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.

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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 showed that strong enough disorder could arrest transport completely, leading to the “absence of diffusion in certain random lattices”. 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.

Writing in Nature Physics, Jacob Smith and collaborators report the observation of signatures of many-body localization in a one-dimensional chain of ytterbium ions. 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.

Unlike previous studies of many-body localization with neutral atoms, ions naturally interact with one another over long distances. The interplay between Coulomb repulsion and trapping forces gives birth to a crystalline configuration, and off-resonant laser fields couple the spins 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 disfavor 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. 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. In the experiment of Smith et al., these counting arguments suggest a critical power law of three-halves. Although their current work primarily focuses on $\alpha = 1.13$,
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 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, Senemoff 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 points1. Haldane showed that a gap could also be opened by breaking time-reversal symmetry2. But a third mechanism is that of a bond-density wave3, 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 π/3 rotation symmetry of the honeycomb lattice down to 2π/3, just as the Kekulé bond-density does in the benzene molecule4.

Cheianov et al. proposed the following microscopic mechanism to open a Kekulé gap in graphene5,6. 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 temperature7,8.

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 graphene2, 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 proposed5,6 to open a Kekulé gap can work at temperatures extending up to 300 K (ref. 1). They achieve this by growing