Comment on “Anomalously Large Gap Anisotropy in the a-b Plane of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$”

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79.60.Bm, 73.20.Dx, 74.72.Hs
In a recent Letter [1], Shen and collaborators reported that angle-resolved photoemission spectra (ARPES) in Bi-2212 cuprate superconductor far below $T_c$ has anomalously large anisotropy and then concluded that the symmetry of Cooper pair is likely to be $d_{x^2-y^2}$, i.e., $\Delta_k = \Delta (\cos k_x a - \cos k_y a) [2]$. In this Comment we point out that the interpretation done by Shen et al., where the shift of edge near Fermi level has been identified with the gap $\Delta_k$, is not unambiguous, and that a possibility of $d_{xy}$ pairing, i.e., $\Delta_k = 2\Delta \sin k_x a \sin k_y a$, cannot be ruled out.

The ARPES intensity is proportional to $A(k, \omega) \equiv -1/\pi \cdot \text{Im}G^R(k, \omega)$ given in the superconducting state as follows:

$$A(k, \omega) = z_k \frac{-\omega - \tilde{\xi}_k}{2\tilde{E}_k} \cdot \frac{1}{\pi} \left\{ \frac{\tilde{\gamma}_k}{(\omega + \tilde{E}_k)^2 + \tilde{\gamma}_k^2} - \frac{\tilde{\gamma}_k}{(\omega - \tilde{E}_k)^2 + \tilde{\gamma}_k^2} \right\} + A_{\text{inc}}(k, \omega), \quad (1)$$

where $z_k$ is the renormalization amplitude, $\tilde{E}_k \equiv (\Delta_k^2 + \tilde{\xi}_k^2)^{1/2}$ and $\tilde{\gamma}_k$ being the dispersion and damping of quasiparticles. The first term of Eq. (1) gives coherent contribution due to quasiparticles and the second term, $A_{\text{inc}}(k, \omega)$, represents incoherent background. In the photoemission experiment ($\omega < 0$), the first term in the coherent part, if it exists, gives dominant contribution.

First of all, it is remarked that the peak position of the coherent component is shifted downward by amount of $(\Delta_k^2 + \tilde{\xi}_k^2)^{1/2} + \tilde{\xi}_k$ when the superconductivity sets in. The maximum gap $2\Delta$ at $T = 0$ is related to the transition temperature $T_c$ as $2\Delta(0) \approx 3.5k_B T_c$ if it is estimated by the weak coupling treatment assuming $d_{x^2-y^2}$ pairing. Since $T_c = 78\text{K}$ and then the maximum gap $2\Delta(0) \approx 2.7 \times 10^2\text{K}$, such a shift of peak position should be detectable there far below $T_c$ within their relative experimental resolution of $\sim 5\text{meV} [1]$.

Secondly, the damping rate of quasiparticles in the normal state is given roughly as $\tilde{\gamma} \approx [(k_B T)^2 + (\omega/\pi)^2]^{1/2} [3]$. Therefore, narrowing of the coherent peak around $\omega \sim -30\text{meV}$, which are the case in a typical example of Fig. 1 in Ref. [4], seems to be detectable when the temperature is decreased from 85K down to 20K provided wave number $k$ is located at the position such that $\Delta_k = 0$. 


Thirdly, the spectral weight just below the Fermi level in the superconducting state is half of that in the normal state if $|\tilde{\xi}_k|$ is much less than $\Delta_k$. This is because half of the spectral weight of normal quasiparticles is transferred to above the Fermi level due to gap formation. Namely, ARPES intensity of coherent part in the superconducting state near the Fermi level is rather harder to observe than in the normal state if the gap $\Delta_k$ takes maximum there.

Now we encounter difficulty in interpretation of Ref. [1]. The ARPES at the location $A$ on $\Gamma-\bar{M}$ line in Fig. 1 does not show visible shift of peak position at all, but exhibits narrowing of the peak width suggesting a separation of coherent peak and incoherent background. If the gap had maximum at $A$, the peak should have shifted downward about 15meV in contrary to the observation in Fig. 1. Therefore, as an alternative interpretation, it seems more appropriate to consider that the gap $\Delta_k$ vanishes along the $k_x$-axis ($k_y = 0$), parallel to Cu-O bond, and that we observed the narrowing of the coherent peak at $\omega = \tilde{\xi}_k$ which had been located just below the Fermi level at $\tilde{\xi}_k \sim -30$meV. The present interpretation is also consistent with the so-called aging effect reported in Ref. [1], because the inhomogeneity of the surface caused by deficit of oxygen or so is expected to give an excess of damping of quasiparticles leading to broadening of the coherent peak.

On the other hand, at the location $B$ on $\Gamma-Y$ line, where the coherent component is hardly seen in the normal state (note that the maximum intensity at $A$ and $B$ in the normal state are almost the same while the incoherent background at $B$ is larger than that at $A$ by 30-40%), there appears a peak around $\omega \sim -30$meV far below $T_c$ without showing apparent shift of the edge near the Fermi level. If the gap vanished at $B$ as interpreted in Ref. [1], the narrowing of the coherent peak should have been observed. The intensity profile at $B$ in Fig. 1 rather looks as if new peak is added to the incoherent background when the temperature is decreased far below $T_c$. So it seems more natural to consider that $B$ is located just at or above the Fermi level and a new peak appears around $\omega = -\tilde{E}_k \simeq -30$meV but with a reduced weight $z_k(-\tilde{\xi}_k + \tilde{E}_k)/2\tilde{E}_k < z_k/2$. 
In conclusion, ARPES data of Ref. [1] are also understood even if we assume $d_{xy}$ pairing which has gap vanishing along $\Gamma-\bar{M}$ line and reaching maximum around $B$. Theoretical arguments favoring such pairing in cuprates have been put forth in various contexts [4,5]. Kane et al. has also suggested in a very recent Letter [6] that results of scanning tunneling microscope in Bi-2212 sample are understood on the basis of $d_{xy}$ pairing [7].
REFERENCES

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[2] T. Takahashi has recently succeeded in reproducing qualitatively the same ARPES as Ref. [1] by somewhat different method. (private communication)

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[6] J. Kane, Q. Chen, and K.-W. Ng, and H.-J. Tao, Phys. Rev. Lett. 72, 128 (1994). Note that $k_x$-axis in their paper is at an angle of 45° measured from Cu-O bond. Namely, the pairing of the type $\Delta(\theta) = \Delta_0(\cos k_x a - \cos k_y a)$ in their paper has $d_{xy}$-symmetry in a frame of reference in the present Comment where $k_x$-axis is parallel to the Cu-O bond.

[7] For YBCO, M. Sato et al. has observed an aspect suggesting the $d_{xy}$ pairing similarly to Ref. [1] (private communication).