THERMAL FORCES ON VORTICES AND ENTROPY TRANSPORT BY VORTEX FLOW IN TYPE-II SUPERCONDUCTORS

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Since the equilibrium properties of Abrikosov vortices in type-II superconductors, especially the degree of excitation in the core, depend on temperature,[1] it is reasonable to expect the dynamic properties of vortices to be related to nonequilibrium thermal conditions. An experimental investigation has yielded the observation of two thermomagnetic effects[2,3] which are associated with the motion of vortices. We have measured the temperature gradient produced by the transport of entropy when vortices flow across a type-II superconducting sample.[4] We have also observed potential differences produced by temperature gradients in the sample. These potential differences are good evidence for the existence of the inverse effect (i.e., the motion of vortices along an imposed temperature gradient). Thermal gradients seem, therefore, to be a new driving force for moving vortices.

The experimental arrangement is shown schematically in Fig. 1. The sample was a rectangular slab, about 4 cm long by $\frac{1}{2}$ cm wide by 0.16 cm thick, made from an alloy of In with 40 at.% Pb. It was located in an evacuated can immersed in a liquid-helium bath. The two ends of the sample were clamped to two heavy aluminum posts which extended into the helium bath through Stycast 2850 epoxy seals. These posts served as supports, current leads, and thermal shorts between the sample ends and the bath. Carbon resistance thermometers mounted on each edge of the sample, half-way between the two posts, measured the longitudinal and transverse temperature differences. Pairs of potential leads attached at various points along the sides of the sample measured longitudinal and transverse voltages. All the leads entered the evacuated can at the bath temperature, T_b, and made very poor thermal connection between the bath and the sample. A magnetic field, $\vec{B}$, was applied perpendicular to the broad face of the sample.

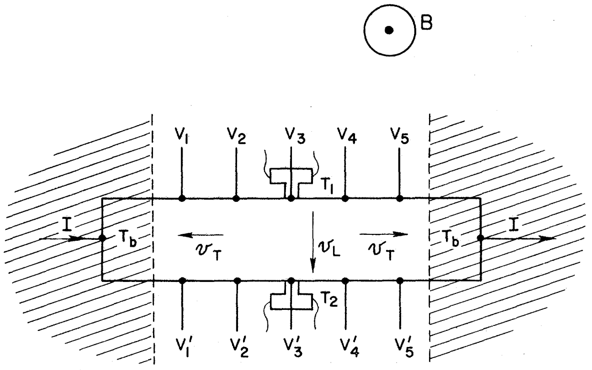

FIG. 1. Schematic diagram of the experimental arrangement. v_L is the component of vortex velocity due to the Lorentz force, and v_T, that due to the thermal force.

To measure the transport of entropy by vortices, the transverse temperature difference, $\Delta T_{\rm tr} = T_1 - T_2$, was measured as a function of the current in the sample. A transverse temperature difference was observed when and only when the current in the sample was large enough to overcome the pinning of vortices and cause them to flow across the sample. Using the longitudinal potential difference V_l as a measure of the transverse vortex flow rate,[5] we observe that at low flow rates the magnitude of $\Delta T_{\rm tr}$ is proportional to the flow rate (see Fig. 2). The sign of $\Delta T_{\rm tr}$ was observed to change upon reversal of either current or magnetic field. The edge of the sample where vortices were created was always cooler than the edge where they were destroyed. We also measured the longitudinal temperature difference, $\Delta T_l = (\frac{1}{2})(T_1 + T_2) - T_b$, which increased as a function of current because of the dissipation produced by the moving vortices.[6] The rise in temperature at the center of the sample, where $\Delta T_{\rm tr}$ was measured, was probably the cause for the nonlinearity in $\Delta T_{\rm tr}$ shown in Fig. 2.

From the above measurements one can calculate the entropy s per unit length of a vortex. If the dissipation produced by the moving vortices is uniform throughout the specimen, the temperature distribution along the length of the sample is parabolic, and the thermal conductivity κ may be calculated from the ratio of ΔT_l to the total power dissipated in the sample. Finally, Ts is proportional to $\kappa \Delta T_{\rm tr}/V_l$

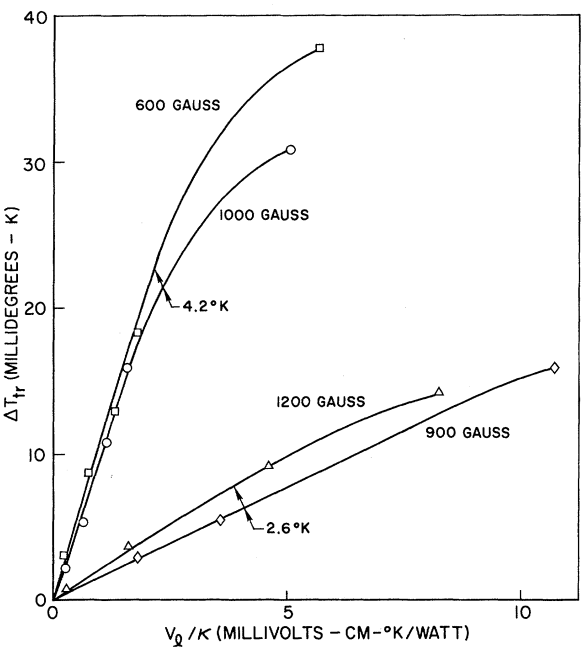

FIG. 2. Transverse temperature difference $\Delta T_{\rm tr}$ as a function of V_l/κ, where V_l is the longitudinal voltage and κ is the thermal conductivity calculated from ΔT_l and the power dissipated in the sample (sample No. 2). The explanation of the field dependence is not completely clear.

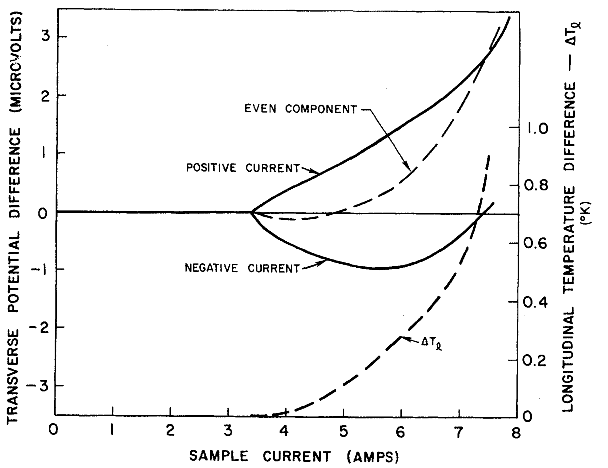

FIG. 3. Transverse voltage, $V_5 - V_5'$, and longitudinal temperature rise, ΔT_l, versus sample current (sample No. 4).

and so is proportional to the initial slope of the curves in Fig. 2. For 4.2°K and 1000 G, Ts is 8×10^{-7} erg/cm vortex. Because of the simplicity of the above measurements compared to calorimetric techniques, this effect may prove to be a useful tool for investigating the temperature and magnetic-field dependence of the entropy of vortices.

To investigate whether a thermal gradient can drive vortices, transverse potential differences were measured when temperature gradients were established by the self-heating of the sample. As shown in Fig. 3, the transverse potential difference $V_5 - V_5'$ had a large component even in current. The magnitude of the even component of voltage was proportional to the longitudinal temperature gradient at the position of the probes, and the sign of the even component of voltage changed upon reversing the magnetic field. In one sample, probes measured the transverse potential differences at five points along the sample (as shown in Fig. 1) for several values of positive and negative magnetic field and several temperatures. In all cases, the magnitude of the even component of voltage was roughly proportional to the local gradient of the temperature as determined from ΔT_l and the assumed parabolic shape of the temperature distribution. The sign of the even component of voltage was consistent with the motion of vortices away from the warmer parts of the sample. The even component of voltage disappeared when the sample warmed enough to go normal. By comparing the transverse and longitudinal voltages we can arrive at the current equivalent of the thermal force on a vortex. In sample No. 4 at 4.2°K and 600 G, a thermal gradient of 1°K/cm produces a force equivalent to that of a current density of 3 A/cm^2. Another way of checking this effect was to display on an x-y recorder the transverse voltage as a function of the longitudinal temperature difference, ΔT_l, after suddenly turning on the current. An initial quick increase in the voltage was followed by a slow change which was linear in ΔT_l. This behavior agrees with the assumed model. When the current was shut off, however, the voltage disappeared immediately, whereas the sample cooled slowly. The lack of thermally produced voltages in the absence of a current can be explained by the fact that the critical current density for the sample was about 40 A/cm^2. The thermal driving force was thus inadequate to move vortices except when added to a Lorentz force such that their vector sum was larger than the pinning force. Use of the analogy with thermomagnetic effects[2] along with the Onsager reciprocity relations permits an estimate of the thermal force from the inverse effect (i.e., from the temperature gradient produced by moving vortices, described above). This calculation yields numbers in the range 3 to 10 A/cm^2 for several specimens of the same alloy under the same conditions. These numbers are consistent with the measured value.

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[1] See for example K. Maki, Physics 1, 21 (1964); Physics 1, 127 (1964); Physics 1, 201 (1964); and Phys. Rev. 139, A702 (1965).

[2] The effects seen are analogous to the Ettingshausen effect—a transverse temperature difference produced by a longitudinal electrical current in a magnetic field—and the Nernst effect—a transverse electric field produced by a longitudinal temperature gradient in a magnetic field.

[3] The Peltier effect has recently been observed by A. T. Fiory and B. Serin, Phys. Rev. Letters 16, 308 (1966).

[4] A temperature difference caused by an entropy flow associated with the motion of normal regions in a type-I superconductor has been predicted by Yu. V. Sharvin, Zh. Eksperim. i Teor. Fiz.—Pis'ma Redakt. 2, 183 (1965) [translation: JETP Letters 2, 183 (1965)].

[5] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. 139, A1163 (1965); G. B. Yntema, Bull. Am. Phys. Soc. 10, 580 (1965); B. D. Josephson, Phys. Letters 16, 242 (1965); I. Giaever, Phys. Rev. Letters 15, 825 (1965); P. R. Solomon, Phys. Rev. Letters 16, 50 (1966); J. Pearl, Phys. Rev. Letters 16, 99 (1966).

[6] A model which gives a reasonable picture of the dissipation of moving vortices was presented recently: J. Bardeen and M. J. Stephen, Phys. Rev. 140, A1197 (1965).

OBSERVATION OF MAGNON-PHONON INTERACTION AT SHORT WAVELENGTHS

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Measurements have been made of the magnon and phonon dispersion relations in uranium dioxide at 9°K. These measurements provide evidence of a strong interaction between the magnon and phonon excitations and enable a value to be deduced for the coupling constant. The interaction of long-wavelength magnons in ferromagnetic materials has been studied previously with ultrasonic techniques; however, inelastic scattering of slow neutrons enables both the magnon and phonon dispersion relations to be determined for short wavelengths. In those magnetic materials which have been studied by earlier workers,[1] the magnons and phonons either interacted with one another very weakly or else their frequencies were very different. The results could then be understood without introducing any magnon-phonon interaction. In this note we report measurements of both the magnon and the phonon spectra of antiferromagnetic uranium dioxide, which lead to a magnon-phonon coupling constant of 9.6 ± 1.6°K. Since the Néel temperature[2] is 30.8°K, this coupling constant is of a similar magnitude to the direct magnetic interactions.

The specimen, a single crystal of close to stoichiometric composition, was aligned with a $(1\bar{1}0)$ plane horizontal, and cooled to 9°K. The experiments were conducted on the triple-axis crystal spectrometer[3] at the C5 facility of the NRU reactor at Chalk River. The constant-"$\vec{Q}$" technique[3] was used throughout the experiments with the analyzer energy held fixed at either 13.70 or 11.37 meV. The centers of the neutron groups then give the frequencies of the excitations in the crystal.

The magnetic structure of uranium dioxide consists of ferromagnetic sheets perpendicular to an [001] axis, with the magnetic moments aligned in the sheets.[2,4] Since in the paramagnetic phase there are three equivalent [001] axes, the antiferromagnetic specimen had a domain structure corresponding to the different possible orientations of the ferromagnetic sheets.

A careful study was made of the interaction between the magnons and the transverse acoustic (TA) phonons propagating in the $[00\zeta]$ direction ($\zeta = aq/2\pi$). Figure 1 shows a reciprocal lattice diagram of uranium dioxide illustrating two of the regions in which the measurements were made at 9°K. Also shown are the nuclear and magnetic reciprocal lattice points in the $(1\bar{1}0)$ plane.