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Observation of *d*-wave-like gap in the underdoped high-T_c superconductor $La_{1.93}Sr_{0.07}CuO_4$

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Introduction

One of the central issues in the research of the high-T_c cuprates superconductors is whether the pseudogap is a distinct phenomenon from superconuctivity or a gap due to local pairing or incoherent superconducting fluctuations above T_c. A recent angle-resolved photoemission (ARPES) study of $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_8$ (Bi2212) has revealed the presence of two distinct energy gaps in different regions of momentum space [1,2]. One is the antinodal region as mentioned above, and increases with underdoping. The other opens in the near-nodal region showing a coherent peak, and does not increase with underdoping. However, it is not clear whether the reduction of T_c with underdoping is due to the reduction of arc length or the gap size around the node. In order to give more insight to this issue, we have investigated the gap near the node direction in underdoped $La_{2-x}Sr_xCuO_4$ (LSCO) by ARPES.

Experimental condition

Single crystals of underdoped LSCO (x=0.07) with T_c = 14 K were grown by the floating zone method. ARPES experiments were carried out using a SES-2002 analyzer at BL - 28A. We used circular polarized beam with hν = 55 eV. Experimental energy and angular resolution were ~ 20 meV and ~0.5 deg, respectively. Measurement temperature was T ~ 7.6 K which is below T_c. Samples were cleaved *in situ*.

Result and Discussion

Figure 1 (a) shows energy distribution curves (EDC's) at Fermi momenta (k_F's) illustrated in panel (c). These k_F's have been determined by the peak positions of the momentum distribution curves (MDC's) at the E_F. One can clearly see that the leading edge midpoint (LEM) is shifted towards higher binding energies as going away from the nodal direction, indicating an anisotropic gap opening. Fig.1 (b) shows angular dependence of the binding energy of LEM plotted as a function of *d*-wave order parameter $|\cos(k_x)-\cos(k_y)|/2$. This plot clearly indicates the gap opening near the node direction obeys pure *d*-wave. We have obtained the gap size in the anti-nodal direction Δ_0 by extrapolating the liner dependence from $|\cos(k_x)-\cos(k_y)|/2=0$ toward $|\cos(k_x)-\cos(k_y)|/2=1$. The obtained Δ_0 is ~12 meV, which is larger than the magnitude of the T_c ~ 14 K when we assume d-wave BCS formula $2\Delta/k_BT_c = 4.3$.

If we assume that the pseudogap in the anti-nodal region precludes contribution to the superconductivity and the superconductivity comes mainly from the nodal direction, the effective superconducting gap is given by Δ_{SC} = (arc length) × Δ_0 [3]. Here, arc length is defined by the momentum length on the Fermi surface where clear quasi-particle (QP) peak exists. In the present result, the coherent QP exists only around the nodal direction as shown in the EDC's A and B [Fig.1 (a)], while EDC's D and E have broad spectral line shape without peak due to the pseudogap effects. Thus, according to the Fermi arc picture mentioned above, the discrepancy between BCS formula and obtained Δ_0 can be understood from the reduction of the Fermi arc length.

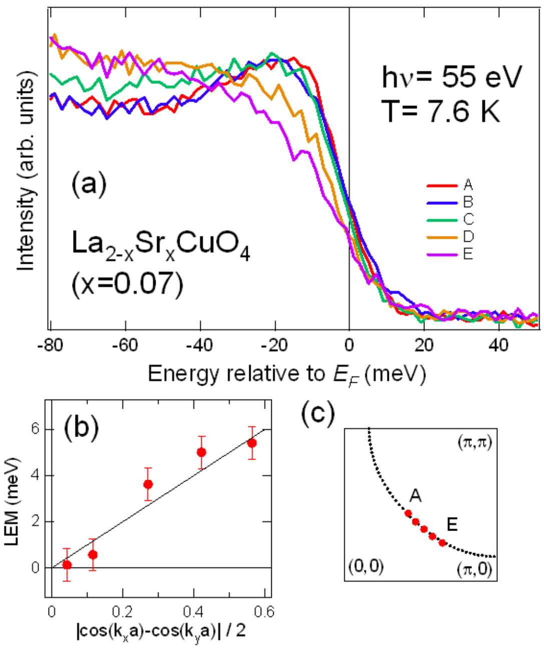

Figure 1: Energy gap of LSCO (x=0.07) near the nodal region. (a) EDC's at k_F. (b) Angular dependence of binding energy of LEM for each EDC in panel (a). (c) k_F positions for each EDC in panel (a).

References

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