Determination of magnetic-field penetration depth in a superconducting single-crystal $YBa_2Cu_3O_7$ thin film from polarized-neutron reflection

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The depth to which a magnetic field penetrates into a superconducting single-crystal film of $YBa_2Cu_3O_{7-\delta}$ (2000-Å thick, deposited on a {100} surface of a $SrTiO_3$ single crystal) along the **c** axis is $\Lambda_c = 970 \pm {}^{600}_{250}$ Å at $T = 5.2$ K, according to an experiment involving the specular reflection of polarized thermal neutrons.

The specular reflection of polarized thermal neutrons has been used successfully to measure the depth (Λ) to which a magnetic field penetrates into ordinary superconductors.[1] Using this method to determine λ in a $YBa_2Cu_3O_7$ ceramic, Felici *et al.*[2] found the value $\Lambda = 225 \pm 75$ Å at a temperature of 4.8 K. They cited reasons for believing that the value which they found was an experimental upper estimate of Λ in this method. In the analysis of errors in Ref. 2, the demagnetizing factor of the sample was ignored. Our calculations show that incorporating the demagnetizing field corrects the value $\Lambda = 225$ Å upward by about 10%. The values of Λ for ceramics measured by other methods[3] exceed this value by a factor of three to ten. The reasons for this pronounced difference in the experimental values of Λ found by the different methods have remained unclear.

In the present letter we are reporting the first measurements of the depth to which a magnetic field penetrates into a thin-film single-crystal sample of $YBa_2Cu_3O_7$. The measurements were carried out by the method of the specular reflection of polarized thermal neutrons. The experiments were carried out at the IBR-2 pulsed reactor of the Joint Institute for Nuclear Research (with an SPN-1 spectrometer).

Specific features of neutron experiments on superconducting thin films were discussed in detail in Ref. 4. Here we would like to point out, in particular, that in experiments on single-crystal thin films one measures the depth to which the magnetic field penetrates along a certain crystallographic direction, in our case along the crystallographic **c** axis. The sample consisted of a film with $T_c = 92$K which was synthesized by laser sputtering on a polished {100} surface of a $SrTiO_3$ single crystal by the method described in Refs. 5 and 6. The area of the sample was 6×8 mm^2. However, the effective cross-sectional area of the beam incident on the surface of the sample, at an angle $\theta = 4.52 \times 10^{-3}$ rad with $\Delta\theta/\theta = 0.03$ in our case, was 6×0.04 mm^2, and it substantially limited the rate at which a statistical base could be built up. In an effort to reconstruct the shape of the neutron-optics potential of the film we measured the spectrum (Fig. 1) of the reflection coefficient of the surface of the film for neutrons, $R(\lambda_\perp)$ ($\lambda_\perp = 2\pi/k_\perp$, where $k_\perp$ is the component of the neutron wave vector which is

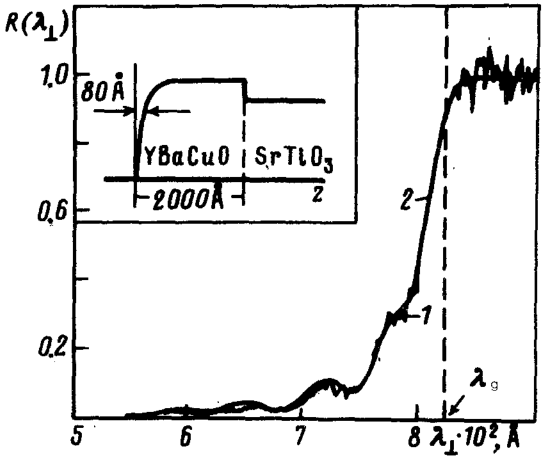

FIG. 1. The neutron reflection coefficient R as a function of $\lambda_\perp = 2\pi/k_\perp$ ($k_\perp$ is the component of the neutron wave vector normal to the reflecting surface. 1—Experimental results at 300 K; 2—theoretical, calculated from the model potential shown in the inset.

normal to the surface), at room temperature. We found a film thickness $d = 2000 \pm 20$. And the value $\lambda_g = 820 \pm 5$ Å for the neutron-optics parameter which is related to the number of atoms per unit volume (ρ) and the average coherence length of neutron-nucleus scattering (b) by $\lambda_g = \sqrt{\pi/\rho b}$. In fitting the experimental curve of $R(\lambda_\perp)$ (curve 1 in Fig. 1) with the theoretical value $R_T(\lambda_\perp)$ curve 2 in Fig. 1), we used the neutron-optics parameters of the SrTiO$_3$ substrate, which were found from a similar experiment with a clean substrate. The theoretical curves of $R_T(\lambda_\perp$ were calculated by the methods of Refs. 4 and 7. The particular shape of the neutron-optics potential of the film, unperturbed by the magnetic field, which is the best fit of the experimental $R(\lambda_\perp)$ curve at room temperature, is shown in the inset in Fig. 1. The sample was then cooled in a zero magnetic field to a temperature of 5.2 K. A magnetic field H was then applied in the direction parallel to the surface of the film.

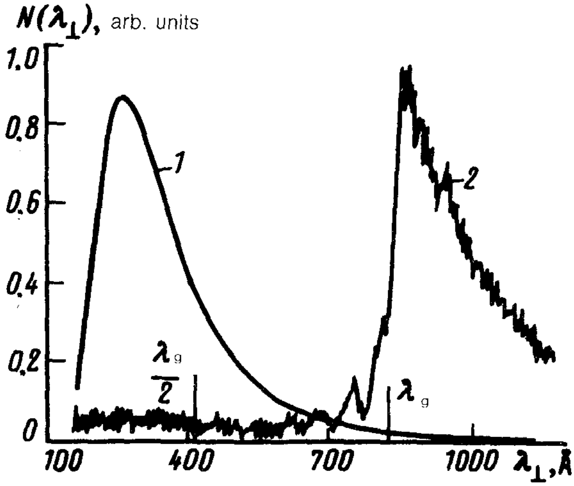

FIG. 2. 1—The $N(\lambda_\perp)$ spectrum of the incident neutrons; 2—spectrum of the reflected neutrons, $N_+(\lambda_\perp)$, at $T = 5.2$ K and $H = 200$ Oe [at this scale, $N(\lambda_\perp)$ is close to $N_+(\lambda_\perp)$].

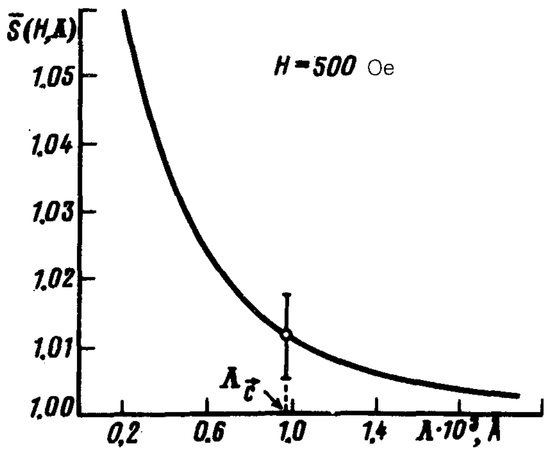

FIG. 3. Comparison of the theoretical behavior of the integral effect, $\bar{S}(\Lambda,H)$, as a function of the penetration depth Λ at a field $H=500$ Oe (curve) with an experimental value.

The actual measurements of the penetration depth were carried out at two values of the field: $H_1=200$ Oe and $H_2=500$ Oe. We measured the spectra (Fig. 2) of neutrons reflected from the film surface for two orientations of the neutron spin: $N_+(\lambda_\perp)$ (the spin of the neutron is directed along the magnetic field) and $N_-(\lambda_\perp)$ (opposite the field). The reflection coefficients for neutrons with opposite spin directions, $R_+(\lambda_\perp)$ and $R_-(\lambda_\perp)$, should be different in the region $\lambda_\perp<\lambda_g$. The reason for this difference lies in an expulsion of the magnetic field from the film. A calculation[4] based on a model has made it possible to allow for the effect of a nonuniform distribution of the magnetic field in the film on the shape of its neutron-optics potential and to construct (with allowance for the resolution of the instrument) the function $S(\lambda_\perp)=N/N_+$, which is simultaneously a function of Λ and H. In the process we assumed that the magnetic induction in the film behaves in accordance with

$$B(z)=H\times\cosh\,[(2z-d)/2\Lambda]/\cosh\,(d/2\Lambda), \tag{1}$$

where the coordinate z is reckoned from the surface of the film along the inward normal, i.e., along the **c** axis. In an effort to reduce the statistical error in an estimate of the effect of a deviation of S from 1, we summed each of the $N_\pm(\lambda_\perp)$ spectra over the interval of $\lambda_\perp$ values from $\lambda_g/2$ to λ_g and found the quantity

$$\bar{S}(H,\Lambda)=\sum_{\frac{1}{2}\lambda_g}^{\lambda_g} N_-(\lambda_\perp)\Big/\sum_{\frac{1}{2}\lambda_g}^{\lambda_g} N_+(\lambda_\perp). \tag{2}$$

The measured values of $\bar{S}$ are

$\bar{S}(H=500\ \text{Oe})=1.012\pm0.007$ and $\bar{S}(H=200\ \text{Oe}=1.004\pm0.007$.

We compared the results with the function $\bar{S}(H,\Lambda)$ calculated from the model of Ref. 4, which is shown in Fig. 3 for a field $H=500$ Oe. We then determined Λ_c at $T=5.2$ K: $\Lambda_c=970\pm^{600}_{250}$ Å.

A future improvement in the statistical base will make it possible not only to experimentally determine the parameters Λ_c and Λ_{ab} more accurately but also to determine the behavior B(z), by making use of the spectral dependence $S(\lambda_\perp)$.

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