Quantization of magnetic flux at temperatures above the superconducting transition temperature

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We investigated experimentally the quantization of the magnetic flux under conditions of fluctuation pairing. The conductivity oscillations of hollow thin-wall aluminum microcylinders were observed in a longitudinal magnetic field up to 8 °K. Qualitative agreement with theory is obtained under the assumption that the coherence length of the investigated samples is anomalously large.

Fluctuation pairing in superconducting has been the subject of persistent attention in recent years, both in theory and experiment. The purpose of the present paper is to study the quantization of the fluxoid at temperatures exceeding the superconducting transition temperature T_c. Kulik has demonstrated earlier the feasibility of manifestation of coherent quantum effects[1] under conditions of fluctuation pairing.

The experimental procedure used by us is analogous to that used in the study of the Parks-Little effect. Thin-wall microcylinders were obtained by evaporating aluminum on a glass filament in an oxygen atmosphere at a pressure 7×10^{-5} mm Hg. The diameter (ϕ) of the sample was determined from the period of the quantum oscillation. The critical temperature was obtained from the expression[2,3]

$$R'_\square = \frac{R^N_\square}{\tau_0 T_c} T - \frac{R^N_\square}{\tau_0}, \qquad (1)$$

where

$$\frac{1}{R'_\square} = \frac{1}{R_\square(T)} - \frac{1}{R^N_\square}; \quad \tau_0 = \frac{R^N_\square e^2}{16\hbar} = 1.52\cdot 10^{-5} R^N_\square.$$

$R^N_\square$ and $R_\square(T)$ are the resistances of the film per unit area in the normal state and at the temperature T. The plot of (1) crosses the temperature axis at $T = T_c$. Figure 1 shows a plot of $R'_\square(T)$ for a sample having the following characteristics: $\phi = 0.23$ μ, film thickness 110 Å, $R^N_\square = 17$ ($\Omega/\square$), $\xi(0) = 780$ Å. The coherence length was determined from the relations $\xi(0) = 0.85 \times (\xi_0 l)^{1/2}$ and $\rho_n l = 1.6\times 10^{-11}$ Ω-cm^2. The slope of the $R'_\square(T)$ plot determines the value of $R^N_\square/\tau_0 T_c$. The resultant value $(\tau_0)_{\rm exp}$ is 5–6 times larger than $\tau_0 = 1.52 \times 10^{-5} R^N_\square$, thus indicating that it is necessary to take into account the additional Maki-Thomson term[4] in the relation that describes the temperature dependence of the fluctuation conductivity. A similar discrepancy with τ_0 is observed also in a number of studies[3,5] of the conductivity of aluminum films at $T > T_c$.

The critical temperature determined by the method describes above delimits two temperature regions. In the region below the critical temperature T_c, the quantization of the fluxoid (the Parks-Little effect) has been investigated quite fully by many workers.[6–9] No investigations were made at temperatures above T_c. We have established that the quantum oscillations of the conductivity are retained in the region $T > T_c$ and are reliably observed up to 8 °K.

A plot of $R(H)$ obtained by automatic recording at temperatures far from T_c is shown in Fig. 2. The compensated background amounts to approximately 8000 Ω. On the left side of the figure is shown the scale of the resistance oscillations.

The temperature dependence of the oscillating part of the fluctuation conductivity, as obtained by Kulik, is given by

$$\Delta\sigma = \sigma_{Al}\,\lambda\sqrt{\frac{\pi}{2}\,\frac{1}{\lambda}}\exp(-\lambda), \qquad (2)$$

where

$$\sigma_{AL} = \frac{e^2}{16\hbar d}\,\frac{1}{\ln(T/T_c)}, \quad \lambda = \frac{L}{\xi(T)} = \frac{\pi\phi}{\xi(T)},$$

$$\xi(T) = \frac{\xi_0}{\sqrt{\ln(T/T_c)}}.$$

In expression (2) we supplement σ_{AL} with the Maki-Thomson correction and rewrite this relation in the form

$$\frac{\Delta\sigma}{\sigma'} = \lambda\sqrt{\frac{\pi}{2}\,\frac{1}{\lambda}}\exp(-\lambda), \qquad (3)$$

where $\sigma' = \sigma(T) - \sigma_N$.

A comparison of the temperature dependence described by (3) with the experimentally obtained values of $\Delta\sigma/\sigma' = f(T)$ is shown in Fig. 3. The experimental data are represented by the point. Curve *a* is a plot of (3). Against the background of the expected abrupt decrease of the ratio $\Delta\sigma/\sigma' = f(T)$ with increasing temperature,

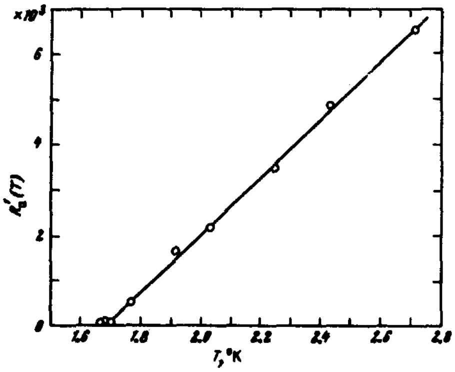

FIG. 1.

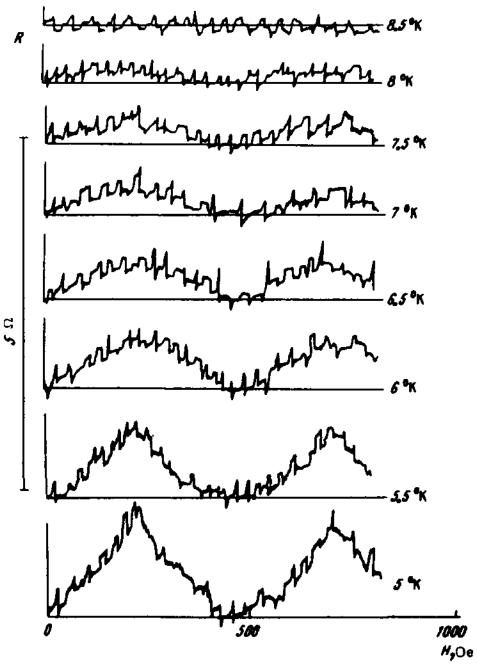

FIG. 2.

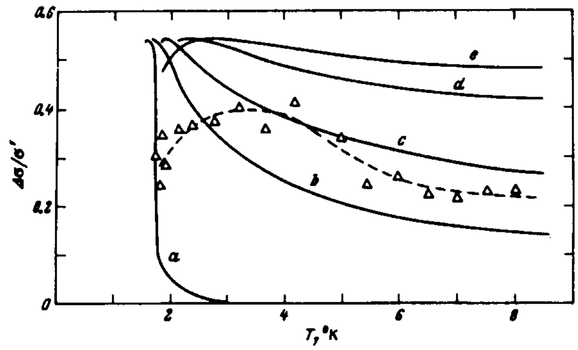

FIG. 3.

the experimental values of this quantity do not change significantly over the entire investigated temperature interval. A temperature dependence of the ratio $\Delta\sigma/\sigma' = f(T)$ qualitatively similar to that observed experimentally can be obtained by assuming that the coherence length is much larger than $\xi(0) = 780$ Å. Curves *b*, *c*, *d*, and *e* of Fig. 3 are platted respectively for $\xi(0) = 3500$, 5000, 8000, and 10 000 Å. For Al films with thickness on the order of 100 Å, however, such values of the coherence length are unjustifiably overestimated.

We can attempt to explain the origin of the quantum oscillations of the conductivity at such high temperatures by using the fact that the critical temperature of the superconducting transition of aluminum films depends strongly on their thickness. Assume that in our samples there is produced a situation wherein sections of film with different thicknesses form closed belts on the surface of a cylinder. In this case the critical temperatures of the belts will be different, and quantum oscillations of the conductivity will be observed up to a temperature equal to the maximum critical temperature of one of the belts. However, the highest critical temperature[10,11] of thin aluminum films known to us does not exceed 6 °K. Films with such parameters were obtained by evaporation on substrates at cryogenic temperatures. Films evaporated at room temperatures have values of T_c not exceeding 2.5 °K.[3,5] Consequently, to obtain qualitative agreement of this model with experiment we must also admit of the possibility of obtaining aluminum film with a critical temperature now lower than 8 °K.

Thus, the obtained data allow to draw the following conclusions: 1. The quantum oscillations of the conductivity of thin-wall microcylinders are preserved up to temperatures at least four times larger than T_c. 2. The temperature dependence of the ratio of the oscillating part of the conductivity to the value of the paraconductivity agrees qualitatively with the theory if it is assumed that the coherence length of the investigated samples is anomalously large.

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