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FLUCTUATION PHENOMENA IN LAYERED SUPERCONDUCTORS

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1. Introduction

Although there has been a great deal of interest in the properties of high temperature superconductors, many, if not most of these properties have previously been observed in other layered superconductors[1]. One such property is the role of Gaussian fluctuations above the transition temperature T_c , a principal topic of this meeting. Gaussian fluctuations above T_c were studied in a number of low- T_c layered superconductors back in the 1970's. The second principal topic of this meeting, the role of vortex fluctuations, has also been seen in similar low- T_c materials, but only recently, since the novel behaviors were not as evident. With regard to both topics, the low- T_c compounds most similar to the high- T_c cuprates are the transition metal dichalcogenides (TMDs) and their intercalates. As for the high- T_c cuprates, those materials are layered, and TMDs contain examples which are strikingly similar to high- T_c materials in just about every way except for the value of T_c .

1.1. CHARGE-DENSITY WAVES

An interesting property shared by the metallic TMDs and to some extent, also the metallic graphite intercalation compounds, is the presence of two-dimensional charge-density waves (CDWs) in the "normal" state, above the superconducting transition T_c . In low dimensional systems, the Fermi surface is susceptible to substantial nesting. CDWs arise from nesting wavevectors that span a finite fraction of the Fermi surface, strongly modifying, or even destroying, parts of it. In the CDW regime, above T_c and below the "true normal" metallic state-CDW transition, the physical

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T_c , and anomalies at higher T are most likely associated with something like a CDW. Furthermore, since the anisotropy of the electronic energy gap observed in ARPES in Bi2212 far above T_c is almost identical with that observed below T_c , it is very likely that the ARPES experiments do not measure the superconducting gap at all.

With such interesting caveats in mind, I shall focus upon what is *really* known about superconducting fluctuations. In this brief lecture, I will mention the FD and the fluctuation conductivity (FC), focussing specifically upon layered superconductors.

2. Fluctuation Diamagnetism

Aside from questions regarding trapped magnetic flux, a superconductor ideally behaves as a perfect diamagnet below T_c , with $\chi = -1/4\pi$. However, above the zero-field transition temperature T_{c0} , $\chi(T)$ decreases from the normal state behavior, in a manner which appears to diverge as $T \rightarrow T_{c0}+$. This divergent diamagnetic part, FD, is due to superconducting fluctuations. Since measurement of χ necessarily requires the application of a magnetic field H , there are complications that arise in attempting to calculate the FD in the presence of the magnetic induction B . The same problems arise in the calculation of the FC and other measureable quantities for $B \neq 0$.

In order to make any progress at all, it has generally been necessary to assume B spatially constant. Since the electrons forming superconducting electron pairs interact with B mainly through the coupling of the magnetic vector potential A to their overall charge $2e$, and to a usually much smaller amount through the coupling of B to their spins, B tends to break up pairs. For $B = 0$, the paired electrons move in opposite directions, with total momentum zero. For $B \neq 0$, however, they move in Landau orbits, in which they tend to move in the same direction, which causes orbital pairbreaking. In weak fields, electron pairs move primarily according to the crystal quantization axes and the associated Brillouin zone. In a strong field, however, B itself acts as the quantization axis for the pair motion[10]. In a *very* strong field, B also tends to align the paired electron spins, breaking up the favored singlet pair spin state. This Zeeman (or Pauli) pairbreaking effect is only significant for fields sufficiently strong that $g\mu_B B \geq k_B T_c$, whereas orbital pairbreaking is manifest in the reduction of T_c from T_{c0} to $T_c(B)$, where $T_c(B)$ is the temperature at the upper critical field H_{c2} .

Unfortunately, it is presently known that $H \neq 0$ changes the nature of the normal-superconducting phase transition, which is only approximated by the *mean-field* $H_{c2}(T)$ curves. In nearly all low- T_c circumstances, it was difficult to observe significant differences from this mean-field behavior.

power law behaviors both in the T dependences of the zero-field FD and in the B dependences of M at T_{c0} .

2.1. DIMENSIONAL CROSSOVER

Using the Lawrence-Doniach (LD) model of layered superconductors[15], it was shown[4] that layered superconductors exhibit *dimensional crossover* in the FD, both in the T dependence of the zero-field $\chi(T)$, and in the field-dependence of the FD at T_{c0} . At $B = 0$, dimensional crossover was shown to occur[4] at the temperature T_0 given by $\xi_{\perp}(T_0) = s/2$, where s is the layer repeat distance and $\xi_{\perp}(T)$ is the coherence length normal to the layers. This has the simple interpretation of the layers fluctuating together in the three-dimensional (3D) regime near to T_{c0} , and independently in the two-dimensional(2D) regime far above T_{c0} . Dimensional crossover occurs at T_0 , at which coherent regions centered on adjacent layers barely touch.

Since layered superconductors exhibit a crossover in the field dependence of $M(T_{c0})$, one can find the dimensional crossover field B_0 by equating the 3D and 2D limiting forms. This leads to $B_0 = \zeta^2 \Phi_0 / (4\pi s^2)$, where the flux quantum $\Phi_0 = hc/2e$, $\zeta = C_2/\gamma C_3$, $\gamma = (M/m)^{1/2}$ is the anisotropy parameter, and $C_3 = 0.09133$ and $C_2 = 0.34589$ are constants appropriate for bulk[14] and thin film[4] superconductors. We note that such dimensional crossover occurs for $B \parallel \hat{c}$. Physically, for $B < B_0$, the vortices extend over many layers, so the fluctuations associated with the vortices in the vortex liquid are 3D in nature. Such 3D vortices are known as *Abrikosov* vortices. On the other hand, for $B > B_0$, the vortices fluctuate on individual layers. These vortices are known as *pancake* vortices. The fluctuation of these types of vortices in the vicinity of T_c is the second major topic of this conference.

Of course, there are additional complications in real superconductors, which usually make the identification of dimensional crossover in the field strength less obvious. In the dirty limit, for which the in-plane coherence length $\xi_{\parallel}(T)$ is less than the mean-free path ℓ , $M(B)$ in an isotropic superconductor was shown to fall off much faster than the $B^{1/2}$ rise predicted in the static limit[14], due to *dynamical cutoff effects*[16]. This dynamical cutoff mechanism was shown[4, 17] to also exist in layered superconductors with $B \parallel \hat{c}$. In essence, there are two crossover fields: one is the dimensional crossover field B_0 , and the other is the dynamical crossover field B_S , which is defined [6, 16] as the field at which $M(B)$ is 1/2 the 3D static "Prange value", $\propto \sqrt{B}$. For clean layered and isotropic superconductors, Gerhardt[17] showed that the dynamical cutoff also contributed, but an additional cutoff B_{NL} in the field strength due to *non-local* effects was more important. Thus, there are again two cutoff fields, B_0 and B_{NL} . FD exper-

the work of Dorin *et al.*[27], both FC tensor elements were evaluated for $B||\hat{c}$. They found that $\sigma_c(T)$ could exhibit a peak just above T_{c0} , whereas $\sigma_{ab}(T)$ was always decreasing monotonically with decreasing T above T_{c0} . This peak was enhanced with increasing $B||\hat{c}$. Using this detailed theory, excellent agreement with experiments on YBCO was recently found by Axnäs *et al.*[29], which data was presented in this conference.

4. Summary

Gaussian fluctuations in layered superconductors have been the subject of study for many years. Although the FD was studied in detail long ago, the FC was studied only approximately until very recently, since the MT and DOS diagrams were previously neglected. Recent comparisons with experiment on YBCO have shown that the DOS diagrams are very important, and can lead to qualitatively different behaviors for the FC parallel and perpendicular to the layers. In both cases, Gaussian fluctuations fit the data above T_c very well, even for YBCO. To date, nearly all calculations of fluctuation quantities were for $B||\hat{c}$. Nevertheless, it should be possible to treat an arbitrary B , but the evaluation of the required matrix elements for the fluctuation quantities will be considerably more complicated.

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