QUANTUM GASES

Joint forces against disorder

A new experiment with ultracold gases shows how weakly-interacting atoms cooperate to restore long-range coherence against disorder-induced localization. It should shed new light on long-standing questions on the complex interplay of interactions and disorder in quantum systems.

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Imagine a troop of soldiers trying to clear a path through a dense jungle. They have to decide between acting independently so as to explore a larger area but lacking mutual help or cooperating so as to coordinate their action but spending more time to explore a given acrea. A quite similar question also holds for quantum particles in dirty materials, although in a slightly different way: Do disorder and interactions cooperate or compete to determine whether a material behaves like a metal or like an insulator? Writing in *Nature Physics*, Benjamin Deissler and colleagues[1] show that weak repulsive interactions act against disorder to restore metallic-like behavior in ultracold Bose gases.

Disorder palys an important role in many condensed-matter systems and strongly influences a variety of phenomena such as electronic conductivity or superfluidity in liquid helium. Anderson showed more than fifty years ago that disorder alone can lead to metal/insulator transitions by spatial localization of quantum particles[2]. In most materials however, Anderson localization is hardly separable from other metal/insulator transitions, such as those induced by crystal structures (leading to band insulators) or particle-particle interactions (leading to Mott insulators). Hence, very many parameters determine the metallic or insulating nature of materials and drawing a clear and comprehensive picture is hampered by the interplay of all these effects in most condensed-matter systems.

Ultracold atoms avoid these drawbacks for they are versatile and controllable systems. Several research groups currently make special effort to use them as playgrounds to similate theoretical models in real experiments. Disordered systems is a particular field where ulracold atoms are promising to address open questions[3].

The first step was to demonstrate Anderson localization of quantum particles. This was successfully achieved two years ago in two complementary experiments[4,5]: Using a gas of ultracold atoms in a controlled disordered potential created by laser light in conditions of negligible interactions, exponential decay of the atomic density profile was observed. This was the first direct evidence of Anderson localisation of matterwaves. Now, the experiment reported on page XXX of this issue makes a key step ahead in the physics of disordered systems with the introduction of controlled interactions.

In their experiment, Deissler *et al* first create a periodic potential using two strong counter-propagating laser beams. Bosonic ^{39}K atoms are then trapped in a perfectly periodic one-dimensional array of wells (the nodes of the corresponding standing wave) and can jump from one to another by quantum tunneling. Disorder is subsequently introduced using a second, independent and much weaker standing wave with an incommensurate spatial period. This mimics disorder in the form of random-like shifts of the depth of the wells. Aubry and André have shown in the early 1980's that such a model exhibits a metal-insulator transition[6]: For low disorder, the quantum states are extended over the full system as in a metal. Conversely, when the disorder strength increases, the states become exponentially localized thus leading to absence of long-range coherence, as in an insulator. Control of the tunneling rate and disorder strength in the same experiment as that of Deissler *et al* allowed demonstration of this localization/delocalization scenario[1].

Now, how do interactions affect this transition? In order to address this question, Deissler *et al* used another control knob available to ultracold atoms: a magnetic field which modifies the atomic internal structure and thus the interaction strength (Feshbach resonance techniques). For a given amount of disorder and interactions, the Bose gas is produced close to its ground state. The momentum distribution is then precisely measured by releasing the atoms from the disordered lattice and canceling the interactions (time-of-flight technique). Subtle Fourier analysis of the data then provides information on localization properties, spatial correlations and phase coherence. Repeting the experiment for a variety of parameters, Deissler *et al* hence evidence the main features of a delocalization crossover induced by weak repulsive interactions[7,8]: For very weak interactions, the bosons populate low-energy states thus forming independent, strongly-localized islands with no phase coherence. When interactions are increases, more islands are populated. When many are populated, they overlap and start to form locally-coherent patches. For stronger interactions, these patches inflate so as to minimize the interaction energy and finally condense into a single patch with long-range coherence (see Fig. 1).

This experiment constitutes an important step ahead in the understanding of disordered systems with ultracold atoms, showing that weakly-interacting bosons do cooperate to counteract localization in disordered systems, thus turning an insulator -like material into a metal-like material. The next step would be to study strongly-interacting Bose gases, for which theory predicts that interactions should conversely cooperate with disorder to enhance localization. In strongly-correlated Bose lattices, Fisher *et al* predicted the formation of an intriguing Bose glass phase[9], the nature of which is still debated. Recent experiments with ultracold atoms in this regime suggest supression of the gap[10] and destruction of the condensed fraction[11]. Further efforts are needed to measure key features, such as compressibility and supression of the superfluid fraction, a related but more elusive quantity than the condensed fraction.

So far, disordered quantum gases have focused on bosons, which are relevant to ^{4}He in porous media. With a view towards systems of direct relevance to metal-insulator transition in electronic systems, a future challenge would be to study the fermion counterparts of this physics, a new story to be written.

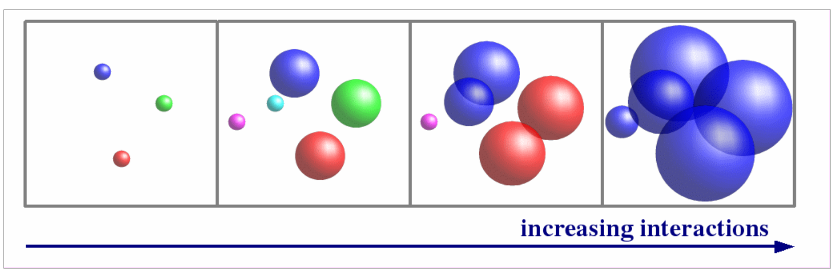

Figure 1 | Effect of weak repulsive interactions in a disordered Bose gas. For very weak interactions, the bosons populate a couple of independent islands with random phases (represented by different colors). When interactions increase, more islands are populated and inflate. When two islands overlap, they rapidely form a locally coherent patch. For sufficiently large interactions, a single patch is formed with long-range

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