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

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The quadrupole interaction of ^{111}Cd ions following the decay of ^{111}In implanted by $(\alpha, 2n)$ reactions into a cubic (fcc) Ag lattice has been measured with the time-differential perturbed-angular-correlation method. A nonvanishing quadrupole interaction corresponding to a distribution of electric field gradients was observed. The "smeared out" quadrupole interaction frequency has a centroid $\bar{\omega}$ from 2.04 to 1.50 MHz depending on the temperature and the time the irradiated Ag was allowed to "heal." In addition, about 3% of the ^{111}In-^{111}Cd ions experience a quadrupole interaction with a sharp frequency $\omega_Q = 157 \pm 2$ MHz. The temperature dependence of the healing process was investigated. At room temperature no further healing occurs after 6 days once the $\bar{\omega} = 1.50$ MHz was reached. Annealing for 12 hours at 600°C causes the quadrupole interaction to vanish conpletely. Various quadrupole-perturbation and "healing" mechanisms are discussed. The most likely cause of the quadrupole perturbation in the cubic Ag lattice are vacancies and/or Ag interstitials.

I. INTRODUCTION

It has been often assumed that the hyperfine interactions of ions that are implanted by nuclear reactions or Coulomb excitation into host lattices are the same as those experienced by ions that are implanted by more conventional means (diffusion, alloying, isotope-separator implantation, etc.) except for transient fields.[1,2] Recent experiments, however, cast some doubt on these assumptions.[3]

The present work describes the time-differential observation of a nonvanishing static quadrupole interaction of ^{111}In-^{111}Cd 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 indicate the presence of considerable radiation damage of the cubic Ag host lattice. A preliminary report of this work has been published.[4]

Earlier studies[5,6] of the quadrupole interaction of ^{111}Cd nuclei implanted into Ag by the $(\alpha, 2n)$ reactions have been made by observing the attenuation of the time-integrated directional correlation, a method which provides only crude information about some average hyperfine interaction experienced by the implanted ion.

II. METHOD OF MEASUREMENT

The method of observation employed in this work is based upon measurements of the directional correlation of γ rays emitted by radioactive implanted ions as a function of the time t during which the intermediate nuclear state I of the ions is exposed to a perturbing interaction. This time-differential perturbed directional correlation (TDPAC) is a very sensitive tool for investigating details of the perturbing hyperfine interaction.

If the perturbing interaction is polytropic, i.e. if the perturbing fields acting on the ensemble of decaying nuclei in a sample do not have any preferred direction as a whole (e.g., polycrystalline sample), the TDPAC function is of the form[7]

$$W(\theta, t) = \sum_{\lambda} G_{\lambda\lambda}(t) A_{\lambda\lambda} P_{\lambda}(\cos\theta), \tag{1}$$

where the directional-correlation coefficients $A_{\lambda\lambda}$ ($A_{00} = 1$) depend on the nuclear decay and $G_{\lambda\lambda}(t)$ [$G_{00}(t) \equiv 1$] are the differential attenuation coefficients which contain all the information about the perturbing interaction. If no perturbing interaction is present $G_{\lambda\lambda}(t) \equiv 1$. For a static quadrupole interaction of a nuclear state of spin $I = \frac{5}{2}$ involving an axially symmetric electric field gradient (EFG) V_{zz}, the attenuation coefficient $G_{22}(t)$ is explicitly[7]

$$G_{22}(t) = 0.2000 + 0.3714\cos\omega_Q t + 0.2857\cos 2\omega_Q t + 0.1429\cos 3\omega_Q t, \tag{2}$$

where the quadrupole frequency

$$\omega_Q = \frac{3}{20\hbar} eQV_{zz} \tag{3}$$

is proportional to the quadrupole moment Q of the intermediate nuclear state. In many papers the frequency

$$\nu_Q = eQV_{zz} \tag{4}$$

which is independent of the spin of the nuclear

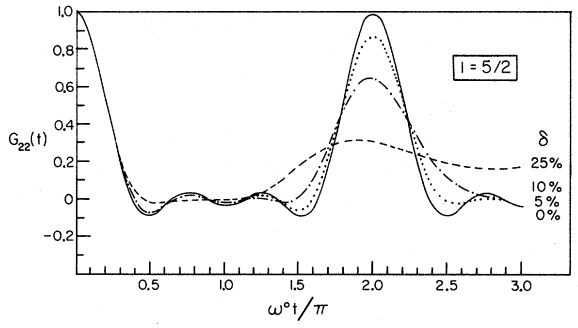

FIG. 1. Theoretical time-differential attenuation coefficients $G_{22}(t)$ for an axially symmetric static quadrupole interaction in a nuclear state $I=\frac{5}{2}$. The solid line shows $G_{22}(t)$ for $\delta=0$. The dotted lines show the attenuation coefficients for various relative widths δ of a Gaussian frequency distribution.

state I is used to characterize the strength of the quadrupole interaction. The quadrupole frequency ω_Q is related to the quadrupole strength ν_Q (for $I=\frac{5}{2}$) by

$$\omega_Q = \frac{3\pi}{10}\nu_Q . \tag{5}$$

For a unique sharp value of ω_Q the time dependence of $G_{22}(t)$ is periodic with a period of $T_Q = 2\pi/\omega_Q$ as shown by the solid line in Fig. 1. A unique value of ω_Q corresponds to the assumption that the EFG's acting on the nuclear quadrupole moments are exactly the same at every nuclear site. For nuclei in an actual crystal lattice slight variations of the EFG may be expected, e.g., caused by lattice imperfections or impurity ions.

A variation of the EFG from nucleus to nucleus results in a probability distribution $P(\omega_Q)$ of the quadrupole frequency ω_Q. The frequency distribution may be assumed to be represented by a Gaussian distribution

$$P(\omega_Q)d\omega_Q = \frac{1}{\sqrt{2\pi}\sigma} e^{-(\omega_Q-\bar{\omega})^2/2\sigma^2} d\omega_Q \tag{6}$$

with a centroid at $\bar{\omega}$ and a width σ. The dotted lines in Fig. 1 show the resulting attenuation coefficients

$$\bar{G}(\bar{\omega},t) = \frac{\int_0^\infty G_{\lambda\lambda}(\omega_Q,t)P(\omega_Q)d\omega_Q}{\int_0^\infty P(\omega_Q)d\omega_Q} \tag{7}$$

for various relative widths $\delta=\sigma/\bar{\omega}$. It should be noted that the time integrated attenuation coefficients $\hat{G}_{\lambda\lambda}(\bar{\omega}\tau)=\int_0^\infty e^{-t/\tau}G_{\lambda\lambda}(t)dt/\tau$ (τ = lifetime of intermediate nuclear state) which are observed in integral correlation measurements are very insensitive to the presence of a frequency distribution. In fact the $\hat{G}_{22}(\bar{\omega}\tau)$ for $\delta=0$ and $\delta=0.25$ differ by less than 3% for a given $\bar{\omega}\tau$.

III. TIME-DIFFERENTIAL DIRECTIONAL-CORRELATION MEASUREMENTS

The radioactive nuclei used in the present investigation are ^{111}In nuclei which decay to ^{111}Cd with a half-life of $T_{1/2}=65$ h. The decay is shown in Fig. 2. The unperturbed directional correlation of the ^{111}Cd γ rays is given by[8]

$$W(\theta) = 1 - (0.180\pm0.002)P_2(\cos\theta) + (0.002\pm0.003)P_4(\cos\theta). \tag{8}$$

In the following discussion the $P_4(\cos\theta)$ will be neglected, since within experimental error it is vanishingly small.

The experiments consisted of bombarding polycrystalline Ag foils at room temperature with 22-MeV α particles from the Purdue tandem accelerator and with α particles of various energies (22, 30, 35, 40, and 45 MeV) from the Argonne cyclotron, thus producing, by an $(\alpha,2n)$ reaction, ^{111}In nuclei in the Ag lattice with recoil energies in the MeV range. The ^{111}In 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 ^{111}In ions come to rest somewhere in the cubic Ag lattice, they decay by electron capture to ^{111}Cd and subsequently populate the $I=\frac{5}{2}$, 247-keV state of ^{111}Cd of $\tau=123$-nsec lifetime whose hyperfine interaction with the atomic and lattice fields can be investigated by observing the time evolution of the orientation of this state through a TDPAC measurement.

The time-differential directional correlation of the ^{111}Cd γ rays emitted by the implanted ^{111}In-^{111}Cd ions was measured by two NaI(Tl) scintillation de-

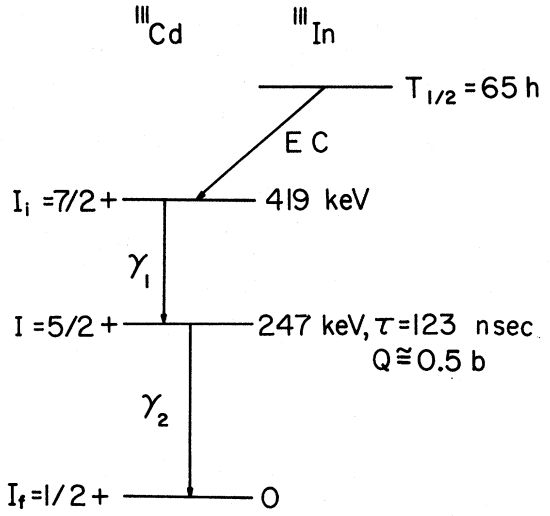

FIG. 2. Decay scheme of ^{111}In-^{111}Cd.

tectors in conjunction with a time-to-amplitude-conversion (TAC) electronics. The coincidence counting rate $C(\theta, t)$ was observed at two angles $\theta = \pi/2$ and $\theta = \pi$ between the two detector axes as a function of the time delay t between the formation of the 247-keV state (i.e. the emission of the 172-keV γ radiation), and the decay time of the 247-keV state (i.e. the emission of the 247-keV γ radiation). The pulses caused by the 172-keV γ ray in the scintillation detectors after amplification by several nsec amplifiers initiated the starting signal for the time-to-amplitude converter (TAC) and the 247-keV γ rays provided the stopping signal. The delay-time-analog output pulses of the TAC were observed in a multichannel analyzer that was gated by single-channel analyzers which selected the energies of the γ rays (fast-slow coincidence electronics). The time resolution of the equipment for prompt γ rays was 5 nsec. The normalized time-differential coincidence counting rate $C(\theta, t)$ is given by

$$C(\theta, t)dt = N_0 e^{-t/\tau} W(\theta, t)dt = N_0 \sum_{\lambda} e^{-t/\tau} G_{\lambda\lambda}(t) A_{\lambda\lambda} P_{\lambda}(\cos\theta)dt . \quad (9)$$

For the ^{111}Cd cascade with $A_{\lambda\lambda} = 0$ for $\lambda > 2$ the attenuation factor $G_{22}(t)$ is easily obtained from the measured values of $C(\pi/2, t)$ and $C(\pi, t)$:

$$G_{22}(t) = \frac{1}{A_{22}} \frac{C(\pi, t) - C(\pi/2, t)}{C(\pi/2, t) + \frac{1}{2}C(\pi, t)} . \quad (10)$$

The value A_{22} for the ^{111}Cd γ-γ cascade is $A_{22} = -0.180 \pm 0.002$ [see Eq. (7)].

Narrow (~3-mm) strips of the irradiated Ag foils were used as sources for the TDPAC measurements. For the measurements with the source at 77°K the Ag foils were placed in liquid nitrogen in a Dewar vessel specially designed to avoid absorption and scattering of the ^{111}Cd γ radiation.

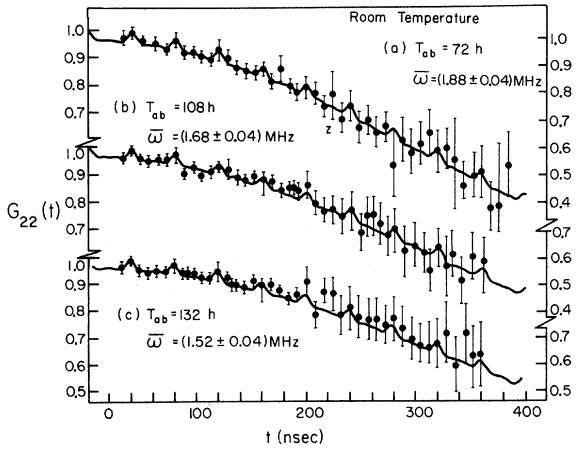

FIG. 3. The time-differential attenuation coefficients $G_{22}(t)$ of the ^{111}Cd γ-γ directional correlation observed at room temperature. Curves a, b, and c were observed at 72, 108, and 132 h after the end of the α bombardment.

The measurements were started about 24 h after the α irradiation to allow shorter-lived radioactivities to decay. A typical run lasted only about 12 h, since it was immediately discovered that the TDPAC depended on the time elapsed between the end of the irradiation and the beginning of the run. This time interval, the "healing" time, is denoted by T_{ab}. In some cases the average of several runs was taken for better statistics in order to explore details of the time dependence of $G_{22}(t)$.

Figure 3 shows the observed $G_{22}(t)$ coefficient measured at *room temperature* for different values of T_{ab}. The curves a, b, c, clearly show the presence of a perturbation and also show that the perturbation decreases [i.e., $G_{22}(t)$ increases] with increasing time T_{ab} ("healing" effect). After $T_{ab} \simeq 10$ days, however, no further "healing" was observed and the $G_{22}(t)$ curves were the same, independent of T_{ab}. In addition to the smooth decrease of $G_{22}(t)$ with delay time t, small peaks at periodic intervals were observed. These peaks seem to be more pronounced for Ag foils irradiated with cyclotron α beams ($I_{\alpha} \simeq 10$ μA/h) than for those obtained with tandem α beams at the same α energy ($E_{\alpha} = 22$ MeV, $I_{\alpha} = 0.5$ μA/h). This effect may be caused by the different time structure of the pulsed (frequency modulated) cyclotron beam as compared to the dc-type α beam of the tandem or it may be related to the higher beam intensity of the cyclotron beam. No clear-cut influence of the α-bombarding energy on the differential $G_{22}(t)$ was observed.

Annealing of the Ag for 24 h at 600°C before the α irradiation showed no effect. On the other hand, annealing the Ag foils for 12 h at 600°C *after* bombardment had a dramatic effect in completely removing the perturbation, i.e. for these annealed foils, $G_{22}(t) \equiv 1$ was observed (curve a in Fig. 5).

In order to obtain more information about the "healing" effect, i.e. the reduction of the perturbation with increasing T_{ab}, the TDPAC was measured with the irradiated Ag foil at liquid nitrogen temperature (Fig. 4). It is clear that the "healing" effect is considerably slowed down at the lower temperature as compared to the room temperature measurements shown in Fig. 3. This fact is emphasized by the $G_{22}(t)$ curves in Fig. 5 where the room temperature and the liquid nitrogen temperature curves are plotted for the same "healing" times T_{ab}.

There are indications in Fig. 3 that, at room temperature, the small peaks referred to earlier disappeared with increasing T_{ab}. To further in-

vestigate this effect the averages of several room temperature measurements were taken for T_{ab} = 1–12 days and for T_{ab} = 12–20 days. These averages are plotted in Fig. 6, which shows clearly that the peaks disappear with increasing "healing" time T_{ab}.

IV. ANALYSIS OF THE DATA

It is well known that the atomic shell of the ^{111}Cd ion recovers within a short time ($<10^{-11}$ sec) from the preceding electron capture in a metallic environment.[7] Time-dependent electric field gradients due to vacancy diffusion may produce small perturbations. Within the time range of interest here (100 nsec) and since the relaxation times are of the order of several μsec at room temperature,[9] 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 Q of the 247-keV ^{111}Cd state with possible static-electric field gradients V_{zz} (which for simplicity are assumed to be axially symmetric) are expected to cause a perturbation of the ^{111}Cd directional correlation. In a perfect cubic lattice the EFG's of substitutional ions vanish. Lattice defects caused by the recoiling ^{111}In ions and by the primary α particles, however, may cause the presence of EFG's in the cubic (fcc) Ag lattice. Similarly, ^{111}In-^{111}Cd ions coming to rest at interstitial sites may be exposed to EFG's.

The observation of the quadrupole frequency ω_Q of the 247-keV ^{111}Cd state serves as a probe of the

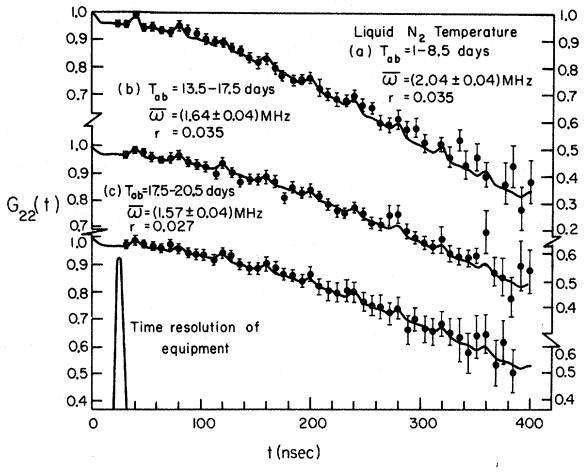

FIG. 4. The time-differential attenuation coefficients $G_{22}(t)$ of the ^{111}Cd γ-γ directional correlation observed at liquid N_2 temperature. Curves a, b, and c were measured for healing times T_{ab} of 1–8.5 days, 13.5–12.5 days, and 17.5–20.5 days after the end of the α bombardment.

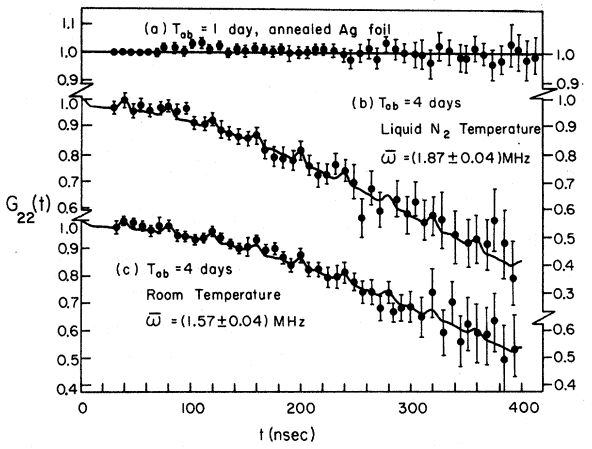

FIG. 5. The time-differential attenuation coefficients $G_{22}(t)$ of the ^{111}Cd γ-γ directional correlation. Curve a shows the attenuation coefficient after 1 day of annealing at 600°C temperature. Curves b and c show the room temperature and liquid N_2 temperature results for the same healing time T_{ab}.

symmetry of the site where the parent ^{111}In nucleus has come to rest. Hence, the $G_{22}(t)$ were analyzed on the basis of an axially symmetric static quadrupole perturbation of the ^{111}Cd γ-γ directional correlation. The presence of the small peaks on top of the gradually declining $G_{22}(t)$ curves seemed to indicate the presence of a small component with a sharp quadrupole frequency ω_Q in addition to a smeared-out quadrupole interaction with a centroid at $\bar{\omega}$ and a relative spread of δ. Thus the $G_{22}(t)$ curves were analyzed on the basis of a main component of intensity $(1-r)$ which is given by Eqs. (6) and (7), superimposed on a small component of intensity r that is given by Eq. (2). Computer fits for the three parameters $\bar{\omega}$, ω_Q, δ, and

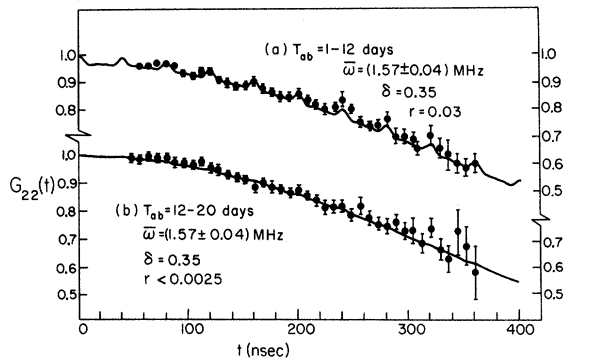

FIG. 6. The time-differential attenuation coefficients $G_{22}(t)$ of the ^{111}Cd γ-γ directional correlation at room temperature. Curves a and b were observed at healing time T_{ab} = 1–12 days and T_{ab} = 12–20 days. The peaks clearly disappear.

r are shown by solid lines in Figs. 3–6. Table I summarizes the results of the various measurements.

Whereas $\bar{\omega}$ and r change considerably with healing time T_{ab}, δ is essentially independent of T_{ab}, within rather large limits of error, and ω_Q is independent of T_{ab} within small limits of error. Attempts to fit the $G_{22}(t)$ curve on the basis of the assumption that a fraction ϵ of the ^{111}Cd nuclei experience a unique quadrupole interaction with a sharp frequency ω_Q while the fraction $(1-\epsilon)$ is unperturbed, failed. Similarly, attempts failed to fit the observed $G_{22}(t)$ curves to an exponential, $e^{-\lambda t}$, which is characteristic for a relaxation perturbation.

The constant value of ω_Q is of particular interest. The observation of this sharp quadrupole frequency seems to be caused by a vacancy in *one* of the $\langle 100\rangle$ sites closest to the decaying ^{111}In-^{111}Cd ion which is assumed to be in a substitutional site. An estimate[10,11] of the EFG produced by such a single vacancy gives a gradient of $V_{zz} \simeq 6\times 10^{17}$ V/cm^2. The electric quadrupole moment of the 247-keV state of ^{111}Cd is $Q=(0.44\pm 0.07)\times 10^{-24}$ cm^2.[12] From these values the quadrupole frequency ω_Q can be computed from Eq. (3) and one obtains $\omega_Q \cong 10^8$ sec^{-1} in good qualitative agreement with the observed value of $\omega_Q=(1.57\pm 0.02)\times 10^8$ sec^{-1}.

The main component of the perturbation is clearly caused by EFG's that have a probability distribution. The results reported here are consistent with a Gaussian distribution of the EFG's, although it should be pointed out that the form of the $G_{22}(t)$ curves is quite insensitive to the detailed shape of any smeared-out distribution. In any case, the experiments show that the ^{111}Cd nuclei experience a smeared-out EFG in the cubic Ag lattice. The EFG's may either be caused by vacancies or interstitials produced by the recoiling ions and/or by the primary α beam, thus destroying the cubic symmetry near the ^{111}In-^{111}Cd impurity ion or, the EFG, are the result of a random occupation by the ^{111}In-^{111}Cd ions of various interstitial sites of noncubic symmetry.

The temperature dependence of the "healing" effect, i.e. of the reduction of the average quadrupole frequency $\bar{\omega}$ with increasing time T_{ab} may shed some light on the cause of the quadrupole perturbation. Figure 7 shows the rate at which the frequency $\bar{\omega}$ decreases with increasing T_{ab}. It is quite clear that the "healing" effect at room temperature has several components; after $T_{ab}>6$ days no further healing takes place.

If the assumption is made that the healing effect is caused by the migration of vacancies or normal Ag interstitials to some sink (lattice defects, impurities, etc.) several atomic distances away from the decaying ^{111}In-^{111}Cd ion in a substitutional site, or by a migration of the ^{111}In-^{111}Cd ion from an interstitial site of noncubic symmetry to a substitutional site, the healing effect can be characterized by an activation energy E. If one assumes that the healing effect can be characterized by a *single* activation energy E the annealing rates R_1 and R_2 at temperatures T_1 and T_2, respectively, are related by[13]

$$\ln\frac{R_1}{R_2}=-\frac{E}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right). \tag{11}$$

A comparison of the room-temperature and the liquid-nitrogen-temperature healing curves in Fig. 7 indicates that the fast component of the room-temperature healing curve corresponds to a 5 times larger annealing rate than the liquid-nitrogen-temperature curve. From this informa-

TABLE I. Parameters from the analysis of the $G_{22}(t)$ curves.

Temperature of Ag foil	Time after irradiation (days)	Centroid frequency $\bar{\omega}$ (MHz)	Relative spread δ	Fraction of sharp frequency r	Sharp frequency ω_Q (MHz)
298°K	3	1.88±0.04	0.35	0.040	157±2
	4.5	1.68±0.04	0.35	0.035	157±2
	5.5	1.52±0.04	0.35	0.030	157±2
	6.3	1.50±0.10	0.35	0.025	157±2
	7.5	1.50±0.08	0.35	~0.02	157±2
	8.5	1.52±0.07	0.35	<0.02	···
	13	1.50±0.07	0.35	<0.02	···
	16	1.50±0.10	0.35	<0.02	···
77°K	4.5	2.04±0.04	0.35	0.035	157±3
	15.2	1.64±0.08	0.35	0.035	157±3
	19	1.57±0.07	0.35	0.027	157±3

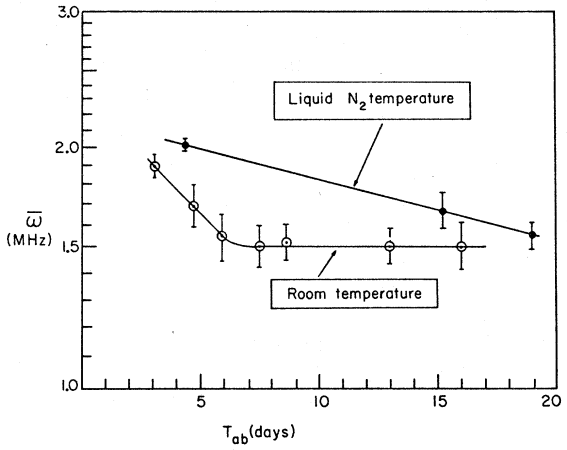

FIG. 7. Rate at which the frequency $\bar{\omega}$ decreases with healing time T_{ab} at room and liquid N_2 temperatures.

tion an activation energy of the "fast" healing process of about $E_F \cong 0.01$ eV can be computed from Eq. (11). This value of the activation energy is orders of magnitude smaller than would be expected for normal interstitial Ag or vacancy migration (~0.5 eV).[14] Hence, it is unlikely that the observed healing effects at room temperature and at 77°K are caused by a simple vacancy migration process with a single activation energy.

It is well known that annealing processes in metals may proceed in several stages[14,15] with several values of activation energies. In fact our data are consistent with three stages of the annealing process. Above $T \cong 400$°K the activation energy seems to be fairly large ("hard core"). Around $T = 300$°K the activation energy for vacancy migration is about 0.8 eV.[16] If one takes this value for the analysis of the present data, one finds an activation energy of 0.2 eV for the annealing process at 77°K. This value is in very good agreement with the observed activation energy for the recovery process for lattice point defects (e.g., interstitials, crowdion type) of Ag in this temperature range.[14,15] Hence, the observed change in $\bar{\omega}$ with healing time T_{ab} is completely consistent with the expected recovery of the Ag lattice from vacancies and/or Ag interstitials.

Another possible mechanism which could possibly explain the "fast" healing component is the migration of ^{111}In-^{111}Cd ions that sit in interstitial sites of *noncubic symmetry* to the nearest isolated vacancies. Being then in a substitutional site, the ion would not experience a quadrupole interaction in the cubic Ag lattice. The activation energy for this process may be small enough to explain the observed data. The most likely initial interstitial site, however, for an In ion to come to rest after the α bombardment is the center of the fcc elementary cell of Ag, a site which due to its cubic symmetry is not expected to be exposed to EFG fields. The complete disappearance of the quadrupole frequency $\bar{\omega}$ after annealing at 600°C for 12 h is easily explained by a migration of vacancies or Ag interstitials to sinks, since for an activation energy of $E \cong 0.8$ eV the migration rate is about 10^4 times higher at 873°K than at room temperature.

V. CONCLUSIONS

Several conclusions can be drawn from the results of the present experiment.

(1) ^{111}In-^{111}Cd ions recoiling after an $(\alpha, 2n)$ reaction into a cubic Ag lattice experience a nonvanishing quadrupole hyperfine interaction.

(2) The quadrupole perturbation can be described by two components:

(a) A weak (about 3%) component with a sharp frequency ω_Q. This frequency ω_Q is independent of temperature T and "healing" time T_{ab}.

(b) A main component that corresponds to a "smeared-out" quadrupole frequency with a centroid $\bar{\omega}$ which decreases with healing time T_{ab}.

(3) The "sharp frequency" component with ω_Q can be interpreted as caused by EFG's resulting from vacancies in the closest neighbor ⟨100⟩ site of the In-Cd impurities that occupy substitutional sites in the Ag lattice.

(4) The temperature dependence of the decrease of $\bar{\omega}$ with increasing healing time T_{ab} seems to indicate that the healing effects cannot be solely attributed to a simple vacancy or normal Ag interstitial migration with a single activation energy.

(5) The observed rate of healing of the lattice defects gives activation energies which are in good agreement with the activation energies observed in isothermal recovery of point defects in Ag.[15] Hence, it seems very likely that the observed quadrupole interaction is caused by vacancies and/or Ag interstitials in the cubic Ag lattice.

(6) A possible alternate, but less likely explanation of the healing effect may be the migration of the ^{111}In-^{111}Cd impurity from a noncubic interstitial site to an isolated vacancy.

(7) The quadrupole interaction can be removed completely from the neighborhood of the In impurity sites by annealing at 600°C for several hours.

For nuclear physics experiments designed to determine nuclear magnetic moments and electric quadrupole moments by implanting recoiling nuclei into suitable hosts, it is important that the assumption that ions recoiling into a cubic metal lattice experience small or nonvanishing quadrupole in-

teractions is often not correct. The presence of this "induced" quadrupole interaction must be considered in g-factor measurements where the excited nuclei are recoiled into ferromagnetic hosts, if the lifetime of the excited nuclear state is in the several nsec region. 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 EFG-producing or EFG-modifying effects revealed in this work.

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