Angle-Resolved Photoemission Study on Strongly Correlated Electron Materials

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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).

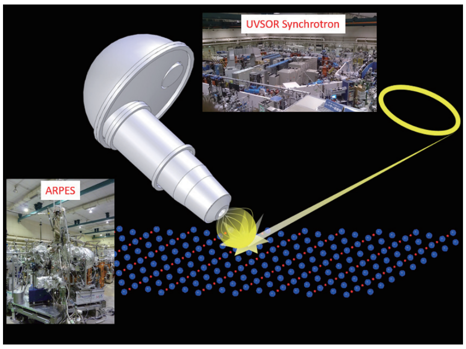

Figure 1.

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

Spintronics is an emerging field that aims to utilize the spin as well as the charge of electrons, and its progress is expected to strongly shape the future of electronics. To realize spin-based devices, it is crucial to understand the magnetism of surfaces, interfaces, and nanostructures at a fundamental level. Spin- and angle-resolved photoemission spectroscopy (spin-resolved ARPES) is one of the most powerful experimental methods for this purpose, because it can provide the full information of the electronic states—energy, momentum, and spin orientation. However, conventional Mott-type spin detectors suffer from an extremely low efficiency of about 10^{-4}, which has been a serious obstacle for decades. The development of very-low-energy-electron-diffraction (VLEED) detectors, with roughly 100 times higher efficiency, has made spin-resolved ARPES feasible in practice, yet most existing systems still use single-channel detection, where efficiency and angular resolution remain limited.

To overcome these limitations, our group reconstructed the BL5U beamline at UVSOR in 2017, creating a high-photon-flux and high-energy-resolution ARPES station. Building on this foundation, we initiated a long-term project to establish a next-generation spin-resolved ARPES system with multi-channel detection, which we call "image-spin" detection. The aim of this project is not only to improve detection efficiency and momentum resolution by factors of 100 and 10, respectively, but also to develop a platform that enables user-friendly and systematic spin-resolved measurements at synchrotron light sources. By pushing the limits of both efficiency and resolution, such a system can provide unprecedented opportunities for studying spin-dependent band structures, many-body interactions, and exotic electronic phases that cannot be accessed with conventional methods.

In 2024, we made substantial progress with the introduction of a spin manipulator combined with an ultra-bright electron gun. In our previous report, we demonstrated that this system could already achieve 100 times higher efficiency and 10 times better momentum resolution than conventional single-channel systems, but these improvements were restricted to one axis (the in-plane *x*-axis of the sample) and to a photon energy range of only 40–80 eV. Over the past year, careful optimization of the electron lens parameters allowed us to extend spin detection to two in-plane axes (*x* and *y* directions), as shown in Figures 2 and 3. At the same time, the usable photon energy range was expanded to 21–120 eV. This not only enables the study of a wider variety of materials, but also allows systematic comparisons across different excitation energies, which is particularly important for disentangling bulk and surface contributions in complex systems.

An additional improvement in 2024 was the refinement of the spin target handling. The magnetization procedure, which had previously required frequent manual intervention, was motorized to allow precise and reproducible control during experiments. This change enhanced the stability of the spin-resolved signals and improved the reliability of the data.

Our plan for FY2025 is to complete the lens calibration for the out-of-plane (*z*-axis) direction, so that spin polarization can be measured along all three spatial axes. Achieving this goal will make it possible to obtain the full spin information of electronic states in a truly three-dimensional manner, establishing a comprehensive framework for future spin-resolved studies at UVSOR.

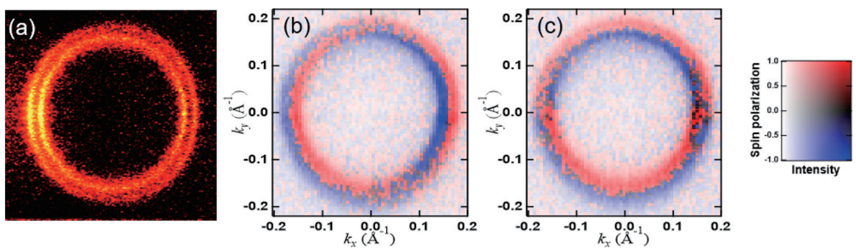

Figure 2. (a) Fermi surface image of Au(111) obtained using ordinary ARPES. Spin-resolved Fermi surface image of Au(111) with the spin detection axis aligned along the k_y (b) and k_x (c) directions.

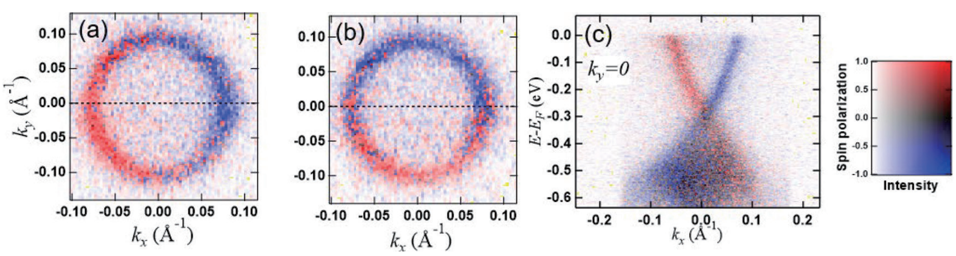

Figure 3. Spin-resolved Fermi surface images of the topological insulator Bi_2Se_3 with spin the detection axis aligned along the k_y (a) and k_x (b) directions. (c) Spin ARPES image along $k_y = 0$ in (a).

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