

## Chapter 2. Theory of Electron Transmission Through a Quantum Dot: Coulomb Blockade and the Kondo Effect

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## 2.1 Project Description

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When electrons are confined to a small region of a semiconductor they form a quantum dot, and the energy and the charge on the quantum dot are quantized. It has been possible to study the transmission of electrons through a quantum dot by coupling the states in the dot to external leads via a tunnel barrier. Furthermore, the charge on the dot can be controlled by a nearly metallic gate. The discrete charging energy gives rise to the phenomenon of Coulomb blockade, which manifests itself in the form of periodic peaks in the transmission (or conductance) as a function of gate voltage. This phenomenon has been under intensive study recently, and the quantum dot has been described as an "artificial atom."<sup>1</sup>

Several years ago, we pointed out that another consequence of the analogy with the artificial atom is that we may observe physics connected with the Kondo problem in quantum dots. The Kondo problem usually refers to the coupling of the electron spins localized on an impurity atom to the spin of the conduction electrons in the metallic host. Here the electron state on the quantum dot plays the role of the localized spin while the electrons in the source and drain leads play the role of the conduction electrons. We predicted unusual temperature lineshape for the Coulomb blockade peaks due to the Kondo phenomenon. In particular, the lineshape is predicted to

broaden with decreasing temperature, in sharp contrast with conventional wisdom.<sup>2</sup> Subsequently, other signatures in the presence of a magnetic field were also predicted.<sup>3</sup> In the past year, these predictions were observed experimentally by Professor Marc A. Kastner's group.<sup>4</sup>

The experimental observation of Kondo phenomena in quantum dots has prompted us to further explore this interesting problem. One particular extension is to consider the effect of several electron states on the quantum dot in addition to the state exhibiting the Kondo effect because it is particularly well coupled to the leads. It is possible that each additional electron would prefer to occupy a different electron state, rather than doubly occupying the state already occupied. This could be favored by the exchange effect. In this case, we predict that the Kondo effect with the first electron state will be interrupted each time an additional electron is introduced onto the dot. However, as the gate voltage is further increased, the Kondo effect with the original state (which remains singly occupied and therefore carries a localized spin) can be rejuvenated, only to be interrupted by the introduction of yet another electron. This will give rise to a series of Coulomb blockade peaks with highly asymmetric line-shape. This example shows that the flexibility of the quantum dot system may lead to a much richer class of phenomena than in the traditional impurity system.

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1 M.A. Kastner, "Artificial Atoms," *Phys. Today* 46(1): January 24 (1993).

2 T.K. Ng and P.A. Lee, "On Site Coulomb Repulsion and Resonant Tunnelling," *Phys. Rev. Lett.* 61: 1768 (1988).

3 Y. Meir, N. Wingreen, and P.A. Lee, "Low Temperature Transport Through a Quantum Dot: The Anderson Model Out of Equilibrium," *Phys. Rev. Lett.* 70: 2601 (1993).

4 D. Goldhaber-Gordon, H. Shtrikman, D. Malahu, D. Abusch-Magder, U. Meirav, and M.A. Kastner, "Kondo Effect in a Single Electron Transistor," *Nature* 391: 156 (1998).

