Fluctuations in mercury filaments five atoms in diameter

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We investigate the temperature dependence of the resistance and the current-voltage characteristics of mercury filaments five atoms in diameter in channels of chrysotile asbestos.

We measured the temperature dependence of the resistance of a bundle of mercury filaments of ~20 Å diameter in the range from 300 to 2 °K. These filaments were obtained by pressing the liquid metal into channels of natural chrysotile asbestos,[1] and differ from the previously investigated filaments[2,3] only in that their diameter is smaller. In[2] and[3] the filament diameters were 50–90 Å, but in our case the diameter was 20 Å (the scatter of the diameters was about ~20%). The measurements were made by a contact method at a pressure 13 kbar, thereby excluding breaks in the filaments along the channels. The filament diameters were determined, just as in[1], from pore diagrams. In our case the samples became conducting at a pressure of 8 kbar, corresponding to diameters 22.5 Å. Such small diameters of metallic filaments (5 atoms in diameter) have caused the following singularities to appear in the temperature dependence of the resistance:

1) The melting temperature of the mercury was

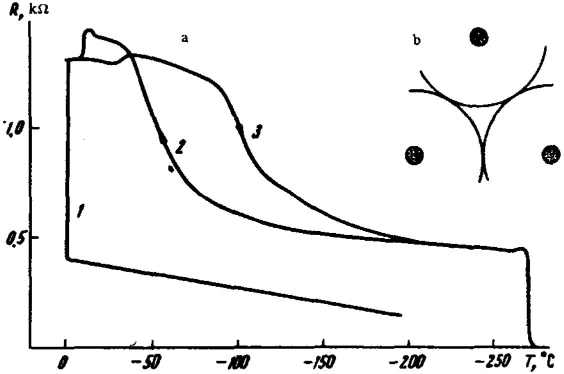

FIG. 1. Temperature dependence of the resistance of mercury filaments 5 atoms in diameter: a—1) temperature dependence of resistance of bulk mercury at 7.5 kbar; 2, 3) temperature dependence of the resistance of mercury filaments in asbestos channels: b—schematic representation of the cross section of the chrysotile fibers with channels filled with mercury.

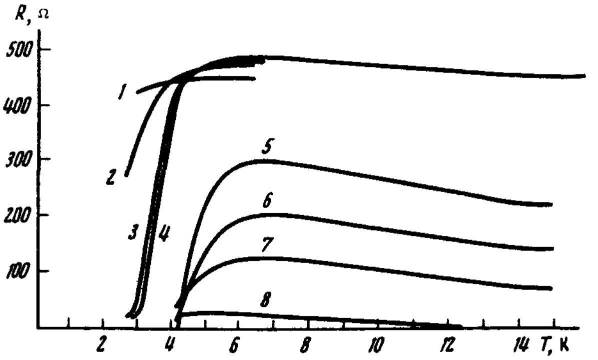

FIG. 2. Superconducting transition of mercury filaments of 20 Å diameter: 1) current 1.3 mA, 2) 400 μA, 3) 130 μA, 4) 13 μA, 5—8) part of the superconducting transition in enlarged scale (currents 170 μA, 350 μA, 700 μA, and 1.4 mA, respectively).

greatly decreased in the asbestos channels in comparison with bulk mercury (see Fig. 1). At the employed pressure (13 kbar), the melting temperature of bulk mercury is – 29 °C. The filaments with 50—90 Å diameter melt at a temperature ~ – 30 °C.[1] As seen in Fig. 1, the melting temperature of filaments of 20 Å diameter is even lower (– 40 to 60 °C). In addition, after solidification, an appreciable supercooling was observed, to temperatures ~ – 100 °C, and a certain increase of the resistance when the mercury filaments go from the liquid to the solid state and vice versa. This increase may be due to fluctuation formation of a new phase, which can greatly change the resistance of the thin filaments.

2) The limitation of the mean free path of the electrons by the terminal walls has led to a decrease in the temperature variation of the resistance (Fig. 1). Thus, when the temperature changed from 77 to 15 °K, the resistance of the sample changed by only ~10%, and a change from room temperature to 15 °K leads to a resistance change by a factor of approximately 3.5, corresponding to an increase of the mean free path from 7 Å in liquid mercury to ~25 Å at helium temperature This figure is close to the filament diameter.

3) The superconducting position of mercury in the asbestos channels (Fig. 2) has a temperature spread of almost 4 °K, which in all probability is due to fluctuations, which are significant for such thin elements. For filaments with larger diameters[2] and for mercury films (see, e.g.[4]), the smearing of the transition is only several tenths of a degree. In our samples, the additional conductivity due to the formation of fluctuation pairs in the region from 4.2 to 6.5 °K is given by

$$\sigma' = A\left(\frac{T_c}{T - T_c}\right)^{3/2}\sigma$$

where σ is the conductivity of the sample in normal states, and $A \sim 10^{-2}$, in accord with the results of[5] on the character of the temperature dependence of the filaments. The coefficient A is of approximately the same order as the theoretical estimate.[9] Below the transition, the fluctuations destroy the superconductivity and the fluctuation resistance should take the form

$$R \sim R_N \exp\left[B\left(\frac{T_c - T}{T_c}\right)^{3/2}\right],$$

where R_N is the resistance of the sample in the normal state.[6] Mercury filaments of 20 Å diameter have a similar temperature dependence of the resistance in a region 2.5—3.3 °K, with a coefficient $B \sim -4 \times 10^{-2}$, which is also close to the theoretical estimates of this coefficient, although somewhat worse than for the coefficient A.

The critical density of the current for the superconducting transition is ~10^5 A/cm². A magnetic field of 30 kOe shifts the transition only by ~0.3 °K, indicating that the critical field of such samples is large. Filaments of 50—90 Å diameter[3] had a critical magnetic field ~70 kOe (at $T = 0$ °K) with a quadratic temperature dependence of the field. If this dependence is used to estimate the field of our examples, we obtain a critical magnetic field ~200 kOe at $T = 0$ °K.

We measured the current-voltage characteristics of the mercury filaments in asbestos channels (Fig. 2). In the region from 12.2 to 2.8 °K, they are in qualitative agreement with the results of the theory proposed in[7], but at lower temperatures abrupt jumps appear in the resistance. These results were obtained both at 400 Hz and with direct current. In the latter case, the more sensitive circuit made it possible to measure more carefully the section of the current-voltage characteristics ahead of the jump (dashed curve). In this current region, the resistance behaves nonlinearly also ahead of the jump, and differs from zero even at the smallest currents. The current-voltage characteristics of mercury filaments of 60—90 Å diameter take the form of stepped curves, not similar to those of Fig. 2.[2] Filaments with diameter 30—40 Å, have current-voltage characteristics similar to the curves of Fig. 2, although their transition to the superconducting state is much less smeared out (~0.5 °K).

4) The samples investigated by us have an unusual temperature dependence of the resistance near the superconducting transition. As seen from Fig. 2, there exists a resistance minimum at 13—15 °K. The resis-

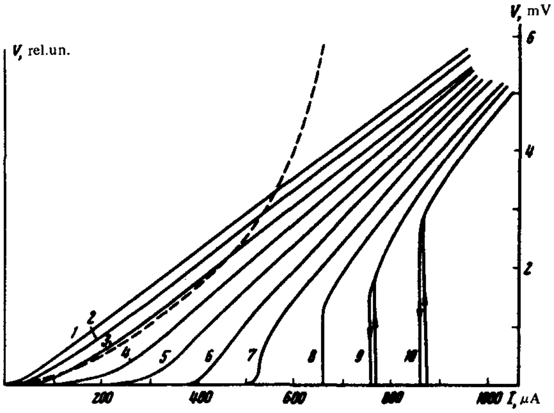

FIG. 3. Current-voltage characteristics of mercury filaments of 20 Å diameter: 1) temperature 4.2 °K, 2) 3.86 °K, 3) 3.32 °K, 4) 3.19 °K, 5) 2.95 °K, 6) 2.78 °K, 7) 2.6 °K, 8) 2.42 °K, 9) 2.32 °K, 10) 2.26 °K; dashed curve—section of current-voltage characteristics in enlarged scale (right-hand scale) at 2.5 °K.

tance then increases by ~5% and the superconducting transition begins near 6.5 °K. The nature of this increase of the resistance remains unclear. Neither asbestos nor mercury contains magnetic impurities capable of leading to a minimum of the resistance (the Kondo effect), as indicated by the absence of a similar minimum in mercury filaments with diameters 30—40 and 50—90 Å.[2] This increase appears only for various thin filaments of ~20 Å diameter. In this case, only the presence of the paramagnetic properties of the surface can be of significance. It is also possible that in such thin filaments, which are bound only by a dielectric matrix (~5—7 atoms in diameter), some lattice instability sets in ahead of the phase transitions. When the current density is increased, the curves become smoothed out as a result of a lowering of the hump (Fig. 3).

In conclusion, we wish to emphasize that metallic filaments in chrysotile asbestos are probably not the equivalent of the object whose model was considered in[8], for not only are the metal filaments themselves large in diameter, but the distances between them are also large (~200—300 Å), although some collective effects can be expected even in such a system of parallel current-carrying conductors. More promising is the filling of a mordenite-type matrix with metal.

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