since absorption is primarily governed by the densities of states in the valence and conduction bands.

An interpretation similar to the one proposed here seems feasible for the case of impurity-valence band transitions,[1,2] with shallow acceptors or perhaps excited states of the "deep" acceptors playing the role of capturing centers.

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DETERMINATION OF EFFECTIVE MASSES FROM GIANT QUANTUM OSCILLATIONS IN ULTRASONIC ABSORPTION

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We have observed "giant quantum oscillations" in the absorption of ultrasonic waves in gallium and have determined the effective mass from the width of the absorption peaks. While quantum oscillations in the attenuation of longitudinal sound waves in a parallel magnetic field have been observed in metals,[1] semimetals,[2] and semiconductors,[3] this is the first time that the sharp spikelike character of the oscillations has been observed experimentally and used to determine effective masses. The so-called "giant quantum oscillations" have been first predicted theoretically by Gurevich et al.[4] When

$$(2kT/m^*)^{1/2}q\tau \gg 1, \tag{1}$$

where m^* is the effective mass, q is the wave number of the ultrasonic wave, and τ is the electron-scattering time, the attenuation coefficient Γ of a longitudinal ultrasonic wave in a parallel magnetic field is given by[4]

$$\Gamma = \Gamma_0 \frac{\beta H}{8kT} \sum_{n, s_z} \cosh^{-2}\left[\frac{\beta H(n+\frac{1}{2}) + s_z \mu H - \zeta}{2kT}\right], \tag{2}$$

where Γ_0 is the attenuation coefficient at zero magnetic field, $\beta = e\hbar/m^*c$, μ is the magnetic moment of the electron, and ζ is the Fermi energy. n and s_z are the Landau level number and spin quantum number, respectively. We assume initially that a given absorption peak corresponds either to a single term in the double summation of of Eq. (2), or two terms having maxima at the same field. The latter case corresponds to an effective g value which is an exact even multiple of the ratio of the free-electron mass to the cyclotron mass. Under this assumption the line shape of a single absorption peak i is given by

$$\Gamma_i = A \cosh^{-2}[(B_i\beta H - \zeta)/2kT], \tag{3}$$

where A and B_i are constants. Here we have neglected the slight variation across the absorption peak of the amplitude factor $\beta H/8kT$ in Eq. (2). The field H_i at the center of the peak satisfies the relation

$$B_i = \zeta/\beta H_i = [(\Delta H^{-1})H_i]^{-1}, \tag{4}$$

where ΔH^{-1} is the usual de Haas–van Alphen period. From Eqs. (3) and (4),

$$\Gamma_i = A \cosh^{-2}[\beta(H - H_i)/2kTH_i(\Delta H^{-1})]. \tag{5}$$

The full width $(\delta H)_i$ at half-height is then given

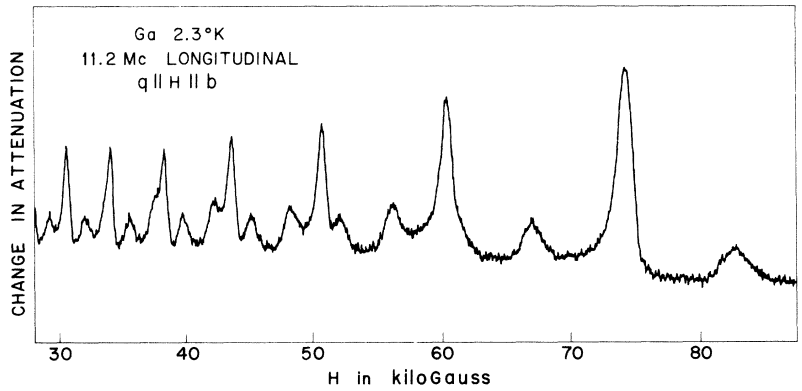

FIG. 1. Recorder tracing of the change in ultrasonic attenuation of 11.2-Mc/sec longitudinal sound waves propagated along the b axis in gallium as a function of magnetic field intensity H at 2.3°K. The magnetic field was oriented along the b axis.

by

$$(\delta H)_i = 3.53kTH_i(\Delta H^{-1})/\beta. \quad (6)$$

The "giant oscillations" are periodic in H^{-1} and the period is very close to the de Haas–van Alphen period ΔH^{-1} (the fractional difference between the two periods equals approximately the square of the ratio of the sound velocity to the Fermi velocity). Thus one can determine the effective mass $m^* = e\hbar/\beta c$ either by measuring the period and fitting the line shape of the peaks to Eq. (5) or by measuring the half-width and using Eq. (6).

In the more general case when two terms in the double summation of Eq. (2) give rise to two peaks which overlap, the line shape is given approximately by

$$\Gamma_i = A\left[\cosh^{-2}\left(\frac{B_1\beta H - \zeta}{2kT}\right) + \cosh^{-2}\left(\frac{B_2\beta H - \zeta}{2kT}\right)\right], \quad (7)$$

where B_1 and B_2 are constants. The peak described by Eq. (7) is very nearly symmetric about the field $\bar{H}$ at which the two terms on the right side of Eq. (7) become equal. Letting

$$\bar{B} \equiv \tfrac{1}{2}(B_1 + B_2) = [\bar{H}(\Delta H^{-1})]^{-1} \quad (8)$$

and

$$\alpha = \bar{H}(\Delta H^{-1})(\bar{B} - B_2), \quad (9)$$

we obtain

$$\Gamma_i = A\left\{\cosh^{-2}\left[\beta\frac{(1+\alpha)H - \bar{H}}{2kT\bar{H}(\Delta H^{-1})}\right] + \cosh^{-2}\left[\beta\frac{(1-\alpha)H - \bar{H}}{2kT\bar{H}(\Delta H^{-1})}\right]\right\}. \quad (10)$$

In principle, by fitting the line shape of the observed absorption peaks to Eq. (10), one can therefore determine both the effective mass and the parameter α which is related to the spin splitting.

The attenuation of 11.2-Mc/sec longitudinal sound waves propagated along the b axis of gallium has been measured, at liquid helium temperatures, in a parallel magnetic field up to 90 kG. Sharp spikelike absorption peaks were observed with a period of 32×10^{-7} G^{-1}. This period is close to the de Haas–van Alphen period measured by Shoenberg.[5] The amplitude of the oscillations becomes larger and the width δH decreases as the temperature is lowered. Figure 1 shows a recorder tracing of the change in attenuation as a function of the magnetic field intensity H at 2.3°K. The width δH at various temperatures was determined. By using Eq. (6) we have obtained $\beta \approx 23\times10^{-20}$ cgs units. The same value of β was obtained at all temperatures within experimental accuracy of about 15%. This value is to be compared with the more accurate values of 31.6×10^{-20} and 33.8×10^{-20} cgs units obtained by Shoenberg[5] for the magnetic field oriented 10° from b in the bc plane and 11.1° from b in the ab plane. The discrepancy may be due in part to a broadening of the peaks which is caused by spin splitting and in part to experimental factors (e.g., field inhomogeneity across the sample). It is also possible that the present theory is only an approximate one.

In addition to the dominant period of the "giant oscillations," a subsidiary period of about 15×10^{-7} G^{-1} appears at low temperatures. The parameter $(2kT/m^*)^{1/2}q_T$ was estimated to be

about 5 at 2°K. It is expected that similar "giant oscillations" will occur also in the velocity of sound waves and that they can be used in a similar fashion to determine effective masses.

Experiments designed to determine the line shape of the "giant oscillations" with greater precision are now in progress. The results of such experiments should permit the use of Eq. (10) to determine the parameters β and α.

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STUDY OF ULTRASLOW ATOMIC MOTIONS BY MAGNETIC RESONANCE*

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Magnetic resonance has been widely used to study phenomena such as atomic diffusion and molecular reorientation. It is applicable[1] when the mean time, τ, between atomic jumps is either (a) sufficiently short to narrow the resonance linewidth or (b) of the correct magnitude to produce spin-lattice relaxation. Case (a) occurs when τ is less than $1/\Delta\omega$ where $\Delta\omega$ is the rigid lattice linewidth. Case (b) occurs when τ is of the order of $1/\omega_0$, where ω_0 is the Larmor frequency. Typically, case (a) is found when $\tau < 100$ μsec, case (b) when $\tau \sim 10^{-8}$ sec. In this Letter we report a new, experimentally simple technique which enables us to study motions of a much slower rate, the criterion being roughly $\tau < T_1$, where T_1 is the spin-lattice relaxation time.

The method is in many ways equivalent to case (b) with ω_0 set equal to zero; however, by means of a trick we achieve this condition with the actual field H_0 at a large value (10 000 gauss), thereby achieving important experimental advantages. An important problem in interpretation is understanding the effect of atomic motion on the relaxation time when the static field is comparable to or less than the local field of the neighboring nuclei ($\omega_0 \leq \Delta\omega$). The conventional theory of Bloembergen, Purcell, and Pound breaks down under these circumstances (in the limit of slow motion with which we are concerned). By generalizing the methods of Redfield et al.,[2,3] we have been able to solve this problem.

In this Letter we report the results of measurements of self-diffusion in lithium metal, a system chosen because the previous work of Holcomb and and Norberg[4] gave information about τ. Combining their data with ours, we have measured τ for this system over eight decades, from 2×10^{-9} second to 2×10^{-1} second, extending their data by nearly four decades.

The experimental method is based on the technique of adiabatic demagnetization.[3] If a spin system is demagnetized adiabatically from a high field to zero field, the order remains the same throughout the cycle. In the high field, the order consists of an excess of spins pointing along the applied field. In zero field the order consists of alignment of spins preferentially along the local fields due to their neighbors. Ordinarily, the order in zero field can be maintained for a time comparable to the spin-lattice relaxation time. If atomic jumps take place the situation is changed. When a spin jumps, its orientation does not change since the jumping time is very short compared to any precession period. But the local field in the new site is different from that at the old one, since the dipolar coupling falls off strongly with distance. To some degree, therefore, jumping randomizes the spin orientation in the local field and destroys the order. Clearly we can maintain the order only for a time comparable to τ. We can therefore detect jumping by measuring