The Mixed State in ‘1212’ Superconductors

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INTRODUCTION

Since the discovery of high-temperature superconductors (HTSs), many attempts have been made to explain the vortex state in these materials (Zhu et al., 1999; Kolacek & Vasek, 2000; Kim et al., 2000) but to date no consensus has yet been reached. One particular vortex-state phenomenon that remains controversial is the sign reversal of the Hall resistivity, which is seen in practically all HTSs. A thorough understanding of the mixed state would allow for the understanding of flux pinning in these materials. Aside from solving an old mystery, this would also make it possible to optimize the pinning capability of HTSs. Such optimization would make it possible to greatly improve the current-carrying ability of these materials, thus making them even more viable for industrial applications, especially in power transmission.

This study offers to shed light on these issues by examining and comparing the mixed state of two isomorphic superconductors, TlBa2CaCu2O8-δ (Tl-1212, Tc~ 90 K) and HgBa2CaCu2O8+δ (Hg-1212, Tc~ 120 K). Since the structural anisotropy of these two are practically identical, any similar properties in their mixed state could be ascribed mainly to the physical structure of an HTS and any dissimilar properties could be ascribed mainly to the electronic structure of an HTS. The 30-K difference in the Tc of these species has been ascribed to differences in electronic structure, primarily the redistribution of oxygen in the unit cell as a result of exchanging Tl²⁺ cations with Hg²⁺ cations (Gapud et al., 1999). This study is also expected to shed more light on this possibility. It is also possible for such oxygen redistribution to alter mixed-state behavior.

The following phenomena were studied in particular: (1) transitions in the H-T phase diagram, (2) the behavior of the mixed-state component of the Hall angle, tan θH, and (3) the sign reversal of Hall resistivity.

EXPERIMENTAL DETAILS

High-quality, thin-film samples (thickness of around 0.7 µm) were used in this study. The Hg-1212 films were fabricated using a recently patented cation exchange process (Wu et al., 1999; Yan et al., 1998) in which Tl-1212 precursor films are converted into Hg-1212 films. Because of this, the superconducting ‘1212’ layered structure is preserved under the cation exchange. The Tl-1212 films were fabricated using a modified crucible process (Siegal et al., 1997; Siegal et al., 1998) in which DC-sputtered superconducting films were further improved by annealing in Tl vapor.

Basically, two measurement programs were conducted: (1) Magnetoresistivity, both as a function of temperature and field, and (2) Hall resistivity. In both, thin (38 µm) Pt-wire leads were fused to DC-sputtered silver contacts using silver adhesive, making for negligible contact resistance signal-to-noise ratio of at least ~10⁶.
Thermovoltaic effects were eliminated by taking data while reversing the current at about 1 Hz. Resolutions are as follows: temperature, ~0.01 K; voltage, ~10 nV; current, ~10 μA. Magnetic fields of 0 to 5.5 T were provided at the central core of a 6-T superconducting magnet.

Transition lines in the H-T phase diagram were determined from measurements of magneto resistivity and from current-voltage (I-V) data. In all these measurements, a four-point configuration was used. Hall measurements utilized a five-point contact configuration, and any misalignment effects were eliminated by taking data for reversed magnetic field.

DISCUSSION OF RESULTS

The irreversibility lines of 1212 species were already shown to overlap when H is plotted against reduced temperature, T/T_c, which supported the assertion that the 30-K difference in T_c is largely independent of the physical structure (Gapud et al., 1999). Fig. 1 shows that the other transition lines overlap as well. H_c2(T) was obtained from constant-field resistivity curves by defining the temperature T at which the resistivity in field H = H_c2 is halfway into the transition to superconductivity. H'(T) line was obtained in a similar way, but with the temperature T being the critical temperature for the field H = H'. Between H' and H_c2 another transition had been found, the H_v line, defined as the field above which magneto resistivity has H^1/2 dependence, thus marking a transition to thermally activated flux flow or a “real” vortex liquid from a “glassy” vortex liquid (Kang et al., 1998). Since these transitions are determined mainly by intrinsic pinning mechanisms, which in turn are largely dictated by physical anisotropy, such overlap for an isomorphic pair is not surprising.

The mixed-state behavior of tan θ_H is obtained by subtracting the normal-state portion, A H/T^2, which leaves tan θ_H = tan θ_m - A H/T^2. A is the slope obtained from plotting tan θ_m/H versus T^2 for each constant-field curve. tan θ_m is plotted for both species in Fig. 2. Above a certain temperature, the curves of each species overlap, signifying field independence – and therefore independence of pinning effects. Below this temperature, one would expect to see effects due to pinning. But here one sees divergent behavior between the two species which is too subtle to be detected in the H-T phase diagram.

This is consistent with differences in the Hall sign reversal for both species. Fig. 3, also plotted in reduced temperature, T/T_c, at all fields, Hg-1212 has a much greater tendency towards double sign reversal than Ti-1212, with a subtle double reversal at 4 T. At first
glance, the implications of Fig. 2 and Fig. 3 seem to contradict those of the H-T phase diagram, Fig. 1, which implies that the intrinsic pinning is similar for both species. However, the magnetically divergent behavior in $\tan \theta_m$ and in the Hall sign reversal is not necessarily due to differences in pinning. There is already evidence that Hall sign reversal is not affected by artificial pinning sites but is dependent on the doping level, which is also consistent with the time-dependent Ginzburg-Landau model (Kopnin et al., 1993), one of the popular models to date. Sign reversal has been shown to occur mainly for underdoped HTSs (Nagaoka, 1998), and the second sign reversal occurs for the lowest doping levels (Kang et al., 1999).

The results therefore imply that the electronic structure of Hg-1212 and TI-1212 differ such that Hg-1212 is actually at a lower doping level than TI-1212. It would seem, then, that the divergent magnetic behavior in the mixed state as illustrated by $\tan \theta_m$ is more an effect of differing doping levels and less an effect of pinning.

Since there is a magnetic dependence in this regime, this further suggests the existence of differing spin structure between the species, either as a result of the different properties of the Hg$^{2+}$ cation and the Tl$^{3+}$ cation, or the different distribution of oxygen, or both, and this could provide an important mechanism behind the 30-K difference in their $T_c$.

In summary, similar pinning continues to be observed in '1212' superconductors Hg-1212 and TI-1212, but observations in the mixed state have uncovered and magnified subtle differences in the electronic structure behind the 30-K difference in $T_c$, implying that TI-1212 is actually less underdoped than Hg-1212. The exchange of cations and/or the resultant redistribution of oxygen could also produce a difference in magnetic spin structure, causing magnetically divergent behaviors only seen in the mixed state. All this strongly suggests that the vortex state in HTSs is governed more by doping level, electronic structure, and spin structure, than by intrinsic pinning.
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REFERENCES


