Angle-Resolved Photoemission Study on Strongly Correlated Electron Materials

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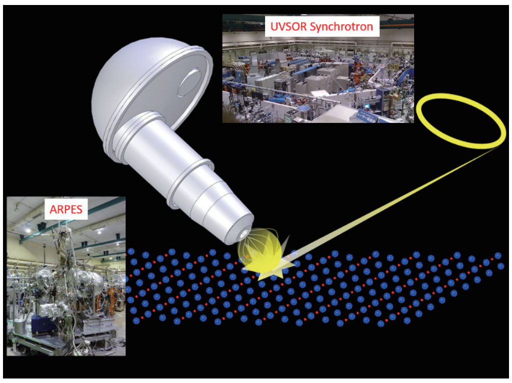
Strongly correlated electron materials have attracted more attentions in the last few decades because of their unusual and fascinating properties such as high-T_c superconductivity, giant magnetoresistance, heavy fermion and so on. Those unique properties can offer a route toward the next-generation devices. We investigate the mechanism of the physical properties as well as the electronic structure of those materials by using angle-resolved photoemission spectroscopy (ARPES). ARPES is a powerful experimental technique, directly measuring the energy (E) and momentum (k) relation, namely the band structure of solids. In the last quarter of a century, the energy resolution and angular resolution of ARPES have improved almost three order of magnitude better, which makes us possible to address the fine structure of the electronic structure near the Fermi level: Superconducting gap, kink structure and so on. The main target materials of our group is high-T_c superconductors, such as cuprates and iron pnictides and use UVSOR-III as a strong light source.

Our group is also developing high-efficiency spin-resolved ARPES system. Spintronics is a rapidly emerging field of science and technology that will most likely have a significant impact on the future of all aspects of electronics as we continue to move into the 21st century. Understanding magnetism of surfaces, interfaces, and nanostructures is greatly important for realizing the spintronics which aims to control and use the function of spin as well as the charge of electrons. Spin-resolved ARPES is one of the most powerful experimental techniques to investigate the magnetic properties of such materials.



Selected Publications

- K. Tanaka *et al.*, "Distinct Fermi-Momentum-Dependent Energy Gaps in Deeply Underdoped Bi2212," *Science* **314**, 1910–1913 (2006).
- K. Tanaka *et al.*, "Quantitative Comparison between Electronic Raman Scattering and Angle-Resolved Photoemission Spectra in $Bi_2Sr_2CaCu_2O_{8+\delta}$ Superconductors: Doping Dependence of Nodal and Antinodal Superconducting Gaps," *J. Phys. Soc. Jpn.* **88**, 044710 (2019).
- S. Ideta, K. Tanaka *et al.*, "Experimental Investigation of the Suppressed Superconducting Gap and Double-Resonance Mode in $Ba_{1-x}K_xFe_2As_2$," *Phys. Rev. B* **100**, 235135 (7 pages) (2019).
- S. Ideta, K. Tanaka *et al.*, "Hybridization of Bogoliubov Quasiparticles between Adjacent CuO_2 Layers in the Triple-Layer Cuprate $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ Studied by Angle-Resolved Photoemission Spectroscopy," *Phys. Rev. Lett.* **127**, 217004 (6 pages) (2021).

1. Hybridization of Bogoliubov Quasiparticles between Adjacent CuO_2 Layers in the Triple-Layer Cuprate $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$[1)]

It has been known that one of the most efficient ways to increase the critical temperature (T_c) of high-T_c cuprate superconductors (HTSCs) is to increase the number of neighboring CuO_2 planes (n). T_c generally increases from single-layer (n = 1), double-layer (n = 2), to triple-layer (n = 3) and then decreases for $n \geq 4$. Although several mechanisms have been proposed to explain the n dependence of T_c, it is still not clear because of the lack of detailed knowledge about the electronic structure of the multi-layer ($n \geq 3$) cuprates. In this study, we performed ARPES of optimally doped triple-layer $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi2223, T_c = 110 K) in the superconducting states at UVSOR BL7U.[1)]

Figures 1(a)–(h) show hybridization of Bogoliubov quasiparticles (BQPs) between the outer CuO_2 plane (OP) and the inner CuO_2 plane (IP). The OP and IP are hybridized with each other and open a gap at the crossing point (an anti-crossing gap between the two BQP bands) as shown in Figure 1(i). We noticed that the magnitude of the gap ($\Delta_{t\perp}(k)$) gradually increases as one goes away from the node toward the antinode and the momentum dependence of $\Delta_{t\perp}(k)$ can be reproduced by assuming the interlayer single-particle hopping parameter $t\perp$ ~ 56 meV using the tight-binding model for coupled CuO_2 planes. In order to reproduce the high energy kinks for the OP and IP bands of the measured ARPES spectra, we have performed model calculation including the coupling to several oxygen-derived phonons. Taking into account the contribution of acoustic phonons, the flatness of the top of the IP band seen in the experiment is reproduced to some extent.

The most intriguing and important question relevant to the present study is how much the interlayer single-particle hopping and the obtained $\Delta_{t\perp}(k)$ contribute to the enhancement of T_c in Bi2223. In order to discuss a possible mechanism for the T_c enhancement in triple-layer cuprates, a simple four-well model calculation is performed assuming contributions from four bosonic modes, namely, the acoustic phonon, the c-axis buckling phonon, the in-plane breathing phonon, and spin fluctuations. The present model calculation suggests that the electron–phonon coupling alone may not be sufficient to cause the observed T_c in the triple-layer cuprate, and the combination of spin fluctuations and phonons is essential (not shown).

As another candidate of the anticrossing gap, the effect of interlayer Cooper-pair hopping could not be isolated from the present data, but might be important to increase the T_c of Bi2223. To answer the question of how interlayer interactions, *i.e.*, single-particle hopping versus Cooper-pair hopping, contribute to the enhancement of superconductivity, further systematic studies are needed both experimentally and theoretically. The momentum-dependent hybridization gap, which is proportional to the square of the SC order parameter, would be a key piece of information to solve the T_c-enhancement mechanism of the multilayer cuprates.

2. Development of Spin-Resolved ARPES with Image-Spin Detection

Our group is developing a new high-efficient spin-resolved ARPES system with multi-channel detection (we call "image-spin" detection) in beamline BL5U at UVSOR. We successfully obtained spin-resolved signal of Au(111) surface and achieved 100 times better efficiency and several times better momentum resolution than the current synchrotron-based spin-resolved ARPES systems in the world. In 2021, we installed a spin-manipulator lens system, where the direction of the spin can be changed to any directions. The calibration of the lens parameters will be done in 2022.

Reference

1) S. Ideta *et al.*, *Phys. Rev. Lett.* **127**, 217004 (6 pages) (2021).

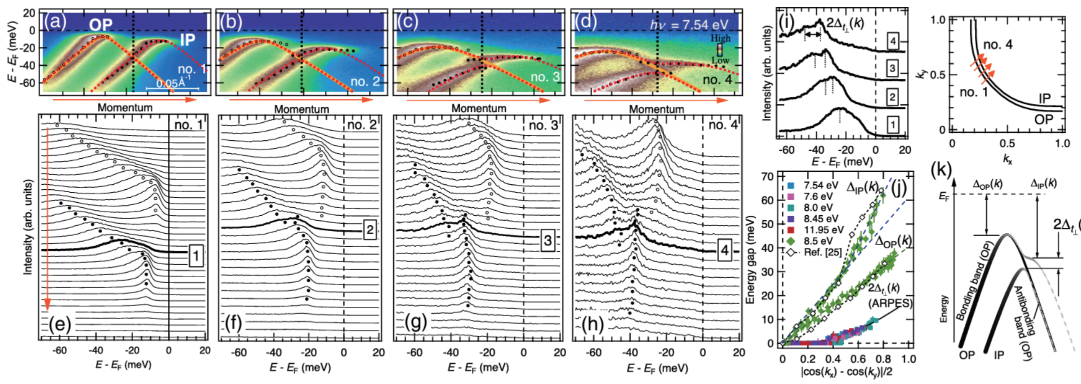


Figure 1. ARPES spectra of the OP and IP bands in Bi2223. (a)–(d): *E*-*k* plots near E_F. (e)–(h): Energy-distribution curves (EDCs) corresponding to (a)–(d). (i): EDCs at momenta where the OP band and the IP band cross extracted from panels (e)–(h). (j): Momentum dependence of $\Delta_{t\perp}(k)$ plotted against the d-wave order parameter. (k): Schematic illustration of the hybridization between the OP and IP BQP bands in the off-nodal region.

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