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Comparison of the scaling analysis of mixed-state magnetization data with direct measurements of the upper critical field for $YBa_2Cu_3O_{7-x}$

I L Landau

Department of Chemistry and Biochemistry, University of Berne, Freiestrasse 3, CH-3012 Berne, Switzerland
and
Kapitza Institute for Physical Problems, 119334 Moscow, Russia

E-mail: landau@iac.unibe.ch

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Abstract
By comparison of recent direct measurements of the temperature dependence of the upper critical field H_{c2} of an $YBa_2Cu_3O_{7-x}$ high-T_c superconductor with the scaling analysis of magnetization data, collected in fields $H \ll H_{c2}$, we demonstrate that the temperature dependence of the Ginzburg–Landau parameter κ is negligible. Another conclusion is that the normalized temperature dependence of H_{c2} is independent of the orientation of the magnetic field with respect to the crystallographic axes of the sample. We also discuss the fact that isotropy of the temperature dependence of H_{c2} straightforwardly follows from the Ginzburg–Landau theory if κ does not depend on the temperature.

Evaluation of the upper critical field H_{c2} and its temperature dependence represents a difficult task if high-T_c superconductors (HTSC) are concerned. The problem is that H_{c2} is very high and can be directly measured only in magnetic fields of megagauss amplitudes. This is an obvious reason that only a few such studies have been published so far and that not all of them may be considered as reliable measurements. We could find only a very few works in which measurements were extended to a considerable range of T/T_c, and all of them were made on $YBa_2Cu_3O_{7-x}$ samples [1–5].

At the same time, H_{c2} represents one of the main parameters of a superconductor and knowledge of it is of primary importance. This is why several indirect approaches have been proposed and used in order to evaluate $H_{c2}(T)$ from equilibrium magnetization data collected in fields $H \ll H_{c2}$ [6–12]. However all these approaches are based on certain assumptions, which are not necessarily satisfied in experiments. This makes existing $H_{c2}(T)$ results questionable.

We shall not consider all theoretical methods for the analysis of magnetization data. Our goal is to discuss a scaling procedure proposed in [12] in order to compare the normalized temperature dependences of H_{c2} obtained by employing this procedure with direct measurements of the upper critical field. As we demonstrate below, good agreement between the results provides convincing evidence of the validity of this scaling analysis and allows us to draw some conclusions about the temperature dependence of the Ginzburg–Landau parameter κ for HTSCs.

The scaling procedure is based on a single assumption that κ is temperature independent. In this case, equilibrium mixed-state magnetizations measured at different temperatures but in the same normalized fields $H/H_{c2}(T)$ are proportional to $H_{c2}(T)$. According to [12], this leads to the following relation between magnetizations of a sample at two different temperatures:

$$M(H, T_0) = M(h_{c2}H, T)/h_{c2} + c_0(T)H, \qquad (1)$$

where $h_{c2} = H_{c2}(T)/H_{c2}(T_0)$ is the normalized upper critical field and $c_0(T) = \chi_n(T_0) - \chi_n(T)$ (χ_n is the normal-state magnetic susceptibility of a sample). The first term on the right in equation (1) describes properties of the mixed state of ideal type-II superconductors, while the second one is introduced

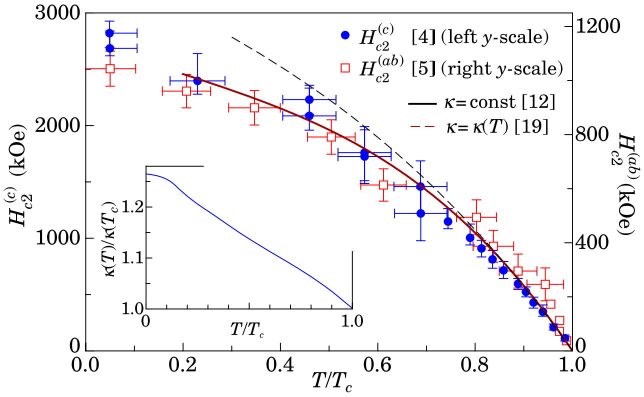

Figure 1. Experimental $H_{c2}^{(c)}(T/T_c)$ and $H_{c2}^{(ab)}(T/T_c)$ data from [3] and [4], respectively. The solid line is obtained in [12] by scaling of magnetization data for the case $\kappa = \text{const}$ and fitted to data points. The dashed line was obtained in [19] in an analogous way, but assuming $\kappa(T)$ as shown in the inset. The inset shows $\kappa(T)$ according to the Helfand–Werthamer theory [20].

(This figure is in colour only in the electronic version)

in order to account for all other temperature dependent contributions to magnetization, which are unavoidable for HTSCs.

By a suitable choice of h_{c2} and $c_0(T)$, individual $M(H)$ curves measured at different temperatures may be merged into a single master curve $M_{\text{eff}}(H, T_0)$. In this way the temperature dependence of the normalized upper critical field is obtained [12]. The temperature dependence of the upper critical field may be written as

$$H_{c2}(T) = H_{c2}(0)F(1 - T/T_c). \qquad (2)$$

The scaling procedure allows to find the function F, while the value of $H_{c2}(0)$ remains unknown. This approach turned out to be quite effective for the analysis of reversible magnetization data for HTSCs as well as for other superconducting materials with sufficiently high values of κ [12–18].

The main and unexpected result of this scaling analysis is that the functions $F(1 - T/T_c)$ are practically identical for most HTSCs, which can hardly be considered a simple coincidence. As was argued in [12], this fact represents a strong indication that this approach to the analysis of experimental data is generally correct. At the same time, it does not necessary mean that κ is temperature independent. Indeed, the universality of $H_{c2}(T/T_c)$ will not be altered if κ is temperature dependent, but this dependence is the same for different HTSCs. Furthermore, the scaling method can be modified to account for temperature variations of κ if $\kappa(T)$ is known *a priori* [19]. It was demonstrated that even a rather weak temperature dependence of κ, which follows from the BCS theory [20] (see the inset of figure 1), noticeably changes the resulting $h_{c2}(T)$ curves, i.e., the knowledge of $\kappa(T)$ is essential for obtaining correct $h_{c2}(T)$ results.

As far as we are aware, there are no reliable data on $\kappa(T)$ for HTSCs. In other words, while the assumption about temperature independence of κ may be considered reasonable, it has never been verified. This is why we consider recent direct measurements of $H_{c2}(T/T_c)$ in pulsed magnetic fields [3–5] as a providing unique opportunity for such a verification.

In figure 1, we plot $H_{c2}^{(c)}(T/T_c)$ (left y-scale) and $H_{c2}^{(ab)}(T/T_c)$ (right y-scale) from [4] and [5], respectively. The experiments of [5] were carried out on thin (0.1 μm) epitaxial $YBa_2Cu_3O_{7-x}$ film oriented perpendicularly to the applied film. The zero-field resistive transition was about 4 K wide with the zero-resistance state below 83.5 K. For this plot T_c was chosen by extrapolation of the $H_{c2}(T)$ curve, presented in figure 4 of [5], to $H_{c2} = 0$. This gives $T_c = 87.5$ K, which is the very upper end of the resistive transition[1].

For measurements of $H_{c2}^{(ab)}(T/T_c)$, a single-crystalline sample with $T_c \approx 90$ K was used [4]. An important advantage of this work is that a new method of radio frequency transmission was developed. This technique allows for evaluation of H_{c2} with substantially better accuracy than for previously used magnetoresistance measurements.

As may be seen in figure 1, the two data sets match each other quite well and the difference between them does not exceed the uncertainty of the results. This means that the function F in equation (2) may be considered as isotropic.

The normalized temperature dependences of H_{c2} obtained by scaling of magnetization data in [12] and [19] are also shown in figure 1 by the solid and the dashed lines, respectively. The two curves were obtained from the same experimental data assuming different $\kappa(T)$ dependences. One may see that the solid line corresponding to $\kappa(T) = \text{const}$ fits experimental $H_{c2}(T)$ data points better than the other. This shows that the temperature dependence of κ is even weaker than predictions of the Helfand–Werthamer theory [20] and the choice $\kappa = \text{const}$ is justified.

There are two main conclusions which can be made on the basis of the presented analysis: (i) The temperature dependence of the Ginzburg–Landau parameter κ in HTSCs is negligibly small. This follows from the good agreement between the normalized $H_{c2}(T)$ curve obtained by scaling of magnetization data and direct H_{c2} measurements (see figure 1). (ii) $H_{c2}(T)/H_{c2}(0)$ is isotropic. This statement was initially made on the basis of the analysis of magnetization data collected on polycrystalline samples [13]. Now it is also confirmed by direct comparison of $H_{c2}(T)$ curves for two different orientations of the magnetic field (figure 1).

While the two conclusions were made independently, they are connected in the framework of the Ginzburg–Landau theory. Indeed, according to the Ginzburg–Landau theory, $H_{c2}(T) = \sqrt{2}\kappa H_c(T)$ where H_c is the thermodynamic critical field. Because H_c is always isotropic, anisotropy of H_{c2} may arise from the anisotropy of κ only. If κ does not depend on temperature, as follows from the discussion above, $H_{c2}^{(c)}(T)/H_{c2}^{(ab)}(0) = H_c(T)/H_c(0)$, i.e., the anisotropy of H_{c2} should be temperature independent.

Although direct measurements of $H_{c2}(T)$ are only available for $YBa_2Cu_3O_{7-x}$ samples, there cannot be much doubt that both conclusions are also valid for many other

[1] It is unclear why $T_c = 90.5$ K was used in [5], in which data of [3] are re-plotted as a function of T/T_c. As may be seen in figure 5 of [3], this value of T_c is well above superconducting transition for this sample.

superconductors exhibiting the same normalized $H_{c2}(T/T_c)$ curves [12, 13].

In conclusion, it was demonstrated that temperature dependences of the normalized upper critical field which were established by scaling of magnetization data collected in fields $H \ll H_{c2}$ are in very good agreement with recent direct measurements of $H_{c2}(T)$ in megagauss magnetic fields [3, 4]. This agreement shows that the temperature dependence of the Ginzburg–Landau parameter for HTSCs is rather weak. Another result of the presented analysis is that $H_{c2}(T)/H_{c2}(0)$ is isotropic.

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