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Magnetic field dependent electronic Raman response of cuprate superconductors

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ABSTRACT

The theory of electronic Raman scattering in cuprate superconductors based on the t–J model is evolved to describe the magnetic field dependent electronic Raman response. The magnetic field dependence of Raman response in the overdoped regime is studied at different doping cases. The results show that the peak and intensity in the B_{1g} and B_{2g} symmetry give depletion as the magnetic field increased. We indicate the decrease of the superconducting order parameter Δ under the magnetic field. The overall density of Cooper pairs is also investigated and yields suppression with the increase of the magnetic fields.

Since the discovery of cuprate superconductors by Bednorz and Müller [1], intensive experiments have been given to the studies of the various properties of high temperature superconductivity. Although it is still not clear but a common view is the existence of the electron Cooper pairs plays a crucial role in the high temperature superconductivity. Among these experiment tools, electronic Raman scattering arises from quasi-particle excitations around the Fermi surface and provides spectroscopic information about the quasiparticle excitation spectra [2]. In the superconducting state, the peak which arises from the low frequency tail of the Raman continua reflects the breaking of the Cooper pairs, commonly called the opening of the superconducting gap 2Δ-peak [3–7], and its behavior is partially well described by the phenomenological Bardeen–Cooper–Schrieffer formalism and some microscopic models [8–12]. However, seldom theoretical studies have been made so far for the magnetic field dependent Raman scattering. Researchers have mainly focused on the effect of magnetic fields on transport properties [13,14]. Theoretical frameworks are also necessary for understanding fundamental spectroscopic experiments of high temperature superconductors in magnetic fields. These properties are also critical to the understand of high temperature superconductivity.

The cuprate superconductors have high upper critical fields. Enhanced magnetic fields are known to be detrimental to the superconductivity. By Raman spectroscopy it is found that the excitations across the superconducting gap is suppressed by increasing magnetic fields [15,16]. Experimentally, the position of the pair-breaking peak is associated with the size of the Cooper pair breaking excitation and shows a softening at higher fields. The peak intensity is proportional to the density of the superconducting condensate and becomes weak as the fields increased [15,16]. On the other hand, it is indicated by the inelastic neutron-scattering experiments that the external magnetic fields have a strong effect on the spin dynamics in cuprate superconductors [17], thus there is an intimate relationship between the spin fluctuation and superconductivity. So from the theoretical point of view, the spin fluctuation induced by the external magnetic field is essential to account for the magnetic field dependent electronic Raman response.

It is argued that the existence of the CuO_2 plane structure in cuprate superconductors dominates its characteristic feature, and it has been shown from the ARPES experiments that its essential physics is properly accounted by the t–J model on a square lattice [18–20]. In our previous studies, we have well investigated the doping and temperature dependent Raman scattering in cuprate superconductors based on the t–J model within the kinetic energy driven superconductivity [11,12], and qualitatively reproduce some main features of electronic Raman response in cuprate superconductors. Our results have shown that as the temperature increased, the intensities and positions of the pair-breaking peaks in both B_{1g} and B_{2g} channels are suppressed. When increasing the doping concentration, the intensities of the pair-breaking peaks in B_{1g} and B_{2g} symmetry are strongly increased, and the energy scale of the B_{2g} symmetry gives a domelike shape of the doping dependent, which the pair-breaking peak energy increases with increasing doping in the underdoped regime, and reaches a maximum in the optimal doping, then decreases in the overdoped regime [11,12].

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Following our previous studies, for the discussion of the magnetic field dependent Raman response of cuprate superconductors, the t–J model can be expressed by including the Zeeman term as

$$H = -t \sum_{i\hat{\eta}\sigma} C^{\dagger}_{i\sigma} C_{i+\hat{\eta}\sigma} + t' \sum_{i\hat{\tau}\sigma} C^{\dagger}_{i\sigma} C_{i+\hat{\tau}\sigma} + \mu \sum_{i\sigma} C^{\dagger}_{i\sigma} C_{i\sigma} + J \sum_{i\hat{\eta}} \mathbf{S}_i \cdot \mathbf{S}_{i+\hat{\eta}} - \epsilon_B \sum_{i\sigma} \sigma C^{\dagger}_{i\sigma} C_{i\sigma}, \tag{1}$$

with t, t' for the nearest, second-nearest neighbor pairs, respectively, J stands for the exchange energy, and $\hat{\eta} = \pm\hat{x}, \pm\hat{y}$, $\hat{\tau} = \pm\hat{x} \pm \hat{y}$. $C^{\dagger}_{i\sigma}(C_{i\sigma})$ is the electron creation (annihilation) operator, $\mathbf{S}_i = (S^x_i, S^y_i, S^z_i)$ are spin operators, and μ is the chemical potential. $\epsilon_B = g\mu_B B$ is the Zeeman magnetic energy, with the Lande factor g, Bohr magneton μ_B, and an external magnetic field B.

The t–J model is subject to a local constraint $\sum_\sigma C^{\dagger}_{i\sigma} C_{i\sigma} \leqslant 1$ to avoid the double occupancy and can be treated properly under a scenario of charge-spin separation fermion-spin theory [21]. We follow this scheme and decouple the electron operator in the t–J model as

$$C_{i\uparrow} = h^{\dagger}_{i\uparrow} S^-_i, \qquad C_{i\downarrow} = h_{i\downarrow} S^+_i, \tag{2}$$

where the spinful fermion operator $h_{i\sigma} = e^{-i\Phi_{i\sigma}} h_i$ represents the charge carrier and is called dressed holon, the spin operator S_i represents the spin degree of freedom with no charge. The spinless fermion $h_{i\sigma}$ obeys the anticommutation relation, and the spin operators S^+_i and S^-_i obey Pauli spin algebra.

Within this formalism, the t–J model can be expressed as,

$$\begin{aligned} H = &-t \sum_{i\hat{\eta}} \left(h^{\dagger}_{i+\hat{\eta}\uparrow} h_{i\uparrow} S^+_i S^-_{i+\hat{\eta}} + h^{\dagger}_{i+\hat{\eta}\downarrow} h_{i\downarrow} S^-_i S^+_{i+\hat{\eta}} \right) \\ &- t' \sum_{i\hat{\tau}} \left(h^{\dagger}_{i+\hat{\tau}\uparrow} h_{i\uparrow} S^+_i S^-_{i+\hat{\tau}} + h^{\dagger}_{i+\hat{\tau}\downarrow} h_{i\downarrow} S^-_i S^+_{i+\hat{\tau}} \right) \\ &- \mu \sum_{i\sigma} h^{\dagger}_{i\sigma} h_{i\sigma} + J_{\text{eff}} \sum_{i\hat{\eta}} \mathbf{S}_i \cdot \mathbf{S}_{i+\hat{\eta}} - 2\epsilon_B \sum_i S^z_i, \end{aligned} \tag{3}$$

with $J_{\text{eff}} = (1-\delta)^2$, and $\delta = \langle h^{\dagger}_{i\sigma} h_{i\sigma} \rangle = \langle h^{\dagger}_i h_i \rangle$ is the hole doping concentration.

We obtain the mean-field spin Green function and the dressed holon diagonal and off-diagonal Green's functions within the kinetic energy driven superconductivity in the presence of an external magnetic field as,

$$D^{(0)}(\mathbf{k}, \omega) = \frac{1}{2} \sum_{\nu=1,2} \frac{B_{\mathbf{k}}}{\omega_\nu(\mathbf{k})} \frac{1}{\omega - \omega_\nu(\mathbf{k})}, \tag{4}$$

$$g(\mathbf{k}, \omega) = Z_F \sum_{\nu=1,2} U^2_\nu(\mathbf{k}) \frac{1}{\omega - E_\nu(\mathbf{k})}, \tag{5}$$

$$\mathcal{J}^+(\mathbf{k}, \omega) = -\frac{Z_F}{2} \sum_{\nu=1,2} \frac{\bar{\Delta}(\mathbf{k})}{E_\nu(\mathbf{k})} \frac{1}{\omega - E_\nu(\mathbf{k})} \tag{6}$$

where $\omega_1(\mathbf{k}) = \omega_{\mathbf{k}}$, $\omega_2(\mathbf{k}) = -\omega_{\mathbf{k}}$, $E_1(\mathbf{k}) = E_{\mathbf{k}}$, $E_2(\mathbf{k}) = -E_{\mathbf{k}}$, $U^2_1(\mathbf{k}) = 1/2(1 + \bar{\xi}_{\mathbf{k}}/E_{\mathbf{k}})$, $U^2_2(\mathbf{k}) = 1/2(1 - \bar{\xi}_{\mathbf{k}}/E_{\mathbf{k}})$. $\omega_{\mathbf{k}}$ is the mean field spin excitation spectra, Z_F is the dressed holon quasiparticle coherent weight, and the quasiparticle spectrum $E_{\mathbf{k}} = \sqrt{\bar{\xi}^2_{\mathbf{k}} + \bar{\Delta}^2(\mathbf{k})}$, in which $\bar{\xi}_{\mathbf{k}} = Z_F \xi_{\mathbf{k}}$, $\xi_{\mathbf{k}}$ is the mean field dressed holon excitation spectrum, and the effective dressed holon pair gap function $\bar{\Delta}(\mathbf{k}) = Z_F \Delta(\mathbf{k}) = Z_F \Delta(\cos k_x - \sin k_x)/2$ with the superconducting order parameter Δ. Formally, we can write here the mean field spin excitation spectra $\omega_{\mathbf{k}}$ in the external magnetic field as

$$\omega_{\mathbf{k}} = \sqrt{\omega^2_{0\mathbf{k}} + 4B^2} \tag{7}$$

in which $\omega_{0\mathbf{k}}$ has the same expression of the mean field spin excitation spectra for the no magnetic field case given in Ref. [21]. The change of the spin excitation spectra reflects the influence of external magnetic field on spin fluctuation. Meanwhile, the other parameters $B_{\mathbf{k}}$, $\xi_{\mathbf{k}}$ in the magnetic field is found to have the same form as the no magnetic field cases shown in Ref. [21].

All these parameters are determined by the self-consistent equations automatically. However, these self-consistent equations are not intended to show here again and one can refer to Ref. [21]. As even though the spin excitation spectra $\omega_{\mathbf{k}}$ here is changed under the external magnetic field, it is found that the forms of the Green functions shown in Eqs. (4), (5), (6) behave consistently with the no magnetic field case in Ref. [21]. So the self-consistent equations derived by these Green functions and expressed by the mean field spin excitation spectra $\omega_{\mathbf{k}}$, the mean field dressed holon excitation spectrum $\xi_{\mathbf{k}}$, the quasiparticle spectrum $E_{\mathbf{k}}$ and the effective dressed holon pair gap function $\bar{\Delta}(\mathbf{k})$ must naturally have the same forms in the no magnetic field case in Ref. [21]. But, the values of these parameters determined by the self-consistent equations in the external magnetic field now are different from these in the no magnetic field case, as the mean field spin excitation spectra $\omega_{\mathbf{k}}$ now is changed and has an additional $4B^2$ under the radical sign, thus the values of the quasiparticle spectrum $E_{\mathbf{k}}$ and the pair gap function $\bar{\Delta}(\mathbf{k})$ will naturally be changed by the external magnetic field.

In this charge-spin separation fermion-spin scheme, the electron diagonal and off-diagonal Green's functions $\langle\langle C_{i\sigma}(t); C^{\dagger}_{j\sigma}(t')\rangle\rangle$, $\langle\langle C^{\dagger}_{i\uparrow}(t); C^{\dagger}_{j\downarrow}(t')\rangle\rangle$ are expressed by the convolutions of the diagonal and off-diagonal dressed holon Green functions with the mean-field spin Green function, given by

$$G(\mathbf{k}, \omega) = \frac{Z_F}{2N} \sum_{\mathbf{p}} \sum_{\nu,\mu=1,2} \frac{B_{\mathbf{p}}}{\omega_\mu(\mathbf{p})} U^2_\nu(\mathbf{p}+\mathbf{k}) \cdot \frac{n_F[E_\nu(\mathbf{p}+\mathbf{k})] + n_B[\omega_\mu(\mathbf{p})]}{\omega + E_\nu(\mathbf{p}+\mathbf{k}) - \omega_\mu(\mathbf{p})} \tag{8}$$

$$\Gamma^+(\mathbf{k}, \omega) = -\frac{Z_F}{4N} \sum_{\mathbf{p}} \sum_{\nu,\mu=1,2} \frac{\bar{\Delta}(\mathbf{p}+\mathbf{k})}{E_\nu(\mathbf{p}+\mathbf{k})} \frac{B_{\mathbf{p}}}{\omega_\mu(\mathbf{p})} \cdot \frac{n_F[E_\nu(\mathbf{p}+\mathbf{k})] + n_B[\omega_\mu(\mathbf{p})]}{\omega + E_\nu(\mathbf{p}+\mathbf{k}) - \omega_\mu(\mathbf{p})} \tag{9}$$

with $n_B(\omega)$ and $n_F(\omega)$ are the boson and fermion distribution functions, respectively.

The electronic Raman scattering measures the properties of Raman response function $\tilde{R}(\mathbf{q}, \omega)$, which is proportion to the imaginary part of the Raman density–density correlation function $\tilde{\chi}(\mathbf{q}, \omega)$,

$$\tilde{R}(\mathbf{q}, \omega) = -\frac{1}{\pi}\left[1 + n_B(\omega)\right] \text{Im}\,\tilde{\chi}(\mathbf{q}, \omega), \tag{10}$$

the density–density correlation function $\tilde{\chi}(\mathbf{q}, \omega)$ is defined as $\tilde{\chi}(\mathbf{q}, \tau - \tau') = -\langle T\rho_\gamma(\mathbf{q}, \tau)\rho_\gamma(-\mathbf{q}, \tau')\rangle$ with the effective charge density $\rho_\gamma(\mathbf{q})$ taken as $\rho_\gamma(\mathbf{q}) = \sum_{\mathbf{k}\sigma} \gamma_{\mathbf{k}} C^{\dagger}_{\mathbf{k}+\frac{\mathbf{q}}{2}\sigma} C_{\mathbf{k}-\frac{\mathbf{q}}{2}\sigma}$. $\gamma_{\mathbf{k}}$ is the Raman vertex determined by the incident or scattered light polarization vectors, thus it depends on the momentum throughout the Brillouin on the square lattice given in Ref. [11].

Above these, one can get the Raman density–density correlation function $\tilde{\chi}(\Omega)$ in the case of the low temperatures and momentum transfers taken as zero $q \to 0$,