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Quadrupole moments of the first 2^+ states of doubly even nuclei in the $Z = 50$ region

I M Naqib†, A Christy‡, I Hall§, M F Nolan§‖ and D J Thomas§¶

† Physics Department, University of Kuwait, Kuwait

‡ Department of Physics, Preston Polytechnic, Preston PR1 2TQ, UK

§ Oliver Lodge Laboratory, University of Liverpool, PO Box 147, Liverpool L69 3BX, UK

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Abstract. Quadrupole moments measured by Coulomb excitation in the $Z = 50$ region, including previously unpublished measurements for ^{100}Mo and ^{116}Cd, are summarized and compared with the magnitudes given by an approximate relation derived from collective model sum rules.

NUCLEAR REACTIONS ^{100}Mo, ^{116}Cd $(\alpha, \alpha'\gamma)$, $E = 8{\cdot}5$ MeV; $(^{16}O, ^{16}O'\gamma)$. $E = 33$ MeV; measured σ of 2^+ level. Deduced Q. Enriched targets.

1. Introduction

In the past few years the quadrupole moments Q_{2^+} of the first 2^+ states of many doubly even nuclei in the $Z = 50$ region have been measured by Coulomb excitation (the so-called reorientation experiments). Although these nuclei had been thought to be vibrational, most of the measured moments are non-zero and some are quite large, i.e. comparable with the magnitude given by the rotational model. This suggested that these nuclei might be thought of as transitional between the harmonic vibrational model and the rotational model. This has some theoretical support since the Alaga particle–vibrator coupling model, which has been quite successful in this mass region, has been shown by Lopac (1970) to be capable of reproducing some of the properties of a transitional nucleus.

Recently Naqib (1975) derived an approximate relation between the quadrupole moment and certain E2 transition probabilities. This relation, derived from the leading terms of sum rules proposed by Kumar (1972), is discussed in §4. It does not depend on the assumption of a specific collective model and reproduces exactly both the harmonic vibrator and rotor limits for the quadrupole moment. The natural question then is whether the relation works satisfactorily for transitional nuclei and Naqib (1975) found that it does indeed reproduce very well the quadrupole moments of the transitional Os isotopes. It therefore seemed worthwhile to test the relation in the $Z = 50$ region since, as mentioned above, there are some grounds for thinking

‖ Present address: Department of Audiology, University of Manchester, Manchester M13 9PL, UK.

¶ Present address: National Physical Laboratory, Teddington TW11 0LW, UK.

that nuclei in this region may be regarded as transitional. Furthermore, there are now many published quadrupole moment measurements in this region. These were reviewed by Hall (1975) but there have since been some significant amendments and additions and the present situation is summarized in §3. The comparison of sum-rule prediction with experiment is the subject of §5.

Section 2 gives briefly details of measurements on ^{100}Mo and ^{116}Cd which had not previously been published but which are included in §3.

2. Measurement of Q_{2^+} for ^{100}Mo and ^{116}Cd

The quadrupole moments of the first 2^+ states of ^{100}Mo (536 keV) and ^{116}Cd (517 keV) were determined using the reorientation effect in Coulomb excitation. ^{100}Mo was chosen to complete measurements of the $N = 58$ isotones. ^{116}Cd was chosen as part of a further study of the Cd isotopes following some disagreement in the published results for these isotopes; see §3.

The method is essentially a comparison of the Coulomb excitation of the 2^+ state for two bombarding ions (^{4}He and ^{16}O in this case) using apparatus described earlier (Christy *et al* 1970, Thomas *et al* 1973). The excitation was measured by detecting the $2^+ \rightarrow 0^+$ decay γ rays in coincidence with backscattered particles. A 40 cm^3 Ge(Li) detector at an angle of 66° to the beam direction was used in the ^{116}Cd measurement. A 5·08 cm × 5·08 cm NaI(Tl) detector at an angle of 58° to the beam direction was used for the yield measurements for the ^{100}Mo case following a short Ge(Li) run to confirm that there were no target contaminants. Particular experimental details are given in table 1.

The data were analysed using the de Boer–Winther multiple Coulomb excitation programme. The levels included in the analyses are shown in figure 1. The $B(\mathrm{E2}, 0^+ \rightarrow 2^+)$ were not determined in the present work. The values of the E2 matrix elements used in the analysis are given in table 2. In the case of ^{100}Mo these were taken from Barrette *et al* (1972). In the case of ^{116}Cd they were deduced from the $B(\mathrm{E2})$ values given by McGowan *et al* (1965) for the higher states whilst $B(\mathrm{E2}, 0^+ \rightarrow 2^+)$ was taken from Christy and Häusser (1972). Since the analysis of

Table 1. Experimental details and results of reorientation measurements in ^{100}Mo and ^{116}Cd.

	^{100}Mo		^{116}Cd	
Target enrichment	98·7%		98·2%	
Bombarding ion	^{4}He	^{16}O	^{4}He	^{16}O
Target thickness (μg cm^{-2})	200	160	520	570
Target backing	carbon	copper	carbon	copper
Effective bombarding energy (MeV)	8·47	32·72	8·44	32·14
Ratio of coincidence yield per scattered particle	1:7·97 ± 0·09		1:7·59 ± 0·11	
Deduced Q_{2^+} (*e*b) for $2'^+$ interference:				
constructive	−0·39 ± 0·08		−0·64 ± 0·12	
destructive	−0·13 ± 0·08		−0·46 ± 0·12	

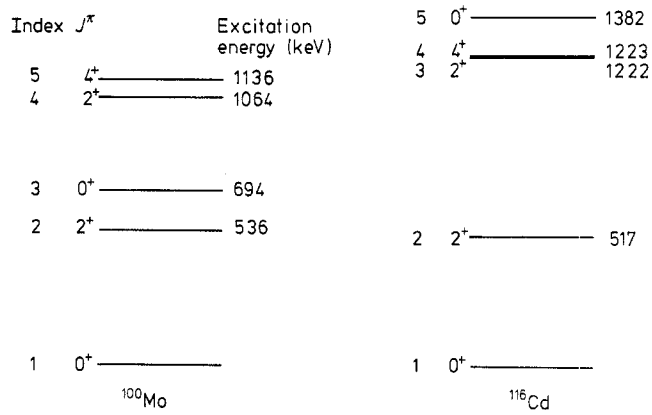

Figure 1. Energy levels included in the analysis of the Coulomb excitation of ^{100}Mo and ^{116}Cd.

the present experiment was completed, Esat *et al* (1976) have reported a value of $B(E2, 0^+ \rightarrow 2^+)$ for ^{116}Cd approximately 20% lower than that adopted by Christy and Häusser (1972). Such a change in $B(E2, 0^+ \rightarrow 2^+)$ would have affected our deduced Q_{2^+}, although not very significantly because the $B(E2, 0^+ \rightarrow 2^+)$ cancels to first order in the ratio of excitation for the two ions. This uncertainty in $B(E2, 0^+ \rightarrow 2^+)$ does have some effect on the comparison of sum-rule prediction with experiment and we return to this point in §5.

Table 2. Reduced E2 matrix elements† (*e*b) used in the analysis of the ^{100}Mo and ^{116}Cd experiments.

		^{100}Mo				
Level		1	2	3	4	5
0^+	1	0	−0·73	0	±0·11	0
2^+	2	−0·73	M_{22}	−0·43	−0·94	−1·33
$0'^+$	3	0	−0·43			
$2'^+$	4	±0·11	−0·94		0	
4^+	5	0	−1·33			
		^{116}Cd				
Level		1	2	3	4	5
0^+	1	0	−0·79	±0·15	0	0
2^+	2	−0·79	M_{22}	−0·66	−1·32	−0·31
$2'^+$	3	±0·15	0·66			
4^+	4	0	−1·32		0	
$0'^+$	5	0	−0·31			

† The matrix elements are defined by

$$M_{rs} = \langle s||i^{\lambda}\mathcal{M}(E\lambda)||r\rangle$$

where $\mathcal{M}(E\lambda)$ is the multipole operator and $\lambda = 2$. Thus $M_{rs}^2 = (2I_r + 1)\, B(E2, r \rightarrow s)$ and the quadrupole moment of the 2^+ state is $Q_{2^+} = -0{\cdot}758\, M_{22}$.

The relative phases of the matrix elements are unknown and there is therefore a significant uncertainty in the interference from $0^+ \rightarrow 2'^+ \rightarrow 2^+$ excitation. Thus two alternative results for Q_{2^+} were deduced for each nucleus corresponding to constructive and destructive $2'^+$ interference and these are shown at the bottom of table 1. The results have not been corrected for atomic screening, vacuum polarization, virtual excitation of the giant dipole resonance or quantal effects. All of these effects are small and for the first two the differential effect between ^{4}He and ^{16}O excitation is almost zero. The last two have small non-zero differential effects but they are of opposite sign and the net total effect is that our results may be subject to a systematic error of up to approximately 0·03 *e*b. This is not significant compared with the random errors in our results.

3. Q_{2^+} data in the $Z = 50$ region

The quadrupole moments measured by Coulomb excitation in the $Z = 50$ region are shown graphically in figures 2–6.

As noted at the end of §2, each measurement gives two alternative values of Q_{2^+} corresponding to both possible phases of the $2'^+$ interference. In figures 2–6, however, only the value corresponding to constructive $2'^+$ interference is plotted for each measurement. This preference is based on both theoretical arguments and experimental evidence. In the phonon-mixing model (Tamura 1968), the vibrational limit of the pairing-plus-quadrupole model (Kumar 1969), the Davydov model (Isakev and Lemberg 1969) and the Alaga model (Alaga 1973) the $2'^+$ interference and Q_{2^+} are connected by the following phase relation: the $2'^+$ interference is constructive or destructive according to whether Q_{2^+} is negative or positive respectively. The preference for constructive $2'^+$ interference then follows from the fact that the measured moments are predominantly negative, although in principle this argument is ambiguous in the few cases where the alternative Q_{2^+} results are of opposite sign. This choice is further supported by proton scattering data (Tamura 1968) and electron scattering data (Gillespie *et al* 1976) analysed in terms of the phonon-mixing model. We note here also the remark by Naqib (1975) that the relation given by equation (1) (§4) fits better the preferred set of Q_{2^+}. In addition to these model-dependent

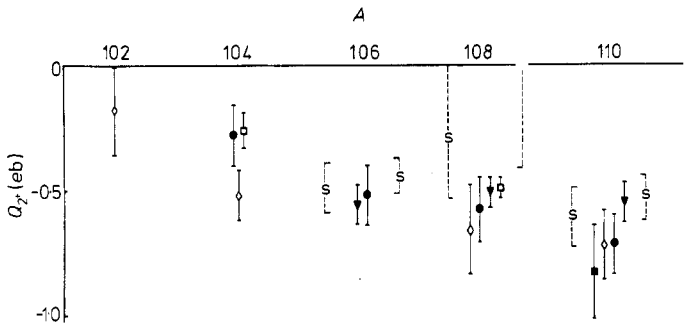

Figure 2. Quadrupole moments of the Pd isotopes. □, Chalk River (Ward *et al* 1971); ●, Liverpool (Christy *et al* 1970, Harper *et al* 1971); ■, Oak Ridge (Robinson *et al* 1969); ▼, Purdue (Lutz *et al* 1972); ◇, Uppsala (Hasselgren *et al* 1976 and private communication). The brackets ⌊ and ⌋ indicate the predictions of equation (1) as explained in §5.

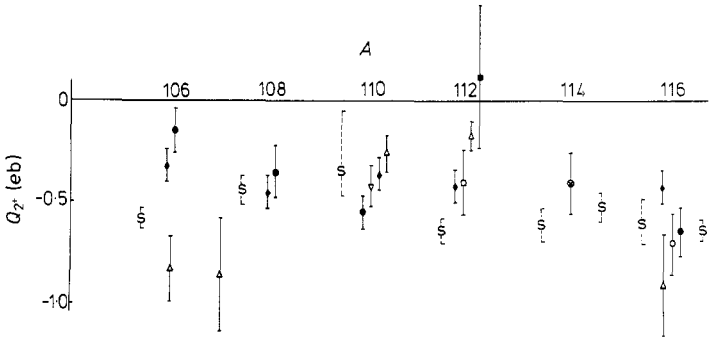

Figure 3. Quadrupole moments of the Cd isotopes. ○, Caltech (Stokstad *et al* 1967) (result corrected for deorientation); ◆, Canberra (Esat *et al* 1976 and private communication); □, Chalk River (Häusser *et al* 1971); ●, Liverpool (Harper *et al* 1971, Hall *et al* 1974, present work); ■, Oak Ridge (Stelson 1968); ▽, Rehovot–Köln (Berant *et al* 1971); △, Rutgers (Kleinfeld *et al* 1970b, Steadman *et al* 1970); ⊗, weighted mean of several results given in compilation of Christy and Häusser (1972).

arguments there is some purely experimental evidence. By comparing reorientation experiments on ^{114}Cd with different sensitivity to the $2'^+$ interference, Larsen *et al* (1972) found better agreement for the case of constructive $2'^+$ interference. More recently, direct measurements have been made by Hasselgren *et al* (1976) on ^{108,110}Pd and Fahlander *et al* (1976) on ^{102}Ru using a γ angular correlation method and the $2'^+$ interference was found to be constructive in all three cases.

Overall the Q_{2^+} data agree very satisfactorily. The Pd and Te data strongly suggest a trend of $|Q_{2^+}|$ increasing with increasing $B(\mathrm{E2}, 0^+ \rightarrow 2^+)$ and decreasing E_{2^+}. The one serious discrepancy in the data occurs in the case of ^{106}Cd and for the purposes of the comparison in §5 it is unclear which measurement(s) to prefer. On the one hand one might expect only a small variation of Q_{2^+} across the Cd isotopes because the $B(\mathrm{E2}, 0^+ \rightarrow 2^+)$ and E_{2^+} vary rather less than in the Pd and Te isotopes. On the other hand, a minimum in $|Q_{2^+}|$ at around ^{112}Cd (very pronounced according to the Rutgers measurements) might be anticipated because of a minimum here in the quantity $R_4 = E_{4^+}/E_{2^+}$, a key parameter in the VMI model (Mariscotti *et al* 1969, Scharff-Goldhaber 1974). Resolution of this particular question must await further and more accurate measurements.

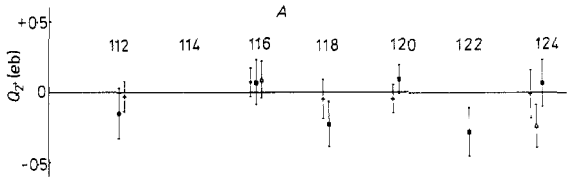

Figure 4. Quadrupole moments of the Sn isotopes. ■, Oak Ridge (Stelson *et al* 1970); +, Pittsburgh (Graetzer *et al* 1975); △, Rutgers (Kleinfeld *et al* 1970a). There are no sum-rule predictions here; this diagram is included for completeness of the data survey.

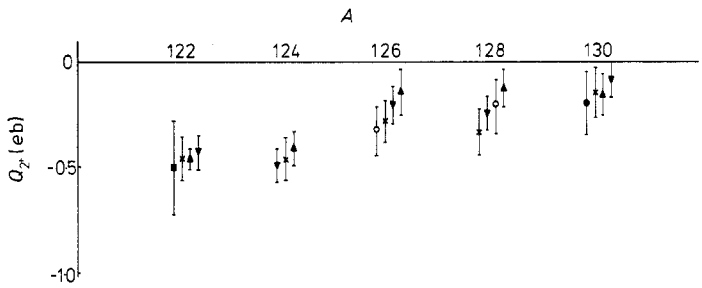

Figure 5. Quadrupole moments of the Te isotopes. ○, Caltech (Stokstad and Hall 1967) (results corrected for deorientation); ▲, Köln (Kleinfeld *et al* 1975, Bockisch and Kleinfeld 1976); ●, Liverpool (Christy *et al* 1970); ×, Montreal (Barrette *et al* 1974); ■, Oak Ridge (Stelson 1968); ▼, Purdue (Larsen *et al* 1974, Ragland *et al* 1975).

4. Approximate relation for $|Q_{2^+}|$ for even–even nuclei

The existence of correlations between Q_{2^+} and other nuclear spectroscopic properties has been suggested by several theoretical investigations in recent years. In the VMI model (Mariscotti *et al* 1969) the major spectroscopic properties of the nucleus are related to the energies of the first 2^+ and 4^+ states (E_{2^+} and E_{4^+}). Cline (1973) presented some evidence for a correlation between Q_{2^+}/Q_{ROT} and the normalized energy difference $(E_{4^+} - E_{2^+})/E_{2^+}$ which he found to agree with the argument by Kumar (1970) that this difference is essentially proportional to the oblate–prolate difference in the collective potential energy.

The collective model sum rules (Kumar 1972, 1975, Cline 1973) provide a method for analysing systematics of nuclear E2 data by relating sets of these data (in the form of sums over products of E2 matrix elements) to the various distribution quadrupole moments of the nuclear surface in the intrinsic frame. Since the latter parameters lend themselves to simple physical interpretation, the method can be employed to carry out self-consistency checks over data sets for the same nucleus and thus test the validity of describing the nucleus in terms of a few collective degrees

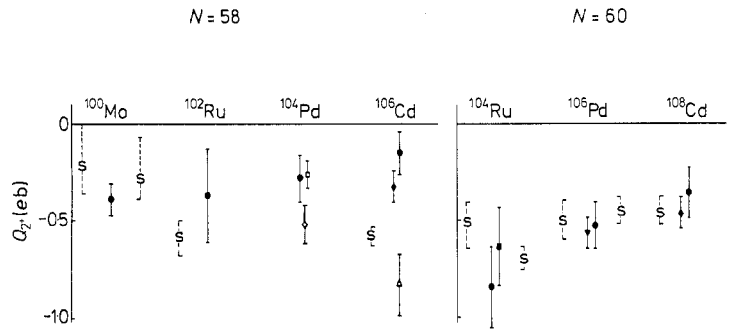

Figure 6. Quadrupole moments of $N = 58$, 60 isotones. ◆, Canberra (Esat *et al* 1976 and private communication); □, Chalk River (Ward *et al* 1971); ●, Liverpool (Harper *et al* 1971, Hall *et al* 1974, Nolan *et al* 1973, present work); ■, Oak Ridge (Stelson 1968); ▼, Purdue (Lutz *et al* 1972); △, Rutgers (Kleinfeld *et al* 1970b); ◇, Uppsala (Hasselgren *et al*, private communication).

of freedom. Alternatively, it can be used to present E2 systematics over regions of the periodic table in terms of the corresponding intrinsic shape parameters which reveal the underlying trends in shape evolution or transition (Cline 1973). The method has the advantage of being independent of any specific collective model although it is based on the generalized collective description of the nucleus.

In principle, application of the sum rules requires the availability of extensive and reliable experimental E2 data (i.e. E2 matrix elements), although in practice the sums are found to converge rather rapidly after the first few terms (Cline 1973, Kumar 1975).

Recently Naqib (1975) investigated a particular aspect of the sum-rules method, namely the equivalence relations among the three sum rules which correspond to the various recoupling schemes of the product $\{[\mathrm{E2} \times \mathrm{E2}]^J \times [\mathrm{E2} \times \mathrm{E2}]^J\}^0$. From the relations obtained and by making the approximation of setting all E2 matrix elements which represent cross-over transitions to zero, Naqib obtained the following two approximate relations:

$$|Q_{2^+}|^2 = \frac{32\pi}{35}(B(\mathrm{E2}; 4^+ \rightarrow 2^+) - B(\mathrm{E2}; 2'^+ \rightarrow 2^+)) \tag{1}$$

$$B(\mathrm{E2}; 4^+ \rightarrow 2^+) = \frac{10}{7}(B(\mathrm{E2}; 2^+ \rightarrow 0^+) + B(\mathrm{E2}; 2^+ \rightarrow 0'^+)). \tag{2}$$

Apart from the cross-over approximation the validity of the above equations depends on the assumption that the nuclear motion can be described in terms of a few collective degrees of freedom. The two points are intimately related: the cross-over approximation may be justified on the strength of the collective description. Indeed, in the theoretical limits of a rigid rotor or a harmonic vibrator, the cross-over transitions vanish and equations (1) and (2) reduce to the correct model expressions for $|Q_{2^+}|$ and $B(\mathrm{E2}; 4^+ \rightarrow 2^+)$.

It appears then that the validity of the approximate equations (1) and (2) might extend from the soft vibrational to the rigid rotational nuclei, improving as one or other of these two limits is approached. Encouragingly, preliminary tests of equation (1) by Naqib (1975) showed remarkable agreement with experiment for the transitional osmium isotopes where the values of the cross-over ratio, $B(\mathrm{E2}; 2'^+ \rightarrow 0^+)/(B\mathrm{E2}; 2^+ \rightarrow 0^+)$ are as much as 10%. This agreement may be due to some cancellation of the cross-over terms on both sides of the equivalence relations from which the approximate formulae were derived.

5. Comparison of approximate sum-rule relation with experiment

The test of equation (1) against the Q_{2^+} data shown in figures 2–6 necessitated a literature search for the $B(\mathrm{E2})$ values required. These values are compiled in table 3. They are all from published measurements. We have not included values which have been deduced from experiment by model-dependent analyses or values which have been adopted in some experiments on the basis of systematic trends.

The $|Q_{2^+}|$ given by equation (1) are shown in column I of table 3. The errors given are those propagated through equation (1) from the errors in the measured

Table 3. Reduced transition probabilities and predictions for $|Q_{2^+}|$. The meaning of columns I and II is explained in §5.

	$B(E2, J_i \rightarrow J_f)^\dagger$ ($e^2 \times 10^{-50}$ cm^4)				$\lvert Q_{2^+}\rvert$ (eb)	
	$2^+ \rightarrow 0^+$	$2^+ \rightarrow 0'^+$	$4^+ \rightarrow 2^+$	$2'^+ \rightarrow 2^+$	I	II
^{100}Mo	10·5 ± 0·5	3·8 ± 0·6	19·5 ± 1·7	17·8 ± 2·1	$0{\cdot}22^{+0{\cdot}14}_{-0{\cdot}22}$	$0{\cdot}28^{+0{\cdot}11}_{-0{\cdot}21}$
^{102}Ru	14·6 ± 1·8		20·1 ± 3·8	8·2 ± 1·2	0·59 ± 0·09	
^{104}Ru	18·6 ± 1·3	1·52 ± 0·15	21·7 ± 3·8	12·3 ± 1·9	0·52 ± 0·12	0·69 ± 0·06
^{104}Pd	10·6 ± 0·6					
^{106}Pd	12·4 ± 0·8	1·8 ± 0·4	22 ± 3	13·6 ± 1·8	0·49 ± 0·10	0·44 ± 0·07
^{108}Pd	14·6 ± 1·0	2·7 ± 0·6	28 ± 4	24·8 ± 5·5	$0{\cdot}30^{+0{\cdot}23}_{-0{\cdot}30}$	$0^{+0{\cdot}41}_{-0}$
^{110}Pd	17·2 ± 1·2	2·3 ± 0·4	31 ± 4	18 ± 3	0·61 ± 0·12	0·53 ± 0·09
^{106}Cd	7·98 ± 0·48		13·7 ± 1·7	2·1 ± 0·7	0·58 ± 0·05	
^{108}Cd	8·34 ± 0·58		12·4 ± 1·5	5·6 ± 1·6	0·44 ± 0·07	
^{110}Cd	8·66 ± 1·22		14·3 ± 1·7	10·1 ± 2·9	$0{\cdot}35^{+0{\cdot}12}_{-0{\cdot}30}$	
^{112}Cd	10·0 ± 0·6		19·8 ± 2·3	5·8 ± 1·1	0·64 ± 0·06	
^{114}Cd	10·3 ± 0·4	1·97 ± 0·37	21·1 ± 2·4	8·1 ± 2·3	0·61 ± 0·08	0·52 ± 0·07
^{116}Cd	12·6 ± 0·4	1·98 ± 0·37	19·5 ± 4·1	7·3 ± 2·0	0·59 ± 0·11	0·63 ± 0·05
^{122}Te	13·2 ± 1·2	2·3	19·6	17·1		
				35 ± 16		
^{124}Te	10·54 ± 0·14		14·4	31·5		
				20		
^{126}Te	9·4 ± 0·4		15·9	12·6		
			12·8 ± 5·6	20		
				20		
^{128}Te	7·6 ± 0·6			4·9		
^{130}Te	6·0 ± 0·6		5·0			

† References for the B(E2) values: ^{100}Mo, Barrette *et al* (1972); ^{102}Ru, McGowan *et al* (1968). For all the other nuclei the $B(E2, 2^+ \rightarrow 0^+)$ have been taken from Christy and Häusser (1972) and the B(E2) values for the higher states have been taken from the following: ^{104}Ru, McGowan *et al* (1968); Pd, Robinson *et al* (1969, 1971); Cd, McGowan *et al* (1965), Milner *et al* (1969), Grabowski and Robinson (1973); Te, Stokstad and Hall (1967), Barrette *et al* (1974), Stelson and McGowan (1961), Kleinfeld *et al* (1975).

B(E2) values. Column II gives the $|Q_{2^+}|$ deduced by substituting 'theoretical' values of $B(E2, 4^+ \rightarrow 2^+)$ from equation (2) into equation (1). There are no significant differences between the values given in columns I and II, which simply means that equation (2) works reasonably well. In figures 2–6 the left-hand brackets show $|Q_{2^+}|$ from column I and the right-hand brackets show $|Q_{2^+}|$ from column II. Of course the sign of Q_{2^+} is not given by equation (1), but the data clearly show that the quadrupole moments are negative. In comparing the predicted $|Q_{2^+}|$ with experiment there are some points of detail which we note below.

The predicted Q_{2^+} depend on the B(E2) values compiled in table 3. Now the experimental values of Q_{2^+} also depend (though not as strongly) on these B(E2) values since the latter are required in the analysis of the reorientation experiments. Clearly a fair comparison of predicted and experimental quadrupole moments—and also of various experimental results for the same nucleus—should be based on a common and consistent set of B(E2) values. In the present comparison this is not always strictly the case for a number of reasons. Some of the Q_{2^+} and B(E2) values

for the higher states may have been deduced from experiment having assumed or determined values of $B(E2, 2^+ \rightarrow 0^+)$ different from those presently adopted. For example, Esat *et al* (1976) report both Q_{2^+} and $B(E2, 2^+ \rightarrow 0^+)$ for the Cd isotopes and in the case of ^{116}Cd their value of $B(E2, 2^+ \rightarrow 0^+)$ is approximately 20% lower than that given in the Christy–Häusser compilation. This makes a differenc of 0·07 *e*b in $|Q_{2^+}|$ for ^{116}Cd in column II of table 3, i.e. strictly speaking the Canberra Q_{2^+} for ^{116}Cd should be compared with $0{\cdot}56 \pm 0{\cdot}05$ *e*b rather than $0{\cdot}63 \pm 0{\cdot}05$ *e*b in column II. In the following cases the experimental values of Q_{2^+} are subject to revision in the light of later measurements of some of the $B(E2)$ values required in the analysis of the reorientation experiments.

(*a*) *^{108}Pd.* At the time of the Liverpool measurement (Harper *et al* 1971) there were two alternative values of $B(E2, 2'^+ \rightarrow 2^+)$ from the Coulomb excitation work of Robinson *et al* (1969). Further work by Robinson *et al* (1971) removed the ambiguity and it turned out that the wrong $B(E2, 2'^+ \rightarrow 2^+)$ had been used by Harper *et al*. We have not re-analysed the Liverpool experiment but estimate that the correct choice of $B(E2, 2'^+ \rightarrow 2^+)$ would have increased $|Q_{2^+}|$ by approximately 0·07 *e*b over that shown in figure 2.

(*b*) *^{106,112}Cd.* Here again the Liverpool measurement for ^{106}Cd (Hall *et al* 1974) and the Rutgers measurements for ^{106,112}Cd (Kleinfeld *et al* 1970b, Steadman *et al* 1970) preceded publication of unambiguous values of $B(E2, 2'^+ \rightarrow 2^+)$ for these nuclei (Grabowski and Robinson 1973). We have not attempted to correct the Rutgers results but we estimate that the Liverpool $|Q_{2^+}|$ for ^{106}Cd should be approximately 0·03 *eb* lower than the published value shown in figure 3. Because it is not practically possible to re-analyse all of the Q_{2^+} and $B(E2)$ data we have simply taken the published Q_{2^+} and $B(E2)$ from the quoted references and have ignored any slight inconsistencies. Judging by the above estimates these would not anyway be very significant at the level of accuracy of the Q_{2^+} data and the predictions of equation (1).

It may be seen in figures 2, 3 and 6 that equation (1) approximately reproduces the magnitudes of the quadrupole moments of these isotopes of Ru, Pd and Cd although obviously the experimental errors preclude an exacting test at this stage.

For the Te isotopes no predictions from equation (1) can sensibly be given. For ^{128,130}Te this is simply because some of the requisite $B(E2)$ values have not been measured. For ^{122,124,126}Te the situation regarding the published $B(E2)$ values is confused. Many of the $B(E2)$ values have been published without errors but in any case the majority of combinations have $B(E2, 4^+ \rightarrow 2^+) < B(E2, 2'^+ \rightarrow 2^+)$ which gives an imaginary $|Q_{2^+}|$ in equation (1). It would be desirable to have further $B(E2)$ measurements to be sure of this point but it is possible that this is a real failure of equation (1). In the VMI model parametrization (Scharff-Goldhaber and Goldhaber 1970) the 'deformed' nuclei have values of $R_4 = E_{4^+}/E_{2^+}$ in the range 2·23–3·33 with vibrational-like nuclei near the 2·23 limit. The Ru, Pd and Cd nuclei tabulated here all fall in this range. The Te isotopes, on the other hand, all fall in the 'spherical region' $1{\cdot}82 < R_4 < 2{\cdot}23$. Thus, although theoretically equation (1) might be supposed to hold down to $R_4 = 2{\cdot}0$ (the value for an ideal harmonic vibrator), its range of applicability for real nuclei may be limited approximately to that of the deformed region of the VMI model.

Acknowledgment

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