Pairing with strings attached

Charge carriers in an engineered bilayer Mott insulator are predicted to form tightly bound, mobile pairs, glued together by string excitations of the antiferromagnetic order — a scenario that can be tested with quantum gas microscopy experiments.

Martin Gärttner and Markus Garst

Many unconventional superconductors, like the cuprates or bilayer graphene, materialize close to Mott insulating phases. In a Mott insulator each lattice site is, on average, occupied by a single electron, and the motion of electrons is inhibited by a strong on-site Coulomb repulsion. When electrons are removed from the material, the resulting holes are both mobile and charged so that the material becomes conducting. However, these holes are also strongly correlated resulting in a metal that can develop unconventional superconductivity. Although it is important for the quest for room-temperature superconductivity, a complete understanding of the underlying pairing mechanism is still lacking. Now, writing in *Nature Physics*, Annabelle Bohrdt and collaborators propose a setup of a bilayer Mott insulator where pairing of holes is expected to occur in a regime that is accessible with state-of-the-art quantum gas microscopy experiments[1].

Today, the advanced control of ultracold atomic gases routinely allows simulation of the fermionic Hubbard model, which is believed to capture the essence of many strongly correlated electron systems. With the recently developed quantum gas microscopes[2], individual particles and their local correlations can be traced with unprecedented resolution. This provides insights that are often inaccessible with standard methods of experimental solid-state physics. These new techniques have been already successfully applied to study important quantum phenomena like the superfluid–Mott insulator transition[3], itinerant ferromagnetism[4], many-body localization[5], and long-range antiferromagnetic correlations[6]. Using these tools in the investigation of unconventional superconductivity would be more than valuable. However, pairing of fermionic particles in a Hubbard model with repulsive on-site interactions has not yet been observed in quantum simulations.

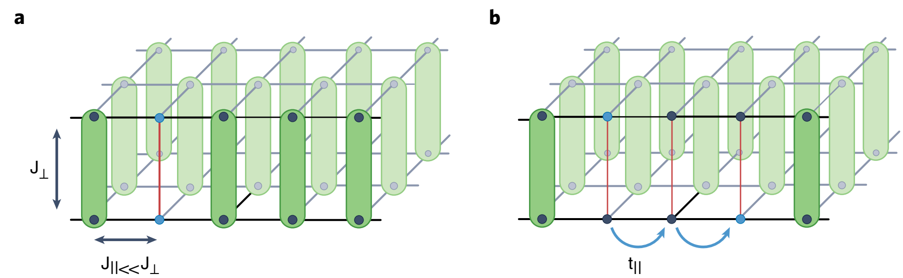

Fig. 1 | Pairing in bilayer Mott insulators. a, In case of an interlayer exchange coupling $J_\perp$ that is much larger than the intralayer exchange $J_{||}$ and vanishing interlayer tunnelling, spin singlets form across interlayer bonds (green). Two holes (blue) in different layers form a bound pair by breaking only a single interlayer bond (red). **b**, Hopping of a hole within the layer with amplitude $t_{||}$ leaves a trace of broken bonds giving rise to a binding potential growing linearly with distance.

The Hubbard model is characterized by just two energy scales: the hopping strength, which describes the tunnelling of electrons between adjacent lattice sites, and the on-site Coulomb interaction[7]. In the limit of strong Coulomb interactions a Mott insulator arises when each lattice site is occupied by one electron. The superexchange mechanism — the virtual hopping of electrons — then generates an effective exchange interaction between the electron spins, which favours antiferromagnetic ordering. When sufficiently many electrons are removed, superconductivity is indeed expected to develop, but only for temperatures well below the scale set by the effective exchange interaction. Currently, this temperature regime is hard to achieve with ultracold atomic quantum simulators.

To realize pairing at accessible temperatures, Bohrdt and colleagues propose a specific bilayer Mott insulator where holes in different layers attract each other and form pairs. The holes' binding energy is on the order of the exchange interaction such that pairing effects might be revealed for temperatures that are accessible in present-day quantum gas microscopes. To understand the essence of the proposal, consider an antiferromagnetic state with two missing spins, acting as two holes. Each hole costs an energy proportional to the exchange interaction times the number of broken nearest-neighbour bonds. Importantly, the energy cost is less if the two holes occupy adjacent sites because the joining bond only counts once — the two holes seem to form a bound state (Fig. 1a).

However, this advantage in exchange energy is usually more than compensated by a disadvantage in kinetic energy, as the hopping strength is much larger than the exchange energy for strong on-site repulsion. Following an earlier proposal[8], Bohrdt and co-workers resolved this issue by working in a bilayer system where the interlayer hopping is switched off artificially, so that the gain in exchange energy prevails (Fig. 1a). In this way, the number of electrons in each layer is conserved. This can be realized in an ultracold atomic setup with the help of a strong potential gradient, which energetically confines the particles to each layer.

For the resulting state to be conducting, the holes need to be mobile within the layers. Bohrdt and colleagues argued that the interlayer bound state of holes remains stable even for a large intralayer hopping. When the first hole is hopping away, it leaves a trace of broken interlayer bonds that can be identified as a string excitation of the antiferromagnetic order (Fig. 1b). The string of broken bonds will be healed when the second hole is retracing the path in the adjacent layer. This amounts to a characteristic binding potential that grows linearly with the length of the string. In analogy with quark confinement, the resulting bound states for such a potential are often called mesons[9]. Vibrations of the string correspond to various meson states, which are predicted to show up as resonances in the two-hole spectral function. This could be probed by angle-resolved photoemission spectroscopy.

This theoretical work illustrates an unconventional pairing mechanism in an engineered bilayer antiferromagnetic Mott insulator with various non-trivial predictions. Its experimental implementation with ultracold atomic gases[10] might be a first step in the exploration of unconventional superconductivity with analog quantum simulators.

Martin Gärttner[1]✉ **and Markus Garst**[2]
[1]*Physics Institute & Kirchhoff-Institute for Physics, Heidelberg University, Heidelberg, Germany.*
[2]*Institute of Theoretical Solid State Physics & Institute of Quantum Materials and Technology, Karlsruhe Institute of Technology, Karlsruhe, Germany.*
✉*e-mail: martin.gaerttner@kip.uni-heidelberg.de*

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Competing interest

The authors declare no competing interests.