ble. 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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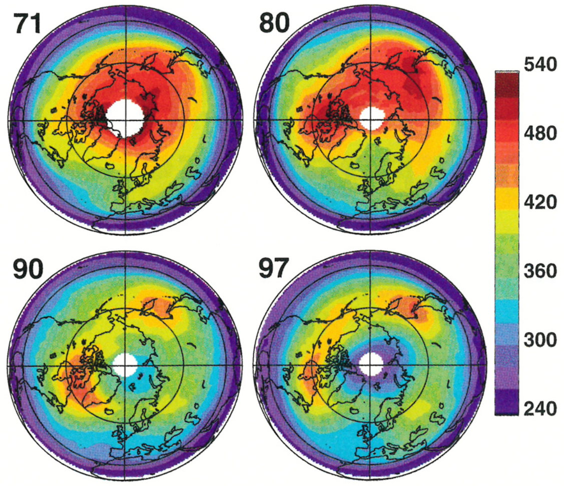
Springtime Arctic Ozone Levels Fall Further in 1997

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



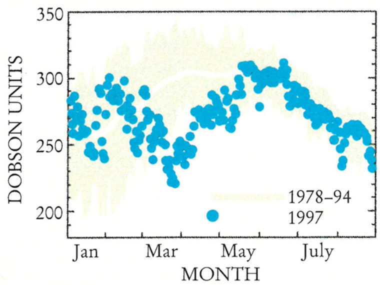
MARCH MONTHLY AVERAGE TOTAL OZONE in the Arctic has declined over the past few decades. Strong depletion occurred in 1997 in a large region (blue and purple) centered on the pole, in conditions qualitatively very similar to those that produce the Antarctic ozone hole. The data shown were taken by the Nimbus 4 BUV satellite (1971), the Nimbus 7 TOMS satellite (1980 and 1990), and the Earth Probe TOMS (1997). The scale at right is in Dobson units, a linear measure of the amount of ozone in a vertical column of atmosphere. (Both figures on this page courtesy of Goddard Space Flight Center.)

past 26 years. The continuing decline comes despite the 1987 Montreal Protocol's limits on the use of chlorofluorocarbons (CFCs). Although the protocol has been successful and levels of CFCs have peaked in the troposphere, it takes many years for such changes to propagate up from the troposphere to the stratosphere. Levels of stratospheric ClO are expected to peak and start declining in a few years. While not as extreme as the Antarctic ozone hole, the Arctic depletion is "another warning that we have to continue watching the stratosphere very carefully," said Mario Molina (MIT). "We can't be complacent and think that the problem is solved. We have to keep researching it aggressively."

The key ingredients for major depletion at either pole are a long-lived polar vortex, low temperatures (which allow the formation of polar stratospheric clouds in which crucial chemical processes are enhanced), the catalyst ClO and sunlight, which powers the depletion processes. (See PHYSICS TODAY, December 1995, page 21, and July 1992, page 17.) The clear culprits in the Arctic in the spring of 1997 and recent years are colder-than-usual stratospheric temperatures at the time of year when sunlight returns to the northernmost latitudes. Less clear is the cause of the cooling and how all the relevant processes combine in the Arctic.

Richard Stolarski (NASA's Goddard Space Flight Center), a coauthor on the lead *Geophysical Research Letters* paper, points to three possible explanations for the Arctic cooling.[2] First, it could be an effect of the overall declining ozone levels—the presence of ozone in the stratosphere helps to warm it by absorbing solar radiation. Thus, loss of ozone and stratospheric cooling combine in a vicious circle. Second, the lower temperatures could be another effect of greenhouse gases such as CO_2. Better known for their global warming effects nearer sea-level, such gases should lead to cooling of the stratosphere. This cooling effect of greenhouse gases is more certain than their warming of Earth's surface, Molina told us. The third possibility is that unrelated variations in climate—the vagaries of weather—are to blame. Most likely, said Stolarski, a combination of all three factors is at work in the Arctic. What happens in coming years over the Arctic will depend on, and perhaps reveal, the relative importance of these three processes.

GRAHAM P. COLLINS



MINIMUM TOTAL OZONE observed north of latitude 40° N each day over a range of years. In 1997 (blue dots) the ozone was depleted in late February and March, falling well below the seasonal trend exhibited by the range of minimum values observed from 1978 to 1994 (green shading; white line is the average minimum value for those years).

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