PERSISTENT RING CURRENTS IN AN IDEAL BOSE GAS

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In their fundamental paper on the theory of electrical resistivity, Kohn and Luttinger[1] considered a gas of particles which do not interact with each other, but do interact with randomly located scattering centers. They proved that this system has a normal electrical resistivity, and that the statistics (Fermi-Dirac or Bose-Einstein) of the particles does not make any qualitative difference.

Their proof breaks down, however, below the Bose-Einstein condensation point, where one single-particle quantum state is occupied by a macroscopic number of particles. We have investigated this case for a system contained in a ring-shaped volume, and find that persistent ring currents are set up by the usual method. That is, the ring is placed between the poles of a magnet, then cooled below the Bose-Einstein transition temperature, and finally removed from the external magnetic field. Within the assumptions of the model, the lifetime of these currents is infinite, independently of the physical size of the ring.

The phenomenology corresponding to this model is similar to, but not identical with, the London[2] equations. In particular, the "flux quantum" hc/e enters the equations explicitly. If the "bosons" are taken to be electron pairs,[3] the charge e is twice the electronic charge. The relation between the flux Φ through the ring, and the "external" flux Φ_e, is given in the model by

$$\Phi - m\Phi_1 = (\Phi_e - m\Phi_1)/(1+qN_0). \qquad (1)$$

Here Φ_1 is the "flux quantum," m is the integer closest to the ratio Φ_e/Φ_1 at the time the system is cooled through the transition temperature, N_0 is the number of condensed bosons (electron pairs), and q is the quantity

$$q = e^2 \mathfrak{L}/(2\pi\rho)^2 M, \qquad (2)$$

where $\mathfrak{L}$ is the self-inductance of the ring, ρ is its mean radius, and e and M are the charge and mass of the boson. In applications to superconductors, e and M should be taken as twice the charge and mass of an electron, respectively, and in the limit of low temperatures, N_0 is half the number of conduction electrons in the sample.

As the ring is cooled down through the transition temperature, without being moved, Φ_e remains constant, but small ring currents are generated which make the actual flux Φ very close to an integral number of flux units, $m\Phi_1$.[4] When the ring is then pulled out of the external magnetic field, Φ_e decreases to zero, and Eq. (1) predicts a new value for the final flux Φ maintained by the persistent currents. This final flux may differ appreciably from an integral number of flux "quanta," the difference being given by

$$(\Phi - m\Phi_1)/\Phi_1 = -m/(1+qN_0). \qquad (3)$$

With the experimental conditions of reference 4, m is of order unity and qN_0 much larger than 1; thus quantization should be maintained. But it should be possible to construct experimental conditions so as to observe the predicted deviation (3).

It is well known[3] that the Meissner effect in actual superconductors can be understood in precise analogy to such a Bose-Einstein gas model, the "bosons" being attractively correlated electron pairs. It seems likely, therefore, that the model calculation of persistent currents reported here can also be extended to an appropriate calculation for actual superconductors. There are, of course, significant differences between this model and actual superconductors, the most important difference being the complete absence, in the model, of an energy gap. We conclude that an energy gap is not required for the understanding of persistent currents; for if it were, we would not have been able to obtain persistent currents in the model.

The strictly infinite lifetime of ring currents in this model can be traced directly to difficulties in the foundations of nonequilibrium statistical mechanics[5]; these difficulties are present in the Kohn-Luttinger theory, but are concealed in this theory by the extensive averaging necessary at high temperatures.

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which many of these ideas were conceived.

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[3]J. M. Blatt, Progr. Theoret. Phys. (Kyoto) 24, 851 (1960).

[4]After completion of this work, the author received a preprint by Deaver and Fairbank, reporting this very effect [B. S. Deaver, Jr., and W. M. Fairbank, Phys. Rev. Letters 7, 43 (1961)].

[5]J. M. Blatt, Progr. Theoret. Phys. (Kyoto) 22, 745 (1959).

MILLIMETER CYCLOTRON RESONANCE EXPERIMENTS IN DIAMOND

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Cyclotron resonance has been observed in several semiconducting diamonds at 70 kMc/sec and at helium temperatures. For magnetic fields below 33.5 kilo-oersteds, two strong lines have been observed having effective masses of $(0.70\pm 0.01)m_0$ and $(1.06\pm 0.04)m_0$ with little or no anisotropy. The experiments will be described in this Letter.

The 4-mm wave spectrometer system is similar to a 2-mm spectrometer described previously,[1] with the following exceptions. A three-port circulator[2] and a commercial 1N2792 crystal detector are used to observe the signal reflected from the microwave cavity which operates in the TM_{013} mode and has a loaded Q factor of about 1500. As previously, the samples are positioned in the high axial electric field of the cavity for cyclotron resonance. The static magnetic field is obtained from a commercial 12-inch electromagnet with a 9/16-inch pole face gap. The light modulation of carriers and detection system as described previously is used.

The diamond crystals which were investigated are of the IIb variety.[3] Resonance was observed in only a few of the samples, and there appears to be a qualitative agreement of crystal perfection as determined from x-ray data with the observed linewidths in the spectrum. Some samples having $\omega\tau$ less than unity exhibited the characteristic nonresonant microwave magnetoresistance. Figure 1 shows a typical experimental trace in one of the better samples.

The curve is a reproduction of a recorder trace of the absorption at 69.2 kMc/sec as a function of magnetic field. The data were obtained at an ~0.1-microwatt rf power level at 1.2°K with a low level of light excitation. Lines are observed at $0.70m_0$ and at $1.07m_0$ having linewidths given by $\omega\tau\approx 13$ and $\omega\tau\approx 7$, respectively. The recorder trace of absorption is taken as a linear function of magnet current but the magnetic field is linear only through the low-field line. The high-field line falsely appears to be asymmetrical and much broader than twice the low-field line, but this results from a progressive increase in nonlinearity of the magnetic field.

Absorption line intensities decrease upon moving the sample to a region of weaker rf electric field, thus indicating that cyclotron rather than paramagnetic resonance is observed. Detailed anisotropy measurements indicate that little or no anisotropy exists in either resonance within the limits of accuracy of the experiment. At 4.2°K, the spectrum below 33.5 kilo-oersteds is very similar with the exception of unresolved structure on the low-field side of the low-mass line. On occasion at relatively low rf level, both at 4.2°K and 1.2°K, a weak line at about $0.5m_0$ is observed which may be a "quantum effect" line.

An attempt to observe resonance in the conduction band by exciting carriers across the gap (5.5 ev) with a hydrogen arc has not been successful.

The carriers which are observed have been excited with a tungsten light source which does not visibly glow, thus suggesting that the resonances are due to carriers in the valence band since the

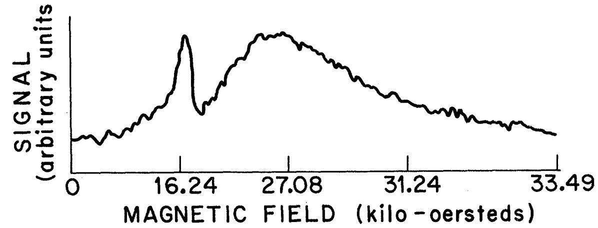

FIG. 1. Experimental trace of cyclotron resonance absorption in diamond at 69.2 kMc/sec and 1.2°K.