Angle-Resolved Photoemission Study on Strongly Correlated Electron Materials

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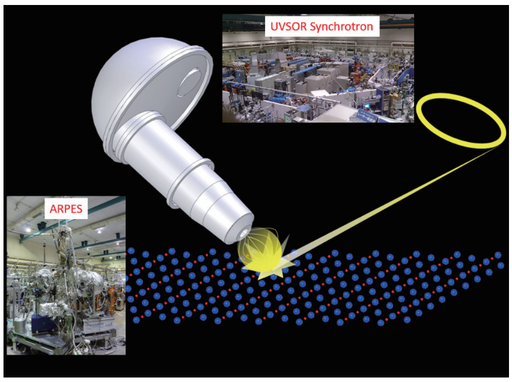
Strongly correlated electron materials has attracted more attentions in the last few decades because of their unusual and fascinating properties such as high-T_c superconductivity, giant magnetoresistance, heavy fermion and so on. Those unique properties can offer a route toward the next-generation devices. 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, W. S. Lee, D. H. Lu, A. Fujimori, T. Fujii, Risdiana, I. Terasaki, D. J. Scalapino, T. P. Devereaux, Z. Hussain and Z.-X. Shen, "Distinct Fermi-Momentum-Dependent Energy Gaps in Deeply Underdoped Bi2212," *Science* **314**, 1910–1913 (2006).
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- K. Tanaka, N. Hieu, G. Vincini, T. Masui, S. Miyasaka, S. Tajima and T. Sasagawa, "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, N. Murai, M. Nakajima, R. Kajimto and K. Tanaka, "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).

1. Quantitative Comparison between ARPES and ERS on Multilayer Cuprates Superconductor[1)]

It has been well 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 of the optimally doped region ($T_{c:max}$) generally increases from single layer (n = 1), double layer (n = 2), to triple layer (n = 3) and then decreases for n > 4. In order to explain the n dependence of T_c, several mechanisms have been proposed. However, it has been unclear which parameter governs the n dependence of $T_{c:max}$ because of the lack of detailed knowledge about the electronic structure of the multilayer cuprates. In this study, we have performed angle-resolved photoemission spectroscopy (ARPES) and electronic Raman scattering (ERS) to clarify the electronic structure of optimally doped triple-layer $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi2223) which has the highest $T_{c:max}$ (~110 K) among Bi-based HTSCs.

Since the superconducting gap in the cuprates has a d-wave symmetry, we need k-selective experimental probes. Although ARPES and ERS are the most powerful k-selective probes, the gap sizes estimated from these two techniques are not always identical. To clarify the origin of the discrepancy, we have examined a direct comparison of ARPES and ERS through the Kubo formula analysis. In a previous study on the double layer Bi2212, we proved that this method is valid and advantageous.[2)]

In ERS study on optimally doped Bi2223, we found that B_{1g} spectra, which is sensitive to the antinodal region in the k-space, showed double peaks as shown in Figure 1a (blue curve). This is the first observation of multiple peaks in B_{1g} spectra in HTSCs. On the other hand, ARPES study on Bi2223 reveals two Fermi surfaces (FSs), which can be attributed the FS closer to the Γ point to that of the outer CuO_2 plane (OP) and the other to that of the inner CuO_2 plane (IP), assuming that the doping level is higher in the OP than in the IP. From those observations, we think that the double peak in ERS is originated from two different bands which form different FSs observed by ARPES.

To confirm our interpretation of the double peak, we calculated the Raman spectra from the ARPES, using the Kubo formula. For triple layer compounds, by separating the IP and OP bands of ARPES, we can calculate their separate contribution to the Raman spectra, and verify if the two B_{1g} Raman peaks truly originate from the two separate bands. The ARPES intensities for the IP and OP bands were separated by a Gaussian fit of the energy distribution curves using three Gaussian peaks, one for the IP and OP band each and one for the high energy incoherent intensity that originates from the strong correlations effects in the antinodal part of the k-space.

The calculated B_{1g} and B_{2g} Raman spectra for the optimally doped Bi2223 are compared with the experimental ones in Figure 1. One can find that the calculated spectra from the ARPES data successfully reproduce the experimental Raman spectra. The striking result is that, in the B_{1g} configuration, the IP and OP bands exhibit peaks at different energies that are close to the experimental B_{1g} peak energies. Here the OP peak position is slightly underestimated, which may be due to the fact that a small portion of the antinodal part of the momentum space is missing in our input ARRPES data. By summing the separate contribution of IP and OP, we obtain a thick orange line. A rather good correspondence of the calculated and experimental IP and OP peaks provides strong proof that the double B_{1g} Raman peak truly originates from the two separate bands of Bi2223 and, therefore, that it is a signature of the double superconducting gap of this material.

This results clarify systematic doping dependence of superconducting gaps of IP and OP in ERS, which reveals that the both the pair-breaking energy and the gap ratio are larger in triple layer cuprates than in single and double layer cuprates (not shown).

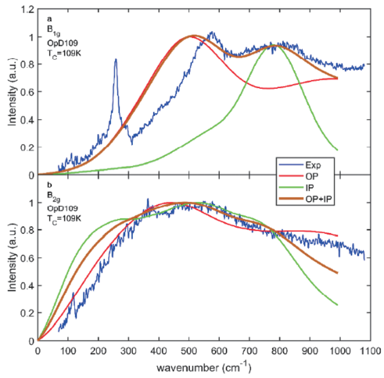

Figure 1. Comparison of the Raman spectra calculated from the ARPES (orange cruve) and the experimentally observed Raman spectra (blue curve) for B_{1g} (a) and B_{2g} (b) polarizations. The red and green curves are obtained from the ARPES data for the OP and IP, respectively. In the total curve IP+OP (thick orange), the contributions both from IP and OP are taken into account

2. Development of Low Temperature 6-Axis Manipulator for High-Resolution ARPES

We have developed low temperature 6-axis manipulator for high energy resolution ARPES measurements and achieved one of the lowest temperature 6-axis manipulators in the synchrotron radiation facilities in the world. To achieve lower temperature, we have started computational thermal simulation.

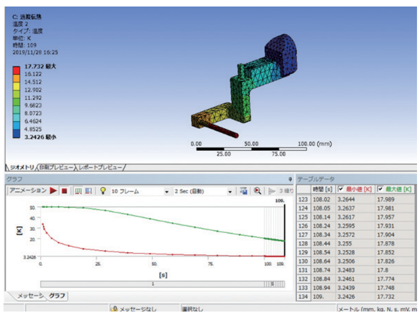

Figure 2. Modeling and simulation of thermal analysis for 6-axis manipulator.

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1) G. Vincini *et al.*, *Supercond. Sci. Technol.* **32**, 113001 (2019).
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