indicates that the resistance to motion of dislocations by the conduction electrons plays an important role in deformation processes at low temperatures, in contrast to ideas about totally thermally activated processes at barriers, and that the viscosity for dislocation in motion is closely related to the ultrasonic attenuation by electrons.

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[1]F. R. N. Nabarro, *Theory of Crystal Dislocations* (Clarendon Press, Oxford, England, 1967).

[2]W. P. Mason, in *Dislocation Dynamics*, edited by A. R. Rosenfield, G. T. Hahn, A. L. Bement, and R. I. Jaffee (McGraw-Hill, New York, 1968), p. 487, and Phys. Rev. 143, 229 (1966).

[3]V. Ya. Kravchenko, Fiz. Tverd. Tela 8, 927 (1966) [Sov. Phys. Solid State 8, 740 (1966)].

[4]B. R. Tittmann and H. E. Bommel, Phys. Rev. 151, 178 (1966).

[5]H. Kojima and T. Suzuki, Phys. Rev. Lett. 21, 896 (1968).

[6]G. A. Alers, O. Buck, and B. R. Tittmann, Phys. Rev. Lett. 23, 290 (1969).

[7]G. Kostorz, Scr. Met. 9, 95 (1970).

[8]M. Suenaga and J. M. Galligan, Scr. Met. 4, 697 (1970), and 5, 61 (1971).

[9]A. V. Granato, Phys. Rev. Lett. 27, 660 (1971), and Phys. Rev. B (to be published).

[10]M. Suenaga and J. M. Galligan, in Proceedings of the Spring Meeting of the Metallurgical Society of the American Institute of Mining and Metallurgical Engineers, Atlanta, Georgia, 17 May 1971 (unpublished).

[11]J. S. Koehler, in *Imperfections in Nearly Perfect Crystals*, edited by W. Shockley (Wiley, New York, 1952), p. 197.

[12]A. V. Granato and K. Lucke, J. Appl. Phys. 27, 583 (1956).

[13]M. Suenaga and J. M. Galligan, unpublished data.

[14]A. Hikata and C. Elbaum, Phys. Rev. Lett. 18, 750 (1967).

[15]G. H. Huffman and N. Louat, Phys. Rev. Lett. 24, 1055 (1970).

[16]M. Suenaga and K. M. Ralls, J. Appl. Phys. 37, 4197 (1966).

[17]B. R. Tittmann, Phys. Rev. B 2, 625 (1970), and J. Phys. Chem. Solids 31, 1687 (1970).

[18]D. G. Farrell and B. S. Chandrasekhar, Phys. Rev. 177, 694 (1969).

[19]V. P. Galaiko and I. I. Falko, Zh. Eksp. Teor. Fiz. 52, 976 (1967) [Sov. Phys. JETP 25, 646 (1967)].

[20]F. B. McLean and A. Houghton, Phys. Lett. 25A, 736 (1967).

[21]K. Maki, private communication with B. R. Tittmann.

[22]K. Maki, in *Superconductivity*, edited by R. D. Parks, (Marcel Dekker, New York, 1969), Vol. 2, p. 1035.

[23]K. Maki and P. Fulde, Solid State Commun. 5, 21 (1967).

[24]F. B. McLean and A. Houghton, Phys. Rev. 157, 350 (1967).

[25]K. Maki, Physics (Long Is. City, N.Y.) I, 21 (1964).

Nuclear Quadrupole Interaction in Cadmium Metal

P. Raghavan and R. S. Raghavan

Physik Department der Technischen Universität München, 8046 Garching bei München, Germany

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The nuclear quadrupole interaction of the 247-keV level of ^{111}Cd in pure Cd metal has been measured by the time-differential perturbed angular correlation method. The interaction frequency $\nu_Q = (e^2qQ/h) = 125(1)$ MHz at 298°K. A measurement at 77°K shows an increase of ν_Q by 10% instead of a decrease expected from the contraction of the unit lattice of Cd metal.

Cadmium metal has been the subject of several recent solid-state investigations, both theoretical and experimental,[1] partly because of its exceptional nature among hcp metals. One of the few types of information which is still lacking is the quadrupole interaction (QI), presumably because the vanishing quadrupole moments of all stable Cd isotopes prevent the application of conventional resonance techniques. We report here the discovery of a strong QI in pure Cd metal at 298°K by the method of time-differential perturbed angular correlations (TDPAC) involving the 247-keV level in ^{111}Cd. An interaction of this strength has not been reported before although Kraushaar and Pound[2] attempted to measure it in the same level using the inherently less sensi-

tive time-integral correlations and estimated a QI more than an order of magnitude smaller than the present result. We report in addition a result at $T = 77°K$ which suggests that the QI varies anomalously with temperature.

The angular correlation of a cascade of two γ rays displays a measurable perturbation by the QI in a noncubic site if the intermediate level has a nonvanishing quadrupole moment Q and the interaction frequency is not too small compared to $(2\pi\tau)^{-1}$, where τ is the mean life of the level. In the case of a pure QI the TDPAC function can be written for the present case as[3]

$$W(\theta, t) = 1 + A_2 G_2(t) P_2(\cos\theta), \quad A_4 \approx 0, \tag{1}$$

where θ is the angle between the two γ rays, A_2 is the correlation coefficient, and $G_2(t)$ describes the perturbation. For the case of an axially symmetric, static electric field gradient (EFG), $G_2(t)$ for a nuclear level with spin $I = \frac{5}{2}$ is given by

$$G_2(t) = \tfrac{1}{5}[1 + \tfrac{13}{7}\cos\omega_0 t + \tfrac{10}{7}\cos 2\omega_0 t + \tfrac{5}{7}\cos 3\omega_0 t]. \tag{2}$$

Here $\omega_0 = (3e^2qQ)/2I(2I-1)\hbar$ and q is the EFG at the nuclear site. When the lifetime of the intermediate level is long enough and the coincidences of the two γ rays can be observed as a function of time, the exponential decay curve is modulated by $G_2(t)$, the amplitude of modulation being determined by A_2, the angle θ, and by factors which reduce the ideal A_2 due to finite geometries. The experiment consists in observing these modulations and extracting ω_0 therefrom.

The well-known 247-keV level ($I = \frac{5}{2}$) in ^{111}Cd with a half-life of 84 nsec is very suitable for TDPAC measurements. In the present experiments this level is populated in the 48-min decay of ^{111m}Cd obtained by neutron irradiation of 91.5% enriched pure ^{110}Cd metal[4] for a few minutes. Although the short lifetime of the source presents some inconvenience, this manner of populating this level ensures that the source is pure Cd at all times and no uncertainty due to the decay and subsequent electronic relaxation of a neighboring element in the host arises.

The 150–247 keV γ-γ coincidences in ^{111}Cd were observed by two 38-mm-diam×25-mm NaI(Tl) detectors and recorded in a multichannel analyzer by standard time spectrometry. The system time resolution under experimental conditions was 2.5 nsec. Experiments were done with detectors at 180°. The low-temperature run was made in a similar manner but with the source sealed in a plastic envelope and immersed in liquid nitrogen. The sources, 7-mg/cm^2 thick metal foils (7×4 mm^2), were used directly after the irradiation without any further treatment.

Figure 1 shows the time spectrum recorded at room temperature, which displays clearly the modulations of the exponential decay by the precession of the quadrupole moment in the EFG of Cd metal. The solid line is a fit by the function $N = N_0 \exp(-\lambda t)[W(\theta, t)] + C$, where $W(\theta, t)$ is given by (1), λ is the decay constant of the intermediate level, and C is a constant accounting for the random coincidences. The ω_0 extracted from

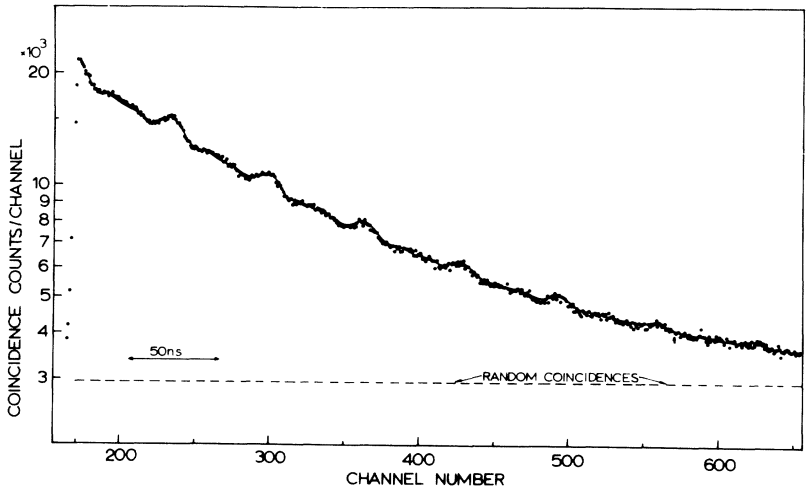

FIG. 1. Decay curve of the 247-keV level in ^{111}Cd modulated by the quadrupole interaction in Cd metal at 298°K. The solid line is the least-squares fit by the function $N = N_0 \exp(-\lambda t)[1 + A_2 G_2(t) P_2(\cos\theta)] + C$, where $\theta = 180°$ and $G_2(t)$ is the theoretical function for an axially symmetric, static EFG and for nuclear spin $I = \frac{5}{2}$.

the fit was $\omega_0 = 117.8(8) \times 10^6$ sec^{-1} corresponding to $\nu_Q(298°K) = e^2qQ/h = 125(1)$ MHz. Similar measurements at $T = 77°K$ yielded $\nu_Q(77°K) = 136.8(15)$ MHz.

The following conclusions can be drawn from the above results:

(1) The main modulation peaks show within experimental errors no tendency to decay. Thus lattice damage due to the irradiation or the recoil from the 150-keV γ ray as well as relaxation effects are negligible. The results show that the EFG is axially symmetric, static and unique at both the temperatures.

(2) Das and Pomerantz[5] have estimated the EFG in hcp metals arising from the ionic cores in the lattice. Using the value of Q estimated from the measured QI of Cd in In metal,[6] we can compute the EFG in Cd metal from the present result. Compared with the theoretical calculation of Das and Pomerantz, this value is too large by more than a factor of 2, showing that either (a) the quadrupole moment used is incorrect or (b) the ionic cores contribute only partly to the EFG, the rest coming from other sources, viz., the conduction electrons.

(3) The low-temperature result strengthens the second possibility. The Cd unit lattice is very elongated ($c/a = 1.886$ at 298°K)[7] and along with zinc, is exceptional compared to all other hcp metals which have $c/a \leq 1.633$. As the temperature decreases, c/a near 0°K becomes 1.8616,[1] i.e., the unit cell approaches spherical symmetry. The EFG at 77°K is therefore expected to *decrease* by a few percent ($\approx 10\%$ at 0°K) if it is produced solely by the ionic cores. The fact that we observe an *increase* of 10% indicates also a *variation* of the electronic EFG strong enough to overcompensate the expected decrease of the ionic EFG. Cd is a divalent metal with two s valence electrons which in principle should produce only a small correction to the ionic EFG. This is the case, for example, in the isoelectronic Be metal.[8] But our results draw immediate comparison to the rapid decrease of the Knight shift in Cd metal as the temperature decreases from the melting point (594°K) to 4°K.[9-11] This has been explained as due to the variation from s to p character of the electronic wave function produced by the electron-phonon interaction.[12] The p admixture in the wave function is usually responsible for creating an electronic EFG.[13] Thus an explanation of our results on the lines similar to those advanced for the Knight-shift behavior might be possible.

We believe that the simplicity and relative precision of the TDPAC technique in this case promises valuable information bearing on the origin of the EFG in Cd metal which could be hard to reach by other methods. We are currently undertaking more detailed measurements on the dependence of the QI with temperature.

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[1]R. V. Kasowski, Phys. Rev. 187, 885, 891 (1969), and references therein.

[2]J. J. Kraushaar and R. V. Pound, Phys. Rev. 92, 552 (1953).

[3]R. M. Steffen and H. Frauenfelder, in *Perturbed Angular Correlations*, edited by E. Karlsson, E. Matthias, and K. Siegbahn (North-Holland, Amsterdam, 1964).

[4]The enriched ^{110}Cd metal was obtained from V/K Technabexport, Moscow, through Rohstoff-Einfuhr und Handelsgesellschaft Ost MbH, Düsseldorf, Germany. It had a stated purity of 99.97%.

[5]T. P. Das and M. Pomarantz, Phys. Rev. 123, 2070 (1961).

[6]H. J. Behrend and D. Budnick, Z. Phys. 168, 155 (1962).

[7]E. R. Jette and F. Foote, J. Chem. Phys. 3, 605 (1935).

[8]M. Pomerantz and T. P. Das, Phys. Rev. 119, 70 (1960).

[9]E. F. W. Seymor and G. A. Styles, Phys. Lett. 10, 70 (1964).

[10]F. Borsa and R. G. Barnes, J. Phys. Chem. Solids 27, 567 (1966).

[11]S. N. Sharma and D. L. Williams, Phys. Lett. 25A, 738 (1967).

[12]R. V. Kasowski and L. M. Falicov, Phys. Rev. Lett. 22, 1001 (1969).

[13]C. P. Slichter, *Principles of Magnetic Resonance* (Harper and Row, New York, 1963), p. 174-176.