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The Upper Critical Field of High Temperature Superconductors

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Abstract

Resistive and magnetic measurements of the superconducting transition in good quality single crystals of $YBa_2Cu_3O_{7-\delta}$ and $La_{2-x}Sr_xCuO_4$ and in good polycrystalline samples of $Ba_{1-x}K_xBiO_3$ are used to derive the temperature dependence and anisotropy of the upper critical field. Comparison of the results shows several common features, most notably the existence of upward curvature in the temperature dependence of the upper critical field. The definition of T_c from resistance curves and the origin of the upward curvature in the upper critical field are discussed.

Keywords: upper critical field
high T_c superconductivity
$Ba_{1-x}K_xBiO_3$
$La_{2-x}Sr_xCuO_4$
$YBa_2Cu_3O_{7-\delta}$

INTRODUCTION

One of the most important quantities characterizing the superconducting state of high temperature superconductors is the upper critical field. Much information about the superconducting energy gap, the strength of the coupling, the dimensionality and anisotropy, coherence length, and Ginzburg-Landau effective mass may be obtained by measuring the temperature dependence and anisotropy of H_{c2}. In part, there is a good theoretical foundation for relating the upper critical field to these various parameters. For example, the Werthamer Hohenberg Helfand (WHH) formalism[1,2] provides a sophisticated method for calculating H_{c2} in terms of normal state properties like the Fermi surface properties and the electron lifetime, and superconducting properties like the transition temperature and the coherence length. This method has been quite successfully applied to the weak coupling BCS superconductors.[3] In principal, this formalism can also be applied to lower dimensional superconductors in the strong coupling regime to explain the effects of dimensional crossover and Fermi surface anisotropy on H_{c2}. However, a good theoretical foundation for understanding these effects is not yet established.

The high temperature superconductors display several unusual features in their upper critical fields which may provide clues to the nature of their superconducting states. In this paper we will examine the systematics of some of these features in high temperature superconductors using new data on high quality single crystals of the copper-oxide superconductors and polycrystalline samples of the new $Ba_{1-x}K_xBiO_3$ system. We concentrate on three

features: the broadening of the resistive transition in a magnetic field, the upward curvature in the upper critical field versus temperature curve, and the anisotropy of H_{c2} with the magnetic field parallel and perpendicular to the c axis.

$YBa_2Cu_3O_{7-\delta}$

The resistive transition in zero and various applied fields and the diamagnetic shielding transition in a dc field of 0.5 G is shown in Figure 1 for a high quality single crystal of $YBa_2Cu_3O_{7-\delta}$ with the field along the c direction. The resistance was measured by a four probe ac method at 28 Hz with a measuring current of 1 mA. The significant broadening of the resistive transition with field is typical of this high temperature superconductor.[4] It has been observed by various investigators in both single crystal and polycrystalline samples. The detailed shape of the transition curves in a field varies from sample to sample which led to the assumption that the broadening may be due to the quenching of weak links which arise from inhomogeneities in the sample.[4] The crystal used for the data of Figure 1 is of exceptional quality as indicated by the very sharp resistive transition in zero field of less than 100 mK (the temperature interval separating adjacent data points) and the dc diamagnetic transition width of $\Delta T < 1$ K, yielding a relative width $\Delta T/T_c$ of 10^{-2}. This sample is considerably more homogeneous than those used in earlier work.[4] It should be noted that any transition of width larger than 100 mK for $YBa_2Cu_3O_{7-\delta}$ must be attributed to inhomogeneities and cannot be due to superconductive fluctuations. Despite the high quality of our sample, the field induced broadening

of the resistive transition is as large as that observed in much less homogeneous samples. This strongly suggests that the broadening in field is an intrinsic effect of $YBa_2Cu_3O_{7-\delta}$ unrelated to sample quality.

The increasing broadening of the resistive transition with magnetic field makes it difficult to define uniquely the upper critical field. Various definitions have been proposed like the onset, midpoint, zero or inflection point of the resistive transition. These various methods lead to quite different values of the upper critical fields in this material. It seems obvious that the onset of bulk superconductivity is associated with the appearance of a diamagnetic signal. Thus, for a homogeneous sample the R=0 temperature should coincide with the diamagnetic onset temperature. This is indeed true in zero applied field for the sample of Figure 1 where the R=0 point of 91.3 K differs from the diamagnetic onset temperature of 92.2 K measured in 2 G by less than 1 %. We adopt this "diamagnetic onset" criterion, taking as the definition of T_c the temperature where bulk superconductivity as determined from the magnetization measurement first appears. For the $YBa_2Cu_3O_{7-\delta}$ crystal of Figure 1, this agrees with the temperature where R=0. We maintain this definition of T_c also for the transition curves in finite fields. Figure 2 displays H_{c2} versus temperature determined from the data in Figure 1 using the R=0 temperatures. The data in Figure 2 for the field along **c** lie approximately on a straight line. However the extrapolation of the H_{c2} values to the temperature axis lies considerably below the observed zero field transition temperature. This implies that the H_{c2} curve must bend sharply near the

temperature axis. Indeed in earlier magnetization measurements[5] on another $YBa_2Cu_3O_{7-\delta}$ single crystal the H_{c2} versus temperature slope very close to T_c was determined to be about 100 times less than that observed in Figure 2. The origin of the sharp bend is not understood at present. The upper critical field in the **ab** plane obtained from resistivity data similar to that in Figure 1 is also shown in Figure 2. The slope of H_{c2} versus temperature for the field in the **ab** plane(-4.2T/K) is approximately a factor of 7 larger than that in the **c** direction(-0.52T/K). In addition, definite upward curvature is observed for the field in the **ab** plane. This observation is consistent with earlier results from other laboratories on crystals whose zero field transitions were not as sharp as that reported here. We conclude that the upward curvature in the **ab** plane is an intrinsic feature of $YBa_2Cu_3O_{7-\delta}$.

$La_{2-x}Sr_xCuO_4$

Good quality single crystals of $La_{2-x}Sr_xCuO_4$ are much harder to grow than $YBa_2Cu_3O_{7-\delta}$, and to date there has been relatively little work reported on single crystal samples.[6] In Figure 3 we show the resistive transitions in zero and finite field along the **c** direction for a single crystal of $La_{2-x}Sr_xCuO_4$. Although the transitions are broader than those of the $YBa_2Cu_3O_{7-\delta}$ crystal of Figure 1, they are considerably more narrow and smooth than those of earlier single crystal samples. The diamagnetic transition is shown in the inset to Figure 3. Unlike for $YBa_2Cu_3O_{7-\delta}$, at the low field diamagnetic onset the zero field resistance maintains approximately 50% of its normal state value. Using the diamagnetic onset criterion, we take the 50%

resistance temperature as the definition of T_c in finite field. The resulting upper critical field curves for the two crystallographic directions are shown in Figure 4. As for $YBa_2Cu_3O_{7-\delta}$, there is upward curvature for the field in the ab plane but nearly linear behavior for the field along c. In addition, the extrapolation of the high field points in both field directions to zero field lies significantly below the observed zero field transition, indicating structure in the upper critical fields near T_c. The ratio of the slopes at the highest fields in the two directions for $La_{2-x}Sr_xCuO_4$ (-7.14T/K for H||c and -0.90 T/K for H||ab) is about 8, very similar to that in $YBa_2Cu_3O_{7-\delta}$.

$Ba_{1-x}K_xBiO_3$

The discovery[7-11] of superconductivity in $Ba_{1-x}K_xBiO_3$ provides the opportunity to examine the role of two dimensionality and anisotropy on the unusual features of the upper critical field in high T_c superconductors. As $Ba_{1-x}K_xBiO_3$ is cubic, there is no significant anisotropy expected in the upper critical field, and any unusual features cannot be attributed to low dimensionality. Single crystal samples of $Ba_{1-x}K_xBiO_3$ are not yet available and most polycrystalline samples show very broad transitions. Recently, Hinks et al.[9] have developed a new technique for making polycrystalline samples which show sharp transitions. Resistive transitions in zero and finite fields and the diamagnetic shielding transition in a field of 2 G are shown in Figure 5. The diamagnetic onset occurs at T_c=25.7K, where the resistivity is roughly 90% of its normal state value. This is consistent with the granular nature[11] of the material which produces significant normal regions in the current path[11]. As in

good samples of $La_{2-x}Sr_xCuO_4$, an applied magnetic field displaces the transition curve in parallel to lower temperature, making the shape of the $H_{c2}(T)$ curve nearly insensitive to the definition of T_c. Following the diamagnetic onset criterion we take the 90% resistive point as the definition of T_c, giving the H_{c2} curves shown in Figure 4(labeled BaKBiO). Even in this cubic material, the critical field curve shows significant upward curvature extending over nearly the entire superconducting range. As with the other materials, near T_c there is noticeable flattening of the H_{c2} curves.

Discussions and Conclusions

The data presented above indicate several common features among $YBa_2Cu_3O_{7-\delta}$, $La_{2-x}Sr_xCuO_4$, and $Ba_{1-x}K_xBiO_3$. (1) The anisotropy ratio of the upper critical fields in the two directions is approximately the same for $YBa_2Cu_3O_{7-\delta}$ and $La_{2-x}Sr_xCuO_4$. If this ratio is taken as a measure of the coupling between the Cu-O layers, both materials show about the same degree of two dimensional behavior. (2) There is significant flattening of the H_{c2} curves near T_c in all three materials. (3) There is upward curvature in the critical field in the ab plane of single crystals of both $YBa_2Cu_3O_{7-\delta}$ and $La_{2-x}Sr_xCuO_4$ and in polycrystalline samples of $Ba_{1-x}K_xBiO_3$.

The upward curvature of H_{c2} is contrary to predictions of WHH type[1-3] calculations which always give linear behavior near T_c and concave downward behavior at lower temperatures. The Cu-O materials have two features which violate the WHH assumptions: highly anisotropic Fermi surfaces and potentially strong coupling. The fact that the upward curvature is also observed in the cubic

$Ba_{1-x}K_xBiO_3$ system implies that anisotropy of the Fermi surface is not necessary for its occurrence. There has been some theoretical work[12,13] on the effects of strong coupling on the upper critical field of isotropic superconductors which predicts upward curvature over a limited temperature range below T_c, but there are no predictions for upward curvature over the entire temperature range beginning at T_c. Thus, upward curvature in the upper critical field is a common feature in good samples of all the high T_c superconductors discovered to date. This upward curvature violates the predictions of available theory. Further theoretical work is needed to explain the origin and significance of this effect.

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FIGURE CAPTIONS

Figure 1. Resistive transition in zero and finite field along the c direction for a single crystal of $YBa_2Cu_3O_{7-\delta}$. The curves shown from right to left are for 0, 0.25, 1, 2, 3, 4, 5, 6, 7, and 8 Tesla. **Inset**: Diamagnetic shielding transition in 0.2 G for the same crystal .

Figure 2. Upper critical field H_{c2} versus temperature for the $YBa_2Cu_3O_{7-\delta}$ crystal of Figure 1 for H||c direction and H||ab plane.

Figure 3. Resistive transitions in zero and finite field along the c direction for a single crystal of $La_{2-x}Sr_xCuO_4$. The curves shown from right to left are for 0, 0.5, 1, 2, 3, 4, 5, 7, and 8 Tesla. **Inset**: Diamagnetic shielding transition in 0.5 G for the same crystal .

Figure 4. Upper critical field curves for the $La_{2-x}Sr_xCuO_4$ crystal of Figure 3 for H||c direction and H||ab plane (curves labeled La) and for the $Ba_{1-x}K_xBiO_3$ sample of Figure 5 (curve labeled BaKBiO).

Figure 5. **Upper Part:** Resistive transitions in zero and finite field for polycrystalline $Ba_{1-x}K_xBiO_3$. The curves shown from right to left are for 0, 0.5, 1, 2, 3, 4, 5, 6, 7, and 8 Tesla.

Lower Part: Diamagnetic shielding transition in a field of 2 G for the same sample.

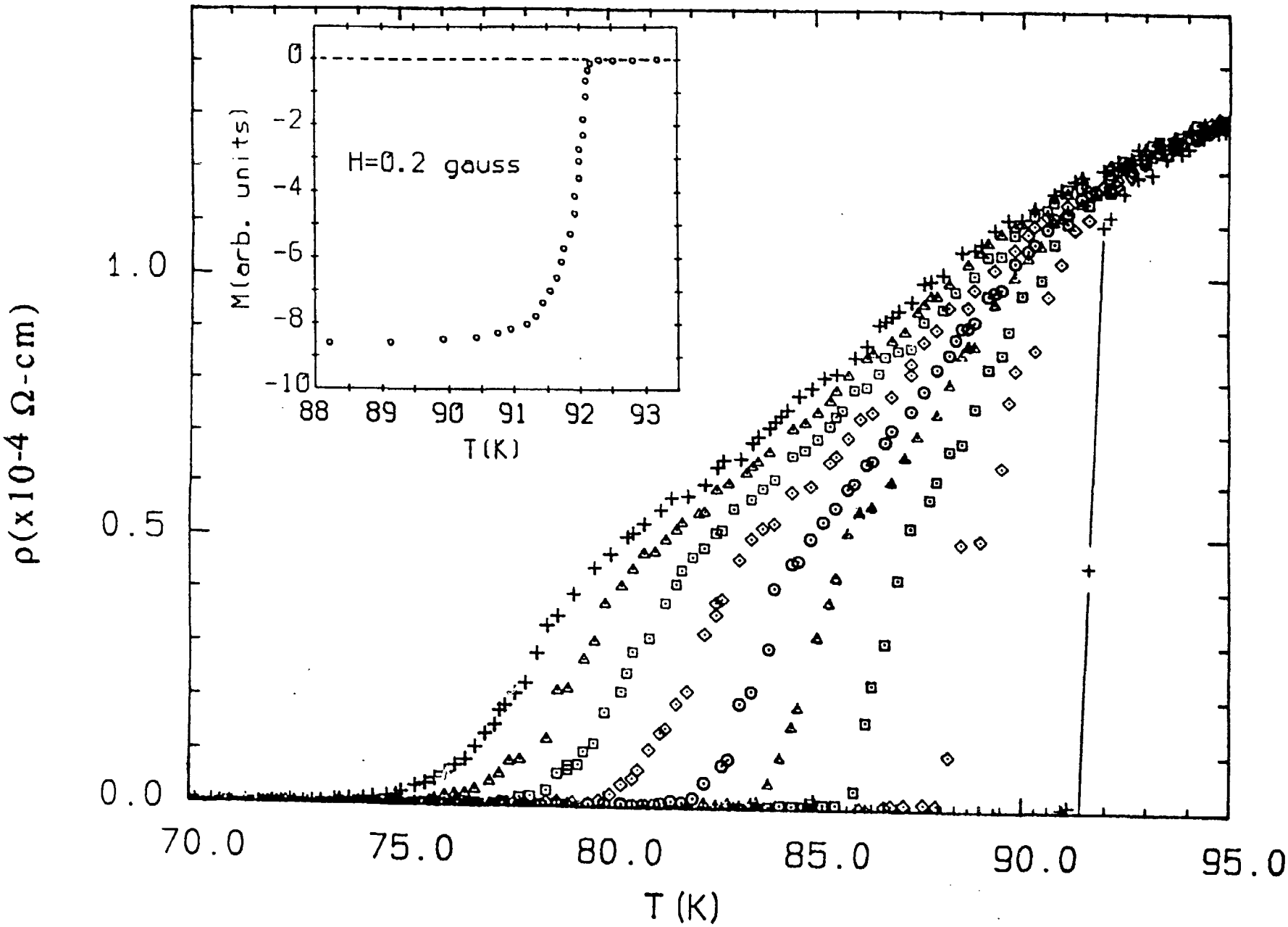
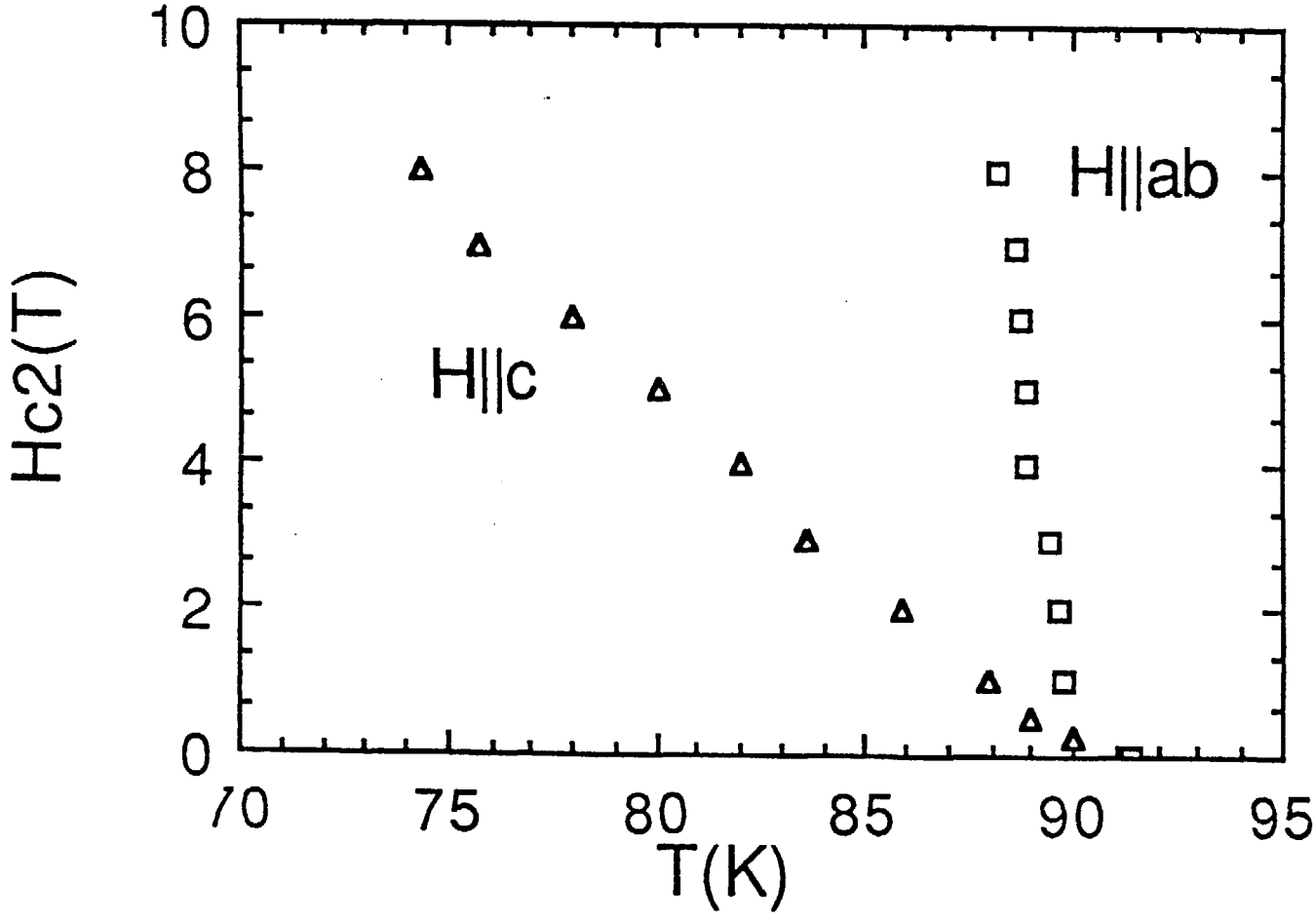

ρ(x10-4 Ω-cm)
1.0
0.5
0.0
70.0
75.0
80.0
85.0
90.0
95.0
T (K)
M(arb. units)
0
-2
-4
-6
-8
-10
88
89
90
91
92
93
T(K)
H=0.2 gauss

fig 2



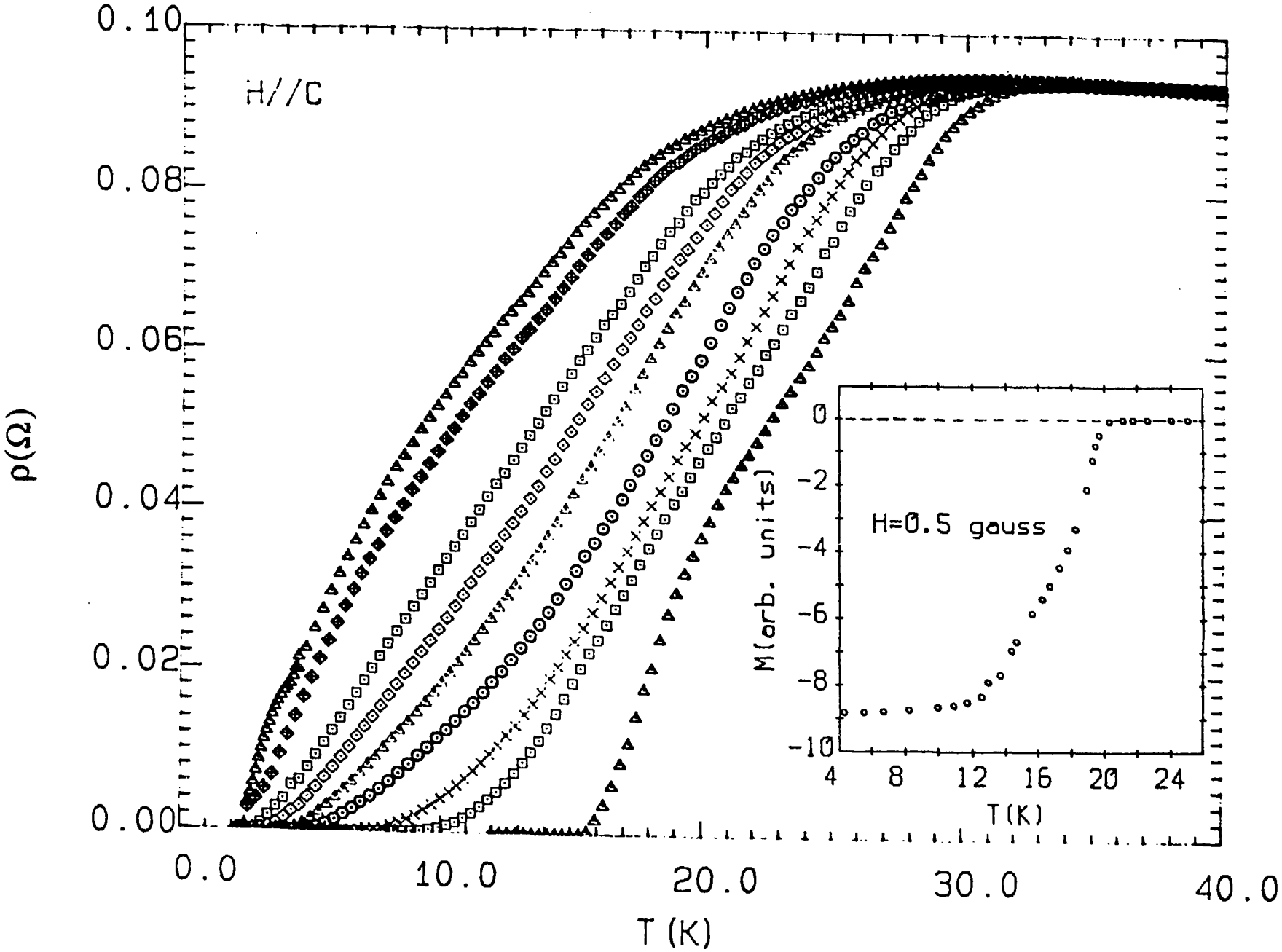

H//C
ρ(Ω)
0.10
0.08
0.06
0.04
0.02
0.00
0.0
10.0
20.0
30.0
40.0
T (K)
H=0.5 gauss
M(arb. units)
0
-2
-4
-6
-8
-10
4
8
12
16
20
24
T(K)

Fig 3

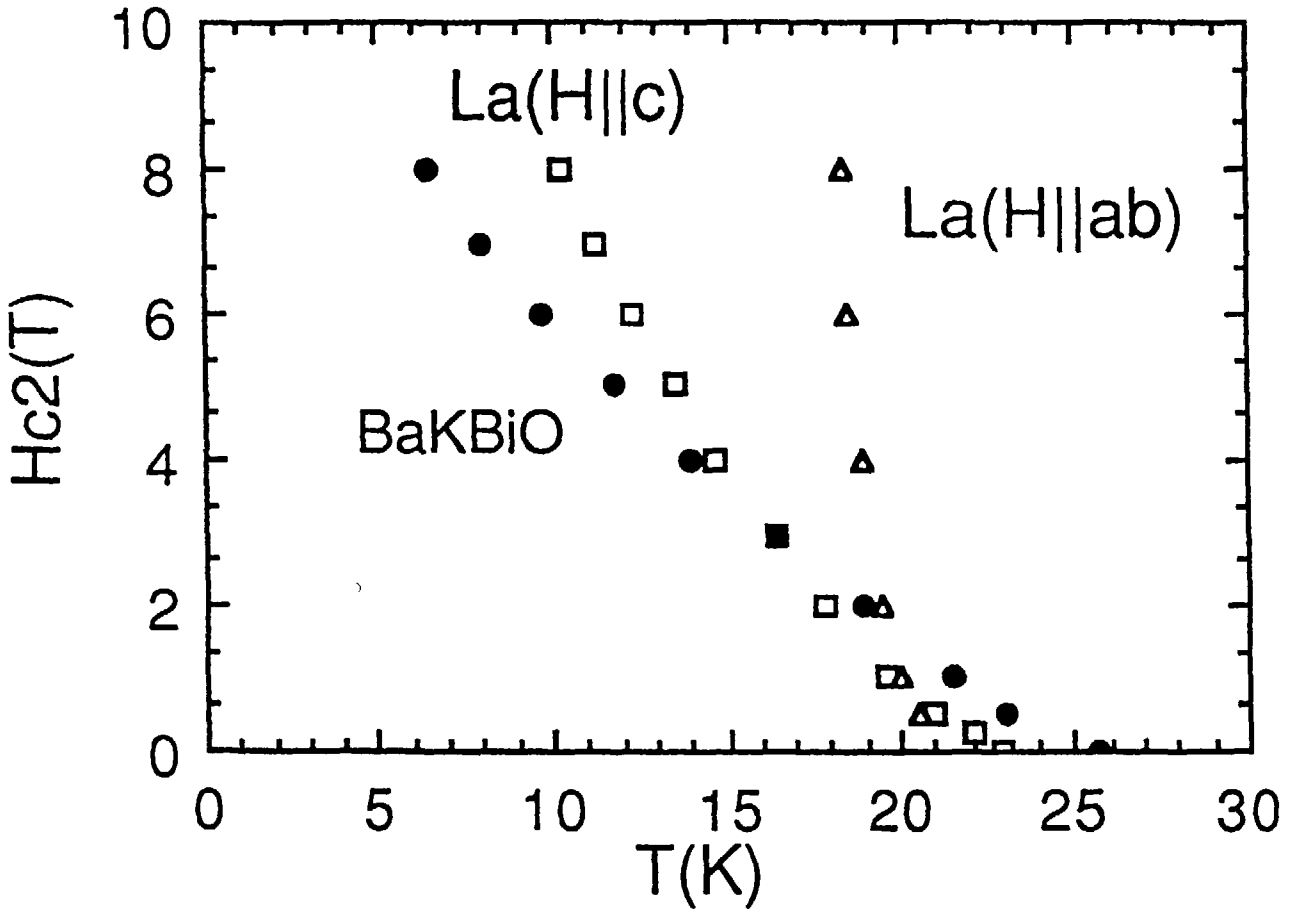
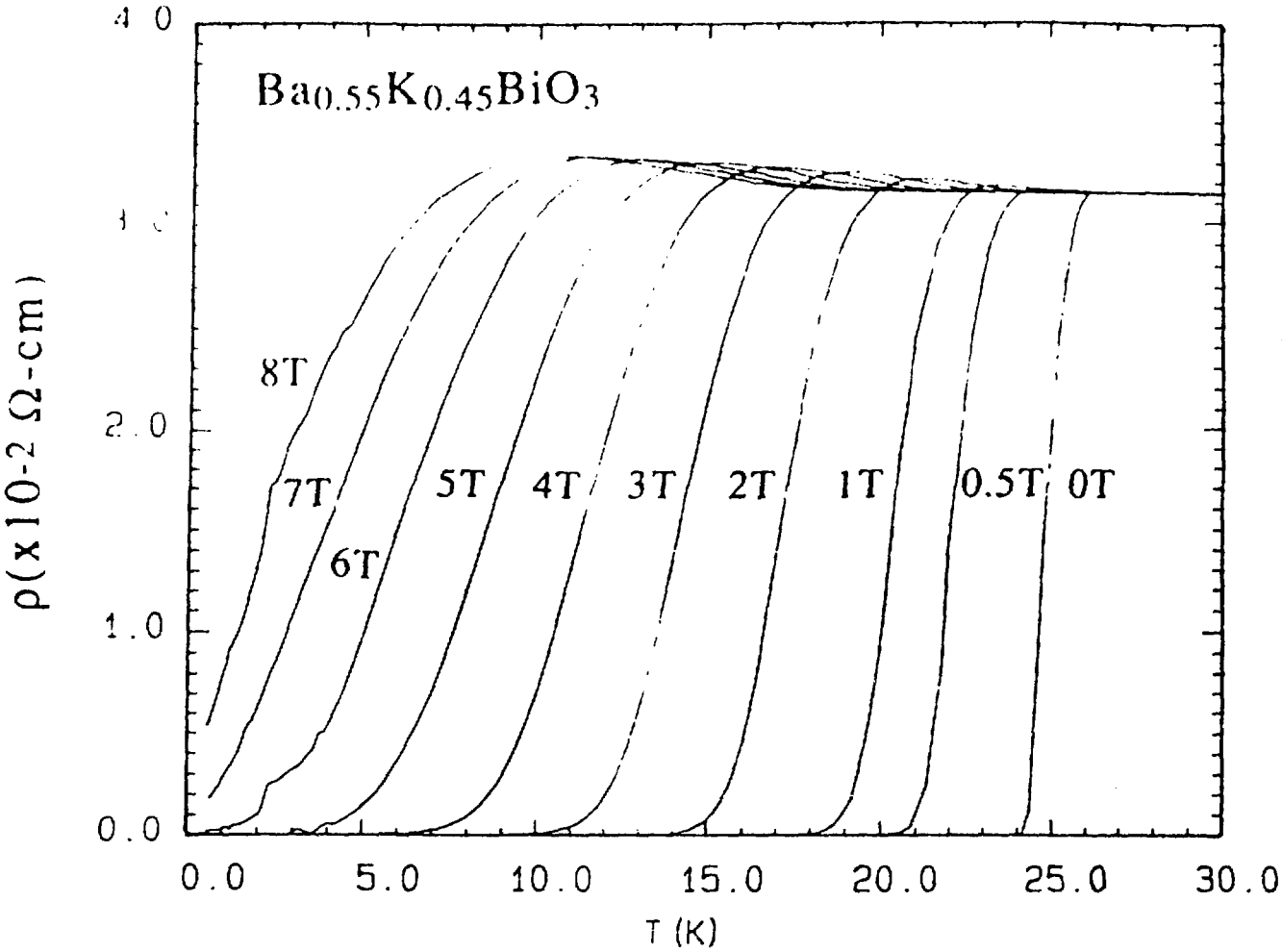
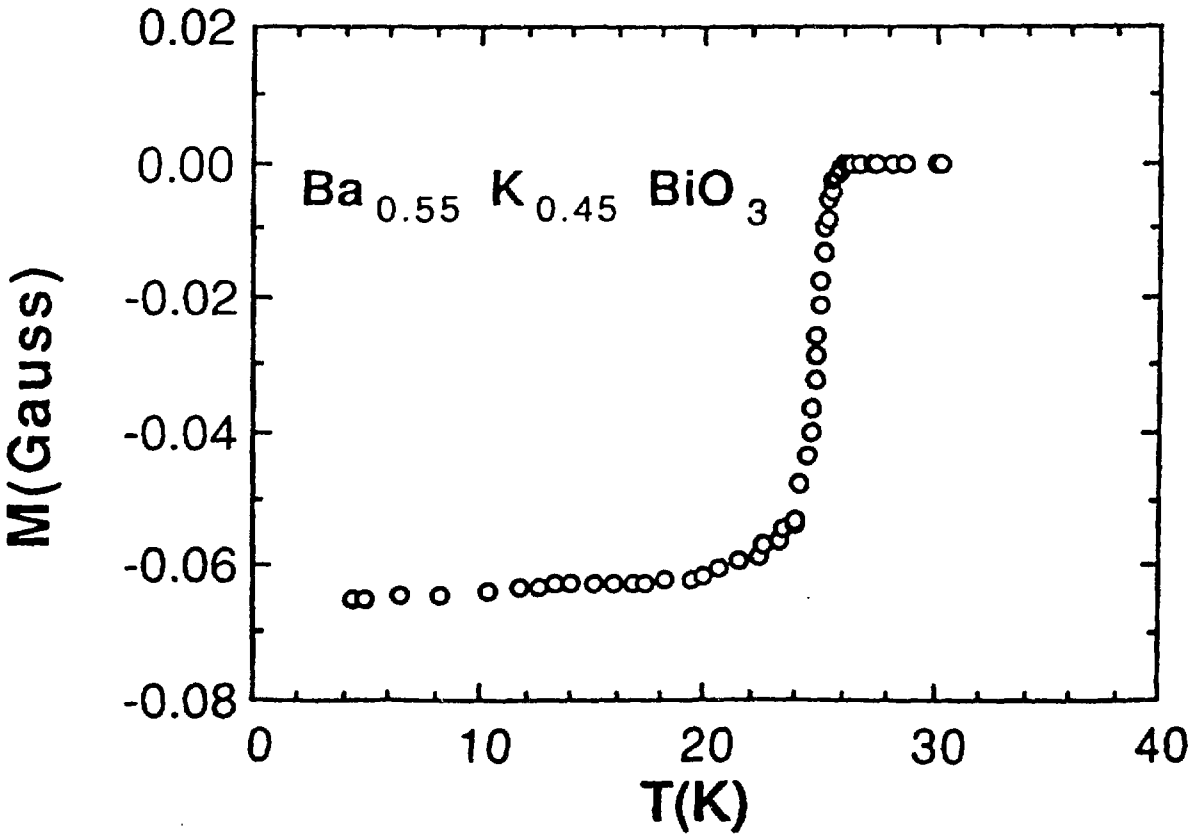


Fig.7

fig 3


Ba0.55K0.45BiO3
ρ(x10-2 Ω-cm)
8T
7T
6T
5T
4T
3T
2T
1T
0.5T
0T
2.0
1.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
T (K)


Ba 0.55 K 0.45 BiO 3
M(Gauss)
0.02
0.00
-0.02
-0.04
-0.06
-0.08
0
10
20
30
40
T(K)