Many-body localization of cold ^{40}K atoms

"Observation of many-body localization of interacting fermions in a quasi-random optical lattice", arXiv:1501.05661

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Recommended with a commentary by L. I. Glazman, Yale University

In the seminal 1958 paper, Anderson cites the problem of spin diffusion as a motivation to study the quantum effect of localization [1]. The conclusion about the stability of a localized phase was actually reached there for a single quasiparticle hopping between sites with random, broadly distributed energies.

The single-particle localization theory, applicable to various systems comprised of non-interacting particles, provided a framework for understanding a broad range of physical phenomena including, *e.g.*, the metal-insulator transition in electric conduction of solids [2]. In the latter example, the interference correction to Drude conductivity of the metallic phase serves as a harbinger of the transition to localized, insulating state. The interaction between electrons leads to temporal noise of a self-consistent potential acting on electrons. The noise results in electron phase relaxation, which in turn reduces the role of interference effects. Would the interaction destroy the effect of localization?

Getting back to Ref. [1], we note that a highly-excited spin system can hardly be described in terms of non-interacting quasiparticles. Anderson made, however, an insightful remark: as long as the system is isolated from a "real external bath", the localization effect preventing thermal equilibration within an isolated body, may withstand interactions. This view, for the case of short-range interaction, was re-affirmed in a later paper [3].

The problem of many-body localization (MBL) was revisited a decade ago by Basko, Aleiner, and Altshuler [5] who investigated the mobility edge of weakly-interacting electrons in a random potential. The MBL problem for finite-bandwidth fermions was addressed by Oganesyan and Huse [4]. The conclusion was that interaction does not destroy the localization effect in an isolated electron system: an initial local perturbation of an intensive quantity (such as density) would not decay to zero at arbitrarily long time.

These works brought the MBL problem back into focus and were followed by a substantial number of theory papers (various aspects of theory being currently explored are well represented by the list of references in the experimental paper [6]). On the experimental side, cold atoms are by far the best systems to study MBL with. An ensemble of cold atoms can be effectively isolated from a thermal bath, which is the crucial ingredient for the MBL (on the contrary, electrons in a solid interact very effectively with phonons).

Paper [6] describes a beautiful demonstration of MBL in a one-dimensional lattice loaded with ^{40}K atoms forming an interacting Fermi-system. (Unlike real solids hosting electrons, the optical lattice is rigid, so cold atoms do not encounter phonons.) The localization of single-particle states was achieved by spatial modulation of the on-site energies, $E_i = \Delta\cos(\beta i + \phi)$; here i is the lattice site label. An irrational value of β makes the lattice quasi-random. At almost any irrational β, single-particle states are localized if Δ exceeds the critical value, $\Delta_{\rm cr} = 2J$, set by the nearest-neighbors hopping matrix element J. In the experiment [6], lattice was loaded with equal densities of two species of ^{40}K differing by their hyperfine states. Interaction U between the atoms of two different states was controlled by means of Feshbach resonance. In total, all three relevant parameters, Δ, J, and U were independently tunable.

The initial state was prepared by a quench which ideally would make all odd lattice sites empty, $N_o(t = 0) = 0$, and even sites occupied with some number (from 0 to 2) of atoms, $N_e(t = 0) = 0 \div 2$. In reality the imbalance $\mathcal{I} = (N_e - N_o)/(N_e + N_o)$ in the initial state was $\mathcal{I}(t = 0) \gtrsim 0.9$. Clearly, such a "charge-density wave" state is very far from a thermal equilibrium state of the same total energy. A finite value of the long-time asymptote, $\mathcal{I}_\infty \equiv \mathcal{I}(t \to \infty) \neq 0$, provides a criterion for the presence of MBL.

The experimental limitation for evolution time was $t \lesssim 40\tau$, where $\tau = \hbar/J$ is the inter-site tunneling time. Despite the limitation, a drastic difference between the delocalized and localized phases was evident in the evolution. At $\Delta/J = 0$, the value $\mathcal{I}(t)$ was indistinguishable from zero at $t \gtrsim 4$. In a localized phase, at $\Delta/J = 3$, the imbalance was reaching $\mathcal{I}(t) \approx 0.2$ at $t \gtrsim 10$, hardly varying at later times. Thus, the evolution time limitation did not affect much the measurement of $\mathcal{I}_\infty$. The spatial inhomogeneity introduced by trap played a bigger role in smearing the transition between the delocalized and localized phases.

The data indicate that the transition to the localized phase is continuous: even in the absence of smearing $\mathcal{I}_\infty$ would raise from zero with Δ crossing the critical value $\Delta_{\rm cr}(U)$. The first and most important conclusion of the experiment is that the MBL persists at *any* value of the interaction strength U. The function $\Delta_{\rm cr}(U)$ turned out to be non-monotonic, with maximum around $U \approx 5J$. The $U = 0$ value of $\Delta_{\rm cr}$ agrees with the prediction of the single-particle theory. The large-U asymptote of $\Delta_{\rm cr}(U)$ depends on the fraction of doubly-occupied sites in the initial state. In the absence of doublons, atoms behave as hard-core particles in the limit $U \to \infty$; their behavior is indistinguishable from spinless free fermions, therefore $\Delta_{\rm cr}(U \gg J) = \Delta_{\rm cr}(0)$. Experiment agrees with that consideration. Compared to single atoms, the doublons have harder time tunneling, resulting in a narrow ($\sim J^2/U$) doublon bandwidth. Thus $\Delta_{\rm cr}(U)$ is suppressed compared to $\Delta_{\rm cr}(0)$ if the double-occupancy fraction is high; that feature is also observed in [6].

Apart from demonstrating that MBL is a robust phenomenon, the experiment [6] provides an incentive for further studies. Among various directions, an investigation of the critical behavior close to the MBL transition, studies of MBL in higher dimensions, and observation of MBL suppression by coupling to a thermal bath seem within the reach of cold-atoms experiments.

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[1] P.W. Anderson, "Absence of Diffusion in Certain Random Lattices", Phys. Rev. **109**, 1492 (1958)

[2] Patrick A. Lee and T. V. Ramakrishnan, "Disordered electronic systems", Rev. Mod. Phys. **57**, 287 (1985)

[3] L. Fleishman and P. W. Anderson, "Interactions and the Anderson transition", Phys. Rev. B **21**, 2366 (1980)

[4] Vadim Oganesyan and David A. Huse, "Localization of interacting fermions at high temperature", Phys. Rev. B **75**, 155111 (2007)

[5] D.M. Basko, I.L. Aleiner, and B.L. Altshuler, "Metal-insulator transition in a weakly interacting many-electron system with localized single-particle states" Annals of Physics **321**, 1126 (2006)

[6] Michael Schreiber, Sean S. Hodgman, Pranjal Bordia, Henrik P. Lüschen, Mark H. Fischer, Ronen Vosk, Ehud Altman, Ulrich Schneider, and Immanuel Bloch, "Observation of many-body localization of interacting fermions in a quasi-random optical lattice", arXiv:1501.05661