Anomalous Angle-resolved Photoemission Spectra in The Colossal Magnetoresistive Bilayer Manganites

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Abstract. We have discussed anomalous angle-resolved photoemission spectra in the colossal magnetoresistive bilayer manganites by using quantized massive gauge fields, which are introduced theoretically in the path-integral method, around the photohole.

1. Introduction

La$_{1.2}$Sr$_{1.8}$Mn$_2$O$_7$ (LSMO) is a prototypical bilayer manganite that exhibits the colossal magnetoresistance (CMR) effect [1]. The CMR effect exploits a metal-insulator transition between a low-temperature ferromagnetic-metallic ground state and a high-temperature paramagnetic-insulating phase. Recently, by angle-resolved photoemission (ARPES) measurements, Mannella et al. [2] have found out experimental evidence that a very similar pseudogap state, which has been observed in underdoped high Tc cuprates, with a nodal-antinodal dichotomous character exists in the ferromagnetic metallic ground state of LSMO. That is, sharp quasiparticle peaks are only found close to the nodal points, while the spectra near the antinodal points look quite similar to the spectra for corresponding momenta in the pseudogap state of underdoped high Tc cuprates. This ARPES experiment for LSMO might demonstrate that its electronic structure and the collective excitations are strikingly similar to those found in the pseudogap phase of high Tc cuprates. The present author [3-5] has argued that the collective modes around the hole correspond to the quantized massive gauge fields, which are based on the gauge-invariant effective Lagrangian density in underdoped high Tc cuprates and diluted magnetic semiconductors. In this study, we discuss the quantized massive gauge fields-dressing of the photohole in the colossal magnetoresistive bilayer manganites, extending the previous theoretical formula [3-5].

2. A model and ARPES spectra

It has been known that the ferromagnetic ordering is due to double-exchange-like interactions of Mn 3d-$e_g$ state in LSMO. It has been suggested that the ferromagnetic interaction induced by the hole seems to be cooperative and non-linear. In order to argue in the gauge-invariant formula, we shall introduced the non-linear gauge fields (Yang-Mills fields) $A_\mu^n$, which mediate the effective ferromagnetic interaction induced by the hole. In addition, based on the important idea [6], it has been proposed that the hedgehog-like soliton in three-dimensional system is specified by rigid-body rotation, which is related to gauge fields of SO(4) symmetry for S$^3$ [7-10]. Thus it is thought that the non-linear gauge fields $A_\mu^n$ introduced by the hole have a local SO(4) symmetry. Then it is assumed that the SO(4) quadruplet fields, $A_\mu^n$, are spontaneously...
broken around the doped hole through the Anderson-Higgs mechanism, in LSMO. After the symmetry breaking $\langle 0|\phi_\alpha|0 \rangle = \langle 0, 0, 0, \mu(\hat{k}_p) \rangle$, we can obtain the effective Lagrangian density. The value of $\mu(\hat{k}_p)$ of the symmetry breaking depends strongly on the direction of the Fermi momentum $\hat{k}_p$. The value of $\mu(\hat{k}_p)$ increases from zero in the nodal direction to the large value in the antinodal direction.

$$
L_{\text{eff}} = \frac{1}{2} \left( \partial_{\mu} S^j - g_1 \varepsilon_{ijk} A^i_{\alpha} S^k \right)^2
+ \bar{\psi} \left( i \partial_0 - g_2 T_{\alpha} A^0_{\alpha} \right) \psi
- \frac{1}{2m} \bar{\psi} \left( i \nabla - g_2 T_{\alpha} A^0_{\alpha} \right)^2 \psi
- \frac{1}{4} \left( \partial_{\mu} A^0_{\alpha} - \partial_{\alpha} A^0_{\mu} + g_3 \varepsilon_{abc} A^b_{\alpha} A^c_{\mu} \right)^2
+ \frac{1}{2} \left( \partial_{\mu} \phi a - g_4 \varepsilon_{abc} A^b_{\mu} \phi c \right)^2
+ \frac{1}{2} m_1^2 \left[ (A_{\mu}^1)^2 + (A_{\mu}^2)^2 + (A_{\mu}^3)^2 \right]
+ m_1 \left[ A_{\mu}^1 \partial_{\mu} \phi_2 - A_{\mu}^2 \partial_{\mu} \phi_1 \right]
+ m_1 \left[ A_{\mu}^2 \partial_{\mu} \phi_3 - A_{\mu}^3 \partial_{\mu} \phi_2 \right]
+ m_1 \left[ A_{\mu}^3 \partial_{\mu} \phi_1 - A_{\mu}^1 \partial_{\mu} \phi_3 \right]
+ g_4 m_1 \left\{ \phi_4 \left[ (A_{\mu}^1)^2 + (A_{\mu}^2)^2 + (A_{\mu}^3)^2 \right] \right\}
- g_4 m_1 \left[ A_{\mu}^1 \phi_1 A_{\mu}^4 + \phi_2 A_{\mu}^4 + \phi_3 A_{\mu}^3 \right]
- \frac{m_2^2}{2} (\phi_4)^2
+ \frac{m_2^2 g_4}{2 m_1} \phi_4 (\phi_4)^2
- \frac{m_2^2 g_4^2}{8 m_1^2} (\phi_4 \phi_4)^2,
$$

where $S^j$ is the spin of Mn, $\psi$ is the Fermi field of the hole, $m_1 = \mu(\hat{k}_p) \cdot g_4$, $m_2 = 2(2)^{1/2} \lambda \cdot \mu(\hat{k}_p)$. Here $\hat{j}$ corresponds to the reverse direction of the spin one of the hole. The effective Lagrangian describes three massive gauge fields $A^1_{\mu}$, $A^2_{\mu}$, and $A^3_{\mu}$, and one massless gauge field $A^0_{\mu}$. The generation function $Z[J]$ for Green functions is shown as follows,

$$
Z[J] = \int \mathcal{D}A \mathcal{D}B \mathcal{D}C \mathcal{D}\bar{\phi} \mathcal{D}\psi \mathcal{D}\phi \exp i \int d^4x \left( L_{\text{eff}} + L_{\text{GR+FP}} + J \cdot \Phi \right),
$$

$$
L_{\text{GR+FP}} = B^a \partial^\mu A^a_{\mu} + \frac{1}{2} \alpha B^a B^a + i C^a \partial^\mu \phi^a C^a + J \cdot \Phi,
$$

where $B^a$ and $C^a$ are the Nakanishi-Lautrup (NL) fields and Faddeev-Popov fictitious fields, respectively.

$$
J \cdot \Phi \equiv J^a_{\mu} A^a_{\mu} + J^a_B B^a + J_S \cdot S + J_C^a C^a + J_C^C C^C
$$

$$
+ \bar{\eta} \psi + \eta \psi^+ + J^a_{\phi} \phi_a
$$

where $J \cdot \Phi$ represents the interaction terms between fields $\Phi$ and external sources $J$. BRS-quartet [11,12] in the present theoretical formula are $(\phi_1, B^1, C^1, \bar{C}^1)$, $(\phi_2, B^2, C^2, \bar{C}^2)$,
and fictitious ones. Because masses of \( A^1_{\mu}, A^2_{\mu} \) and \( A^3_{\mu} \) are created through the Anderson-Higgs mechanism by introducing the hole, the fields \( A^1_{\mu}, A^2_{\mu} \) and \( A^3_{\mu} \) exist around the hole within the length of \( \sim 1/m_1 \equiv R_C \). Where \( m_1 = \mu \cdot g_4 \) is the mass, which is introduced through the symmetry breaking in Eq. (1), of gauge fields \( A^1_{\mu}, A^2_{\mu} \) and \( A^3_{\mu} \). From the first term in Eq. (1), the spins \( S \) of Mn atoms are induced in the ferromagnetic state, where the average spin is parallel to \( \hat{j} \) direction, within the length of \( \sim R_C \) around the hole. That is, the effective Lagrangian represents that the ferromagnetically aligned Mn spins form clusters, in which the hole is trapped, with the radius, \( R_C \approx 1/m_1 \). Now we shall consider the anomalous feature of ARPES spectra in LSMO from the present theoretical view. The creation of a photohole is more likely to produce massive collective gauge fields \( A^1_{\mu}, A^2_{\mu} \) and \( A^3_{\mu} \), whose effective mass is \( \sim m_{1, eff}(k_F) \). The ARPES spectra in LSMO are given approximately by

\[
A(p, \varepsilon) \propto \frac{\text{Im}\Sigma(p, \varepsilon)}{|\varepsilon - \varepsilon_k - \text{Re}\Sigma(p, \varepsilon)|^2 + |\text{Im}\Sigma(p, \varepsilon)|^2},
\]

\[
\text{Im}\Sigma(k, \varepsilon) \propto -g_2^2 \int dp_1 \int_{-\infty}^{\infty} d\omega \int_{-\infty}^{\infty} d\varepsilon_1 \times \frac{\text{Im}D_R(k - p_1, \omega)A(p_1, \varepsilon_1)}{\omega + \varepsilon_1 - \varepsilon - i\delta} \times \left( \frac{\tanh \frac{\varepsilon_1}{2T} + \coth \frac{\omega}{2T}}{2T} \right).
\]

\[
\text{Re}\Sigma(k, \varepsilon) \propto P \int |\text{Im}\Sigma(k, \varepsilon)/(\varepsilon - \omega')|d\omega'/\pi.
\]

Where \( D_R(k, \omega) \sim \{g_{\mu\nu}/(\omega^2 - (k^2 + m^2_1)) + \Pi \} \) is the Fourier transform of the Green function, \( \langle A^a_{\mu}A^a_{\nu} \rangle_{a=1,2,3} \) of the massive gauge fields \( A^1_{\mu}, A^2_{\mu} \) and \( A^3_{\mu} \) in the ’t Hooft-Feynman gauge. \( A(p_1, \varepsilon_1) \) is the hole spectral function. The loss peaks of ARPES spectra occur when \( \text{Im}\Sigma(k, \varepsilon) \) is large. This loss feature, caused by massive collective gauge fields, will have a broad energy distribution because of the momentum dependence of the massive collective mode spectrum as well as the recoil energy of the hole when a massive collective excitation is emitted. Distortion effects by massive collective gauge fields in the antinodal points in ARPES spectra are very large, because the mass \( m_1(k_F) \) of the massive gauge fields \( A^1_{\mu}, A^2_{\mu} \) and \( A^3_{\mu} \) is very large. Thus quasiparticle peaks of ARPES spectra disappear around the antinodal points. On the other hand, since the mass \( m_1(k_F) \) is reduced remarkably around the nodal points, quasiparticle peaks appear around the nodal points. This is consistent with the recent experimental results [2].

3. Conclusion
It is suggested strongly that the pseudogap state in the colossal magnetoresistive bilayer manganite is much related with the quantized massive gauge fields around the photohole.

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