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Nature 15, Nov (2006).

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J.K. Chin, D.E. Miller, Y. Liu, C. Stan, W. Setiawan, C. Sanner, K. Xu, W. Ketterle
To appear in *Nature*.

Commentary by Tin-Lun (Jason) Ho

At present, there are worldwide experimental efforts to use cold atoms in optical lattices to simulate strongly correlated condensed matter systems. Should such efforts be successful, the great flexibility in cold atom experiments in varying parameters such as density, dimensionality, external potential, and interactions, will provide new ways to study strongly correlated quantum systems. However, to simulate strongly correlated electronic systems successfully, many experimental advances are needed -- developing powerful cooling methods to reach quantum degeneracy in optical lattices, finding ways to detect subtle quantum correlations, establishing reliable temperature scales, etc. The list goes on. The three papers selected in this Commentary, which are interesting in their own right, all play a role in the on-going effort to study strongly correlation physics with cold atoms.

Experiments (**I**) and (**II**) demonstrate the effect of statistics on correlation functions (the Hanbury Brown and Twiss effect) in quantum gases. The idea is that Fermi (Bose) statistics will cause suppression (enhancement) in the density-density correlation function due to destructive (constructive) interference in the measurement process. (**I**) is an extension of a previous experiment by the same group on a Mott state of bosons to a filled band of fermions. In this experiment, the Fermi gas is suddenly released from the optical lattice and undergoes ballistic expansion. After the gas has expanded to a sufficiently large size, one shines a laser of appropriate frequency on the gas and records an absorption image on a screen normal to the direction z of the incident laser. The resulting image gives a 2D column density $n(\vec{r}) = \int n(\vec{r},z)dz$ of the gas. Although $n(\vec{r})$ is featureless, its correlation function $< n(\vec{r})n(\vec{r}') >$ averaged over the 2D screen revealed a lattice of dark spots. This is consequence of Pauli exclusion of the Bloch fermions, which prevents two fermions with the same crystal momentum to be detected at the same time. This causes a decrease in correlation when two Bloch states are separated by a reciprocal lattice vector, for they would then be in the same state. The lattice of dark spots is a reflection of the reciprocal lattice.

In (**II**), a gas of He-3 (or He-4) is released from a source of size s. It falls down under gravitational pull while expanding in the process. Joint detection of particles is made by a pair of detectors separated by Δz some distance L below the source. In the case of He-3, the resulting correlation function $< n(z)n(z+\Delta z) >$ has a hole near Δz=0 with a width given by $(\hbar / sM)t$, where t is the time for the gas to fall down a distance L from the source. In the case of He-4, a bump of the same size was observed instead. (See fig.2 in the paper). While these effects are expected, it is important that they are verified, for these methods will be useful in studying the statistics of the excitations in strongly correlated systems.

Experiment (**III**) is a study of the effect of a periodic potential on fermion superfluids in strongly interacting regime. These fermion superfluids are remarkable because they can be turned into Bose-Einstein condensates of molecules by simply changing a background magnetic field. This is the so-called BEC-BCS crossover where the Cooper pairs can be changed continuously into tightly bound molecules. In (**III**), the density of the fermion superfluid is such that there are two fermions per site in the lattice. The increase of lattice potential changes a BCS superfluid to a band insulator. The absence of superfluidity is detected by sweeping the system to the BEC side and then detect the superfluidity at that end. This sweeping progress is needed because direct determination of superfluidity in the strongly interacting regime remained difficult at present. The MIT group has observed the loss of superfluidity at rather moderate lattice potentials. The band gap associated with the critical lattice potential is a measurement of the strength of the superfluid order of the fermion system.

It should be noted that the fermion superfluidity in these rather shallow lattices is unrelated to the superfluidity in the Mott regime with doping. (The latter is a problem of central interest in condensed matter, and can only be realized in deep lattices). On the other hand, (**III**) brings out a new and interesting aspect of BEC-BCS crossover, i.e. how the crossover family is affected by lattice potential. Note that two fermion per site in the BCS regime corresponds to one boson per site in the BEC regime. The band insulator in the BCS regime is therefore continuously connected to the bosonic Mott insulator in the BEC regime. Such connection, however, does not exist for systems with four fermions per site. This is because while there are Bose Mott insulators with two bosons per site, band insulators with two filled bands must have eight fermions per site, due to three degenerate p-bands. This means that a doubly occupied bosonic Mott insolator must undergo a quantum phase transition to a fermion superfluid (in the presence of lattice) as the system is tuned to the BCS side. It is intriguing to think about the global phase diagram in the space of magnetic field (which describes BEC-BCS crossover), density, and lattice height.