Dynamics of the Composite Gauge Bosons in the Strongly-Correlated Electron Systems

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Since the discovery of cuprate high-temperature superconductors, there has been a lot of interest in theoretical studies on the strongly-correlated electron systems. It is now accepted that the t-J model is one of the canonical models of the high-T_c superconductors, and this model has been studied extensively by various methods.

Most difficult aspect of the t-J model is the existence of a local constraint on the physical states, excluding the double-occupancy of electrons at each site. Many recent studies employ the slave-boson or the slave-fermion formalism for incorporating this constraint. Some experimentally-observed exotic behaviours of the high-T_c materials in the metallic phase, like (i) the resistivity rising linealy with the temperature and (ii) the difficulty in the Fermi-liquid picture to reconcile the sign of Hall coefficient and the large electronic fermi surfaces, are expected to be explained when the spin and charge degrees of freedom of electrons behave almost independently; this phenomenon is called the charge-spin separation (CSS)[1].

It is also expected that the phenomenon of CSS may be naturally explained in the slave-boson or the slave-fermion formalism. Actually, the straightforward application of the mean-field (MF) theory to the t-J model in the slave-boson (or slave-fermion) formalism implies that holons and spinons should appear as quasi-particles having almost no interactions. The involved MF's live on links of the lattice and describe the nearest-neighbour (NN) pairings of holon-holon and/or spinon-spinon. However, such MF studies are not sufficient by themselves; one should check the stability of MF's. In the t-J model, the stability of MF's is subtle since these MF's are agents of the local $U(1)$ "gauge" symmetry that exists in the original Hamiltonian of the t-J model in the slave-boson (-fermion) representation. In fact, in order to respect this gauge symmetry, we have to take into account the phase degrees of freedom of MF variables. These phases behave as gauge bosons, though there is *no* Maxwell term (i.e., no kinetic term) for them in the original Hamiltonian. That is, they should be regarded as *composite* gauge bosons. Some phenomenological consequences of such gauge bosons were explored in Ref.[2] in the framework of perturbation theory in the uniform-RVB MF theory. Study of the global properties of the dynamics of these composite gauge bosons, e.g., its phase structure, is crucial to determine whether and where the CSS occurs in the t-J model. Actually, the qualitative results of a straightforward MF theory mentioned above are validated *a posteriori* only if the CSS takes place, as such a MF theory assumes the weakness of coupling of gauge bosons to holons and to spinons. In other words, identification of the parameter region in which the CSS occurs implies the identification of region in which the MF theory is applicable.

The phase structure of the gauge theory of *elementary* gauge bosons has already been studied extensively in the framework of lattice gauge theory both by the analytic and numerical methods. Most relevant phase transition to the present study is the confinement-deconfinement (CD) phase transition at finite temperature (T). This phase transition was first studied by Polyakov and Susskind [3] by analytic method and later confirmed by numerical Monte-Carlo calculations. From the knowledge of these studies, one may draw the following picture of the gauge dynamics in the t-J model. If the composite gauge bosons in the t-J model live in a confinement phase, the gauge coupling is so strong that only gauge-invariant (i.e., gauge-charge neutral) objects are physically observable (that is amost the definition of the confinement); possible quasi-particles are thus electrons themselves, spin and charge density waves of electrons, etc. On the other hand, if they are in a deconfinement phase (i.e., no confinement occurs), the gauge coupling is weak enough that *gauge-variant* (gaugenonneutral) objects are observable; the quasi-particles are holons, spinons and gauge bosons. Just in this deconfinement phase, the CSS phenomenon may and must occurs. The perturbative calculation assuming small gauge coupling is justified in that phase. This characterization of CSS phenomenon in terms of deconfinement phase of $U(1)$ gauge theory is pointed out in Ref.[4].

Motivated by this observation, we studied the dynamics of the composite gauge boson at finite T in the CP^{N-1} model coupled with fermions[4]. There we derived the relevant gauge system of the composite gauge boson and mapped it to the classical (isotropic) XY spin model, according to the Polyakov-Susskind method [3]. We first examined the pure CP^{N-1} model. As is well-known, the CP^1 model is a low-energy effective theory of the $S = \frac{1}{2}$ antiferromagnetic (AF) Heisenberg model. Our study in Ref.[4] shows that, in the $(2+1)$ dimensional CP^{N-1} model, a deconfinement phase exists only at $T = 0$, and in that phase the quasi-particle excitation is the gapless spin wave. At any finite T, the model is in a confinement phase, and there is a mass gap in spin excitation. This result is desired, because the long-range Neel order exists only at $T = 0$ in the 2D AF Heisenberg model. Thus our method for composite gauge bosons was checked to predict the correct phase structure of the CP^1 model. By applying the same method and techniques to the CP^1 model coupled with gapless fermions in a gauge invariant manner, we also examined the effect of fermions to the gauge dynamics. By using the hopping expansion of the fermion kinetic term, we obtained a modified gauge theory having a deconfinement phase at $T < T_{CD}$, where the critical temperature of CD transition T_{CD} is calculable and becomes finite. Thus we showed the CSS occurs for $T < T_{CD}$. Very recently, similar problem was studied by the perturvative loop expansion of fermions[5]. Mapping to the Polyakov-Susskind model was also employed there and the existence of a deconfining phase was rederived.

In the recent paper[6], we applied the formalism and the results developed in the previous paper to the full-fledged t-J model. In the previous paper, we considered only a single kind of composite gauge boson. However, in the t-J model there appear multiple MF's in general, thus multiple gauge bosons. Each MF bears its own physical meaning. Coexistence of the multiple gauge bosons and interactions among them requires an independent analysis. In fact the gauge bosons are classified into two groups according to their transformation properties, and the coexistence of these groups gives rise to an important modification of the Polyakov-Susskind theory. Actually we showed that the reference XY spin model that appears in the Polyakov-Susskind theory is modified from the isotropic XY model to an anisotropic XY model. This implies that the gauge dynamics in the deconfinement phase is realized not in the Coulomb phase but in the *Higgs* phase.

All the basic steps of our approach to study the mechanism of CSS are listed up as follows;

(i) Introduction of MF variables;

(ii) Integration over holon and spinon variables by the hopping expansion;

(iii) Identifying the lattice gauge theory by keeping the leading contributions;

(iv) Mapping the lattice gauge theory to a classical XY spin model;

(v) Calculation of T_{CD}, using the mapped spin model.

All further detales are found in Ref.[4, 6].

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