Comment on "Thermal hysteresis in the normal-state magnetization of $La_{2-x}Sr_xCuO_4$"

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(Received 7 October 2004; revised manuscript received 19 April 2005; published 4 November 2005)

The aim of this comment is to explain why the thermal hysteresis in magnetization is observed in $La_{2-x}Sr_xCuO_4$ (LSCO) and presumably in all cuprates but not in the BCS superconductors such as Nb or Pb. The key to understanding the hysteresis in LSCO is the localization of pairs within the CuO_6 pyramids and formation of charged and magnetic stripes in the CuO_2 planes. Due to the chemical equilibrium the spin system of the localized triplet pairs is disordered due to their decay into mobile fermions. The explanation in terms of normal state vortices is shown to be invalid.

DOI: 10.1103/PhysRevB.72.176501 PACS number(s): 74.72.Dn, 74.25.Ha, 74.25.Qt

In a recent paper[1] Panagopoulos *et al.* discovered thermal hysteresis in magnetization of $La_{2-x}Sr_xCuO_4$ (LSCO) within the superconducting doping range $0.05 \leq x \leq 0.30$. The hysteresis was observed in the normal state up to a temperature $T_s(x)$. In the case of $x=0.11$ the effect was observed at room temperature. They observe that $T_s(x)$ like $T_c(x)$ are nonzero within the range $x > x_1 \approx 0.05$ and $x < x_2 \approx 0.30$. The authors propose a "vortex" interpretation of their result. This is an "unorthodox" interpretation in terms of pinned vortices which conventionally exist only in the superfluid state since their existence requires presence of supercurrents. The authors hint that the effect may possibly be explained also in terms the stripes,[2,3] but then the origin of disorder required to explain the hysteresis remains unknown.

In order to get some clue, the authors measured the magnetization of two BCS superconductors Nb and Pb and find no hysteresis. This is a very interesting result because it means that there is a hidden disordered magnetic component in the case of LSCO which is nonexistent in ordinary BCS superconductors. This is a riddle that demands a simple explanation.

One obvious difference between the two families of superconductors is the size of the pairs, which in the case of cuprates is of the order of angstroms[4,5] and 10^4 Å for the BCS. In both cases the superfluidity is due to singlet pairs with associated condensation energy. The small size of the pairs can be perilous to the superconductivity, if within the chemical lattice there exist sites where a pair can get localized. This requires the localization site to have dimensions about the size of a pair. Also the pairs should gain energy in localization. This is possible if Hund's rule is operating for the pair within the localization site, which means that the spin of the pair becomes unity. The occupied site has a nominal charge of two and a magnetic moment. In cuprates the singlet pair system remains superconducting because the condensation energy is winning. Clearly the occupied localization sites can serve as a model for one-dimensional (1D) stripes, since the number of pairs is less than the number of localization sites. In cuprates obvious candidates for localization sites are the CuO_6 octahedra in compounds with one CuO_2 plane and the CuO_5 pyramids for multiplane cases. In the normal state one can neglect the interplane coupling and the octahedra occupied by a pair form 1D stripes within each CuO_2 plane. Since the most likely arrangement of planar localized spins in antiferromagnetic, this explains the occurrence of the antiferromagnetic spin fluctuations in the cuprates.[6,7] Clearly more general 2D arrangements are possible[8] but would not change the conclusions to be made here. The fact that the present model is capable of explaining both superfluidity and antiferromagnetism, there might be a subtle relation to the SO(5) model,[9,10] which also combines the two.

Due to the small size the pairs can be called bosons (B^{++}). The existence of pairs within the chemical lattice in the normal state is restricted by chemical equilibrium of the bosons decaying into fermions $B^{++} \rightleftharpoons 2h^{+}$. The same is true also for the localized bosons. This means that a site previously occupied by a boson becomes subsequently empty. This gives the required disorder for the spin system and hence for the magnetization. The localization takes place even in the superfluid state. However, when T_c is approached from below the condensation energy gets weaker, so the localization starts eating more and more of the mobile singlet pairs. In fact we have established from many experiments[6,7,11,12] that all pairs become localized at $T=T_{BL} \geq T_c$ and above. Therefore all mobile fermions that one measures with the Hall effect in the plane direction in this temperature range come from the decay of localized pairs. The temperature T_{BL} is close to the Hall coefficient maximum (minimum in the Hall number), observed experimentally in many if not in all high T_c compounds. The temperature dependence of the Hall coefficient can be used to[6] deduce the function $f(T)$ which is proportional to over all density of the localized pairs above T_{BL}. Clearly the existence of localized triplet pairs above T_c constitutes an explanation for the pseudogap phenomenon by furnishing the explanation for many experiments.[6,7,11,12]

One should also remember that in LSCO the CuO_2 planes are corrugated: Some of the oxygens are above and some below the average. This is understood by the tilting of axes of the pyramides or the octahedra when occupied by a pair.[2,3] With this same localization idea one can understand why multiplane compounds with inner planes have the highest T_c: Within the inner planes there are no localization sites and hence no corrugation. This has also been seen in experiments.[14] The above picture with localized pairs is used to explain the main features of resistivities. The localized pairs explains the c-axis transport[12] by predicting different scattering rates for the c direction and the ab plane direction, as advocated by P. W. Anderson.[13] The boson decay also helps to understand why one observes more general 2D order[8] instead of the rigid stripes. In fact in the normal state the bosons develop magnetic domain structure, due to the disorder coming from the boson decay. Such a domain structure above T_c has been observed with superconducting quantum interference device (SQUID) microscope in LSCO by Iguchi *et al.*[15] According to them no vortices are seen above T_c, but the observation of the Nernst effect[16] can be understood with the domain structure alone without invoking vortices in the normal state. Clearly now with the domain structure the thermal hysteresis is understood in the same way as in ordinary magnetic materials with magnetic domains.

There are a few other points observed by the authors but remain poorly understood. The highest value for $T_s(x)$ was observed near $x=0.11$. Qualitatively the $T_s(x)$ curve is proportional to $T_c(x)$, so that near the foot points x_1 and x_2

$$T_c(x_i) = T_s(x_i) = 0, \quad i = 1,2. \tag{1}$$

These features can now be easily understood within the chemical equilibrium theory which exhibits the scaling. A good example of the scaling is density of pairs n_B for $T > T_{BL}$

$$n_B(x,t) = n_0(x) f(t), \tag{2}$$

with $f(0)=1$ and $f(\infty)=0$. Here $t=T/T^*$ is the scaled temperature, where $T^*(x)$ is the scaling temperature connected with the binding energy E_B of a pair by $E_B=2k_B T^*(x)$ within the chemical equilibrium theory. Now characteristic temperatures $T_c(x)$, $T_{BL}(x)$, and presumably also $T_s(x)$ are proportional to $T^*(x)$. From the experimentally observed Hall coefficient scaling, one can deduce that the scaling temperature behaves like $T^* = \gamma(x_2 - x)$. Also for the transition temperature one can easily derive a parabolic formula[11,17]

$$T_c(x) = C(x - x_1)(x_2 - x), \tag{3}$$

where the second factor comes from $T^*(x)$ and C is a constant. The physical reason why $T_c(x)$ vanishes at the foot points is different for x_1 and x_2: For $x < x_1$ the pairs remain localized at all temperatures and for $x > x_2$ the binding energy of the pairs vanishes. For $x < x_1$ the localized pairs exist but their spin system can be in spin glass state.[18] Near $x \sim x_2$ small binding means large size of a pair. In fact near $x=x_2$ one has a nearly BCS type of behavior whereas for $x \sim x_1$ the behavior is bosonlike. We can now understand why at $x=0.24 \approx x_2$ Panagopoulos *et al.*[1] obtain $T_s \approx T_c \approx 0$, which means no normal state hysteresis. It is also well known that in LSCO the stripes are almost nonexistent in the overdoped samples. The recent neutron scattering experiments[19] show that the dynamical spin susceptibility maximum is smaller by a large factor from the values obtained for underdoped compounds despite the fact that the carrier density is higher. The physical reason is that the pairs cannot become localized due to their large size, when the binding energy E_B gets small and hence the radius large. Clearly in the BCS case there is no mechanism of localization and hence no stripes and no hysteresis.

Our conclusion is that we can explain many of the features observed by Panagopoulos *et al.*[1] In particular we have indicated that the questionable vortex analogy is not needed, but the hysteresis observed is due to magnetic domain structure formed by the localized triplet pairs. Such domains have also been observed experimentally.[15] Notably they do not see any vortices above T_c. Even if the vortices above T_c were to exist they would not in any way help to understand the pseudogap. Besides the pseudogap, the present theory explains a host of other properties in the cuprates. In addition we have pointed out a possible reason for different hysteresis behavior of the BCS superconductors and the cuprates, whereas Panagopoulos *et al.*[1] cannot provide an explanation. The authors hint from their vortex analogy of a possibility for room temperature superconductivity. This speculation is not valid since the pairs become localized even though they may survive up to room temperature in the cases with room-temperature T_s. The secret here is how to patch up the localization sites.

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