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Coulomb Excitation of ^{142}Ce and ^{144}Nd

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Abstract

The $N = 84$ nuclei ^{142}Ce and ^{144}Nd have been Coulomb-excited using ^{4}He, ^{12}C and ^{16}O projectiles. Scattered particles were detected at a mean laboratory angle of 170·6° with an annular silicon surface-barrier detector. The static quadrupole moment of the 2_1^+ state was determined for both nuclei. In addition, various electromagnetic transition probabilities involving the 2_2^+, 2_3^+, 3_1^- and 4_1^+ states were measured. Taken in conjunction with previous information, the results show that the properties of ^{142}Ce and ^{144}Nd are well described by the vibrational U(5) limit of IBM-2, and strongly support the proposition that the 2_3^+ level in each nucleus is an essentially pure one d-boson mixed-symmetry state.

1. Introduction

This paper presents the results of Coulomb-excitation studies of the $N = 84$ nuclei ^{142}Ce and ^{144}Nd. The main objective of the work was the determination of electromagnetic matrix elements relevant to the identification of the collective 2^+ states of mixed proton–neutron symmetry expected on theoretical grounds to occur at an excitation energy E_x of about 2 MeV in both nuclei.

The initial predictions of mixed symmetry states were made primarily, but not exclusively, within the framework of the interacting boson model (IBM) (see e.g. Iachello 1984 and references therein). Unlike the original version of the model (IBM-1), the version known as IBM-2 distinguishes between neutron (ν) and proton (π) bosons, and predicts the existence of states of mixed proton–neutron symmetry, i.e. states which are not fully symmetric with respect to the interchange of proton and neutron bosons. Because IBM-1 has had widespread success in describing the low-lying states of nuclei, the mixed-symmetry states will usually be expected to occur at higher excitation energies than the totally symmetric states.

As indicated above, the IBM is not the only model which predicts the occurrence of mixed-symmetry states. For example, treatments of symmetry mixing have been published based on the vibrational model (Faessler and Nojarov 1986), the shell model and the particle–core coupling model (Heyde and Sau 1986). Indeed, the latter authors have argued that mixed-symmetry modes are a general feature of any two-component nuclear system.

Most of the initial interest in mixed-symmetry states centred on the $J^{\pi} = 1^+$ mode expected (Iachello 1981, 1984) to occur in well deformed axially-symmetric

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nuclei at $E_X \approx 3$ MeV with large M1 strength to the ground state. Experimental evidence for the existence of these 1^+ states has been obtained in strongly deformed nuclei ranging from ^{46}Ti to ^{238}U, mainly from electron and photon scattering (Bohle *et al.* 1984*a*, 1984*b*; Berg *et al.* 1984; Heil *et al.* 1988; Hartmann *et al.* 1987). The excitation has been pictorially described as a type of 'scissors' mode, involving small-amplitude oscillations of the angle between the symmetry axes of the deformed proton and neutron distributions; however, this interpretation has recently been disputed (Speth and Zawischa 1988; Freeman *et al.* 1989).

Iachello (1984) pointed out that for spherical nuclei a collective $J^\pi = 2^+$ mixed-symmetry state would be expected at $E_X \approx 2$–3 MeV, with $B(\mathrm{E2}; 0_1^+ \rightarrow 2^+) \approx 3$ W.u. He showed that in the U(5) limit (purely vibrational motion)

$$B(\mathrm{E2}; 0_1^+ \rightarrow 2^+) = \{5N_\pi N_\nu/(N_\pi + N_\nu)\}(e_\pi - e_\nu)^2\,, \tag{1}$$

where e_π and e_ν are the proton- and neutron-boson effective charges. Thus, experimental investigation of the mixed-symmetry 2^+ state would be of great importance since it could provide a direct measure of the difference between e_π and e_ν. In a geometrical picture this mode can be described (Faessler and Nojarov 1986) as a low-lying isovector quadrupole vibration with the protons and neutrons oscillating out of phase. An enhanced M1 strength to the lowest fully symmetric 2^+ state would also be expected (Van Isacker *et al.* 1986). There is very little experimental information regarding mixed-symmetry states in spherical nuclei.

Hamilton *et al.* (1984) have suggested that the 2_3^+ levels in the $N = 84$ isotones ^{140}Ba, ^{142}Ce and ^{144}Nd are good candidates for vibrational mixed-symmetry states. They carried out calculations in the U(5) limit of IBM-2 and obtained good agreement with experimental branching ratios and E2/M1 mixing ratios for the 2_3^+ levels; they concluded that for the nuclei concerned $e_\pi = 0\cdot12$ *e*b and $e_\nu = 0\cdot24$ *e*b, i.e. that $e_\nu > e_\pi$, which is rather surprising since neutrons carry no charge. However, as stressed by, for example, Faessler and Nojarov (1986), it is the absolute transition strengths which are of crucial importance in testing the theory. This is true not only for the 2_3^+ level but also for other levels in order to fix the parameters of the theory. For ^{140}Ba and ^{142}Ce there is no previous information on absolute electromagnetic transition strengths apart from $B(\mathrm{E2}; 0_1^+ \rightarrow 2_1^+)$.

In the present work we have used Coulomb excitation to study levels in ^{142}Ce and ^{144}Nd. Energy-level diagrams are shown in Fig. 1. Among the information obtained we have been able to determine $B(\mathrm{E2}; 0_1^+ \rightarrow 2_3^+)$ for ^{142}Ce. This value can be combined with previous measurements of branching ratios and mixing ratios (Peker 1984) to determine the M1 and E2 strengths for the proposed mixed-symmetry to full-symmetry transition $2_3^+ \rightarrow 2_1^+$. In the case of ^{144}Nd these transition strengths were already known from the nuclear-resonance-fluorescence work of Metzger (1969) and the branching- and mixing-ratio measurements of Snelling and Hamilton (1983). We are therefore able to compare the theoretical predictions with results obtained from two completely different experimental techniques. We have also carried out improved determinations of the static quadrupole moment, $Q(2_1^+)$, of the 2_1^+

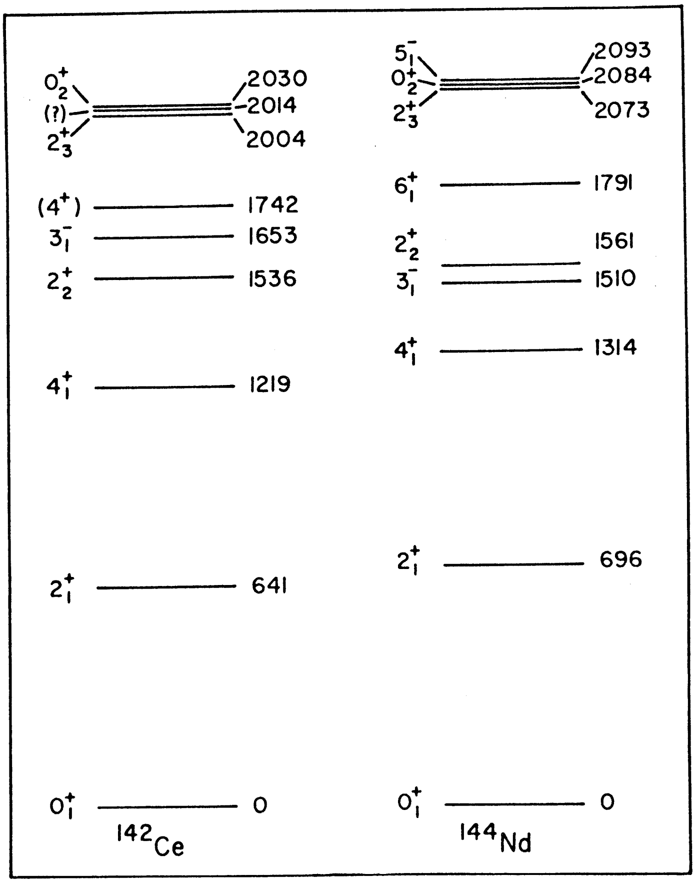

Fig. 1. Level schemes of ^{142}Ce and ^{144}Nd taken from Peker (1984) for ^{142}Ce, and from Tuli (1979), Snelling and Hamilton (1983) and Krane *et al.* (1983) for ^{144}Nd. Excitation energies are given in keV.

states of ^{142}Ce and ^{144}Nd (Hamilton *et al.* used this quantity as an important test of their model predictions), and have determined various other transition strengths in the two nuclei. Taken in conjunction with previous experimental work (e.g. Metzger 1969; Snelling and Hamilton 1983; Fahlander *et al.* 1980), the results permit a comprehensive comparison of the properties of ^{142}Ce and ^{144}Nd. Hence they provide a crucial test of the IBM-2 U(5) calculations of Hamilton *et al.*, which predict not only the absolute strengths of transitions involving symmetric and mixed-symmetry states, but also that these strengths should be equal in these two nuclei. Finally, we have determined $B(\mathrm{E3};\, 0_1^+ \to 3_1^-)$ for both ^{142}Ce and ^{144}Nd. A brief report covering part of the present work has appeared elsewhere (Vermeer *et al.* 1988).

2. Experimental Procedure

Principles of the experimental procedure have been given in previous publications (see e.g. Esat *et al.* 1976; Fewell *et al.* 1979). In the present case, beams of ^{4}He, ^{12}C and ^{16}O projectiles, obtained from the 14UD accelerator at

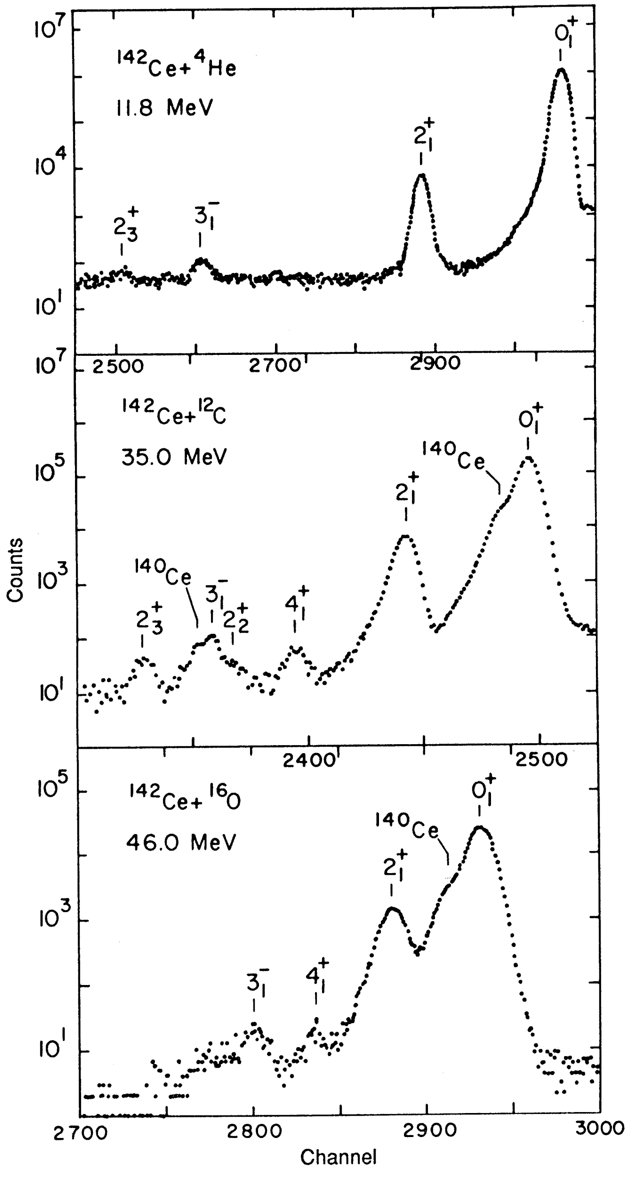

Fig. 2. Spectra obtained from bombardment of a ^{142}Ce target with ^{4}He, ^{12}C and ^{16}O projectiles at a mean laboratory scattering angle of 170·6°. States of ^{142}Ce are indicated by their spin and parity.

the ANU, were used to bombard targets of ^{142}Ce and ^{144}Nd. The beam energy was known to an accuracy of better than 0·1% (Spear *et al.* 1977). Targets were prepared by evaporating CeF_3 and NdF_3 onto thin carbon foils. The isotopic enrichments were 93·4% and 97·5% for ^{142}Ce and ^{144}Nd respectively. Target thicknesses were measured by Rutherford scattering. It was found that the targets used for ^{4}He bombardment had partial thicknesses of 58 and 38 μg cm^{-2} for ^{142}Ce and ^{144}Nd respectively, and those used for ^{12}C and ^{16}O

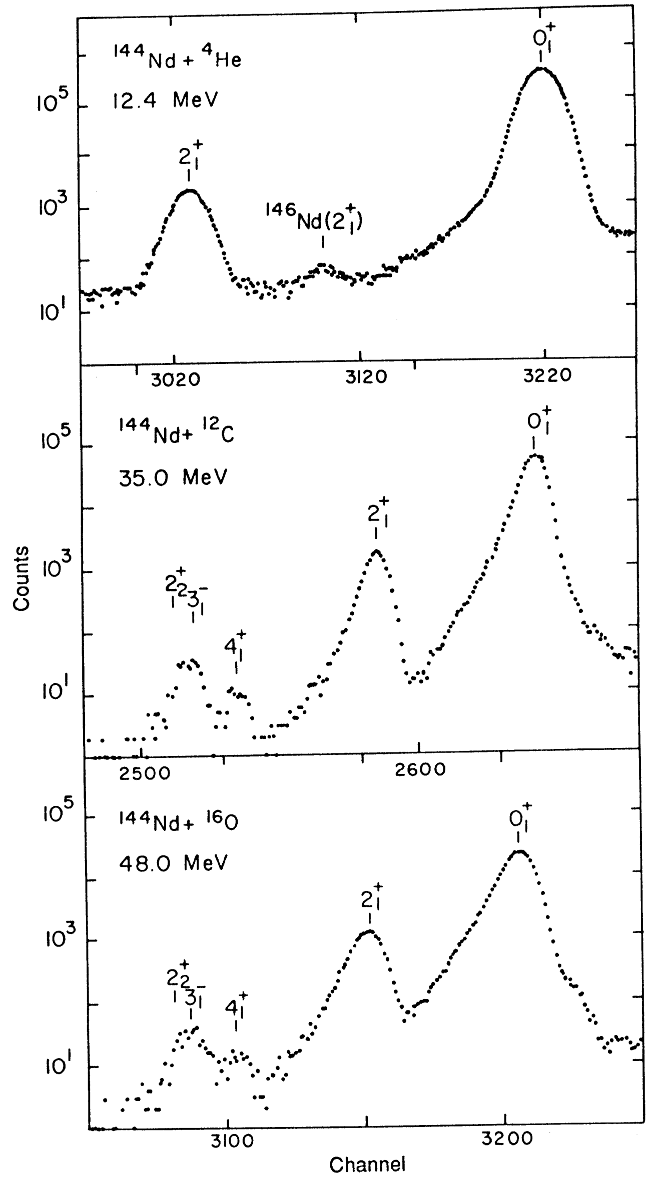

Fig. 3. As for Fig. 2, but for a ^{144}Nd target. In extracting the area of the 3_1^- peak the small contribution (a few per cent) of the partially resolved 2_2^+ peak was calculated using known B(E2) values (see text).

bombardment were 4·8 and 3·0 μg cm^{-2} respectively. Backscattered particles were detected at a mean laboratory scattering angle of 170·6° using an annular silicon surface-barrier detector. Typical spectra are shown in Figs 2 and 3. Rutherford backscattering measurements with low-energy carbon beams showed no evidence of significant target contaminants, except for a small amount of Mo in the ^{142}Ce targets. Scattering from Mo isotopes produces

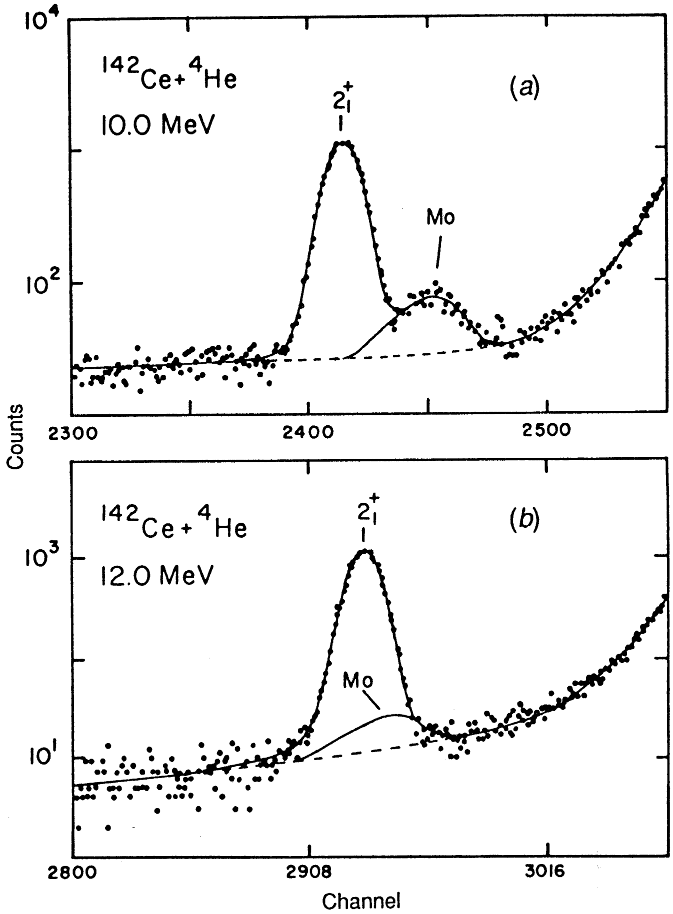

Fig. 4. Spectra obtained with ^{4}He projectiles on ^{142}Ce, showing cases where the Mo contaminant peak is (*a*) resolved from the ^{142}Ce 2_1^+ peak, and (*b*) not resolved. In case (*b*) the contribution attributed to Mo is calculated as described in the text. In both cases the full curves show fits to the data, and the dashed curve shows the underlying tail from the 0_1^+ peak.

peaks in sensitive regions of the spectra only for ^{4}He; for ^{12}C and ^{16}O the Mo peaks occur at energies which are too small to be troublesome. For some ^{4}He spectra the peak corresponding to the Mo contaminant was clearly resolved (Fig. 4), providing further information on the quantity of Mo present. In order to permit accurate subtraction of Mo contributions when determining excitation probabilities (Section 3), the variation of yield for Mo as a function of bombarding energy was determined by bombarding a target consisting of natural Mo deposited on a thin Au backing with ^{4}He projectiles at the energies actually used in the experiment.

3. Analysis and Results

Spectra were analysed using well established lineshape fitting procedures (Esat *et al.* 1976; Fewell *et al.* 1979) to extract excitation probabilities $P_{\rm exp}(J_n^\pi)$

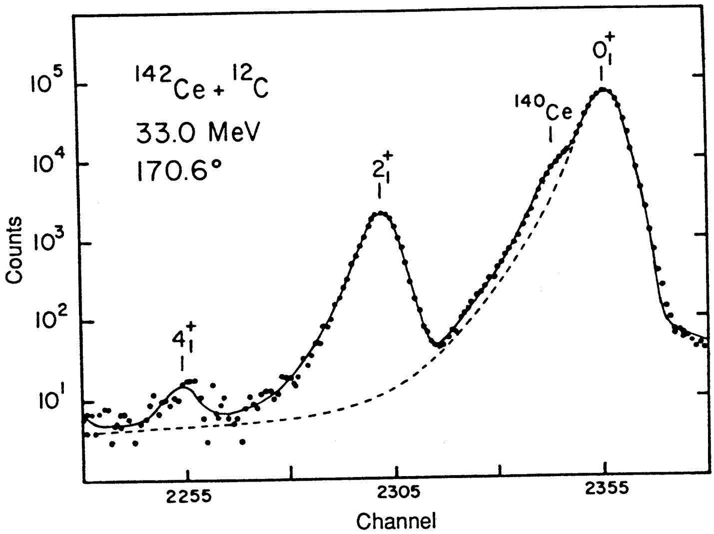

Fig. 5. Portion of spectrum obtained with 33-MeV ^{12}C projectiles on ^{142}Ce. The full curve shows a fit to the data obtained as described in the text. Peaks corresponding to states in ^{142}Ce are indicated by their appropriate J_n^π values. The dashed curve represents the tail of the 0_1^+ peak. Also shown are contributions from ^{140}Ce.

for various states, where the experimental excitation probability is defined as

$$P_{\exp}(J_n^\pi) = A(J_n^\pi)/\{A(0_1^+) + A(J_n^\pi)\}, \qquad (2)$$

the quantities A being the areas of the appropriate spectral peaks. Allowance was made for small contributions to the spectra from minor isotopes of the target element ('isotopic impurities') using the supplier's isotopic assay in conjuction with B(E2) values for excited states of these isotopes obtained from the literature. An example of the fits obtained is shown in Fig. 5. Values of $P_{\exp}(2_1^+)$ were determined for all spectra. Excitation probabilities for the 4_1^+, 2_2^+, 3_1^- and 2_3^+ states of ^{142}Ce and for the 4_1^+ and 3_1^- states of ^{144}Nd were determined from some spectra where the corresponding peaks were sufficiently prominent to provide useful results. The values obtained are listed in Tables 1 and 2.

It is essential for the valid application of Coulomb-excitation theory that the data analysed should be obtained at bombarding energies sufficiently low that nuclear interference is negligible (Spear *et al.* 1978). 'Unsafe' energies may be detected by plotting the ratio $P_{\exp}/P_{\text{Coul}}$ as a function of bombarding energy E, where P_{Coul} is the excitation probability calculated assuming pure Coulomb excitation. The onset of nuclear interference usually manifests itself in a decrease of $P_{\exp}/P_{\text{Coul}}$ below a hitherto constant value as E is increased. Safe-energy plots for the 2_1^+ data are shown in Fig. 6; $P_{\exp}/P_{\text{Coul}}$ is plotted as a function of E and of s, the distance of closest approach of the nuclear surfaces, defined by the expression

$$s(\theta_{\text{c.m.}}) = \frac{0\cdot 72 Z_1 Z_2}{E}\left(1 + \frac{A_1}{A_2}\right)(1 + \operatorname{cosec}\tfrac{1}{2}\theta_{\text{c.m.}}) - 1\cdot 25(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}})\ \text{fm}, \qquad (3)$$

Table 1. Measured excitation probabilities $P_{exp}(2_1^+)$ for ^{142}Ce and ^{144}Nd

Bombarding energies E have not been corrected for energy loss in the target

Projectile	^{142}Ce		^{144}Nd	
	E (MeV)	$P_{exp}(2_1^+)\times 10^2$	E (MeV)	$P_{exp}(2_1^+)\times 10^2$
^4He	10·0	0·2494(27)	10·5	0·2406(29)
	11·0	0·4042(28)	11·5	0·3924(47)
	11·2	0·4458(40)	11·8	0·4497(54)
	11·4	0·4836(43)	12·1	0·5086(61)
	11·6	0·5312(47)	12·4	0·5659(68)
	11·8	0·5645(53)	12·7	0·6326(76)
	12·0	0·6127(53)	13·0^A	0·6942(83)
^{12}C	32·0	2·479(21)	32·0	1·892(20)
	33·0	2·893(24)	33·0	2·233(25)
	34·0	3·303(26)	34·0	2·586(30)
	35·0	3·777(33)	35·0	3·039(33)
	36·0^A	4·240(32)	36·0	3·430(35)
	37·0^A	4·739(36)		
^{16}O	45·0	4·863(40)	44·0	3·380(44)
	46·0	5·426(42)	45·0	3·844(71)
	47·0	5·998(48)	46·0	4·294(55)
	48·0	6·486(57)	47·0	4·741(62)
	49·0	7·151(59)	48·0	5·264(68)
	50·0^A	7·693(61)	49·0	5·742(75)

^{A} These energies were deemed to be unsafe and data were not used in Coulomb-excitation analysis.

Table 2. Measured excitation probabilities $P_{exp}(J_n^\pi)$ for ^{142}Ce and ^{144}Nd for states other than 2_1^+

Bombarding energies E have not been corrected for energy loss in the target

Target	Projectile	E (MeV)	$P_{exp}(J_n^\pi)\times 10^4$ 2_2^+	2_3^+	3_1^-	4_1^+
^{142}Ce	^4He	11·8	0·055(28)	0·25(3)	0·585(37)	0·067(28)
^{142}Ce	^{12}C	35·0	1·04(24)	1·84(16)	4·569(28)	2·57(21)
^{144}Nd	^{12}C	32·0			3·0(2)	0·56(8)
		33·0			3·7(2)	0·94(12)
		34·0			5·2(3)	1·02(12)
		35·0			6·1(3)	1·66(18)
		36·0			9·1(4)	1·76(17)
^{144}Nd	^{16}O	46·0			7·2(5)	
		47·0			10·1(5)	3·1(4)
		48·0			12·7(7)	4·7(4)
		49·0			14·2(8)	4·9(4)

where Z_1, A_1 and Z_2, A_2 are the atomic numbers and masses of projectile and target respectively, $\theta_{c.m.}$ is the scattering angle in the centre-of-mass system, E is the laboratory bombarding energy in MeV, and the nuclear radius is taken to be $1\cdot25A^{1/3}$ fm. The values of P_{Coul} were calculated using matrix elements ultimately determined in the present work. Energies deemed to be unsafe were 36- and 37-MeV ^{12}C and 50-MeV ^{16}O for ^{142}Ce, and 13-MeV ^4He for

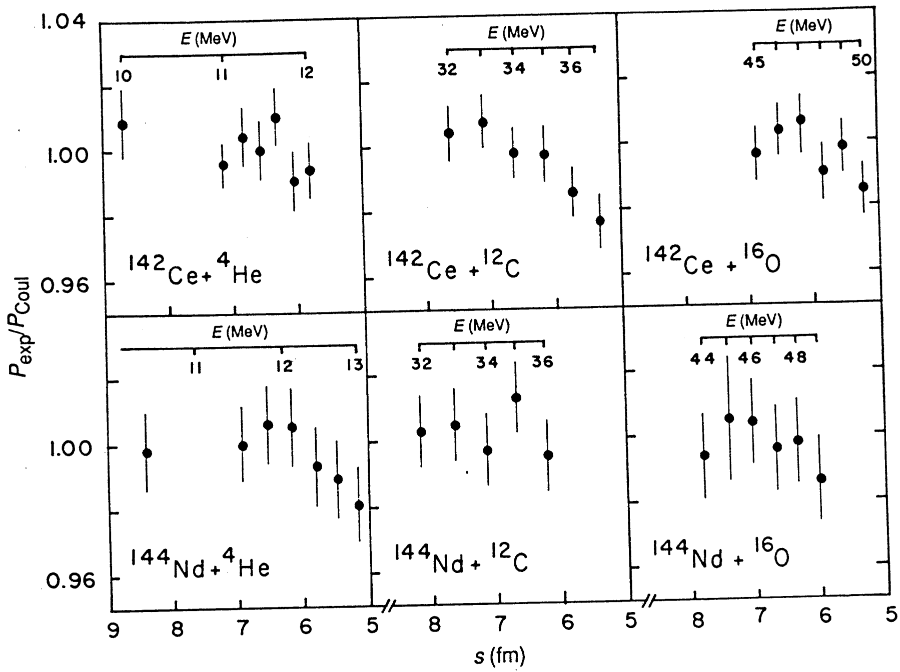

Fig. 6. Safe-energy plots for excitation of the 2_1^+ states of ^{142}Ce and ^{144}Nd by ^{4}He, ^{12}C and ^{16}O.

^{144}Nd; the corresponding data were not included in the Coulomb-excitation analysis used to determine matrix elements. We have assumed that energies found to be safe for the 2_1^+ state would also be safe for the 2_2^+, 2_3^+, 3_1^- and 4_1^+ states. Although this is not necessarily true in principle (Spear *et al.* 1978), it is a reasonable assumption at the level of precision corresponding to the statistical quality of the data obtained for the higher states.

Values of P_{exp} obtained at bombarding energies found to be free from nuclear interference were fitted using theoretical excitation probabilities calculated with the Winther–de Boer (1966) semi-classical Coulomb excitation code. For both ^{142}Ce and ^{144}Nd, the 2_1^+, 4_1^+, 2_2^+, 3_1^- and 2_3^+ excited states were included in the analysis. For ^{142}Ce, virtually no information existed on pertinent matrix elements; therefore sufficient data were obtained to determine the following quantities:

$$B(\mathrm{E2};\, 0_1^+\to 2_1^+),\quad Q(2_1^+),\quad B(\mathrm{E2};\, 4_1^+\to 2_1^+),\quad B(\mathrm{E2};\, 2_2^+\to 2_1^+),\quad B(\mathrm{E2};\, 0_1^+\to 2_2^+),$$

$$B(\mathrm{E2};\, 0_1^+\to 2_3^+),\quad B(\mathrm{E3};\, 0_1^+\to 3_1^-)\quad \text{and}\quad B(\mathrm{E4};\, 0_1^+\to 4_1^+).$$

For ^{144}Nd, it was assumed on the basis of published information (Metzger 1969; Fahlander *et al.* 1980; Snelling and Hamilton 1983) that the matrix elements

$$\langle 0_1^+ \| M(\mathrm{E2}) \| 2_2^+\rangle,\quad \langle 2_1^+ \| M(\mathrm{E2}) \| 2_2^+\rangle,\quad \langle 0_1^+ \| M(\mathrm{E2}) \| 2_3^+\rangle \quad\text{and}\quad \langle 2_1^+ \| M(\mathrm{E2}) \| 2_3^+\rangle$$

Table 3. Transition strengths and $Q(2_1^+)$ values obtained in the present work

	^{142}Ce	^{144}Nd
$Q(2_1^+)$ (eb)	$-0\cdot16(5)^A$	$-0\cdot15(6)^{A,B}$
$B(E2;\ 0_1^+\to2_1^+)$ (e^2b^2)	$-0\cdot479(4)^A$	$-0\cdot491(4)^{A,B}$
$B(E2;\ 4_1^+\to2_1^+)$ (e^2b^2)	$0\cdot117(10)$	$0\cdot100(9)$
$B(E2;\ 2_2^+\to2_1^+)$ (e^2b^2)	$0\cdot162(37)$	
$B(E2;\ 0_1^+\to2_2^+)$ (e^2b^2)	$<0\cdot008$	
$B(E2;\ 0_1^+\to2_3^+)$ (e^2b^2)	$0\cdot070(11)$	
$B(E2;\ 2_3^+\to2_1^+)$ (e^2b^2)	$0\cdot033(11)^C$	
$B(M1;\ 2_3^+\to2_1^+)$ (μ_N^2)	$0\cdot26(5)^C$	
$B(E3;\ 0_1^+\to3_1^-)$ (e^2b^3)	$0\cdot202(13)$	$0\cdot263(10)$
$B(E4;\ 0_1^+\to4_1^+)$ (e^2b^4)	$<0\cdot036$	

[A] These values assume $P_4(2_3^+)>0$; see Table 4 for alternative values.
[B] These values assume $P_4(2_2^+)<0$; see Table 4 for alternative values.
[C] Calculated using measured value of $B(E2;\ 0_1^+\to2_3^+)$ and the branching and mixing ratios listed by Peker (1984).

Table 4. Values of $Q(2_1^+)$ and $B(E2;0_1^+\to2_1^+)$ obtained for various possible combinations of the signs of $P_4(2_3^+)$ and $P_4(2_2^+)$

It is assumed that $P_4(2_2^+)=0$ for ^{142}Ce

Sign $P_4(2_3^+)$	Sign $P_4(2_2^+)$	^{142}Ce $B(E2;\ 0_1^+\to2_1^+)$ (e^2b^2)	^{142}Ce $Q(2_1^+)$ (eb)	^{144}Nd $B(E2;\ 0_1^+\to2_1^+)$ (e^2b^2)	^{144}Nd $Q(2_1^+)$ (eb)
+	−	0·479(4)	−0·16(5)	0·491(4)	−0·15(6)
−	−	0·482(4)	−0·37(5)	0·492(4)	−0·28(6)
+	+	0·479(4)	−0·16(5)	0·491(4)	−0·05(6)
−	+	0·482(4)	−0·37(5)	0·492(4)	−0·19(6)

Table 5. Effects of various small corrections and uncertainties in the determination of $Q(2_1^+)$ and $B(E2;0_1^+\to2_1^+)$ for ^{142}Ce

The values are very similar for ^{144}Nd

Effect	$\Delta B(E2;\ 0_1^+\to2_1^+)$ (e^2b^2)	$\Delta Q(2_1^+)$ (eb)
Electron screening	−0·004	+0·004
Vacuum polarisation	+0·007	−0·011
Nuclear polarisation	−0·0003	−0·032
Quantal correction	+0·002	−0·022
GDR correction	−0·0001	+0·048
Uncertainties in 2_3^+ level parameters	±0·0004	±0·025
Uncertainty in beam energy	±0·0024	±0·003

had the magnitudes 0·055(6), 0·69(10), 0·25(3) and 0·34(11) eb, respectively. The usual small corrections (Fewell *et al.* 1979) were applied for electron screening, vacuum polarisation, nuclear polarisation, effects of target thickness, E1 interference from the giant-dipole resonance (GDR), and use of the semi-classical approximation ('quantal correction').

The results obtained are summarised in Table 3. The value obtained for $Q(2_1^+)$ and, to a lesser extent, for $B(E2;\ 0_1^+\to2_1^+)$, is sensitive to interference terms from higher states. The sign of the interference term involving the state J_n^π depends on the sign of $P_4(J_n^\pi)$, where $P_4(J_n^\pi)$ is defined by

$$P_4(J_n^\pi) = \langle 0_1^+ \| M(\mathrm{E2}) \| 2_1^+ \rangle \langle 2_1^+ \| M(\mathrm{E2}) \| 2_1^+ \rangle \langle 0_1^+ \| M(\mathrm{E2}) \| J_n^\pi \rangle \langle 2_1^+ \| M(\mathrm{E2}) \| J_n^\pi \rangle . \quad (4)$$

For most nuclei the 2_2^+ state produces the major interference effect. However, in the present case $\langle 0_1^+ \| M(\mathrm{E2}) \| 2_2^+ \rangle$ is very small and the largest effect comes from the 2_3^+ state. Results obtained for alternative signs of $P_4(2_2^+)$ and $P_4(2_3^+)$ are given in Table 4. It is expected on rather general theoretical grounds (Kumar 1969) that $P_4(2_2^+) < 0$; the discussion presented later in this paper will be based on this assumption, but would not be significantly affected if $P_4(2_2^+)$ were taken to be positive. A list of the effects of various small corrections and uncertainties in the determination of $Q(2_1^+)$ and $B(\mathrm{E2};\, 0_1^+ \to 2_1^+)$ is given in Table 5.

In order to visualise the influence of each set of data on the determination of $Q(2_1^+)$ and $B(\mathrm{E2};\, 0_1^+ \to 2_1^+)$, an approximate expression for the excitation probability P of the form

$$P = fB(\mathrm{E2};\, 0_1^+ \to 2_1^+)\{1 + \rho Q(2_1^+)\} \quad (5)$$

is useful. The quantities ρ (the sensitivity parameter) and f are calculated from the Winther–de Boer program. Fig. 7 shows plots of P_{exp}/f as a function of ρ. The fits to the data are represented by straight lines with intercepts on the vertical axis equal to $B(\mathrm{E2};\, 0_1^+ \to 2_1^+)$ and slopes of $B(\mathrm{E2};\, 0_1^+ \to 2_1^+)\, Q(2_1^+)$.

4. Comparison of Present Results with Previous Work

(a) Quadrupole Moments $Q(2_1^+)$

^{142}Ce. For ^{142}Ce we obtain $Q(2_1^+) = -0\cdot16(5)\, e$b, assuming $P_4(2_2^+) = 0$ and $P_4(2_3^+) > 0$. The only previous experimental value is $-0\cdot12(9)\, e$b, obtained by Engler (1970) using Coulomb excitation by ^{16}O projectiles. The present result is superior because of better statistical accuracy and a better knowledge of higher state matrix elements and various small corrections. Engler took into account only the 2_2^+ level when considering the effects of higher states, and used calculated values for $\langle 2_1^+ \| M(\mathrm{E2}) \| 2_2^+ \rangle$ and $\langle 0_1^+ \| M(\mathrm{E2}) \| 2_2^+ \rangle$ which differ substantially from the values measured in the present work.

^{144}Nd. For ^{144}Nd we obtain $Q(2_1^+) = -0\cdot15(6)\, e$b, assuming $P_4(2_2^+) < 0$ and $P_4(2_3^+) > 0$. Crowley *et al.* (1971) obtained $Q(2_1^+) = -0\cdot39(21)\, e$b from Coulomb excitation with ^{16}O projectiles. However, when results of γ-ray yield measurements were combined with their particle data, they obtained $-0\cdot07(15)\, e$b. Furthermore, they were unable, because of insufficient experimental information, to allow for interference from the 2_2^+ and 2_3^+ states.

(b) Values of $B(\mathrm{E2};\, 0_1^+ \to 2_1^+)$

^{142}Ce. The present value of $B(\mathrm{E2};\, 0_1^+ \to 2_1^+) = 0\cdot479(4)\, e^2\mathrm{b}^2$ is in satisfactory agreement with previous values listed by Raman *et al.* (1987). The data are plotted in chronological order of publication in Fig. 8.

^{144}Nd. Our value of $B(\mathrm{E2};\, 0_1^+ \to 2_1^+) = 0\cdot491(4)\, e^2\mathrm{b}^2$ is in significant disagreement with the value $0\cdot58(1)\, e^2\mathrm{b}^2$ reported recently by Ahmad *et al.* (1988)

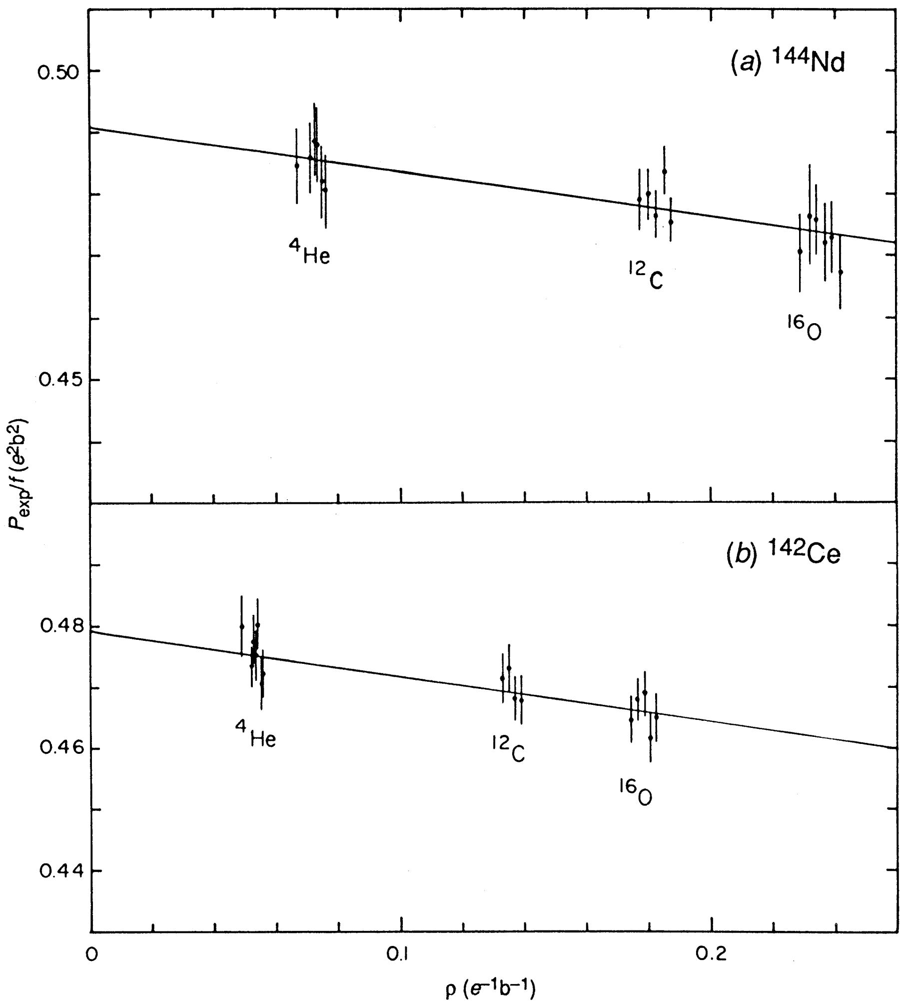

Fig. 7. Plots of $P_{\rm exp}/f$ against the sensitivity parameter ρ: (*a*) ^{144}Nd with $Q(2_1^+) = -0\cdot15(6)$ *e*b and $B(\mathrm{E2};\, 0_1^+\!\to\!2_1^+) = 0\cdot491(4)\; e^2\mathrm{b}^2$ and (*b*) ^{142}Ce with $Q(2_1^+) = -0\cdot16(5)$ *e*b and $B(\mathrm{E2};\, 0_1^+\!\to\!2_1^+) = 0\cdot479(4)\; e^2\mathrm{b}^2$. It is assumed that $P_4(2_3^+) > 0$ for both nuclei, and that $P_4(2_2^+) < 0$ for ^{144}Nd.

from Coulomb excitation with ^{4}He projectiles. It is, however, in excellent agreement with the four most recent determinations prior to that of Ahmad *et al.* (Eccleshall *et al.* 1966; Burginyon *et al.* 1967; Crowley *et al.* 1971; Fahlander *et al.* 1980); the weighted mean of these four is $0\cdot499(17)\; e^2\mathrm{b}^2$. All the data listed by Raman *et al.* (1987) are plotted, together with the present value, in Fig. 8.

(*c*) Values of $B(\mathrm{E2};\, 4_1^+\!\to 2_1^+)$

We are not aware of any previous measurement of this quantity for ^{142}Ce. For ^{144}Nd our value of $0\cdot100(9)\; e^2\mathrm{b}^2$ is in good agreement with the value of $0\cdot86(16)\; e^2\mathrm{b}^2$ reported by Fahlander *et al.* (1980) from Coulomb-excitation measurements.

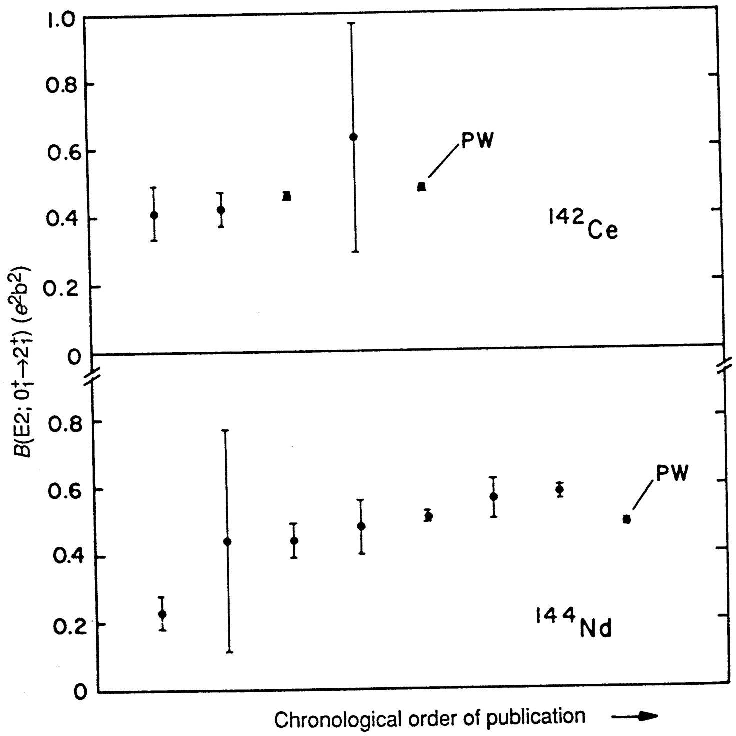

Fig. 8. Previous values of $B(\mathrm{E2};\, 0_1^+ \to 2_1^+)$ for ^{142}Ce and ^{144}Nd plotted in chronological order of publication, together with that of the present work (PW). The results shown for ^{142}Ce are from Coulomb excitation (Andreev *et al.* 1961; Eccleshall *et al.* 1966; Engler 1970; present work) and from inelastic electron scattering (Pitthan 1973). Those for ^{144}Nd, all from Coulomb excitation, are from Lemberg (1960), Nathan and Popov (1960), Ecceshall *et al.* (1966), Burginyon *et al.* (1967), Crowley *et al.* (1971), Fahlander *et al.* (1980), and Ahmad *et al.* (1988).

Table 6. Comparison of experimental values of transition strengths, quadrupole moments $Q(2_1^+)$, and mixing ratios $\delta(2_3^+ \to 2_1^+)$ for ^{142}Ce and ^{144}Nd with the predictions of IBM-2 calculations

Unless indicated otherwise, experimental values are from the present work (Table 3)

	Theory[A] IBM-2 U(5)	Experiment ^{142}Ce	^{144}Nd
$Q(2_1^+)$ (eb)	−0·11	−0·16(5)	−0·15(6)
$B(\mathrm{E2};\, 0_1^+ \to 2_1^+)$ $(e^2\mathrm{b}^2)$	0·52	0·479(4)	0·491(4)
$B(\mathrm{E2};\, 4_1^+ \to 2_1^+)$ $(e^2\mathrm{b}^2)$	0·17	0·117(10)	0·100(9)
$B(\mathrm{E2};\, 2_2^+ \to 2_1^+)$ $(e^2\mathrm{b}^2)$	0·17	0·16(4)	0·095(30)[B]
$B(\mathrm{E2};\, 0_1^+ \to 2_2^+)$ $(e^2\mathrm{b}^2)$	0	<0·008	0·0030(6)[B]
$B(\mathrm{E2};\, 0_1^+ \to 2_3^+)$ $(e^2\mathrm{b}^2)$	0·058	0·070(11)	0·065(16)[C,D]
$B(\mathrm{E2};\, 2_3^+ \to 2_1^+)$ $(e^2\mathrm{b}^2)$	0·016	0·033(11)	0·023(15)[C,D]
$B(\mathrm{M1};\, 2_3^+ \to 2_1^+)$ (μ_N^2)	0·23	0·26(5)	0·15(4)[C,D]
$\delta(2_3^+ \to 2_1^+)$	+0·30	+0·41(7)[E]	+0·31(11)[D]

[A] Hamilton *et al.* (1984). [B] Fahlander *et al.* (1980). [C] Metzger (1969). [D] Snelling and Hamilton (1983). [E] Peker (1984).

(d) Values of $B(\mathrm{E}3;0_1^+\rightarrow3_1^-)$

For both ^{142}Ce and ^{144}Nd the only previous data are from the Coulomb-excitation experiment of Hansen and Nathan (1963). It is well known that the results of that experiment are unreliable because of problems with nuclear interference (Spear 1989). The present values correspond to E3 transition strengths of 24·1(16) and 30·5(12) W.u. for ^{142}Ce and ^{144}Nd respectively. These enhancements are similar to those of other nuclei in this mass region (Spear 1989).

5. Discussion

(a) Comparison of Results with IBM-2 Predictions

Table 6 presents a comparison between experimental results for ^{142}Ce and ^{144}Nd and predictions based on the calculations of Hamilton *et al.* (1984) made using the U(5) limit of IBM-2 with boson effective charges $e_\nu = 0\cdot24$ *e*b and $e_\pi = 0\cdot12$ *e*b, structure parameters $\chi_\nu = -1\cdot3$ and $\chi_\pi = 0$, and boson numbers $N_\nu = 1$, $N_\pi = 4$. This parameter set gives identical predictions for ^{142}Ce and ^{144}Nd because it uses $N_\pi = 4$ for both nuclei. The best value to use for N_π is uncertain because of the possible $Z = 64$ shell closure (see e.g. Casten 1985; Wolf and Casten 1987). The calculations assume that the 2_1^+ level is a pure one d-boson symmetric state, the 2_2^+ and 4_1^+ levels are pure two d-boson symmetric states, and the 2_3^+ level is a pure one d-boson mixed-symmetry state.

The overall agreement between theory and experiment is excellent; the experimental values for the two nuclei are very similar, and the magnitudes agree very well with the theoretical predictions. Of particular significance is the agreement for the proposed mixed-symmetry state (2_3^+). For both nuclei the results fulfil the requirements for a mixed-symmetry state: (i) There is a large M1 strength to the lowest fully symmetric state [$B(\mathrm{M}1;2_3^+\rightarrow2_1^+) = 0\cdot15(3)$ W.u. and 0·08(2) W.u. for ^{142}Ce and ^{144}Nd respectively]; these values are considerably larger than typical M1 strengths for nuclei in this mass region (Endt 1981). (ii) The values of $B(\mathrm{E}2;0_1^+\rightarrow2_3^+)$ are moderately large [3·2(5) and 2·9(7) W.u. respectively] and agree with Iachello's estimate of about 3 W.u.

Detailed IBM-2 calculations by Robinson *et al.* (1988) suggested that the properties of a mixed-symmetry state in ^{142}Ce and ^{144}Nd are shared between the 2_2^+ and 2_3^+ levels, i.e. that both levels are highly mixed combinations of one d-boson mixed-symmetry and two d-boson symmetric configurations. The present results do not support this view: in both nuclei the properties of the 2_3^+ level are exactly those expected for a pure one d-boson mixed symmetry state, and the 2_2^+ level has the properties of a two d-boson symmetric state [the very small value of $B(\mathrm{E}2;0_1^+\rightarrow2_2^+)$ precludes a substantial mixed-symmetry component in the 2_2^+ level]. The situation in ^{142}Ce and ^{144}Nd appears to be in strong contrast with that in two other cases of suggested symmetry mixing in nuclei outside the well-deformed regions of the periodic table: for both the light nucleus ^{56}Fe (Eid *et al.* 1986) and the O(6) nucleus ^{134}Ba (Molnár *et al.* 1988), it seems that the properties of a theoretical mixed-symmetry state would have to be shared between two or more experimental levels.

The most controversial aspect of the parameter set used by Hamilton *et al.* (1984) is the positive value for $(e_\nu - e_\pi)$, obtained from an analysis of

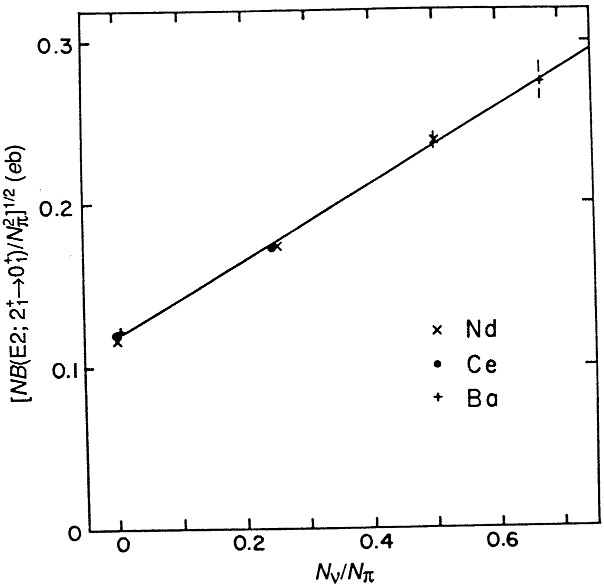

Fig. 9. A plot of the quantity $[NB(\mathrm{E2};2_1^+\to0_1^+)/N_\pi^2]^{1/2}$ against N_ν/N_π for some nuclei in the region of present interest, where N_ν and N_π are the neutron and proton boson numbers respectively, and $N=N_\nu+N_\pi$. The straight line is a least-squares fit to the data. Unless specifically indicated, the experimental errors are negligible compared with the size of the data points. This plot is an updated version of Fig. 1 of Hamilton *et al.* (1984); values obtained in the present work have been used for ^{142}Ce and ^{144}Nd, and an additional data point has been added (for ^{142}Ba). Values for ^{138}Ba, ^{142}Ba, ^{140}Ce, ^{144}Nd and ^{146}Nd are taken from the compilation of Raman *et al.* (1987).

$B(\mathrm{E2};\,0_1^+\to2_1^+)$ values for various vibrational nuclei in the mass region $A=138$–46, using the formula

$$\{NB(\mathrm{E2};2_1^+\to0_1^+)/N_\pi^2\}^{1/2}=e_\pi+(e_\nu N_\nu/N_\pi),\tag{6}$$

where $N=N_\nu+N_\pi$. A plot of $\{NB(\mathrm{E2};2_1^+\to0_1^+)/N_\pi^2\}^{1/2}$ against N_ν/N_π is shown in Fig. 9, which is an updated version of Fig. 1 of Hamilton *et al.* The straight line is a least-squares fit to the data, corresponding to $e_\pi=0\cdot12$ eb and $e_\nu=0\cdot23$ eb. These values are in excellent agreement with those obtained by Hamilton *et al.* ($0\cdot12$ and $0\cdot24$ eb respectively). This approach has been criticised by Scholten *et al.* (1986) on the grounds that there may be a strong mass dependence of the effective charges; the application of equation (6) assumed constant effective charges. Puddu *et al.* (1980) chose $e_\nu=e_\pi=0\cdot12$ eb in their study of Xe, Ba and Ce isotopes with $N<82$. Similarly, Robinson *et al.* (1988) reported that the choice of $e_\nu=e_\pi=0\cdot12$ eb gave the optimum reproduction of experimental $B(\mathrm{E2})$ values in ^{142}Ce and ^{144}Nd. However, it is evident from equation (1) that equal values for e_ν and e_π imply zero E2 strength between the ground state and the lowest 2^+ mixed-symmetry state, which is inconsistent with the observation that the strength of this transition is about 3 W.u. From equations (1) and (2) of Hamilton *et al.* (1984), it is seen that $(e_\nu - e_\pi) > 0$ fixes $P_4(2_3^+) > 0$, and theoretical predictions are obtained which are in excellent agreement with experiment (Table 6). In particular, the experimental values of $B(\mathrm{E2}; 0_1^+ \to 2_3^+)$ imply (equation 1) values for $|e_\nu - e_\pi|$ of 0·132(10) and 0·127(16) *e*b for ^{142}Ce and ^{144}Nd respectively, in excellent agreement with the value of $(e_\nu - e_\pi) = 0 \cdot 12$ *e*b obtained by Hamilton *et al.*

Table 7. IBM-2 parameters required to fit the data of Tables 4 and 6 for $(e_\nu - e_\pi) > 0$, i.e. $P_4(2_3^+) > 0$, and for $(e_\nu - e_\pi) < 0$, i.e. $P_4(2_3^+) < 0$

	^{142}Ce		^{144}Nd	
	$P_4(2_3^+) > 0$	$P_4(2_3^+) < 0$	$P_4(2_3^+) > 0$	$P_4(2_3^+) < 0$
e_ν (eb)	0·244(8)	0·033(8)	0·243(12)	0·038(12)
e_π (eb)	0·112(2)	0·165(2)	0·115(4)	0·166(4)
χ_ν	−1·9(3)	−18(5)	−1·6(6)	−12(6)
χ_π	−0·03(30)	−0·77(20)	−0·1(5)	−0·54(29)

It is possible to test the sign of $(e_\nu - e_\pi)$ from its indirect effect on the value of $Q(2_1^+)$. Referring again to equations (1) and (2) of Hamilton *et al.*, we have $\langle 0_1^+ \| M(\mathrm{E2}) \| 2_1^+ \rangle = (5/N)^{1/2}(e_\pi N_\pi + e_\nu N_\nu)$ which must be positive, $\langle 2_1^+ \| M(\mathrm{E2}) \| 2_1^+ \rangle$ must be negative since the experimental value of $Q(2_1^+)$ is negative, and $\langle 2_1^+ \| M(\mathrm{E2}) \| 2_3^+ \rangle$ must be negative since the experimental value of the mixing ratio $\delta(2_3^+ \to 2_1^+)$ is positive (Table 6) and an analysis of *g*-factors in this mass region by Sambataro *et al.* (1984) concluded that $g_\mathrm{p} \sim 1$ and $g_\mathrm{n} \sim 0$, so that $\langle 2_1^+ \| M(\mathrm{M1}) \| 2_3^+ \rangle$ is negative. Therefore, since $\langle 0_1^+ \| M(\mathrm{E2}) \| 2_3^+ \rangle = (5N_\nu N_\pi/N)^{1/2}(e_\nu - e_\pi)$, a negative value for $(e_\nu - e_\pi)$ would result in $P_4(2_3^+) < 0$. This would give $Q(2_1^+) = -0 \cdot 37(5)$ and $-0 \cdot 28(6)$ for ^{142}Ce and ^{144}Nd respectively (Table 4). These values, when combined with other data (Table 6), would require an unacceptable set of IBM-2 parameters. This is shown in Table 7, which gives values of parameters obtained when the data of Table 6 are used in the expressions for $\langle 0_1^+ \| M(\mathrm{E2}) \| 2_1^+ \rangle$, $\langle 2_1^+ \| M(\mathrm{E2}) \| 2_1^+ \rangle$, $\langle 0_1^+ \| M(\mathrm{E2}) \| 2_3^+ \rangle$ and $\langle 2_1^+ \| M(\mathrm{E2}) \| 2_3^+ \rangle$ given by Hamilton *et al.* (1984), assuming the values of $Q(2_1^+)$ given in Table 4 for the alternative signs of $P_4(2_3^+)$ [it is assumed that $P_4(2_2^+) < 0$ but the alternative choice of $P_4(2_2^+) > 0$ would make no significant difference to the argument]. Since both ^{142}Ce and ^{144}Nd lie at the start of a neutron shell and in the middle of a proton shell, it would be expected (Puddu *et al.* 1980) that $\chi_\nu \sim -1$ and $\chi_\pi \sim 0$. It is seen that for both nuclei the choice of $P_4(2_3^+) < 0$, arising from the assumption that $(e_\nu - e_\pi) < 0$, gives unrealistically large magnitudes for χ_ν. On the other hand, the choice of $P_4(2_3^+) > 0$, i.e. $(e_\nu - e_\pi) > 0$, gives values for both χ_ν and χ_π which are in accord with expectation. Even if $P_4(2_2^+)$ were chosen to be positive for ^{144}Nd (it is zero for ^{142}Ce), a fit to the data including the corresponding value of $Q(2_1^+) = -0 \cdot 19(6)$ *e*b (Table 4) would give $\chi_\nu = -11(6)$. Thus, the measured values of $Q(2_1^+)$ strongly support the positive sign adopted for $(e_\nu - e_\pi)$ by Hamilton *et al.*

It is conceivable that solutions with e_π greater than e_ν could be found by using different values of N_ν or N_π, or by using the full IBM-2 Hamiltonian instead of the strict U(5) limit. However, the relatively simple approach of Hamilton *et al.* gives an excellent description of these nuclei.

In commenting on their surprising conclusion that $e_\nu > e_\pi$, Hamilton *et al.* made two points: (a) the effective-charge parameters involve a (length)^2 factor and the neutrons are filling higher shells than the protons, and (b) a large effective neutron charge would be expected in this region just before the onset of deformation at $N = 88$. It is interesting to note that the shell-model calculations of Heyde and Sau (1986) indicated that in the $N = 84$ mass region it is possible to obtain values of e_ν greater than e_π for $N_\nu = 1$ and $N_\pi \gtrsim 4$ (see Fig. 9 of their paper).

(b) Comparison of Results with Other Calculations

The main emphasis of this paper is the comparison of measured electromagnetic matrix elements in ^{142}Ce and ^{144}Nd with IBM-2 predictions, with particular reference to mixed-symmetry states. However, some of these matrix elements have also been calculated with other nuclear models. A brief discussion of these calculations is given in this section.

Vanden Berghe (1975) applied the two-particle core-coupling model to the $N = 84$ isotones. Using an effective neutron charge $e_n^{\rm eff} = 0\cdot 5e$, he obtained $B(\mathrm{E2};\, 0_1^+ \to 2_1^+) = 0\cdot 319\ e^2\mathrm{b}^2$, which is much smaller than the experimental values (Table 6). Using $e_n^{\rm eff} = e$, he obtained $0\cdot 428\ e^2\mathrm{b}^2$, which is in much better agreement with experiment. The calculated values for $Q(2_1^+)$ were $-0\cdot 23\ e\mathrm{b}$ ($e_n^{\rm eff} = 0\cdot 5e$) and $-0\cdot 32\ e\mathrm{b}$ ($e_n^{\rm eff} = e$), which fall within the range of experimental values covered by the alternative signs for $P_4(2_3^+)$ (see Table 4). However, the calculation is very sensitive to the relative amounts of $2f_{7/2}$ and $3p_{3/2}$ configurations assumed for the two extra-core neutrons; an earlier calculation by Heyde and Brussaard (1967) assumed a pure $2f_{7/2}$ configuration and gave the wrong sign for $Q(2_1^+)$.

Table 8. Comparison between experimental values of transition strengths (from Table 6) and values calculated by Faessler and Nojarov (1986) using an extension of the vibrational model with large (L) and small (S) bases of single-particle states

		$B(\mathrm{M1};\, 2_3^+ \to 2_1^+)$ ($10^{-3}\ \mu_N^2$)	$B(\mathrm{E2};\, 2_3^+ \to 2_1^+)$ ($10^{-4}\ e^2\mathrm{b}^2$)	$B(\mathrm{E2};\, 0_1^+ \to 2_3^+)$ ($e^2\mathrm{b}^2$)
^{142}Ce	Calc. (L)	11	0·46	0·14
	Calc. (S)	108	44	0·16
	Expt	260(50)	330(110)	0·070(11)
^{144}Nd	Calc. (L)	9	0·51	0·15
	Calc. (S)	128	38	0·19
	Expt	150(40)	230(150)	0·065(16)

Table 9. Comparison between B(E2) values (e^2b^2) calculated for ^{144}Nd by Gupta (1988), using the pairing-plus-quadrupole model, and experimental values (from Table 6)

Quantity	Theory (Gupta 1988)	Experiment (Table 6)
$B(\mathrm{E2};\, 0_1^+ \to 2_1^+)$	0·71	0·491(4)
$B(\mathrm{E2};\, 0_1^+ \to 2_2^+)$	0·010	0·0030(6)
$B(\mathrm{E2};\, 0_1^+ \to 2_3^+)$	0·0004	0·065(16)
$B(\mathrm{E2};\, 2_2^+ \to 2_1^+)$	0·140	0·095(30)
$B(\mathrm{E2};\, 4_1^+ \to 2_1^+)$	0·27	0·100(9)

Faessler and Nojarov (1986) interpreted the 2^+ mixed-symmetry state as an isovector quadrupole vibration (involving separate quadrupole vibrations of the protons and neutrons). Their calculated values of transition strengths are compared with experiment in Table 8. The 'large basis' calculations include all proton states from the oscillator shells $\mathcal{N} \leq 4$ and all neutron states with $\mathcal{N} \leq 5$; the 'small basis' calculations are restricted to states of the $\mathcal{N}=4$ proton shell and the $\mathcal{N}=5$ neutron shell. The calculated values of $B(\mathrm{E2}; 0_1^+ \to 2_3^+)$ are 2 to 3 times larger than experiment, which may be due to the neglect of mixing with the giant isovector quadrupole resonance. Calculated values for $B(\mathrm{E2}; 2_3^+ \to 2_1^+)$ and $B(\mathrm{M1}; 2_3^+ \to 2_1^+)$ are smaller than experiment, some by very large amounts; however, the small-basis values are much closer to experiment than are those calculated with the large basis.

Gupta (1988) performed extensive calculations for ^{144}Nd using the pairing-plus-quadrupole model. He obtained $Q(2_1^+) = -0\cdot38\,e$b, which is in good agreement with the experimental value for $P_4(2_3^+) < 0$, but not with that for $P_4(2_3^+) > 0$ (see Table 4). His calculated $B(\mathrm{E2})$ values are compared with experiment in Table 9; the agreement is not good.

6. Summary

Quadrupole moments $Q(2_1^+)$ and various other electromagnetic matrix elements have been measured for the $N = 84$ nuclei ^{142}Ce and ^{144}Nd using Coulomb excitation. When taken in conjunction with other experimental information, the results show that these two nuclei have very similar properties, and that these properties are in excellent agreement with predictions made by Hamilton *et al.* (1984) using the U(5) limit of IBM-2. The results support the parameter set that they use, including the controversial assumption of a larger effective charge for neutron bosons than for proton bosons. The observed properties of the 2_3^+ state in both nuclei agree with those expected for a pure one d-boson mixed-symmetry state.

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