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Effect of weak interlayer coupling on critical fluctuation in high T_c superconductors

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Abstract

The magnetization and/or resistivity of high T_c superconductors ($YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystal, $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) single crystal, $Tl_2Ba_2CaCu_2O_8$ (Tl-2212) film, $HgBa_2Ca_2Cu_3O_8$ (Hg-1223) film) have been measured as a function of magnetic field H and temperature T. The extracted fluctuation part of the magnetization and conductivity exhibits a critical behavior consistent with the three-dimensional XY model. The dynamic critical exponent z does not sensitively vary with a type of the superconductors. The value of z ranges from 1.5 to 1.8 ± 0.1. However, the static critical exponent ν is the most largely increased in Tl-2212 that has a weaker interlayer coupling strength than YBCO; the value of ν is 0.669, 0.909, 1.19, and 1.338 for YBCO, Bi-2212, Hg-1223, and Tl-2212 respectively. The results indicate that the weak interlayer coupling along the c-axis of high T_c superconductors near T_c does not influence the dynamic critical exponent z (the same value of superfluid ^{4}He), but significantly increases the static critical exponent ν.

Keywords: Critical fluctuation, Interlayer coupling, 3D-XY model

I. Introduction

High-T_c superconductors have short coherence lengths that introduce appreciable fluctuation effects and scaling behavior. The fluctuation of order parameter and vector potential has been widely studied to understand the nature of the superconducting phase transition of high-T_c superconductors at zero and non-zero magnetic fields. The fluctuation effects have been observed in several measurements, e.g., penetration depth, magnetic susceptibility, resistivity, and specific heat [1-9].

The observation of fluctuation effects for $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystal are consistent with fully three-dimensional critical behavior (3D-XY scaling model) [10-11]. The fluctuation conductivity $\sim H^{-(2+z-d)/2} F(t/H^{1/2\nu})$ where dynamic critical exponent $z = 1.5$, static critical exponent $\nu = 0.669$, dimension $d = 3$, F is a scaling function, $t \equiv 1 - T/T_{c0}$, and T_{c0} is zero resistance temperature at zero field [3, 5]. The 3D-XY scaling behavior for the magnetization is $M/H^{0.5} \sim F(t/H^{1/2\nu})$, where the static critical exponent of ν is the same as for fluctuation conductivity.

The universality class where the critical fluctuation belong for YBCO single crystal has been the same as that of superfluid ^{4}He : the exponent for the coherence length $\nu \approx 0.669$ and the dynamic critical exponent of $z \approx 1.5$ in the presence of magnetic field. Note that z determines dynamic universality class.

For $Bi_2Sr_2CaCu_2O_8$ (Bi-2212), $HgBa_2Ca_2Cu_3O_8$ (Hg-1223), and $Tl_2Ba_2CaCu_2O_8$ (Tl-2212) which have longer c-axis and larger anisotropy along c-axis than

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YBCO, the fluctuation-induced magnetization has been reported to be consistent with 2D scaling [9], however. The two dimensional nature stems most likely from the layered crystal structure as well as the weak c-axis coupling. The two dimensionality does not necessarily mean that the interlayer interaction is zero. A weak interlayer coupling in Bi-2212, Hg-1223, and Tl-2212 exists (though it is weaker than for YBCO), therefore it would be expected that the critical fluctuation will obey 3D-XY scaling as observed in YBCO. The fluctuation magnetization in Bi-2212 and Bi-2223 obeys the 3D-XY model [9].

In the mixed state, the weak interlayer coupling in high T_c superconductors (Bi-2212, Hg-1223, and Tl-2212) results in the weak pinning allowing the vortex pancakes to move more freely. The effect of the intrinsic weak pinning of the vortices on the critical dynamics has not been discussed within the framework of 3D-XY model, though the strong pinning effect on the critical exponents was discussed [12, 13].

We report on the critical fluctuation associated with the magnetization and conductivity σ_{xx} near the critical temperature of YBCO single crystal, Bi-2212 single crystal, Hg-1223 film, and Tl-2212 film. The 3D-XY critical scaling theory for magnetization and fluctuation conductivity is used to probe how the interlayer coupling is associated with the critical exponents.

II. Experiment

The preparation methods of the high T_c superconductors of YBCO detwined single crystal, Bi-2212 single crystal, Hg-1223 film, and Tl-2212 film were described elsewhere [14-17]. The resistance was measured with a 4-terminal method while applying a magnetic field (up to 9 T) parallel to the c-axis of the sample. The zero resistance temperature T_{c0} was 93.4 K, 84 K, 131 K, and 102 K for YBCO, Bi-2212, Hg-1223, and Tl-2212 respectively.

A) $YBa_2Cu_3O_{7-\delta}$ single crystal

Fig. 1 shows the longitudinal resistivity ρ_{aa}(//a-axis) and ρ_{bb}(//b-axis) for the YBCO single crystal at zero magnetic field [14]. The fluctuation conductivities $\sigma^*_{aa}(T, H)$ and $\sigma^*_{bb}(T, H)$ were obtained by a background subtraction of a linear-in-T resistivity

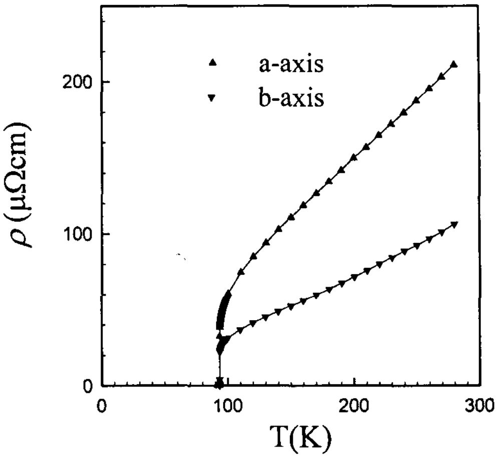

Fig. 1. Longitudinal resistivity ρ_{aa} (//a-axis) and ρ_{bb} (//b-axis) for the YBCO single crystal at zero magnetic field. At zero field, the zero-resistance transition temperature is 93.4 K. The resistive transition width (10-90 %) is 0.15 K.

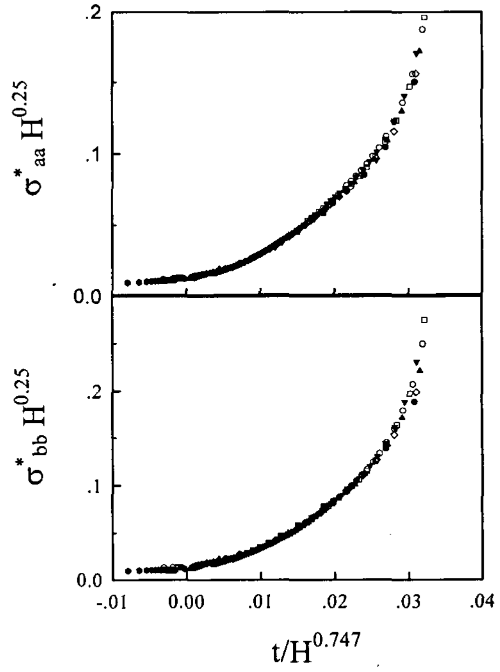

Fig. 2. Fluctuation conductivities of the YBCO single crystal scaled with z = 1.5. The resistivity is measured at temperature intervals of 1 K from 85 to 94 K. (From Ref. 14)

from $\rho_{aa}(T, H)$ and $\rho_{bb}(T, H)$ above T_{c0}. The background resistivity is linear for $T > 150$ K. The longitudinal conductivity, σ_{xx}, can be expressed as $\sigma^*_{xx} + \sigma_{B.G}$ where σ^*_{xx} and $\sigma_{B.G}$ are the fluctuation and background conductivity respectively. The $\sigma_{B.G}$ is the inverse of the background resistivity $\sigma_{B.G}(T)$. By subtracting $\sigma_{B.G}$ from σ_{xx}, the fluctuation conductivity σ^*_{xx} was obtained.

In the presence of a magnetic field, Fig. 2 shows that the fluctuation conductivities σ^*_{aa} and σ^*_{bb} (for $85 \leq T \leq 95$ K) collapse onto a function of $t/H^{1/2\nu}$, consistent with the 3D-XY scaling $\sigma^* \sim H^{-(2+z-d)/2}F(t/H^{0.747})$. Here $d = 3$, F is a scaling function, and the theoretical value $\nu = 0.669$ is used. The best scaling could be achieved by using T_c as its value in $H = 0$, i.e, 93.4 K, as in references [2-4, 6, 7]. This agrees with the resistivity data of Howson *et al.* [6] that do not scale with the lowest-Landau-level model. Overend *et al.* [18] reported that the specific heat data scale with 3D-XY model in magnetic fields up to 8 T and the lowest-Landau model does not work below 6 T. These findings are consistent with theoretical arguments that predict that below fields of order 10 T, the scaling should be governed by the zero-field critical point rather than the lowest-Landau-level scaling [19]. The best scaling of the fluctuation conductivities σ^*_{aa} and σ^*_{bb} indicates that the dynamic critical exponent $z = 1.5 \pm 0.1$, which is close to the value appropriate for the dynamic universality class of superfluid ^{4}He. The value of z indicates that the universality class of $YBa_2Cu_3O_{7-\delta}$ is the same as that of superfluid ^{4}He.

B) $Bi_2Sr_2CaCu_2O_8$ single crystal

We turn now to a discussion of the critical behavior in other high T_c systems that are more anisotropic than YBCO. One of them is $Bi_2Sr_2CaCu_2O_8$ system that has been reported to have two-dimensional like behavior for vortex. The distance between CuO_2 blocks (where two or three CuO_2 layers in unit cell are here called as a CuO_2 block) is 15.45 Å for Bi-2212 whereas it is 11.7 Å for YBCO. The longer interlayer distance along c-axis in Bi-2212 allows vortex to move more freely.

The magnetization of the $Bi_2Sr_2CaCu_2O_8$ single crystal was measured with SQUID (Superconducting Quantum Interference Device) for $1 \leq H \leq 5$T. Fig. 3

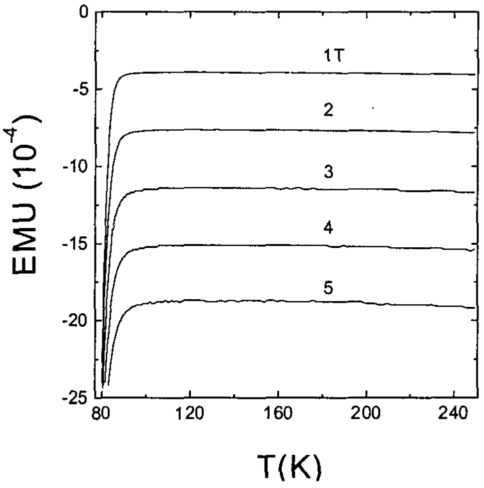

Fig. 3. Magnetic moment for the $Bi_2Sr_2CaCu_2O_8$ single crystal at H = 1, 2, 3, 4, and 5 T. The magnetic field was applied parallel to the c-axis of the sample. The fitting T region for subtracting the background magnetization is above 120 K.

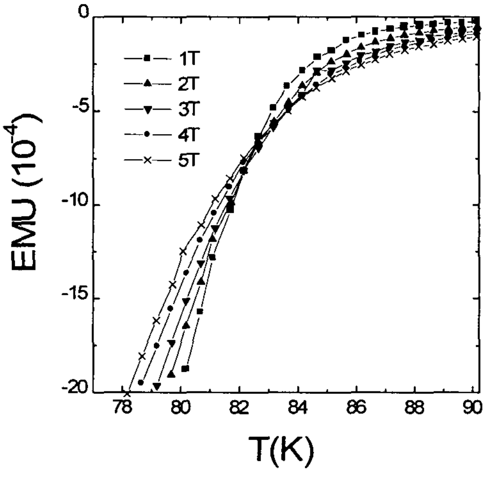

Fig. 4. Superconducting magnetic moment for the $Bi_2Sr_2CaCu_2O_8$ single crystal at H = 1, 2, 3, 4, and 5 T after the linear-with T background subtraction. The magnetic field was applied parallel to the c-axis of the sample. (From Ref. 20)

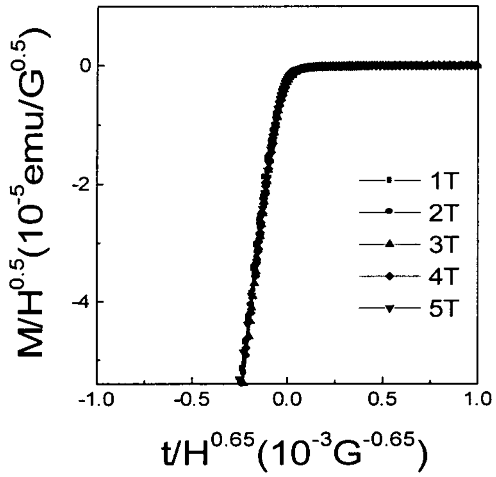

Fig. 5. The 3D-XY scaling for the magnetization: $M/H^{0.5} \sim F(t/H^{1/2\nu})$. T_{c0} is a zero resistance temperature of 84 K at zero field. The units of M and H are emu and Gauss respectively. The static critical exponent of ν is 0.769 ± 0.1.

shows the background magnetization above T_c that is approximately linear with temperature ($T > 120$ K).

A linear fit over $T > 120$ K was chosen. After the background magnetization at each field was subtracted, superconducting magnetization data were used for the fluctuation study in Fig. 4.

The 3D-XY scaling theory for the magnetization was reported to be $M/H^{0.5} \sim F(t/H^{1/2\nu})$. Here T_{c0} is fixed to a zero resistance temperature of 84 K. Fig. 5 shows that the fluctuation magnetization near T_c obeys 3D-XY scaling and the static critical exponent of ν is 0.769 ± 0.1. This value is larger than 0.669 of YBCO. The critical temperature region is ± 8 K near T_{c0}. The units of M and H are emu and Gauss respectively.

Fig. 6 shows the longitudinal resistivity ρ_{xx} for the sample at several values of applied magnetic fields with H parallel to the c-axis [20]. The inset in Fig. 6 shows that zero-field resistivity is linear for $T > 130$ K. In order to investigate whether the fluctuation conductivity of Bi-2212 obeys 3D-XY scaling, the fluctuation conductivity $\sigma^*_{xx}(T, H)$ was obtained by a

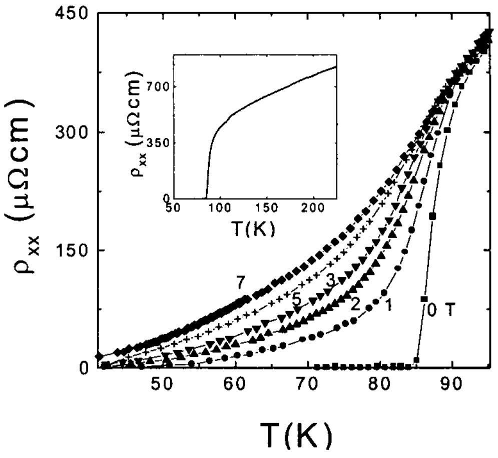

Fig. 6. Longitudinal resistivity for the $Bi_2Sr_2CaCu_2O_8$ single crystal at H = 0, 1, 2, 3, 5, and 7 T. The magnetic field was applied parallel to the c-axis of the sample. The inset shows a normal state resistivity curve in H = 0.

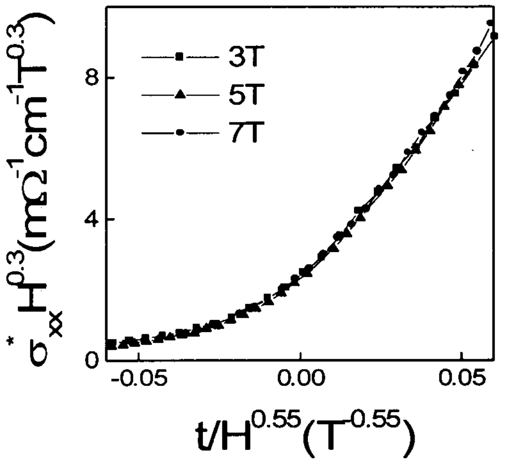

Fig. 7. 3D-XY scaling for the fluctuation conductivity: $\sigma^*_{xx} \sim H^{-(2+z-d)/2} F(t/H^{1/2\nu})$ where dynamic critical exponent z = 1.6, static critical exponent $\nu = 0.909 \pm 0.1$, dimension d = 3, F is a scaling function, $t \equiv 1 - T/T_{c0}$, and T_{c0} (= 84 K) is zero resistance temperature at zero field.

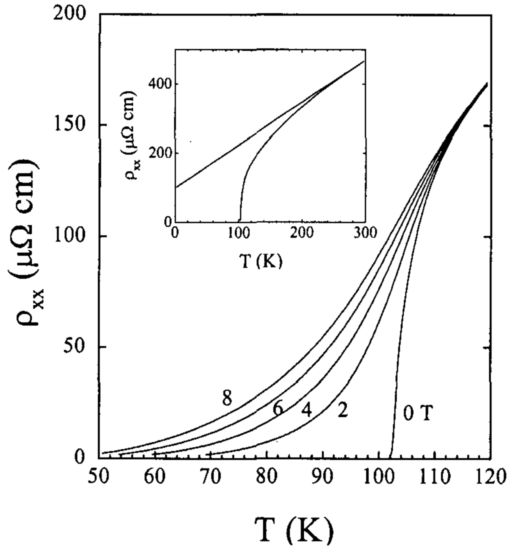

Fig. 8. Longitudinal resistivity $\rho_{xx}(T, H)$ for the Tl$_2$Ba$_2$CaCu$_2$O$_8$ film at H = 0, 2, 4, 6, and 8 T. The magnetic field was applied parallel to the c-axis of the sample. The inset shows a normal state resistivity curve in H = 0. The straight line is the background resistivity. (From Ref. 21)

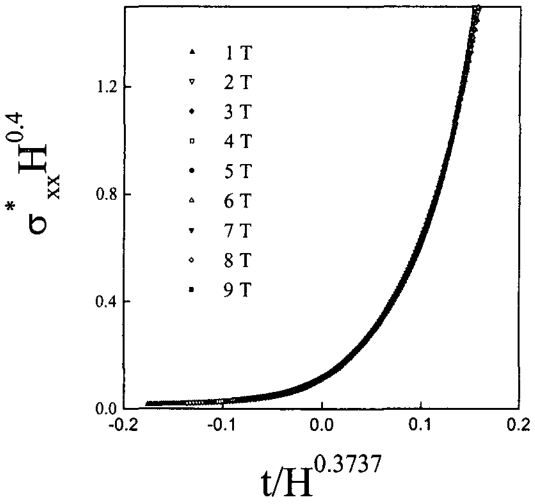

Fig. 9. $\sigma^*_{xx}H^{0.4}$ vs $t/H^{0.3737}$ for the Tl$_2$Ba$_2$CaCu$_2$O$_8$ film. $t \equiv 1 - T/T_{c0}$ and T_{c0} is a zero resistance temperature of 102 K. The units of σ^*_{xx} and H are respectively $\mu\Omega^{-1}$ cm^{-1} and Tesla. The σ^*_{xx} is extracted by the linear-with-T resistivity fitting. The dynamic critical exponent z is 1.8 ± 0.1 which is the same value as for YBCO film. However, the static critical exponent ν of 1.338 is two times larger than for YBCO.

background subtraction of a linear-in-T resistivity from $\rho_{xx}(T, H)$ above 130 K.

The fluctuation part of the conductivity, $\sigma^*_{xx}(T, H)$, shown in Fig. 7 exhibits 3D-XY scaling behavior near T_{c0}: $\sigma^* \sim H^{-(2+z-d)/2} F(t/H^{1/2\nu})$. The critical temperature region is about the same as for the magnetization in Fig. 5. The fluctuation conductivity at low fields (H = 1, 2 T), that are not shown in Fig. 7, slightly deviates from the scaling curve as in references [12,13,21], indicating that the crystal has some pinning centers. From the 3D-XY scaling for high fields, dynamic critical exponent z = 1.6 ± 0.1 and static critical exponent $\nu \approx 0.909 \pm 0.1$ are obtained. As in fluctuation magnetization, the static critical exponent ν is larger than that of YBCO, whereas the dynamic critical exponent z is almost the same as in YBCO. This result indicates that as temperature reaches T_c, the coherence length $\xi(T)$ in Bi-2212 increases faster than for YBCO. The universality class determined by the dynamical critical exponent is similar to the one of superfluid ^{4}He for YBCO film.

If a dimension for Bi-2212 is chosen to be 2, a Kosterlitz-Thouless transition should be associated. However, it has been unknown whether or not a high T_c system is exactly 2-dimensional. With d = 2, the value of z is 0.6 which leads the fluctuation dynamics in Bi-2212 to a universality class completely different from that of YBCO. As long as weak coupling exists along c-axis, fluctuation dynamics should obey 3D-XY model.

C) Tl$_2$Ba$_2$CaCu$_2$O$_8$ film

Similarly Tl-2212 system has a larger anisotropy than YBCO and the distance between CuO$_2$ blocks is 14.7 Å. This superconductor has been considered as one of the most anisotropic superconductors like Bi-2212. The Tl-2212 epitaxial film used in this study was prepared at Superconductor Technologies Inc. [17], which was 500 nm thick. The sample was grown by excimer laser ablation with a post-deposition anneal on substrate of $LaAlO_3$. Film waspatterned using standard photolithography for resistivity measurement.

Fig. 8 shows the longitudinal resistivity $\rho_{xx}(T, H)$ of Tl-2212 film for 0 – 9 T field parallel to the c-axis. Zero resistance temperature at zero magnetic field ($\equiv T_{c0}$) is 102 K. The resistive transition temperature (10 to 90 %) is about 3 K. The inset of Fig. 8 shows that zero field resistivity is linear for $T > 220$ K. The resistivity curve extrapolates to non-zero value at zero temperature, indicating that some random disorders exist. Note that the random disorder has been reported to be irrelevant on static critical behavior [22,23]. The zero resistance temperature is very much decreased upon applying magnetic field, compared with that of YBCO. All of the resistivity data used for studying fluctuation conductivity were taken above the resistive transition temperature at each magnetic field value and shouldbe Ohmic behavior.

A linear resistivity fit for Tl-2212 film is used for the background resistivity above 220 K. Since the resistivity of the sample was curved below 220 K, a linear resistivity fit over $220 \leq T \leq 300$ K was chosen. Note that a polynomial fit $a + bT + cT^2$ or a linear fit near transition temperature display qualitatively the same scaling behavior of fluctuation conductivity as for the linear-with-T resistivity fit above 220 K [12].

The fluctuation conductivity of Tl-2212 film obeys 3D-XY scaling behavior shown in Fig. 9 ; $\sigma^* \sim H^{-(2+z-d)/2} F(t/H^{1/2\nu})$ where dynamic critical exponent $z = 1.8 \pm 0.1$, static critical exponent $\nu = 1.338$, dimension $d = 3$, F is a scaling function, and $t \equiv 1 - T/T_{c0}$. Surprisingly the static critical exponent ν is two times larger than for YBCO, whereas the dynamic critical exponent z is almost the same as for YBCO, indicating that coherence length ratio $\xi(T)/\xi(0)$ in Tl-2212 increases faster as temperature reaches T_c and the universality class determined by the dynamical critical exponent is similar to one for YBCO film. For a note, in YBCO film, the pinning due to the inherent random disorder increases the dynamic critical exponent z to 1.86 ± 0.1 from the value of 1.5 that is for YBCO single crystal [12, 13]. The value of the static critical exponent ν, however, is not changed by the inherent disorder in YBCO film [13].

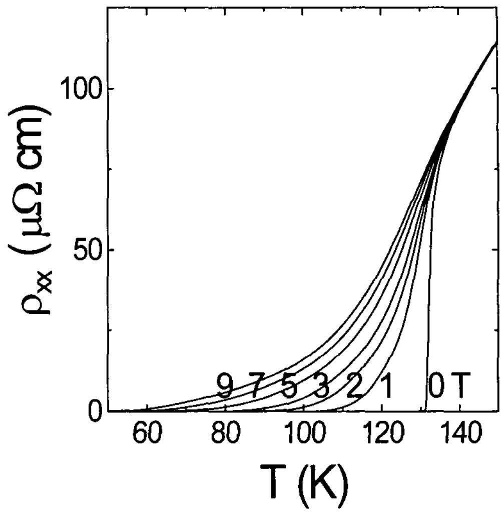

Fig. 10. Longitudinal resistivity $\rho_{xx}(T, H)$ for the $HgBa_2Ca_2Cu_3O_8$ film at H = 0, 1, 2, 3, 5, 7, and 9 T.

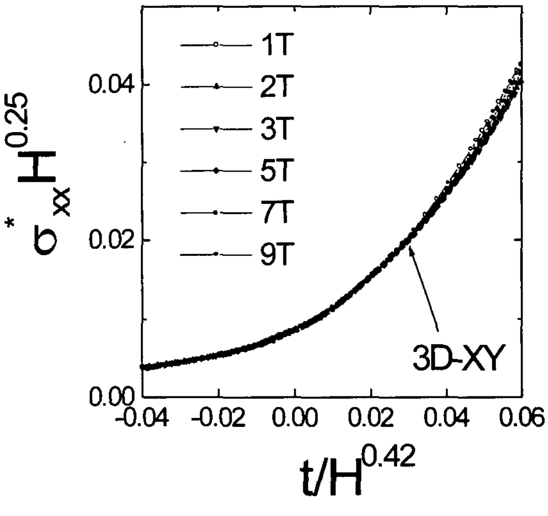

Fig. 11. $\sigma^*_{xx} H^{0.25}$ vs $t/H^{0.42}$ for the $HgBa_2Ca_2Cu_3O_8$ film. $t \equiv 1 - T/T_{c0}$ and T_{c0} is a zero resistance temperature of 131 K. The units of σ^*_{xx} and H are respectively $\mu\Omega^{-1}\,cm^{-1}$ and Tesla. The σ^*_{xx} is extracted by the linear-with-T resistivity fitting. The temperature below which 3D-XY scaling starts to break is marked by arrow. From 3D-XY scaling, dynamic critical exponent $z = 1.5 \pm 0.1$ and static critical exponent $\nu \approx 1.19 \pm 0.1$ are obtained.

D) $HgBa_2Ca_2Cu_3O_8$ film

An interesting approach to understand how the critical dynamics evolves with c-axis distance in high T_c superconductor is to study the critical fluctuation of Hg-system with increasing number of CuO_2 layers. The fluctuation conductivity data of Hg-1212 and Hg-1234 are being analyzed and will be reported soon. In this report, Hg-1223 will be discussed. The Hg-1223 is more anisotropic along c-axis than YBCO. It has a block of 3 CuO_2 layers in one unit cell. The distance between the blocks is 15.8 Å.

The in-plane longitudinal resistivities $\rho_{xx}(T, H)$ of Hg-1223 film have been measured as a function of magnetic field H ($0 \leq H \leq 9$ T) and temperature T near T_c. The fabrication process of Hg-1223 film is described in Ref. 16. Fig. 10 shows the longitudinal resistivity $\rho_{xx}(T, H)$ at several values of applied magnetic field with H parallel to the c-axis. Zero resistance temperature at zero magnetic field ($\equiv T_{c0}$) is observed at 131 K. The zero resistance temperature is much decreased upon applying a magnetic field, in contrast with that of YBCO, but in a similar fashion with Bi-2212 and Tl-2212. The field dependence of both $\rho_{xx}(T, H)$ and zero resistance temperature explains that compared with YBCO, in $HgBa_2Ca_2Cu_3O_8$ pancake vortices move more freely and an interlayer coupling strength between vortices is weaker.

Fig. 11 displays that the extracted fluctuation part of the conductivity $\sigma_{xx}(T, H)$ from the resistivity data exhibits 3D-XY scaling behavior near T_{c0}. The temperature below which 3D-XY scaling starts to break down is marked by an arrow. From 3D-XY scaling, dynamic critical exponent $z = 1.5 \pm 0.1$ and static critical exponent $\nu \approx 1.19 \pm 0.1$ are obtained.

From comparison with YBCO the weak interlayer coupling results in increasing ν, however, does not change the university class of superfluid ^{4}He. The interlayer coupling in Hg-1223 significantly influences the static critical exponent ν and does not change the dynamical critical exponent z, which is consistent with the previous findings for Bi-2212 and Tl-2212. Theoretical calculation will be needed to account for how the anisotropic coupling affects critical dynamics.

III. Conclusion

In summary, the fluctuation in conductivity or magnetization of YBCO, Bi-2212, Tl-2212, and Hg-1223 obeys 3D-XY scaling, even though the high T_c superconductors have different crystal structures and physical properties. The static critical exponent ν for coherence length ξ(T) increases with increasing the distance between CuO_2 blocks in the superconductors. As long as even weak coupling exists along c-axis, fluctuation dynamics should be governed by 3D-XY model; the static critical exponent depends only on the coupling strength. The fast drop of zero resistance temperature upon increasing magnetic field implies that the larger anisotropy along c-axis allows vortices to move more freely, which may cause growing the effective size of vortex near diamagnetic critical temperature. This explains that the value of ν is increased due to the anisotropy. However, the dynamic critical exponent z in Bi-2212, Tl-2212, and Hg-1223 is not severely influenced by the weak interlayer coupling, supporting that the universality class of superfluid ^{4}He is not altered by interlayer coupling strength.

Acknowledgments

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