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"ELECTRIC FIELDS" IN SUPERCONDUCTORS*

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This Letter reports the first experimental evidence of the existence of an electric field in a type-I superconductor in the presence of a quasistatic magnetic field. This effect was predicted by London,[1] who remarked that in the hydrodynamic model of a charged superfluid, under quasi steady-state conditions ($\partial v/\partial t = 0$), the equation of motion predicts an electric field

$$\vec{E} = (1/e)\nabla \tfrac{1}{2}mv^2 \qquad (1)$$

(v is the velocity of the electron superfluid), which corresponds to the Bernouilli pressure of an uncharged fluid. To obtain the voltage between two points A and B inside the superconductor, the electric field (1) must be integrated along a line going from A to B:

$$V_A - V_B = \frac{m}{2e}(v_A^2 - v_B^2).$$

Let us apply this result to two different situations:

(A) Let us consider a superconducting slab in a transverse magnetic field with an external current I_T flowing through it [Fig. 1(a)]. This is the conventional geometry used to measure the Hall effect in normal metals. This current will flow in the surface layer like the Meissner current J_M, and a simple analysis shows that the electric field $\vec{E}$ of Eq. (1) integrated across the upper ($J = J_M + J_T$) and lower ($J = J_M - J_T$) surfaces corresponds to a Hall voltage (at 0°K) of

$$V_H = 2\lambda J_T H/ne, \qquad (2)$$

where n is the total density of electrons.

In type-I superconductors, for which London's Eq. (1) is replaced by a nonlocal relation between current and magnetic field, we might expect a modification of Eq. (1). However, an electric field must still exist, as we can see by considering the origin of the Laplace force on the lattice. The total force exerted on the superconducting wire is the Laplace force $I_T H$ per unit length. This force must be transmitted from the superfluid electrons to the lattice; since there is no momentum transfer from the superconducting electrons, the origin of the Laplace force is the action of the Hall electric field on the positive ions. If we suppose that the current I_T flows uniformly in two surface layers of thickness λ, the above argument gives the value

$$V_A - V_B = V_H = 2\lambda J_T H/n_I e$$

for the Hall voltage, where $n_I e$ is the total charge density of ions. This result shows that the Hall constant is $R = 1/n_I e$, that is to say, $R = 1/ne$, where ne is the total charge density of electrons which is independent of temperature ($n = n_n + n_S$, where n_n is the number of normal electrons and n_S is the number of super electrons per cm^3).

(B) Let us now consider an isolated superconducting sample in an external magnetic field, for example, a cylinder with its axis perpendicular to the field [Fig. 1(b)]. The voltage between points A and B is then[1] (London effect)

$$V_A - V_B = V_L = e\lambda^2 H_0^2/2m, \qquad (3)$$

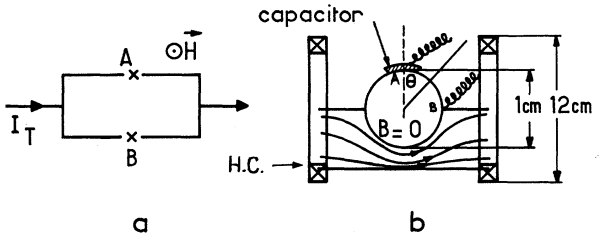

FIG. 1. Cross section of sample. (a) Hall case. (b) London case.

where H_0 is the field at the surface of the sample at point A.

Several attempts have been made to measure this electric field. Lewis[2] measured the voltage between the pole and equator of a vanadium sphere placed in an external modulated field (case 2), and Jaggi[3] measured the "self Hall effect" of lead with an external modulated current. Both Lewis and Jaggi used direct Ohmic contacts in their experiments and found a null result. In that case the voltmeter measures the difference in electrochemical potential between the two contacts. But in the superconducting state, the electrochemical potential $\mu = \mu_C + \frac{1}{2}mv_S^2 - eV$ (μ_C being the chemical potential and V the electrostatic potential) is the same everywhere, and this explains the negative result obtained by the above authors. This proves also that a contact potential builds up to compensate exactly the Hall voltage.[4]

A well-known method for measuring contact potentials is the classical Kelvin[5] method using a vibrating capacitor. We establish a capacitive coupling between the voltmeter and the superconductor and employ a dynamic measurement method, where the external magnetic field is modulated instead of the capacitor. We place a cylindrical sample in an alternating magnetic field ($\omega = 413$ Hz) normal to its axis [Fig. 1(b)] and measure the contact potential at point A. Thus we have only studied case two experimentally. For a magnetic field of the form $H_0e^{j\omega t}$, we expect a voltage proportional to $H_0{}^2e^{2j\omega t}$, and thus we detect the second harmonic, whose amplitude should be proportional to $H_0{}^2$. Care must be taken to eliminate induction signals at frequency ω which could saturate the synchronous detection amplifiers. We accomplish this by using a filter which passes the signal at 2ω and not that at ω. A block diagram of the experimental setup is shown in Fig. 2.

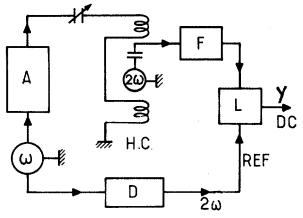

FIG. 2. Schematic block diagram of experiment. A, power amplifier 75 W (MacIntosh); D, frequency doubler (413 Hz); F, filter $\tau = 10^{-3}$; L, lock-in amplifier (H.R. 8); and H.C., Helmholtz coils.

In the case of an alternating magnetic field at the present frequency, the inertia term gives rise to a voltage of the order of 10^{-13} V, which is indeed negligible with respect to the London voltage.

In Fig. 3 the experimental results for lead at 4.2°K show that the amplitude of the signal at 2ω is indeed linear in $H_0{}^2$. The signal diminishes rapidly at about 280 G (applied field) for lead, where the sample enters the intermediate state. The field at the surface of the sample is then 560 G in this particular geometry. The eddy currents in the normal regions heat the sample and the whole specimen is driven into the normal state.

Fitting our experimental result in the expression (3) for the London voltage, we obtain $\lambda \simeq 380$ Å for lead, which is somewhat smaller than the usual value of $\lambda_0 = 390$ Å. The precision of our experimental results is about 10%, and it is impossible to detect the variation of λ with H_0. The length of our capacitor is much smaller than the length of circumference of our cylindrical sample, and thus we measure the exact value of V_L. If this is not the case, we measure a mean value of $V_L \cos^2\theta$.

The same experiment has been performed with Nb and PbIn below H_{c1}, and the results are quite similar.

In summary, we have verified London's prediction of the existence of an electric field in a superconductor. The corresponding voltage is however canceled by a contact potential.

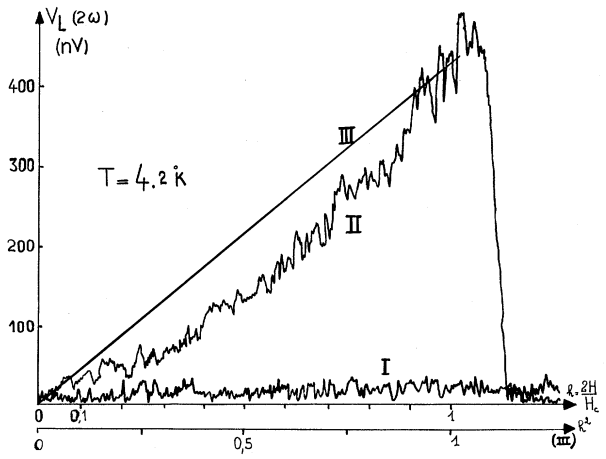

FIG. 3. Curve I is the "London" voltage plotted versus the normalized magnetic field $h = 2H/H_C$ with two direct Ohmic contacts. Curve II is the London voltage versus normalized magnetic field h with a capacitive contact. Curve III is the London voltage versus h^2.

We are presently studying the same phenomenon in the Hall-effect geometry (previously referred to as case A), but the signal is quite small (10^{-11} V cm^2/A) and consequently difficult to detect.

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ELECTRICAL CONDUCTIVITY OF POTASSIUM CHLORIDE

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The electrical conductivity of potassium chloride is discussed within the framework of a four-defect model of the crystal. The four defects are mobile anion and cation vacancies and immobile divalent cation impurities and divalent cation impurity-cation vacancy complexes. The Teltow formulation of the four-defect model fails to describe precisely the measured electrical conductivity of KCl over the entire intrinsic and extrinsic range.

The electrical conductivity of alkali-halide crystals has usually been discussed in terms of a four-defect model of an ionic crystal, the four defects being anion vacancies, cation vacancies, divalent impurity cations, and divalent cation impurity-cation vacancy complexes. In the Teltow formulation[1] of the four-defect model the defects are treated as noninteracting particles, the divalent cation impurities and cation vacancies are considered as complexes only when they are on nearest-neighbor lattice sites, and the mobility of the ions is given by the product of a jump-attempt frequency (ν) and a Boltzmann factor. It has been customary in the analysis of conductivity data to extract values for the various parameters, assumed to be temperature independent in the Teltow formulation, i.e., the entropy (s) and enthalpy (h) of Schottky-defect formation, the entropies ($\Delta s_\pm$) and enthalpies ($\Delta h_\pm$) of vacancy motion, and the binding energy of the complexes. It is our intent to show the limitations of the Teltow formulas for KCl.

In the intrinsic region where the effect of the impurity content is negligible, the Teltow expression for the conductivity reduces to the sum of two exponentials,

$$\sigma T = \frac{Na^2e^2\nu}{k}\left[\exp\left(S_+ - \frac{W_+}{kT}\right) + \exp\left(S_- - \frac{W_-}{kT}\right)\right], \quad (1)$$

where N is the number of cations per unit volume, a is the lattice parameter, e is the electronic charge, $S_\pm = (\frac{1}{2}s + \Delta s_\pm)/k$ and $W_\pm = \frac{1}{2}h + \Delta h_\pm$. A test of the Teltow formulation is to see if a sum of two exponentials will describe the intrinsic conductivity and gives results consistent with analyses of conductivity over a wider temperature range which includes the extrinsic region.

The electrical conductivity of "pure" Harshaw KCl crystals has been measured from 480 to 750°C using standard ac bridge techniques at 1 kHz and a furnace design which permits the taking of measurements every 3° or so. A higher density of data points than reported for other experiments of this type has thus been obtained. In Fig. 1 the data from our measurements of the conductivity of Harshaw KCl are shown by open circles and the data from the measurements of the conductivity of zone-refined KCl (data of Ref. 2, run No. 9) are shown by solid squares. The precision of our measurements is estimated to be ±1% for the conductivity and ±0.5°C for the temperature. The least-squares computer fit of Eq. (1) with the 59 experimental data points for $T > 560$°C is shown by the solid line in Fig. 1.

Two difficulties are encountered in the use of Eq. (1) to analyze conductivity data. One is the determination of the temperature at which