Low-field microwave absorption in bismuth-based high-T_c superconducting single crystals: threshold vortex-lattice effects

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A threshold in the magnetic field has been observed for several characteristic effects in the low-field absorption by high-T_c single crystals. A signal of a new type corresponds to the threshold field in the microwave absorption spectrum. The appearance of the new signal in the low-field absorption and of effects which involve a threshold in the magnetic field is linked with a transition from an individual pinning of vortices to a collective pinning.

The first studies of the low-field absorption of microwave power in the high-T_c superconductors revealed several characteristic effects: a hysteresis,[1,2] an anomalous dependence of the absorption signal on the modulation amplitude,[2,3] and frequently repeating noiselike fluctuations,[4,1] which were linked with the dynamics of vortices under conditions corresponding to a trapping of magnetic flux and to a manifestation of an internal Josephson effect. In the present study we have found that all of these

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effects in bismuth-based high-T_c superconducting single crystals occur only in magnetic fields weaker than a certain threshold H^*, which corresponds to a characteristic "spike" in the signal in the microwave absorption spectrum. The field H^* depends strongly on the temperature.

The $Bi_2Sr_2CaCu_2O_y$ crystals, grown by the molten-solution method, were of a single phase and were homogeneous in terms of chemical composition. Their critical temperature was $T_c = 84 \pm 2$ K. The samples were single-crystal wafers with c axis oriented perpendicular to the plane. The low-field signal was measured by a 3-cm-range ESR spectrometer as the field was modulated at frequencies of 100 kHz, 25 kHz, and 80 Hz.

In the crystals which we studied, the low-field absorption signal appears at a temperature $T_c^{\rm lfa} = 87$–88 K, slightly above T_c. After a complicated evolution of the shape of the signal in a narrow temperature interval near $T_c^{\rm lfa}$, the low-field absorption has a three-component structure at $T \lesssim 84$ K (Fig. 1). Two of these components are two lines centered at the point $H \approx 0$: a narrow line (with a width ~ 10 Oe, which varies only slightly down to ~ 50 K) and a broader line which expands rapidly with decreasing temperature. The component of most interest is the third one: a spike in the signal in a nonzero magnetic field. This spike shifts along the field scale as the tem-

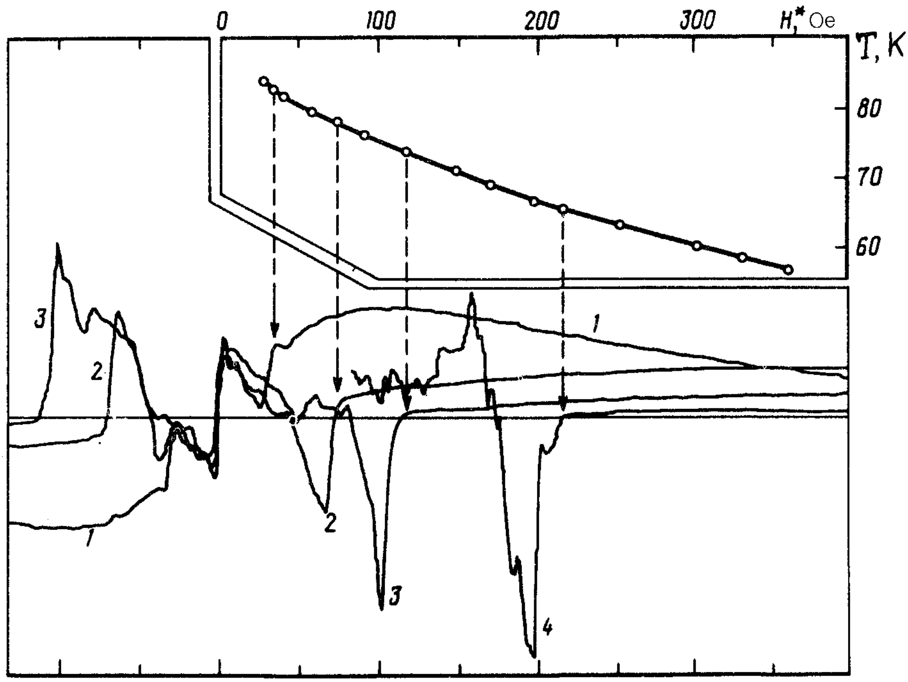

FIG. 1. Spikes, the narrow component, and the wide component of the low-field absorption in $Bi_2Sr_2CaCu_2O_y$. Here and in Fig. 2, we have $\mathbf{H} \parallel \mathbf{c}$ and $f_{\rm mod} = 100$ kHz. T, K: 1—87.2; 2—78.4; 3—74.5; 4—65.2. The arrows show the position of the threshold field H^*. The inset shows the dependence $H^*(T)$.

perature is varied; it has a significant amplitude and a steep high-field slope, which terminates at the field H^*. In the interval 84–56 K the field H^* is an approximately linear function of the temperature, increasing from 20 to 350 Oe (see the inset in Fig. 1).

It was established that fields $\pm H^*$ are physically distinguishable. Specifically, they are threshold fields for several effects which are seen in the crystals which we studied.

1) First, there is hysteresis: The sign and shape of the signal depend on the direction in which the magnetic field is swept, particularly strongly at a low modulation. This effect was found difficult to discern at $H \approx 0$; it increases with increasing H and then abruptly disappears at H^*, although at $|H| > H^*$ the signal is significantly greater than zero (curves 1 and 3 in the Fig. 2).

2) Second, there is the anomalous dependence of the low-field signal on the modulation amplitude: The magnitude and shape of the signal change substantially as

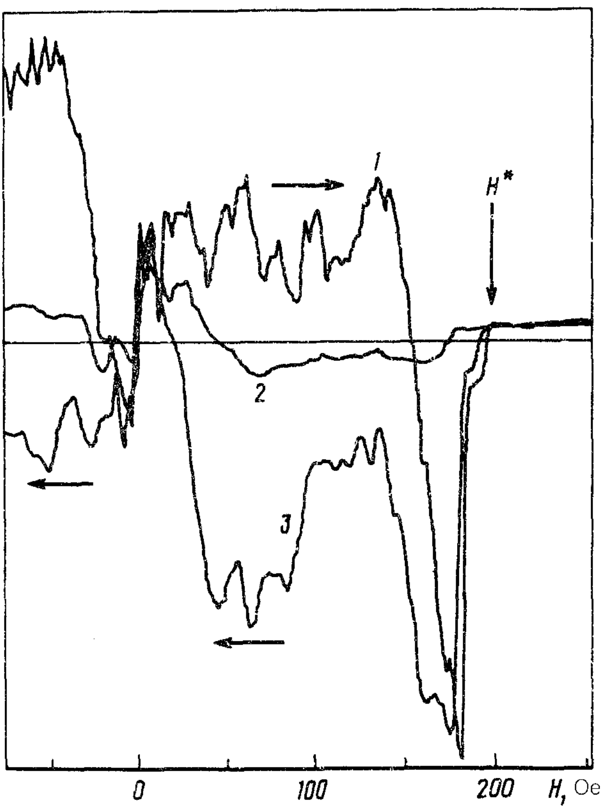

FIG. 2. Manifestation of threshold effects in the low-field absorption ($T = 66.5$ K). 1, 2—Recorded at different amplitudes of the modulation of the magnetic field, specifically, (1) 1 Oe and (2) 10 Oe (the gain has been reduced by a factor of ten for curve 2); 1, 3—recorded during forward and reverse sweeps of the field H.

the modulation is reduced and as the gain is correspondingly increased. In our case the effect is slight at $H \approx 0$; as H is increased, the effect appears, and then it disappears in the field H^* (curves 1 and 2 in Fig. 2).

3) Third, there are the noiselike fluctuations which grow with decreasing temperature. Fluctuations of this sort, with an amplitude far greater than the instrumental noise, and comparable to the amplitude of the low-field signal, appear in the spectra of our samples at temperatures below 80 K (curves 1 and 3 in Figs. 1 and 2). However, they are observed only at $|H| < H^*$, not at $|H| > H^*$.

The field $\pm H^*$, which is seen as a structural feature in the plot of the signal versus H, is thus a threshold for several characteristic effects in the low-field absorption—effects which occur only in field $|H| < H^*$.

We link all three of these effects with a change in the state of a vortex lattice at $H = H^*$. This change corresponds to a transition from an individual pinning of vortices to a cooperative pinning. A situation of this sort may be interpreted as the attainment at $H = H^*$ of an approximate equality of the correlation radius R_c, which has been introduced in the theory of collective pinning,[5] and the period of the vortex lattice, a. Here the field H^* is a threshold for the appearance (at $H > H^*$) of a short-range order in the vortex lattice. There are sharp decreases in the magnetic memory effects (the hysteresis) and in the dependence of the signal on the modulation amplitude; in addition, repeating noiselike fluctuations appear. These fluctuations are characteristic of the case of an individual pinning of vortices and stem from pinning-depinning processes.

Simultaneously, at the transition from individual to cooperative pinning there is a change in the mechanism for the microwave absorption by the vortex lattice. Specifically, the absorption by natural oscillations of pinned vortices at $H < H^*$ gives way to an absorption by oscillations of the vortex lattice under conditions of a collective pinning at $H > H^*$. The change in the mechanism for the microwave absorption at $H \approx H^*$, which is associated with the change in the state of the vortex lattice and in the nature of the pinning of the vortices, can occur in a fairly narrow magnetic-field interval. This effect gives rise to the spikes which are observed in the dP/dH signal at $H \approx H^*$ and which correspond to "steps" on the curve of $P(H)$. This circumstance can be explained in the theory of collective pinning,[5] according to which an exponential dependence of the bulk pinning force on the magnetic induction B in the sample prevails in the region in which the conditions $\xi < R_c < k_h^{-1}$ hold (the notation is that of Ref. 5) and disappears at $R_c \approx a$. Here the threshold magnetic field H^* can be found from

$$r_f^2 = W(0)(4\pi^{1/2} B C_{66}^{3/2} k_h)^{-1}, \tag{1}$$

where r_f is the range of the pinning force, $W(0) = n\langle f_p^2 \rangle$ characterizes the force f_p and the density n of the pinning centers in the interior of the correlation region, and C_{66} is the shear modulus of the vortex lattice.[6] Using Ref. 5, and adopting some suitable values for the parameters, we find $H^* \sim (T_c - T)$ from (1), in agreement with experiment.

In summary, the experimental results correspond to the predictions of the theory of collective pinning.[5]

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