Aust. J. Phys., 1985, **38**, 555–61

Determination of $B(E3; 0_1^+ \rightarrow 3_1^-)$ Values for the Stable Isotopes of Cadmium

M. P. Fewell, R. H. Spear, G. K. Adam and M. T. Esat*

Department of Nuclear Physics, Research School of Physical Sciences,
Australian National University, G.P.O. Box 4, Canberra, A.C.T. 2601.

Abstract

Values of $B(E3; 0_1^+ \rightarrow 3_1^-)$ for the stable isotopes of Cd have been determined from particle spectra obtained using Coulomb excitation by ^{16}O projectiles. The results are: $0{\cdot}16 \pm 0{\cdot}04\ e^2\,b^3$ (^{106}Cd), $0{\cdot}150 \pm 0{\cdot}010\ e^2\,b^3$ (^{108}Cd), $0{\cdot}115 \pm 0{\cdot}013\ e^2\,b^3$ (^{110}Cd), $0{\cdot}114 \pm 0{\cdot}009\ e^2\,b^3$ (^{112}Cd), $0{\cdot}131 \pm 0{\cdot}015\ e^2\,b^3$ (^{114}Cd) and $0{\cdot}100 \pm 0{\cdot}011\ e^2\,b^3$ (^{116}Cd). The corresponding E3 strengths are 34, 31, 23, 22, 24 and 18 single particle units (s.p.u.) respectively. Examination of these and other data reveals no evidence for shell effects in $B(E3; 0_1^+ \rightarrow 3_1^-)$ values near the $Z = 50$ proton shell, in contrast to the situation for $B(E2; 0_1^+ \rightarrow 2_1^+)$ values.

1. Introduction

Properties of the 2_1^+ states of even-mass nuclei have been thoroughly studied throughout the periodic table providing, *inter alia*, valuable insights on the interplay between rotational and vibrational degrees of freedom. Studies of 3_1^- states are much less complete; such studies are important for understanding the octupole vibrational mode of nuclei (Bohr and Mottelson 1975). It has been found that in some mass regions (e.g. Hg–Pb), the characteristics of the octupole excitation are more stable as a function of mass than are those of the quadrupole excitation (Baxter *et al.* 1981), suggesting that the octupole excitation is less sensitive to single-particle effects. To further the systematic study of E3 excitations, we present in this paper a determination of $B(E3; 0_1^+ \rightarrow 3_1^-)$ values of the even-mass stable isotopes of Cd.

In previous studies of these nuclei, we measured static electric quadrupole moments Q_{2+} of the first 2^+ states (Esat *et al.* 1976) and investigated vibrational excitations via inelastic ^4He scattering (Spear *et al.* 1977). The vibrational character of the even-mass Cd isotopes was inferred to be remarkably uniform from the following observations: (*a*) the regularity of the single-quadrupole-phonon and single-octupole-phonon excitations in inelastic ^4He scattering; (*b*) the consistency of the mixing of one- and two-phonon 2^+ states required to fit E2 matrix-element data; and (*c*) the constancy of Q_{2+} among the isotopes. We presented no information on $B(E3; 0_1^+ \rightarrow 3_1^-)$ values. However, it has since been realized that the ($^{16}O, ^{16}O'$)

* ANU Vacation Scholar.

0004-9506/85/040555$02.00

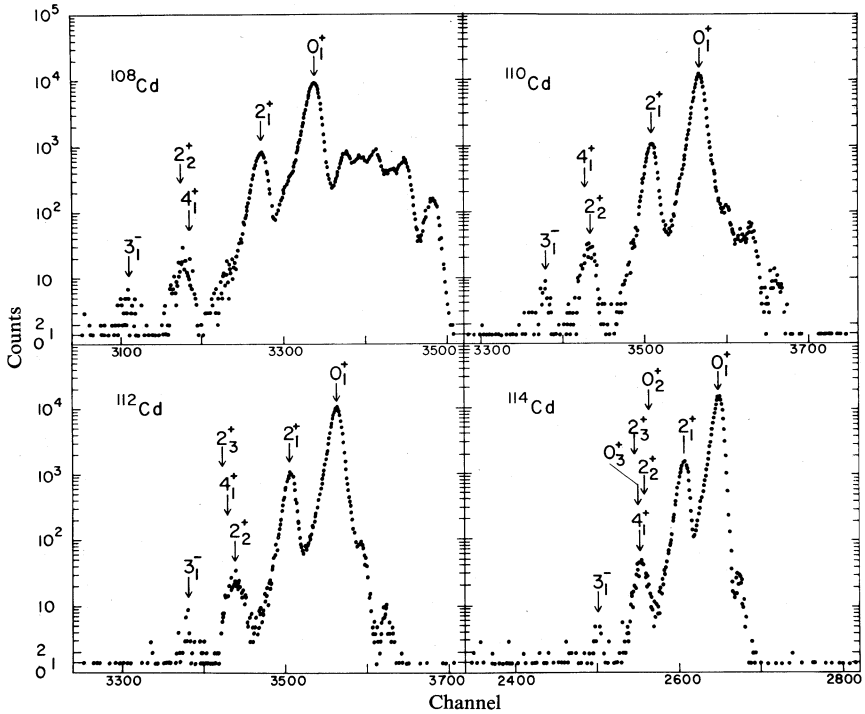

Fig. 1. Spectra of ^{16}O ions scattered from $^{108,110,112,114}Cd$ at bombarding energies of 44·03, 44·03, 43·03 and 41·03 MeV respectively. Peaks corresponding to excited states in the primary isotopes are indicated. Other structure evident in the spectra is due to isotopic contaminants. Channels containing zero counts have not been plotted.

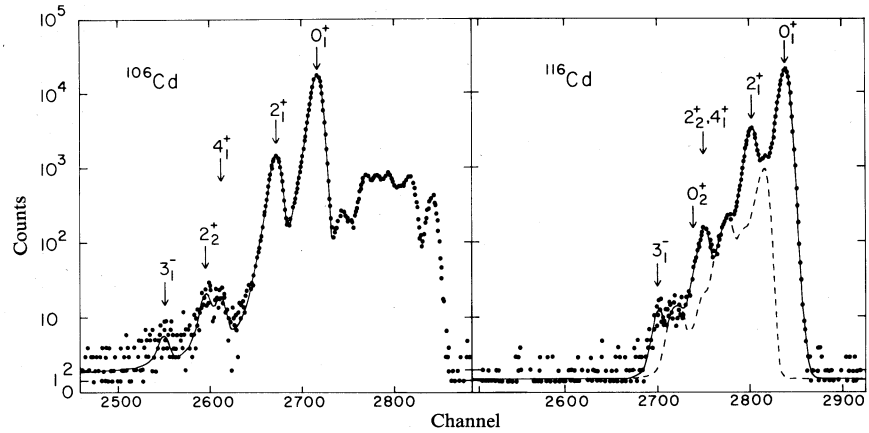

Fig. 2. Spectra of ^{16}O ions scattered from $^{106,116}Cd$ at a bombarding energy of 43·85 MeV. Peaks corresponding to excited states in the primary isotopes are indicated. Other structure evident in the spectra is due to isotopic contaminants in the targets. The full curves are fits to the data obtained as described in Section 2. The dashed curve for ^{116}Cd represents the calculated contribution from isotopic contaminants. Channels containing zero counts have not been plotted.

spectra obtained at energies below the Coulomb barrier by Esat *et al.* (1976) could be analysed to extract B(E3) values. The present paper presents the results of such an analysis for ^{108,110,112,114}Cd, supplemented by new data for ^{106,116}Cd.

Previous B(E3) measurements have been reported for ^{110,112,114,116}Cd by McGowan *et al.* (1965) and for ^{112,114}Cd by Jonsson *et al.* (1978), both from γ-ray spectroscopy. Jonsson *et al.* obtained values considerably larger than those of McGowan *et al.* for ^{112,114}Cd, and suggested that the discrepancy might be due to the neglect of γ-ray anisotropy effects by the other authors. As far as we are aware, no previous information exists on B(E3; $0_1^+ \rightarrow 3_1^-$) in ^{106}Cd and ^{108}Cd.

2. Experimental Procedures and Data Analysis

The data for inelastic scattering of ^{16}O from ^{108,110,112,114}Cd were obtained by Esat *et al.* (1976) using beams of 40–44 MeV ^{16}O projectiles from an EN tandem accelerator. Particles were detected with an annular surface-barrier detector located at a mean laboratory scattering angle of 174·6°. Targets consisted of $CdCl_2$ evaporated onto thin self-supporting carbon foils, the partial thickness of Cd ranging from 3 to 8 $\mu g\,cm^{-2}$. Full details of the experimental procedures and the isotopic compositions of the targets have been given by Esat *et al.* (1976) and Spear *et al.* (1977).

The spectra obtained by Esat *et al.* for ^{106}Cd and ^{116}Cd were no longer available. Therefore, new data were obtained under similar experimental conditions, and with the same targets, using 43·85 MeV ^{16}O projectiles from the ANU 14UD Pelletron accelerator. Typical spectra are shown in Figs 1 and 2. In each case the peak corresponding to the 3_1^- state was identified using known values of the 3_1^- excitation energies (see Table 1) and an internal energy calibration obtained from readily identified peaks in the spectrum.

For the ^{108,110,112,114}Cd spectra, corrections for contributions from Cd isotopes other than the one of interest were negligible and backgrounds were low enough for manual extraction of the peak areas to be quite adequate, given the statistical quality of the data. Representative spectra are shown in Fig. 1. For ^{106}Cd, background problems were more severe, and in the case of ^{116}Cd corrections for other isotopes were significant. Therefore, these spectra were analysed using well-established lineshape-fitting procedures (Esat *et al.* 1976; Fewell *et al.* 1979). The fits obtained are shown by the full curves in Fig. 2.

Although the ^{106}Cd spectrum is the best that could be obtained under the prevailing experimental circumstances, its quality is noticeably inferior to that of the other isotopes, and the value of B(E3; $0_1^+ \rightarrow 3_1^-$) obtained is correspondingly less precise. The peak due to the 3_1^- state in the ^{116}Cd spectrum is not completely resolved from that arising from the very small amount of ^{106}Cd in the ^{116}Cd target. The contributions to the ^{116}Cd spectrum from peaks due to elastic and inelastic scattering from all of the isotopic contaminants are shown by the dashed curve in Fig. 2, which was calculated using the known isotopic composition of the target material (Spear *et al.* 1977) and the previously measured B(E2) values for excited states of the contaminants (Harmatz 1979; Singh *et al.* 1985).

Peak areas obtained from spectrum analysis were used to determine the Coulomb excitation probabilities P_{exp} for the 3_1^- states, where P_{exp} is defined by

$$P_{exp} = d\sigma_{3_1^-}/(d\sigma_{0_1^+} + d\sigma_{2_1^+} + d\sigma_{3_1^-}).$$

3. Results

The multiple Coulomb-excitation program of Winther and de Boer (1966) was used to calculate $B(E3; 0_1^+ \rightarrow 3_1^-)$ for each value of P_{exp} obtained. The results are summarized in Table 1. The bombarding energies shown have been corrected for the effects of target thickness. While, in principle, corrections should also be applied to the bombarding energies for the effects of electron screening, vacuum polarization and nuclear polarization, the net effect of these is negligible in the present case. The calculation of the $B(E3)$ values included the effects of other states using previously measured matrix elements (Spear *et al.* 1977). However, values of $B(E1; 3_1^- \rightarrow 2_1^+)$ and of Q_{3^-}, the quadrupole moment of the 3_1^- state, were not available for any isotope and it was assumed that they were zero. The values of $B(E3; 0_1^+ \rightarrow 3_1^-)$ obtained are somewhat sensitive to this assumption; for example, the inferred value of $B(E3; 0_1^+ \rightarrow 3_1^-)$ for ^{116}Cd would be reduced by 5% if either $B(E1; 3_1^- \rightarrow 2_1^+) = 1{\cdot}4\times10^{-7}\ e^2$ b $(=1{\cdot}9\times10^{-4}$ s.p.u.) or $Q_{3^-} = +0{\cdot}19\ e$ b.

Table 1. Excitation probabilities P_{exp} and deduced values of $B(E3; 0_1^+ \rightarrow 3_1^-)$ for 3_1^- states of Cd isotopes from Coulomb excitation by ^{16}O projectiles of energy E

Excitation energies E_x, all accurate to $\lesssim 1$ keV, are obtained from the following references: Harmatz (1980), Haese *et al.* (1982), de Gelder *et al.* (1983), Peker (1980), Blachot and Marguier (1982) and Blachot *et al.* (1981)

Nucleus	E_x (keV)	E (MeV)	$10^4 P_{exp}$	$B(E3; 0_1^+ \rightarrow 3_1^-)$ (e^2 b^3)
^{106}Cd	2371	43·85	2·4(6)	0·16(4)
^{108}Cd	2202	40·03	1·05(15)	0·142(21)
		41·03	1·49(27)	0·145(27)
		42·03	2·1(3)	0·152(23)
		43·03	2·8(4)	0·147(21)
		44·03	4·0(5)	0·159(18)
^{110}Cd	2079	40·03	1·25(24)	0·120(23)
		44·03	3·8(5)	0·113(15)
^{112}Cd	2005	40·03	1·6(3)	0·120(25)
		41·03	2·3(4)	0·131(22)
		42·03	2·3(5)	0·097(20)
		43·03	3·6(4)	0·114(12)
^{114}Cd	1958	40·03	2·5(4)	0·166(27)
		41·03	2·3(4)	0·115(18)
^{116}Cd	1921	43·85	4·8(6)	0·100(11)

It is essential that data used for Coulomb-excitation analysis should be obtained at bombarding energies sufficiently low for Coulomb–nuclear interference effects to be negligible. All energies used in the present work had been shown by Esat *et al.* (1976) to be 'safe' at the 1% level for Coulomb excitation of the 2_1^+ state. Although it is not necessarily true that energies which are safe for 2_1^+ excitation will also be safe for 3_1^- excitation (McGowan *et al.* 1965; Spear *et al.* 1978*a*), it is extremely unlikely that Coulomb–nuclear interference effects at the energies used in the present work would be significant relative to other uncertainties in the results (Spear *et al.* 1978*b*).

This contention is supported by the fact that, for all isotopes where more than one bombarding energy was used, the values for $B(E3; 0_1^+ \rightarrow 3_1^-)$ show no significant trend to decrease with bombarding energy (Table 1). Consequently, all the data analysed are assumed to be free from significant Coulomb–nuclear interference and have been combined to obtain the weighted mean values of $B(E3; 0_1^+ \rightarrow 3_1^-)$ listed in Table 2.

Table 2. Values of $B(E3; 0_1^+ \rightarrow 3_1^-)$ in e^2b^3 for the stable isotopes of Cd

Nucleus	Present work	McGowan *et al.* (1965)		Jonsson *et al.* (1978)	
	B(E3)	ϵB(E3)	B(E3)	ϵB(E3)	B(E3)
^{106}Cd	0·16(4)				
^{108}Cd	0·150(10)				
^{110}Cd	0·115(13)	0·103(21)	0·119(24)		
^{112}Cd	0·114(9)	0·106(21)	0·129(25)	0·158(27)	0·192(33)
^{114}Cd	0·131(15)	0·090(18)	0·118(23)	0·202(52)	0·265(68)
^{116}Cd	0·100(11)	0·075(15)	0·102(21)		

4. Discussion

In Table 2 the values obtained for $B(E3; 0_1^+ \rightarrow 3_1^-)$ in the present work are compared with those previously reported by McGowan *et al.* (1965) and Jonsson *et al.* (1978). Both of the latter experiments were based upon detection of the γ-ray emitted in the decay of the 3_1^- state to the 2_1^+ state. Consequently they determined $\epsilon B(E3; 0_1^+ \rightarrow 3_1^-)$, where ϵ is the branching ratio of the $3_1^- \rightarrow 2_1^+$ transition. We have deduced values of $B(E3; 0_1^+ \rightarrow 3_1^-)$ from these data using the following values of ϵ: 0·86 for ^{110}Cd (de Gelder *et al.* 1983), 0·82 for ^{112}Cd (Peker 1980), 0·76 for ^{114}Cd (Blachot and Marguier 1982) and 0·73 for ^{116}Cd (Deye *et al.* 1973). It is evident from Table 2 that the present results are significantly more precise than previous work. They are in excellent agreement with those of McGowan *et al.* for ^{110,112,114,116}Cd, suggesting that the lack of anisotropy corrections in that work was not serious. They are substantially smaller however than those of Jonsson *et al.* for ^{112,114}Cd.

Table 3. Transition strengths (s.p.u.) for E3 transitions between the 0_1^+ and 3_1^- states in Cd nuclei

Nucleus	^{106}Cd	^{108}Cd	^{110}Cd	^{112}Cd	^{114}Cd	^{116}Cd
$\lvert M(E3) \rvert^2$	34(9)	31(2)	23(3)	22(2)	24(3)	18(2)

Table 3 lists values of transition strengths (in s.p.u.) for the E3 transitions between the 0_1^+ and 3_1^- states in the Cd nuclei. They are derived from the present data using the relation

$$\lvert M(E3) \rvert^2 = 2{\cdot}404 \times 10^6 \, B(E3; 0_1^+ \rightarrow 3_1^-)/A^2 ,$$

where $B(E3; 0_1^+ \rightarrow 3_1^-)$ is expressed in e^2b^3, and $\lvert M(E3) \rvert^2$ represents the transition strength in s.p.u. (Alexander and Forster 1978). There is little significant variation in strength from one isotope to another, although there is a trend for decreasing

strength with increasing mass. The values are consistent with the observations of Kirson (1982) that $B(E3; 0_1^+ \rightarrow 3_1^-)$ values for all even–even nuclei tend to lie between 10 and 30 s.p.u. and that, in contrast to $B(E2; 0_1^+ \rightarrow 2_1^+)$ values, their variation shows no obvious shell effects. These observations are illustrated in Fig. 3, where E2 and

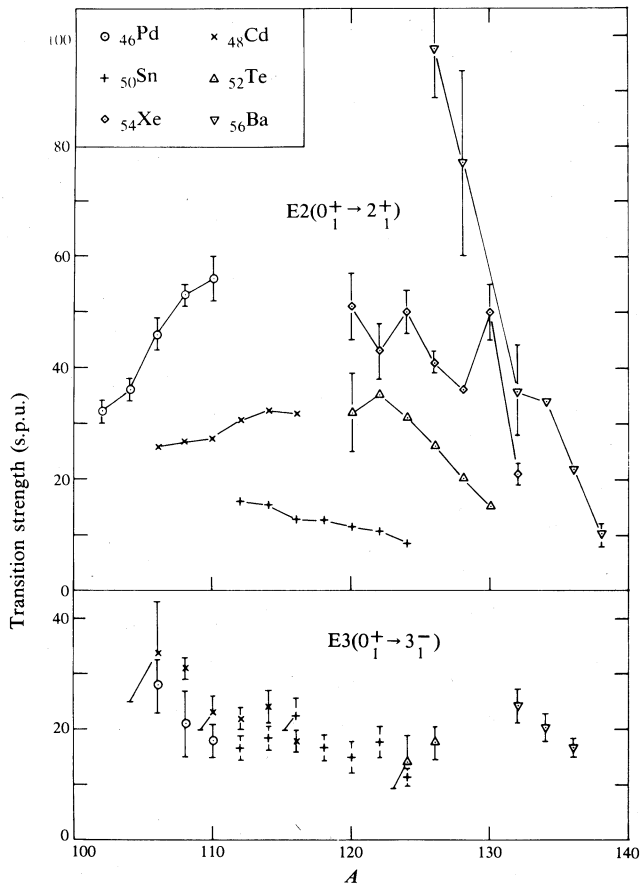

Fig. 3. Transition strengths (s.p.u.) for $E2(0_1^+ - 2_1^+)$ and $E3(0_1^+ - 3_1^-)$ transitions in the mass region near Cd. The E2 data are taken from Endt (1981), except for Cd (Esat *et al.* 1976) and Sn (Jonsson *et al.* 1981). The E3 data are obtained from the following sources: Pd, Robinson *et al.* (1969); Cd, present work; Sn, Jonsson *et al.* (1981); Te, Tamura *et al.* (1982, 1984); and Ba, Burnett *et al.* (1985).

E3 transition strengths are plotted in s.p.u. for elements in the Cd region. The E2 strengths show a pronounced minimum at the $Z = 50$ closed shell, and also decrease markedly at the $N = 82$ nucleus ^{138}Ba. In contrast, the E3 strengths are remarkably uniform and show no indication of shell effects within the accuracy of the data.

References

Alexander, T. K., and Forster, J. S. (1978). 'Advances in Nuclear Physics', Vol. 10 (Eds M. Baranger and E. Vogt), p. 197 (Plenum: New York).

Baxter, A. M., Hinds, S., Spear, R. H., Zabel, T. H., and Smith, R. (1981). *Nucl. Phys.* A **369**, 25.

Blachot, J., Husson, J. P., Oms, J., Marguier, G., and Haas, F. (1981). *Nucl. Data Sheets* **32**, 287.

Blachot, J., and Marguier, G. (1982). *Nucl. Data Sheets* **35**, 375.

Bohr, Aa., and Mottelson, B. R. (1975). 'Nuclear Structure', Vol. 2, Ch. 6 (Benjamin: Reading).

Burnett, S. M., Baxter, A. M., Hinds, S., Pribac, F., Spear, R. H., and Vermeer, W. J. (1985). *Nucl. Phys.* A **432**, 514.

de Gelder, P., Jacobs, E., and de Frenne, D. (1983). *Nucl. Data Sheets* **38**, 545.

Deye, J. A., Robinson, R. L., and Ford, J. L. C. (1973). *Nucl. Phys.* A **204**, 307.

Endt, P. M. (1981). *At. Data Nucl. Data Tables* **26**, 47.

Esat, M. T., Kean, D. C., Spear, R. H., and Baxter, A. M. (1976). *Nucl. Phys.* A **274**, 237.

Fewell, M. P., Baxter, A. M., Kean, D. C., Spear, R. H., and Zabel, T. H. (1979). *Nucl. Phys.* A **321**, 457.

Haese, R. L., Bertrand, F. E., Harmatz, B., and Martin, M. J. (1982). *Nucl. Data Sheets* **37**, 289.

Harmatz, B. (1979). *Nucl. Data Sheets* **27**, 453.

Harmatz, B. (1980). *Nucl. Data Sheets* **30**, 305.

Jonsson, N. G., Bäcklin, A., Kantele, J., Julin, R., Luontama, M., and Passoia, A. (1981). *Nucl. Phys.* A **371**, 333.

Jonsson, N. G., Kantele, J., and Bäcklin, A. (1978). *Nucl. Instrum. Methods* **152**, 485.

Kirson, M. W. (1982). *Phys. Lett.* B **108**, 237.

McGowan, F. K., Robinson, R. L., Stelson, P. H., and Ford, J. L. C. (1965). *Nucl. Phys.* A **66**, 97.

Peker, L. (1980). *Nucl. Data Sheets* **29**, 587.

Robinson, R. L., McGowan, F. K., Stelson, P. H., Milner, W. T., and Sayer, R. O. (1969). *Nucl. Phys.* A **124**, 553.

Singh, K. P., Tayal, D. C., Singh, G., and Hans, H. S. (1985). *Phys. Rev.* C **31**, 79.

Spear, R. H., Warner, J. P., Baxter, A. M., Esat, M. T., Fewell, M. P., Hinds, S., Joye, A. M. R., and Kean, D. C. (1977). *Aust. J. Phys.* **30**, 133.

Spear, R. H., Zabel, T. H., Kean, D. C., Joye, A. M. R., Baxter, A. M., Fewell, M. P., and Hinds, S. (1978*a*). *Phys. Lett.* B **76**, 559.

Spear, R. H., Zabel, T. H., Baxter, A. M., Fewell, M. P., Hinds, S., Joye, A. M. R., and Kean, D. C. (1978*b*). *Aust. J. Phys.* **31**, 377.

Tamura, T., Miyano, K., and Ohya, S. (1982). *Nucl. Data Sheets* **36**, 227.

Tamura, T., Miyano, K., and Ohya, S. (1984). *Nucl. Data Sheets* **41**, 413.

Winther, Aa., and de Boer, J. (1966). *In* 'Coulomb Excitation' (Eds K. Alder and Aa. Winther), p. 303 (Academic: New York).

Manuscript received 12 April, accepted 29 May 1985