The superconducting state in a single CuO$_2$ layer:
Experimental findings and scenario

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The notable results shown by Bozovic et al. from measurements of synthesized one-unit-cell thick of La$_{1.85}$Sr$_{0.15}$CuO$_4$, La$_2$CuO$_4$ HTS/AF/HTS tri-layer junctions query the predictions by prevalent models since there is no observable mixing of superconductivity and anti-ferromagnetism between the layers. In this article we make a brief survey of experimental results on the electronic structure of high-$T_c$ cuprates and magnetic properties. Based on our analysis, we attribute superconductivity of a single CuO$_2$ layer to spin pairing via local exchange interactions.

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Recently, Bozovic et al. synthesized one-unit-cell thick superconducting LSCO, insulating LCO HTS/AF/HTS tri-layer junctions in a way of stacking digitally by using advanced Molecular Beam Epitaxy technology [ Nature 422, 873(2003) ]. The result shown by Bozovic et al. indicating no mixing of superconductivity and anti-ferromagnetism in HTS/AF/HTS layers queries the predictions by prevalent models. The fact that superconductivity holds in one-unit cell thick LSCO layer also questions the idea of the inter-layer coupling as a pairing mechanism. Bozovic et al. have shown that there is 1 eV energy difference between LSCO and LCO, and the quasi-two-dimensional mid-gap states in LSCO, i.e. the energy position of the superconducting state is in between the empty and the valence band of LCO. This observation agrees with some earlier works by other investigators: the normal states of charge carriers are in between two energy bands of LCO, the chemical potential pins in the middle of the gap rather than at the bottom. The doped holes appeared in oxygen band activate $p$ electrons, the density of itinerant electrons is found to be proportional to concentration of the doped holes $x$ (also the density of superfluids $n_s$). Mixing between orbital $2p$ (O) and $3d$ (Cu) has been observed, the mixing ratio is 8 : 2. The mixed states are not located in Cu site or O site, but extended itinerant states with metallic mobility. The superfluid carriers are mainly $p$ electrons rather than $d$ electrons.
High-$T_c$ phenomena occur in a special magnetic structure only. Among the huge number of compounds belong to the family of strongly correlated systems, non-Fermi-liquids, d-f metals and perovskite type materials, high-$T_c$ cuprate is the only one superconductive with high-transition temperature. On the other hand, all high-$T_c$ cuprates with different compositions exhibit universal physical properties such as the phase diagram, non-Fermi-liquid behavior, etc. The superconducting phase emerges in a doping region between insulting (charge transfer type) and Fermi liquid regimes, the transition temperatures vary with the doped hole concentration $x$ accompanied with variation of the number of charge carriers and short range order of anti-ferromagnetism. Itinerant $p$ electron also plays a role of mediation for the superexchange between Cu ions (in Wannier representation), the physical properties of charge carriers ($p$ electrons) and variations of magnetic correlation between local Cu spins influenced by hole doping should be carefully examined since the nearly free local spins created by holes in the anti-ferromagnetic background may interact with charge carriers via Kondo exchange. In the following we list main experimental results on the electronic structure of high-$T_c$ cuprates with brief comments. The article is divided into four parts: i. The physical properties of charge carriers, ii. Varying of anti-ferromagnetic background by changing the doped hole concentration, iii. Interactions between charge carriers and the anti-ferromagnetic background, iv. Physical properties of the superconducting state.

1. Bozovic I. et al. Nature 422, 873(2003). Evidence for quasi-two-dimensional electronic state located in the middle of band gap.
2. Uchida S. et al. PRB. 43, 7942(1991). Electronic state in the middle of band gap shown by optical experiment.
3. Fujimori Lanl. 0011293. Evidence for electronic state in the middle of band gap shown by transfer of spectral weight in ARPES.
4. Ino Lanl. 0005370. Evidence for electronic state in the middle of band gap shown by transfer of spectral weight in ARPES.
5. Ino PRL. 79, 2101(1997). Evolution of chemical potential, pining in the middle of band gap.
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7. Nucker N. et al. PRB. 37, 5158(1988); PRB. 59, 6619(1989). Holes in oxygen sites.
8. Arko A. L. et al. et al. PRB. 40, 2268(1989). The mixing ratio O2p : Cu3d $\sim$ 8 : 2
9. Feng D. L. et al. Science 289, 277(2000). Superfluid density $n_s \propto T_c \propto x$
10. Yoshida T. et al. arXiv: cond-mat/0206469. Quasi-particle peak, the number of charge carriers $n \propto x$ and metallic behavior.

By increasing the doped hole concentration, the long anti-ferromagnetic order of Cu moment in the CuO$_2$ plane turns into short range order, ultimately to disorder companied with delocalization of $d$ electrons on the Cu sites. In a proper doping range, $d$ electron with spin $S = 1/2$ is localized, oriented along b axis. The magnetic correlation between local spins in the CuO$_2$ plane is anisotropic Ising like. Doped
holes in the anti-ferromagnetic bonds suppress local spin correlation and yield the incommensurate splitting of neutron scattering magnetic peak and nearly free local spins. In case of dynamical phase separation, anti-ferromagnetic background is imperfect, flipping local spins create the "defects" in the anti-ferromagnetic background (these "defects" are not static since the holes hop site to site). This is another important effect brought by hole doping, which is overlooked by many people. This factor plays an important role in the variation of the physical properties of high-$T_c$ cuprates with increasing doped hole concentration. In heavy doping region $x > 0.19$, when delocalization of $d$ electrons on Cu site begins, the density of charge carriers changes from $x$ to $1 - x$. On the lower side of this critical doping value, there always exist local Cu$^{2+}$ ions. Above the critical doping level, superconductivity vanishes with collapsed anti-ferromagnetic background.

11. Aeppli G. et al. "Lecture notes for E. Fermi Summer School, Varenna", 1992. Short range anti-ferromagnetic correlation length $\xi_s \sim 0.38/\sqrt{x}$ nm.
12. Birgeneau R. J. et al. "Physical Properties of High Temperature Superconductivity I", edited by Ginsberg D. M. (World Scientific, Singapore, 1989), p154, Fig 1. Local spins parallel to a main axis in the CuO$_2$ plane.
13. Lavrov A. N. et al. PRL. 87, 17001(2001). Anisotropy of susceptibility, spins parallel to b axis. Evidence for the existence of nearly free moments.
14. Dai Peng-Cheng et al. PRB. 63, 54525(2001). Incommensurate splitting of magnetic ($\pi, \pi$) peak persisting into the superconducting state.
15. Yamada K. et al. PRB. 57, 6165(1998). Incommensurate splitting $\delta \propto x$ saturating near the optimal doping.
16. Zhou X. J. et al. Science 286, 268(1999). Phase separation shown by ARPES, proposed charge and magnetic ordering structure.
17. Lake B. et al. Nature 400, 43(1999). Incommensurate splitting, energy of spin gap is independent of momentum.
18. Uchida S. et al. Physica C 282-287, 12(1997). Delocalization of Cu ions. The density of charge carriers changes from $x$ to $1 - x$.
19. Brooks N. B. PRL. 87, 237003(2001). Detecting Cu$^{2+}$ ions by using spin resolved photo emission technique.
20. Tallon J.L. et al. Physica C 349, 53(2001). So called "0.19" problem, delocalization of local charge accompanied with variation of physical properties.

It is observed that the scattering rate of electrons varies about three orders of magnitude near transition temperature $T_c$, electron-phonon interaction is not a main factor to the superconducting transition. On the other hand, anomalous Hall effect observed indicates electron-local-moment scattering. AHE is characterized by linear temperature dependence of Hall number, which is a common feature for many of magnetic materials. Smit and Luttinger attribute AHE to skew scattering. AHE in Kondo-type systems was first discussed by Fert et al. (not like dilute magnetic impurity systems, local moments in high-$T_c$ cuprates are correlated, no saturation at high temperatures). The simultaneous suppression of superconductivity and the superexchange by substitution of Cu by Zn and Ni indicates that $S=1/2$ is required for high-$T_c$ physics. In the doping region ($0.02 < x < 0.15$), the range of anti-
ferromagnetic order is short, the superconducting coherent length is comparable to the magnetic correlation length. The mobility of charge carriers is inversely proportional to anti-ferromagnetic correlation length indicating the magnetic origin of microscopic interactions. Charge carriers in the mid-gap state interacting with mobile "defects" in the anti-ferromagnetic background is the key to superconductivity.

21. Bonn D. A. et al. PRB. 47, 11314(1993). Scattering rate $1/\tau$ varies three order of magnitude near transition temperature.
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26. Fert A. et al. PRL. 28, 303(1972); Levy P M. et al. J. Appl. Phys. 63, 3869(1988). Skew scattering in Kondo-type systems.
27. White P. J. et al. arXiv: cond-mat/9901349, 9901354. Zn substitution.
28. Alloud H. et al. PRL. 67, 3140(1991). Substitution of Cu by Zn suppresses superconductivity and anti-ferromagnetism.
29. Kakurai K. et al. PRB. 48, 3485(1993). Substitution of Cu by Zn suppresses superconductivity and anti-ferromagnetism.
30. Ando Y. et al. PRL. 87, 17001(2001). The mobility of the doped holes is proportional to AF correlation length.

The CuO$_2$ plane is a common structure unit of all high-$T_c$ cuprates. Bozovic et al show quasi-two-dimensionality of the superconducting state and short proximity effect. In the phase diagram, $T_c/T_{c}^{\text{max}}$ is a parabolic function of $x$ near the optimal doping, the curvature $\kappa$ and the optimal doping $x_0$ are universal constants. Excitations in a high-$T_c$ cuprate are complex, especially the pseudogap with $d_{x^2-y^2}$ symmetry and isotropic spin gap. The revival of spin gap responding to external magnetic field reveals that the microscopic in-plane interaction is magnetic, which is agreed with observed time-reversal symmetry breaking effect in polarized photo-emission experiment (need to be confirmed). The intrinsic inhomogeneity of the superconducting state in atomic scale by using STM method queries all proposed k space pairing models.

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32. Xu Zhuan et al. Nature 406, 486(2000). Vortex-like excitation in underdoped samples above $T_c$ (100 ~220 K ), evidence for incoherent pairing.
33. Wen H. H. et al. arXiv: cond-mat/0301367
34. Tallon J. L. et al. PRL. 75, 4114(1995); PRB. 51, 12911(1995). Universal expression for empirical $T_c$ law.
35. Tsuei C. C. et al. PRL. 73, 593(1994). Tri-crystal junction, $d_{x^2-y^2}$ symmetry.
Two interactions are essential to the superconducting state in a single CuO$_2$ layer: the superexchange (coupling constant $K \sim 0.1$ eV) between Cu$^{2+}$ ions and the Kondo exchange between itinerant charge carriers and "defects" in the antiferromagnetic background i.e. nearly free spins (coupling constant $J \sim 0.01$ eV). We interpret the coexistence of anti-ferromagnetism and superconductivity as following: $p$ electron being the mediation for the superexchange between Cu spins is activated by hole doping breaking the long range order of Cu spins. On the other hand, electron spin coupling mediated by nearly free Cu spins via the Kondo exchange gives rise to electron pairing in spin sector. A notable result of spin pairing is that the wavefunction of two opposite spins is symmetric rather than anti-symmetric (susceptibility measurement in NMR and neutron scattering experiment can not determine the symmetry of spin wavefunction). The projection of the orbital wavefunction of the electron pair in the CuO$_2$ plane has the $d_{x^2-y^2}$ symmetry which is forced by spin and crystal symmetries. Orbital wavefunction along c axis is restrained as shown by Bozovic et al. As explained by the K-J model, the two dimensionless quantities $\kappa = 86.2$ and optimal doping $x_0 = 0.16$ in the universal parabolic function of $T_c/T_{c}^{\text{max}}$ are not independent, one relates to another determined by two fundamental constants $K_0$ (for undoped sample) and $J$. The K-J model also explains: the upper limit of $T_c^{\text{max}} \sim 150K$, delocalization of $d$ electron at $x \approx 0.2$, short range magnetic order, spin gap and the pseudogap, low superfluid density $n_s \propto x \propto T_c$, time-reversal symmetry breaking and non-fermi-liquid behavior, etc.

42. Guo W. et al. arXiv: cond-mat/0303155; Physica C 364-365,79(2001). The K-J model.

By summary, we have listed essential literatures of experimental results showing the electronic structure of high-$T_c$ cuprates (limited by article length we have omitted many important works). To understand high-$T_c$ superconductivity, we have to put every piece of experimental findings together to figure out the hidden scheme like a puzzle game. Based on our analysis, we attribute superconductivity of a single CuO$_2$ layer to spin pairing via local exchange interactions.