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Temperature dependence of the second magnetization peak in underdoped $La_{2-x}Sr_xCuO_4$ single crystals

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The characteristic magnetic fields for the second peak (SP) on the dc magnetization curves of high-temperature superconductors with random quenched disorder increase with decreasing temperature T in the low-T range. It was argued that this aspect rules out the existence of an order-disorder transition in the vortex system as the primary cause for the occurrence of the SP, and a model based on a thermally induced square-to-rhombic vortex lattice transition was recently proposed. We investigated the T variation of the field H_{on} for the onset of the SP in the case of underdoped $La_{2-x}Sr_xCuO_4$ single crystals ($x=0.08$) with the external magnetic field oriented along the c axis. It was found that in the low-T domain $H_{on}(T) \propto 1/T^2$, and an inflectionlike point in the $H_{on}(T)$ dependence is still present, similar to that reported for overdoped specimens. We show that the observed behavior and the strong variation in the characteristic fields for the SP with the doping level are in agreement with a dynamic energy balance relation for the order-disorder transition in the vortex system at the SP.

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It is now well established that the vortex system in clean high-temperature superconductors (HTS) at low temperatures T organizes itself into a lattice, which melts through a first-order transition at high T.[1,2] The vortex phase diagram of HTS with random quenched disorder can be understood by considering the competition between the energy of thermal fluctuations, the pinning energy generated by the quenched disorder, E_p, and the elastic energy of the vortex system, E_{el}.[3–5] If the thermal energy is small compared with E_{el} and E_p, when E_p overcomes E_{el} one expects an order-disorder transition in the vortex system induced by the quenched disorder, between a quasiordered vortex solid at low external magnetic fields H (the Bragg glass, stable against dislocation formation) and a high-H disordered vortex phase, where dislocations proliferate.[6] Since in the disordered vortex phase a better accommodation of vortices to the pinning centers is expected, the second peak (SP) appearing on the dc magnetization curves[7,8] was treated as the dynamic signature of the order-disorder transition in the vortex system.[9–11] This approach is supported by the widely accepted crossover elastic vortex creep–plastic creep across the SP.[12–15] In static conditions, the order-disorder transition line at low T was derived[3,9] from the equality

$$E_p(T,H) = E_{el}(T,H), \tag{1}$$

where E_p and E_{el} are directly related to the superconductor parameters, such as the penetration depth λ, the correlation length ξ, the pinning parameter γ, and the anisotropy factor ε.[16] In the case of a δT_c pinning, where vortex pinning results from the local variations in the critical temperature T_c, the pinning parameter $\gamma \propto \lambda^{-4}$, and Eq. (1) leads to a transition field H_t independent of λ. Following Ref. 9, for example, $H_t(T) \propto [\xi(0)/\xi(T)]^3$, i.e.,

$$H_t(T) \propto [1-(T/T_c)^4]^{3/2}, \tag{2}$$

decreasing with T at high T and practically independent of T in the low-T region, where the superconductor parameters vary slowly with T. Quantitative analyses of the $H_t(T)$ dependence in the high-T range using Eq. (2) (or similar relations) were repeatedly performed.[3,5,9,13,14]

However, for various HTS the SP line in the (H,T) plane exhibits a pronounced upward curvature in the low-T domain. [We refer here to HTS for which the field of dimensional crossover in the vortex system[16] $B_{2D} \sim \Phi_0 \varepsilon^2/s^2$ (where s is the distance between the superconducting Cu-O layers) is not too low (like in highly anisotropic $Bi_2Sr_2CaCu_2O_8$ HTS, for example, affecting the SP).[17]] In the case of $La_{2-x}Sr_xCuO_4$ this was explained by postulating that both thermally and quenched-disorder-induced fluctuations contribute to the destruction of the Bragg glass in a wide T range. The transition should then occur when the sum of E_p and thermal energy exceeds E_{el},[11] but in the low-T limit E_p usually overcomes the thermal energy by orders of magnitude.

It was argued[18] that the presence of an upward curvature in the $H_t(T)$ variation at low T, in conflict with Eqs. (1) and (2), rules out the existence of an order-disorder transition in the vortex system, and the square-to-rhombic vortex lattice transition[19,20] was considered as the source for the SP. Over a wide doping level range of $La_{2-x}Sr_xCuO_4$ single crystals[19] as well as for the $BaFe_{2-x}Co_xAs_2$ single crystals investigated in

Ref. 18, the thermally induced square-to-rhombic vortex lattice transition gives

$$H_t(T) \propto (T_0 - T)T^{-\nu}C^{1-\nu}, \quad (3)$$

where $T_0=0.92T_c-0.95T_c$, $C\propto\lambda^2$, and $\nu=0.9-0.95$, leading to an insignificant variation in H_t with the superfluid density $n_s \propto 1/\lambda^2$.

On the other hand, it was pointed out in Ref. 21 that in the conditions characteristic to standard dc magnetization measurements there is another variable which should be considered in a dynamic energy balance equation. This is the T-dependent current density J of the macroscopic currents induced in the sample (proportional to the sample magnetization). At low T, owing to a lower overall magnetization relaxation in the time interval between the moment when the applied H is stable and the moment t_1 at which the magnetization is measured ($t_1 \sim 25$ s in our measurements below), $J(t_1)$ shifts toward the true critical current density, reducing drastically the effective pinning. Consequently, E_p in Eq. (1) should be substituted by an effective pinning energy, which is proportional to the activation energy in the vortex creep process $U[J(t_1),T,H]$. As known, in the low-T range the pinning potential is weakly T dependent and the main role of the thermal energy is to change the probed J in the vortex creep process.[22] Thus, one can switch between J and T as the explicit variable using the general vortex creep relation,[23] $U[J(t_1),T,H]=T\ln(t_1/t_0)$, where t_0 (on the order of 10^{-6} s) is the time scale for creep.[16] Neglecting the variation of t_0 (under the logarithm), with $E_{el}(T,H)\propto \varepsilon\lambda^{-2}H^{-1/2}$ (independent of J) one obtains for the (dynamic) order-disorder transition field at low T

$$H_t(T) \propto \varepsilon^2\lambda^{-4}T^{-2}. \quad (4)$$

Equation (4) predicts a strong variation in H_t with the doping level. With decreasing doping both $n_s(\propto 1/\lambda^2)$ and ε decrease (affecting E_{el}), and H_t is expected to be low. This dynamic approach was suggested by the evolution of the characteristic fields for the SP during magnetization relaxation.[21] As often reported, at high relaxation levels the SP moves to significantly lower H values.

In this work we analyze the behavior of the SP with decreasing T in the case of underdoped $La_{2-x}Sr_xCuO_4$ single crystals ($x=0.08$) with H oriented parallel to the c axis. We found a strong increase of the field H_{on} for the onset of the SP with decreasing T in the low-T range, close to $H_{on}(T) \propto 1/T^2$, as well as an inflectionlike point in the $H_{on}(T)$ variation. This is similar to that reported for overdoped single crystals ($x=0.19$),[21] reflecting the particular $n_s(T)$ variation in the case of two-band superconductivity.[24] The above behavior and the strong shift of the SP to lower H values with decreasing doping level are in agreement with the dynamic energy balance relation for an order-disorder transition in the vortex system at the SP.

The underdoped $La_{1.92}Sr_{0.08}CuO_4$ single crystals were grown by the traveling solvent floating zone technique and have the characteristic dimensions $\sim 1.75\times 1\times 0.7$ mm^3 with the largest side perpendicular to the c axis. The high quality of the investigated specimens was checked using various experimental techniques.[25] The magnetic moment m was always measured in zero-field-cooling conditions with H oriented along the c axis, using a commercial Quantum Design Magnetic Property Measurement System. The onset of the diamagnetic signal for $H=10$ Oe occurs at $T_c \sim 19$ K, and the width of the transition from full superconducting screening to normal is of ~ 2 K.

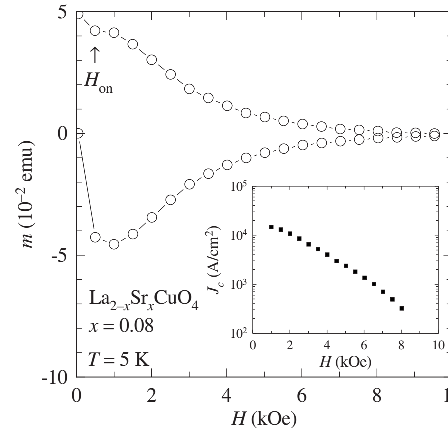

FIG. 1. Main panel: the magnetic hysteresis curve $m(H)$ registered at $T=5$ K for the thoroughly investigated underdoped $La_{2-x}Sr_xCuO_4$ single crystal ($x=0.08$). The external magnetic field H was oriented along the c axis and the step in H was of 0.4 kOe. The critical current density J_c (affected by thermally activated vortex creep) vs H is illustrated in the inset. The notable aspect is that in our underdoped single crystals the second magnetization peak develops at H values very close to the first field of full flux penetration. It is difficult to locate the field H_{on} for the onset of the second magnetization peak on the ascending branch of $m(H)$. H_{on} is indicated by an arrow on the descending branch of the $m(H)$ curve.

The main panel of Fig. 1 illustrates the $m(H)$ curve registered at $T=5$ K with a step in H of 0.4 kOe. The $m(H)$ curve is symmetric above the first field of full flux penetration, which means a negligible influence of surface barriers. The measured magnetic moment m can then be identified with the irreversible magnetic moment, and the determined critical current density $J_c(H)$ is shown in the inset of Fig. 1. The J_c values (affected by thermally activated vortex creep) were extracted from $m(H)$ with the Bean model.[26,27] The notable aspect is that in our underdoped single crystals the SP develops at H values very close to the first field of full flux penetration and the onset field H_{on} is well below the irreversibility line.

A precise location of H_{on} is possible on the descending branch of $m(H)$ if a small H step is used, as illustrated in Fig. 2 for several T values. It is worthy to note that in some works the transition field H_t is identified with H_{on} whereas in others H_t is taken at the inflection point of $m(H)$, between H_{on} and the peak field H_p. For our samples both procedures give a similar $H_t(T)$ variation for $T\geq 6$ K. However, below ~ 6 K the $m(H)$ curves become noisier for H around H_p, due to the occurrence of thermomagnetic instabilities. This appears to be the main impediment for the determination of the real T variation in the characteristic fields for the SP at very low T (especially for overdoped specimens with stronger pinning). At the same time, an inflection point in $n_s(T)$ in the case of two-band superconductivity is clearly visible at low H only

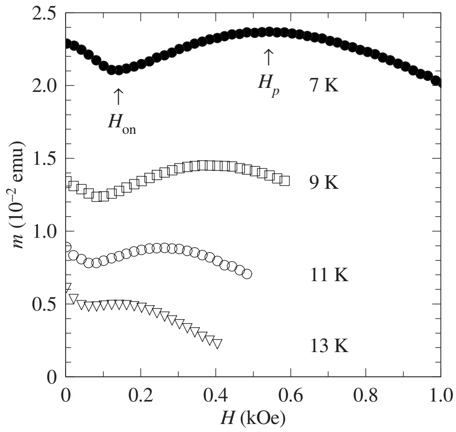

FIG. 2. The $m(H)$ curves for decreasing H (with step of 20 Oe) at several T values, allowing a precise location of the field H_{on} for the onset of the second magnetization peak. H_{on} and the peak field H_p are indicated by arrows.

(Ref. 24). For these reasons, we considered $H_t = H_{on}$.

In Fig. 3 we plotted the measured H_{on} values vs T (in double logarithmic scales). Since in the underdoped specimen the SP appears at low H and the essential field is the magnetic induction at the onset field, B_{on}, we also determined $B_{on} = H_{on} + 4\pi(1-D)M(H_{on})$, where D is the demagnetization factor and M is the volume magnetization. For our crystals $D \sim 0.65$, as extracted from the slope of $M(H)$ for increasing H (in the low-H limit and at low T). As can be seen, H_{on} and B_{on} exhibit a similar and quite complex T variation, with a $1/T^2$ dependence below ~ 6.5 K, an anomalous decrease around 7 K, as well as a downward curvature (in the representation from Fig. 3) above ~ 12 K. For $T \geq 16$ K, an accurate determination of H_{on} was not possible in our measurements.

The $1/T^2$ dependence of H_{on}, B_{on} at low T is in agreement with relation in Eq. (4). The anomalous decrease in the onset field with increasing T around 7 K can be understood by

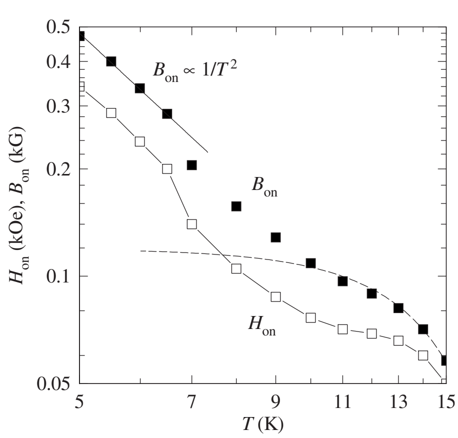

FIG. 3. Temperature T variation in the onset field H_{on} and of the magnetic induction B_{on} at H_{on} (in double logarithmic scales). H_{on} and B_{on} exhibit a similar and quite complex T variation with a $1/T^2$ dependence below ~ 6.5 K (the continuous line), an anomalous decrease with increasing T around 7 K, as well as a high-T form which can be fitted by Eq. (2) (one parameter fit, dashed line).

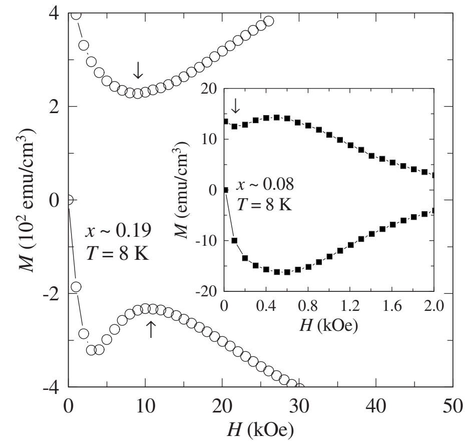

FIG. 4. The magnetization curves $M(H)$ (where M is the volume magnetization) measured in similar conditions at $T=8$ K for the overdoped specimen investigated in Ref. 21 ($x=0.19$, main panel) and for the underdoped single crystal investigated in this work ($x=0.08$, inset). The arrows indicate the position of the onset field H_{on}. As can be seen, $H_{on}(x=0.08)$ is roughly two orders of magnitude lower than $H_{on}(x=0.19)$.

considering the particular T variation in $1/\lambda^2$ in the case of two-band superconductivity,[21] affecting E_{el}. Such an interpretation requires a relatively strong variation in the transition field with λ, which is missing in Eqs. (2) and (3), but is present in relation in Eq. (4). The existence of an inflection point in $n_s(T)$ was reported in Ref. 24 from muon-spin-rotation experiments performed on $La_{1.83}Sr_{0.17}CuO_4$ and was associated with the presence of two superconducting gaps (with d- and s-wave symmetries). For the underdoped specimens analyzed here the $B_{on}(T)$ anomaly appears for T/T_c around 0.35 whereas for the overdoped $La_{1.81}Sr_{0.19}CuO_4$ single crystal investigated in Ref. 21 the anomaly is present for $T/T_c \sim 0.45$. This indicates that the anomalous $B_{on}(T)$ variation from Fig. 3 cannot be interpreted through a dimensional crossover [when $\xi(T)$ approaches s],[28] since for the underdoped specimen this crossover should take place at a higher T/T_c.

For $T/T_c > 0.5$ the T variation in the superconductor parameters becomes important and $B_{on}(T)$ approaches a form which can be fitted by Eq. (2), resulting from the energy balance equation for static conditions and δT_c pinning.[9] Responsible for the latter could be the occurrence of charge phase separation.[25]

As discussed in Ref. 21, the static pinning energy ($J=0$) does not play the primary role for the location of the SP in the dynamic conditions characteristic to dc standard magnetization measurements at low T, where J is not far from the true J_c. At the same time, relation in Eq. (4) indicates a strong variation in the (dynamic) transition field with ε and λ, which will be analyzed below.

In the inset of Fig. 4 we plotted the magnetization curve $M(H)$ registered at $T=8$ K (with a step in H of 1 kOe) for the underdoped single crystal thoroughly investigated here ($x=0.08$), whereas the main panel illustrates the $M(H)$ curve obtained in the same conditions for the overdoped single crystal ($x=0.19$).[21] At $T=8$ K the influence of thermomagnetic instabilities on the H_{on} values is expected to be weak, for both single crystals. As can be seen, $H_{on}(x=0.08)$ is roughly two orders of magnitude lower than $H_{on}(x=0.19)$. This is true for the peak field H_p, as well. More precisely, the H_{on} difference for increasing and decreasing H from the main panel of Fig. 4 indicates that $B_{on}(x=0.19) \approx 10$ kG whereas $B_{on}(x=0.08) \approx 160$ Gs (see Fig. 3). A decrease in B_{on} by a factor of 60–70 immediately results from the variation in ε^2/λ^4 with x, by considering the $\varepsilon(x)$ values from Refs. 29 and 30 ($\approx 1/15$ for $x=0.19$ and $\approx 1/50$ for $x=0.08$), and by taking, for simplicity, $\lambda^2 \propto 1/x$. A comparison of the H_{on} values at low T for $x=0.08$ with those determined for $x=0.13$ in Ref. 11 does not contradict the above conclusion, and the strong $H_{on}(\varepsilon,\lambda)$ dependence from relation in Eq. (4) is plausible.

In summary, we investigated the T variation of the field B_{on} for the onset of the SP in the case of underdoped $La_{2-x}Sr_xCuO_4$ single crystals ($x \sim 0.08$) with the external magnetic field H oriented along the c axis. It was found that $B_{on}(T) \propto 1/T^2$ in the low-T domain, and an inflectionlike point in $B_{on}(T)$ for T around 7 K is present. This anomaly is similar to that reported for overdoped specimens, but located at a lower T/T_c. We conclude that the observed behavior and the strong reduction in B_{on} with decreasing doping can be explained by considering the energy balance relation for the order-disorder transition in the vortex system at the SP in the dynamic conditions specific to standard magnetization measurements.

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