Consistency between the Lorentz-force independence of the resistive transition in the high-T_c superconductors and the standard theory of flux flow

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In a uniform flux-flow state of a type-II superconductor, (i) the resistivity tensor ρ_{ij} is independent of the dissipative transport current density $\mathbf{J}^T$, and (ii) there exists a constraint on the relative orientation of $\mathbf{J}^T$ and the average flux density $\mathbf{B}$. These two simple general properties can already account for the Lorentz-force independence of the resistive transition in high-T_c superconductors for the applied current in the *ab* plane, and the magnetic field making any not-too-small angle with this plane.

Measurements of the resistive transition of high-temperature superconductors (HTSC's) in the presence of an applied magnetic field have shown that the Lorentz-force dependence [or the dependence upon the angle between the applied current density $\mathbf{J}^{\text{ext}}$ (assumed uniform) and the average magnetic flux density $\mathbf{B}$] of the resistivity ρ is practically absent or very weak (see, for example, Refs. 1–4). Iye *et al.*[1(d)] have performed a comparative study on thin film samples of $Bi_2Sr_2CaCu_2O_8$ (Bi2212), $YBa_2Cu_3O_7$ (YBCO), and amorphous MoGe alloy. They observed a nearly ideal Lorentz-force dependence of ρ in the MoGe sample, as expected from the usual flux-flow theory, whereas the Lorentz-force dependence was completely absent in the Bi2212 sample; and an intermediate behavior was observed in YBCO wherein ρ shows a weak (or partial) Lorentz-force dependence.[1(d)] Since the anisotropy is extremely large in Bi2212, moderate in YBCO, and zero in MoGe, this comparison suggests that anisotropy may play an important role for the disappearance of the Lorentz-force dependence of ρ in HTSC's. The large anisotropy in HTSC's is due to the layered crystal structures. Kes *et al.*[5] proposed an explanation for the Lorentz-force independence (LFI) of the in-plane resistivity ($\mathbf{J}^{\text{ext}}$ applied parallel to the *ab* plane), in which they assume that only the transverse component (perpendicular to the layers) of $\mathbf{B}$ is responsible for forming vortices ("pancake" vortices in the Cu-O layers). But this interpretation cannot account for the existence of dissipation when $\mathbf{B}$ is exactly parallel to the layers.[1(c)] An alternative explanation was proposed by Iye *et al.*[1(d)] in terms of hopping of vortex segments (between the layers) across the layers and nucleation of pancake and antipancake vortex pairs. In this mechanism of flux motion the dissipation mainly depends on the nucleation of the pancake and antipancake vortex pairs (which are driven apart by the Lorentz force) and therefore is independent of the relative orientation of $\mathbf{B}$ and $\mathbf{J}^{\text{ext}}$ (both parallel to the layers). A similar explanation was suggested by Ando *et al.*[6] in terms of the dynamics of thermally activated pancake and antipancake vortex pairs. As for the out-of-plane configuration ($\mathbf{J}^{\text{ext}}$ is applied parallel to the *c* axis), for which some sort of a LFI of ρ has also been observed,[2] none of the above explanations applies, because the movements of the pancake vortices in the layers cannot lead to a voltage in the *c* direction. This difficulty has led to suggestions that thermal fluctuations may be important as an source of dissipation.[2,7] The purpose of this paper is to show that, although those nonstandard-flux-flow explanations may still be relevant to the understanding of the out-of-plane LFI, and perhaps also of the in-plane LFI when the angle θ between $\mathbf{B}$ and the *c* axis is very close to 90°, the standard theory of flux flow (in which the usual Abrikosov flux-line lattice is assumed) is actually already sufficient for the explanation of the in-plane LFI for all other values of θ, i.e., for $\mathbf{B}$ pointing in any direction which makes a not-too-small angle with the *ab* plane. As for the cases when the present explanation fails, we find that taking a view from the standard theory of flux flow implies that $\mathbf{J}^{\text{ext}}$ has a nondissipative component along $\mathbf{B}$ which can induce, for example, helical instabilities[8] in the vortex lines, making the analysis of the experimental data more difficult. In other words, the experimenters did not do simple flux-flow experiments in those cases. Our argument invokes only two general properties of a type-II superconductor in a uniform flux-flow state: (i) The resistivity tensor ρ_{ij} (including all the diagonal and Hall elements) is independent of the dissipative transport current $\mathbf{J}^T$, and (ii) there exists a constraint on the relative orientation of $\mathbf{J}^T$ and $\mathbf{B}$. Property (i) is a trivial consequence of the usual theory of linear response, and property (ii) follows simply from the fact that the electric field $\mathbf{E}$ induced by the flux motion is always perpendicular to $\mathbf{B}$. Thus both properties are quite independent of any specific theoreti-

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cal model of flux flow. We shall see that these two simple general properties of flux flow can already imply a type of in-plane LFI, without the need to invoke any non-flux-flow mechanisms of dissipation.

Consider in general an anisotropic superconductor in a uniform flux-flow state. The orientation of $\mathbf{B}$ may be arbitrary with respect to the principal axes of the sample. The energy dissipation in the flux-flow state is generally believed to be due to Joule heating of normal excitations[9] and relaxation of the order parameter.[10] Time-dependent Ginzburg-Landau (TDGL) theory[11,12] is a simple theory which can account of both of these two dissipation mechanisms. Thus TDGL theory is often used to investigate the flux-flow phenomenon. (It has been extended to include the Hall effect in the flux-flow state by allowing the order-parameter relaxation constant to have an imaginary part.[13–15]) One of the most fundamental conclusions of these studies is that, quite independent of the simplifying assumptions of TDGL theory, the macroscopic electric field $\mathbf{E}$, induced by a uniform flux motion with velocity $\mathbf{v}$, obeys[11–15]

$$\mathbf{E} = -(\mathbf{v} \times \mathbf{B})/c, \tag{1}$$

which is valid generally for both isotropic and anisotropic superconductors. Equation (1) was also derived by Josephson[16] from a different argument. The quantities $\mathbf{E}$ and $\mathbf{B}$ are the spatial averages of the corresponding microscopic quantities $\mathbf{e}(\mathbf{x})$ and $\mathbf{b}(\mathbf{x})$, respectively; i.e., $\mathbf{E} = \langle \mathbf{e}(\mathbf{x}) \rangle$ and $\mathbf{B} = \langle \mathbf{b}(\mathbf{x}) \rangle$. Microscopically $\mathbf{e}(\mathbf{x}) = -(1/c)\mathbf{v} \times \mathbf{b}(\mathbf{x})$ is not possible in general,[12] but for the spatially averaged (macroscopic) fields $\mathbf{E}$ and $\mathbf{B}$, Eq. (1) holds.

The dissipative transport current density $\mathbf{J}^T$, which is the spatial average of a local current density $\mathbf{J}(\mathbf{x})$ [i.e., $\mathbf{J}^T = \langle \mathbf{J}(\mathbf{x}) \rangle$], is related to $\mathbf{E}$ by

$$J_i^T = \sigma_{ij} E_j, \tag{2}$$

where σ_{ij} is the flux-flow conductivity tensor, and the convention of summing over repeated indices is employed. [Note that $\mathbf{J}(\mathbf{x})$ must not include a nondissipative component with a nonvanishing average along $\mathbf{B}$.] The inverse of Eq. (2) defines the flux-flow resistivity tensor ρ_{ij} $(= \sigma_{ij}^{-1})$:

$$E_i = \rho_{ij} J_j^T. \tag{3}$$

As we have said, property (i) is a trivial consequence of the usual linear response theory: The transport coefficients (here σ_{ij} or ρ_{ij}) cannot depend on the driving perturbation. Thus ρ_{ij} cannot depend on $\mathbf{J}^T$. This property is clearly true at all applied fields H. It is obeyed, for example, in all previous calculations of ρ_{ij} based on the TDGL theory,[11–15] which, due to the nonlinearity of the TDGL equations, were done explicitly only in either the low- (H near H_{c1}) or the high- (H near H_{c2}) field limits (here H_{c1} and H_{c2} are the lower and upper critical fields, respectively). (See, in particular, Ref. 15 for a newly completed calculation for an anisotropic superconductor in a field oriented arbitrarily with respect to the principal axes.)

Property (ii) is seen when we notice from Eq. (1) that $\mathbf{E}$ is always perpendicular to $\mathbf{B}$:

$$\mathbf{E} \cdot \mathbf{B} = 0. \tag{4}$$

This constraint on the relative orientation of $\mathbf{E}$ and $\mathbf{B}$, when combined with Eq. (3), implies a constraint on the relative orientation of $\mathbf{J}^T$ and $\mathbf{B}$:

$$\rho_{ij} B_i J_j^T = 0. \tag{5}$$

Equation (5) implies that, with $\mathbf{B}$ fixed, one is free to vary two of the three components of $\mathbf{J}^T$ only, and vice versa. Here we see an important difference between the electrical conduction in the flux-flow state and that in the normal state: In the former, $\mathbf{E}$, being *induced* by the motion of vortices, is always perpendicular to $\mathbf{B}$, whereas in the latter the relative orientation of $\mathbf{E}$ and $\mathbf{B}$ can be arbitrary. For isotropic superconductors, Eq. (5) merely implies $\mathbf{J}^T \perp \mathbf{B}$, which can be easily incorporated in flux-flow experiments by applying $\mathbf{B}$ perpendicular to a film or slab sample. Then $\mathbf{J}^{\text{ext}}$, which is often applied along the sample, can be identified with $\mathbf{J}^T$. For anisotropic superconductors, the incorporation of this constraint is far more difficult, and is usually ignored in experiments, so that $\mathbf{J}^{\text{ext}}$ can no longer be identified with $\mathbf{J}^T$ in general.

Consider a coordinate system whose axes coincide with the principal axes of the symmetric part of the tensor ρ_{ij}. (We expect these axes to coincide with the principal axes of a tetragonal high-T_c crystal.) In this system of coordinates the expression for ρ_{ij} is "antisymmetric," by which we mean $\rho_{ij} = -\rho_{ji}$ for $i \neq j$, but the diagonal elements $\rho_{ii} \neq 0$. [As can be shown, if ρ_{ij} is "antisymmetric," so must be σ_{ij} (in the same coordinates system) and vice versa.] In this representation only the diagonal elements of ρ_{ij} are dissipative while all the off-diagonal ones (the Hall elements) are nondissipative.

We focus on the longitudinal resistivity (referred to simply as "resistivity" in this paper). We may ignore all the Hall elements of the tensor ρ_{ij}, since they are usually smaller than the *smallest* of the diagonal ones by $O(10^{-3})$. Then Eq. (5) becomes

$$\rho_{11} J_1^T B_1 + \rho_{22} J_2^T B_2 + \rho_{33} J_3^T B_3 = 0. \tag{6}$$

For the purpose to explain the LFI of the in-plane resistivity in HTSC's, consider the situation where $\mathbf{J}^T$ is in the $x_1 x_3$ plane, and $\mathbf{B}$ is in the (θ, ϕ) direction. Then $(B_1, B_2, B_3) = B(\sin\theta\cos\phi,\ \sin\theta\sin\phi,\ \cos\theta)$. Using Eq. (6), one can easily show that

$$\rho \equiv \frac{\mathbf{E} \cdot \hat{\mathbf{J}}^T}{J^T} = \rho_{11}\rho_{33} \frac{\rho_{33}\cos^2\theta + \rho_{11}\sin^2\theta\cos^2\phi}{\rho_{33}^2\cos^2\theta + \rho_{11}^2\sin^2\theta\cos^2\phi}. \tag{7}$$

At the same time, one can show that $\mathbf{J}^T$ is in the direction which is at an angle θ_J with the x_1 axis [i.e., the unit vector along $\mathbf{J}^T$ is $(\cos\theta_J, 0, -\sin\theta_J)$], where θ_J satisfies

$$\tan\theta_J = -J_3^T / J_1^T = (\rho_{11}/\rho_{33}) \tan\theta \cos\phi. \tag{8}$$

For $\phi = \pi/2$, we have $\theta_J = 0$ independent of the ratio ρ_{11}/ρ_{33} and the angle θ (if $\neq \pi/2$), and the dissipative transport current is always flowing in the x_1 direction.

For this case Eq. (7) reduces simply to

$$\rho = E_1/J_1^T = \rho_{11}. \tag{9}$$

For $\phi \neq \pi/2$, θ_J for an anisotropic system with $\rho_{33} > \rho_{11}$ is always closer to zero than its corresponding value for an isotropic system; i.e., $\mathbf{J}^T$ always tends to flow in a direction closer to the easy axis (of which the resistivity is smaller). For the extremely anisotropic case, $\rho_{33}/\rho_{11} \gg 1$, if θ is not very close to $\pi/2$, we have $\tan\theta_J \ll 1$, so that $\mathbf{J}^T$ is practically also flowing in the x_1 direction. For this case Eq. (7) becomes

$$\rho = \rho_{11}\left[1 + O(\rho_{11}/\rho_{33})\right]. \tag{10}$$

The condition $\rho_{33}/\rho_{11} \gg 1$ is generally satisfied for HTSC's. For example, in the normal state $\rho_{33}^{(n)}/\rho_{11}^{(n)}$ is of $O(10^2)$ for YBCO (Refs. 17, 18) and $O(10^5)$ for Bi2212,[19] and usually the ratio becomes even larger as T decreases.[17–19] For Bi2212 with $\rho_{33}/\rho_{11} \sim O(10^5)$, the error in the approximation of Eq. (10) becomes greater than 5% at $\phi = 0$ only for $\theta > 89.5°$. Thus in the experiments performed on HTSC's where $\mathbf{J}^{\text{ext}}$ is applied in the x_1 direction and $\mathbf{B}$ is applied in the (θ, ϕ) direction, we can essentially identify[20] $\mathbf{J}^{\text{ext}}$ with $\mathbf{J}^T$, and the measured resistivity

$$\rho^{\text{expt}} \equiv \mathbf{E}\cdot\hat{\mathbf{J}}^{\text{ext}}/J^{\text{ext}} \tag{11}$$

with the theoretical resistivity given in Eqs. (7) and (10).

In general, ρ_{11} can still depend on $\mathbf{B}$; i.e., $\rho_{11} = \rho_{11}(B,\theta,\phi)$.[21] In the normal state the field dependence of ρ_{ii} is weak and negligible. In the superconducting state there are several reasons to believe that, for $H \gg H_{c1}$, ρ_{ii} depends on $\mathbf{B}$ via the ratio $B/H_{c2}(\theta,\phi)$ only, i.e.,

$$\rho_{ii}(B,\theta,\phi)/\rho_{ii}^n = f(B/H_{c2}(\theta,\phi)). \tag{12}$$

(a) It has been directly verified for $\mathbf{B} \perp \mathbf{J}^T$.[1(a),1(b),22] (b) Theoretically within the TDGL framework, it has been shown that Eq. (12) is true in the high-field limit (i.e., $H_{c2} - H \ll H_{c2}$) for all θ and ϕ.[15] (c) Freimuth[4] has argued intuitively why Eq. (12) should be true: Flux-flow dissipation should depend the size of the vortex cores, which is $\Phi_0/2\pi H_{c2}$ (where Φ_0 is the flux quantum).

If one neglects the weak anisotropy of HTSC's in the ab plane, $H_{c2}(\theta,\phi)$ is independent of ϕ. We then obtain that $\rho(B,\theta,\phi) \simeq \rho_{11}(B,\theta)$ is independent of ϕ for the situation analyzed, if $\rho_{33}/\rho_{11} \gg 1$, except in the limit $\theta \to \pi/2$. Note that at a fixed θ, the angle between $\mathbf{J}^T$ and $\mathbf{B}$ is ϕ dependent, and so the Lorentz force is not a constant. We have thus explained the LFI of the in-plane resistivity in HTSC's except when θ is very close to $\pi/2$.

Measurements are frequently done in the configuration in which both $\mathbf{J}^{\text{ext}}$ and $\mathbf{B}$ are in the ab (x_1x_2) plane of HTSC's,[1(d),4], but with the angle ϕ between $\mathbf{J}^{\text{ext}}$ and $\mathbf{B}$ continuously varied through a large range covering both $\phi = 0$ and $\phi = \pi/2$. If one neglects in-plane anisotropy, one can assume that $\mathbf{J}^{\text{ext}}$ is in the x_1 direction without loss of generality. Then the polar angles of $\mathbf{B}$ in this case are just $(\theta = \pi/2, \phi)$. But if one lets $\theta \to \pi/2$ in Eq. (6), one finds simply $\mathbf{J}^T \perp \mathbf{B}$ for systems for which in-plane anisotropy can be neglected. Thus one sees that except for $\phi = \pi/2$ one can no longer identify $\mathbf{J}^{\text{ext}}$ with $\mathbf{J}^T$. In other words, if only the assumptions behind the standard flux-flow theory are valid (i.e., a lattice of straight flux lines in uniform translation), and if $\mathbf{J}^{\text{ext}}$ is uniform inside the sample, then one must identify $\mathbf{J}^{\text{ext}}$ as the vector sum of a dissipative transport-current component $\mathbf{J}^T \perp \mathbf{B}$ and a nondissipative supercurrent component $\mathbf{J}^S \parallel \mathbf{B}$, i.e.,

$$\mathbf{J}^{\text{ext}} = \mathbf{J}^T + \mathbf{J}^S. \tag{13}$$

Such a nondissipative component of current, $\mathbf{J}^S$, which corresponds to a uniform translation of the whole "superfluid" along $\mathbf{B}$, is not included in Eq. (5), since only the dissipative part of the current, $\mathbf{J}^T$, is related to $\mathbf{E}$ by Eq. (2), or its inverse Eq. (3).

Experimentally the longitudinal and transverse resistivities in this case are defined by[1(d)]

$$\rho_\parallel \equiv E_1/J^{\text{ext}}, \quad \rho_\perp \equiv E_2/J^{\text{ext}}. \tag{14}$$

Using the present analysis one can easily obtain that (still neglecting in-plane anisotropy[23])

$$\rho_\parallel = \rho_{11}\sin^2\phi, \qquad \rho_\perp = -\rho_{11}\sin\phi\cos\phi, \tag{15}$$

where $\rho_{11} \equiv \rho_{11}(B,\pi/2,\pi/2)$. That is, in this case our analysis based on the standard theory of flux flow does not predict LFI, in agreement with the conclusion of Iye *et al.*[1(d)] In their work $\rho_\parallel$ and $\rho_\perp$ are measured as functions of ϕ on thin film samples of Bi2212, YBCO, and amorphous MoGe alloy. The results for MoGe agree reasonably well with Eq. (15). In YBCO $\rho_\parallel$ has a ϕ-independent component in addition to a ϕ-dependent component, which more or less follows Eq. (15). [The ϕ-dependent parts of $\rho_\parallel$ and $\rho_\perp$ in YBCO show additional ϕ dependences which can be attributed to the presence of twinning.[1(d)]] In Bi2212 $\rho_\parallel$ is found to be practically ϕ independent. Thus it appears that for $\theta = \pi/2$ the partial or full in-plane LFI observed in HTSC's is inconsistent with the standard theory of flux flow. However, we note that the nondissipative supercurrent $\mathbf{J}^S$ along $\mathbf{B}$ also present in the system when $\phi \neq \pi/2$ can induce a helical instability of the vortex lines,[8] causing the local direction of $\mathbf{B}$ to be not even in the ab plane everywhere. Whether taking into account this additional point in the standard theory of flux-flow can explain the observed LFI in HTSC's remains to be investigated, but we note that in the case of a uniform $\mathbf{B}$ even a tilt of $\mathbf{B}$ by a few tenths of a degree away from the ab plane is enough to give practically complete ϕ independence of $\rho_\parallel$ in Bi- and Tl-based samples [of which $\rho_{33}/\rho_{11} \sim O(10^5)$ or larger]. Thus offhand one cannot rule out the possibility of reconciling the standard theory of flux flow with the partial or full in-plane LFI observed in HTSC's at $\theta \simeq \pi/2$, but we concede that invoking the helical instability of the vortex lines to account for the observed LFI in this case is not very different from the postulate of the creation of pancake vortices (cf. Iye *et al.*[1(d)]). In any case it is worth pointing out that the experiments performed at $\theta = \pi/2$ but $\phi \neq \pi/2$ are not standard flux-flow experiments, since the component $\mathbf{J}^S$ along $\mathbf{B}$ that exists in such cases can distort the vortex lines, which can have very different consequences in isotropic and extremely anisotropic superconductors.

A type of out-of-plane LFI has also been observed in the sense that an almost equally broad resistive transition has been observed for $\mathbf{H} \parallel \hat{\mathbf{c}}$ whether $\mathbf{J}^{\rm ext}$ is along $\hat{\mathbf{a}}$ or along $\hat{\mathbf{c}}$ (in both cases the width of the transition is broader for larger H), but a downward shift with essentially no broadening was observed for $\mathbf{H} \parallel \hat{\mathbf{a}}$ whether $\mathbf{J}^{\rm ext}$ is along $\hat{\mathbf{a}}$ or along $\hat{\mathbf{c}}$.[2] From the point of view of the standard theory of flux flow, the case of $\mathbf{H} \parallel \hat{\mathbf{c}}$, $\mathbf{J}^{\rm ext} \parallel \hat{\mathbf{a}}$, is a standard flux-flow experiment with $\rho^{\rm expt}$ measuring $\rho_{11}(B,\theta = 0)$, and the case of $\mathbf{H} \parallel \hat{\mathbf{a}}$, $\mathbf{J}^{\rm ext} \parallel \hat{\mathbf{c}}$, is also a standard flux-flow experiment with $\rho^{\rm expt}$ measuring $\rho_{33}(B,\theta = \pi/2,\phi = 0)$, but the other two cases are not standard flux-flow experiments, with $\mathbf{J}^{\rm ext}$ not identifiable with $\mathbf{J}^T$. For $\mathbf{H} \parallel \mathbf{J}^{\rm ext} \parallel \hat{\mathbf{c}}$, the entire $\mathbf{J}^{\rm ext}$ must be identified with $\mathbf{J}^S$. It can then also induce a helical distortion of the flux lines. Whether this distortion can account for the observed out-of-plane LFI is even less clear than the case of in-plane LFI at $\theta \simeq \pi/2$, but it is appropriate to say that further theoretical attempts to understand the behavior of the out-of-plane resistivity in HTSC's within the flux flow framework must include assumptions which allow local orientations of the flux and current densities to be coordinates and (possibly) time dependent.

In summary, we have contrasted the experimentally observed LFI of the resistive transition in HTSC's with the predictions of the standard theory of flux flow (in which a uniform translation of the usual Abrikosov flux-line lattice is assumed). We find that two simple general properties of a uniform flux flow; i.e., the properties (i) and (ii) listed above can already account for the LFI of the in-plane resistivity for almost all directions of $\mathbf{B}$ except when it is very close to being parallel to the ab plane. For the case when both $\mathbf{B}$ and $\mathbf{J}^{\rm ext}$ are in the ab plane but $\mathbf{B}$ is not perpendicular to $\mathbf{J}^{\rm ext}$, the present analysis indicates that $\mathbf{J}^{\rm ext}$ has a nondissipative component along $\mathbf{B}$, which can induce a helical distortion of the flux lines. We suggest that the standard theory of flux flow, if generalized to include this flux-line distortion, may be sufficient to account for the observed partial or full LFI observed in various HTSC's in this configuration, but we have not yet made a detailed study of this idea. At the present time we can say even less on whether the standard theory of flux flow can in any way be reconciled with the out-of-plane LFI, but the latter appears to be not very well characterized experimentally either. (For example, it has not been presented as an independence of ρ with respect to the angle between $\mathbf{J}^{\rm ext}$ and $\mathbf{B}$). We only note that it also involves nonstandard flux-flow experiments where a nondissipative component of current exists to distort the flux lines. The most important conclusion of this work is that the observation of LFI in HTSC's does not necessarily invalidate the standard theory of flux flow.

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