PHYSICAL REVIEW B **78**, 134527 (2008)

Fluctuations above T_c and the kinetic energy of Cooper pairs in $La_{1.9}Sr_{0.1}CuO_4$ and $Pb_{0.55}In_{0.45}$

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(Received 10 July 2008; revised manuscript received 31 August 2008; published 30 October 2008)

The kinetic energy of the superconducting state of Pb-In and La-SrCuO is shown to be quite distinct although both compounds are known to present magnetic fluctuations in a wide temperature range above T_c. While Pb-In isofield kinetic-energy curves cross each other, and show a predominant mean-field behavior, as observed in the magnetization, similar curves for La-SrCuO do not cross each other, just being continuously dislocated to the high-temperature direction, smoothly extending above T_c. We show that the La-SrCuO isofield kinetic curves obey scaling near the transition and this can be viewed either as the existence of thermal fluctuations or as a sign of a new temperature scale T^e.

DOI: 10.1103/PhysRevB.78.134527 PACS number(s): 74.25.Bt, 74.25.Ha, 74.72.Bk, 74.62.−c

Kinetic energy is a valuable tool to study the properties of the condensate according to recent studies of the optical conductivity in the high-T_c superconductors.[1–4] Kinetic energy can also be obtained from magnetization measurements[5] through the virial theorem of superconductivity,[6] and in this case, in the presence of an external applied field. Recently we have used the latter approach to determine the kinetic energy and found important differences between the so-called low- and high-T_c compounds near the transition to the normal state. Three single crystals of underdoped $YBa_2Cu_3O_{7-x}$ (YBaCuO), an optimally doped single crystal of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BiSrCaCuO), and Nb (Ref. 7) were studied. For the high-T_c compounds the kinetic energy evolves smoothly across the transition without any change, even in the first derivative with respect to the temperature, whereas, for Nb, it falls abruptly at the transition following standard BCS Ginzburg-Landau behavior. In this paper we find that the same features differentiate two other superconductors, a low- and a high-T_c compound, namely, a Pb-In alloy, $Pb_{0.55}In_{0.45}$,[8] and $La_{1.9}Sr_{0.1}CuO_4$ (La-SrCuO).[9] Thus the smooth behavior of the kinetic energy along the transition found here, and before,[7] supports the view of vortex activity above the transition for the high-T_c compounds. The presence of vortex activity above the transition has been systematically claimed by Nernst coefficient studies,[10–12] which do not probe the kinetic energy of the condensate. Thus our approach provides an independent way to obtain information about vortex activity above the transition.

In this paper we also find that the La-SrCuO isofield kinetic-energy curves obey scaling near the transition, that is, they collapse into a universal curve. We consider two kinds of scaling hypotheses: the first one based on fluctuation theory,[13–19] developed after the discovery of the high-T_c superconductors,[20] as obtained by Ullah and Dorsey,[21] and by Rosenstein,[18] who considered in different ways the effects of thermal fluctuations at the mean-field temperature $T_c(H)$. The second scaling law, also considered here, is purely phenomenological and based on a new temperature, $T^e(H)$. It also leads to a collapse of the La-SrCuO isofield kinetic-energy curves into a single universal curve. This new temperature is well above $T_c(H)$, basically being the temperature above which the fluctuations in the magnetization fall in the background noise. Thus our results are suggestive of a superconducting state above the transition for the high-T_c compounds whose interpretation does not necessarily fit into the thermal fluctuation view widely studied in the conventional[22] and in the layered superconductors.[15,16,18,21]

The isofield equilibrium magnetization versus temperature (M vs T) curves for the high-T_c superconductors are fairly well described by fluctuation theory,[15,16,18,21] developed more than a decade ago for layered superconductors near the critical temperature with thermal fluctuations included. An important outcome of these models is a nearly field independent crossing point for all isofield M vs T curves. The position of this crossing point can serve as a guide to determine whether two- or three-dimensional behavior dominates the superconductor. From the other side isofield M vs T curves do not intersect for the low-T_c compounds. Such a noticeable difference is very important because the isofield kinetic energy versus temperature (E_K vs T) approach provides a dual view to it. Thus both views are helpful to distinguish between truly conventional low- and new high-T_c behavior. The isofield E_K vs T curves do not intersect for the high-T_c compounds, whereas for the low-T_c compounds they do. Therefore a study of the kinetic energy vis-vis the magnetization provides further insight into the superconducting state below and above T_c.

A central aspect of our study is the connection between the kinetic energy and the equilibrium magnetization given by the following equation:[5]

$$E_K = -B \cdot M. \qquad (1)$$

This relation holds for a large κ type-II superconductor, in the pinning-free (reversible) regime, otherwise the vortex-pinning center also contributes to it.[5] To obtain the reversible magnetization from irreversible data one must average between zero-field-cooled and field-cooled measurements.[23] For a superconductor with the shape of a flat film, even in the presence of vortex pinning, the reversible perpendicular magnetization can be measured by applying an additional small ac magnetic field in the film plane[24] that forces the irreversible currents to relax. Notice that the above relation demands knowledge of the induction field, $B \equiv H + d.M$, for the samples. Therefore the parameter d, a geometric factor related to the demagnetization factor, must be known. This is possible from the slope of isothermal M vs H curves obtained below the lower critical field, thus in the Meissner region. These curves must render that $d \equiv -H/M$ with a good resolution. For La-SrCuO the demagnetizing effects are well described by considering the sample as a sphere: $d = -4\pi/3$. For the Pb-In alloy the demagnetizing effects were estimated through the ellipsoidal approximation.[8]

The presence of strong superconducting fluctuations inside the normal state are not just a feature of high-T_c superconductors as they are also present in low-T_c compounds. A particularly good example is provided by the set of $\mathrm{Pb}_{1-x}\mathrm{In}_x$ alloys that show field induced fluctuation magnetization extending well above T_c, up to $2T_c$ and to fields $H \sim 1.1 H_{c2}(0)$, as shown in Ref. 8. To avoid that the critical field regime, defined by H_{c3}, which is nearly 1.67 larger that the upper critical field, H_{c2}, be interpreted as a fluctuating regime, some of the samples were electrochemically coated with Cu. This procedure totally eliminates the possibility of surface superconductivity and still a broad fluctuation regime is found for these compounds. However, as shown here by means of the kinetic energy, this fluctuation regime is not of the kind found in the high-T_c compounds. This regime is definitely of a standard low-T_c superconductor, since the isofield kinetic-energy curves intersect each other like they do for Nb.[7] The isofield E_K vs T curves obtained here for Pb-In $[T_c(0) = 6.43\ \mathrm{K},\ H_{c2}(0) = 1.2\ \mathrm{T},\ \kappa = 5.5,\ l = 4.2\ \mathrm{nm}$ (mean-free path), and $\xi(0)/l = 20.3]$ follow from magnetization data previously analyzed and published in Ref. 8. For the La-SrCuO compound the isofield M vs T curves were first investigated in Ref. 9, where the fluctuation regime was compared to induced diamagnetism models with kinetic and total-energy cutoffs, developed using the Gaussian Ginzburg Landau (GGL) approach for two-dimensional (2D)-layered superconductors. The samples of La-SrCuO are grain aligned with a total mass of 48 mg, thus at least 2 orders of magnitude larger than those crystals used in other fluctuation measurements.[25–29] Such a big mass makes it possible to better detect fluctuations because of the larger temperature range employed. The grains have diameters around $5-10\ \mu$m, a dimension much bigger than the superconducting coherence length, which determines the thermal fluctuations of Cooper pairs above the transition. The background was carefully removed by first fitting it to a Curie-like function in a wide temperature region, namely between 80 and 200 K [which roughly corresponds to $3T_c(0)$ and, respectively, $7.5T_c(0)$ since $T_c(0) = 27$ K]. Details of sample preparations, measurements, and background correction for these compounds can be found in Refs. 8 and 9.

It is well known that a 2D regime enhances the thermal fluctuation regime above T_c in a superconductor under an applied external field, as found by Ullah and Dorsey.[21] They treated the Lawrence-Doniach model for a layered superconductor within a Hartree approximation, thus beyond the Gaussian approximation since interactions between the fluctuations were included self-consistently. They found that the transport energy, U_ϕ, scales as

$$\frac{U_\phi}{\sqrt{H}} = f_U\left(\frac{T - T_c(H)}{\sqrt{H}}\right), \tag{2}$$

where f_U is a universal function. Their success to obtain general scaling laws for the transport coefficients generated by heat transfer served as an inspiration for subsequent analysis done in equilibrium thermodynamics. Similar scaling laws were derived for the fluctuation magnetization regime and successfully applied to the high-T_c superconductors.[15,16,18,21] Rosenstein[30] found that in the case of well-pronounced 2D behavior the reversible magnetization follows the scaling law,

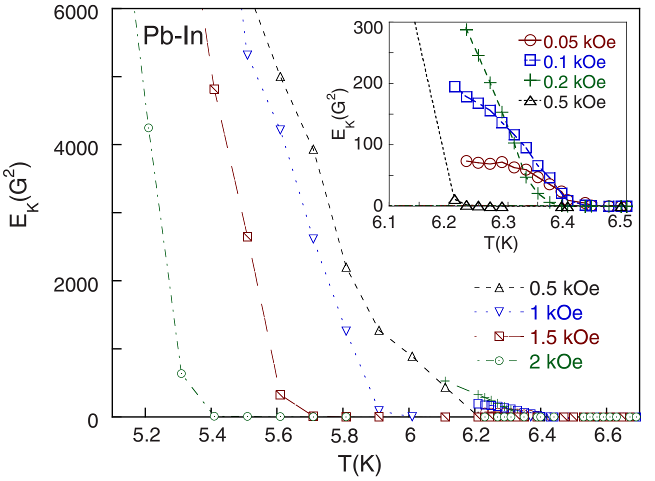

FIG. 1. (Color online) Isofield kinetic-energy curves for Pb-In, as obtained from zero-field-cooled magnetization curves, are shown here in the range 0.05–2 kOe. The inset displays the curves near $T_c(0)$.

$$\frac{M}{\sqrt{HT}} = -f_R\left(\frac{T - T_c(H)}{\sqrt{HT}}\right), \tag{3}$$

where f_R is another universal function. An attempt to obtain a scaling law for the energy within the framework of Eq. (3) is to take the limit of a very small applied field such that $B \approx H$, the kinetic energy becomes $E_K \approx -HM$ leading to the following scaling law:

$$\frac{E_K}{\sqrt{H^3 T}} = f_R\left(\frac{T - T_c(H)}{\sqrt{HT}}\right), \tag{4}$$

which is distinct from the scaling of Eq. (2) for the transport energy. Here we scale the kinetic-energy curves for La-SrCuO according to Eq. (4) which works at least above a certain field value and so follows the 2D scaling law of Rosenstein.[30]

Figure 1 shows the kinetic energy for Pb-In, as obtained from the zero-field-cooled magnetization curves presented in Ref. 8. The inset resolves the low-field regime curves near T_c. Both the main figure and inset show that the curves acquire increasing slope for increasing field H. Notice that the kinetic-energy curves become steeper while the transition temperature $T_c(H)$ decreases for increasing H, rendering the interception of distinct isofield curves unavoidable. The extrapolation of each E_K vs T curve to zero produces virtually the same temperature obtained by similar extrapolation on the corresponding magnetization curve. These linear extrapolations render the mean-field critical temperature $T_c(H)$.[31]

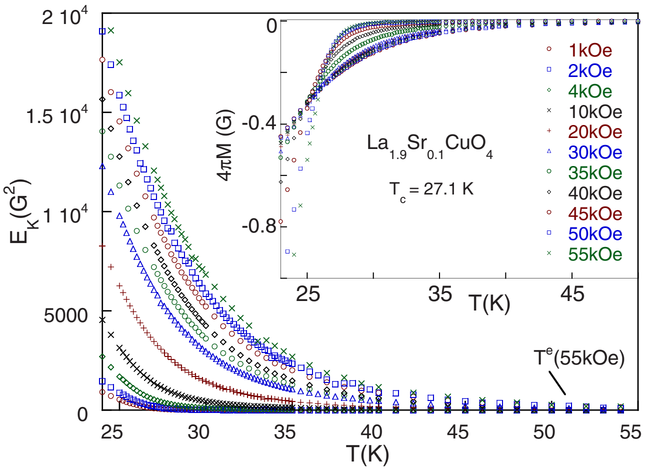

FIG. 2. (Color online) Isofield kinetic-energy curves for the La-SrCuO compound. The inset shows the reversible isofield magnetization curves with their intersecting point. The arrow indicates the position of $T^e(H)$ for $H=55$ kOe.

We mention that the same behavior was found for Nb (Ref. 7) and also for Li_2Pd_3B,[32] and are well explained by the BCS Ginzburg-Landau theory.[33]

Figure 2 shows E_K vs T and M vs T (inset) isofield curves for the La-SrCuO grain aligned sample. They are the zero-field-cooled magnetization curves of Ref. 9 and since they fall into the reversible regime, Eq. (1) applies and we are truly obtaining the kinetic energy. As an example the temperature T^e is displayed for the field $H=55$ kOe. Notice the differences between the E_K vs T and the M vs T curves near the transition for La-SrCuO and how distinct the E_K vs T curves are from those of Pb-In, shown in Fig. 1. This goes against the naive view that a broad fluctuation diamagnetism must mean the same underlying origin. The inset of Fig. 1 shows that the mean-field behavior is dominant for Pb-In, meaning that its fluctuation regime above the transition has a different nature from La-SrCuO, although both exist in a wide range. The major finding of this paper is that such differences become evident when seen from the kinetic-energy point of view.

Figure 3 shows the scaling of the kinetic-energy curves according to Eq. (4). Notice that $T_c(H)$ is a field dependent adjustable parameter whose choice affects the universal curve. For La-SrCuO, we cannot estimate $T_c(H)$ from the linear extrapolation of the reversible magnetization near T_c (Ref. 31) due to the severe rounding of the curves in this region, produced by fluctuation effects. Instead we use a scaling derived by Rosenstein *et al.*[18] for layered systems using the lowest Landau-level approximation. There a universal expression for the magnetization is obtained from a dimensional dependent scaling law, which is a function of the reduced scaled temperature written in terms of the mean-field critical temperature $T_c(H)$. The $T_c(H)$ values used in Fig. 3 are obtained in this way, and are plotted in the inset of Fig. 4. This scaling law produced consistent values of $T_c(H)$ for fields above 20 kOe and gave $dH_{c2}/dT=22.1$ kOe/K, as shown in the inset of Fig. 3, which is just the 2D scaling derived in Ref. 18. The scaling of Fig. 3 does not follow the original proposal of Ullah and Dorsey,[21] given by Eq. (2), because their transport energy is divided by $H^{1/2}$, while Fig. 3 takes a $H^{3/2}$ for the kinetic-energy scaling. An attempt to collapse the E_K vs T curves according to the Ullah and Dorsey prescription, given by Eq. (2), is only satisfactory for temperatures above T_c. It is important to mention that this limitation can be seen in Fig. 1 of Ref. 21, which is the transport energy of YBaCuO.[34] From the other side, the Rosenstein prescription, given by Eq. (4), makes the kinetic-energy curves above 20 kOe collapse above T_c and also below, thus in a much larger temperature range. The fact that the curves of Fig. 3 do not collapse for fields below 20 kOe suggests that the 2D fluctuation regime is only achieved for fields above 20 kOe, even for temperatures above T_c.

Figure 4 shows another way to collapse the isofield kinetic-energy curves of Fig. 2 into a universal curve, now

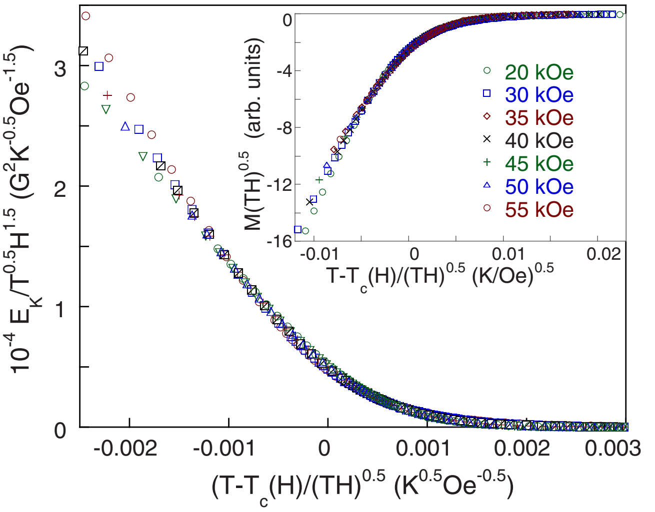

FIG. 3. (Color online) Attempt to collapse the isofield kinetic-energy curves of La-SrCuO, by use of $T_c(H)$. The temperatures $T_c(H)$ are obtained from a 2D-lowest-Landau-level scaling analysis of the magnetization curves, whose collapse is shown in the inset.

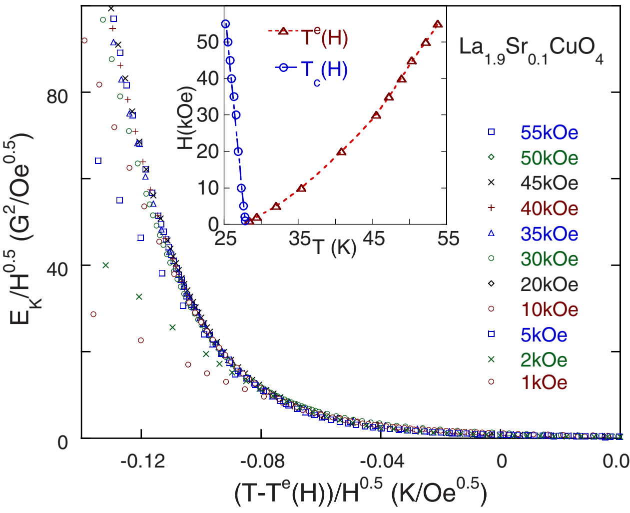

FIG. 4. (Color online) Isofield kinetic-energy curves for La-SrCuO are shown to collapse into a single curve by means of $T^e(H)$. The inset shows values of $T^e(H)$ used for the scaling and also of $T_c(H)$, both plotted versus the magnetic field.

based on a new temperature $T^e(H)$, whose values are plotted in the inset, together with $T_c(H)$, as a function of H. Notice that this new temperature is found well above $T_c(H)$ and features that $dT^e(H)/dH > 0$. The temperature $T^e(H)$ is defined by the vanishing of the kinetic energy, and so, to obtain it some extrapolation procedure must be used.[7] Basically $T^e(H)$ coincides with the temperature above which the fluctuations in the magnetization fall in the background noise. However, the presence of the new temperature $T^e(H)$ makes it possible to retrieve the original Ullah and Dorsey proposal,[21] however, with this new temperature instead,

$$\frac{E_K}{\sqrt{H}} = f^e\left(\frac{T - T^e(H)}{\sqrt{H}}\right), \tag{5}$$

where f^e is a universal function. The temperature $T^e(H)$ can be interpreted as sign of the presence of a pseudogap, whose study is beyond the scope of previous fluctuation theory,[15,16,18,21] since it is not just a matter of thermal fluctuations. The high-T_c compounds are well-known 2D systems that exhibit the pseudogap phase. The proposal of a pseudogap for high-T_c compounds[35,36] naturally extends superconductivity above T_c.[12,36] The pseudogap has the same anisotropy as the superconducting gap in momentum space,[37] a strong indication of a common origin. However, there are still conflicting views[38] as to whether the pseudogap is directly related to the superconducting state or is just an independent competing effect.

In summary we find that the kinetic-energy curves of Pb-In (Fig. 1) (Ref. 8) and of La-SrCuO (Fig. 2) (Ref. 9) are very distinct although both compounds are known to have a very large fluctuation regime. This definitely suggests that superconducting fluctuation above T_c in La-SrCuO has a different nature of Pb-In, similarly to the results obtained in Ref. 7 for Nb, deoxygenated YBaCuO, and Bi2212. Therefore for the high T_c the magnetization shows crossing points just below T_c while the kinetic energy does not show them. Since for the low-T_c compounds are just the opposite, the kinetic energy is a useful tool to distinguish low- and high-T_c behavior. The kinetic curves of La-SrCuO fit two different scaling laws, one according to the traditional view of thermal fluctuations (Fig. 3) and the other indicative of a pseudogap (Fig. 4). Currently it is not possible to favor one view from the other since both scaling laws fit the data nearly in the same temperature range.

We thank Jesús Mosqueira and Félix Vidal for kindly providing us with all the La-SrCuO and Pb-In magnetization data used here. We also thank them for their useful comments. M.M.D. thanks the support of CNPq, FAPERJ, and Instituto do Milênio de Nanotecnologia (Brazil).

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