Kondo Physics Seen in a Quantum Dot

A quantum dot, as its name implies, is a minuscule region of metallic or semiconductor material whose dimensions can be as small as a few tens of nanometers on a side. It has been likened to an artificial atom because it carries a discrete charge and quantized electronic energy levels (see the article by Marc Kastner in PHYSICS TODAY, January 1993, page 24). That analogy has now been taken a step further with the demonstration that a quantum dot interacts with nearby metallic leads in much the same way that a single magnetic impurity interacts with a surrounding metallic substance—in the phenomenon known as the Kondo effect.

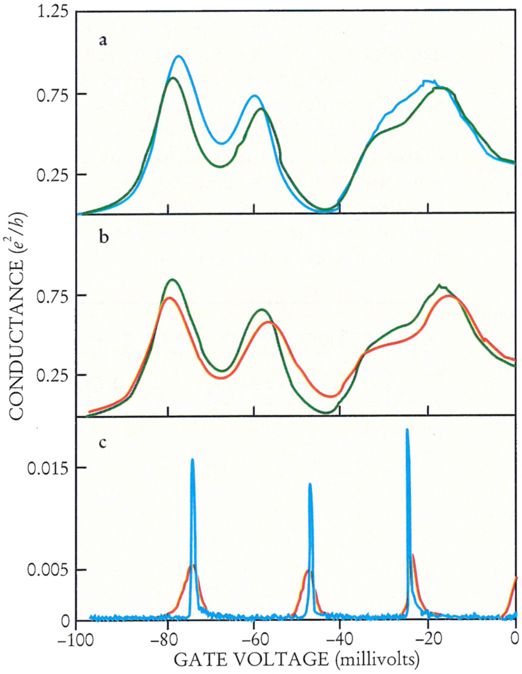
More than 30 years after the discovery of the Kondo effect, which is caused by magnetic impurities in metals, researchers may now be able to study the phenomenon more precisely because a quantum dot with an odd number of electrons seems to mimic the behavior of an individual magnetic atom.

The Kondo behavior was seen recently in an artificially created quantum dot by a group from MIT and the Weizmann Institute of Science in Rehovot, Israel.[1] Specifically, the group used a semiconductor quantum dot sandwiched between two metallic leads. This miniature device—known as a single electron transistor—turns on and off as individual electrons, controlled by a nearby gate electrode, flow on and off the dot.

Kondo effect in metals

The theory of the Kondo effect was developed in the early 1960s to explain a long standing puzzle about the resistance of some metals: Why does the resistance start to increase as the metal is cooled below a certain temperature? The effect is named for Jun Kondo (then at the Electrotechnical Laboratory in Japan), who formulated a quantitative theory of it in 1963. According to the picture that emerged from studies by Kondo and others, the increased resistance comes from magnetic impurities, which do not act simply as constant scattering centers, independent of temperature. Rather, the local moments on the impurity atoms have an antiferromagnetic coupling to the spins of the conduction electrons; the coupling becomes stronger and increasingly impedes the flow of current as the temperature falls.

The concept of the solid-state Kondo effect is quite intriguing because it involves the pairing of an electron localized on the impurity with an electron drawn from the extended states in the metal. Its manifestation in a quantum dot is no less compelling. Ned Wingreen of the NEC Research Institute in Princeton, New Jersey, told us that, while interactions between electrons in a quantum dot are known to be important, the Kondo phenomenon is a true many-body effect requiring coherent overlap between the localized electrons in the dot and a continuum of electron states outside the dot.



ELECTRICAL CONDUCTANCE through a semiconductor quantum dot between two metallic leads, plotted as a function of the gate voltage on the dot. **a** and **b**: The Kondo effect shows up as a nonzero conductance between the first and second peaks and between the third (barely resolved) and fourth peaks. The data were taken at 90 mK (blue curve), 400 mK (green) and 800 mK (red). **c**: When a quantum dot is coupled more weakly to the leads, the Kondo effect is absent. (Adapted from ref. 1.)

Kondo effect in quantum dots

Experimenters have tried to see the Kondo phenomenon in quantum dots ever since its presence was predicted in the late 1980s by Tai-Kai Ng (now at the Hong Kong University of Science and Technology) and Patrick Lee (MIT)[2] and by Leonid Glazman (University of Minnesota) and Mikhail Raikh (University of Utah).[3] Several theory groups have since studied the Kondo effect in quantum dot systems.[4,5] In a 1993 paper,[6] Yigal Meir (Ben Gurion University of the Negev in Israel), Wingreen and Lee did a particularly thorough analysis of the problem, predicting how the Kondo phenomenon would manifest itself in a quantum dot.

No one managed to spot these manifestations in quantum dots until three years ago. Then, Robert Buhrman and Daniel Ralph of Cornell University saw Kondo-assisted tunneling from single atomic-scale charge traps—naturally occurring quantum dots—produced in nanometer-sized metallic contacts.[7] The Cornell team was able to observe the Kondo interaction of an individual charge trap with the metallic electrodes. The role of the freely flipping local magnetic moment in the Kondo phenomenon was played by the quantum flips between two atomic configurations of a bistable charge trap.

The MIT–Weizmann study has now attracted additional interest because it found Kondo physics in a system that should allow quantitative exploration of the phenomenon in a very controlled way: An artificially created quantum dot can be surrounded by various gates and leads, thereby allowing experimenters to vary a number of parameters.

Kondo effects in quantum dots have been elusive because they show up only under a very narrow set of conditions. To see the effects of coupling between the dot and the leads, one needs to make the tunneling rate of the electrons as high as possible. The higher this rate, the higher the temperature at which the Kondo effect survives. However, if one makes the rate too high, the coupling exceeds the spacing between the electron energy levels on the dot, and those electrons become completely delocalized. With a smaller dot, the electrons are more localized to begin with and a higher rate is possible.

Making a smaller dot

Several years ago, Kastner and his second-year graduate student at MIT, David Goldhaber-Gordon, decided to collaborate on the fabrication of an extra small quantum dot with researchers at the Weizmann Institute's Braun Center for Submicron Research. Under the leadership of Mordechai Heiblum, this center had built up an expertise in fabricating nanostructures in gallium arsenide. Goldhaber-Gordon went to Israel in 1995–96 to work with Hadas Shtrikman, Diana Mahalu and Udi Meirav of the Braun Center on new semiconductor heterostructures that would meet the team's requirements.

To make a semiconductor quantum dot, one starts with a two-dimensional electron gas—that is, electrons that are confined in a plane at the boundary between two semiconducting materials. Additional semiconductor layers go on top of this boundary region. At the top of the structure, one lays down electrical gates; the electrical potentials created by these gates confine the electrons below them to a very small region. Typically the quantum dots lie 100 nm below the surface. To make a dot much smaller than 100 nm, one has to form the two-dimensional electron gas closer to the surface. The MIT–Weizmann team met that challenge, and Goldhaber-Gordon took the resulting devices back to MIT, where he, David Abusch-Magder and Kastner made the measurements.

Signatures of the Kondo effect

The MIT–Weizmann researchers studied the conductance through the quantum dot as a function both of the gate voltage V_g applied to the dot itself and of the drain-to-source voltage V_{ds} between the two leads flanking the dot. When the researchers looked at the conductance as a function of V_g (with V_{ds} set close to zero), they found the series of peaks expected for a single-electron transistor, each one corresponding to the movement of an electron onto the quantum dot. (See panels **a** and **b** of the figure on page 17.) The data for the various curves were taken at different temperatures. As expected, the peaks were seen to cluster in pairs. The first two peaks on the left form a pair, as do the third and fourth peaks. The separation between the peaks within a pair is smaller than that between the pairs. A pair of peaks corresponds to the addition of a pair of electrons to the same spatial state—one electron with spin up and the other with spin down. The next electron added goes into the next spatial state. Thus, in the region between the paired peaks, the artificial atom has an odd number of electrons.

The peak structure described so far is what one expects for a simple artificial atom. One tip-off to the presence of the Kondo effect in the MIT–Weizmann experiment was the observation of the nonzero conductance between the paired peaks. There, the quantum dot has an unpaired electron, which is free to form a singlet with the electrons in the leads. As the theorists[2,3] had predicted, this Kondo interaction accounts for the conductance in a region where one ordinarily would expect none.

The enhanced conductance disappeared when the researchers applied a voltage V_{ds} across the quantum dot, just as one would expect if the extra conductance had indeed been caused by the Kondo effect: The applied voltage separates the Fermi energy levels of the two reservoirs, and the dot can no longer interact with both leads.

The MIT–Weizmann group also found that a magnetic field split the unpaired electrons, causing the conductance peaks to split as well, by an amount equal to $2g\mu_B B$. This behavior, too, is consistent with the Kondo effect.

Learning more

One can glean additional insight about the Kondo effect from a quantum dot because the artificial atom behaves as a single impurity, whereas the Kondo phenomenon in metallic systems necessarily averages the effect of many impurities. Several observers are eager to see some of the new studies of the Kondo effect that this new capability should allow. Clearly it won't be easy; demonstrating the Kondo effect was difficult enough. For one thing, the temperature at which the Kondo effect shows up is quite low in these systems. Glazman remarked that the single electron transistor is rather like a smart weapon, allowing great control but being technically difficult to operate. Undaunted, Kastner told us that his group is already going ahead with some more measurements, starting with a detailed exploration of the temperature dependence.

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References

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Springtime Arctic Ozone Levels Fall Further in 1997

Since the mid-1970s, an "ozone hole" has developed in the stratosphere over Antarctica each austral summer. The Arctic, by contrast, has been immune to such severe depletion because it is much less susceptible to developing a strong vortex, a pattern of winds that encircles the pole, isolating a continent-sized body of air in which all the conditions for ozone depletion can be established. In March 1997, however, the Arctic stratosphere behaved more like its southern counterpart than had ever been observed before, and Arctic ozone levels hit record lows for March. (See the figures on page 19.) The observations were reported in eight papers in the 15 November 1997 issue of *Geophysical Research Letters*.[1]

The data in the papers come from a variety of satellite and ground-based studies, combining measures of total ozone levels, ozone levels as a function of altitude, levels of chemicals such as chlorine monoxide (a key catalytic reactant in ozone depletion, produced when chlorofluorocarbons break down), atmospheric temperatures and other meteorological information. The winter of 1996–97 was the fifth in a row during which the stratosphere over the Arctic had been particularly cold, and ozone levels in the last five springs have been the lowest on record. In the spring of 1997, conditions were particularly unusual in that a very stable vortex formed over the North Pole and the large region it encompassed was more severely depleted.

The four images at the top of page 19 show how springtime ozone levels in the Arctic have declined over the