STATISTICAL PHYSICS

Localization goes long

Signatures of many-body localization have been observed in a one-dimensional chain of trapped ions, heralding new studies of the interplay between localization and long-range interactions.

Chris R. Laumann and Norman Y. Yao

The defining feature of quantum mechanics is that the energy levels of an atom are discrete. An excitation can move between two atoms only if the relevant levels align so that the total energy can be conserved — such atoms are in resonance. Spatial disorder shifts the energy levels of neighbouring atoms out of resonance, hindering this transport. Nearly six decades ago, Anderson realized that strong enough disorder could arrest transport completely, leading to the "absence of diffusion in certain random lattices"[1]. In such systems, localized excitations fail to establish equilibrium, and statistical mechanics breaks down. Anderson showed that this breakdown is inevitable for a single excitation hopping in a disordered background. More recently, it has been discovered that localization can persist even in the presence of many strongly interacting excitations — a phenomenon dubbed many-body localization[2–4].

Writing in *Nature Physics*, Jacob Smith and collaborators[5] report the observation of signatures of many-body localization in a one-dimensional chain of ytterbium ions (Fig. 1a). In this system, the hopping excitations consist of spin degrees of freedom formed from a pair of internal hyperfine states. With individual control and read-out over each ion, the authors can initialize the system in an arbitrary spin configuration, vary the effective disorder landscape and directly observe the resulting microscopic spin dynamics. Beginning with the high-energy Néel configuration — alternating up and down spins — the authors track the polarization of each spin as a function of time. They detect two qualitatively different regimes. With weak disorder, the polarizations decay to zero for all spins — a result consistent with thermal equilibration. With strong disorder, the polarizations plateau to a finite value — a key signature of arrested spin transport and many-body localization.

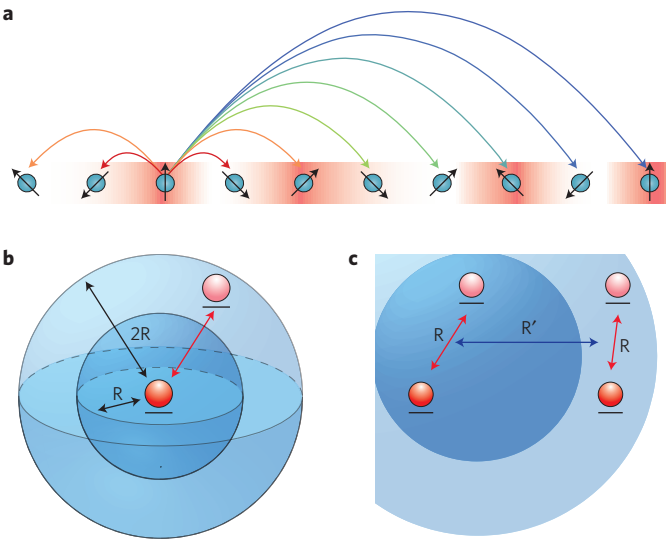

Figure 1 | Interactions in a one-dimensional chain of ions. **a**, Each trapped ion in the chain can be thought of as a spin 1/2. The spins are subject to a random site-dependent field (red) in the transverse direction and interact through long-range Ising-type interactions that fall off as a power law. **b**, A single excitation (red sphere) can delocalize over a pair of resonant sites when the strength of the hopping is greater than the misalignment between their local energy levels. At scale R, there are $\sim R^d$ sites in a d-dimensional system, each with a probability $\sim 1/R^\alpha$ of being resonant. Taking long-range interactions into account, a pair of excitations delocalized over separate resonant pairs of sites at scale R can in turn resonantly exchange energy across the separation R'. **c**, Long-range interactions allow two excitations (red and orange spheres), each delocalized over separate resonant pairs of sites at scale R, to in turn resonantly exchange energy across another separation R'.

Unlike previous studies of many-body localization with neutral atoms[6–9], ions naturally interact with one another over long distances (Fig. 1a). The interplay between Coulomb repulsion and trapping forces gives birth to a crystalline configuration, and off-resonant laser fields couple the spin with the vibrations of this crystal. This produces long-range Ising-type interactions between the spins which fall off as a tunable power law. From the perspective of resonances, it is clear that long-range interactions disfavour localization — if an excitation can hop directly over a large distance, it has a significantly higher chance of finding a resonant site.

To gain a more precise understanding, one can follow Anderson's original argument and count hopping resonances for a single excitation[1]. Two effects compete. The number of sites out to a distance R grows as R^d in a d-dimensional system. However, the strength of hopping typically decays as a power law, $1/R^\alpha$, with separation. As the probability of resonance scales directly with this hopping strength, the total number of resonant sites scales as the product, $R^{d-\alpha}$ (Fig. 1b). Thus, for sufficiently long-range power laws, the excitation always finds resonant partners at arbitrarily large distances. This simple counting argument predicts a critical power law, $\alpha_c = d$, below which localization is inconsistent.

Resonance counting in the presence of multiple interacting excitations is much more challenging. Essentially, the complication is that the motion of one excitation can push another pair of sites into or out of resonance. One approach to dealing with this is to identify a hierarchy of resonances (Fig. 1c), leading to modifications of the counting arguments and more restrictive conditions on the value of the critical power law[10,11]. In the experiment of Smith *et al.*, these counting arguments suggest a critical power law of three-halves[12]. Although their current work primarily focuses on $\alpha = 1.13$,

Smith and collaborators can tune α between 0.95 and 1.81, straddling from below the single-particle criterion ($\alpha_c = 1$) to above the interacting criterion ($\alpha_c = 3/2$). Their work opens the door to controlled experimental investigations across this critical regime.

Ion traps provide a versatile experimental platform for studying interacting quantum dynamics. Looking forward, however, there are a number of challenges that may be summarized by the need for longer times and larger systems. First, as no physical system is ever truly isolated, thermal (or other) noise eventually overwhelms quantum localization. Ideally, then, the timescale for extrinsic decay needs to be separated as much as possible from that of the quantum dynamics. In the current experiment, the authors estimate this separation as about an order of magnitude. This will presumably get larger as the platform matures. With a somewhat larger separation, it may be possible to tune the noise couplings intentionally in order to use the sensitivity of the observed dynamics as a probe of localization — an approach used with some success in neutral atom experiments[8].

Second, the long-range resonant structures that lead to delocalization are often too large to arise in small systems[11]. As the current study has only 10 ions, the observed crossover to localization may seem very different as the system sizes get larger — indeed, it must if the hierarchical counting arguments mentioned above are correct. With only a few more ions, the experiments will quickly outstrip our ability to simulate these systems numerically and will become the only game in town.

Classically, energy is continuous, and 'classical atoms' need not be resonant in order to exchange energy. This observation suggests that systems of interacting classical degrees of freedom cannot localize — a result supported by nearly 150 years of research into classical chaos and equilibration. Many-body localization is a direct manifestation of quantum mechanics at high energy, about which much theory has been written, but relatively little is truly known. The experiments reported here represent early steps into this largely unexplored landscape. ❐

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TWO-DIMENSIONAL MATERIALS

Heavy going

Chiral symmetry breaking is imaged in graphene which, through a mechanism analogous to mass generation in quantum electrodynamics, could provide a means for making it semiconducting.

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Thanks to the presence of Dirac points in the electronic band structure, graphene can host emergent quasiparticles that behave as massless Dirac fermions. But engineering a sizeable mass for the Dirac fermions in graphene is important for a range of technological applications as it would open up a bandgap and turn graphene into a semiconductor. Writing in *Nature Physics*, Christopher Gutiérrez and colleagues[1] now experimentally show how a bandgap at the Dirac points can be opened by breaking an effective chiral symmetry.

The asymptotic and distinctive V-shaped density of states near the Dirac points of graphene protect them against weak electron–electron interactions. So what mechanisms are available for opening a bandgap? For pristine graphene, Semenoff predicted that a charge-density wave, which penalizes the occupancy of electrons in one triangular sublattice of the underlying honeycomb lattice with respect to another, could open a bandgap at the two inequivalent Dirac points[2]. Haldane showed that a gap could also be opened by breaking time-reversal symmetry[3].

But a third mechanism is that of a bond-density wave[4], which breaks neither time-reversal symmetry, nor the conservation of electronic charge. This instability was christened a Kekulé bond-density wave because it breaks the $\pi/3$ rotation symmetry of the honeycomb lattice down to $2\pi/3$, just as the Kekulé bond-density does in the benzene molecule[4].

Cheianov *et al.* proposed the following microscopic mechanism to open a Kekulé gap in graphene[5,6]. The enlarged unit cell of graphene with the Kekulé pattern can be pictured by tiling the honeycomb lattice with a three-colour code; say red, blue and green. If a dilute density of adatoms is then randomly placed on the graphene at high temperature, the system would minimize its free energy by optimizing two free-energy gains against one free-energy loss below some ordering temperature[5,6].

An electronic energy is gained by opening a Kekulé bandgap at the two inequivalent Dirac points of graphene. An effective two-body interaction between adatoms is also gained by occupying a fraction of the sites of the honeycomb lattice assigned one of the three colours. This effective two-body interaction is mediated by the Dirac fermions of graphene when the chemical potential matches the energy of the Dirac points. Elastic energy is lost by displacing the carbon atoms so as to form the short and long bond lengths that characterize the Kekulé bond-density wave.

Although a Kekulé instability has been observed in artificial graphene[7], realizing and observing such bond-density waves in pristine graphene has proved challenging experimentally, partly because of incommensurate phenomena encountered when using proximity effects.

Using scanning tunnelling microscopy (STM)-based techniques, Gutiérrez *et al.* show that the microscopic mechanism previously proposed[5,6] to open a Kekulé gap can work at temperatures extending up to 300 K (ref. 1). They achieve this by growing