Superconductor Theory Under Cold-Atom Scrutiny

Snapshot measurements of cold-atom gases reveal hidden spin correlations that could force an update of some superconductivity theories.

By **Konrad Viebahn**

Our understanding of nature is inherently bound to the experimental tools we build to observe the world. Superconductivity, for example, has been traditionally studied using current and voltage meters under a variety of temperatures and other environmental conditions. From these observations, theorists have developed models—notably the Bardeen-Cooper-Schrieffer (BCS) theory, which assumes that the zero-resistance flow in a superconductor arises from electrons forming so-called Cooper pairs. This theory has been successful in explaining a large class of superconductors, but Tarik Yefsah from the Ecole Normale Supérieure in Paris and colleagues have now observed behavior that contradicts BCS predictions [**1**]. Using a recently developed technique called atom-resolved continuum quantum gas microscopy, the researchers directly observed spatial correlations in cold atoms that mimic superconducting electrons. These high-precision measurements revealed an unexpected anticorrelation between opposite-spin atoms, implying deficiencies in the BCS theory. This and other surprising results demonstrate once again how new observational lenses can put long-standing theoretical models into question.

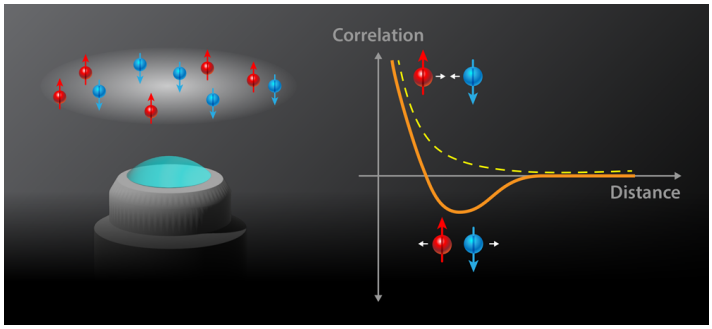

Figure 1: A continuum quantum gas microscope can image a 2D collection of cold atoms (left). In the case of a fermionic gas, the technique can differentiate between spin-up and spin-down atoms. Using the microscope data, researchers can compute the correlation function (right). The observations (solid orange line) disagree with the Bardeen-Cooper-Schrieffer theory (dashed yellow line) in that they show an anticorrelation "dip" for opposite spin atoms at a particular interparticle distance.
Credit: APS/Alan Stonebraker

Predicting the collective behavior of electrons within materials is a formidable challenge. The many-body problem for classical particles is already difficult, but it is made unbelievably more complex for electrons and other fermions by the infamous "sign problem": The wave function of fermionic particles changes sign upon particle exchange. This antisymmetric behavior gives rise to Pauli's exclusion principle and makes modeling fermionic many-body systems incredibly challenging. Despite this difficulty, theorists have successfully developed simplified models that allow analytical or numerical solutions to complex condensed-matter problems. One celebrated example is the BCS theory of superconductivity, which describes a Fermi gas and its response to an effective—that is, mean-field—attractive interaction. This simple theory describes the pairing of electrons, which in turn explains how superconductivity emerges in certain materials.

Experimental observations have largely agreed with BCS predictions, but directly measuring electron behavior in a material is challenging. In recent decades, ultracold atoms have emerged as a powerful alternative platform for studying

fermionic many-body problems. Fermionic atomic isotopes, such as lithium-6, provide a direct experimental realization of interacting Fermi gases, exhibiting pairing behavior as predicted in the BCS theory. A key advantage of ultracold-atom systems is that they are microscopically well understood and require comparatively few modeling assumptions. Moreover, the interaction strength between atoms can be precisely tuned via so-called Feshbach resonances—an established method for controlling atom interactions with a magnetic field. This control allows researchers to explore not just the weakly interacting Fermi gas but the entire range of states extending from a BCS state to a Bose-Einstein condensate (BEC) of tightly bound dimers [**2**]. The crossover between BCS and BEC is considered a "Rosetta stone" for quantum many-body physics: The qualitatively different behavior on either side of the crossover poses a challenge to theories that try to unify models of the two regimes. Deciphering the crossover's secrets can help find a common language for describing superconductivity and connected phenomena.

One of the main limitations of cold-atom systems, however, is temperature. Whereas nanokelvin temperatures realized in the lab appear cold on an absolute scale, the intrinsic energy scales of these dilute gases are so low that the relative temperature (compared to the Fermi temperature) remains significantly higher than what is typically found in condensed-matter systems. Nevertheless, experiments with ultracold atoms have recently observed fascinating phenomena within the BEC-BCS crossover, such as excitation spectra [**3**, **4**], images of Cooper pairs [**5**], and unconventional heat engines [**6**].

Previous studies relied on average-density images of bulk Fermi gases. The advantage of continuum quantum gas microscopy is that it can resolve individual atoms in large 2D samples [**1**, **7**]. The method works like a photographer yelling "freeze" just before taking a photo. Laser beams pin down atoms in the 2D gas, and then, in a flash, a fluorescence image captures where the atoms are positioned. Since spin-up and spin-down fluoresce at different laser frequencies, individual-spin information can be extracted. The fermionic sign problem leads to complicated spatial arrangements in free space, which are mathematically captured by correlation functions. These functions provide quantitative answers to questions like: Given a particle at position x, what is the likelihood of finding a particle (with a specific spin) at $x + d$? For instance, the exclusion principle causes a distinct suppression of same-spin particles at close distances (the "Fermi hole" [**7**]). Meanwhile, density–density correlations shoot up at short interparticle distances, serving as a direct signature of fermion pairing—an effect that becomes more pronounced moving toward the BEC regime.

Using the high spatial resolution of continuum quantum gas microscopy, Yefsah and colleagues achieved unprecedented signal to noise in their correlation measurements. They discovered a highly nonlocal anticorrelation, namely an unexpected "dip" in the spin-up–spin-down correlation function (Fig. **1**). This seeming avoidance of opposite-spin particles was surprising because mean-field BCS theory predicts no such dip; rather, it constrains this correlation function to be greater than or equal to unity. The researchers performed auxiliary-field quantum Monte Carlo calculations, which confirmed the existence of this dip below unity. They also observed that the Fermi hole does not shrink near the crossover as BCS theory predicts, but rather remains analogous to that of an ideal, noninteracting Fermi gas. These results clearly demonstrate that the mean-field assumptions in the BCS theory are critically deficient—not just in the strongly correlated crossover regime but deep into the weakly attractive side. This deficiency calls for renewed theoretical investigation of beyond-mean-field effects.

Experimental surprises, such as the unexpected dip in the pair correlation function, perfectly illustrate how advancing experimental techniques—in this case, high-precision continuum quantum gas microscopy combined with numerical calculations—can deepen our understanding of many-body physics and bring up new theoretical questions. The experimenters have taken a significant step forward. Now it is the theorists' turn to develop new concepts (efforts are already underway [**8**]) and refine our fundamental theories of superconductivity.

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