PHYSICAL REVIEW B VOLUME 42, NUMBER 13 1 NOVEMBER 1990

Flux density in the mixed state in the high-T_c superconductors and the predictions of Abrikosov theory

A. F. Khoder and M. Couach
Centre d'Études Nucléaires de Grenoble, Service des Basses Températures, Boîte Postale No. 85X, 38041 Grenoble CEDEX, France

J. L. Jorda
Moltech S.A. 1227 Carouge, Switzerland

(Received 30 May 1990; revised manuscript received 22 August 1990)

The high-T_c superconductors are known to exhibit a large domain of reversibility in the (H,T) plane. In this domain, measurements of χ'_H, the differential ac susceptibility in a static magnetic field H, can yield equilibrium values for dM/dH where, as expected, $\chi'_H = dM/dH > 0$, provided that the diffusion time of the vortices into the bulk of the sample is short compared to the experimental time scale $\tau_E = f^{-1}$, where f is the frequency [A. F. Khoder and M. Couach (unpublished)]. An irreversibility line $(H,T)_f$ is obtained for each frequency. In the reversible domain above this line, the measured χ'_H for our Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O samples are shown to agree with the predictions of the Abrikosov-Ginsburg-Landau theory. This indicates the absence of any phase transition along the irreversibility line and in the reversible domain.

The aim of this Rapid Communication is to present the results of an investigation by ac susceptibility of the reversible mixed state in high-T_c superconductors and indicate the far-reaching implications of these results with respect to any phase transition in the domain under scrutiny. Details on the samples and the experimental procedures will be published elsewhere.[1,2]

The domain in the (H,T) plane where high-T_c compounds display reversible magnetic properties and the large extent of this region are currently topics of great basic interest. Questions about the nature of the reversible phase(s) in the mixed state (liquid, glass, or lattice) have been raised[3,4] and various theories have been developed which predict a variety of complicated phase diagrams in the (H,T) plane.[5,6]

Reversibility (or irreversibility) lines have been drawn in the (H,T) plane whose shape and position depend on the experimental technique and the experimetal time scale τ_E. Measurements of χ_{ac}, the ac susceptibility, lead to a well-defined criterion for such lines where τ_E enters as a parameter. Exploiting the χ_{ac} technique we have investigated the reversibility regime in Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O ceramic compounds with T_{co}, the transition temperature in zero magnetic field of 85 and 107 K, respectively.

Our work focused on the entire reversible range below $T_{c2}(H)$ where χ_{ac}, in the presence of a dc magnetic field, showed no diamagnetic response. Indeed in this region and under these conditions, $\chi'_H = dM/dH$ is expected to display a positive value. This phenomenon, known as the differential paramagnetic effect (DPE) has been exploited by Hein and Falge[7] more than two decades ago to identify and examine reversibility in superconductors. Due to the high values of κ and the low values of H_{c1} in these ceramic compounds, the positive χ'_H signals in the region of reversibility are very weak, typical data are displayed in Fig. 1.

The Abrikosov-Ginsburg-Landau theory leads to two simple expressions for the equilibrium magnetization M of the mixed state with an applied field H in two distinct regimes.[8] (i) In the high-flux-density regime, $H \sim H_{c2}$, it is well known that

$$\chi'_H = \frac{dM}{dH} = \frac{1}{(2k^2-1)\beta_A} . \tag{1}$$

(ii) In the intermediate-flux-density regime, $H_{c1} \ll H \ll H_{c2}$, it has been shown[8] that

$$\chi'_H = \frac{dM}{dH} = \frac{H_{c1}}{H \ln\kappa} . \tag{2}$$

With $\kappa \sim 100$–300 and $\beta_A \approx 1$, we expect from Eq. (1) that χ'_H will show a steplike increase when T decreases through $T_{c2}(H)$, from 0 to a value between $(0.5$–$5.0) \times 10^{-5}$ MKSA. This steplike increase is not observed in our measurements although the expected value is within the range of sensitivity of our experimental setup. This is perhaps not surprising, however, if one considers anisotropy averaging over $T_{c2}(H)$, possible temperature dependence of κ, and sample inhomogeneity, contributing to a broadening of $T_{c2}(H)$.

The behavior predicted for the intermediate-flux-density regime is, however, clearly evident in Fig. 1. First, we note the linear dependence of χ'_H on temperature, reflecting the well-established linear variation of H_{c1} with T in this region. Second, the magnitude of χ'_H in the linear region is seen to scale inversely proportional to H as required by Eq. (2). This inverse dependence on H is illustrated in more detail and this feature emerges clearly in Fig. 2.

Here, we display χ'_{H_i}/χ'_{H_j}, where both members of a ratio are measured at the same chosen temperature, plotted versus the corresponding ratio H_j/H_i of the static magnetic fields. Each pair of χ'_{H_i},χ'_{H_j} and the corresponding H_i,H_j is entered only once in the graph (i.e., the inverse of the ratios of two corresponding pairs are omitted). Some

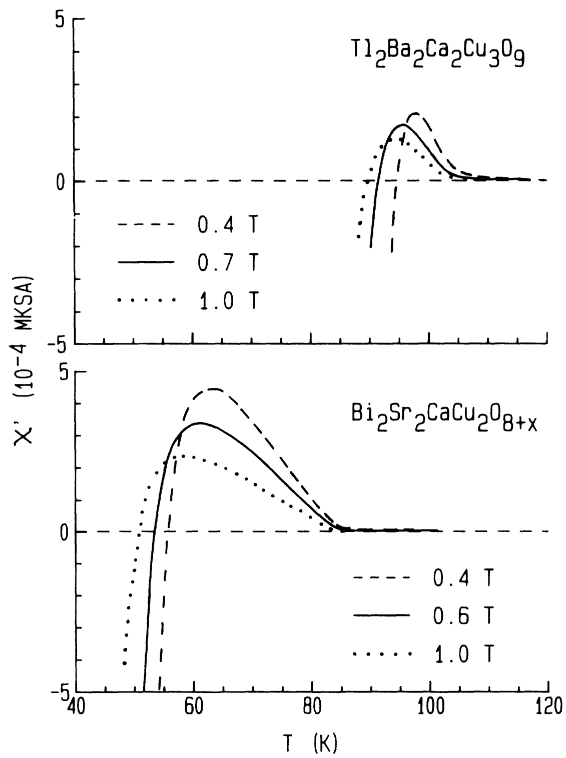

FIG. 1. Display of typical ac susceptibility data vs T in static magnetic fields of different intensities. The range where $\chi_H > 0$ (i.e., the DPE is observed) identifies the reversible regime where Eqs. (1) and (2) are applicable. The ac field has 35-Oe amplitude parallel to H and 6.7-Hz frequency.

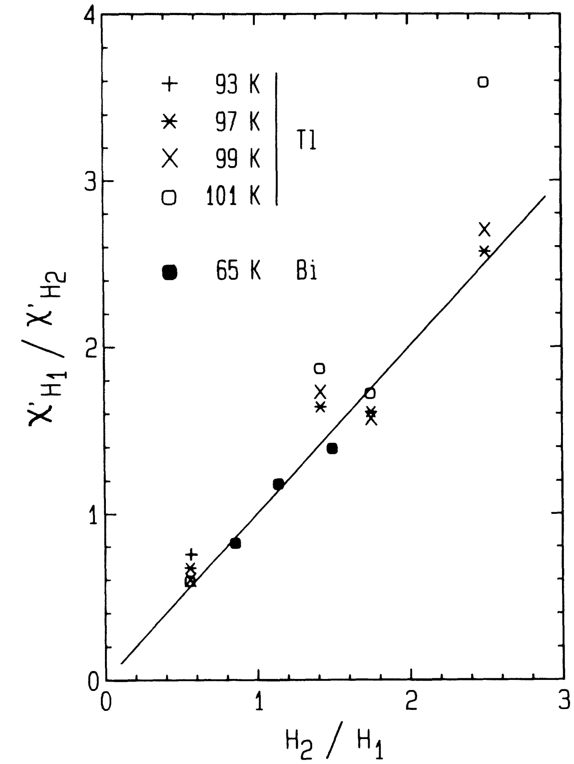

FIG. 2. Verification of the $1/H$ functional dependence of χ'_H on the reversible regime. In this format, Eq. (2) predicts the solid line of unit slope.

scatter appears in the data points at the four temperatures selected for the Tl-Ba-Ca-Cu-O sample. For the Bi-Sr-Ca-Cu-O sample, only the data points for $T=65$ K are presented. We stress that here, the data points remain essentially the same over the entire range from 65 K to near 80 K.

The mode of representation exploited in Fig. 2 eliminates the dependence of χ'_H on H_{c1} and κ contained in Eq. (2) and focuses on the variation with $1/H$. In this format, Eq. (2) predicts a solid straight line with unit slope for all reversible type-II superconductors in the appropriate flux-line-density regime.

The agreement between our experimental results and Eq. (2) is remarkable. The Abrikosov-Ginsburg-Landau theory which generates Eq. (2) also, concomitantly, predicts a (triangular) lattice of the flux line vortices in the mixed state. It would be indeed surprising, even if not excluded, that the magnetic properties of a *liquid* or *glass* phase would mimic exactly the same functional dependence on $1/H$ and H_{c1} as the ordered phase. We maintain that our observations, in the reversible domain we have identified and explored by our approach, confirm the existence of an Arbrikosov ordered phase in this domain, since these data are in harmony with Eq. (2) developed within this framework.

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