merger occurs. Relativistic hydrodynamic calculations indicate that induced heating will occur in the neutron stars, resulting in thermal energies of 10^{52} to 10^{53} ergs in each star. This causes intense neutrino pair production, and these pairs partially recombine to produce 10^{51} to 10^{52} ergs of a relativistically flowing electron-positron plasma. Annihilation of this plasma produces a GRB with a spectrum that peaks at 100 keV, similar to what is observed. The GRB lasts for tens of seconds. The process cuts off when a black hole (or holes) is formed from the neutron stars. Improved simulations are under way to refine these predictions.

Between the extremes set by the supermassive black hole formation model and the merging neutron star pair model is the "collapsar" model presented by Andrew MacFayden and Stan Woosely (University of California, Santa Cruz). In this scenario, runaway accretion onto the neutron star formed by a failed supernova event in a massive rotating star produces a black hole surrounded by an accretion disk with relativistic jets of matter emanating from the poles of the hole to produce a GRB. This theory is described in a recent issue of *Science* (*4*).

NASA has enthusiastically responded to these developments with plans for at least three missions to help unravel the GRB mystery. The focus in the near term is to provide accurate localizations for as many GRBs as possible. HETE-2 (High Energy Transient Explorer–2; the first was lost in November 1996) will be launched in 1999. If it is put into an equatorial orbit, then it will localize roughly 50 GRBs per year with 10–arc minute to 10–arc second accuracy, according to George Ricker (Massachusetts Institute of Technology). Proposals for an even better GRB localizer are now being reviewed by NASA in the form of a MID-sized EXplorer-(MIDEX) class mission. Farther down the road is the Gamma-Ray Large Area Space Telescope (GLAST), with a planned launch in 2005. This mission will be able to detect high-energy gamma ray photons with energies of up to 300 GeV from a variety of astrophysical sources, including GRBs, to help constrain the physics of the acceleration processes. Because GRBs are apparently the most energetic events in the universe, next to the Big Bang itself, then what we learn from future ground- and space-based observations of this phenomenon will likely extend our knowledge at the frontiers of physics and present an ongoing challenge to observers and theorists alike.

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PERSPECTIVES: CONDENSED MATTER PHYSICS

Kondo Effect in Quantum Dots

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A simple picture of electrons in metals would suggest that the resistivity should decrease straightforwardly as the temperature is lowered. Yet for certain metals, the resistivity goes through a minimum and starts to rise as they are cooled. This peculiar behavior, discovered over 60 years ago, has come to be called the Kondo effect after Jun Kondo, who in 1964 gave the first correct explanation of this effect in terms of magnetic impurities (*1*). About a decade ago, three groups of theorists (*2–4*) predicted that the effect would also manifest itself in the low-temperature transport of electrons through a quantum dot. Recently, Goldhaber-Gordon and colleagues at the Massachusetts Institute of Technology (MIT) and the Weizmann Institute of Science (*5*) announced the first observation of the predicted effects. On page 540 of this issue, Cronenwett and co-workers at Delft University of Technology (*6*) report on more detailed results.

Both groups conducted their studies on single-electron transistors made by depositing metal gates over a two-dimensional electron gas formed in a GaAs/AlGaAs heterostructure. Applying a negative voltage to these gates depletes the regions below them, creating a small dot, or an atom-like box for electrons, coupled by tunneling to two separate two-dimensional electron gases acting as source and drain leads (see figure).

Many experimenters have investigated the source-to-drain current I_{sd} of such single-electron transistors as a function of the voltage V_{sd} between the leads (*7*). Especially interesting is a plot of linear conductance $G = I_{sd}/V_{sd}$, with V_{sd} kept very small, as a function of the voltage V_g on the dot. The result is a series of periodically spaced peaks, each indicating the change in the number of electrons N in the dot by one (see figure). Understanding electron transport through single-electron transistors is facilitated by the introduction of a function $D_{loc}(E)$, called the local density-of-states, representing the spectrum of energy required to add an electron to the dot. The energy required to add an electron to an empty dot is E_1, the energy of the lowest spatial state of the dot. A second electron, with a spin of the opposite direction, goes into the same spatial state, but its addition costs a larger energy $E_1 + U$, where U is the Coulomb repulsion energy between the two electrons. Because a third electron can no longer enter the E_1 state, it enters the next available spatial state with energy E_2. Taking account of the Coulomb interaction with the first two electrons, its addition requires an energy $E_2 + 2U$. Continuing this, we see that $D_{loc}(E)$ has peaks at $E = E_1$, $E_1 + U$; $E_2 + 2U$, $E_2 + 3U$; and so forth, which occur in pairs as indicated by the semicolons. (The peak widths are finite because of finite escape time onto the leads.) Two peaks within a pair are separated by U, whereas the separation between different pairs, corresponding to different spatial states, is larger. Note also that in the region covered by each pair, N is odd and the dot is magnetic (spin 1/2), whereas, between the pairs, N is even and the dot is nonmagnetic (spin 0).

When a voltage V_g is applied to the dot, $D_{loc}(E)$ is replaced by $D_{loc}(E - eV_g)$, where e is the electron charge. Each time one of the peaks of $D_{loc}(E - eV_g)$ lines up with the Fermi level E_F of the leads, a peak shows up in G, and these peaks are also clustered into pairs. Outside these peaks, G vanishes because electron tunneling into or out of the dot requires finite energy and is impossible. This so-called Coulomb blockade in single-electron structures is well established by experiments and is also reproduced in (*5*) and (*6*) at temperatures much greater than 100 mK.

What is remarkable about the MIT-Weizmann and Delft experiments is that, as the samples are cooled further, the inner shoulders of each pair of peaks in $G(V_g)$ broaden and are enhanced, whereas no broadening is seen outside of the pairs where the dot is nonmagnetic. This is what theories (*2–4*) predicted to be a signature of the Kondo effect in dot systems.

The Kondo effect is essentially a screening of the dot (or impurity) spin by nearby free electrons and so takes place

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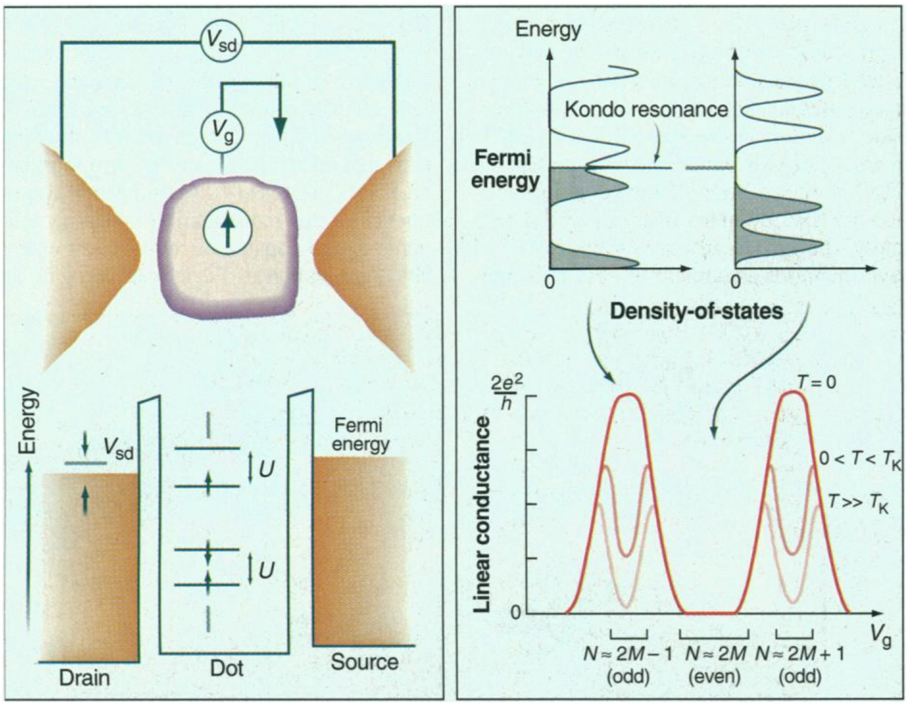
only when the dot is magnetic. Below a characteristic temperature T_K called the Kondo temperature, the unpaired electron in the dot hybridizes with the conduction band states in the leads. Once this takes place, it is no longer appropriate to talk about an isolated dot. We should rather regard the dot plus the screening cloud as a new "quasi-dot" of spin zero. This hybridization produces in the local density-of-states of the quasi-dot a sharp peak (Kondo resonance) at $E = E_F$, which enhances G.



Kondo dot. (Left) Single-electron quantum dot transistor in a semiconductor heterostructure and its energy diagram. If the number of electrons N in the dot is odd, the unpaired electron causes the dot to have a local moment. At temperatures less than T_K, this local moment is screened by the nearby electrons in the leads, forming a "quasi-dot" of spin 0 (the Kondo effect). **(Right)** This screening produces a sharp peak (Kondo resonance) in the density-of-states of the quasi-dot at an energy equal to the Fermi energy of the leads, resulting in temperature-sensitive enhancement of conductance. On the other hand, if N is even, there is no Kondo effect because the dot has no local moment. Sweeping the gate voltage V_g changes N, resulting in periodic enhancement of the linear conductance.

According to (*2–4*), $G(V_g)$ at zero temperature assumes a constant value independent of V_g over the magnetic region where N is odd (bright red curve in the lower right part of figure). On the other hand, in the nonmagnetic region where N is even, no Kondo resonance occurs and the Coulomb blockade picture remains true. At finite temperatures, the Kondo effect is attenuated (*3*), and, instead of the plateaus, we would observe temperature-sensitive, asymmetric growth of the Coulomb blockade peaks as seen in the experiments (medium red curve). Eventually, the Kondo effect disappears for $T >> T_K$ (light red curve).

The observation of the Kondo effect in dot systems is a difficult task, because T_K in usual single electron transistors is much too low. Enhancing T_K requires, among other things, reducing the dot size and the dot-to-lead tunnel barriers. The MIT-Weizmann group made special efforts to meet these requirements.

The Kondo physics outlined above is identical to that of the conventional Kondo effect in bulk metals. An important difference, however, is that, in the latter, the Kondo resonance enhances scattering of conduction electrons by the magnetic impurities and impedes the flow of current. In dot systems, the Kondo resonance enhances conductance, because the electrons are transported only through the dot.

The dot systems offer the exciting possibility of driving them into nonequilibrium by making V_{sd} finite (*8*), something unachievable in magnetic impurity systems. The experiments (*5*, *6*) explored this situation as well. When differential conductance dI_{sd}/dV_{sd} is plotted against V_{sd}, while fixing V_g in a magnetic region, it decays rapidly as V_{sd} departs from 0. This zero-bias maximum disappears as temperature is raised above several hundred millikelvin, in agreement with theory (*8*): Because V_{sd} is equal to the separation between the Fermi levels of the two leads, finite V_{sd} splits the Kondo resonance into two peaks. This, together with the suppression of these peaks by dissipation, results in the temperature-sensitive suppression of the zero-bias maximum.

Another manifestation of the nonequilibrium Kondo effect arises in the presence of a magnetic field B. Theory predicts that the zero-bias peak in dI_{sd}/dV_{sd} is split into two peaks separated by $2g\mu_B B/e$, where μ_B is the Bohr magneton and g is a material-dependent g factor (*8*). Similar magnetic field–induced splitting of a peak in differential conductance may take place because of Zeeman splitting of a single-particle state, even in the absence of the Kondo effect. However, the splitting in this case is equal to $g\mu_B B$, that is, half the splitting in the Kondo case. In principle, this difference in the magnitude of splitting may be used to identify the Kondo effect. The results of the two experiments (*5*, *6*) are not in good agreement, leaving the question open.

A dot coupled to leads offers a single-impurity Kondo system with a number of controllable parameters and is therefore a valuable testing ground for the theories of the Kondo effect. To take full advantage of this, however, we need a better controlled sample with higher T_K (namely, smaller dimensions). Of course, the real fascination of the dot system lies in the new physics it may reveal. Aside from those discussed above, many new effects have already been predicted, such as zero-bias minimum and boson-assisted transport (*9*), many-level effects (*10*), ac transport (*11*), and a dc transport through an Aharonov-Bohm ring containing one (*12*) and two (*13*) dots. All of these pose challenges to experimentalists in terms of both sample fabrication and observation techniques.

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