From chains to plane with a fermionic cold atom quantum simulator

Direct observation of incommensurate magnetism in Hubbard chains
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The Hubbard model [1] occupies a central place in our understanding of the effect of interactions on quantum systems. It is the simplest model describing the competition between the kinetic energy of quantum particles in a periodic potential (described by a tight binding hopping of amplitude t) and an interaction U that is taken as local – in condensed matter this is a caricature of the screened Coulomb interaction in an electronic system. For fermionic particles, this model describes, for a density of one particle per site $n = 1$, the Mott insulating phase that occurs because of the repulsion U and the formation of the corresponding antiferromagnetic correlations. How doping affects this magnetic order is one of the crucial remaining questions, since this interplay between spin and charge degrees of freedom opens the possibility to realize exotic phases. In particular the fact that the model could lead to a superconducting phase stemming from purely repulsive interactions has been advocated and is an exciting possibility.

Unfortunately despite the simplicity of the model, this question remains largely unsolved. The Hubbard model admits controlled solutions only in spatial dimensions $d = 1$ (or for few legs ladders) [2] and $d = \infty$ [3] and one must resort to uncontrolled approximations (mean-field, slave bosons, cluster solutions, etc. to quote a few) for the other situations. In the same way numerical methods have still a hard time to give unambiguous answers in the interesting regime of parameters and temperatures, even if considerable progress was accomplished [4]. Specific one dimensional methods such as DMRG and variants face an exponential complexity (and computer time) when increasing the number of coupled chains, while cluster methods or direct methods (such as Quantum Monte Carlo) suffer from sign problems. Recent Diagrammatic Monte-Carlo methods offer a promising route but because of their diagrammatic nature are so far been efficient for small interactions.

Given the importance of the solution and the difficulty of both analytical and numerical approaches, another route that has been extensively used was to simulate the Hubbard model in a “quantum simulator” [5, 6], namely an experiment for which the Hubbard model is an excellent microscopic description, and not a caricature. Such an approach is possible with cold atomic gases: the fact that these are neutral makes the contact interaction a perfect description of the microscopic system, and using lasers it is possible to create a periodic potential making the atoms move in a controlled periodic lattice made of light.

Various experiments have shown the viability of such an approach showing for example the existence of the Mott insulator and of the antiferromagnetic correlations at half-filling (for more details see the references [2-8] of the paper). Recently several groups have acquired the capability ("fermions microscope") to directly image the whole lattice and thus to perform (destructive) measurements of the separate populations of spin up and spin down on each site, opening several directions in which to probe the interplay between charge and spin correlations in such systems.

Several important steps were already reported in the literature. Antiferromagnetic correlations were reported by several groups (see for example the journal club "Spin and charge correlations in the Hubbard model: a cold atoms perspective" of 2016)). Measurements on how defects such as holes correlate with the magnetic order have also been performed. The reported correlations were of quite short range (with typical correlation length of the order of two lattice spacings $\xi \sim 2a$). This is unfortunately due the quite high temperature $T \sim 0.25t$. For values of U of about $U = 10$ this means an antiferromagnetic exchange $J = 4t^2/U \sum 0.4t$. Thus capturing long range magnetic correlations is difficult. However, shaping of the confining potential has allowed to reach correlation lengths of about $\xi \sim 10a$, and a controlled doping of the 2D antiferromagnetic phase [7].

The present paper carries the "simulation" of the Hubbard model one step further by exploiting heavily the possibility to directly image the full lattice in a one shot measurement. This allows for several important measurements to be performed.

First the possibility to post-select the data allows to work with systems for which the number of holes/doublons is zero and thus to study the *half filled case* even for a relatively high original temperature. The measurements confirms the π vector modulation of the magnetic order corresponding to the antiferromagnetic correlations. Measurements in 1D chains with a controlled number of holes allows to evidence, as was known theoretically, that in 1D the holes shift the magnetic order by one site and create domain walls. These predictions (e.g. by the so-called bosonization technique) were well established both analytically and numerically but were not directly evidenced experimentally before. The linear variation of the modulation vector which behaves as $\pi(1 + n)$ was also clearly established.

Second the local knowledge of the system allows for another way to post-select the data. One can also only select samples without holes but with a fixed imbalance of spin up and down and thus study, with the same imperfect (finite temperature) experimental system, the effects of the *polarisation* of the spin system on the wavector of the modulation in a half-filled system. Measurement showed the theoretically predicted $\pi(1 + 2m)$ behavior.

This experiment thus provides an important experimental test of these two theoretical predictions for the Hubbard model, each one being at the heart of descriptions such as Tomonaga-Luttinger liquids. However by themselves the results would not be that crucial, besides the experimental verification itself. These properties were well proven theoretically, and well tested in reliable 1D numerical simulations. The incommensurability of the magnetization at half filling was even well tested experimentally in quantum spin systems under magnetic field (see e.g. the references in the paper for neutron experiments or [8] where domain walls profiles were observed by NMR).

What is truly crucial in the present paper is the fact that such measurements can now be made for Hubbard systems, and *how* they were performed. As already mentioned above, the fact that one can access the density on all site in single shot measurements opens the way to measure in addition to the traditional local objects (directly accessible by e.g. neutron or NMR etc. experiments in condensed matter) non-local and topological order parameters making the 'experimental" quantum simulator as flexible as more conventional numerical simulations. In addition and more importantly there is nothing special to one dimension in these measurements and the systems can be used in a controlled way to tackle the physics of coupled 1D chains by transverse tunneling, and thus to explore the crossover between the 1D and the 2D behavior. The sizes that are analyzed (about 50 atoms) are a strong challenge for numerics when the coupling between the chains is introduced, and make such systems take their full importance and impact as quantum simulators.

This is exploited in part in the rest of the manuscript where the evolution of the spin-spin correlation as a function of the transverse coupling are discussed, showing an evolution from the domain wall picture (holon) across a hole, to a more polaronic type of correlations in the two dimensional material. No doubts that more refined correlations and analyzes will be carried out in the future. This opens a host of exciting possibilities for analyzing very controlled realizations of quasi-one dimensional material and to go detailed measurements towards the physics of two dimensional Hubbard model (such as e.g. investigation of stripes).

Of course life is still not totally rosy in the world of quantum simulations. The main limitations remain:

1. The temperature is still quite high blurring many of the interesting quantum features and making the various correlations decay very fast with distance. Contrarily to other case (such as the case of attractive interactions) cranking up the (repulsive) interaction would not solve here the problem since this leads to a decrease of the antiferromagnetic exchange. One should thus make progress with the handling of temperature. This is clearly a difficult problem but [7] shows that progress in that direction are certainly possible.

2. The measured correlations remain for the moment equal time correlations. This is a definitive minus compared what is offered by e.g. neutrons or other probes (ARPES, NMR etc.). Although not crucial in itself it will be an interesting extension to have. Several proposals have been made to do so, but clearly a routine implementation of such procedures is not yet realized.

In conclusion, clearly spectacular progress have been accomplished in the mere two years during which fermion microscopes and similar techniques have been introduced. The possibility to measure each spin component and each site of the systems allows a large variety of order parameters to be accessed and it a definite additional asset. This is the promise of many interesting new results to come in the coming years. Stay tuned!

References

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