Superconducting fluctuations in the destructive regime of ultrathin, superconducting cylinders

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Abstract

We have carried out experiments on ultrathin superconducting cylinders, which revealed the existence of a destructive regime predicted to occur around half-integer flux quanta in doubly connected samples with diameters smaller than the zero-temperature superconducting coherence length. At half-integer flux quanta, the resistance showed a broad resistance drop as the temperature was lowered, followed by a temperature independent resistance at the lowest temperatures. We show that the temperature dependence of the conductance at half-integer flux quanta can be attributed to superconducting fluctuations.

Key words: quantum phase transition; 1D superconductivity; superconducting fluctuations

Recently, experiments [1] on doubly connected, superconducting cylinders with diameters d smaller than the zero temperature ($T = 0$) superconducting coherence length ξ_0 have revealed the existence of a destructive, non-superconducting regime in the $T = 0$ limit, as predicted by de Gennes [2]. In this regime, the loss of the superconducting state is a direct consequence of the fluxoid quantization imposed by the superconducting global phase coherence in samples with a doubly connected geometry. This fluxoid quantization leads to the conventional Little-Parks effect, where the superconducting transition temperature T_c oscillates as a function of magnetic flux Φ with a period equal to the superconducting flux quantum $\Phi_0(= \mathrm{h}/2\mathrm{e})$. However, in sufficiently small cylinders the kinetic energy of the supercurrent can exceed the superconducting condensation energy as Φ approaches half-integer multiples of Φ_0. This results in the loss of global phase coherence, manifested as the appearance of a finite resistance, around half-integer flux quanta even in the $T = 0$ limit, and the occurence of a superconductor-normal metal (S-N) quantum phase transition.

In the destructive regime, measurements of the resistance as a function of temperature $R(T)$ showed a broad drop in the resistance at the relatively higher temperatures. We examine the temperature dependence of the conductance in this region and find that the excess conductivity $\Delta\sigma$ ($= \sigma - \sigma_N$, where σ_N is the normal state conductivity) exponentially grows with decreasing temperature. We show that this behavior may be attributed to the superconducting fluctuations present in the destructive regime.

In the following, we present data on a superconducting Al cylinder previously reported to have $d =$ 150 nm and $\xi_0 \approx 161$ nm [1]. Similar behavior was also observed in a $Au_{0.7}In_{0.3}$ [3] cylinder. A schematic of the sample preparation, and an image of a comparable cylindrical sample is given in Fig. 1. Further experimental details have been presented elsewhere [4,5].

Figure 2a shows the $R(T)$ curves at fixed values of Φ measured down to 0.30 K. At integer flux quanta, the resistive transitions exhibited the expected T_c shift, with very little broadening of the resistive transition. In comparison, a relatively broad drop in resistance was found for half-integer flux quanta.

Such behavior is different from the transition broadening resulting from flux motion, as the field in the par-

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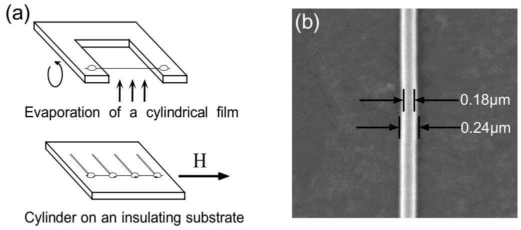

Fig. 1. (a) Schematic for sample preparation. Material is evaporated onto an insulating fiber. The cylinder is then mounted onto an insulating substrate and leads attached for electrical transport measurements. The arrow indicates the direction of the applied magnetic field. (b) SEM image of a cylinder with a 300Å thick wall.

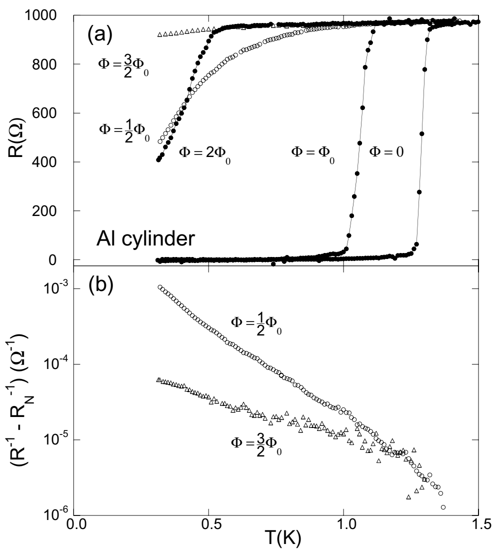

Fig. 2. (a) Resistance as a function of temperature at integer and half-integer multiples of the magnetic flux quantum, as indicated. Lines connect the data points. (b) Semilog plot of the excess conductance as a function of temperature at $\Phi = \frac{1}{2}\Phi_0$ and $\frac{3}{2}\Phi_0$.

allel orientation does not induce vortices in thin cylindrical films. If a small misalignment of the cylinder does lead to field-induced vortices, a higher field would generate a higher number of vortices and result in a wider transition. Nevertheless, the $\Phi = \Phi_0$ and $2\Phi_0$ curves showed significantly narrower resistive transitions than what is seen at $\frac{1}{2}\Phi_0$ and $\frac{3}{2}\Phi_0$.

It is clear, however, that the substantial drop in resistance is related to superconductivity. As the finite resistance at the lowest temperatures only indicates the loss of global phase coherence, it is possible that local pair formation may still survive. In particular, it is reasonable to ask whether the behavior is consistent with the presence of superconducting fluctuations.

In this case, the temperature dependence of the conductance is given by the Aslamasov-Larkin (AL) theory for fluctuation enhanced conductivity. The normal state conductivity is supplemented by superconducting fluctuations, such that the excess conductivity [6]

$$\Delta\sigma = (\rho^{-1} - \rho_{\rm N}^{-1}) \approx \frac{2e^2}{m^*}\sum < |\psi_{\bf k}|^2 > \tau_k/2 \qquad (1)$$

where $\psi_{\bf k}$ is the Fourier coefficient of the superconducting order parameter in momentum (k) space, and τ_k is the relaxation time in the time-dependent Ginzburg Landau equation. The temperature dependence of $\Delta\sigma$ is found by integration of Eq. 1 over k space, which leads to $\Delta\sigma \sim (\frac{T}{T-T_c})^{3/2}$ in one dimension (1D).

As can be seen in Fig 2b, the excess conductance at half-integer Φ_0 did not exhibit the behavior predicted by the standard AL theory, but instead showed an exponential dependence on temperature. Such a dependence, however, may still be consistent with fluctuation enhanced conductivity. The AL temperature dependence directly results from the T-dependence of τ_k and $|\psi_{\bf k}|^2$, determined by assigning an energy of k_BT to each orthogonal mode, *i.e.* each k value [6]. In the present case, this energy may not be assumed to be k_BT, as done in the standard calculation at relatively high temperatures. The Bose-Einstein distribution must be included in the temperature range considered. While a thorough calculation of $\Delta\sigma$ in this case remains to be carried out, it is reasonable to expect that such a consideration would introduce an exponential temperature dependence to the expression for $\Delta\sigma$, consistent with the experimental data.

In summary, we have examined the $R(T)$ in the destructive regime of ultrathin superconducting cylinders. An analysis of the broad resistance drop indicates that the excess conductance follows an exponential temperature dependence. Although an exact calculation of $\Delta\sigma$ remains to be carried out, this dependence appears to be consistent with the presence of superconducting fluctuations.

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