# Observation of a new phase transition of the vortex lattice in a single-domain $TmBa_2Cu_3O_{7-x}$ single crystal as it is rotated in an external magnetic field

O. V. Petrenko and V. I. Voronkova
*M. V. Lomonosov Moscow State University, 117234 Moscow, Russia*

A. D. Caplin and D. Lacey
*Centre for HTS, Blackett Laboratory, Imperial College, London SW7 2BZ, UK*

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The angular variation of the magnetic moment of a single-domain $TmBa_2Cu_3O_{7-x}$ single crystal in a magnetic field has been studied. There is a sharp phase transition of the vortex lattice from an essentially unpinned state with vortex "chains," at small values of the angle ($\theta$) between the external magnetic field and the *ab* plane of the crystal, to a mixed state, which contains both vortex chains and ordinary Abrikosov vortices and which is characterized by a strong vortex pinning, at $\theta > \theta_{cr} = (2°-9°)$. The field dependence $\theta_{cr}(H)$ is very nonmonotonic. © *1995 American Institute of Physics.*

In ordinary type-II superconductors, the coherence lengths and the magnetic-field penetration depths are much larger than the length scales of the crystal structure. The vortex lattice can be described well by the 3D-anisotropic Ginzburg–Landau and London models.

The situation is different in the layered high-$T_c$ superconductors, which are characterized by much shorter coherence lengths (for $YBa_2Cu_3O_7$, $\xi_c \approx 4$ Å at $T=0$ K). Because of this situation, the interaction of the superconducting $CuO_2$ layers is very weak, so the structure of the vortex lattice becomes quasi-two-dimensional and can be described better by the Lawrence–Doniach model.[1,2] According to experimental data, however, that model is more suitable for describing the superconducting properties of the highly anisotropic Bi- and Tl-based high-$T_c$ superconductors than superconductors of the 1-2-3 type. The latter are assumed to correspond to the case described by the approximation of a 3D-anisotropic effective-mass tensor. Nevertheless, certain effects which stem from the layered structure may be manifested even in these cases, when the external magnetic field is parallel to the $CuO_2$ planes.

In the quasi-2D case at $T<T^*$, where $T^*$ is the temperature of the 3D $\rightarrow$ 2D dimensional transition[3] (for $YBa_2Cu_3O_{7-x}$, this temperature is[4] $T^* \approx 80$ K), the vortex lattice of the high-$T_c$ superconductor should undergo two phase transitions in succession as the angle $\theta$ increases from zero.[5] First, at a certain angle $\theta = \theta_L$, the lattice should make an abrupt switch from an orientation strictly parallel to the $CuO_2$ planes (from the "lock-in" state) to a new phase regime, the "staircase" regime. In the lock-in state, the vortices have Josephson cores and can move freely (without pinning) along the super-

conducting planes.[2] In the staircase regime, in contrast, the vortices consist of 2D disks with normal cores, which lie in the planes and which are connected to each other by core-free vortex segments. These segments remain parallel to the planes.[5]

As the angle $\theta$ is increased further, there should be yet another phase transition, to a state characterized by an ordinary tilted lattice of Abrikosov vortices.[2] According to Ref. 6, this transition should occur when the projection of the magnetic field onto the $c$ axis of the crystal satisfies

$$H_c = H\sin\theta \geqslant H_{ab}/\epsilon, \tag{1}$$

where $\epsilon$ is the anisotropy factor.

The first of these phase transitions (out of the lock-in regime) has been observed previously in several experiments; so far there is no experimental information on the second phase restructuring of the vortices.

An alternative description of the structure of the vortex lattice has been generated in the 3D anisotropic London approximation with boundary conditions for real planar samples of finite dimensions, as are customarily used in experiments.[7] According to this description, the Gibbs potential in an oblique magnetic field has a minimum value when vortices of two different types coexist in the superconductor. The vortices of one type lie parallel to the $c$ axis of the crystal and form the usual triangular Abrikosov lattice. The vortices of the other type are parallel to the external magnetic field; i.e., they lie at some angle with respect to the $c$ axis, forming "chains."

Experiments on Bitter decoration of 1-2-3 high-$T_c$ superconductors have revealed both a mixed vortex lattice[8] and a lattice consisting exclusively of vortex chains.[9] The latter phase state, however, has been successfully observed only in an untwinned $YBa_2Cu_3O_{7-x}$ single crystal in low magnetic fields.[9]

As a test sample for a detailed study of possible phase states of the vortex lattice for various angles of the external magnetic field with respect to the superconducting planes, we selected a single-domain $TmBa_2Cu_3O_{7-x}$ single crystal grown from molten solution under specially selected cooling conditions. The crystal had a transition temperature $T_c \approx 85$ K and dimensions of (0.75 mm)$\times$(0.75 mm)$\times$(39 $\mu$m). The angular variation of the magnetic moment in various static magnetic fields $M(\theta,H)$ was studied on an Oxford Instruments VSM$^{5H}$ vibration magnetometer. This instrument had two independent pairs of pickup coils, which could simultaneously measure the components of the magnetic moment parallel to and perpendicular to the magnetic field [$M_{\parallel}(\theta,H)$, and $M_{\perp}(\theta,H)$, respectively].

In the experiments the sample was cooled in a zero magnetic field at a tilt angle $\theta \approx 0°$ (within 0.01°) established beforehand at a temperature $T > T_c$.

A study of the $M(\theta,H=\text{const})$ dependence at low temperatures ($T \ll T^*$) revealed a sharp increase in the steepness of the curve beginning at a certain critical angle $\theta_{cr}$ (curve a of Fig. 1 shows the method for determining the angle $\theta_{cr}$). Long after the field was applied, before the measurements of the angular distribution $M(\theta,H=\text{const})$ were begun, the step on the curve became even more prominent (curve b in Fig. 1). This effect was seen both in measurements of the signal $M_{\perp}(\theta,H=\text{const})$ and in measurements of $M_{\parallel}(\theta,H=\text{const})$ (see the inset in Fig. 1). This phase restructuring is unrelated to a

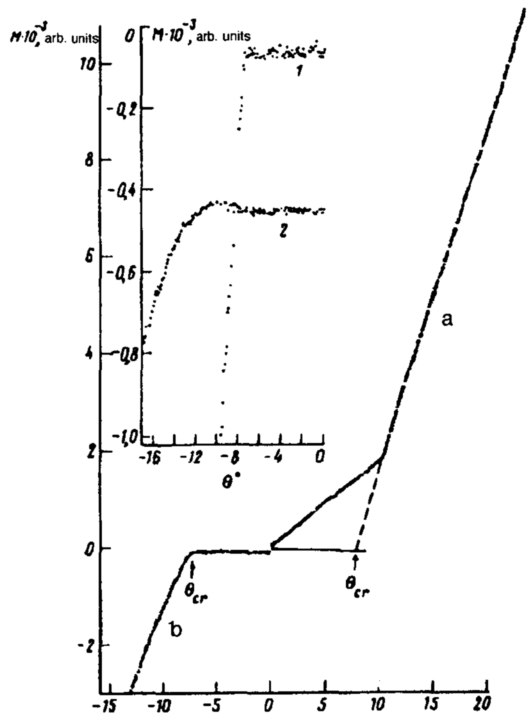


FIG. 1. Angular variation of the magnetic moment $M_\perp(\theta)$ at $T=15$ K and $H=0.75$ T. a—Wait of 5 min after the application of the magnetic field; b—60 min. The inset shows the components $M_\perp(\theta)$ (1) and $M_\parallel(\theta)$ (2) in larger scale.

transition out of the lock-in state, since in that state there should be a complete screening of the field component normal to the superconducting layers.[5] However, the experimental values of the magnetic moment $M(\theta,H)$ at $\theta<\theta_{cr}$ are three orders of magnitude lower than the theoretical values for Meissner screening. Furthermore, since the crystal is planar, the demagnetizing factor strongly reduces the actual value of $\theta_L$ (Ref. 10). For this test sample, this factor should be an order of magnitude lower than the measured values of $\theta_{cr}$. Furthermore, the field dependence of $\theta_L$ should be $1/H$ (Ref. 10), while the experimental data indicate that $\theta_{cr}$ increases with increasing magnetic field, at least at $H>1$ T (Fig. 2). Further evidence for the absence of Meissner screening comes from a comparative analysis of data obtained as the sample was cooled in zero and nonzero magnetic fields.

In general, the model of Ref. 7 gives a qualitative description of the experimental data. The rapid increase in the angle $\theta_{cr}$ with decreasing magnetic field below 1 T (Fig. 2) is evidence that the attraction between vortices caused by the anisotropy promotes the formation of a state with pure chains in sufficiently low fields. This $\theta_{cr}(H)$ behavior agrees with the prediction[7] of the existence of a certain minimum field $H_{cr}$ below which a phase consisting exclusively of vortex chains is realized. The increase in $\theta_{cr}$ with the field and the tendency for this angle to reach saturation in strong fields also agree with

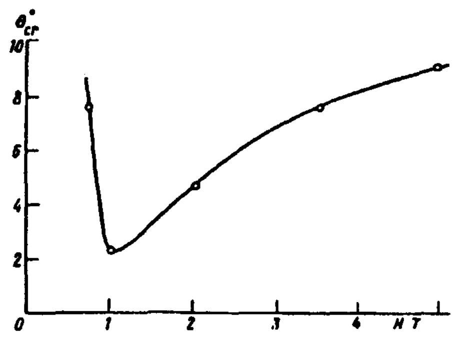


FIG. 2. Field dependence of the critical angle, $\theta_{cr}(H)$, for the phase transition of the vortex lattice at $T=15$ K. The curve is simply drawn through the points to aid the eye.

theoretical predictions that the concentration of vortex chains should asymptotically approach unity with increasing field at high values of $H$ (Ref. 7). In the latter case, and under the strict equality $\theta=0°$, the concentration of Abrikosov vortices should be zero according to that model.

The nonmonotonic $\theta_{cr}(H)$ behavior is supported at a qualitative level by the shape of the $M_{\perp}(H,\theta)$ hysteresis loop at a constant small tilt angle $\theta\approx 0.2°$ at $T=50$ K (Fig. 3). These results indicate that an effective pinning of the vortices (a mixed vortex lattice) occurs in a certain intermediate field interval, in total agreement with the model of Ref. 7.

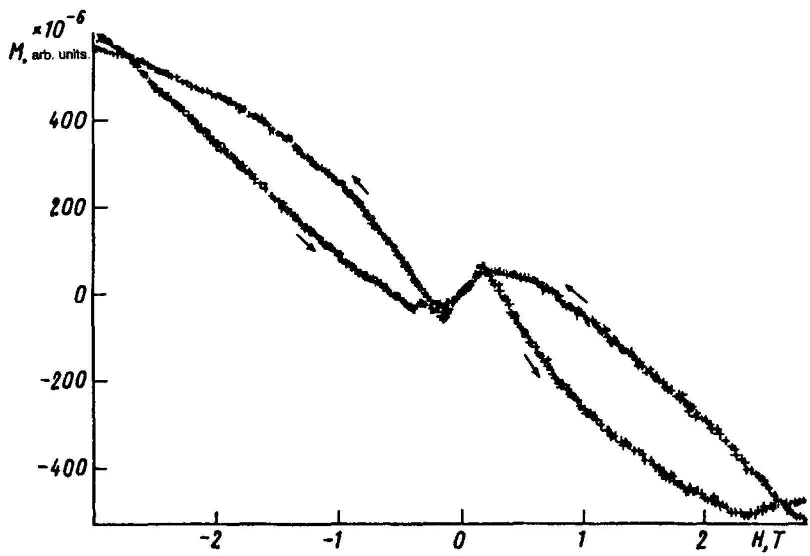


FIG. 3. Field hysteresis loop, $M_{\perp}(H,\theta\approx 0.2°)$, at $T=50$ K.

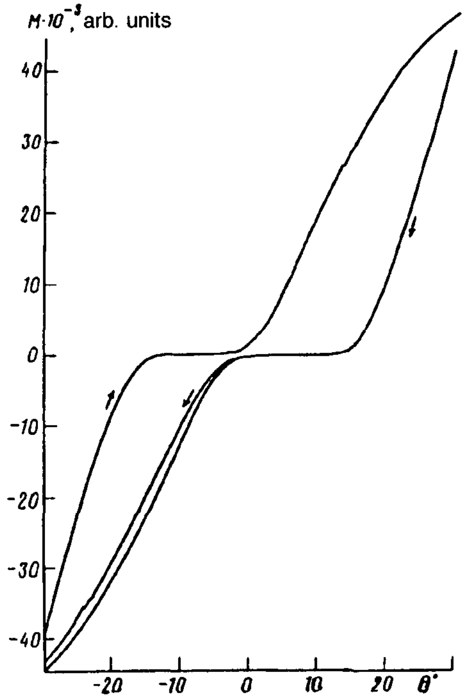


FIG. 4. Angular hysteresis loop $M_{\perp}(\theta,H=2\ \mathrm{T})$ at $T=15$ K.

The unusual shape of the angular hysteresis loop $M_{\perp}(\theta,H=\text{const})$ is unrelated to the projection of the magnetic moment $M_c(H)$ onto the orthogonal axis (Fig. 4). The $M_{\|}(H,\theta=90°)$ hysteresis loop in a magnetic field parallel to the $c$ axis of the crystal has a different shape.

The vortices must be highly mobile if the isotropic lattice of Abrikosov vortices which arises near $T_c$ is to transform into an equilibrium state corresponding to vortex chains at low temperatures, weak magnetic field, and small angles $\theta$, as the superconductor is cooled. Such a restructuring is ordinarily incomplete, because of the pinning, which greatly reduces the mobility of the vortices. The strong pinning by twins in the $YBa_2Cu_3O_{7-x}$ crystal, for example, makes it totally impossible to observe the formation of vortex chains.[11] Under ordinary experimental conditions, at $\theta<\theta_{cr}$, vortex chains coexist with remnants of the Abrikosov lattice (curve a in Fig. 1). After a sufficiently long wait, however, the residual Bean currents may fall below the sensitivity of the measurement instrument because of relaxation of the magnetic moment. This circumstance would make it easier to see the effect (curve b in Fig. 1). The choice of a single-domain crystal as a test sample is thus also an important consideration.

We should also mention a possible interpretation of the experimental data in terms of a transition from the staircase regime to a phase state characterized by an ordinary tilted lattice of Abrikosov vortices. A pinning of Abrikosov vortices having normal cores should be much more effective than a pinning of composite vortices in the staircase regime, and this circumstance should be reflected on the plot of $M(\theta,H)$. For a magnetic field $H=0.75$ T and an angle $\theta_{cr}=7.5°$ (Fig. 1), we find from (1) a completely reasonable anisotropy factor for this compound: $\epsilon=7.6$. However, there are also arguments against this interpretation: the nonmonotonic dependence $\theta_{cr}(H)$ and the approximate equality $M_{\parallel}(H,\theta)-M_{\parallel}(H,\theta=0°)\approx M_{\perp}(H,\theta)\cdot\tan\theta$ at $H\geqslant 0.75$ T.

In summary, on the basis of experimental data in the literature,[8,9] the interpretation of the observed phase transition as a transition from a state with pure vortex chains at small values of $\theta$ and $H$ to a state characterized by a mixed phase at large values of this angle and the field looks more convincing.

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