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Spin Backflow in the Vicinity of Spin Polarons in the $t-J$ Model

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We investigate the spin backflow current in a spin-1/2 Heisenberg quantum antiferromagnet associated with the motion of a hole. The spin backflow is studied here with two different methods: (a) starting from the wave function of the hole-like quasiparticle obtained in the self-consistent Born approximation and (b) an approximation-free exact diagonalization technique. Spin currents calculated analytically are in a good agreement with small cluster diagonalization studies.

The motion of a single vacancy (hole) in a 2D antiferromagnet (AF) was extensively investigated using various analytical approaches as well as with exact diagonalization of small clusters[1]. Consensus has been achieved regarding, e.g., the ground-state energy and the quasiparticle (QP) bandwidth.

The aim of this work is to present a more detailed picture of the quasiparticle. An interesting aspect of the deformation of the spin-background is contained in the bond-spin currents

$$\mathbf{j_r} = \langle n_0 (\mathbf{S}_{\mathbf{r}_1} \times \mathbf{S}_{\mathbf{r}_2})^z \mathbf{e} \rangle \tag{1}$$

relative to the position of the hole. Here n_0 is the position operator for a hole at $\mathbf{r}=0$ and $\mathbf{e}$ is a unit vector $\mathbf{e}=\mathbf{r}_2-\mathbf{r}_1$. This quantity follows from the equation of motion for the spin density $\dot{\mathbf{S}}_\mathbf{r} = it\sum_{\mathbf{e},ss'}(\hat{\sigma}_{ss'}c^\dagger_{\mathbf{r},s}c_{\mathbf{r}+\mathbf{e},s'} - \mathrm{H.c.}) - 2iJ\sum_\mathbf{e} \mathbf{S}_\mathbf{r}\times\mathbf{S}_{\mathbf{r}+\mathbf{e}}$, where $\hat{\sigma}$ are Pauli spin matrices. Here the first term is the spin current induced by the hopping of the hole and the second term ($\sim \mathbf{j_r}$) describes the backflow in the spin system. In the following we limit ourselves to the study of the z component of the current. We note that nonvanishing cross-products are necessary prerequisites of unconventional ground states with spiral or chiral order.

The quasiparticle wave function is derived on the level of a self-consistent Born approximation (SCBA) using a reformulation of the t-J Hamiltonian in terms of spinless fermions and Schwinger bosons [2]. By means of linear spin wave theory we introduce the proper collective excitations of the Heisenberg antiferromagnet. The QP-wave function is given by [3,4]

$$|\Psi^{(n)}_\mathbf{k}\rangle = a_\mathbf{k}\Big[h^\dagger_\mathbf{k} + N^{-\frac{1}{2}}\sum_{\mathbf{q}_1} M_{\mathbf{k}\mathbf{q}_1} G_{\bar{\mathbf{k}}_1}(\bar{\omega}_1) h^\dagger_{\bar{\mathbf{k}}_1}\alpha^\dagger_{\mathbf{q}_1}$$
$$\ldots + N^{-\frac{n}{2}}\sum_{\mathbf{q}_1,\ldots,\mathbf{q}_n} M_{\mathbf{k}\mathbf{q}_1} G_{\bar{\mathbf{k}}_1}(\bar{\omega}_1)\ldots M_{\bar{\mathbf{k}}_{n-1}\mathbf{q}_n}$$
$$\times G_{\bar{\mathbf{k}}_n}(\bar{\omega}_n)\, h^\dagger_{\bar{\mathbf{k}}_n}\alpha^\dagger_{\mathbf{q}_1}\ldots\alpha^\dagger_{\mathbf{q}_n}\Big]|0\rangle.$$

where $h^\dagger_\mathbf{k}$ is the creation operator for a (spinless) hole in a Bloch state, $\alpha^\dagger_\mathbf{q}$ creates an AF magnon with energy $\omega_\mathbf{q}$ and the fermion-magnon coupling is given by $M_{\mathbf{kq}}$. We calculate the Green's function for the hole $G_{\bar{\mathbf{k}}_n}(\bar{\omega}_n)$ in SCBA, where $\bar{\mathbf{k}}_m = \mathbf{k} - \sum_1^m \mathbf{q}_i$ and $\bar{\omega}_m = \epsilon_\mathbf{k} - \sum_1^m \omega_{\mathbf{q}_i}$.

In Fig. 1 the spatial dependence of the bond spin currents is shown for $\mathbf{k}=(5/8\pi, 5/8\pi)$ and $J/t=0.4$. The calculation was performed using a $N=16\times16$ unit cell and the number of excited magnons in the wave function $|\Psi^{(n)}_\mathbf{k}\rangle$ was restricted to $n=3$ [4].

In Fig. 2(a) $j_\mathbf{r}$ is presented for various bonds $\mathbf{r}$ defined in the inset. $j_\mathbf{r}$ is an odd function with respect to the wave vector (at $k=0$). Because of the symmetry it vanishes also at $\mathbf{k}=(\pi,0)$. Since the ground state has AF long-range order, the points $\mathbf{k}$ and $\mathbf{k}+(\pi,\pi)$ are equivalent, and therefore, $j_\mathbf{r}$ vanishes also at $\mathbf{k}=(\pi/2,\pi/2)$.

To test the validity of the approximations made we have performed exact diagonalization of $N=\sqrt{18}\times\sqrt{18}$ and $N=\sqrt{20}\times\sqrt{20}$ sites clusters. In such a small system there are only a few nonequivalent points in the Brillouin zone,

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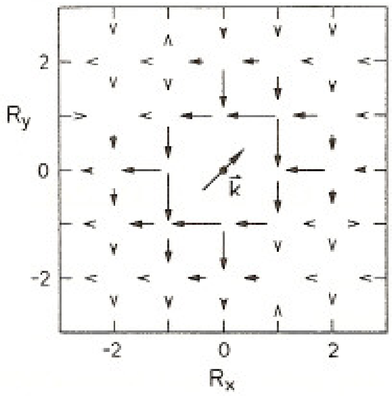

Figure 1. Bond spin currents $\mathbf{j_r}$ for $J/t = 0.4$ and $\mathbf{k} = (5/8\pi, 5/8\pi)$. The unit cell was $N = 16 \times 16$. The length of arrows is proportional to $|\mathbf{j_r}|$.

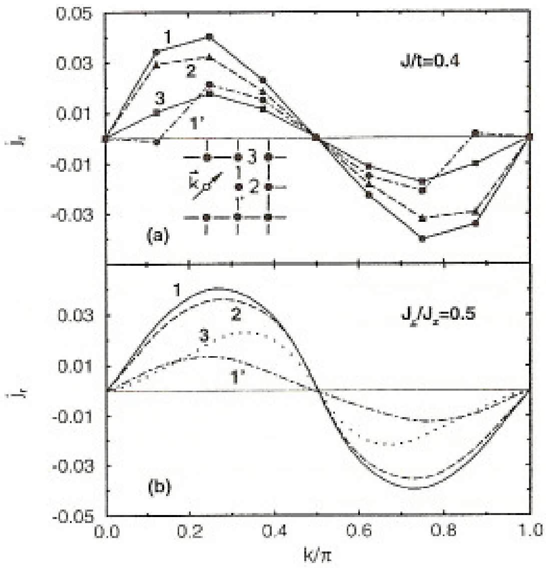

Figure 2. Momentum dependence of bond spin current along $\mathbf{k} = (k, k)$ for $J/t = 0.4$. (a) Results of the SCBA. The lines connecting the symbols are a guide to the eye only. (b) Results obtained with the exact dagonalization of $N = 18$ sites system and $J_\perp/J_z = 0.5$.

therefore we introduced in the hopping part of the $t - J$ model the phase factors corresponding to the effect of a vector potential [5]. We considered the variation of the phase in the direction which corresponds to the momentum $\mathbf{k} = (k, k)$. In Fig. 2(b) we present results obtained for a unit cell with 18 sites and anisotropic Heisenberg coupling $J_\perp/J_z = 0.5$. The symmetry of $j_\mathbf{r}$ around $\mathbf{k} = (\pi/2, \pi/2)$ is the same as the result obtained within the SCBA. However, comparing the results for $N = 18$ and $N = 20$ sites system in the isotropic limit ($J_\perp = J_z$) we found rather strong finite size effects and the analysis will be presented elsewhere.

In conclusion we have investigated spin-current correlation function around a mobile spin vacancy using the self-consistent Born approximation for the hole self-energy and the corresponding wave function. Using the same method we also found that various correlation functions decay far from the hole as a power-law. Nevertheless the QP spectral weight is finite. In the vicinity of the hole we compared the results with small cluster diagonalization studies. The agreement of the short-range behavior with the exact diagonalization results shows that approximations made in the model and by introducing the SCBA are not harmful. In particular both approaches yield a sign change of $j_\mathbf{r}$ at $\mathbf{k} = (\pi/2, \pi/2)$.

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