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[1]P. K. Larsen and K. Saermark, Phys. Letters 24A, 374, 668 (1967). Similar observations have been made in bismuth: V. F. Gantmakher and V. T. Dolgopolov, Zh. Eksperim. i Teor. Fiz.—Pis'ma Redakt. 5, 17 (1967) [translation: JETP Letters 5, 12 (1967)].

[2]G. N. Kamm and G. A. Alers, J. Appl. Phys. 35, 327 (1964).

[3]One of us, JRH, has studied the propagation of helicon pulses in metallic sodium (to be published).

THERMOMAGNETIC EFFECTS IN SUPERCONDUCTING NIOBIUM†

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The observations of a Peltier effect[1] and an Ettingshausen effect[2] in type-II superconductors in the flux-flow state have been explained in terms of the motion of individual fluxoids by the original authors and in subsequent, more detailed treatments.[3-5] We wish to report detailed observations of both effects in pure niobium, which cannot be explained in terms of a simple fluxoid model, and which moreover suggest that in the flux-flow state the normal current makes a contribution to the entropy flow.

This investigation was made possible by Dr. R. W. Meyerhoff of the Union Carbide Corporation,[6] who provided us with a specimen of pure niobium with a ratio of 3000 between the room-temperature resistance and the value at 9.5°K. The specimen was in the form of a strip 2.5 cm long by 0.52 cm wide by 0.02 cm thick. A uniform magnetic field could be applied perpendicular to the plane of the strip. The specimen was clamped at its ends to current leads of high electrical conductance made of a slightly impure indium alloy, and these leads were in the normal state at all temperatures at which measurements were made. All the data were taken with a current density of 1330 A/cm^2. Quantities measured in the direction of current flow will be given a subscript x, while those transverse to the current will be denoted with a subscript y.

Carbon resistance thermometers and Constantan heaters of matched resistance were mounted at each end of the specimen at the In-Nb junctions. With current flowing, the power dissipated in the heater at the cold junction was adjusted so that the thermometer readings were unchanged when the current direction was reversed and the power moved to the opposite junction. This power equals twice the Peltier power. The temperature difference across the specimen never exceeded a few millidegrees. The Peltier power was divided by the current to yield the usually defined Peltier coefficient,[7,8] Π_x. We estimate the relative accuracy of the values of Π_x in the flux-flow state to be better than 5%.

Thermometers were also mounted on each edge of the specimen at its center, and the temperature difference ΔT_y determined for each current direction. Appropriate power was dissipated in the heaters at the ends to nullify the effects of Peltier heat. The thermal conductivity of the specimen, κ, was also measured as a function of magnetic field[9] while the current was flowing through it. Instead of the Ettingshausen coefficient,[7] we define a quantity $\Pi_y = -(\Delta T_y)\kappa/wJ_x$, where w is the width of the specimen and J_x the current density, which is the analog of Π_x. The relative accuracy of these measurements is estimated to be 10%.

In addition, appropriately placed probes permitted the longitudinal voltage (see Fig. 3) developed across the specimen to be measured, as well as the Hall voltage near each junction. The two Hall voltages so determined were averaged to allow for slightly different behavior at each junction. The voltages were converted to a longitudinal electric field, E_x, and a Hall field, E_y. These data are similar to those published[10] for niobium. We remark that between about $0.95H_{c2}$ and H_{c2} both electric fields show a relatively rapid increase compared to their rates of change at lower magnetic fields.

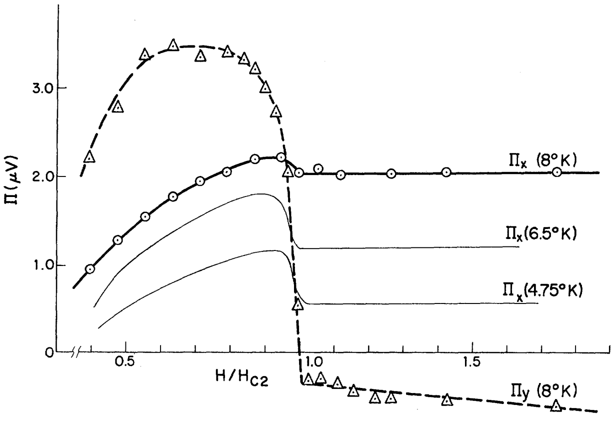

FIG. 1. Components of the Peltier coefficient Π_x and Π_y, which is related to the Ettingshausen coefficient, are plotted as a function of the ratio of the applied magnetic field to the upper critical field. The value of Π_x for the In lead has been subtracted from the data, leaving only the contribution due to Nb. At lower temperatures Π_y at H_{c2} becomes more negative, and the peak value in the flux-flow state decreases.

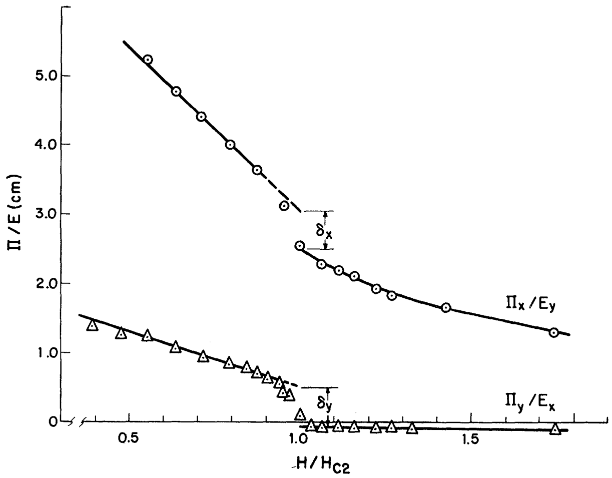

FIG. 2. The coefficients have been divided by the measured flux-flow electrical field E_x, and the Hall field E_y. δ is obtained by extrapolation to H_{c2} as shown.

In Fig. 1, the values of Π_x and Π_y at 8°K are plotted as a function of magnetic field. Because at 8°K the increase in Π_x near H_{c2} is small, we show in Fig. 1 the curves obtained at 6.5 and 4.75°K. Π_y is negative and proportional to magnetic field in the normal state. Just below H_{c2}, it rapidly increases to a value comparable to Π_x. The negative sign in the normal state was checked by an independent measurement of the Nernst coefficient.[7]

The striking feature of the data in Fig. 1 is the rapid increase in both the coefficients between H_{c2} and $0.95H_{c2}$. The increases occur despite decreases in both the electric fields and the fluxoid velocity, and a rapid decrease in κ as the field is reduced below H_{c2}. Thus the Π's are not proportional to the electrical fields. This point is illustrated further in Fig. 2, where the data at 8°K for Π_x/E_y and Π_y/E_x are shown. (The data obtained at lower temperatures are qualitatively similar.) On a single fluxoid model,[3-5] Π_x/E_y and Π_y/E_x should each be equal to CTS_L, where S_L is the entropy transported per unit length of a fluxoid and C is a constant.[11] We note that the apparent magnitudes of S_L deduced from Π_x/E_y are greater at all fields than those deduced from Π_y/E_x. However, if the approximate linear field dependence at low fields is extrapolated to H_{c2}, the quantities δ_x and δ_y are equal[12] within experimental error not only at this temperature but at 6.5 and 4.75°K.

These results imply that at H_{c2} a component of entropy transport appears which is associated with motion of fluxoids. This component is added algebraically to the normal state entropy transport at H_{c2}. However, entropy transport by the normal current density continues to exist below H_{c2}. This existence is clearly manifest in the data for Π_y at lower temperatures where this quantity remains negative to fields appreciably less than H_{c2}.

The data can be consistently described by assuming that

$$\Pi(H) = \Pi_f(H) + \Pi_n(H), \qquad (1)$$

where Π_f arises from the fluxoid contribution to the entropy flow, and Π_n from the normal current contribution. TS_L is then proportional to $(\Pi - \Pi_n)/E$. In order to effect this separation we assume that since at 8°K the normal state value[13] of Π_y is small, Π_n makes a small contribution to the values of Π_y/E_x in Fig. 2 so that the curve approximates closely to the fluxoid contribution to the entropy transport. Since this component presumably makes an identical contribution to the longitudinal entropy transport, subtracting it from Π_x should yield Π_{nx}. The values of Π_{nx} so deduced are shown in Fig. 3. It is to be noted that Π_{nx} decreases as the field is decreased below H_{c2}, and its dependence on field is similar in form to that exhibited by the flux-flow voltage. The

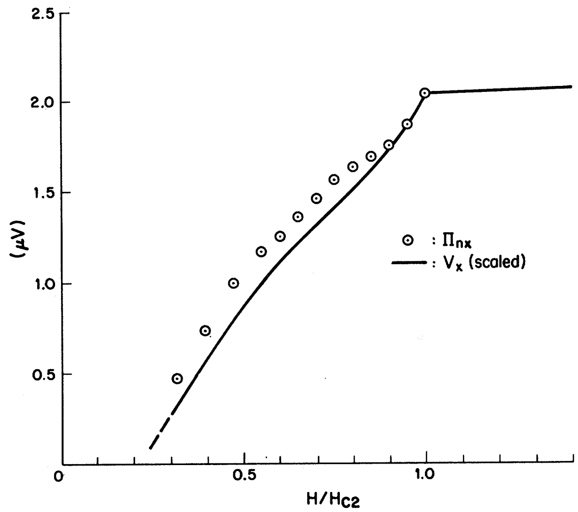

FIG. 3. Π_{nx} is the deduced normal current contribution to the entropy transport. The measured flux-flow voltages V_x have been scaled to give the value $\Pi_{nx}(H_{c2})$ at H_{c2}.

data at lower temperatures are harder to analyze because $|\Pi_{ny}(H_{c2})|$ is large. However, if we assume that for both the longitudinal and transverse coefficients $\Pi_n(H) = (H/H_{c2})\Pi_n(H_{c2})$, then the deduced fluxoid contributions to the entropy transport in the two directions agree to within about 25%, which we regard as further evidence in support of the contention that the data are described by Eq. (1). At all temperatures $\Pi_f(H)/E$ exhibits a rapid increase between H_{c2} and $0.95H_{c2}$ followed by a slower increase as the field is further reduced similar to the variation of Π_y/E_x illustrated in Fig. 2.

After this work was completed, we learned the results of a study by Caroli and Maki[14] of the microscopic theory of thermomagnetic effects at fields close to H_{c2}. In the pure limit, the derived transport equations contain terms associated with the normal current of the type we observe at all fields. Detailed analysis of the data between $0.95H_{c2}$ and H_{c2} indicate agreement with some aspects of the theory.

We are indebted to Dr. C. Caroli and Dr. K. Maki for informing us of their work before publication, and to Dr. Sang Boo Nam for his interest in this investigation.

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[1]A. T. Fiory and B. Serin, Phys. Rev. Letters 16, 308 (1966).

[2]F. A. Otter, Jr., and P. R. Solomon, Phys. Rev. Letters 16, 681 (1966).

[3]M. J. Stephen, Phys. Rev. Letters 16, 801 (1966).

[4]A. G. van Vijfeijken, Phys. Letters 23, 65 (1966).

[5]T. Ohta, Japan. J. Appl. Phys. 6, 645 (1967).

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[7]For definitions and a discussion of the various galvanomagnetic coefficients see, e.g., E. H. Putley, The Hall Effect and Related Phenomena (Butterworths Scientific Publications, Ltd., London, 1960).

[8]In 0 magnetic field, Π_x equals the absolute Peltier coefficient of the In leads, and at fields exceeding the upper critical field H_{c2} of Nb, it equals $\Pi_{\mathrm{In}}-\Pi_{\mathrm{Nb}}$. As a check on these measurements the thermoelectric power, ϵ, between the leads and the specimen was measured independently in both 0 and high magnetic fields, and the values of Π_x and ϵ so determined satisfied the Thomson relation[7] $\Pi_x = T\epsilon$ to better than 10%, where T is the absolute temperature. Since the values of ϵ had the greater uncertainty, we believe that our determinations of the absolute Peltier coefficients in the flux-flow state are also reliable to at least the foregoing accuracy.

[9]In the vicinity of H_{c2}, $\kappa \propto (H_{c2}-H)^{1/2}$, in agreement with the recent calculation of K. Maki, Phys. Rev. 156, 437 (1967).

[10]W. A. Reed, E. Fawcett, and Y. B. Kim, Phys. Rev. Letters 14, 790 (1965).

[11]In Gaussian units, $\Pi/E = (c/\phi_0 J_x)TS_L$, where c is the velocity of light and φ_0 is the flux quantum. For the current density used in this experiment, $(c/\varphi_0 J_x) = 3.65\times 10^4\ \mathrm{cm^2/erg}$.

[12]δ is approximately proportional to T^2 and at a given T corresponds to a change in TS_L of the order of magnitude of $(\xi_0{}^2\gamma T^2)$, where γ is Sommerfeld electronic-specific-heat coefficient and ξ_0 is the coherence length.

[13]It is to be noted that at all temperatures, Π_x in the normal state is comparable with the values in the flux-flow state, accounting for the large normal current contribution to the entropy transport below H_{c2}.

[14]C. Caroli and K. Maki, to be published.