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EXPERIMENTAL EVIDENCE FOR THE CORRELATION-PRODUCED MAGNETOPLASMA MODE IN POTASSIUM

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We have measured the real part of the surface impedance $R(H)$ of potassium at 1.2°K in a magnetic field normal to the sample surface. We find a sharp peak in $R(H)$ at the value of H where Cheng, Clarke, and Mermin predicted a new correlation-produced magnetoplasma mode should exist. We interpret the peak in $R(H)$ as confirmation of the existence of the mode, and we ascribe to surface roughness the overall variation in $R(H)$.

Cheng, Clarke, and Mermin[1] (CCM) have recently predicted and given the dispersion relation for a new class of magnetoplasma modes which propagate along the magnetic field in a degenerate electron gas such as is found in the alkali metals. These modes are unique in that their very existence depends on the presence of nonvanishing Fermi-liquid parameters; by contrast, the magnetoplasma modes which propagate across the magnetic field are modified,[2-5] rather than caused, by Fermi-liquid correlation effects. The new modes should, by carrying energy away from the sample surface, make a positive contribution to $R(H)$, the real part of the surface impedance. We have measured the surface impedance of potassium at 1.2°K in a magnetic field $\vec{H}$ normal to the sample surface. We find a positive anomaly in $R(H)$ at that value of $\vec{H}$ for which a new mode is predicted to exist, and we interpret this as confirmation of the CCM prediction.

The surface impedance was measured at 24 GHz using circularly polarized radiation[6] and at both 24 and 72 GHz using linearly polarized radiation.[7] Magnetic fields up to 100 kOe were applied perpendicular to the surface of a disk-shaped specimen which was ≈1 cm in diameter and between 0.01 and 0.05 cm thick. The polycrystalline specimens were prepared by pressing lumps of potassium between sheets of Mylar. The high-purity potassium had residual resistivity ratios ranging from 5000 to 13 000.[8]

In Fig. 1, we exhibit a recorder trace showing $R(H)$ as a function of the magnetic field. The dotted line superposed on the same figure represents $R(H)$ as computed classically[9-11] for a surface which scatters the electrons diffusely (the

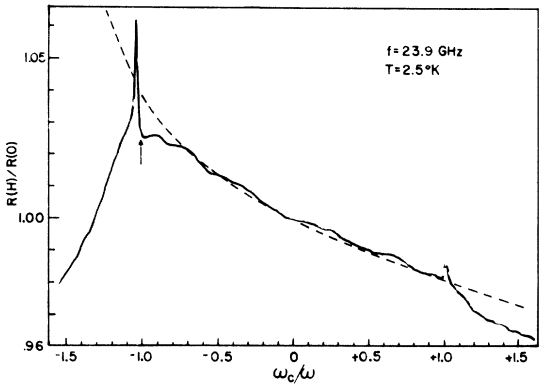

FIG. 1. The dashed curve is the normalized surface resistance as a function of magnetic field predicted by the free-electron model with diffuse surface scattering. The solid line denotes relative values of the surface resistance of potassium in the field-normal geometry measured with predominantly circularly polarized radiation. We attribute the peak at $\omega_c/\omega = -1.025$ to a magnetoplasma wave mode which arises from electron-electron correlations, and the general decreases in $R(H)$ for $\omega_c/\omega < -1.05$ we attribute to surface roughness. Since the experiment yields only a rough estimate of the absolute value of $R(H)$, the ordinate scale of the experimental curve was chosen to cause it to parallel the theoretical curve.

ordinate scale applies to the theory and is only approximate for the experiment). The magnetic field for Azbel'-Kaner cyclotron resonance (AKCR) is indicated by the arrow at $\omega_c/\omega = -1$.

The "noninteracting" theoretical curve is conspicuously lacking in any structure in the neighborhood of AKCR. The experimental curve, on the other hand, shows a sharp positive peak centered at $\omega_c/\omega = 1.025 \pm 0.005$.[12] The narrow positive peak in $R(H)$ we attribute to the excitation of the $l = 2$ mode proposed by CCM.

In addition to the peak at $\omega_c/\omega = 1.025$ it is clear from Fig. 1 that $R(H)$ decreases at magnetic fields above cyclotron resonance while the theoretical curve continues to rise. This decrease we attribute to surface roughness of the potassium specimen. Although it is not possible for us to calculate surface impedance in the presence of surface roughness and Fermi-liquid correlations, we can calculate surface impedance for each of these two effects separately and can obtain thereby some justification for these assertions.

To discuss the experimental peak at cyclotron resonance in the presence of interactions among the conduction electrons, we use the formula given by Platzman and Jacobs[13] for the surface impedance of a specular slab:

$$\frac{Z}{Z_0} = \frac{2i}{\pi} \int_0^\infty \frac{dk}{k^2 - k_0^2 - i\omega\mu_0\sigma(k,\omega)}. \quad (1)$$

The quantity $\sigma(q, \omega)$ is the frequency and wave-number–dependent conductivity for the infinite medium computed within the framework of the Landau Fermi-liquid theory. When we use the expression for σ given by Platzman and Jacobs and search for real values of k for which the denominator of the integrand vanishes (in the collisionless limit), we recover the dispersion relation given by CCM for the case where $A_n \equiv 0$ for $n > 2$. The zero of the denominator exists only for

$$1 - C_2 < \omega_c/\omega < 1 - 5C_2/3,$$

where $C_2 = A_2/(1 + A_2)$. Over this small range of magnetic field, the mode makes a positive contribution to the real part of the surface impedance. This justifies our earlier assertion that the existence and excitation of the $l = 2$ mode can account for the narrow peak in $R(H)$.

There are two difficulties with this explanation. When the size of this added surface resistance is calculated using (1), it turns out that the fractional change of the surface impedance caused by correlations, i.e., the relative magnitude of the peak, is of order

$$\frac{\Delta R}{R} \approx \left[\frac{\omega}{\omega_p} \frac{c}{V_F}\right]^{4/3} (C_2)^2 \approx 2 \times 10^{-6},$$

which is approximately four orders of magnitude smaller than we believe the experimental peak to be.

Preliminary calculations indicate that the effect of the mode on the surface impedance may be increased by nearly three orders of magnitude if one assumes diffuse scatter rather than specular.[14] This enhancement is reasonable if it turns out that the Gantmakher-Kaner (GK) oscillations[15] provide the mechanism which excites the new mode. Earlier calculations of transmission of waves through potassium slabs[16] have indicated that the transmission amplitude of the GK signal near cyclotron resonance is much greater when electrons scatter diffusely at the surface than when they scatter specularly. Similarly, rough scatter (which will be explained below) may be even more effective than diffuse scatter in producing GK oscillations. The wavelength of the new mode equals that of the GK signal at mode cutoff, and they both increase as the field drops below cutoff, although at somewhat different rates. Collisions, which damp the mode, render its k somewhat indeterminate, and so might allow interaction between the mode and the GK oscillation to occur at fields below the cutoff. If this indeed happens, then diffuse or rough scatter at the boundary, which gives rise to a much enhanced GK oscillation in the depth of the sample, would be much more effective in exciting the mode than would specular boundary scatter.

The second, quantitative, difficulty with our proposed explanation for the behavior of $R(H)$ is related to the overall shape of the curve. On the high-field side of the $l = 2$ mode the specular formula predicts a rising $R(H)$ curve. We suggest that this overall change in shape is also due to an incorrect treatment of surface scattering and surface roughness.

To visualize the effect of surface roughness, consider those electrons which are located close enough to the surface to experience strong skin-effect fields and which, at the same time, have V_z so small that they stay in the skin depth. Such electrons will, at $\omega = \omega_c$, exchange energy resonantly with a circularly polarized field, even if they strike a specularly reflecting surface. However, if they strike a diffuse surface, they are knocked out of resonance. This difference cre-

ates a difference in shielding current which, near $\omega = \omega_c$, modifies the calculated surface resistance.

This idea of resonant electrons requires that the surface be plane to within a skin depth over distances comparable with a cyclotron orbit diameter. If the surface is not plane and smooth to this accuracy, then all electrons which could have been resonant will collide with depressions of the surface before they have completed even a single orbit, i.e., before resonance has been established. This is what we mean by a rough surface. This, we believe, corresponds to the actual situation in potassium. The effect of a rough surface can be physically simulated in a Boltzmann equation description of the conductivity by introducing a mean free time $\tau(z)$ which depends on the distance z from the surface of the metal. By letting τ have the bulk value τ_B when z is greater than some distance δ from the surface (δ of the order of the skin depth) and some much smaller value τ_S (of the order $1/\omega_c$) when z is closer than δ to the surface, one has a situation where electrons with small V_z experience an effective $\omega_c\tau$ of much less than unity if they are close to the surface and a much greater $\omega_c\tau$ if they are deeper. Those which start their flights at the surface with a large V_z, and would not therefore strike the rough surface again are, by virtue of their rapid motion through the region δ, out of the disturbed region in a time short compared with τ_S, i.e., before the fictitious scattering can act. Those which start their flight at the surface with a small V_z will, because they stay in the region δ, experience the enhanced scattering rate τ_S^{-1} which approximates their collisions with depressions in the surface. Thus $\tau(z)$ can simulate the rough surface.

Using this simple model we have performed a detailed calculation of the surface impedance in the neighborhood of AKCR. No correlations were included. We find that the rough-surface scattering, i.e., a nonuniform $\tau(z)$ does change the shape of the absorption spectrum causing a decrease for a range of fields above cyclotron resonance. The details of this calculation will be published elsewhere.

The data in potassium show a sharp resonance in the vicinity of AKCR which is not present in any analysis which leaves out electron-electron interactions. A study of the Fermi-liquid theory shows that such a peak or mode is present and could account for the observed behavior of the surface impedance. Unfortunately a detailed quantitative comparison between a model theory and experiment is not available since the strength and shape of the absorption spectrum depend in an essential way on the nature of the rough potassium surface.

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