New insights from ARPES study on High Temperature Superconductors

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One of the goals in condensed matter physics is the understanding of various emergent properties of matter due to many body interactions -e.g. superfluidity, superconductivity, colossal magnetoresistance and so on. Superconductors have absolutely zero resistance to electrical currents up to a certain temperature- known as critical temperature (Tc). Superconductivity was discovered in 1911, and the maximum Tc for conventional superconductors is around 30K. High temperature (High Tc) superconductors were discovered in 1987, where Tc can be over 135K. Low temperature conventional superconductivity is well understood under the framework of the BCS (Bardeen, Cooper, Schrieffer) theory. On the other hand, despite immense efforts by both theoretical and experimental physicists for the last two decades, the microscopic mechanism behind high temperature superconductivity still remains an unsolved problem. In high temperature superconductors, electrons interact very strongly, making the problem very challenging both for theory and experiment. My Ph.D. research project focuses on the understanding of the many-body physics in high temperature superconductors using Angle Resolved Photoemission Spectroscopy (ARPES). Our experiments are carried out at the Synchrotron Radiation Center (SRC) at the University of Wisconsin, Madison using mostly low energy synchrotron radiation from the 011 4 meter NIM-UNDULATOR and 071 PGM beamlines. As a part of my thesis work I have been associated with SRC for last five and half years, and was able to obtain significant results in the field of High temperature superconductivity. Below I would like to present a brief account of the motivation behind our recent work, and the implications of our findings.

The phase diagram (Fig1) of high temperature superconductors is complicated. The parent compounds for these materials are antiferromagnetic Mott insulators. Upon doping they become superconductors and with increased doping, Tc increases. At certain doping, called optimal doping, Tc reaches a maximum value, and again decreases with further doping, until it finally becomes zero again. The superconducting region of the phase diagram has a typical dome shape for all high temperature superconductors. The doping range between the doping where there is just the onset of superconductivity and the optimal doping (where Tc reaches the maximum value) is called the underdoped regime. Remaining part of the doping range is known as overdoped regime. The region in the phase diagram outside the superconducting dome is called the normal state, i.e. the system is not superconducting. However, the normal state in the underdoped regime is known as the pseudogap state. Up to now we don't even know how to characterize properly the normal state of High Tc superconducting systems, in particular the pseudogap state. This in turn makes very difficult to understand the SC transition and in particular the microscopic pairing mechanism in High Tc systems. In contrast, the normal state in regular BCS superconductors is pretty well understood in the framework of Fermi liquid theory. As to both spectroscopic and transport measurements in the high Tc superconductors are concerned, the pseudogap state shows really bizarre properties, which are very different from those of Fermi liquid systems. Quite generally, all scenarios (they are far from being theories) attempting to explain non-Fermi liquid behavior in the Pseudogap state come in two broad categories. According to one scenario, the Pseudogap phase is associated with some sort of ordering whose origin is unknown; it could be a charge density wave for example. In the other scenario, the Pseudogap phase is the precursor to the superconducting state. In our recent most work [1], we tried to address these two scenarios. The transition from the superconducting state to the normal state is a second order phase transition. Any second order phase transition is always associated with a continuously broken symmetry, and hence a continuous change of some order parameter at the transition temperature. The transition from superconducting (for both regular BCS and high temperature superconductors) to non superconducting states at Tc, breaks the so called U1 gauge symmetry and the corresponding superconducting order parameter for the SC state is $\Delta e^{i\phi}$ where Δ is known as superconducting energy gap and ϕ determines the macroscopic phase coherence in the superconducting state. For regular BCS superconductors, the gap is isotopic in momentum space-this is known as s-wave symmetry. But for high temperature superconductors, the superconducting gap is anisotropic in momentum space, $\Delta = \Delta(k) = \Delta_{max}$ {Cos (k_x)-Cos (k_y)}-this is known as d wave symmetry. Because of d wave symmetry of the order parameter, SC gap becomes exactly zero at four points in the momentum space, known as nodes. As a direct consequence of the gap vanishing at the nodes, the low-lying excitations in the High Tc superconducting state are also point like in momentum space. In regular BCS superconductors, as T approaches Tc from zero temperature, Δ changes monotonically with temperature, becoming identically zero above Tc, and finally above Tc a closed Fermi surface is recovered. This is more or less the case in the normal state for the overdoped regime of the phase diagram for High temperature superconductors as well. But the situation is radically different in the underdoped regime, where the Pseudogap phase exists. A closed Fermi surface doesn't appear even above Tc in the underdoped regime, i.e. in the Pseudogap state. Rather some parts of the Fermi surface are still gapped out in the Pseudogap state. This kind of disconnected Fermi surface is known as Fermi arc. At some higher temperature (T*) the system recovers the full Fermi surface. Depending on doping, T* can be as high as 10-15 times Tc. Hence in the underlying physics of high temperature superconductors, at least in the underdoped regime, T* is as important as Tc in terms of being a relevant energy scale in the problem. Hence to understand the microscopic physics behind superconductivity in High Tc systems, one needs to understand the interplay between these two energy scales, Tc and T*. Our recent most work [1], precisely addresses this issue. We found out that superconducting gap anisotropy in the underdoped side is absolutely temperature independent all the way up to Tc. This is extremely unusual, as Tc is associated with a second order phase transition, as I discussed above. We also found out that the four nodes (where the superconducting gap is exactly zero) persist up to Tc and there is a discontinuous change from node to Fermi arc at Tc. This discontinuity depends on Tc/T*. We also found that the energy gap in the pseudogap state is closely associated to the one in the superconducting state. All of these major results more ore less point towards a Puseudogap state, which is a precursor of superconductivity. The superconducting transition proceeds in two steps: (1) at T*, short-range superconducting order sets in and (2) at Tc, macroscopic phase coherence sets in to propel the system into macroscopic superconductivity.

To properly characterize the Pseudogap state one needs to address another major question-what is exactly the ground state of the pseudogap phase? In other words, if we could lower the temperature in the Pseudogap state without crossing the superconducting dome, how will the low energy excitations look like in the zero temperature limit? In another recent work [2], we tried to address this issue. We have shown how one can extract information about the ground state of the pseudogap state using scaling analysis of finite temperature ARPES data. Our analysis clearly shows that, just like Superconducting state, the Pseudogap state also has a "d wave" ground state. As I mentioned before, parent compounds for these High Tc materials are insulators and they become superconducting when they are doped. In principle, electronic excitations for these systems should depend upon doping and the temperature of the sample. But we found that in the Pseudogap state, the only parameter which controls the single particle excitations in the system is the reduced temperature "t"=T/T*, where T is the temperature of the sample and T* is the temperature below which the Pseudogap phase forms. Hence in some sense, the reduced temperature “t” is the only relevant energy scale in the Pseudogap state. This remarkable property of the Pseudogap state is not understood in the framework of any existing theory. New physical ideas will be necessary to understand these materials.

ARPES directly measures the probability of removing an electron having a given momentum $\vec{k}$ and energy ω from the systems i.e. the spectral function- $A(\vec{k},\omega)$, which, in principle, contains all the microscopic information about the single particle excitations in the system. But in order to understand the collective excitations of a system under the influence of an external probe (e.g. an external magnetic field, electric field and so on), we have to go beyond the single particle excitation description. In linear response approximation, the response function of any physical system is proportional to the “two particle correlation” function of the observable to which the external probe couples. For instance the response of a system to a magnetic field i.e. the spin susceptibility can be shown to be proportional to the spin-spin correlations, measured by Inelastic Neutron Scattering (INS) and Nuclear Magnetic Resonance (NMR) experiments. Similarly the response of a system to an electric field i.e. the electrical conductivity is proportional to the current-current correlation. One could measure current-current correlations in Optical conductivity experiments, charge-charge correlations in Raman Scattering experiments and so on. In general, it is very difficult to exactly calculate these “two particle correlations” from single particle excitations because of “vertex corrections” i.e. corrections due to many-body interactions which are beyond the single particle description. Because of the strong correlation in High Tc superconducting systems, it is very difficult to calculate theoretically "two particle correlations" starting from single particle excitations. One simple approximation to calculate "two particle correlations" is the so-called Random Phase Approximation (RPA). In this approximation the "vertex corrections" are neglected. Recently [3] we have shown how to calculate various “two particle correlation functions” using experimental spectral function measured directly by ARPES and the RPA approximation. With our technique, starting from ARPES data, we can calculate what is seen in INS, NMR, Optical Conductivity, Raman Scattering experiments, so that results from these completely different kinds of experiments can be directly compared with each other in terms of common underlying microscopic Physics. I personally believe that the ability to compare the response functions measured directly by experiments like INS, NMR to that ones, calculated starting from spectral function measured by ARPES can shed “a lot” of light on the microscopic mechanism of superconductivity in High Tc systems. This new method is definitely the first important step in this direction. For almost all High Tc materials, INS experiments found a universal feature in the dispersion of the magnetic excitations-namely the famous “hour glass” shape, in the superconducting state. We find the same result for spin susceptibility using our ARPES data on High Temperature Superconducting sample of $Bi_2Sr_2CaCu_2O_{8+\delta.}$. There have been extensive efforts from theoretical point of view, to understand the INS results on High Tc materials. Despite the quite different Physics underlying various theoretical approaches, the results for spin susceptibility in High Tc systems are quite similar, leading to one of the current dilemmas facing the field of the High Tc systems. Our method provides a way to look into the whole scenario from a new perspective using the experimental spectral function. Our analysis shows that, one could easily explain the dispersion of magnetic excitation in the superconducting state of High Tc systems even without invoking “vertex corrections”. Our results show that the "Neutron mode" can be simply explained as a spin-exciton instead of some exotic collective mode.

As I mentioned above, off late charge ordering phenomena have been proposed to be a possible candidate for explaining the pseudogap state. Recently we have proposed a novel autocorrelation analysis [4] of ARPES data to look into this issue. Our autocorrelation analysis categorically shows that charge ordering is absent in the pseudogap phase. Scanning Tunneling Spectroscopy

(STS) is another important experimental technique to look into single particle excitations. STS looks into the direct space of any system; on the other hand ARPES has information about the momentum space of the system. Hence in some sense ARPES and STS are complementary to each other. Recently there have been some beautiful STS experiments on High Tc systems. It would be quite interesting if we have a common platform from which we can look at both STS and ARPES data. Our autocorrelation analysis provides the unique opportunity to look at STS results from ARPES perspective. Recent Fourier transformed STS (FT-STS) data in the SC state of High Tc systems show very well defined dispersive features. These features have been proposed to be originated by scattering of quasiparticles from impurities in the superconducting state. But as STS does not have access to momentum space information, to explain these FT-STS data, one needs to invoke some kind of a model-called "Octet model". This model works surprisingly well for the FT-STS data in the SC state. But somehow this model fails to explain non-dispersive features found in FT-STS data in the pseudogap state. On the other hand, autocorrelation analysis gives a completely model independent explanations for these FT-STS data for both the superconducting state and the pseudogap state. I am pretty confident that autorrelation analysis of ARPES data together with the technique of FT-STS will be able to unravel lots of mysteries in the High Tc systems.

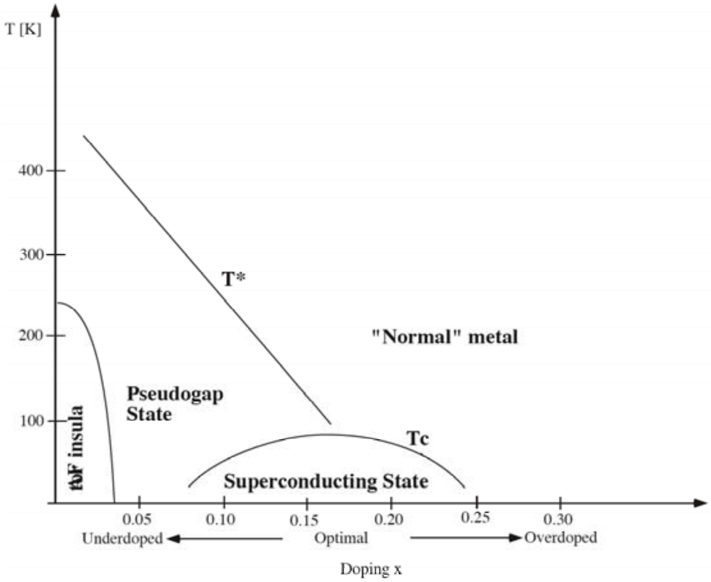

Figure1: Phase diagram of hole doped high temperature superconductors is shown. In no sense this phase diagram is complete. Lots of other in between co existing phases have been proposed as well. Here I only point the very generic ones.

References

[1] Arxiv:0708.4099 accepted for publication in PRL

[2] Nature Physics 2,447-451,July 2006

[3] PRB 75,172504(2007)

[4] PRL 96,107006(2006), PRB 76,012504(2007)