Angular Resistivity Study in $CeCoIn_5$ Single Crystals

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Abstract. Angular dependent resistivity measurements were performed on $CeCoIn_5$ single crystals at a temperature T of 2.3 K in the low field region ($H \leq 1$ T). The resistivity curves scale below a certain critical angle θ_c ($\theta = 0^o$ when H is parallel to the c-axis). The critical angle θ_c is related with the anisotropy γ of the material. The explicit functional dependence of resistivity on field and angle is obtained based on the time-dependent Ginzburg-Landau theory. The scaling is consistent with this functional dependence.

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Thermal conductivity measurements indicate that $CeCoIn_5$ is in the superclean regime, in which vortex viscosity may be greatly enhanced and leads to anomalous vortex dynamics [1]. It is of great interest to know how vortices behave in magnetic field and to compare this behavior with the one obtained in high transition temperature T_c superconductors.

Angular dependent resistivity measurements were performed at 2.3 K for $H \leq 1$ T. It is found that the resistivity curves scale with the perpendicular field component $H\cos\theta$, which is a result of flux-flow dissipation. We also obtained the explicit functional dependence of the resistivity on field and angle, which is consistent with the scaling observed experimentally.

The single crystal has a T_{c0} = 2.3 K in zero field. The in-plane resistivity ρ_{ab} was determined using an algorithm described elsewhere [2]. The samples were rotated in an applied magnetic field from $H||c$-axis ($\theta = 0^o$) to $H||I||a$-axis ($\theta = 90^o$).

Typical resistivity curves are shown in Fig. 1. The resistivity is largest at $\theta = 0^o$ and decreases monotonically as θ increases. At $\theta = 90^o$, the resistivity has a nonzero minimum, therefore there is still a small amount of dissipation in the system.

In another protocol, we scanned the field and measured ρ_{ab} at fixed angles. A plot of ρ_{ab} vs the perpendicular field component $H\cos\theta$, measured at different angles, is shown in Fig. 2. For angles smaller than a critical angle $\theta_c \approx 54^o$, the different resistivity curves overlap, i.e. the resistivity depends only on the perpendicular field component: $\rho(H,\theta) = \rho(H\cos\theta)$.

Similar scaling behavior in the mixed state was previously reported in $Bi_2Sr_2CaCu_2O_8$ [3] and MgB_2 [4]. In highly anisotropic superconductors like $Bi_2Sr_2CaCu_2O_8$, the magnetic field penetrates in the forms of two dimensional pancake vortices, therefore vortex dissipation depends only on, hence scales with, the field component perpendicular to the ab-planes [5]. On the other hand, based on the anisotropic Ginzburg-Landau theory, Blatter et al. [6] obtained the same scaling expression; i.e., $\rho(H,\theta) = \rho(H,\varepsilon_\theta) = \rho(H\cos\theta)$ for $\theta < \theta_c$, where $\varepsilon_\theta = (\cos^2\theta+\gamma^{-2}\sin^2\theta)^{1/2}$ for superconductors with anisotropy γ. Therefore, this general relationship explains the scaling of the resistivity observed in the mixed state of both highly anisotropic as well as less anisotropic superconductors.

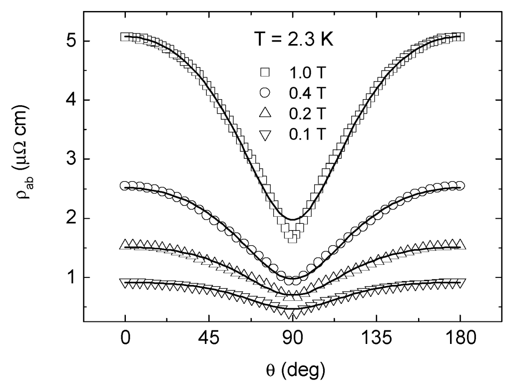

FIGURE 1. Resistivity ρ_{ab} vs angle θ measured at 2.3 K. The solid lines are fits of the data with Eq. (3).

The above scaling implies that the resistivity should depend on field and angle as $H\cos\theta$ for $\theta < \theta_c$. Also note that the data of Fig. 2 show that $\rho(H\cos\theta)$ is nonlinear. Next we obtain an explicit functional

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dependence for resistivity in the mixed state. Consider one coordinate frame *(x,y,z)* associated with the crystallographic axes in which the current I is along the y-axis. Another coordinate frame *(x′,y′,z′)* is obtained by rotating the first one around the x-axis such that z' is always along the magnetic field H and θ is the angle between z and z', hence, the c-axis and H (see Inset to Fig. 3). Based on the dissipation energy conservation and the continuity equation, we write:

$$\frac{j_{yy}^2}{\sigma_{ab}^{(yy)}} = \frac{j_{y'y'}^2}{\sigma_{ab}^{(y'y')}} + \frac{j_{z'z'}^2}{\sigma_{ab}^{(z'z')}} \qquad (1)$$

and

$$\frac{1}{\sigma_{ab}^{(yy)}} = \frac{\cos^2\theta}{\sigma_{ab}^{(y'y')}} + \frac{\sin^2\theta}{\sigma_{ab}^{(z'z')}}, \qquad (2)$$

respectively. The first term on the right hand side of Eq. (2) is the flux-flow dissipation, while the second term is a result of quasiparticle dissipation and thermal activation, which explains the non-zero resistivity at $\theta = 90^o$. Based on the time-dependent Ginzburg-Landau theory, Kopnin calculated the flux-flow conductivity for anisotropic superconductors [7]: $\sigma^{(y'y')} = uaH_{c2}(\theta)\sigma_n(\theta)/2H$, with $u = \xi^2/l_E^2$ (ξ is coherence length and l_E is characteristic length which determines the scale of spatial variations of the gauge-invariant potential Φ), a is a coefficient given by numerical calculations using the vortex order parameter obtained by solving the GL equation, and $H_{c2}(\theta) = H_{c2}/(\cos^2\theta+\gamma^{-2}\sin^2\theta)^{1/2}$. With this expression for $\sigma^{(y'y')}$, Eq. (2) becomes:

$$\rho_{ab}^{(yy)} = \frac{m_1\cos^2\theta}{\sqrt{(\cos^2\theta+\gamma^{-2}\sin^2\theta)^{1/2}}} + \beta\sin^2\theta \qquad , \quad (3)$$

where $m_1 = 2H\rho_n/uaH_{c2}$ and β are fitting parameters; β represents the quasiparticle dissipation. The solid lines in Fig. 1 are fits of the data with Eq. (3). Note that Eq. (3) describes the experimental data very well except in the vicinity of 90°. This small discrepancy could be the result of the lock-in transition in which the dissipation is greatly reduced around 90°. The field dependence of m_1 is plotted in Fig. 3. Note that m_1 is linear in H, which is consistent with its definition.

Equation (3) is also consistent with the scaling $\rho(H\cos\theta)$. Indeed, it gives the scaling when the second term is substantially smaller than the first term and when $\gamma^{-2}\sin^2\theta << \cos^2\theta$, i.e. $\theta << \tan^{-1}\gamma \approx 63^o$ ($\gamma \approx 2$). The first condition is satisfied since in the mixed state the flux-flow dissipation is much larger than the quasiparticle dissipation. The second condition is experimentally satisfied, i.e., $\rho(H\cos\theta)$ scales for $\theta \leq 54^o$ (Fig. 2). This indicates the consistency between the the experimental data and the explicit functional dependence of resistivity given by Eq. (3).

In summary, angular dependent resistivity was measured in the mixed state, which shows

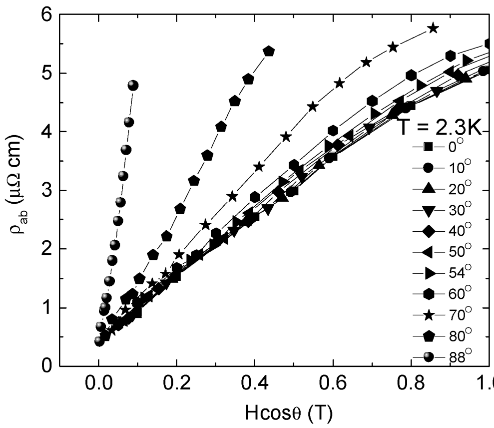

FIGURE 2. Resistivity ρ_{ab} vs the perpendicular field component $H\cos\theta$, measured at 2.3 K and fixed angles θ.

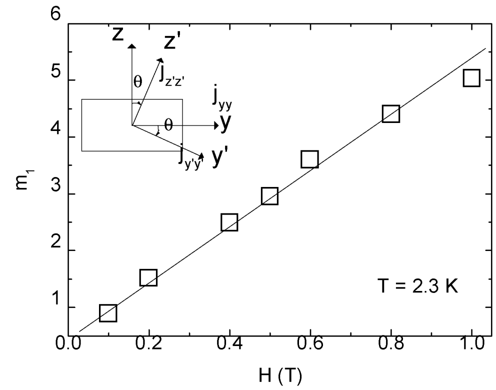

FIGURE 3. The field H dependence of the fitting parameter m_1. The solid line is a guide to the eye.

$H\cos\theta$ scaling, a result of flux-flow dissipation. The explicit functional dependence of ρ_{ab} on H and θ obtained is consistent with the $H\cos\theta$ scaling.

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REFERENCES

1. Y. Kasahara *et al.*, *cond-mat/0506071*.
2. C. N. Jiang *et al.*, *Phys. Rev. B* **55**, 3390 (1997).
3. H. Raffy *et al*., *Phys. Rev. Lett.* **66**, 2515 (1991).
4. Ferdeghini *et al*., *Eur. Phys. J. B* **30**, 147 (2002).
5. P. H. Kes *et al*., *Phys. Rev. Lett.* **64**, 1063 (1990).
6. G. Blatter *et al*., *Phys. Rev. Lett.* **68**, 875 (1992).
7. N. Kopnin, *Theory of Nonequilibrium Superconductivity,* Oxford: Clarendon press, 2001, pp. 238-245.

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