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# Fluctuational Ettingshausen effect in single crystals of $YBa_2Cu_3O_{7-\delta}$

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We have studied the Ettingshausen effect in single crystals of $YBa_2Cu_3O_{7-\delta}$ near the superconducting transition temperature $T_c$. Two distinct regimes were found in the field dependence of the Ettingshausen coefficient — a low-field regime where flux-flow dominates and a high-field regime where fluctuation dominates. The result is in agreement with Ullah and Dorsey's scaling theory for fluctuational Ettingshausen effect, and seems also consistent with Maki's mean-field theory when the temperature of the sample is several Kelvins away from $T_c$.

## 1. INTRODUCTION

Ettingshausen effect is a thermomagnetic effect in which a transversal temperature gradient is generated by a longitudinal current together with a magnetic field at the third perpendicular direction. For high-temperature superconductors this effect is usually negligible in normal state, but becomes measurable in mixed state, due to the entropy transfer associated with the vortex motion [1,2]. The study of Ettingshausen effect could provide us useful information on how vortex moves in the mixed state and how vortex degrades as the temperature and/or field is increased above the upper-critical-point. The first, and to our knowledge, the only successful measurement of the Ettingshausen effect on high-temperature superconductors was performed by Palstra and co-workers on a $YBa_2Cu_3O_{7-\delta}$ single crystal [3], where the temperature dependence of the Ettingshausen coefficient was measured at several fixed fields. Here we report the detailed field dependence of the Ettingshausen coefficient in $YBa_2Cu_3O_{7-\delta}$ single-crystal samples at several fixed temperatures near the superconducting transition. Our results reveal that there are two distinct regimes in the field dependence of the Ettingshausen coefficient, one corresponds to flux flow and the other corresponds to fluctuation.


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## 2. EXPERIMENTAL

The samples used in this experiment are $YBa_2Cu_3O_{7-\delta}$ high-quality single crystals with $T_c$ of ~92K and transition width of ~0.3K. An *ac* current of frequency $f$ =12.34Hz was applied to the sample along the *ab* plane, meanwhile a magnetic field was gradually swept in the direction perpendicular to the *ab* plane. The Ettingshausen signal, an *ac* temperature gradient along the third perpendicular direction, was recorded by using a type-E thermocouple, half micro-inch in diameter.

## 3. RESULTS AND DISCUSSION

Ettingshausen coefficient is defined as: $\alpha_{xy} = j^h_y / E_x$, where $E_x$ is the longitudinal electric field, and $j^h_y$ the transversal heat current density due to the effect. $\alpha_{xy}$ can be derived using the data of transversal temperature gradient and the longitudinal resistivity, assuming that the thermal conductivity is nearly a constant in the vicinity of the upper-critical-field [4]. In mixed state $\alpha_{xy}$ is directly related to the transport energy of a vortex: $\alpha_{xy}=U_\phi/\phi_0$ (where $\phi_0$ is the flux quantum).

Figure 1 shows the field dependence of $\alpha_{xy}$, measured on one of the single crystal samples at a current density of $j$=985A/cm$^2$. Similar results were obtained on another sample and at a much lower

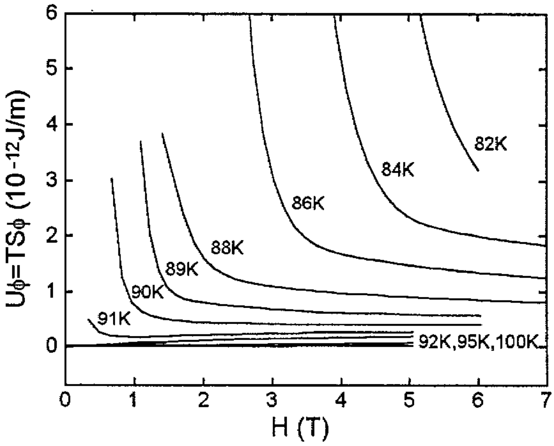


FIG. 1 The field dependence of the Ettingshausen coefficient $\alpha_{xy}$ of a $YBa_2Cu_3O_{7-\delta}$ single-crystal sample.

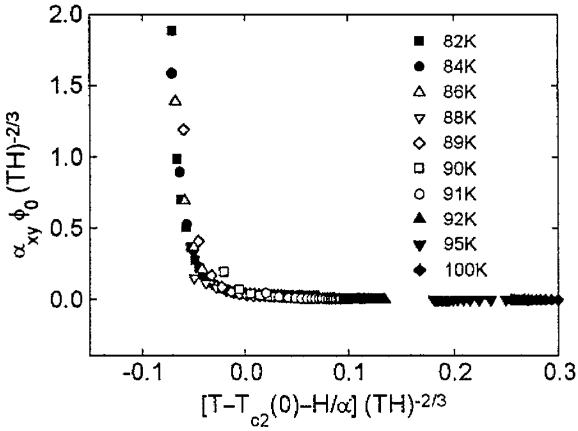


FIG. 2 A test of UD's scaling theory for the Ettingshausen coefficient near the superconducting transition, by taking $T_c$=91.4K and $\alpha \equiv dH_{c2}(T)/dT$=–0.67 T/K.

current density. It can be seen that the field dependence of $\alpha_{xy}$ exhibits two distinct regimes below the zero-field transition temperature $T_c$: a low-field regime where $\alpha_{xy}$ decreases rapidly with the magnetic field $H$, and a high-field regime where $\alpha_{xy}$ flats over with $H$. The behavior of $\alpha_{xy}$ in the low-field regime is consistent with Maki's theory of flux-flow Ettingshausen effect [5], *i.e.*, $\alpha_{xy} \propto H_{c2}(T)-H$ (where $H_{c2}(T)$ is the upper-critical-field). The condition $\alpha_{xy}$=0 naturally defines the $H_{c2}(T)$ of the sample which separates the two regimes. Consequently, above $H_{c2}(T)$ (the high-field regime) is a fluctuation regime. Using the $H_{c2}(T)$ thus obtained, all curves in Fig. 1 seem to scale onto one single curve (Fig. 2), in agreement with Ullah and Dorsey's (UD's) scaling theory for fluctuational Ettingshausen effect [6]:

$$\alpha_{xy}^{3D}(TH)^{-2/3} \propto F_{3D}[\varepsilon_H\,(TH)^{-2/3}] \qquad (1)$$

Besides, we also notice that at temperatures far above $T_c$, *e.g.*, 95K, the Ettingshausen coefficient seems to obey Maki's mean-field theory of fluctuational Ettingshausen effect [7], in which a linear field dependence of $\alpha_{xy}$ is predicted.

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