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Superconducting critical fields of copper in proximity with Nb–Ti

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Abstract. We report the first measurements of magnetization curves of superconducting 10–20 μm thick copper in proximity with niobium–titanium. Very sharp first order transitions are observed at the breakdown fields H_b. From the temperature dependence of H_b, it seems that the pair penetration depth in copper is not limited by the electronic mean free path even at $T = 5$ mK.

If a normal metal is in good electrical contact with a superconductor, Cooper pairs can leak from the superconductor into the normal metal. The characteristic length describing the exponential attenuation of the pair potential in the normal metal is K_N^{-1}, the pair penetration depth. For $T \gg T_{CN}$ in the "clean" limit, that is, for a mean free path 1_N large compared to the coherence length ξ_N, the pair penetration depth K_N^{-1} is given by [1]

$$K_N^{-1} = \xi_N = \frac{\hbar v_F}{2\pi k_B T} \tag{1}$$

where T_{CN} is the transition temperature of the normal metal and v_F is the Fermi velocity in N. In the "dirty" limit ($1_N < \xi_N$), for a simple metal, the pair decay length is given by

$$\xi_N = \left(\frac{\hbar v_F 1_N}{6\pi k_B T}\right)^{1/2} \tag{2}$$

From (1) and (2) it is clear that in a metal with low T_{CN} these characteristic lengths can be increased to considerable values by reducing the temperature. We have studied proximity effects under magnetic fields in specimens of thick copper in contact with thick niobium–titanium alloys. The specimens consisted of commercial wires [2] of one single filament of Nb–Ti enbedded in a copper matrix. Two samples are reported here. Sample I has a superconducting core with a diameter $d_s = 70$ μm and a copper matrix 20 μm thick, and sample II has $d_s = 50$ μm and a matrix 10 μm thick. Measurements were made in the temperature range 5 mK $< T <$ 9 K. The specimens were cooled in direct contact with a dilute solution of ^{3}He–^{4}He inside the mixing chamber of a dilution refrigerator. Temperatures were measured with a CMN thermometer inside the same mixing chamber. The specimens were in the form of a bundle of insulated wires about

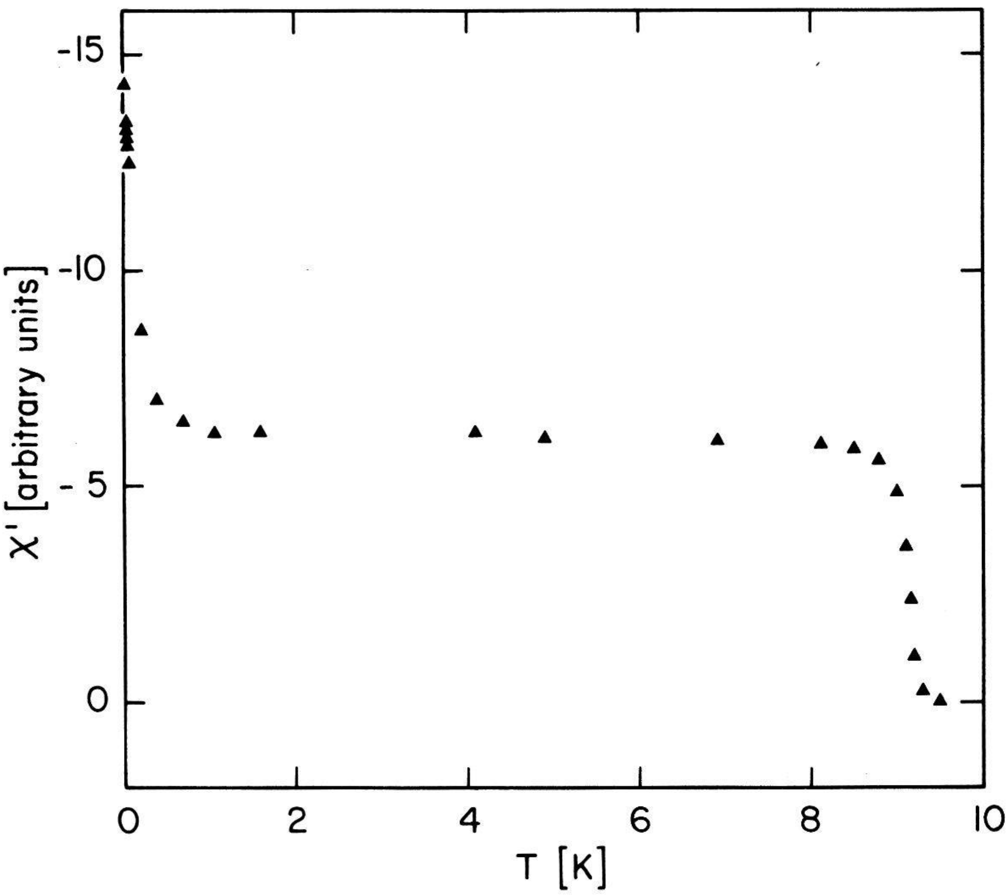

Figure 1
In phase component of the magnetic susceptibility of specimen I as function of temperature.

3 mm long and 3 mm in diameter. Magnetization measurements were made at constant temperature using a superconducting flux transformer between the sample and a SQUID detector. Susceptibility was measured using an a.c. bridge with a SQUID as a null detector. A d.c. magnetic field parallel to the wires was used for the measurements as function of field. Residual fields in the sample regions were about 2 mGauss.

Figure 1 shows the magnetic susceptibility of sample I as function of temperature. These measurements were taken with a field of 1 mGauss peak to peak, and at a frequency of 80 Hertz. We observe a diamagnetic transition at about 9 K followed by a sharp increase in the diamagnetic signal below about 1 K. Similar behaviour is observed for sample II.

De Gennes and co-workers [3] have calculated the screening distance ρ of magnetic fields in the normal metal in the weak field limit

$$\rho = K_N^{-1}\left(\log \frac{K_N^{-1}}{\lambda(0)} - 0.116\right) \tag{3}$$

where $\lambda(0)$ is the local penetration depth in N at the S–N interface. The ratio $\lambda(0)/K_N^{-1}$ may be considered as the Ginsburg–Landau parameter κ_N at the interface ($x = 0$). Due to the space variation of the pair potential in the normal metal and the temperature dependence of the coherence length, the Ginsburg–Landau parameter is strongly space and temperature dependent. At a given

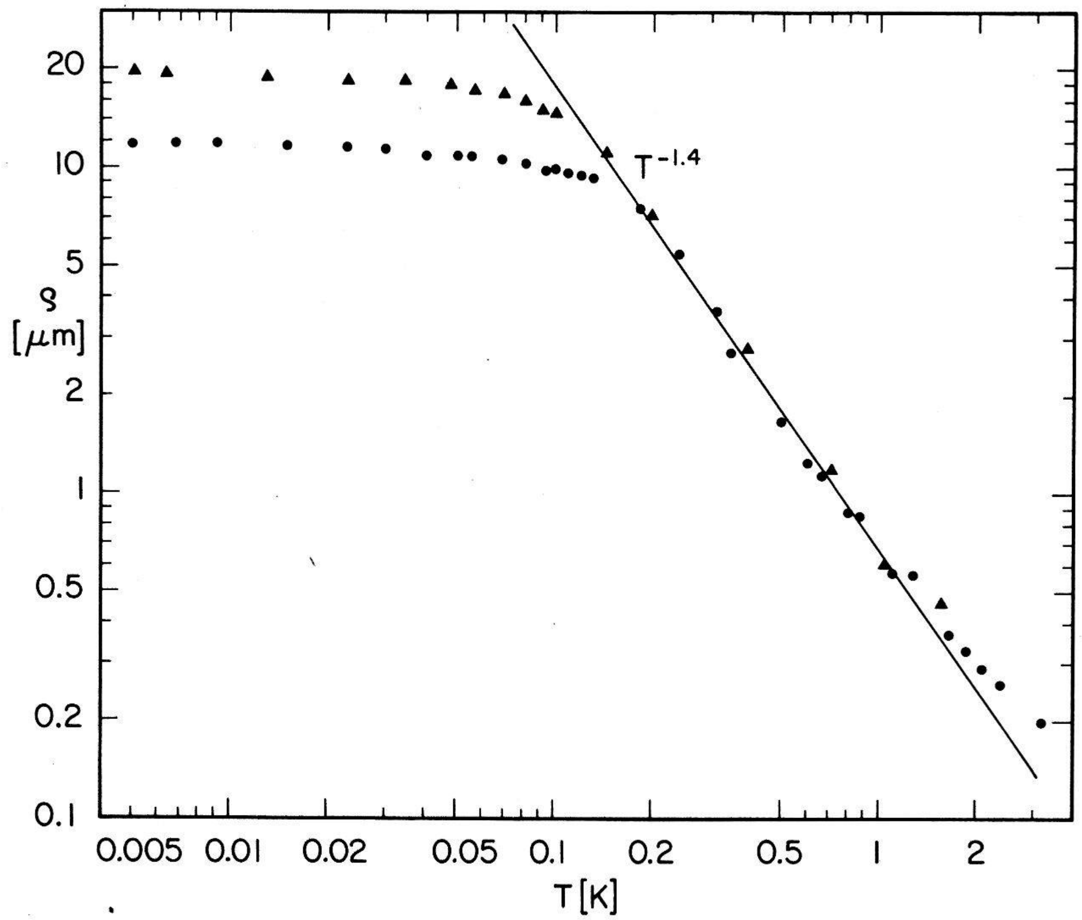

Figure 2
Screening distance ρ as function of temperature for specimen I (▲) and specimen II (●).

temperature T, κ_N is smallest at the interface and decreases as the temperature is reduced.

In order to observe an appreciable screening of the magnetic field in the normal metal, the condition $\kappa_N(0) < 1$ has to be satisfied. Our results in Fig. 1 clearly demonstrate the existence of a Meissner effect at the lowest temperatures. Values of ρ can be obtained experimentally from the data of Fig. 1 by a simple calculation. Figure 2 shows our results for sample I and for sample II. We observe an increase in ρ from 2 K down to about 0.2 K, followed by a saturation at lower temperatures indicating that below these temperatures the magnetic field is expelled from the entire specimen. The saturation values occur at $\rho = 19.5\ \mu$m for sample I, and $\rho = 12\ \mu$m for sample II. A partial Meissner effect in copper in similar samples has been reported by Oda and Nagano [4].

Electrical resistivity measurements were made with the specimens above 9 K. From these measurements we calculate a mean free path in the copper $1_N = 5.3\ \mu$m. This means that in our range of temperature we should go from the "clean" limit to the "dirty" one as the temperature is reduced. From Fig. 2 we observe $\rho \propto T^{-1.4}$ down to 200 mK. This strong temperature dependence of ρ suggests that down to 200 mK the sample is in the "clean" limit. At these temperatures the values of the Ginsburg–Landau parameter at the interface must be quite small, so that the factor in parenthesis in formula (3) is weakly dependent on T.

The Orsay group has analyzed the situation of a normal layer of finite thickness in the limit $\kappa_N \ll 1$. From permeability measurements it was observed that when $d_N \simeq K_N^{-1}$, the penetration depth in N remained constant up to a critical field H_b, at which a sharp transition occurred. Tunnelling measurements in the same system (InBi/Zn) showed a sharp transition in the density of states at the same value of H_b. A theoretical interpretation of H_b has been given in [5]. The transition at H_b is of first order and similar to the one at the thermodynamical critical field H_c in a type I superconductor. Supercooling and superheating are predicted in this case.

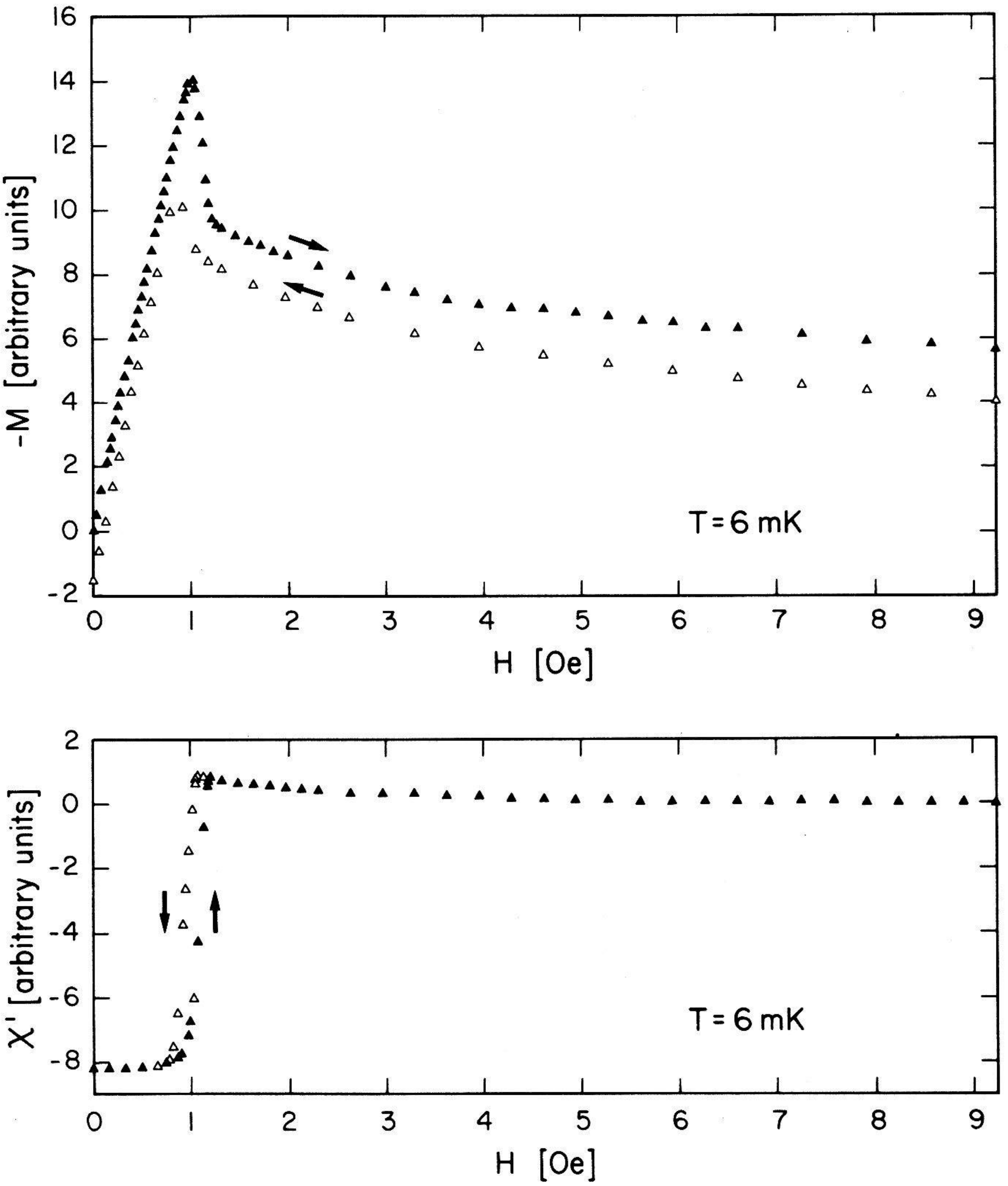

Figure 3
Upper part, d.c. magnetization of specimen I as function of magnetic field at $T = 6$ mK. Lower part, in phase component of the magnetic susceptibility as function of fields at the same temperature as above.

In the limit $\exp(K_N d_N) > 1$ where d_N is the thickness of the normal metal and $\kappa_N(0)\exp(K_N d_N) \ll 1$, H_b is given by

$$H_b = 3.8 H_N \exp(-K_N d_N) \tag{4}$$

with

$$H_N = \frac{\phi_0 K_N^2}{2\pi\kappa_N(0)} \tag{5}$$

where ϕ_0 is the flux quantum.

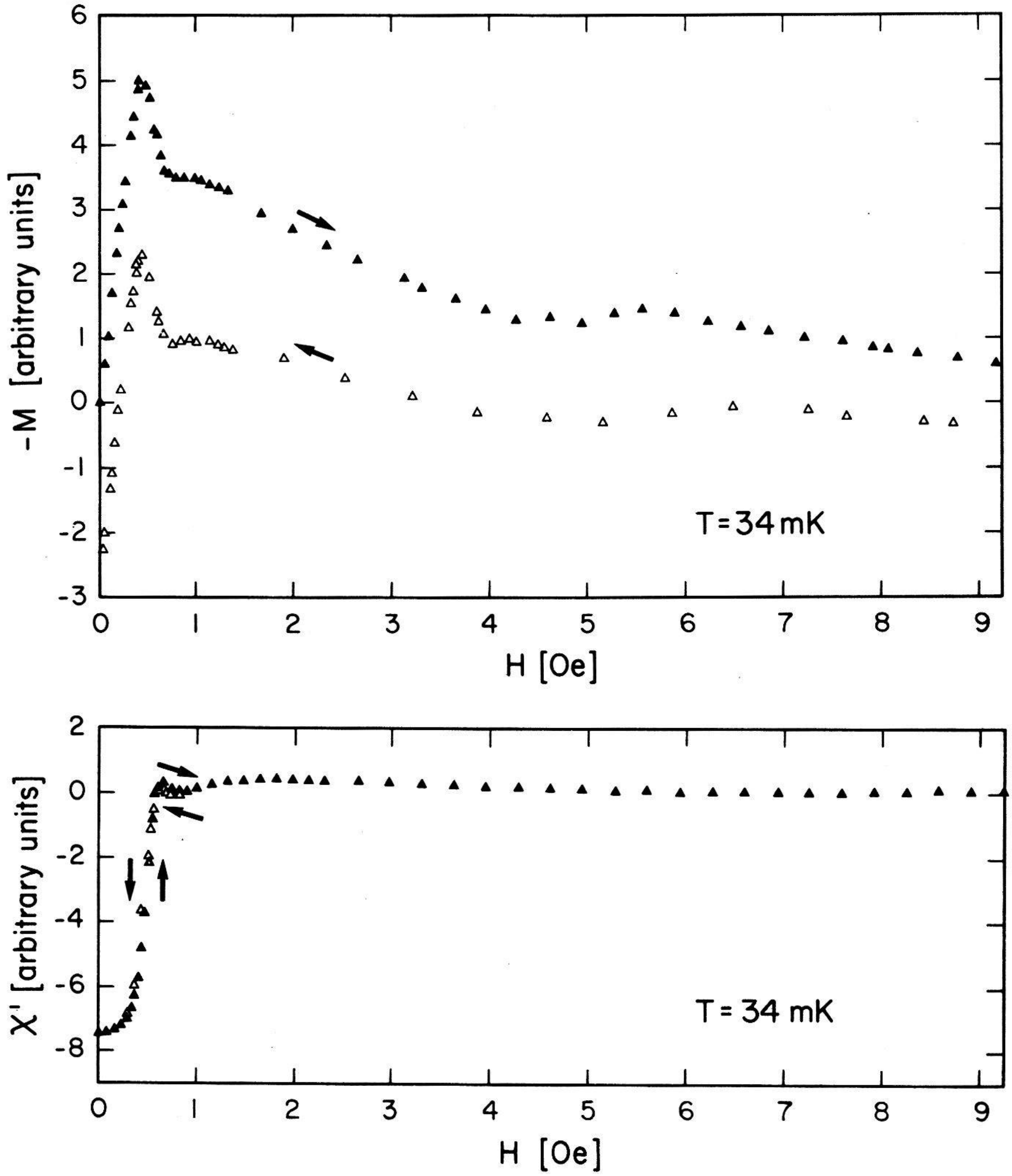

Figure 4
Upper part, d.c. magnetization of specimen I at $T = 34$ mK. Lower part, magnetic susceptibility as function of fields.

Figure 3 shows for sample I a magnetization curve in the upper part and the in-phase component of the magnetic susceptibility in the lower part, as function of magnetic field at $T = 6$ mK. We observe a sharp first order transition in the copper at a breakdown field H_b of 1.02 Gauss. Similar data at higher temperatures for the same specimen are displayed in Fig. 4 and Fig. 5.

We observe that at the lowest temperatures the copper behaves like a type I superconductor. Moreover, the transition at H_b, as seen in the a.c. susceptibility, is hysteretic indicating some supercooling. As the temperature is raised, the

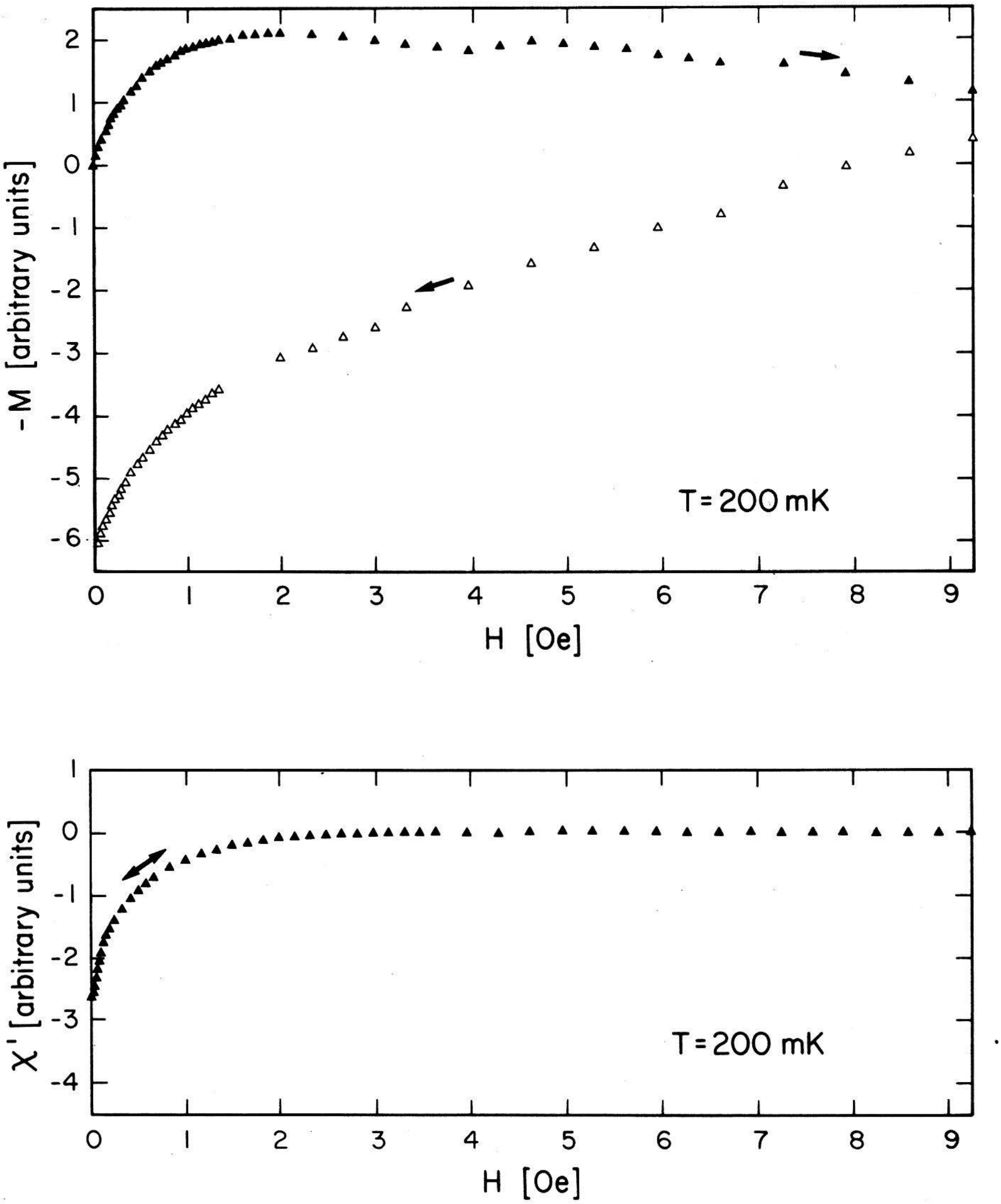

Figure 5
Same as Fig. 3 and Fig. 4 but at $T = 200$ mK.

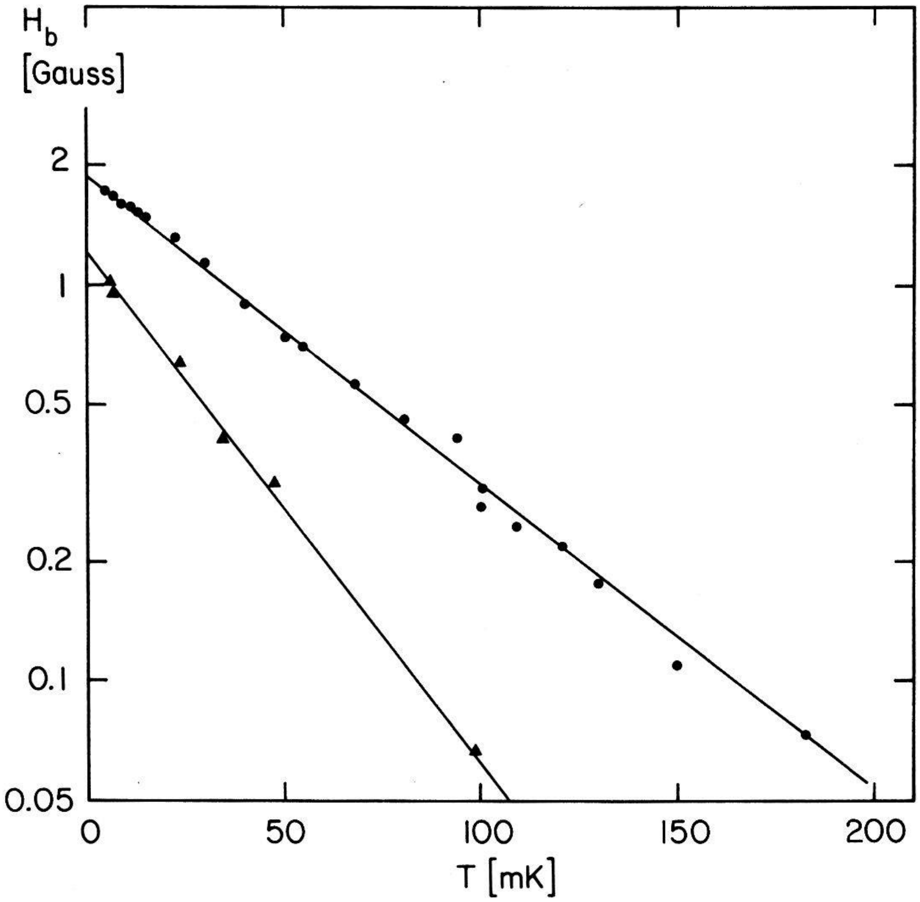

Figure 6
Breakdown fields H_b as function of temperature for sample I(▲) and sample II (●).

hysteresis decreases continuously until it disappears, as seen in Fig. 4 for $T = 34$ mK. At even higher temperatures the field penetrates continuously and no transition is observed (Fig. 5).

In Fig. 6 we have plotted the measured values of H_b as a function of T taken from similar curves as the ones in Fig. 3 and Fig. 4 for both samples. The lines correspond to a fit of the type $H_b = H_N \exp(-K_N d_N)$ with $K_N \propto T$ and H_N a constant for each sample.

The temperature dependence of K_N indicates that even at 5 mK the "clean" limit expression correctly describes the behaviour of the pair penetration depth. The fact that the data are described rather well with H_N independent of temperature seems to indicate, remembering the expression for $H_N = \phi_0 K_N^2/2\pi\kappa_N(0)$, that $\kappa_N(0)$ must be roughly proportional to T^2.

In conclusion, we have measured magnetization curves of superconducting copper in proximity with niobium–titanium in the region $\kappa_N \ll 1$. From the temperature dependence of the breakdown fields H_b we conclude that the pair penetration depth in copper follows $K_N^{-1} \propto T^{-1}$ down to 5 mK. This appears to indicate that K_N^{-1} is not limited by the electronic mean free path in copper. As far as we know, these are the first observations of H_b in a metal with extremely low T_{CN}.

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