Analysis of the diverging effective mass in $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ for high- T_c mechanism and pairing symmetry

Hyun-Tak Kim

*Metal–Insulator Transition Center,
 ETRI, Daejeon 305-700, South Korea
 School of Advanced Device Technology,
 UST, Daejeon 305-700, South Korea
 htkim@etri.re.kr
 htkim580711@gmail.com*

Accepted 5 December 2017
 Published 14 December 2017

In order to clarify the high- T_c mechanism in inhomogeneous cuprate layer superconductors, we deduce and find the correlation strength which has not revealed before, contributing to the formation of the Cooper pair and the two-dimensional density of state, and demonstrate the pairing symmetry in the superconductors which is still controversial. To the open questions, the fitting and analysis of the diverging effective mass with decreasing doping, extracted from the acquired quantum-oscillation data in underdoped $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ superconductors, using the extended Brinkman–Rice (BR) picture, reveal the nodal constant Fermi energy with the maximum carrier density, a constant Coulomb correlation strength $\kappa_{\text{BR}} = U/U_c > 0.90$, and a growing Fermi arc from the nodal Fermi point to the isotropic Fermi surface with an increasing x . The growing of the Fermi arc indicates that a superconducting gap develops with x from the node (underdoped) to the anti-node (optimally or over-doped). The large κ_{BR} results from the $d_{x^2-y^2}$ -wave metal–insulator transition for the pseudogap phase in lightly doped superconductors, which can be direct evidence for high- T_c superconductivity. The quantum critical point is regarded as the nodal Fermi point satisfied with the BR picture. The experimentally measured mass diverging behavior is an average effect and the true effective mass is constant. As an application of the nodal constant carrier density, the superconducting node gap analyzed by an angle-resolved photoemission spectroscopy (ARPES) is a precursor of s -wave symmetry in underdoped cuprates. Furthermore, the half-flux quantum, induced by the circulation of d -wave supercurrent and observed by the phase sensitive Josephson- π junction experiments, is not shown due to “anisotropic or asymmetric effect” appearing in superconductors with trapped flux.

Keywords: Diverging effective mass; Brinkman–Rice picture; high- T_c mechanism, d -wave MIT.

PACS numbers: 64.60.Ak, 74.72.-h

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution 4.0 (CC-BY) License. Further distribution of this work is permitted, provided the original work is properly cited.

1. Introduction

Since the discovery of the high- T_c cuprate superconductor in 1986, numerous studies and theories have been presented.^{1–5} Nevertheless, the mechanism underlying high- T_c superconductivity has not been clarified because underdoped cuprate superconductors are highly inhomogeneous due to severe nonstoichiometry arising from strong oxygen disorder,^{6,7} although the critical or overdoped crystals are more homogeneous,^{8,9} have a large continuous cylindrical Fermi surface,¹⁰ and show s -wave symmetry.¹¹ The homogeneous region was investigated about 3 nm in an underdoped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ (BSCCO)¹² and approximately 100 nm in a stoichiometric overdoped $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ (YBCO)^{8,9} with the scanning tunneling microscopy. Therefore, it is very difficult to measure the homogeneous region in order to know the true value. Inhomogeneity hinders the analysis of the intrinsic physical value because the obtained experimental value is an averaged value. The true nature of the superconductor should be deduced through the detailed analysis of the averaged data. Based on these deductions, we will be able to identify the mechanism of high- T_c superconductivity. Thus, the understanding of inhomogeneity for underdoped cuprate superconductors, rather than theoretical studies, is most important in high- T_c superconductors.

To understand high- T_c superconductivity based on inhomogeneity, several important issues unexplored or controversial issues must be resolved. Above all, the cause of the nodal constant Fermi velocity must be understood,^{13–15} including the relationship between the pseudogap and superconductivity, the identity of the pairing symmetry of the superconducting gap and the magnitude of the density of states as an effective mass connected to correlation between carriers. The diverging effective mass (DEM) in the normal state of a superconductor is an excellent example of converging the issues related to correlation theories explaining the mechanism of high- T_c superconductivity.^{16–18}

The DEM data in Fig. 2(a) were obtained from quantum-oscillation measurements in underdoped YBCO crystals.^{10,19,20} The results indicated an increasing value of effective mass as x decreased, although the extent of the metal region decreased as well.^{19,20} This finding is anomalous and remains an unsolved problem, as the oscillation and the effective mass coming from the metal phase should decrease. Thus, the DEM has been unfitted and its physical meaning still remains unclear.^{19,20}

Here, we fit and analyze the DEM data [Fig. 3(c) in Ref. 19 and Fig. 2(a) in this paper] of the quantum oscillation measured at the node in underdoped YBCO crystals by using the extended Brinkman–Rice (BR) picture explaining the metal–insulator transition (MIT) in inhomogeneous systems. Additionally, the nodal constant Fermi energy and the identity of the pairing symmetry are revealed by analyzing the angle-resolved photoemission spectroscopy (ARPES) data of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO) and YBCO and the phase sensitive experiment of YBCO.

2. The Extended Brinkman-Rice Picture

We briefly introduce the extended BR picture explaining the MIT as a two-phase model applied to an inhomogeneous system of a local metal region and an insulator region in the measurement region (black circle) [Fig. 1(a)].^{17,18,21} This model has two conditions: (1) a fractional effective charge $e' = \rho e$ with band filling

Fig. 1. (Color online) The extended BR picture. (a) The concept drawing of an inhomogeneous two-phase model. In the measurement region, the violet region is metal, and the yellow region is nonmetal or insulator. (b) Equation (1) shows two divergences of the BR-DEM (red bullets) at $\rho = 1$ and the Kim-DEM at $\kappa_{BR} = 1$. (c) The drawing of Eq. (1) at $\kappa_{BR} = 1$ shows the hole-driven MIT (BR-transition 2). The yellow portion represents the semiconductor regime and $\Delta\rho$ at red dot corresponds to hole doping and the impurity-doped insulator. The MIT is shown at red dot line between the doped insulator and metal specifying excitation. $n_c \equiv N_c \propto \Delta\rho$ which is the doping concentration for the MIT. The quantum critical point (QCP) is given at the transition point. (d) Two kinds of percolations are described. ρ in two cases is the same.

$0 < \rho = n_{\text{metal}}/n_{\text{total}} \leq 1$, defined by an average of metal carriers, n_{metal} , to the measurement region, where n_{total} is the total number of lattices in the measurement region and (2) a fractional effective Coulomb energy $0 < U/U_c = \kappa_{\text{BR}}\rho^2 < 1$, where $U = \rho^2 U'$ is defined in Refs. 17 and 18, $U' = \kappa_{\text{BR}} U_c$ is the on-site Coulomb energy, U_c is the critical Coulomb energy, and $\kappa_{\text{BR}} = U/U_c$ at $\rho = 1$ is the true correlation strength in the BR picture.¹⁶ Because metal has an electronic structure of one electron per atom (lattice) in real space and half filling in k space ($\rho = 1$), the physical meaning of U is that the metal region (violet part) widens as ρ increases [Fig. 1(a)]. Thus, the DEM was calculated as^{17,18}

$$\frac{m^*}{m} = \frac{1}{1 - (\frac{U}{U_c})^2} = \frac{1}{1 - \kappa^2 \rho^4}. \quad (1)$$

The detailed derivation is given in Ref. 18.

Equation (1) is plotted in Fig. 1(b), which shows two divergences at $\rho = 1$ (BR-DEM) and $\kappa_{\text{BR}} = 1$ (Kim-DEM). The BR-DEM is the true effect, while Kim-DEM is the measurement (average) effect and represents the percolation phenomenon. The BR-DEM and the Kim-DEM terminologies were first used to distinguish two divergences by authors in a previous paper.²² The MIT (BR transition 2) as $\Delta\rho$ between $\rho_{\text{max}} < 1$ and $\rho = 1$ at $\kappa_{\text{BR}} = 1$ [the yellow region in Fig. 1(c)] is called a hole-driven MIT or a BR-transition 2, while, the MIT between $\max(\kappa_{\text{BR}}) < 1$ and $\kappa_{\text{BR}} = 1$ at $\rho = 1$ is named the BR-transition 1. The MIT occurs via a semiconductor [yellow region in Fig. 1(c)], when a critical hole concentration of $n_c \approx 1 \times 10^{18} \text{ cm}^{-3}$ is doped (or excited) into an insulator or a Mott insulator.²¹ The MIT point is regarded as an MIT instability and corresponds to the QCP because this model is defined at $T = 0 \text{ K}$. Generally, there are two types of percolations based on the band-filling factor ρ . One occurs when the extent of the metal region increases in the constant measurement region [Case 1 in Fig. 1(d)], while in the other, the measurement region enlarges with respect to the constant metal region [Case 2 in Fig. 1(d)].

3. Fitting Idea and Fitting of the DEM Data

In order to fit the DEM data in Fig. 2(a) with Eq. (1), the following assumption is required. Underdoped YBCO crystals are inhomogeneous and have two phases as a metal and an insulator (pseudogap phase). The metal phase is also composed of two kinds of metals at the node ($\pi/2, \pi/2$) and anti-node ($0, \pi$) (or nonnode) [Fig. 2(b)]. Because the quantum oscillation is defined in k -space, the insulator phase without the Fermi surface does not emerge in k -space. The metal phase appears on the Fermi surface in the Fourier transformation. Thus, we should consider two metal phases, one at the node and one except the node (nonnode). Because the measurements^{19,20} were taken at the node, the carrier density of the metal phase at the node denotes $n_{\text{metal node}}$ in ρ , and n_{total} includes the carrier densities at the node and nonnode (all regime except the node); $n_{\text{total}} = n_{\text{metal node}} + n_{\text{metal nonnode}}$ is given. When

Fig. 2. (Color online) The fitting of the DEM. (a-1) The DEM data (black dot) extracted from quantum oscillation data in Fig. 3(c) by Sebastian *et al.*¹⁹ are closely fitted by Eq. (1) when $\kappa_{\text{BR}} = 1$. Upper x -axis is expressed as a function of band filling ρ . QCP means the quantum critical point. (a-2) The inverse effective masses, m/m^* , of Fig. (a-1) are shown. At $x = 0.54$ far from the transition point, the fitting of Eq. (1) was slightly deviated from the experimental data showing the linear behavior; the data may have a large experimental error. (b) A schematic percolation diagram showing an increase of metal region (pink) with x [left figure corresponding to Case 1 in Fig. 1(d)]. Based on $\rho_i = x_c/x_i$, as x (pink) increases, such as $x_1 \approx 0.49 < x_2 \approx 0.50 < x_3 \approx 0.51 < x_4 \approx 0.54$,¹⁹ $\rho = (\text{red/pink})$ decreases [right figure corresponding to Case 2 in Fig. 1(d)]; $\rho_1 > \rho_2 > \rho_3 > \rho_4$ with respect to $x_1 < x_2 < x_3 < x_4$ is a percolation. The extent of the metal region (red dot) at the node is constant because the numerator of ρ is x_c . (c) A schematic figure of the Fermi point and surface in k -space based on an analysis of Figs. 2(a) and 2(b). Because the extent of the metal region (pink region) increases as x increases [Fig. 2(b)], in k -space, the Fermi surface grows from the Fermi point at the node (red dot) to the Fermi arc (pink arc) at the anti-node. However, the magnitude of the Fermi point at the node (red dot) is constant irrespective of increasing of x . There is no Fermi energy (or dot or surface) at the anti-node $(0, \pi)$.

two systems of the extended BR picture and this YBCO system are compared, $n_{\text{metal nonnode}}$ corresponds to an insulator component in the extended BR picture [Fig. 1(b)] because $n_{\text{metal nonnode}}$ does not logically contribute to the quantum-oscillation data measured at the node.

In other words, because $\rho = n_{\text{metal}}/n_{\text{total}}$ is defined, the extent of the metal region at the node, $n_{\text{metal node}}$, corresponds to the critical doping, $x_c \equiv x_{c \text{ node}}$,

and the size of the measurement region, including the metal regions at node and nonnode; n_{total} , is regarded as x , because $x = x_{\text{c node}} + x_{\text{nonnode}}$. Thus, $\rho \equiv n_{\text{metal}}/n_{\text{total}} \approx x_{\text{c}}/x$ is given. As x increases, ρ decreases, and vice versa. This is the percolation phenomenon corresponding to Case 2 in Fig. 1(d). The above assumption is a key idea in fitting. The ARPES spectrum intensity and the optical conductivity measured at node were increased as doping increased.^{14,23} We analyze that, according to doping, the region of metal widens such as Fig. 1(a).

We fit the experimental data in Fig. 2(a-1) for the DEM in Fig. 3(c) of Ref. 19 with the fitting idea and Eq. (1) when $\kappa_{\text{BR}} = 1$ and $\rho \approx x_{\text{c}}/x$. The fitting result is shown in Figs. 2(a-1) and 2(a-2). Four data points are closely fitted to Eq. (1) although the data near $x = 0.54$ are slightly deviated. It may be a large experimental error. This process reveals that the magnitude of the metal region (numerator, x_{c}) at the node is constant regardless of x , although the size of the metal region (denominator, x) increases with increasing hole doping x (an increase in the Fermi energy) [Fig. 2(b)], indicating that the Fermi energy at the node is constant. Moreover, an MIT at the hole doping x_{c} occurs at the node. x_{c} corresponds to $n_{\text{c}} \propto \Delta\rho$ in Fig. 1(c) and $n_{\text{metal node}}$ is formed. Based on the fitting, we expect that, as hole doping x increases, the Fermi surface grows from the nodal Fermi point to the anti-nodal Fermi arc [Fig. 2(c)]. The measured Fermi arc^{24–26} is an intermediate process in reaching the isotropic Fermi surface. The origin of the nodal Fermi point is that the MIT occurs at the node, rather than at the anti-node,^{13–15} and the nodal Fermi point (or velocity¹⁴) was revealed.^{13,15}

The nodal Fermi points with the maximum number of carriers are formed [red balls in Fig. 2(c)] by the d -wave MIT (Fig. 3). The inhomogeneity disappears and the homogeneous metal phase is obtained at the node where $\rho = 1$.^a The nodal point is regarded as the QCP, which is defined as a point where the MIT occurs at $T = 0$ K. The true effective mass is constant. The diverging behavior of the measured effective mass in Fig. 2(a-1) is an average (measurement) effect, as this effect is fitted by Eq. (1).

4. Correlation Strength κ_{BR} and Experimental Confirmation

In order to obtain a value of $\kappa_{\text{BR}} = U/U_{\text{c}}$, we assume that $m^*/m = 1/(1 - \rho^4)$ (Kim-DEM) at $\kappa_{\text{BR}} = 1$ is approximately equal to $m^*/m = 1/(1 - \kappa_{\text{BR}}^2)$ (BR-DEM) at $\rho = 1$ near the diverging point near $\rho = 1$ and $\kappa_{\text{BR}} = 1$ [Fig. 1(b)]. $m^*/m \approx 4.5$ at $x = 0.49$ is given.^{19,20} κ_{BR} is determined to be approximately 0.89. However, because x can approach x_{c} , the effective mass can increase greatly. Thus,

^aFor the valance band in inhomogeneous cuprate systems with two phases [Fig. 1(a)], $n_{\text{total}} = n_{\text{metal}} + n_{\text{pseudo-gap}}$ is given, where n_{metal} is the carrier density in metal, $n_{\text{pseudo-gap}}$ is the bound charge density in the pseudo-gap potential, n_{total} is the total carrier density in the d -band and constant. When $n_{\text{pseudo-gap}}$ decreases, n_{metal} increases. Thus, when $n_{\text{pseudo-gap}} = 0$ due to the d -wave MIT, the measurement region becomes the homogeneous metal with $\rho \equiv n_{\text{metal}}/n_{\text{total}} = 1$. The DEM becomes maximum near $\rho = 1$. Thus, the large κ_{BR} is predicted from Eq. (1).

Fig. 3. (Color online) d -wave MIT. (a) The pseudogap at the anti-node. ARPES spectra measured at 10 K for hole-doped nonsuperconducting single crystals ($y = 6.35, 6.45, 6.60$) of YBCO_y. Pseudogaps of approximately -0.2 eV are clearly shown at the X and Y antinodes (inverse bold triangles ∇, ∇, ∇). The value is independent of hole doping. This was cited from Fig. 4.3 in Yagi's Ph.D. paper.²⁹ (b) The d -wave MIT from the pseudogap to the metal at the node. ARPES spectra measured at 10 K at the node for lightly doped single crystals of YBCO_y with $y = 6.25$ (pseudogap of -0.1 eV), 6.30, 6.35 and 6.40, without T_c . These data were cited from Fig. 5.1 in Yagi's Ph.D. paper.²⁹ (c) The doping dependence of pseudogaps in (a) and (b). As y increases, the pseudogap at the anti-node remains unchanged (a), while the edge of the pseudogap [white arrows, bottom figures in (b)] decreases at the node. The MIT occurs at the node (d -wave MIT). This shows that the pseudogap has the d -wave symmetry.

we suggest $\kappa_{BR} > 0.9$. This finding is evidence that the metal phase at the node is strongly correlated. The strong correlation is attributed to the d -wave MIT of the pseudogap phase (refer footnote a) (Fig. 3), which can be the cause of high- T_c in the cuprate systems. The pseudogap follows the d -wave nature²⁷ and competes with superconductivity.²⁸

We confirm the fitting result with the experimental data obtained from the lightly hole-doped insulators (semiconductor or pseudogap) of YBCO_y. Figure 3 shows the ARPES spectra measured at 10 K for single crystals of YBCO_y.²⁹ A

summary of Figs. 3(a) and 3(b) is given in Fig. 3(c). As the doping y increases, the pseudogap at the anti-node does not change, while the pseudogap rapidly decreases and finally disappears at the node [Fig. 3(b)]. This is the d -wave MIT at the node, which indicates that the pseudogap has $d_{x^2-y^2}$ -wave symmetry. This is also the origin of the Fermi arc. Thus, the fitting result as the Fermi arc in Fig. 2(c) is proved by the ARPES data.²⁶

Moreover, it is necessary to review whether the nodal Fermi points [red balls in Fig. 2(c)] including maximum carriers contribute to forming the superconducting gap or remain unchanged below T_c . If the nodal Fermi points keep the metallic state, the absence of the node gap should be observed and the pairing symmetry is d -wave; otherwise, the pairing symmetry³⁰ is regarded as s -wave. Therefore, we discuss the presence of the node gap for resolving this problem on the basis of ARPES data.

5. Application to ARFES Data, Couping Constant of Δ and T_c in BCS Theory

We analyze the well-measured ARPES data to confirm the presence of a small superconducting gap at the node. The ARPES data measured in an underdoped YBCO_{7- δ} crystal showed the absence of a gap at the anti-node, a large gap at the off-node, and a small superconducting gap at the node,³¹ suggesting the presence of the Fermi arc at the normal state. In addition, the superconducting node gap was also observed in a YBCO_{7- δ} crystal.³² The ARPES data, which were measured in underdoped and optimally-doped single crystals of LSCO proved by the Fermi arc,²⁶ showed small superconducting gaps at the node. Near optimal doping, the gap anisotropy with small and large gaps were also exhibited in ARPES. The magnitude of the node gap decreased with increasing doping concentration, which was also observed in lightly doped cuprates.³³ The presence of the node gap was discussed with various scenarios including the possible effects of chemical disorder, electronic inhomogeneity and a competing phase.³³ It has been suggested that the node gap is generic in all cuprate superconductors.³³ Moreover, a small gap near node disappeared near T_c .²⁶ This suggests that the node gap is a superconducting gap and intrinsic.¹³ The gap anisotropy was also observed in cuprate superconductors.^{25,34} The gap anisotropy measured in an under-doped BSCCO showed that the pseudogap has d -wave symmetry.^{13,15} The ARPES data measured in the high resolution system for an underdoped BSCCO crystal also showed a small gap at the node.²⁵ These data also indicated that the hump at the anti-node disappears at the node. We suggest that the node gap is formed by changing from the homogeneous metal state (nodal Fermi points) to the gap state at low temperatures. The magnitude of the small gap at the node was measured as approximately $\Delta_{\text{sup}} \approx 10$ meV at the node for YBCO, BSCCO,²⁵ Ca_{2- x} Na _{x} CuO₂Cl₂ and Nd_{2- x} Ce _{x} CuO₄,³³ and LSCO with $x = 0.15$.³³ The forming mechanism of the superconducting node gap is shown in Fig. 4.

Fig. 4. (Color online) A mechanism for the formation of the superconducting node gap. The $d_{x^2-y^2}$ electronic structure can be formed when the MIT occurs at the node in an isotropic pseudogap structure (blue dashed ring). The small pink circles in the large pink circle are regarded as the nodal Fermi points made by the d -wave MIT near doping x_c . The pink circle is the Fermi surface formed by the increased doping. The red-dashed arrow indicates that bound charges in the pseudogap potential at the node are excited to the Fermi energy, due to the d -wave MIT (conceptual indication). The small green circles in the large green circle are superconducting intrinsic gaps at the node when the nodal Fermi points become a superconductor (pink circle > green circle).^{13,15} The green ring is the isotropic superconducting s -wave-like gap resulting from the Fermi arc at optimal doping. If the superconducting energy gap has $d_{x^2-y^2}$ -wave-pairing symmetry, the d -wave-MIT should occur at the anti-node. However, this research does not support the d -wave-pairing symmetry. The constant maximum carrier density at the nodal Fermi point (or velocity) was first disclosed.¹³

Furthermore, we deduce the strength of the coupling constant between the superconducting gap and T_c . At the optimal doping, we obtain coupling constants $b \equiv 2\Delta_{\text{sup}}/k_B T_{c,\text{max}} \approx 4.0$ at $\Delta_{\text{sup}} \approx 10$ meV and $T_{c,\text{max}} \approx 93$ K for YBCO and $b \approx 5.95$ at $\Delta_{\text{sup}} \approx 10$ meV and $T_c \approx 39$ K for LSCO data. In the case of low- T_c superconductors, $b \approx 3.5$ is known, but high- T_c superconductors are slightly over $b \approx 4.0$. The difference in b values may arise from the correlation strength, κ_{BR} , increasing the density of states. Namely, the high- T_c cuprate superconductors have larger κ_{BR} than the low- T_c superconductors because of the d -wave electronic structure of the pseudogap phase in the a - b plane of CuO_2 in the cuprate superconductors.

6. Analysis of the Half-Flux-Quantum Image for Pairing Symmetry

As for pairing symmetry, we analyze a representative image of the half-flux quantum known as evidence of d -wave symmetry measured by a SQUID microscope.³⁵ The image showed “anisotropy” in color tone of the image (Fig. 5), which is the phenomenon observed in superconductors with trapped flux; the image in Fig. 5(a) is

Fig. 5. (Color online) (a) and (b) Trapped magnetic flux images. The half magnetic flux imaged by a SQUID microscope at an underdoped YBCO superconducting ring on the tricrystal substrate. Anisotropy is shown, which is denying of d -wave symmetry.³⁵ (c) Flux image of ring-type measured in an optimal-doped single-layer tetragonal $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$ superconducting ring without a junction.³⁶

not evidence of d -wave symmetry. For an optimally doped sample of $\text{Tl}_2\text{Ba}_2\text{CuO}_{6+\delta}$, a homogeneous ring-type image in color tone is suggested as evidence of s -wave symmetry.³⁶ The magnetic flux for all crystals with an incomplete Fermi surface is necessarily trapped. The high- T_c mechanism and the deep analysis on the pairing symmetry are given in Ref. 37.

Conclusion

The analysis of the measured DEM fitted by Kim-DEM [Fig. 1(b)] revealed that, as the hole doping increased, the Fermi surface grew from the nodal Fermi point to the isotropic Fermi surface like s -wave symmetry. This finding indicates that the underdoped state is intermediate to the isotropic state. The high- T_c mechanism is caused by a strong correlation ($\kappa_{\text{BR}} > 0.9$) induced by the maximum carrier density ($\rho \approx 1$) generated by the d -wave MIT at the node in the pseudogap CuO_2 layer, which can be explained in the context of the BCS theory. The superconducting intrinsic gap is formed at the QCP at node.

Acknowledgments

We introduced this research to Prof. S. Sebastian (an author in Ref. 23) in 2014 APS March meeting (Denver) and have received correct comments on the experiments. We acknowledge Prof. T. Tohyama and Prof. D. N. Basov for their valuable comments and Prof. T. Yoshida, Dr. M. Hashimoto, Prof. H. Yagi, Dr. S. Yasmine and Prof. S. Sebastian for reading, comments and permission to use data. This was supported by both the creative project (17ZB1220) in ETRI and an MS&ICT project (2017-0-00830) on MIT.

References

1. T. Tohyama, *Jpn. J. Appl. Phys.* **51**, 010004 (2012).
2. R. A. Klemm, *Layered Superconductors*, Vol. 1 (Oxford University Press, UK, 2012).
3. Ø. Fischer *et al.*, *Rev. Mod. Phys.* **79**, 353 (2007).
4. S. P. Kruchinin, H. Nagao and S. Aono, *Modern Aspect of Superconductivity: Theory of Superconductivity* (World Scientific, Singapore, 2010).
5. S. P. Kruchinin, *Rev. Theor. Phys.* **2**, 1 (2014).
6. K. McElroy *et al.*, *Science* **309**, 1048 (2005).
7. S. Zhou, H. Ding and Z. Wang, *Phys. Rev. Lett.* **98**, 076401 (2007).
8. A. D. Beyer *et al.*, *Europhys. Lett.* **87**, 37005 (2009).
9. M. L. Teague *et al.*, *Europhys. Lett.* **85**, 17004 (2009).
10. N. D. Leyraud *et al.*, *Nature* **447**, 565 (2007).
11. Q. Li *et al.*, *Phys. Rev. Lett.* **83**, 4160 (1999).
12. K. M. Lang *et al.*, *Nature* **415**, 412 (2002).
13. H. T. Kim, *J. Phys. Soc. Jpn.* **71**, 2106 (2002). See the analyzing part of ARPES data in the last section of right side in the second page; this mentions a *d*-wave metal-insulator transition at node from the pseudo-gap insulator to metal.
14. I. M. Vishik *et al.*, *Phys. Rev. Lett.* **104**, 207002 (2010).
15. H. T. Kim, B. J. Kim and K. Y. Kang, *Physica C* **460**, 943 (2007).
16. W. F. Brinkman and T. M. Rice, *Phys. Rev. B* **2**, 4302 (1970).
17. H. T. Kim, *Physica C* **341**, 259 (2000).
18. H. T. Kim, <http://arXiv.org/abs/cond-mat/0110112>.
19. S. E. Sebastian *et al.*, *Proc. Natl. Acad. Sci.* **107**, 6175 (2010).
20. J. Singleton *et al.*, *Phys. Rev. Lett.* **104**, 086403 (2010).
21. H. T. Kim *et al.*, *New J. Phys.* **6**, 52 (2004).
22. M. Kang, S. W. Kim and J. W. Ryu, *J. Appl. Phys.* **118**, 035105 (2015).
23. Y. S. Lee *et al.*, *Phys. Rev. B* **72**, 054529 (2005).
24. T. Yoshida *et al.*, *Phys. Rev. Lett.* **91**, 027001 (2003).
25. A. Kaminski *et al.*, *Phys. Rev. Lett.* **84**, 1788 (2000).
26. T. Yoshida *et al.*, <http://arXiv.org/abs/1203.0600>.
27. T. Timusk and B. Statt, *Rep. Prog. Phys.* **62**, 61 (1999).
28. T. Kondo *et al.*, *Nature* **457**, 296 (2009).
29. Y. Hajime, Photoemission study of the high-temperature superconductor YBa₂Cu₃O_y, Tokyo University Ph.D. thesis (2005), http://wyvern.phys.s.u-tokyo.ac.jp/f/Research/arch/thesis_yagi.pdf.
30. T. Hasegawa *et al.*, *Physica B* **197**, 617 (1994).
31. S. Yasmine, ARPES investigations on in situ PLD grown YBa₂Cu₃O_{7-δ}, Université de Neuchâtel (Swiss) Ph.D. thesis (2011), <http://doc.rero.ch/record/200236/files/00002351.pdf>.
32. M. Okawa *et al.*, *Phys. Rev. B* **79**, 144528 (2009).
33. K. M. Shen *et al.*, *Phys. Rev. B* **69**, 054503 (2004).
34. Z. X. Shen *et al.*, *Phys. Rev. Lett.* **70**, 1553 (1993).
35. C. C. Tsuei and J. R. Kirtley, *Rev. Mod. Phys.* **72**, 969 (2000).
36. C. C. Tsuei *et al.*, *Science* **271**, 329 (1996).
37. H. T. Kim, <https://arXiv.org/abs/1710.07754>.