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A precursor superconductivity approach to magnetic field effects in the pseudogap phase

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Abstract

We demonstrate that the observed dependences of T_c and T^* on small magnetic fields can be readily understood in a precursor superconductivity approach to the pseudogap phase. In this approach, the presence of a pseudogap at T_c (but not at T^*) and the associated suppression of the density of states lead to very different sensitivities to pair-breaking perturbations for the two temperatures. Our semi-quantitative results address the puzzling experimental observation that the coherence length ξ is weakly dependent on hole concentration x throughout most of the phase diagram. We present our results in a form which can be compared with the recent experiments of Shibauchi et al. and argue that orbital effects contribute in an important way to the H dependence of T^*. © 2002 Published by Elsevier Science Ltd.

Keywords: D. Superconductivity; Pseudogap; Magnetic fields

In the pseudogap phase, there are pronounced differences between the behavior of the pseudogap onset temperature T^* and the superconducting transition temperature T_c with respect to magnetic fields. In the underdoped regime, T_c is far more field sensitive than is T^*, and it has been argued that this lends support for the notion that the pseudogap is unrelated to the superconductivity. Contrary to this inference, we demonstrate here that these field dependences can be readily explained as a direct consequence of the pseudogap in a precursor superconductivity approach. In this approach, the presence of a pseudogap at T_c (but not at T^*) and the associated suppression of the density of states lead to very different sensitivities to pair-breaking perturbations for the two temperatures. Another effect of the pseudogap is that the coherence length ξ does not necessarily coincide with other length scales in the system, as occurs in BCS theory. In this paper, we illustrate these pseudogap effects at T_c from the standpoint of Landau–Ginsberg theory and give a comparison of semi-quantitative results with recent experiments.

The various approaches to understanding the pseudogap phase of the high temperature superconductors seem to be divided roughly into two schools: those in which the pseudogap is associated with a competing energy gap (or hidden order parameter [1]) and those in which the pseudogap derives from the superconductivity itself. This latter 'precursor superconductivity' school has multiple interpretations as well. The phase fluctuation [2] and the spin–charge separation schools [3] are to be distinguished from the present scheme in which the pseudogap arises in a mean-field generalization of BCS theory that allows the consideration of a strong pairing attraction. In contrast, the phase fluctuation school builds on *strict* BCS theory, but adds fluctuation effects which we neglect here. Our approach is often referred to as a BCS–Bose Einstein crossover scenario, since a sufficiently strong attractive interaction allows pairs to form at a temperature T^* which is higher than the T_c at which they Bose condense. In the present paper, we use a formalism for treating the BCS–BEC crossover which we have extensively discussed and developed previously [4–6].

A fundamental feature of the crossover scenario is that increasing the attractive coupling strength g introduces bosonic as well as fermionic excitations. The presence of non-zero momentum bosonic pair excitations is responsible for both the pseudogap that develops for temperatures $T_c < T < T^*$ as well as for the fact that below T_c, the excitation gap Δ is distinct from the superconducting order parameter Δ_{sc}. The dispersion relation for fermions below T_c has the BCS form with the full excitation gap Δ given by

$$\Delta^2 = \Delta_{sc}^2 + \Delta_{pg}^2 \quad (1)$$

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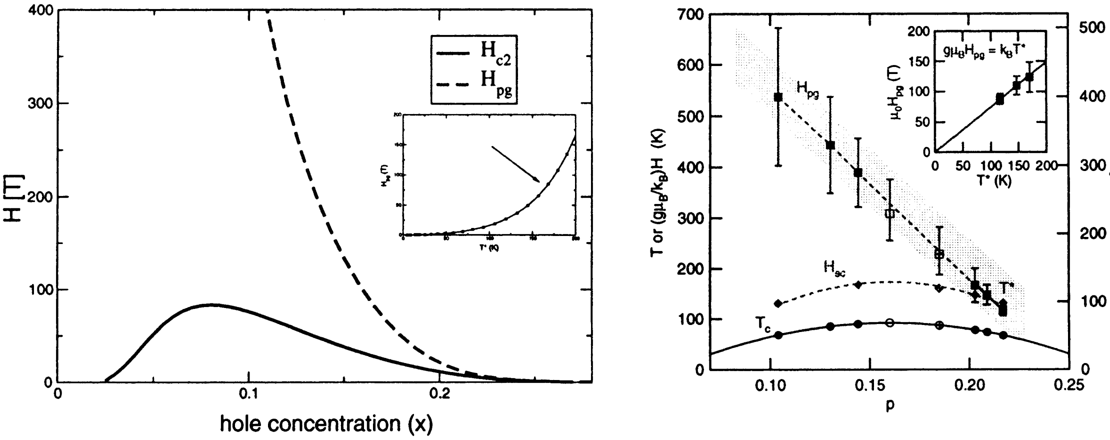

Fig. 1. Magnetic fields required at $T = 0$ to destroy superconductivity (H_{sc} or H_{c2}) and the pseudogap (H_{pg}) as extrapolated from (left) a calculation of ξ, ξ^* and (right) experiment [10], plotted vs. hole concentration. Insets plot H_{pg} vs. T^*.

where $\Delta_{pg}(T)$ is an energy scale associated with the presence of pairs of non-zero momentum, calculated self-consistently in our crossover formalism.

Notably, Δ_{pg} vanishes at zero temperature (yielding $\Delta = \Delta_{sc}$) due to the total Bose condensation of all pairs.

From this point of view, BCS theory is a weak coupling limit in which there are no non-zero-momentum pair excitations, and consequently T^* coincides with T_c and $\Delta = \Delta_{sc}$ at all temperatures below T_c.

We associate over- and under- doping with small and large normalized coupling constants, respectively. In all our calculations the coupling g enters in a dimensionless ratio with the bandwidth. It is presumed that as the Mott insulator is approached, the characteristic electronic energy scales decrease—so that even if g is relatively x-independent, its effectiveness increases with underdoping.

The existence of a pseudogap above T_c which develops as the coupling is increased differentiates the physics of the underdoped cuprates from that of the overdoped (BCS) state.

We characterize the field sensitivity of T_c through the coherence length ξ defined by

$$-\frac{1}{T_c}\frac{dT_c}{dH}\bigg|_{H=0} = \frac{2\pi}{\Phi_0}\xi^2 \tag{2}$$

where $\Phi_0 = hc/2e$ is the charge-2 flux quantum. Similarly, we define a length scale ξ^* for T^*. In the case of T_c, where there is a true phase transition, we consider the free energy density of a linearized Landau–Ginsberg theory near T_c:

$$F = \left[-\tau\left(1 - \frac{T}{T_c}\right) + \eta^2\left(-i\nabla - 2\frac{e}{c}A\right)^2\right]|\Delta_{sc}|^2 \tag{3}$$

The stiffness of the superconducting order parameter with respect to spatial variations is characterized by η^2, whereas τ essentially measures the density of states at the Fermi surface. As in BCS theory, $\xi^2 = \eta^2/\tau$, although we must now consider the effect of the pseudogap on η^2 and τ. In our formalism, the calculation of the (coupling dependent) parameters η^2 and τ is based on the application of the semi-classical phase approximation to evaluate the pairing susceptibility in a small magnetic field H [7]; the details are given in Ref. [8]. Although there is no phase transition at T^*, the pairing susceptibility provides natural analogs η^{*2}, τ^* with $\xi^{*2} = \eta^{*2}/\tau^*$. In BCS theory, τ merely cancels the density of states appearing in η^2, resulting in a coherence length $\xi = Cv_F/T_c$, where C is a universal constant.[1] In the pseudogap phase, this cancellation no longer occurs, and τ plays a more interesting role in determining ξ. In general, we find that ξ is different from Cv_F/T_c [8].

The doping dependence of ξ and ξ^* can be understood first from the fact that the spatial stiffness η^2 (as well as η^{*2}) decreases with underdoping because the stronger pairing interaction reduces the pair size [9]. Second, τ and τ^* measure the density of states at the Fermi energy at the respective temperatures. The pseudogap present at T_c (but not T^*) suppresses the density of states, causing τ to decrease rapidly with underdoping relative to τ^*. There is no analogous suppression of η relative to η^*, allowing ξ to differ from ξ^* in the pseudogap phase. We find that ξ^* decreases with underdoping, while the competition between the spatial stiffness and the density of states at T_c results in a broad doping range over which ξ is relatively constant, with a dramatic increase in ξ as the superconductor–insulator boundary is approached. Quantitative results for the behavior of ξ, ξ^* as functions of hole concentration x are given elsewhere [8].

In this paper, we concentrate on an alternative representation of these calculations, defining characteristic magnetic fields $H_{sc} = \Phi_0/2\pi\xi^2$ and $H_{pg} = \Phi_0/2\pi\xi^{*2}$. By extrapolating straight-line phase boundaries $T_c(H)$ and $T^*(H)$ from the zero-field slopes, we may interpret these

[1] $\xi^2_{BCS} = 7\zeta(3)/48\pi^2(v_F/T_c)^2$ in 3D and $7\zeta(3)/32\pi^2(v_F/T_c)^2$ in 2D.

as the fields required at zero temperature to destroy superconductivity and close the pseudogap, respectively. This allows us to compare with the recent study of BSSCO 2212 by Shibauchi et al. [10]. Fig. 1 shows that our calculation (left) captures the convergence of H_{pg} and H_{sc} in the overdoped region as well as the divergence of these fields on the underdoped side as a consequence of the opening of the pseudogap at T_c. We find, as observed experimentally, that on the overdoped side, T_c and T^* are both sensitive to magnetic fields, whereas T^* is far less field sensitive than T_c on the underdoped side. We plot H_{pg} vs. T^* (left, inset) and in this way we can compare the apparent 'Zeeman scaling' reported by Shibauchi et al. [10] ($2\mu_0 H_{pg} = k_B T^*$) with our calculations, which include only orbital magnetic effects. (One might expect that as the appropriate fields become stronger, a more complete theoretical treatment will need to incorporate Zeeman coupling effects.) We find a curvilinear relationship $H_{pg}(T^*)$, which is in reasonable agreement with experiment over the narrow range of dopings at which H_{pg} was measured directly (right, inset). More experimental data at lower doping will ultimately be needed to discern the relative importance of orbital and Zeeman coupling in determining the magnetic field sensitivities of these energy scales in the pseudogap phase.

In conclusion, we have demonstrated that a precursor pairing scenario is associated with very different magnetic field sensitivities for T^* and T_c. This observation is contrary to the widely held belief that if the pseudogap is associated with superconducting pairing, then T^* and T_c should depend similarly on the magnetic field strength. Here we associate the different H dependences with the fact that a pseudogap is present at T_c and absent at T^*. The presence of a pseudogap significantly modifies the behavior of the Landau–Ginsberg coefficients relative to BCS theory. Moreover, the calculated field dependences of T^* and T_c appear to be in reasonable accord with experimental data.

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