The fluctuation of a local magnetic field in underdoped cuprates

I. Kanazawa [a,1]

[a] *Department of Physics, Tokyo Gakugei University, Koganei-shi, Tokyo 184-8501, Japan*

Abstract

We have proposed the relationship between the spin freezing temperature and the planar hole content (P_{sh} <∼ 0.02) in underdoped cuprates from the chiral-like spin-glass mechanism.

Key words: high-Tc cupratus; spin glass; spin chirality

1. Introduction

Nuclear magnetic-nuclear quadrupole resonance [1] and muon spin resonance experiments [2] show that there exists the phenomenon, generally interpreted in terms of "glassy spin-freezing", in underdoped cuprates. Niedermayer *et. al.* [2] found a very interesting result that the spin freezing temperature T_f exhibits the same linear dependence on the planar hole content, P_{sh}, for Y. Ca-123 and La. Sr-214 in lightly doped systems. (P_{sh} <∼ 0.02). This transition has been ascribed to a freezing of the spins of the doped holes into a spin-glass state which is superimposed on the preexisting 3D AF long range order of the Cu^{2+} spins [2]. The present author has proposed the chiral-like spin-glass mechanism in underdoped high-Tc cuprates in the mean-field approximate using the replica method [3,4]. Recently Mook *et. al.* [5] by means of inelastic neutron scattering measurements in underdoped high-Tc cuprates (YBCO) detected longitudinal with respect to c-axis magnetic moment of unknown origin. In the present study, we will present the relationship between the spin freezing temperature and the planar hole content (P_{sh} <∼ 0.02) and an origin of the magnetic moments longitudinal to c-axis from chiral-like spin-glass mechanism.

2. A model system

Though the symmetry breaking $\langle 0|\phi_a|0\rangle = \langle 0, 0, \mu(k_{\rm F})\rangle$, we can obtain the effective Lagrangian density, $\mathcal{L}_{\rm eff}$, at small doping of holes [3,4]. The value, $\mu(k_{\rm F}) = \langle 0|\phi_3|0\rangle$, of the symmetry breaking depends strongly on an angle of Fermi momentum, $k_{\rm F}$, on the Fermi surface. That is, the value $\mu(k_{\rm F})$, is much correlated to the gap energy of the high energy pseudogap. Thus, the value, $\mu(k_{\rm F})$, is higher around the hot spot.

$$
\begin{aligned}
\mathcal{L}_{\rm eff} = & \frac{1}{2}\left(\partial_i S_c^j - g_1 \varepsilon_{abc}\varepsilon_{jik} A_i^b S_a^k\right)^2 \\
& + \psi^+ \left(i\partial_0 - g_2 T_a A_0^a\right)\psi \\
& - \frac{1}{2m}\psi^+ \left(i\nabla - g_2 T_a A^a_{(\mu\neq 0)}\right)^2 \psi \\
& - \frac{1}{4}\left(\partial_\nu A_\mu^a - \partial_\mu A_\nu^a + g_3\varepsilon_{abc} A_\mu^b A_\nu^c\right)^2 \\
& + \frac{1}{2}\left(\partial_\mu \phi_a - g_4 \varepsilon_{abc} A_\mu^b \phi_c\right)^2 \\
& + \frac{1}{2} m_1^2 \left[(A_\mu^1)^2 + (A_\mu^2)^2\right] \\
& + m_1 \left[A_\mu^1 \partial_\mu \phi_2 - A_\mu^2 \partial_\mu \phi_1\right] \\
& + g_4 m_1 \Big\{ \phi_3 \left[(A_\mu^1)^2 + (A_\mu^2)^2\right] \\
& - A_\mu^3 \left[\phi_1 A_\mu^1 + \phi_2 A_\mu^2\right] \Big\} - \frac{m_2^2}{2}(\phi_3)^2 \\
& - \frac{m_2^2 g_4}{2m_1}\phi_3(\phi_a)^2 - \frac{m_2^2 g_4^2}{8m_1^2}(\phi_a\phi_a)^2, \qquad (1)
\end{aligned}
$$

[1] E-mail:kanazawa@u-gakugei.ac.jp

where S_a^i is the spin parameter, ψ is Fermi fields of the hole, $m_1 = \mu \cdot g_4$, $m_2 = 2\sqrt{2}\lambda \cdot \mu$. The effective Lagrangian describes two massive vector field A_μ^1 and A_μ^2, and one massless U(1) gauge field A_μ^3. From the first term in Eq. (1), the spin S_a^i is much distorted from the anti-ferromagnet state 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_μ^3 [6]. When $S(i)$, $S(j)$ and $S(k)$ are spins on triangle sites i, j and k within $\sim \pi R_c^2\left(\tilde{i}\right)$ around the hole at the site $\tilde{i}$, the chiral spin liquid parameter $q_{\tilde{i}}$ is introduced as follows [7], $q_{\tilde{i}} \equiv \sum_{(ijk)\in\pi R_c^2(\tilde{i})} S(i)\cdot(S(j)\times S(k))$, where (ijk) are local triplet sites of spins. Because the hole state trapped into the hedgehog-like soliton is thought as that the instanton-like fluctuation [8] is stabilized by the hole [9,10], we assume that $q_{\tilde{i}}$ is approximately proportional to the topological number of the instanton $\sim c/4\pi \int \mathrm{d}x\mathrm{d}y(S\cdot\partial_x S\times\partial_y S) \sim c/2\pi\cdot\int \mathrm{d}S_{\mu\nu}(\partial_\mu A_\nu^3 - \partial_\nu A_\mu^3)$ [11]. When the carrier is located at the position $r_{\tilde{i}}$ and $|r - r_{\tilde{i}}| \gg 1/|m_1| \sim R_c$ is assumed, the gauge field $A_\mu^3(r, r_{\tilde{i}})$ at the position r is represented as $A_\mu^3(r, r_{\tilde{i}}) \propto q_{\tilde{i}}/|r - r_{\tilde{i}}|$. Thus, we can introduce the interaction between the chiral spin-disordered hedgehog-like solitons at positions $r_{\tilde{i}}$ and $r_{\tilde{j}}$ as $V_{\tilde{i}\cdot\tilde{j}} \propto (q_{\tilde{i}}\cdot q_{\tilde{i}})/|r_{\tilde{i}} - r_{\tilde{j}}|$. For the mean-field approximate, it is assumed that $V_{\tilde{i}\cdot\tilde{j}}$ describes N hedgehog-like soliton's interaction, which mediated by the massless U(1) A_μ^3 fields in pairs $(\tilde{i},\tilde{j})$ via infinite-range Gaussian-random interaction for simplifying discussion [11],

$$P(V_{\tilde{i}\tilde{j}}) = \frac{1}{(2\pi\langle V_{\tilde{i}\tilde{j}}^2\rangle)^{1/2}} \exp\left(\frac{-V_{\tilde{i}\tilde{j}}^2}{2\langle V_{\tilde{i}\tilde{j}}^2\rangle}\right) \tag{2}$$

Now we can get the spin-glass-like behavior from the analogy of the Sherrington-Kirkpatrik (SK) formula by using the replica method. We can define the order parameter $\bar{G} \equiv \int_0^1 \mathrm{d}x Q(x)$, where $Q(x)$ is the Parisi order parameter and is derived from $Q^{\alpha\beta} = \langle q_{\tilde{i}}^\alpha q_{\tilde{i}}^\beta\rangle$, in Parisi's theoretical formula [12]. In the temperature region below $T_f = \left(N\left\langle V_{\tilde{i}\tilde{j}}{}^2\right\rangle\right)^{1/2}/k_B$, we got the phase of the order parameter $\bar{G} \neq 0$ and $\langle q_{\tilde{i}}^\alpha\rangle = 0$, which corresponds to the chiral spin-glass phase, within the mean-field approximate. From the avarage of $\left|r_{\tilde{i}} - r_{\tilde{j}}\right|^2 \propto 1/P_{sh}$ and $N \propto P_{sh}$, we can get approximately the relation, $T_f = \left(N\left\langle V_{\tilde{i}\tilde{j}}{}^2\right\rangle\right)^{1/2}/k_B \propto P_{sh}/k_B$. Where P_{sh} is the planar hole content. This relation is consistent with the recent experiment [2]. It is known from the present theory that there exists the spin chirality $q_{\tilde{i}} = \sum_{(ijk)\in\pi R_c^2(\tilde{i})} S(i)\cdot(S(j)\times S(k))$ around the hole at the position $\tilde{i}$ in the chiral spin glass pahse. This spin chirality $q_{\tilde{i}}$ means that spin-components longitudinal to c-axis are induced strongly around the hole. These induced magnetic components, which are longitudinal to c-axis, around the hole might correspond to ones observed by Mook *et. al.* [5].

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