COLD-ATOM PHYSICS

Polarons leave a trace

Spin and charge interplay leads to stringlike excitations in the 2D Hubbard model

By Peter Schauss

The physics of large many-particle quantum systems is barely tractable with first-principles approaches but can often be explored through quantum simulation, in which a well-controlled system, such as interacting ultracold atoms, acts as an analog quantum computer for a problem of interest. Great progress has been made in the experimental preparation of low-entropy states of ultracold atoms in optical lattices for this purpose. Typical target systems are numerically intractable and not realized in nature in their ideal form, such as the Fermi-Hubbard model. On page 251 of this issue, Chiu *et al.* (*1*) used single-atom and single-site resolved imaging of ultracold atoms on a lattice to study the doped Fermi-Hubbard model and report the nature of its microscopic correlations in real space.

Hubbard models are a class of models in which interacting quantum particles move by tunneling between sites on a lattice. Quantum simulation of the Fermi-Hubbard model becomes particularly interesting in the case of strong interactions, in which calculations on classical computers are very hard and limited to small systems. Several mysteries remain unresolved, such as the nature of the low-temperature quantum phases.

Chiu *et al.* tackled the question of the interplay of spin and charge in the two-dimensional (2D) Hubbard model. They found string patterns, which are correlated 1D excitations in the 2D system. Ultracold atomic quantum systems are intriguing systems for quantum simulation because of their extremely good isolation from the environment and superior parameter tunability (*2*, *3*). Quantum gas microscopes can detect hundreds of individual ultracold atoms in optical lattices with single-site resolution. This enables the quantum simulation of increasingly complex phenomena in the 1D and 2D Hubbard model by use of quantum gas microscopes.

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Although the particle interactions are simple, the Hubbard model contains a wide variety of interesting quantum effects. One recent breakthrough in quantum simulation of the Fermi-Hubbard model was the detection of antiferromagnetic correlations at one atom per site, called half-filling (*4*–*10*). These antiferromagnetic correlations in a spin-balanced Fermi lattice system arise as a consequence of Pauli blocking, the inability of two fermions to occupy the same quantum state. In perturbation theory, this leads to a reduction of kinetic energy of neighboring spin states with opposite spins compared with equal spins. These correlations can extend over the entire system (*11*).

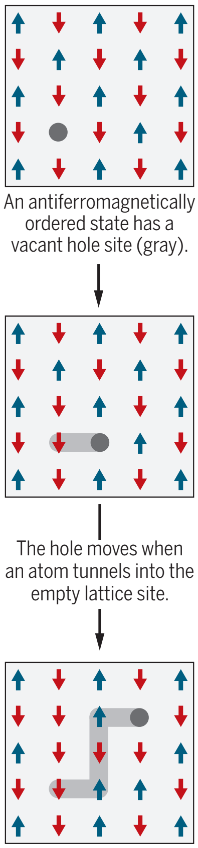
In contrast to the 1D Fermi-Hubbard model in which spin and charge decouple (*12*, *13*), the 2D case adds fundamental difficulties because of the lack of an effective low-energy theory that describes the spin and charge interplay. In particular, Chiu *et al.* studied stringlike excitations on the antiferromagnetic background in the doped Hubbard model below half filling. The origin of the strings can be understood in a simple semiclassical picture (see the figure). Considering an antiferromagnetically ordered state with few hole-like excitations, the holes shift if a neighboring atom tunnels to the empty lattice site. If the hole moves over several lattice sites, a stringlike excitation stretches from the initial to the final hole position, and is characterized by inverted antiferromagnetic order compared with the background.

This model is highly simplified. First, the system has no preferred spin axis and cannot be mapped to classical spins. Also, the temperature in the real system is finite and leads to thermal excitations in the antiferromagnetic background. Additionally, the holes influence the magnetic correlations around them, and the resulting "dressed holes" can be described as quasiparticles, known as polarons (*14*). These polarons can then be thought of as leaving a trace in the magnetic correlations along the path they have taken in the 2D system. Because of the variety of different paths, these string correlations do not show up as correlation in two-point correlation functions and represent a type of hidden order.

Chiu *et al.* used a variety of analysis techniques to study the statistical distribution of these stringlike traces. The possibility of overlapping strings and the projection of the quantum spins caused by the measurement complicates this analysis. To avoid detection bias, they used different string detection algorithms and compared these with simulated data created from different theory models. The large statistical samples needed to observe significant numbers of long strings in the systems made the data acquisition and evaluation challenging.

Strings attached

Chiu *et al.* studied stringlike excitation in a lattice of two atomic fermions (red and blue).



An antiferromagnetically ordered state has a vacant hole site (gray).

The hole moves when an atom tunnels into the empty lattice site.

The stringlike excitation (gray background) has inverted antiferromagnetic order.

On the basis of these evaluations, Chiu *et al.* finally found evidence of the presence of correlated strings. The analytic string theory, which is consistent with the experimental findings, gives an intuitive view on the coupling of spin and charge excitations in the Fermi-Hubbard model. This study relies heavily on the repeatable preparation of low-entropy samples in the optical lattice that can be imaged with single-atom and single-site resolution. These findings alone are a demonstration of the wide range of strongly correlated effects that can be directly studied with quantum gas microscopes (*15*), including hidden order.

The results provide a real-space view on the interplay between spin and charge excitations in the Hubbard model that is complementary to condensed matter experiments. The theoretical models investigated could guide promising new descriptions of the low-energy behavior of the Fermi-Hubbard model. Furthermore, the measurements motivate quantum simulation using ultracold atoms in optical lattices to explore new types of strongly correlated states arising in Hubbard systems. ■

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