Nematic order and non-Fermi liquid behavior from a Pomeranchuk instability in a two-dimensional electron system

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Abstract. Interactions in Fermi systems can induce a "Pomeranchuk instability" leading to orientational symmetry breaking, that is, nematic order. In a metallic system close to such an instability the Fermi surface is easily deformed by anisotropic perturbations, and exhibits enhanced collective fluctuations. We discuss electrons on a square lattice near a Pomeranchuk instability with d-wave symmetry. The strong response of such a system to a small orthorhombic perturbation can explain naturally the large in-plane anisotropy of electronic and magnetic properties observed in detwinned YBCO crystals. Fluctuations in a quantum critical regime near the instability provide a mechanism for non-Fermi liquid behavior. They lead to a singular forward scattering interaction, which destroys fermionic quasi-particles on the whole Fermi surface except at "cold spots" on the Brillouin zone diagonal. The decay rate for DC transport is linear in temperature except at the cold spots, where conventional Fermi liquid behavior survives. In clean systems this gives rise to a \(T^{3/2}\) temperature dependence of the DC resistivity, as observed in some overdoped cuprates. In the presence of disorder, the resistivity is linear in \(T\) at low temperatures.

1. Introduction

Interactions can generate a spontaneous breaking of the rotation symmetry of an itinerant electron system without breaking translation invariance. From a Fermi liquid perspective, such an instability is driven by forward scattering interactions and leads to a symmetry breaking deformation of the Fermi surface. In isotropic three-dimensional Fermi liquids this instability sets in when Landau parameters exceed certain critical negative values, as derived long ago by Pomeranchuk [1].

Pomeranchuk instabilities leading to symmetry-breaking deformations of the Fermi surface in two-dimensional (layered) systems have attracted much interest in the last few years. Interactions favoring a Pomeranchuk instability with \(d_{x^2-y^2}\)-wave symmetry have been found in the two most intensively studied single-band models for cuprate superconductors, that is, the two-dimensional t-J [2] and Hubbard [3, 4] model. These models thus exhibit enhanced "nematic" correlations, as usually discussed in the context of fluctuating stripe order [5]. Signatures for incipient nematic order with d-wave symmetry have been observed in various cuprate materials [6]. A Pomeranchuk instability was recently invoked to explain a new phase
observed in ultrapure crystals of the layered ruthenate metal Sr$_3$Ru$_2$O$_7$ [7, 8], and also to account for a puzzling phase transition in URu$_2$Si$_2$ [9].

Electron systems in the vicinity of a Pomeranchuk instability have peculiar properties due to a ”soft” Fermi surface, which can be easily deformed by anisotropic perturbations. Critical fluctuations near a Pomeranchuk quantum critical point provide an interesting route to non-Fermi liquid behavior in two dimensions [10, 11, 12, 13].

2. In-plane anisotropy of magnetic excitations in YBCO

Recently, high quality neutron scattering data for fully untwinned YBa$_2$Cu$_3$O$_y$ (YBCO) revealed a pronounced in-plane anisotropy in the pattern of magnetic excitations [14]. This is remarkable, since the copper-oxide planes in YBCO exhibit only a weak structural orthorhombicity, and the influence of the copper-oxide chains on the electronic structure of the planes is also rather weak.

The observed in-plane anisotropy can be explained very naturally by an enhancement of the weak band structure anisotropy due to an incipient d-wave Pomeranchuk instability. To substantiate the idea of a Pomeranchuk based mechanism for the observed in-plane anisotropy, we have computed the dynamical magnetic susceptibility $\chi(q, \omega)$ for the two-dimensional $t$-$J$ model [15]. The calculations were done within the slave-boson mean-field approximation allowing for d-wave pairing. The bilayer structure of YBCO was taken into account by solving the model on a lattice consisting of two square lattice sheets coupled by an interlayer hopping amplitude. The small in-plane anisotropy of the LDA band structure was modelled by a small anisotropy of the hopping amplitudes, such as $t_x = t(1 + \alpha/2)$, $t_y = t(1 - \alpha/2)$ for the nearest neighbor hopping in $x$ and $y$ direction, respectively. Model parameters appropriate for YBCO were taken from band structure calculations and experimental values from the literature.

The results obtained for $\chi(q, \omega)$ share many salient features with the experimental observations for YBCO. In the d-wave pairing state, the strongest spectral weight appears in the odd channel (transverse momentum $q_z = \pi$) at the in-plane momentum $q = Q \equiv (\pi, \pi)$ and the so-called resonance peak energy $\omega = \omega_{Q}^{\text{res}}$. For $\omega < \omega_{Q}^{\text{res}}$ the resonance peak spreads into a diamond-shaped shell around $Q$ in $q$ space, as seen in Fig. 1. Close to the resonance energy, the incommensurate (IC) signals at $q = (\pi, \pi \pm \eta)$ and $(\pi \pm \eta, \pi)$ tend to be stronger than the diagonal incommensurate signals (DIC) at $(\pi \pm \eta', \pi \pm \eta')$, especially for a large hole density $\delta$. For $\omega \ll \omega_{Q}^{\text{res}}$ the IC signals completely disappear and the weight remains large only around the DIC positions. The IC and DIC signals appear only in the d-wave pairing state, not in the normal state (at higher temperatures). The expected enhancement of the in-plane anisotropy of magnetic excitations due to interaction enhanced d-wave Fermi surface deformations are confirmed by the $t$-$J$ model calculations. The effect is particularly pronounced at low doping and relatively high temperature. At low temperatures the tendency to a Pomeranchuk instability is suppressed by the pairing gap, but the in-plane anisotropy is still enhanced considerably by correlations.

3. Non-Fermi liquid from Fermi surface fluctuations

Dynamical fluctuations of the soft Fermi surface close to a Pomeranchuk instability in two dimensions lead to a strongly enhanced decay rate for fermionic excitations and thus to a breakdown of Fermi liquid theory [10, 11, 12, 13].

To explore this route to non-Fermi liquid behavior, the following model has been analyzed,

$$H = H_0 + \frac{1}{2V} \sum_{k,k',q} f_{kk'}(q) n_{k}(q) n_{k'}(-q),$$

where $H_0$ is a tight-binding kinetic energy on a square lattice, $n_{k}(q) = \sum_\sigma c_{k-q/2,\sigma}^\dagger c_{k+q/2,\sigma}$, and $V$ the volume of the system. Since the Pomeranchuk instability is driven by interactions with
Figure 1. Momentum space maps of the spectral weight of dynamical magnetic excitations as obtained from a bilayer $t-J$ model calculation with parameters appropriate for YBCO. All results are for the odd channel. The temperature is far below the pairing temperature. Energies $\omega$ are chosen at various values $\omega \leq \omega^\text{res}$. The slight in-plane anisotropy imposed by the orthorhombic structure is enhanced by correlation effects.

small momentum transfers, that is forward scattering, we choose a coupling function $f_{kk'}(\mathbf{q})$ which contributes only for relatively small momenta $\mathbf{q}$. We consider an interaction of the form

$$f_{kk'}(\mathbf{q}) = u(\mathbf{q}) + g(\mathbf{q}) d_k d_{k'}$$

with $u(\mathbf{q}) \geq 0$ and $g(\mathbf{q}) < 0$, and a form factor $d_k$ with $d_{x^2-y^2}$ symmetry, such as $d_k = \cos k_x - \cos k_y$. The coupling functions $u(\mathbf{q})$ and $g(\mathbf{q})$ vanish if $|\mathbf{q}|$ exceeds a certain small momentum cutoff $\Lambda$. This ansatz mimics the effective interaction in the forward scattering channel as obtained from renormalization group calculations [3] for the two-dimensional Hubbard model. The uniform term originates directly from the repulsion between electrons and suppresses the electronic compressibility of the system. The $d$-wave term drives the Pomeranchuk instability.

The putative continuous Pomeranchuk transition in the model (1) can actually be preempted by a first order transition at low temperatures [16]. However, for reasonable choices of hopping and interaction parameters the system is nevertheless characterized by a drastically softened Fermi surface on the symmetric side of the first order transition, and hence by strongly enhanced Fermi surface fluctuations [17]. The first order character of the transition is suppressed by the uniform repulsion $u$ in (2), and for a favorable but not unphysical choice of model parameters a genuine quantum critical point can be realized [17].

In the quantum critical regime the dynamical forward scattering interaction diverges with a singularity familiar from other quantum phase transitions in itinerant electron systems with dynamical exponent $z = 3$. The singular forward scattering leads to large self-energy contributions $\Sigma(\mathbf{k}, \omega)$, which are proportional to $d_k^2$ [11, 12]. At the quantum critical point, $\text{Im}\Sigma(\mathbf{k}_F, \omega)$ and thus the quasiparticle scattering rate are of order $|\omega|^{2/3}$. Fermi liquid behavior is thus destroyed over the whole Fermi surface except near the Brillouin zone diagonal. Close to the quantum critical point the scattering rate in the ground state obeys the $|\omega|^{2/3}$-law down to
a small energy scale $\omega_c$ of order $\xi^{-3}$, where $\xi$ is the correlation length. In the quantum critical regime at low finite temperatures the self-energy has a part due to quantum fluctuations, which obeys $(\omega/T)$-scaling, but also a classical part, which is proportional to $T \xi(T)$ near the Fermi surface, with $\xi(T) \propto (T \log T)^{-1/2}$. The classical contribution violates $(\omega/T)$-scaling. The momentum dependent transport decay rate $\gamma_{kF}(T)$ is linear in temperature for all momenta on the Fermi surface except at the cold spots on the Brillouin zone diagonal [13]. Adding a conventional $T^2$-term to $\gamma_{kF}(T)$ yields an overall resistivity $\rho(T)$ proportional to $T^{3/2}$ at low temperatures. In the presence of impurities, the residual resistivity at zero temperature is approached linearly.

Strong d-wave Fermi surface fluctuations could be at least partially responsible for the non-Fermi liquid behavior observed in the "strange metal" regime of cuprate superconductors near optimal doping. In our model calculation we have obtained a strongly anisotropic anomalously large decay rate for single-particle excitations. Large anisotropic decay rates have been extracted from the linewidth of low-energy peaks in the photoemission spectra observed in optimally doped cuprates, using in particular momentum scans perpendicular to the Fermi surface at various fixed energies.[18, 19] The line shape of these scans is almost Lorentzian, which is consistent with our results. Most recent measurements indicate that the previously suggested non-Fermi liquid behavior in the nodal direction, which could not be explained by d-wave fluctuations, is not tenable any more [20]. Concerning transport, an anisotropic scattering rate with nodes on the Brillouin zone diagonal can very naturally account for the pronounced anisotropy between the intra- and inter-plane mobility of charge carriers, as pointed out by Ioffe and Millis [21] in their phenomenological "cold spot" scenario. Strikingly, recent measurements of the momentum resolved transport decay rate in $Tl_2Ba_2CuO_6+\delta$ revealed a $T$-linear contribution with a $d$-wave form factor, in addition to a less momentum dependent Fermi liquid type background [22, 23], precisely as in our result for $\gamma_{kF}(T)$ [24].

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