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Electronic transport properties of the single-impurity Anderson model*

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We investigate the electronic transport properties of the single-impurity Anderson model. By employing the cluster expansions, the equations of motion of Green's functions are transformed into the corresponding equation of motion of connected Green's functions, which contains the correlation of two conduction electrons beyond the Lacroix approximation. With the method we show that the asymmetric line shape of zero bias conductance manifests itself as the Fano effect, and the Kondo effect is observed in the narrow peak of differential conductance curve of the system. The Fano and the Kondo effects can coexist in the single-impurity Anderson model when the impurity level is adjusted to an appropriate position.

Keywords: Anderson model, Fano effect, Kondo effect
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1. Introduction

The Anderson model[1] was first introduced to describe a magnetic impurity in a bulk metal. Schrieffer and Wolff[2] have shown that, in the limit of $U \to \infty$, this model is equivalent to the s–d model when the impurity level $\varepsilon_{\rm d}$ is well below the Fermi level $\varepsilon_{\rm F}$: thus a Kondo effect[3] is obtained in this limit. The Kondo effect leads to a decrease in conductance of the bulk metal at a sufficiently low temperature. This phenomenon can be interpreted as a strong destructive interference between the incoming and outgoing conduction electron waves. The destructive interference effect comes from the resonant scattering of conduction electrons via a spin singlet formed at the characteristic Kondo temperature.[4,5]

However, in quantum dot systems, the Kondo effect leads to an increase in conductance of mesoscopic systems. In the Kondo regime, a Kondo singlet is formed between localized spin of a quantum dot and electrons in reservoirs, which provides a new channel for mesoscopic current. The observation[6,7] of the Kondo effect in quantum dot systems has renewed experimental and theoretical interest in this many-body effect. The Kondo effect has been investigated extensively in quantum dot systems such as semiconductor quantum dots,[6,7] carbon nanotubes,[8] and single molecules contacted by metal leads.[9,10] All the aspects of these quantum dot systems have been researched in detail in recent years, such as transmission phase shift,[11] temperature-dependent properties,[12] and magnetic flux effects,[13,14] etc., from the Kondo regime to the mixed-valence regime and the empty state regime,[15] from equilibrium properties to non-equilibrium properties.[16]

The Fano effect, which results from the interference of discrete and continuum levels,[17] is a ubiquitous phenomenon observed in a large variety of experiments including atomic photoionization,[18] electron and neutron scattering,[19,20] Raman scattering,[21] and photo-absorption in quantum well structures.[22,23] In a mesoscopic system the existence of asymmetric conductance line shapes as a symbol of the Fano effect requires two conditions: (i) a discrete resonant scattering path and a continuum nonresonant scattering path coexist; (ii) these two scattering paths interfere.

Recently, the interest in the Fano effect has been renewed by two well-known experiments. One is the scanning tunnelling microscope (STM) experiment[24] designed to study the Kondo effect, in which the tunnelling spectra manifest themselves as Fano resonance which is determined by two interfering paths—the Kondo resonance, which serves as one discrete

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resonant scattering path, and the conduction band, which serves effectively as another quasicontinuum nonresonant path modified by broadened impurity level.[25] The other is the single-electron transistor (SET) experiment,[26] in which the Fano effect has been observed in conductance through SET, where the nature of the direct transmission path has not yet been fully clarified.[27,28]

The STM and SET systems can be reduced to the single-impurity Anderson model[1] theoretically, namely, a quantum dot coupling to the left and right electron reservoirs.[29−32] It is just the model that we intend to investigate. The Hamiltonian of the model has already been solved by using several methods,[33−37] however in previous papers the zero bias conductance and the differential conductance of the system are not discussed. In this paper, by employing the cluster expansions, the equations of motion of Green's functions are transformed into the corresponding equation of motion of connected Green's functions, which contains the correlation of two conduction electrons beyond the Lacroix approximation. With the method we calculate the zero bias conductance and the differential conductance of the system, and show that the asymmetric line shape of zero bias conductance manifests itself as the Fano effect, and the Kondo effect is observed in the narrow peak of differential conductance curve of the system.

2. Model and Green's function

The single-impurity Anderson model can be described by the following Hamiltonian:

$$H = \sum_{\alpha k\sigma} \varepsilon_{\alpha k} C^{\dagger}_{\alpha k\sigma} C_{\alpha k\sigma} + \sum_{\sigma} \varepsilon_{\mathrm{d}\sigma} d^{\dagger}_{\sigma} d_{\sigma} + \frac{U}{2} \sum_{\sigma} n_{\sigma} n_{\bar{\sigma}} + \sum_{\alpha k\sigma} (V_{\alpha} d^{\dagger}_{\sigma} C_{\alpha k\sigma} + V^{*}_{\alpha} C^{\dagger}_{\alpha k\sigma} d_{\sigma}), \quad (1)$$

where $\alpha =$ L or R denotes the left or right electron reservoirs, and $\sigma =\uparrow$ or $\downarrow$ denotes spin up or down. The first term on the right-hand side in the above Hamiltonian describes electrons in the left and the right electron reservoirs, and the second one describes electrons of the impurity site. The third one corresponds to the on-site Coulomb interactions, and U is the on-site Coulomb repulsion. The fourth one describes the tunnelling through the impurity, and V_{a} represents the s–d hybridization.

Following Zubarev,[38] the retarded Green's function $\langle\langle A(t); B(t')\rangle\rangle$ is defined as

$$\langle\langle A(t); B(t')\rangle\rangle = -\mathrm{i}\theta(t-t')\langle [A(t), B(t')]_{\pm}\rangle. \quad (2)$$

By the Fourier transformation of the time variable, the retarded Green's function satisfies the following equation:

$$\omega\langle\langle A; B\rangle\rangle = \langle [A, B]_{\pm}\rangle + \langle\langle [A, H]_{-}; B\rangle\rangle. \quad (3)$$

Equation (3) is named as the equation of motion (EOM) of Green's function, the EOM can be expressed as

$$\omega\langle\langle d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle = 1 + \varepsilon_{\mathrm{d}\sigma}\langle\langle d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle + \sum_{\alpha k} V_{\alpha}\langle\langle C_{\alpha k\sigma}; d^{\dagger}_{\sigma}\rangle\rangle + U\langle\langle \hat{n}_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle \quad (4)$$

for the Hamiltonian (1). And for the high-order Green's function

$$\begin{aligned}\omega\langle\langle \hat{n}_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle = {} & n_{\bar{\sigma}} + (\varepsilon_{\mathrm{d}\sigma} + U)\langle\langle \hat{n}_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle \\ & + \sum_{\alpha k} V_{\alpha}\langle\langle \hat{n}_{\bar{\sigma}} C_{\alpha k\sigma}; d^{\dagger}_{\sigma}\rangle\rangle \\ & + \sum_{\alpha k} V_{\alpha}\langle\langle d^{\dagger}_{\bar{\sigma}} C_{\alpha k\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle \\ & - \sum_{\alpha k} V^{*}_{\alpha}\langle\langle C^{\dagger}_{\alpha k\bar{\sigma}} d_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle, \end{aligned} \quad (5)$$

we make use of a cluster expansions to separate the connected part of the Green's function instead of the Lacroix decoupling scheme,[34,39]. As an example, the high-order Green's function $\langle\langle \hat{n}_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle$ is expressed as

$$\langle\langle \hat{n}_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle = \langle \hat{n}_{\bar{\sigma}}\rangle\langle\langle d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle + \langle\langle \hat{n}_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}},$$

where $\langle\langle \cdots \rangle\rangle_{\mathrm{c}}$ represents a connected Green's function and it is straightforward to derive its EOM. We write the EOM of the connected Green's function $\langle\langle \hat{n}_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}}$ as

$$\begin{aligned}(\omega - \varepsilon_{\mathrm{d}\sigma} - U(1-n_{\bar{\sigma}}))\langle\langle \hat{n}_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}} = {} & U n_{\bar{\sigma}}(1-n_{\bar{\sigma}})\langle\langle d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle \\ & + \sum_{\alpha k} V_{\alpha}\langle\langle \hat{n}_{\bar{\sigma}} C_{\alpha k\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}} \\ & + \sum_{\alpha k} V_{\alpha}\langle\langle d^{\dagger}_{\bar{\sigma}} C_{\alpha k\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}} \\ & - \sum_{\alpha k} V^{*}_{\alpha}\langle\langle C^{\dagger}_{\alpha k\bar{\sigma}} d_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}}. \end{aligned} \quad (6)$$

It is not difficult to obtain the EOM of the other connected Green's functions such as $\langle\langle d^{\dagger}_{\bar{\sigma}} C_{\alpha k\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}}$, $\langle\langle C^{\dagger}_{\alpha k\bar{\sigma}} d_{\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}}$, $\langle\langle d^{\dagger}_{\bar{\sigma}} C_{\alpha' k'\bar{\sigma}} C_{\alpha k\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}}$, $\langle\langle C^{\dagger}_{\alpha' k'\bar{\sigma}} d_{\bar{\sigma}} C_{\alpha k\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}}$, and $\langle\langle C^{\dagger}_{\alpha' k'\bar{\sigma}} C_{\alpha k\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}}$. In order to truncate the EOM, let $\langle\langle d^{\dagger}_{\bar{\sigma}} C_{\alpha' k'\bar{\sigma}} C_{\alpha k\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}}$, $\langle\langle C^{\dagger}_{\alpha' k'\bar{\sigma}} d_{\bar{\sigma}} C_{\alpha k\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\mathrm{c}}$, and

$\langle\langle C^{\dagger}_{\alpha' k'\bar{\sigma}} C_{\alpha k\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\rm c}$ involved with the correlation of two conduction electrons be zero, then one will reach the Lacroix approximation.

As a consequence of a coherent superposition of spin flip cotunnelling events, the formation of the Kondo resonance is inevitably involved with the correlation of two conduction electrons. Therefore the Lacroix approximation must be improved in order to discus the electron transport properties of the single-impurity Anderson model. To surpass Lacroix approximation it is necessary to consider the EOM of the connected Green's functions of $\langle\langle d^{\dagger}_{\bar{\sigma}} C_{\alpha' k'\bar{\sigma}} C_{\alpha k\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\rm c}$, $\langle\langle C^{\dagger}_{\alpha' k'\bar{\sigma}} d_{\bar{\sigma}} C_{\alpha k\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\rm c}$, and $\langle\langle C^{\dagger}_{\alpha' k'\bar{\sigma}} C_{\alpha k\bar{\sigma}} d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle_{\rm c}$ involving the correlation of two conduction electrons, and to assume the higher-order correlation Green's functions to be zero. After a lengthy but direct calculation, in the limit of $U\to\infty$, $\langle\langle d_{\sigma}; d^{\dagger}_{\sigma}\rangle\rangle$ is obtained finally as

$$G_{{\rm d}\sigma}=\frac{1-n_{\bar{\sigma}}-\sum\limits_{\alpha k}\frac{V_{\alpha}\langle d^{\dagger}_{\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle}{\omega-\varepsilon_{\alpha k}}-\frac{V^2_{\alpha}}{n_{\bar{\sigma}}}\sum\limits_{\alpha k}\frac{\langle d^{\dagger}_{\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle}{\omega-\varepsilon_{\alpha k}}\sum\limits_{\alpha k'}\frac{\langle d^{\dagger}_{\bar{\sigma}}C_{\alpha k'\bar{\sigma}}\rangle}{\omega-\varepsilon_{\alpha k'}}}{\omega-\varepsilon_{{\rm d}\sigma}-\sum\limits_{\alpha k}\frac{V_{\alpha}V^{*}_{\alpha}}{\omega-\varepsilon_{\alpha k}}+\sum\limits_{\alpha k}\frac{V_{\alpha}V^{*}_{\alpha}}{\omega-\varepsilon_{\alpha k}}\sum\limits_{\alpha k}\frac{V_{\alpha}\langle d^{\dagger}_{\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle}{\omega-\varepsilon_{\alpha k}}-\sum\limits_{\alpha k}\sum\limits_{\alpha' k'}\frac{V_{\alpha}V^{*}_{\alpha'}\langle C^{\dagger}_{\alpha' k'\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle}{\omega-\varepsilon_{\alpha k}}+\delta},\tag{7}$$

where

$$\begin{aligned}\delta=&\frac{V^2_{\alpha}}{n_{\bar{\sigma}}}\sum_{\alpha kk'}\frac{\langle d^{\dagger}_{\sigma}d^{\dagger}_{\bar{\sigma}}C_{\alpha k'\bar{\sigma}}C_{\alpha k\sigma}\rangle_{\rm c}-\langle d^{\dagger}_{\sigma}C^{\dagger}_{\alpha k'\bar{\sigma}}d_{\bar{\sigma}}C_{\alpha k\sigma}\rangle_{\rm c}}{\omega-\varepsilon_{\alpha k}}\\&+\frac{V^2_{\alpha}}{n_{\bar{\sigma}}}\sum_{\alpha kk'}\frac{\langle\hat{n}_{\bar{\sigma}}C^{\dagger}_{\alpha k'\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle_{\rm c}-\langle d^{\dagger}_{\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle\langle C^{\dagger}_{\alpha k'\bar{\sigma}}d_{\bar{\sigma}}\rangle}{\omega-\varepsilon_{\alpha k}}\\&+\frac{V^2_{\alpha}}{n_{\bar{\sigma}}}\sum_{\alpha kk'}\frac{\langle d^{\dagger}_{\sigma}d^{\dagger}_{\bar{\sigma}}C_{\alpha k'\bar{\sigma}}C_{\alpha k\sigma}\rangle_{\rm c}-\langle d^{\dagger}_{\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle\langle d^{\dagger}_{\sigma}C_{\alpha k'\sigma}\rangle}{\omega-\varepsilon_{\alpha k}}\\&-\frac{V^3_{\alpha}}{n_{\bar{\sigma}}}\sum_{\alpha kk'}\frac{\langle d^{\dagger}_{\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle\langle C^{\dagger}_{\alpha k"\sigma}C_{\alpha k'\sigma}\rangle+\langle\hat{n}_{\sigma}d^{\dagger}_{\bar{\sigma}}C_{\alpha k'\bar{\sigma}}\rangle_{\rm c}}{(\omega-\varepsilon_{\alpha k})(\omega-\varepsilon_{\alpha k'})},\end{aligned}\tag{8}$$

and the average functions $\langle d^{\dagger}_{\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle$ and $\langle C^{\dagger}_{\alpha' k'\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle$ can be calculated by spectral theorem as follows:

$$\langle d^{\dagger}_{\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle=-\frac{1}{\pi}\int f(\omega){\rm Im}\langle\langle C_{\alpha k\bar{\sigma}}; d^{\dagger}_{\bar{\sigma}}\rangle\rangle,\tag{9}$$

$$\langle C^{\dagger}_{\alpha' k'\bar{\sigma}}C_{\alpha k\bar{\sigma}}\rangle=-\frac{1}{\pi}\int f(\omega){\rm Im}\langle\langle C_{\alpha k\bar{\sigma}}; C^{\dagger}_{\alpha' k'\bar{\sigma}}\rangle\rangle,\tag{10}$$

where $f(\omega)=1/[\exp((\omega-E_{\rm F})/T)+1]$ is the Fermi-distribution function. The EOM of the corresponding Green's functions reads

$$\langle\langle C_{\alpha k\bar{\sigma}}; d^{\dagger}_{\bar{\sigma}}\rangle\rangle=\Big(\frac{V^{*}_{\alpha}}{\omega-\varepsilon_{\alpha k}}\Big)G_{{\rm d}\bar{\sigma}}(\omega),\tag{11}$$

$$\langle\langle C_{\alpha k\bar{\sigma}}; C^{\dagger}_{\alpha' k'\bar{\sigma}}\rangle\rangle=\Big(\frac{\delta_{\alpha\alpha' kk'}}{\omega-\varepsilon_{\alpha k}}+\frac{V_{\alpha}V^{*}_{\alpha'}}{\omega-\varepsilon_{\alpha' k'}}\Big)G_{{\rm d}\bar{\sigma}}(\omega).\tag{12}$$

For simplicity, we consider the nonmagnetic case, i.e. $n_{{\rm d}\downarrow}=n_{{\rm d}\uparrow}=n/2$, with n being total number of d electrons

$$n=2n_{\bar{\sigma}}=\int f(\omega')\rho(T,\omega'){\rm d}\omega',\tag{13}$$

where $\rho(T,\omega)=-(1/\pi){\rm Im}G_{\rm d}(\omega)$ is the density of states at a finite temperature. Equations (7)–(12) constitute a closed set of equations, which can be solved self-consistently and numerically.

3. Zero bias conductance and differential conductance

The current from the left to the right electron reservoirs can be calculated from the time evolution of the occupation number in the left electron reservoir as follows:

$$J_{\rm L}(t)=-e\Big\langle\frac{{\rm d}N_{\rm L}}{{\rm d}t}\Big\rangle,\tag{14}$$

where $N_{\rm L}=\sum_{k,\sigma}C^{\dagger}_{k{\rm L},\sigma}C_{k{\rm L},\sigma}$, Using the Green's function of the Keldysh type[40] $G^{<}_{{\rm dL}k\sigma}(t,t)$ corresponding to the states at the dot and in the left electron reservoir, the current can be expressed as

$$I_{\rm L}=\langle J_{\rm L}(t)\rangle=-\frac{2e}{h}\sum_{k,\sigma}{\rm Re}[V_{\rm L}G^{<}_{{\rm dL}k\sigma}(t,t)].\tag{15}$$

According to the Langreth's rule and using the steady-state condition $I=(I_{\rm L}-I_{\rm R})/2$, the current can be

expressed as

$$I = \frac{2e}{h}\Gamma \int \mathrm{d}\omega\rho(\omega)[f_{\mathrm{R}}(\omega) - f_{\mathrm{L}}(\omega)]\mathrm{Im}G_{\mathrm{d}\sigma}(\omega), \quad (16)$$

where $\Gamma = |V_{\mathrm{L}}|^2$. For the zero bias voltage we find the conductance

$$G = -\frac{2e^2}{h}\Gamma \int \mathrm{d}\omega\rho(\omega)\frac{\beta \mathrm{e}^{\beta(\omega-\varepsilon_{\mathrm{F}})}}{[\mathrm{e}^{\beta(\omega-\varepsilon_{\mathrm{F}})}+1]^2}\mathrm{Im}G_{\mathrm{d}\sigma}(\omega). \quad (17)$$

For a finite temperature the zero bias conductance G can be calculated numerically through Green's function $G_{\mathrm{d}\sigma}(\omega)$ at the impurity. Because only the conduction electrons near the Fermi level ε_{F} participate in the transport current, the density of states for conduction electrons is taken as a constant $\rho(\varepsilon) = 1/(2D)$ when $-D < \varepsilon < D$, and the quantum dot level broadening is given by $\Delta = \pi|V_\alpha|^2\rho(\varepsilon)$.[1] The Fermi energy ε_{F} (meV) is a reference mark of the unit of energy.[5] The parameters are considered as follows. The hopping matrix element V_{a} between the quantum dot and the electron reservoirs is taken as 0.1. The total number of d electrons is adopted to be 0.8, which determines self-consistently the chemical potential. The half width D is assumed to be 1 meV, which determines the energy scale. The temperature T is taken as $10^{-5}\Delta$, which is lower than the Kondo temperature ($T_{\mathrm{K}} = (D\Delta)^{1/2}\exp(\pi(\varepsilon_{\mathrm{d}} - \varepsilon_{\mathrm{F}})/(2\Delta))$).[1] The relative position of the level $\Delta\varepsilon = \varepsilon_{\mathrm{F}} - \varepsilon_{\mathrm{d}}$ can be varied by the gate voltage applied to the quantum dot. Figure 1 presents the zero-bias conductance G through the single-impurity Anderson model. An asymmetric conductance line shape is shown, which comes from the Fano effect. It is consistent with the experimental observations in Refs.[21, 23].

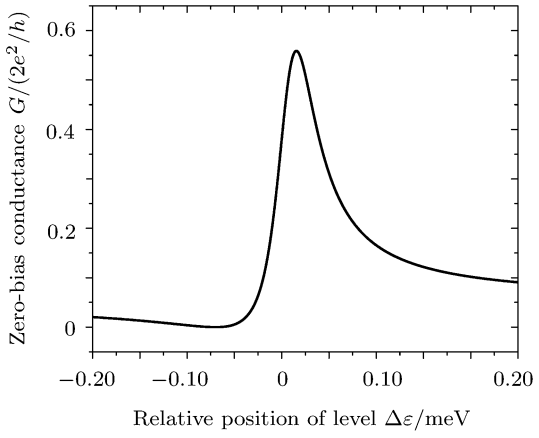


Fig.1. Zero bias conductance through the single-impurity Anderson model. In our calculation $V_{\mathrm{L}} = V_{\mathrm{R}} = 0.1$ and T is taken as $10^{-5}\Delta$.

In a similar way we calculate the source–drain voltage characteristics of the system. It is assumed that the potential V is applied to the left electron reservoir and the potential is kept being zero in the right electron reservoir. The relative position of level $\Delta\varepsilon = \varepsilon_{\mathrm{F}} - \varepsilon_{\mathrm{d}}$ maintains 0.04 meV, which lies in the Kondo regime. The hoping matrix element V_{a} is taken as 0.1. The temperature T is adopted to be $10^{-5}\Delta$ lower than Kondo temperature T_{K}. Figure 2 presents the variation of the differential conductance $\mathrm{d}I/\mathrm{d}V$ with the source–drain voltage. Because the relative position $\Delta\varepsilon$ of the level of the quantum dot lies in the Kondo regime, the differential conductance curve shows a very narrow peak at low voltages, which is just the Kondo resonance observed experimentally as reported in Refs.[6,7]. The broad maximum seen in Fig.2 comes from the Lorentzian resonance tunnelling when the chemical potential $\varepsilon_{\mathrm{F}} + eV$ approaches ε_{d}.

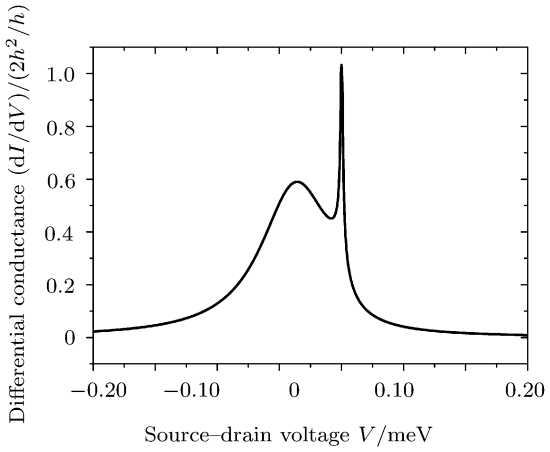


Fig.2. Differential conductance through the single-impurity Anderson model. In our calculation $V_{\mathrm{L}} = V_{\mathrm{R}} = 0.1$, $T = 10^{-5}\Delta$, and $\Delta\varepsilon = \varepsilon_{\mathrm{F}} - \varepsilon_{\mathrm{d}} = 0.04$ meV.

Combining Figs.1 and 2, we observe that the asymmetric line shape of the zero bias conductance manifests itself as Fano effect and the Kondo resonance is observed in differential conductance of the system. It indicates that the Fano effect and the Kondo resonance can coexist in the single-impurity Anderson model system when the impurity level ε_{d} is adjusted to the position $\varepsilon_{\mathrm{F}} - \varepsilon_{\mathrm{d}} = 0.04$ meV. The Kondo effect comes from the many-body effect between the localized spin of a quantum dot and electrons in reservoirs, which provides a new channel for mesoscopic current. The Fano effect comes from the interference of resonant and nonresonant paths—the Kondo resonance serving as the discrete resonant scattering path and the conduction band serving as the continuum nonresonant path.

4. Summary

The STM and SET experiments show that the Fano effect and the Kondo resonance can coexist in a system. Both the STM and SET systems reduce to the single-impurity Anderson model. In this paper, by employing the cluster expansion method, the single-impurity Anderson model has been solved, which contains the correlation of two conduction electrons beyond the Lacroix approximation. With the method we have calculated the zero bias conductance and the differential conductance of the system, and show that the asymmetric line shape of zero bias conductance manifests itself as the Fano effect, and the Kondo effect is observed in the narrow peak of differential conductance curve of the system. Through calculation, we have theoretically shown that the Fano effect and the Kondo resonance can coexist in the single-impurity Anderson model system when the impurity level $\varepsilon_{\rm d}$ is adjusted to an appropriate position.

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