Conduction Mechanisms of Chiral-like Spin Solitons with Carriers in the Spin-Frustrated and Layered Organic Conductor

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Abstract. We have proposed the conduction mechanism of the hole-induced chiral-like spin solitons in the layered organic conductor with triangular lattice, and have discussed the pressure effect of diffusivity of those hole-induced solitons.

1. Introduction
In quasi-two-dimensional \( \kappa - (ET)_2X \) salts \([1,2]\), dimers of ET = bis[ethylenedithio]-tetrathiafulvalence molecules are arranged in an anisotropic triangular lattice, with a charge state of one hole per dimer. The mechanism of Cooper pairing in these organic superconductors is one of the fundamental but still be controversial in condensed matter physics \([3,4]\). The similarities between the layered organics and high-Tc cuprates superconductors have been suggested strongly \([1,5]\). Recently, Shimizu et al.\([6]\) found no indication of long-range magnetic ordering down to 32 mK, and have suggested that a quantum spin liquid is realized in the close proximity of the superconducting state appearing under pressure in the layered organic conductor \( \kappa - (ET)_2Cu_2(CN)_3 \). Recently, the present author \([7]\) has proposed freezing mechanism of hole-induced chiral-like spin solitons in the spin glass phase in underdoped high-Tc cuprates using the gauge-invariantly theoretical formula \([8]\). In this study, we will present the localization mechanism of hole-induced chiral-like spin solitons in the layered organic conductor with triangular lattice, extending the previous theories \([7,8]\).

2. A model system and the conduction mechanism
I Taking into account that the symmetry in the \((2 + 1)\)-dimensional quantum antiferromagnet insulator near the metallic phase is invariant under local SU(2) \([9]\), we assume that the perturbing gauge fields \( A^a_\mu \) introduced by the hole has a local SU(2) symmetry. That is, since the distortion around the hole is due to strong many-body effects, the distortion effects around the hole is nonlinear (Yang-Mill fields-like). Then it is assumed that SU(2) gauge fields \( A^a_\mu \) are spontaneously broken through the Anderson-Higgs mechanism due to the strong distortion around the hole. We set the symmetry breaking \( \langle 0|\phi_a|0 \rangle = \langle 0, 0, \mu(k_F) \rangle \) of the Bose field \( \phi_a \) in the Lagrangian density as follows,

\[
L = \frac{1}{2} \left( \partial_i N^j_c - g_t \varepsilon_{abc} \varepsilon_{ijk} A^b_k A^c_i \right)^2
\]
\[\begin{align*}
+ & \psi^+(i\partial_0 - g_2 T_a A^a_0) \psi \\
- & \frac{1}{2m} \psi^+ \left( i \nabla - g_2 T_a A^a_{(\mu\neq0)} \right) \psi \\
- & \frac{1}{4} \left( \partial_{\nu} A^a_{\mu} - \partial_{\mu} A^a_{\nu} + g_3 \varepsilon_{abc} A^b_{\mu} A^c_{\nu} \right)^2 \\
+ & \frac{1}{2} \left( \partial_{\mu} \phi_a - g_4 \varepsilon_{abc} A^b_{\mu} \phi_c \right)^2 \\
- & \lambda^2 \left( \phi_a \phi_a - \mu^2 \right)^2
\end{align*}\] (1)

\( \hat{k}_F \) is the vector of the Fermi momentum. After the symmetry breaking \( \langle 0 | \phi_a | 0 \rangle = \langle 0, 0, \mu(\hat{k}_F) \rangle \), that is, transition of fields \( \phi_a \) with a zero asymptotics at infinity,

\[(\phi_1, \phi_2, \phi_3) \rightarrow (\phi_1, \phi_2, \mu(\hat{k}_F) + \phi_3)\]

makes the isotopic-symmetry breaking explicit, and we can obtain the effective Lagrangian density \( \mathcal{L}_{eff} \). That is, \( \langle 0 | \phi_3 | 0 \rangle \) can be regarded as a kind of the disorder parameter \( 10 \). The value, \( \mu(\hat{k}_F) \), of the symmetry breaking depends on the direction of Fermi momentum, \( \hat{k}_F \), on the Fermi surface.

\[\mathcal{L}_{eff} = \frac{1}{2} \left( \partial_{\mu} N^j_c - g_1 \varepsilon_{abc} \varepsilon_{jik} A^b_{\mu} N^k_a \right)^2 + \psi^+(i\partial_0 - g_2 T_a A^a_0) \psi - \frac{1}{2m} \psi^+ \left( i \nabla - g_2 T_a A^a_{(\mu\neq0)} \right) \psi - \frac{1}{4} \left( \partial_{\nu} A^a_{\mu} - \partial_{\mu} A^a_{\nu} + g_3 \varepsilon_{abc} A^b_{\mu} A^c_{\nu} \right)^2 + \frac{1}{2} \left( \partial_{\mu} \phi_a - g_4 \varepsilon_{abc} A^b_{\mu} \phi_c \right)^2 + \frac{1}{2} m_1^2 \left[ (A^1_{\mu})^2 + (A^2_{\mu})^2 \right] + m_1 \left[ A^1_{\mu} \partial_{\mu} \phi_2 - A^2_{\mu} \partial_{\mu} \phi_1 \right] + g_4 m_1 \left\{ \phi_3 \left[ (A^1_{\mu})^2 + (A^2_{\mu})^2 \right] - A^3_{\mu} \left[ \phi_1 A^1_{\mu} + \phi_2 A^2_{\mu} \right] \right\} - \frac{m_2^2}{2} (\phi_3)^2 - \frac{m_2^2 g_4}{2 m_1} (\phi_3 (\phi_2)) - \frac{m_2^2 g_4^2}{8 m_1^2} (\phi_2 (\phi_3))^2, \] (2)

where \( N^i_c \) is the spin parameter, \( \psi \) Fermi field of the hole, \( m_1 = \mu \cdot g_4, m_2 = 2\sqrt{2} \lambda \cdot \mu \), and \( T_a \) are the SU(2) generators. The effective Lagrangian describes two massive vector field \( A^1_{\mu} \) and \( A^2_{\mu} \), and one massless U(1) gauge field \( A^3_{\mu} \). Because masses of \( A^1_{\mu} \) and \( A^2_{\mu} \) are formed through the Higgs mechanism by introducing the hole, the fields \( A^1_{\mu} \) and \( A^2_{\mu} \) exist around the hole within the length of \( 1/m_1 \approx R_c \). Taking into account the interaction between the hole \( \psi \) and the gauge fields \( A_{\mu} \) in the third term in eq.(2) and the interaction between the gauge fields \( A_{\mu} \) and the boson field \( \phi \) in the fifth term in eq.(2), we get the effective value, \( \mu_{eff} \), from the sum of the polarization bubble by hole-electron propagator in the random phase approximation as follows,

\[ \mu_{eff} \sim \frac{1}{1 + \sum_{q} D_R(q, \omega) \sum_{k} g_2^2 G(k + q) G(-k)} \]

\[ = \frac{1}{1 + \sum_{q} \sum_{k} M_{qk}} \] (3)
The matrix, $M_{qk}$, is $D_R(q, \omega)g_{2}^{2}G(k + q)G(-k)$. This matrix means the mixing term between the hole-induced chiral-like spin soliton with the radius $\sim R_c$ and other holes. Where $D_R \sim \frac{g_{\mu\nu}}{(\omega^2 - (q^2 + m_1^2) + \Pi}$ is the Green function of massive gauge fields $A_1^{\mu}$ and $A_2^{\mu}$ in the 't Hooft-Feynman gauge. $G(k)$ is the Green function of the hole. When the pressure on the sample increases, the matrix, $M_{qk}$, increases. As a result, the effective value, $\mu_{eff}$, decreases. From the first term in eq.(2), the spin $S^a_i$ is much distorted within the length of $\sim R_c$ around the hole. Furthermore, the spin order will be distorted in the long range by the massless U(1) gauge field $A_2^{\mu}$. When $S(i)$, $S(j)$ and $S(k)$ are spins on triangle sites $i$, $j$ and $k$ within $\sim \pi R_c^2$ around the hole at the site $i$, the chiral spin liquid parameter $q_i$ is introduced as follows [11], $q_i \equiv \sum_{(ijk) \in \pi R_c^2} S(i) \cdot (S(j) \times S(k))$, where $(ijk)$ are local triplet sites of spins. Now we shall consider the conduction mechanism of hole-induced chiral-like spin solitons with defects of short range type. From Eq. (2), we can obtain the Green functions of the massive gauge fields $A_1^{\mu}$, and $A_2^{\mu}$ around the hole in 't Hooft-Feynman gauge as follows, that is, the Fourier transform of $\langle A_1^{\mu}A_2^{\mu}\rangle_{a=1,2}$ is

$$D_R(p_1, \varepsilon_1) \sim \frac{g_{\mu\nu}}{\varepsilon_1^2 - (p_1^2 + m_1^2) + \Pi}$$. \hfill (4)

The thermal Green function $g(k, \varepsilon_n)$, ($\varepsilon = (2n + 1)\pi T$, $T$ being the temperature), of the hole is given as follows,

$$g(k, \varepsilon_n) = \frac{1}{i\varepsilon_n - \xi - \sum(k, \varepsilon_n)}, \hfill (5)$$

where $\xi = k^2/2m - E_p$

$$\sum(k, \varepsilon_n) = -\frac{g_{2}^{2}}{(2\pi)^2} \int dp_1 \int_{-\infty}^{\infty} d\omega \int_{-\infty}^{\infty} d\varepsilon_1 \frac{\text{Im}g(k - p_1, \omega)\text{Im}D_R(p_1, \varepsilon_1)}{\omega + \varepsilon_1 - i\varepsilon_n - i\delta} \left(\text{tanh}\frac{\varepsilon_1}{2T} + \coth\frac{\omega}{2T}\right). \hfill (6)$$

The propagator $\Gamma(q, \omega_l)$ of the hole by the scattering is represented as,

$$\Gamma(q, \omega_l) \sim \frac{n_i u^2}{1 - n_i u^2 X(q, \omega_l)}. \hfill (7)$$

Here $\omega_l$ is $2\pi l T$, $l$ is integer, $u$ is the scattering amplitude by defects of short range type, and $n_i$ is average concentration of the hole.

$$X(q, \omega_l) = \sum_k g(k + q, \varepsilon_n + \omega_l) \cdot g(-k, \varepsilon_n)$$

$$\times \int_{-\infty}^{\infty} d\xi \int d\Omega \left[i\varepsilon_n + i\omega_l - \xi - v q + i\text{Im} \sum(k, \varepsilon_n + \omega_l) \cdot \text{sgn}(\varepsilon_n + \omega_l)\right]^{-1} \cdot \left[i\varepsilon_n - \xi + i\text{Im} \sum(k, \varepsilon_n) \cdot \text{sgn}(\varepsilon_n)\right]^{-1}, \hfill (8)$$

where $v = k/m$.

The integration over $d\Omega$ is over the angle of $v$. If $\varepsilon_n(\varepsilon_n + \omega_l) < 0$, $X(q, \omega_l)$ is evaluated for small $q$ and $\omega_l$ as follows,

$$X(q, \omega_l) \sim \frac{1}{\text{Im} \sum(k, \varepsilon_n)} \left[1 - Dq^2 \frac{1}{\text{Im} \sum(k, \varepsilon_n)} - |\omega_l| \frac{1}{\text{Im} \sum(k, \varepsilon_n)}\right]. \hfill (9)$$
Here \( D = \frac{v_F^2}{d \cdot \text{Im} \sum (k, \varepsilon_n)} \) is the diffusion constant. \( v_F \) and \( d \) are Fermi velocity and dimension of system, respectively. Thus \( \Gamma(q, \omega) \) is represented as

\[
\Gamma(q, \omega) \propto \left( \frac{1}{\text{Im} \sum (q, \varepsilon_n)} \right)^2 \left[ Dq^2 + |\omega| \right].
\]

(10)

Taking into account \( \text{Im} \sum (k, \varepsilon_n) \) in the diffusion constant \( D \), Eq. (10) shows that the massive gauge fields \( A^1_{\mu} \) and \( A^2_{\mu} \) around the hole influence strongly the diffusive and localization property of the hole transport. When the pressure on the sample increases, the matrix \( M_{qk} \) in eq.(3) increases, and the effective value, \( \mu_{\text{eff}} \), decreases. Then, the effective mass, \( m^1_{\text{eff}} \sim \mu_{\text{eff}} g_4 \), of the gauge fields \( A^1_{\mu} \) and \( A^2_{\mu} \) decreases. As a result, \( \text{Im} \sum (k, \varepsilon_n) \) is reduced remarkably. Thus increase of the pressure on the sample induces strongly the increase of the diffusion constant, \( D \), of the hole-induced chiral-like spin soliton. This is consistent with recent experimental results [12].

3. Conclusion

The conduction mechanism of hole-induced chiral-like spin solitons in the layered spin-frustrated organic conductor is proposed. The pressure effect of diffusive property of those solitons has been discussed.

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