New phases and tuned interactions in 1D optical lattices

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Abstract

We treat interacting bosons in a 1D optical lattice, considering the "extended Bose-Hubbard model";

$$\hat{H} = \frac{V_0}{2}\sum_i n_i(n_i-1) + V_1\sum_i n_i n_{i+1} - t\sum_i (b_i^\dagger b_{i+1} + h.c.) - \mu\sum_i n_i$$

In an optical lattice, the parameters V_0 and t are easily varied, which opens the thrilling possibility of tuning the system into different phases of matter! What's important here is the energy cost V_0 for having a pair of particles on the same site, compared to the cost V_1 for each pair of nearest neighbors. Under the right circumstances, an increased ground state degeneracy is introduced, yielding fractionally charged excitations and revealing connections to quantum Hall physics.

Interacting bosons in optical lattices

Basics By using counter-propagating laser beams, one can trap cold atoms in 1D, 2D or 3D lattices. If dipolar atoms are used, they will be affected by both an on-site contact interaction, and a long-range dipole-dipole interaction decreasing with distance as $1/r^3$. Depending on the depth of the potential wells, the atoms will also be more or less free to tunnel between different lattice sites.

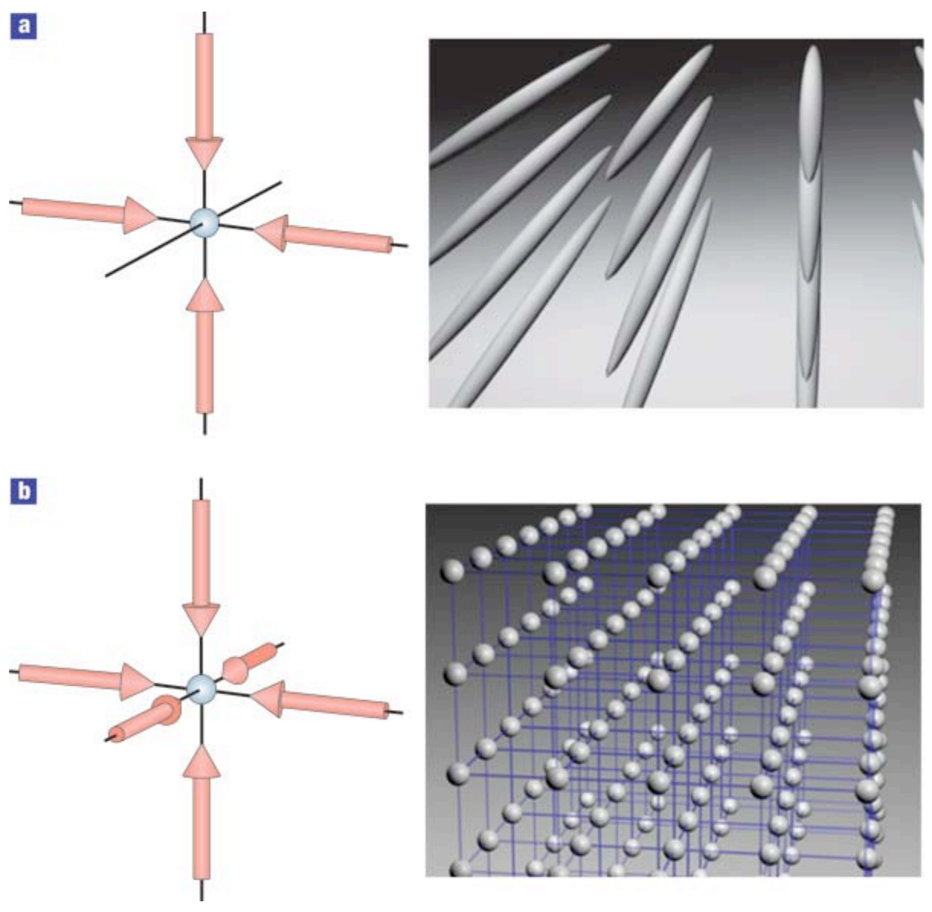

Figure by I. Bloch, paper in Nature

When studying this system theoretically, one commonly truncates the Hamiltonian, keeping only the on-site and nearest neighbor electrostatic interaction and the nearest neighbor hopping terms, see equation above.

Tunable parameters in the Hamiltonian

What's especially nice about the optical lattices is that the interaction and hopping parameters in the Hamiltonian are unusually controllable, which means that various exotic phases of matter may be realized. Only your imagination sets the limit!! (Well, ok... a bit exaggerated maybe. But play with the idea! :))

In this work we exploit this fact to explore a certain phase with degenerate ground states and fractionally charged excitations.

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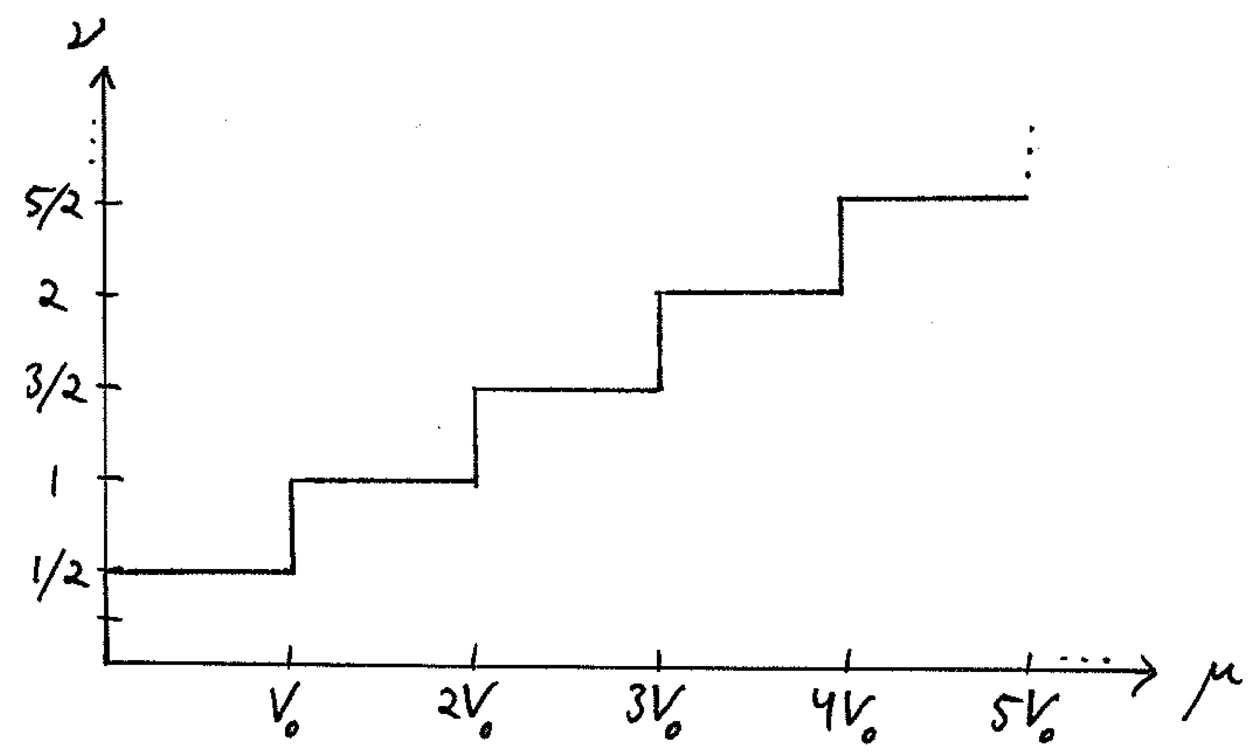
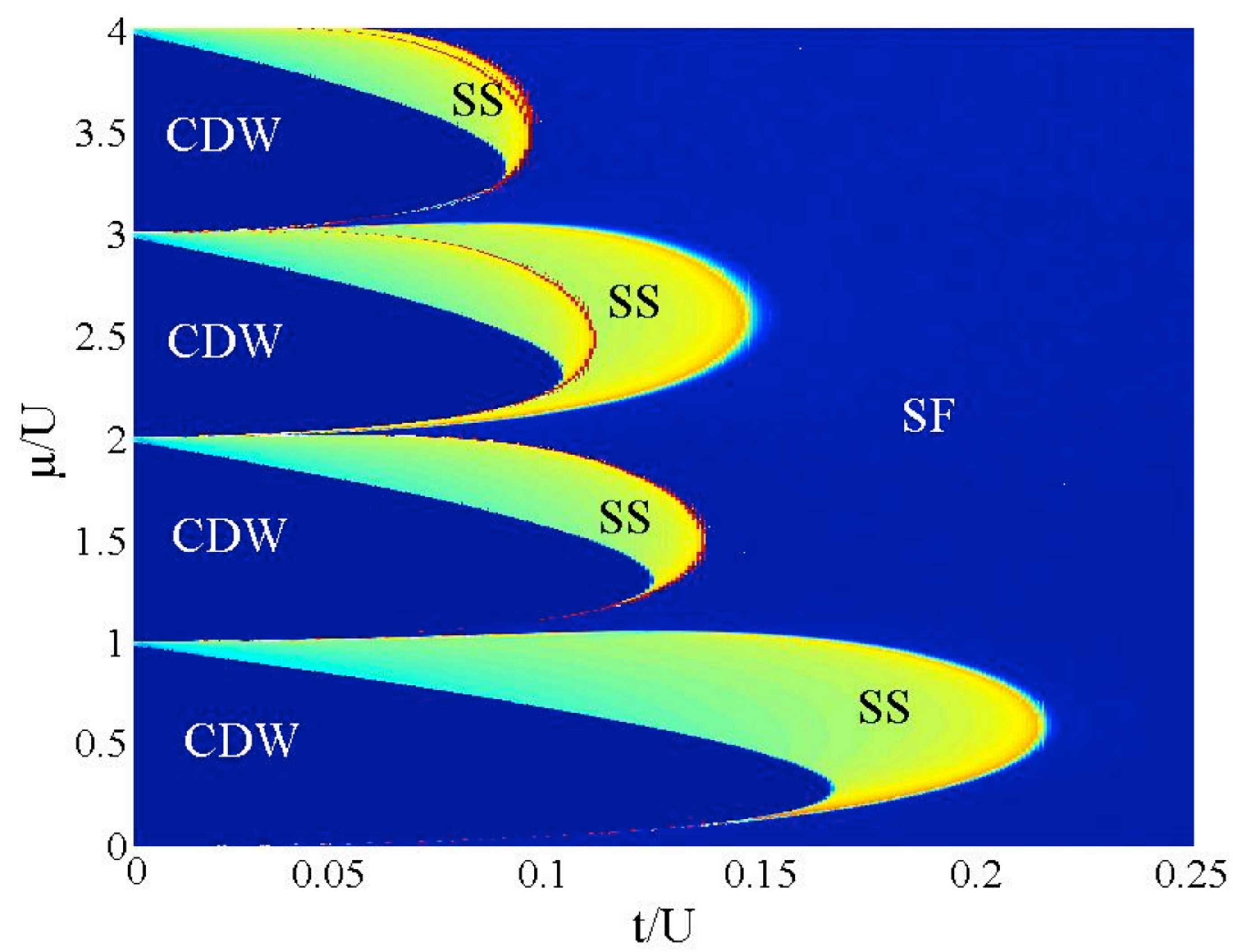
Solving the problem for $V_0=2V_1$

t=0 At this point in parameter space, the energy is minimized by all lattice states of periodicity two, at specific filling fractions $\nu = k/2$ determined by the value of the chemical potential (see figure below). In other words, all states with unit cell [*m,k-m*] for *m=0,1,...,k* will be degenerate ground states.

The exact degeneracy of these states has interesting consequences. The low-energy excitations of the system will consist of fractionally charged domain walls between the different ground states. The lattice states [*m,k-m*] are also familiar from fractional quantum Hall physics, where this phase is described by the so-called Read-Rezayi states. There, the fractionally charged quasiparticles obey non-Abelian statistics (as opposed to bosonic, fermionic or anyonic statistics).



t>0 As the hopping term is increased, the system will eventually change from the insulating phase to a superfluid one. The phase diagram as a function of *t* and the chemical potential reveals so-called Mott lobes.



What do fractional charges look like!?

Imagine a system of particles, all carrying the same charge q. How can it possibly be that the *charge carriers* of such a system have a charge that is *a fraction of q*, say q/3 or q/2?? It sounds weird, but has actually been realized experimentally in the fractional quantum Hall system. So what do these charge carriers, or quasiparticles, look like? Can we picture them in some way?

Consider a system of fixed filling fraction, e.g. $\nu = 3/2$,

and assume that the states 3030... and 2121... are degenerate ground states. A minimal excitation may now be created by forming a domain wall between [30] and [21];

...3030303031212121...

How should we interpret this state? Notice that every pair of adjacent sites in this state host exactly two particles---the only exception is the two sites marked i red above, where we instead have four particles on two sites. Clearly, the charge deviation from the background at the domain wall is 4q/2-3q/2=q/2.

We have constructed a fractional charge of size q/2!

References: For nice reviews on optical lattices and quantum Hall physics, see e.g.:
"Ultracold Dipolar Gases in Optical lattices", C. Trefzger et al., arXiv:1103.3145
"The Quantum Hall Effect: Novel Excitations and Broken Symmetries", S. Girvin, arXiv:cond-mat/9907002v1