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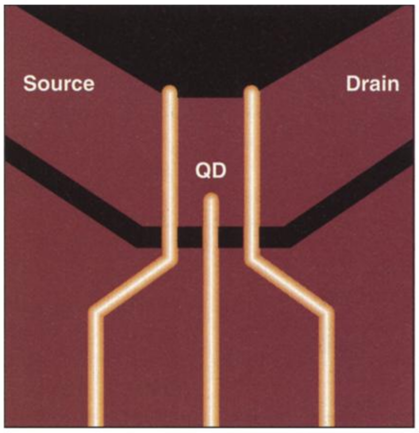
PERSPECTIVES: MESOSCOPIC PHYSICS

Quantum Dots as Tunable Kondo Impurities

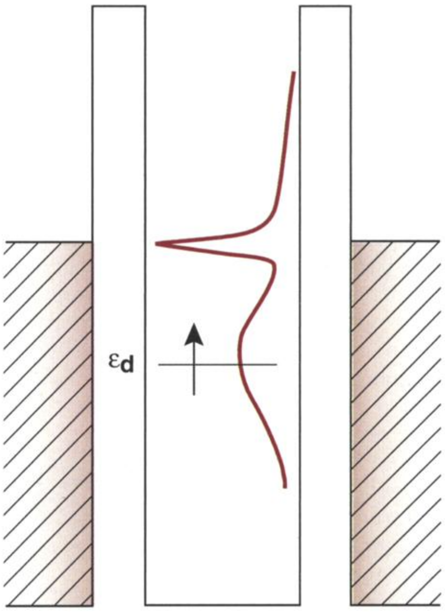
Jan von Delft

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*).



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).

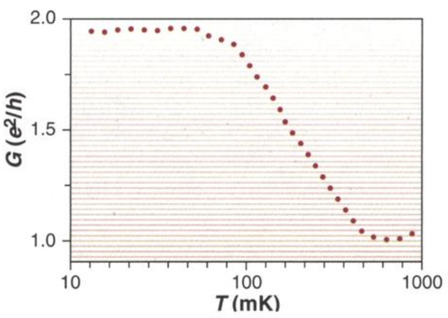
The similarities between magnetic impurities and QDs are best understood in terms of the much-studied Anderson model (AM), which describes a localized electron state (to be called *d* level) coupled to a band of delocalized conduction electrons (see the top right figure). If conditions are such that 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 top right 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, ε_d, and a sharp Kondo resonance at the chemical potential of the leads.

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 $T << T_K$. 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.



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)

In this regard, the QD studied by van der Wiel *et al.* (*7*) performs particularly well: Its conductance shows a Kondo resonance (see the bottom 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

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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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PERSPECTIVES: PLANETARY SCIENCE

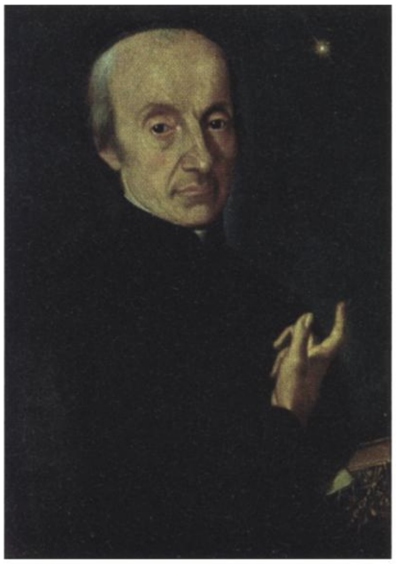
Asteroids Come of Age

Richard P. Binzel

Just a few months shy of the bicentennial of the discovery of the first asteroid, four reports in this issue on pages 2088, 2085, 2101, and 2097 (*1*) present results from the first ever rendezvous mission with an asteroid. No longer just "star-like" points in the sky, asteroids have become the focus of dedicated geological and geophysical studies aimed at gaining insights into planetary formation and addressing practical concerns for the long-term safety of our planet. These studies are yielding new links to meteorites and planetary origins.

At the dawn of the 19th century, a Hungarian baron, Franz von Zach, was organizing a group of "Celestial Police" astronomers to search the sky for the "missing planet" predicted to exist between Mars and Jupiter by the Titius-Bode relationship for planetary distances (*2*). Meanwhile, an Italian monk in Palermo, Giuseppe Piazzi (see the figure, this page), was systematically revising an existing star catalog when on 1 January 1801 he came upon an object that "might be something better than a comet" (*3*) moving slowly north and west in the evening sky. Astronomers, aided by the eminent mathematician Karl Friedrich Gauss, calculated an orbit for the new object, named Ceres (*4*), and showed that it fit the location for von Zach's planet. Surprise and dismay greeted the discovery of a second object, Pallas, in 1802, followed by Juno (1804) and Vesta (1807), leading astronomers to conclude that the "missing planet" was in pieces. On the basis of "star-like" telescopic appearance, William Herschel coined the term "asteroids" for these newest members of the solar system.

One century after their discovery, astronomers generally considered asteroids the "vermin of the sky," because their trails on photographic plates exposed for studying nebulae were a nuisance. Tracking them required laborious manual computing of their orbits and ephemerides (*5*). Yet insights into their nature were emerging. In 1867, the American astronomer Daniel Kirkwood noted gaps in asteroid orbital distances from the sun that corresponded to the locations of jovian resonances (*6*), presaging our current understanding that Jupiter's gravity was responsible for interrupting the formation of a sizable planet. Kiyotsugu Hirayama's realization in 1918 that many asteroids orbit together as "families" formed by the catastrophic breakup of larger parent bodies uncovered the role of collisions for controlling their sizes, shapes, spins, and surfaces.



Happy 200th birthday. Giuseppe Piazzi (1746–1826) inaugurated the 19th century with the discovery of the first asteroid, Ceres, on 1 January 1801.

CREDIT: OSSERVATORIO ASTRONOMICO DI PALERMO G.S. VAIANA

The rising tide of planetary science in the 1960s and 1970s (*7*) brought an as yet unending wave of telescopic measurements that revealed the diversity of asteroids. For example, Ceres has a low albedo and colors matching primitive (unheated) carbonaceous chondrite meteorites, whereas its sister Vesta shows a bright variegated surface covered by lava flows, indicating a history of substantial heating with a compelling link to basaltic meteorites (*8*). A majority of asteroids hold the middle ground. These "S-class" asteroids display albedos and spectral colors that resemble the most common meteorites, the gently heated ordinary chondrites. This link is appealing, but not all pieces fit the puzzle (*9*): S-class asteroids display redder overall colors and subdued spectral absorption bands compared with their would-be meteorite mates. If S-class asteroids could be shown to match ordinary chondrites, this would place a wealth of laboratory data on meteorite chemistry and chronology into a planetary formation context (*10*).

Heightening appreciation of asteroids and their meteorite manna as solar system building blocks turned the 1990s into a renaissance age. The first asteroid flybys courtesy of the Galileo Jupiter mission provided the first detailed look at their cratered and somewhat splotchy landscapes (*11*). Meanwhile, Hubble Space Telescope observations (*12*) and advances in ground-based planetary radar imaging (*13*) are providing a continuing series of views of their sometimes bizarre configurations.

The newfound respect for asteroids was won in large measure through the work of the late astrogeologist Eugene Shoemaker. When NASA moved toward focused low-cost missions, a near-Earth asteroid rendezvous (NEAR) mission was the first selection within the Discovery program. The target of the NEAR-Shoemaker mission is

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