Core Size Effect on the Vortex Quasiparticle Excitations in Overdoped $La_{2-x} Sr_x CuO_4$

Single Crystals

Z. Y. Liu$^1$, H. H. Wen$^1$ T. Xiang$^{2,1}$, Seiki Komiya$^3$, X. F. Sun$^3$, Yoichi Ando$^3$

$^1$ National Laboratory for Superconductivity, Institute of Physics, Chinese Academy of Sciences, P. O. Box 605, Beijing 100080, P. R. China

$^2$ Institute of Theoretical Physics and ICTS, Chinese Academy of Sciences, P. O. Box 2735, Beijing 100080, P. R. China

$^3$ Central Research Institute of Electric Power Industry, Komae, Tokyo 201-8511, Japan

(Dated: November 12, 2018)

PACS numbers: 74.20.Rp, 72.25.-q, 74.25.Fy, 74.72.Dn

Low temperature specific heat has been measured for an overdoped $La_{2-x} Sr_x CuO_4$ ($x = 0.22$) single crystal. The quasiparticle density of states (DOS) in the mixed state is found to deviate from the predicted scaling law $C_{v, \text{vol}} = H f(T/H^{1/2})$. However, this scaling behavior is nicely reconciled if one considers the normal core region ($\xi \approx 21 \AA$) which gives small contribution to the total DOS. The radius of the core and other parameters derived are consistent with reported values. Our results suggest that there is no zero-bias conductance peak (ZBCP), which is predicted by the simple Bogoliubov-de-Gennes theory in the vortex core of a $d$-wave superconductor.

Another important but controversial issue is the vortex core state in the cuprate superconductors. By solving the mean-field Bogoliubov-de Gennes (BdG) equation, theoretically it is suggested that a zero-bias conductance peak (ZBCP) exists in the vortex core\[15,16\]. However, this is in sharp contrast with the experimental observations\[17,18,19,20,21,22\]. The absence of ZBCP was attributed to the presence of $id_{xy}$ or is components\[21\]. In this Letter we show that the DOS due to vortex quasi-particle excitations deviates from Simon-Lee scaling law, but it can be nicely reconciled if the vortex core size is taken into account. Furthermore a consequence from our analysis is the absence of ZBCP in the vortex core and the disappearance is intrinsic rather than due to the second component of order parameters.

The single crystals measured in this work were prepared by the travelling solvent floating-zone technique. In this Letter we present data of an overdoped single crystal ($x = 0.22$, $T_c = 27.4 K$) as characterized by AC susceptibility and DC magnetization (shown by the inset in Fig.1). The quality of our sample has also been characterized by x-ray diffraction patterns showing only (001) peaks, and resistive measurement showing a rather narrow transition temperature $\Delta T_c \leq 2 K$. A piece about 28.55 mg in mass, $3.66 \times 2.3 \times 0.5 mm^3$ in dimension, was chosen for the specific heat measurement. The heat capacity data presented here were taken with the relaxation method\[22\] based on an Oxford cryogenic system Maglab. The heat capacity is determined by a direct measurement of the thermal time constant, $\tau = (C+C_{\text{add}})/\kappa_w$, here $C$ and $C_{\text{add}}$ are the heat capacity of the sample and addenda (including a small sapphire substrate, small printed film heater, tiny Cernox temperature sensor, $\phi 25 \mu m$ gold wire leads, Wakefield thermal conducting grease (100$\mu g \ )$ respectively, where $\kappa_w$ is the thermal conductance between the chip and a thermal...
FIG. 1: Specific heat coefficient \( C/T \) vs. \( T^2 \) at magnetic fields ranging from 0 to 12 T for the overdoped single crystal. The inset shows the diamagnetic transition at around 27.4 K determined by the crossing point of the extrapolating line of the most steep part with the normal state background \( M = 0 \).

link. The value \( C_{\text{add}} \) has been measured and subtracted from the total capacitance, thus \( C \) value reported here is only the capacitance of the sample. We have also checked the field dependence of \( C_{\text{add}} \) and found that the change ( if any ) of \( C_{\text{add}} \) under 12 T is in the same order of the noise background here ( 20 nJ/K at 5 K and 40 nJ/K at 20 K ). The influence of the magnetic field ( 12 T ) on the readout of the thermometer is below 0.02 K and can be neglected. During the measurement the field was applied parallel to \( c \)-axis and the sample was cooled to the lowest temperature under a magnetic field (field-cooling) followed by data acquisition in the warming up process.

Fig.1 shows the specific heat coefficient \( C/T \) as a function of \( T^2 \) in magnetic fields ranging from 0 to 12 T. The separation between each field can be well determined. In low temperature region the curves are rather linear showing that the major part is due to phonon contribution \( C_{\text{ph}} = \beta T^3 \). In addition the curve at zero field extrapolates to a finite value ( \( \gamma_0 \) ) at 0 K instead of zero as observed in other cuprate superconductors. This may be interpreted as potential scattering to the vanishing gaps near the node of \( d_{x^2-y^2} \) gap function due to small amount impurities [8]. As also observed by other groups for \( \text{La} - 214 \) system, the anomalous upturn of \( C/T \) due to the Schottky anomaly of free spins is very weak [11]. This avoids the complexity in the data analysis. It is known that the phonon part has a very weak field dependence, this allows to remove the phonon contribution by subtracting the \( C/T \) at a certain field with that at zero field. The results after the subtraction are shown in Fig.2. The subtracted values \( \Delta \gamma = \gamma_H - \gamma_0 = C(T, H)/T - C(T, H = 0)/T \) show a rather linear \( T \) behavior in low temperature region ( below 8 K ) as indicated by the solid lines. Our analysis is based on the data below 12 K. In the following we will show that the field dependent slope of the linear part in low temperature region shown in Fig.2 directly deviates from the Simon-Lee [14] scaling law ( eq.1 ).

According to the scaling law, the low temperature expansion of right hand side reads

\[
C_{\text{vol}} = b_0 H + b_1 T \sqrt{H} + b_2 T^2 + o(T^3)
\]

where \( b_0 = 0 \) because \( C_{\text{vol}}/T \) should be finite when \( T = 0 \) and \( H \neq 0 \). Since \( o(T^3) \) is very small in low temperature region, one has \( C_{\text{vol}}/T = b_1 \sqrt{H} + b_2 T \). When \( H_{c1} << H << H_{c2} \), the total specific heat contains four parts: Doppler shift term from the region outside the core \( C_{\text{vol}} \), the inner vortex core term \( C_{\text{core}} \propto HT \), the small impurity scattering term \( \gamma_0 T \) and the phonon term \( C_{\text{ph}} \). At zero field, the total specific heat contains three parts: the small impurity scattering term \( \gamma_0 T \) and the phonon term \( C_{\text{ph}} \) both depend on magnetic field weakly, and a quadratic term \( b_2 T^2 \) due to the thermal excitation near the nodal region. Thus \( \Delta \gamma \) can be written as:

\[
\Delta \gamma = \gamma_H - \gamma_0 = b_1 \sqrt{H} + (b_2 - \alpha) T + \gamma_{\text{core}} H
\]

From eq.3 it is clear that \( \Delta \gamma \) depends on \( T \) through the second term, however the slope \( b_2 - \alpha \) is \( H \) independent according to the definition. This clearly indicates that the Simon-Lee scaling law cannot be directly applied to interpret the field dependent slope of \( \Delta \gamma \) vs. \( T \) as shown in Fig.2.

In order to understand the underlying physics, still based on the Simon-Lee scaling law, we propose that the
core size effect has a sizable influence on the total vortex quasi-particle excitations. By taking account the vortex core size \((2\xi)\), one can rewrite \(\Delta \gamma\) as:

\[
\Delta \gamma = (b_1 \sqrt{H} + b_2 T) \times (1 - \xi^2/R_n^2) - \alpha T + \gamma_{\text{core}} H
\]

where \(\xi\) is the radius of the normal core, \(R_n\) is the radius of a single vortex \(R_n^2 = \phi_0/\pi H\). Thus eq.4 can be written as:

\[
\Delta \gamma = b_1 \sqrt{H} \times (1 - \frac{\pi \xi^2}{\phi_0} H) + b_2 \frac{\pi \xi^2}{\phi_0} H T + \gamma_{\text{core}} H
\]

One immediately realizes that the third term in eq.5 is just what we need for interpreting the difficulty as mentioned above. Next let us have a closer inspection at the data and derive some parameters. At zero temperature, only the first term and the last term are left. The values of \(\Delta \gamma(T = 0)\) are determined from the extrapolation of the linear lines in Fig.2 to 0 K and presented in Fig.3. The solid line is a fit to the data using the first term in eq.5 yielding \(b_1 = 1.9 \pm 0.042 mJmol^{-1} K^{-2/2}\) and \(\pi \xi^2/\phi_0 = 0.0067 \pm 0.002\) and thus \(\xi = 21 A\). The value \(\xi = 21 A\) derived here is quite close to that found in Nernst\[24]\ and STM measurements\[19\]. We also tried to use the first term together with the last term to fit the data but find out that the contribution from the last term is extremely small. The first term here describes the zero temperature data very well, indicating the absence of a bulk second order parameter such as \(id_{xy}\) or \(is\) since otherwise the nodal point would be filled completely and the Doppler shift had very weak effect on the quasi-particle excitations. The inset of Fig.3 shows the field dependence of the slope of the linear part in Fig.2. It is clear that the slope increases with \(H\) above 1 T. This can be exactly anticipated by the second and third terms in eq.5. From the inset of Fig.3 one obtains \(a = b_2 = 0.21 mJmol^{-1} K^{-3}\) and \(b_2 \pi \xi^2/\phi_0 = 0.015 mJmol^{-1} K^{-2/2}\). By taking \(\xi = 21 A\), we obtain the following values: \(\alpha = 2.449 mJmol^{-1} K^{-3}\) and \(b_2 = 2.239 mJmol^{-1} K^{-3}\). It is known that \(\alpha = \phi_0/\pi H\), we further obtain \(\gamma_n = 26.63 mJmol^{-1} K^{-2}\). In addition, it is predicted that \(b_1 = k_\gamma \phi_0/\sqrt{H_c^2}\) which yields also \(\gamma_n = 23.3 mJmol^{-1} K^{-2}\) if taking \(k = 1\) and \(H_c^2 = \phi_0/\pi \xi^2\). Two different approaches lead to rather close values of \(\gamma_n\). This value is also close to that found in \(Y = 123\)\[12\].

The nice fitting in Fig.3 with only the first term of eq.5 suggests that the core region has very small contribution to the DOS since otherwise the last term \(\gamma_{\text{core}} H\) should be sizeable. This implies that the low energy DOS inside the vortex core is very small, ruling out the presence of ZBCP as expected by the BdG theory for a d-wave superconductor\[12\]\[16\]. This conclusion is further strengthened in the following by the fact that the core size effect has a sizeable influence on the DOS due to Doppler shift, but the contribution from inner part of the core is small. In order to further test our idea (eq.5), we present the scaling of \(\Delta \gamma T - (b_2 - \alpha) T^2\) vs. \(T \sqrt{H}\) in Fig.4 with \(b_2 - \alpha\) derived above. The quality of our scaling is remarkable. This can be easily understood from eq.5 when the correction \(\pi \xi^2/\phi_0 = 0.08 << 1\) at 12 T) to the first term is very small. The slight scattering in the high temperature and field region is due to the noise of the data. Worthy of noting is that to have this nice scaling we need to take \(\gamma_{\text{core}} = 0\), again showing a small contribution from the inner vortex core. The solid line is a theoretical curve from eq.5 by using the parameters derived above. Both the nice scaling and the consistency between the experimental data and eq.5 suggest that the Simon-Lee scaling law can be reconciled by considering the vortex core size effect. Meanwhile the scaling according to the original Simon-Lee theory is also presented in the inset of Fig.4, showing a rather poor scaling quality.

In low temperature region, our analysis indicates that the field induced DOS can be well described by Volovik’s theory or Simon-Lee scaling law although a correction due to the core size effect is needed. This means that the prerequisite for the theory, i.e., the \(d_{x^2−y^2}\) pairing symmetry is well satisfied. Therefore it naturally rules out the possible presence of a second order parameter like \(id_{xy}\) or \(is\) either due to overdoping\[6\] or due to the field effect\[22\] in the present overdoped sample. Meanwhile another seemingly contradicted phenomenon is that the vortex core region contributes very little (at least much
FIG. 4: Scaling of the data $C_{\text{scal}} = C(H) - C(H = 0) + (\alpha - b_2)T^2$ vs. $T\sqrt{H}$. The solid line is a theoretical fit according to eq.5 with fitting parameters derived in the text. A perfect scaling and a nice consistency between data and the scaling law with core-size correction is clear. The inset shows the scaling according to Simon and Lee (eq.1) where $C_{\text{scal}} = C(H) - C(H = 0) + \alpha T^2$.

smaller than that induced by the Doppler shift if the super-current would flow in the same area) to the total DOS. This suggests that there is no ZBCP within the normal core since otherwise the normal core region should give rise to a sizable signal. Our conclusion is consistent with the tunnelling results [17, 18, 20, 21] and certainly clears up the concerns about the surface conditions in the STM measurement since our specific heat data reflect the bulk property. Recent results from NMR also show the absence of ZBCP inside the vortex core [22]. In this sense our data together with the earlier NMR data present a bulk evidence for an anomalous vortex core. Interestingly it is widely perceived that the normal state in overdoped region shows a Fermi liquid behavior even when the superconductivity is completely suppressed [24]. Clearly the mean-field frame of BdG theory based on the conventional d-wave superconductivity is not enough to interpret the anomalous vortex core state.

In conclusion, the quasiparticle density of states (DOS) due to Doppler shift in the mixed state of an overdoped $La_{2-x}Sr_xCuO_4$ ($x = 0.22$) single crystal is found to deviate from the proposed scaling law of Simon and Lee. However, this law is reconciled if one considers the core size effect. The contribution from the inner vortex core is small comparing to that due to the Doppler shift in the same area. Our results suggest the absence of the ZBCP in the vortex core although it is expected by the Bogoliubov de-Gennes theory for a d-wave superconductor.

ACKNOWLEDGMENTS

This work is supported by the National Science Foundation of China (NSFC 19825111, 10174090, 10274097), the Ministry of Science and Technology of China (project: 11990061), the Knowledge Innovation Project of Chinese Academy of Sciences. We are grateful for fruitful discussions with D. H. Lee, P. C. Dai, S. H. Pan and Y.Y. Wang.

Correspondence should be addressed to hhwen@aphy.iphy.ac.cn

[1] C. C. Tsuei, and J. R. Kirtley, Rev. Mod. Phys. 72, 969 (2000), and references therein.
[2] C. C. Tsuei, et al., Nature 387, 481 (1997), and references therein.
[3] Z. X. Shen, et al., Phys. Rev. Lett. 70, 1553 (1993); D. J. Scalapino, Phys. Rep. 250, 330 (1995).
[4] W. N. Hardy, et al., Phys. Rev. Lett. 70, 3999 (1993).
[5] A. G. Sun, et al., Phys. Rev. Lett. 72, 2267 (1994).
[6] N. C. Yeh, et al., Phys. Rev. Lett. 87, 8703 (2001).
[7] N. Bulut and D. J. Scalapino, Phys. Rev. Lett. 68, 706 (1992), G.-q. Zheng, et al., Phys. Rev. Lett. 88, 7703 (2002).
[8] K. A. Moler, et al., Phys. Rev. Lett. 73, 2744 (1994). K. A. Moler, et al., Phys. Rev. B 55, 12753 (1997).
[9] B. Revaz, et al., Phys. Rev. Lett. 80, 3364 (1998).
[10] D. A. Wright, et al., Phys. Rev. Lett. 82, 1550 (1999).
[11] N. E. Phillips, et al., Physica C 259-261, 546 (1999).
[12] N. B. Kopnin and G. E. Volovik, JETP Lett. 64, 690 (1996).
[13] G.E. Volovik, JETP Lett. 58, 469 (1993); ibid 65, 491 (1997).
[14] S. H. Simon, P. A. Lee, Phys. Rev. Lett. 78, 1548 (1997).
[15] Y. Wang, A. H. MacDonald, Phys. Rev. B 52, R3876 (1995).
[16] M. Franz, Z. Tesanovic, Phys. Rev. Lett. 80, 4763 (1998).
[17] I. Maggio-Aprile, et al., Phys. Rev. Lett. 75, 2754 (1995).
[18] Ch. Renner, et al., Phys. Rev. Lett. 80, 3606 (1998).
[19] S. H. Pan, et al., Phys. Rev. Lett. 85, 1536 (2000).
[20] B. W. Hoogenboom, et al., Phys. Rev. Lett. 87, 267001 (2001).
[21] Y. Dagan, G. Deutscher, Phys. Rev. Lett. 87, 177004 (2001).
[22] V. F. Mitrovic, et al., Nature 413, 501 (2001).
[23] R. Bachmann et al., Rev. Sci. Instrum. 43, 205 (1972).
[24] Yayu Wang, et al., Science 299, 86 (2003).
[25] R. B. Laughlin, Phys. Rev. Lett. 80, 5188 (1998).
[26] C. Proust, et al., Phys. Rev. Lett. 89, 147003 (2002).