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Microscopic neutron investigation of the Abrikosov state of high-temperature superconductors

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Abstract. Using small angle neutron scattering we have been able to observe for the first time a well-defined vortex lattice (VL) structure both in the hole-doped LSCO and electron-doped NCCO superconductors. Our measurements on optimally doped LSCO reveal the existence of a magnetic field-induced phase transition from a hexagonal to a square coordination of the VL. Various scenarios to explain such phase transition are presented. In NCCO also a clear square VL could be detected, which is unexpectedly kept down to the lowest measurable magnetic fields.

Keywords. High-temperature superconductivity; vortex lattice structures; small angle neutron scattering.

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1. Introduction

Apart from the unusual electronic and magnetic behaviour of the cuprate high-temperature superconductors (HTSC), experiments reveal a tremendously rich variety of mesoscopic phenomena associated with the flux vortices in the mixed state [1]. Because of their two-dimensional electronic structure, the HTSC are highly anisotropic. The anisotropy is characterized by the ratio $\gamma = \lambda_\perp/\lambda_\parallel$, where $\lambda_\perp, \lambda_\parallel$ are the superconducting penetration depths for currents flowing perpendicular and parallel to the two-dimensional CuO_2 planes. In $La_{2-x}Sr_xCuO_{4+\delta}$ (LSCO) the degree of anisotropy ($\gamma = 20$ for $x = 0.15$) lies between that of the $YBa_2Cu_3O_x$ (YBCO) and $Bi_2Sr_2CaCu_2O_{8+x}$ materials [2]. The cuprates are also extreme type-II superconductors, indicated by the high value of the Ginzburg–Landau parameter $\kappa = \lambda/\xi$, where ξ is the superconducting coherence length. In HTSC the combination of high transition temperature T_c, high γ and high κ leads to exotic vortex behaviour, such as the phenomenon of vortex lattice (VL) melting (see figure 1 and ref. [1]). For a conventional (isotropic) pairing mechanism such anisotropic conduction properties can lead to distortions of the vortex lattice as the applied field is tilted towards the CuO_2 planes, but the local coordination remains six-fold [3].

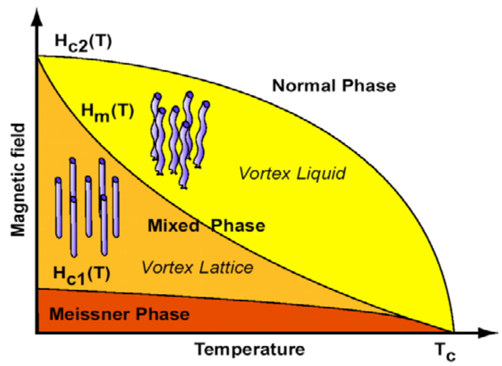

Figure 1. Schematic magnetic phase diagram of HTSC. For more details, see ref. [1].

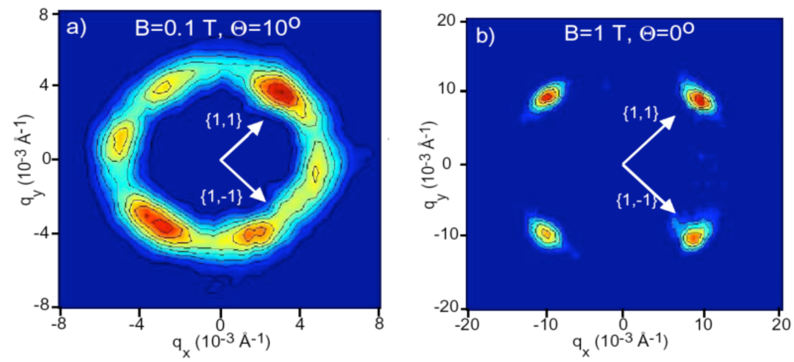

Figure 2. Vortex lattice measured in the superconducting phase of optimally-doped LSCO at (**a**) $H = 0.1$ T (hexagonal structure) and (**b**) $H = 1$ T (square structure) [4].

In the present paper, recent neutron results obtained in the Abrikosov phase of the hole-doped LSCO and electron-doped $Nd_{2-x}Ce_xCuO_4$ (NCCO) HTSC as a function of doping are presented. The very high-quality LSCO crystals have been grown by the traveling solvent floating zone (TSFZ) technique by the group of Profs N Monomo, M Oda and M Ido of Hokkaido University, while the NCCO crystals were grown by the group of Prof. K Yamada, Tohoku University.

2. Vortex lattice in optimally (hole)-doped LSCO

Using small angle neutron scattering (SANS) we have succeeded, for the first time, to measure a well-ordered vortex lattice (VL) structure at all doping regimes of LSCO. In the optimally to overdoped regime a field-induced transition from hexagonal to square coordination is reported around $H = 0.4$ T (see figure 2 and ref. [4]) with the square lattice oriented along the anti-nodal direction of the d-wave

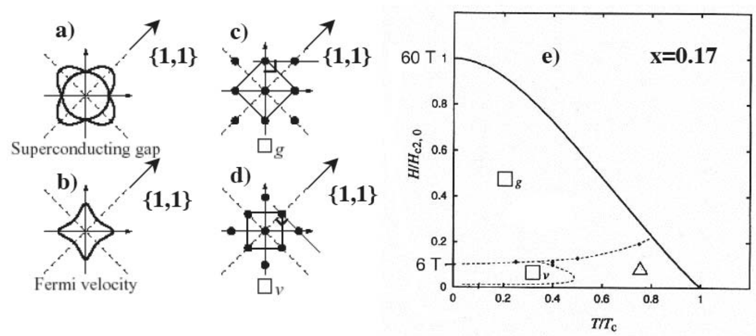

Figure 3. Both d-wave superconducting gap (panel a) and Fermi velocities (panel b) anisotropies will result in square lattices (panels c–d), but with different orientations with respect to the gap nodes. The resulting phase diagram taken from Nakai *et al* [8] for optimally-doped LSCO is given in panel e.

superconducting gap [5]. In a recent experiment, Brown *et al* [6] have observed a similar phase transition in the YBCO superconductor, however with two main differences: first, the critical field at which the transition occurs is at least an order of magnitude higher than in LSCO; second, the square VL in YBCO is oriented along the nodal direction of the d-wave gap function.

Various scenarios are able to explain such a hexagonal-to-square field-induced transition. It has been proposed that the importance of anisotropic vortex cores in a d-wave superconductor [7] would result in a square VL at high fields. Alternatively, coupling to other sources of anisotropy such as those provided by charge/stripe fluctuations or Fermi velocity anisotropies [8] should as well be considered. While the d-wave scenario favours a square VL aligned along the nodal direction (as observed in YBCO [6]), an anisotropy of the Fermi velocity would result in a VL aligned along the anti-nodal direction (as observed in LSCO [4]). These two competing scenarios are visualized in figure 3.

In order to lift this apparent contradiction, Nakai *et al* [8], based on photoemission data [9] suggested that the observed orientation of the square lattice in optimally doped LSCO above 0.4 T is stabilized by the proximity of a van Hove singularity close to the Fermi level at the $(\pi, 0)$ anti-nodal point of the Brillouin zone. The extreme case of a van Hove singularity coinciding with the Fermi level, would result in a maximum anisotropy of the Fermi velocity along the nodal and anti-nodal directions. Such a strong anisotropy seems to be absent in YBCO, which would explain the different square lattice orientations. Nakai *et al* [8] furthermore predict that in LSCO, at high-enough fields ($H > 6$ T), a second phase transition into a square VL oriented along the nodal direction should be observed due to the increasing importance of the d-wave anisotropy at high fields. So far our experiments realized up to 10.5 T [10,11] did not reveal such a transition, and experiments at even higher field values are necessary.

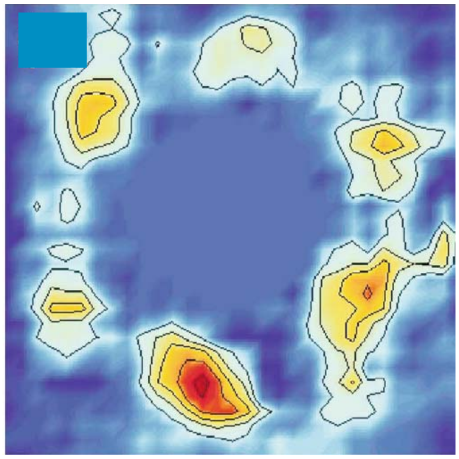

Figure 4. Small angle neutron diffraction pattern showing the existence of an ordered vortex phase at low fields (150 Oe) and temperature (6.2 K). The intensity of this pattern rapidly falls as the field is increased towards the vortex-glass phase [14].

3. Vortex lattice in underdoped LSCO

The situation seems to be completely different in the underdoped regime of LSCO since a well-ordered hexagonal VL could be observed only at very low fields (see figure 4) [12]. By combining neutron scattering and muon spin rotation [12] it was concluded that the observed vanishing intensity with increasing field in the underdoped regime of LSCO is due to the a transition to a so-called vortex-glass state [13]. Such a state, exemplified in figure 5, is expected to occur when strong disorder is present. The transition from a well-ordered VL to a vortex-glass was studied carefully. In figure 6 we show the integrated intensity as a function of applied magnetic field in double logarithmic scale. The intensity decreases very fast with the applied magnetic field and follows approximately an $I \sim H^{-2}$ dependence over several decades. Eventually, the scattered signal from the VL becomes comparable with the overall background noise.

4. Vortex lattice in electron-doped NCCO

Successful measurements of a VL in the electron-doped $Nd_{2-x}Ce_xCuO_4$ with $x = 0.15$ [14] close to optimal doping could be performed.

Here again a square lattice (see figure 7) oriented along the Cu–O axis was observed. However, the VL properties are markedly different from optimally-doped LSCO. First, the square lattice structure remained down to very low magnetic fields. Thus, a hexagonal-to-square transition as found in optimally-doped LSCO could not be observed. Second, the VL could only be observed for relatively low magnetic fields ($H < 0.5$ T) in strong contrast to optimally-doped LSCO [10,11].

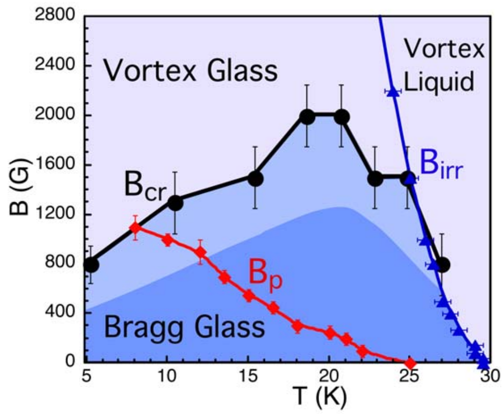

Figure 5. The magnetic phase diagram derived from the changes observed in the μSR field distributions. $B_{\rm cr}$ indicates the onset of the broadening at high field, which is significant only below 25 K, and should be considered as an upper limit for the Bragg-glass to vortex-glass transition. This uncertainty in the exact position of the transition is represented schematically by the shading below the line $B_{\rm cr}$. $B_{\rm irr}$ indicates the irreversibility line as determined by bulk measurements of the field-cooled–zero-field-cooled (FC–ZFC) magnetization using a SQUID magnetometer. The position of the feature in the magnetization curves $B_{\rm on}$ is also plotted [12].

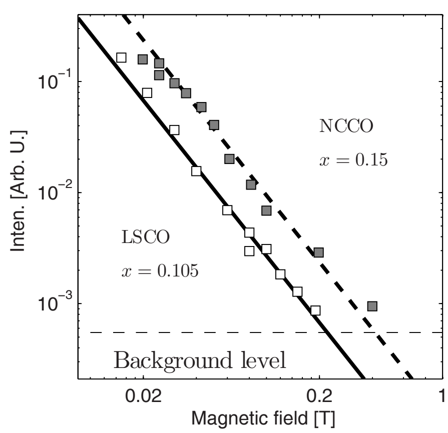

Figure 6. Integrated intensity as a function of applied magnetic field for LSCO $x = 0.10$ and NCCO (dashed line). Notice that both axis are logarithmic. The solid and dashed line are $I \sim H^2$ [14].

The scattered intensity as a function of applied field is shown in figure 6. As for underdoped LSCO the intensity follows an $I \sim H^{-2}$ dependence. This might suggest that the VL undergoes a transition to a vortex-glass as in underdoped LSCO.

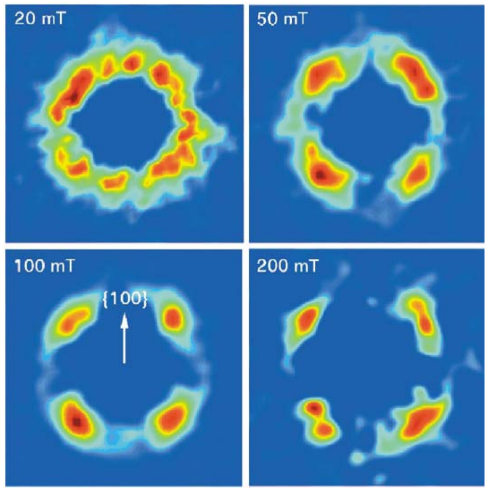

Figure 7. Vortex lattice in the electron-doped HTSC NCCO at various magnetic fields between 20 and 200 mT [14].

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