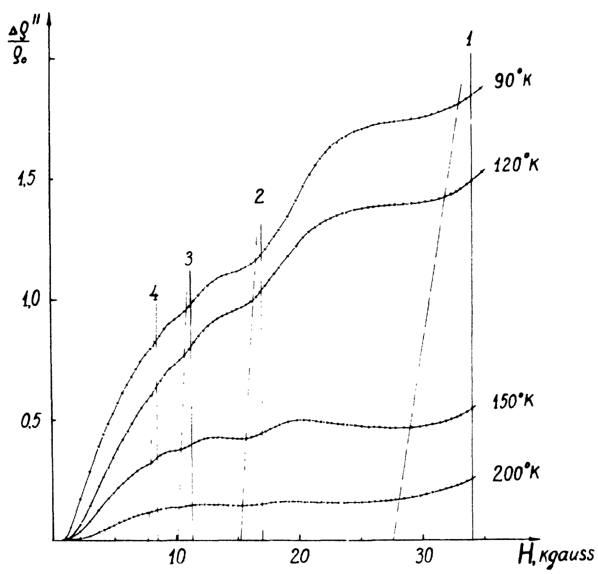

FIG. 3. The curves of the longitudinal magnetoresistance for n-InSb sample with carrier concentration 4×10^{13} cm^{-3} at different temperatures. The broken inclined lines show the displacement of the minimum positions when the temperature is changed.

should change when the relative intensity of acoustical and optical scattering varies. The curves obtained demonstrate the difference between this new oscillatory effect and the well known Shubnikov–de Haas oscillations. As we have seen, the period of the new type of oscillations is independent of the carrier concentration and the amplitude decreases with temperature in the region of liquid nitrogen and below. However, the period of the Shubnikov–de Haas oscillations is determined by the carrier concentration only and these oscillations can be observed at very low temperatures and only under degenerate conditions. The new oscillatory effect can be observed for any statistics. The specimens investigated in the present work were nondegenerate.

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EVIDENCE FOR A NEW COLLECTIVE RESONANCE IN A "FREE-ELECTRON" METAL*

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From cyclotron resonance[1] and de Haas–van Alphen studies,[2] the Fermi surface of K is known to be spherical within 1% with an effective mass of 1.21. Band studies[3] show that the energy gaps at Brillouin zone edges are $\mathcal{E}_g \lesssim 0.2$ eV compared to the Fermi energy $E_F = 2.2$ eV. The direct interband optical threshold would arise from transitions in the Brillouin zone near N. To second order in $\mathcal{E}_g/E_F$, the theoretical threshold energy E_t is given by the free-electron model: $E_t = 1.2$ eV.

Mayer and El Naby[4] have studied the reflectance of polarized light from mirror surfaces of metallic K in the temperature range -183°C to >85°C (the melting point) under conditions of high vacuum. We believe their data to be the best yet obtained[5] on the spectra of the alkali metals within their spectral range of 0.5-2.6 eV.

From their data [see Fig. 1(b)] the following salient results emerge:

(1) There is a sharp absorption threshold in $\mathcal{E}_2$ at $\hbar\omega \leq 0.5$ eV.

(2) Beyond the threshold $\mathcal{E}_2$ rises sharply to a peak at 0.6 eV and then falls gradually out to 2.0 eV.

(3) At their lowest temperature (-183°C), $\mathcal{E}_2$ drops to zero (within experimental error) for $0.5 \leq \hbar\omega \leq 0.7$ eV. This observation rests on three experimental points. Moreover, in Fig. 2 we show that as the temperature is lowered, the difference D between the total $\mathcal{E}_2$ and the Drude background diminishes monotonically as well as finally reversing sign at -183°C.

(4) At the peak, the excess absorption (over

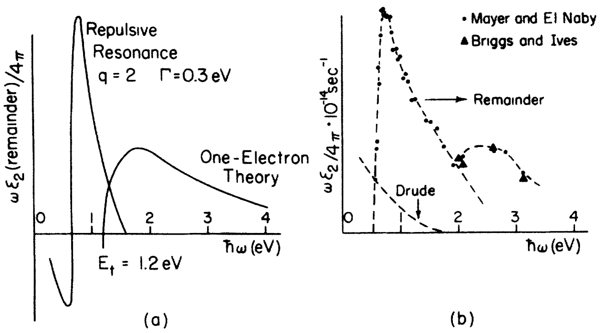

FIG. 1. (a) Theoretical and (b) experimental plots of $\omega\mathcal{E}_2/4\pi$ with the Drude background subtracted. The experimental points shown are for $T = 20°\text{C}$. Two theoretical curves are shown in (a). The one-electron curve describes direct interband absorption as calculated in reference 6. The resonance curve is taken from reference 7. The parameters q and Γ have the meaning defined there, with estimated values indicated in the figure.

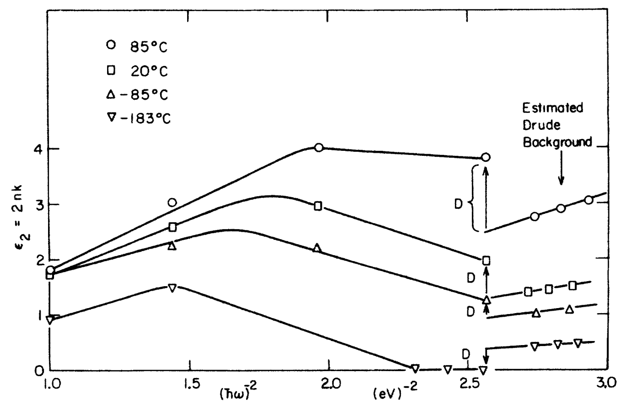

FIG. 2. A sketch to emphasize the antiresonance which occurs near 0.5 eV. For the sake of clarity only a few experimental points are shown. The Drude background at the right of the figure is estimated from dc-conductivity measurements. Note that the difference D between the total $\mathcal{E}_2$ and the Drude background decreases monotonically as a function of decreasing temperature, and that at -183°C $\mathcal{E}_2$ is zero to within the limits of experimental accuracy for $0.5 \leq \hbar\omega \leq 0.7$ eV.

the Drude background) is almost temperature independent.

(5) The peak not only continues to exist in the liquid state ($T = 85°\text{C}$) but actually narrows somewhat on the high-energy side.

(6) There is additional structure in $\mathcal{E}_2$ for the crystal near 2 eV which disappears in the liquid. In this range there is good agreement with earlier room temperature data of Briggs and Ives [see Fig. 1(b)].

(7) The real part $\mathcal{E}_1$ of the dielectric constant appears to behave normally[6] and yields $\hbar\omega p = 4.25$ eV, in 1% agreement with the free-electron value.

Can the foregoing facts be interpreted within the conventional theory of normal metals? We believe not. The following conventional explanations come to mind:

(A) The absorption edge is a direct interband transition initiating at E_F near the point N of the bcc Brillouin zone. To account for the large deviation of E_t from the free-electron value 1.2 eV, this explanation would require a gross and arbitrary distortion of the energy bands of the final state without significant changes in the bands at E_F. Such a distortion contradicts current understanding of both one-electron energy bands[3] and many-electron treatments of the electron gas.

(B) Indirect transitions from the Fermi surface to the second band minimum at N would indeed occur at the observed E_t. The resulting line shape would resemble that of the normal interband threshold which is shown in Fig. 1(a). For both direct and indirect transitions realistic band structures give broad thresholds because of momentum space arguments.[7] One cannot obtain a sharp edge without arbitrary distortions of the band structure as in (A). Moreover, the expected strong temperature dependence of indirect transitions is absent.

The experimental line shape resembles that of an asymmetric Breit-Wigner resonance.[8] In an earlier Letter,[9] similar asymmetric resonances in insulators were exhibited. There, interference was between the interband background (which generally contains structure itself) and metastable excitons. If we discard (A) and (B) but stay within the Landau quasiparticle framework, a nonresonant background can only arise from structure-free Drude contributions to $\mathcal{E}_2$. The observed structure can then arise only from a new collective excitation interfering with the Drude background via the Breit-Wigner interference mechanism.

The striking feature of the resonance in K is its positive asymmetry.[8] This contrasts with the negative asymmetry of metastable excitons[9] in insulators and suggests that the resonance may arise from the Drude background via an effectively repulsive electron-electron interaction. The sign of the interaction plus the probable nature[3] of the band structure of K make the interpretation of the resonance as a metastable exciton implausible.

What, then, is the nature of the proposed new collective state? Having ruled out as implausible the foregoing possibilities, we believe the most likely explanation for this "Mayer-El Naby" resonance is that the Landau framework itself fails for K, i.e., that K can no longer be regarded as a normal metal. Preliminary data kindly provided us by Professor Mayer show evidence for similar phenomena in Cs. Should Na also prove to be abnormal, the argument[10] between Cohen and Matthias concerning its electronic ordering at $T=0$ would be resolved in favor of both, i.e., Na, like K, may be neither normal nor superconducting.

Because the collective resonance occurs at $\hbar\omega \sim \frac{1}{4}E_F$, a detailed explanation requires studying Landau quasiparticle interactions "off the energy shell." The theoretical questions raised by the resonance are thus complex. With regard to experiment, however, one can say that tunneling,[11,12] optical and magneto-optical studies, and soft x-ray emission and absorption experiments all may exhibit these collective effects. To characterize collective resonances as such, sufficient resolution is required to display the antiresonance at low temperatures. Having established the presence of both resonance and antiresonance in the solid, the persistence of the collective state into the liquid is then definitive. The latter also suggests studies of liquid metal alloys in order to vary r_s in hopes of finding a transition back to the normal state as r_s decreases.

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COHERENT PAIRING OF THE SECOND KIND FOR STRONGLY INTERACTING FERMIONS*

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Mayer and El Naby[1] have recently observed a remarkable resonance in the optical absorption of metallic potassium at 0.6 eV. Phillips and the present author[2] have inferred from the resonance that K is not a normal metal. Is there then another metallic state distinct from either the normal or the superconducting state?

Coherent, singlet pairs of conduction electrons occur in the superconducting state.[3] We propose to look for new coherently paired states before broadening the search to include states of more complex collective character.

Generalization of the s-wave pairing in superconductors to p-wave pairing, d-wave pairing, etc. has been proposed.[4] Such l-dependent pairing can exist at equilibrium only in a macroscopically anisotropic system and is therefore relevant only to the excited states of isotropic systems. We propose instead possible radial dependences of the s-wave singlet pairing alternative to those in superconductors.

The BCS integral equation for the energy-gap parameter of isotropic systems is

$$\Delta(\epsilon)+\int d\epsilon\, n(\epsilon)K(\epsilon,\epsilon')\tanh\tfrac{1}{2}\beta E(\epsilon')/E(\epsilon')\Delta(\epsilon')=0, \quad (1)$$

with ϵ the single-particle energy relative to the Fermi energy, $n(\epsilon)$ the density of single-particle states, $\beta=1/k_BT$ and E the Bogoliubov quasiparticle energy[3,5]

$$E=[\epsilon^2+\Delta^2(\epsilon)]^{1/2}. \quad (2)$$

The symmetric kernel $K(\epsilon,\epsilon')$ is the sum of all