Vanishing of the upper critical field in $Bi_2Sr_2CaCu_2O_{8+\delta}$ from Landau-Ott scaling

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We apply Landau-Ott scaling to the reversible magnetization data of $Bi_2Sr_2CaCu_2O_{8+\delta}$ published by Wang *et al.* [Phys. Rev. Lett. **95**, 247002 (2005)] and find that the extrapolation of the Landau-Ott upper critical field line vanishes at a critical temperature parameter T_c^* a few degrees above the zero resistivity critical temperature T_c. Only isothermal curves below and near T_c were used to determine this transition temperature. This temperature is associated with the disappearance of the mixed state instead of a complete suppression of superconductivity in the sample.

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There are conflicting views about the nature of the upper critical field $H_{c2}(T)$ in the present literature, possibly because this concept involves multiple distinct phenomena. The traditional Abrikosov[1] view is of densely packed vortices with nearly touching cores that make the normal state percolate inside the superconducting state. The collapse happens at a well defined temperature T_c because the coherence length $\xi(T)$, which sets the vortex core area, diverges at T_c, making the upper critical field $H_{c2}(T)=\Phi_0/2\pi\xi(T)^2$ vanish there $[H_{c2}(T\to T_c)\to 0]$. Recently, this view was challenged by Wang *et al.*[2,3] who proposed a quite distinct scenario for $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi 2212). Their T_c just sets the loss of phase coherence but not of the diamagnetic superconducting signal. Therefore, they suggested that Cooper pairs still exist above T_c, and so do the vortices. Consequently, the field $H_{c2}(T)$ does not vanish at T_c and, in fact, can be quite large there. Their view has grown out of the Nernst effect[2] and sensitive torque magnetometry[3] experiments. The latter remarkably contain isothermal magnetization curves below and also *above* T_c. They report on two new temperatures above T_c, the highest one, T^*, associated with local correlations affecting spin degrees of freedom and the lowest one, T_{onset}, with the onset of vorticity and supercurrents. The vanishing of the upper critical field takes place at a much higher temperature, where the Nernst signal extrapolates to zero. In practical terms, the upper critical field becomes an inherently unmeasurable quantity for the high-T_c materials[3] in this scenario.

In this Brief Report, we apply a scaling method developed by Landau and Ott[4] to the reversible magnetization data obtained from the torque magnetometry measurements of Wang *et al.* and report a temperature T_c^*, above T_c, which does not coincide with any of the above temperatures and, in fact, is much lower than T_{onset}. The upper critical field and the Nernst effect are related through the transport entropy per unit length of the vortex line. In fact, the Nernst coefficient is just the product of the transport entropy per unit length of the vortex line and the resistivity. The Caroli-Maki-Hu relation[5–8] provides the way to connect the transport entropy per unit length of the vortex line to the reversible magnetization $M(H,T)$, which in turn leads to the upper critical field. This last connection can be achieved, for instance, using the celebrated Abrikosov expression:[1,9]

$$M(H,T)=\frac{H_{c2}(T)-H}{\beta_A(2\kappa^2-1)}, \tag{1}$$

where β_A is a constant that depends on the vortex arrangement and κ is the Ginzburg-Landau parameter, an intrinsic property of the superconductor. It turns out that this expression is also the starting point for Landau and Ott who proposed a traditional view of the upper critical field and applied it successfully to several of the high-T_c materials,[4,10–14] including Bi 2212. Their proposal renders a scaling method that can be directly sought in the transport entropy per unit length of the vortex line obtained from the Nernst effect, but this is not done here. Remarkably, this scaling procedure retrieves a nearly linear borderline in the H vs T diagram very similar to the original Abrikosov proposal described by Eq. (1). This is quite a surprising fact, considering that these boundary lines for the high-T_c materials, including Bi-2212, usually display an upward (positive) curvature, such as for the irreversibility line[15] and also for the melting transition line.[16,17] The Landau-Ott approach relies on the very basic assumption that the magnetic susceptibility $\chi(h)\equiv M(H,T)/H$ is a sole function of the reduced field $h=H/H_{c2}(T)$, such that all its temperature dependence is contained in the upper critical field. Their proposal is inspired by Eq. (1), which does satisfy this condition in the case that κ is a temperature independent parameter. From this assumption, the scaling relation connecting magnetization values at two different temperatures, T_0 and T, may be derived as follows:

$$M(H,T_0)=M(h_{c2}H,T)/h_{c2}, \tag{2}$$

where $h_{c2}=H_{c2}(T)/H_{c2}(T_0)$. This relation implies that all isothermal reversible magnetization curves collapse into a single curve by a judicious choice of the parameter $h_{c2}(T)$. The collected set of scaling parameters $h_{c2}(T)$, once plotted versus T, leads to the curve $H_{c2}(T)$ once $H_{c2}(T_0)$ is explicitly known. In this way, Landau and Ott retrieved their $H_{c2}(T)$ curve from the background-free reversible magnetization of many high T_c materials. A direct consequence of their method is the existence of a temperature parameter T_c^*, where the upper critical field extrapolates to zero: $H_{c2}(T_c^*)=0$. This temperature has been found to coincide with T_c for the high-

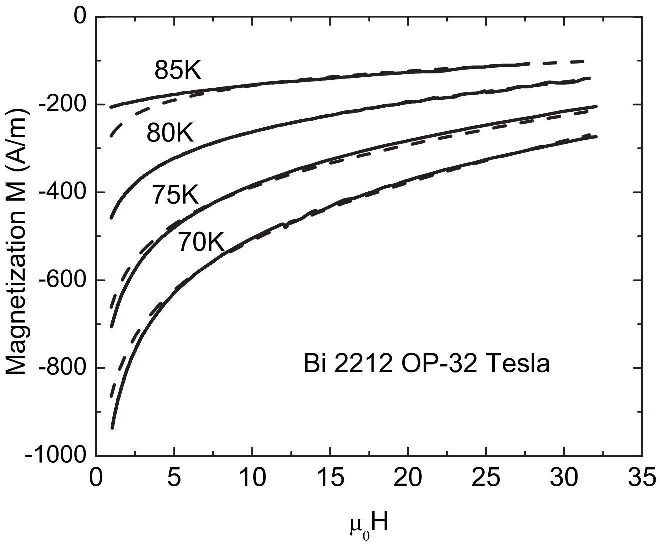

FIG. 1. Isothermal magnetization versus applied field lines are shown here. The solid lines are retrieved from Ref. 2 for the (OP) Bi2212 compound and correspond to the temperatures of 70, 75, 80, and 85 K. The dashed lines are polynomial fits obtained through Eq. (3) and are referred to as M_{eff} curves in the text.

T_c materials,[4,10–14] a fact that has been invoked by Landau and Ott as indicative of the correctness of their method. Recently, their analysis was applied to the low-T_c materials[18,19] and there, these two temperatures were also found to coincide.

We report here that the $H_{c2}(T)$ curve, as obtained from the torque magnetometry data of Wang *et al.* for Bi2212, does not vanish at T_c according to the Landau-Ott scaling. Wang *et al.* considered two compounds, underdoped (UD) and optimally doped (OP) Bi 2212, with T_c equal to 50 and 87.5 K, respectively. Two kinds of field sweeps were used to obtain their isothermal curves. The first one takes a field range up to 14 T for both the UD and OP compounds, and the second a range of 32 T, but in this last case, measurements were only taken for the OP compound. We applied the Landau-Ott scaling to these data sets and found the striking result that T_c^* is equal to 57 K for the UD compound and 93 K for the OP compound, significantly higher than the corresponding T_c values, even considering the maximum error bar of 0.8 K in our calculations. To determine the temperature T_c^*, we have only considered the isothermal magnetization curves of Wang *et al.* that fall under two conditions: (1) below and (2) close to T_c. This is the temperature range that the Landau-Ott scaling must hold although it was found to hold relatively much below T_c for some low-temperature compounds.[18]

Figure 1 shows the fitting of four isothermal magnetization curves to the polynomial

$$M_{eff}(H) = h_{c2}\sum_{i=0}^{n} A_i[\ln(H/h_{c2})]^i + c_0 H. \quad (3)$$

Wang *et al.* reported that their fully reversible magnetization data have the paramagnetic background carefully removed. We notice that a parameter c_0 still had to be included here. This parameter is part of the Landau-Ott prescription for the removal of a residual background field. Figure 1 shows (solid lines) the four closest curves to T_c obtained from Fig. 4(a) of Ref. 2 for the OP compound that belong to the 32 T data set: 70, 75, 80, and 85 K. The 80 K data curve is taken as the reference curve ($h_{c2}=1$). For instance, we achieved a fairly good description of it through a fourth order polynomial ($n=4$) with coefficients (A_4,A_3,A_2,A_1,A_0) equal to (+0.6438, −2.2732, +2.9544, +81.0093, −455.1729). The remaining three isothermal curves are also fitted by this polynomial with the (h_{c2},c_0) parameters equal to (1.73, −1.55), (1.37, −0.7), and (0.64, 2.5) for the 70, 75, and 85 K curves, respectively. The average mean square deviation from this fit is of the order of 3% for these three curves and of the order of 0.07% for the 80 K curve. The same kind of polynomial analysis was applied for the 14 T data sets, obtained from Fig. 2(a) and 2(b) of Ref. 2 for the UD and OP compounds, respectively. The major plots of Fig. 2 show the collapsed curves after the Landau-Ott scaling. The original isothermal magnetization curves are shown in the insets. Notice that, firstly, a residual background must be removed to obtain M_{eff}, as previously explained. Figure 3 shows the collected scaling parameters $h_{c2}(T)$ for the selected set of temperatures. Surprisingly, their linear fit extrapolates away from T_c, revealing the existence of the temperature parameter T_c^*. Notice that this analysis was done for the OP compound using both the 14 and 32 T data sets and both render virtually the same T_c^*, with less than 0.8 K difference. We stress that the present results are invariant under the choice of the reference isothermal curve. To check this, we have taken in Fig. 3 the

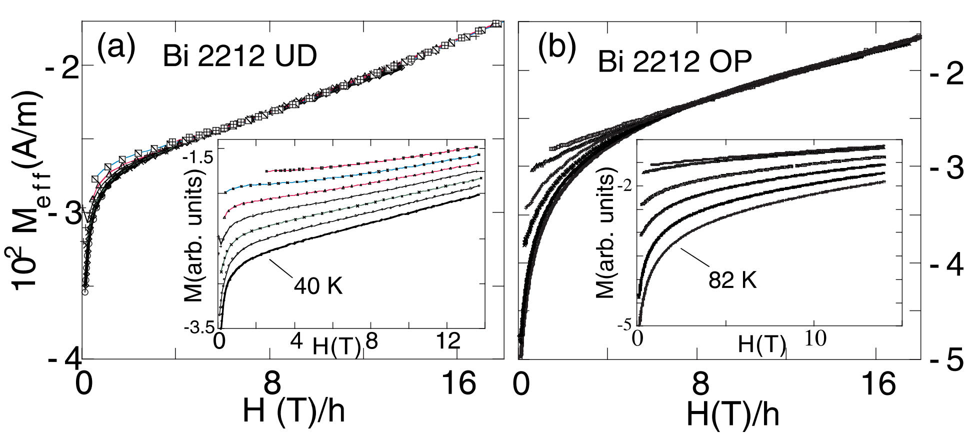

FIG. 2. (Color online) Isothermal curves (UD: T=40, 41, 42, 43, 44, 45, and 46 K; OP: 82, 83, 84, 85, 86, and 86.3 K) are scaled according to the Landau-Ott scaling.

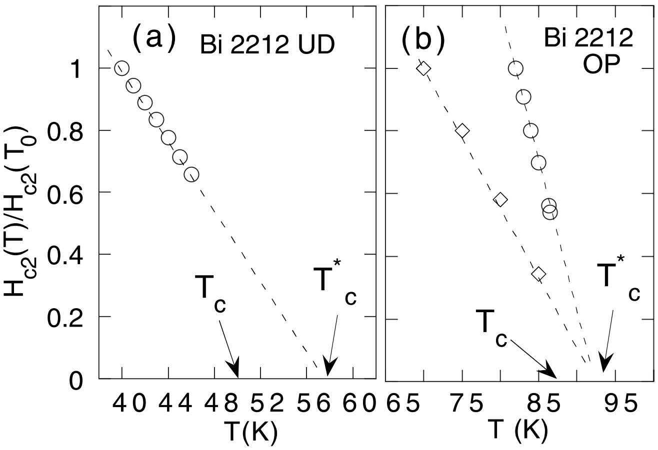

FIG. 3. $H_{c2}(T)$ obtained through the Landau-Ott scaling normalized by the T_0=40 K (OD, 14 T), 70 K (OP, 32 T), and 85 K (OP, 14 T) curves. The linear extrapolation to zero field defines the temperature T_c^*.

70 K curve as the reference isothermal curve, thus differently from Fig. 1, which takes the 80 K curve instead. Again, we have obtained the same T_c^* under the same precision window.

Figure 1 shows that the polynomial fits break down at low field. These fits are good within a window of nearly 25 T, which does not include the approximately initial 5 T range. In this low field range, the fits overestimate the diamagnetism well below T_c and underestimate it close to T_c. So it is conceivable that the H_{c2} data points of Fig. 3 can be affected by this polynomial fit break down. Besides, the H_{c2} points, lower than those reported in Fig. 3, could make this line turn down and extrapolate to the observed T_c value or, at least, to a T_c^* lower than the values indicated in Fig. 3.

In support for the existence of a distinct critical temperature T_c^*, we notice that long ago, Huebener and co-workers[20–22] had to introduce a new temperature in their best fit analysis of the reversible magnetization obtained from the Nernst effect. In other words, the $YBa_2Cu_3O_{7-\delta}$ data that best fit to Eq. (1) yields an upper critical field that extrapolates to zero away from T_c. They reported a zero resistivity transition temperature equal to 93.0 K (see Table I of Ref. 21) which does not coincide with the higher temperature of 93.8 K found by extrapolation of their upper critical field line to zero (see Fig. 8 of Ref. 21).

In conclusion, we find here that the Landau-Ott scaling applies to the data of Wang *et al.* and removes the extremely large upper critical field values near T_c because now, $H_{c2}(T)$ vanishes at T_c^*, a parameter not considered in their analysis. Wang *et al.* fitted Bi 2212 and also $NbSe_2$ magnetic torque data to $M \sim -[H_{c2}(T)-H]$ [Eq. (1)] to show that the high-T_c materials have unusual behavior as compared to the low-T_c materials. They found that Abrikosov's picture holds for $NbSe_2$, since $H_{c2}(T)$ vanishes near T_c, but not for Bi 2212, where it is extremely large: $H_{c2}(86\text{ K})=90$ T. According to the Landau-Ott view,[4] the $H_{c2}(T)$ curves of Fig. 3 set the disappearance of the mixed state rather than to a complete suppression of superconductivity in the sample. Thus, the present view of $H_{c2}(T)$ is not inconsistent with incoherent superconductivity above T_c, whose onset and disappearance must be referred by names other than $H_{c2}(T)$.

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