Construction of a non-Fermi liquid ground state

"Non-Fermi *d*-wave phases of strongly interacting electrons"

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Recommended and a Commentary by Patrick Lee, MIT

Landau's Fermi liquid theory is one of the most successful theories in modern physics. It gives a satisfactory description of essentially all the clean metals that we know. An extreme example can be found in heavy fermion compounds, where the theory survives despite a mass enhancement of thousands. Even in one dimension, the Luttinger liquid can be considered a cousin of Landau's Fermi liquid, where the Fermi wave vector survives as the point where the electron momentum distribution function $n(\boldsymbol{k})$ has a singularity instead of a step discontinuity. A few exceptions have been found in the vicinity of quantum critical points, but it is the linear in temperature resistivity found in high T_c superconductors that puts the notion of non-Fermi liquid to the forefront of research, even though the intervention of superconductivity makes it difficult to ascertain whether the non-Fermi liquid behavior survives as a ground state property over a range of doping. It has long been recognized that finding an exception to the Landau paradigm will be considered a major breakthrough. The paper by Jiang *et al.* has achieved an important step towards this challenge.

This paper is the culmination of an effort started five years ago by Motrunich and Fisher[1] to create a description of the Bose metal state in two dimensions. It has long been recognized that a promising path to create a non-Fermi liquid state is fractionalization (also known as parton construction). One example is to write the electron operator c_σ as a product of a ferminic spinon f_σ and a bosonic holon b^+. The trouble is that bosons typically either Bose-condense, or are gapped. The Bose condensate immediately gives rise to a Fermi liquid while the gapped state gives rise to an insulator. Thus the bottleneck in creating a non-Fermi liquid metal lies in the difficulty of creating a Bose metallic ground state. In Ref 1, Motrunich and Fisher proposed decomposing the boson further into a product of two fermions, d_1 and d_2. They made a bold proposal that the Fermi surface and d_1,d_2 are elongated in the x and y directions, respectively. This is to avoid the pairing instability which tends to appear if the two Fermi surfaces coincide. The constraint that each site is occupied by either d_1

or d_2 can be implemented exactly on a computer by projecting the product of the Slater determinants to the constrained sub-space. In a subsequent collaboration with D.N. Sheng and others,[2] they showed that the projected wave function based on this decomposition is an excellent variational ground state wave function for a boson Hamiltonian which includes a four site ring term. Furthermore, on various ladder systems with finite widths, they performed DMRG calculations which reproduce many of the features of the projected wave functions. For example, the boson momentum distribution function $n_b(\boldsymbol{k})$ shows peaks at momenta given by sums or differences of the Fermi momenta. This series of papers[1–4] demonstrated that a Bose metal is indeed a possible ground state for a reasonable and local Hamiltonian.

The current paper takes the obvious next step of applying this insight to the t-J model supplemented by a ring term. The ansatz is to write the electron $c_\sigma(\boldsymbol{r})$ as a product of three fermions, $d_1(\boldsymbol{r})d_2(r)f_\sigma(\boldsymbol{r})$. Again they compare the projected wave function with the DMRG solution on a two leg ladder. They show that over a large parameter space, a non-Fermi liquid state emerges. The DMRG solution and the projected wave function are in remarkable agreement for properties such as the electron momentum distribution function $n(\boldsymbol{k})$ and density-density and spin-spin correlation functions.

Since this is a quasi-one dimensional system, the meaning of non-Fermi liquid is that it does not resemble any Luttinger liquid solution which up to now has been used to describe all solutions of the quasi-one dimensional fermion problem. A remarkable signature of this can be seen in the electron momentum distribution function $n\,(k_y, k_x)$. In the two leg ladder, $k_y = 0$ or π. The solution that emerges shows singularity at a certain k_x which *coincides* for both $k_y = 0$ and π. (see their figure 5a) It is as if $k_y = 0$ is described by an electron Fermi surface and $k_y = \pi$ is described by a hole Fermi surface, and these Fermi momenta are locked, as if the bands have total integer filling. Furthermore, the authors compute the central charge c which counts the number of gapless modes. c is expected to be 2 for each spinful Luttinger liquid and 1 (charge mode only) for a paired state. In the parameter range where a Luttinger liquid is the ground state, the authors found $c = 2$ as expected. However in the exotic ground state, they found $c = 3$ which suggests a paired state plus a Luttinger liquid. Indeed, d_{xy} pairing is found to have slow power decay law. However, from the $n(\boldsymbol{k})$ described above, it appears that both $k_y = 0$ and $k_y = \pi$ possess Fermi singularity and naively one may have expected $c = 4$ from these modes alone. These results are strong indications that the ground states are indeed exotic states which lie outside of the Luttinger liquid paradigm, i.e., they cannot be accessed perturbatively by turning on interactions between free fermions.

The detailed picture discovered in this paper may be special to quasi-one dimensional physics, and it remains to see how well this procedure generalizes to 2D. It is certainly a pleasant surprise how well the parton construction has worked so far and we can look forward to further development in the future.

[1] Motrunich, O.I. and Fisher, M.P.A. *d*-wave correlated critical Bose liquids in two dimensions. Phys. Rev. B **75**, 235116 (2007).

[2] Sheng, D.N., Motrunich, O.I.,Trebst, S., Gull, E., Fisher, M.P.A. Strong-coupling phases of frustrated bosons on a two-leg ladder with ring exchange, Phys. Rev. B **78**, 054520 (2008).

[3] Block, M.S., Mishmash, R.V., Kaul, R.K., Sheng, D.N., Motrunich, O.I. Exotic gapless Mott insulators of bosons on multileg ladders. Phys. Rev. Lett. **106**, 046402 (2011).

[4] Mishmash, R.V., Block, M.S., Kaul, R.K., Sheng, D.N., Motrunich, O.I., Fisher, M.P.A. Bose metals and insulators on multileg ladders with ring exchange. Phys. Rev. B **84**, 245127 (2011).