Spin correlation effects and the transverse magnetoresistance in YBCO single crystals with different oxygen contents

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The linear (in the magnetic field) magnetoresistance measured in $YBa_2Cu_3O_x$ crystals in the normal state is explained in terms of the interaction of current carriers with spin correlations in the CuO_2 layer. The temperature dependence of this contribution is compared with the behavior of the spin correlation function calculated in the two-dimensional Heisenberg model. Estimates are obtained for the exchange integral in the cuprate layer for samples with oxygen content $x=6.88$ and 6.62. © *1995 American Institute of Physics.*

In this paper we study the spin correlation phenomena in the normal-state magnetoresistance of high-T_c yttrium single crystals. The results obtained pertain to the range of oxygen concentrations x in which YBCO exhibits metallic conductivity and superconductivity. According to the inelastic neutron scattering investigations,[1–3] in this range the magnetic system of YBCO consists of a collection of dynamical antiferromagnetic correlations of the d spins of copper in the CuO_2 layer (DACS). As a result of the strong interaction between the electronic and spin degrees of freedom in the cuprate layer, as the layer is saturated with carriers, the magnetic correlation length ξ_m decreases and the spin-excitation spectrum becomes appreciably distorted—a gap, whose width increases with x, appears in the low-frequency part of the spectrum. Nuclear magnetic resonance data[4–6] show that the carriers strongly affect the magnetic subsystem. At the same time, a complete picture of the spin correlation phenomena in doped cuprate systems has not yet been established. The temperature dependence of the spin correlation function and ξ_m for CuO_2 layer is not clear. Very few papers on the inverse effect of magnetic correlations on the carrier subsystem have been published. This effect could be substantial. In particular, the number of studies in which the electron-spin interaction is thought to be responsible for the appearance of high-T_c superconductivity has been increasing.

In our recent studies[7] we determined the transverse magnetoresistance of three YBCO single crystals with different oxygen contents. At temperatures $T \geqslant 1.5T_c$, where the effect of superconducting fluctuations is weak, the field dependences $\Delta R/R_0(H)$ are described well by the expression

$$\Delta R/R_0 = AH^2 + B|H|. \tag{1}$$

The linear contribution was small for sample 1 with oxygen content $x=6.95$ and sharply higher for samples 2 and 3 ($x=6.88$ and 6.62, respectively). The analysis of the anisotropy of the coefficient B and of its dependence on the oxygen content, performed in Ref. 7, suggested that the "linear" magnetoresistance is due to the interaction of current carriers with the DACS. This result was based on an analysis performed by Turov and Shavrov,[8] according to which the magnetoresistance of antiferromagnetic metals can contain a contribution which is linear in the magnetic field as a result of the presence of terms[1)] of the form $M_i H_j$ or $L_i H_j$ in the expression for $\Delta R/R_0$. Here M_i, L_i, and H_j are, respectively, the components of the ferromagnetic and antiferromagnetic vectors and of the magnetic field. In the standard mean-field theory these contributions evidently reduce to zero, together with the vanishing of long-range order. However, some experiments show that this is not the case. For example, in Ref. 10 , where UPt_3 was studied, a linear contribution to the magnetoresistance was observed below and above the Néel point. We assume that if the lifetime τ_m of DACS is much longer than the interaction time of τ_h of a carrier with the correlated region, the Turov–Shavrov analysis remains valid for a fluctuating magnetic system. The analog of the antiferromagnetic vector is then the effective order parameter L^{eff}, whose mean-squared modulus is proportional to $\langle|S(k)|\rangle$, where $S(k)$ is the Fourier transform of the pair spin correlation function.[11] If this concept is correct, then information about the behavior of the spin correlation function for a cuprate layer with different degrees of doping can be obtained by studying the behavior of the linear contribution to the normal magnetoresistance of YBCO with different oxygen contents (just as for other high-T_c cuprate superconductors). This is a very important problem, especially since there is still no theoretical description of spin correlations which interact with the strongly correlated electronic system of the cuprate layer. At present, we have only the expression obtained by Chakravarty[12] for $S(k)$ on the basis of the two-dimensional (2D) Heisenberg model (in the classical rotator limit):

$$S(k)=\frac{Ct^2 \exp[2/t]}{(1+t)^4}, \tag{2}$$

where C is a constant, $t=T/2\pi\rho_s$, and ρ_s is the spin stiffness of the magnetic system, which is related to the exchange interaction I by the relation $2\pi\rho\simeq 1.15\ I$. As shown in Ref. 13 , for the lanthanum system the 2D Heisenberg model describes well the correlation phenomena in the dielectric cuprate layer, but the agreement with Chakravarty's theory breaks down even for low degrees of doping. Our objective in the present work is to check the applicability of the Turov–Shavrov and Chakravarti results for describing the "linear" magnetoresistance of YBCO—a high-T_c superconductor with metallic conductivity—as well as to investigate (on the basis of the present approach) the possible transformation of the spin correlation function at different degrees of doping of the CuO_2 layer on the basis of the temperature dependence of the coefficient B for samples with different oxygen contents.

The temperature dependences of the normal magnetoresistance of the system $YBCO_x$ were obtained for single crystals, with oxygen indices $x=6.95$, 6.88, and 6.62, which were described in Ref. 7. (samples 1, 2, and 3). The superconducting transition temperatures of the samples were equal to 92.8, 91.5, and 34 K, respectively. The measurements were performed in stationary magnetic fields of up to 15 T, oriented perpendicular to the ab plane of the crystals. According to Fig. 1, the quantity

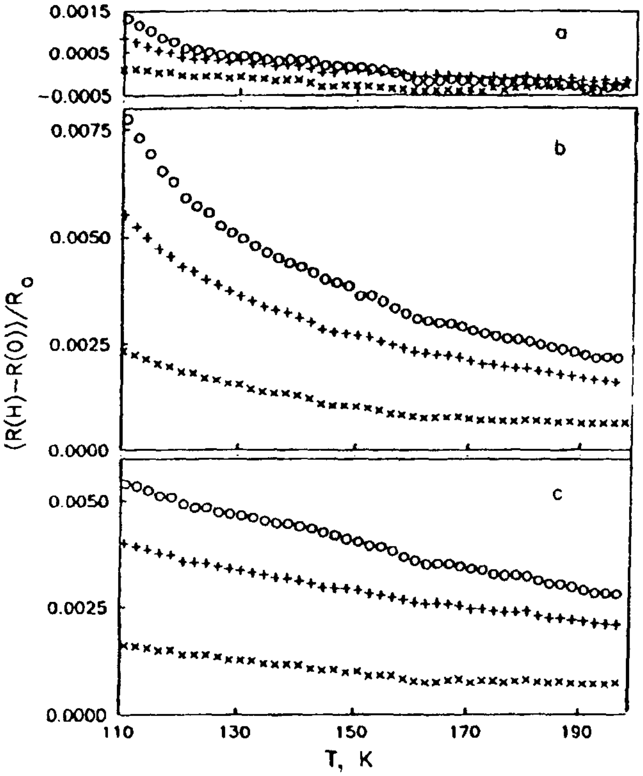

FIG. 1. Temperature dependences of the magnetoresistance in the ab plane of $YBa_2Cu_3O_x$ single crystals. a—Sample 1; b—sample 2; c—sample 3 in the fields $H=4.95$ T (×), 10.82 T (+), and 14.36 T (O); $R_0=R(220$ K).

$\Delta R/R_0=[R(T,H)-R(T,0)]/R_0$, where $R_0=R(220\text{ K}, 0)$, in the normal region is much smaller for the oxygen-saturated sample than for samples 2 and 3. In accordance with Ref. 7 , this difference is associated mainly with the component of the magnetoresistance which is linear in the magnetic field. Estimates obtained in Ref. 7 for the characteristic frequencies of the DACS show that for sample 1 the times τ_m and τ_h are close to one another, whereas for samples 2 and 3 the inequality $\tau_m \gg \tau_h$ holds reliably.

The coefficient B is shown in Fig. 2 as a function of the temperature. Its numerical value was found at each temperature with the help of expression (1). The results are presented only for samples 2 and 3, since B, because of its smallness in the case of sample 1, cannot be determined accurately enough for quantitative analysis. The data are normalized to the value of the coefficient at 220 K. Note the tendency (most strongly manifested in the case of sample 3) of the curves $B(T)/B_0$ to reach saturation at high temperatures.

The temperature dependence $B(T)$ plotted in the reduced coordinates $\ln[(B(T)/B_0)(1+t)^2/t]$ versus $1/t$, in which $B(T)\sim\sqrt{\langle|S(k)|\rangle}$ is, according to Eq. (2), a

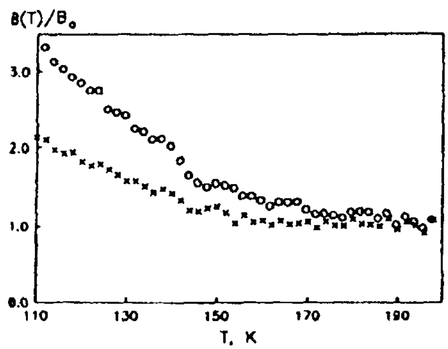

FIG. 2. Temperature dependence of the normalized linear (in the magnetic field) contribution to the magnetoresistance of samples 2 (O) and 3 (×). $B_0 = B(220\ \mathrm{K})$.

linear function, is compared in Fig. 3 with the behavior of the spin correlation function determined from Chakravarty's theory. First, the values of the magnetic stiffness were estimated by an iteration method. Figure 3 was constructed for the third iteration, after which the parameter $2\pi\rho_s$ stabilized within 2% at 334 K for sample 2 and at 283 K for sample 3. One can see that in certain temperature intervals the relation (2) describes satisfactorily the behavior of the coefficient B. The high-temperature limit of this interval is probably determined by the violation of the necessary condition $\tau_m \gg \tau_h$ and by the related conditions $\xi_m / a > 1$, where a is the lattice constant in the CuO_2 layer. Above this limit, $B(T)$ tends to saturate, which could indicate a change in the mechanism responsible for the appearance of a component which is linear in the field. It is interesting that, within the limits of accuracy ($\pm 7\%$) of the determination of B, the data constructed in the reduced coordinates for both samples fall on the same line; this serves as an additional confirmation of the correctness of our concept.

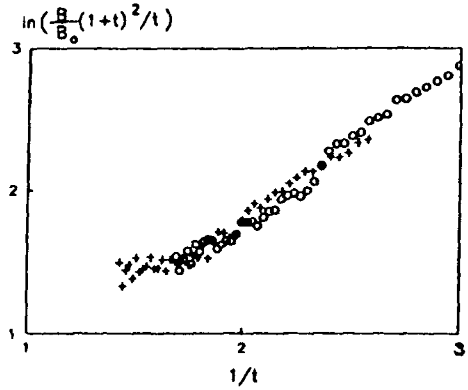

FIG. 3. Illustration of the applicability of expression (2) for describing the temperature dependence $B(T)$. O—sample 2; +—sample 3; $t = T/2\pi\rho_s$.

At present, it is very difficult to compare our data with the results obtained in other studies, since there are no experimental results or a theoretical description of the behavior of the function $S(k)$ for a doped cuprate layer. Taking into account the relation between the magnetic stiffness and the exchange integral, we obtain from the values obtained for ρ_s a temperature of 290 K for I for sample 2 and 245 K for sample 3. This is much lower than the published values for a dielectric cuprate layer. For example, according to Ref. 1, $I = 1700$ K for $YBa_2Cu_3O_{6.15}$ and according to the data of Ref. 13 , $I = 1200$ K for La_2CuO_4.

The decrease in the exchange constant accompanying the appearance of free carriers in the layer can be explained by the competition between the exchange interactions. In Ref. 14 it was shown on the basis of the band model that when a transition into the metallic state occurs, an additional indirect exchange interaction of the RKKY type should come into play. For cuprate systems this interaction is of a ferromagnetic character. In this case the total exchange interaction $I = I_1 + I_{RKKY}$ naturally decreases (here I_1 is the exchange interaction responsible for the antiferromagnetic ordering in the dielectric phase). The possibility that the spin stiffness of the system is lower in the doped cuprate layer than in an undoped layer also follows from the calculation performed in Ref. 11 . At the same time, in Ref. 15 it is noted that the spin-hole interaction has a multifactor effect on the magnetic subsystem of a cuprate layer. As the carrier concentration increases, the spin-excitation spectrum becomes strongly distorted, the relative contribution of different sections of the spectrum to the scattering changes, and incoherent scattering plays a larger role. These tendencies can greatly complicate the x dependence of the correlation parameters. They could conceivably be responsible for the fact that the spin stiffness for sample 2 is greater than for the "less-doped" sample 3.

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[1)]The matter of the nature of the Turov–Shavrov effect in the compound $YBa_2Cu_3O_x$ falls outside the scope of the present paper. This effect could be due to the weak ferromagnetism of the CuO_2 layers, which could arise upon doping of the system.[9] In this case a dependence of the type $\Delta R/R_0 = B|H|$, where $B \sim L_i$, could be due to the reversal of, in an external field, of a weakly ferromagnetic moment m_z, which in turn is attributable to the components of the antiferromagnetic vector in the CuO_2 layer.

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