Localized electronic states and photoemission
superconducting condensate in Bi$_2$Sr$_2$Ca$_1$Cu$_2$O$_{8+x}$

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Abstract

We present the first detailed angle-resolved photoemission evidence that there are two types of carriers that contribute to the photoemission superconducting condensate in Bi$_2$Sr$_2$Ca$_1$Cu$_2$O$_{8+x}$. Our data indicate that both itinerant and somewhat localized normal state carriers can contribute to the formation of Cooper pairs.
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One of the long-standing controversies in the cuprate superconductors is the nature of the normal state. In addition to the by now classic linear resistivity up to high temperatures, the changes with stoichiometry from underdoped to overdoped remain difficult to fit into a single picture. Among the most difficult matters has been whether there are one or two types of carriers. X-ray absorption, neutron scattering and ab-plane optical conductivity studies indicate that there are somewhat localized carriers, with a wavefunction diameter of about 1 nm. However, there has not been direct spectroscopic evidence that such carriers exist, nor that such carriers contribute to the superconducting condensate. In this report, we provide such data and discuss the implications. To avoid misleading the reader, we emphasize that the samples on which we report are exceptional. Most of our samples (>95%) that exhibit a superconducting condensate also exhibit an itinerant band in the normal state. However, there are a small number of samples (about 3%) that exhibit a superconducting condensate in the absence of a normal state itinerant band. This report concentrates on these exceptional samples.

Synchrotron-radiation angle-resolved photoemission experiments were performed at the Wisconsin Synchrotron Radiation Center. The details of the experimental procedure are provided elsewhere. We used a 50 mm hemispherical electron energy analyzer, mounted on a two-axis goniometer. The samples were transferred through a load-lock chamber and cleaved in situ, at 35K, in a vacuum of $8 \times 10^{-11}$ torr. Photoemission spectra were taken below the superconducting transition temperature, $T_c = 83$K. We then raised the sample temperature to 95K, and took normal state photoemission spectra.

Figures illustrate superconducting state and normal state spectra taken along the three major symmetry directions, including the Cu-O-Cu bond axis in real space, and the Bi-O-Bi a-axis and b-axis. The superconducting state and normal state spectra in a given symmetry direction were taken on the same sample; only the temperature is different. Figures provide what is to our knowledge the first spectroscopic evidence that a superconducting condensate can be observed in the absence of a normal state itinerant band.

Several noteworthy points emerge from Figs. The size of the gap, as noted in the
figure captions, is not the same in the three high-symmetry directions. We define the energy position of the midpoint of the leading edge of the superconducting state spectrum as the gap. Our estimates of the gap size are: \( \Delta_{\Gamma-M} = 20 \text{ meV} \), \( \Delta_{\Gamma-Y} = 14 \text{ meV} \), and \( \Delta_{\Gamma-X} = 10 \text{ meV} \). Along the \( \Gamma - M \) and \( \Gamma - X \) directions, the data of Figs. 2-3 yield estimates of the gap size similar to the estimates obtained from samples that exhibit a normal state itinerant band. However, the two types of samples yield very different estimates of the gap size along \( \Gamma - Y \): \( \Delta_{\Gamma-Y} = 14 \text{ meV} \) (Fig. 1) compared to 0-2 meV. 

We compared the angular extent of the gap and condensate observed for the data of Figs. 1-3 to samples that exhibit a normal state itinerant band. Note that the gap in Figs. 1-3 is observed for almost the exact same locations in the Brillouin zone as for samples that exhibit a normal state itinerant band. This result indicates that the superconducting gap is forming near the Fermi surface, as it should, independent of the nature of the carriers.

We observe no normal state itinerant band for the samples illustrated in Figs. 1-3. Since the normal state itinerant band would have at most a factor of two reduction in spectral area (see above), the absence of such a band is conclusively established.

There are at least two interpretations of our data. As Ma and Lee have noted, the results could be explained if the scattering in the normal state was sufficiently strong, and the normal state scattering was largely eliminated in the superconducting state. There are reports that the normal state scattering rate of the cuprates is higher than elemental metals. In addition, there are reports that below \( T_c \), the scattering rate of the quasiparticles remaining outside the condensate drops dramatically. However, such an interpretation does not fully account for the data in Figs. 1-3. The scattering rate in question must be an inelastic scattering channel to be suppressed by the opening of a superconducting gap. As the data in earlier reports make clear, however, the normal state quasiparticle spectral feature has an energy width of 150 meV, much larger than the superconducting gap. Thus, the opening of a superconducting gap of about 25 meV will not suppress an inelastic scattering channel that must lead to the removal of a normal state quasiparticle spectral feature having an energy width of about 150 meV.
Instead, our data can be consistently interpreted in a simpler way, viz, that the samples have somewhat localized carriers in the normal state that contribute to the photoemission superconducting condensate spectral feature. This interpretation is supported by other evidence as well. We have recently reported [15] that cobalt-doping of Bi-2212 leads to the three classic characteristics of Anderson localization, including the removal of the normal state quasiparticle spectral features due to localization. Such data indicates that somewhat localized carriers still contribute to the superconducting state, since a superconducting transition is observed in resistivity measurements, for both cobalt-doped samples and the present samples.

Our data do not allow us to determine the nature of the somewhat localized carriers. There have been several proposals in the literature on such carriers. The speculations include a type of Peierls distortion in two dimensions. [16] In particular, note that the difference between the superconducting and normal state spectra is not limited to the spectral area of the photoemission superconducting condensate. Instead, the data indicate that spectral area at higher binding energy than the condensate appears in the superconducting state and is lost in the normal state. Such a result follows from a picture in which the distortions within the CuO$_2$ unit are randomly arranged above $T_c$ but become ordered below $T_c$. The random arrangement above $T_c$ means that the electron wavevector, $k$, is not a good quantum number. Consequently, we would not observe a distinct itinerant quasiparticle band state. However, such models [16] suggest that below $T_c$ the electron wavevector becomes a good quantum number and the quasiparticle band is therefore observed, as is the superconducting condensate. Our data, while consistent with such an interpretation, do not conclusively establish the model.

In summary, we have observed a superconducting condensate, and spectral features at higher binding energy, in the superconducting state, as one would expect from the literature [11,12,17–19] for typical samples. Above $T_c$, however, we do not observe any itinerant quasiparticle band. The data establish that both itinerant and more localized carriers contribute to the condensate. We do not yet have conclusive evidence on the nature of the more
localized carriers.

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REFERENCES

[1] For a review, see B. Batlogg, Physica B 169, 7 (1991).

[2] M. Ma and P.A. Lee, Phys. Rev. B 32, 5658 (1985).

[3] A.J. Mills and Boris I. Shraiman, Phys. Rev. B 46, 14843 (1992).

[4] Alan J. Heeger and Gang Yu, Phys. Rev. B 48, 6492 (1993).

[5] A.A. Samokhvalov, N.A. Viglin, B.A. Gizhevskii, N.N. Loshkareva, V.V. Osipov, N.I. Solin and Yu.P. Sukhorukov, JETP 76 463 (1993).

[6] T. Rentschler, S. Kemmler-Sack, P. Kessler and H. Lichte, Physica C 219, 167 (1994).

[7] A. Bianconi, S. Della Longa, M. Missori, C. Li, M. Pompa, A. Soldatov, S. Turtu and S. Pagliuca, in the Proceedings of the Beijing International Conference: High Temperature Superconductivity (BHTSC 92), edited by Z.Z. Gan, S.S. Xie, Z.X. Zhao (World Scientific, Singapore, 1992), p. 147-55.

[8] S.J.L. Billinge and T. Egami, in Lattice Effects in High $T_c$ superconductors, edited by Y. Bar-Yam, T. Egami, J. Mustre-de-Leon, A.R. Bishop (World Scientific,Singapore, 1992), p. 93-104; see also T. Egami, Intl. Conf. on Nano-Engineering and High- Temperature Superconductors, I. Bozovic and D. Pavuna, eds., World Scientific (1994).

[9] D.N. Basov, A.V. Puchkov, R.A. Hughes, T. Strach, J. Preston, T. Timusk, D.A. Bonn, R. Liang and W.N. Hardy, Phys. Rev. B 49, 12165 (1994).

[10] R.J. Kelley, Jian Ma, G. Margaritondo and M. Onellion, Phys. Rev. Lett. 71, 4051 (1993).

[11] Jian Ma, C. Quitmann, R.J. Kelley, G. Margaritondo, and M. Onellion, submitted.

[12] R.J. Kelley, Jian Ma, R. Joynt, H. Berger, G. Margaritondo, and M. Onellion, submitted.
[13] D.A. Bonn, P. Dosanjh, R. Liang and W.N. Hardy, Phys. Rev. Lett. 68, 2390 (1992).

[14] C.G. Olson, R. Liu, D.W. Lynch, R.S. List, A. J. Arko, B.W. Veal, Y.C. Chang, P.Z. Jiang, A.P. Paulikas, Phys. Rev. B 42, 381 (1990).

[15] P. Alméras, H. Berger, G. Margaritondo, Jian Ma, C. Quitmann, R.J. Kelley, M. Onellion, submitted.

[16] J.N. Liu, X. Sun, R.T. Fu and K.Nasu, Phys. Rev. B 46, 1710 (1992).

[17] C.G. Olson, R. Liu, A.-B. Yang, D.W. Lynch, A.J. Arko, R.S. List, B.W. Veal, Y.C. Chang, P.Z. Jiang and A.P. Paulikas, Science 245, 731 (1989).

[18] Y. Hwu, L. Lozzi, M. Marsi, S. La Rosa, M. Winokur, P. Davis, M. Onellion, H. Berger, F. Gozzo, F. Lévy and G. Margaritondo, Phys. Rev. Lett., 67, 2573 (1991).

[19] Z.-X. Shen, D.S. Dessau, B.O. Wells, D.M. King, W.E. Spicer, A.J. Arko, D. Marshall, L.W. Lombardo, A. Kapitulnik, P. Dickinson, S. Doniach, J. DiCarlo, A.G. Loeser and C.H. Park, Phys. Rev. Lett., 70, 1553 (1993).
FIGURES

FIG. 1. (a). Angle-resolved photoemission (ARUPS) spectra of the superconducting state (35K), and the normal state (95K) along Γ − Y direction. The gap opening at $\theta = 13^\circ$ is $\Delta_{\Gamma-Y} = 14$ meV. (b). ARUPS normal state spectra (95K) along the same direction in the wider binding energy range. Note that no distinct itinerant band feature is visible.

FIG. 2. (a). Angle-resolved photoemission (ARUPS) spectra of the superconducting state (35K), and the normal state (95K) along Γ − X direction. The gap opening at $\phi = 13^\circ$ is $\Delta_{\Gamma-X} = 10$ meV. (b). ARUPS normal state spectra (95K) along the same direction in the wider binding energy range. Note that no distinct itinerant band feature is visible.

FIG. 3. (a). Angle-resolved photoemission spectra of the superconducting state (35K), and (b) the normal state (95K) along Γ − $\bar{M}$ direction. The gap opening at $\theta/\phi = 18^\circ/18^\circ$ is $\Delta_{\Gamma-\bar{M}} = 20$ meV. Again, no normal state itinerant band is visible.