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Nonequilibrium probe of paired electron pockets in the underdoped cuprates

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We propose an experimental method that can be used generally to test whether the cuprate pseudogap involves precursor pairing that acts to gap out the Fermi surface. The proposal involves angular-resolved photoemission spectroscopy (ARPES) performed in the presence of a transport current driven through the sample. We illustrate this proposal with a specific model of the pseudogap that contains a phase-incoherent paired electron and unpaired hole Fermi surfaces. We show that even a weak current tilts the paired band and modifies the pairing gap in a characteristic way directly measurable by ARPES. Stronger currents can also reveal the Fermi surface through direct suppression of pairing. The proposed experiment is sufficiently general such that it can be used to reveal putative Fermi surfaces that have been reconstructed from other types of periodic order and are gapped out due to pairing. The observation of the predicted phenomena should help resolve the central question about the existence of pairs in the enigmatic pseudogap regime.

1. Introduction

The experimental and theoretical effort to understand the pseudogap phase of the underdoped cuprate superconductors has lasted for decades [1–5]. Most of the current proposed explanations for the phase can be classified into one of two seemingly separate scenarios. One scenario interprets the pseudogap as a superconducting precursor state in which electrons pair incoherently above T_c [6,7], and is supported by some transport [8], Nernst [9], and proximity effect [10] experiments. The other links the pseudogap to an ordering phenomenon that competes with superconductivity. Evidence for this scenario includes angle-resolved photoemission (ARPES) [11–14], electrical transport [15], quantum oscillations [16–19], X-ray diffraction [20,21], neutron scattering studies [22,23,21], and STM [24–28]. Recently, observations that support charge density wave (CDW) ordering have been reported in NMR [29] and X-ray scattering [30–32] experiments. Although the two scenarios are typically treated as separate interpretations of the pseudogap, the phenomena of paired excitations and competing order are not necessarily mutually exclusive.

In La-based cuprates, for instance, there is evidence for the simultaneous presence of a competing order [33–37] and pairing [9,10]. The coexistence of the two phenomena has also served as a basis for some theoretical models of the pseudogap [38,39].

Whether precursor pairing exists in conjunction with competing order in the pseudogap regime is an important question. Here, we propose and model an experiment that can help resolve this question by directly testing whether the pseudogap contains any putative (or “ghost”) Fermi surfaces that are gapped out *specifically* due to pairing. The recent quantum oscillation and photoemission experiments on the cuprates give an impetus to investigate a pseudogap scenario in which both pairing and competing order are incorporated simultaneously. While quantum oscillations in the pseudogap regime provide evidence for coherent electron Fermi pockets at finite magnetic fields [40], evidence for such pockets is not observed in photoemission at zero magnetic field [41–43]. However, these observations can be reconciled with a scenario in which parts of the *putative* Fermi surfaces evade photoemission detection due to a strong pairing gap, which in turn is suppressed by a finite magnetic field. This restores the previously hidden Fermi surfaces and gives rise to the observed quantum oscillations. A rigorous microscopic theory for such a scenario was recently developed in Ref. [39], but a direct experimental test of the scenario is still lacking.

In this work, we propose an ARPES experiment performed while a transport current is driven through the sample. We show

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that an *arbitrarily weak* current can shift the quasiparticle spectrum and reveal the hidden paired bands which should appear as new Fermi surfaces in ARPES. The specific way in which the current shifts the spectrum would also be indicative of a gap originating from pairing. For these weak currents, the heating and the influence of the current-induced magnetic field on the path of the photo-ejected electron should be small. Large currents can lead to complete depairing, and this should, in principle, also reveal the hidden Fermi surfaces. However, such large currents may be impractical due to Joule heating and magnetic field effects. To illustrate our proposal, we apply the method to a particular theoretical model [39], in which the pseudogap emerges from a fluctuating critical antiferromagnetic state with paired electron and unpaired hole pockets in the anti-nodal and nodal regions, respectively. We emphasize that the applicability of the proposed method is not limited to the model, but can be generally used to test the existence of putative Fermi surfaces that have been reconstructed due to other types of order [5], including CDW [30–32], but are gapped out due to pairing. The main idea of our proposal may also be useful when considering the application of transport current in conjunction with other spectroscopic techniques that probe electronic structure.

2. Theoretical model

To be concrete, we illustrate our proposal using a model of the pseudogap presented in Ref. [39]. The model is supported by three recent experimental developments. First, recent work has observed a proximity-induced pseudogap [10] and supports the idea that the pseudogap is connected to paired quasiparticles. Second, the experimental discovery [16,40,17] of small Fermi pockets in the pseudogap phase of underdoped cuprates motivates a description which incorporates Fermi surface reconstruction. Third, there is a nodal–anti-nodal dichotomy [44,45,41,46] observed in STM [47] and Raman [48] experiments, where nodal excitations have an energy which decreases with decreasing doping, and anti-nodal excitations have a larger energy that increases with decreasing doping. These key ingredients, namely pairing, Fermi surface reconstruction, and the nodal–anti-nodal dichotomy, are incorporated in the theory proposed in Ref. [39].

According to the theory, the pseudogap phase emerges from a strongly fluctuating critical antiferromagnetic state with reconstructed Fermi-surfaces consisting of electron-like pockets in the anti-nodal regions $(\pi/a, 0)$ and $(0, \pi/a)$ and hole-like pockets in the nodal regions $(\pm\pi/2a, \pm\pi/2a)$. The components of the *physical* electron are described in a rotated reference frame set by the local spin-density wave (SDW) order $\varphi = z^*_\sigma \sigma_{\sigma\sigma'} z_{\sigma'}$, where the bosonic spinon field z_σ defines the SU(2) rotation. This parametrization gives rise to an emergent gauge field, which plays a crucial role in the pairing of the fermions. The pseudogap phase is characterized by strongly *s*-wave paired (but uncondensed) electron pockets and hole pockets [49] that remain unpaired (a weak *p*-wave pairing in the hole pockets is assumed to be suppressed by temperature). This is shown to be equivalent to *d*-wave pairing when the Brillouin zone is unfolded [50,39,51]. Also, the apparent discrepancy between *full* pockets in the nodal regions and the Fermi *arcs* observed in ARPES can be reconciled with a model [52] that is consistent with what we consider here [39]. To reiterate, it is possible that the quantum oscillation experiments [16,17] are observing anti-nodal electron pockets, which are paired at zero field, but are driven normal by the magnetic field. We show that our proposal can falsifiably test this paired electron pocket scenario on Ref. [39] at zero field.

We consider a hole-doped cuprate superconductor in the pseudogap regime subjected to a uniform current $\mathbf{J}$ as shown in Fig. 1(b). Our main goal is to determine key qualitative features of an ARPES spectrum measured in the presence of the current. A minimal model, which is consistent with the model in Ref. [39] and captures the key features necessary to address an ARPES experiment in the presence of current, is

$$H = \sum_{\mathbf{k}\in RBZ} \sum_{\alpha=\pm} [\xi_{\mathbf{k}f} f^\dagger_{\mathbf{k}\alpha} f_{\mathbf{k}\alpha} + \xi_{\mathbf{k}h} h^\dagger_{\mathbf{k}\alpha} h_{\mathbf{k}\alpha}] - \sum_{\mathbf{k}\in RBZ} [\Delta f^\dagger_{\mathbf{k}+} f^\dagger_{-\mathbf{k}-} + h.c.] + \frac{\Delta^2}{\lambda}, \quad (1)$$

where $f_{\mathbf{k}\pm}$ and $h_{\mathbf{k}\pm}$ are the annihilation operators for the electron-like and hole-like excitations with momentum $\mathbf{k}$, respectively, and $\pm$ labels the charge associated with the emergent gauge field. We note that $f_{\mathbf{k}\alpha}$ becomes the physical electron in the SDW ordered state, where the spinon field z_σ condenses and the $\pm$ indices become equivalent to the electron spin indices. Pairing in the electron pockets is included at the mean-field level by introducing a real *s*-wave pair potential Δ. The spectra are given by $\xi_{\mathbf{k}f,h} = (\xi_\mathbf{k} + \xi_{\mathbf{k}+\mathbf{Q}})/2 \pm [(\xi_\mathbf{k} - \xi_{\mathbf{k}+\mathbf{Q}})^2 + 4\varphi^2]^{1/2}/2$, where $\xi_\mathbf{k} = -2t\,(\cos k_x a + \cos k_y a) - 4t' \cos k_x a \cos k_y a - \mu$. Here, $\mathbf{Q} = (\pi/a, \pi/a)$, and we will take $t' = -0.3t$ and $\mu = -0.6t$ [53]. The quantity φ is the uniform SDW order parameter, but we stress that φ is used here merely to parameterize the underlying Brillouin zone folding, and that in reality, spin fluctuations are expected to suppress long-range antiferromagnetic order in the pseudogap phase. In the above, $\lambda > 0$ is the effective attractive interaction for the electrons generated by the gauge fluctuations. Since the pseudogap phase is not characterized by long-range SDW order the attractive interaction mediated by the gauge fluctuations is, in principle, long-ranged [39].

We emphasize here that a calculation of the current within model (1) would give rise to a phase-coherent superflow, which is not correct in the pseudogap regime. However, the excitation spectrum in the presence of current should be correctly obtained

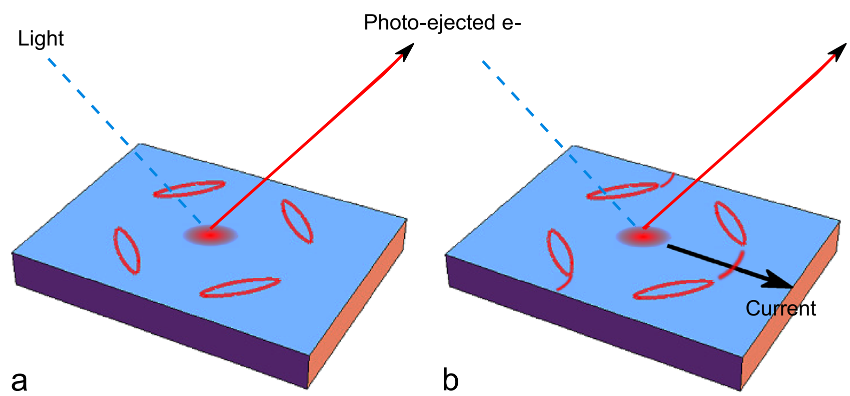

Fig. 1. (Color online) A qualitative illustration of the experimental setup and the predicted phenomenon: (a) the incident light and ejected electrons that initially leave the electron pockets hidden due to a pairing gap; (b) the electron-pockets are partially revealed in the ARPES signal due to a current running through the sample along the anti-nodal direction.