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Theory of extreme correlations using canonical Fermions and path integrals

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HIGHLIGHTS

- Spectral function of the Extremely Correlated Fermi Liquid theory at low energy.
- Electronic origin of low energy kinks in energy dispersion.
- Non Hermitian representation of Gutzwiller projected electrons.
- Analogy with Dyson–Maleev representation of spins.
- Path integral formulation of extremely correlated electrons.

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ABSTRACT

The t–J model is studied using a novel and rigorous mapping of the Gutzwiller projected electrons, in terms of canonical electrons. The mapping has considerable similarity to the Dyson–Maleev transformation relating spin operators to canonical Bosons. This representation gives rise to a non Hermitian quantum theory, characterized by minimal redundancies. A path integral representation of the canonical theory is given. Using it, the salient results of the extremely correlated Fermi liquid (ECFL) theory, including the previously found Schwinger equations of motion, are easily rederived. Further, a transparent physical interpretation of the previously introduced auxiliary Greens function and the 'caparison factor', is obtained.

The low energy electron spectral function in this theory, with a strong intrinsic asymmetry, is summarized in terms of a few expansion coefficients. These include an important emergent energy scale Δ_0 that shrinks to zero on approaching the insulating state, thereby making it difficult to access the underlying very low energy Fermi liquid behavior. The scaled low frequency ECFL spectral function, related simply to the Fano line shape, has a peculiar energy dependence unlike that of a Lorentzian. The resulting energy

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dispersion obtained by maximization is a hybrid of a massive and a massless Dirac spectrum $E^*_Q \sim \gamma\, Q - \sqrt{\Gamma_0^2 + Q^2}$, where the vanishing of Q, a momentum type variable, locates the kink minimum. Therefore the quasiparticle velocity interpolates between $(\gamma \mp 1)$ over a width Γ_0 on the two sides of $Q = 0$, implying a kink there that strongly resembles a prominent low energy feature seen in angle resolved photoemission spectra (ARPES) of cuprate materials. We also propose novel ways of analyzing the ARPES data to isolate the predicted asymmetry between particle and hole excitations.

1. Introduction

The intensely studied t–J model is often regarded as the effective low energy Hamiltonian for describing several observed phenomena in cuprate superconductors [1]. Here the $U \to \infty$ limit is presupposed, and hence the Hilbert space is restricted to a maximum of single occupancy at each site, i.e. Gutzwiller projected [2]. A few words on the choice of the t–J model are relevant here. The implied infinite U limit eliminates high energy (U scale) electronic states, known as the upper Hubbard band states. The residual low energy ($\lesssim$ 100 meV scale) excitations are probed by sensitive spectroscopies and transport phenomena, making the t–J model suitable for our task. At reasonably high U, say comparable to the band width in a Hubbard model, this elimination of the upper Hubbard band must already occur in part. Therefore the limit $U \to \infty$ must be regarded as a useful mathematical idealization of the very strong, or extreme correlation phenomenon. The resulting Gutzwiller projected electron operators, denoted by Hubbard's convenient notation of X operators [3], are rendered non canonical. The non-canonical nature of the electrons precludes the Wick's theorem underlying the Feynman diagram approach, whereby leading to the fundamental difficulty of the t–J model, namely the impossibility of a straightforward Feynman type perturbative expansion. This situation leads to enormous calculational difficulties, so that systematic and controlled analytical calculations with this model have been very difficult.

In a series of recent papers [4,6–8,5,9,10], we have shown that it is possible to overcome some of these difficulties by using alternate methods based on Schwinger's treatment of field theory with time dependent potentials. This idea yields exact equations of motion for the electron Greens function. These equations have the nature of functional differential equations, and provide a powerful launching pad for various approximations. The specific approximation pursued is a systematic expansions in a parameter λ related to double occupancy. Using this we have presented an analytical theory of the normal state of the t–J model termed the extremely correlated Fermi liquid (ECFL) theory. An interesting feature of the theory is that we find a non-Dysonian representation of the projected electron Greens function. This is a significant structural departure from the usual field theories, and arises in a most natural fashion. The Greens function is determined by a *pair* of self energies, denoted by $\Phi(\vec{k}, i\omega_n)$ and $\Psi(\vec{k}, i\omega_n)$, instead of the standard Dyson self energy $\Sigma(\vec{k}, i\omega_n)$ (see Eq. (21) below). The latter can be reconstructed from the pair by a simple inversion. Starting with rather simple pairs of self energies, it is found that non trivial complexity is introduced into the Dyson self energy through this inversion process. Explicit self consistent calculations in parameter λ have been carried out to $O(\lambda^2)$ so far, and yield reliable results for electron densities $0 \leq n \lesssim .7$. The detailed dynamical results of the ECFL theory have been benchmarked against independent theories in overlapping domains; e.g. against high temperature series results in Ref. [11]. The ECFL theory has been shown to have a momentum independent Dyson self energy in the limit of infinite dimensions [10]. This enables benchmarking against the dynamical mean field theory (DMFT) in Ref. [9]. Importantly, the results from the ECFL theory for the spectral function compare well with a large U Hubbard model solved by the DMFT method, and not just infinite U. The ECFL theory has also been benchmarked in Ref.