Singular Dynamics of a Fermion Coupled to the Planar Antiferromagnet

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Abstract. A model for a single fermion coupled to the planar antiferromagnetic spin background via the local spin - fermion coupling is studied. Within the perturbation theory as well as the selfconsistent calculation of the quasiparticle spectra the fermion self energy shows a nonanalytical behaviour $\Sigma''(\omega > 0) \propto \omega^{\alpha}$, $\alpha \leq 1$. The original Hamiltonian is approximated with an effective single level model with a linear coupling to soft bosons. Exact results of the latter model again indicate on the orthogonality catastrophe in this system.

In order to understand the character of quasiparticles (QP) in strongly correlated systems, a number of authors have so far considered the problem of a single charge carrier introduced by doping the planar antiferromagnetic (AFM) insulator [1]. We consider in this paper the spin-hole (fermion) model which represents well the qualitative features of more complete two-band Hubbard model for the CuO_2 layers as well as the t-J model in superconducting oxides [2]. One of the most important qualitative questions is the correct description of the low frequency excitation spectra, connected with the existence of the QP peak [3]. This question is clearly related also to the possible breakdown of the Landau Fermi liquid description at arbitrary doping, as deduced from experiments [4].

We investigate the low energy features of a simplified version of the spin-hole model [2], where we retain the Heisenberg interaction among the localized spins (J), fermion hopping between two sublatices (neighbouring sites) A and B (t) and the local spin-fermion coupling (V),

$$H = -t\sum_{s}(c^{\dagger}_{As}c_{Bs} + c^{\dagger}_{Bs}c_{As}) + J\sum_{<ij>} \mathbf{S}_i\cdot\mathbf{S}_j + V(\mathbf{s}_A\cdot\mathbf{S}_A + \mathbf{s}_B\cdot\mathbf{S}_B).$$

We perform the expansion of spin operators $\mathbf{S}_i$ into AFM linear spin waves and use a suitable transformation of fermion operators $c_{A(B),\pm\frac{1}{2}}$ into $\tilde{c}_{1(2),\pm}$ to get

$$H_{mag} = \epsilon\sum_{i=1}^{2}(\tilde{n}_{i+} - \tilde{n}_{i-}) + \sqrt{2}J\sum_{q\sim 0}|\mathbf{q}|\alpha^{\dagger}_{\mathbf{q}}\alpha_{\mathbf{q}} + \frac{32^{-1/4}V}{\sqrt{N}}\sum_{\substack{i=1\\ q\sim 0}}^{2}\left(|\mathbf{q}|^{-1/2}\tilde{c}^{\dagger}_{i+}\tilde{c}_{i-}\alpha^{\dagger}_{\mathbf{q}} + \mathrm{H.c.}\right) + \sum_{q\sim(\pi,\pi)} \dots,$$

where $\epsilon = (t^2 + \frac{1}{16}V^2)^{1/2}$ and for the low energy excitations only the most important long-wavelength part is presented.

Fermion self-energy $\Sigma(\omega)$ corresponding to H_{mag} can be studied using the perturbation expansion. Within the lowest non-trivial order the result is similar as in Ref. 3, namely $\Sigma(\omega) \propto V^4\epsilon^{-2}J^{-2}\omega\log(-\omega)$. Terms of higher order in V are also singular, $\propto \log^n(-\omega), n = 1, 2\dots$, and are therefore difficult to deal with. On the other hand contributions to $\Sigma(\omega)$ can be partly summed up on a self-consistent (SC) way as in Ref. 3 yielding a non-analytical result $\Sigma(\omega) \propto \sqrt{-\omega}$ for $|\omega|/J \ll 1$.

These results can to some extent be improved by approximating the original (two level) Hamiltonian $H_{\rm mag}$ with a simpler one, which mimics two magnon processes among the lower energy $(-\epsilon)$ states $\tilde{c}_{1(2),-}$ within $H_{\rm mag}$. We thus introduce an effective linear interaction between the fermion (c) and magnons (β_q)

$$H_{\rm eff} = J \sum_{q\sim 0} |\mathbf{q}|\, \beta^\dagger_{\mathbf{q}} \beta_{\mathbf{q}} + \frac{V^2}{\epsilon\sqrt{N}} \sum_{q\sim 0} c^\dagger c\, (\beta^\dagger_{\mathbf{q}} + \beta_{-\mathbf{q}}).$$

Most divergent terms of $\Sigma(\omega)$ within $H_{\rm mag}$ show the same form of singularities as calculated using $H_{\rm eff}$, e.g. the order $2n$ within $H_{\rm mag}$ corresponds to the order n within the perturbation expansion in V etc.

Solution for the fermion Green's function within $H_{\rm eff}$ can be obtained exactly using a canonical transformation [5]. The result is

$$G(\omega) = -i \int_0^\infty e^{\alpha h(t)} e^{i\omega t} dt, \qquad h(t) = -\int_0^{q_m} \frac{1 - e^{-iJqt}}{q} dq,$$

and $2\pi\alpha = V^4(\epsilon J)^{-2}$. For small values $\omega/J > 0$ and $\alpha < 1$ it is easy to see that ${\rm Im}G(\omega) \propto \omega^{\alpha-1}$ and $\Sigma''(\omega) \propto \omega^{1-\alpha}$, while for arbitrary values of the parameters the solution has to be obtained numerically (see Figure). To conclude we point out that at least within the effective model the QP peak does not exist. The nonanalytical self-energy shows the similarity with the orthogonality catastrophe [4].

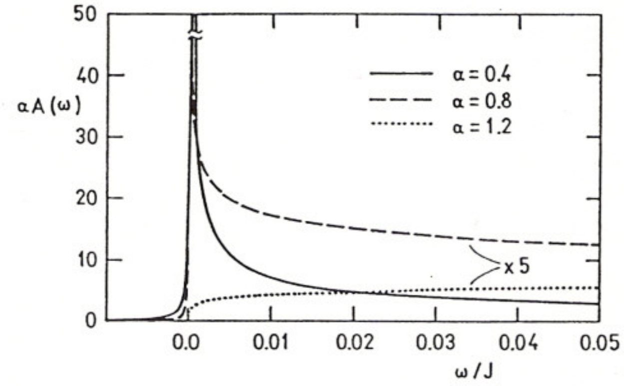

Figure: Spectral function $A(\omega) = -\frac{1}{\pi}{\rm Im}G(\omega)$ vs. ω/J for various values of α.

References

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