Nernst Effect, Seebeck Effect, and Vortex Dynamics in the Mixed State of Superconductors

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Based on the vortex dynamics with the Magnus force and a two-fluid model we have derived a set of explicit expressions between the Nernst and Seebeck coefficients, and the Hall and longitudinal resistivities in the linear response regime of the mixed state of superconductors. Effects of vortex pinning are included. The expressions are found to be in agreement with available experimental data. Present results are valid for large as well as for small Hall angle samples, and if Hall angle terms are dropped we recover previous theoretical results. On the other hand, the similar expressions based on an alternative vortex dynamics with various normal current drag forces on vortices are in qualitative disagreement with experiments, which implies the absence of those normal current drag forces.

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I. INTRODUCTION

Up till now, the vortex equation of motion is still a highly controversial subject. No model seems to be able to give a consistent explanation of ample experimental data of the related transport phenomena of Hall, Nernst, and Seebeck effects. It starts with the obvious observation that because the motion of vortices in the mixed state of type II superconductors generates voltages by the Josephson relation, the electric measurements for the longitudinal and Hall resistivities should be the natural way to test vortex dynamics. However, for any given effective equation of motion for vortices, it has been proved to be a difficult task to calculate the longitudinal resistivity in the mixed state of a superconductor, and even more so for the Hall resistivity, because of the roles played by vortex pinning and interaction. It is then not surprising that no consensus on the basic vortex equation of motion has been reached solely based on the tests of electric transport measurements. Thermoelectric transport measurements, the Seebeck and Nernst effects, provide additional tests. A correlation between those two sets of measurements should provide a powerful check for the vortex dynamics. This had been explored before and it is worthwhile to point out that there is no report yet on a direct measurement of the Seebeck effect in a conventional superconductor. The appearance of the oxide superconductors generates renewed interests in both vortex dynamics and the thermoelectric measurements. The experimental data seem to converge, but theoretical approaches are phenomenological and results are very diverse. Furthermore, there is no proper account of the pinning effect in the existing theoretical models.

In order to have a better understanding of this problem, an attempt has been made in the present paper to provide a picture to put all those effects into one macroscopic framework, based on the vortex dynamics with the Magnus force and a two-fluid model. We will show that this framework accounts well the relevant experiments, so long as the vortex-antivortex pair fluctuations are insignificant. The core result is a set of explicit relationships between the electric transport properties, the Hall and longitudinal resistivities, and the thermoelectric transport properties, the Nernst and Seebeck effects. Present results are similar to previous ones, but important differences remain. In the course of the comparison between the derived relationships and experiments there is no fitting parameter. Regarding to the special feature in the thermoelectric transport measurements that the magnitudes of supercurrent and normal current are equal to each other, the good agreement between present results and the experimental data strongly indicates the absence of normal current drag forces in the vortex dynamic equation.

II. DERIVATION BASED ON THE MAGNUS FORCE AND THE TWO-FLUID MODEL

We consider a two-dimensional superconductor film. The magnetic field is applied perpendicular to the film. In the presence of temperature gradient a thermal force will act on a vortex due to the entropy carried...
by its core. Quantitatively, for a vortex with a unit length mass $m_v$ and velocity $\mathbf{v}_l = \dot{\mathbf{r}}$, the equation of motion is

$$m_v \dot{\mathbf{v}}_l = q_v n_s(T) \hbar \left[ \mathbf{v}_{s,\text{total}} - \mathbf{v}_l \right] \times \dot{\mathbf{r}} - \eta \mathbf{v}_l + \mathbf{F}_{\text{pin}} + \mathbf{f} - s_\phi \nabla T ,$$  \hspace{1cm} (1)

with vorticity $q_v = \pm 1$, Planck constant $\hbar$, the superfluid electron number density $n_s$, the vortex friction $\eta$, the pinning force $\mathbf{F}_{\text{pin}}$, the fluctuating force $\mathbf{f}$, and the temperature $T$. Pinning is due to the inhomogeneity in the sample. Another inhomogeneous consequence, core-less Josephson vortices in weak links, will not be considered here, although they can be discussed within Eq.(1) with a different set of transport coefficients. The total superfluid velocity at the vortex is $\mathbf{v}_{s,\text{total}} = \mathbf{v}_{s,in} + \mathbf{v}_s$. Here $\mathbf{v}_{s,in}$ is the contribution due to other vortices describing the vortex interaction, and $\mathbf{v}_s$ relates to the externally applied supercurrent $\mathbf{j}_s$ by

$$\mathbf{j}_s = e n_s(T) \mathbf{v}_s ,$$  \hspace{1cm} (2)

with $e$ the electric charge of the carriers. The existence of the Magnus force, the first term at the right hand side of Eq.(1), has been shown to be followed from basic properties of a superconductor. The last term at the right hand side of Eq.(1) is the thermal force due to the presence of a temperature gradient $\nabla T$, with $s_\phi$ the unit length entropy transported by a vortex. This thermal force may be viewed as an additional supercurrent $\mathbf{j}_T = e n_s \mathbf{v}_T$ in Eq.(1), if

$$q_v \frac{n_s(T) \hbar}{2} \mathbf{v}_T \times \dot{\mathbf{r}} \equiv -s_\phi \nabla T .$$  \hspace{1cm} (3)

An alternative vortex equation of motion has been advocated recently, with various extra normal fluid dragging force terms. We will return to the discussion of its implications for the Seebeck and Nernst effects later (c.f. Eqs.(15-22)).

In the presence a supercurrent vortices will move, and moving vortices generate the measured electric field by the Josephson relation. In the steady state and in the linear response regime, the average vortex velocity is a linear function of the driven supercurrent. Because by the Josephson relation the measured electric field $\mathbf{E}$ is proportional to the average vortex velocity, we have

$$\mathbf{E} = \rho_s [\mathbf{j}_s + \mathbf{j}_T] ,$$  \hspace{1cm} (4)

with the superfluid resistivity tensor $\rho_s$ as

$$\rho_s = \begin{pmatrix} \rho_{s,xx} & \rho_{s,xy} \\ \rho_{s,yx} & \rho_{s,yy} \end{pmatrix} .$$  \hspace{1cm} (5)

It is should be pointed out that there may be various kinds of vortex motions contributing to $\mathbf{E}$, such as due to vortex vacancies and dislocations. Their contributions are additive. The presence of the Magnus force may result in a possible large Hall angle as well as its sign change. The absence of this force will rule out the Hall voltage contribution of vortices. It has been shown that the motion of vortex vacancies in a pinned vortex lattice can lead to the anomalous Hall effect, the sign change of the Hall angle in the mixed state below the superconducting transition temperature, and a consistent explanation for the Hall resistivity data may be obtained based on Eq.(1). In the rest of the paper no attempt will be made to explicitly calculate the superfluid resistivity tensor $\rho_s$. Nevertheless we should pointed out that the effects of pinnings are contained in $\rho_s$.

The presence of the temperature gradient may also generate a normal current $\mathbf{j}_n$ because the normal fluid carries entropy. By the Ohm’s law, we have

$$\mathbf{j}_n = \sigma_n \left[ -S_n \nabla T + \mathbf{E} \right] .$$  \hspace{1cm} (6)

Here $S_n$ is the normal fluid Seebeck coefficient and $\sigma_n$ the normal fluid conductivity tensor,

$$\sigma_n = \begin{pmatrix} \sigma_{n,xx} & \sigma_{n,xy} \\ \sigma_{n,yx} & \sigma_{n,yy} \end{pmatrix} .$$  \hspace{1cm} (7)
A small normal fluid Nernst effect has been neglected here. In the thermal electric measurements, the total electric current $j$ in the sample is zero:

$$j = j_s + j_n = 0,$$  \hspace{1cm} (8)

with the normal fluid current given in terms of the normal fluid density $n_n(T)$ and velocity $v_n$, as $j_n = e n_n v_n$. Therefore eliminating both the super and normal currents $j_s, j_n$ from Eqs.(4,6) and using Eqs.(3,8) we arrive at the following result

$$E = \rho [\sigma_n \nabla T + \frac{2c_s \phi}{q_v h} \nabla \times j],$$ \hspace{1cm} (9)

with the mixed state resistivity tensor $\rho$ as

$$\rho = [\sigma_s + \sigma_n]^{-1},$$ \hspace{1cm} (10)

defined in the electric transport measurements $E = \rho j$ with $\nabla T = 0$. Here the superfluid conductivity tensor $\sigma_s$ is given by $\sigma_s = \rho_s^{-1}$. In an explicit form, we rewrite Eq.(9) as

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} S_n [\rho_{xx} \sigma_{n,xx} + \rho_{xy} \sigma_{n,xy}] - \frac{2c_s \phi}{q_v h} \rho_{xy} S_n [\rho_{xx} \sigma_{n,xx} + \rho_{xy} \sigma_{n,xy}] + \frac{2c_s \phi}{q_v h} \rho_{xx} S_n [\rho_{yx} \sigma_{n,xy} + \rho_{yy} \sigma_{n,yy}] + \frac{2c_s \phi}{q_v h} \rho_{yx} S_n [\rho_{yx} \sigma_{n,xy} + \rho_{yy} \sigma_{n,yy}] + \frac{2c_s \phi}{q_v h} \rho_{yx} \end{pmatrix} \begin{pmatrix} \nabla_x T \\ \nabla_y T \end{pmatrix}. \hspace{1cm} (11)$$

Eq.(11) gives an one-to-one relationship between the electric and thermoelectric measurements in the linear response regime, the core result of the present paper. By simultaneous measurements of longitudinal and Hall resistivities, and the Seebeck and Nernst effects in one sample, there will be no adjusting parameter in the comparison between Eq.(11) and experimental data. To see this, we note that the mixed state resistivity tensor $\rho$ can be obtained by the electric measurements, although ideally $\rho$ could be calculated based on Eq.(1). In principle the normal fluid Seebeck coefficient $S_n$ and the conductivity tensor $\sigma_n$ can be calculated, too. However, close to the transition temperature both $S_n$ and $\sigma_n$ are expected to be equal to the corresponding normal state values, therefore can be directly measured. The only unknown quantity now is the unit length entropy $s_\phi$, carried by a vortex. Its value could be calculated by a consideration of the temperature dependence of the core entropy. In this case the Nernst and Seebeck effects are known from other measurements, and their measurements will provide a stringent check of the consistency of the physics leading to Eq.(11). Even if $s_\phi$ is treated as an unknown quantity, the measurement of the Nernst effect can fix its value. Therefore there is no fitting parameter for the Seebeck effect. We note that as the temperature approaches the transition temperature, $\rho, \sigma_n \rightarrow 1$, the unit matrix, and $s_\phi \rightarrow 0$, we obtain the normal state values for the Nernst and Seebeck effects, as expected.

If there is a rotational symmetry in the sample, that is, $\rho_{xx} = \rho_{yy}$ and $\rho_{yx} = -\rho_{xy}$, from Eq.(11), we have a simpler expression for the Seebeck effect as

$$\frac{E_x}{\nabla_x T} = \frac{E_y}{\nabla_y T} = S_n \rho_{xx} \sigma_{n,xx} [1 + \tan \theta \tan \theta_n] + \frac{2c_s \phi}{q_v h} \rho_{xx} \tan \theta, \hspace{1cm} (12)$$

and for the Nernst effect as

$$\frac{E_y}{\nabla_y T} = -\frac{E_x}{\nabla_x T} = -\frac{2c_s \phi}{q_v h} \rho_{xx} + S_n \rho_{xx} \sigma_{n,xx} [\tan \theta - \tan \theta_n]. \hspace{1cm} (13)$$

Here $\theta = \tan^{-1}(\rho_{yx}/\rho_{xx})$ and $\theta_n = \tan^{-1}(\rho_{n,yx}/\rho_{n,xx})$ are the Hall angles of the mixed state and the normal fluid, respectively. We should pointed out that the relationship between the vorticity $q_v$, the sign of the carrier electric charge $e$, and the direction of the applied magnetic field $B$ is

$$\frac{q_v e}{|e|} = \frac{B}{|B|}. \hspace{1cm} (14)$$

Thus, the Seebeck effect is even with respect to the direction of the applied magnetic field, and the Nernst effect is odd, since the Hall angle is odd for a rotational symmetric sample. If the differences in the Hall angle terms were ignored, expressions similar to Eqs.(12,13) have been obtained previously by various methods. However, the Hall angle terms can be important, because the Hall angle can be in principle close to $\pi/2$ and large Hall angle data in the mixed state have been indeed reported. The differences between Eqs.(11,12,13) and those obtained in Ref.8 can be therefore differentiated experimentally.
III. FURTHER DISCUSSIONS

Although Eq.(11), or the special case, Eqs.(12,13), looks simple enough, there are quite a few confusions in its derivation and comparison with experiments. We discuss them below.

There are several important differences between Eq.(11) and Eqs.(12,13), which are particularly pertinent in the comparison with experiments. First, the vortex pinning is automatically included in Eq.(11), as contained in the mixed state resistivity tensor $\rho$. Secondly, as a special case of the first point, effects of the vortex guided motion due to a possible correlated pinnings is included. Therefore Eq.(11) also applies to the case of no rotational symmetry in a sample. The guided motion not only generates a large even part with respect to the direction of the applied magnetic field in $\rho_{xx,xy}$, also may result in $\rho_{xx} \neq \rho_{yy}$. A special attention should be paid to this effect in an interpretation of experimental data. Thirdly, another special case of the first point, Eq.(11) applies to the case of the anomalous Hall effect, because with considerations of the vortex many-body correlation and pinning effect Eq.(1) can lead to this effect. Finally, it should be emphasized that the base for Eq.(11) is Eq.(1), and an alternative vortex dynamics model will generally give a difference expression (c.f. Eq.(18)). We also note that the present results are concrete in contrast to those based on general symmetry considerations.

Two remarks on different kinds of vortex motions are in order. First, in the derivation of Eq.(11) we notice that the effective supercurrent $j_T$ in Eq.(3) due to the thermal force should carry the sign of the vorticity, but it has been treated as if independent of it as the real supercurrent $j_s$. Although different vortex motions have different contributions to the superfluid resistivity tensor $\rho_s$, as long as the motions are all vortex like, there is no need to concern with the vorticity dependence in $j_T$. Interestingly, this is also true for the vacancy motion, because of the absence of a normal core for a vacancy as pointed out in Ref. [3] in the discussion of the anomalous Hall effect. However, it is not true for antivortices, and leads to the second remark. We note that the thermal force, Eq.(3), is the same for both vortices and antivortices. Therefore the effective supercurrent $j_T$ takes opposite signs for vortices and antivortices, respectively. Then in the connection between the electric and the thermoelectric transport measurements, the contributions due to vortices and antivortices should be carefully separated out, as noted by Ri et al. [1]. Fortunately, the generating of free antivortices through vortex-pair fluctuations is energetically the most unfavorable one below the transition temperature. Therefore it can be ignored below the transition temperature (Kosterlitz-Thouless transition in 2-d cases).

It is appropriate to further discuss the important differences between the present results and previous work. One of them has been stated above: the proper consideration of the Hall effect terms. Because of this, it appears that present results, Eq.(11) or Eqs.(12,13), are different from all those in previous work. For example, in Ref. [2] it has been suggested that $\tan \theta = \tan \theta_n$, in Ref. [4] there is no second term in Eq.(13), and in Ref. [5] the contribution of normal fluid resistivity is not present. The approach of Ref. [6] is inappropriate regarding to the use of the Ohm’s law for the normal fluid: it fails to consider the electric field, and the mixed state resistivity used there is actually given by superfluid resistivity tensor $\rho_s$, not by the two-fluid type $\rho$ as given by the present Eq.(10). The pinning has not been discussed in Refs. [7,8,9]. In Ref. [10] the pinning effect has been considered, but it is found there that there is a drastic change of equation of motion for a vortex, and, in their Burdeen-Stephen limit a violation of the Onsager relation has been found. The approach in Ref. [11] is very similar to that of the present paper. However, the effect of the pinning has been assumed to be modeled by percolation. Further, three additional parameters, $N_s/N_n, f_s, f_n$, have been introduced into their model, which, in the light of the present model, looks redundant.

Now we discuss the comparison of Eq.(11) with experiments with an emphasis on features overlooked before. It is a general experimental observation that Eqs.(12,13) or the similar ones in the literature are consistent with experimental data. A careful analysis has revealed a small discrepancy, $\sim 20\%$ depending on applied magnetic fields and samples, in the comparison of Eq.(12) with the Seebeck effect data of the oxide superconductor YBCO samples, peaked at a temperature about 10K below the transition temperature. There are many possible mechanisms responsible for this discrepancy, such as the decrease of $S_n$ as lowering the temperature calculated in Ref. [12]. In view of the above discussion of the guided motion, its effects are also likely responsible for this discrepancy. For the Hall angle term in Eq.(13), a careful measurement reveals that it has no observable effect near the transition temperature. The measured normal Hall angle is $\tan \theta_n \sim 0.01$, but the Nernst effect data require that $|\tan \theta - \tan \theta_n| << 0.005$. This is bored out by Eqs.(11,13): As the temperature approaches the transition temperature, $\rho \to \rho_n$, therefore $\tan \theta \to \tan \theta_n$, the Hall angle contribution to the Nernst effect then disappears. It should be pointed out that this disappearance of Hall
angle terms in Eq.(13) occurs just near the transition temperature, not in the whole mixed state regime as claimed in Ref.\textsuperscript{7}. It is also interesting to pointed out that this suggests $\sigma_s = 0$ in the mixed state as approaching the transition temperature from below. Based on the above discussions we concluded that Eq.(11) is in good agreement with available experimental data.

We note that in the above discussion only the macroscopic anisotropy due to the vortex guide motion has been considered. This may not be enough, because of the microscopic anisotropy due to the electronic and lattice structures as well as the symmetry of the pairing wavefunction. For such cases, both $s_e$ and $S_n$ should be represented by tensors. The vortex viscosity $\eta$ as well as the Magnus force may also adopt tensor forms. The formal equation, Eq.(9), however, will remain unchanged, but the detailed equation, Eq.(11), will become quite complicated. We will no pursue this question any further, but simply mention here that this may have been indicated experimentally in an oxide superconductor.\textsuperscript{8}

One point we should emphasize here is that, although the Hall angle is usually small, large Hall angles in the mixed state, $|\tan \theta| \sim 1$, have been reported for both conventional\textsuperscript{9} and oxide superconductors. Simultaneous measurements on such samples will provide a unique test of Eq.(11). Further experiments are clearly needed in this direction.

### IV. ALTERNATIVE VORTEX DYNAMICS MODEL

As mentioned at the beginning of the paper and expressed by Eq.(8), the magnitudes of super and normal currents are equal to each other. This is quite different from the electric measurements where the normal current is usually much smaller than the supercurrent. This feature will allow us to study rather conveniently the consequence of a possible normal current drag force. If there were a drag force due to a normal current in Eq.(1), its effect can be effectively treated as an additional supercurrent in Eq.(1), as for the case of the thermal force in Eq.(3). Then we would simply repeat the calculation leading to Eq.(11), or Eqs.(12,13), and obtain modified ones. Therefore the effects of the normal current drag force would appear in the modified equations, which can be compared with experiments. We present such an analysis below.

A recently proposed alternative vortex dynamics model with various normal fluid dragging force terms has the following form\textsuperscript{3}: 

$$
0 = q_e \frac{n_s(T)h}{2} [v_{s,total} - v_i] \times \hat{z} - D' [v_n - v_i] \times \hat{z} + D [v_n - v_i].
$$

(15)

For usual superconductors, the numerical parameter $\omega_0 \tau << 1$. In this case it has been found that $D' = \frac{q_e h}{2}[n_e - n_n]$ and $D = \omega_0 \tau \frac{h}{2} n_s$, with $n_e = n_n + n_s$ the total fluid density.\textsuperscript{3} Putting the pinning force, the noise, and the thermal driving force into Eq.(15), and expressing the super and normal fluid velocities by the corresponding electric currents, the equivalent alternative vortex dynamics equation is:

$$
0 = -\alpha q_e \frac{n_s(T)h}{2} v_i \times \hat{z} - D v_i + q_e \frac{n_s(T)h}{2} v_{s,\text{in}} \times \hat{z} + (\dot{j}_s + \dot{j}_n) \times \Phi_0 - \frac{n_e}{n_n} \dot{j}_n \times \Phi_0
$$

$$
+ \omega_0 \tau \frac{n_e}{n_n} \left( \frac{B}{|B|} \times \dot{j}_n \right) \times \Phi_0 + F_{\text{pin}} + f - s_\phi \nabla T.
$$

(16)

Here $\Phi_0$ is the magnetic flux quantum in the direction of the magnetic field $B$, and $\alpha$ a numerical parameter whose precise value is unimportant presently. For this alternative vortex dynamics model, the measured electric field in the linear response regime is

$$
E = \rho_s^a \left[ j_s + j_n - \frac{n_e}{n_n} j_n + \omega_0 \tau \frac{n_s}{n_n} \frac{B}{|B|} \times j_n \right].
$$

(17)

Here $\rho_s^a$ may be called the superfluid resistivity tensor, and the superscript $a$ standard for the alternative vortex dynamics. Eliminating the super and normal currents with the aid of the Ohm’s law, Eq.(6), and of the two fluid model, Eq.(8), we have,
\[ \mathbf{E} = \rho^a \left[ \frac{n_e}{n_n} \sigma_n S_n \nabla T + \frac{2 e s_\phi}{q e \hbar} \nabla T \times \hat{z} - \omega_0 \tau \frac{n_s}{n_n} \frac{B}{|B|} \times \sigma_n S_n \nabla T \right], \] 
(18)

with the mixed state resistivity tensor
\[
\rho^a = \left[ \left( \rho^a_n \right)^{-1} + \frac{n_e}{n_n} \sigma_n - \omega_0 \tau \frac{n_s}{n_n} \frac{B}{|B|} \times \sigma_n \right]^{-1}.
(19)

We note that here Eq.(19) is completely different from the usual two fluid resistivity formula of Eq.(10).

Assuming the rotational symmetry in the sample, the expressions similar to Eqs.(12,13) for the alternative vortex dynamics are
\[
\frac{E_x}{\nabla_x T} = S_n \rho_{xx}^a \sigma_{n,xx} \left[ \frac{n_e}{n_n} (1 + \tan \theta^a \tan \theta_n) + \omega_0 \tau \frac{n_s}{n_n} \frac{B}{|B|} (\tan \theta^a - \tan \theta_n) \right] + \frac{2 e s_\phi}{q e \hbar} \rho_{xx}^a \tan \theta^a,
(20)
\]
and for the Nernst effect as
\[
\frac{E_y}{\nabla_x T} = -\frac{2 e s_\phi}{q e \hbar} \rho_{xx}^a + S_n \rho_{xx}^a \sigma_{n,xx} \left[ \frac{n_e}{n_n} (\tan \theta^a - \tan \theta_n) - \omega_0 \tau \frac{n_s}{n_n} \frac{B}{|B|} (1 + \tan \theta^a \tan \theta_n) \right].
(21)
\]

For the case of small Hall angle terms, where \( \omega_0 \tau << 1 \), we have the ratio
\[
\tan \theta_{th}^a = \frac{E_y}{E_x} = -\frac{n_n}{n_e} \frac{2 e s_\phi}{q e \hbar} \frac{\rho_{n,xx}}{S_n}.
(22)
\]

The same ratio from Eqs.(12,13) is
\[
\tan \theta_{th} = -\frac{2 e s_\phi}{q e \hbar} \frac{\rho_{n,xx}}{S_n}.
(23)
\]

In the low temperature limit, \( \frac{n_n}{n_e} \to 0 \). The normal fluid Seebeck coefficient also goes to zero in the same way as \( n_n \). The entropy \( s_\phi \) carried by a vortex, \( s_\phi \to 0 \) in a rate slower than that of \( n_n \), because its rate is determined by the core level spacing, not by the energy gap as in \( n_n \). Therefore, as lowering the temperature to zero, the ratio \( \tan \theta_{th}^a \) given by Eq.(22) goes to zero, and the ratio \( \tan \theta_{th} \) given by Eq.(23) goes to infinite. Experimentally, it has been found that the magnitude of the ratio goes to infinite in the low temperature limit. This is in agreement with Eq.(23). This also shows that Eq.(22) is in qualitative disagreement with experimental observations. Since Eq.(22) is a direct consequence of Eq.(15), one concludes that this disagreement implies the alternative vortex dynamics model, Eq.(15), is inconsistent with experiments.

V. SUMMARY

To summarize, based on the vortex dynamic equation with the Magnus force and a two-fluid model, relationships between Nernst, Seebeck effects, and the Hall and longitudinal resistivities have been derived in the linear response regime. A unified macroscopic description of the electric and thermoelectric coefficients in the mixed state of superconductors has been obtained. When the Hall angle terms become negligible, we recover previous results. The present derived relationships is consistent with existing experiments. Therefore it provides an additional experimental confirmation for the underlining vortex dynamic equation. The alternative vortex dynamical model with various extra normal fluid dragging force terms is in qualitative disagreement with experiments.

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