

Investigation of the Reorientation Effect in  $\text{Cd}^{110}$  and  $\text{Cd}^{114}$ 

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In contrast to earlier measurements reporting a large negative quadrupole moment for the  $2^+$  state in  $\text{Cd}^{114}$  near the rotational model value of  $-0.65e$  b, new detailed investigations of the reorientation effect in  $\text{Cd}^{114}$  yield  $Q_{2+} = (-0.28 \pm 0.09)e$  b with  $B(E2; 0 \rightarrow 2) = (0.513 \pm 0.005)e^2$  b<sup>2</sup>, or  $Q_{2+} = (-0.03 \pm 0.09)e$  b with  $B(E2; 0 \rightarrow 2) = (0.512 \pm 0.005)e^2$  b<sup>2</sup>. For  $\text{Cd}^{110}$ ,  $Q_{2+} = [-(0.42 \text{ or } 0.21) \pm 0.10]e$  b with  $B(E2; 0 \rightarrow 2) = (0.432 \pm 0.006)e^2$  b<sup>2</sup>.

Since the first experimental observations of the reorientation effect in Coulomb excitation were reported indicating large static quadrupole moments for first excited  $2^+$  states of the so-called vibrational nuclei near  $A \approx 110$ ,<sup>1</sup> considerable theoretical effort has been focused on explaining these unexpectedly large  $Q_{2+}$  values. In assessing the experimental results and their theoretical implications, the value of  $Q_{2+}$  for  $\text{Cd}^{114}$  has assumed a particular significance; the first measurements<sup>2</sup> for  $\text{Cd}^{114}$  have been followed by new discordant results<sup>3-8</sup> which not only leave the  $Q_{2+}$  value for  $\text{Cd}^{114}$  ambiguous but also reflect on the credibility of the conclusions reached regarding the large  $Q_{2+}$  values for the other nuclei in this mass region determined with similar experimental techniques. The  $Q_{2+}$  values now span the full range from a value near zero, expected for a traditional model of harmonic vibrations, to the rotational-model value. Inconsistent results also have been reported for  $B(E2; 0 \rightarrow 2)$ . As was pointed out in Ref. 4, the 10% spread in the  $B(E2)$  values, when reflected in the deduced  $Q_{2+}$ , is itself sufficient to account for the range of  $Q_{2+}$  values. The most disturbing disagreement occurs among the three experiments employing the more straightforward technique of determining the Coulomb excitation probability from direct inelastic-scattering measurements.<sup>2,4,5</sup> None agree simultaneously on both the  $B(E2; 0 \rightarrow 2)$  and  $Q_{2+}$  values.

In view of the inconsistencies in  $Q_{2+}$  for  $\text{Cd}^{114}$  and the interest in the variation of  $Q_{2+}$  with neutron number for the Cd isotopes, we report herein on new and more detailed investigations of the reorientation effect in  $\text{Cd}^{114}$  and in  $\text{Cd}^{110}$  with  $\text{He}^4$  and  $\text{O}^{16}$  projectiles. The results presented combine independent measurements performed at the Weizmann Institute of Science and at the Institut

für Kernphysik, University of Köln. We emphasize that the agreement between these measurements is excellent.

The excitation probabilities for  $\text{He}^4$  and  $\text{O}^{16}$  projectiles were obtained by comparing well-resolved elastically and inelastically scattered particle groups detected in a cooled annular surface-barrier silicon counter at a mean scattering angle of  $176^\circ$ . The  $\text{He}^4$  and  $\text{O}^{16}$  projectile energies were varied from 8 to 16 MeV and from 37 to 48 MeV, respectively. The solid angle of  $\sim 40$  msr subtended by the annular counter represents an improvement of a factor of  $\sim 50$  over that achieved in a previous counter experiment,<sup>4</sup> and a factor of 10 over the measurement with a magnetic spectrometer.<sup>5</sup>

Examples of spectra obtained by scattering  $\text{He}^4$  and  $\text{O}^{16}$  projectiles from  $\text{Cd}^{114}$  are presented in Fig. 1 (similar spectra were obtained for  $\text{Cd}^{110}$ ). In the  $\text{He}^4$  spectra the excellent separation between the elastic and inelastic peaks, the large inelastic peak-to-valley ratios, and the smooth flat background combined to make the analysis straightforward. To assess the accuracy of the computer peak-fitting procedures adopted in the analysis of the  $\text{O}^{16}$  spectra, additional measurements were carried out to study elastic-peak line shapes, and to check on the consistency with which excitation probabilities could be extracted from spectra exhibiting different peak-to-valley ratios. Details regarding target contaminants, line-shape studies, and computer fitting procedures will be presented in a forthcoming publication; but we note here that the overall consistency of the results, over a wide range of excitation probability, lends credence to the peak-unfolding procedure used and to the assignment of errors.

Interference between nuclear processes and Coulomb excitation has been noted previously<sup>5,9,10</sup>

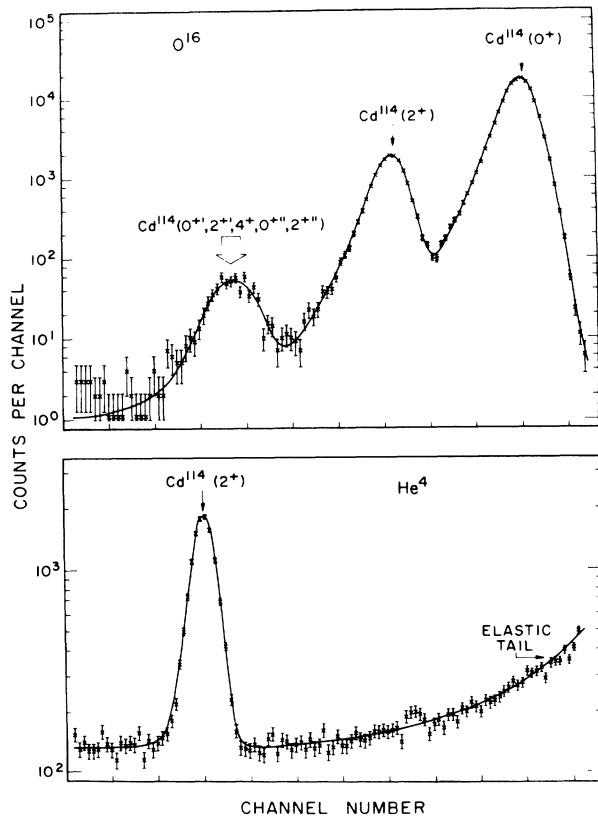


FIG. 1. Spectra of 42-MeV  $O^{16}$  and 8.015-MeV  $He^4$  ions scattered from  $Cd^{114}$  for  $\theta_{lab} = 176^\circ$ . The line through the data points represents a fit using a line shape derived from the elastic-peak line shape.

as a possible source for the experimental discrepancies mentioned above. We have carried out detailed studies of this effect, and our  $He^4$  data presented in Fig. 2(a) show that, in agreement with Refs. 4 and 9 but contrary to the conclusions of Refs. 5 and 10, we do not observe at about the 1% precision level any deviation from the pure-Coulomb-excitation prediction for  $He^4$  energies up to 10 MeV. The  $O^{16}$  data indicate that that appreciable interference does occur at  $O^{16}$  bombarding energies above 46 MeV.

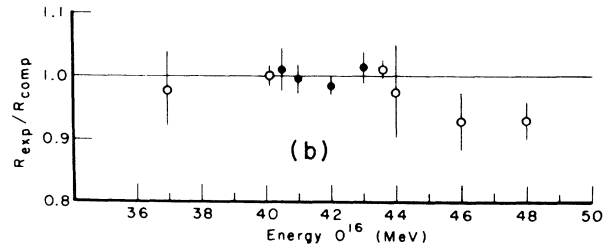
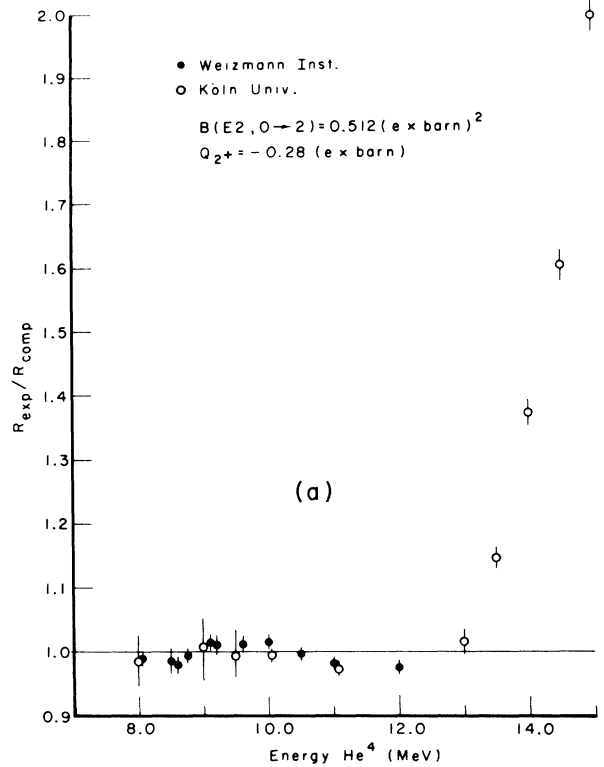


FIG. 2.  $R_{exp}/R_{comp}$  for  $Cd^{114}$  plotted against incident projectile energy (a) for  $He^4$  ions, and (b) for  $O^{16}$  ions.  $R = d\sigma_{inel}/(d\sigma_{e1} + d\sigma_{inel})$ ; quantum effects have not been included in calculating  $R_{comp}$ .

The  $B(E2; 0 \rightarrow 2)$  and  $Q_{2+}$  values deduced from the  $He^4$  and  $O^{16}$  data are given in Table I. In the

TABLE I. Best-fit  $B(E2; 0^+ \rightarrow 2^+)$  and  $Q_{2+}$  values obtained from the  $He^4$  and  $O^{16}$  data.  $\eta_f$  refers to the number of degrees of freedom in the fits. Excitation of the first  $2^+$  state via the giant dipole resonance is not included in the analysis.

Isotope	Interference term	$B(E2; 0^+ \rightarrow 2^+)$ ( $e^2 b^2$ )	$Q_{2+}$ (e b)	$\chi^2/\eta_f$	$\eta_f$
$Cd^{110}$	+	$0.432 \pm 0.006$	$-0.42 \pm 0.10$	1.08	8
	-	$0.432 \pm 0.006$	$-0.21 \pm 0.10$	1.11	8
$Cd^{114}$	+	$0.513 \pm 0.005$	$-0.28 \pm 0.09$	0.59	19
	-	$0.512 \pm 0.005$	$-0.03 \pm 0.09$	0.72	19

analysis, matrix elements involving known excited states above the first  $2^+$  state were taken from Milner *et al.* and McGowan *et al.*<sup>11</sup> The two solutions quoted reflect the ambiguity in the unknown relative signs of the excitation amplitudes to the higher  $2^+$  states. A combination of signs corresponding to the two extreme limits for  $Q_{2^+}$  are presented. The present  $B(E2; 0 \rightarrow 2)$  value for  $\text{Cd}^{114}$  confirms the measurements in Refs. 2-4 and 8, and agrees marginally with Ref. 9. However the  $B(E2; 0 \rightarrow 2)$  values obtained by Saladin *et al.*<sup>5</sup> and by Milner *et al.*<sup>11</sup> are about 10% higher than those reported herein. One of the solutions for the  $\text{Cd}^{114}$   $Q_{2^+}$  value is consistent with zero, while the other solution,  $(-0.28 \pm 0.09)e$  b, is about half the rotational-model value of  $-0.65e$  b. Table II shows other published measurements. For  $\text{Cd}^{110}$  we obtain  $Q_{2^+} = [-(0.42 \text{ or } 0.21) \pm 0.10]e$  b with  $B(E2; 0 \rightarrow 2) = (0.432 \pm 0.006)e^2 b^2$ .<sup>12</sup>

Since for both the Pittsburgh measurement<sup>5</sup> and the one reported herein the assessed errors on the absolute excitation probabilities are  $\sim 1\text{-}2\%$ , we examine the discrepancies between these two experiments in more detail in Fig. 3. All the data taken as a function of the scattering angle, the projectile species, and the energy can be illustrated together by plotting the ratio  $R_{\text{exp}}/R_{\text{comp}}(Q=0)$  against a sensitivity parameter  $\rho$ , defined by<sup>8</sup>  $R(Q) = R(Q=0)(1 + \rho Q_{2^+})$ ;  $R_{\text{comp}}(Q=0)$  is the computed excitation probability for  $Q_{2^+} = 0$ , and  $R_{\text{exp}}$  is the measured excitation probability.

TABLE II. Summary of measurements for  $\text{Cd}^{114}$ . When quoted in the literature we have included  $Q_{2^+}(\text{min})$  and  $Q_{2^+}(\text{max})$  values corresponding to the two extreme choices for the sign of the interference terms via the higher  $2^+$  states.

$B(E2; 0^+ \rightarrow 2^+)$ ( $e^2 \times 10^{-48} \text{cm}^4$ )	$Q_{2^+}(\text{min})$ ( $e \times 10^{-24} \text{cm}^2$ )	$Q_{2^+}(\text{max})$ ( $e \times 10^{-24} \text{cm}^2$ )	Ref.
$0.48 \pm 0.05$	$-0.49 \pm 0.23$		3
$0.503 \pm 0.013$	$-0.76 \pm 0.26$		2
$0.560 \pm 0.045$	$-0.85 \pm 0.14$	$-0.59 \pm 0.14$	2
		$-0.64 \pm 0.19$	6
$0.560 \pm 0.017$	$-0.68 \pm 0.09$	$-0.43 \pm 0.09$	5
$0.509 \pm 0.009$	$0.05 \pm 0.27$	$0.21 \pm 0.28$	4
		$-0.53 \pm 0.17$	7
$0.498 \pm 0.027$	$-0.40 \pm 0.12$		8
$0.506 \pm 0.027$		$-0.32 \pm 0.12$	8
$0.576 \pm 0.023$			11
$0.536 \pm 0.011$		0 (assumed)	9
$0.547 \pm 0.013$	$-0.623$ (assumed)		9
$0.553 \pm 0.014$		$-0.43$ (assumed)	10

For clarity, our twelve  $\text{He}^4$  data points below 10 MeV and nine  $\text{O}^{16}$  data points below 45 MeV have been grouped together and are plotted as two points since the variation in  $\rho$  is small for each projectile species at the same scattering angle. Similarly, the four  $\text{He}^4$  data points below 10 MeV from Ref. 5 have been combined. The spread in the  $\rho$  parameter for the  $\text{O}^{16}$  points from Ref. 5 reflects a spread in scattering angle from  $45^\circ$  to  $142.8^\circ$ .

It is clear that the two  $\text{O}^{16}$  measurements agree at backward scattering angles (large  $\rho$  values), but that the Pittsburgh forward angle data (small  $\rho$  values) yield increasingly larger excitation probabilities as the scattering angle decreases than are consistent with our  $\text{O}^{16}$  and  $\text{He}^4$  measurements. In assessing the discrepancy between measurements it is important to note that if the analysis of the Pittsburgh  $\text{He}^4$  data includes all data points taken with bombarding energies up to and including 10 MeV, their  $\text{He}^4$  datum point falls considerably lower than the best fit through their  $\text{O}^{16}$  data; combining their  $\text{O}^{16}$  data at the backscattering angles with their  $\text{He}^4$  data at  $135^\circ$  yields a  $Q_{2^+}$  value which is within 1 standard deviation of our result. As possible sources of error for the Pittsburgh forward angle data we note that, as the scattering angle decreases, the uncertainty in  $R_{\text{exp}}/R_{\text{comp}}(Q=0)$  is increasingly sensitive to the

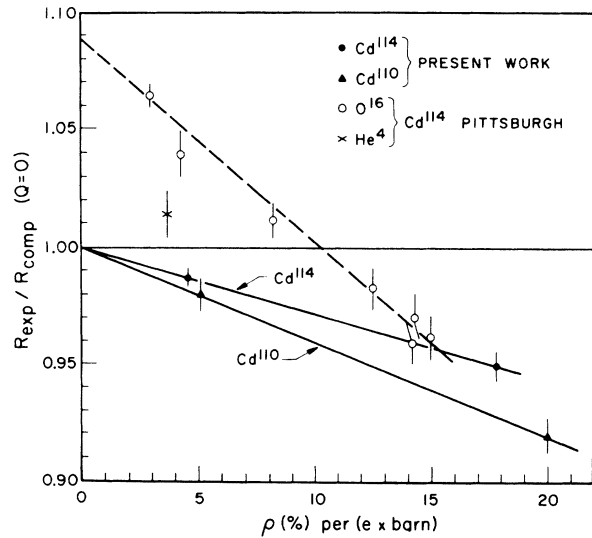


FIG. 3.  $R_{\text{exp}}/R_{\text{comp}}(Q=0)$  plotted versus the sensitivity parameter  $\rho$  defined by  $R(Q) = R(Q=0)(1 + \rho Q_{2^+})$ .  $R_{\text{comp}}$  and  $\rho$  are calculated with a multiple-Coulomb-excitation program. The sign of the interference term was chosen to yield the most-negative  $Q_{2^+}$  value. Quantum effects are not included in  $R_{\text{comp}}$  and  $\rho$ .  $B(E_2; 0 \rightarrow 2)$  is  $0.513e^2 b^2$  and  $0.432e^2 b^2$  for  $\text{Cd}^{114}$  and  $\text{Cd}^{110}$ , respectively.

uncertainties in the determination of the scattering angle and the background under the inelastic peak.

We conclude from the measurements presented herein that  $Q_{2+}(\text{Cd}^{114})$  is significantly smaller than the rotational-model value. The larger negative moment previously associated with  $\text{Cd}^{114}$  was based principally on the results from Refs. 2 and 5. However, a recent investigation<sup>8</sup> of systematic errors associated with particle- $\gamma$  coincidence experiments has shown that the  $Q_{2+}$  value derived from Ref. 2 has to be decreased by about a factor of 2. If, in addition, the result from Ref. 5 is also modified for reasons already cited, the emphasis shifts from the larger moments. The remaining results in Table II are not inconsistent with a  $Q_{2+}(\text{min})$  of about half the rotational-model value. The scatter in these values, however, is large and probably not completely statistical, so that an error-weighted average of all the data cannot be taken appropriately. We point out that the most recent results, from this measurement and from Ref. 8, are consistent with each other; their mean is  $(-0.32 \pm 0.08)e b$ , which, as noted above, is significantly different

from the larger moments on which past theoretical comparisons were based.

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<sup>1</sup>J. deBoer and J. Eichler, in *Advances in Nuclear Physics*, edited by M. Baranger and E. Vogt (Plenum, New York, 1968), Vol. 1, p. 1.

<sup>2</sup>R. G. Stokstad *et al.*, Nucl. Phys. **A92**, 319 (1967).

<sup>3</sup>J. J. Simpson *et al.*, Nucl. Phys. **A94**, 117 (1967).

<sup>4</sup>J. J. Simpson *et al.*, Phys. Lett. **27B**, 633 (1968).

<sup>5</sup>J. X. Saladin *et al.*, Phys. Rev. **186**, 1241 (1969).

<sup>6</sup>G. Schilling *et al.*, Phys. Rev. **C 1**, 1400 (1970).

<sup>7</sup>D. S. Andreyev *et al.*, Phys. Lett. **32B**, 187 (1970).

<sup>8</sup>A. M. Kleinfeld *et al.*, Nucl. Phys. **A158**, 81 (1970).

<sup>9</sup>B. Wakefield *et al.*, Phys. Lett. **31B**, 56 (1970).

<sup>10</sup>R. J. Pryor *et al.*, Phys. Lett. **32B**, 26 (1970).

<sup>11</sup>W. T. Milner *et al.*, Nucl. Phys. **A129**, 687 (1969); F. K. McGowan *et al.*, Nucl. Phys. **66**, 97 (1965).

<sup>12</sup>While this paper was in the process of publication R. P. Harper *et al.*, Nucl. Phys. **A162**, 161 (1971), reported a coincidence experiment on  $\text{Cd}^{110}$  which agrees with this result.

## Reaction $D(d, n)^3\text{He}$ at $0^\circ$ with Polarized Beam: A New Source of Polarized Neutrons from 7 to 18 MeV\*

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Experimental results are reported for the neutron polarization from the reaction  $D(d, n)^3\text{He}$  at  $0^\circ$  with the incoming beam polarized to the extent  $p_3 = p_{33} \approx 0.82$  perpendicular to the direction of motion, where  $p_3$  and  $p_{33}$  are components of vector and tensor polarizations, respectively. The measured neutron polarization varies in the range 0.65 to 0.72 for  $E_d$  in the range 4.1 to 15.1 MeV. The measurements are consistent with a process in which the neutron spin suffers little interaction. The influence of the deuteron  $D$  state is noted. Comparison is made to several other sources of polarized neutrons, with the conclusion that near  $E_n = 10$  MeV this process is outstanding.

The reaction  $D(d, n)^3\text{He}$  is a very high-yield source<sup>1,2</sup> of monoenergetic neutrons with energies in the neighborhood of  $E_n = 10$  MeV. It is also very sharply peaked forward in the laboratory system, such that by  $\theta = 30^\circ$  (lab) the cross section is down by a factor of 10 compared to  $0^\circ$ . The forward peaking becomes more pronounced as energy increases. With an unpolarized deuteron beam incident, it is necessary to work near the cross-section minimum to obtain polarized neutrons. The highest neutron polar-

ization for this reaction was reported by Spalek *et al.*<sup>3</sup> to be about 0.43 at  $E_d = 12$  MeV and  $31.1^\circ$  (lab). Under these conditions the cross section is 20 times smaller than that at  $0^\circ$ .

Polarizing the incident beam changes the situation completely. The purpose of this note is to present measurements of the neutron polarization from the  $d-d$  reaction at  $0^\circ$ , where a polarized deuteron beam is used. The resulting values of neutron polarization are large and remarkably constant for  $E_d$  in the range 4 to 15