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QUANTUM OSCILLATIONS OF THE VELOCITY OF SOUND IN CADMIUM*

by

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ABSTRACT

Large amplitude quantum oscillations in the longitudinal sound velocity, $\left| \frac{\Delta V}{V} \right| \sim 10^{-3}$, were observed in cadmiun. The oscillations were studied as a function of magnetic field up to 70 kOe and as a function of temperature in the region 1.5 K $\leq$ T $\leq$ 4.2 K.

We report the first observation of quantum oscillations in the longitudinal sound velocity in single crystal cadmium The experiments were performed with the propagation vector, $\vec{q}$, of the longitudinal sound wave along the hexagonal axis, [0001]. Magnetic fields up to 70 kOe, generated by a superconducting solenoid, were applied along the [0001] axis and at an angle $\sim 2°$ from the [0001] axis, in a $(11\bar{2}0)$ plane. Changes in the sound velocity due to the magnetic field were measured by a technique used previously.[1,2] Fractional changes of the order 5×10^{-5} in the sound velocity V could be resolved. Attenuation measurements were also made using conventional pulse-echo techiques.

In Fig. 1, the magnetic field dependence of the velocity oscillations is shown for several temperatures, for 10.6 MHz longitudinal sound waves. A Fourier analysis [3] of the data indicates that the strongest contribution to the oscillations corresponds to a de Haas-van Alphen (dHvA) frequency $f_D = 1.61 \times 10^7$ Oe. This is the frequency D of Fletcher et al.[4] Also present, with much smaller amplitudes, are the frequencies $f_M = 5.5 \times 10^6$Oe. and $f_C = 1.28 \times 10^7$Oe. The frequency M has been observed previously by Grassie [5] and by Joseph et al.[6] very close to the [0001] axis. The frequency C has been observed by Fletcher et al. A Fourier analysis of the attenuation data showed them to be a superposition of the same dHvA frequencies, but with amplitudes proportionately quite different from those of the velocity curves.

The effective masses of the carriers associated with the dHvA oscillations were determined in the standard manner,[1] from the temperature dependence of the oscillation amplitudes at constant magnetic field. From the velocity oscillations, for $\vec{H} \parallel [0001]$, we found $m_M^* = (0.15 \pm 0.02)m_o$, $m_C^* = (0.38 \pm 0.04)m_o$, and $m_D^* = (0.40 \pm 0.04)m_o$. For the magnetic field in the orientation masses. From the velocity oscillations we obtained $m_D^* = (0.42 \pm 0.04)m_o$ and, from the attenuation oscillations, we found $m_M^* = (0.15 \pm 0.02)m_o$ and $m_C^* = (0.38 \pm 0.04)m_o$. We believe our results to be the first measurements of the effective masses associated with the orbits M, C, and D.

Quantum oscillations in the sound velocity may be treated using a thermodynamic argument to obtain the electronic contribution to the elastic constants.[7,8] The treatment of Rodriguez,[7] which is appropriate for desity of states oscillations and which, therefore, should be valid for $q\ell \lesssim 1$, has been used to calculate the amplitudes of the velocity oscillations in Zn,[1] Ga,[9] Aℓ,[10] and Cu.[10] Rodriguez assumes the longitudinal sound velocity to be determined by the bulk modulus and that the latter quantity is given by the second derivative of the free energy with respect to volume. Using this approach, and the Lifshitz-Kosevitch expression for the free energy of an electron in a magnetic field,[11] one obtains an expression for the fractional velocity shift $\Delta V/V$. See Ref. 7 Eq. (29), Ref. 9 Eq. (1), and Ref. 10 Eq. (3). The last reference includes the effects of electron scattering through the use of a Dingle temperature T_D.

In our experiments, T_D was determined from a comparison of the experimental amplitudes A with Eq. (3) of Ref. 10. In Fig. 2, a plot of $\ln\left[\frac{AH^{1/2}}{T}\sinh\left(\frac{2\pi^2 kT}{\hbar\omega_c}\right)\right]$ vs. 1/H is shown for the amplitude A associated with the D oscillations, for the magnetic field in the orientation of Fig. 1. The amplitude A was obtained from a Fourier analysis of the velocity oscillations in a small magnetic field interval (∿2 kOe) and was associated with the average value of H in that interval. The solid line in Fig. 2 represents a least squares fit to the data points and, from its slope, we obtained T_D = 2.2K. This value of T_D corresponds to an electron relaxation time $\tau \sim 5 \times 10^{-13}$ sec., from which we estimate $q\ell \sim 0.01$, for 10.6 MHz sound waves.

Finally, we wish to compare the peak-to-peak amplitude of the D oscillations, obtained from the Fourier analysis of the lowest curve of Fig. 1 (T = 1.53 K), with the amplitude calculated from Eq. (3) of Ref. 10. From experiment, we find $|\Delta V/V| = 9 \times 10^{-4}$, a value which is reproducible to within 20%. In Eq. (3) of Ref. 10 we use the free electron value E_F = 8.85 eV.,[12] the above values of T_D and m_D^* , and the mean value of the magnetic field for the data of Fig. 1, H = 68.9 kOe. Taking the electron g-factor equal to 2 and the geometrical factor $|\partial^2 S/\partial k_z^2|$

equal to 2π, we calculate $|\Delta V/V| = 5.7 \times 10^{-4}$. We consider the approximations involved in the theory [9,10] and the fact that neither the electron g-factor nor the geometrical factor is known for the D orbit.

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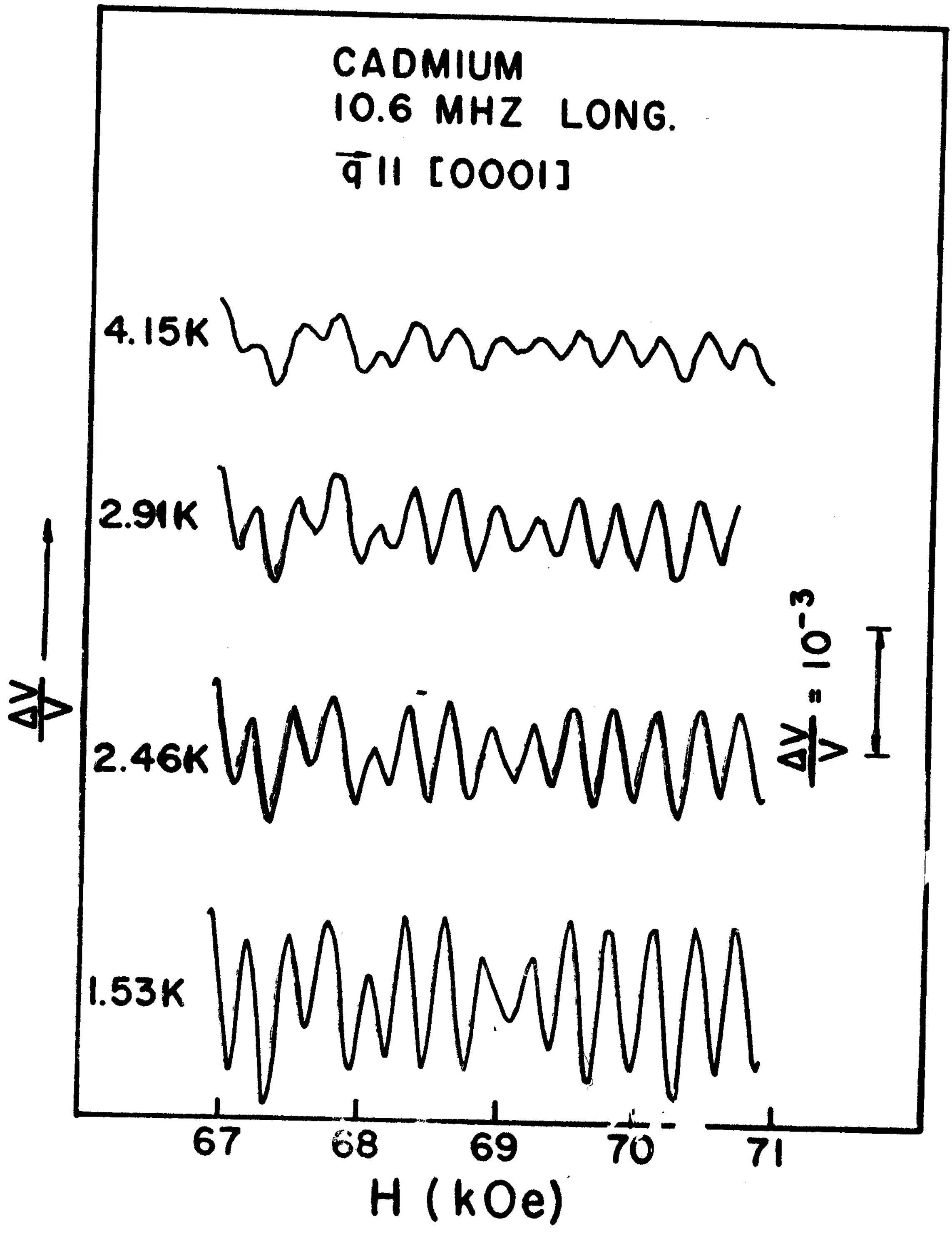
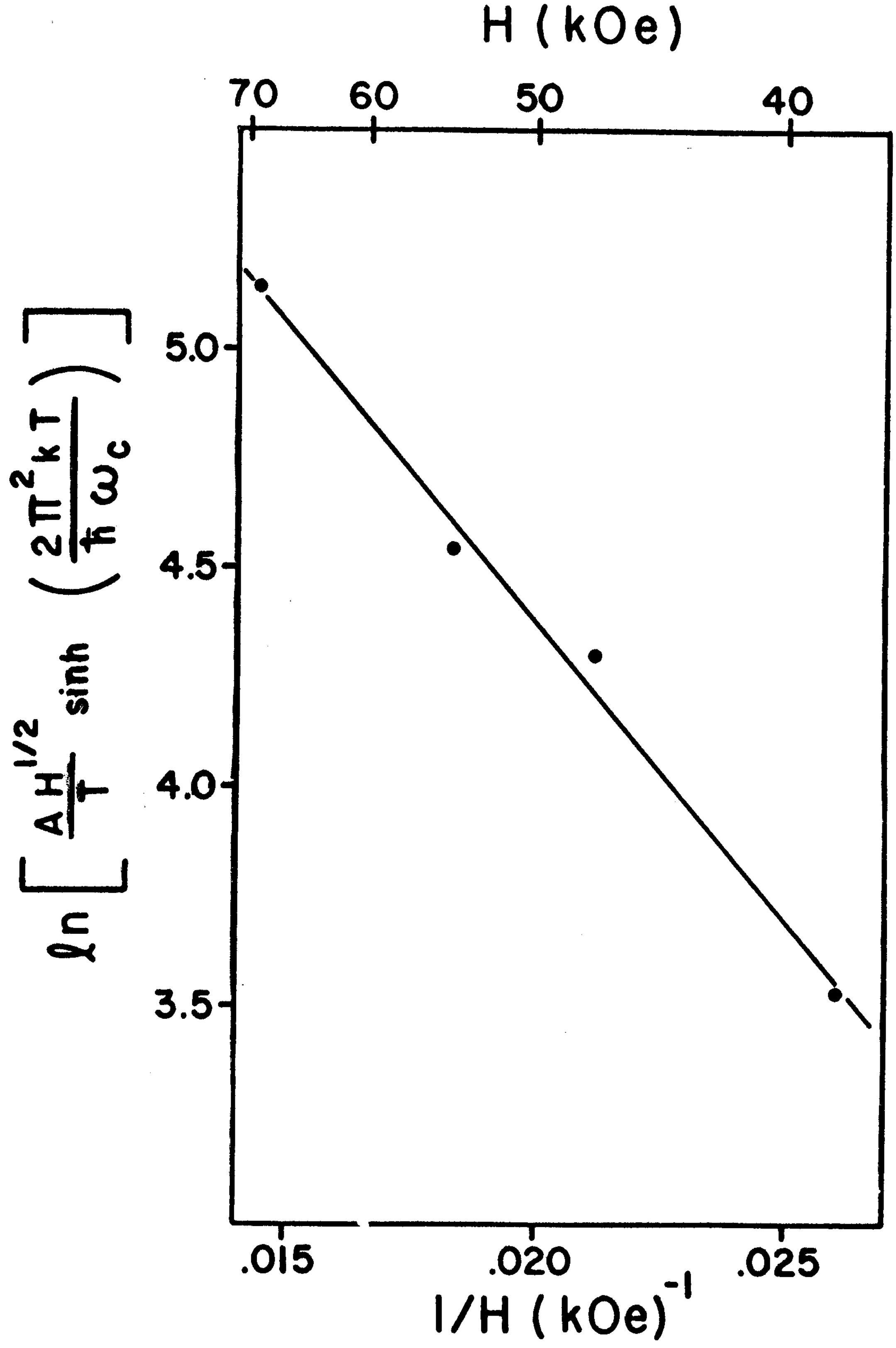
FIGURE CAPTIONS

Fig. 1 Magnetic field dependence of the fractional change in sound velocity. The magnetic field is at an angle $\sim 2^0$ from the |0001| axis, in a $(11\bar{2}0)$ plane.

Fig. 2 Magnetic field dependence of the amplitude A associated with D orbit, for H oriented as in Fig. 1. T = 1.53 K.


CADMIUM
10.6 MHZ LONG.
$\vec{q}$ || [0001]
4.15K
2.91K
2.46K
1.53K
ΔV/V
ΔV/V = 10⁻³
67
68
69
70
71
H (kOe)



H (kOe)
70
60
50
40
5.0
4.5
4.0
3.5
$\ln\left[\frac{AH^{1/2}}{T}\sinh\left(\frac{2\pi^2 kT}{\hbar\omega_c}\right)\right]$
.015
.020
.025
$1/H\ (kOe)^{-1}$