

RESEARCH SUMMARY

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My research over the past decade focused on the number of various issues related to the interplay between fermionic and magnetic excitations in strongly correlated electron systems:

Kohn-Luttinger effect in 3D and 2D electron systems

properties of low dimensional frustrated and unfrustrated spin systems, Haldane effect and related phenomenon

order from disorder in frustrated (e.g., Kagome) antiferromagnets

confinement vs unconfinement of spinons in quantum antiferromagnets

NMR and resonance Raman scattering in undoped and weakly doped antiferromagnets

quantum-critical behavior in magnetic and electronic systems

fermionic and magnetic excitations in weakly doped cuprates, properties of a single hole in a quantum antiferromagnet

evolution of the Fermi surface near a magnetic transition in a fermionic system; Luttinger theorem near a spin-density wave instability

order from disorder in double exchange model for manganites

spin-fermion model for high-temperature superconductivity

Over the last couple of years, my primary interest is in the identification of the microscopic mechanism responsible for the high-temperature superconductivity in the cuprate oxides and the nature of the superconducting pairing state. These two issues represent one of the most exciting theoretical challenges in theoretical many body physics. In the so-called conventional superconductors, at frequencies less than or comparable to the Debye frequency, the attractive phonon-induced interaction between electrons wins out over the repulsive screened Coulomb interaction and brings about superconductivity. The pairing of electrons in the superconducting state is in an s -wave channel. For the cuprate superconductors, it has been shown to a great clarity that the pairing state is unconventional and has a d -wave symmetry.

The approach that I am pushing forward is based on the assumption that this unconventional pairing state is caused by the interaction between the electrons and their own collective spin fluctuations (failed spin waves). This type of interaction gives rise to the d -wave superconductivity provided that the system is not far away from an antiferromagnetic instability. Parent compounds of the high T_c cuprates are all antiferromagnets (incidentally, they are the best known quasi-2D antiferromagnets). The materials with the highest T_c are paramagnets, but they are located in their phase diagram reasonably close to a phase boundary to an antiferromagnetic state and have been shown in nuclear magnetic resonance and inelastic neutron scattering experiments to exhibit significant antiferromagnetic correlations.

The weak coupling theory of spin-mediated superconductivity was developed long time ago. The analysis of the experimental data for the cuprates, however, demonstrates that weak coupling theory cannot even quantitatively describe the physics of the cuprates. The

two most important differences with the weak-coupling are the unconventional, non-Fermi-liquid normal state behavior and the presence of the pseudogap phase in between the antiferromagnetic and the superconducting regions on the phase diagram. This pseudogap phase is neither magnetic nor superconducting, but possesses the properties of both phases.

My idea is that the unconventional normal state behavior and the presence of the pseudogap are associated with the fact that at frequencies and/or temperatures of experimental relevance, the system falls into a quantum-critical regime, where its behavior is qualitative different from that in a Fermi liquid. Together with my postdoc Artem Abanov (now at LANL), a student Rob Haslinger (now at LANL), A. Finkelstein (Weizmann), J. Schmalian (Iowa State) and the others we studied this behavior in great detail and found that it gives rise to the new phases of matter that do not exist at weak coupling. Contrary to earlier phenomenological studies of spin-mediated pairing, our approach is fully microscopic: we depart from a well defined low-energy Hamiltonian for a system of fermions interacting with their collective spin degrees of freedom, and *derive* the expressions for fully renormalized fermionic and spin propagators.

Let me briefly summarize in most general wording what we are doing. We are trying to understand whether the unusual physics of the cuprates can be explained using a minimal model of fermions interacting with just one collective bosonic degree of freedom. These unusual features include the non-Fermi-liquid behavior in the normal state, the existence of the pseudogap phase, and the development of the specific resonances in the d -wave superconducting state. We argue that all these features are correlated. On general grounds, the low-energy fermions should display Fermi liquid behavior at energies low compared to the Fermi energy, E_F . We found that near a magnetic instability, the energy, ω_{sf} , up to which Fermi liquid behavior does exist turns out to be small compared to E_F , and the ratio E_F/ω_{sf} increases as the system moves towards the antiferromagnetic phase, and the spin excitations soften. This opens a window of energies where the system behavior on one hand is still a low-energy one, and hence is universal, but on the other hand it is not a Fermi-liquid. After several years of work, we now fully understand that fermions at these intermediate energies are fully incoherent, diffusive quasiparticles. We then analyzed the pairing of these fermions and found the totally new effect that is not present in the canonical theory of superconductivity. Namely, there are two *different* critical temperatures for the pairing of coherent and incoherent fermions. The one for coherent fermions yields a true d -wave superconductivity, but at $T < T_c \propto \omega_{sf}$ that decreases with underdoping. The pairing of incoherent, non-Fermi-liquid fermions occurs already at $T^* \propto E_F$, but it does not give rise to a true superconductivity - incoherent fermions pair into spin-singlet pairs that still remain incoherent and do not superconduct. Still, the development of the singlets is a measurable effect as it reduces, e.g., the fermionic density of states at low energies. We believe that the phase between T^* and T_c is exactly the pseudogap phase detected in the experiments. Still, a lot of work is needed to fully understand the new phenomenon of the pairing of incoherent, quantum-critical fermions.

This problem is in fact more general than high-temperature superconductivity. We found close relations between the behavior of the cuprates and the behavior of strongly coupled phonon superconductors, the heavy-fermion materials near ferro- and antiferromagnetic instabilities, and also organic superconductors. We are currently studying phonon superconductors in great detail and plan to study the quantum-critical physics of heavy-fermion and

organic materials in the near future.

More specifically, my research over the past few years can be divided into three categories:

1. *A study of the normal state properties of the cuprates.* In this study, we performed the full scale calculations for the normal state properties of the spin-fermion model that involves low-energy fermions interacting with their own spin collective excitations. Our key achievement is the development of a controlled way to perform calculations in the strong coupling limit by extending the model to a large number of fermionic flavors N and developing a field-theoretical expansion in $1/N$. The results of these studies have been published in several short articles and are summarized in a self-review invited article in *Advances in Physics*.

2. *A study of the system behavior in the superconducting state.* The goal of these calculations is to make specific predictions of how the experimental data should look like if the d -wave pairing is mediated by spin fluctuations. For this we obtained, within the same spin-fermion model, the results for both magnetic and electronic observables at $T < T_c$, when the system develops a true superconductivity. We found several “fingerprints” of the spin-mediated pairing in the spin susceptibility, the electronic spectral function, the tunneling conductance, the optical conductivity and the Raman intensity. Our results for all these observables have been fully confirmed in the experiments performed near the optimal doping. The results of these studies have been published in several short articles, an invited self-review article, and will appear in the new major book on “Superconductivity”.

3. *A study of the pseudogap physics in the cuprates.* This is the area of my current research and the issue that I mostly plan to focus on in the nearest future. Our idea is that the pseudogap phase is a new state of matter brought about by the fact that the fermions can form singlet pairs at T^* , but these pairs remain diffusive and do not superconduct down to T_c . At present, we are the only group that obtained these two temperatures in the actual calculations. The topic of our research at the moment is which fluctuations are responsible for the destruction of the supercurrent. We argue that these cannot be phase fluctuations favored by several groups on purely phenomenological grounds, as the detailed calculations show that the latter are relevant only in a near vicinity of T_c and are small below T^* . We found that the destruction of the supercurrent is due to the softness of the longitudinal fluctuations of the superconducting order parameter. This softness is a peculiarity of the incoherent pairing, and has no analog for conventional superconductors. We are currently expanding our knowledge of the role of the longitudinal fluctuations. This research so far produced two papers in *Europhys. Lett.* and two *PRB* (RC) papers. I am working on the long invited self-review article and also on several short papers on the current research.

The goal of all these studies is indeed to obtain the full picture of what are the phases in the cuprates, and how the system moves from one phase to the other. I believe that we are on the right track and plan to continue working on deepening our understanding of these exciting materials. Simultaneously, I also plan to extend our studies to strongly coupled phonon superconductors, heavy-fermion and organic materials where, I believe, the physics is very similar to that in the cuprates.