Magnetization of highly anisotropic superconductors

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An additional peak has been found on the curve of $-M(H)$ of single crystals of layered YBCO (1-2-3) and BSCCO (2-2-1-2) superconductors. This additional peak, whose height and position depend on the field orientation, appears in addition to the structural feature which corresponds to $H_{c1}^{\parallel}$, i.e., the critical field for the penetration of vortices along Cu–O layers. The strength and temperature dependence of the first critical field are determined for the Bi 2-2-1-2 compound.

The high-T_c superconductors have a layered structure, and their superconducting properties are extremely anisotropic. The ratio of effective masses in the Ginzburg–Landau theory, for example, is $\simeq 25$ for the YBCO (1-2-3) compound and reaches $\simeq 4000$ for the BSCCO (2-2-1-2) compound. This pronounced anisotropy leads to specific features in the vortex structure of the mixed state of these substances. These features have recently been examined in detail in a number of theoretical and experimental studies.[1–7] It has been established that the vortices lie predominantly along Cu–O layers. As a result, even small deviations ($\simeq 1°$) of the external field $\vec{H}$ from the direction of the symmetry axes of the crystal result in a noncollinearity of the magnetic induction $\vec{B}$ averaged over the volume in the crystal and of its magnetic moment. Until recently, the experiments have been aimed at learning about anisotropic superconductors in strong fields $H \gg 10^3$ Oe$\gg H_{c1}$, deep in the region of a mixed state. In the present letter, in contrast, we are reporting a study of the magnetization of high-T_c single crystals in fields corresponding to the onset of the mixed state and the genesis of its structure.

The $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O$ (Bi 2-2-1-2) single crystals used in these experiments were thin platelets with typical dimensions $\simeq 1\times 1\times(0.02\text{–}0.07)$ mm (the *c* axis ran along the smallest dimension). The Bi 2-2-1-2 single crystals, with lattice constants $a = 0.543$ nm and $c = 3.08$ nm, were grown by the procedure described in Ref. 8. They had a transition temperature $T_c \simeq 95$ K, a transition width $\approx 1\text{–}2$ K, and a ratio $M_{FC}/M_{ZFC} \simeq 0.5\text{–}0.6$ in weak fields ($\leqslant 1$ Oe), both parallel to and perpendicular to the *ab* plane. The magnetization component of the samples parallel to the field (M_{ZFC}) was measured over the temperature range 4.2–80 K after the sample was cooled in a "zero" field in a niobium SQUID magnetometer (designed by A. A. Jurgens). The measurements over the temperature range between 77 K and T_c were made with the high-T_c-superconductor SQUID magnetometer described previously.[9] The behavior of the magnetic moment of the YBCO crystal in a field parallel

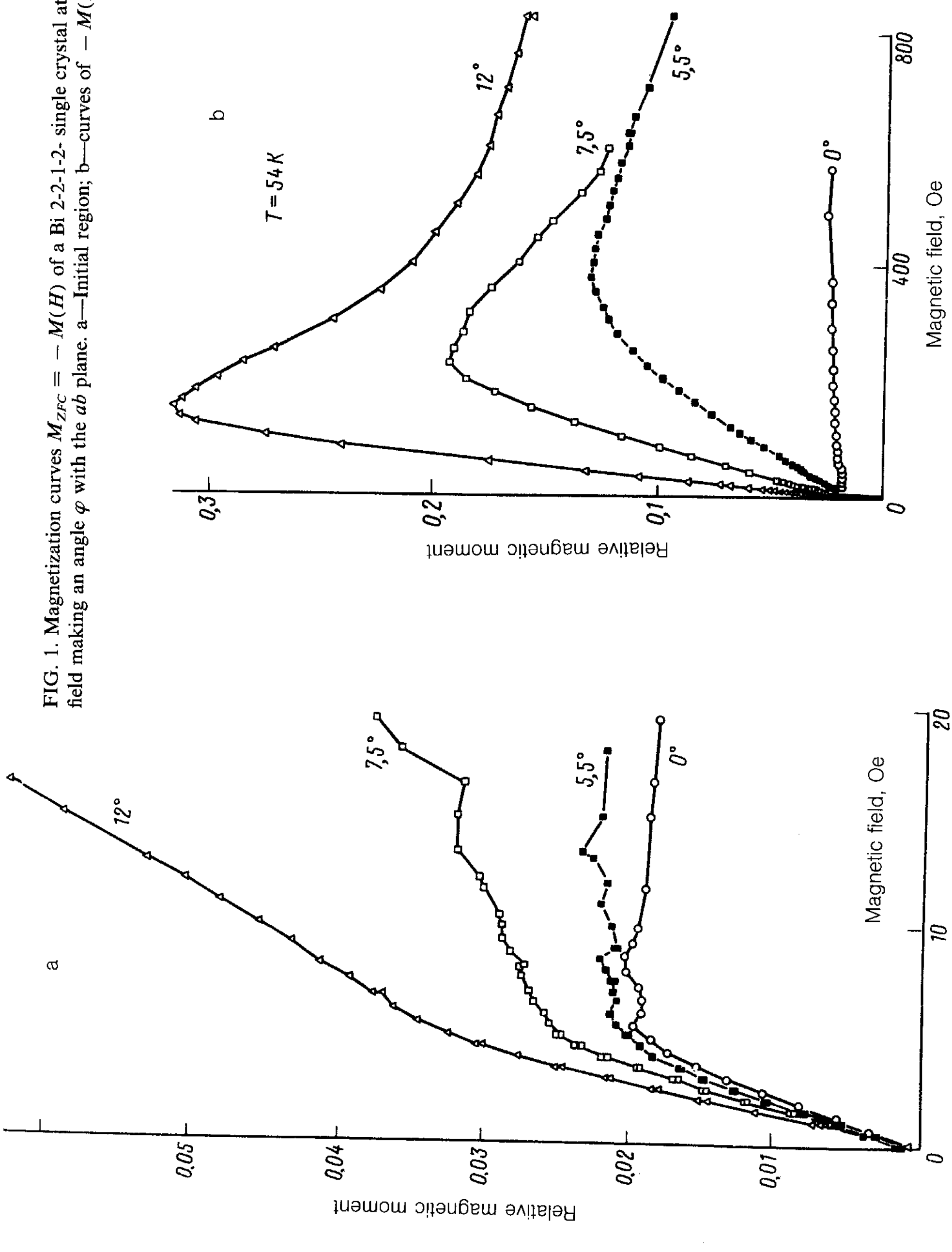

FIG. 1. Magnetization curves $M_{ZFC} = -M(H)$ of a Bi 2-2-1-2- single crystal at $T \cong 54$ K for an external field making an angle φ with the ab plane. a—Initial region; b—curves of $-M(H)$ at a larger field scale.

to the crystallographic axes was typical of a type-II superconductor. On the curve of $-M(H)$ there is a clearly expressed Meissner region, which gives way at $H=H_{c1}$ to a mixed state, in which the diamagnetic moment decreases smoothly as the field is increased further. On the magnetization curve of Bi 2-2-1-2, on the other hand, in a field parallel to the *ab* plane of the single crystal, the corresponding decrease in the absolute value of the diamagnetic moment at $H>H_{c1}$ is much less obvious (Fig. 1a). The difference can be attributed to the anomalously large value of H_{c2} in this substance,[10] but one cannot rule out the possibility that the reason is instead a finite angle φ between H and the plane of the crystal. An increase in φ would lead to a significant increase in the slope of the $-M(H)$ curve at $H>H_{c1}^{\parallel}$. The value of the first critical field, $H_{c1}^{\parallel}$, taken as the point at which the $M=-H/4\pi$ curve intersects the extrapolation of the $-M(H)$ curve from the region $H>H_{c1}^{\parallel}$, remains constant within $\simeq 5\%$ as φ increases from 0 to 11° (Fig. 1a). At $\varphi \neq 0$, the absolute value of the moment reaches a maximum $M^{\max}$ in a field $H_p \gg H_{c1}^{\parallel}$ (Fig. 1b). Both $M^{\max}$ and H_p depend on the angle φ. The behavior can be described within the experimental errors by

$$H_p(\varphi)=H_p^{\perp}\sin^{-1}\varphi;\qquad M^{\max}(\varphi)=M^{\max\perp}\sin\varphi, \tag{1}$$

where $H_p^{\perp}$ is the field (determined experimentally) at which the vortices penetrate into the sample in the $H\perp(ab)$ geometry, and $M^{\max\perp}$ is the maximum value of the magnetic moment in this geometry. Expressions (1) were verified by measurements on two Bi 2-2-1-2 crystals at $T=4.5$, 18, 24, 38, 54, 64, 72, and 82 K for angles $\varphi \simeq 0$, 5°, 10°, 15°, and 22° (see the inset in Fig. 2).

This result can be interpreted under the assumption that there are two critical fields for the vortex structure in highly anisotropic superconductors in "oblique" fields (making an angle with the crystallographic axes). First, there is the field $H_{c1}^{\parallel}$, at which the vortices first penetrate into the sample and lie between superconducting layers parallel to the basal plane. This "parallel" vortex structure becomes more compact as the field is increased further, but the vortices still do not intersect the Cu–O layers until, finally, at the field $H_p(\varphi)=H_p^{\perp}\sin^{-1}\varphi$, they begin to penetrate the *ab* plane. According to this picture, this component of the magnetic moment of the crystal along the external field is a superposition of the moments directed parallel and perpendicular to the *ab* plane. The magnitude of each of these moments is determined by the corresponding component of the external field. A similar description of the magnetization curves of anisotropic superconductors has been used to interpret measurements on oriented YBCO crystallites.[11]

Theoretical work on the thermodynamic-equilibrium penetration of flux into a layered superconductor[2-4] leads to the conclusion that in an oblique field slightly stronger than $H_{c1}^{\parallel}$ there is an additional peak on the curve of $-M(H)$ (in addition to the peak corresponding to the lower critical field). The position of this new peak reflects the beginning of a rotation of the vortex structure and a penetratin of vortices through Cu–O planes. The theoretical results agree quantitatively with the experimental data.

The governing role played by the magnitude of the anisotropy for observing a magnetization curve with two critical fields has been confirmed by experiments on

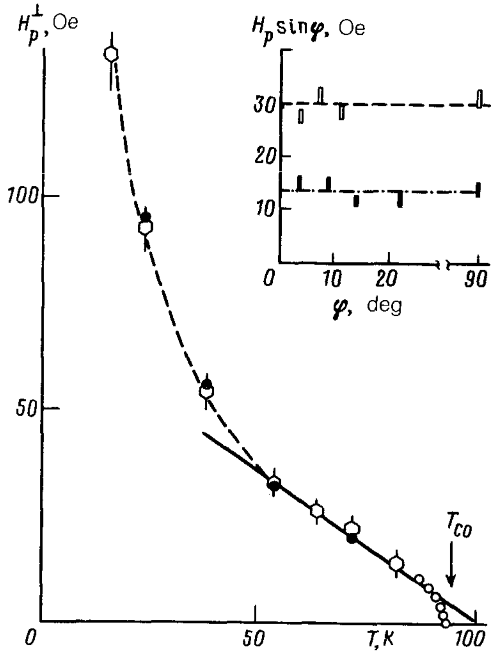

FIG. 2. Temperature dependence of the transverse vortex penetration field $H_p^\perp(T)$ for one of the Bi 2-2-1-2-crystals (the demagnetizing factor is $N \simeq 0.92$). ●, O—Direct measurements with $\varphi = 90°$ in low- and high-temperature SQUID magnetometers, respectively; O—average value for $\varphi \neq 0$, corrected on the basis of expression (1). Here T_{c0} is the onset temperature of the superconducting transition (according to measurements of the magnetic moment at $H \leqslant 10^{-2}$ Oe). The inset shows $H_p \sin\varphi = f(\varphi)$ for two Bi 2-2-1-2 crystals at $T \simeq 54$ K and H_p, which is the field corresponding to the second peak on the $-M(H)$ curve.

YBCO crystals. The experiments were carried out at angles $\varphi \cong 10°$, 20°, and 30° over the temperature interval 64–82 K. These experiments revealed the appearance of something — something only resembling a second-peak on the $-M(H)$ curve in an oblique field at angles $\varphi = 10°–20°$. The position of this feature is also described by (1).

Figure 2 shows the temperature dependence of the penetration fields $H_p^\perp$ determined in direct experiments and calculated from the values of $H_p(\varphi)$ for one of the Bi 2-2-1-2 crystals. After the results found are corrected for the value of the demagnetizing factor, $N \simeq 0.92$, they give us an estimate of $H_{c1}^\perp$ which is close to that reported in Refs. 12–15. The substantial increase in $H_p^\perp$ at $T < 50$ K might stem from a significant strengthening of effects of the long-term relaxation of the moment; such a strengthening has been observed in this temperature range. Consequently, the results found may differ from the equilibrium values. This interpretation is supported by the data of Ref. 16, which describe a sharp decrease in the vortex mobility below 40–50 K in Bi 2-2-1-2. A similar effect was observed in Ref. 15, where it was linked with an increased role of the Bean–Livingston barrier at low temperatures. Figure 3 shows $H_{c1}^{\parallel}(T)$ for Bi 2-

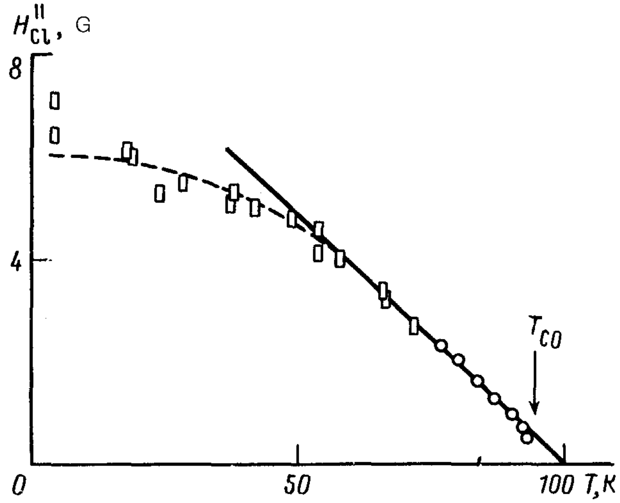

FIG. 3. Temperature dependence of the first critical field parallel to the *ab* plane of the Bi 2-2-1-2 crystal, $H^{\parallel}_{c1}(T)$. □, ○—results of measurements in low- and high-temperature SQUID magnetometers, respectively.

2-1-2 according to measurements with $\varphi = 0$. The value of $H^{\parallel}_{c1}$ is extremely small. The data on $H^{\parallel}_{c1}$ for Bi 2-2-1-2 in the literature are contradictory, but values of $H^{\parallel}_{c1}$ for $T \cong 4.2$ K close to our own values were reported in Refs. 12–14.

Near T_c in the Bi 2-2-1-2 system, one observes substantial deviations of the temperature dependence of the first critical fields from the linear dependence $H_{c1} \simeq T_c - T$ which follows from the Ginzburg–Landau model. A linear extrapolation to $H_{c1} = 0$ ends up $\Delta T \simeq 3$–5 K above the temperature T_{c0}, of the onset of the superconducting transition (according to measurements of the magnetic moment in weak fields $H \leqslant 10^{-2}$ Oe). This deviation of the $H_{c1}(T)$ dependence from linearity near T_c has been observed previously[17] in a study of 1-2-3 YBCO single crystals. The experimental data were approximated by an $H_{c1}(T) \simeq (T_c - T)^{\alpha}$ law with $\alpha \cong 0.6$ and 0.8, for fields parallel and perpendicular to the *ab* plane, respectively. The results were interpreted as a manifestation of fluctuation effects. The approximately equal values of ΔT observed for these two classes of superconductors, which differ substantially in the degree of anisotropy, are evidence in favor of this suggestion. We recall that fluctuation effects develop in a temperature region proportional to ξ_{av}^{-6}, where $\xi_{\text{av}} = (\xi_a \xi_b \xi_c)^{1/3}$ in the average coherence length, which is roughly the same for the YBCO 1-2-3 and Bi 2-2-1-2 systems ($\simeq 10$ and $\simeq 11$ Å, respectively).[10,18]

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