MESOSCOPIC PHYSICS:

Quantum Dots as Tunable Kondo Impurities

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Recent experimental advances in mesoscopic physics are enabling various interesting phenomena, studied in bulk systems for many years, to be reexamined in much more detail and with much greater control than before. This has led to fascinating new insights into fundamental properties of solids, such as the Kondo effect for magnetic impurities in metals. At low temperatures, delocalized conduction electrons tend to compensate or "screen" the spins of the localized impurity electrons. This screening occurs through subtle many-body correlations, extensively studied (1) since Kondo first discussed them in 1964, that produce anomalies in the resistivity, susceptibility, and many other properties of bulk magnetic alloys. Recently, signatures of these correlations have also been observed in electron transport through quantum dots (QDs, see the first figure) that were purposefully constructed to behave as "tunable Kondo impurities" (2-6). On page 2105 of this issue, van der Wiel *et al.* report the first, albeit indirect, observation of almost complete screening of the local spin of such a QD (7).

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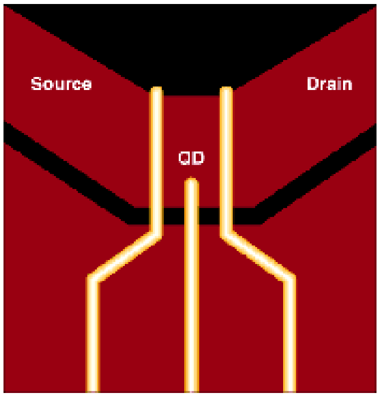
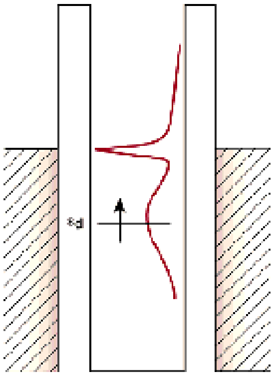
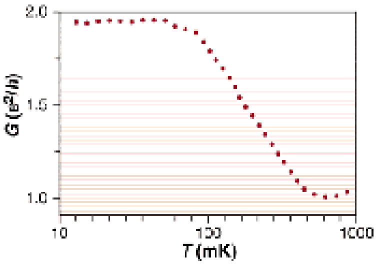


Experimental realization of a quantum dot (QD). A QD is a small puddle of charge containing a well-defined number of electrons and is typically fabricated by putting metallic gates (yellow) on a semiconductor region that behaves as a two-dimensional electron gas (red).

The similarities between magnetic impurities and QDs are best understood in terms of the much-studied Anderson model (AM), which describes a localized electron state (to be called *d* level) coupled to a band of delocalized conduction electrons (see the third figure). If conditions are such that the *d* level contains a single electron, the latter behaves as a magnetic impurity with spin-1/2. This spin does not, however, survive down to arbitrarily low temperatures. Instead, as the temperature T is lowered below a certain crossover value, called the Kondo temperature T_K, coherent virtual transitions between the *d* level and the conduction band begin to "screen" the spin of the *d* level. The most spectacular consequence is that the impurity density of states develops a so-called Kondo resonance, a sharp peak near the chemical potential of the leads (see the second figure). The Kondo resonance reaches its maximum, called the "unitarity limit," when the ground state wave function is a spin singlet (which has zero spin), meaning that the local spin is completely screened.



Effective screening. Energy diagram for a QD whose density of states (dashed line) has a broad single-particle resonance at the energy of the local level, e_d, and a sharp Kondo resonance at the chemical potential of the leads.



Toward the unitary limit. Temperature dependence of the height of the peak in $G(V)$, which saturates near the unitarity limit of $2e^2/h$ for van der Wiel *et al.*'s QD.

CREDITS: FIGURES ADAPTED FROM (7)

Since 1988, several theorists (8-11) have studied realizations of the AM involving a QD coupled to two leads. They pointed out that for a very small QD with a sufficiently large energy level spacing, the topmost nonempty energy level can be associated with the AM's *d* level. If the QD's electron number is odd, this level will contain a single electron. It was therefore predicted that such a QD should mimic a magnetic spin-1/2 impurity, whose spin should be screened for $T \ll T_K$. The QD's differential conductance as a function of source-drain bias voltage, $G(V)$, roughly reflects the QD's density of states, and therefore the emergence of a Kondo resonance in a QD was predicted to cause a sharp zero-bias peak in $G(V)$.

The first direct observation of this Kondo resonance in a QD was achieved in 1998 by Goldhaber-Gordon *et al*. (2, 3). The key to success was to make the QD as small as possible and its coupling to the leads rather strong, thereby reaching Kondo temperatures as large as 1 K. Their results have since been confirmed and extended by several other groups (4-6), establishing conclusively that a suitably constructed QD does indeed constitute an artificial, "tunable Kondo impurity." It is tunable because its parameters can, in contrast to those of actual magnetic impurities, be tuned through the metallic gates that define the QD. This appealing feature allows many long-standing predictions of the AM to be tested in unprecedented detail.

In this regard, the QD studied by van der Wiel *et al*. (7) performs particularly well: Its conductance shows a Kondo resonance (see the third figure) whose maximum height is very close to the predicted unitarity limit, namely $2e^2/h$. This amounts to an almost complete screening of the local spin. The intuitive reason why this screening produces such a strong enhancement of the conductance is that the ground state singlet wave function is a coherent superposition of localized states on the QD and delocalized states in both leads. Moreover, the study beautifully confirms the predictions that log (T_K) should depend quadratically on the energy of the *d* level and that the conductance should be a universal function of T/T_K.

Experimental data should, however, not be expected to show perfect quantitative agreement with predictions based on the AM, because the latter, having only one localized level, is too simple to fully capture the properties of a real QD, which has many levels. Rather, the challenge now is to extend our understanding of Anderson-type models in novel directions.

Recent and ongoing research investigates nonequilibrium effects due to finite bias voltage, time-dependent effects due to an AC driving field or sudden changes in system parameters, phase-coherent transport through a tunable Kondo impurity, the effect of additional levels in the QD, two or more coupled Kondo QDs, and more exotic Kondo effects that can arise, for example, when two orbital levels are tuned to be degenerate using a magnetic field.

For the first time in years, experiment is ahead of theory on several of these fronts, which not long ago were inaccessible to experiment. The field has been reinvigorated by the advent of artificial, tunable Kondo impurities. Stay tuned!

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