Spin-battery and spin-current transport through a quantum dot

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We compare various recently proposed spin-battery devices which provide source of spin current. We sort them into three types according to the chemical-potential setup: the symmetric dipolar, the asymmetric dipolar, and the unipolar spin batteries. We propose a model in which these three different types of spin battery are coupled to the same quantum dot to generate spin-current transport. We find that the dipolar spin batteries give similar results while very different results are found for the unipolar device.

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I. INTRODUCTION

Traditional electronics is based on the flow of electron charge, the electron spin is ignored. However, the new and emerging technology of spintronics proposes to not only use electron charge but also the electron spin for information processing.[1,2] Many spintronic devices such as the spin valve and magnetic tunneling junction[3] are associated with the flow of spin polarized charge current. In these systems both charge current and spin current coexist. More recently, there has been an increasing interest in the generation of pure spin current without an accompanying charge current. Many schemes have been proposed theoretically to design such devices called ''spin battery'' or ''spin cell,'' which can drive a spin current to flow into external circuits.[4–15] For example, several works have reported that a ferromagnetic resonance process or a rotating external magnetic field can generate a pure spin current which injects into adjacent conductors.[8–10] Hirsch investigated the spin-current flow and the spin Hall effect;[4] Long *et al.* proposed a gate-controllable spin battery.[11] Very recently, it was reported that all-optical injection of pure spin current has been realized experimentally by using the quantum interference of two-color laser fields with cross-linear polarization in ZnSe[14] and GaAs[15] semiconductors.

The generation of a pure spin current without an accompanying charge current is possible if all spin-up electrons flow in one direction and equal amount of spin-down electrons flow in the opposite direction. In this case the net charge current J_e vanishes while a finite spin current J_s exists, because

$$\begin{cases} J_s = \dfrac{\hbar}{2}(J_\uparrow - J_\downarrow) \\ J_e = e(J_\uparrow + J_\downarrow), \end{cases} \tag{1}$$

where J_σ on the right-hand side is the electron current with spin index $\sigma \equiv \pm \equiv \uparrow, \downarrow$. All the theoretical and experimental works on pure spin-current generation mentioned above succeed in producing this kind of electron flow. However, many important properties of spin battery have not been studied up to now, including a careful discussion on the spin chemical potential that is established across a spin battery. Furthermore, to the best of our knowledge no one has investigated a ''circuit'' where a spin battery is connected to another quantum device. It is the purpose of this paper to report our theoretical investigations along this line.

We will consider the similarities and differences of various spin battery devices from spin-current transport point of view. We find that all theoretically proposed spin-battery devices can be sorted into three types: the symmetrical dipolar, the asymmetrical dipolar, and the unipolar spin battery. What is important to this work is not the specific designs of each type of spin battery, but their generic chemical-potential setup that drives a spin-current flow. We will then use this generic chemical-potential setup as the source of spin current which will be allowed to flow into a simple mesoscopic system, a quantum dot (QD). This way, we provide a general investigation on spin-current transport behavior under the driving of various spin batteries. We find similar results for symmetric and asymmetric dipolar spin batteries, but rather different results for the unipolar spin battery.

The rest of the paper is organized as follows. In the following section, we discuss the various existing spin-battery proposals and sort them into three types. We discuss the generic chemical-potential setup of the devices. In Sec. III, we use the generic chemical-potential setup as the spin-current source, and derive spin-current transport properties through a quantum dot using the Keldysh nonequilibrium Green's function formalism. Section IV presents the numerical results while the last section is a short summary.

II. GENERIC CHEMICAL-POTENTIAL SETUP OF SPIN BATTERY

To establish the driving force of a spin battery, we recall the makes of a traditional charge battery. A charge battery must have two outlets—the positive and negative poles. The electrochemical potential of each pole is the same for both spin-up and spin-down electrons: electron spin never enters the picture of charge battery. In an open circuit, the chemical potential μ of the two poles are different: the difference is the electromotive force, see Fig. 1(a). However, spin batteries are much different. First, a charge current must be conserved during a transport process while a spin current need not be[8,9] because of the existence of various spin-flip mechanisms which can change the value of spin current during its

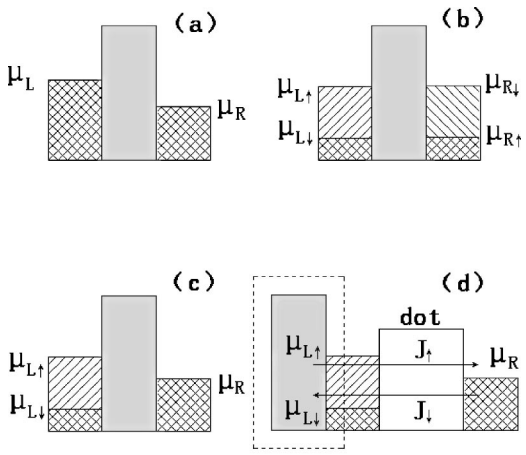

FIG. 1. Schematic plot of the position of chemical potential in the pole(s) for: (a) charge battery; (b) for symmetric dipolar spin battery; (c) for completely asymmetric dipolar spin battery; (d) for unipolar spin battery. In (d), the device in the dotted box is the unipolar spin battery and others are for external circuit.

flow. Typical spin flips are due to spin-orbital coupling, magnetic impurity scattering and so on. Therefore, a spin battery may work even if it has only one pole as shown in Refs. 8–10. Second, the charge degree of freedom is a scalar while spin degree of freedom is a vector, so that the spin-motive force is also a vector and the spin current is actually a tensor.[16] Third, in order to drive a spin current, the chemical potentials for spin-up and spin-down electrons are required to be different. These differences between a charge battery and a spin battery dictates different transport properties for their circuits.

According to the numbers of electrodes and the spin-dependent chemical potential distribution in the electrodes, we found that all existing spin batteries can be classified into three types. We call the first type symmetric dipolar spin battery: these devices have two poles labeled the left and the right pole. In an open circuit, their built-in mechanism can generate a spin-motive force between the two poles so that the spin-dependent chemical potential (i.e., $\mu_{\alpha\uparrow} \neq \mu_{\alpha\downarrow}, \alpha = L,R$) can be established in each pole. The device is symmetric because $\mu_{L\uparrow} = \mu_{R\downarrow}$ and $\mu_{R\uparrow} = \mu_{L\downarrow}$ [see Fig. 1(b)]. In this case, the splitting $|\mu_{\alpha\uparrow} - \mu_{\alpha\downarrow}|$ of the chemical potential in the left and the right pole are identical, and the poles are completely equivalent. For the existing spin-battery proposals, for example, the spin battery induced by spin Hall effect,[4] by spin-dependent photon assisted tunneling,[5] and others[6,7,13–15] are symmetric dipolar spin batteries.

The second type spin battery can be called asymmetric dipolar spin battery. This kind of devices also has two poles but only one of them has a splitting in chemical potential for spin-up and spin-down electrons, the other pole is spin independent [see Fig. 1(c)]. Notice that if this kind of spin battery is connected to an external circuit, it can still drive spin-up electrons to move in one direction while spin-down electrons moving in the opposite direction, i.e., a spin current is driven in the whole circuit. Belonging to this type are the recently proposed gate-controllable spin battery,[11] the quantum spin pump,[12] and others.

We call the third type spin battery ''unipolar'' because this kind of devices has only one pole. Because a spin current need not to be conserved, a single pole is actually enough for a spin battery to work. This kind of spin batteries often have a built-in spin flip mechanism: it draws in electrons with one spin orientation from its pole, then flips the spin inside the spin battery, followed by pushing out the electron with opposite spin orientation. In an open circuit, a spin-dependent chemical potential (i.e., $\mu_{L\uparrow} \neq \mu_{L\downarrow}$) is established in the spin-battery pole [see Fig. 1(d)]. If this kind of spin battery is connected to an external circuit which is not closed, it drives a spin current in that circuit. Because there are always some spin-flip mechanism in the external circuit, the spin current will gradually weaken along its way and finally disappear. Because of the absence of a closed loop circuit, the charge current must be zero in steady state. This means that the spin-up electrons flowing out and the spin-down electrons flowing into the battery must be equal [see Fig. 1(d)]. Some proposed spin batteries where the built-in spin flip mechanism is a ferromagnetic resonance or a rotating external magnetic field[8–10] are unipolar type.

It is interesting to connect these three types of spin batteries to a simple mesoscopic device, a QD, and investigate spin-current transport through the QD under the driving force of the spin batteries. In the last two decades, charge transport through a QD driven by a charge battery has been investigated extensively.[17] A series of Coulomb oscillation peaks with almost equal interval emerge in the curves of linear conductance versus gate voltage.[18–20] This is the Coulomb blockade phenomenon where between two successive Coulomb peaks, the conductance is very small. What happens for spin-current transport through a QD driven by a spin battery? What are the differences in spin-current transport driven by the different kinds of spin batteries? These questions will be investigated in the following sections.

III. SPIN CURRENT DRIVEN BY A SPIN BATTERY: MODEL AND ANALYSIS

We now present the detailed theoretical investigation of a QD connected to a spin battery. As mentioned above, we do not discuss the detailed physical mechanisms of various spin batteries which can be found in the original literature,[4–15] but we use the generic chemical potential setups of Fig. 1 to drive a spin current through a QD. The QD is described in the following Anderson Hamiltonian:

$$H = H_l + H_c + H_t, \tag{2}$$

where

$$H_l = \sum_{k\sigma} \varepsilon_k^L a_{k\sigma}^\dagger a_{k\sigma} + \sum_{k\sigma} \varepsilon_k^R b_{k\sigma}^\dagger b_{k\sigma}, \tag{3}$$

$$H_c = \sum_{\sigma} \varepsilon_{c\sigma} c_\sigma^\dagger c_\sigma + E_c c_\uparrow^\dagger c_\uparrow c_\downarrow^\dagger c_\downarrow, \tag{4}$$

$$H_t = \sum_{k\sigma} L_k a_{k\sigma}^\dagger c_\sigma + \sum_{k\sigma} R_k b_{k\sigma}^\dagger c_\sigma + \text{H.c.} \tag{5}$$

Here H_l describes the noninteracting left and right leads, $a^\dagger_{k\sigma}(a_{k\sigma})$ and $b^\dagger_{k\sigma}(b_{k\sigma})$ are the creation (annihilation) operators for electrons in the left and right lead, respectively. k is the electron momentum quantum number and σ is the spin index. H_c models the QD with one energy level having spin index σ. The intradot Coulomb interaction is given by the interaction energy E_c. The single-particle energy level of the QD $\varepsilon_{c\sigma}$ is doubly degenerate in the absence of an external magnetic field B, but it is $\varepsilon_{c\sigma}=\varepsilon_c+\sigma B/2$ due to the Zeeman splitting when $B\neq 0$. H_t is the Hamiltonian for tunneling between the leads and the QD, where L_k, R_k are the hopping matrix elements.

It is worthy to note that the Hamiltonian Eqs. (2)–(5) appear to be identical to that of a QD coupled to two leads under a charge bias voltage.[18,21] While this is true for the QD, the transport physics is qualitatively different when we couple the QD to a spin battery so that the electron distribution in the leads is different from the usual charge transport situations. For QD coupled to a charge battery, electrons in each lead are at local equilibrium and its chemical potential is spin independent. For our present system of a QD coupled to a spin battery, the chemical potential in each lead is spin dependent, as shown in Fig. 1. Then, for the unipolar spin battery we connect our QD to the spin battery as shown in Fig. 1(d): the QD still has two leads but we assume that spin flip is strong in the right lead so that electron distribution is always in local equilibrium inside it. This way, a spin current flowing out from the unipolar spin battery passes through the QD, and disappears in the right lead [see Fig. 1(d)].

Our theoretical analysis is based on the Keldysh nonequilibrium Green's function formalism. The spin current J_s and the charge current J_e is defined in Eq. (1) above, where the electron current J_σ for spin component σ can be calculated by the following formula:[21,22]

$$J_\sigma=\frac{1}{\hbar}\int d\varepsilon[f^L_\sigma(\varepsilon)-f^R_\sigma(\varepsilon)]\frac{\Gamma^L\Gamma^R}{\Gamma^L+\Gamma^R}\left[-\frac{1}{\pi}\mathrm{Im}\,G^r_{\sigma\sigma}(\varepsilon)\right], \tag{6}$$

where $f^\alpha_\sigma(\varepsilon)=\{\exp[(\varepsilon-\mu_{\alpha\sigma})/k_BT]+1\}^{-1}$ is the Fermi-Dirac distribution function of electrons with spin index σ in the α lead. $\Gamma^L=\Sigma_k 2\pi|L_k|^2\delta(\varepsilon-\varepsilon^L_k)$ and $\Gamma^R=\Sigma_k 2\pi|R_k|^2\delta(\varepsilon-\varepsilon^R_k)$ are the line-width functions which also describe the coupling strength between the leads and the QD. The retarded Green's function $G^r_{\sigma\sigma}(\varepsilon)$ is the Fourier transform of $G^r_{\sigma\sigma}(t)$, which is defined as $G^r_{\sigma\sigma}(t)=-i\theta(t)\langle\{c_\sigma(t), c^\dagger_\sigma(0)\}\rangle$.

Using the standard equation of motion technique, for the Hamiltonian (2)–(5), the retarded Green's function $G^r_{\sigma\sigma}(\varepsilon)$ can be solved:[11,21,23]

$$G^r_{\sigma\sigma}(\varepsilon)=\frac{\varepsilon-\varepsilon_{c\sigma}-E_c(1-n^-_\sigma)}{(\varepsilon-\varepsilon_{c\sigma})(\varepsilon-\varepsilon_{c\sigma}-E_c)-\Sigma^r_\sigma[\varepsilon-\varepsilon_{c\sigma}-E_c(1-n^-_\sigma)]} \tag{7}$$

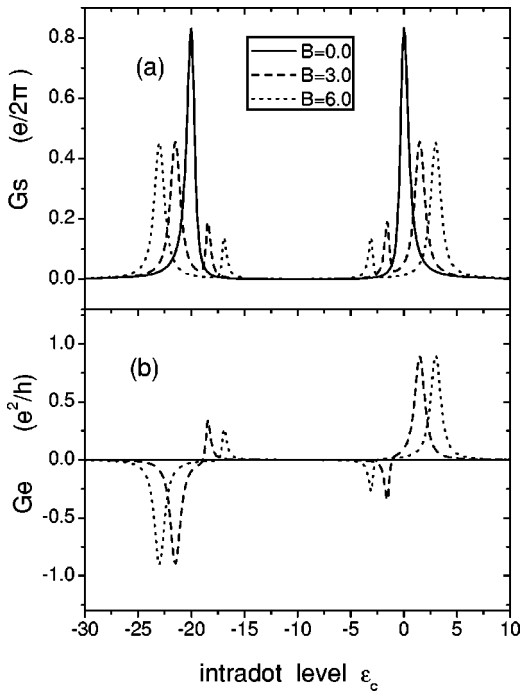

FIG. 2. The spin conductance G_s (a) and the charge conductance G_e (b) vs ε_c under the dipole spin battery for different magnetic field B, where $\mu_{\alpha\sigma}=0$ and $E_c=20$.

where $\Sigma^r=-i/2[\Gamma_L+\Gamma_R]$ is the retarded self energy due to tunneling coupling, and n^-_σ is the intradot electron occupation number at state $\bar{\sigma}$. Here n_σ needs to be calculated self consistently and its self-consistent equation is $n_\sigma=\int d\varepsilon/2\pi\,\mathrm{Im}\,G^<_{\sigma\sigma}(\varepsilon)$, where $G^<_{\sigma\sigma}(\varepsilon)$ is the standard lesser Green's function. As usual, $G^r_{\sigma\sigma}(\varepsilon)$ has two resonances: one at energy $\varepsilon_{c\sigma}$ for which the associated state $\varepsilon_{c\sigma}$ is empty; the other is at $\varepsilon_{c\sigma}+E_c$ for which the associated state $\varepsilon_{c\sigma}$ is occupied.[11]

Next, we solve the Green's function $G^<_{\sigma\sigma}(\varepsilon)$ which is needed in the self-consistent computation of the occupation number. For interacting systems, $G^<_{\sigma\sigma}(\varepsilon)$ cannot be obtained from the equation of motion without introducing additional assumptions.[24] Recently, we found that quantity $\int d\varepsilon G^<_{\sigma\sigma}(\varepsilon)$, which is actually what we need here, can be solved exactly.[25] This allows us to bypass any approximation involved in computing $G^<_{\sigma\sigma}(\varepsilon)$. Following the approach of Ref. 25, $\int d\varepsilon G^<_{\sigma\sigma}(\varepsilon)$ is easily obtained as:

$$\int d\varepsilon G^<_{\sigma\sigma}(\varepsilon)=\int d\varepsilon\frac{f^L_\sigma\Gamma^L+f^R_\sigma\Gamma^R}{\Gamma^L+\Gamma^R}[G^a_{\sigma\sigma}-G^r_{\sigma\sigma}]. \tag{8}$$

This completes the analytical derivation.

In the numerical calculations, we set $\Gamma^L=\Gamma^R=\Gamma/2$, and set $\Gamma=1$ as the energy unit for simplification. We fix the intradot Coulomb interaction energy E_c and the temperature scale k_BT to be 20Γ and 0.1Γ, respectively. Compared with typical experimental parameters this choice is reasonable: in a QD experiment, the Coulomb interaction energy E_c can reach 2.0 meV with a coupling constant Γ which is 20 times

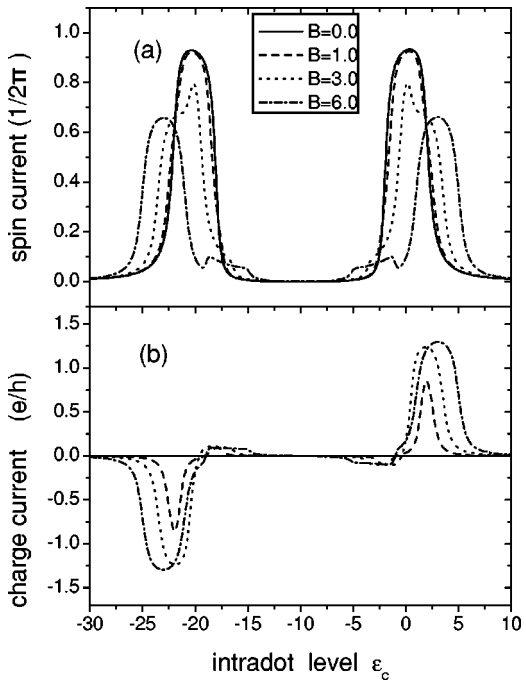

FIG. 3. The spin current J_s (a) and the charge current J_e (b) vs ε_c driven by a symmetric dipolar spin battery for different magnetic field B, where $\mu_{L\uparrow}=\mu_{R\downarrow}=-\mu_{L\downarrow}=-\mu_{R\uparrow}=2$ and $E_c=20$.

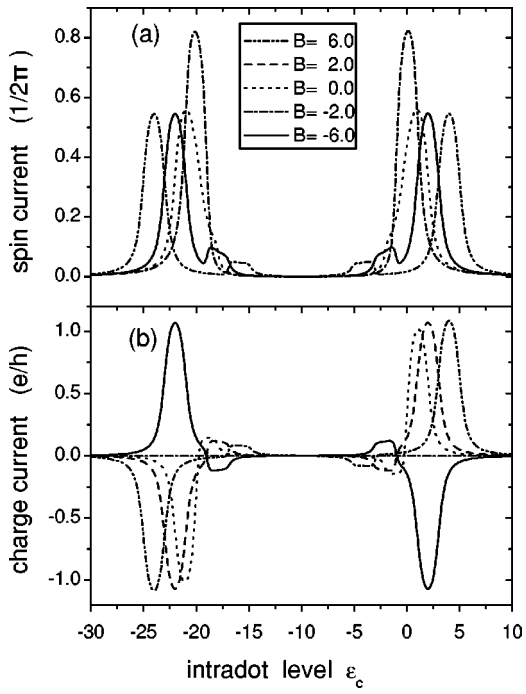

FIG. 4. The spin current J_s (a) and the charge current J_e (b) vs ε_c under a completely asymmetric dipolar spin battery for different magnetic field B, where $\mu_{L\uparrow}=-\mu_{L\downarrow}=2$, $\mu_{R\sigma}=0$, and $E_c=20$. Notice that the curves for $B=-6.0$ in (a) completely overlap with the curves for $B=2.0$ so that the latter cannot be seen in the figure.

smaller than E_c, and in the low temperature limit $T=100$ mk, i.e., $k_BT\approx0.01$ meV is experimentally realizable.

IV. NUMERICAL RESULTS

We first consider the situation where our QD is coupled to a symmetric or an asymmetric dipolar spin battery, where the electrochemical potentials are shown in Figs. 1(b) and 1(c). Figure 2 plots the linear spin conductance $G_s=dJ_s/dV$ ($V\equiv V_{L\uparrow}-V_{R\uparrow}=V_{R\downarrow}-V_{L\downarrow}$) and the linear charge conductance $G_e=dJ_e/dV$ versus the intradot level ε_c, which can be controlled by a gate voltage experimentally. With or without an external magnetic field, the linear conductances G_s and G_e under the symmetric dipolar battery are completely the same as the one under an asymmetric dipolar battery. Without an external magnetic field, linear transport of electron density (or electron number) can be described by the quantity $G_\sigma\equiv dJ_\sigma/dV$ for spin σ. A double peak structure at $\varepsilon_c=0$ and $\varepsilon_c=-E_c$ is seen for both dipolar spin batteries. Since $G_\uparrow=-G_\downarrow$, the charge conductance $G_e=0$ exactly. On the other hand, the spin conductance G_s is very large and has two peaks [solid line in Fig. 2(a)]. In this case, a pure spin current flows in the system. When there is a magnetic field, each peak in the spin conductance will split into two peaks due to the Zeeman splitting, and one of these two peaks is strongly suppressed because of Coulomb blockade effect. Meanwhile, the charge conductance emerges and it also has two large peaks and two small peaks [see Figs. 2(a) and 2(b)]. Notice that the spin conductance is always positive, but the charge conductance can be positive or negative depending on the value of the intradot level ε_c. In fact, for nonzero magnetic field, the dipolar spin battery drives a charge polarized spin current, in which spin-up electrons and spin-down electrons move in opposite directions but their values are not equal.

Next, we investigate the case of finite spin-motive force. Figs. 3 and 4 show results for the symmetric dipolar spin battery and the asymmetric dipolar spin battery, respectively. The spin current and the charge current have the following features.

(i) The spin current is always positive but charge current can be positive or negative.

(ii) There are two peaks with an interval of E_c, because of the Coulomb interaction.

(iii) For the symmetric dipolar spin battery, the charge current is exactly zero in the absence of external magnetic field B. With an increasing B, the charge current increases rapidly. The spin current, on the other hand, always has a large peak value regardless of B. If the direction of the magnetic field changes, the charge current and the spin current have the symmetry property $J_s(-B)=J_s(B)$ and $J_e(-B)=J_e(B)$.

(iv) For the completely asymmetric dipolar spin battery, although the charge current J_e is not zero at $B=0$, J_e is still exactly zero at $B=\mu_{L\downarrow}=-2$ for any ε_c. The spin current and charge current also have the following symmetry: $J_s[-(B-\mu_{L\downarrow})]=J_s(B-\mu_{L\downarrow})$ and $J_e[-(B-\mu_{L\downarrow})]=-J_e(B-\mu_{L\downarrow})$. These behaviors are very similar to that of symmetric dipolar spin battery.

Finally, we investigate transport behavior under the driving force of an unipolar spin battery. Because this spin battery has only one pole, the charge current must be zero in the steady state, i.e., $J_\uparrow=-J_\downarrow$. Let us consider an unipolar spin battery with a spin-dependent chemical potential $\mu_{L\sigma}$ con-

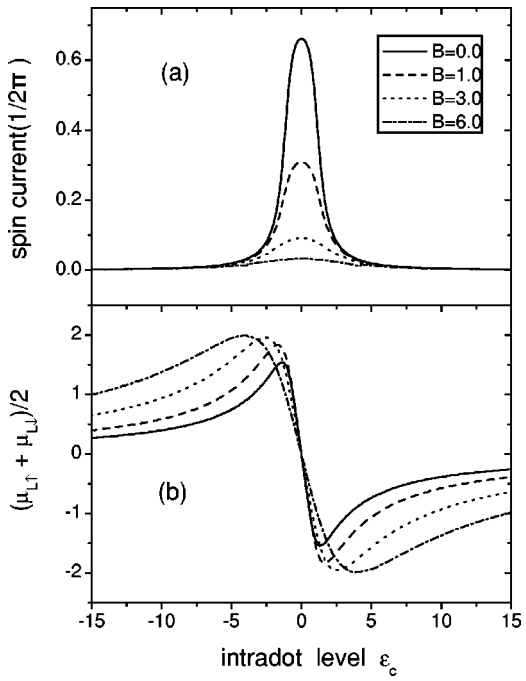

FIG. 5. The spin current J_s (a) and the position of chemical potential $(\mu_{L\uparrow}+\mu_{L\downarrow})/2$ (b) vs ε_c under the unipolar spin battery for different B, where $\mu_{R\sigma}=0$ and $E_c=0$.

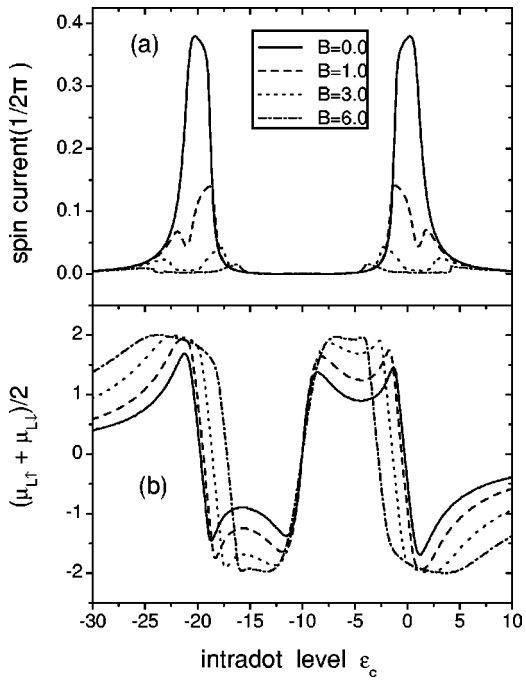

FIG. 6. The spin current J_s (a) and the position of che mical potential $(\mu_{L\uparrow}+\mu_{L\downarrow})/2$ (b) vs ε_c under the unipolar spin battery for different B, where $\mu_{R\sigma}=0$ and $E_c=20$.

nected to a QD device [see Fig. 1(d)]. Just after the QD is connected to the spin battery, $J_\uparrow$ is generally not equal to $-J_\downarrow$ and a charge current J_e is not zero in the transient time. Then the electron number in the left lead, i.e., in the region of the dotted box in Fig. 1(d), will deplete or accumulate so that the chemical potential $\mu_{L\sigma}$ is changed.[26,27] For the proposed unipolar spin-battery device in Refs. 8–10, the difference $\mu_{L\uparrow}-\mu_{L\downarrow}$ in an open circuit depends on the frequency of the ferromagnetic resonance or a rotating external magnetic field. Therefore, in our numerical calculations, we assume that the difference $\mu_{L\uparrow}-\mu_{L\downarrow}$ is fixed. After some relaxation time, the system reaches a steady state for which $J_\uparrow=-J_\downarrow$,[26,27] where the spin current and the position of chemical potential versus the intradot level are shown in Fig. 5 (without intradot interaction, $E_c=0$) and Fig. 6 (with the interaction).[26,27] At $B=0$, the spin current has one or two peaks for the case of $E_c=0$ or $E_c\neq 0$. Then, as B is increased, the spin current is strongly suppressed. For large values of B, the spin current is very small for any ε_c regardless of the intradot interaction. These behaviors are very different from the dipolar spin battery, where the spin current is always large at resonance whether $B=0$ or not. The reason that a finite B suppresses spin current is because for an unipolar spin battery $J_\uparrow$ must equal to $-J_\downarrow$, therefore to obtain a large spin current one requires two states $\varepsilon_{c\uparrow}$ and $\varepsilon_{c\downarrow}$ inside the energy range (the bias window) of the integration of Eq. (6). This energy range is from $\mu_{R\uparrow}$ to $\mu_{L\uparrow}$ and from $\mu_{L\downarrow}$ to $\mu_{R\downarrow}$ for the two spin polarizations, respectively. But this condition is not generally satisfied when $B\neq 0$ which shifts the levels apart. For the dipolar spin battery, on the other hand, in order to obtain a large spin current it only requires one of the two states $\varepsilon_{c\uparrow}$ or $\varepsilon_{c\downarrow}$ to be inside the bias window, a condition that is easily satisfied. Finally, the position of the steady state chemical potential, $(\mu_{L\uparrow}+\mu_{L\downarrow})/2$, versus the intradot level ε_c is shown in Figs. 5(b) and 6(b). It shows that $(\mu_{L\uparrow}+\mu_{L\downarrow})/2$ may be higher or lower than $\mu_R=0$. This means that electrons in the left lead can be depleted or accumulated depending on the position of the intradot level ε_c. At the peak position of the spin current, $(\mu_{L\uparrow}+\mu_{L\downarrow})/2$ changes its sign.

V. SUMMARY

By comparing all the recently proposed spin-battery device models, we found that they can be classified into three types: the symmetric dipolar, the asymmetric dipolar, and the unipolar spin batteries. Despite the very different physical mechanisms inside each spin-battery device, the generic chemical potential setup can be summarized in Fig. 1. When the three different types of spin battery is connected to a QD device, spin-current flow is induced. We found that the both dipolar spin batteries give similar transport results, while it is very different for the unipolar spin battery. For the latter, the spin-current is drastically suppressed in the presence of a magnetic field.

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[23] Here we have taken the same decoupling approximation as those of Refs. 11,21. In this approximation, the intradot energy level renormalization has been neglected. Because our system is in the Coulomb blockade regime (i.e., temperature T is higher than the Kondo temperature T_K), the level renormalization is very small and our approximation is reasonable. If the system is in the Kondo regime ($T<T_K$), one needs to take a higher-order decoupling approximation. For the latter, we guess that a nontrivial energy level renormalization and an anomalous Kondo behavior will emerge when $\mu_{\alpha\uparrow}\neq\mu_{\alpha\downarrow}$, which is similar to some recent analysis on spin polarized transport in the Kondo regime. See, for example, N. Sergueev, Q.-f. Sun, H. Guo, B.G. Wang, and J. Wang, Phys. Rev. B **65**, 165303 (2002); J. Martinek, Y. Utsumi, H. Imamura, J. Barnas, S. Maekawa, J. Konig, and G. Schon, Phys. Rev. Lett. **91**, 127203 (2003); M.-S. Choi, D. Sanchez, and R. Lopez, cond-mat/0305107 (unpublished).
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[26] In our numerical calculations, we use the steady states condition $J_\uparrow=-J_\downarrow$, and self-consistently calculate the position of chemical potential, $(\mu_{L\uparrow}+\mu_{L\downarrow})/2$, at fixed $\mu_{L\uparrow}-\mu_{L\downarrow}$. Note when $(\mu_{L\uparrow}+\mu_{L\downarrow})/2$ is changed, the electron number in the left lead will have a depletion or an accumulation. In principle, this depleted or accumulated electron density will affect the position of $\mu_{L\sigma}$, $\mu_{R\sigma}$, and the intradot level ϵ_c; i.e., the distance of $\mu_{L\sigma}-\epsilon_c$ and $\mu_{R\sigma}-\epsilon_c$. This effect has been investigated previously Ref. 27. In our calculation, we assume that the depleted or accumulated electron density only affect $\mu_{L\sigma}-\epsilon_c$ but not $\mu_{R\sigma}-\epsilon_c$. This assumption should be reasonable because of two reasons: (i) The depleted or accumulated electron density in the left lead is near the left barrier, hence its effect is larger for $\mu_{L\sigma}-\epsilon_c$; (ii) In an experiment, the intradot level ϵ_c is generally controlled by a gate voltage, and $\mu_{R\sigma}$ is the chemical potential of the right bulk reservoir. Therefore both ϵ_c and $\mu_{R\sigma}$ are fixed by external paraemters (gate and right reservoir). Numerically, we iteratively adjust the parameter $\mu_{L\sigma}-\epsilon_c$ until $J_\uparrow=-J_\downarrow$ is satisfied, this way it is not necessary to calculate the depleted or accumulated electron number. Of course, one can also calculate this electron number, for example using the technique of Ref. 27.
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