# Recent Transport Studies of High Temperature Superconductivity at ISSP†

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Two topics from our recent transport studies on high $T_c$ materials are reported. Systematic studies of correlation between the pressure dependence of the Hall effect and that of $T_c$ have been undertaken in order to address to the question, whether the principal cause of the pressure dependence of $T_c$ is through a change in the carrier density. Dissipation in the mixed state of $YBa_2Cu_3O_{7-y}$ studied as a function of magnetic field angle with respect to the basal plane have revealed an anomalous peak at $\theta \sim 5^\circ$, which is attributed to depinning of the lateral segment of a staircase flux line out of the intrinsic pinning potential.

## I. PRESSURE DEPENDENCE OF $T_c$ AND HALL COEFFICIENT

Since the earliest days of high $T_c$ research, pressure has been recognized as one of the key parameters that strongly affect the transition temperatures of cuprate superconductors. Indeed, it was the finding of a large $T_c$ enhancement by pressure in the La 2-1-4 system which paved the road to the discovery of the Y 1-2-3 compound by Wu *et al.*[1] Since then, a number of new cuprate superconductors have been discovered, and pressure effect on $T_c$ has been investigated for most of the known systems. A cummulative plot of the pressure coefficient $d\ln T_c/dP$ against $T_c$ among hole-doped cuprate superconductors shows a general trend in a form of a bell-shaped curve.[2] Namely, $|d\ln T_c/dP|$ tends to be larger for lower $T_c$, and the sign of the pressure coefficient changes from positive to negative as one goes from the underdoped to the overdoped region.

It is expected that the pressure effect furnishes a key insight into the basic mechanism of high temperature superconductivity. In order to understand the pressure effect, it is crucial to sort out various routes through which pressure may affect the superconductivity, since pressure perturbs various parameters of a particular solid. One of the central issues to be clarified is whether or not the pressure induces any change in the carrier concentration. In this work, we focus upon the pressure dependence of the Hall coefficient in order. to gain insight into the possible pressure-induced change in the mobile carrier density. Earlier experiments on $YBa_2Cu_3O_7$[3] and $La_{2-x}Sr_xCuO_4$[4] did not detect appreciable changes of $R_H$ with pressure.

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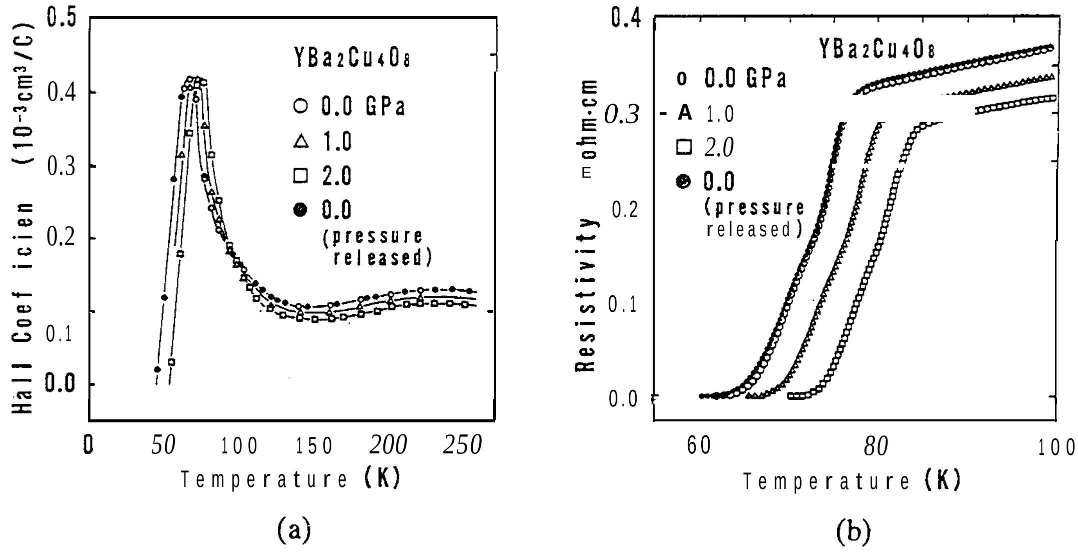



**FIG. 1. Temperature dependences of (a) the Hall coefficient at $H = 9$ T and (b) the resistivity at $H = 0$ in $YBa_2Cu_4O_8$. The two sets of ambient pressure data were taken before and after the pressure experiment.**

**Here, we present new** results on $YBa_2Cu_4O_8$, $YBa_2Cu_3O_7$, $Bi_2Sr_2CaCu_2O_8$ and $Tl_2Ba_2CuO_{6+y}$

Figure 1 shows the pressure-induced changes in the temperature dependences of Hall coefficient $R_H(T)$ and the resistivity $\rho(T)$ in $YBa_2Cu_4O_8$. This material is particularly stable against pressure cycling, as seen by the excellent agreement between the two sets of ambient pressure data taken before and after the pressure experiment. The resistive transition shows nearly parallel shift with pressure. The enhancement of $T_c$ amounts to $\sim 10$ K at 2 GPa. The pressure coefficient of $T_c$ is $d\ln T_c/dP \sim 4.6$ %/GPa for this sample. Values as large as 7 to 8 %/GPa are reported in literatures. The Hall coefficient decreases with pressure as $(d\ln R_H/dP) \sim -7.7$ %/GPa. The Hall coefficient is relatively temperature independent above $\sim 120$ K but shows an abrupt increase below this temperature. This anomalous increase of $R_H$ near $T_c$ is shifted to higher temperatures upon application of pressure in the same way as $T_c$ is shifted. The absolute value of the resistivity also decreases with pressure by $d\ln\rho/dP \sim -6$ %/GPa.

Table I summarizes $T_c$, $R_H$, and their pressure coefficients for the presently investigated materials, $YBa_2Cu_4O_8$, $YBa_2Cu_3O_7$, $Bi_2Sr_2CaCu_2O_8$ and $Tl_2Ba_2CuO_{6+y}$. The data for $La_{2-x}Sr_xCuO_4$ taken from our earlier work[4] are also listed for comparison.

We first look at general trends of the correlation between the pressure-induced changes in $R_H$ and $T_c$ with the relation between the doping and $T_c$, and then discuss specific issues on individual materials afterwards. In order to grasp the overall features of the pressure effect, we naively suppose for the moment that the value of $1/eR_H$ reflects the mobile hole density in the

TABLE I. Summary of $T_c$, the Hall coefficient, and their pressure coefficients for the superconducting cuprates. The nominal hole density per Cu atom, $n_h$, is calculated from the value of $1/eR_H$.

| | $T_c$ (K) | d $\ln T_c$/dP (%/GPa) | $R_H$ ($10^{-3}$cm$^3$/C) (T =250 K) | d $\ln R_H$/dP (%/GPa) | d $\ln T_c$ / d $\ln R_H$ | $V_o/eR_H$ | $n_h$ |
|---|---|---|---|---|---|---|---|
| $YBa_2Cu_4O_8$ | 72.9 | 4.6 | 0.13 | -7.7 | -0.60 | 9.7 | 2.4 |
| $YBa_2Cu_3O_7$ | 91.4 | 0.72 | 0.69 | -9.0 | -0.080 | 1.6 | 0.52 |
| $Bi_2Sr_2CaCu_2O_{8+y}$ | 84.9 | -0.91 | 1.41 | -10.8 | 0.084 | 2.0 | 1.0 |
| $Tl_2Ba_2CuO_{6+y}$ | 47.0 | -9.3 | 1.43 | -8.6 | 1.1 | 0.76 | 0.76 |
| $La_{1.92}Sr_{0.08}CuO_4$ | 22.4 | 13.8 | 7.20 | < 1 | | 0.08 | 0.08 |
| $La_{1.88}Sr_{0.12}CuO_4$ | 31.0 | 9.1 | 2.86 | < 1 | | 0.21 | 0.21 |
| $La_{1.84}Sr_{0.16}CuO_4$ | 38.0 | 5.5 | 0.83 | < 1 | | 0.71 | 0.71 |
| $La_{1.80}Sr_{0.20}CuO_4$ | 32.6 | 5.6 | 0.54 | < 1 | | 1.1 | 1.1 |
| $La_{0.76}Sr_{0.24}CuO_4$ | 19.3 | 10.2 | 0.18 | < 1 | | 3.3 | 3.3 |

$CuO_2$ plane, being fully aware that the actuall situation is more complex, as we discuss later on. From Table I, we can see that the behavior of the $La_{2-x}Sr_xCuO_4$ system is different from others in that $R_H$ does not change with pressure and that $T_c$ increases with pressure both in the underdoped and overdoped regions. In all other cuprate presetly studied, the Hall coefficient decreases with pressure at a rate ~ 8-10 %/GPa. In the present naive interpretation, this means that the mobile hole density increases by ~ 8-10 %/GPa. The pressure coefficient of $T_c$ takes a large positive value for $YBa_2Cu_4O_8$, which we think to be in the underdoped region, although this point is still controversial. It is small for $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$, which are close to the optimum doping. And it is negative and large for $Tl_2Ba_2CuO_{6+y}$, which is in the overdoped region.

The pressure effects in these systems can be summarized as follows:

(1) Pressure makes the mobile hole density increase.

(2) This in turn gives rise to a change in $T_c$, depending on the location of the particular system on the $n_h$-*versus*-$T_c$ *curve* (sketched in Fig. 2-(a)).

Thus, in this most naive level of interpretation for the Hall effect, the pressure dependence of $T_c$ may be reduced to the carrier density dependence of $T_c$. However, this kind of interpretation is at best provisional. Indeed, when we try to construct a more coherent picture of the Hall effect, we run into some difficulties. The major difficulties stem from the wide variation of the Hall coefficient among the cuprates both in its magnitude and temperature dependence.' Fig. 3 is a plot of $T_c$ *vs.* $R_H$ for these cuprate superconductors. The arrows indicate the direction to which the system moves with pressure.

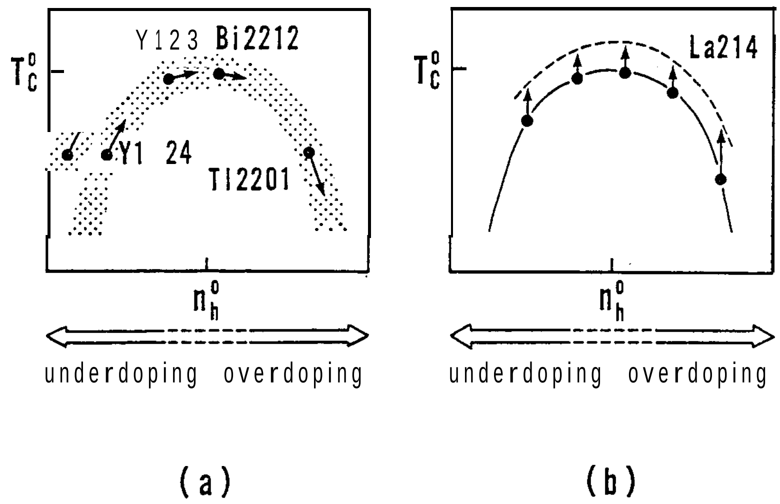



FIG. 2. Simplified sketch of the effect of pressure on $T_c$ for the superconducting cuprates. The left panel (a) illustrates the behavior of the four compounds investigated in the present work. The right panel (b) shows the behavior of the $La_{2-x}Sr_xCuO_4$ system.

As seen in the figure, the values Of $R_H$ for $YBa_2Cu_4O_8$ and $YBa_2Cu_3O_7$, for example, differ by a factor of ~ 5. It is obviously unrealistic to consider that the values of $1/eR_H$ *in* both cases give the actual hole densities. Strictly speaking, an exact correspondence between $1/eR_H$ and the carrier density is only assured for an exceptionally simple case of a single parabolic band. When the Fermi surface possesses complex curvatures, the overall $R_H$ is to be determined by integrating contributions from different parts of the Fermi surface. Such situation is often approximated by a multi-carrier model, in which $R_H$ is determined by a delicate balance among contributions from more than one type of carrier pockets. If one stands on such multi-carrier models, whether the observed change of $R_H$ should be considered large or small depends on the degree of compensation. If the observed $R_H$ is actually an outcome of an almost perfect compensation among different types of carriers, the change of $R_H$ by only ~ 10 % may rather be regarded as minimal. However, it is quite unlikely that such an accidental cancellation actually occurs in all these cuprates. If the observed $R_H$ *is* dominated by one type of the carriers, we can still regard the $1/eR_H$ as a measure of the majority carrier and use it to extract at least qualitative trends of carrier density change.

Shown also in Fig. 3 is a set of data for $Tl_2Ba_2CuO_{6+y}$ with different oxygen contents.[6] The effect of applying pressure is found to be qualitatively similar to the effect of increasing the oxygen content. Namely, in both cases, the system moves toward the normal metallic phase as signaled by a decrease of $T_c$ and a decrease of $R_H$. The relation between the change in $R_H$ and the change in $T_c$ is found to bed $\ln T_c/d \ln R_H \sim 5.2$ (for $T_c \sim 50$ K) in the case of oxygen content control.[6] In the present case of pressure experiment, the corresponding value is $d \ln T_c/d \ln R_H$

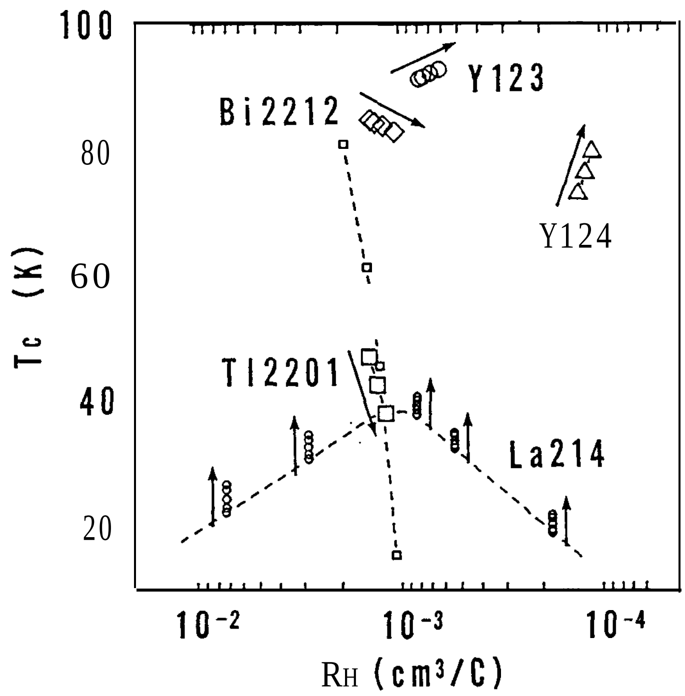



**FIG. 3. Plot of $T_c$ against the Hall coeffcient, $R_H$, and their changes with pressure. Note that $R_H$ decreases toward the right, so that the nominal hole density increases to the right. Each arrow indicates the direction to which the system moves with increasing pressure. The small squares for the $Tl_2Ba_2CuO_{6+y}$ system are the data taken from Ref. 6, corresponding to the change with the oxygen stoichiometry.**

~ 1.1. The difference indicates, not surprisingly, that the hole density is not the only controlling parameter for $T_c$.

As has become clear by our present and earlier[4] studies, the pressure effect in the $La_{2-x}Sr_xCuO_4$ system appears to be different from other cuprate systems, as sketched in Fig. 2-(b). Of particular interest is the fact that $T_c$ increases with pressure for the whole range of strontium content $x$. While the pressure coefficient of $T_c$ is small in $YBa_2Cu_3O_7$ at the optimum doping, it is considerably large in $La_{1.85}Sr_{0.15}CuO_4$. Even more intriguing is the comparison between the $La_{2-x}Sr_xCuO_4$ ($x > 0.15$) system and the $Tl_2Ba_2CuO_{6+y}$ system, which are considered as two prototypes of the overdoped cuprate superconductors, but the pressure effect on $T_c$ is opposite. One possible interpretation is that the pressure effect other than the charge redistribution always act to enhance $T_c$, and that the reduction of $T_c$ in the $Tl_2Ba_2CuO_{6+y}$ system is because the effect of hole density increase wins over other pressure effects.

## II. DISSPATION IN THE MIXED STATE

**Dissipation in** the mixed state of a type II superconductor arises from motion of flux lines, which is determined by competition between driving force and pinning force acting on them. The flux pinning is usually governed by various types of defects either inevitably present or intentionally introduced. When the flux lines are parallel to-the basal plane of a highly anisotropic layered superconductor, an intrinsic pinning potential originating from the layered structure may gain importance.' The driving force acting on flux lines comes from the Lorentz force $J$ x $B$ in the case of tranport experiments. The competition between the driving force and the pinning force depends on many parameters, including magnetic field, tranport current density, their directions with respect to the crystal axes, their mutual orientation, and temperature. In what follows, we present our recent experimental results with particular emphases on angular dependences. The behavior of $YBa_2Cu_3O_{7-y}$ (YBCO) and $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) are compared.

Difference in the magnitude of anisotropy between YBCO and BSCCO is manifest in the anglar dependence of resistivity as the direction of a magnetic field of fixed intensity is swept from the *ab*-plane ($\theta = 0°$) to the c-axis ($\theta$ = 90 "). Fig. 4 shows such traces for BSCCO, which shows a sharp cusp at $\theta = 0°$.[8] In fact, BSCCO comes very close to the two-dimensional limit. A flux line piercing through a layered superconductor with very weak interlayer coupling may be viewed as a stack of two-dimensional (2D) vortex discs (pacakes)? In the two-dimensional limit, pancake vortices in adjacent layers are completely decoupled, so that the only scaling parameter is the area1 density of pancakes in each layer, which is given the normal compoent of the magnetic field $H \sin \theta$. The inset of Fig. 4 is a replot of the data in the main panel with the abscissa scaled by the normal component of the applied field. It is seen that such s scaling makes all the data merge into a single curve in this linear plot. This demonstrates that the the two-dimensional limit model works quite well in the linear scale. Namely, the parallel field component contributes very little to the dissipation. It should be added, however, that if one looks more closely at the behavior in the immediate vicinity of $\theta$ = 0" in a logarithmic scale, one decerns deviation from the two-dimensional model." The anisotropy of YBCO, on the other hand, can be fitted reasonably well to the anisotropic Ginzburg-Landau model. The anisotropy ratio of the coherence lengths, which is related with the effctive mass anisotropy, is $(\xi_a/\xi_c) = (m_c/m_a)^{1/2} \approx 5$ for a fully oxygenated YBCO."

The transport behavior at elevated current densities is drastically different from that in the low current density limit. Fig. 5 shows examples of the $\theta$ dependence of resistivity in YBCO at high current densities.[12] The traces are quite different in shape from those for low current densities. A local minimum at $\theta$ = 90" is due to enhanced pinning when the flux lines are aligned with the twin planes. A pronounced peak at $\sim 5°$ emerges at higher current densities.[12] This effect is most distinct when the e-rotation axis is chosen parallel to the current direction, i.e.

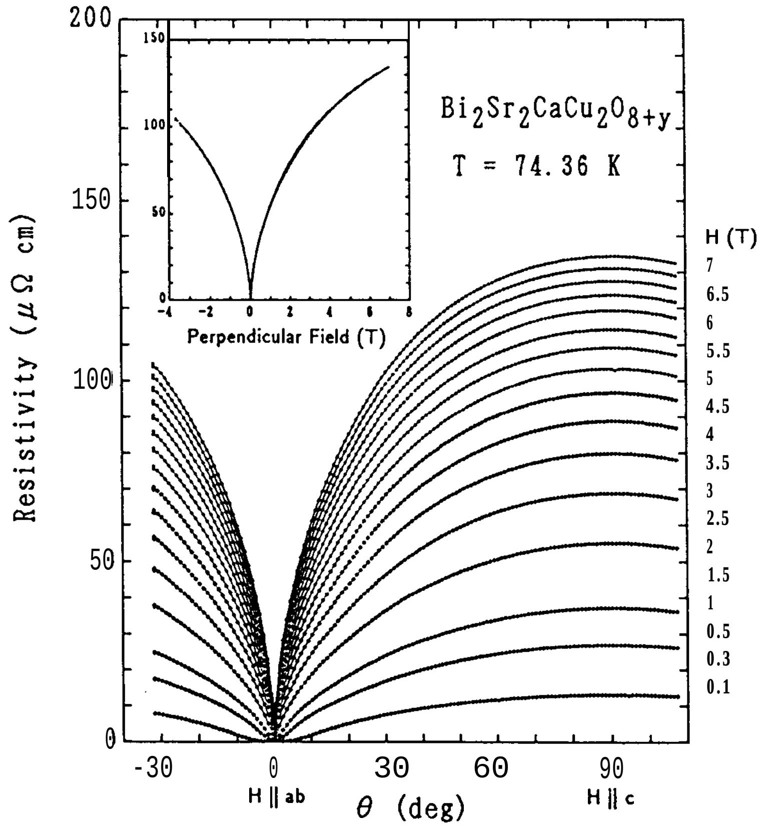



FIG. 4. **Angular dependence of resistivity in $Bi_2Sr_2CaCu_2O_{8+y}$ The inset shows a replot of the same data as a function of the normal component of the magnetic field.**

transverse magnetoresistance geometry, (Fig. 5-(a)). When the field is rotated within the plane containing the c-axis and the current direction, the angular dependence is rather featureless even at higher current densities (Fig. 5-(b)). In both cases, the temperature dependence shows the activated behavior. The angular dependences of the activation energy extracted from these data for the two e-rotation modes are plotted in the inset of Fig. 6. The dip of the activation energy at around 5 " corresponds to the anomalous enhancement of dissipation seen in Fig. 5. A similar effect is also observed in BSCCO as shown in Fig. 7.[10] It is noted that the characteristic angle is as small as $\theta \sim 0.1$ " for BSCCO.

Before discussing its physical origin, we summarize the salient features of the anomalous dissipation peak: (i) The characteristic angle for the maximum enhancement is typically $\theta \sim 5$ for YBCO and $\theta \sim 0.1$ " for BSCCO. (ii) The enhancement is most clearly observed in the transverse magnetoresistance geometry for YBCO, indicating that the effect is caused by macroscopic Lorentz force. (iii) The characteristic angle appears to be independent of temperature, and only weakly dependent on current density. (iv) The peak position shifts towards higher

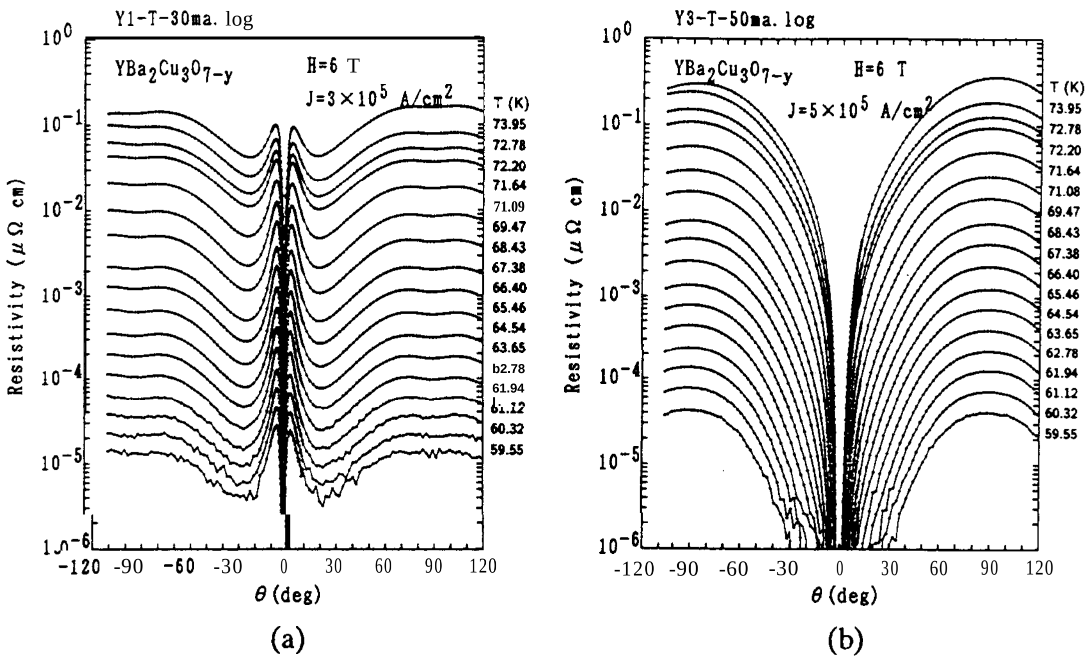



**FIG. 5. Angular dependence of resistivity in $YBa_2Cu_3O_{7-y}$ at a high current density for different temperatures. In (a), the field is rotated in a plane perpendicular to the current direction (transverse magnetoresistance configuration). In (b), the field is rotated in a plane containing the c-axis and the current direction.**

angles with decreasing field strength.

**As stated** earlier, a flux line piercing through a layered superconductor may be viewed as being composed of 2D vortices (pancakes) localized in individual layers and lateral segments (strings) in the interlayer spacings which connect the pancakes. As $\theta$ is decreased, the pancakes in adjacent layers become laterally separated, *i.e* the length of the strings increases, and the density of the pancakes decreases. In order to simplify the argument, we assume that the contributions to dissipation from the motion of the pancakes and from the motion of the strings can be treated separately to a first approximation. This assumption obviously becomes invalid for larger $\theta$, but is convenient in considering the situation at small $\theta$. With the transport current in the basal plane, the pancakes are always subject to the Lorentz force irrespective of the relative direction of $J$ and macroscopic H. Therefore, this part of dissipation is more or less the same for the two modes of &rotation corresponding to Figs. S-(a) and (b). By contrast, the Lorentz force on the strings depends on the angle between $J$ and $H$ in the usual way. The main pinning mechanism for the strings is the intrinsic pinning. On the other hand, the pancakes are pinned by twin boundaries and by point defects.

At the low current densities the vertical motion of the strings is prohibited by strong in-

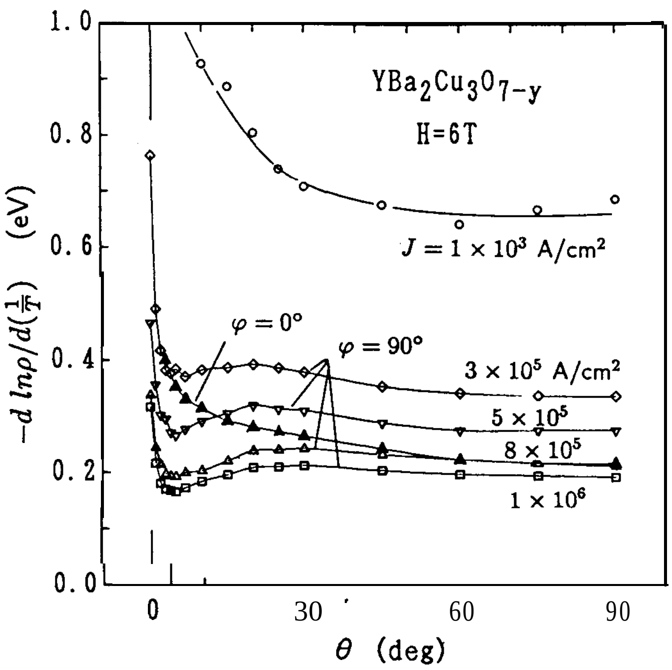



FIG. 6. The activation energy (slope of the Arrhenius plot of resistivity) for different current densities. The solid triangles correspond to the case when the field rotation is made from the c-axis to the current direction. Other open symbols represent the data taken in the transverse magnetoresistance configuration.

trinsic pinning, so that the dissipation is mostly due to the lateral motion of the pancakes. This yields a monotonic angular dependence. The angular dependence remains monotonic even at high current densities, if the $\theta$ is rotated in the plane containing the current direction (Fig. 5-(b)). However, if the o-rotation is done in the plane perpendicular to the current direction (Fig. 5-(a)), the motion of the strings is triggered by a strong Lorentz force at high current densities. The experimental observation suggests that the lowering of the pinning potential by the Lorentz force occurs more strongly for the intrinsic pinning of the strings than for the extrinsic pinning of the pancakes. Thus the contribution of the motion of strings to dissipation becomes visible at higher current densities, which gives rise to the observed anomalous angular dependence of dissipation. It is expected that the anomalous disspation peak may become more pronounced if more **extrinsic** pinning centers are introduced into the system, because they would effectively pin the pancakes and enhance the relative importance of the motion of the strings. It should be noted that if one describes the motion of a flux in terms of flux loop nucleation, the lateral motion of a pancake corresponds to nucleation of a small loop, while the vertical motion of a string corresponds to nucleation of an elongated loop.

The next question is why the anomalous dissipation due to the vertical motion of the strings

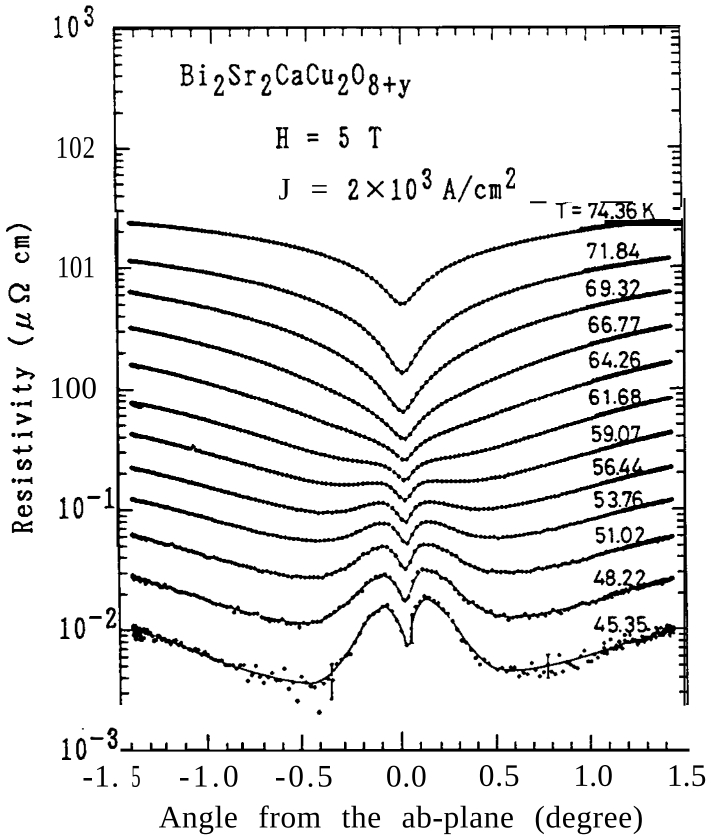
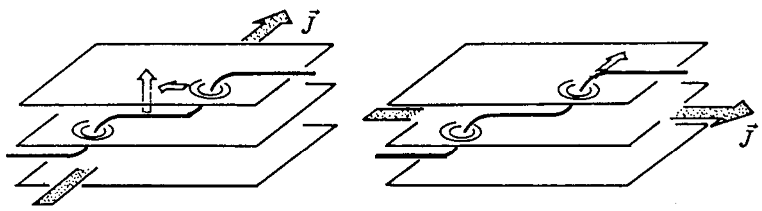



**FIG. 7. Anomalous angular dependence of dissipation in $Bi_2Sr_2CaCu_2O_{8+y}$. Note that the angular range is much narrower than $YBa_2Cu_3O_{7-y}$**

has such a sharp &dependence. On the higher angle side, the description in terms of pancakes and strings becomes meaningless when $\tan\theta \approx 1$. On the lower angle side, the activation energy is expected to increase sharply as $\theta \to 0$, because the intrinsic pinning energy for a string increases with its length given by $l = d/\tan\theta$ ($d$ being the layer spacing). In the limit of $\theta \to 0$, the Therefore, the dissipation due to the vertical motion of strings is expected only in a certain range of $\theta$.

Although we believe that it captures an essential physics of the anomalous angular dependence, the above picture based on individual flux motion is surely a gross oversimplification. A quantitative explanation for the effect should be only attained by properly incorporating the collective nature of the flux dynamics. In fact, the dependence of the characteristic angle on the field strength suggests an importance of the interaction between the flux lines. The flux line dynamics should be more appropriately described in terms of collective motion of highly correlated flux lines that form a flux lattice (or glass, or liquid). It should be also mentioned that possible phase transitions of a flux line lattice embedded in a strongly layered structure as a function



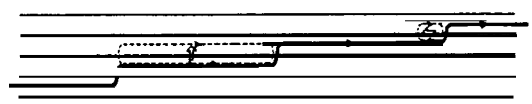



**FIG. 8.** A staircase flux line in a highly anisotropic layered superconductor, when the field is applied at a small angle from the basal plane. The two-dimensional vortex discs (pancakes) are loosely connected with the lateral segments (strings). The lower figure illustrates that the flux motion can be described in terms of vortex loop nucleation.

of field angle is discussed by several authors.[13] The observed anomaly may be related with such phase transitions, although the Lorentz force being important implies that one has to consider not just an equilibrium structure of the flux line system but also their dynamics.

## III. CONCLUSION

By a series of studies of the pressure effect on $T_c$ and the Hall effect, we have found a general trend among cuprate superconductors. In all compounds other than $La_{2-x}Sr_xCuO_4$, the pressure induced change in the Hall coefficient of $d\, lnR_H/dP \sim -8\text{-}10\ \%/GPa$ are found. This is in qualitative agreement with the picture that the pressure-induced charge redistribution is a principal route of the pressure effect on $T_c$. There are, however, many problems at a quantitative level, such as the absolute values and temperature dependences of the Hall coefficient. The origin of the difference in the pressure effect between the $La_{2-x}Sr_xCuO_4$ system and other cuprate systems, once elucidated, may furnish crucial information on the mechanism of high temperature superconductivity.

Flux dynamics in the parallel and nearly parallel field geometries are profoundly influenced by the strong intrinsic pinning potential due to the layered structure. We have found an anomalous peak in the angular dependence of resistivity. We attribute this phenomenon to the vertical motion, driven by a strong Lorentz force, of strings, which are otherwise strongly pinned by the intrinsic pinning potential due to the layered structure.

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