Thermal Conductivity as a Probe of H_{c2} in the Cuprate Superconductor $YBa_2Cu_3O_{6.54}$

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Introduction

What controls the critical temperature T_c in the high-T_c cuprate superconductors is widely considered a key issue in the field of superconductivity. Two paradigms have been proposed to account for the dome-like region of superconductivity [1]. In the first, the amplitude of the superconducting order parameter grows monotonically as the doping p is reduced, but its phase is increasingly disordered [2], causing T_c to fall at low p. This would lead to strong phase fluctuations and a superconducting gap above T_c in the underdoped regime. In the second paradigm, the fall of T_c at low p is due to a state that competes with superconductivity, leading to a small superconducting gap and a small superconducting upper critical field H_{c2} in the underdoped regime. This question is currently a topic of intense debate since the doping dependence of H_{c2}, which has so far been obtained from indirect measurements, is the subject of contradictory reports [3]. This calls for a direct and unambiguous measurement of H_{c2} in underdoped cuprates.

Experimental

We have measured the thermal conductivity κ in ultraclean crystals of underdoped $YBa_2Cu_3O_{6.54}$ (YBCO) as a function of magnetic field at low temperatures. With increasing field, κ was found to exhibit a rapid rise followed by a plateau. With decreasing field, this sharp drop in κ occurs because the long electronic mean free path in the normal state is suddenly curtailed when vortices appear in the sample and scatter the electrons. As such, it is a direct measure of H_{c2}. This is precisely the behavior expected of clean type-II superconductors (see, *e.g.*, ref. [4]), and observed in pure materials such as Nb and KFe_2As_2 (see, *e.g.*, ref. [5]).

Results and Discussion

The direct observation of H_{c2} in a cuprate material with a high T_c is our main finding. Our data at lower and higher temperatures up to 15 K show that $H_{c2}(T)$ is essentially constant in that range. When compared with the vortex-solid melting field $H_{vs}(T)$ determined from high-field resistivity measurements, we observe $H_{c2} = H_{vs}$ in the $T = 0$ limit. This shows that there is no vortex-liquid phase at $T = 0$. With increasing temperature the vortex-liquid phase grows rapidly, causing $H_{vs}(T)$ to fall below $H_{c2}(T)$.

Conclusions

Our measurements provide the first direct measure of H_{c2} in a clean cuprate with a high T_c. The low value of H_{c2} in the underdoped region and the fact that $H_{c2} = H_{vs}$ in the $T = 0$ limit suggest a scenario where, below optimal doping, superconductivity is suppressed by a competing phase, possibly involving charge density-wave order, as recently observed in underdoped YBCO [6].

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References

[1] M.R. Norman *et al.*, *Adv. Phys.* **54**, 715 (2005).
[2] V.J. Emery & S.A. Kivelson, *Nature* **374**, 434 (1995).
[3] J. Chang *et al.*, *Nature Physics* **8**, 751 (2012).
[4] I. Vekhter & A. Houghton, *Phys. Rev. Lett.* **83**, 4626 (1999).
[5] J.Ph. Reid *et al.*, *Phys. Rev. Lett.* **109**, 087001 (2012).
[6] T. Wu *et al.*, *Nature* **477**, 191 (2011); G. Ghiringhelli *et al.*, *Science* **337**, 821 (2012); J. Chang *et al.*, *Nature Physics* **8**, 871 (2012).