Muon-method study of the superconductivity in $YBa_2Cu_3O_7$

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A Meissner phase exists for the $YBa_2Cu_3O_7$ system. The volume of the superconducting region is at least 80%. At $T = 50$ K, the value of H_{c1} is 35 Oe. The penetration depth is $\lambda_0 = 3200$ Å. Irreversibility effects are observed.

Measurements of the resistance of the $YBa_2Cu_3O_7$ sample studied in the present experiments revealed that the superconducting transition occurs at $T_c = 95$ K and that the width of the transition is 1.5 K. The sample was a sheet 34 mm in diameter and 10 mm thick with a density of 3.5 g/cm^3. The initial polarization of the μ^+ mesons was directed along the axis of the disk, while the external magnetic field H_0 was directed perpendicular to the polarization. The temporal spectrum $N(t)$, of decay positrons emitted at an angle of 0° with respect to the direction of the initial polariza-

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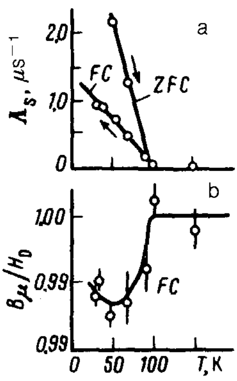

FIG. 1. Temperature dependence of Λ_S and B_μ at a constant external field $H_0 = 200$ Oe.

tion of the muons was measured:

$$N(t) = N_0 e^{-t/\tau}[1 + a_s e^{-\Lambda_s t}\cos(\omega_s t) + (a_b + a_N)e^{-\Lambda_N t}\cos(\omega_0 t)] + C_b, \tag{1}$$

where τ is the lifetime of the μ^+ mesons ($\tau = 2.2$ μs), $\omega_s = \gamma B_\mu$, $\omega_0 = \gamma H_0$ ($\gamma = 2\Pi \cdot 13554$ Oe$^{-1}\cdot$s^{-1}), and B_μ is the average field at a muon which is stopped in the superconducting region. The first term in (1) describes the behavior of the polarization of muons which are stopped in the superconducting region (a_s), while the second stems from background processes which result from the stopping of muons in the walls of the cryostat, in the counters (a_B), and in regions of the sample with a normal conductivity (a_N): $C_b/N_0 = 0.001$, $a_S + a_b + a_N \cong 0.257$, $a_b \cong 0.045$.

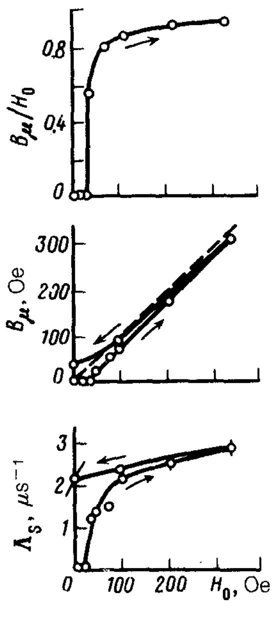

FIG. 2. External-field dependence of Λ_S and B_μ at a constant temperature $T = 50$ K.

TABLE I. Characteristics of the fields frozen in the sample after the external field H_0 is removed.

T, K	H_0, Oe	Λ_f, μs^{-1}	B_f, Oe	a_f/a
50 (ZFC)	20	0.14 ± 0.02	0	1.09 ± 0.14
50 (ZFC)	40	0.95 ± 0.14	18.6 ± 1.0	0.95 ± 0.09
50 (ZFC)	320	2.13 ± 0.52	25.1 ± 4.4	0.92 ± 0.15
30 (FC)	200	2.20 ± 0.30	33.9 ± 6.6	0.85 ± 0.05

Measurements in a zero external magnetic field ($H_0 < 0.1$ Oe) showed that at $T \leqslant 100$ K the spin relaxation rate of the μ^+ meson, Λ, remained constant at $\Lambda_0 = 0.11 \pm 0.01\ \mu s^{-1}$.

During cooling in a field (FC) $H_0 = 200$ Oe, an increase in the relaxation rate is observed at $T < T_c$, so we have $\Lambda_{FC} = (1 - T/T_c)(1.4 \pm 0.1)\ \mu s^{-1}$ (Fig. 1a). This rate differs from that in the case of cooling in a zero field (ZFC), followed by the application of a field $H_0 = 200$ Oe and a temperature increase to $T = T_c$ $[\Lambda_{ZFC} = (1 - T/T_c)(4.6 \pm 0.5)\ \mu s^{-1}]$. In contrast with ordinary type II superconductors, for which the induction in the sample, B_μ, is greatly different from H_0 under FC conditions,[1,2] the value of B_μ for $YBa_2Cu_3O_7$ turns out to be close to H_0 (Fig. 1b).

The relaxation rate $\Lambda_{FC}(T)$ is determined by the field strength, the distance between vortices, and the field penetration depth $\lambda(T)$. For a triangular lattice of vortices one can derive[1]

$$\Lambda_{FC}(T) \approx \frac{1}{\sqrt{8\pi^3\sqrt{3}}} \frac{\gamma \Phi_0}{\lambda^2(T)}, \quad \Phi_0 = 2 \times 10^{-7}\ \text{Oe}\cdot\text{cm}^2. \tag{2}$$

It is thus possible to determine that the dependence $\lambda(T)$ satisfies the relation $\lambda(T) = \lambda_0/\sqrt{2}(1 - T/T_c)^{-1/2}$, and that the effective magnetic-field penetration depth is $\lambda_0 \cong 3200$ Å.

Analysis of the average field in the sample, B_μ, and the relaxation rate Λ_S as functions of the external field H_0 (Fig. 2) at $T = 50$ K shows that we have $H_{c1} \cong 35$ Oe at this temperature. At $H_0 \lesssim 25$ Oe, the volume of the Meissner phase is greater than 80%, and at $H_0 \gtrsim 40$ Oe no less than 80% of the muons are precessing at the frequency of the field B_μ. In other words, the superconductivity is a bulk superconductivity. The penetration of the field into the sample in the region 25 Oe $< H <$ 35 Oe is related to a demagnetizing factor $n \cong 0.3$.

As the external field H_0 is lowered from 320 Oe to 0, the $B_\mu(H_0)$ dependence is characteristic of a type II superconductor. At $T = 30$ K and 50 K, the average field which is frozen in the sample (B_f) after the field H_0 is removed is considerably weaker than H_0 (Table I). It occupies more than 85% of the volume of the sample (a_f/a); we have $B_f \cong H_{c1}$ and $\Lambda_f \cong (1\text{–}2)\ \mu s^{-1}$, with $a = a_S + a_N$.

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