Spin and charge correlations in the Hubbard model: a cold atoms perspective

"Site-resolved observations of antiferromagnetic correlations in the Hubbard model",
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Recommended with a commentary by Thierry Giamarchi, DQMP, University of Geneva.

Understanding the phases and correlations of strongly correlated systems is a longstanding problem. A paradigmatic description of such systems is provided by simplified models such as the Hubbard model. This model, which has the essential ingredients of a band (described by a tight binging hopping t) and (local) interactions (denoted U) has been shown to exhibit many of the features of more realistic condensed matter systems such as a Mott transition at half filling (one particle per site) and antiferromagnetic correlations. The model is indeed reducible to an Heisenberg model with a magnetic exchange $J \sim 4t^2/U$ in that limit. Upon doping the properties of the Hubbard model are still a challenge with reliable solutions only existing in one and infinite dimensions.

Besides analytical or numerical approaches, a route to tackle such models has recently been provided by experiments on cold atomic systems. Indeed the use of optical lattices and of Feschbach resonances allows to realize a near ideal system of particles hopping on a tight-binding lattice, and to control the hopping t and the interaction U at will – providing an excellent realization of the Hubbard model [1]. Experiments on ^{6}Li atoms have shown that realizing the fermionic Hubbard model was indeed possible and have evidenced the existence of an incompressible Mott insulator phase at half filling [2, 3].

Going beyond, and in particular even showing the existence of the antiferromagnetic correlations (not to even mention the properties of the doped phases) has however proven to be extremely challenging. This is due to two severe limitations of the cold atoms realization:

1. The temperature (even if absolute value in the nK range) is in fact extremely hot for fermions. Typical best values have been in the range of $T_F/6$ where T_F is the Fermi temperature. For a typical condensed matter material this would correspond to $T \sim 2000K$. This is in particular typically above the AF ordering temperature $T_{AF} \sim J \sim 0.4t$ for typical values of $U = 10$ (actually for cold atomic systems it is better to count in entropy per particle since they are isolated systems but I will stick to temperatures for simplicity in this commentary).

2. More importantly: the atoms are placed in a trap potential which corresponds to a chemical potential varying as $\mu(r) = \frac{1}{2}\omega_0^2 r^2$ from the center of the trap. The system is thus inherently

inhomogeneous, with both Mott insulator regions at the center, and regions of lower densities at the periphery, which are usually considerably more disordered. Global measurements thus provide an average over all these reasons blurring their physical properties.

Nevertheless given the importance of the task the quest for observing the phases of Hubbard model has been actively pursued. In particular concerning the AF correlations remarkable results have been obtained by the Rice [4] and ETHZ groups [5] by using either new cooling techniques in optical lattices or shuffling entropy for anisotropic lattices ones. As a result short distance AF correlations have been observed even if the temperature remains clearly too high to get long range (or quasi-long range) order.

In the two recent paper mentioned at the beginning of this commentary an important step forward has been made towards the possibility to use cold atoms for the Hubbard model. Indeed recently fermionic microscopes allowing a local access to the density of spin up and spin down fermions in an optical 2D lattice were developed in several groups. The two above papers use these brand new fermion microscopes to observe the AF correlations in a Mott region of the Hubbard model, for 2D and 1D systems respectively. The measurement technique is extremely powerful (see e.g. Fig. 1 of paper (2) for an explanation on the measurement technique) since *all* values of $n_{i,\sigma}$ where i is the site and σ the spin can be measured for a single shot experiment. By repeating the experiments and thus doing the quantum average this allows in particular for *any* correlation of the form $\langle n_{i,\sigma} n_{j,\sigma'} \rangle$ to be measured, giving access to all charge and spin correlations as a function of distance. This allows to see clear (short range) AF correlations (see e.g. Fig. 2 of paper (2) or Fig. 2 of paper (1)). More importantly this allows to make detailed comparison with the expected decay of the correlations as a function of the distance (for example the expected exponential decay at finite temperature in a one dimensional system) and use the spin-spin correlations as a nice thermometer of the system.

This measurement technique thus offers several key advantages

1. By being a *local* measurement technique it avoids most of the unpleasant effects of the trapping potential. It only incorporates the regions in which the MI is well established, and therefore is well within an homogeneous phase. This gives confidence to spatial dependence of the correlations as *directly* extracted from the measurement.

2. Quite importantly it also avoid the regions of high entropy and therefore gives measurements which show a "temperature" (entropy per particle) in the right ballpark to be in the AF phase. Moderate progress in preparing/cooling the systems should thus be able to put the systems in an interesting range of temperatures.

3. Since *all* correlation functions can be measured these measurements potentially open the door for looking at the interplay between charge and spin correlations, a relatively uncharted territory. The one-shot measurements also allows (as was done for the bosons [6]) for the possibility to measure non-local order parameters.

4. Finally the control over the optical lattice allows to take these measurements in any intermediate between one- and two- dimensions allowing to tackle issues such as the dimensional crossover in strongly correlated systems.

Although there is nothing in itself unexpected or spectacular in getting AF correlations in a Hubbard model at half filling the two above-mentioned papers thus contain important ingredients for the future, and we can certainly expect much more to come from these types of systems very soon.

References

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