48	0	M1	$7/2^+ \rightarrow 7/2^+$
286.10	286.12	0.01(2)	−0.01(3)	0	0		$1/2^+ \rightarrow 3/2^+$
	256.25	0.03(2)	0.02(3)	0	0		$1/2^+ \rightarrow 5/2^+$
	235.97	0.00(2)	0.02(3)	0	0		$1/2^+ \rightarrow 3/2^-$
329.86	329.85	0.38(3)	−0.02(5)	0.40	0		$3/2^- \rightarrow 3/2^+$
	300.00	−0.06(2)	0.00(3)	−0.10	0	E1	$3/2^- \rightarrow 5/2^+$
	279.72*	0.18(10)	0.05(15)	0.21	0	0.12(11)	$3/2^- \rightarrow 3/2^-$
	250.35*	−0.56(3)	−0.10(4)	−0.61	0	−4.1(7)	$3/2^- \rightarrow 5/2^-$
	206.11	0.12(5)	0.04(6)	0.14	0	E2	$3/2^- \rightarrow 7/2^-$
	43.80	−0.51(4)	−0.02(5)	−0.50	0	E1	$3/2^- \rightarrow 1/2^+$
334.38	334.38*	0.68(2)	0.12(3)	0.68	0.18	−0.62(4)	$5/2^+ \rightarrow 3/2^+$
	304.52*	0.52(2)	0.01(3)	0.53	0	−0.07(4)	$5/2^+ \rightarrow 5/2^+$
	272.93	−0.16(2)	0.08(3)	−0.14	0	8.5(1.8)	$5/2^+ \rightarrow 7/2^+$
	254.68	0.40(2)	0.02(3)	0.46	0	E1	$5/2^+ \rightarrow 5/2^-$
	210.65	−0.12(2)	0.03(3)	−0.14	0		$5/2^+ \rightarrow 7/2^-$
	204.27	0.22(4)	0.00(6)	0.20	−0.01	E2	$5/2^+ \rightarrow 9/2^+$
342.62	342.50*	−0.62(3)	−0.03(3)	−0.60	0	1.30(25)	$3/2^+ \rightarrow 3/2^+$
	312.69*	0.12(2)	−0.01(3)	0.12	0	0.20(4)	$3/2^+ \rightarrow 5/2^+$
	292.41	0.36(6)	−0.03(9)	0.40	0		$3/2^+ \rightarrow 3/2^-$
	262.91	−0.17(5)	0.02(7)	−0.10	0	E1	$3/2^+ \rightarrow 5/2^-$
342.84	281.29	−0.28(7)	−0.14(9)	−0.33	0		$9/2^+ \rightarrow 7/2^+$
	212.65*	0.60(7)	−0.05(10)	0.60	0	−0.35(35)	$9/2^+ \rightarrow 9/2^+$
	62.45*	0.29(6)	−0.07(8)	0.24	0.05	0.29(5)	$9/2^+ \rightarrow 7/2^+$
350.47	350.47	0.06(4)	0.03(5)	0	0		$1/2^- \rightarrow 3/2^+$
	300.00	−0.05(2)	0.01(3)	0	0		$1/2^- \rightarrow 3/2^-$
369.39	134.48	0.40(13)	−0.12(19)	0.46	0		$5/2^- \rightarrow 5/2^+$
376.28	314.78	0.52(4)	−0.03(6)	0.48	0		$7/2^- \rightarrow 7/2^+$
	296.51*	−0.03(2)	0.06(3)	0.01	0.02	−0.16(2)	$7/2^- \rightarrow 5/2^-$
	252.6	0.48(6)	0.11(9)	0.48	0	M1	$7/2^- \rightarrow 7/2^-$
	201.60*	0.48(11)	0.46(17)	0.48	0.12	1.5(9)	$7/2^- \rightarrow 9/2^-$
	141.49	−0.35(4)	0.04(6)	−0.36	0	E1	$7/2^- \rightarrow 5/2^+$
445.00	383.52*	0.54(10)	−0.03(15)	0.49	0.10	−0.46(12)	$9/2^+ \rightarrow 7/2^+$
	314.78	0.34(9)	0.18(12)	0.48	0		$9/2^+ \rightarrow 9/2^+$

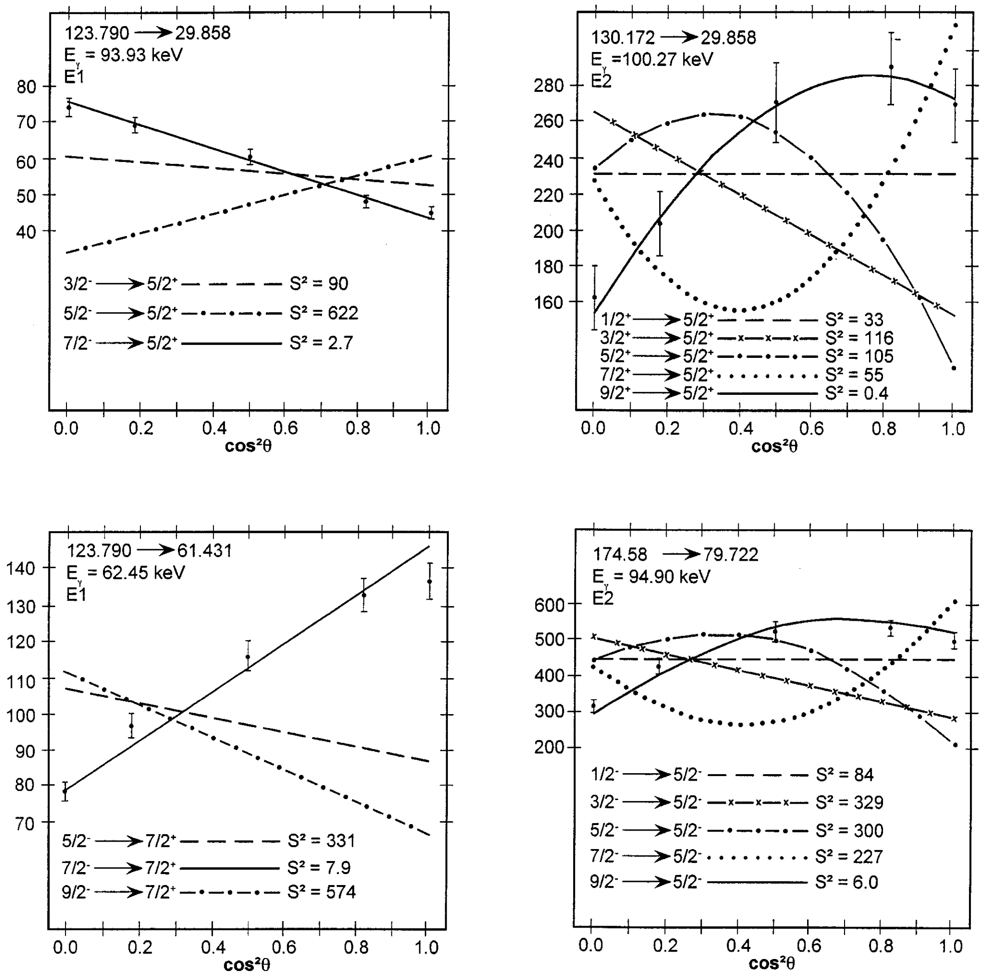

Fig. 2. Fitted (α–γ) angular correlations for the 93.93 keV E1 transition from the 123.790 keV level to the 29.858 keV level, the 62.45 keV E1 transition from the 123.790 keV level to the 61.431 keV level, the 100.27 keV E2 transition from the 130.172 keV level to the 29.858 keV level and the 94.90 keV E2 transition from the 174.58 keV level to the 79.722 keV level

The level at 79.722 keV was shown from an earlier short report of the present work [15] to be $5/2^-$ if the ground state spin of ^{227}Th were $1/2^+$ (Fig. 1).

Two α–γ angular correlations are obtained following population of the 61.431 keV level – a 61.431 keV E2 transition to the ground state and a 31.58 keV transition to the 29.858 keV level – from which $J^\pi = 7/2^+$ (Fig. 1).

Since a mixed E2/M1 transition has been reported [2] for the 29.858 keV transition to ground $(3/2^+)$ then the 29.858 keV level can be assigned $J^\pi = 5/2^+$.

It was only possible to extract a 29.858 keV correlation following population of the 61.431 keV level and decay via the 31.58–29.858 keV cascade. Despite this correlation being somewhat contaminated by the decay of the 79.722 keV level to the 50.133 keV level (due to inadequate α-resolution) it was found that $\delta(\mathrm{E2/M1}) \approx 0.4$.

4.2 The four levels between 100 keV and 200 keV

The 123.790 keV level decays by means of a 93.93 keV E1 transition to the 29.858 keV $(5/2^+)$ level and a 62.45 keV E1 transition to the 61.431 keV $(7/2^+)$ level leading to a $J^\pi = 7/2^-$ assignment (Fig. 2).

The 130.172 keV level decays by means of a 100.27 keV E2 transition to the 29.858 keV $(5/2^+)$ level leading to a $J^\pi = 9/2^+$ assignment (Fig. 2). A 68.72 keV mixed E2/M1 transition to the 61.431 keV $(7/2^+)$ level was masked by the fluorescent gold x-rays produced from the backing foil of the ^{227}Ac source.

A close lying doublet is placed at 174.58 and 174.62 keV excitation [2]. The 94.90 keV E2 transition is attributed to the decay from the 174.58 keV level to the 79.722 keV $(5/2^-)$ level from which we assign $J^\pi = 9/2^-$ (Fig. 2).

Obtaining unambiguous α–γ correlations following population of the 174.62 keV member of the doublet is rather more problematical. The correlation extracted for a 113.159 keV peak has contributions from the decay of both 174.58 and 174.62 keV levels to the 61.431 keV $(7/2^+)$ level, the former transition being E1 and the latter E2 [2]. A 113.159 keV E1 transition has a total internal conversion coefficient $\alpha_T = 0.362$ while an E2 transition of the same energy has $\alpha_T = 5.78$ [2]. If both levels were excited equally following α-decay then the E1 γ-transition would have approximately five times the intensity of the E2 γ-transition. However, the 'experimental' Legendre polynomial coefficients $a_2 = -0.18(1)$ and $a_4 = -0.035(15)$ are

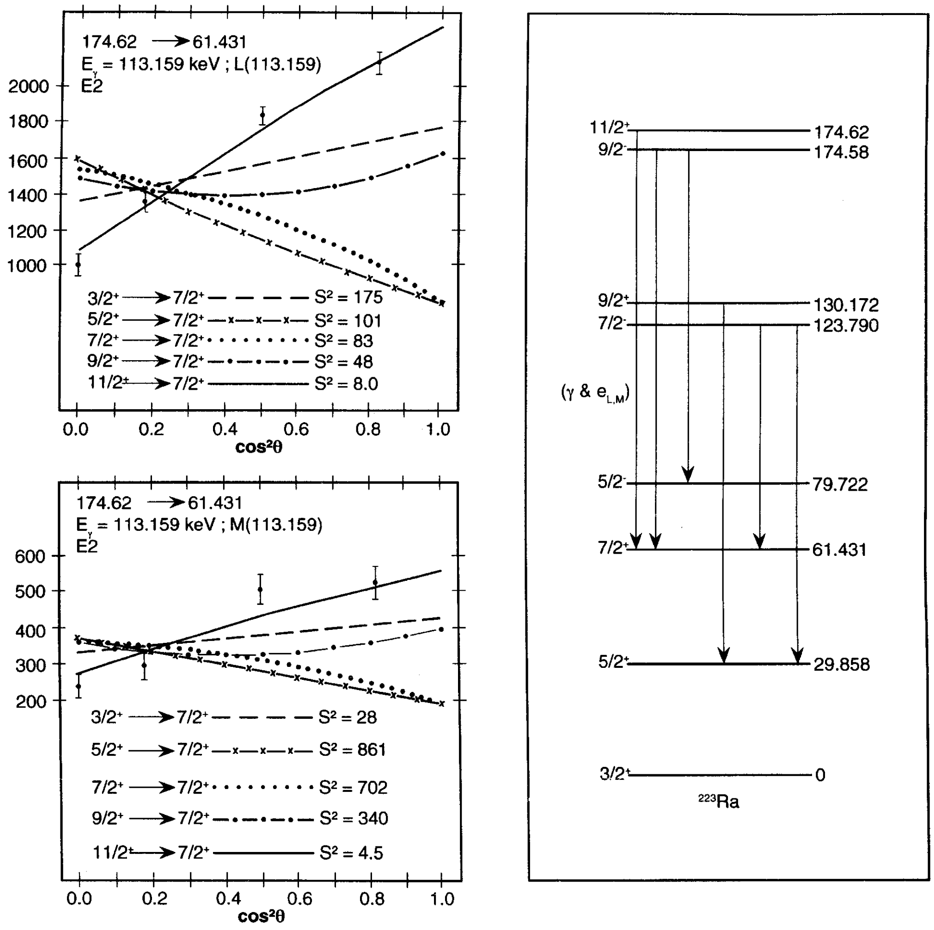

Fig. 3. Fitted $(\alpha - e_L)$ and $(\alpha - e_M)$ angular correlations for the 113.159 keV E2 transition from the 174.62 keV level to the 61.431 keV level. The partial γ-ray decay scheme for levels between 100 and 200 keV excitation energy shows only those transitions for which angular correlations have been extracted – the γ-rays from the 174.58 keV and 174.62 keV levels to the 61.431 keV level give rise to an unresolved doublet as explained in the text

not consistent with the correlation being predominantly due to the E1 transition from the 174.58 keV ($9/2^-$) level, since the theoretical coefficients are $a_2 = -0.33$, $a_4 = 0$ for this hypothesis. Likewise all spin hypotheses involving a pure E2 transition from the 174.62 keV level to the 61.431 keV ($7/2^+$) level are rejected at the 0.1% confidence level. This suggests that the 174.62 keV to 61.431 keV ($7/2^+$) E2 component provides the largest total decay intensity. Accordingly, we measured four point $\alpha - e_L$ and $\alpha - e_M$ angular correlations following L and M internal conversion of the composite 113.159 keV transition, using a previously described arrangement [15]. The ratio of the total L internal conversion to total M internal conversion was consistent with the 113.159 keV transition being dominated by the E2 component allowing the E1 component to be neglected. From the fits shown in Fig. 3 we assign $J^\pi = 11/2^+$ to the 174.62 keV level.

4.3 The four levels between 200 and 300 keV

Three angular correlations were obtained for decays from the 234.802 keV level (Fig. 4). We assign $J^\pi = 5/2^+$ from the correlation of the 184.65 keV E1 transition to the 50.133 keV ($3/2^-$) level. See Table 1 for other results.

The 247.39 keV level is assigned $J^\pi = 11/2^-$ from the angular correlation of the 117.20 keV E1 transition to the 130.172 keV ($9/2^+$) level (Fig. 4).

The 280.20 keV level can be restricted to $J^\pi = 5/2^+$ or $7/2^+$ because of the 250.35 keV M1 transition to the 29.858 keV ($5/2^+$) level and the 150.16 keV transition to the 130.172 keV ($9/2^+$) level. We assign $J^\pi = 7/2^+$ since the 250.35 keV correlation (Fig. 5) rules out $5/2^+$. With the $7/2^+$ assignment we find the correlation for the 219.00 keV transition consistent with pure M1 (Table 1).

The 286.103 keV level has been assigned $1/2^+$ following γ–γ angular correlation analyses [2]. The 'experimental' Legendre polynomial coefficients for α–γ correlations via this level are consistent with the isotropy expected for γ-decay from a spin 1/2 level (Table 1 and Fig. 5).

4.4 The three levels between 300 and 340 keV

The level at 315.55 keV is too weakly excited in the present work to extract any correlations following its decay.

Six angular correlations were obtained from the γ-decays of the 329.859 keV level. We assign $J^\pi = 3/2^-$ from the correlation of the E1 transition to ground ($3/2^+$) (Fig. 6). See Table 1 for other results.

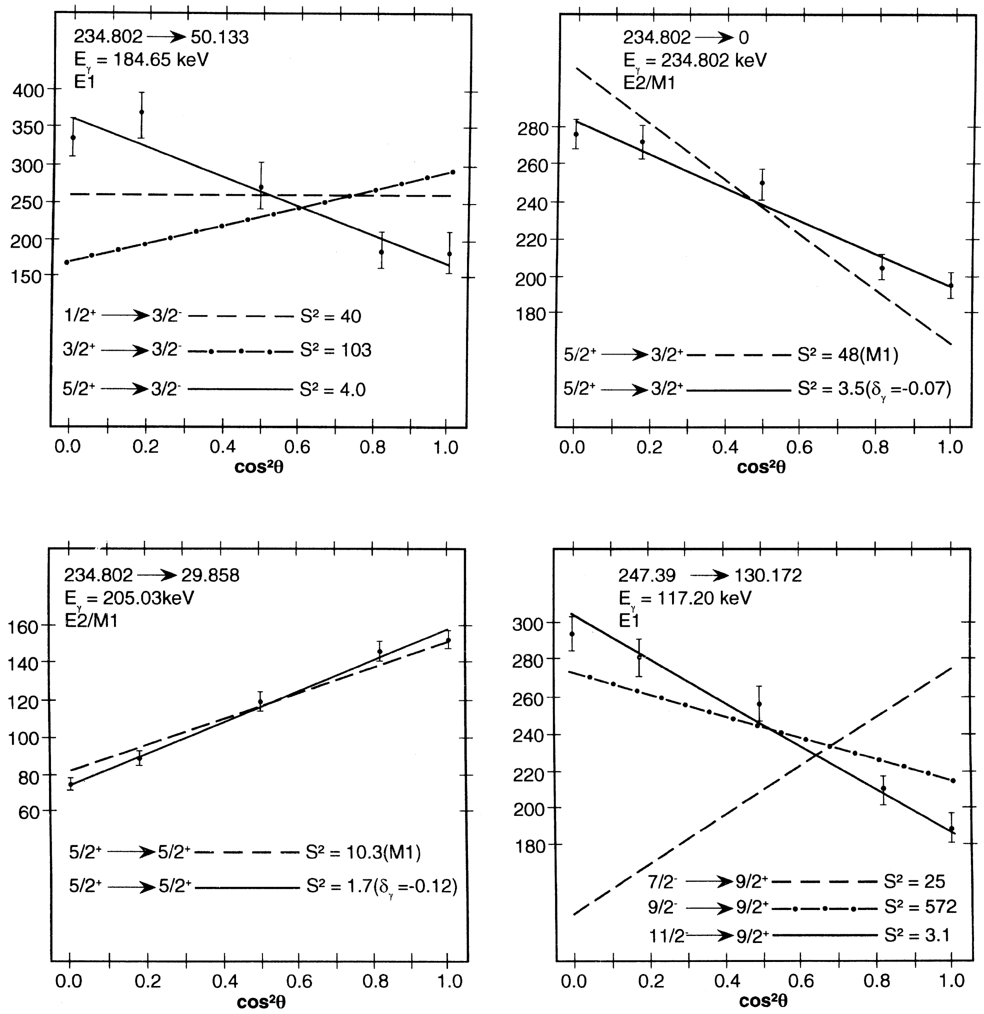

Fig. 4. Fitted (α–γ) angular correlations for the 184.65 keV E1 transition from the 234.802 keV level to the 50.133 keV level, the 205.03 keV (E2/M1) transition from the 234.802 keV level to the 29.858 keV level, the 234.802 keV (E2/M1) transition from the 234.802 keV level to the ground state and the 117.20 keV E1 transition from the 247.39 keV level to the 130.172 keV level

Six angular correlations were obtained following the γ-decay of the 334.386 keV level. We assign $J^\pi = 5/2^+$ from the correlation of the 210.65 keV E1 transition to the 123.79 keV ($7/2^-$) level (Fig. 6). See Table 1 for other results.

4.5 The four levels between 340 and 370 keV

Four correlations were extracted following the γ-decay of the 342.622 keV level. We assign $J^\pi = 3/2^+$ from the correlation of the 292.41 keV E1 transition to the 50.133 keV ($3/2^-$) level (Fig. 7). See Table 1 for other results.

Two correlations were extracted following the γ-decay of the 342.84 keV level but the extracted correlations are not sufficient to deduce the spin of the level uniquely. From the decay scheme [2] J^π for the level can be limited to $(5/2, 7/2, 9/2)^+$ and the correlation of the 212.65 keV transition to the 130.172 keV ($9/2^+$) level rules out $5/2^+$. However, we note that the $J^\pi = 9/2^+$ assignment is favoured [1] based on rotational band systematics and this is the value assumed when quoting mixing ratios from this level (Table 1).

The 350.47 keV level has been assigned $J^\pi = 1/2^-$ from a previous short report of the present work [15]. The angular correlation of the 300.00 keV transition to the 50.133 keV ($3/2^-$) level is also isotropic within experimental errors (Table 1) as expected for the γ-decay of a $1/2^-$ level.

Only one correlation with adequate statistics could be extracted from the γ-decay of the 369.39 keV level, from which we deduce that $J^\pi = 5/2^-$ (Fig. 7)

4.6 Levels above 370 keV

Only the 376.278 and 445.00 keV levels were excited with sufficient intensity to enable reliable angular correlations to be extracted.

Five correlations were extracted following the decay of the 376.278 keV level. We assign $J^\pi = 7/2^-$ from the correlation of the 314.78 keV E1 transition to the 61.431 keV ($7/2^+$) level (Fig. 8). See Table 1 for other results

The 445 keV level is assigned $J^\pi = 9/2^+$ from the correlation of the 314.78 keV M1 transition to the 130.172 keV ($9/2^+$) level (Fig. 8). The multipole mixing ratio obtained for the 383.52 keV transition is given in Table 1.

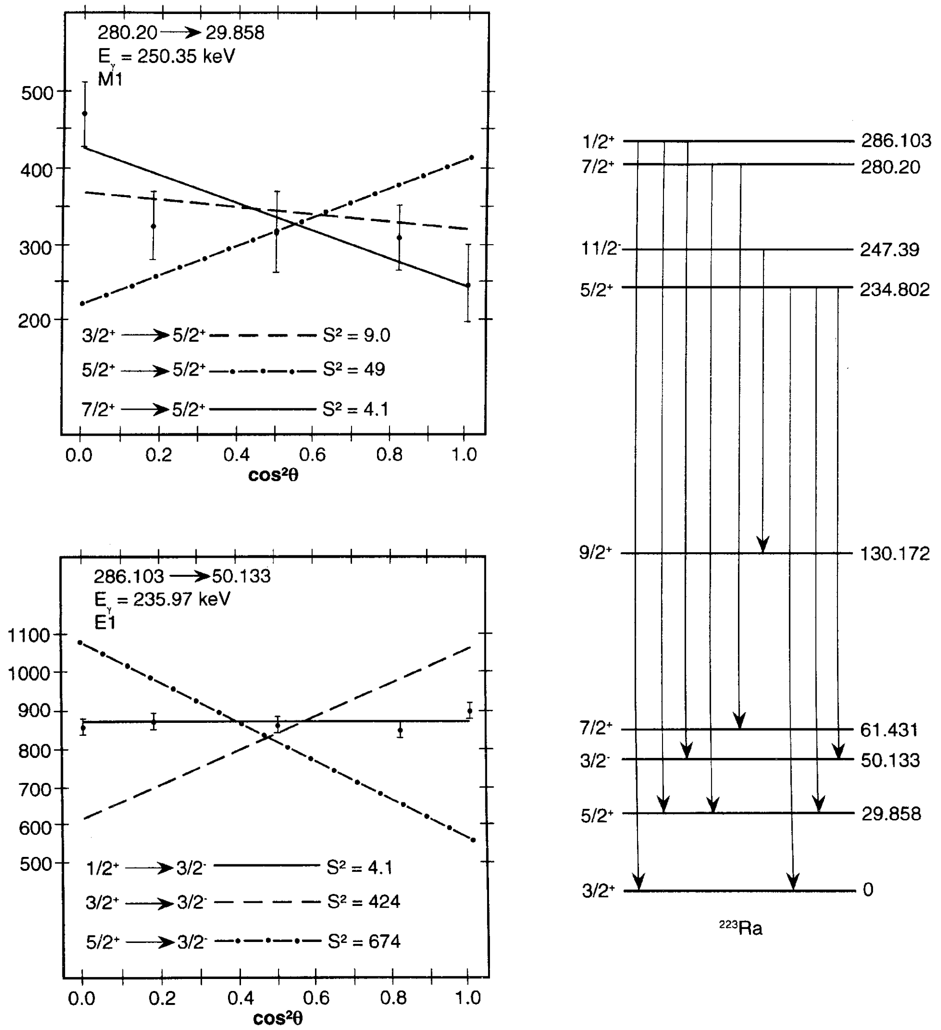

Fig. 5. Fitted (α–γ) angular correlations for the 250.35 keV M1 transition from the 280.20 keV level to the 29.858 keV level and the 235.97 keV E1 transition from the 286.103 keV level to the 50.133 keV level. The partial γ-ray decay scheme for levels between 200 and 300 keV excitation energy shows only those transitions for which angular correlations have been extracted

5 Discussion

All the J^{π} values measured in the present work confirm previous tentative assignments [1]. Only two transitions are found with mixing ratios (Table 1) not consistent with tabulated values [2]. The mixing ratio obtained for the 234.802 keV transition to ground is not quite consistent with the previously assigned M1 multipolarity but is within the magnitude of the errors quoted for the internal conversion measurements [26] from which M1 was deduced. The mixing ratio of the 304.159 keV transition from the 334.386 keV level differs considerably from the accepted value [2]. The original data from which the accepted value is derived [26] show that measured internal conversion subshell ratios $K/L_1/L_2$ are consistent with the multipolarity obtained here. However, the original authors in attempting to obtain absolute electron intensities per α-decay explain what appears to be a normalisation problem for some of the most intense electron lines in the spectra by E0 penetration effects which we feel is not warranted in view of the present results.

The nucleus ^{223}Ra lies in the nuclear mass region where stable octupole deformation is believed to exist at low excitation energies. Analysis of the level structure in this mass region [1, 7] offers convincing evidence that nuclear properties are better described theoretically with the inclusion of stable octupole deformation rather than by a reflection symmetric quadrupole deformation alone. As well as many of the features of the level ordering, the de-coupling parameters 'a' for the $K = 1/2^{\pm}$ bands have opposite signs and close numerical values as expected for octupole deformation. Also, the similarity of the measured magnetic dipole moments of the band head $K = 3/2^{\pm}$ states has been used as convincing evidence of the need to include octupole deformation. Clearly the intrinsic g-factor g_K is even more sensitive to the details of deformation than the magnetic dipole moment since the ballasting effect of the rotational g-factor g_R is removed. In this work we have investigated experimentally the evolution of g_K with spin and theoretically the evolution of bandhead g_K values with deformation, using calculations of single particle wavefunctions in a reflection asymmetric Woods-Saxon potential [20].

We first evaluate the quantity $\left(\frac{g_k - g_R}{Q_0}\right)$ which is also closely related to the magnetic properties of the $K = 3/2^{\pm}$ bands and is amenable to experimental investigation. Oc-

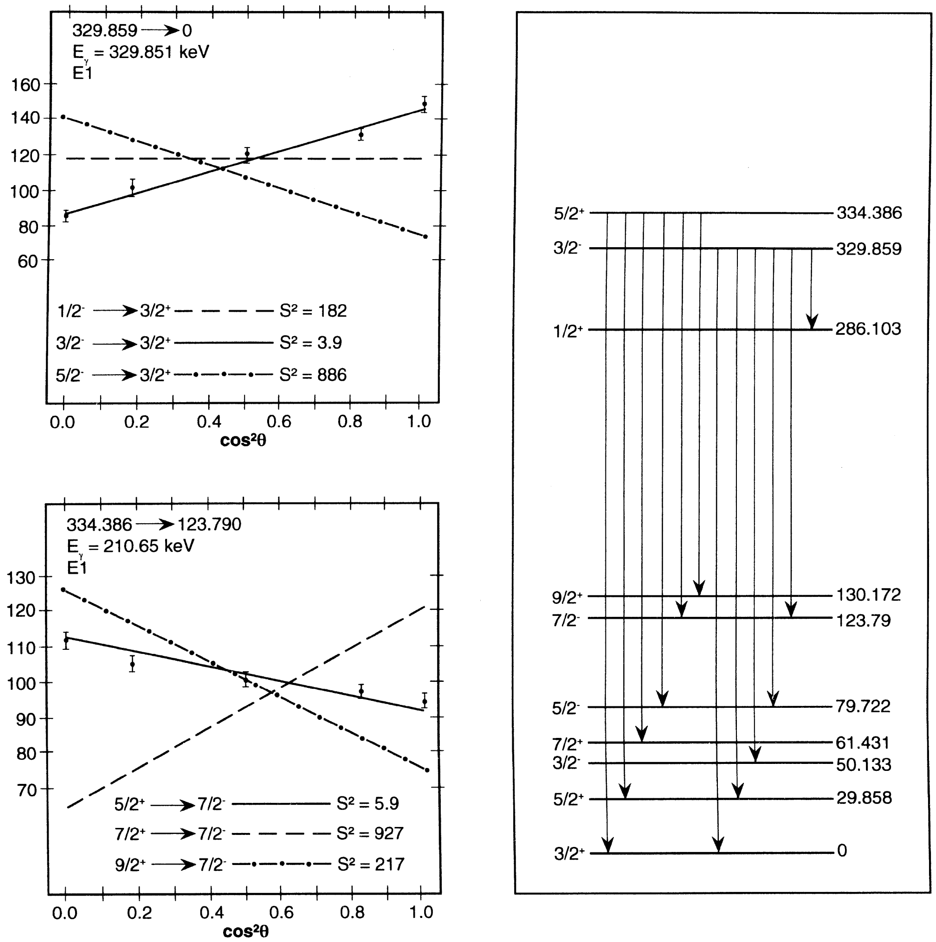

Fig. 6. Fitted (α–γ) angular correlations for the 329.851 keV E1 transition to the ground state and the 210.65 keV E1 transition from the 334.386 keV level to the 123.790 keV level. The partial γ-ray decay scheme for levels between 300 and 340 keV excitation energy shows only those transitions for which angular correlations have been extracted

tupole deformation in the strong coupling limit predicts that $\left(\frac{g_K-g_R}{Q_0}\right)$ should be equal for both positive and negative parity bands. This prediction was examined [7] for ^{227}Ac which was the only nucleus with the available experimental information. For this odd proton nucleus, because the reflection symmetric single particle scheme would have to produce a positive parity orbital [651]$3/2^+$ with spin up and a negative parity orbital [532]$3/2^-$ with spin down to generate the same K, it seems unlikely that they should produce the same g_K and hence the same $\left(\frac{g_K-g_R}{Q_0}\right)$. However, since octupole deformation mixes the two reflection symmetric orbitals a parity doublet based on such mixed orbitals should have a hybridized wave function (i.e. a wavefunction with approximately equal admixtures) and hence similar magnetic moments and g_K values for both parities. This was largely borne out for the $K = 3/2^\pm$ bands studied in ^{227}Ac. For the odd neutron nucleus ^{223}Ra, the contribution from the orbital angular momentum to the g_K-factor should be zero to first order and it is not quite so clear what effect opposite parity orbitals will have on the contribution of the intrinsic spin to g_K.

We evaluate $\left(\frac{g_K-g_R}{Q_0}\right)$ for the $K = 3/2^\pm$ parity doublet bands in the odd neutron nucleus ^{223}Ra using similar techniques as in the study of ^{227}Ac [21, 22].

The branching ratio R for each pair of E2 and (M1 + E2) intra band transitions from the same level spin I (K = 3/2) is given by

$$\mathrm{R} = \frac{\mathrm{T(M1+E2; I \to I-1)}}{\mathrm{T(E2; I \to I-2)}} = \frac{2\mathrm{K}^2(2\mathrm{I}-1)}{(\mathrm{I}+1)(\mathrm{I}+\mathrm{K}-1)(\mathrm{I}-\mathrm{K}-1)}\left(\frac{\mathrm{E}_{\mathrm{I}\to\mathrm{I}-1}}{\mathrm{E}_{\mathrm{I}\to\mathrm{I}-2}}\right)^5\left(1+\frac{1}{\delta^2}\right)$$

where δ is the multipole mixing ratio of the M1 + E2 transition which can be determined since R is the experimental ratio of the γ-ray intensities.

For each of these transitions within a rotational band between neighbouring states, once δ is known then $\left(\frac{g_K-g_R}{Q_0}\right)$ (in units barns^{-1}) can be determined since

$$\frac{1}{\delta} = \sqrt{\frac{\mathrm{T(M1; I \to I-1)}}{\mathrm{T(E2; I \to I-1)}}} = -\frac{1.07(\mathrm{I}^2-1)^{1/2}}{\mathrm{E}_\gamma}\left(\frac{g_K-g_R}{Q_0}\right);\ \mathrm{K} \neq 1/2$$

with E_γ in MeV. The sign of the multipole mixing ratio δ [17] has been determined to be negative relative to the sign of $\left(\frac{g_K-g_R}{Q_0}\right)$ [23] and is the convention adopted here.

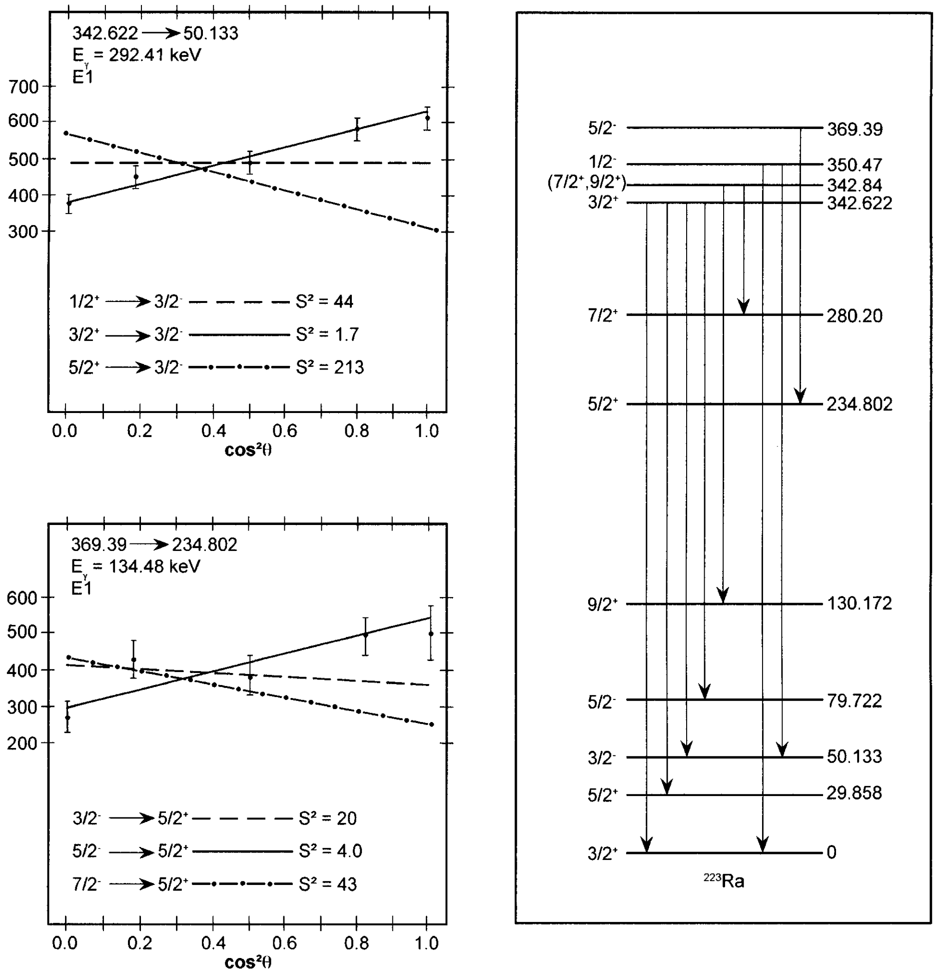

Fig. 7. Fitted (α–γ) angular correlations for the 292.41 keV E1 transition from the 342.622 keV level to the 50.133 keV level and the 134.48 keV E1 transition from the 369.39 keV level to the 234.802 keV level. The partial γ-ray decay scheme for levels between 340 and 370 keV excitation energy shows only those transitions for which angular correlations have been extracted

Finally, the magnetic dipole moment μ can be expressed in terms of g_K, g_R [21, 24] as

$$\mu = g_R I + \frac{K^2}{(I+1)}(g_K - g_R);\ K \neq 1/2$$

$$\mu = \frac{3}{5}\left(g_R + \frac{3g_K}{2}\right) \text{ for } I = K = 3/2 \text{ bandheads}$$

Since experimentally $\mu = +0.2705(19)$ n.m., for the $I = K = 3/2^+$ ground state and $\mu = +0.43(6)$ n.m., for the $I = K = 3/2^-$, 50.133 keV state [2] then a numerical relationship exists between g_R and g_K for each band separately.

Therefore, because the measured spectroscopic quadrupole moment $Q_S = +1.254 \pm 0.003$b. [2] is related to the intrinsic quadrupole moment Q_0 by

$$Q_S = \frac{I(2I-1)}{(I+1)(2I+3)} Q_0;\ I = K$$

then

$$Q_S = \frac{1}{5} Q_0 \text{ for } I = K = 3/2$$

and hence $Q_0 = +6.270 \pm 0.015$b so that g_R and g_K can be determined from each value of $\left(\frac{g_K - g_R}{Q_0}\right)$ assuming that Q_0 remains constant throughout the $K = 3/2^\pm$ bands.

Figure 9 shows values of $\left(\frac{g_K - g_R}{Q_0}\right)$ for the $K = 3/2^\pm$ band members while Table 2 lists the values of $\left(\frac{g_K - g_R}{Q_0}\right)$ and deduced values of g_R and g_K for the listed multipole mixing ratios.

In Table 2, the only transitions for which the sign of the multipole mixing ratio is known are the 29.858 keV $5/2^+ \to 3/2^+$ transition and the 31.58 keV $7/2^+ \to 5/2^+$ transition obtained from the present α–γ correlation study. For the 29.858 keV transition the value of δ adopted in Table 2 was the most accurate measurement of this quantity [25] closest to the value found in the present work, see Sect. 4.1. For the 31.58 keV transition δ was obtained from the weighted average of four measurements namely 0.28(5) [this work], 0.25(4) from the branching ratio using tabulated intensities [2], 0.26(2) from [25] and 0.274(13) obtained from a least squares fit to internal conversion subshell data [26] assuming 6% intensity errors. For the 68.72 keV transition δ was obtained from a least squares fit to internal conversion subshell data [26] assuming 10% intensity errors. For the 29.60 keV transi-

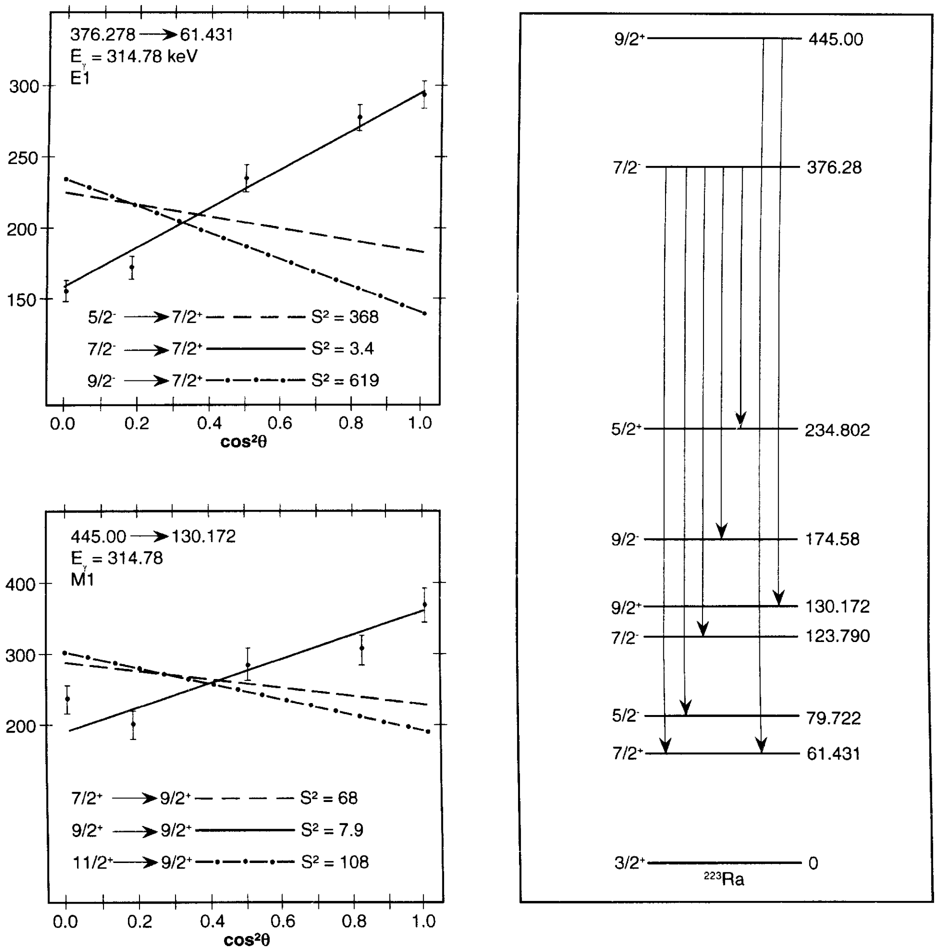

Fig. 8. Fitted (α–γ) angular correlations for the 314.78 keV E1 transition from the 376.278 keV level to the 61.431 keV level and for the 314.78 keV M1 transition from the 445.00 keV level to the 130.172 keV level. The partial γ-ray decay scheme for levels above 370 keV excitation energy shows only those transitions for which angular correlations have been extracted

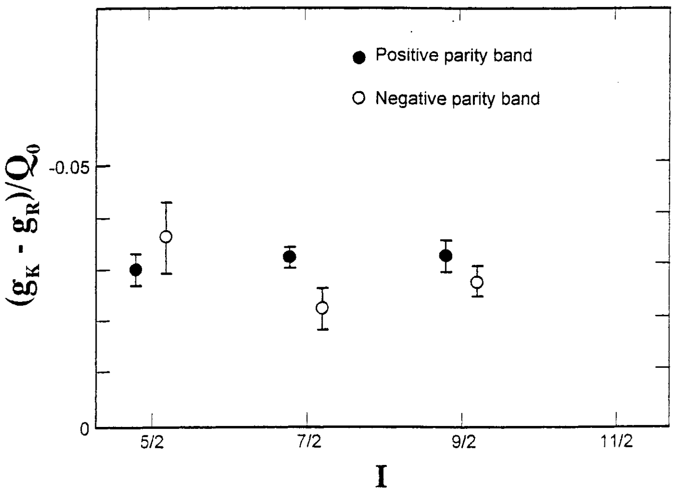

Fig. 9. Plots of the deduced values of $(g_K - g_R)/Q_0$ for the $K = 3/2^{\pm}$ bands in ^{223}Ra. The transitions are identified from the spin I of each decaying level and parity π

Table 2. Calculated values of $-\left(\frac{g_K - g_R}{Q_0}\right)$ in units b^{-1} and g_K for $K = 3/2^{\pm}$ bands in ^{223}Ra, $\bar{g}_R = 0.30 \pm 0.01$ for both bands (see text)

$I(\rightarrow I-1)$	E_γ (keV)	δ	$-\left(\frac{g_K - g_R}{Q_0}\right)$	g_K
$K = 3/2^+$ band $\rightarrow \mu = 0.2705(19)$ n.m.				
5/2	29.86	0.40(2)	0.030(2)	0.11(1)
7/2	31.58	0.27(1)	0.033(1)	0.10(1)
9/2	68.72	0.46(4)	0.032(3)	0.10(2)
$K = 3/2^-$ band $\rightarrow \mu = +0.43(6)$ n.m.				
5/2	29.60	0.33(6)	0.037(7)	0.07(4)
7/2	44.10	0.55(8)	0.022(3)	0.16(2)
9/2	50.84	0.40(4)	0.027(3)	0.13(2)

tion δ was obtained from internal conversion data [26]. For the 44.10 keV transition δ was obtained from a weighted average of two measurements namely 0.65(17) from the branching ratio using tabulated intensities [2] and 0.52(9) from internal conversion subshell data [26] assuming 10% intensity errors.

We assume all the signs of δ in Table 2 are positive to correspond with the two measured signs, since a negative sign gives an unphysical value for g_R.

The following procedure was adopted to evaluate an average value of g_R from all the measurements. Initially

Table 3. Calculations of g_K (in n.m.) for a deformed ^{223}Ra nucleus with (a) Reflection symmetry (reproducing the intrinsic quadrupole moment Q_0). (b) Reflection asymmetry (deformations from [1]). For large β_3 deformations parity π is not a good quantum number

(a) Reflection symmetry

β_2	β_4	$g_K(\pi = +)$	$g_K(\pi = -)$
0.17	0	−0.13	−0.26
0.145	0.133	0.04	−0.41

(b) Reflection asymmetry

$\beta_2 = 0.129$	$\beta_4 = 0.075$	$\beta_5 = 0.01$	$\beta_6 = 0.004$
β_3	$g_K(\pi = +)$		$g_K(\pi = -)$
0	−0.13		−0.33
0.01		−0.11	
0.05		0.13	
0.1		0.31	

g_R and g_K were treated as independent quantities to be determined simultaneously from $\left(\frac{g_K-g_R}{Q_0}\right)$ and μ for the positive and negative parity bandheads. However, since there is no 'a priori' reason to suppose that g_R should differ between positive and negative parity bands we determined the weighted average from these independent values as $\overline{g}_R = 0.30 \pm 0.01$ which is less than Z/A = 0.395 for this odd neutron nucleus as expected [27]. The weighted average obtained for g_R is the magnitude used in Table 2 where the values of g_K were then deduced from the values of $\left(\frac{g_K-g_R}{Q_0}\right)$.

Table 3 gives the calculated values of g_K for different deformation parameters. For the reflection symmetric potentials we have chosen firstly a value of β_2 to reproduce the intrinsic ground state quadrupole moment $Q_0 = 6.27$ barns alone and secondly values of β_2 and β_4 to reproduce Q_0 and the hexadecapole moment for ^{226}Ra [10]. For the reflection asymmetric cases we have chosen values of $\beta_2 = 0.129$, $\beta_4 = 0.075$, $\beta_5 = 0.01$, $\beta_6 = 0.004$ and β_3 has been varied from 0 to 0.1. These values of deformation parameters (with $\beta_3 = 0.1$) are the ones used previously [1] for which we reproduce the calculated g_K and hence magnetic dipole moment. For simplicity we have chosen to allow β_3 to vary without modification of the other deformation parameters as the modest parameter changes required do not affect our overall conclusions. In all these calculations we have used the 'universal' Woods-Saxon parameters $V_0 = -40.6$ MeV, $R_0 = 8.17$ fm., a = 0.70 fm., $V_{so} = 15.8$ MeV, $R_v = 7.94$ fm., a = 0.70 fm. with $g_\ell = 0$ and $g_s = 0.6$ g_s (free).

Two striking results are immediately apparent from the calculations. Firstly, from Table 2 the values of g_K obtained from experimental measurements for the members of the positive and negative parity bands independently are consistent with their being single valued close to the weighted average of $g_K = 0.11 \pm 0.01$. Secondly, it is clear from the theoretical calculations in Table 3 that reflection asymmetry with $\beta_3 \sim 0.05$ is essential to reproduce the positive values of g_K deduced experimentally from the current work, irrespective of whether there are any variations in g_K among the transitions.

There are very few regions of the periodic table where the case for stable octupole deformation in the ground state or at low excitation energies has been established beyond any reasonable doubt. However, in the case of ^{223}Ra this proposition now seems increasingly likely.

Despite the obvious experimental difficulties it is extremely important that a more accurate experimental value for the magnetic dipole moment of the $K = 3/2^-$ bandhead is established. The currently accepted value of μ for the $K = 3/2^-$ bandhead is consistent with that for the ground state $K = 3/2^+$ bandhead but the quoted error of ∼14% is clearly not restrictive enough to constrain the values of g_K for the negative parity band further.

6 Conclusions

J^π assignments to low lying states in ^{223}Ra have been placed on a firm experimental basis.

Extracted values of $\left(\frac{g_K-g_R}{Q_0}\right)$ are reasonably constant for the $K = 3/2^\pm$ bands as expected for stable octupole deformation.

Small positive values of g_K are extracted for both positive and negative parity bands in agreement with calculations of g_K requiring deformed reflection asymmetric potentials with $\beta_3 \approx 0.05$. These conclusions further support evidence that ^{223}Ra is a good example of an octupole deformed nucleus at low excitation energies.

T. H. Hoare and P. M. Jones would like to thank the Engineering and Physical Sciences Research Council (U.K.) for financial support in the form of Ph.D. studentships while this work was carried out.

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