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Quantum spin transport through Aharonov–Bohm ring with a tangent magnetic field*

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Quantum spin transport in a mesoscopic Aharonov–Bohm ring with two leads subject to a magnetic field with circular configuration is investigated by means of one-dimensional quantum waveguide theory. Within the framework of Landauer–Büttiker formalism, the polarization direction of transmitted electrons can be controlled either by the AB magnetic flux or by the tangent magnetic field. In particular, the spin flips can be induced by hopping the AB magnetic flux or the tangent field.

Keywords: quantum spin transport, Aharonov–Bohm ring, quantum waveguide theory
PACC: 7210, 7335, 0365

1. Introduction

Spin-dependent transport phenomena in low-dimensional quantum structures are currently attracting a lot of interest because of potential applications in semiconductor electronics and quantum computation.[1−3] How to control and manipulate electron spin is an important step to investigate spin coherent electronic systems. One pioneer device of electron spin is the so-called spin-field-effect transistor proposed by Datta and Das.[4] The key idea is that, when an electron transmits on its way from the source to the drain, the spin precession of the electron is determined by the spin-orbit coupling. It is well known that in semiconductor heterostructures the spin-orbit interaction makes energy band splitting of conduction electrons in the absence of external field. Such a splitting produces the spin precession while an electron goes through the semiconductor channel. Experimentally, the Rashba spin orbit coupling can be tuned by an perpendicular electric field so that a spin-polarized current injected from the ferromagnetic injector electrode can be modulated spin-dependently on its way to the drain by an external gate.[5,6] Other proposals of spin field transistor were reported recently.[7−12]

However, more sophisticated structures are conceivable where spin modulation could arise from electron interference. The quantum interference ring is an effective device. The Aharonov–Casher (AC) effect[13] originates from the spin-orbit coupling between the moving magnetic polar and the electric field. It can be used to implement the spin current modulation manifested by the AC effect. In an AC ring, the magnetic moment of charge carriers is influenced by an electric field through the spin-orbit interaction and there is an energy splitting between the spin-up and spin-down electrons. The local spin orientation on the ring is determined by a spin cyclic evolution over the ring. The relationship between quantum spin polarizability and precession in the quantum transport in the AC ring can be established, so that the spin polarization is controllable through the external electric field by means of the AC effect. So the AC ring can serve as a tunable spin switch by adjusting the electric field.[14,15] In addition to the AC ring, the Aharonov–Bohm (AB) ring with a non-uniform magnetic field may also control the polarization direction of spin current.[16−19] The conventional AB effect is anticipated to modulate the charge current.[20−22] The coupling of the carrier spin to an applied magnetic field can be used to control the spin degrees of freedom. In this respect, the magnetic field whose direction varies on mesoscopic length scales is of particular interest. Besides the usual Zeeman spin splitting, a variety of additional effects that

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are absent in conventional charge quantum transports can be produced. In Ref.[16], the energy-averaged transmission amplitudes are obtained numerically by the recursive Green function method. In this paper we use one-dimensional quantum waveguide theory[20] to study the spin-dependent coherent transport through a ballistic mesoscopic AB ring coupled symmetrically to two leads in the presence of a tangent magnetic field. Transmission amplitude is obtained through the Griffith boundary condition.[23] We show how to use tangent magnetic fields to control the spin for the charge carriers in the way of transversing the AB ring. The polarization of the transmitted particle can be controlled and even reversed not only by tuning the AB magnetic flux but also by the tangent magnetic field.

2. Theoretical model

2.1. Aharonov–Bohm ring in a tangent magnetic field

First we consider a conducting ring subject to a tangent magnetic field $\boldsymbol{B}$ lying in the x-y plane and an additional magnetic flux Φ along the z-direction through the ring as depicted in Fig.1.

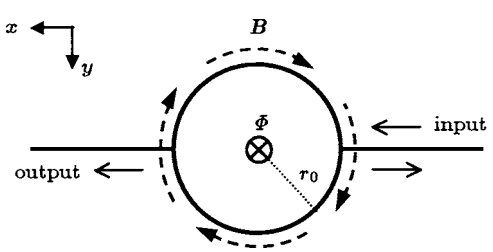


Fig.1. Geometry of the AB ring with a tangent magnetic field. The polarized electrons are input from the right lead and transmitted to the left lead.

Such a circular magnetic field configuration can be viewed as being generated by a line electrical current in the z-direction near the center of the ring[24] or can be achieved in a ferromagnetic ring. The one-particle Hamiltonian for non-interacting electrons with the effective mass m, momentum $\boldsymbol{p}$ and spin vector σ is given by

$$H = \frac{1}{2m}\left(\boldsymbol{p} + \frac{e}{c}\boldsymbol{A}\right)^2 + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B}, \tag{1}$$

where $\mu = g\mu_{\mathrm{B}}$ is the magnetic moment of a charge carrier, μ_{B} the Bohr magneton, g the gyromagnetic factor, c the velocity of light in vacuum, $-e$ the electron charge and $\boldsymbol{A}$ the magnetic vector potential. In the cylindrical coordinate, the Hamiltonian is reduced to

$$H = \frac{\hbar^2}{2mr_0^2}\left(\mathrm{i}\frac{\partial}{\partial\varphi} - \frac{\Phi}{\Phi_0}\right)^2 + \mu\left(-\sigma_x B\sin\varphi + \sigma_y B\cos\varphi\right), \tag{2}$$

where φ is the azimuthal angle, r_0 the ring radius, and $\Phi_0 = ch/e$ the quantum unit of magnetic flux. The circular magnetic field is assumed to be $\boldsymbol{B} = (-B\sin\varphi, B\cos\varphi, 0)$. The eigenstate of Hamiltonian takes the form

$$\Psi^s(\varphi) = \mathrm{e}^{\mathrm{i}n\varphi}\xi^s \tag{3}$$

with the energy eigenvalue

$$E^s = \frac{\hbar^2}{2mr_0^2}\left[\left(n + \frac{\Phi}{\Phi_0} + \frac{1}{2}\right)^2 + s\sqrt{\left(n + \frac{\Phi}{\Phi_0} + \frac{1}{2}\right)^2 + Q_{\mathrm{B}}^2} + \frac{1}{4}\right], \tag{4}$$

where n is orbital quantum number and $Q_{\mathrm{B}} = \mu B/\left(\frac{\hbar^2}{2mr_0^2}\right)$. The spinor parts ξ^s of Eq.(3) are given by

$$\xi^+ = \begin{pmatrix} \cos\dfrac{\theta}{2} \\ -\mathrm{i}\mathrm{e}^{\mathrm{i}\varphi}\sin\dfrac{\theta}{2} \end{pmatrix},$$

$$\xi^- = \begin{pmatrix} \sin\dfrac{\theta}{2} \\ \mathrm{i}\mathrm{e}^{\mathrm{i}\varphi}\cos\dfrac{\theta}{2} \end{pmatrix}, \tag{5}$$

which are just the eigenstates of the spin vector $\hat{n} = \left(\cos(\varphi - \frac{\pi}{2})\sin\theta, \sin(\varphi - \frac{\pi}{2})\sin\theta, \cos\theta\right)$ and the polar angle θ is defined by

$$\tan\theta = \frac{Q_{\mathrm{B}}}{n + \dfrac{\Phi}{\Phi_0} + \dfrac{1}{2}}. \tag{6}$$

It is obvious that the polar angle θ depends on not only the tangent magnetic field but also the electron energy in the ring.

2.2. Quantum spin transport through an AB ring with two leads

Next we consider the AB ring coupled symmetrically to the incoming and outgoing leads as shown in Fig.1. Assume that electrons have momentum $\hbar k$ and energy $E = \hbar^2k^2/2m$ in two leads. Following the conservation law of energy of electrons from the leads to ring, when $E > \mu B + \hbar^2/8mr_0^2$, we can obtain four different orbital quantum numbers from Eq.(4), i.e. the

Zeeman term causes a slight difference in kinetic energy between the spin(+) and spin(−) electrons travelling clockwise (1) or anticlockwise (2) around the ring. Those are

$$n_1^- = n_0 + n_1, \tag{7a}$$
$$n_1^+ = n_0 + n_2, \tag{7b}$$
$$n_2^- = -n_0 + n_2, \tag{7c}$$
$$n_2^+ = -n_0 + n_1, \tag{7d}$$

and

$$n_0 = -\frac{\Phi}{\Phi_0} - \frac{1}{2}, \tag{8}$$
$$n_1 = \frac{1}{2}\sqrt{4W + 1 - 4\sqrt{Q_{\rm B}^2 + W}}, \tag{9}$$
$$n_2 = \frac{1}{2}\sqrt{4W + 1 + 4\sqrt{Q_{\rm B}^2 + W}}, \tag{10}$$

where $W = E/(\hbar^2/2mr_0^2)$. The eigenstates corresponding to $n_{1,2}^{\pm}$ are

$$\xi_1^+ = \begin{pmatrix} \cos\dfrac{\theta_+}{2} \\ -\mathrm{i}\mathrm{e}^{\mathrm{i}\varphi}\sin\dfrac{\theta_+}{2} \end{pmatrix}, \tag{11a}$$

$$\xi_1^- = \begin{pmatrix} \sin\dfrac{\theta_-}{2} \\ \mathrm{i}\mathrm{e}^{\mathrm{i}\varphi}\cos\dfrac{\theta_-}{2} \end{pmatrix}, \tag{11b}$$

$$\xi_2^+ = \begin{pmatrix} \cos\dfrac{\theta_-}{2} \\ \mathrm{i}\mathrm{e}^{\mathrm{i}\varphi}\sin\dfrac{\theta_-}{2} \end{pmatrix}, \tag{11c}$$

$$\xi_2^- = \begin{pmatrix} \sin\dfrac{\theta_+}{2} \\ -\mathrm{i}\mathrm{e}^{\mathrm{i}\varphi}\cos\dfrac{\theta_+}{2} \end{pmatrix}, \tag{11d}$$

where $\theta_\pm$ are defined by

$$\tan\theta_\pm = \frac{2Q_{\rm B}}{\sqrt{4W + 1 \pm 4\sqrt{Q_{\rm B}^2 + W}}}. \tag{12}$$

The incident electrons at $\varphi = 0$ propagate coherently along the four available channels and interfere at $\varphi = \pi$. For a specific case of $Q_{\rm B} = 0$, an electron transmitting clockwise and anticlockwise will pick up opposite geometric phases and the variation of the total phase around the loop is the AB phase $2\pi\Phi/\Phi_0$, i.e. $n_1^\pm - n_2^\pm = -2\Phi/\Phi_0$, and the well-known result can be obtained from the definition of four different $n_{1,2}^\pm$ in Eq.(7).

The transport in non-interacting mesoscopic systems is well described in the framework of the Landauer–Büttiker formalism. The conductance G at zero temperature is determined with the Landauer–Büttiker formula[25]

$$G = \frac{e^2}{h}\left|t\right|^2, \tag{13}$$

which states that conductance G is proportional to the transmission probability $T = \left|t\right|^2$, where t is the single particle transmission amplitude of electrons. We approach this transport problem in quantum wave guide theory.[20]

Generally, the wave functions in the two arms can be expressed in terms of the reflection and transmission of electrons when they transport through the ring,

$$\Psi_1 = \sum_{s=\pm} B_1^s \mathrm{e}^{\mathrm{i}n_1^s\varphi}\xi_1^s + C_1^s \mathrm{e}^{-\mathrm{i}n_2^s\varphi}\xi_2^s, \tag{14}$$
$$\Psi_2 = \sum_{s=\pm} B_2^s \mathrm{e}^{\mathrm{i}n_2^s\varphi}\xi_2^s + C_2^s \mathrm{e}^{-\mathrm{i}n_1^s\varphi}\xi_1^s, \tag{15}$$

with $\varphi = x/r_0$. We assume that a polarized electron is injected to the input lead and transmit in the x-direction, and the spin state of the injected electron is

$$\Psi_i = (a_1, a_2)^{\rm T}\,\mathrm{e}^{\mathrm{i}kx}. \tag{16}$$

Consider the reflection and transmission of electrons. The wave functions of the electrons in the input and output leads, respectively, are

$$\Psi_{\rm r} = \Psi_i + (r_1, r_2)^{\rm T}\,\mathrm{e}^{-\mathrm{i}kx}, \tag{17}$$
$$\Psi_{\rm l} = (t_1, t_2)^{\rm T}\,\mathrm{e}^{\mathrm{i}kx}, \tag{18}$$

where r_i and t_i are the spin-resolved reflection and transmission amplitudes, respectively. To calculate the transmission probability through the AB ring, we use the local coordinate system for each segment, where the x coordinate axis is taken along the direction of electron current.[20,26] The origin of each local coordinate is taken at each intersection. The choice of the coordinate origin is trivial because it can present only an extra, but trivial phase factor in the transmission amplitude. Using the Griffith boundary condition[23] that states that at each intersection the wave function is continuous and the current density is conserved, we have

$$\Psi_{\rm r}|_{x=0} = \Psi_1|_{\varphi=0} = \Psi_2|_{\varphi=0}, \tag{19}$$
$$\Psi_{\rm l}|_{x=0} = \Psi_1|_{\varphi=\pi} = \Psi_2|_{\varphi=\pi}, \tag{20}$$
$$\left.\frac{\mathrm{d}\Psi_{\rm r}}{\mathrm{d}x}\right|_{x=0} = \left.\frac{1}{r_0}\frac{\partial\Psi_1}{\partial\varphi}\right|_{\varphi=0} + \left.\frac{1}{r_0}\frac{\partial\Psi_2}{\partial\varphi}\right|_{\varphi=0}, \tag{21}$$
$$\left.\frac{\mathrm{d}\Psi_{\rm l}}{\mathrm{d}x}\right|_{x=0} = \left.\frac{1}{r_0}\frac{\partial\Psi_1}{\partial\varphi}\right|_{\varphi=\pi} + \left.\frac{1}{r_0}\frac{\partial\Psi_2}{\partial\varphi}\right|_{\varphi=\pi}, \tag{22}$$

where the azimuthal angle φ is taken as 0 in the input intersection and π in the output intersection. The set of equations have twelves coefficients or unknowns. After some tedious calculations, the transmission amplitude is expressed analytically by

$$\begin{aligned}(t_1,t_2)^{\mathrm{T}} =&2r_0k\sigma_z\Big[\frac{r_0k}{2}\gamma_1(f_1+f_4)\\&+\frac{r_0k}{2}\gamma_2(f_2+f_3)+\gamma_2 n_{22}(f_2-f_3)\\&+\gamma_1 n_{11}(f_1-f_4)\Big]^{-1}(a_1,a_2)^{\mathrm{T}},\end{aligned}\tag{23}$$

where

$$n_{11}=\begin{pmatrix} n_1^- & 0\\ 0 & n_1^+\end{pmatrix},\tag{24a}$$

$$n_{22}=\begin{pmatrix} n_2^- & 0\\ 0 & n_2^+\end{pmatrix},\tag{24b}$$

$$\gamma_1=\begin{pmatrix} \sin\dfrac{\theta_-}{2} & \cos\dfrac{\theta_+}{2}\\ \mathrm{i}\cos\dfrac{\theta_-}{2} & -\mathrm{i}\sin\dfrac{\theta_+}{2}\end{pmatrix},\tag{24c}$$

$$\gamma_2=\begin{pmatrix} \sin\dfrac{\theta_+}{2} & \cos\dfrac{\theta_-}{2}\\ -\mathrm{i}\cos\dfrac{\theta_+}{2} & \mathrm{i}\sin\dfrac{\theta_-}{2}\end{pmatrix},\tag{24d}$$

$$D_1=\begin{pmatrix} \mathrm{e}^{\mathrm{i}n_1^-\pi} & 0\\ 0 & \mathrm{e}^{\mathrm{i}n_1^+\pi}\end{pmatrix},\tag{24e}$$

$$D_2=\begin{pmatrix} \mathrm{e}^{-\mathrm{i}n_2^-\pi} & 0\\ 0 & \mathrm{e}^{-\mathrm{i}n_2^+\pi}\end{pmatrix},\tag{24f}$$

$$f_1=\left(-(D_1)^2-(\gamma_2D_2M_3)^{-1}(\gamma_1D_1+\gamma_2D_2N_3)\right)^{-1}\left(r_0kL_2^{-1}-(\gamma_2D_2M_3)^{-1}\right),\tag{25a}$$

$$f2=\left(-(D_2^{-1})^2-(\gamma_1D_1^{-1}N_2)^{-1}(\gamma_2D_2^{-1}+\gamma_1D_1^{-1}M_2)\right)^{-1}\left(r_0kL_1^{-1}-(\gamma_1D_1^{-1}N_2)^{-1}\right),\tag{25b}$$

$$f3=\left(-(D_2)^2-(\gamma_1D_1M_1)^{-1}(\gamma_2D_2+\gamma_1D_1N_1)\right)^{-1}\left(r_0kK_1^{-1}-(\gamma_1D_1M_1)^{-1}\right),\tag{25c}$$

$$f4=\left(-(D_1^{-1})^2-(\gamma_2D_2^{-1}N_4)^{-1}(\gamma_1D_1^{-1}+\gamma_2D_2^{-1}M_4)\right)^{-1}\left(r_0kK_2^{-1}-(\gamma_2D_2^{-1}N_4)^{-1}\right),\tag{25d}$$

and

$$M_1=(D_1-D_1^{-1})^{-1}(\gamma_1^{-1}\gamma_2D_2^{-1}-D_1^{-1}\gamma_1^{-1}\gamma_2),\tag{26a}$$

$$M_2=(D_1-D_1^{-1})^{-1}(\gamma_1^{-1}\gamma_2D_2^{-1}-D_1\gamma_1^{-1}\gamma_2),\tag{26b}$$

$$M_3=(D_2-D_2^{-1})^{-1}(\gamma_2^{-1}\gamma_1D_1^{-1}-D_2^{-1}\gamma_2^{-1}\gamma_1),\tag{26c}$$

$$M_4=(D_2-D_2^{-1})^{-1}(\gamma_2^{-1}\gamma_1D_1^{-1}-D_2\gamma_2^{-1}\gamma_1),\tag{26d}$$

$$N_1=-(D_1-D_1^{-1})^{-1}(\gamma_1^{-1}\gamma_2D_2-D_1^{-1}\gamma_1^{-1}\gamma_2),\tag{26e}$$

$$N_2=-(D_1-D_1^{-1})^{-1}(\gamma_1^{-1}\gamma_2D_2-D_1\gamma_1^{-1}\gamma_2),\tag{26f}$$

$$N_3=-(D_2-D_2^{-1})^{-1}(\gamma_2^{-1}\gamma_1D_1-D_2^{-1}\gamma_2^{-1}\gamma_1),\tag{26g}$$

$$N_4=-(D_2-D_2^{-1})^{-1}(\gamma_2^{-1}\gamma_1D_1-D_2\gamma_2^{-1}\gamma_1),\tag{26h}$$

$$K_1=\gamma_1D_1n_{11}M_1-\gamma_1D_1^{-1}n_{11}M_2+\gamma_2D_2^{-1}n_{22},\tag{26i}$$

$$K_2=\gamma_2D_2^{-1}n_{22}N_4-\gamma_2D_2n_{22}N_3+\gamma_1D_1n_{11},\tag{26j}$$

$$L_1=\gamma_1D_1n_{11}N_1-\gamma_1D_1^{-1}n_{11}N_2-\gamma_2D_2n_{22},\tag{26k}$$

$$L_2=\gamma_2D_2^{-1}n_{22}M_4-\gamma_2D_2n_{22}M_3-\gamma_1D_1^{-1}n_{11}.\tag{26l}$$

3. Numerical results and discussion

In this section, to explore physics in Eq.(23) clearly, we evaluate the spin-resolved transmission probability numerically. Two ways to control the polarization of transmitted particles are presented. One is by the AB magnetic flux, and the other is by a tangent magnetic field. In our calculation, we take $kr_0 = 60.239$, which is typical experiment parameter for InAs or GaAs ring.[14] The transmission properties depend on the initial polarized spin state in our device. We will take the initial spin polarized along the $+y$ and $+z$ directions, respectively.

If the spin of the injected charge carriers is polarized along the $+y$ direction, i.e. $a_1 = 1/\sqrt{2}$ and $a_2 = \mathrm{i}/\sqrt{2}$ in Eq.(16), the probabilities of transmitted electron with the $+y$ and $-y$ directions in the output lead are

$$T_y^+ = \frac{1}{2}\left|(t_1 - \mathrm{i}t_2)\right|^2,\tag{27}$$

$$T_y^- = \frac{1}{2}\left|(t_1 + \mathrm{i}t_2)\right|^2,\tag{28}$$

respectively. In Fig.2, it is shown that the spin-resolved transmission probabilities T_y^+ (dash line), T_y^- (dot line) and total transmission probability $T_y = T_y^+ + T_y^-$ (solid line) vary with the AB flux for some Q_{B} . When $Q_{\mathrm{B}} = 0$, spin flip does not occur, i.e. $T_y = T_y^+$, and the transmitted spin always has the same polarization as the injected spin, and the transmission probability oscillates periodically with the AB flux with a

period Φ_0. This feature does not rely on the initial polarized spin state. The oscillation of the transmission probability is induced by the AB phase interference between the carriers travelling in two arms of the ring.[20] When $Q_{\rm B} \neq 0$, the spin flip appears and the transmission amplitudes are controlled by both the AB magnetic flux and the tangent magnetic field. There are two particular cases: $T_y^- = 0$ for $\Phi/\Phi_0 = 0$, and $T_y^+ = 0$ for $\Phi/\Phi_0 = 0.5$. They are shown more clearly in Fig.3, which illustrates variations of spin-resolved transmission probabilities T_y^+ (dash line) and T_y^- (solid line) with the tangent magnetic field $Q_{\rm B}$ for some AB magnetic fluxes. The spin polarized carrier is transmitted keeping its initial polarized spin direction for a zero AB magnetic flux, while for $\Phi = 0.5\Phi_0$ the transmitted carrier has the reversely polarized spin direction relative to the incident spin direction. This feature has been demonstrated in Ref.[16] and indicates that the AB ring with a tangent magnetic field can act as a tunable spin switch.

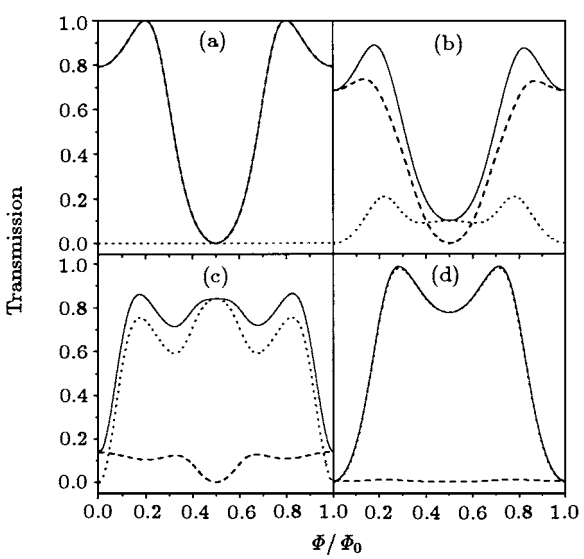


Fig.2. Spin-resolved transmission probabilities T_y^+(dashed line), T_y^-(dotted line) and total transmission probability T_y (solid line) as a function of the AB magnetic flux Φ for some tangent magnetic fields, (a) $Q_{\rm B} = 0$, (b) $Q_{\rm B} = 30$, (c) $Q_{\rm B} = 80$, (d) $Q_{\rm B} = 100$.

From Fig.3(b), we can identify another modulation way for a tunable spin switch. When Φ is taken as $0.3\Phi_0$, $T_y^- = 0$ for $Q_{\rm B} = 0$, while $T_y^+ = 0$ for $Q_{\rm B} = 105$. One can reverse the polarization of the transmitted carrier in a controllable way by tuning the tangent magnetic field from $Q_{\rm B} = 0$ to $Q_{\rm B} = 105$.

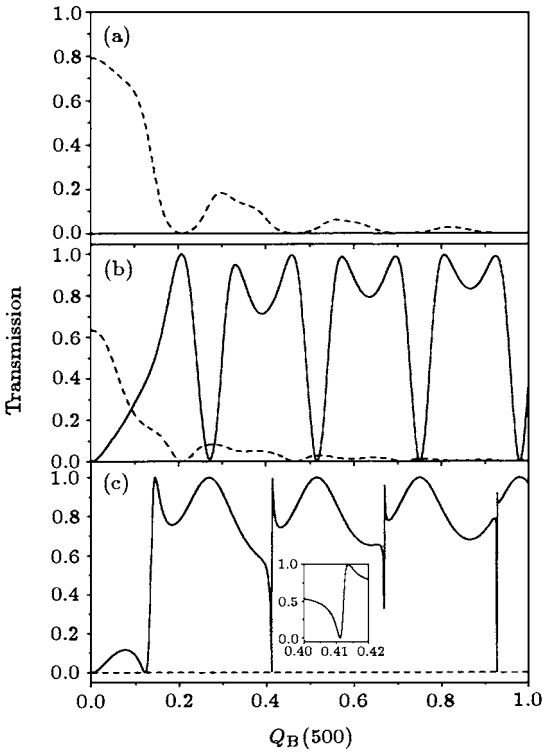


Fig.3. Variations of spin-resolved transmission probabilities T_y^+ (dashed line) and T_y^-(solid line) with the tangent magnetic field for some AB magnetic fluxes, (a) $\Phi/\Phi_0 = 0$, (b) $\Phi/\Phi_0 = 0.3$, (c) $\Phi/\Phi_0 = 0.5$, and the inset shows an enlargement near $Q_{\rm B} = 0.41(500)$.

In Fig.4 plotted are the variations of spin-resolved transmission probabilities $T_z^+ = |t_1|^2$ (dash line) and $T_z^- = |t_2|^2$ (solid line) with the tangent magnetic field for different AB magnetic fluxes, when the spin state of incident charge carrier is polarized along the $+z$ direction, i.e., $a_1 = 1$ and $a_2 = 0$ in Eq.(16). When $\Phi = 0$, both Fig.3(a) and Fig. 4(a) show that the transport properties are independent of the initial spin state. The transmission probability approaches to zero for a large $Q_{\rm B}$ and spin flip does not always occur. When $\Phi \neq 0$, T_y^+ decreases to zero while T_z^+ oscillates with $Q_{\rm B}$. In addition, it is only the particle polarized along the y-direction initially that is not transmitted at $\Phi = 0.5\Phi_0$ regardless of $Q_{\rm B}$.

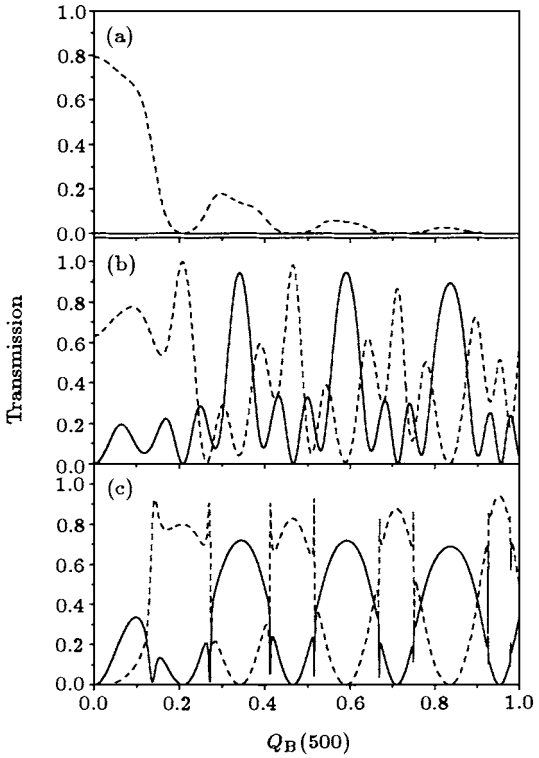


Fig.4. Variations of spin-resolved transmission probabilities T_z^+ (dashed line) and T_z^- (solid line) with the tangent magnetic field for some AB magnetic fluxes, (a) $\Phi/\Phi_0 = 0$, (b) $\Phi/\Phi_0 = 0.3$, (c) $\Phi/\Phi_0 = 0.5$.

From Fig.3, and Fig.4 we see that, for other cases of $\Phi/\Phi_0 \neq 0$, the transmission probabilities have the periodic behaviour for a large Q_B, but become anomalous when Q_B is less than 100. The adiabatic limit is given by $Q_B \gg \sqrt{W} = kr_0$.[17,18] The anomalous oscillations of the transmission probability originate from the nonadiabatic phase. Because the incident particles are mostly reflected at $\Phi/\Phi_0 = 0$ for a large Q_B, the proposal of the tuning AB magnetic flux is only effective in nonadiabatic spin transports. Figures 4(b) and (c) show that the proposal of tuning tangent magnetic field can also be used in an adiabatic regime. For example, for $\Phi/\Phi_0 = 0.5$, the polarization of transmitted particle changes from the +z to $-z$ directions if we modulate Q_B from 105 to 172.

Within the simplified model we further investigate the magnetic flux and tangent magnetic field dependences of quantum spin transport for different incident polarized spin states. According to the above analysis, two better ways are identified to control the polarized direction of transmitted spin. One is to modulate the magnetic flux in a nonadiabatic regime for the y-polarized incident spin state, the other is to modulate the tangent magnetic field in an adiabatic regime for the z-polarized incident spin state.

4. Conclusion

Quantum spin transport is investigated in a mesoscopic Aharonov–Bohm ring with two leads, subject to a magnetic field with circular configuration, by means of one-dimensional quantum waveguide theory. The spin-resolved transmission is calculated analytically through the Griffith boundary condition. Transmission probabilities are determined by either the AB magnetic flux or the tangent magnetic field. It is demonstrated that not only AB magnetic flux but also tangent magnetic field can be used to control spin flip and to tune the polarization of transmitted particles. In an adiabatic regime, the modulation by an tangent magnetic field is more effective for the incident spin state polarized perpendicularly to the ring. Such a device can be useful for controlling the spin polarized current and act as a spin switch for different incident spin states.

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