Temperature dependence of the upper critical field of high-T_c superconductors from isothermal magnetization data. Influence of a temperature dependent Ginzburg-Landau parameter.

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Abstract

We show that the scaling procedure, recently proposed for the evaluation of the temperature variation of the normalized upper critical field of type-II superconductors, may easily be modified in order to take into account a possible temperature dependence of the Ginzburg-Landau parameter κ. As an example we consider $\kappa(T)$ as it follows from the microscopic theory of superconductivity.

Key words:
high-T_c superconductors, upper critical field, equilibrium magnetization, mixed state
PACS: 74.60.-w, 74.-72.-h

1   Introduction

As we have recently shown in Ref. [1], the temperature variation of the normalized upper critical field H_{c2} of a type-II superconductor may be obtained by scaling the data of the reversible isothermal magnetization M, measured as a function of external magnetic fields H at different temperatures. One of the advantages of this approach is that no particular *a priori* assumption for the field dependence of the magnetization, $M(H)$, needs to be made. This is why the proposed scaling procedure is expected to be equally valid for any type-II superconductor, regardless of its anisotropy, the type of pairing or the

value of the Ginzburg-Landau (GL) parameter κ. The scaling relation introduced in Ref. [1] is based, however, on the assumption that κ is temperature independent. In this particular case, the magnetic susceptibility $\chi(H, T)$ of a type-II superconductor in the mixed state is a universal function of $H/H_{c2}(T)$ [2] and, according to Ref. [1], the relation between the values of M at two different temperatures is

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

with $h_{c2} = H_{c2}(T)/H_{c2}(T_0)$ representing the upper critical field, normalized by its value at some chosen temperature $T_0 < T_c$. The term $c_0(T)H$ of this equation was introduced in order to take into account the contribution to the sample magnetization due to the temperature dependent paramagnetic susceptibility χ_n of the material in the normal state. Since $c_0(T) = [\chi_n(T) - \chi_n(T_0)]$, this second term in Eq. (1) can be omitted, if χ_n does not vary with temperature.

The scaling procedure based on Eq. (1) was applied to numerous data sets of the reversible magnetization of HTSC's which are available in the literature and it turned out that it works rather well for single crystals and grain aligned samples [1,3], as well as for HTSC ceramics [4]. A surprising result of the work presented in Refs. [1,3,4] is that all the different superconducting cuprates may be divided into two groups. For each group, the corresponding $h_{c2}(T/T_c)$ curves are practically identical for all materials of this group. The smaller group of the two appears to include compounds of the series $Y_2Ba_4Cu_7O_{15+x}$ (Y-247), underdoped $YBa_2Cu_3O_{7-x}$ (Y-123), and $Tl_2Ba_2CaCu_2O_{8+x}$ (Tl-2212) [1] [3,4]. All other varieties of HTSC's belong to the other group. This universality of $h_{c2}(T/T_c)$ for seemingly very different HTSC compounds emerges as a rather unexpected result but at the same time it indicates that the scaling procedure outlined in Ref. [1] is a valid tool for the analysis of data of the reversible magnetization in the mixed state of type-II superconductors.

As was already argued in Ref. [1], this universality does not necessarily mean that the GL parameter κ in HTSC's is indeed temperature independent. It only indicates that, if κ is temperature dependent, its temperature dependence is nearly the same for all compounds in each of the above mentioned groups. For completeness, however, it seems of interest to also check the influence of possible temperature variations of κ on the resulting $h_{c2}(T/T_c)$ curves and in

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[1] The situation with this particular Tl compound is not yet clear. While the $h_{c2}(T/T_c)$ curves for a single crystalline sample of Tl-2212 is very close to those for Y-247 and underdoped Y-123 compounds [3], a similar curve for a ceramic sample exhibits a quite different shape (see the data for sample Tl#3 in Ref. [4]). It is possible that some difference in the oxygen content of these two samples is responsible for this effect.
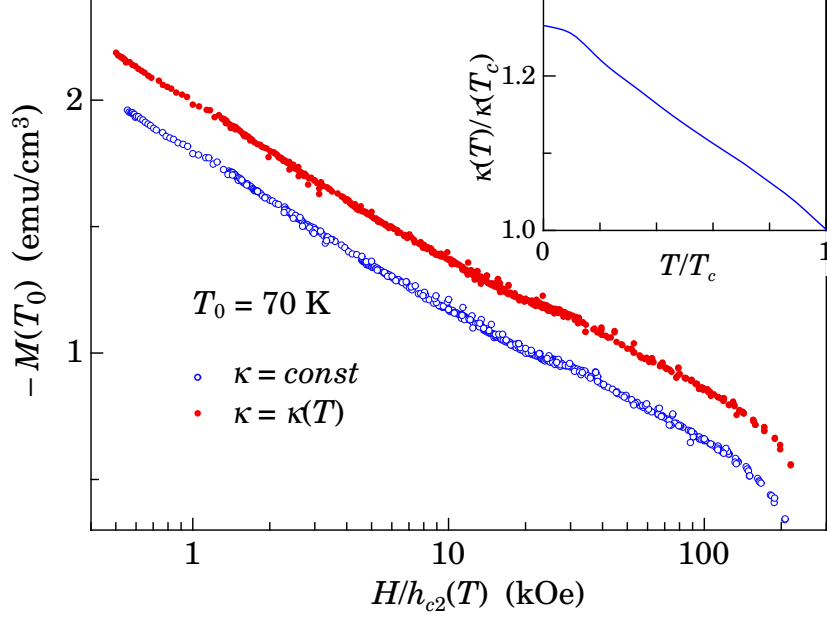
Fig. 1. $M_{eff}(H, T_0)$ calculated using Eq (1) ($\kappa = const.$) and Eq. (2) ($\kappa = \kappa(T)$) for sample Bi#1. The curve corresponding to $\kappa = \kappa(T)$ is shifted upwards by 0.2 emu/cm^3 for clarity. The inset shows the calculated temperature dependence of the GL parameter κ normalized by its value at $T = T_c$ (see to Refs. [5] and [6]).

this work we present and discuss the necessary corrections to Eq. (1). Since a reasonably simple modification of Eq. (1) can only be made if $\kappa \gg 1$, we shall focus our discussion on this situation, which is definitely met for cuprate superconductors.

In magnetic fields H much larger than the lower critical field H_{c1}, the magnetic moment of a superconductor is inversely proportional to κ^2 [2]. This allows for a rather simple modification of Eq. (1). Indeed, if κ is temperature dependent, Eq. (1) is to be be replaced by

$$M(H/h_{c2}, T_0) = \frac{M(H, T)}{[\kappa(T)/\kappa(T_0)]^2 h_{c2}} + c_0(T)H. \qquad (2)$$

The condition $H \gg H_{c1}$ is always satisfied for our type of experiments because equilibrium-magnetization data are only accessible above the irreversibility field H_{irr}. The irreversibility line $H_{irr}(T)$ in the H-T phase diagram of HTSC's is known to correspond to fields much higher than $H_{c1}(T)$.

As may be seen, Eq. (2), in comparison with Eq. (1), contains an additional un-known parameter $\kappa(T)/\kappa(T_0)$. In principle, all three parameters $h_{c2}(T)$, $c_0(T)$ and $\kappa(T)/\kappa(T_0)$ may be evaluated by scaling the magnetization data collected at different temperatures with the procedure which is described in Ref. [1]. However, because reversible $M(H)$ data for HTSC's are only available in a
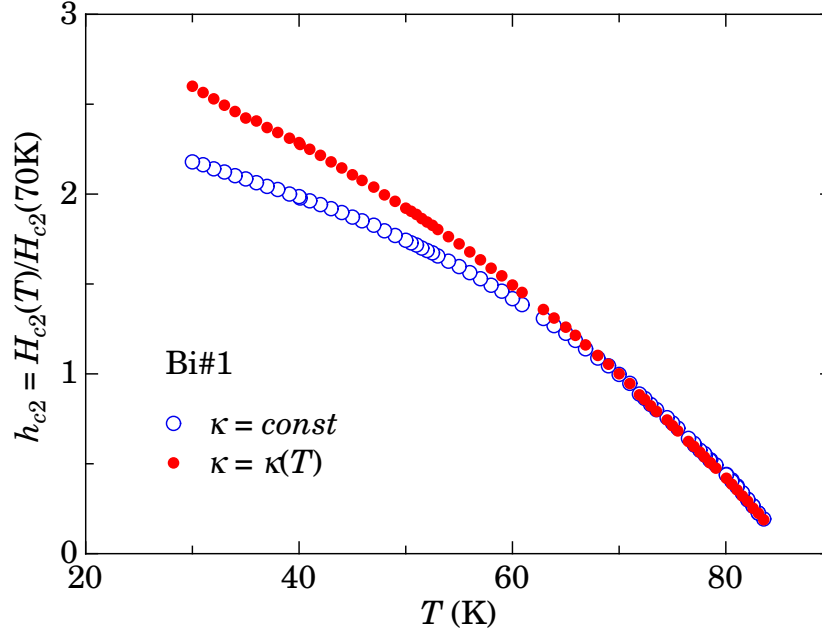
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Fig. 2. Temperature dependence of H_{c2} normalized by its value at $T_0 = 70$ K for sample Bi#1. The curve calculated assuming that the GL parameter is temperature independent ($\kappa = const.$) is shown for comparison.

rather limited range of magnetic fields and because two of the unknown parameters appear together as a product in the denominator of the first term on the right hand side of Eq. (2), this scaling procedure cannot deliver all three parameters independently with adequate certainty. Thus, in order to use Eq. (2) for the scaling procedure, the temperature dependence of $\kappa(T)$ must, as before, *a priori* be assumed. [2] In the following discussion we consider, as an example, $\kappa(T)$ as it is calculated from the microscopic theory of superconductivity [5,6] (see the inset of Fig. 1). Once this assumption is made, Eq. (2) may be used for the analysis of experimental data exactly in the same way as Eq. (1) was employed in our previous studies [1,3,4]. In the following we denote the values of M calculated from Eqs. (1) or (2) as $M_{eff}(H, T_0)$, simply to distinguish them from experimentally measured magnetizations.

2 Analysis of experimental data

We now apply Eq. (2) for the analysis of magnetization data that were presented in previous publications of other authors. Most of these results were already analyzed with the assumption that κ does not vary with temperature [1,4]. Some characteristics of the samples are listed in Table 1.

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[2] The previous assumption, in Ref. 1, was $\kappa = const$

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Eq. (2) may be used to merge the $M(H)$ curves, measured at different temperatures, into a single $M_{eff}(H, T_0)$ curve by a suitable choice of scaling parameters $h_{c2}(T)$ and $c_0(T)$ (see Ref. [1] for details). Fig. 1 displays the resulting $M_{eff}(H, T_0)$ curves calculated using Eq. (1) ($\kappa = const$) and Eq. (2) ($\kappa = \kappa(T)$) for sample Bi#1 (see Table I). The $M_{eff}(H, T_0)$ curves presented in Fig. 1 were obtained from more than 60 individual $M(H)$ curves measured at different temperatures between 30 and 83.5 K (see Ref. [7] for the original experimental data). As may be seen, the shapes of the $M_{eff}(H, T_0)$ curves, representing the field dependence of the equilibrium magnetization at $T = T_0$, are practically identical and not altered significantly by the different assumptions for $\kappa(T)$.

The resulting temperature dependencies of the normalized upper critical fields h_{c2} for the same sample are shown in Fig. 2. A difference between the two considered cases may clearly be seen only if the data set extends to temperatures well below T_c. Fig. 3 displays $H_{c2}(T)/H_{c2}(0.9T_c)$ data calculated using Eq. (2) for several samples listed in Table I. It is obvious that the assumed temperature dependence of κ does not change the previously established fact that the $h_{c2}(T/T_c)$ curves for different HTSC's are identical.
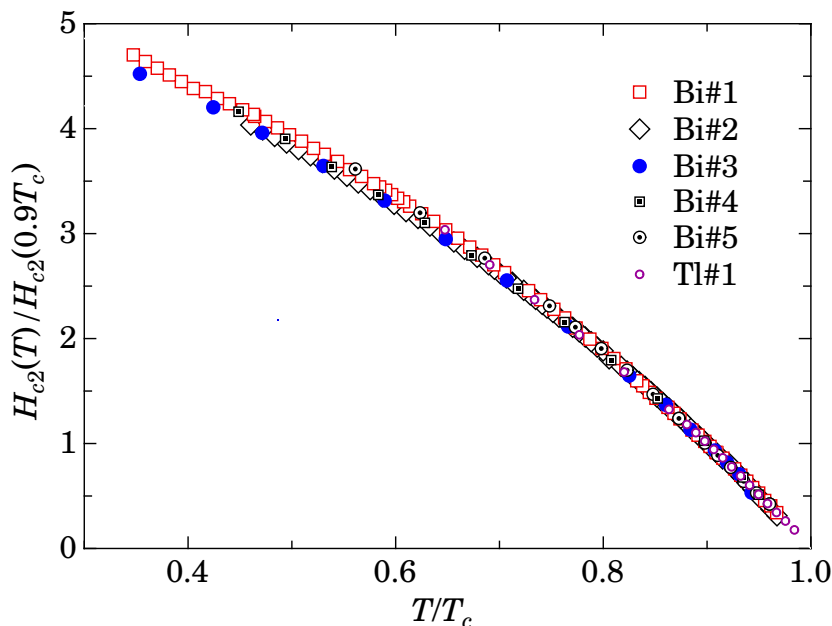

Fig. 3. Temperature dependence of H_{c2} normalized by its values at $T = 0.9T_c$ for samples listed in Table I.

As has briefly been mentioned above, the $h_{c2}(T)$ curves for Tl-2212, Y-247 and oxygen deficient Y-123 compounds are quite different from those for many other HTSC's. The result for an oxygen-deficient sample Y-123 sample is shown in the main-frame Fig. 4. Similar to the case presented in Fig. 2, the assumed temperature dependence of κ reduces the curvature of the
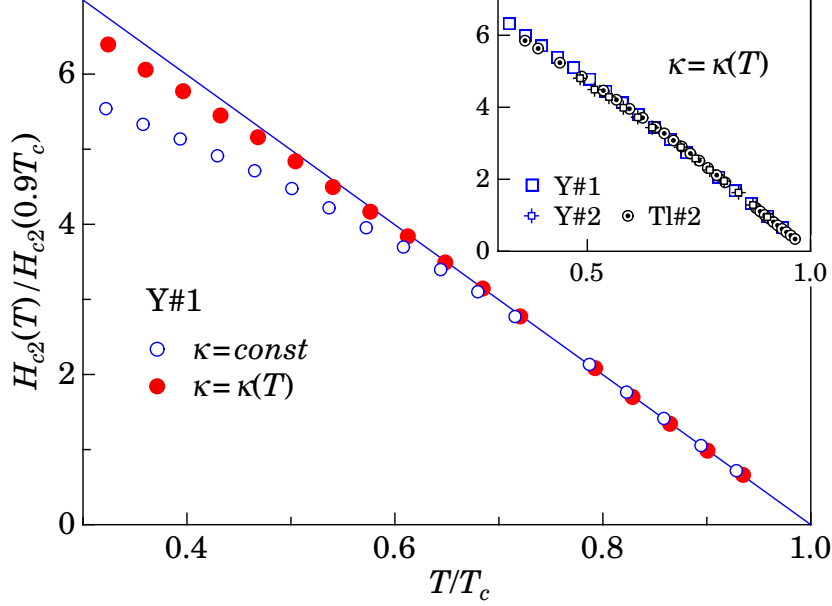
Fig. 4. Temperature dependence of H_{c2} normalized by its values at $T = 0.9T_c$ for an underdoped Y-based sample Y$\#$ 1. The solid line is the best linear fit to the data points for $T/T_c \geq 0.8$. The $H_{c2}(T)/H_{c2}(0.9T_c)$ curve calculated assuming κ being independent of temperature is shown for comparison. The inset shows analogous $h_{c2}(T/T_c)$ data for several samples listed in Table I.

calculated $h_{c2}(T)$ curves in comparison with $h_{c2}(T)$ for $\kappa = const$.

3 Conclusion

We considered the influence of a possible temperature variation of the Ginzburg-Landau parameter κ on the results that follow from the analysis of equilibrium magnetization data of type-II superconductors using the scaling procedure proposed in Ref. [1]. We showed that assuming $\kappa(T)$, as it follows from the microscopic theory of superconductivity, results in a slight but noticeable change of the calculated temperature dependencies of the normalized upper critical fields $h_{c2}(T/T_c)$ in comparison with those that are calculated by assuming κ as being independent of temperature. The main qualitative conclusions following from our previous studies [1,3,4] remain, however, unchanged. All investigated HTSC's may be divided in two groups with identical $h_{c2}(T/T_c)$ curves for all the compounds belonging to each group. We also note that the $h_{c2}(T)$ curves for both groups are qualitatively the same as for conventional superconductors. They are linear in T at temperatures close to T_c with downward deviations from linearity at lower temperatures.

Table 1
Sample identification.

No.	Refs.	Compound	Sample	T_c (K)
Bi#1	[7]	$Bi_{2.12}Sr_{1.9}Ca_{1.2}Cu_{1.96}O_{8+x}$	single crystal	86.9
Bi#2	[7]	$Bi_{2.12}Sr_{1.9}Ca_{1.2}Cu_{1.96}O_{8+x}$	ceramic	86.4
Bi#3	[8]	$Bi_2Sr_2CaCu_2O_{8+x}$	single crystal	84.8
Bi#4	[9]	$Bi_2Sr_2CaCu_2O_{8+x}$	single crystal	66.8
Bi#5	[10]	$Bi_2Pb_{0.2}Sr_2CaCu_2O_8$	single crystal	86.7
Tl#1	[12]	$Tl_{0.7}Bi_{0.2}Sr_{1.8}Ba_{0.2}Ca_{1.9}Cu_3O_x$	ceramic	115.8
Tl#2	[11]	$Tl_2Ba_2CaCu_2O_{8+x}$	single crystal	102.4
Y#1	[13]	$YBa_2Cu_3O_{6.69}$	ceramic	55.5
Y#2	[13]	$YBa_2Cu_3O_{6.81}$	ceramic	62.0

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