Adiabatic Electron Pumping through a Quantum Dot with a Discrete Level

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Abstract

An adiabatic electron pumping through a quantum dot with a discrete energy level under a magnetic field is investigated theoretically. Adiabatic spin pumping takes place under two time dependent external sources, the Zeeman energy and the difference in the tunneling coupling to the dot between the left and right leads. The behavior of the pumped spin as a function of the amplitude of the magnetic field is different whether the dot level is above the Fermi level in leads.

Key words: adiabatic electron pumping; spin dependent transport; Coulomb blockade; quantum dot

An adiabatic electron pump is the device that produces a finite charge transfer through a quantum dot when the dot is modified slowly by two external time dependent sources and it is returned to its initial configuration after a certain period [1]. It is originally investigated by Thouless in a certain one dimensional system [2]. Electrons are transferred under zero source-drain voltage. In a recent experiment [3], this pump is realized for an open quantum dot by applying two time dependent gate voltages to the dot.

We theoretically investigate an adiabatic electron pumping under a magnetic field. In such a system, adiabatic spin pumping is expected; Some theoretical proposals have been made for the Tomonaga-Luttinger liquid [4] and for a open quantum dot [5]. In the following we discuss how spin pumping is realized in a quantum dot system with a discrete energy level.

In general, to observe adiabatic pumping charge, we need two periodic external sources, $X_1(t)$ and $X_2(t)$ with a common frequency ω. When they are applied to the dot system, charge redistribution of the dot system takes place, which is the source of pumping charge. It is expressed in terms of the scattering matrix S of the dot system [6]. Then pumping charge Q after a period $\tau = 2\pi/\omega$ is given by a two dimensional integral of X_1 and X_2;

$$Q = e \int\int dX_1 dX_2 \Pi(X_1, X_2) \tag{1}$$

where $\Pi(X_1, X_2)$ can be calculated from the scattering matrix S [7]. A pumping current I is then given by $I = \omega Q/2\pi$. For simplicity, we discuss the zero temperature limit.

We consider a single closed quantum dot system as follows. The dot has a single discrete energy level E_0 and couples to the two leads with a dot-lead coupling $\Gamma = \Gamma_L + \Gamma_R$, where $\Gamma_\alpha = \pi\rho|T_\alpha|^2$ $(\alpha = L, R)$ with a tunneling matrix element T_α between the dot and lead α, and the density of states ρ at the Fermi level in the leads. When a magnetic field is applied, the dot level splits into $E_\sigma = E_0 - \sigma E_Z (\sigma = \pm)$ with the Zeeman energy $E_Z = g\mu_B B$. The Coulomb interaction is taken into account. To describe this system, we adopt the Anderson model [8,9],

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$$H = \sum_{k,\sigma,\alpha=L,R} \epsilon_k c^\dagger_{k\sigma\alpha} c_{k\sigma\alpha} + \sum_{\sigma=\pm} E_\sigma d^\dagger_\sigma d_\sigma + U n_+ n_- + \sum_{k,\sigma,\alpha=L,R} \left(T_\alpha c^\dagger_{k\sigma\alpha} d_\sigma + \text{h.c.} \right), \quad (2)$$

where $c^\dagger_{k\sigma\alpha}$ creates an electron with energy ϵ_k and spin σ in lead α, $d^\dagger_\sigma$ creates an electron in the dot with spin σ, $n_\sigma = d^\dagger_\sigma d_\sigma$, and U is the strength of the Coulomb interaction. We only pay attention the Coulomb blockade effect so that the mean field approximation [10] is adopted: $Un_+n_- = \sum_\sigma U\langle n_{-\sigma}\rangle d^\dagger_\sigma d_\sigma - U\langle n_+\rangle\langle n_-\rangle$, where $\langle n_\sigma\rangle$ is the expectation value of n_σ for given values of X_1 and X_2 and is determined self-consistently.

Now we investigate how adiabatic spin pumping takes place through the dot. We choose the following set of X_1 and X_2; One is the Zeeman energy, $E_Z(t)$, and the other is the difference in the dot-lead coupling between the left and right barriers, $(\Gamma_L - \Gamma_R)/\Gamma$, while $\Gamma_L + \Gamma_R$ is the constant value of Γ. We particularly discuss the case where $-|E_Z| \leq E_Z(t) \leq |E_Z|$ with the amplitude of the Zeeman energy $|E_Z|$. For these two parameters, the pumping charge Q_σ for spin σ is calculated using Eq. (1) with σ. Spin pumping is characterized by the pumped spin per cycle, $Q_+ - Q_-$. We find Π_σ in Eq. (1) depends only on E_Z [11].

Figure 1 shows $Q_+ - Q_-$ as a function of $|E_Z|$ for $E_0/\Gamma = 2$ (thick solid line), 1 (thin solid line), -0.5 (thick broken line), and -1 (thin broken line). For all of E_0, $Q_+ - Q_-$is finite when $|E_Z|$ is nonzero; With the aid of the Zeeman effect, spin pumping takes place. A qualitative difference, however, appears between the solid and broken lines corresponding to whether the dot level is above the Fermi level in the leads. This difference stems from whether the Coulomb blockade effect is effective.

When the dot level is well above the Fermi level in leads, the pumping charge increases around $|E_Z| \sim E_0$ (See the solid lines in Fig.1.) This is similar to the usual resonant tunneling; The effect of the Coulomb interaction just shift the dot level. When $|E_Z| \gg E_0 + \Gamma$, the pumped spin is the maximum and twice the unit charge. This corresponds that the unit charge is pumped per cycle for each of up and down spins with the opposite directions [11].

When the dot level is lower than the Fermi level in the leads, the situation is qualitatively different. (See the broken lines in Fig.1.) Pumping charge increases from $|E_Z| = 0$. The result indicates the electronic state in the dot changes qualitatively around $E_Z = 0$. In fact, it is associated with the appearance of the spontaneous magnetization [11], which changes the sign of the magnetization at $E_Z = 0$. The Coulomb blockade effect is effective in this situation. When $|E_Z| \gg \Gamma$, the pumped spin reaches the maximum value but it is less than twice the unit charge. This result means the

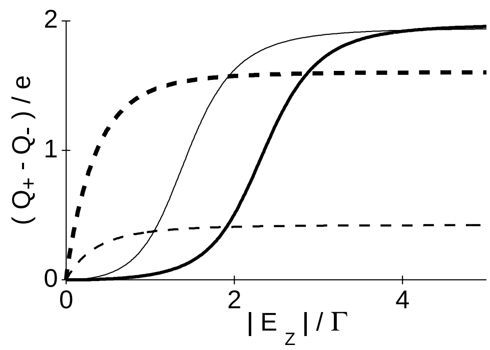

Fig. 1. Pumped spin $Q_+ - Q_-/e$ per cycle as a function of the amplitude of magnetic field in terms of the Zeeman energy, $|E_Z|$ normalized by the level width Γ for several values of the position of the dot level E_0; $E_0/\Gamma = 2$ (thick solid line), 1 (thin solid line), -0.5 (thick broken line), and -1 (thin broken line).

Coulomb blockade effect suppress the pumping charge.

In conclusion, we have investigated the adiabatic spin pumping through the closed quantum dot with the aid of the Zeeman effect. The behavior of the pumped spin as a function of the amplitude of the magnetic field is different whether the dot level is above the Fermi level in the leads.

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