Mott made easy

The realization of a Mott insulating state in a system of ultracold fermions comprising far more internal components than the electron, provides an avenue for probing many-body physics that is difficult to access in solids.

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The $^{173}\text{Yb}$ system is therefore invariant under any unitary transformation within this six-dimensional hyperfine-spin space — affording it the symmetries associated with the $\text{SU}(N = 6)$ group. By contrast, two-component electron systems usually possess $\text{SU}(N = 2)$ symmetry. Aside from their applications in high-energy physics, the symmetries of $\text{SU}(N \geq 3)$ have been used to study quantum antiferromagnetism, albeit only as a mathematical tool. Now, with the work by Taie et al., experimental explorations of these highly symmetric Mott insulators have really begun.

Taie et al. found cooling their multicomponent $^{173}\text{Yb}$ system towards the Mott insulating state to be more effective than the more widely used two-component systems. In fact, they showed that driving fermions adiabatically into a Mott insulating state can lead to a type of cooling analogous to Pomeranchuk cooling — an idea corroborated by simulation studies.

The analogy is based on the fact that fermions can hold more entropy in a Mott insulating state than in a Fermi-liquid state. This is because every site in a Mott insulating state contributes to entropy through spin configurations, unlike in a Fermi liquid, in which only fermions close to Fermi surfaces contribute. The Mott insulating state realized in the experiment by Taie et al. has one atom per site. Because the entropy per site scales as $\ln(N)$, as $N$ increases, the system can accommodate more entropy. This in turn leads to a significant reduction in the temperature at which the Mott-insulating state can be achieved — effectively cooling the system through transfer of entropy from orbital motions to spin configurations in a manner reminiscent of Pomeranchuk cooling. This cooling results in a less compressible gas, invoking the signature of the Mott insulator.

One of the key features associated with the $\text{SU}(6)$ symmetry realized by Taie et al. is the strong quantum hyperfine-spin fluctuations enabled by large values of $N$ (ref. 6). This may seem to contradict the standard lore in solids that quantum fluctuations of large spins are weak, but the reasoning is straightforward. Large spin can build up in solids, as Hund’s rule dictates, if the electron shells of cations are partially filled. Although the value of spin $S$ may be large, its symmetry remains $\text{SU}(2)$.

Quantum fluctuations, which arise from the non-commutativity between three spin components, become weaker as $S$ increases. By contrast, the $^{173}\text{Yb}$ system enjoys a much higher symmetry than these electron systems, and thus the hyperfine spins fluctuate in a much larger internal phase space — meaning that large values of $N$ enhance, rather than suppress, these fluctuations. Quantum fluctuations in the $^{173}\text{Yb}$ system are actually even stronger than those of spin-1/2 electrons.

These strong quantum fluctuations enhance the tendency of the $\text{SU}(N \geq 3)$ antiferromagnets to form singlets. Just like quantum chromodynamics, in which the $\text{SU}(3)$ colour singlet states of baryons consist of three quarks, the minimum site number required to form an $\text{SU}(N)$ singlet is just $N$. This means that in the $^{173}\text{Yb}$ system probed in the experiment by Taie et al., quantum-antiferromagnetic fluctuations are dominated by six-site correlations, whose physics cannot be reduced into two-site correlations as in the extensively studied case of $\text{SU}(2)$ quantum magnets in solids.

The experiment performed successfully by Taie et al. provides a new opportunity to study novel Mott insulators that are difficult to realize in solids. Indeed, the reduction in temperature of an $\text{SU}(6)$ gas relative to an $\text{SU}(2)$ gas may prove essential to our realization of exotic spin order in these systems. However, in order to study $\text{SU}(6)$ quantum antiferromagnetism, for example, further cooling is necessary. Although it is still beyond the current experimental capability, one hopes that...
techniques for sufficient cooling will be achieved in the near future. These advances will not only enhance our understanding of the Mott insulating state, but may also enable realization of exotic spin-liquid states\cite{11,12} and fermionic superfluid states induced by doping these unusual Mott insulators.

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