Angle-Resolved Photoemission Study on Strongly Correlated Electron Materials

UVSOR Synchrotron Facility
Division of Advanced Solid State Physics

TANAKA, Kiyohisa
Associate Professor
[k-tanaka@ims.ac.jp]

Education
2000 B.S. The University of Tokyo
2005 Ph.D. The University of Tokyo

Professional Employment
2005 Postdoctoral Fellow, Stanford University and Lawrence Berkeley National Laboratory
2008 Assistant Professor, Osaka University
2013 Associate Professor, Osaka University
2014 Associate Professor, Institute for Molecular Science
Associate Professor, The Graduate University for Advanced Studies

Member
Graduate Student
KAWANO, Kento*
MASUDA, Keisuke*
ZHU, Yupeng†
Secretary
ISHIHARA, Mayumi
KAMO, Kyoko
YOKOTA, Mitsuyo

Keywords Strongly Correlated Electron System, Synchrotron Light, Photoemission

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 strucature 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 (Figure 1).

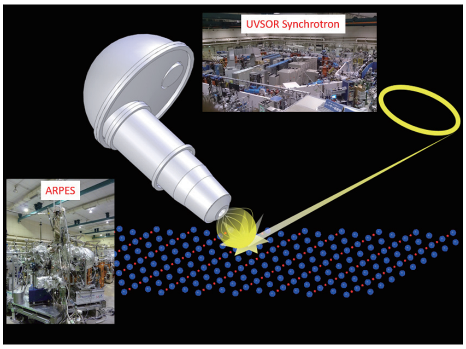

Figure 1.

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).
- W. S. Lee, I. M. Vishik, K. Tanaka, D. H. Lu, T. Sasagawa, N. Nagaosa, T. P. Devereaux, Z. Hussain and Z.-X. Shen, "Abrupt Onset of a Second Energy Gap at the Superconducting Transition of Underdoped Bi2212," *Nature* **450**, 81–84 (2007).
- 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. Evidence of Strong Violation from Fermi Arc Picture in Heavily Underdoped Bi2212

Understanding the complex nature of cuprate superconductors, especially the origin of their high superconducting transition temperature (T_c), is one of the greatest challenges in condensed matter physics. An early experimental observation in this regard is the famous Uemura plot. It shows that the T_c in the high-T_c cuprate superconductors is correlated with the muon spin relaxation rate σ_0 that is proportional to the superfluid density divided by the effective mass ($\sigma_0 \propto n_s/m^*$). This relation holds not only for all high-T_c cuprate superconductors but also for many other superconductors. While there have been various attempts at a theoretical explanation of the Uemura relation, a connection to other experimentally probed properties of cuprates is still lacking.

ARPES is a powerful experimental technique, directly measuring 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, especially the superconducting (SC) gap. Indeed, the first direct experimental evidence of *d*-wave symmetry of the SC gap has been reported by ARPES, where the SC gap follows the d-wave order parameter $\Delta(k) = \Delta_0(\cos k_x a - \cos k_y a)/2$, here a is the lattice constant. In ARPES field, T_c of cuprates has been believed to be explained by so-called "Fermi arc" picture. According to this picture, Fermi arc is a region where the SC gap closes above T_c in the momentum space and the "effective SC gap" Δ_{SC} can be defined by the gap magnitude at the edge of the Fermi arc as shown in Figure 2 (a). Since Δ_{SC} and T_c show linear correlation among different doping and even among different families of cuprates as shown in Figure 2 (d), this picture is well accepted as a phenomenological model to explain T_c in cuprates.

Recently, we have studied heavily underdoped Bi2212, whose T_c is only 30 K but still high-T_c, and found strong violation from the Fermi arc picture. In this doping, there is almost no temperature dependence of the SC gap across T_c as shown in Figure 2 (b)–(c). Therefore, Δ_{SC} should be extremely small (~1 meV) and should not be enough to explain 30 K of T_c. To understand the origin of the superconductivity in this doping, we have performed new way of ARPES analysis, where information of the spectral weight difference across T_c can be estimated. Interestingly, this new analysis shows that the doping dependence of the spectral weight along the Fermi surface quantitatively scales with the superfluid density (and T_c) for a wide range of carrier concentrations (not shown). Our new results represent the first evidence showing the close relationship between the superfluid density and T_c from ARPES. Our results also show that the whole Fermi surface contributes to superconductivity and the superfluid density can be more important than the SC gap. This is completely new idea to understand high-T_c superconductivity from ARPES.

Since it is well known that ARPES intensity strongly depends on the matrix element, which can be changed by measurement geometry, polarization, photon energy and so on, our spectral weight analysis should be affected by the measurement conditions. To make sure that our observation is universal, we have to perform many ARPES studies by changing measurement geometry, polarization and photon energy. To perform measurements with different measurement geometry, a low temperature 6-axis manipulator is necessary, since measurement geometry should be able to be changed to study the same sample surface with different geometries. We are using our home-made 6-axis manipulator which is one of the lowest temperature 6-axis manipulators in the world to complete this study.

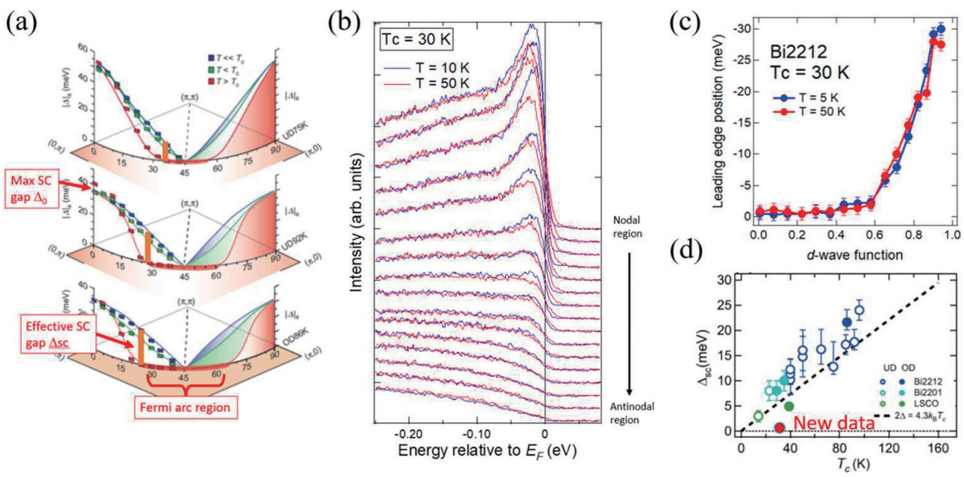

Figure 2. (a) Temperature and doping dependence of SC gap in cuprates and Fermi arc picture. (b) Temperature dependence of ARPES spectra along Fermi surface of heavily underdoped Bi2212. (c) Temperature dependence of SC gap obtained by the leading-edge position. (d) Comparison of the effective SC gap in different families of cuprates including current study.

* carrying out graduate research on Cooperative Education Program of IMS with Nagoya University

† carrying out graduate research on Cooperative Education Program of IMS with Southern University of Science and Technology, China