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Detecting Spin Bias with Circularly Polarized Light *

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We theoretically study the spin transport through a two-terminal quantum dot device under the influence of a symmetric spin bias and circularly polarized light. It is found that the combination of the circularly polarized light and the applied spin bias can result in a net charge current. The resultant charge current is large enough to be measured when properly choosing the system parameters. The resultant charge current can be used to deduce the spin bias due to the fact that there exists a simple linear relation between them. When the external circuit is open, a charge bias instead of a charge current can be induced, which is also measurable by present technologies. These findings indicate a new approach to detect the spin bias by using circularly polarized light.

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Over the past few decades, spintronics has attracted numerous attention from both theoretical and experimental communities.[1,2] One of the key ingredients for driving and controlling functional spintronics devices is the effective generation and detection of spin current in nanostructures. For generating a spin current, many methods have been proposed, which include not only the conventional ones such as spin filtering[3−5] and spin pumping[6−9] but also the novel ones such as piezo-spintronic effect[10] and spin Seebeck effect.[11−15] There are also some schemes proposed to detect the spin current. Almost all the detection schemes are based on the physical consequences induced by the spin current in various specific systems, which can be measured in experiments. For example, the spin Hall currents in some spin-orbit coupled systems have been detected by spin accumulation at the sample boundaries.[16,17] In addition, the spin Hall current can also be electrically detected by measuring the charge bias induced by the inverse spin Hall effect.[18−20] However, compared with the abundance of the studies on the generation of the spin current, the studies on the detection schemes are yet sparse in literature.

In this Letter, we propose another way to detect the spin bias, which is usually the driving source of a pure spin current, with the employment of circularly polarized light. Based on the nonequilibrium Green function method, we investigate the spin-dependent electronic transport through a two-terminal quantum dot (QD) device irradiated by a circularly polarized light and biased by a symmetric spin bias. Our results show that a charge current or charge bias can emerge in such a system and a simple one-to-one correspondence exists between the spin bias and the induce charge current or charge bias. Therefore, one can detect the spin bias by measuring the induced charge signals.

As depicted in Fig. 1, the system under consideration is composed of a QD exposure to a circularly polarized light and two normal leads. There is no temperature gradient and charge bias in the studied system. The system is only biased by a symmetric spin bias $V_{\rm s}$, which makes in the leads the chemical potentials spin-dependent with $\mu_{{\rm L}\sigma} = \mu_{{\rm R}\bar{\sigma}} = E_{\rm F} + \frac{\sigma e V_{\rm s}}{2}$ ($\sigma = \uparrow, \downarrow$ or $\pm$, $\bar{\sigma} = -\sigma$). The circularly polarized light applied here plays the similar role as a rotating magnetic field plays in Ref. [6], thereby providing a spin-flip mechanism that allows electrons to tunnel between the QD and the leads with a photon-assisted spin-flip process.[21] Without the spin bias, the chemical potentials in the leads are independent of electron spin, then the probability of the photon-assisted tunneling for electrons with up-spin is equal to that for electrons with down-spin, thus the circularly polarized light alone can only pump a pure spin current in which the two spin component currents satisfy $I_\uparrow = -I_\downarrow$. However, when the spin bias is turned on and thus the chemical potentials become spin-dependent, the tunneling probabilities of electron will become spin-dependent too, then a breakdown of the balance between the two spin component currents will take place, i.e., $|I_\uparrow| \neq |I_\downarrow|$. As a result, a nonzero charge current $I_{\rm c} = I_\uparrow + I_\downarrow$ forms in the system though the two spin component currents still have opposite signs.

In the following we demonstrate the feasibility of the detection of the spin bias via the induced charge current through detailed calculations. For simplicity, we only consider a noninteracting QD with a single energy level. Thus the present system can be described by the following Hamiltonian

$$H = \sum_{\alpha={\rm L,R}} H_\alpha + H_{\rm d} + H_{\rm T} + H'(t), \tag{1}$$

$$H_\alpha = \sum_{k\sigma} \epsilon_{k\alpha} C^\dagger_{k\alpha\sigma} C_{k\alpha\sigma}, \tag{2}$$

$$H_d = \sum_\sigma \varepsilon_d d^\dagger_\sigma d_\sigma, \tag{3}$$

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$$H_T = \sum_{k\alpha\sigma}(t_{k\alpha}C^{\dagger}_{k\alpha\sigma}d_\sigma + t^{*}_{k\alpha}d^{\dagger}_\sigma C_{k\alpha\sigma}), \quad (4)$$

$$H'(t) = \gamma d^{\dagger}_\uparrow d_\downarrow e^{-i\omega t} + \gamma d^{\dagger}_\downarrow d_\uparrow e^{i\omega t}, \quad (5)$$

where $C^{\dagger}_{k\alpha\sigma}$ ($C_{k\alpha\sigma}$) is the creation (annihilation) operator of electrons with momentum k and σ-spin in the α ($\alpha = \mathrm{L}, \mathrm{R}$) lead, $d^{\dagger}_\sigma$ (d_σ) is the creation (annihilation) operator of electrons with σ-spin in the QD, $\epsilon_{k\alpha}$ is the single-electron energy for electrons with the momentum k in the α lead, ε_d is the single dot energy level, $t_{k\alpha}$ is the tunneling coefficient for electron tunneling between the α lead and the QD, and γ and ω are the amplitude and frequency of the applied circularly polarized light, respectively.

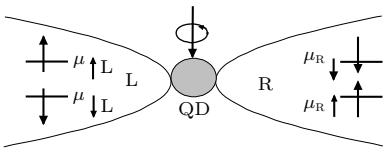

Fig. 1. A schematic representation of a two-terminal QD device, which consists of a QD subjected to a circularly polarized light and two normal conducting leads biased by a symmetric spin bias.

Following the similar procedures as adopted in Ref. [7], the time-averaged spin component current in the left lead can be expressed as

$$I_\sigma = \frac{1}{2N\tau}\frac{2e}{h}\mathrm{Re}\int dE[G^{\mathrm{r}}(E,E)\Sigma^{<}_{\mathrm{L}}(E) + G^{<}(E,E)\Sigma^{a}_{\mathrm{L}}(E)]_{\sigma\sigma}, \quad (6)$$

where $\tau = 2\pi/\omega$ is the varying-period of the circularly polarized light and $N \to \infty$, $G^{\mathrm{r(a)}}$ is the delayed (advanced) Green function of the QD, $\Sigma^{\mathrm{a}}_\alpha$ is the advanced self-energy contributed by the α lead and in the wide-band approximation[22] its matrix elements are $\frac{i}{2}\Gamma_\alpha\delta_{\sigma\sigma'}$ with Γ_α denoting the line width function of the α lead, $\Sigma^{<}_\alpha$ is the lesser self-energy due to the α lead, whose matrix elements are $i\Gamma_\alpha f_{\alpha\sigma}(E)\delta_{\sigma\sigma'}$ with $f_{\alpha\sigma}(E) = \frac{1}{e^{(E-\mu_{\alpha\sigma})/k_{\mathrm{B}}T}+1}$ being the spin-dependent Fermi distribution function of the α lead. According to the Dyson equation, the delayed dot Green function G^{r} can be evaluated as

$$G^{\mathrm{r}}(t,t') = G^{\mathrm{r}0}(t-t') + \int dt_1 G^{\mathrm{r}}(t,t_1)H'(t_1)G^{\mathrm{r}0}(t_1-t'). \quad (7)$$

Performing a double-time Fourier transform on the two sides of the above equation, we can arrive at

$$G^{\mathrm{r}}(E,E') = 2\pi G^{\mathrm{r}0}(E)\delta(E-E') + \int \frac{dE_1}{2\pi}G^{\mathrm{r}}(E,E'+E_1)H'(E_1)G^{\mathrm{r}0}(E'), \quad (8)$$

where $G^{\mathrm{r}0}(E)$ is the delayed dot Green function when the circularly polarized is absent, which can be easily expressed as $G^{\mathrm{r}0}_{\sigma\sigma'}(E) = (E - \varepsilon_{\mathrm{d}} + i\frac{\Gamma_{\mathrm{L}}+\Gamma_{\mathrm{R}}}{2})^{-1}\delta_{\sigma\sigma'}$, and in spin space $H'(E)$ is given by $H'_{\sigma,\bar{\sigma}}(E) = 2\pi\gamma\delta(E-\sigma\omega)$, which can be obtained from the Fourier transform of $H'(t)$. Thanks to the simplicity of $G^{\mathrm{r}0}(E)$ and $H'(E)$, the Green function $G^{\mathrm{r}}(E,E')$ can be exactly worked out from Eq. (8) as[6]

$$G^{\mathrm{r}}_{\sigma\sigma}(E,E') = \frac{2\pi\delta(E-E')G^{0\mathrm{r}}_{\sigma\sigma}(E)}{1-\gamma^2 G^{0\mathrm{r}}_{\sigma\sigma}(E)G^{0\mathrm{r}}_{\bar{\sigma}\bar{\sigma}}(E+\bar{\sigma}\omega)}, \quad (9)$$

$$G^{\mathrm{r}}_{\sigma\bar{\sigma}}(E,E') = 2\pi\delta(E-E'+\bar{\sigma}\omega) \cdot \frac{\gamma G^{0\mathrm{r}}_{\sigma\sigma}(E)G^{0\mathrm{r}}_{\bar{\sigma}\bar{\sigma}}(E+\bar{\sigma}\omega)}{1-\gamma^2 G^{0\mathrm{r}}_{\sigma\sigma}(E)G^{0\mathrm{r}}_{\bar{\sigma}\bar{\sigma}}(E+\bar{\sigma}\omega)}. \quad (10)$$

With the solved G^{r}, the Green function $G^{<}(E,E')$ can be calculated by the Keldysh equation

$$G^{<}(E,E') = \int \frac{dE_1}{2\pi}G^{\mathrm{r}}(E,E_1)\Sigma^{<}(E_1)G^{\mathrm{a}}(E_1,E'), \quad (11)$$

with $\Sigma^{<} = \Sigma^{<}_{\mathrm{L}} + \Sigma^{<}_{\mathrm{R}}$. Using these equations, we can straightforwardly obtain the spin component current in Eq. (6) as

$$I_\sigma = I_{1\sigma} + I_{2\sigma} + I_{3\sigma}, \quad (12)$$

with

$$I_{1\sigma} = \frac{e\Gamma_{\mathrm{L}}\Gamma_{\mathrm{R}}}{h}\int dE\{|G^{\mathrm{r}0}_{\sigma\sigma}(E)|^2[f_{\mathrm{L}\sigma}(E) - f_{\mathrm{R}\sigma}(E)]\} /\{|1-\gamma^2 G^{0\mathrm{r}}_{\sigma\sigma}(E)G^{0\mathrm{r}}_{\bar{\sigma}\bar{\sigma}}(E+\bar{\sigma}\omega)|^2\}, \quad (13)$$

$$I_{2\sigma} = \frac{e\gamma^2{\Gamma_{\mathrm{L}}}^2}{h}\int dE\{|G^{\mathrm{r}0}_{\sigma\sigma}(E)|^2|G^{\mathrm{r}0}_{\bar{\sigma}\bar{\sigma}}(E + \bar{\sigma}\omega)|^2[f_{\mathrm{L}\sigma}(E) - f_{\mathrm{L}\bar{\sigma}}(E+\bar{\sigma}\omega)]\}/\{|1 - \gamma^2 G^{0\mathrm{r}}_{\sigma\sigma}(E)G^{0\mathrm{r}}_{\bar{\sigma}\bar{\sigma}}(E+\bar{\sigma}\omega)|^2\}, \quad (14)$$

$$I_{3\sigma} = \frac{e\gamma^2\Gamma_{\mathrm{L}}\Gamma_{\mathrm{R}}}{h}\int dE\{|G^{\mathrm{r}0}_{\sigma\sigma}(E)|^2|G^{\mathrm{r}0}_{\bar{\sigma}\bar{\sigma}}(E + \bar{\sigma}\omega)|^2[f_{\mathrm{L}\sigma}(E) - f_{\mathrm{R}\bar{\sigma}}(E+\bar{\sigma}\omega)]\}/\{|1 - \gamma^2 G^{0\mathrm{r}}_{\sigma\sigma}(E)G^{0\mathrm{r}}_{\bar{\sigma}\bar{\sigma}}(E+\bar{\sigma}\omega)|^2\}. \quad (15)$$

Then the spin and charge currents flowing through the system can be described as $I_{\mathrm{s}} = I_\uparrow - I_\downarrow$ and $I_{\mathrm{c}} = I_\uparrow + I_\downarrow$. Here the spin-dependent electronic current $I_{1\sigma}$ is driven by the applied spin bias and the circularly polarized light can only modify its magnitude, while the spin-dependent electronic current $I_{2\sigma}(I_{3\sigma})$ results from the process that electrons firstly tunnel from the left lead into the QD and then tunnel to the left (right) lead with their spin flipped by the circularly polarized light. Obviously if the system is only under the influence of the symmetric spin bias, $I_\sigma = I_{1\sigma}$ and Eq. (13) can be reduced to

$$I_{1\sigma} = \frac{e\Gamma_{\mathrm{L}}\Gamma_{\mathrm{R}}}{h}\int dE\frac{[f_{\mathrm{L}\sigma}(E) - f_{\mathrm{R}\sigma}(E)]}{(E-\varepsilon_{\mathrm{d}})^2 + (\Gamma_{\mathrm{L}}+\Gamma_{\mathrm{R}})^2/4}. \quad (16)$$

Thus $I_{1\uparrow} = -I_{1\downarrow}(I_\uparrow = -I_\downarrow)$ and only a pure spin current without any charge current can be formed in the system. On the other hand, if the circularly polarized light is applied to the system alone, i.e., $f_{\mathrm{L}\sigma} = f_{\mathrm{L}\bar{\sigma}} = f_{\mathrm{R}\sigma} = f_{\mathrm{R}\bar{\sigma}}$, the probability of the photon-assisted tunneling of electrons is independent of the electron spin, then we can readily reproduce the result obtained in Ref. [6] that $I_\uparrow = -I_\downarrow$ and only a

pure spin current can emerge in the system which is pumped by the circularly polarized light. However, when both the spin bias and circularly polarized light are present, due to the chemical potentials (the Fermi distribution functions) in the leads becoming spin-dependent, the photon-assisted tunneling probability of electrons becomes spin-dependent either, thereby leading to $|I_\uparrow| \neq |I_\downarrow|$ and the formation of a nonzero charge current. Therefore, the spin bias or the circularly polarized light alone can only generate a pure spin current, while their combination can generate a net charge current which is spin-polarized in general. As we will discuss in the following, the dependence of the induced charge current on the spin bias can allow one to deduce the spin bias from the induced charge current.

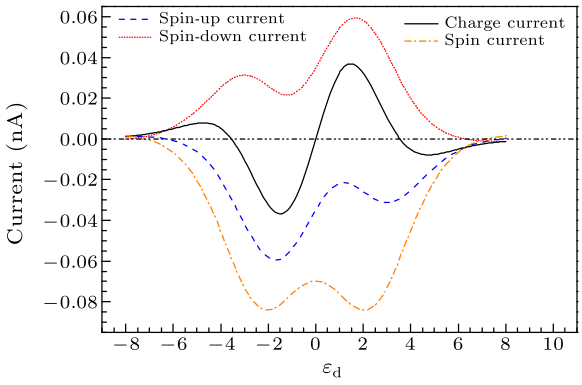

Fig. 2. The tunneling spin-up current, spin-down current, charge current and spin current versus ε_d for $\Gamma_L = \Gamma_R = 0.5$, $\omega = 2.0$ and $V_s = 10\,\mu V$.

In the following we set the Fermi energy as $E_F = 0$, the amplitude of the circularly polarized light as $\gamma = 2.0$ and the temperature as $k_B T = 1.0$ with the energy unit being 10 μeV. Firstly, we illustrate the tunneling currents as a function of the dot energy level in Fig. 2. As shown in Fig. 2, when the spin bias and the circularly polarized light are applied to the studied system simultaneously, the absolute value of the spin-up current is generally different from that of the spin-down current though they have opposite signs. As discussed above, this difference arises from the spin-dependent tunneling probabilities of electrons induced by the spin-dependent chemical potentials in the leads and consequently results in a nonzero charge current. Hence, in addition to a spin current, a net charge current also exists in the studied system for most choices of the dot energy ε_d. The induced charge current is centrally symmetric with respect to $\varepsilon_d = 0$, while the spin current is mirror symmetric with respect to it. This is due to the fact that the coexistence of the spin bias and the circularly polarized light does not destroy the particle-hole symmetry that the spin current caused by spin pumping or a spin bias possesses, and thus the spin-up and spin-down currents always obey the relation $I_\uparrow(-\varepsilon_d) = -I_\downarrow(\varepsilon_d)$. More importantly, as the dot energy ε_d varies, the induced charge current can reach the order of 0.01 nA, which can be measured by the present technology.[23]

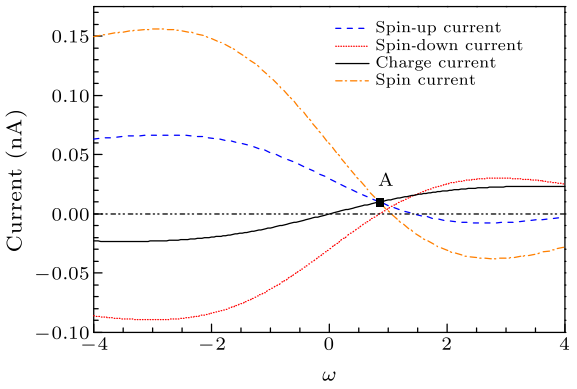

Fig. 3. The tunneling spin-up current, spin-down current, charge current and spin current versus ω for $\Gamma_L = \Gamma_R = 0.2$, $\varepsilon_d = 1.5$ and $V_s = 10\,\mu V$.

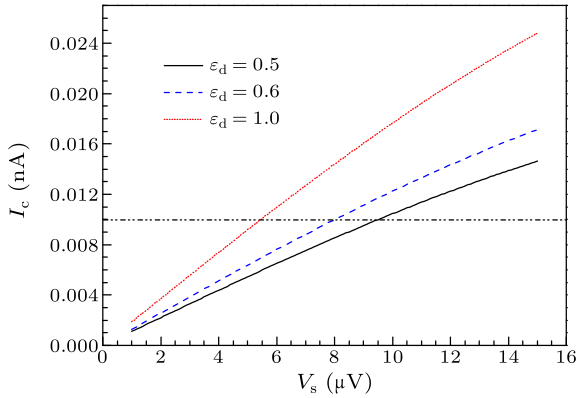

Fig. 4. The induced charge current versus V_s for $\Gamma_L = \Gamma_R = 0.2$, $\varepsilon_d = 0.5$ and $\omega = 2.0$.

Figure 3 shows the tunneling currents against the frequency of the circularly polarized light ω. The sign of the frequency is determined by the handedness of the light. In general, the frequency of a left-handed circularly polarized light is positive and the frequency of a right-handed one is negative. If the spin bias or circularly polarized light exists alone, the spin-up and spin-down electrons will have identical tunneling probabilities, thus the spin-up and spin-down currents should be symmetrical about the axis $I_s = 0$. However, when they both exist, this symmetry is broken and a nonzero charge current can be produced as shown in Fig. 3. Interestingly, the induced charge current is also a centrally symmetric function of the frequency ω. This result indicates that the induced current can also be used to judge the handedness of a circularly polarized light. Moreover, at point A the spin-up current is nonzero while another spin component current is suppressed completely, i.e., a fully spin-polarized current is generated, which means that a spin filter effect can be realized in the studied system when properly choosing the system parameters.

To show the feasibility of our detection scheme, the induced charge current as a function of the spin bias is displayed in Fig. 4. It is clear that the induced current is approximately linear with the spin bias. This linear relation enables us to detect the spin bias by measuring the induced charge current. Meanwhile, such

a simple relation makes our detection scheme more convenient than other proposals, where the relations between the induced signals and spin bias are usually nonlinear and complicated. Since the induced charge current is a monotone increasing function of the spin bias (see Fig. 4) and the lower limit of a measurable charge current is about 0.01 nA,[23] a lower limit of the measurable spin bias also exists. As shown in Fig. 4, the lower limit of a measurable spin bias can be modulated by changing the dot energy level. For example, as the dot energy level $\varepsilon_{\rm d}$ decreases from 1.0 to 0.5, the lower limit of the measurable spin bias decreases from 10 μV to 5 μV. Hence, when choosing the dot energy level as $\varepsilon_{\rm d} = 0.5$, one can detect the spin bias in a larger range. This implies that the measuring range of the spin bias can be enlarged by varying the system parameters.

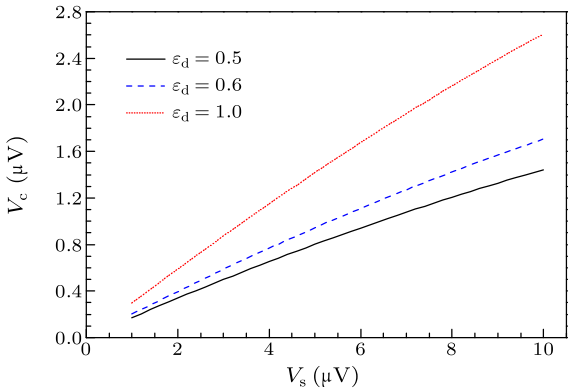

Fig. 5. The induced charge bias versus $V_{\rm s}$. The other parameters are the same as those in Fig. 4.

Now let us consider an open external circuit where a charge bias $V_{\rm c}$ is induced instead of a charge current. Due to the induced charge bias $V_{\rm c}$ the chemical potential in the right lead is shifted from $\mu_{{\rm R}\sigma} = -\frac{\sigma eV}{2}$ to $\mu_{{\rm R}\sigma} = -\frac{\sigma eV}{2} + V_{\rm c}$. Under the condition for an open external electric circuit $I_{\rm c} = 0$, the induced charge bias $V_{\rm c}$ can be solved from Eqs. (12)–(15). The relation between $V_{\rm s}$ and $V_{\rm c}$ is plotted in Fig. 5. We can see that the induced charge bias is almost a perfect linear function of the spin bias $V_{\rm s}$, which is consistent with the result found in Fig. 4. As pointed out by Ref. [18], the magnitude of a spin bias is estimated to be in the range between 1 μV and 10 μV. In Fig. 5, when the spin bias varies in this typical range, the induced charge bias is always over 0.1 μV, which is three orders of magnitude larger than the lower limit of a measurable charge bias 0.1 nV.[24] Obviously the detection scheme based on measuring the induced charge bias is more reliable than that based on measuring the induced charge current.

Finally, we discuss the reliability for our detection scheme. The device proposed here can be easily realized by the current semiconductor technology. The system parameters can also be conveniently tuned to satisfy the conditions set by us. For example, when the QD is fabricated with Ge in which the effective mass of electron $m = 0.98m_e$ (m_e is the mass of a free electron)[25] and the QD size is adjusted between 500 nm and 280 nm, the QD energy, which is about $\frac{3h^2}{8mL^2}$, can vary between 0.5 and 1.5. Thus the QD energy can be tuned experimentally according to those values chosen in Figs. 4 and 5. Here we would like to point out that though the middle scattering region of our proposed device is a QD, it could also be a nonmagnetic narrow strip, a quantum wire and even a carbon nanotube.

In summary, when a two-terminal QD device is subject to a spin bias and circularly polarized light, a charge current or charge bias is induced. The spin bias can be detected by measuring the induced charge signals based on some simple relations. The detailed calculations show that the induced charge current and especially charge bias is large enough to be measured by the present technology. Moreover, some other interesting properties of the spin-dependent electron transport through the studied system are also revealed, which may be helpful for the measurement of the induced charge signals in experiments. Therefore, our proposal can offer a new promising way to detect a spin bias.

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