Octupole Collectivity in Nuclei Deduced from Coulomb Excitation Measurements

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Abstract

$E1$,$E2$ and $E3$ matrix elements have been measured using Coulomb excitation for ^{148,150}Nd and ^{226}Ra. The behaviour of the quadrupole and octupole matrix elements is roughly consistent with that expected for a rotating axially symmetric shape, although deviations are seen for the Nd isotopes. The results are compared with theoretical expectations.

Introduction

The observation of interleaved positive and negative parity states connected by dominant $E1$ transition matrix elements in nuclei with $Z \approx 60, N \approx 88$ (e.g. Sujkowski *et al.*, 1977) and $Z \approx 88, N \approx 134$ (e.g. Fernández-Niello *et al.*, 1982) is regarded as compelling evidence that these nuclei have some degree of reflection asymmetry in the intrinsic frame. These data have been interpreted using geometric models within the mean field approach as arising from the presence of static octupole deformation, i.e. $\beta_3 \neq 0$ (e.g. Åberg *et al.*, 1990). The theoretical descriptions suggest, however, that even in the most favourable cases the nuclear potential energy is rather soft to octupole deformation, so that rigid nuclear pear-shapes do not exist, at least in the ground state. It remains an experimental challenge to determine a suitable fingerprint which provides some clues as to the nature of this particular degree of freedom. As with quadrupole degrees of freedom, it is expected that the most reliable measurements of collective octupole strength are the $E\lambda$ matrix elements connecting the rotational states in the octupole and ground state bands. For low-lying states in nuclei the isovector $E1$ photon transition transitions are very weak compared with the Giant Dipole Resonance strength (Zilges *et al.*, 1992) and these transitions are usually dominated by single particle effects (Butler and Nazarewicz, 1991). On the other hand the predominantly isoscalar ground state $E3$ transitions typically exhaust $4-7\%$ of the energy weighted sum rule (Kirson, 1982; Pignanelli *et al.*, 1990) and can have strengths larger than 50 single particle units (Spear and Catford, 1990). This quantity is therefore largely independent of single particle effects and may therefore be a useful gauge of octupole collectivity.

While observation of real photon $E3$ emission from well deformed nuclei is not yet technically possible, the determination of $E3$ matrix elements from Coulomb excitation is feasible (Butler, 1988). The probability for excitation of states coupled by the $E3$ operator is typically 10 times larger than that for $E1$, whereas for de-excitation the $E1$ transition rate is many orders of magnitude faster than for $E3$. This greatly simplifies the analysis of Coulomb excitation data, in which the electric matrix elements connecting nuclear states are determined model independently by performing many independent measurements of observables which are sensitive to these matrix elements (Cline, 1986). Results of such measurements of $E1$, $E2$ and $E3$ matrix elements in ^{148,150}Nd and ^{226}Ra are presented here.

Coulomb Excitation Measurements

The decay scheme for states in ^{148}Nd populated by Coulex with ^{92}Mo ions is shown in figure 1. For ^{148}Nd the following experiments were carried out: i) Particle-γ

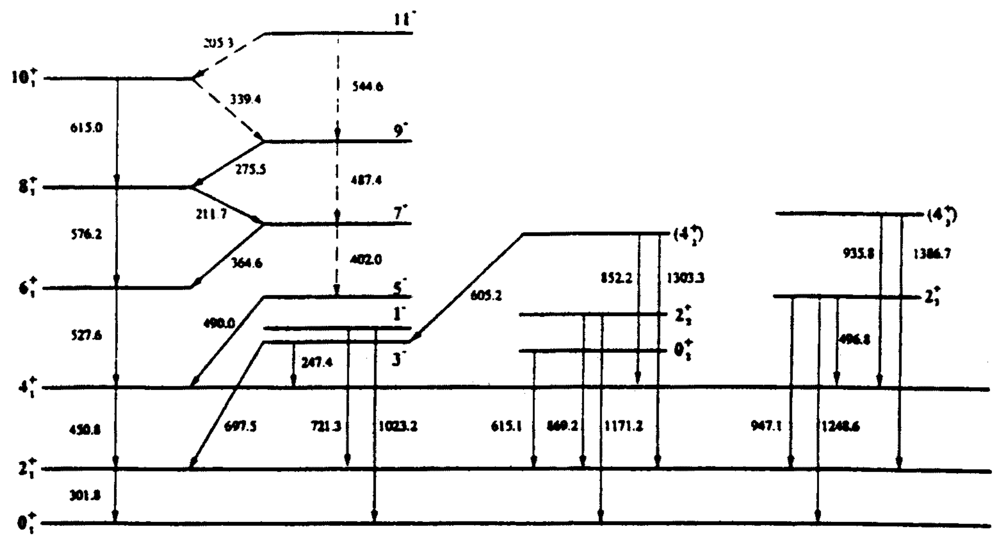

Figure 1: Level scheme of ^{148}Nd as populated by Coulex with 330 MeV ^{92}Mo ions.

and particle-γ-γ coincidences were measured following bombardment with 330 MeV ^{92}Mo ions, provided by the NSF at the Daresbury Laboratory. The γ-rays were detected in POLYTESSA consisting of 20 Compton suppressed Ge spectrometers (CSS) and the scattered ions were detected in position sensitive avalanche detectors (PSAD). ii) Gamma-ray intensities were measured in coincidence with the detection of ^{58}Ni ions, provided by the NSRL, University of Rochester, using 5 CSS's and a PSAD system. The primary beam energy was 200 MeV. iii) An isotopically pure beam of ^{148}Nd, provided by HHIRF, Oak Ridge, was excited by a 0.2 mg/cm^2 ^{208}Pb target. Both Nd and Pb ions were detected in kinematic coincidence using a PSAD.

The γ-rays were detected in 16 CSS's in the Spin-Spectrometer, which additionally measured the total energy and the multiplicity of the γ-ray decay. The analysis of these data have allowed the decay scheme to be tentatively extended beyond that shown in figure 1: the ground band to 14^+, the octupole band to 13^-, the β-band to 8^+, and the γ-band to 6^+. iv) Lifetimes of excited states in ^{148}Nd were measured using the recoil distance method, following inelastic scattering of ^{58}Ni ions at a bombarding energy of 210 MeV. In this experiment, the backscattered ions were detected in a PSAD, and the γ-rays were detected in a CSS placed at 0°. These measurements are described in more detail elsewhere (Ibbotson *et al.*, 1991, 1992).

Similar measurements of particle-γ yields following bombardment with ^{58}Ni and ^{92}Mo ions were carried out for ^{150}Nd. The decay scheme for this nucleus, deduced from previous (der Mateosian, 1986) and present measurements is shown in figure 2. Lifetimes of excited states in ^{150}Nd were also measured, using the DSAM. In this

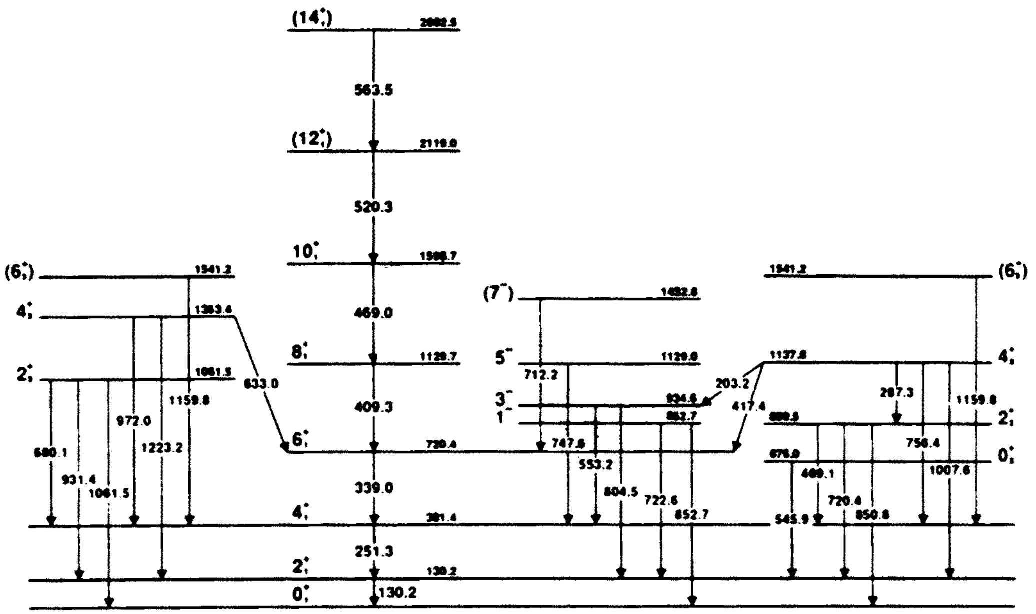

Figure 2: Level scheme of ^{150}Nd as populated by Coulex with 330 MeV ^{92}Mo ions.

experiment a layer of 0.65 mg/cm^2 ^{150}Nd, deposited onto 20 mg/cm^2 Ni foil, was bombarded with 330 MeV ^{92}Mo ions. Lineshapes were obtained using 5 CSS placed at 37°. Further details of these measurements are given elsewhere (Butler *et al.*, 1992; Clarkson, 1992).

For ^{226}Ra elastic and inelastic scattering of 15-17 MeV ^{4}He ions into the focal plane of a Q3D spectrometer was performed in order to determine the excitation probabilities of the low-lying states. In addition, particle-γ coincidences following bombardment with 63 MeV ^{16}O and 135 MeV ^{32}S ions, were collected using a PSAD and 4 Ge(Li) detectors. The ^{4}He, ^{16}O, and ^{32}S ions were provided by the Munich tandem accelerator. Particle-γ coincidences were also taken following bombardment with 4.7 MeV/u ions from the GSI UNILAC. In this experiment the arrangement consisted of five PSAD's and seven Ge detectors (three Compton suppressed); information on γ-ray multiplicity was also obtained using an array of six NaI detectors. The deduced level scheme for ^{226}Ra is shown in figure 3. Further details of these measurements are given elsewhere (Wollersheim *et al.*, 1992).

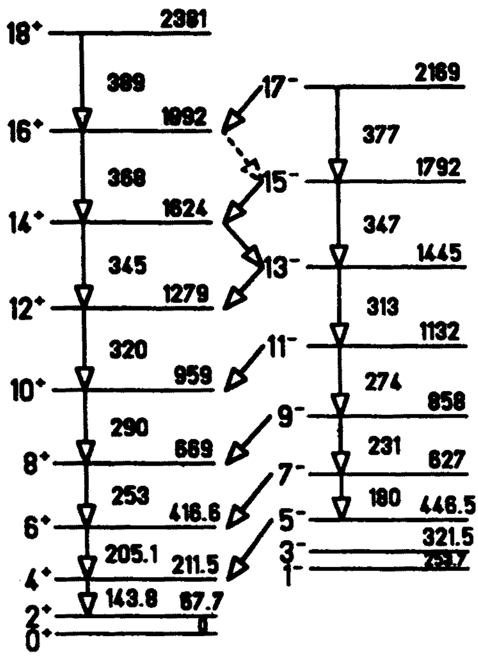

Figure 3: Level scheme of ^{226}Ra and the transitions observed in the present experiment.

Determination of Matrix Elements

The γ-ray transition intensities, and where available mean lifetimes, were fitted using the semi-classical Coulomb excitation, de-excitation least-squares search code, GOSIA (Czosnyka *et al.*, 1987), to extract the $E1$, $E2$ and $E3$ matrix elements. In the fitting procedure $E4$ excitation is also included, although the fitted values for matrix elements of multipole operators with $\lambda \leq 3$ are rather insensitive to the variation in the values of matrix elements with $\lambda \geq 4$. The influence of the virtual excitation of the Giant Dipole Resonance, as well as excitation of highly excited members of the low-lying collective bands, was also investigated and found to have negligible effect. For ^{226}Ra the matrix elements connecting the $0^+, 2^+, 3^-$ and 4^+ states are determined from the inelastic α-scattering cross-sections. For ^{148,150}Nd, there is good agreement between the values obtained from the particle-γ data and those reported elsewhere for the matrix elements connecting the ground state with the 1^- state (Pitz *et al.*, 1990) and the 2^+ and 3^- states (Ahmad *et al.*, 1988). The fitted values for the $E1$, $E2$ and $E3$ matrix elements are shown in figure 4 for ^{148}Nd. The errors shown take

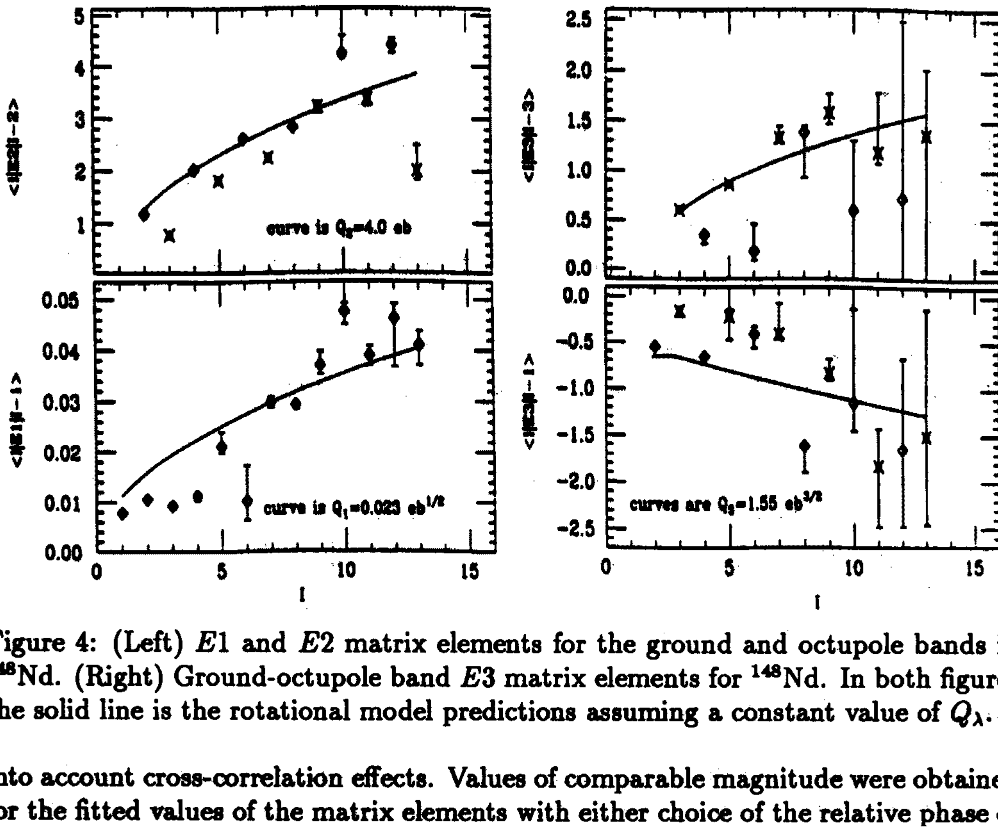

Figure 4: (Left) $E1$ and $E2$ matrix elements for the ground and octupole bands in ^{148}Nd. (Right) Ground-octupole band $E3$ matrix elements for ^{148}Nd. In both figures the solid line is the rotational model predictions assuming a constant value of Q_λ.

into account cross-correlation effects. Values of comparable magnitude were obtained for the fitted values of the matrix elements with either choice of the relative phase of $E1$ and $E3$ matrix elements.

The values of the $E\lambda$ matrix elements are given, in the rotational model, by the relationship:

$$< I\|E\lambda\|I' >= (2I+1)^{\frac{1}{2}}(I0\lambda0|I'0)Q_\lambda a_\lambda$$

where Q_λ is the intrinsic $E\lambda$ moment and $a_1 = \sqrt{3/4\pi}$, $a_{\lambda\geq2} = \sqrt{(2\lambda+1)/16\pi}$. It can be seen from figure 4 that the values of $< I \parallel E2 \parallel I' >$ for ^{148}Nd follow the expected behaviour for a constant value of Q_2, although loss in collectivity is seen for the lower spin members of the negative parity band. Deviations from a constant moment are observed for Q_3 for both ^{148}Nd (fig. 4) and ^{150}Nd (Butler *et al.*, 1992).

This may be explained in several ways: mixing of the low-lying negative parity states with higher K^- bands; mixing with 2 quasi-particle states (see discussion in Mach *et al.*, 1992); coupling to other bands (the E3 matrix elements coupling the negative parity states to the β-band are unexpectedly large in ^{148}Nd). For ^{148}Nd the branching ratios for the $E1$ decays of the 1^- and 3^- states to the $(I+1)^+$ and $(I-1)^+$ states in the ground state band are consistent with Alaga rule predictions assuming a pure $K^\pi = 0^-$ configuration, as observed for the lowest 1^- state in heavier rare-earth nuclei (Zilges *et al.*, 1990).

For ^{226}Ra the values of Q_λ are plotted for each matrix element as a function of spin in figure 5. Both Q_2 and Q_3 exhibit remarkable constancy with spin which suggests that the negative parity states have a pure collective configuration corresponding to $K^\pi = 0^-$. The upper part of figure 5 shows the values of the spectroscopic quadrupole moment Q_s, derived from the diagonal $E2$ matrix elements, plotted as a ratio of the value of Q_2 derived from the $2^+ \rightarrow 0^+$ matrix element. The values of this ratio are compared with the predictions of the rigid asymmetric rotor model (Davydov and Filippov, 1958). The data are consistent with axial symmetry, i.e. $\gamma = 0°$. This gives some justification to the application of the simple rotational model given above.

Figure 6 shows the derived values for the transition electric dipole moment, Q_1, for ^{226}Ra. Above spin $5\hbar$ the values increase steadily with increasing angular momentum, although the quadrupole shape and octupole collectivity remain constant over this spin range (see fig. 5). This is at variance with the expected behaviour for Q_1 calculated (Butler and Nazarewicz, 1991) using a macroscopic-microscopic model, at least at modest ($I \leq 12$) spin values.

Comparison with Theoretical Calculations

Table 1 gives the values of Q_λ derived from the matrix elements for each of the nuclei studied here assuming the validity of the axially symmetric rotational model. The values of the deformation parameters β_λ are related to Q_λ by the following

Table 1: Values of Q_λ and β_λ for ^{148,150}Nd and ^{226}Ra

Nucleus	moment (efm$^\lambda$)	deformation parameter
^{148}Nd	$Q_2 = 400$	$\beta_2 = 0.18$
	$Q_3 = 1550$	$\beta_3 = 0.12$
^{150}Nd	$Q_2 = 540$	$\beta_2 = 0.25$
	$Q_3 = 1050$	$\beta_3 = 0.08$
^{226}Ra	$Q_2 = 750$	$\beta_2 = 0.17$
	$Q_3 = 3100$	$\beta_3 = 0.11$

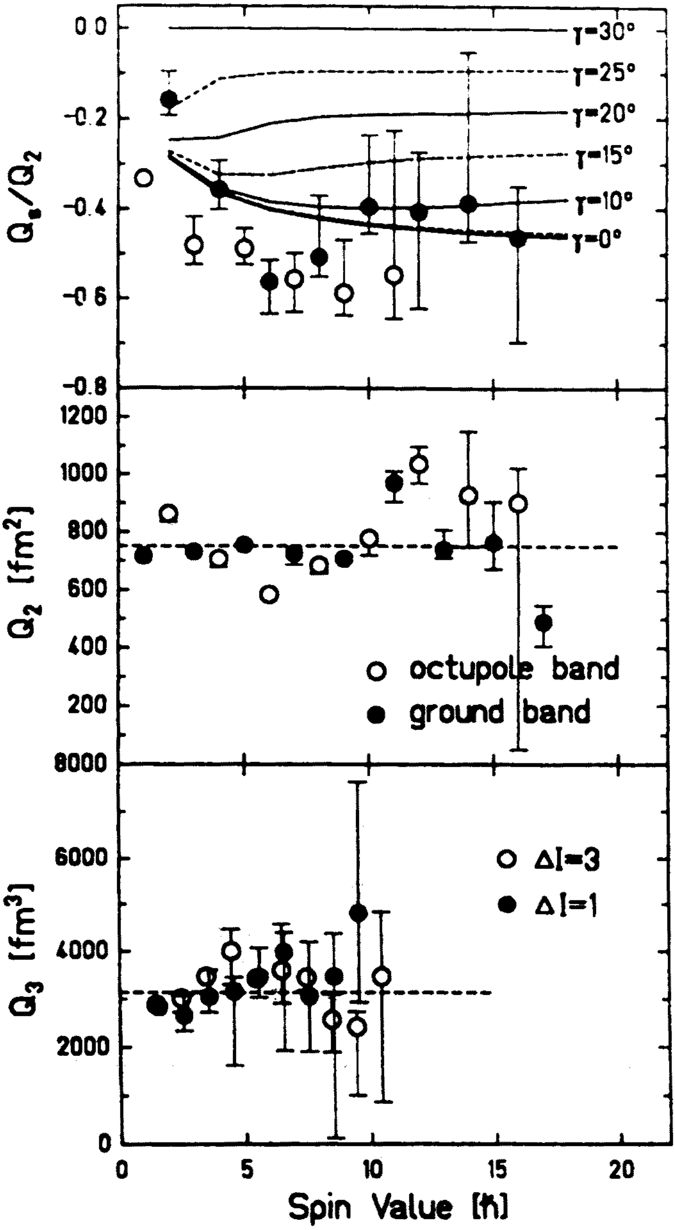

Figure 5: Ratio of the quadrupole moments Q_s/Q_2 (top), electric transition quadrupole moments Q_2 (centre) and octupole moments Q_3 (bottom) for the yrast band in ^{226}Ra.

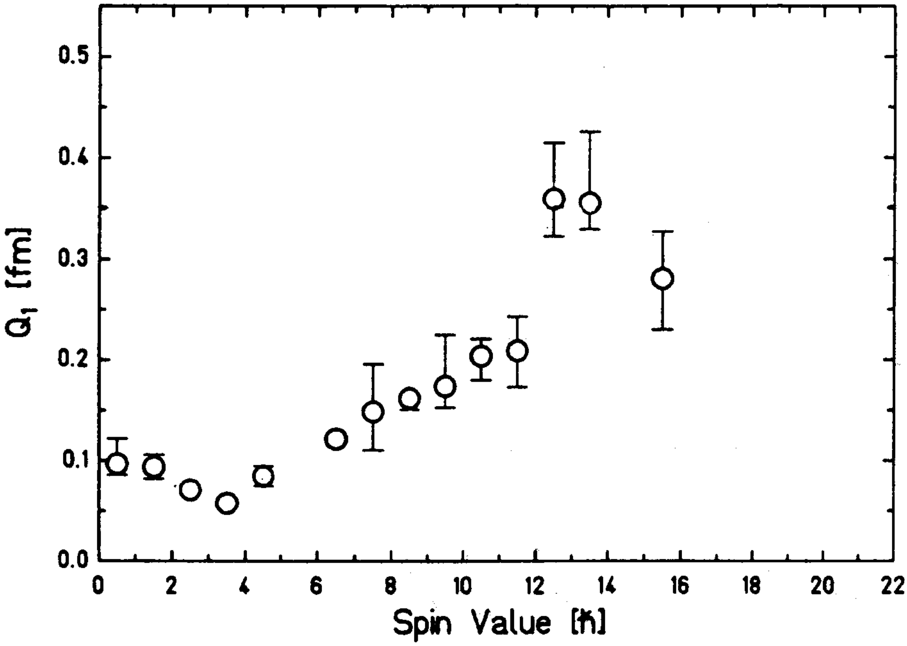

Figure 6: Electric transition dipole moments Q_1 for the yrast band in ^{226}Ra.

expression ($\lambda \geq 2$):

$$Q_\lambda = b_\lambda Z e R_0^\lambda(\beta_\lambda + \text{higher order terms})$$

where $b_\lambda = 3/\sqrt{(2\lambda+1)\pi}$. The higher order terms are given for $\lambda \leq 6$ in Leander and Chen (1988). The values of β_λ given in table 1 are derived using values of Q_4 derived from the measured ground state $E4$ matrix element in each case and using the liquid drop equilibrium values (Nazarewicz *et al.*, 1984) for β_5 and β_6 . The mass dependence of R_0 was taken to be $R_0 = 1.2A^{\frac{1}{3}}$. Mean field calculations which allow octupole deformation have been made (Urban *et al.*, 1988) for ^{148}Nd which give mean values of the deformation parameters of $\beta_2 = 0.20$, $\beta_3 = 0.075$ at spin $7 - 8\hbar$. For the ground state of ^{148}Nd the predicted octupole deformation is zero (see also Sobiczewski *et al.*, 1988). The nucleus ^{150}Nd is not expected to have permanent octupole deformation at any spin value (Nazarewicz and Tabor, 1992). The values of β_2, β_3 deduced in the above manner for ^{226}Ra are consistent with a number of calculated values, e.g. Chasman (1986), Nazarewicz *et al.* (1987), and Sobiczewski *et al.* (1988). The measured values of the ground state transition moment $< 0^+ \parallel E3 \parallel 3^- >$ for ^{148,150}Nd and ^{226}Ra are also in good agreement with the values calculated using the microscopic Hartree-Foch method (Egido and Robledo, 1991, 1992).

It should be emphasised that the effective value of β_3 extracted using the above expressions depends not only on the mean value of octupole deformation but also on the curvature of the nuclear potential with respect to octupole deformation. Nazarewicz and Tabor (1992) have recently investigated the effect of changes in the form of the octupole potential on the energy splitting ΔE of the lowest positive and negative parity states and on the value of the $B(E3)$ between these states. Using a simple model for octupole deformation developed by Krappe and Wille (1969) they find that the $B(E3)$ value is very insensitive to the value of V_0, the barrier height at $\beta_3 = 0$, in constrast to the behaviour of ΔE. They also point out that Rohoziński and Greiner (1983) have investigated another important mechanism that can influence the parity splitting and $B(E3)$ values, i.e. the coupling to higher-lying octupole states with $K > 0$ through Coriolis and centrifugal interaction. The calculations of Rohoziński and Greiner (1983) show that the behaviour of the $B(E3)$ is quite insensitive to the degree of Coriolis coupling, in contrast to the behaviour of the parity splitting, at the small values of mean octupole deformation considered here.

In conclusion, the behaviour of the $E2$ and $E3$ matrix elements for the three nuclei studied in this work is roughly consistent with that expected for a rotating axially symmetric shape. Deviations from this model are seen particularly for the $E3$ matrix elements in ^{148,150}Nd. Two different mechanisms can be invoked to explain why the $E3$ moment should remain constant while the parity splitting changes with spin. The observed increase in value of Q_1 for $I > 5\hbar$ in ^{226}Ra is unexpected.

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