Depairing field, onset temperature and the nature of the transition in cuprates

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Abstract

The depairing (upper critical) field H_{c2} in hole-doped cuprates has been inferred from magnetization curves M-H measured by torque magnetometry in fields H up to 45 T. We discuss the implications of the results for the pair binding energy, onset temperature, fluctuation diamagnetism and the nature of the Meissner transition at T_c.

Key words: Magnetization, Upper Critical Field, Vortex Liquid, Cuprates
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In hole-doped cuprates, the depairing field at which the pair condensate is destroyed (or "upper critical field" H_{c2}) has been notoriously difficult to measure. Recently, progress has been achieved using the vortex-Nernst effect [1–3] and high-field torque magnetometry [4,5].

High-field measurements of M are technically difficult because the large Ginzburg-Landau parameter, small crystal volumes (0.1-0.3 mm^3) and high field scales of H_{c2} (50-200 T) all result in a very small sample moment. Fortunately, torque magnetometry is well-suited for this purpose [6]. The crystal is glued to the end of a soft cantilever with its axis **c** at a small angle to **H**. The observed magnetization $M_{eff} = \Delta\chi H_z + M(T, H_z)$, where $M(T, H_z) < 0$ is the magnetization produced by supercurrents ($\hat{\mathbf{z}}||\mathbf{c}$ and T is the temperature). The dominant contribution to the paramagnetic background $\Delta\chi$ comes from the strongly anisotropic orbital (van Vleck) term χ_i^{orb}. Its weak T-linear behavior allows the diamagnetic term M to be extracted with high resolution [5]. Here we discuss some of our torque measurements on $La_{2-x}Sr_xCuO_4$ (LSCO), $Bi_2Sr_{2-y}La_yCuO_6$ (Bi 2201) and $Bi_2Sr_2CaCu_2O_8$ (Bi 2212) from the underdoped (UD) to overdoped (OD) regimes.

Figure 1 shows the M-H curves in optimally-doped (OP) Bi 2212 ($T_c \sim 86.5$ K) at temperatures 35 to 90 K (left panel), and from 80 to 110 K (right panel). The curves are all fully reversible (pinning effects appear only below 35 K at low fields < 1 T). At the lowest T, the curve of M vs. H is very similar to that in a low-T_c type II superconductor. Above H_{c1}, $|M|$ decreases as $\log H$ over a very broad field range. A notable feature is the very high H_{c2}, which we estimate to be 150-200 T by extrapolation. (These values are much larger than inferred from measurements of the resistivity ρ vs. H. The "knee" feature in ρ usually used to fix "H_{c2}" actually occurs just above the vortex-solid melting field $H_m \ll H_{c2}$.)

As T nears T_c, a major difference from BCS superconductors emerges. There, $H_{c2}(T)$ decreases to zero linearly, viz. $H_{c2}(T) \sim t$ with $t = 1 - T/T_c$. Accordingly, the high-field limit of M in Fig. 1b should decrease and reach zero at T_c. Instead, we find that

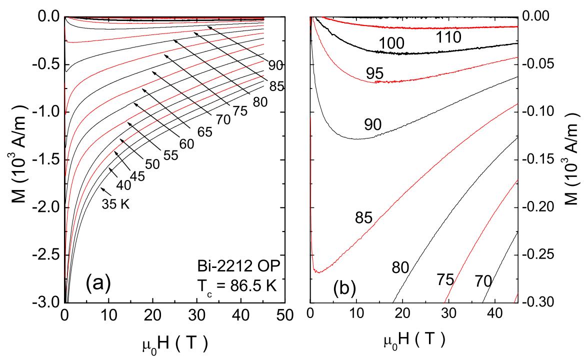

Fig. 1. Magnetization curves M vs. H in OP Bi 2212 at T = 35-90 K (Panel a) and at T = 75-110 K (b). At low T, $|M| \sim \log H$ initially, but goes to zero at H_{c2} = 150-200 T. Notably, $H_{c2}(T)$ shows no tendency towards zero as $T \to T_c^-$. Above T_c (86.5 K), $|M|$ remains quite large in fields up to and above 45 T.

it remains high above our maximum field (45 T), even when T exceeds T_c (right panel). The diamagnetic signal remains quite large at 45 T up to 110 K.

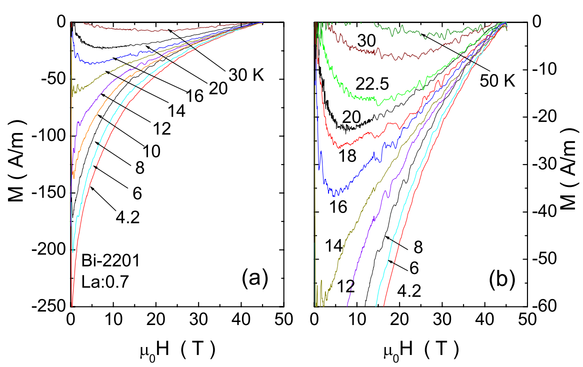

Fig. 2. Magnetization curves M vs. H in UD Bi 2201 shown for T = 4.2-30 K (Panel a), and in expanded scale (Panel b). At each T, the field at which $|M| \to 0$ is taken to be $H_{c2}(T)$. The convergence of all curves implies that $H_{c2(T)}$ is independent of T to our resolution. Above $T_c \sim 14$ K, M remains sizeable and strongly H dependent.

This key feature – seen in all the hole-doped cuprates studied – is most apparent in single-layer UD Bi 2201, where complete suppression of diamagnetism is attainable below 45 T. Figure 2 shows the M-H curves in a crystal with $T_c \sim 14$ K. Hysteretic behavior is not observed down to 4 K. In comparison with OP Bi 2212, the magnitude $|M|$ in weak H and low T is quite a bit smaller (250 A/m compared with 4000 A/m), but it displays the same $\log H$ dependence in $H < 20$ T. At high fields, M approaches zero at the field $H_{c2}(0) \sim 43$ T. In Panel b, we show that $H_{c2}(T)$ remains nominally T-independent even above T_c. In the interval around T_c, the M-H curves display the same pattern as shown for OP Bi 2212. Significant diamagnetism remains at T up to 30 K.

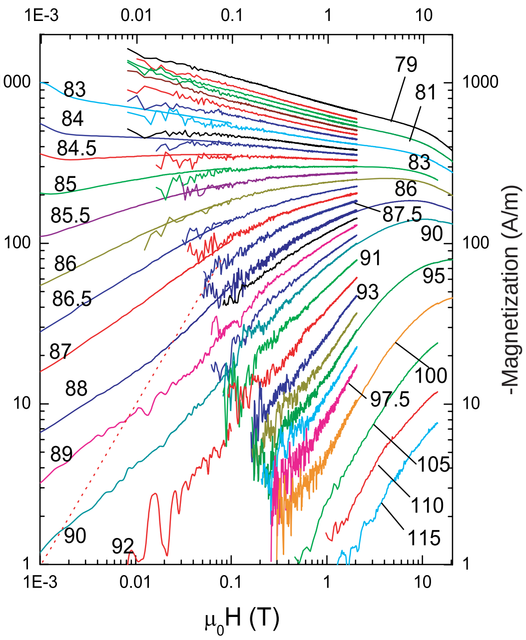

Fig. 3. The field dependence of $M(T, H)$ in OP Bi 2212 from H = 10 Oe to 20 T at T = 79-115 K. The log-log plot shows that, as $H \to 0$, $M(H)$ follows the fractional power-law $M \sim H^{1/\delta}$. The plot combines SQUID results (10 to 1000 Oe) and toque magnetometry results (500 Oe to 2 T). Torque results up to 20 T are also shown at selected T. Linear response $M \sim H$ at 87 K would appear as the dashed line (from Ref. [4]).

The diamagnetic signal M above T_c is robust to fields of 45 T and considerably larger in magnitude than "fluctuating diamagnetism" in low-T_c superconductors [9]. We discuss why the fluctuations are distinctly non-Gaussian. In BCS superconductors, a key feature is the linear decrease to zero of the T-dependent critical field $H_{c2}(T)$ as $T \to T_c^-$. This feature dictates the behavior of fluctuations above T_c in Gaussian GL treatments. In particular, t enters in $M(t, h)$ as the ratio $|t|/h$. Consequently, above T_c, the field dependence of M is dictated by the field scale $H_{c2}(0)t$, which is the "mirror image" of $H_{c2}(T)$, vanishing linearly in $|t|$ as $T \to T_c$ from above. Accordingly, M measured in low-T_c superconductors are nicely scaled when plotted in terms of the "Prange" variable $x = [\frac{dH_{c2}}{dT}]_c(T - T_c)/H \sim 1.4|t|/h$ [9].

As noted above, $H_{c2}(T)$ does not vanish linearly in $|t|$ in hole-doped cuprates [3–5]. This invalidates the Gaussian approach which depends on series expansion in terms of the order parameter and its derivative. Above T_c, the M-H curves in Bi 2212 are also qualitatively different from low-T_c superconductors. Instead of linear response, the M-H curves are strongly nonlinear even in low H. Figure 3 shows in log-log scale the variation of M over a broad range of H (10 G to 30 T) at $T = 79$-115 K. As emphasized in Fig. 4a, the M-H curves display strong curvature at temperatures near $T_c = 87$ K. In weak H, $M(H)$ fits well to the power law

$$|M| \sim H^{1/\delta}, \tag{1}$$

with a strongly T dependent exponent $\delta(T)$. Between T_c and 105 K, $\delta(T)$ decreases from ~ 10 to 1 (Fig. 4b). The vanishing of $\delta(T)$ defines the temperature T_s slightly below T_c at which M is *independent* of H up to a few T (this feature – dubbed the separatrix [4] – has been known for a long time).

These anomalous magnetization patterns are incompatible with Gaussian fluctuations, but consistent with the phase-disordering scenario [7] in which, above T_c, the condensate amplitude is large, but phase rigidity and long-range phase coherence are lost. Near T_c, the M-H curves are strikingly similar to those calculated for a 2D superconductor near its Kosterlitz Thouless (KT) transition [8]. As discussed later, the appropriate comparison is with the 3DXY model with very large anisotropy.

The M-H curves in Figs. 1-3 together imply the following physical picture (see Ref. [4]). On cooling from 300 K, the system first crosses the pseudogap temperature T^*. The pseudogap affects primarily the spin degrees of freedom, especially the relaxation rate $1/T_1T$ in NMR and the bulk susceptibility. Evidence for Cooper charge pairing appears only at $T_{onset} = 0.5$-$0.7\ T^*$. Below T_{onset} (the "Nernst" region), both the Nernst signal and diamagnetism increase steeply to merge smoothly with the corresponding signals below T_c. Within each CuO_2 layer, the pair condensate is robust with a very large pair-binding energy. However, because of thermal generation of mobile 2D vortices, phase coherence is confined to a length scale given by the phase correlation length ξ_ϕ [4]. The "hot 2D vortex liquid", nonetheless, displays a fairly large diamagnetic response.

It is instructive to contrast cuprates from a percolative system (e.g. granular Al) in which superconducting islands are gradually phase coupled by the proximity effect as T decreases. In high-quality crystals of the cuprates, the zero-field transition is invariably very sharp. At T_c, full flux expulsion appears [4]. The resistive transition is also abrupt, in contrast to the long tail seen in granular Al.

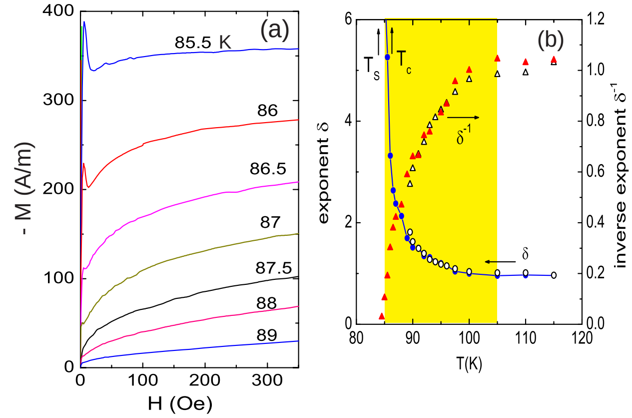

Fig. 4. (Panel a) The weak-field M-H curves near T_c (= 87 K) in OP Bi 2212. The power-law variation with fractional exponent is evident in all curves shown. Below T_c, full flux expulsion occurs for $H < H_{c1}$ (visible as a spike). The curve at 85.5 K is very close to the separatrix temperature T_s. Panel (b) displays the T dependence of the exponent $\delta(T)$ (circles) for 2 crystals of OP Bi 2212. The reciprocal $\delta(T)^{-1}$ is plotted as solid and open triangles for the 2 samples. As $T \to T_s^+$, $\delta(T)^{-1}$ decreases smoothly to 0. In the shaded region where $\delta > 1$ (from T_s to 105 K), linear magnetic response is absent even at 10 Oe (adapted from Ref. [4]).

Two features seem to be crucial. The first is the pre-emption of the 2D KT transition in individual layers by the 3D transition caused by interlayer coupling, as occurs in layered magnets [10]. Below $T_{onset} \sim 130$ K, the in-plane ξ_ϕ (inferred from the susceptibility $\chi = M/H$) grows as in the KT transition [4]. Below 105 K, however, M becomes increasingly non-linear (Fig. 4a). The increase in $\delta(T)$ reflects rapid upward renormalization of the interlayer coupling strength. In the interval between T_c and 105 K, the fractional power-law implies that χ can approach -1 in the limit $H \to 0$. However, this London rigidity is fragile and easily suppressed by field. At T_c ($\sim$2 K above T_s), the Meissner state appears [4]. As apparent in Fig. 4a, full flux expulsion occurs below the lower critical field $H_{c1}(T)$, seen as sharp spikes in Fig. 4a. Significantly, the 3D Meissner state is observed at fields $H < H_{c1}$, yet at higher H (> a few T), the M-H profiles revert to the 2D pattern seen high above T_c. This field-induced crossover from 3D to 2D behavior – with its intrinsic non-monotonicity – is very different from low-T_c superconductors.

The second feature is the termination of the melting curve $H_m(T)$ at T_c. Far from being accidental, we believe this is intrinsic to the nature of the transition. Within the vortex-solid state, spontaneously created vortices are ineffectual in destroying phase coherence because they are not able to diffuse. Hence, T_c cannot lie below the high-T termination of $H_m(T)$. On the other hand, T_c cannot lie above the termination point. This would correspond to a strictly 2D transition that is incompatible with the observed full Meissner effect. These 2 features distinguish the cuprate transition from that in granular Al.

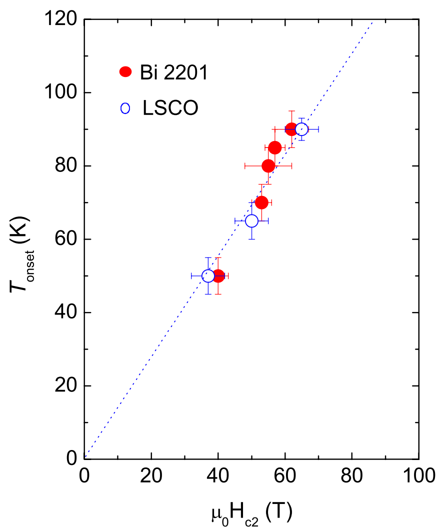

Fig. 5. Plot of T_{onset} vs. $H_{c2}(0)$ in the single-layer cuprates Bi 2201 and LSCO. Both quantities are inferred from the M vs. H curves measured by high-field torque magnetometry. The broken line is Eq. 2 with $g \simeq 2.1$.

Lastly, we discuss an interesting relation between H_{c2} and T_{onset}. Measurements on several Bi 2201 and LSCO crystals from UD to OD regime reveal that $H_{c2}(0)$ and T_{onset} (measured from both the Nernst signal and magnetization) scale together as shown in Fig. 5. Within the experimental uncertainties, T_{onset} is linear in $H_{c2}(0)$. Expressing $H_{c2}(0)$ as a Zeeman energy, viz.

$$k_B T_{onset} = g\mu_B H_{c2}(0), \quad (2)$$

we find that the g-factor $g \simeq 2.1$ (μ_B is the Bohr magneton). The data in Fig. 5 are restricted to Bi 2201 and LSCO. As noted in Fig. 1, $H_{c2}(0)$ in OP Bi 2212 is much larger given its T_{onset} ($\sim$130 K). Figure 5 ties together the energy scale implied by T_{onset} and the pair binding energy at low T for Bi 2201 and LSCO. The linear fit with $g \sim 2.1$ suggests that the Pauli limit may be relevant to the high-field depairing process. The implication of this relationship is currently being explored.

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