Melting and Dimensionality of the Vortex Lattice in Underdoped YBa$_2$Cu$_3$O$_{6.60}$

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Muon spin rotation (μSR) measurements of the magnetic field distribution in the vortex state of the oxygen deficient high-$T_c$ superconductor YBa$_2$Cu$_3$O$_{6.60}$ reveal a vortex-lattice melting transition at much higher temperatures than that in the fully oxygenated material. The transition is best described by a model in which adjacent layers of “pancake” vortices decouple in the liquid phase. Evidence is also found for a pinning-induced crossover from a solid 3D to quasi-2D vortex lattice, similar to that observed in the highly anisotropic superconductor Bi$_2+x$Sr$_{2-x}$CaCu$_2$O$_{8+y}$.

74.60.Ge, 74.25.Dw, 76.75.+i, 74.72.Bk

In the high-temperature superconductors there exist several exotic vortex lattice (VL) phases owing to the weak coupling between the superconducting CuO$_2$ layers (which gives rise to highly flexible vortices), a relatively short coherence length (which enhances their susceptibility to pinning) and high values of $T_c$ (which permit large thermal energies to be reached in the vortex state). To date much attention has been paid to VL melting and pinning effects in the highly anisotropic superconductor Bi$_2+x$Sr$_{2-x}$CaCu$_2$O$_{8+y}$ (BSCCO) and in YBa$_2$Cu$_3$O$_{7-δ}$ (YBCO) for near optimal oxygen concentrations (i.e. $δ \approx 0.05$, giving the highest value of $T_c$). The vortices in BSCCO are often described as stacks of two-dimensional (2D) “pancakes”, which can become misaligned at elevated temperatures and/or in the presence of random pinning sites. On the other hand, in “optimally” doped YBCO the vortices behave in a three-dimensional (3D) manner. This difference is attributed to the mass anisotropy $γ = (m_c/m_a)^{1/2} = λ_c/λ_a \approx 5-7$ in YBCO and $γ \approx 50-250$ in BSCCO, where $λ_a$ and $λ_c$ are the magnetic penetration depths describing the screening of flux by supercurrents flowing in and out of the CuO$_2$ layers, respectively. An added complication in many studies of YBCO is the presence of twin-plane boundaries which may act as extended pinning sites for vortices.

The muon spin rotation (μSR) technique measures the muon precession frequency distribution and thus the internal magnetic field distribution $n(B)$, also known as the μSR line shape, which has proven to be a powerful tool for investigating VL phases. In optimally doped YBCO, strong local pinning broadens the μSR line shape as predicted for small random displacements of 3D vortex lines. By contrast, random pinning in BSCCO leads to a field-induced reduction of the μSR line width associated with a dimensional crossover from a 3D-VL to a quasi-2D system consisting of independent weakly interacting VLs in different CuO$_2$ layers. In the quasi-2D region, the repulsive interaction between pancake vortices in the layers exceeds the strength of their interlayer coupling, so that random pinning results in a misalignment of the pancake vortices in the field direction.

The effect on the μSR line shape of thermal fluctuations of the vortex positions has been the focus of numerous studies in BSCCO. As explained in Ref. [1], the typical time scale for vortex fluctuations is short enough that the muon detects a fluctuation-averaged field. This results in a reduction of both the width and the skewness of the μSR line shape. In clean samples the VL melts in a first-order phase transition (see, for example, Ref. [2]). Recent μSR measurements in BSCCO have been interpreted as evidence for a two-stage VL transition: first the intralayer coupling of the pancake vortices is overcome by thermal fluctuations, then their interlayer coupling is lost.

In the less anisotropic compound YBCO, a melting transition has been observed by small-angle neutron scattering, magnetization, transport, specific heat and Hall probe ac susceptibility measurements (see, for example, Ref. [3]). However, unlike in BSCCO, the vortex-liquid phase is found only in a very narrow region below the second-order phase transition at $B_{c2}(T)$. A melting transition near $B_{c2}(T)$ is difficult to study with the μSR technique, because even for a 3D VL, the μSR line shape narrows and becomes more symmetric due to the overlap of the vortices.

It is well established that removal of oxygen from the CuO chain layers in YBCO weakens the coupling between the superconducting CuO$_2$ layers. Here we report μSR measurements of the VL in the oxygen-deficient compound YBa$_2$Cu$_3$O$_{6.60}$, which has an increased anisotropy ratio $γ \approx 22-36$ (see, Ref. [4]). We observe an expanded vortex-liquid region and a pinning-induced crossover from a 3D to a quasi-2D system, qualitatively resembling the vortex phase diagram of BSCCO.

The μSR experiments were performed on the M15 and
M20 surface muon beamlines at TRIUMF, Canada, using the experimental setup described in Ref. [14]. Measurements of the internal magnetic field distribution were made in both twinned and detwinned crystals of underdoped YBa$_2$Cu$_3$O$_{6.60}$, with superconducting transition temperatures $T_c = 59(0.1)$ K. These samples were previously studied with $\mu$SR at low temperatures [4]. The crystals were mounted with their $c$-axis parallel to both the applied magnetic field $H$ and the muon beam direction. The positive muons were injected into the sample with their initial spin polarization perpendicular to $H$. As described fully elsewhere [17], $n(B)$ or the muon precession frequency distribution $n(\omega = \gamma \mu B)$, where $\gamma \mu$ is the muon gyromagnetic ratio, is obtained by monitoring the $e^+$ count rate as the muon decay pattern sweeps by the positron detectors.

Figure 1 shows the evolution of the fast Fourier transform (FFT) of the muon precession signal upon warming the sample, following field cooling to $T = 2.4$ K in a magnetic field $H = 1.49$ T. At $T = 20.5$ K the FFT shows the basic features expected for a well-ordered 3D solid VL — in particular a high-field “tail” associated with the region close to the vortex cores. However, at $T = 40$ K the FFT is completely symmetric and the line width is drastically reduced — both of which characterize a vortex-liquid phase. Despite these obvious changes in the $\mu$SR line shape, the melting transition cannot usually be determined accurately by visual inspection, because the output frequency spectrum is artificially broadened by the finite time range and the “apodization” needed to eliminate “ringing” in the FFT [18]. To quantify these changes in the field distribution we calculate the skewness parameter $\alpha$, $\alpha = \langle (\delta B)^3 \rangle^{1/3}/\langle (\delta B)^2 \rangle^{1/2}$, where $\langle (\delta B)^n \rangle = \langle B - \langle B \rangle \rangle^n$. To obtain reliable values for the moments $\langle (\delta B)^n \rangle$ we fit the $\mu$SR spectra in the time domain to a polarization function calculated assuming a Ginzburg-Landau (GL) model for the VL field profile $B(r)$, as described in Ref. [14]. The fitted function $B(r)$ properly accounts for the long high-field “tail” in $n(B)$ when the VL is 3D. This method of analysis also provides a means of monitoring the $\mu$SR line width through the fitted value of $1/\lambda_{ab}^2$. A hexagonal arrangement of vortices was assumed, consistent with recent neutron scattering measurements on untwinned YBCO [19].

Figure 2 shows the temperature dependence of $\alpha$ and $1/\lambda_{ab}^2$ at three of the fields considered. The observed values of $\alpha \approx 1.2$ are in agreement with values previously obtained in the 3D-VL phase of BSCCO [2,5,14,13] and that predicted for $s$- and $d$-wave VLS at low reduced fields $B/B_{c2}$ [20]. For temperatures above $T_m$ the fitted values of $1/\lambda_{ab}^2$ and hence $\alpha$ drop to zero. This does not mean that the superfluid density has decreased to zero, but rather that the $\mu$SR spectrum no longer contains a component corresponding to an ordered 3D vortex structure. For $T > T_m$ the $\mu$SR spectra fit well to a single Gaussian function, with a line width much greater than that due to nuclear dipoles.

In Ref. [21] a sharp transition was observed in ac susceptibility measurements on twinned YBa$_2$Cu$_3$O$_{6.60}$ crystals below a characteristic field $H^* \approx 0.07$ T, possibly associated with a melting transition. Above $H^*$, where the transition was found to be continuous, it was suggested that a quasi-2D system exists which is highly sensitive to pinning-induced disorder. In the present study, where $H > H^*$, the field distributions for $T < T_m$ and $0.1 < H < 1.49$ T fit well to the GL model for an ordered 3D VL. The rms deviation of the vortices from their ideal positions in the hexagonal VL was found [4] to be $< 8 \%$. These results suggest that the VL for our samples in this region of the $B$-$T$ phase diagram exhibits a 3D behavior, most likely consisting of stacks of strongly coupled pancake vortices. Above $T_m$, thermal fluctuations of the vortices lead to a loss of long-range spatial order.

The top panel of Figure 3 shows the $\mu$SR line shape in the twinned sample of YBa$_2$Cu$_3$O$_{6.60}$ after cooling in a field $H \approx 2.89$ T to $T = 2.5$ K, followed by an increase of $\Delta H \approx 0.01$ T. Notice that the small background signal is positioned at the external field $H = 2.90$ T, whereas the signal originating from the sample looks as though the external field is still $H = 2.89$ T. This implies that the VL is strongly pinned. However, unlike in the line shapes observed at the lower fields, the “tail” appears on the low-field side of the cusp. Numerical calculations performed in Ref. [22], which account for the sample geometry effect, show that such a line shape can originate from a system of 2D pancake vortices that are ordered in the planes but uncorrelated between adjacent layers. The low-field “tail” is specifically associated with a lower flux density at the sample edges due to a nonuniform demagnetization. Thus clear evidence is observed for a pinning-induced dimensional crossover above a critical field $B_{c2}(T)$.

By contrast, at the same field $H = 2.9$ T in the detwinned sample the “tail” extends to the high-field side of the distribution, as expected for an ordered 3D vortex structure. It is tempting to attribute the opposite skewness of the $\mu$SR line shapes in the two samples to the presence of twin planes. However, because the twin planes extend the full depth of the sample, they would displace the 2D VLs by the same amount in all layers. Since the two samples were not from the same growth batch, the difference is more likely related to the concentration and randomness of pointlike defects. This result stresses the sensitivity of the VL structure to disorder at this field.

The middle panel of Fig. 3 shows that the vortices begin to depin at $T_p \approx 19.8$ K due to thermal fluctuations, and reposition themselves with an average field $B \approx 2.90$ T at $T = 23$ K (bottom panel of Fig. 3). Additional $\mu$SR spectra taken without shifting the field show that the VL melts at $T_m \approx 20$ K. Figure 4 summarizes our results in a phase diagram. The upper critical field line represents an approximation assuming $B_{c2}(T) = B_c(0)[1-(T/T_c)^2]$ and $B_{c2}(0) = 70$ T. The data for the twinned and detwinned samples appear to fall on the same melting line. A fit of the data below
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\[ H = 2.9 \, \text{T} \] to the phenomenological melting curve [11]

\[ B_m(T) = \frac{K}{\lambda_{ab}(T)^2}, \] (1)

yields \( m = 1.6(1) \), where \( \lambda_{ab} = \lambda_{ab}(0)[1 - (T/T_c)^4]^{-1/2} \), and \( K \) and \( m \) are constants. This is well below either the predicted value \( m = 4 \) when interlayer coupling of the pancake vortices is dominated by electromagnetic interactions, or \( m = 3 \) when Josephson coupling becomes important [23]. As discussed in Refs. [11,23], for finite Josephson coupling an exponent \( m = 2 \) is expected for an additional thermodynamic transition at \( B < B_c \) which decouples the layers in the liquid phase. The decoupling line is predicted to be [23]

\[ B_{dc}^4(T) = \frac{\Phi_0^3 c_D}{4\pi \mu_0 k_B s^4 \lambda_{ab}^2} T, \] (2)

where \( c_D \approx 0.1 \) is a decoupling constant and \( s \) is the interlayer spacing. The dashed curve in Fig. 4 is a fit to Eq. (2). Taking \( s = 11.7 \, \text{Å} \) [23], \( \lambda_{ab}(0) = 1642 \, \text{Å} \) [1] and \( \gamma = 22-36 \) [12], we calculate \( c_D = 0.025-0.067 \) from the fit. A value \( c_D = 0.076 \) was obtained for BSCCO in Ref. [11]. To determine whether the melting transition (i.e., to a liquid of vortex lines) coincides with the low-field interlayer decoupling transition, more measurements in the vicinity of the phase transition are needed. We note that, contrary to the conclusion in Ref. [11], recent detailed \( \mu \)SR measurements in BSCCO [3] suggest that \( B_m(T) < B_{dc}^4(T) \).

In conclusion, we have observed changes in the \( \mu \)SR line shape of underdoped YBa\(_2\)Cu\(_3\)O\(_{6.60}\) which identify a VL melting transition far below that of optimally doped YBCO. More precisely, fits to the data suggest that there is a decoupling transition from a liquid of vortex lines to a liquid of 2D vortices. Our measurements also establish the existence of a pinning-induced dimensionl crossover to a quasi-2D vortex system, similar to that observed in the highly anisotropic material BSCCO.

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**FIGURE CAPTIONS**

Figure 1. Fourier transform of the muon precession signal in twinned YBa\(_2\)Cu\(_3\)O\(_{6.60}\) at \( T = 20.5 \, \text{K} \) and \( T = 40 \, \text{K} \), in a field \( H = 1.49 \, \text{T} \).

Figure 2. Temperature dependence of the skewness \( \alpha \) [top] and \( 1/\lambda_{ab}^2 \) [bottom] in detwinned YBa\(_2\)Cu\(_3\)O\(_{6.60}\) at \( H = 1.25 \, \text{T} \) [crosses] and in twinned YBa\(_2\)Cu\(_3\)O\(_{6.60}\) at applied magnetic fields \( H = 0.74 \) [open circles] and 1.49 T [solid circles].

Figure 3. Fourier transforms of muon precession signals in twinned YBa\(_2\)Cu\(_3\)O\(_{6.60}\). Top panel: after field cooling at \( H = 2.89 \, \text{T} \) to \( T = 2.5 \, \text{K} \) followed by an increase in the field to 2.90 T. Middle and bottom panels: after subsequently warming the sample to \( T = 19.8 \, \text{K} \) and 23.0 K, respectively.

Figure 4. The vortex \( B-T \) phase diagram for YBa\(_2\)Cu\(_3\)O\(_{6.60}\). Open and solid circles correspond to the twinned and detwinned samples, respectively. The dashed curve \( B_{dc}^4(T) \) is a fit to Eq. (2); the solid curve \( B_{2c}(T) \) is a theoretical line for the upper critical field (see text) and the solid curve \( B_{dc}^3(T) \) is a fit of all of the data to Eq. (1). The transition line \( B_{cr}(T) \) is approximate.

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quasi-2D vortex solid

$v_{cr}(T)$

$v_{m}(T)$

$v_{dc}^J(T)$

3D vortex solid

$T (K)$

$B(T)$

$B_{c2}(T)$