Critical Fields in High T_c Superconductors

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Using microwave methods one can determine upper critical fields which lie beyond the field of the laboratory magnet, and avoid ambiguities associated with the broadened transitions in high T_c superconductors.

Upper critical field B_{c2} is one of the fundamental parameters which characterize a type-II superconductor. The common definition for B_{c2} is that the superconducting state persists until the applied field $\mu_o H_a$ reaches some value B_{c2}, when the transition to the normal state occurs. But this is not the only significance of the upper critical field. Namely, at fields $B<B_{c2}$, the magnetic flux penetrates the superconductor in a quantised form. Each flux quantum Φ_0 is carried by a superconducting current vortex whose core contains normal electrons. The radius of the vortex is given by the coherence length ξ, which itself is a very important physical quantity. There is a simple relationship between B_{c2} and ξ ($B_{c2} = \Phi_0 / 2\pi\xi^2$) so that, in practice, ξ is evaluated from the measurement of B_{c2}. Of course, ξ is a field independent quantity since at all fields $B<B_{c2}$ the vortices have the same radius, only the number of vortices increases with B. The field at which the vortices of size ξ reach maximum close packing is B_{c2}. Clearly, the determination of B_{c2} is of far more general importance than just the knowledge of the field value where the normal state is restored. When the temperature dependence of $\xi(T)$ is determined, one can compare it with the predictions of various theoretical models, gaining insight into the nature of the superconducting state.

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In classical low temperature superconductors the upper critical field could be determined with great precision by resistance measurements, because the transition to the normal state was always sharp. When the transitions were detected at different temperatures, one obtained the temperature dependence of B_{c2}. Usually, $B_{c2}(T)$ increased linearly from zero value at T_c and saturated at low temperatures to a maximum value $B_{c2}(0)$.

Broadened Transitions

Early measurements on high T_c superconductors revealed that $B_{c2}(T)$ increased rapidly to the limit of even the most powerful magnets when the temperature was lowered by only a few degrees below T_c. At lower temperatures, the external field was simply not high enough to drive the sample to the normal state so that B_{c2} could not be measured. There was also another difference with respect to classical superconductors. The resistive transitions in external magnetic fields, which could be observed near T_c in high-T_c superconductors, appeared to be significantly broadened. Therefore, the question arose as to which criterion should be used for the normal to superconducting transition, and the determination of B_{c2}. It was found that regardless of the criterion used, e.g. zero resistance, 50% of the normal state R_n, or other, the resulting curves of $B_{c2}(T)$ had an unusual positive curvature below T_c (Fig. 1).

The ambiguity of the criterion for B_{c2}, and the puzzle about the curvature was solved by the analysis of the measured reversible magnetization. The values of B_{c2} obtained in this analysis, appeared higher than those determined by any criterion in resistivity measurements, and showed linear dependence below T_c (Fig. 1). It was realized that the unusual behaviour of the resistance curves was due to the magnetic flux motion near T_c, which causes some dissipation even in the superconducting state. This phenomenon is enhanced in high-T_c superconductors and gives rise to broadened transitions. The zero resistance criterion was associated with the irreversibility line $B_{irr}(T)$, i.e. the line below which there is practically no flux motion, while other criteria $0<R<R_n$ had no precise meaning, but represented various degrees of flux line mobility [1].

Scaling Properties

The upper critical field can also be extracted from the analysis of the superconducting fluctuations. According to the general theory of phase transitions, the order parameter fluctuates near T_c. This means that above T_c superconducting droplets appear in the predominantly normal medium, and decay after a short lifetime. Below T_c, normal droplets appear and decay in the predominantly superconducting medium. When fluctuations contribute to various thermodynamic and transport quantities (magnetization, specific heat, fluctuation conductivity) one expects the so-called scaling properties. For a given quantity, a set of experimental curves as functions of field and temperature can be made to collapse into a universal curve by some rescaling of the quantities on the axes. The scaling law results from a theoretical model of fluctuations [2,3]. The upper critical field B_{c2} enters the relevant expressions so that its value can be determined as that which results in the optimum scaling of the given set of experimental curves. In high T_c superconductors the fluctuations are greatly enhanced and the scaling procedure works very well. It was found [4–6] that the values of $B_{c2}(T)$ lay on a

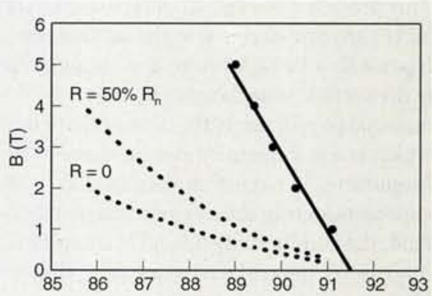

Fig. 1. Upper critical field $B_{c2}(T)$ in single crystal $YBa_2Cu_3O_{7-\delta}$ (data taken from Ref. [1]). The linear extrapolation of the reversible magnetization yields data points on the straight line. Resistance measurements with various criteria result in much lower field values lying on the lines with a positive curvature.

straight line below T_c and the slope dB_{c2}/dT agreed with those determined previously from linear extrapolation of the reversible magnetization (Fig.1). Thus the scaling procedure of various thermodynamic and transport quantities emerged as a reliable method for the determination of $B_{c2}(T)$.

Scaling has recently shown advantages even in the $K_xBa_{1-x}BiO_3$ superconductor which apparently has sharp resistive transitions [7]. With zero resistance criterion, one obtains the irreversibility line with a positive curvature (Fig. 2). The crossection of the linear extrapolations of the normal state and resistive transition section, which might look as a reasonable criterion for the determination of B_{c2}, turns out to be misleading too. Therefore, one can analyse the upper tail of the resistance curve (inset of Fig.2) which is dominated by the fluctuation conductivity. The scaling of this quantity yields much higher values of B_{c2}, lying on a straight line. Such values could not be detected directly on the resistance curves. Similar behaviour was also observed in overdoped $Tl_2Ba_2CuO_6$ [8], Sr deficient $Bi_2Sr_2CuO_y$ [9] and $Bi_2Sr_2CaCu_2O_8$ [10], but no fluctuation scaling was attempted.

Although the scaling procedure has an obvious advantage, it keeps the same limitations on the determination of B_{c2} within the fields accessible by the laboratory magnet, and this is not enough for high T_c superconductors.

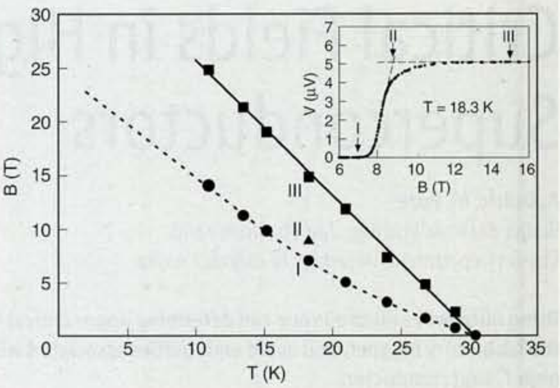

Fig. 2. Upper critical field $B_{c2}(T)$ in $K_xBa_{1-x}BiO_3$ (data taken from Ref. [7]). Zero resistance criterion (position I in the inset), yields lower curved line. Linear extrapolation to the normal state (position II in the inset) does not alter the result significantly. Only the fluctuation scaling procedure yields B_{c2} on a straight line. This value is also marked on the resistivity curve (position III in the inset).

Microwave Method

An alternative method for the determination of B_{c2} has emerged from the temperature and field dependent microwave absorption. When a normal conducting sample is exposed to a microwave field, current is induced on the surface and within the penetration depth (skin effect). This process gives rise to microwave losses which are proportional to the surface resistance $R_s = Re\,(Z_s)$, where $Z_s = (i\mu_o\omega/\sigma)^{1/2}$ is the surface impedance. The only material parameter is the conductivity σ, which is a real quantity at microwave frequencies in normal metals. In the superconducting state in zero magnetic field, the conductivity becomes complex $\sigma = \sigma_1 - \sigma_2$, the real part expressing the response of uncondensed electrons (quasiparticles), and the imaginary part that of superconducting pairs. With the superconductor in the mixed state, the situation is more complicated. The microwave current drives vortex oscillations and yields a contribution to the microwave dissipation. The total response of the superconductor to the microwave field is expressed by the effective conductivity [11]

$$\frac{1}{\delta_{eff}} = \frac{1 - b\,(\frac{v}{v_f})}{(1-b)\,\sigma + b\sigma_n} + \frac{b}{\sigma_n}\frac{v}{v_f} \qquad (1)$$

where $b=B/B_{c2}$ is the reduced field, σ_n the normal conductivity, and the ratio v/v_f is the vortex mobility factor, which attains unity in the flux flow regime. With the effective conductivity used in the expression for the surface impedance Z_s, one obtains the analytical expression which can be used to make fits to the experimental curves. One of the fit parameters is the upper critical field B_{c2}, which can thus be determined.

It is important to note that this method does not require the knowledge of a complete experimental curve from $B = 0$ up to B_{c2}, but only some initial fraction of it suffices. An example of $YBa_2Cu_3O_{7-\delta}$ single crystal is shown in Fig. 3 [12].

At lower temperatures B_{c2} is clearly beyond the field of the laboratory magnet used in the experiment (2.25 T). Yet, the fit of the theoretical expression to the available experimental data suffices to determine B_{c2} as high as 40 T (Fig. 4).

The situation at temperatures closer to T_c is different. The low field segments of the experimental curves can be fitted by the theoretical expression using σ_{eff}. These segments suffice to determine B_{c2} values. Indeed, the extensions of the theoretical curves rise further to the normal state and show where B_{c2} is. On the contrary, the experimental curves do not rise to the normal state because of the fluctuations which dominate at higher fields. The high field segments of the experimental curves can also be used to determine B_{c2}. Namely, in this region, the total conductivity is the sum of normal and fluctuation contributions. One can use the scaling procedure for the fluctuation conductivity [13], which yields the values of B_{c2} as fit parameters. Thus, each experimental curve near T_c can be used to determine the B_{c2} value twice, from low field and high field segments, in two different procedures. It is most reassuring that both procedures yield the same B_{c2} value, thus demonstrating the consistency of the method.

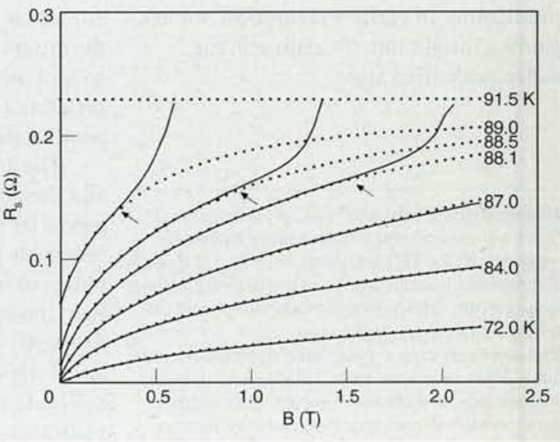

Fig. 3. Experimental microwave surface resistance R_s in a single crystal $YBa_2Cu_3O_{7-\delta}$ (dots) and theoretical fits (solid lines) using mean field σ_{eff} in the mixed state. The arrows indicate the crossover from the mixed state to the fluctuation region.

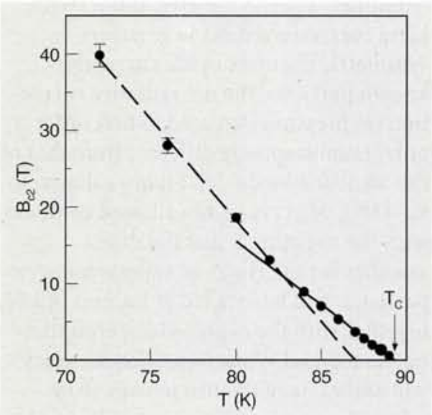

Fig. 4. Upper critical field in a single crystal $YBa_2Cu_3O_{7-\delta}$ determined from the fits in Fig. 3. Note that B_{c2} could be determined up to 40 T even though the experimental R_s was measured only up to 2.25 T.

The temperature at which the coherence length diverges $(B_{c2} \rightarrow 0)$ is defined as T_c (Fig. 4). At about 83 K, one observes a change in the slope of $B_{c2}\,(T)$ which may result from the crossover from three to two dimensional superconductivity.

Outlook

The determination of the upper critical field, or equivalently the coherence length, has fundamental importance for the study of the nature of the superconducting state. It has recently been shown theoretically that for the gap anisotropy with the symmetry of the pairing state $d_{x^2-y^2}$ one should have an anisotropy of B_{c2} in the *ab* plane (copper-oxide plane) which has fourfold symmetry near T_c [14]. Also, at lower temperatures, the temp-erature dependences of *s*-wave and *d*-wave superconductors are expected to bedifferent [15].

The microwave technique promises to provide solid experimental data to answer the above questions. Yet, some associated problems have to be solved beforehand. Vortex motion driven by the microwave current is not completely in the flux flow regime so that the mobility factor v/v_f, which can be temperature and field dependent, should be precisely determined [16]. The anisotropy study would require measurements with several different field and current geometries, e.g. dc field in the ab plane, and the current along the c axis, or in the ab plane perpendicular to the dc field, or in the ab plane parallel to the dc field. This will increase the number of experimentally determined parameters and eliminate the uncertainties. Thus, one may expect that the experiments underway in many laboratories will promote exciting discoveries in the field.

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