Quantum insulation: Intemperate atoms can't come to equilibrium

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Two physical phenomena, localization and ergodicity-breaking, are conjoined in new experimental and theoretical work. Before we consider possible implications for fundamental physics and for prospective quantum computing, let's first look at these two topics in turn. It will bear providing some specific examples before getting to the quantum details.

Localization

When electrons pass through a material they encounter various degrees of resistance, causing them to lose energy along their journey. In the 1950s physicist Philip Anderson, predicted that in some disordered materials (such as a semiconductors) electrons—-or more specifically the electrons viewed as a series of quantum waves—-could get trapped. They become immobilized not by losing all their energy but by an interference effect by which the waves become bottled up in a certain region.

This assertion, later demonstrated in experiments, is at odds with conventional thermodynamics. Electrons, at one temperature (in effect) entering a material at a different energy, ought to "thermalize," that is, come to a common temperature. But localization seems to sidestep this: the electrons waves remain intact but segregated. They don't come to the temperature of their surroundings.

Many-body localization (MBL) has become a hot topic in physics. In 2006 only three journal articles mentioned MBL; in 2015 the number was 190. In November 2015 the Kavli Institute for Theoretical Physics held a special meeting devoted to the subject.

Ergodicity

The term ergodic dates back to the nineteenth century and was coined by Ludwig Boltzmann to describe statistically how a system of particles evolves over time.

Throw a thousand identical dice and record the numerical results. Then throw a single similar die a thousand times. The average showing should be very similar. This is an example of an ergodic system. One hallmark is that space and time averages of the system should be similar. The average die values for the "dice system" taken singly over a long time or with multiple dice at one instant.

Open the stopper of a perfume bottle in a closed room and come back after a long time. There will be an equal likelihood of a perfume molecule being in all the parts of the room. This is another ergodic example. A more technical way of saying this is that the total description of the ensemble of molecules explores all possible configurations of the molecules. "Anything that can happen will happen." One possible state of the system includes the chance that all the molecules will return to the bottle whence than had come. But since there are trillions of other configurations where this does not happen in practice our observation is of molecules all around the room. At the end we have no sense, sampling the molecules, that they were once all in the bottle. The system no longer remembers its origin.

What about non-ergodic systems? Consider one person sitting in a restaurant selecting from a menu of items. She visits the restaurant 100 times. Compare her choices to those of one hundred people at one time ordering menu items. Here the average statistics for ordered items will be very different? Why? Because humans are more choosey than dice.

Recent experimental work

In experiments conducted at the Max Planck Institute in Garching, Germany and at the Joint Quantum Institute at the University of Maryland in the U.S., confined atoms displayed localization and behavior that was non-ergodic. In the Max Planck work, neutral atoms are stored in an optical lattice; in the JQI setup, a string of ions is stored.

Instead of electrons moving through a solid material, the atoms, each with its own characteristic spin orientation, reside in a laser-driven crate environment. Here the disorder (imposed upon the confining laser beams) imposes localization In the German experiment, particles (the atoms) are localized. In the U.S. experiment, it is the spins of ions that are localized.

To be more specific about the JQI experiment: special modulated laser beams introduce disorder into the system of ions. Instead of the spins all interacting witheach other, thereby losing their original collective spin configuration, the disorder has the effect of localizing the spins in their abstract spin "space." Without the disorder localization does not occur. When the disorder climbs above a critical value, localization does occur; the atoms do not mix up their spins; they do not "thermalize. "They are stuck near to their initial spin configuration," says Jacob Smith, one of the JQI experimenters. The atomic spins retain a sense of their origin. They are behaving non-ergodically.

New theoretical work

So, do localization and non-ergodicity go together? Not necessarily says a new report by four JQI theorists published in *Physical Review Letters*.

Xiaopeng Li, the lead author on the new theory paper, commented on this bizarre behavior where particles could be de-localized (they keep moving; they are not confined) and yet be non-ergodic in nature—-which is say that they do not thermalize. "Our theory points to a possible physical picture that some particles are inert but others are active. An analogue for the case of dice would be if even numbers were equally likely but odd ones were forbidden. This exotic phase of matter provides one scenario for the localization transition of a quantum system."

And since thermalization is one of the leading causes of quantum decoherence, exploiting non-ergodic systems—-whether the constituent particles were localized or extended—-might help in the storage of quantum information. Non-ergodic systems might not be implemented in the form of conventional solid matter, but might be possible in the form of trapped atoms, as the experiments mentioned above indicated.

Sankar das Sarma, the leader of team of JQI theorists working on this problem, describes non-ergodic in terms of temperature. "We take it for granted that all systems left to themselves attain a temperature; that is, they achieve thermodynamic equilibrium. But is this always true? In the simplest term, ergodicity assures (almost always) the achievement of a temperature. Non-ergodic systems are not in thermal equilibrium—-ever!—-and cannot be characterized by a temperature. Isolated localized systems are always non-ergodic since there is no way to transport energy from one point to another to achieve equilibrium."

That a body of particles could be un-localized and also non-ergodic at the same time came as a surprise to the theorists, who modeled the interactions among the particles using extensive computer simulations. "We have to be cautious," said das Sarma. "I believe our results are correct for what we do, but whether it applies in the thermodynamic limit of a macroscopic system is still an open question of great interest. But it might contribute to the effort to fight against intrinsic decoherence. It could help create quantum insulating systems—-heat insulators."

More information: Many-Body Localization and Quantum Nonergodicity in a Model with a Single-Particle Mobility Edge *Phys. Rev. Lett.* 115, 186601 – Published 28 October 2015. dx.doi.org/10.1103/PhysRevLett.115.186601

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