Vortex fluctuations and two-dimensional Coulomb-gas scaling for crystalline $YBa_2Cu_3O_{7-x}/PrBa_2Cu_3O_{7-x}$ superlattices

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An analysis of resistance data for crystalline $YBa_2Cu_3O_{7-x}/PrBa_2Cu_3O_{7-x}$ superlattices that reveals a new fine structure is presented. This fine structure, which is directly related to the two-dimensional (2D) to three-dimensional crossover close to T_c, gives a measure of the effective anisotropy of the various superlattices. The data is remarkably well explained by the 2D Ginzburg-Landau Coulomb-gas model and the fine structure can be attributed to the coupling between the superconducting $YBa_2Cu_3O_{7-x}$ layers

The high-T_c superconducting materials can be thought of as consisting of superconducting parallel planes associated with the CuO_2 planes in the material. A large anisotropy between the directions parallel and perpendicular to the planes indicate that these superconducting planes are weakly coupled. Quasi-two-dimensional (2D) effects are expected to show up in the experiments provided the interplane coupling is small enough. The resistance for 2D superconductors is close to the transition dominated by thermally created vortices and vortex-antivortex unbinding.[1–3] Consequently effects related to vortex unbinding may also be expected to show up in the high-T_c materials provided the anisotropy is large enough. Several claims of observing such vortex unbinding effects in high-T_c materials have recently been made.[4,5] In particular it has been shown that the resistance data from Ref. 5 for a $Bi_2Sr_2CaCu_2O_8$ crystal closely obeys the same resistance scaling function as the ideal 2D superconductors.[6] This suggests that the superconducting planes for this particular material are effectively decoupled above the critical temperature T_c. The possibility of such an effective decoupling above T_c has recently been established through Monte Carlo simulations on the level of a 3D anistropic XY model.[7]

The effect of the coupling between superconducting planes can be systematically studied in the recently epitaxially grown $YBa_2Cu_3O_{7-x}/PrBa_2Cu_3O_{7-x}$ superlattices.[8,9] The resistance data analyzed in the present paper are for superlattices consisting of alternating layers of N_Y unit-cell-thick layers of $YBa_2Cu_3O_{7-x}$(YBCO) alternating with N_P unit-cell-thick layers of $PrBa_2Cu_3O_{7-x}$(PBCO) (see Ref. 8 for details on experiments and samples). For fixed N_P the interplane coupling increases with increasing N_Y since the anisotropy decreases. Likewise, for fixed N_Y the interplane coupling decreases with increasing N_P. The experimental data for these materials have already generated lively discussions and several tentative explanations have been proposed.[10–14]

A major object with this Brief Report is to demonstrate that more information can be extracted from an analysis based on a phenomenological description of vortex fluctuations. This additional information is directly related to the interplane coupling. It thus adds to the understanding of these materials and may provide possible ways of distinguishing between various models, based on more microscopic considerations, which have been proposed as explanations for some aspects of the data.[11–14]

The method we use to analyze the data is based on the 2D Coulomb-gas scaling concept and the Ginzburg-Landau Coulomb-gas model.[1] The Ginzburg-Landau Coulomb-gas description of vortex fluctuations for 2D superconductors leads to the existence of an effective temperature scaling variable X.[15,1] This means that the resistance ratio R/R_N, where R is the flux flow resistance caused by vortices and R_N is the normal state resistance, is a universal function of X.[15] In other words the resistance data R/R_N for all realizations of a 2D superconductor which are well described by the Ginzburg-Landau Coulomb-gas model should fall on a single curve when plotted versus the scaling variable X.[1] The functional form of this scaling curve has been well established from data for type-II superconducting films in the interval $-14 < \ln(R/R_N) < -1.5$. Furthermore the established functional form has been tied directly to the Ginzburg-Landau Coulomb-gas model through extensive Monte Carlo simulations.[16] We want to stress very strongly that the functional form of this scaling curve, within the region for which it has been established, describes *non-critical* properties of vortex fluctuations. It does *not* reflect any critical phase transition properties; the scaling curve relates to a region outside the critical region for the Kosterlitz-Thouless transition.[1,17] The scaling variable X is given by $X = [T/n^{2D}(T)]/[T_{KT}/n^{2D}(T_{KT})]$ where n^{2D} is the (areal) density of superconducting electrons for the 2D superconductors unrenormalized with respect to vortex fluctuations and T_{KT} is the Kosterlitz-Thouless temperature.[1] We assume that a standard Ginzburg-Landau description applies to the temperature variation of n^{2D} in the absence of vortex fluctuations, i.e., $n^{2D}(T) \propto T_{c0} - T$ where T_{c0} is the Ginzburg-Landau temperature. This phenomenological assumption has turned out to be a good approximation for type-II superconducting films.[1] We conclude from our analysis below that it is a very good approximation also for YBCO films. T_{KT} and T_{c0} are used as two fitting parameters in our analysis and X reduces to

$$X = \frac{T}{T_{c0} - T} \frac{T_{c0} - T_{KT}}{T_{KT}}. \quad (1)$$

For 2D superconductors the significance of these two parameters are the following: T_{c0} is the temperature where the phase transition would have been if the superconductor was well described by a phenomenological Ginzburg-Landau theory and if there were no vortex fluctuations. T_{KT} is the temperature where a phase transition caused by the vortex fluctuations takes place.[18,1] For the layered materials the interpretation is somewhat modified. These materials have a 3D phase transition caused by the interplane coupling at a critical temperature T_c below which there is true long-range order. Thus we will characterize YBCO/PBCO superlattices in terms of three temperatures $T_{KT} < T_c < T_{c0}$ where T_{c0} is the Ginzburg-Landau temperature relating to the temperature dependence of n^{2D}, T_c is the critical temperature for the 3D phase transition caused by the interplane coupling, and T_{KT} is the temperature where the vortex fluctuations would have caused a Kosterlitz-Thouless transition to take place in the absence of the interplane coupling.

The actual procedure of analyzing the data is very simple.[19] We start from the $R(T)$ data for a given sample. The normal state resistance R_N is extracted from the nearly T-independent part of the data somewhat above the transition. To be definite we have used $R_N = R(T = 100$ K) for all the samples analyzed. Thus for a given sample we have $R(T)/R_N$ and want to know to what extent the data is described by the known 2D scaling function $R(X)/R_N$. The data falls on the scaling curve provided $R(T)/R_N = R(X)/R_N$ and this condition gives a corresponding function $X(T)$ for each sample. Now if the description applies then $T/X(T) \propto T_{c0} - T$ [compare Eq. (1)]. In Fig. 1 we have illustrated this procedure for the four samples $(N_Y, N_P) = (1,16)$, $(2,16)$, $(3,16)$, and $(3,4)$. As seen in Fig. 1, the data fall on straight lines for each sample to a very good approximation. The straight lines in Fig. 1 are least squares fits to the linear part of the data. For the $(1,16)$ and the $(2,16)$ data this means all the measured data, whereas the data points for $(3,16)$ and $(3,4)$ at the very lowest temperatures deviate from the linear part and are exluded from the least-squares fits. From the fitted straight lines we get the corresponding values of T_{c0} and T_{KT}. In Fig. 2 we have plotted the R/R_N data versus the scaling variable X obtained from Eq. (1) using the determined values of T_{c0} and T_{KT}. The solid drawn curve in Fig. 2 is the 2D resistance scaling function. As seen in Fig. 2 the data for $(1,16)$ and $(2,16)$ data falls on the 2D scaling curve to a remarkable degree, whereas the $(3,16)$ and $(3,4)$ data deviate slightly for lower resistances. We interpret the agreement between the data and the 2D scaling curve in Fig. 2 as strong evidence that the resistance close to the transition for these YBCO/PBCO superlattices is caused by quasi-2D vortex-fluctuations and, furthermore, that these vortex

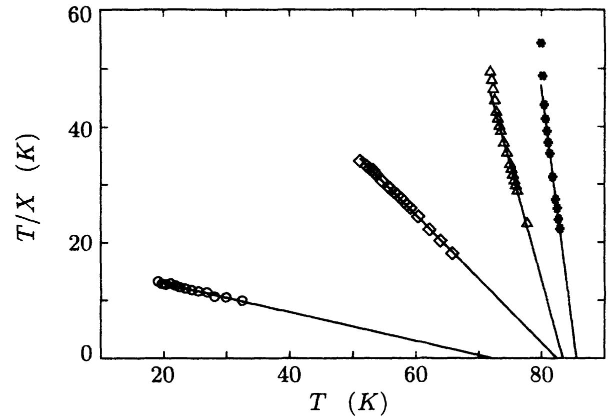

FIG. 1. YBCO/PBCO superlattice data plotted as T/X vs T. Circles, diamonds, triangles, and asterisks correspond to (N_Y, N_P) =(1, 16), (2, 16), (3, 16), and (3,4) superlattices, respectively. The straight lines are least-squares fits to the linear parts of the data and give the values of the parameters T_{c0} and T_{KT}. [(T_{c0}, T_{KT}) =(72.2, 14.3), (82.5, 43.2), (83.5, 66.6), (85.6, 76.4) (K) for (N_Y, N_P) =(1, 16), (2, 16), (3, 16), and (3, 4), respectively.]

fluctuations are very well described by the 2D Ginzburg-Landau Coulomb-gas model.

How is this at all possible given the existence of the interplane coupling between the YBCO layers? The answer we suggest is based on recent Monte Carlo simulations for the 3D anistropic XY model which can be taken as a simple model of coupled superconducting planes.[7] These simulations show that the vortex density per superconducting plane for a given small interplane coupling as a function of the scaling variable X collapses onto the same scaling curve as the 2D XY model immediately above T_c. At and below T_c the Monte Carlo simulations show that the interplane coupling takes over and the vortex density drops below the scaling curve for the 2D XY model—the more so the stronger the interplane coupling.[7]

Figure 3 is a blowup of Fig. 2 focusing on the deviations from the 2D resistance scaling curve. The order of

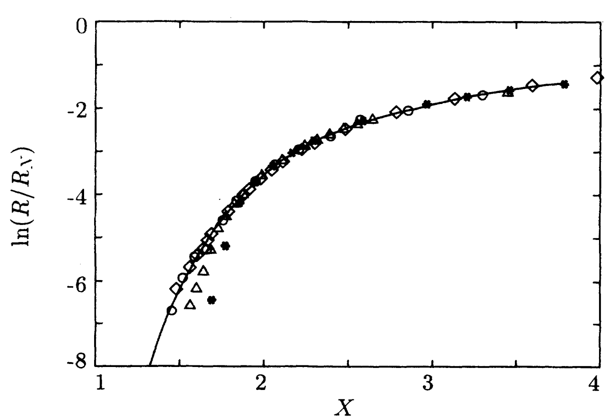

FIG. 2. Comparison between the YBCO/PBCO superlattice data and the 2D universal resistance function (solid curve in the figure). The data symbols are the same as in Fig. 1.

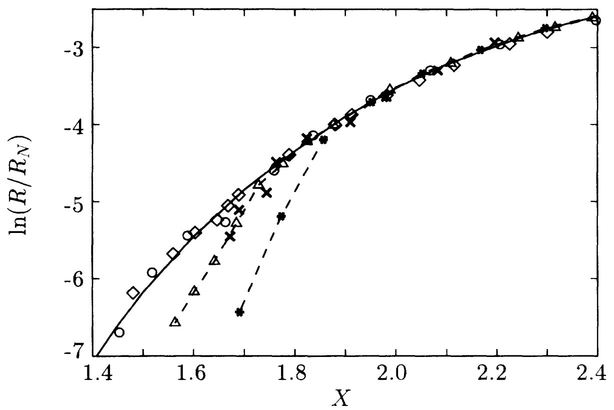

FIG. 3. Blowup of Fig. 2 showing the deviations from the 2D universal resistance function. Also shown is the data for a $Bi_2Sr_2CaCu_2O_8$ crystal (Ref. 5) (crosses in the figure).

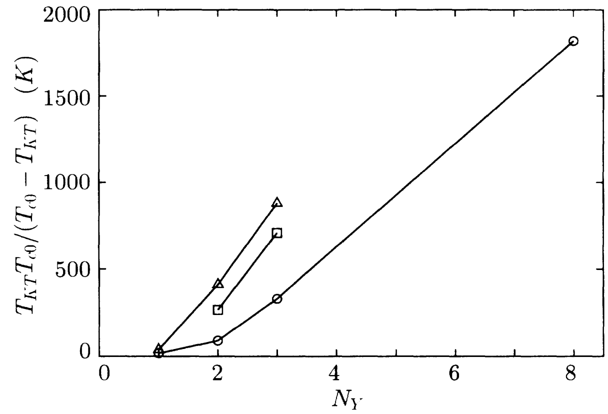

FIG. 4. The quantity $T_{KT}T_{c0}/[T_{c0} - T_{KT}]$ plotted vs the YBCO thickness N_Y for three different values of PBCO thickness N_P, i.e., $N_P = 16$ (circles), 4 (squares), and 2 (triangles). Solid lines are guides to the eye.

increasing coupling is (1,16), (2,16), (3,16), and (3,4); the first three corresponding to an increase in N_Y for constant N_P and the last to a decrease in N_P for constant N_Y. As seen in Fig. 3 the (1,16) and (2,16) data do not deviate from the 2D scaling curve over the range of data taken. This indicates a very weak interplane coupling. The (3,16) data on the other hand deviates and the (3,4) data even more, indicating a successive increase of the interplane coupling. This is perfectly consistent with the expectations from the Monte Carlo simulations.[7] All the (N_Y, N_P) superlattices we have been able to analyze in the same way confirm that the stronger the interplane coupling the larger the deviation from the 2D resistance scaling curve. Thus this analysis correlates the size of the effective interplane coupling with the deviation of the resistance data from the 2D scaling curve. We have illustrated this in Fig. 3 by analyzing the $Bi_2Sr_2CaCu_2O_8$-crystal data from Ref. 5 in the same way. As seen in Fig. 3 this suggests that a $Bi_2Sr_2CaCu_2O_8$ crystal has the same effective anisotropy as the (3,16) YBCO/PBCO superlattice (although better $Bi_2Sr_2CaCu_2O_8$ data would be needed to make this estimate firm). Or in other words the $Bi_2Sr_2CaCu_2O_8$ crystal is intrinsically as two dimensional as the (3,16) YBCO/PBCO superlattice.

Our analysis is completely consistent with a resistive behavior caused by free quasi-2D vortices. These vortices are produced by breaking thermally created vortex-antivortex pairs.[1] Below the critical temperature T_c the interplane coupling causes the effective vortex-antivortex interaction to be linear with separation for larger distances.[20] This means that there are no free vortices below T_c and hence no resistance. Above T_c the linear term in the effective vortex-antivortex interaction vanishes.[20] This means that free vortices are produced, since T_c is larger than T_{KT} and T_{KT} is the temperature at which the production of free vortices becomes possible *if* it were not prohibited by the linear term in the effective vortex-antivortex interaction.

Figure 4 displays information from our analysis of the YBCO/PBCO superlattices plotted as $T_{KT}T_{c0}/[T_{c0} - T_{KT}]$ versus N_Y for three different constant values of N_P, i.e., $N_P = 2$, 4, 16. The idea behind this figure is as follows. The criterion for T_{KT} is given by[1,18]

$$T_{KT} = \frac{\pi\hbar^2}{8k_B m^* \epsilon} n^{2D}(T_{KT}) \approx \frac{\pi\hbar^2}{8k_B m^* \epsilon} n^{2D}(0)(1 - T_{KT}/T_{c0}), \quad (2)$$

where m^* is the effective electron mass (for the direction parallel to the YBCO layer), k_B is the Boltzmann constant, and ϵ is the Columb-gas dielectric constant.[1] The value of ϵ has been determined to be $\epsilon \approx 1.65$ for the Ginzburg-Landau Coulomb gas.[1,16] Provided that N_Y is large enough so that the intrinsic properties of the material does not change by adding another unit-cell-layer material, then a change of the thickness, Δd, is directly related to the change in the areal superfluid density of the layer $\Delta n^{2D} = n^{3D}\Delta d$ where n^{3D} is the 3D superfluid density of the material. This density is related to λ, the London penetration depth (for the direction parallel to the YBCO layer), by

$$n^{3D} = \left(\frac{\phi_0}{2\pi}\right)^2 \frac{m^*}{\pi\hbar^2}\frac{1}{\lambda^2},$$

where ϕ_0 is the flux quantum. Consequently we expect that

$$\Delta\left(\frac{T_{KT}T_{c0}}{T_{c0} - T_{KT}}\right) = \frac{1}{8 \times 1.65 k_B}\left(\frac{\phi_0}{2\pi}\right)^2 \frac{1}{\lambda^2(0)}\Delta d.$$

Furthermore $\Delta d \approx 12\Delta N_Y$ Å for YBCO and putting everything together gives

$$\frac{T_{KT}T_{c0}}{T_{c0} - T_{KT}} = \text{const} + 7.1 \times 10^8 \frac{1}{\lambda^2(0)} N_Y \quad (3)$$

provided T is in units of K and λ in Å. Thus we expect that, for large enough N_Y, the data points in Fig. 4 should fall on straight lines and the slopes of these straight lines should give an estimate of $\lambda(0)$. By letting the straight lines be defined by the two last data points for each N_P sequence we obtain $\lambda(0) \approx 1540$, 1270, 1230 Å for $N_P = 16, 4, 2$, respectively. Furthermore a direct extrapolation of the slopes in Fig. 4 to $N_P = 0$ comes close to $\lambda(0) \approx 1200$ Å for the pure YBCO material. A typical value quoted in the literature for this value is $\lambda(0) = 1400$ Å.[21] The value we get is very close to this value considering the fact that it has been extracted by fitting the YBCO/PBCO superlattice data to the 2D resistance scaling function followed by an extrapolation to the 3D YBCO crystal. This success of the analysis is an additional argument in favor of our interpretation. Figure 4 also suggests that the condition $\Delta n^{2D} = n^{3D} \Delta d$ is reached to a good approximation already for $N_Y = 2$.

In short the present analysis suggests that YBCO/PBCO superlattices, on a phenomenological level, are very good realizations of coupled superconducting planes. The analysis supports the prediction[7] of an effective 3D to 2D decoupling of vortex fluctuations above T_c. The information on the interplane coupling, obtained from the phenomenological analysis, also may provide restrictions on possible microscopic mechanisms responsible for the interplane coupling. It further suggests that fundamental aspects of the layered structure can be systematically probed by investigating sequences of YBCO/PBCO superlattices and that these aspects will be of direct relevance for our understanding of high-T_c materials with large anisotropy.

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