Total suppression of superconductivity by high magnetic fields in \(\text{YBa}_2\text{Cu}_3\text{O}_{6.6}\)

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(Dated: March 23, 2022)

We have studied in fields up to 60T the variation of the transverse magnetoresistance (MR) of underdoped \(\text{YBCO}_{6.6}\) crystals either pure or with \(T_c\) reduced down to 3.5K by electron irradiation. We evidence that the normal state MR is restored above a threshold field \(H'_c(T)\), which is found to vanish at \(T'_c > T_c\). In the pure \(\text{YBCO}_{6.6}\) sample a 50 Tesla field is already required to completely suppress the superconducting fluctuations at \(T_c\). While disorder does not depress the pseudogap temperature, it reduces drastically the phase coherence established at \(T_c\), and weakly \(H'_c(0)\), \(T'_c\) and the onset \(T'_c\), of the Nernst signal which are more characteristic of the 2D local pairing.

PACS numbers: 74.25.Fy, 74.40.+k, 74.62.Dh, 74.72.Bk

Since the discovery of high temperature superconductivity the knowledge of the normal state properties of the cuprates at \(T < T_c\) has been somewhat hard to explore since the upper critical fields of these materials are usually much higher than any available experimental field. This has only been possible using very high field facilities in systems with relatively low \(T_c\) such as \(\text{La}_{2-x}\text{Sr}_x\text{CuO}_4\) (LSCO) \(^1\) or \(\text{Bi}_{2}\text{Sr}_{2-}\text{La}_x\text{CuO}_{6+\delta}\) (La-Bi2201) \(^2\).

In fact, the determination of \(H_{c2}\) in high-\(T_c\) cuprates remains a controversial issue. It was pointed out for long that taking \(H_{c2}(T)\) from the onset of the resistive transition in magnetic fields is questionable, due to the large liquid flux regime above the melting line. This leads to a \(T\) dependence of \(H_{c2}\) with an upward curvature, similar to that found for the irreversibility line deduced from the zero resistivity values \(^3\)\(^4\). Other authors have analysed the magnitude of the magnetoconductance fluctuations near \(T_c\) in a Ginzburg Landau formalism to obtain the coherence length and then \(H_{c2}\) \(^5\)\(^6\). These approaches assume that \(T_c\) is altogether the onset of the amplitude of the superconducting order parameter and of phase coherence, at variance with Emery and Kivelson’s proposal \(^7\) that only the phase coherence is broken at \(T_c\), while the condensate amplitude remains finite. This suggestion has gained strong support from high frequency conductivity measurements of the short time scale phase coherence \(^8\). Further support has been provided by the observation above \(T_c\) of a large Nernst effect \(^9\)\(^10\) combined with a diamagnetic magnetization \(^11\). In this context the \(H_{c2}\) line determined as the field at which the Nernst and diamagnetic signals reach zero \(^12\) does extend well above \(T_c\). However, presumably for sensitivity considerations, most of these experiments have been performed below \(T_c\).

In this letter, we propose a relatively simple method, based on an analysis of the transverse magnetoresistance (MR) to determine the \(T\) dependence of the magnetic field \(H'_c\) at which the normal state transport is fully restored. We therefore provide for the first time an experimental determination of the \((H, T)\) range of superconducting fluctuations, which extends up to \(T'_c > T_c\). This detection by transport properties of the flux flow processes evidenced by Nernst measurements up to \(T_c \approx T'_c\) therefore strongly validates the vortex scenario. This is reinforced by the parabolic variation found for \(H'_c(T)\) which could thus be identified to the microscopic depairing field as expected in the framework of the 2D Kosterlitz Thouless transition \(^13\). Furthermore our data have been taken on underdoped \(\text{YBa}_2\text{Cu}_3\text{O}_{6.6}\) (YBCO) which is found here to display a good metallic behavior, away from the metal insulator crossover. This allows us altogether to perform a study of the incidence of defects on \(H'_c\), \(T'_c\) and \(T_c\).

The samples used in this study have been described before, as well as the electron irradiation procedure using the low temperature facility of the Van der Graaff accelerator at the LSI (Ecole Polytechnique, Palaiseau) \(^10\). Pulsed magnetic fields have been applied along the \(c\) axis in order to best suppress superconductivity. Resistivity data have been taken initially on two irradiated samples at the NHMFL in Los Alamos using short field pulses (20ms), which implies ac measurements at high frequency (250kHz). The other data have been taken at the LNCMP in Toulouse with a long pulse (125ms) magnet and ac measurements at 50kHz.

The resistivity increase \(\delta \rho = \rho(H, T) - \rho(0, T)\) induced by the magnetic field \(H\) is displayed in Fig.1a for the pure \(\text{YBCO}_{6.6}\) crystal for 60K\(< T < 150K\). At high temperature in the normal state, \(\delta \rho\) increases as \(H^2\) as usually observed for the classical transverse magnetoresistance in low magnetic field. The value of the MR coefficient defined as \(a_{\text{trans}}(T) = \delta \rho(T)/\rho(T, 0)H^2\) is \(\approx 5x10^{-6} \ T^{-2}\) at 150K in good agreement with that obtained for \(H < 14T\) \(^1\)\(^3\)\(^5\). This observation is good evidence that the weak field regime \(\omega_c \tau < 1\) with \(\omega_c\) the cyclotron frequency and \(\tau\) the scattering time, applies up to 60T. As \(T\) decreases, the variation of \(\delta \rho\) progressively deviates from the \(H^2\) dependence. In order to better capture this evolution, we have plotted \(\delta \rho\) versus \(H^2\) in Fig.1b. One can see that the normal state \(H^2\) dependence of \(\delta \rho\) remains
clearly defined at high field and the MR curve departs from this limiting behaviour at a field value $H'_c$ which increases steadily as $T$ decreases. This is for us the indication that $H'_c$ is the field at which the superconducting contribution to the conductivity is suppressed.

Above $H'_c$ the linear fits of $\delta\rho$ vs $H^2$ indicated as broken lines in Fig.1b allow us to estimate the zero field normal state resistivity from the zero field intercept $\delta\rho_0(T) = \rho(0, T) + \delta\rho_0(T)$ and the normal state MR coefficient as $a_{trans}(T) = \delta\rho_n(T)/\rho_n(T)H^2$. The $\rho_n(T)$ data displayed in Fig.2 can be well fitted down to 60K by a $T^2$ law : $\rho_n(T) = \rho_0 + AT^2$ with $\rho_0 = 38.4 \mu\Omega.cm$ and $A = 0.0066\mu\Omega.cm/K^2$. A similar $T^2$ dependence of the resistivity has been reported in various underdoped cuprates [16].

As seen in the inset of Fig.2 where $a_{trans}$ is plotted versus $T$ in a log-log scale, the MR coefficient follows a $T^{-4}$ power law down to $\sim 80K$. This $T^{-4}$ dependence, which has been found for the orbital MR for $T > 100K$ in underdoped and optimally doped YBCO [14], has been referred as the “modified Kohler’s rule” $a_{orb} \propto \tan^2 \Theta_H$ where $\Theta_H$ is the Hall angle. Although a quantitative comparison of our data with this expression cannot be done here as we have only measured the transverse MR [16], our observation of a $T^{-4}$ dependence confirms that we do measure the normal state MR above $H'_c$. Below 80K $a_{trans}$ saturates as clearly seen also in Fig.1d. A saturation of $a_{orb}$ has been observed in LSCO at low $T$ [14] and has been interpreted as the contribution of a large impurity scattering term in this system. One also might expect that the contribution of the residual $\rho_0$ becomes dominant at low $T$ in our YBCO$_{6.6}$ crystal. Another possible explanation of the saturation of the MR might come from the breakdown of the weak field limit as $T$ (and thus $\rho_n$) decreases [17]. Indeed, taking a hole doping of 0.09 per Cu in the CuO$_2$ plane gives $\omega_{c,T} \approx 1$ at 60T for $\rho \approx 40\mu\Omega.cm$.

Although it is not possible to determine accurately $\rho_n(T)$ and $H'_c$ at low $T$, the values of $\rho$ taken at 51T displayed in Fig.2 decrease with $T$ down to 4.2K. This behavior is confirmed on another sample on which measurements have been done down to 1.6K, which evidences that YBCO$_{6.6}$ displays a metallic behavior in contrast to underdoped “low $T_c$” cuprates for which upturns of the resistivity were found at low $T$ [11,12].

Our approach provides a reliable way to determine $H'_c$ by distinguishing the normal state resistivity from the superconducting contribution above 60K, but would become ambiguous below, as the normal state is obviously not fully accessible with such limited fields. In order to get insight into the shape of the $H'_c$ line below $T_c$, samples with lower $H'_c$ were required. We have attempted to do so, by depressing $T_c$ with low $T$ electron irradiation [20]. The resistivity data are reported in Fig.3 for an irradiated sample with $T_c = 6.8K$. In that sample the

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**FIG. 1:** (Color online) Magnetoresistance (above $T_c$) and resistivity (below $T_c$) are plotted versus $H$ (left) and $H^2$ (right) for a pure YBCO$_{6.6}$ crystal. In (b) the data depart from the normal state $H^2$ dependence (dashed lines) below a threshold field $H'_c$ (arrows). In (c) the arrow indicates the determination of “$H_{c2}$” if a linear extrapolation is used as often done [3,4], which leads to a very small value of $\sim 20T$.

**FIG. 2:** (Color online) Temperature dependence of the resistivity for pure YBCO$_{6.6}$. Zero field data are represented by the nearly continuous curve while data are taken at 51T. Diamonds correspond to the normal state resistivity $\rho_n(0,T)$ extrapolated to zero field, which is fitted by a $T^2$ variation (solid line). The inset shows the transverse MR coefficient $a_{trans}$ vs $T$ in a log-log scale. The data follows a $T^{-4}$ dependence at high $T$. 
large resistivity (> 400µΩ cm) yields $\omega_c T < 0.1$, which ensures that the weak field limit is always valid. From 30 to 100K the $\delta \rho$ vs $H$ curves display a clear upward curvature, which allows us to evidence unambiguously the normal state $H^2$ term and to determine $H_c(T)$. Below 30K the superconducting contribution is quite large but saturates rapidly in field, as can be seen in Fig.3c and 3d from the parallel behavior of the resistivity curves at high field. By continuity with the high $T$ analysis, $H_c(T)$ can be defined as shown in fig.3d [18].

The $T$ dependences of $H_c$ deduced from this analysis are reported for the two samples in Fig.4 altogether with data for two other irradiated samples (which are less accurate as measurements have been performed using short field pulses). For all the irradiated samples studied, the $H_c$ line is well fitted by a simple quadratic formula $H_c(T) = H_c(0) \left[1 - (T/T_c)^2\right]$. This legitimates the use of such a fit for the pure sample for which low $T$ data were not accessible. These fits yield $H_c(0) = 65(\pm 3)$, 50(±3), 41(±3), 34(±4)T and $T_c = 108(\pm 3)$, 86(±3), 81(±3), 75(±4)K respectively for the different samples with decreasing $T_c = 57K$, 25K, 6.8K and 3.5K.

The experimental observation of a $H_c(T)$ line which terminates at $T_c$ well above $T_c$ with a quadratic $T$ dependence is strikingly similar to that expected for the mean field crossover above the 2D Kosterlitz-Thouless (KT) transition [12]. In such an approach the phase coherence is destroyed at $T_c$ by a proliferation of thermal vortices, while $H_c(T)$ represents the line above which local superconductive pairing vanishes. So our results share a lot of similarities with those deduced from the anomalous Nernst effect which has been interpreted within this vortex fluid picture [20]. We can then directly compare $T_c$ with the onset $T_v$ for the Nernst signal measured previously on the same samples [10]. One can see in the inset of Fig.4 that $T'_c$ is systematically found to be higher than $T_v$, so that the MR measurements are sensitive to fluctuations above the vortex regime (such as amplitude fluctuations).

Let us emphasize that the lack of detection of a flux flow contribution to the conductivity has been often taken as detrimental to the vortex scenario, although it has been argued that it could be negligible [21]. In the two fluid model the conductivity is the sum of the superfluid $\sigma_s$ and the normal quasiparticle $\sigma_n$ conductivities. Our experimental result allows us to estimate a small but sizable $\sigma_s \simeq 0.1 \sigma_n$ at $T_c$ and 20T in the pure sample. This small superconducting contribution to the magnetoconductivity has been misregarded so far in most attempts to determine $H_a$ below $T_c$, the residual variation of $\rho$ in high field being attributed to the normal state. This ambiguity had been indeed noticed by some authors [22].

One important aspect of our experimental results is that it allows us to study the influence of disorder on the phase diagram. As already observed by Nernst measurements for $T_v$ [10], the introduction of defects considerably expands the range of superconducting fluctuations since $T_c$ decreases whereas we find here that $T_c$ and $H_c$ are only slightly depressed. In the most irradiated sample with $T_c = 3.5K$, the $H_c$ line terminates at $T'_c \simeq 75K$, i.e. $\simeq 20T_c$, while $H'_c$ is only reduced by a factor 2. This weak variation of $H'_c$ which is related to the pairing strength in the KT approach, appears coherent with the absence of
variation of the superconducting coherence peak at the antinodal direction probed by ARPES in electron irradiated optimally doped Bi2212 \(^{24}\). In the KT approach the value of \(T_c\) is directly related to the value of the local phase stiffness at \(T_c\) which is depressed from its 0K value by thermal excitation of quasiparticles \(^{22}\). As in plane defects, such as Zn substitutions are well known to decrease markedly the \(T = 0\) phase stiffness \(^{22}\), this naturally gives an explanation of the contribution of phase decoherence to the observed quasi linear decrease of \(T_c\) \(^{20}\).

It seems legitimate to assimilate \(H'_c\) with the upper critical field \(H_{c2}\) inferred from Nernst or magnetization measurements \(^{11,12}\). An estimate of \(H_{c2}\) below \(T_c\) has been taken as the extrapolated field for which the Nernst signal should vanish \(^{12}\). Experiments above \(T_c\) are hardly possible, the Nernst signal becoming then very small. In our experiments, the \(H'_c(T)\) line is most directly accessible above \(T_c\). We observe in the most irradiated samples that \(H'_c\) only begins to decrease for \(T > T_c\). So our results on samples with low \(T_c\) agree with those obtained on families of ”low \(T_c\)” cuprates where \(H_{c2}\) was found nearly constant through \(T_c\) \(^{12}\). On the contrary, for the pure sample, we show that \(H'_c\) starts to decrease below \(T_c\) thereby vanishing at \(T'_{c} \approx 2T_c\). In optimally doped Bi2212 a similar decrease of \(H_{c2}\) from \(\approx\) 200T at 35K to \(\approx\) 90T at \(T_c = 86K\) has been inferred from diamagnetism data \(^{11}\). To clarify why \(H'_c(0)\) is much smaller than 200T in YBCO\(_{6,6}\) we have analysed preliminary resistivity data taken on an YBCO-\(c\) crystal in which \(T_c\) was depressed to 30K by electron irradiation. Even in that case it was impossible to restore the normal state below 35K with a magnetic field of 55T, resulting in \(H'_c(0) > 70-80T\). This ascertains that in the pure compounds \(H'_c(0)\) is much larger in YBCO than in YBCO\(_{6,6}\). So, the variation of \(H'_c(0)\) from the underdoped case to the optimally doped one parallels the variation of \(T_c\) rather than that of the pseudogap which is known to increase markedly upon underdoping.

In conclusion we have presented here a powerful method based on resistivity measurements which allowed us to measure directly the \(T\) dependence of the mean field \(H_{c2}\) in the largest domain where superconductivity is experimentally detectable, at least as fluctuations. The decrease of the phase stiffness induced by the defects naturally yields the subsequent depression of the KT transition temperature that is of \(T_c\). Furthermore \(H_{c2}, T'_c\) and \(T_v\) which are related to pair formation are depressed, although moderately, by the defects, in contrast to the pseudogap \(T^*\) which has been found insensitive to disorder \(^{27}\). So all experimental evidences obtained so far in YBCO indicate that \(T^*\) is not directly related to the pairing energy scale. This remark sustains the proposal done by P. Lee et al \(^{20}\) for an experimental confusion between two types of pseudogaps, one linked to a survival above \(T_c\) of the actual SC gap and the other one initially detected by NMR, and associated with singlet formation.

The experiments at the LNCMP have been financed by the contract FP6 ”Structuring the European Research Area, Research Infrastructure Action” contract R113-CT2004-506239. FRA and HA acknowledge the NHMFL for financial support during their visit to NHMFL and thank F. Balakirev for his help during the experiments and for his critical reading of the manuscript.

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