Theory of Resistive Behaviors in Vortex States Induced by Strong Quantum Fluctuation in Type II Superconductors

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Abstract

Transport data in the vortex liquid regime of underdoped cuprates and organic materials show evidences of strong quantm superconducting fluctuation such as a field-tuned superconductor-insulator transition (FSIT) behavior. Two typical examples of strong quantum fluctuation effects, the FSIT behaviors in dirty films of s-wave pairing materials and the field-induced quantum fluctuation effects in κ-(ET)$_2$ organic superconductors, are discussed through comparison between resistivity data and theoretical curves.

Key words: vortex states; field-tuned superconductor-insulator transition; cuprates; organic superconductors

1. Introduction

It is well understood that the fan-shaped broadening of resistance curves in (typically) optimally-doped high T_c cuprates under nonzero fields ($H > 0$) is due to the thermal superconducting fluctuation [1]. However, the resistivity vanishing in other cuprates with lower T_{c0} in $H > 0$ is relatively sharp. This trend in underdoped cuprates means not a weaker but a stronger fluctuation effect: The field-tuned superconductor-insulator transition (FSIT) behavior, observed in strongly underdoped samples [2], cannot occur without a strong quantum superconducting fluctuation [3]. Further, resistivity curves vanishing rapidly much below (appropriately-defined) $H_{c2}(T)$ or $T_{c2}(H)$ (and thus, suggesting a strong fluctuation) are seen even in overdoped [4], electron-doped [5] cuprates, and organics [6,7] under *large* $h = H/H_{c2}(0)$ values.

To understand the sharp resistive vanishing much below T_{c2} and the FSIT behaviors consistently, it is valuable to, separately from cuprates, first examine such phenomena in conventional materials by combining our theory for the quantum regime [3,8] with appropriate microscopic models for those systems. Here, computed results of resistivity are reported and compared with available experimental data of dirty thin films with s-wave pairing [9–11] and quasi 2D organic superconductors [6,7]. Data of underdoped cuprates [2] will be discussed elsewhere[12].

2. FSIT behaviors in s-wave dirty films

A high field Ginzburg-Landau (GL) theory incorporating microscopic details of s-wave dirty amorphous thin films with thickness d was given in Ref.[3]. In quasi 2D case where $k_F d > 1$, the microscopic disorder is measured solely by the reduced sheet resistance R_n/R_q ($\propto d^{-1}$), where $R_q = 6.45$ (k Ω) is the quantum resistance, and thus, both strengths of the (quantum) fluctuation and the vortex pinning are enhanced with increasing R_n/R_q. Results of computed resistance R are shown in Figs.1 and 2, where the conductance R^{-1} includes its vortex-glass fluctuation contribution R_{vg}^{-1} creating the FSIT behavior and a sum of fluctuation contributions excluded from the GL description which should be [3] the origin of the negative magnetoresistance correction *peculiar* [12] *to* the s-wave pairing case

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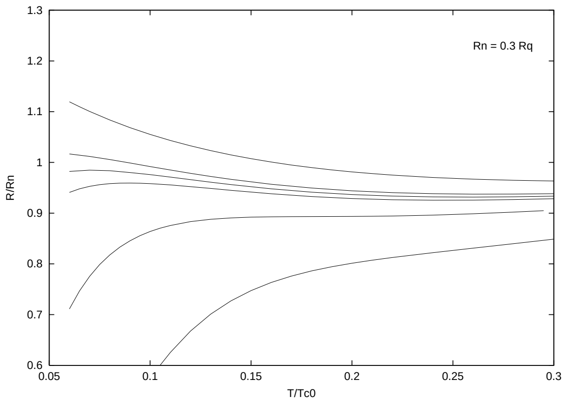

Fig. 1. Low T resistance (R/R_n v.s. T/T_{c0}) curves computed according to the theory of Ref.[3] assuming an s-wave dirty film with $R_n = 0.3R_q$. The magnetic field is varied from $h = H/H_{c2}(0) = 0.9$ (top curve) to 0.8 (botom one), and $R_c = 0.99R_n$ and $H_c = 0.865H_{c2}(0)$ are obtained.

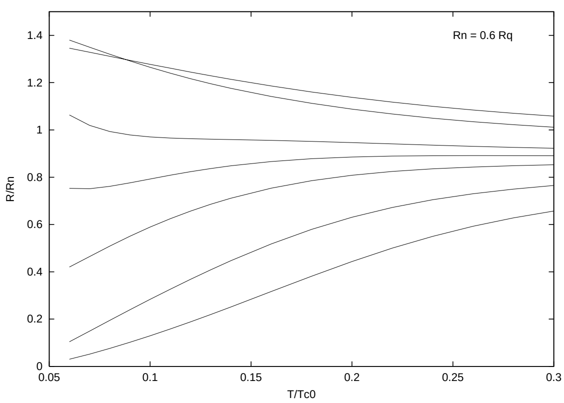

Fig. 2. Corresponding results in $R_n = 0.6R_q$ to Fig.1. The varied h-range is from 0.7 to 0.98, and $R_c = 0.77R_n$ and $H_c = 0.8H_{c2}(0)$ are obtained.

(see the higher h curves in Fig.2).

We find through computed curves that, in an intermediate T range, the $R(= G^{-1})$-curve at an *apparent* critical field H_c, where $R(T \to 0)$ takes a T-independent value R_c, is insulating if $R_n/R_q < 0.5$ and is superconducting otherwise. The former and latter behaviors were found in Ref.[9] and Ref.[10], respectively. Further, we find that $R_c \simeq R_n$ when $R_n/R_q < 0.5$, while R_c/R_n decreases with increasing R_n ($> 0.5R_q$). The former is familiar through data of low R_n materials [13], while the latter seems to be consistent with a recent report [11].

3. Quantum Fluctuation and H_{c2}

Fitting to data of organic materials was performed (Fig.3) by assuming the clean limit at the electronic level and adding R_{vg}^{-1} to the conductance. The fan-shaped broadening below 2 (T) is due primarily to the thermal fluctuation, while the higher field behavior following the normal resistance (dashed curve) until rapidly dropping much below T_{c2} is a consequence of the quantum fluctuation enhanced by increasing H. Namely, the resistively-determined "$H_{c2}(T)$" in this case is generally lower than the thermodynamic $H_{c2}(T)$. Further, the fact that the above-mentioned high field resistive behavior is visible in materials besides cuprates implies that, contrary to the argument in Ref.[4], it has nothing to do with microscopic ingredients peculiar to the cuprates such as antiferromagnetic vortex core states.

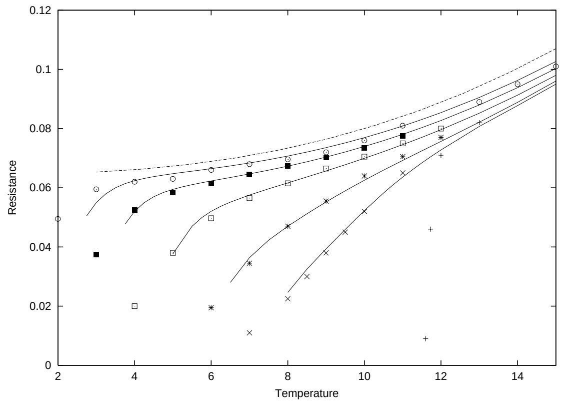

Fig. 3. Fitting results to resistance data [6] in H(T) = 1, 2, 4, 6, and 8 of κ-$(ET)_2Cu[N(CN)_2]Br$. Theoretical (solid) curves are obtained assuming $T_{c0} = 12$ (K), $H_{c2}(0) = 20$ (T), and $\lambda(0) = 8800$ (A). We note that $T_{c2}(2(T)) = 11$ (K) and $T_{c2}(8(T)) = 8$ (K).

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