Section 2 Quantum-Effect Devices

Chapter 1. Statistical Mechanics of Quantum Dots

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1.1 Project Description

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We are investigating equilibrium properties of quantum dots (isolated metallic systems with sizes smaller than the typical length of an electron dephasing). Until recently, we concentrated on such properties of an individual dot as capacitance and electric and magnetic susceptibility. The most dramatic manifestation of the quantum nature of the magnetic polarizability takes place for a multiply connected geometry, e.g., for a ring, and is known as a persistent current. This current is a metallic system response to the magnetic flux through the hole. It can exist even when there is no field in the material, and it does not dissipate.

Due to the impurity or surface scattering of the conductivity electrons, there is certain dispersion of the properties in the ensemble of macroscopically equivalent samples. Therefore, we must consider the sample to sample (mesoscopic) fluctuations as well as ensemble averaged properties such as persistent current.

Earlier[1] we developed a theory on the persistent current neglecting the interaction between the electrons. This problem involves two energy scales: (1) the mean energy spacing between the exact one electron states in a random potential Δ, and (2) the inverse typical time of an electron diffusion around the sample $h/t = E_c$, also known as the Thouless shift. The dimensionless ratio E_c/Δ is the sample conductance in natural units e^2/h. We found that the mean root square of the mesoscopic fluctuations of the persistent current is of the order of $E_c e/h$, while the averaged persistent current, although nonzero, is much smaller and determined by Δ.

The persistent current was recently observed[2] and found to be orders of magnitude larger than the theoretical predictions *in the absence of the interaction between electrons.* Also, superconductive-like fluctuations cannot explain why the effect is so large. On the other hand, the magnitude of the observed persistent current is more or less consistent with the charging energy e^2/R, where R is the radius of a ring. This was one of the motivations for us to study dielectric properties of mesoscopic systems.

We have developed a technique to investigate the local charge fluctuations and local electric fields within a mesoscopic system. We have found that, due to quantum interference, there are long range correlations in these local fluctuations (similar to the well-known Friedel oscillations). These correlations determine the additional energy caused by the Coulomb interaction between the fluctuations, and, therefore, their contribution to the thermodynamics.

We have calculated the distribution of electric fields outside a disordered, neutral quantum dot as well as the quantum correction to its polarizability. Although both of the effects are small, they are very important ideologically from the point of view of the scaling theory of metal-insulator transition, which we believe are observable.

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[1] B.L. Altshuler , Y. Gefen, and Y. Imry, *Phys. Rev. Lett.* 66: 88 (1991); B.L. Altshuler and B.Z. Spivak, *Zh. Eksp Teo.* 92: 607 (1987).

[2] L.P. Levy, G. Doland, J. Dunsmuir, and H. Bouchiat, *Phys. Rev. Lett.* 64: 2074 (1990); V. Chandrasekhar, R.A. Webb, M.Y. Brady, M.D. Ketchen, W.J. Gallagher, and A. Kleinsasser, *Phys. Rev. Lett.* 67: 3578 (1991).

These small effects are caused by the screening of the Coulomb interaction. Due to this screening, additional energy is determined only by the charge distribution in a layer near the sample surface of a width of the screening length. As a result, interaction between the charge fluctuations is not sufficient to account for the persistent current. On the other hand, there is another magnetic flux dependent contribution to the Coulomb energy: the interaction between the charge fluctuations and the confining potential in a quantum dot (e.g., a finite work function of a metallic grain is determined by a dipole layer on the surface). The energy of the local charge fluctuations in the field of this layer apparently depends on the magnetic field and explains the observed persistent current. This interaction can have a number of important and observable consequences such as substantial mesoscopic fluctuations of the work function and its dependence on the external parameters such as low magnetic field.

Publications

Altshuler, B.L. "Thermodynamics of Mesoscopic Systems." Paper presented at the International Symposium on Nanostructures and Mesoscopic Systems, Santa Fe, New Mexico, May, 1991.