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Quasiparticle spectra in a t-J model with electron-phonon interactions

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The change of the spectral properties of the single-particle Green's function due to a coupling to optical phonons is investigated for strongly correlated electrons. Except at the bottom of the band the quasiparticle pole is considerably broadened due to phonon-induced decay processes, and phonon-satellite structures appear. The overall coherent bandwidth is, however, not significantly changed. The phonon induced mass renormalization of a single carrier which propagates in the t-J model on scale J is found to be much larger than in the corresponding uncorrelated model, except in the limit of $J \to 0$.

The role of electron-phonon (e-p) interactions in the strongly correlated high-T_c superconductors (HTSC's) is still far from clear. On one hand there is evidence of substantial e-p interactions in a marked change of phonon frequency renormalization when passing through T_c [1]. On the other hand it has been argued that these interactions are not particularly relevant to explain the high-T_c [2]. The problem is complicated by the coherent motion of dressed carriers on a reduced energy scale J *and* with a reduced spectral weight, $a_{\mathbf{k}} < 1$, which arises from the strong coupling of the carriers to the Cu-spins. As a consequence the width of the band is not much larger than the phonon cutoff, which signals a possible breakdown of the standard strong coupling theory.

Our aim here is to study the changes of the quasiparticle properties of a single hole in a generic model for the HTSC's when a coupling to optical phonons is included. The Hamiltonian [3]

$$H = -t \sum_{<ij>s} \tilde{c}^{\dagger}_{is}\tilde{c}_{js} + J \sum_{<ij>} \mathbf{S}_i \cdot \mathbf{S}_j + \sum_{ils} M_l \tilde{c}^{\dagger}_{is}\tilde{c}_{is}(b^{\dagger}_{i+l} + b_{i+l}) + \Omega \sum_i b^{\dagger}_i b_i, \qquad (1)$$

consists of the usual t-J model and a coupling of charge carriers to Einstein phonons with energy Ω and the e-p coupling matrix element M_l. Eq. (1) follows from the corresponding Hubbard-Holstein model [4] provided the e-p interaction is not too large. Otherwise the physics may be described by an effective negative-U Hubbard model and bipolaron formation [5].

We calculate the single-particle Green's function $G_{\mathbf{k}}(\omega)$ in two steps: (1) The t-J part of H is rewritten in terms of slave fermions and Schwinger bosons, characterizing charge and spin degrees of freedom, respectively. By applying linear spin wave theory we introduce the proper collective excitations, i.e. antiferromagnetic magnons. (2) $G_{\mathbf{k}}(\omega)$ for the hole, which couples to both magnons and phonons, is calculated within a selfconsistent Born Approximation (SCBA) [6]. The validity of this approach is well established for the t-J model, and the results agree with exact diagonalization [7, 8]. Here we will be interested in the regime $J < t$ relevant for the copper oxides, which implies strong fermion-magnon coupling. The e-p coupling will be considered weak.

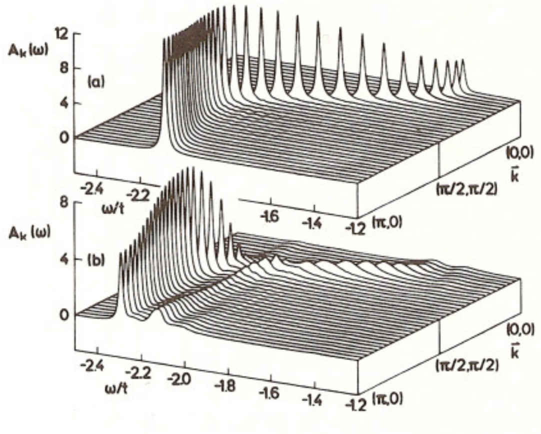

Figure 1. Spectral function $A_{\mathbf{k}}(\omega)$ for $\mathbf{k}$ along $(\pi,0) \to (\frac{\pi}{2},\frac{\pi}{2}) \to (0,0)$ for $J/t = 0.4$, $\Omega/t = 0.1$ and e-p coupling (a) $M = 0$ and (b) $M/t = 0.4$.

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Within SCBA, strong correlations and the renormalization by phonons are treated on the same footing. The low-energy part of the spectral function $A_{\mathbf{k}}(\omega) = -\frac{1}{\pi}\mathrm{Im}G_{\mathbf{k}}(\omega)$, displayed in Fig. 1 for the case $M_l = \delta_{l,0}M$, shows the energy dependence of the quasiparticle (QP) peak. Away from the bottom of the band the QP pole is strongly damped due to phonon-induced decay processes. However the overall bandwidth is not significantly changed. For $M/t = 0.4$, which is a typical value for the copper oxides [4], we find pronounced phonon-satellite structure at low energy.

The effective mass of a single hole measured at the bottom of the band is however strongly enhanced, except in the limit $J \rightarrow 0$ where the spectral weight of the QP tends to zero [3] and the motion becomes almost completely incoherent. We define the phonon induced mass renormalization by $m^*_{\|}/m_{\|} = 1 + \lambda^*$, $m_{\|} = (\partial^2\epsilon_{\mathbf{k}}/\partial\mathbf{k}^2)^{-1}_{\|}$.

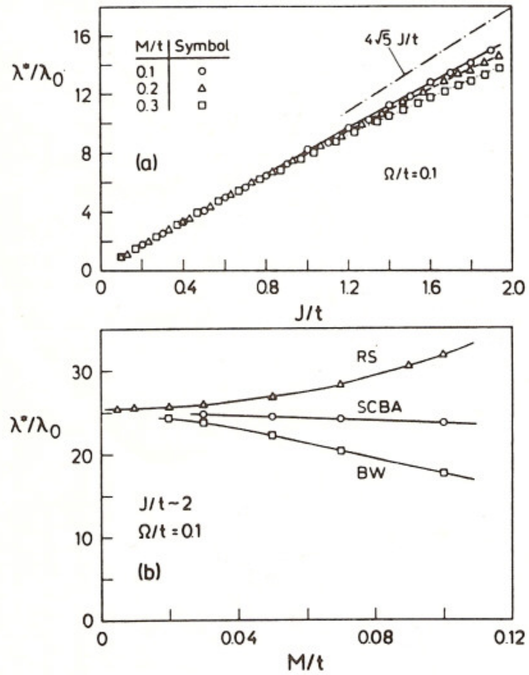

Figure 2. (a) Phonon-induced mass renormalization λ^*/λ_0 vs. J/t for three different M/t values and $\Omega/t = 0.1$. Here λ_0 is the renormalization for noninteracting fermions. (b) Comparison of SCBA with Rayleigh-Schrödinger (RS) and Brillouin-Wigner (BW) perturbation theory.

The QP-mass in the pure t-J model at the minimum of $\epsilon_{\mathbf{k}}$ at $\mathbf{k} = (\frac{\pi}{2}, \frac{\pi}{2})$ is highly anisotropic, $m_{\|} < m_{\perp}$, and $m_{\|} \sim t/J$ for $J < t$. In Fig. 2(a) we compare λ^* with the mass renormalization λ_0 for uncorrelated fermions, i.e., model Eq. (1) without single occupancy constraint and $J = 0$. *The enhancement is a consequence of the slow coherent motion of the spin polarons which makes the e-p interaction more effective.* These trends can be explained using a dominant pole approximation for G and treating phonon exchange within perturbation theory [3]. For $J > t$ the spectral weight $a_{\mathbf{k}}$ of the spin polaron approaches 1, and we may approximate G for the spin-polaron by a single pole with $a_{\mathbf{k}} = 1$. The M-dependence of the renormalization due to phonons obtained in SCBA can then be directly compared with RS and BW perturbation theory. Fig. 2(b) shows that λ^*/λ_0 calculated within SCBA is between the results of these methods, as one may have expected on the basis of certain limitations of these methods [9]. Further studies for finite doping concentration are required to judge possible consequences for quasiparticle interactions and for the Migdal-Eliashberg theory of superconductivity.

REFERENCES

1. C. Thomsen and M. Cardona, in *Physical Properties of HTSC's'*, ed. D. M. Ginsberg (World Scientific, Singapore, 1989).
2. P. W. Anderson, Physica C **185-189**, 11 (1991); J. R. Schrieffer, *ibid.* 17 (1991).
3. A. Ramšak, P. Horsch, and P. Fulde, Phys. Rev. B **46**, 14305 (1992).
4. J. Zhong and H.-B. Schüttler, Phys. Rev. Lett., **69**, 1600 (1992).
5. J. Micnas, J. Ranninger, and S. Robaszkiewicz, Rev. Mod. Phys. **62**, 113 (1990).
6. S. Schmitt-Rink *et al.*, Phys. Rev. Lett. **60**, 2793 (1988); C. L. Kane *et al.*, Phys. Rev. B **39**, 6880 (1989).
7. G. Martínez and P. Horsch, Phys. Rev. B **44**, 317 (1991).
8. A. Ramšak and P. Prelovšek, Phys. Rev. B **42**, 10415 (1990).
9. G. D. Mahan, *Many Particle Physics*, (Plenum, New York, 1981).