Physics

VIEWPOINT

Many-Body Localization Needs a Bath

Theoretical work proves that interacting quantum systems can enter a many-body localized phase in which they cannot reach thermal equilibrium without an external bath.

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We learn in our statistical mechanics classes that a system of many interacting degrees of freedom isolated from the external environment will, under its own internal dynamics, reach thermal equilibrium after a sufficiently long time. When this is true—as is often the case—the system serves as a "bath" for its own subsystems: Any small part of the full system sees the rest of the system as a reservoir with which it can exchange energy, particles, and quantum entanglement. This process is called thermalization.

However, there are some systems of interacting quantum particles or spins that are believed not to be able to serve as a bath for themselves. Such many-body localized (MBL) [1] systems remain localized in states that are close to their initial conditions (see Fig. 1). Bringing them to thermal equilibrium requires an external bath. But so far, there has been no rigorous proof of the existence of such many-body localization. Now, theoretical work by John Imbrie at the University of Virginia, Charlottesville [2], provides such a proof—although relying on one very reasonable assumption.

The concept of localization was introduced by Philip Anderson in 1958 [3], when he showed that interacting spins in lightly doped semiconductors may not be able to thermally equilibrate without any help from phonons (the material's lattice vibrations). The relationship between Anderson localization and thermalization received little attention for almost half a century. But more recently, this topic was turned into a trending research field by great progress seen in many-body atomic, molecular, and optical physics, and quantum information. Such developments have allowed researchers to engineer and investigate experimentally a wide variety of systems—from trapped cold atoms to spin ensembles—containing many interacting quantum degrees of freedom that are well isolated from their environment.

For quantum particles or waves in a disordered medium that do not interact with each other, Anderson localization is well understood. It has been experimentally observed for phonons [4], photons [5], and ultracold atoms [6]. In 2006, Denis Basko, Igor Aleiner, and Boris Altshuler investigated whether an Anderson-localized system at nonzero temperature would remain localized when small interactions between nearby particles are introduced [7]. Studying such systems with perturbation theory, they found that this is indeed true to all orders of approximation, thus establishing the concept of the MBL phase as a state of matter at nonzero temperature. One striking feature of such MBL systems is that they have strictly zero thermal and electrical conductivity: they are perfect insulators.

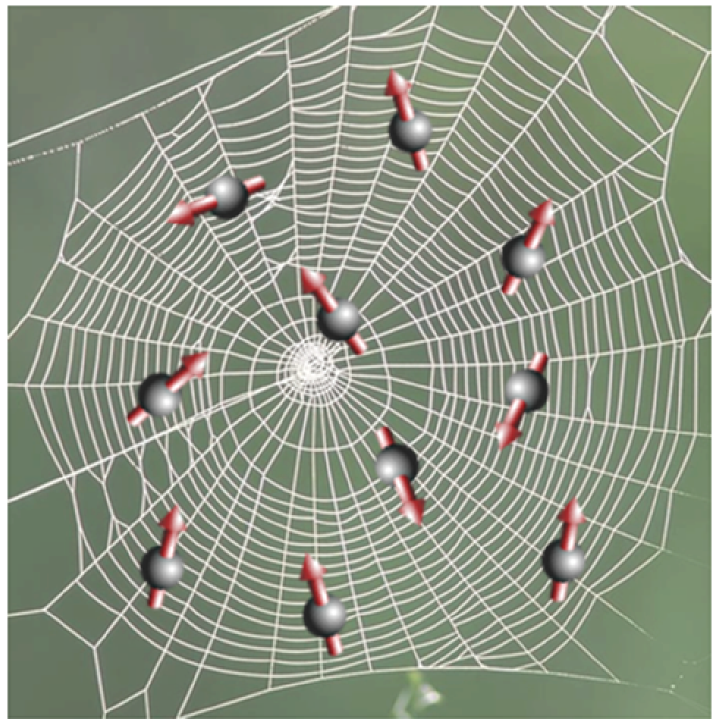

Figure 1: The work of Imbrie [2] provides the proof that quantum systems can enter a many-body localized (MBL) phase, in which they cannot thermally equilibrate under their own internal dynamics. A MBL ensemble of spins, for instance, would remain "trapped" in a state that would not be able to thermalize in the absence of an external bath. (Chris Laumann/University of Washington)

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However, even if "true to all orders" in perturbation theory, the conclusion by Basko, Aleiner, and Altshuler does not rule out another possibility: many-body localization might only be metastable, with the system appearing localized but actually thermalizing on long time scales because of subtle effects that are not captured by perturbation theory. One such scenario has been published earlier this year [8].

Imbrie's new work [2] makes important progress towards a conclusive proof of a MBL phase by essentially ruling out all such nonperturbative effects for certain systems. Treating a particular model of interacting spins, he shows that all eigenstates of its Hamiltonian are MBL. As a consequence, the system—evolving under its own Hamiltonian—cannot reach a non-MBL state, and thermalization is blocked. His conclusion holds for a broad class of 1D systems with short-range interactions between particles or spins on a lattice. An example that could be realized experimentally with ultracold atoms is a Bose-Hubbard system: Bosonic atoms hop on a 1D lattice in which the potential energy varies randomly from site to site, and the atoms interact when they are on the same site.

This result gives us confidence that some 1D systems undergo a true many-body localization phase transition between a delocalized or thermal phase (in which the system is a bath for itself) and the MBL phase (in which it fails to be a bath for itself). This novel quantum phase transition is a topic of active research, but it remains poorly understood [1]. Recent experiments—one with ions trapped in 1D (but with longer-range interactions than those considered by Imbrie) [9] and others with ultracold atoms with short-range interactions (but trapped in more than one dimension) [10]—explored such a possible phase transition. However, in these cases, which are not covered by Imbrie's proof, it remains possible that many-body localization is not a true phase but only a metastable regime: These systems might be almost localized but still become a bath for themselves on extremely long time scales (too long to be detected in these experiments) because of nonperturbative effects.

It is important to note that Imbrie's proof is valid under an assumption that is actually very reasonable, which he calls "limited level attraction": the hypothesis that the eigenenergies of the system's Hamiltonian do not accumulate too strongly near degenerate points (states with almost the same energies). This is a realistic scenario for all known systems. On the one hand, in systems that thermalize, near-degenerate eigenstates show energy-level repulsion due to quantum-mechanical effects. On the other hand, in MBL systems, energy levels neither attract nor repel each other. No scenario with strong level attraction is known that would violate Imbrie's assumption, but Imbrie could not mathematically prove that this seemingly obvious assumption is true. His proof thus remains, in principle, incomplete until this assumption is proven or a general proof that does not rely on this assumption is found.

Many intriguing questions remain open. First, what is the nature of the quantum phase transition between quantum thermalization and many-body localization? Second, what are the possible systems in which there is a sharply distinct MBL phase that is stable against all nonperturbative effects? Imbrie's proof partially answers the second question, saying that the MBL phase is indeed stable in certain 1D systems with short-range interactions. So in those systems, the quantum phase transition does indeed exist. But Imbrie's proof does not work for longer-range interactions or in more than one dimension. Does this limitation reflect the impossibility of a stable MBL phase outside of the cases his approach can tackle, or is this just a limitation of the mathematical approach he uses, and we may thus find stable many-body localization in a much wider class of systems?

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