Anomalous microwave absorption in Bi 2212 high-temperature superconductors with the paramagnetic Meissner effect

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The results of the experimental study of an anomaly in low magnetic field microwave absorption in polycrystalline Bi high-temperature superconductors are presented. These results show the presence of the so-called paramagnetic Meissner effect. The data obtained are evidence for the common origin of the two effects which may occur due to the presence in the samples of weak links with inverse Josephson coupling (the π-contacts).

1. In our recent experiments[1] we observed that in certain polycrystalline samples of Bi 2212 and Bi 2223 metal oxides the magnetic-field-cooled (FC) susceptibility in the superconducting (SC) state becomes paramagnetic in magnetic fields below 1 Oe [the paramagnetic Meissner effect or the Wohlleben effect (WE)$^{1)}$]. No significant difference between samples with and without the WE was found in their stoichiometry, structure, microstructure, ac susceptibility, resistivity, and specific heat. At the same time, we found that the samples showing the WE often exhibit a pronounced anomaly in their differential low magnetic field microwave absorption (MWA).[1] The correlation which we noticed between the presence of the WE and appearance of the MWA anomaly gives us ground to believe that they both have common source. The study of the characteristics of microwave absorption in such samples can therefore shed more light on the nature of the two phenomena.

In this paper we present the results of an experimental study of the differential low magnetic field microwave absorption in those samples of Bi 2212 high-temperature superconductor (HTS) which show the Wohlleben effect. On the basis of these data we discuss the properties of unusual Josephson junctions whose presence in the samples may cause the observed effects.

2. We studied the polycrystalline samples of $Bi_2Sr_2CaCu_2O_y$ compound prepared by a solid-state reaction with subsequent annealing close to the melting point[3,4] (samples KN99F and KN100F) and by a melt cast process[4,5] (sample KAMU96). The measurements of dc susceptibility in the field range from several Oe to 10 mOe were

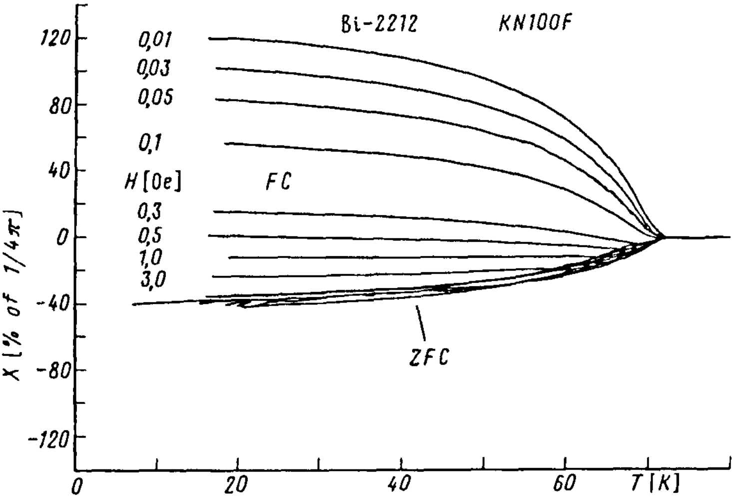

FIG. 1. Temperature dependence of the *dc* susceptibility in the SC state for the sample KN100F.

carried out with a specially designed SQUID magnetometer which was previously described in Ref. 1. The differential microwave absorption was measured using a conventional X-band Bruker ESR spectrometer (for details of the technique see, e.g., Ref. 6). The incident microwave power was at the level 10–200 mW, the amplitude of the ac modulating field (100 kHz) was varied between 0.04 and 2 Oe, and the dc magnetic field was swept from -20 Oe to $+20$ Oe.

Figure 1 shows the results of measurements of the dc susceptibility χ for the sample KN100F, whose onset of the resistive SC transition occurs at $T_c^{\text{onset}} = 76$ K. The diamagnetic zero-field-cooled (ZFC) susceptibility is almost field independent. At the same time, the FC susceptibility decreases with decreasing field H and becomes positive at $H < 0.5$ Oe. The field dependence of χ can be fitted by the expression $\chi(H) = 0.187G/[4\pi(H+0.12\text{ Oe})] - 0.3/4\pi$. The temperature and field dependences of the FC susceptibility for the two other samples studied in the present experiment have the same qualitative features which are generally characteristic of the samples showing the WE.

The experimentally detected field derivative of the absorbed power dP/dH for the sample KAMU96 is plotted as a function of H in Fig. 2 (curve a). Curve b in the same figure is the result of a numerical integration of the curve a, i.e., the field dependence of the absorbed power $P(H)$. The field dependence of dP/dH appeared only in the SC state and was absent above T_c. The magnitude of the microwave response was a linear function of both the incident power and the modulation field. It is evident from Fig. 2 that the dP/dH curve consists of a broad line and a narrow line which are superimposed on each other and centered near $H = 0$. These two signals have opposite phases. The signs of the phases were compared with the sign of the derivative of the ESR absorption signal of a standard reference sample (like, e.g., the organic radical DPPH) recorded during the same experiment. It turned out that the phase of the

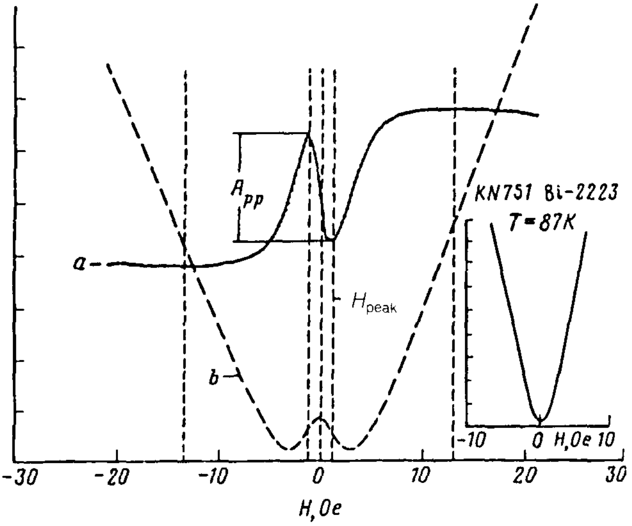

FIG. 2. Curve *a* is a plot of the differential microwave absorption dP/dH as a function of the magnetic field H for the sample KAMU96 at $T=62$ K; curve *b*—$P(H)$ dependence obtained by numerical integration of curve *a*. The insert shows a typical $P(H)$ dependence for the sample without the WE.

broad signal corresponds to the minimum of absorption at $H=0$, while the phase of the narrow signal corresponds to the maximum of absorption at zero field. We call the first signal a "normal" signal and the second signal an "anomalous" signal. In general, the field dependence of the low magnetic field microwave absorption of the samples with the WE illustrated by curve *b* is thus nonmonotonic. The characteristic feature is the presence of a local maximum of absorption at zero field. Similar signals were observed for two other samples—KN99F and KN100F. We also stress that this peculiarity was not found in the samples without the WE. For such samples we always detected a minimum of absorption at zero field. This is illustrated in the inset in Fig. 2, where the $P(H)$ curve for a sample without the WE is shown (see also Refs. 1 and 6).

Figure 3a shows the temperature dependences of the peak-to-peak amplitudes $A_{\rm pp}$ (defined in Fig. 2) of the "normal" and "anomalous" MWA signals for the samples studied by us. In Fig. 3b we show the temperature dependence of the field at the peak of the "anomalous" signal $H_{\rm peak}$, i.e., the half-width of the local maximum near $H=0$ (the definition of $H_{\rm peak}$ is given in Fig. 2). As can be seen from Fig. 3a, upon transition to the SC state first the "normal" MWA signal appears and then the "anomalous" signal develops a few degrees below. Upon further cooling, the two signals reach a maximum and then their amplitudes begin to decrease. As to the value of $H_{\rm peak}$, it increases rather rapidly near T_c and saturates at low temperatures. During the saturation the "anomalous" peak of dP/dH transforms to a plateau, which causes a large error in the determination of the value of $H_{\rm peak}$ near 20 K.

3. It is known that the field dependence of the microwave losses in HTS at

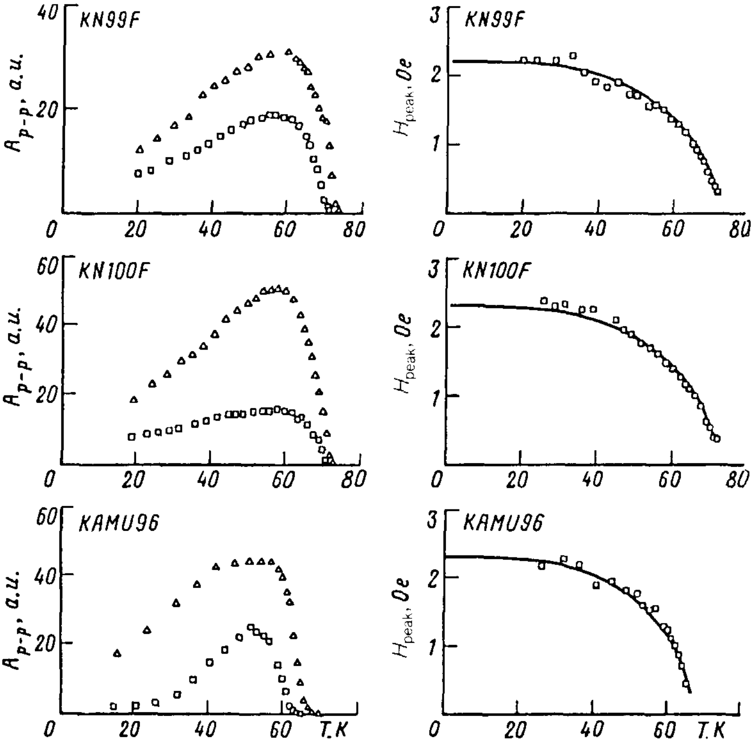

FIG. 3. Temperature dependences: a—of the amplitude of the "normal" (triangles) and "anomalous" (squares) MWA signals (left panel); b—field at the "anomalous" MWA peak H_{peak} (right panel) for the samples KN99F, KN100F, and KAMU96.

$H<H_{c1}$ is caused by absorption of the microwave power P by a network of inter- and intragranular Josephson junctions.[7] Normally the shape of the dP/dH curve resembles that of the derivative of an ESR signal centered near $H=0$. However, it is a nonresonant effect and the center of this line, in contrast with the ESR, corresponds to the minimum of the absorbed microwave power. As can be seen from Fig. 2, the qualitative difference in the behavior of the HTS samples with the WE is that at $H=0$ the magnitude of the microwave losses has a local maximum.

It was assumed earlier[1] that the WE may be caused by the appearance in the SC phase of spontaneous orbital currents and orbital magnetic moments connected with them, which form a kind of "orbital glass."[8] The reason for the appearance of such currents could be the existence in the samples of weak links with an inverse Josephson coupling or a negative critical current (the π contacts). During the tunneling through this junction the Cooper pair undergoes a phase shift π, e.g., due to a spin-flip tunneling via magnetic impurities in the barrier. The properties of a loop with such a π contact were theoretically investigated in Ref. 9.[2)] The authors showed that under the condition $(2\pi/c)LI_c>\Phi_0$ the ground state of the loop is the state with a current and with a flux (here L is the inductance of the loop, I_c is the Josephson critical current, and Φ_0 is the flux quantum). If this condition is satisfied, the dependence of the current I_s is the SC loop of the area S on the external flux, $\Phi_{\text{ext}}=HS$, has a hysteresis.[10] The hysteresis center corresponds to $\Phi_{\text{ext}}=\Phi_0/2$ for the zero phase shift of the Cooper pair (the 0 contact) and to $\Phi_{\text{ext}}=0$ for the phase shift π (the π contact). This hysteretic dependence of I_c on Φ_{ext}, centered near $\Phi_{\text{ext}}=0$, may lead to the appearance of spontaneous magnetization (i.e., to the appearance of WE) and to the absorption of microwave power by a SC loop with a π contact in the absence of a dc external field.[2] When such a loop is threaded only by a microwave flux, the phase slips will occur due to hysteretic behavior of $I_s(\Phi_{\text{ext}})$, which will lead to a dissipation of the microwave energy. If the studied system consists of SC loops with both π and 0 contacts, the absorption should first reach a maximum at $\Phi_{\text{ext}}=0$, then decrease, and subsequently reach the next maximum when the external flux approaches the hysteresis region centered near $\Phi_{\text{ext}}=\Phi_0/2$ for the loop with the 0 contact.[2] In reality, because of the random orientation of the loops relative to the direction of the external field, and because of the scattering of the values of S and I_c, we can expect to see a smooth dependence of dP/dH on H with two peaks of opposite phases. The values of the magnetic field at these peaks correspond to some effective area and to the critical current of the loops with π and 0 contacts (for the system of SC loops with 0 contacts this situation was modeled in Ref. 11). As can be seen in Fig. 2, these peculiarities of the MWA are indeed observed for the samples with the WE.

Let us now discuss the temperature dependence of $H_{\text{peak}}(T)$ shown in Fig. 3b. On the basis of the above discussion we can assume that H_{peak} is a measure of the width $\Delta\Phi$ of the hysteresis of the curve $I_s(\Phi_{\text{ext}})$ centered at $\Phi_{\text{ext}}=0$. Since $\Delta\Phi\sim LI_c$, the variation of the peak position of the "anomalous" MWA signal with temperature should reflect the temperature dependence of the Josephson critical current of the π contact, $I_c(T)$. Using the Ambegaokar-Baratoff expression[12] for the Josephson critical current $I_c(T)\sim\Delta(T)\tanh[\Delta(T)/2k_BT]$ and solving numerically the standard BCS integral equation for the SC gap $\Delta(T)$, we can simulate the temperature dependence of H_{peak} (the solid lines in Fig. 3b). The result is in good agreement with the experimental data. From the condition for hysteresis, $(2\pi/c)LI_c>\Phi_0$, we can roughly estimate the lower limit of the area S of a loop with a π contact. If we assume that $LI_c/c=SH_{\text{peak}}(0)$, then for $H_{\text{peak}}(0)\approx2.5$ Oe (Fig. 3b) we would obtain $S\geqslant1.3\ \mu\text{m}^2$. The small value of the estimated loop's area may account for the intragranular localization of π contacts.

4. In summary, we have presented here the results of an experimental study of an anomaly in differential low magnetic field microwave absorption in the samples of Bi 2212 HTS which exhibit the Wohlleben effect (paramagnetic FC susceptibility at low fields). The analysis of the field and temperature dependences of the differential absorption, dP/dH, allows us to conclude that the anomaly in the MWA has a common origin with the WE and is probably caused by the presence in the samples of the Josephson weak links with π contacts. It should be noted that there are different points of view as to the possible microscopic origin of such contacts, e.g., the existence of magnetic impurities in the junction or anisotropic (i.e., d-wave) pairing in HTS.

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(1) Since the observed phenomenon is not strictly related to the Meissner effect, we would like to follow the suggestion of Sigrist and Rice[2] to call it the Wohlleben effect.

(2) The SC pairing of *d* type, as an alternative reason for the appearance of the phase shift π, was discussed recently in Ref. 2.

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