Simulating Gauge Field with Ultracold Atoms

Edward Su, Wujie Huang, Junru Li, Boris Shteynas and Wolfgang Ketterle

MIT-Harvard Center for Ultracold Atoms, Research Laboratory of Electronics
and Department of Physics, Massachusetts Institute of Technology

Abstract

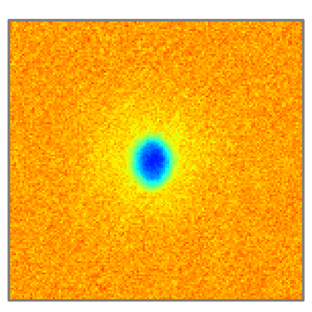
Our projects focus on simulating condensed matter system with ensemble of neutral ultracold atoms such as ^{23}Na and ^{6}Li. With the assistance of Optical Lattice which allows the manipulations on the lattice depth and geometry and also Feshbach Resonance which provides possibility to control the atom-atom interaction, quantum simulation with ultracold atoms has not only reproduced many phenomena in CM system but also gone beyond. Remarkable achievements include BEC-BCS crossover[1]. Now we are able to introduce gauge field for the neutral atoms by using laser assistant tunneling. This technique opens the possibility for simulating processes in CM system involving magnetic field and gauge potential in the Hamiltonian with our ultracold atoms system which are typically charge free. Hot directions are Quantum Hall Effects and direct observation of Hofstadter Butterfly which hasn't been done in CM system.

Bose-Einstein Condensates and Degenerate Fermi Gas

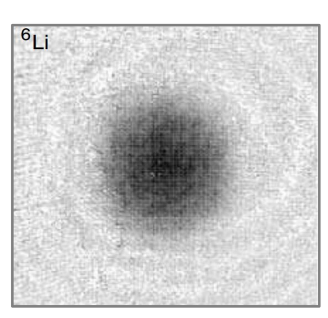
When the system is cooled to an extremely low temperature (~ nK), bosons will condensate on the ground state of the external potential (BEC) while Fermions will fill the Fermi Sea showing the Fermi distribution which deviates dramatically from the classical Boltzmann distribution.

Generating ultracold atom ensembles

- Hot atoms emitted from the oven (~600K, 10^3m/s)
- Atoms slowed down by a single laser beam along Zeeman slower (~10m/s)
- Caught and Cooled in Magneto-Optical Trap (MOT) (~$10^2 \mu$K, ~m/s), the phase space density increased to reach the threshold for evaporative cooling.
- Evaporative Cooling all the way down to quantum degeneracy, BEC (10^2nK)
- For fermions, atoms are mixed with the bosons in MOT and cooled to degeneracy by colliding with colder bosons, in other words Sympathetic Cooling.

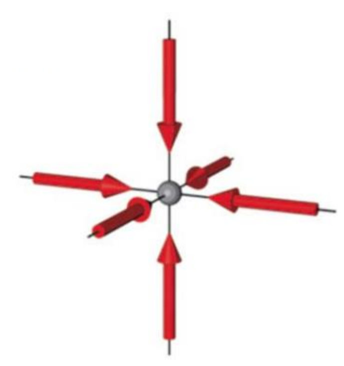


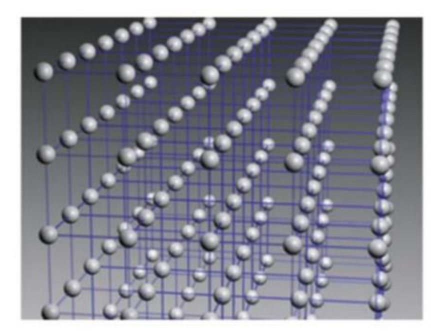
A Bose-Einstein Condensate after 10ms of free expansion. The darkness indicates high optical density, namely atom density in this case. The temperature of the sample is around



Large degenerate Fermi Sea with the temperature T = 95nK, $0.05T_F$.

Constructing Lattice with Laser Beams



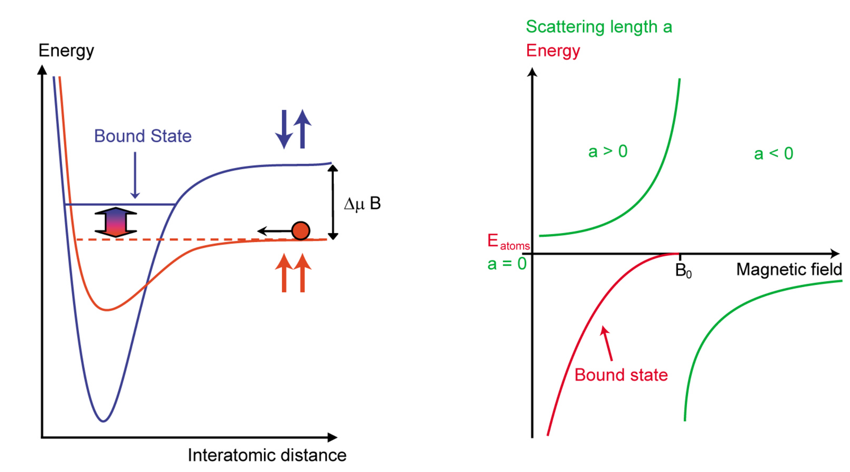


[2]

By taking the advantage of the dipole force, far-detuned laser beams in standing wave configuration can form a periodical potential for ultracold atoms, which simulates the crystal lattice structure but at the same time provides more freedom on lattice geometry and depth.

All of 1D, 2D, 3D square lattices and even triangle, hexagonal and even Kagome lattices are achievable.

Tuning the Interaction with Feshbach Resonance



[4]

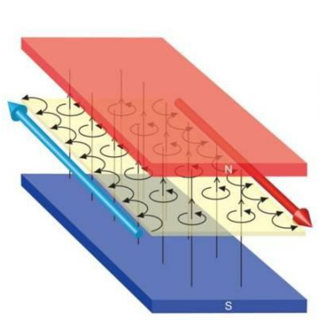
The interaction between two atoms can be tuned with external magnetic field.

$$a(B) = a_{bg}\left(1 - \frac{\Delta}{B - B_0}\right)$$

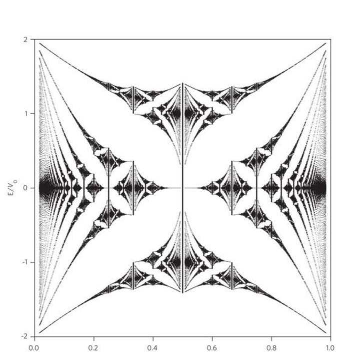
Synthetic Gauge Field for Neutral Atoms

Lattice Physics in Extreme Conditions

Transportation properties of electrons in condensed matter systems show interesting behaviors under extreme conditions such as high magnetic fields and low temperature. Examples include the Quantum Hall Effect, Fractional Quantum Hall Effect.



Quantum Hall Effect. When magnetic field is so strong and temperature is low enough that thermal energy of the electrons is comparable to the Landau energy splitting, the Hall conductance will show quantized structure. The conductance can only be the fraction or integer times of the conductance quantum.



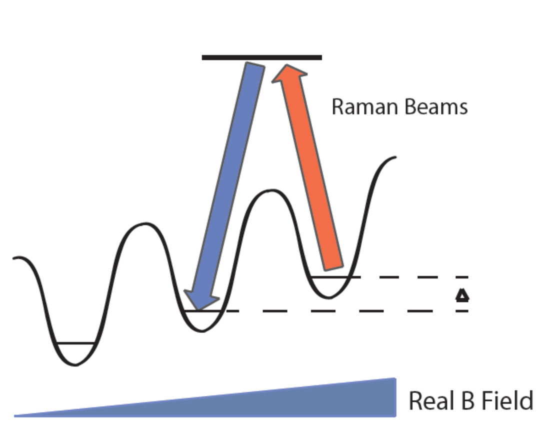
Hofstadter Butterfly. The atom hopping in 2D square lattice with magnetic field can be described by single-particle Harper Hamiltonian

$$H = -J \sum_{<m,n>,\pm} e^{\pm i 2\pi\alpha m} \hat{a}^{\dagger}_{m\pm1,n}\hat{a}_{m,n} + \hat{a}^{\dagger}_{m,n\pm1}\hat{a}_{m,n} + h.c.$$

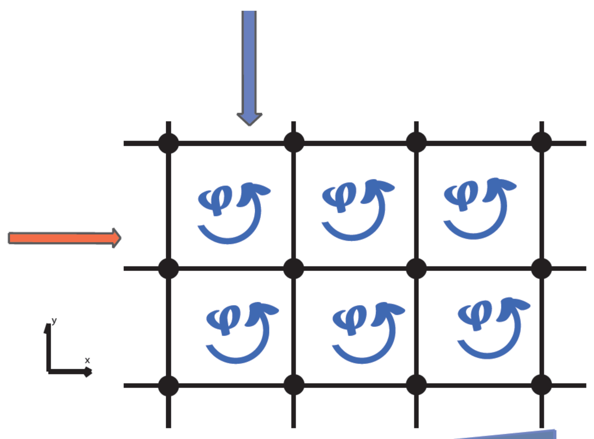
The solution of this simple Tight-bonding Hamiltonian rises the famous Hofstadter butterfly structure which has not been directly observed in natural crystals yet due to the ridiculously high field required.

Generating Synthetic Gauge Field For Neutral Atoms

The philosophy of generating a gauge field is by introducing a phase shift with the nearest-neighbor hopping process of the cold atom instead of engineering the field itself. The idea can be experimentally realized by so-called Laser Assistant Tunneling in which atoms can only tunneling from one site to another with the assistance of two laser beams through Raman process.



In this scheme, the tunneling is initially suppressed by tilting the lattice with a real magnetic field. Then with the assistance of two ramen beams, the tunneling can be restored but atoms will gain phase when hopping along the tilted direction.



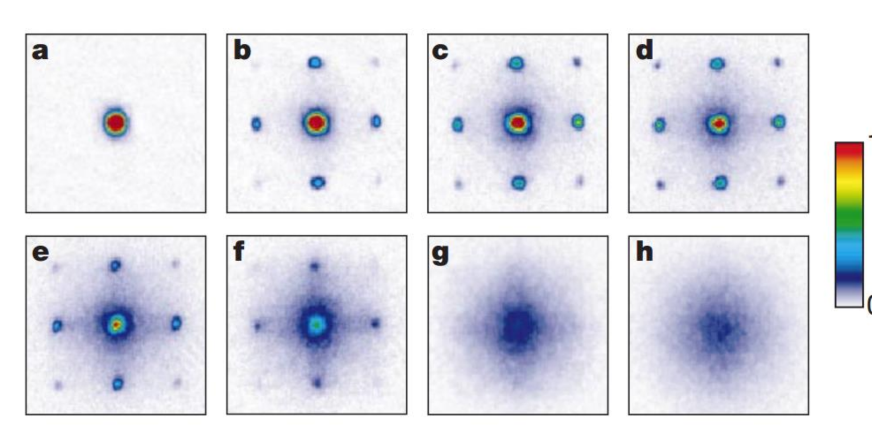
Implementing the idea in the 2D case. The lattice is tilted only along x direction. Therefore the atom gain a non-zero phase after a full circle in a lattice cell which is equivalent to a non-zero magnetic flux. The situation is similar to the case in AB effect where we have certain flux generated by an infinite long solenoid.

$$H = -\sum_{m,n}\left(K e^{-i\phi_{m,n}} \hat{a}^{\dagger}_{m+1,n}\hat{a}_{m,n} + J\hat{a}^{\dagger}_{m,n+1}\hat{a}_{m,n} + h.c.\right)$$

$$\phi_{m,n} = \delta\vec{k}\cdot\vec{R}_{m,n}$$ [5]

Quantum Simulation with Ultracold Atoms

Bose-Hubbard Physics – Superfluid to Mott Insulator Transition



[3]

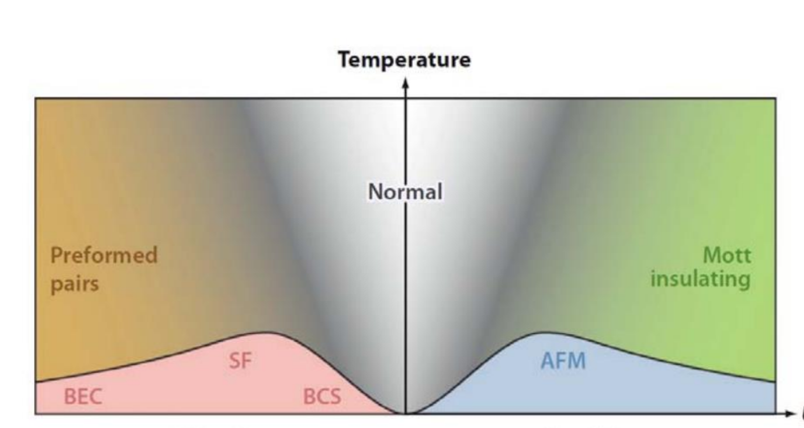
Quantum Phase Transition from Superfluid to Mott Insulator. With the increase of the interaction parameter **U**, the sample in optical lattice gradually lose all the coherence which implies a transition from coherent superfluid to incoherent Mott insulator. The width each peak reveals the information about the temperature of the sample and multiple peaks indicates the Non-adiabatic process during the ramp up of the lattice.

Fermi-Hubbard with ^{6}Li - towards Antiferromagnetism

Behavior of Fermions in Optical Lattice can be modeled by Fermi-Hubbard Hamiltonian in Tight-Binding Limit.

$$H = -t\sum_{<i,j>,\sigma}(\hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + h.c.) + U\sum_i \hat{n}^{\dagger}_{i,\uparrow}\hat{n}_{i,\downarrow} + \sum_i \varepsilon_i \hat{n}_i$$

Compared with the Bose-Hubbard model which demonstrate the Superfluid and Mott Insulate phase as the only two types of the ground state of the system, interestingly, due to the Pauli Exclusion principle, degenerate Fermi gases in optical lattice gives much more interesting and complicated results and behavior, ranging from the Cooper Pair (BCS) states and BEC of the pairs in Fermionic superfluid in the attractive side, to the antiferromagnetism in the repulsive end.



[6]

With Feshbach resonance and tunable lattice depth, we are able to continuously manipulate the interaction and therefore directly observe the crossover between BEC and BCS, which is already achieved.

If the temperature of the system is below t^2/U, it is promising that we could realize for the first time antiferromagnetic phase which has not been directly observed yet in the condensed matter system.

Current Status and Conclusion

1. We just finished the construction stage of the new apparatus after two years of constructing.
2. Using synthetic gauge field to simulate and achieve extreme condition quantum states with bosons and fermions.
3. Achieving degenerate Fermi gas and explore 'exotic' states in Fermi-Hubbard Model.

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