NATURE|Vol 453|12 June 2008

CONDENSED-MATTER PHYSICS

Paralysed by disorder

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In a disordered medium, a quantum particle can literally stop itself in its tracks. This localization phenomenon can be observed directly using the coldest known form of matter, caught in a laser trap.

Those familiar with the game of pachinko — in which, in its simplest incarnation, little balls bounce and cascade chaotically through a regular lattice of pin-like obstacles — have some idea of what a current of electrons goes through when it flows through the ordered crystal lattice of a metallic wire. But now imagine that you are playing quantum pachinko. Instead of little balls, wavelets shoot around the atomic obstacle course. The rules of the game are suddenly very difficult: if the waves have the right energy, they complete the course with aplomb, moving around the lattice essentially unimpeded. But you only need to change things slightly, by putting the obstacles in a marginally more disordered arrangement, to stop those quantum waves in their tracks.

This phenomenon is known as Anderson localization, and influences many physical properties of disordered and amorphous materials[1]. Two papers in this issue[2,3] do their bit for a better understanding of it. They detail how the first direct images of this process of 'localization through disorder' were obtained.

But let's return first to our electrons in a wire. An electron in a conducting material is stuck in one of a series of potential wells, each representing an atom in the crystal lattice of the conductor. Quantum mechanics says that in each well, the electron can only occupy certain energy levels. The positioning of these levels depends on the depth and width of the well. Suppose, for simplicity, that there is only a single possible level in each well (Fig. 1a). In a perfect crystal, with a perfectly regular lattice of identical wells, the levels in each well will then line up exactly, and an electron can thus easily tunnel between the wells. The result: electrons are freely mobile, and the material conducts.

Consider now what happens when the lattice is disordered. This might be because of chemical impurities, defects or an innately amorphous structure. The energy levels no longer line up nicely in neighbouring wells, and the electron is blocked from burrowing through the well wall when it finds an energy mismatch that is too large (Fig. 1b). When a determined electron encounters such an obstacle, it can try to change path, and tunnel into a different well. But at some point, it is always frustrated, coming across a barrier that it cannot surmount. Returning to a quantum-wave picture, this acts as an interference effect: an electron tries to take different paths of effectively random lengths, and so on average it destructively interferes with itself, no matter where in the crystal it tries to go. This was the phenomenon that Philip Anderson originally predicted[4] in 1958.

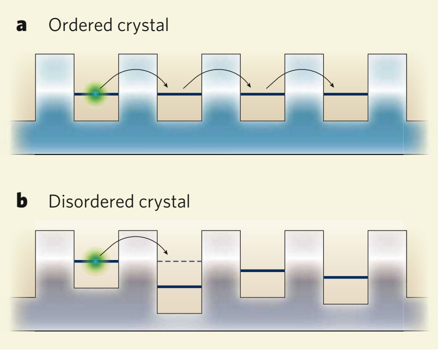

Figure 1 | **Well, well, well. a**, In an ordered crystal lattice, electron energy levels are the same in each atomic potential well. Electrons can easily tunnel between wells, resulting in conduction. **b**, As the two new papers[2,3] demonstrate, in a disordered lattice, energy mismatches between adjacent wells inhibit electron motion and produce localization.

A perhaps more familiar manifestation of Anderson localization comes when one shines light through a stack of glass slides of ever so slightly varying thickness — the transmission of light decreases exponentially as the slides are piled on[5]. For matter waves such as electrons, a direct observation of Anderson localization has been more elusive: the delicate quantum interferences required are destroyed by influences such as the vibrations in a crystal lattice; and it's difficult to image an electron in a crystal directly anyway.

In the new experiments[2,3], ultracold atoms replace the electrons, and the crystal lattice is an optical lattice — one supplied by the forces due to laser light. This set-up allows the localization of the atoms to be seen directly, by illuminating the atoms with laser light and taking their picture. Both groups studied the localization of atoms in a Bose–Einstein condensate, a vapour of atoms so cold (at a temperature of a few nanokelvin above absolute zero) that the atoms move in perfect lock-step. Such a condensate has two agreeable properties: it has a small extent in space, so it is obvious whether or not the atoms are stuck in place; and it has a small spread in momentum, so the wavelengths of the atoms are large enough to get an overview of the surrounding landscape and so 'sense' its disorder.

Bose–Einstein condensates in disordered potentials had already been studied, but two experimental challenges have impeded localization being observed. First, at the densities required to produce the condensate, collisions between atoms smooth out any disorder. Second, disorder has to be produced on length scales smaller than the typical atomic wavelengths. Both groups solved the first problem by allowing the condensate to expand, thus lowering its density, before looking for localization; but they took different approaches to the second problem. Billy *et al.* (page 891)[2] studied atoms moving in a fine-grained 'laser speckle field', such as is produced when a laser beam is scattered by a finely roughened surface. By contrast, Roati *et al.* (page 895)[3] used a superposition of optical lattices made from lasers of unequal wavelengths. This creates a 'quasicrystal' that is a halfway house between a perfectly regular crystal and an entirely amorphous one — with an intermediate degree of disorder that is still sufficient for localization.

Both groups observed the freezing of atomic motion as they introduced disorder in their respective, carefully controlled ways. They also both observed the incontrovertible signature for Anderson localization — that the probability of finding an atom at a particular point in space diminishes exponentially the farther one moves from the original centre of the condensate. But the two experiments also had interesting twists of their own. Billy *et al.* observed, for example, that a fraction of higher-energy atoms partially ignored the disorder and moved around unimpeded. Roati *et al.* also observed a smoother momentum distribution in the localized state — the signature of localization in momentum space — as well as interference patterns due to atoms localized near several sites.

These impressive experiments are the latest in an exciting new thrust of research: the use of ultracold atoms to study condensed-matter phenomena in precise and controlled experiments[6–8], and thus bridge the gap between theory and experiment in condensed-matter physics (for an overview of current efforts in this direction, see the Q&A feature[9] in last week's issue). And on a more applied note, effects such as Anderson localization are gaining technological importance as a way to confine and control optical waves in, for example, engineered optical media[10]. ■

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1. Lee, P. A. & Ramakrishnan, T. V. *Rev. Mod. Phys.* **57,** 287–337 (1985).
2. Billy, J. *et al. Nature* **453,** 891–894 (2008).
3. Roati, G. *et al. Nature* **453,** 895–898 (2008).
4. Anderson, P. W. *Phys. Rev.* **109,** 1492–1505 (1958).
5. Berry, M. V. & Klein, S. *Eur. J. Phys.* **18,** 222–228 (1997).
6. Raizen, M., Salomon, C. & Niu, Q. *Phys. Today* **50,** 30–34 (1997).
7. Bloch, I., Dalibard, J. & Zwerger, W. *Rev. Mod. Phys.* (in the press); preprint at http://arxiv.org/abs/0704.3011 (2007).
8. Greiner, M., Mandel, O., Esslinger, T., Hänsch, T. W. & Bloch, I. *Nature* **415,** 39–44 (2002).
9. Greiner, M. & Fölling, S. *Nature* **453,** 736–738 (2008).
10. Istrate, E. & Sargent, E. H. *Rev. Mod. Phys.* **78,** 455 (2006).