Experimental Studies of Many-Body Localization in Quasi-Random Optical Lattices

1. M. Schreiber, S. S. Hodgman, P. Bordia, Henrik P. Lüschen, M. H. Fischer, R. Vosk, E. Altman, U. Schneider and I. Bloch, "Observation of many-body localization of interacting fermions in a quasi-random optical lattice", Science 349, 842 (2015).
2. P. Bordia, H. P. Luschen, S. S. Hodgman, M. Schreiber, I. Bloch and U. Schneider, "Coupling Identical 1D Many-Body Localized Systems", arXiv:1509.00478.

Recommended with a commentary by Catherine Kallin, McMaster University

The use of systems of cold atoms as "quantum simulators" has blossomed over the past few decades leading to, among other things, the recent experimental studies of many-body localization (MBL) of Schreiber et al. [1] and Bordia et al. [2] Designing these experiments and understanding the results built on earlier experimental demonstrations[3] and discoveries[4] as well as the development of techniques for preparing initial states and reading out their subsequent evolution.

Discussions of MBL usually begin with the well-established phenomenon of Anderson localization of single-particle states. [5] The question which Anderson himself raised was whether this localization would survive in the presence of interactions. This question has been the subject of considerable theoretical study, culminating in recent work suggesting that the combination of randomness and interactions can lead to a complete spectrum of localized many-body states for which thermalization would not occur.[6]

From the perspective of condensed matter physics, it is not clear how MBL phenomena can be realized for electrons in solids since phonons act as a thermal bath. However, theoretical work on MBL suggests that it would be of interest to study whether thermally isolated interacting systems evolve to some kind of internal equilibrium or remain stuck in non-thermal states. In this regard, cold atom systems are ideal since they allow high degrees of isolation; they can be prepared in tailored, out of equilibrium initial states; and the periodic and random potentials as well as the interparticle interactions can be tuned over wide ranges.

Anderson localization was demonstrated for cold atoms in a Bose-Einstein condensate in a quasiperiodic potential.[3] This system is described by the Aubry-Andre Hamiltonian, with bosons hopping with amplitude J in a 1D periodic potential onto which an incommensurate "random" potential of strength Δ is superimposed. This model is known to have all states localized for $\Delta/J > 2$, and the localization length decreases with increasing Δ/J. The bosons are rendered non-interacting by tuning the interparticle Feshbach resonance to zero interaction strength. The condensate was initially confined to a small region by a trap that was then turned off, allowing the bosons to diffuse. For smaller values of Δ, the condensate expanded, but for larger values the size of the condensate cloud remained fixed, demonstrating localization.

Diffusion and transport for interacting cold fermions hopping in a periodic potential were studied in [4]. The effective Hamiltonian for this system is the Hubbard model on a cubic lattice, where the interaction parameter, U, could be positive, negative or zero. The atoms are initially confined to a cloud about 15μ in diameter and then the confinement in the horizontal plane is removed, allowing the cloud to expand freely in two dimensions. For U=0, the expansion is ballistic and the cloud evolves into a square shape, mirroring the square symmetry of the hopping Hamiltonian. For non-zero interactions, the density profile changes drastically, with the pattern at the edges remaining square, but with a circular component at the center where the interactions are most effective. The interpretation is that the circular component is composed of particles moving diffusively, due to interactions, while the motion is ballistic at the edges of the square. A remarkable and unanticipated feature of these observations is that the time evolution of the cloud depends only on |U| and not on the sign of the interaction. The explanation for this was found in a symmetry of the Hubbard model on a bi-partite lattice, where the dynamics are unchanged for U → -U.

In principle, one could study MBL the same way that Anderson localization was studied in Ref. [3], but Ref. [4] showed that free expansion with interactions is complicated by the edges and center behaving differently. Schreiber et al. [1] designed an experiment in which the observable quantity is an internal degree of freedom of a confined system. They developed a method for loading fermionic atoms (using the two lowest hyperfine states of a degenerate Fermi gas of ^{40}K atoms) into every second well of a deep periodic potential. Each well (or lattice site) has either 0, 1 or 2 fermions. They then turn on the quasi-random potential of strength, Δ, while lowering the periodic potential to allow hopping with frequency, J, and tune the Hubbard interaction U via a Feshbach resonance.

As in Ref. [3], the system is described by a 1D Aubrey-Andre model, but for spin ½ fermions with interactions. They monitor the time evolution of the alternating density by measuring the imbalance in occupation of even and odd sites, $I=(N_e-N_o)/(N_e+N_o)$. Results are shown only for times up to 35τ, where $\tau=\hbar/J$ is the tunnelling time, but this is sufficient to see clear effects of disorder and interactions. The experimental system consists of multiple 1D chains or tubes of about 200 sites, each described by the same Hamiltonian (although the trap potential varies from the center tubes to the edge tubes) and the potential wells are sufficiently deep in the orthogonal direction that these tubes are taken to be non-interacting. The measured imbalance is an average over all the 1D tubes.

The initial out-of-equilibrium state is prepared with an imbalance close to 1 (>0.9) and then allowed to relax. After a few tunnelling times, the imbalance approaches a stationary value that is zero for zero disorder, but for stronger disorder is non-zero and increasing with disorder. For example, at Δ/J=8, the stationary imbalance is ~0.6, both for U=0 and U=10J, in striking contrast to the Δ=0 result. For non-interacting fermions the measured stationary imbalance is a monotonically increasing function of the disorder, Δ/J that agrees with numerical results for the Aubrey-Andre model for a finite chain in a trap. (The trap significantly broadens the transition at Δ=2J.)

As a function of interaction strength, U/J, the stationary imbalance has a "W" shape. As discussed above, the dynamics (and consequently the imbalance) are symmetric around U/J=0, and the effect of weak interactions is to slightly reduce the long-time imbalance, i.e.

to reduce the degree of localization, relative to the non-interacting case. However, for |U| > 5J, the long-time imbalance increases with interaction, and at large |U| the system is as or more localized (larger stationary imbalance) than in the non-interacting case, where the large |U| imbalance depends on the fraction of doubly occupied sites in the initial CDW state. The same W shape and dependence on double occupation is seen in model DMRG calculations. All these observations are consistent with MBL for the disordered, interacting case.

Bordia et al.[2] extended this work by studying the effect of coupling the 1D chains. They varied the interchain hopping, J'', by varying the well depth in the orthogonal direction. The system corresponds to ~120 1D chains of ~200 lattice sites, with each chain described by approximately the same Aubrey-Andre model, with interactions. In particular, each chain has the same disorder potential but, due to the trap, the density varies from the center chains to those near the edge. The disorder strength is set at Δ=5J to be well within the localized regime observed in Schreiber et al., while J'' and U are varied. Comparing the time evolution of the imbalance for the 1D ($J''\leq 10^{-3}J$) and the J''=J 2D systems, very different behavior is seen for the non-interacting (Anderson localization) and interacting (MBL) cases. For U=0, the dynamics is almost the same in the 1D and 2D cases, both displaying the same plateau observed in Ref. [1] for times between about 2τ and 40τ. However, the interacting 2D case shows fast decay with no plateau. Note this is not a general random 2D system since the disorder is the same in each chain. Rather it is an array of identical disordered chains where particles can hop freely between chains. The difference between the non-interacting and interacting systems is striking and Bordia et al. interpret the interacting case as the chains collectively acting as thermal baths for each other.

Bordia et al. find an imbalance lifetime for the non-interacting case of about $10^4\tau$, independent of J'', which is attributed to photon scattering and noise in the optical fields. With interactions, the J'' dependence of the imbalance lifetime is linear on a log-log plot and does not saturate even at the smallest $J''/J\sim 10^{-3}$, being still limited by the residual interchain couplings.

In summary, for "decoupled" 1D chains, the experiments find a striking difference in the dynamics between Δ=0, where the initial out-of-equilibrium CDW state quickly thermalizes within only a few τ and large Δ, where the system only thermalizes on a very long timescale that appears to be determined by the small residual interaction between the 1D chains. The dynamics in the latter case of stronger disorder, depend on the strength of interaction, and agree well with numerical results for times less than ~40τ. Furthermore, Bordia et al. found the interacting localized phase to be very sensitive to any hopping between the 1D chains, in sharp contrast to the case of (non-interacting) Anderson localization. These experiments suggest that if one could further isolate the 1D chains from each other, the stationary imbalance in the localized phase could be observed over noticeably longer times than 40τ. Studying the general 2D disordered case would also be of great interest.

3. G. Roati et al., "Anderson localization of a non-interacting Bose-Einstein condensate", Nature 453, 895 (2008).

4. U. Schneider et al., “Fermionic transport in a homogeneous Hubbard model: Out-of-equilibrium dynamics with ultracold atoms”, Nature Physics 8, 213 (2012).
5. P. A. Lee and T. V. Ramakrishnan, “Disordered electronic systems”, Rev. Mod. Phys. 57, 287 (1985).
6. R. Nandkishore and D. A. Huse, “Many-Body Localization and Thermalization in Quantum Statistical Mechanics”, Ann. Rev. Cond. Matt. Phys. 6, 15 (2015).