Remarkably strong pairing of charge carriers in bilayer antiferromagnetic Mott insulators

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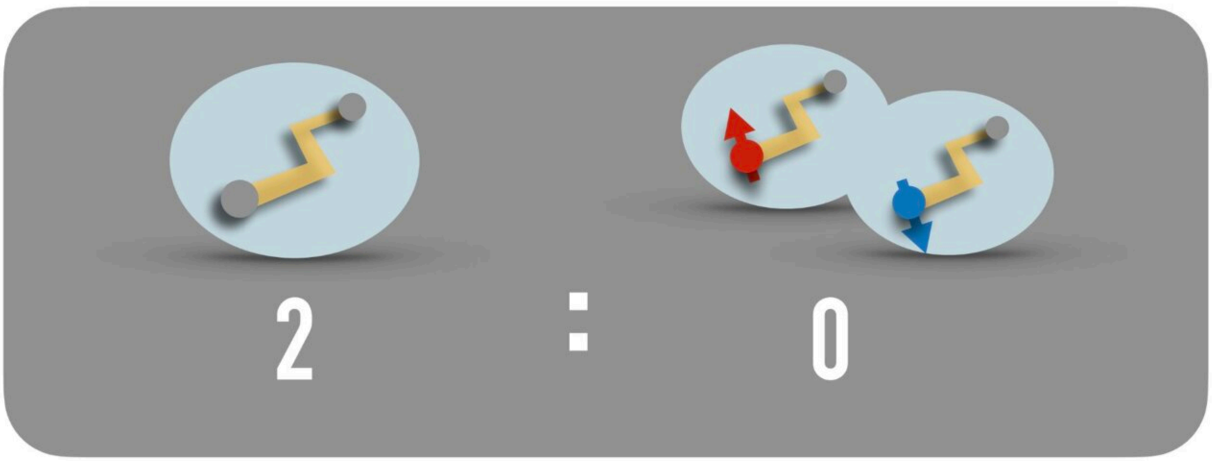


To pair or not to pair: The bound state constituted by two mobile charges without spin (left) wins against independent spin-charge pairs (right) in their competition for the lowest energy. Credit: Bohrdt et al.

Over the past few years, many physicists and material scientists have been investigating superconductivity, the complete disappearance of electrical resistance observed in some solid materials. Superconductivity has so far been primarily observed in materials that are cooled to very low temperatures, typically below 20 K.

Some materials, however, exhibit superconductivity at high temperatures, above 77 K. Many of these materials, also known as high-temperature superconductors, are known to be antiferromagnets.

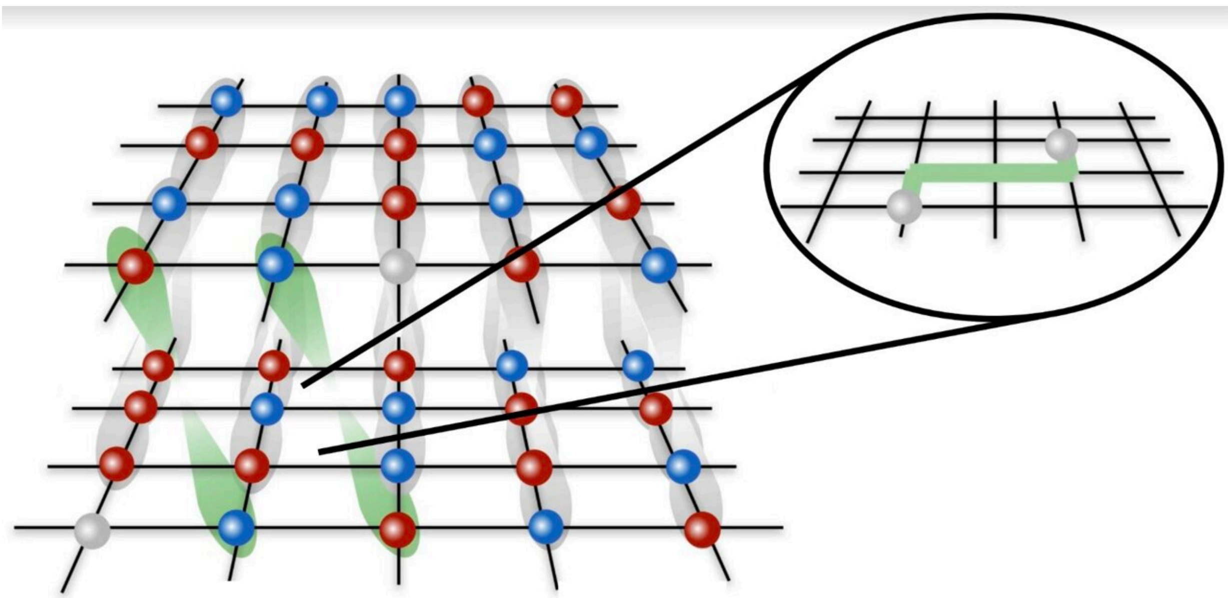
An aspect of high-temperature superconductivity that physicists have been trying to understand better is the formation of pairs of mobile dopants in antiferromagnets, which has been observed in antiferromagnet high-temperature superconductors. Despite extensive studies in this area, the microscopic pairing mechanism underpinning these strongly correlated systems has not yet been universally defined.

Researchers at the Munich Center for Quantum Science and Technology (MCQST), Ludwig Maximilan University of Munich, ETH Zürich and Harvard University have recently unveiled high-temperature pairing of mobile charge carriers in doped antiferromagnetic Mott insulators. Their paper, published in *Nature Physics*, could shed new light on the formation of mobile pairs of dopants in antiferromagnets.

"Since we had been studying the single-dopant problem in great detail before, the next logical step was to study pairs of holes," Fabian Grusdt, one of the researchers who carried out the study, told Phys.org. "So, a few years ago we started to generalize some of our earlier results to the two-dopant case and found first analytical insights into the strong pairing mechanism that can bind holes together. However, we quickly realized that the mutual exclusion-property of two holes in mono-layers settings is a significant obstacle for pairing."

While conducting their studies, Grusdt and his colleagues ultimately realized that bilayer materials could be ideal platforms to examine the formation and pairing of charge carriers, as in these materials the string-based pairing mechanism they observed can develop at its full strength. Due to their properties and experimental relevance, the team decided to study these materials.

"We quickly realized that the pairing mechanism we predicted would lead to significantly enhanced binding energies and would therefore be directly accessible to current ultracold atom systems," Grusdt said. "Once we understood the new mechanism, its conceptual beauty and simplicity made us worry for a while that competing groups might already be pursuing similar approaches, but in the end our enthusiastic work was rewarded."



String-based pairing of mobile charges in a bilayer antiferromagnet: Charged holes moving in opposite layers of a quantum paramagnet create a string of displaced antiferromagnetic bond. By moving in a strongly correlated concert, the charges make optimal use of their kinetic energy, which ultimately leads to a powerful pairing mechanism that can be experimentally realized at surprisingly high temperatures. Credit: Bohrdt et al.

The new mechanism unveiled by Grusdt and his colleagues occurs first in a conceptually simpler regime, known as the "tight-binding" regime. The main idea behind this mechanism is that two paired charges only "pay" the energy necessary to break one, rather than two, antiferromagnetic bonds.

By pairing charges from two different layers of the material in the mixed-dimensional setting used by the researchers, the kinetic energy of the charges, which typically dominates all energy scales, can be suppressed. On the other hand, in the conceptually more complex "strong-coupling regime," the "glue" required to pair two charges derives from a string of displaced antiferromagnetic bonds.

"Creating this string costs significant magnetic energy, but overall, the charges gain sufficient kinetic energy by following each other's paths," Grusdt explained. "To put it plainly: the mobile dopants can move in a strongly correlated concert and delocalize sufficiently to dominate even a large potential energy barrier trying to unbind them. In effect, we revealed an intricate interplay of kinetic and magnetic energy scales, which ultimately allows a binding of energies that systematically exceed those realizable in the tight-binding regime."

The recent work by Grusdt and his colleagues unveils a remarkably strong pairing mechanism that is analytically tractable in a wide range of parameters. This is a particularly notable achievement, as studies in this area of physics typically rely on computationally heavy numerical simulations.

"In the short term, the most significant implication of our work is probably the experimental feasibility of our approach, which has very recently led to the long-sought experimental observation of pairing in a Hubbard-like system of ultracold atoms," Grusdt added. "In the long term, we believe that our approach may possibly motivate the design of new materials with significantly enhanced superconducting temperatures."

In the future, the study conducted by Grusdt and his colleagues and the mechanism they unveiled could pave the way towards the design and fabrication of materials that exhibit superconductivity at significantly higher temperatures. In addition, it could help to improve the current understanding of the pairing mechanism underlying high-temperature superconductivity.

"We now plan to use our recent results as a staging ground for further studies of hole pairing in strongly correlated quantum systems," Grusdt added. "For example, we want to consider additional phonon dressing to find out whether it would enhance or decrease binding energies."

In their next studies, the researchers also plan to study the excitation spectra of paired charges more in depth, to determine how relevant their results are to the pairing mechanisms described by the plain-vanilla Fermi-Hubbard model. In addition, they would like to investigate whether even more exotic structures composed of mobile charges and strings could form in more strongly frustrated regimes of the phase diagram.

More information: Annabelle Bohrdt et al, Strong pairing in mixed-dimensional bilayer antiferromagnetic Mott insulators, *Nature Physics* (2022). DOI: 10.1038/s41567-022-01561-8