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CRITICAL BEHAVIOR OF THE FIELD-DEPENDENT SPECIFIC HEAT OF A YBa$_2$Cu$_3$O$_{7-x}$ SINGLE CRYSTAL

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Abstract. – The heat capacity anomaly of YBa$_2$Cu$_3$O$_{7-x}$ at $T_c$ is reduced in amplitude and broadened upon application of a magnetic field along the c-axis. However, the shift, as measured by the point of maximum increase with decreasing temperature, is much smaller than expected from estimates of the upper critical field. The possibility of critical behavior is discussed.

Following the exciting discovery of superconductivity in YBa$_2$Cu$_3$O$_{7-x}$, measurements of its properties were analyzed in the context of the Ginzburg-Landau model [1]. Most of the results agreed satisfactorily with a strong-coupling picture of a type II superconductor, intermediate between the clean and dirty limits [2]. Recently, however, this agreement has been called into question by reports from IBM [3] that the reported upper critical field is in fact a line separating reversible and irreversible behavior. Similarly, detailed measurements of the reversible magnetization suggest that the true line $H_{c2}(T)$ rises much more steeply than supposed.

We present here heat capacity data on a twinned crystal of YBa$_2$Cu$_3$O$_{7-x}$ taken in magnetic fields up to 6 T applied along the c-axis. The 600 µg sample was grown by flux methods, as described elsewhere [4]. The heat capacity was measured by the ac method reported earlier [5]. Data were taken by cooling the sample in an applied field and then measuring the heat capacity as the temperature was slowly increased. No field dependence of the heat capacity could be detected at 77 K. This temperature was used as a common calibration point for the ac signal. Identical results are obtained if the calibration point is chosen well above $T_c = 90.8$ K.

The effect of magnetic field on conventional type II superconductors is to shift the BCS-like step in the specific heat to a lower temperature $T_{c2}(H)$. By contrast, the lambda-like peak observed in YBa$_2$Cu$_3$O$_{7-x}$ is broadened and reduced, but with little shift. This is shown in figure 1, where the raw data for several runs are superimposed. Three main features appear in the data: i) a deviation from the zero-field results on the high-temperature side which moves to slightly higher temperatures; ii) a maximum negative-tending slope, which moves very little in temperature; and iii) a lower branch point, at which the zero-field and field-cooled data join.

In figure 2, we plot the point of most-negative slope (triangles) and lower branch point (circles) vs. temperature. The line through the triangles represents a thermodynamic $H_{c2}(T)$ with a slope of 8.8 T/K. This compares with a thermodynamic estimate of $\approx 3$ T/K [6]. Note that the lower branch point has an initial slope of 0.5 T/K, a value that has been reported pre-
Fig. 2. Locus of lower branch points (circles) and most-negative slopes (triangles).

Previously as the upper critical field curve. A better representation of the data is the solid curve, which is given by

$$H_{\text{branch}} = 289T (1 - T/T_c)^{1.5}. \quad (1)$$

The amplitude of the specific heat anomaly is also reduced. This is most readily seen by computing the difference between the specific heat measured in zero field and that measured in a field. We show this difference in figure 3. A determination of the difference between the Gibbs free energy in a field from its zero-field value, determined by integrating the magnetization curve, has been reported [6]. The numerical second derivative of the data, in fact, agrees quantitatively with the results of figure 3.

Fig. 3. Difference between zero-field and field-cooled heat capacity.

If we assume that the behavior observed here is due to the intrinsic thermodynamics of \( \text{YBa}_2\text{Cu}_3\text{O}_{7-x} \), we can make scaling arguments concerning the relationship between the reduced temperature \( t = (T/T_c - 1) \) and the applied field. The field enters the superconducting problem through the momentum term 2eA/c, where A is the vector potential. It is straightforward to argue that magnetic field scales as the inverse square of a length. Since the coherence length increases as \( t^{-\nu} \), all thermodynamic functions are functions of \( H/t^{2\nu} \).

A natural interpretation of the curve given by equation (1) is that it represents a particular value of this scaled variable (i.e., a cross-over line). This leads to the conclusion that \( \nu = 0.75 \). This is distinctly different from \( \nu = 0.5 \), which is the mean-field value appropriate for ordinary superconductors.

Estimates of the low-temperature coherence length of \( \text{YBa}_2\text{Cu}_3\text{O}_{7-x} \) have relied on the slope of \( H_{c2} \) vs. \( T \) near \( T_c \). If, as suggested here, that slope is much larger than previously thought, the coherence length is correspondingly smaller. This means, from the Ginzburg criterion, that the width of the true critical region near \( T_c \) is relatively large. Thus, one explanation for the effects observed here is that we are actually in the critical regime. However, the critical behavior expected for a BCS superconductor is analogous to that of a 3D XY model; that is, \( \nu = 0.65 \). While the uncertainties are large, this value appears to be outside the range of error.

Separately [5], we have considered the scaling properties of the field-dependent specific heat in some detail and argued that the increase in the peak amplitude in figure 3 is also consistent with the value \( \nu = 0.75 \). It is possible to fit the zero-field specific heat with a cusped function consistent with that exponent. Such values indicate that, unlike BCS, the order parameter may have more than two components. These results taken together seem to suggest that agreement with simple extensions of Ginzburg-Landau is illusory, and that an understanding of superconductivity in \( \text{YBa}_2\text{Cu}_3\text{O}_{7-x} \) is yet to come.

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