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Investigations of the Vortex Matter in $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ Single Crystals

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Abstract. We report transverse-field muon spin rotation studies of the magnetic field distribution n(B) in the vortex state of the high temperature superconductor $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ (Bi-2212) and present data on three sets of overdoped, nearly optimized and underdoped single crystals which to our best knowledge provide the first evidence that a two-stage melting transition of the vortex matter occurs under equilibrium conditions. In addition, we compare the TF-μSR results with those from DC-magnetization measurements and magneto-optic experiments on the same crystals.

INTRODUCTION

The vortex matter in the cuprate high-T_c superconductors exhibits a complex (H, T)-phase diagram where thermal fluctuations dominate the vortex state well below the upper critical field $H_{c2}(T)$ [1]. Early on, a melting transition of the flux-line lattice (FLL) was proposed [2] and confirmed experimentally [3]. However, the details of this melting transition are not yet fully understood. When a magnetic field is applied perpendicular to the CuO_2 planes the flux-lines can be viewed as stacks of pancake vortices [4]. Both the intra-planar vortex order and the inter-planar coupling between the pancake vortices can be overcome by thermal fluctuations. In principle, these processes may occur independently and at different temperatures. Based on these considerations a two-stage melting transition has been proposed [5]. Recently, experimental evidence for this two-stage melting scenario has been obtained from non-equilibrium experiments [6]. The equilibrium vortex structure, however, can be studied with the technique of transverse-field muon spin rotation (TF-μSR) which has already provided valuable information on the vortex state, in particular, on the vortex matter transition at the irreversibility line (IL) and the so called 'dimensional crossover' from a 3D to a 2D vortex structure [7,8].

TF-μSR EXPERIMENTS

In TF-μSR experiments positive muons come to rest in the bulk of the crystal at interstitial locations, r, which are randomly distributed on the length scale of the magnetic penetration depth λ [9]. An external magnetic field H_{ext} is applied perpendicular to the initial muon spins which start to precess in the local magnetic field $B_{int}(r)$ with the Larmor frequency $\omega_\mu = \gamma_\mu B_{int}(r)$ where $\gamma_\mu = 851.4\ MHz/T$ is the gyromagnetic ratio of the muon. The time evolution of the muon spin polarization function P(t) is then measured by monitoring the decay positrons which are preferentially emitted along the muon spin direction at the instant of decay (for details see [10]). The probability distribution of the local magnetic field n(B), the so called 'μSR-lineshape', is extracted from P(t) either via Fast Fourier Transform or Maximum Entropy techniques and contains detailed information on the vortex structure. For a 3D flux line lattice, n(B) is strongly asymmetric [11] with a pronounced tail towards high fields due to muons that stop near the vortex cores, a cusp which corresponds to the field at the saddle point between adjacent vortices and a cutoff on the low field side corresponding to the field minimum at the point which is most remote from the vortex cores. The asymmetry or 'skewness' of the 'μSR-lineshape' can be characterized by the dimensionsless parameter [7] $\alpha =< \Delta B^3 >^{1/3} / < \Delta B^2 >^{1/2}$, where $< \Delta B^n >$ is the n^{th} central moment of n(B). A value of $\alpha \approx 1$ is typical for the 'μSR-lineshape' due to a static 3D FLL [7,8]. A reduced value of $1 > \alpha > 0$ either indicates a disorder of the static vortex structure or else vortex dynamics in excess of the typical μSR time scale of $\tau < 10^{-6}\ s$ [7,8].

With increasing temperature a FLL will be subject to thermal fluctuations and α will be continuously reduced towards rather small but still positive α-values. In contrast, α has been shown to undergo a sudden and discontinuous change from positive to negative values at the IL. This behavior has been attributed to an one-stage transition where the intra-planar melting and inter-planar decoupling occur simultaneously at T_m [7]. In the following we present TF-μSR data which indicate that a second transition occurs in the irreversible regime well below the IL [12]. Figure 1a summarizes the results for α and the shift of the cusp-field with respect to the external field (cusp-shift, B_{sh}). The data have been obtained by field cooling in an applied field well below the dimensional crossover field H^* [8,12] and the signature of a 3D vortex lattice, i.e. $\alpha \approx 1$, is observed at low temperature. The 'μSR-lineshape' exhibits the most pronounced changes in the vicinity of the IL, where α exhibits a sudden drop and changes sign at T_{dc}. In addition, the T-dependence of the 'μSR-lineshape' exhibits a second anomaly at a temperature T_{ab} well below the IL. We argue that the observed transition may be related to the intra-planar melting of the flux-line lattice to a flux-line liquid phase. This phase persists over a sizable temperature interval for $T_{ab} < T < T_{dc}$ before the individual flux-lines are decoupled at a significantly higher temperature T_{dc} at the IL [12].

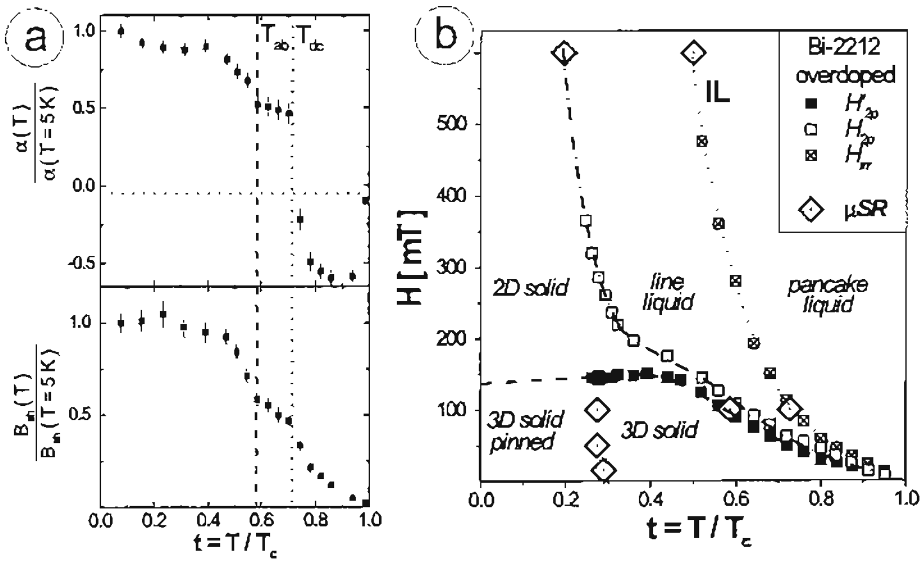

FIGURE 1. (a) Data from field-cooled TF-μSR experiments on overdoped Bi-2212 single crystals ($T_c = 64\ K$) in an applied field of $\mu_o H_{ext} = 100\ mT$. T-dependence of α (top) and the cusp-shift (bottom) of n(B). T_{ab} and T_{dc} denote the temperature for the intra-planar melting and the inter-planar decoupling, respectively. (b) (H, T)-phase diagram constructed from μSR and VSM data. Shown are the irreversibility field H_{irr}, the field for the second peak in $M(H)$, H_{2p}, and for the peak in the corresponding derivative dM/dH, H'_{2p}. The lines are guide to the eye.

For fields $H > H^*$ the low-temperature vortex-state is quasi-2D [7,8]. In this regime the 'μSR-lineshape' becomes almost symmetric giving rise to strongly reduced values of α and B_{sh}. Figure 2a shows the T-dependence for α and B_{sh} which has been obtained for the underdoped set for $H_{ext} = 100\ mT > H^* \sim 7.5\ mT$. The most pronounced changes occur again in the vicinity of the IL. Once more a second anomaly is apparent in the T-dependence of the 'μSR-lineshape' which occurs at a temperature well below the IL. In contrast to the behavior in the FLL state at $H < H^*$ (where α and B_{sh} decrease with increasing T) the 'skewness' now exhibits a small but significant increase and the cusp-shift also becomes somewhat larger. Both effects are indicative of a restoration of the flux-lines as the intra-planar order of the quasi-2D pancake vortex lattice diminishes at T_{ab}. Especially the increase of α signals the formation of vortex-line segments on a length scale along the c-axis direction exceeding the in-plane magnetic penetration depth [8]. At low T the adjustment to the pinning sites was achieved by suppressing the inter-planar coupling of the individual flux-lines in favor of the persistence of quasi-2D intra-planar order of the pancake vortices. At the in-plane melting transition, however, the intra-planar order is lost and there is no further need for the decoupling of the individual vortex lines in order to obtain a favorable adjustment to the pinning sites. The vortex lines therefore become at least partially restored. We note that the same trend has been observed at a higher field of $H_{ext} = 600\ mT$ and $H_{ext} = 1\ T$ for the underdoped and the overdoped Bi-2212 single crystals.

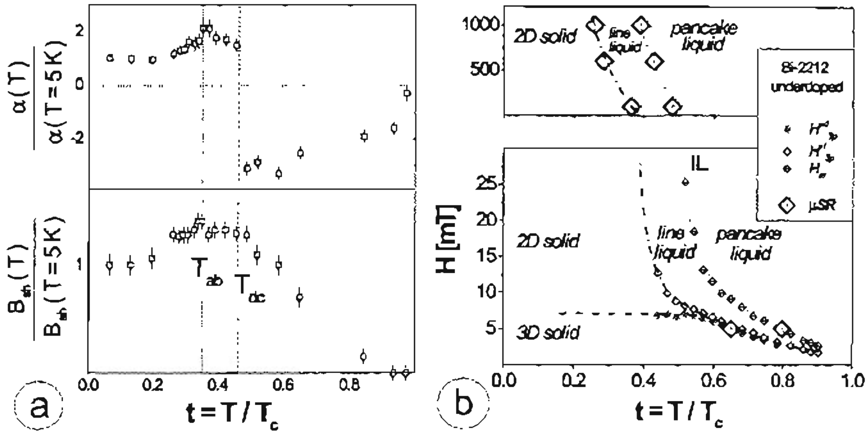

FIGURE 2. (a) Data from field-cooled TF-μSR experiments on a set of underdoped Bi-2212 single crystals (T_c = 77 K) in an applied field of $\mu_o H_{ext}$ = 100 mT. (b) (H, T)-phase diagram constructed from μSR and VSM data. Panels are as described in Figure 1.

DC-MAGNETIZATION MEASUREMENTS

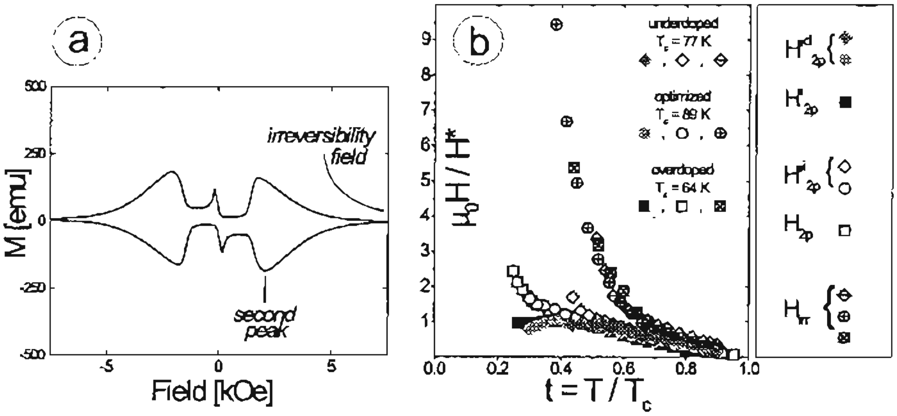

FIGURE 3. (a) representative $M-H$ loop at T = 24 K. (b) Rescaled VSM data (scaling factor H*) for different doping states of Bi-2212 single crystals.

The μSR results support our assumtion that the second-peak effect in the DC-magnetization (Figure 3a) is related to the dimensional crossover [8]. The decoupling of the vortex lines and the concomitant enhancement of the pinning of the quasi-2D pancake lattice increase progressively as the magnetic field is increased above H^* until it goes through a maximum right at the in-plane melting point. At even higher magnetic fields in the line-liquid phase the pinning properties decline due to enhanced thermal fluctuations before the magnetic behavior becomes reversible beyond the irreversibility field. A rather interesting question is how our observation of a two-stage melting transition fits in with the reports of a one-stage melting transition. It seems likely that the key to the answer lies in the c-axis coupling strength. In fact, we obtain a rather unique (H, T) phase diagram from μSR (Figure 1b and 2b) and DC-magnetization (Figure 3b, scaling factor H*) data for a wider series of Bi-2212 single crystals. This would imply that a two-stage melting process is experimentally observable if $H \geq H^*$ while a seemingly one-stage melting process occurs when T_{ab} and T_{dc} do collapse for $H << H^*$. Such a trend is even visible from our data on the Bi-2212 crystals for which the $T_{ab}(H)$- and $T_{dc}(H)$-lines seem to merge for $H << H*$. For the much less anisotropic Y-123 compound H^* should be in excess of 10 T and accordingly most of the experiments have been done for $H < H^*$ where in fact a single-stage transition is observed.

MAGNETO-OPTIC EXPERIMENTS

The magneto optical method is based on the Faraday effect, i.e. the rotation of the polarization plane of linearly polarized ligth which passes a magneto-optically active layer exposed to the magnetic field of the underlying superconductor. Since the rotation angle depends on the magnetic field one can visualize the flux distribution in a polarization microscope. This technique has already been shown to be a powerfull tool to investigate e.g. artificial defects in thin films [13]. In Figure 4 are displayed pictures of the magnetic field distribution received from underdoped Bi-2212 single crystals in an applied field of 10 mT for different temperatures. The experiment has been performed in 10 mT after zero field cooling. Shown are the pictures taken at (a) 10 K in the strong pinning regime, no flux penetrates the sample (sample dark, edges white due to pile up of flux), (b) 34 K in the vicinity of the depinning temperature (different gray scales due to inhomogenuous flux distribution), (c) 36 K in the line-liquid regime above T_{ab} (almost homogenuous contrast due to nearly randomly distributed flux) and (d) 60 K, above T_{ab} (no more contrast due to reversible vortex state and high thermal fluctuations). Details will be presented in forthcoming publications (spatial resolved [14] and time resolved [15]).

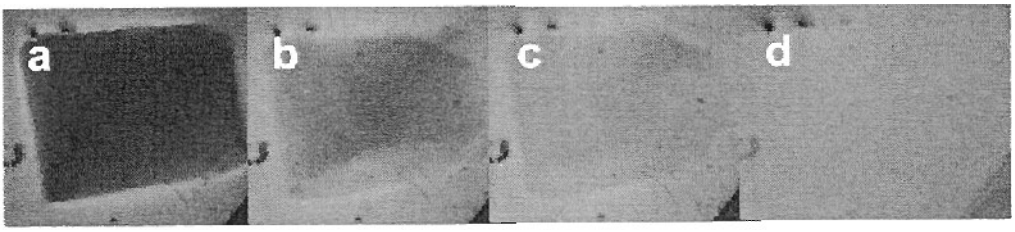

FIGURE 4. Magneto-optical picturing of the magnetic field distribution on a underdoped Bi-2212 single crystal in an applied field of 10 mT after zero field cooling (T = 10 K, 34 K, 36 K and 60 K, from left to right)

SUMMARY

From muon spin rotation measurements on three sets of overdoped ($T_c = 64\ K$), nearly optimized ($T_c = 90\ K$) and underdoped ($T_c = 77\ K$) $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals, we have obtained evidence for a two-stage melting transition of the vortex matter under equilibrium conditions. Two marked changes in the 'μSR-lineshape' have been observed and related to transitions in the vortex state. The well-known transition at the higher temperature T_{dc} coincides with the IL, as determined from DC-magnetization measurements, and is related to the decoupling of the individual flux-lines which results in a pancake liquid state with reversible magnetic behavior. The second transition of the vortex state occurs at a temperature T_{ab} well below the IL. For all sets of Bi-2212 single crystals this transition is found to coincide with the second-peak effect as seen in the DC-magnetization measurements. We interpret this second transition as the intra-planar melting of the vortex structure which leads to a line-liquid state with irreversible magnetic behavior.

The experiments described herein have been performed at the Paul-Scherrer-Institute , Villigen, CH and TRIUMF, Vancouver, Canada. We thank these institutions and their support stuff for continuing assistance. The financial support of the German BMFB and the DFG is gratefully acknowledged.

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