Physics VIEWPOINT

A Glimpse at the Quantum Behavior of a Uniform Gas

An innovative way to image atoms in cold gases could provide deeper insights into the atoms' quantum correlations.

By **Meera Parish**

The macroscopic properties of objects that we encounter in everyday life are ultimately determined by the behavior of these objects' microscopic constituents. For instance, the way that atoms move is key to understanding the pressure of the gas in our tires or the flow of our morning coffee into a cup. However, equally important is how the positions of these particles are correlated—how the particles "dance" together. This dance has already been imaged in highly confined systems in which particles can move only between discrete sites [**1**]. Now three separate experimental groups, one from École Normale Supérieure in Paris and two from MIT, have imaged the positions of individual atoms in a cold, uniform gas, exposing the atoms' quantum correlations [**2–4**].

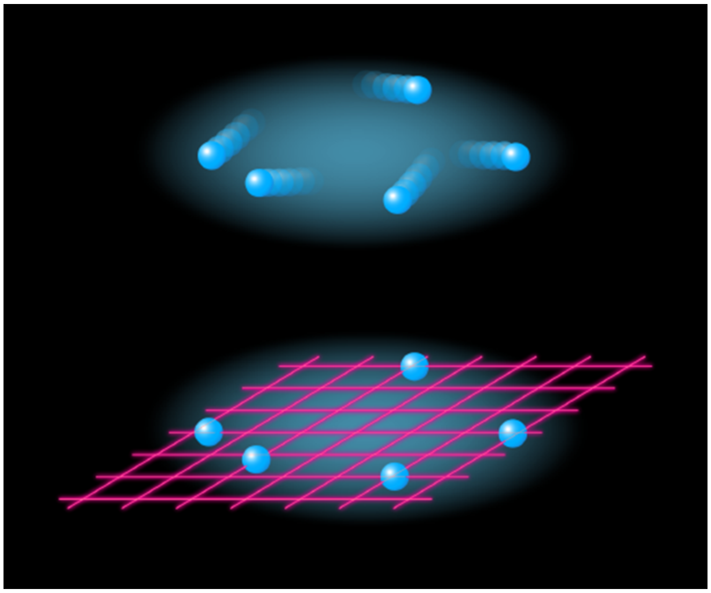

Figure 1: (Top) Three research groups have imaged for the first time the instantaneous positions of atoms in a 2D gas [**2**–**4**]. (Bottom) The teams used intersecting laser beams to form an optical lattice. When this lattice was switched on, the freely moving atoms were pinned suddenly, allowing a snapshot of their positions to be captured.
Credit: APS/Carin Cain

The fundamental quantum nature of particles leads to counterintuitive behavior in a collection of particles, even if there are no forces acting between them. Because quantum particles are indistinguishable, the probability of detecting one at a particular position is independent of which particle is observed. This feature implies that there are two classes of particle: bosons, which can change places without affecting the system's quantum state; and fermions, which flip the sign of the state upon their exchange. The result is that photons and other bosons tend to bunch together, whereas electrons and other fermions tend to avoid each other.

Appreciating the different behavior of bosons and fermions has had huge consequences for our understanding of the Universe. For example, measuring bosonic correlations between photons emitted by a distant star can offer us information about the star's size [**5**]. Closer to home, understanding the fermionic statistics of electrons enabled the semiconductor revolution that underpins the development of modern electronics. What's more, the fact that electrons are fermions underpins the very stability of matter [**6**].

A collection of quantum particles becomes more challenging to describe theoretically when we include Coulomb forces and other interactions between the particles. The issue is one of scale: The system's complexity grows exponentially as the number of interacting particles increases, so the problem can quickly become unsolvable when considering the roughly 10^{23} atoms in a typical piece of material.

One approach to tackling this quantum many-body problem is to use another quantum system to simulate the physics of interest. This concept of a "quantum simulator," envisioned by Richard Feynman more than 40 years ago [**7**], has recently become a reality in several platforms, owing to experimental advances in controlling and manipulating particles. One such platform is the cold atomic gas [**8**], which boasts a unique degree of controllability and is amenable to precise detection measurements. However, the ability to image the positions of atoms in such gases and thus extract spatial atom–atom correlations has so far been limited to setups involving quantum gas microscopes or optical tweezers. In those setups, the atoms are restricted to hopping between discrete sites [**1**] and thus cannot mimic the continuous movement of particles in many macroscopic systems.

The three research teams, led by Tarik Yefsah [**2**], Martin Zwierlein [**3**], and Wolfgang Ketterle [**4**], respectively, have now added a new capability to the cold-atom toolbox by imaging the atoms in a uniform gas, in which the atoms are free to move around (Fig. **1**). The idea might seem simple: Starting from a cold atomic gas, one need only switch on an optical lattice—an array of light created by interfering laser beams. This lattice pins the atoms along their freely roaming paths, providing a snapshot of their instantaneous positions. However, the teams needed to overcome two crucial challenges to achieve this goal.

First, to obtain atomic-scale imaging resolution, the gas needed to be dilute enough that the typical distance between its atoms was larger than the spacing between the sites of the applied pinning lattice. This condition, in turn, required advanced cooling techniques to achieve the extremely low temperatures needed for a gas of up to a few hundred atoms to reach the quantum degenerate regime—the regime in which quantum-mechanical effects become important. Second, the pinning lattice needed to be turned on at the right rate to extract faithful information about the gas's initial state without disturbing it.

The three teams applied this new imaging capability to 2D gases of bosonic or fermionic atoms, using a trapping potential to confine the gases to a plane. Yefsah and colleagues [**2**] performed a thorough study of the two- and three-atom spatial correlations in a 2D gas of noninteracting fermionic atoms. The researchers observed a characteristic feature of fermionic statistics called a Fermi hole: a dip in these correlations as a function of the distance between particle pairs. They also made steps toward extending their approach to 3D gases by varying the trapping potential in the third dimension and probing the resulting effect on atomic dynamics.

Zwierlein and co-workers [**3**] focused on two-atom correlations in 2D gases of either noninteracting or interacting fermionic atoms. Their measurements revealed the Fermi hole, as well as the formation of fermion pairs—analogues of electron pairs in a superconductor—in the case of strong attractive atomic interactions. Lastly, Ketterle's [**4**] and Zwierlein's groups both observed a spatial bunching of atoms in a 2D gas of bosonic atoms, with Ketterle and colleagues showing the suppression of this quantum effect as they increased the gas's temperature.

These three investigations are just the beginning. Scientists could use this atom-resolved imaging technique to probe a range of quantum correlations, including correlations near a quantum phase transition, and two-particle correlations between fermions in the crossover between two and three dimensions [**9**]. It is particularly notable that these three studies involved a relatively small number of atoms, ranging from a few tens to a few hundred. By observing the system behavior for a varying number of atoms, the approach offers the possibility of addressing an intriguing question: How many particles are sufficient to reproduce the behavior of a macroscopic system [**10**]?

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