Comment on "Two-Dimensional Antiferromagnetic Quantum Spin-Fluid State in La_2CuO_4"

I have proposed[1] that a new type of state of the $n=1$ large U Hubbard model—equivalent, roughly, to the Heisenberg Hamiltonian—underlies the unique phenomena found in the high-T_c superconductors. This state is an insulating, featureless singlet which I have called the "resonating valence bond" state. I have proposed in particular that superconductivity follows when carriers are doped into this state, which was supposed to exist in pure La_2CuO_4. It has been controversial whether or not this state exists and is stable, and whether, if it exists, it has an energy gap.[2]

I showed, by means of a local gauge theory due to Baskaran,[3] and an argument due to Affleck, that it is very likely that the state—if it exists—is gapless, even in the presence of phonon-spinon coupling,[4] and a number of independent, plausible, but not rigorous arguments[5] led me to the belief that it has a "pseudo-Fermi surface." In fact, I argued in Ref. 4 that the best mean-field representation of the state and its excitations is that of Baskaran, Zou, and Anderson.[6] This can be shown, by means of the local SU(2) "gauge" symmetry which the problem possesses when expressed in terms of fermionic spin solitons or "spinons," to be an equivalent ground state to the Gutzwiller projected free Fermi seas of Kaplan and Fulde[7] and Rice, Gros, and Joynt.[8]

In this theory the excitation spectrum is simply that of a Fermi sea of neutral fermions $s_{k\sigma}$ with spin, having a kinetic energy

$$E_k^{\rm eff}=J'(\cos k_x \pm \cos k_y). \tag{1}$$

J' is a renormalized J related to the Heisenberg $J=t^2/U$ by a constant of order unity, and the sign is irrelevant under the gauge symmetry. The pseudo-Fermi surface is at $E_k^{\rm eff}=0$.

The spectrum of spin fluctuations has an inverse square-root singularity for small q along the lines in q,ω space given by

$$\omega_0=\mathbf{q}\cdot\mathbf{v}_f^0, \tag{2}$$

where v_f^0 is

$$v_f^0=(J'a/\hbar)(\pm 1, \pm 1).$$

That is,

$$p_q(\omega)d\omega \propto \cos\theta_{q,v_f^0}\, d\omega/(\omega_0^2-\omega^2)^{1/2}.$$

This spectrum should extend out along the lines satisfying Eq. (2) with diminished amplitude. It will be repeated in k space at intervals of $\pm 2k_F^0$, where $k_F^0=2\pi/a$ and $2\pi/c$.

At the point in 2D k space investigated by Shirane *et al.*,[9] there should be back-to-back inverse square-root singularities separated at given ω by $\Delta q=2w/v_F^0$. These will appear as a vertical line along the ω axis if the q resolution is as stated in the reference, and if $J'\gtrsim 1000$ K, a region of values agreeing with what I have estimated on other grounds. The spinon spectrum is probably purely two dimensional, since the particles are solitons and will find it difficult to tunnel between planes.

I thus propose that this singularity is responsible for the inelastic neutron-scattering spectrum observed by Shirane *et al.*[9] The linear specific heat observed by Phillips *et al.*[10] suggests a value in the higher range, but there is an unknown Fermi-liquid factor relating the two.

I anticipate that the pseudo-Fermi surface will persist into the superconducting state, perhaps with smaller effective J', as observed in specific-heat data. It is significant, but of course goes beyond the data of Ref. 9, that according to most phase diagrams (e.g., Johnston *et al.*[11]) the superconducting state arises from the continuation of this phase, not from the antiferromagnetic state.

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