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), a powerful tool in studying the electronic structure of complex materials, based on synchrotron radiation.

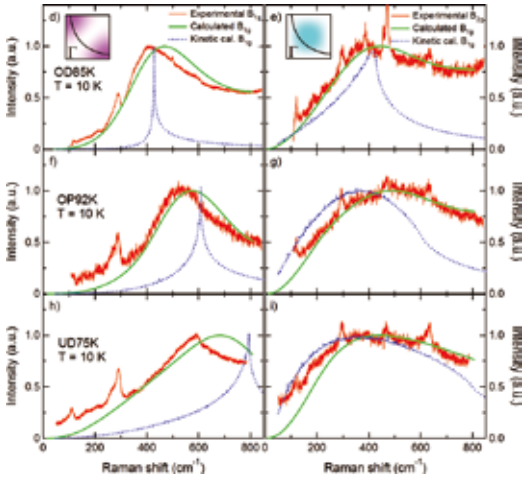

Figure 1. Comparison between experimental ERS spectra (red), calculated ERS spectra from ARPES (green), and kinetic theory (blue) for different carrier concentration of Bi2212 and different momentum space.

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).
- A. Takemori, T. Hajiri, S. Miyasaka, Z. H. Tin, T. Adachi, S. Ideta, K. Tanaka, M. Matsunami and S. Tajima, "Change of Fermi Surface States Related with Two Different T_c-Raising Mechanisms in Iron Pnictide Superconductors," *Phys. Rev. B* **98**, 100501(R) (2018).
- T. Adachi, S. Ideta, Z. Tin, H. Usui, K. Tanaka, S. Miyasaka and S. Tajima, "Electronic Structure of $Sr_{1-y}Ca_yFe_2(As_{1-x}P_x)_2$ (x = 0.25, y = 0.08) Revealed by Angle-Resolved Photoemission Spectroscopy," *J. Phys. Soc. Jpn.* **88**, 084701 (8 pages) (2019).
- 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).

1. Quantitative Comparison between ARPES and ERS on High-T_c Cuprate Superconductor[1)]

Both of ARPES and electronic Raman scattering (ERS) are powerful techniques which can obtain momentum-selected electronic structure. In the study of high-T_c cuprates superconductors, both techniques revealed two energy scales for the gap in different momentum spaces. However, the interpretations were different and the gap values were also different in two experiments. In order to clarify the origin of these discrepancies, we have directly compared experimental ARPES and ERS by using new calculation method of ERS through the Kubo formula.

It is well known that ARPES spectrum is a function of matrix element, Fermi Dirac function and a spectral function A(k,ω). On the other hand, ERS spectrum has been understood by simple model (so-called kinetic theory) for long time, where delta-function density of states along the Fermi surface is assumed. Therefore, quantitative analysis and discussion of ERS spectrum have been difficult. Using the Kubo formula, we noticed that the ERS spectrum can be written by square of the imaginary part of Green's function. This means that ERS spectrum can be calculated by ARPES spectrum, since the imaginary part of Green's function corresponds to the spectral function A(k,ω) in ARPES.

In this study, we have performed ARPES and ERS measurements on the same sample to directly compare the results. From ARPES spectra, we obtained A(k,ω) and calculated ERS spectra and compared to the experimental ERS spectra. For the samples, we prepared $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) with three doping levels, namely, underdoped (UD75K: T_c = 75 K), nearly optimally doped (OP92K: T_c = 92 K), and overdoped (OD85K: T_c = 85 K) samples.

Figure 1 shows the calculated ERS spectra. Here, it should be noted that the intensity distribution of A(k,ω) along the Fermi surface is an unknown parameter and we only showed the best fitted result. Compared to the conventional ERS spectral calculation based on kinetic theory (blue), our new calculation results (green) reproduced spectral features much better. Especially B_{2g} spectra, which is sensitive to the nodal region in the momentum space, were well reproduced. Doping dependence of the intensity distribution of A(k,ω) shows that the spectral function confined in the nodal region distributes to the antinodal region as the doping level increases (not shown).

The peak energies of the calculated ERS spectra were plotted in Figure 2 together with the experimental Raman, ARPES and STM data. From B_{1g} spectra, which is sensitive to the antinodal region in the momentum space, we found that the ARPES antinodal gap is always larger than the experimental B_{1g} peak energy. Since the difference increases with underdoping, this difference is possibly caused by the pseudogap. In Figure 2, we also plotted the pseudogap energy determined by ARPES Bi2212 data taken at 100 K. The pseudogap increases rapidly with underdoping and it seems that the superconducting gap in ARPES is enhanced by underlying- high-energy-pseudogap.

The present results give us the following important messages. First, Raman spectrum can be well reproduced by ARPES spectrum, and Raman and ARPES can be understood with the same gap profile. Namely, the nodal slope of gap profiles is doping independent, as reported by ARPES. The apparent doping dependence of the B_{2g} peak energy is caused by the change of spectral weight of A(k,ω) along the Fermi surface. Second, the antinodal gap of ARPES is a superconducting gap that is strongly affected by the pseudogap, whereas the Raman B_{1g} gap is moderately affected. This probe-dependent effect of the pseudogap is the main source for the difference between the Raman B_{1g} gap and the ARPES aninodal gap energies. Third, while the spectral weight of A(k,ω) is confined into the nodal region in the underdoped sample, the antinodal region gains spectral weight with doping and contributes to superconductivity. Although this is similar to the "Fermi arc" picture reported before, the Fermi surface area contributing to superconductivity is larger than that estimated from the normal state ARPES as a Fermi arc. All these findings reflect the unusual electronic states where superconductivity and coexist even at the lowest temperature.

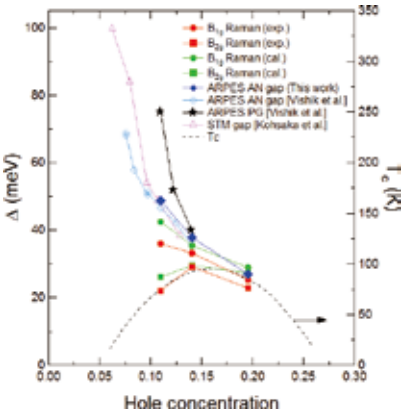

Figure 2. Doping dependence of the peak energies in Bi2212 obtained from ERS calculations in comparison to the experimental data from Raman, ARPES and STM measurements.

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

To perform high energy resolution ARPES measurements, the temperature of samples is important. We developed low temperature 6-axis manipulator by ourselves and achieved 4.5 K with tilting angle −15 ~ 55 deg. and azimuth angle ±120 deg. This is one of the lowest temperature 6-axis manipulators in the synchrotron radiation facilities in the world.

Reference

1) K. Tanaka, N. Hieu, G. Vincini, T. Masui, S. Miyasaka, S. Tajima and T. Sasagawa, *J. Phys. Soc. Jpn.* **88**, 044710 (2019).

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