we should point out the recent observation [M. J. Rice, Phys. Lett. 39A, 289 (1972)] to the effect that the presence of a weak random potential along the strands in the real MVPC compounds will by no means rule out the existence of a 1D metallic state, at least, in the sense of the interrupted-strand model.

[10] A detailed microscopic development of the interrupted-strand model has been recently completed [M. J. Rice and J. Bernasconi, to be published].

[11] See, for example, Ref. 3.

[12] A. S. Berenblyum *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. 13, 619 (1971) [JETP Lett. 13, 440 (1971)].

[13] A similar estimate was found in Ref. 7 in which a simple phenomenological model of the optical properties of a 1D metal, based on the interrupted-strand model, was presented.

Time-Differential Quadrupole Interaction of Cd^{111} Nuclei Implanted by (α, $2n$) Reactions into a Cubic Ag Lattice*

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(Received 22 May 1972)

The quadrupole interaction of Cd^{111} ions following the decay of In^{111} implanted by $(\alpha, 2n)$ reactions into a cubic (fcc) Ag lattice has been measured with the time-differential perturbed angular correlation method. In addition to a smeared-out quadrupole interaction with a centroid frequency of $\bar{\omega}_Q \simeq 2.5$ MHz, about 10% of the implanted Cd^{111} ions experience a unique quadrupole interaction with $\omega_Q{}^0 = 115$, 130, or 140 MHz, depending on the primary α beam. Annealing causes the quadrupole perturbation to vanish completely.

In a recent Letter, McDonald, Lesser, and Fossan[1] reported measurements of the quadrupole interaction of the 247-keV state of Cd^{111} implanted by recoil in Coulomb excitation into polycrystalline Cd metal. The results of these measurements indicate that most of the recoiling Cd^{111} ions come to rest at the regular lattice sites of the polycrystalline Cd catcher and that the quadrupole interaction is the same as the lattice quadrupole interaction in the hexagonal Cd metal which has been observed by perturbed angular correlation methods.[2] No evidence was found of the recoiling ions ending up interstitially or of crystal damage such as nearby vacancies or interstitials in the host lattice produced by the recoiling ion or the primary particle beam.

The present work describes the observation of a nonvanishing static quadrupole interaction of In^{111}-Cd^{111} ions that were implanted into a cubic (fcc) Ag lattice by the recoil experienced in an $(\alpha, 2n)$ reaction. Since the static quadrupole interaction of ions at regular lattice sites in a nondamaged cubic lattice would vanish, the experiments clearly indicate the presence of interstitial occupations by the Cd^{111} ions or, more likely, of considerable damage of the cubic Ag host lattice.

The experiments consisted of bombarding polycrystalline Ag foils at room temperature with 22-MeV α particles from the Purdue tandem accelerator and with 35- and 45-MeV α particles from the Argonne cyclotron, thus producing, by an $(\alpha, 2n)$ reaction, In^{111} nuclei in the Ag lattice with recoil energies in the MeV range. The In^{111} ions slow down, mainly by electronic interactions. Nuclear stopping becomes important at the end of the slowing-down process and host atoms are displaced from their lattice sites by nuclear collisions. After the In^{111} ions come to rest somewhere in the cubic Ag lattice, they decay by electron capture with a half-life of 2.8 days to the 419-keV excited state of Cd^{111}. The 172-keV γ radiation de-exciting this state populates a state of 247-keV excitation energy which has a lifetime of $\tau = 123$ nsec before it decays to the Cd^{111} ground state. During this lifetime the 247-keV, $I = \frac{5}{2}$ Cd^{111} state is exposed to hyperfine fields which can be accurately measured by observing the time dependence of the perturbation of the angular correlation between the 172- and 247-keV γ rays of Cd^{111}.[3]

It is well known that the atomic shell of the Cd^{111} ion recovers within a short time ($< 10^{-11}$ sec) from the preceding electron capture in a metallic environment.[3] Time-dependent electric field gradients due to vacancy diffusion may produce small perturbation. Within the time range of interest here (100 nsec), and since the relaxation times are of the order of several μsec at room temperature,[4] these perturbations can be neglected. Magnetic hyperfine interactions can be excluded since both Cd and Ag are diamagnetic. Consequently only the interaction of the electric quadrupole moment of the 247-keV Cd^{111} state ($Q \cong 0.5 \times 10^{-24}$ cm^2)[5] with possible static electric field gradients (EFG's) V_{zz} (which for simplicity are assumed to be axially symmetric!) is expected to cause a strong perturbation of the Cd^{111} directional correlation. In this way the observation of the quadrupole frequency $\omega_Q = 3\pi\nu_Q/10 = 3eQV_{zz}/20\hbar$ (for $I=\frac{5}{2}$) of the 247-keV Cd^{111} state serves as a probe of the symmetry of the site where the parent In^{111} nucleus has come to rest. The quadrupole frequency ω_Q can be accurately determined by observing the time dependence of the attenuation factor $G_{22}(t)$ in the angular correlation function[3] $W(\theta) = 1 - 0.181 G_{22}(t) P_2(\cos\theta)$[6] of the 172- and 247-keV γ rays of Cd^{111}. For a unique sharp value of V_{zz}, the time dependence of $G_{22}(t)$ is periodic with a period of $T_0 = 2\pi/\omega_Q$. If $V_{zz} = 0$, the attenuation factor is $G_{22}(t) \equiv 1$.

Figure 1 shows the observed time dependence of $G_{22}(t)$ for various time intervals T_{ab} *after the end of the 22-MeV α bombardment* in the Purdue tandem accelerator which produced the In^{111}-Cd^{111} in the Ag foils (curves A, B, and C). During and between these measurements the Ag foils were kept at room temperature. The curves show very clearly that the Cd^{111} nuclei are exposed to nonvanishing perturbations in the "cubic" Ag lattice.

The analysis of the observed time dependence of the perturbation factor $G_{22}(t)$ shows that curve A (observed at $T_{ab} = 36$ h after bombardment) is consistent with a Gaussian distribution of the quadrupole frequency ω_Q around a centroid of $\bar{\omega}_Q = 2.5 \times 10^6$ Hz and a relative width of $\sigma/\bar{\omega}_Q = 0.25$. Attempts to fit the $G_{22}(t)$ curve on the basis of the assumption that a fraction ϵ of the Cd^{111} nuclei experience a unique quadrupole interaction with a sharp frequency $\omega_Q{}^0$, while a fraction $1-\epsilon$ are unperturbed, failed. At room temperature the average quadrupole frequency $\bar{\omega}_Q$ decreases slowly with T_{ab} (curves B and C) and then stays constant after about $T_{ab} = 80$ h.

Annealing of the Ag foil at 600°C for several hours causes the quadrupole perturbation to vanish completely (curve D).

There is an indication of the presence of some small peaks in curve A at periodic intervals of about 55 nsec of the delay time. These periodic peaks are shown in curve A of Fig. 2 which shows the results of a measurement extending from $T_{ab} = 20$ h to $T_{ab} = 100$ h. The presence of these peaks suggests that in addition to the smeared-out quadrupole frequency $\bar{\omega}_Q$ a certain percentage (about 5–7%) of the Cd^{111} nuclei experience a sharp quadrupole frequency of $\omega_Q{}^0 \cong 11.5 \times 10^7$ sec^{-1}, corresponding to a unique EFG of about 8×10^{21} V/m^2 (using $Q = 0.6$ b for the Cd^{111} quadrupole moment).

The same time-delay measurements were performed on In^{111}-Cd^{111} nuclei implanted with a 45-MeV α beam of the Argonne cyclotron (2-h bombardments with 10 μA α current).[7] Two examples

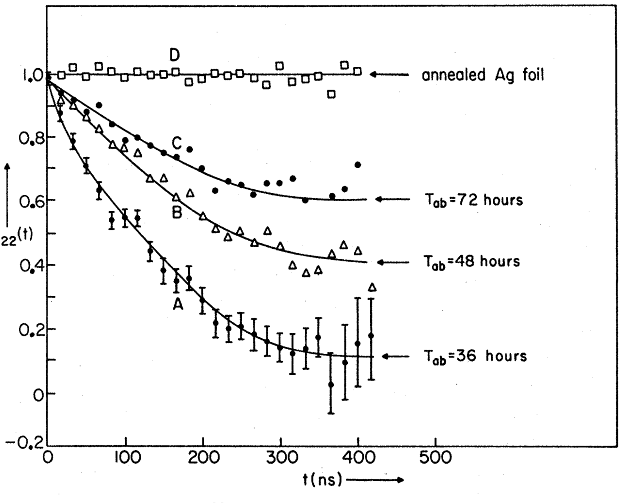

FIG. 1. Time-differential attenuation coefficients $G_{22}(t)$ of the Cd^{111} γ-γ directional correlation of In^{111}-Cd^{111} implanted into Ag by the $(\alpha, 2n)$ reaction with the 22-MeV α beam of the Purdue tandem accelerator. Curves A, B, and C were observed approximately 36, 48, and 72 h, respectively, after the end of the α bombardment. Curve D shows the differential time behavior of $G_{22}(t)$ for an annealed source.

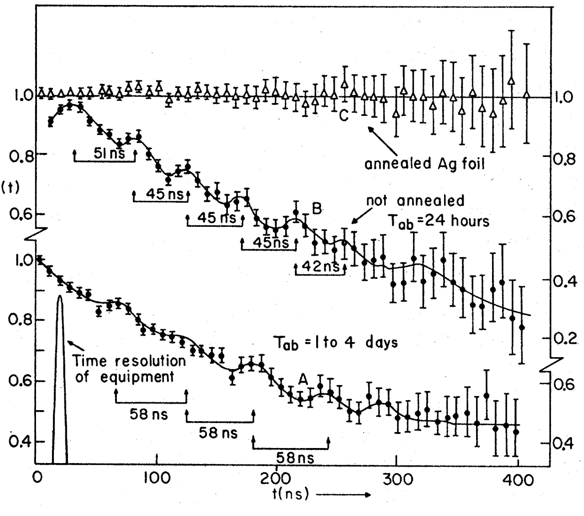

FIG. 2. Time-differential attenuation coefficient $G_{22}(t)$ for In^{111}-Cd^{111} implanted into Ag by $(\alpha, 2n)$ reactions. Curve A shows $G_{22}(t)$ observed for 3 days starting 1 day after the end of a 22-MeV α bombardment with the tandem accelerator. Curve B shows $G_{22}(t)$ observed 1 day after the end of a 45-MeV α bombardment in the Argonne cyclotron. Curve C was obtained with an annealed "cyclotron source."

of the observed $G_{22}(t)$ curves are shown in Fig. 2 (curves B and C). The general behavior pattern of the quadrupole interaction is the same as with the 22-MeV-α tandem bombardments. The periodic peaks are somewhat enhanced and their period corresponds to a sharp quadrupole frequency $\omega_Q{}^0$ of about $\omega_Q{}^0 = 14\times10^7$ sec^{-1} (EFG of about 10^{22} V/m^2) experienced by about 12% of the nuclei. A similar result was observed for sources obtained with a 35-MeV α beam from the Argonne cyclotron, displaying a sharp quadrupole frequency $\omega_Q{}^0$ of about $\omega_Q{}^0 = 13\times10^7$ sec^{-1}. In all cases the periodic peaks disappear gradually within a period of several days after the end of the α bombardment, and the quadrupole perturbations vanish completely after annealing at 600°C (curve C).

Several interesting facts emerge from the analysis of these observations:

(1) The Cd^{111} nuclei experience a smeared-out EFG in the cubic Ag lattice. The EFG's are either due to a random occupation of various interstitial sites of noncubic symmetry or, more likely, caused by vacancies or interstitials produced by the recoiling ions and/or by the primary α beam, thus destroying the cubic symmetry near the In^{111}-Cd^{111} impurity ion. The slow decrease of the average quadrupole interaction strength with time T_{ab} at room temperature (curves A, B, and C of Fig. 1) is easily explained by a gradual healing of the radiation damage of the crystal lattice or by a slow diffusion of the In^{111}-Cd^{111} impurity ions from interstitial to regular lattice sites. It is interesting to note that at room temperature after about 3 days no further "healing" takes place and the effective perturbation stays constant. At higher temperatures ($T > 500$°C) these healing or diffusion effects lead to the occupation of regular cubic lattice sites by the decaying ions within a few hours (annealing) and hence to the complete disappearance of the quadrupole perturbation (curve D of Fig. 1 and curve C of Fig. 2).

(2) The observation of a sharp quadrupole frequency $\omega_Q{}^0$ may be caused by a vacancy in *one* of the $\langle 100\rangle$ sites closest to the decaying ion. An estimate[8,9] of the EFG produced by such a single vacancy gives a gradient of about 10^{22} V/m^2, in qualitative agreement with the observed values of the sharp EFG.

(3) The relative intensity of the sharp quadrupole-frequency peaks and the corresponding $\omega_Q{}^0$ was observed to be somewhat different for different α bombarding energies and/or currents. It should be kept in mind that not only the α energies were different in the tandem and cyclotron bombardments but that the instantaneous current rates in the dc-type tandem α bombardment and the radio-frequency intensity-modulated cyclotron α bombardment were quite different. A further investigation of these phenomena is in progress.

In conclusion it can be stated that the assumption that ions recoiling into a cubic metal lattice experience small or nonvanishing quadrupole interactions is, in general, not correct. Similarly, the use of electrostatic gradients in noncubic crystals for measurements of electric quadrupole moments in nuclear-reaction or Coulomb-excitation recoil implantation experiments must be very carefully scrutinized for the existence of the not completely understood EFG-producing or EFG-modifying effects revealed in this work.

The authors are indebted to Dr. J. McKay and Dr. D. Murnick for helpful discussions concerning radiation damage and implantation phenomena.

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*Work supported by the National Science Foundation.

†Fellow of Consejo Nacional de Investigaciones Científicas y Técnicas de Argentina.

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[3] See, e.g., R. M. Steffen and H. Frauenfelder, in *Perturbed Angular Correlations*, edited by K. Karlsson, E. Matthias, and K. Siegbahn (North-Holland, Amsterdam, 1964), Chap. 1, pp. 1–89.

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