FLUX NONFLOW IN THE "FLUX-FLOW" REGIME IN BULK TIN*

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Contrary to the recent experimental results of Sharvin, we have observed that the laminas characteristic of the intermediate state in type-I superconductors do not move under the influence of a transport current.

Perhaps the most convincing experiment to date on "current-induced flux motion" in superconductors is the one reported by Sharvin.[1,2] Sharvin observed periodic fluctuations in the voltage measured by a microprobe in electrical contact with the superconductor. These fluctuations he attributed to alternating superconducting and normal laminas passing under the probe. This experiment has had wide appeal because of its directness and simplicity. However, Chandrasekhar and co-workers[3] have challenged Sharvin's work by suggesting that the signal may have been due to some instability inherent in the microprobe-superconductor junction.

In order to settle the argument we have repeated Sharvin's experiment with the following improvements: (1) We use a micromagnetometer which is in close proximity to, but not in electrical contact with, the sample; (2) the field probe is movable so that we can detect the laminas whether or not they move; (3) the sample geometry (rectangular) gives a distribution of transport current in the region of the probe that is more uniform than in the disk-shaped samples used by Sharvin. We observe directly that the laminas do not move even when the transport current (less than the critical current) is large enough to give "flux-flow" voltage in the sample. This result supports the thesis of Chandrasekhar and co-workers and requires that the resistive behavior of a type-I superconductor in the regime studied in Refs. (1) and (3) and this work be explained by some mechanism other than motion of the laminas.

The micromagnetometer used in the present experiment consisted of a superconducting microbridge [illustrated in Fig. 1(a)] prepared from a thin film of $\mathrm{In}_{0.98}\mathrm{Pb}_{0.02}$. The sensitive volume of the probe was 3000 Å thick, 3 μ long, and 5 μ high.[4] Rotating a precision screw with a motor drive moved the probe across the sample at a uniform (variable) rate and turned a heliport for automatic position plotting. The probe resistance was measured with a microvoltmeter using the conventional four-lead technique. Because the critical magnetic field of the probe was approximately equal to that of the sample, the probe behaved as if it were "magnetoresistive." The sensitivity of the probe (i.e., the sharpness of the resistance versus magnetic field transition) as well as its critical field could be controlled by varying the current through the probe I_p. The probe was capable of detecting a change in magnetic field of less than 0.5 G or about 0.5% of the applied field.

The sample [Fig. 1(b)] was rolled from a 99.995%-pure tin ingot. It was cut to size, epoxied to an aluminum block, annealed at 80°C for 36 h, ground flat, and annealed at 185°C for three hours. The ratio of the room-temperature resistivity to the resistivity at 4.2°K was 1.2×10^4. Four leads were attached to the ends of the sample to supply the transport current I_S and to measure the voltage V_S. The angle β between the sample surface and the magnetic field direction was held at 20° in order to duplicate Sharvin's experimental conditions.[1] Sharvin showed in an earlier powder-pattern study[5] that such an inclined magnetic field produced a regular array of laminas parallel to the in-surface component of the field. The values of the reduced temperature ($T/T_c = 0.74$) and the reduced field ($H/H_c = 0.90$) were

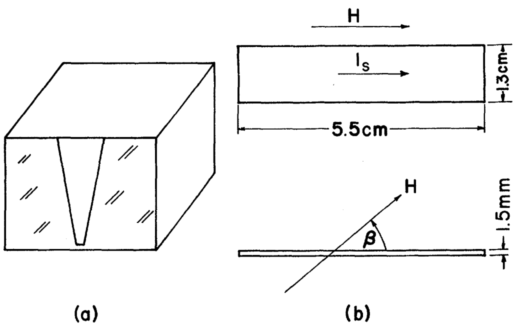

FIG. 1. (a) Thin-film micromagnetometer on the edge of a Pyrex block; (b) bulk tin sample showing the orientation of the magnetic field relative to the sample surface.

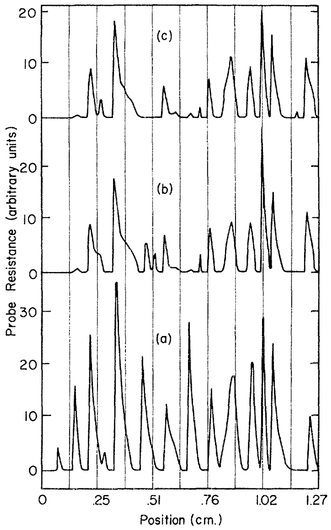

FIG. 2. X-Y recorder tracings of probe resistance as a function of position on the sample. The reduced temperature $T/T_c = 0.74$ and reduced field $H/H_c = 0.98$ were constant for all three traces. The sample transport current I_S was 0 in (a) and 3 A in (b) and (c). The rate of probe travel in (a), (b), and (c) was 0.8 cm/min. There was a 20-min delay between traces (b) and (c).

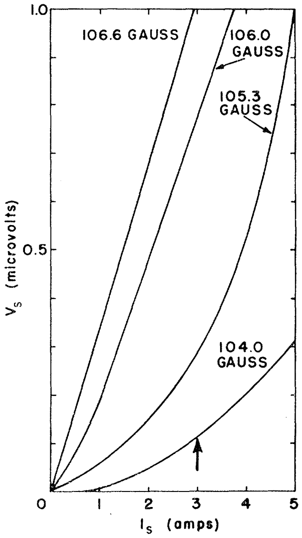

FIG. 3. Voltage-current characteristics for the tin sample at $T/T_c = 0.74$. The sample is normal at $H = 106.6$ G. The values of current and applied field at which the traces shown in Fig. 2 were made are indicated by the arrow.

the same as those used in Sharvin's experiment.

Figure 2 shows X-Y recorder tracings which exhibit the response (resistance) of the microprobe as a function of its linear displacement across the surface of the sample. The peaks[6] occur when the probe is above normal areas, and the valleys represent superconducting areas. The qualitative differences in the traces of Figs. 2(a) and 2(b) are due presumably to the self-field of the transport current rather than to motion of the laminas. The immobility of the laminas is confirmed by the trace in Fig. 2(c) which was taken 20 min after the trace in Fig. 2(b). During this time delay the temperature, the transport current, and the applied field were all held constant. Since the predicted velocity[7] of the laminas, based upon the value of the observed voltage, is of the order of 1 cm per min, any motion of the laminas should have been observed.

Figure 3 shows the voltage-current curves for the sample showing the characteristic resistance of the "flux-flow state." The curve for $H = 104$ G was made immediately after the probe sweep shown in Fig. 2(c) with no experimental variables changed except I_S.

It is obvious from the figures that motion of the macroscopic laminas which are characteristic of the intermediate state in thick type-I samples does not occur and is not necessary for the observation of the so-called "flux-flow" voltage. We hesitate to make any sweeping generalizations concerning "flux flow" in other regimes such as a superconductor in the "$n = 1$ vortex" state.[8]

The question remains: What is the physical origin of the periodic signal observed by Sharvin and/or Chandrasekhar *et al.*? It is conceivable that it arises from the periodic nucleation, growth, and subsequent bursting of helium bubbles which nucleate at the point of the resistive contact (where there is local heating). This phenomenon is accompanied by a periodic changing of the rate of heat transfer at the local "hot spot" and a concomitant periodic behavior of the resistivity of the local region. We have observed this effect on numerous occasions in situations where one has a superconductor in the resistive state in the present of local (current induced) heating. In these instances we have observed periodic voltage (resistance) signals which are certainly as regular as those reported by Sharvin, and of comparable duration and frequency. Although this may not be the explanation of Sharvin's results, it is an example of one mechanism which can lead to spurious time-dependent periodic effects.

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[1] Yu. V. Sharvin, Zh. Eksperim. i Teor. Fiz.—Pis'ma Redakt. 2, 287 (1965) [translation: JETP Letters 2, 183 (1965)]; in Proceedings of the Tenth International Conference on Low Temperature Physics, 1966 (to be published).

[2] Other convincing experiments are the dc-transformer (coupled-superductor) experiments done independently by Giaever and Solomon: I. Giaever, Phys. Rev. Letters 15, 825 (1965); P. R. Solomon, Phys. Rev. Letters 16, 50 (1966).

[3] B. S. Chandrasekhar, D. E. Farrell, and S. Huang, Phys. Rev. Letters 18, 43 (1967).

[4] The superconducting transition temperature of the microscopic bridge (in the presence of current flow) is lower than that of the macroscopic thin-film patches connected by the bridge because of the higher current density in the bridge. Therefore the measured resistance comes entirely from the microbridge.

[5] Yu V. Sharvin, Zh. Eksperim. i Teor. Fiz. 33, 1341 (1957) [translation: Soviet Phys.—JETP 6, 103 (1958)].

[6] The peculiar shape of the peaks (spiked structure) is presumably due to the nonlinear response of the probe to the magnetic field. This is of no serious consequence in the present experiment since the purpose was to measure only the position of the laminas. The asymmetry of the peaks is perhaps due to sample surface roughness effects which could affect the probe-to-sample distance and hence the probe reading.

[7] C. J. Gorter, Physica 23, 45 (1957).

[8] This may be a type-II superconductor or a sufficiently thin type-I superconductor in a perpendicular field —e.g., see G. Lasher, Phys. Rev. 154, A347 (1967).

ELECTRON SCATTERING IN NICKEL AT LOW TEMPERATURES

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The electrical resistivity of pure metals at low temperatures can be expressed as the sum of two terms: an impurity scattering term ρ_0, which is constant, and an "ideal" term ρ_i, which is temperature dependent. In monovalent metals and others which do not belong to the transition or rare-earth groups,

$$\rho_i \approx cT^n,$$

where $n \approx 5$ for $T \ll \theta$.

By contrast it has been observed[1-4] in many transition elements (including the ferromagnets Fe, Co, and Ni) that a T^2 rather than T^5 term predominates at low enough temperatures. Of the order of $10^{-11}T^2$ Ω cm in magnitude, it was first observed in platinum and attributed[5] to mutual interaction of itinerant electrons from different parts or branches of the Fermi surface. In the case of the ferromagnetic metals an alternative explanation was suggested, namely scattering by spin waves or magnons.[6]

In order to resolve which of these explanations is the more important for the ferromagnets, we have measured both the electrical and thermal resistivities on a rod of high-purity nickel[7] (resistivity ratio $\rho_{273}/\rho_4 \approx 2500$). As in the electrical case, the thermal resistivity W can be separated into an impurity term, $W_0(=A/T)$, and an "ideal" term, W_i, i.e., $W = W_0 + W_i$. For many monovalent metals $W_i \approx CT^m$, where $m \approx 2 (T \ll \theta)$.

If electron-electron interaction is important, a term should be observed in the thermal resistivity[8] W which corresponds to the T^2 term in ρ; this term would be proportional to T and give rise to a Wiedemann-Franz-Lorenz ratio, $L_i = \rho_i/W_iT$, having a constant finite value as the temperature approaches 0. On the other hand, if electron-magnon scattering is a major source of resistance, then we should expect this ratio L_i to decrease noticeably at low temperatures: Interband scattering by magnons will become frozen out at temperatures below, say, 20°K in nickel as the wave vector of the excited spin waves becomes smaller.[9] Likewise, intraband scattering by magnons should cause a very low Lorenz ratio as $T \to 0$ because of its inelastic nature.

Our observations show that below 20°K,

$$\rho = \text{constant} + bT^2$$

and

$$WT = \text{constant} + bT^2,$$

i.e., $W = A/T + BT$. Figure 1 illustrates this dependence and the rather puzzling fact that the magnitude of the T^2 term increases significantly below 5°K.[10]

Thus from 5 to 20°K,

$$\rho_i \approx 26 \times 10^{-12} T^2 \ \Omega \text{ cm}$$