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μSR measurements on the vortex lattice of $La_{1.83}Sr_{0.17}CuO_4$

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Abstract

We report μSR measurements of the vortex lattice in the slightly overdoped compound $La_{2-x}Sr_xCuO_4$ ($x = 0.17$). The magnetic phase diagram provides an interesting comparison to the more exotic phases observed in the underdoped ($x = 0.10$) compound. The field induced hexagonal to intrinsic square transition is observed to occur at around 0.4 T in agreement with previous neutron measurements.

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1. Introduction

It is many years since the discovery of high-T_c superconductors (HTSC) created a surge of interest in vortex matter physics [1]. It is thus surprising that it is only recently that a direct observation of a vortex lattice in $La_{2-x}Sr_xCuO_4$ (LSCO), a compound belonging to the family of the first HTSC to be discovered, was reported [2,3]. Using small angle neutron scattering (SANS), a field-induced square VL was observed, oriented along the CuO bonds. The existence of an intrinsic square VL had never been observed in HTSCs, and is indicative of the coupling of the VL to a source of in-plane anisotropy, such as anisotropies in the Fermi velocity [4] or superconducting gap [5].

In the underdoped compound ($x = 0.10$), however, SANS experiments proved difficult due to a field induced transition from a state with quasi-long range translational correlations (Bragg glass) to a vortex line glass (VG), where only short-range correlations exist. This VG phase is best accessed microscopically using μSR and has recently been convincingly reported [6]. Furthermore, careful interpretation of the data has yielded information on higher order correlations in the VG phase [7]. Here we compare these results with new measurements on the $x = 0.17$ compound.

2. Experimental results

Measurements were performed on a high quality LSCO single crystal using the GPS spectrometer at the Paul Scherrer Institute (PSI), Switzerland. The sample was mounted with the magnetic field aligned to within 2° of the *c*-axis, as measured by Laue X-ray diffraction. The sample was mounted on a polycrystalline haematite (Fe_2O_3) plate to ensure stray muons would not add a background frequency, as it is a randomly orientated antiferromagnet with an internal magnetic field of 1.6 T. Typical counting statistics are 20 million muon detection events over three detectors and the data was analysed using a Maximum Entropy Fourier transform technique [8].

Fig. 1 shows the probability of magnetic field, $P(B)$, for the highest and lowest applied fields that were measured. It

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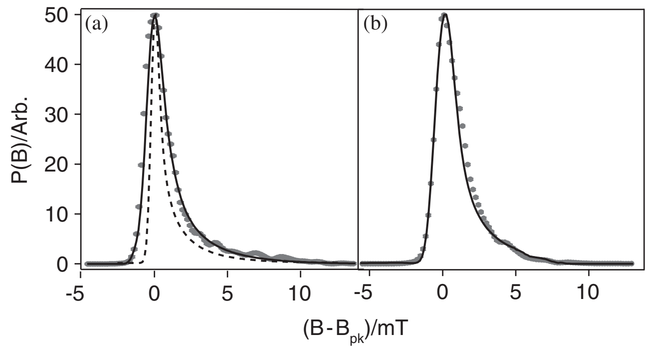

Fig. 1. (a) Points: $P(B)$ for the sample on cooling to $T = 1.5\,\mathrm{K}$ in an applied field of 100 Oe. Dashed line: $P(B)$ calculated with hexagonal symmetry and $\lambda = 2250\,\text{Å}$. Solid line: A simple pinning model has been implemented (see text). (b) Points: $P(B)$ for the sample on cooling to $T = 1.5\,\mathrm{K}$ in an applied field of 6 kOe. Solid line: $P(B)$ calculated with square symmetry and the same penetration depth as in (a), but with a dramatically reduced level of pinning.

is clear that the shape of $P(B)$ at these field extremes is consistent with a Bragg Glass (BG) [6]. The shape is considerably different from the $P(B)$'s obtained in the underdoped case, where a VG state has recently been observed [6]. Over this field range, a VG state is absent in the overdoped compound due to the reduced penetration depth and anisotropy yielding more rigid vortex lines, which are less susceptible to disorder. Fig. 1a also shows two calculated $P(B)$'s. The first uses the London model with finite core cut-off (dashed line) [9], convoluted with the resolution obtained from a Gaussian fit to the normal state. As can be seen, there is a considerable difference between the data and the calculated ideal $P(B)$. Another, more physically realistic solution is plotted with a solid line where a rudimentary model for pinning was used (consisting of a random array of point-like defects which have a finite probability of pinning the vortex within a given distance [10]). At 100 Oe, the pinning probability is found to be approximately three times larger than at 6 kOe, indicating the higher field vortex lattice is considerably less pinned. It is clear that the experimental data plotted in Fig. 1 are represented well by this rather simplistic model, calculated for $\lambda = 2250\,\text{Å}$ and $\xi = 20\,\text{Å}$. The penetration depth used is consistent with surface impedance measurements performed for a similar Sr content to our crystal [11].

A useful exercise to determine the structure of the vortex lattice is to parameterise the $P(B)$'s using $\Gamma = (B_{\mathrm{core}} - B_{pk})/(B_{pk} - B_{\mathrm{min}})$ [12]. This dimensionless quantity simply exploits the fact that the minimum flux density and saddle points in a square lattice will be different from those in a hexagonal lattice. For a hexagonal lattice $\Gamma = 8$ and for a square lattice $\Gamma = 2.5$ [12]. B_{pk} was estimated by fitting a Gaussian to the 10 points surrounding the peak and B_{min} and B_{core} have been estimated by referring to the "default level"—a parameter which represents the noise in the lineshape [8], below which the $P(B)$'s can be taken to be zero. Care must be taken, as noise will tend to obscure the estimation of these fields. It is clear that Γ gradually falls from around 6 at low fields to around 3 at higher fields. The measurement of the core field is intimately related to the counting statistics, as there is a small probability of the muons sampling the core due to the small coherence length in the HTSCs, so it is generally not observable above the experimental noise. Therefore an underestimation of the core field can result in an underestimate of the value of Γ, as is observed.

Fig. 2a shows Γ as a function of field in direct comparison with another dimensionless quantity, σ, derived from Small Angle Neutron Scattering (SANS) measurements performed on the same crystal [2]. In a SANS experiment, the relationship between magnetic field and the position of Bragg spots in reciprocal space is related to the structure dependent quantity $\sigma = (2\pi/q)^2 B/\Phi_0$. It is clear the SANS and μSR data agree exceptionally well with one another. σ can also be plotted as a function of temperature, shown in Fig. 2b for three magnetic fields, indicating there is little temperature dependence of σ and therefore lattice structure.

Fig. 2c shows the field dependence at $T = 1.8\,\mathrm{K}$ of the square root of the second moment of the field distribution [13], $\langle \Delta B^2 \rangle^{1/2}$, for a number of fields and is a good measure of the lineshape width. It is clear there is a distinct field dependence of the width. Firstly, the lineshape narrows as the field is increased up to approximately 0.45 T. This phenomenon could arise in a quasi-two dimensional pancake-vortex system, from static or dynamical transverse fluctuations [14]. However, this would be extremely unlikely in this system considering the effectiveness of the Josephson currents tunneling between planes, which maintain the stiffness of the vortex. Furthermore, results on a sample with a Sr doping of $x = 0.10$ confirm the existence of a glass of vortex lines [6], which is incompatible with fluctuations of pancake vortices. Considering that the underdoped sample has an anisotropy in the region of 40, compared to around 15–20 for this sample, it is considered unlikely this is the reason for the observed reduction in width.

A change in FLL pinning could show a similar behaviour to that observed up to 0.4 T, as an increase in the static disorder would be expected from a reduction of elastic interactions between vortices as the vortices become dilute. As the field is increased, point-like defects have a decreasing effect on the positions of the vortices, as elastic inter-vortex interactions become stronger. It is only at fields above several hundred Gauss that the vortex separation becomes less than the penetration depth, causing the shear modulus for the lattice to increase significantly [1]. We note that a field dependent lineshape width has been observed in YBCO at applied fields of up to 6 T [15] and is explained in that system by the non-local effect of the supercurrent in the vicinity of the gap nodes [16]. However, the reduction in static disorder, resulting in a decrease in lineshape width, is our favoured explanation for the behaviour observed here, as we measured at

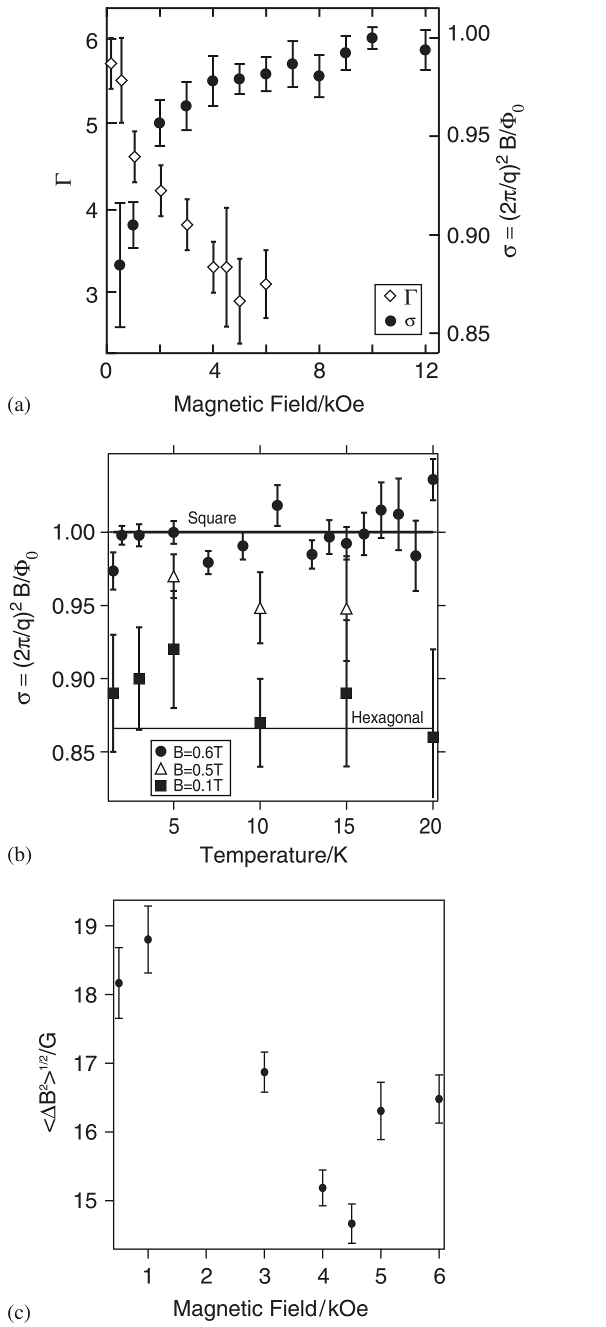

Fig. 2. (a) Circles: field dependence of the dimensionless quantity σ obtained from SANS measurements on the same crystal [2]. σ should be 1 for a square and $\sqrt{3}/2$ for a hexagonal symmetry. Diamonds: field dependence of the dimensionless quantity Γ. (b) Temperature dependence of σ for three magnetic fields. (c) Field dependence of the square root of the second moment of some of our probability distributions.

considerably lower magnetic fields. We note that the underdoped ($x = 0.1$) sample shows similar effects at low field [6].

As the field is increased further, however, the lineshape width increases, corresponding to the hexagonal-square structural transition, as in a square lattice the inter-vortex separation is larger resulting in an increased width. The full temperature and field dependence of

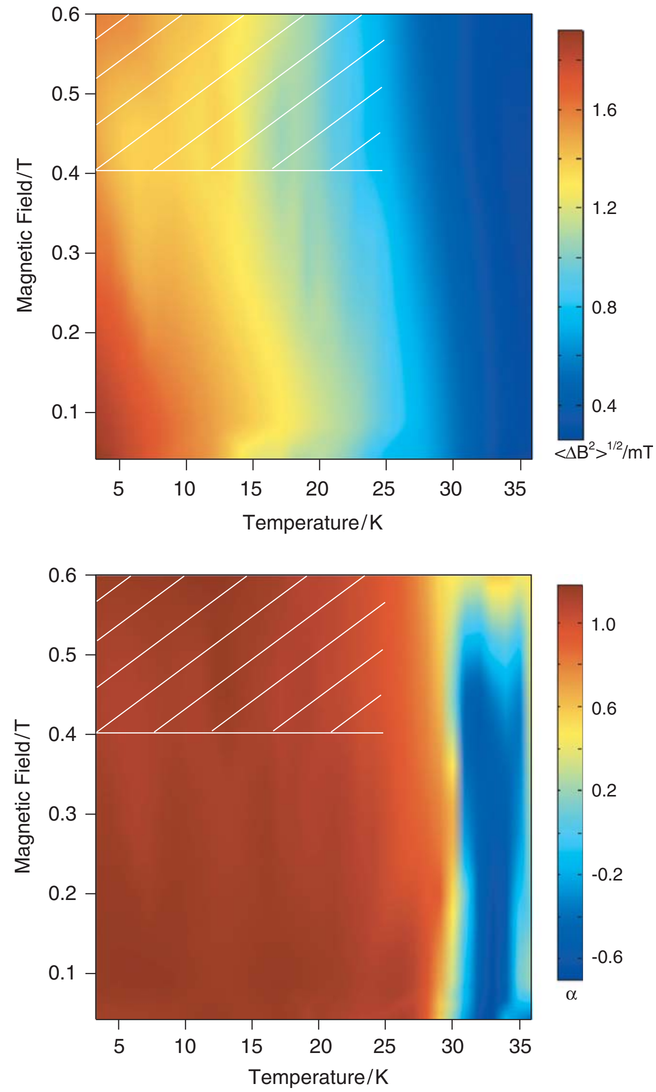

Fig. 3. Top: image plot of the square root of the second moment of all of the probability distributions measured. Bottom: colour image plot of α, a measure of the lineshape skewness. The melting transition can be seen as an abrupt change at around 30 K.

$\langle \Delta B^2 \rangle^{1/2}$ is more easily observed if plotted as an image, in Fig. 3. This summarises the whole μSR data set and can be viewed as a vortex matter phase diagram obtained directly from experimental data. The region in which a square vortex lattice is observed is indicated by the relatively temperature independent hatched area. The lower pane of Fig. 3 shows an image plot of the dimensionless quantity $\alpha = \langle \Delta B^3 \rangle^{1/3} / \langle \Delta B^2 \rangle^{1/2}$, a measure of the skewness of the lineshape [13]. It should be noted that neither $\langle \Delta B^2 \rangle^{1/2}$ nor α show signs of a transition to the VG state observed in the underdoped compound [6] to the highest field we have measured. This is consistent with the SANS measurements, where a square diffraction pattern is observed up to an applied field of 9.5 T [3]. The rapid reduction in $\langle \Delta B^2 \rangle^{1/2}$ and a negative α in the region of 30 K is due to the lattice melting well below the superconducting critical temperature.

In conclusion, we have measured the vortex state of LSCO, confirming the hexagonal to square transition and flux lattice melting, which have been summarised in a vortex matter phase diagram derived directly from experimental data. We thank the EPSRC and the Swiss NSF for financial support. The μSR experiments were performed at the Swiss Muon Source, PSI, Villigen.

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