Physicists tailor magnetic pairings in nanoscale semiconductors

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Electrons love to zip around metals such as copper, especially if the metal is cooled to temperatures near absolute zero. But if they encounter a magnetic atom (say, iron) during their travels, the electrons will try to "screen," or cancel out, the magnetic atom's spin alignment by pairing with it. This pairing modifies the flow of electrons in the metal, in a phenomenon called the Kondo effect.

But what if there weren't just one set of mobile electrons zipping around the metal? What if there were two, and both sets fought equally hard to couple with the magnetic impurity atom? Torn between two lovers, the magnetic atom couldn't decide with which set to partner. The competition would go unresolved, and the atom would join neither, instead existing in a remarkable state of frustrated independence known as the two-channel Kondo state.

In the March 8 issue of *Nature*, researchers at Stanford, Harvard and Israel's Weizmann Institute of Science reported that they have built such a system in a semiconductor nanostructure. By applying voltages to nanoscale electrodes, the scientists can tune how strongly the magnetic atom couples to one set of electrons, or channel, compared to the other set. Their system of correlated electrons demonstrates a two-channel Kondo effect.

"We are observing and controlling how electrons dance with each other," says David Goldhaber-Gordon, an assistant professor of physics at Stanford who in 2001 with theorist Yuval Oreg of Weizmann came up with the idea of how to build the two-channel Kondo system. Their co-authors on the Nature paper are Ronald Potok, a former graduate student at Harvard and Stanford, now at Advanced Micro Devices, who set the stage for the measurements by designing and fabricating the nanostructures and cooling electrons in those nanostructures to unprecedentedly low temperatures; Ileana G. Rau, a Stanford doctoral candidate in applied physics who together with Potok performed the measurements and analysis; and Hadas Shtrikman, a senior staff scientist at Weizmann who grew the materials on which the nanostructures were based.

Building an artificial atom

"I've been interested for quite some time in creating model quantum systems," says Goldhaber-Gordon. "Traditionally, researchers would get excited about a particular theoretical construct and would look for a material that might show the properties of this construct. But maybe sometimes there's no material that shows these properties. Can you then use nanotechnology to create an artificial structure that will be a realization of this theoretical construct?"

Goldhaber-Gordon and colleagues set out to build an artificial structure that could demonstrate the two-channel Kondo effect. They used nanopatterning techniques to create an artificial magnetic atom-basically a "box" containing an odd number of electrons. To it they attached two reservoirs of mobile electrons. The conductance they measured through the nanostructure was strikingly different depending on which reservoir's electrons the artificial magnetic atom paired with. The researchers then tuned the couplings to intermediate values so that the artificial magnetic atom would be equally happy to pair with electrons from either-but not both-of the reservoirs. The frustrated two-channel Kondo state revealed itself in a conductance that depended unusually strongly on electron energy.

The artificial magnetic atom and the two reservoirs are built out of a semiconductor, gallium arsenide, also found in cell phone transistors and laser pointers. Gallium arsenide makes up about 2 percent of the world's semiconductor market, according to Goldhaber-Gordon. "That's important because it means that there's been a lot of development that's gone into making the material perfect and into tuning its properties with nanoscale electrodes," he says.

Gallium arsenide's perfection made it a better starting material than the world's most famous semiconductor, silicon. "To build computer chips you begin with a wafer of silicon, and you grow a thin layer of glass-silicon oxide-on top of it," Goldhaber-Gordon says. "At the interface between those two, you can form a sheet of electrons. But that interface is not so smooth because silicon is a crystal and silicon oxide is amorphous; it doesn't have a regular structure. So on the atomic scale, that interface is rough. Electrons traveling along the interface feel that roughness, and that causes them to jiggle around and not travel in straight lines."

In contrast, in a layered structure in which gallium arsenide replaces silicon and aluminum gallium arsenide replaces silicon oxide, both materials are crystals. Their interface is smooth, so in the best structures electrons can travel as far as a fraction of a millimeter, past millions of atoms, before getting turned around. Such a perfect sheet of electrons is an ideal starting point for further confining electrons to nanostructures such as that used to study the two-channel Kondo effect.

In fact, the main theme of Goldhaber-Gordon's work is confining electrons-to two-dimensional sheets, one-dimensional wires and zero-dimensional "boxes" in which they're confined in all directions. Besides building model systems like the two-channel Kondo system, he hopes to explore the basic science of future transistors. For example, how are familiar relations such as Ohm's law modified as wires get narrower? If you apply a voltage to an electrically conductive material, a current of electrons flows through the material. According to Ohm's law, that current is proportional to the voltage applied. If the wire narrows, the resistance-the ratio between applied voltage and current-goes up. At some point-below about 50 nanometers for typical semiconductors-the wire is so narrow that electrons, like cars in a traffic jam, can't get around each other and instead must go through single file. Resistance is then predicted to vary with voltage, becoming infinite at low voltage. By measuring current-voltage relations, Goldhaber-Gordon can investigate how electrons organize themselves in such narrow confines.

Graphene and beyond

Goldhaber-Gordon's group also is looking at novel materials in which electrons can be confined. A low-tech material they've looked to recently may seem an unlikely candidate for a new conductor-it's pencil lead. Graphite is structured as sheets of packed hexagons, like chicken wire, and the sheets slide off easily as a pencil glides across a sheet of paper. Recently, scientists have discovered how to peel off just a single sheet, called graphene. The hexagonal bonding in graphene makes it an electrical conductor, and this new material may have exotic properties akin to other hexagonally bonded carbon materials, such as nanotubes and buckyballs.

"A lot of what I do I do because I want to understand basic quantum mechanics," Goldhaber-Gordon says. "We've had the equations of quantum mechanics for more than 70 years, and every experimental test we've devised says that they're right, but unfortunately we can't solve them except in very simple cases." Undergraduates routinely calculate the quantum states of a hydrogen atom, which has one electron, but a helium atom, with just two electrons, is so complex that a full understanding of its excited states requires sophisticated approximations and intensive computer power.

"Now imagine 10 electrons or 100 electrons in a semiconductor nanostructure," he says. "It's impossible to do a direct calculation of how they behave, and yet because electrons repel each other we know that they're going to be doing some rich and complicated dances around each other to avoid each other. I want to understand those dances."

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