Complex Materials Research by Angle-Resolved Photoemission Spectroscopy:

Challenging the Mystery of the High T_c Superconductivity

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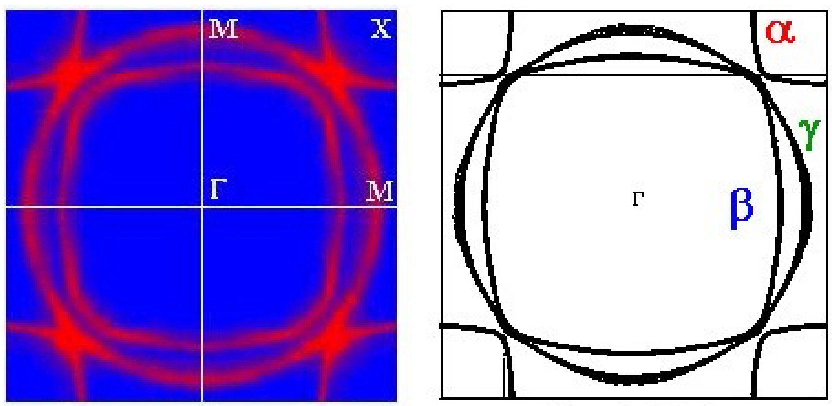
Extensive research efforts to study the novel electronic properties of high-T_c superconductors and their related materials by angle-resolved photoemission spectroscopy at a recently commissioned Beam Line 5-4 (led by Z.-X. Shen) continue to be successful, producing many important results. These results, which are highlighted by five articles recently published in Physical Review Letters and one in Science, brought our understanding steps closer to solving the mystery of the high-T_c superconductivity.

With the development of the latest generation of ultra-high resolution electron spectrometers in the past few years, the technique of angle resolved photoemission spectroscopy (ARPES) has recently experienced a renaissance. Nowhere is this revolution more evident than in the study of the high-temperature superconductors, which more than a decade after their discovery, continue to defy theoretical explanation. Recent ARPES experiments performed at Beam Line 5-4 have led to critical new discoveries about the fundamental nature of these mysterious super-conductors and are now changing the way that the physics community views these materials. An excellent benchmark for the huge leap in detector resolution and technology is the recent work on Sr_2RuO_4. Although it belongs to a slightly different family than the high-temperature superconductors, its exotic superconducting mechanism (T_c = 1K) and complex electronic structure make it itself a fascinating material. In the past, due to poor resolutions, ARPES studies on this material were in disagreement with theory and other experimental techniques.



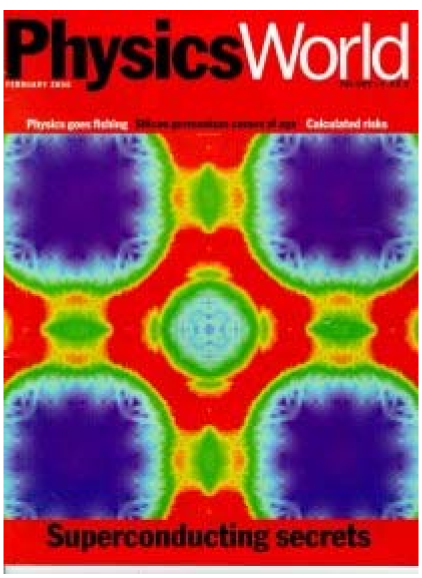
Experiments by Damascelli   Theory by Mazin

However, with the use of the new spectrometer on Beam Line 5-4, this longstanding controversy has finally been resolved by studying the electronic states as a function of momentum and energy with unprecedented details[1]. As a result, the subtle issues that plagued the earlier studies have been clarified, demonstrating both the reliability and unique sensitivity of ARPES as a technique for studying complex materials.

Moving to the high-temperature superconductors, a recent article published in Science by D.L. Feng *et al.*, on the compound $Bi_2Sr_2CaCu_2O_{8+\delta}$, has shown that the photoemission spectra exhibits unexpected sensitivity to the superconductivity[2]. In particular, the intensity of the (p,0) peak in the photoemission spectrum exhibits striking resemblance to the density of paired electrons participating in the superconducting state, as measured by other techniques. This surprising manifestation of collective quantum effects in single-particle excitation spectrum may indicate that the pairing of electrons in the superconducting state cannot be reconciled with more conventional theories, but rather, point to more exotic pairing mechanisms.

Although is, $Bi_2Sr_2CaCu_2O_{8+\delta}$ by far, the most studied superconductor by ARPES, a long-standing mystery has been the absence of so-called bilayer splitting in the electronic structure. It has been theoretically predicted that the interaction between the two adjacent CuO_2 layers in $Bi_2Sr_2CaCu_2O_{8+\delta}$ would result in a doubling in the number of bands. However, such a splitting has never been observed in previous ARPES studies, and hence deemed nonexistent and unimportant. Recent experimental confirmation of this long-sought bilayer splitting by D.L. Feng *et al*. in Physical Review Letters[3] unambiguously demonstrated that the interaction between neighboring CuO_2 planes strongly affects the electronic structure, and that theories must be once again revisited to include the bilayer interaction in any accurate description of $Bi_2Sr_2CaCu_2O_{8+\delta}$.

$YBa_2Cu_3O_{7-\delta}$ is one of the most extensively studied high temperature superconductors not only because it is one of the first true "high" T_c superconductors, but also due to its enormous application potential. All previous photoemission experiments on this material had been plagued by unfortunate surface effects which have obfuscated the measurements. Recently, there was a breakthrough in this challenging problem, made possible by significantly improved sample quality and instrumental resolutions. The article in Physical Review Letters by D.H. Lu *et al*.[4] reports the first observation of the so called "peak-dip-hump" structure on a system other than $Bi_2Sr_2CaCu_2O_{8+\delta}$, finding key similarities in the spectra from $YBa_2Cu_3O_{7-\delta}$ and the more well-understood $Bi_2Sr_2CaCu_2O_{8+\delta}$, as well as some notable differences which may arise from their slightly different crystal structures.



From $YBa_2Cu_3O_{7-\delta}$, the most popular, we move to $Nd_{2-x}Ce_xCuO_4$, the "black sheep" in the family of high-temperature superconductors. Because the doped charge carriers in $Nd_{2-x}Ce_xCuO_4$ are electrons, as opposed to holes for $YBa_2Cu_3O_{7-\delta}$, $Bi_2Sr_2CaCu_2O_{8+\delta}$, and the vast majority of high-T_c's, the properties of $Nd_{2-x}Ce_xCuO_4$ are significantly different from its hole-doped cousins. This disparity, along with the dearth of experimental data, has made the few electron-doped high-T_c superconductors rather poorly understood. In particular, while it is now widely accepted that the superconducting pairing in the hole-doped materials is strongly dependent on the momentum of the electrons (a *d*-wave symmetry), it has been long believed that the pairing in the electron-doped materials had no such momentum dependence (an *s*-wave symmetry). However, new photoemission data from N.P. Armitage *et al.*, published in Physical Review Letters[5], has challenged that long-standing notion by detecting a small but clear momentum asymmetry by utilizing the extremely high energy resolution of the new electron spectrometer on Beam Line 5-4. The detection of this momentum dependence in the superconducting pairing demonstrates that the electron and hole doped materials may not be as disparate as originally believed, moving us closer towards a unified picture of the high-temperature superconductors. Some of the work on $Nd_{2-x}Ce_xCuO_4$ appeared on the cover page of February 2000 issue of Physics World.

Collaboration with a group at University of Tokyo in Japan produced an important result in a more fundamental problem. Spin-charge separation is an exotic phenomenon in which the charge and spin of an electron are separated and behave like independent particles. This phenomenon occurs only in one-dimensional (1D) systems and was first confirmed by an experiment in insulating $SrCuO_2$, performed at SSRL. Observation of such phenomenon in a metallic system would be important and there have been steady efforts to observe spin-charge separation in metallic 1D systems. These efforts, however, have been hindered by materials issues. $PrBa_2Cu_3O_7$ is one of the rare systems that provide possibility of studying doped Cu-O chains. The work by T. Mizokawa *et al.* reported in Physical Review Letters[6] shows two dispersive features, corresponding to the spinon and holon edges. It is the first convincing experimental evidence of spin-charge separation in a doped Cu-O chain.

References:

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6. T. Mizokawa *et al.*, *Physical Review Letters*, vol. 85, no. 22, p. 4779 (2000).

SSRL is supported by the Department of Energy, Office of Basic Energy Sciences. The SSRL Structural Molecular Biology Program is supported by the Department of Energy, Office of Biological and Environmental Research, and by the National Institutes of Health, National Center for Research Resources, Biomedical Technology Program, and the National Institute of General Medical Sciences.