QUANTUM NANORING WITH TWO MAGNETIC IMPURITIES AS A SPIN-POLARIZER

Leila Eslami and Mahdi Esmaeilzadeh

Department of physics, Iran University of Science and Technology. P. O. Box: 16844-13114

Tehran, Iran.

leslami@iust.ac.ir

Abstract

Based on a single-band waveguide theory, we investigate electronic and spintronic properties of a single electron in a quantum nano-ring with two magnetic impurities. We find that the quantum ring with magnetic impurities can act as a spin-polarizer. We also study efficiency of the spin-polarizer and find out that it can be above 65%.

1. Introduction

Spintronics or a spin based electronics studies spin dependent properties of mesoscopic systems to control spin degree of freedom [1, 2]. One of the essential requirements in a spintronic device is to generate spin-polarized current. One of the mechanisms for generating the spin-polarized current is the injection of spin-polarized electrons from ferromagnetic metals to a semiconductor. But it has problem of a large resistance mismatch [3]. The other mechanism which can manipulate electron spin is the exchange interaction between electrons and magnetic impurities [4]. Geometry of the mesoscopic semiconductor has also significant effect on spin properties of the system. During the last several years, mesoscopic quantum ring shaped structures [5] have been extensively under consideration.

Aharonov-Bohm oscillations [6] and spin-polarized transport properties in a quantum ring with a magnetic impurity have been investigated by Joshi *et al* [7]. They have reported that the transmitted electron can be polarized due to the magnetic impurity. Electronic transport properties and phase coherence in a quantum ring with two magnetic impurities has been analyzed by Ciccarello *et al* [8]. They have studied the effect of entanglement between the magnetic impurities on phase coherence of transmitted electron.

In the present work, we study the spin dependent properties of a quantum ring with two magnetic impurities by using waveguide theory. We show that a quantum ring with two magnetic impurities can act as a spin-polarizer. We also study the efficiency of spin-polarizer and show that it can be about the 65%. In Sec. 2 theoretical model is presented. Results and discussion are given in Sec. 3. Finally, a summary and conclusion are presented in Sec. 4.

2. Theoretical Model

Consider a quantum nano ring of length L connected to two external leads as shown in Fig. 1. The ring is divided to two arms of lengths L/4 and 3L/4 by the leads. Two identical spin-1/2 magnetic impurities, labelled A and B, are placed in the longer arm as shown in Fig. 1. Impurities A and B are apart from input and output leads, by L/8. The system of two leads and quantum ring are such narrow that we can account only the lowest electron subband with a good approximation [9]. We model the interaction between the electron and each impurity by exchange interaction [7]. Also, we assume that there is an adjustable magnetic flux within the ring so that no field exist on the ring. The Hamiltonian of the system for regions 1-6 (see Fig. 1) can be written as

$$\mathbf{H} = \begin{cases} \dfrac{P^2}{2m^*} & \text{Regions 1 and 6,} \\ \dfrac{1}{2m^*}\left(\mathbf{P}_1 + \dfrac{e}{c}\mathbf{A}\right)^2 & \text{Region 2,} \\ \dfrac{1}{2m^*}\left(\mathbf{P}_2 + \dfrac{e}{c}\mathbf{A}\right)^2 + \mathbf{H}_{e_1} + \mathbf{H}_{e_2} & \text{Regions 3, 4 and 5,} \end{cases} \tag{1}$$

where $\mathbf{P} \equiv -i\hbar\nabla$ is the momentum of electron, h = 2πħ is the Plank's constant, m^* is the effective mass of electron, -e is the electron charge, c is the speed of light in vacuum, and $\mathbf{A}$ is the vector potential. The vector potential is considered along the ring direction and has a magnitude $|\mathbf{A}| = \phi/L$ where ϕ denotes the magnetic flux passing through the ring. In Eq. (1) H_{e1} and H_{e2} are the potentials of magnetic impurities A and B which are defined as

$$H_{e1} = -J\boldsymbol{\sigma}\cdot\mathbf{S}_1\delta\left(x - \frac{L}{8}\right) \tag{2}$$

and

$$H_{e2} = -J\boldsymbol{\sigma}\cdot\mathbf{S}_2\delta\left(x - \frac{5L}{8}\right), \tag{3}$$

respectively. Here J stands for coupling constant of exchange interaction between electron and each magnetic impurity, $\boldsymbol{\sigma}$, $\mathbf{S_1}$ and $\mathbf{S_2}$ are spin operators of electron, and magnetic impurities A and B, respectively. Let $\mathbf{S} \equiv \mathbf{S}_1 + \mathbf{S}_2 + \boldsymbol{\sigma}$ be the total spin operator of the system. Since the system is isolated, $\mathbf{S}^2$ and $\mathbf{S}_z$ are constants of motion. The stationary state of system can be obtained in regions 1-6 by using quantum waveguide theory [10] and the Griffith boundary conditions [8, 11]. The total transmission coefficient can be found as

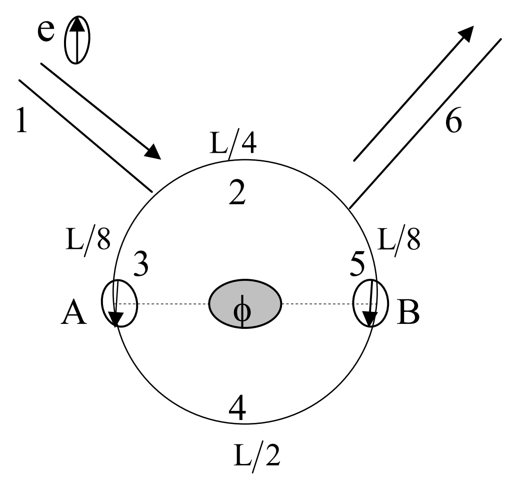

Fig.1: Schematic diagram of a quantum ring with two magnetic impurities labelled A and B. Also, a magnetic flux is threaded through the centre of the ring.

$$T = \langle \psi_6 | \psi_6 \rangle, \tag{4}$$

where $|\psi_6\rangle$ is the stationary state of the electron in the region 6.

3. Results and discussions

Now, we consider the spin state of injected electron and initial spin state of impurities all to be $|\downarrow\rangle$. In this case the electron spin flip can not occur because of spin conservation and the spin of transmitted electron remains $|\downarrow\rangle$. Now we assume that the spin state of injected electron is $|\uparrow\rangle$ and try to find parameters of the system in which the spin state of transmitted electron change to $|\downarrow\rangle$. Note that in a spin-polarizer, e.g. down-spin polarizer, the up-spin state of injected electron change to down-spin state, while the injected electron with down-spin state is transmitted without spin change. The spin-polarization is defined as [7]

$$P \equiv \frac{T_\downarrow - T_\uparrow}{T_\downarrow + T_\uparrow}, \qquad (5)$$

where $T_\uparrow$ and $T_\downarrow$ are transmission coefficient of transmitted electron in up and down spin states, respectively. To study this property of the system, in Fig. 2, we plot the spin-polarization P as a function of the normalized electron wavelength $\kappa L/\pi$ for normalized coupling constant J/κ = 2.5 and for different normalized magnetic flux $\phi/\phi_\circ = 0$, 0.6 and 0.8. Here $\phi_\circ \equiv hc/e$. Note that the spin state of injected electron is assumed to be $|\uparrow\rangle$ and the initial spin state of impurities are assumed to be $|\downarrow\rangle$. As shown in this figure, P = 1 occurs only for $\phi/\phi_\circ = 0.6$ (at $\kappa L/\pi = 1$), which means that the spin state of transmitted electron is purely $|\downarrow\rangle$. So, total spin-polarization is occurred for normalized magnetic flux $\phi/\phi_\circ = 0.6$.

The efficiency of spin-polarizer is defined as

$$\zeta = 1 - R = T \qquad \text{for P = 1}, \qquad (6)$$

where T and R are the total electron transmission and reflection coefficients, respectively.

In Fig. 4 we plot total transmission coefficient T and transmission coefficient of transmitted electron in down spin state $T_\downarrow$ as a function of normalized magnetic flux. Note that, as before, the spin state of injected electron is assumed to be $|\uparrow\rangle$. We see that, at $\phi/\phi_\circ = -0.4$ and 0.6, $T = T_\downarrow = 0.68$. Therefore, the efficiency of the spin polarizer is obtained equal to 68%.

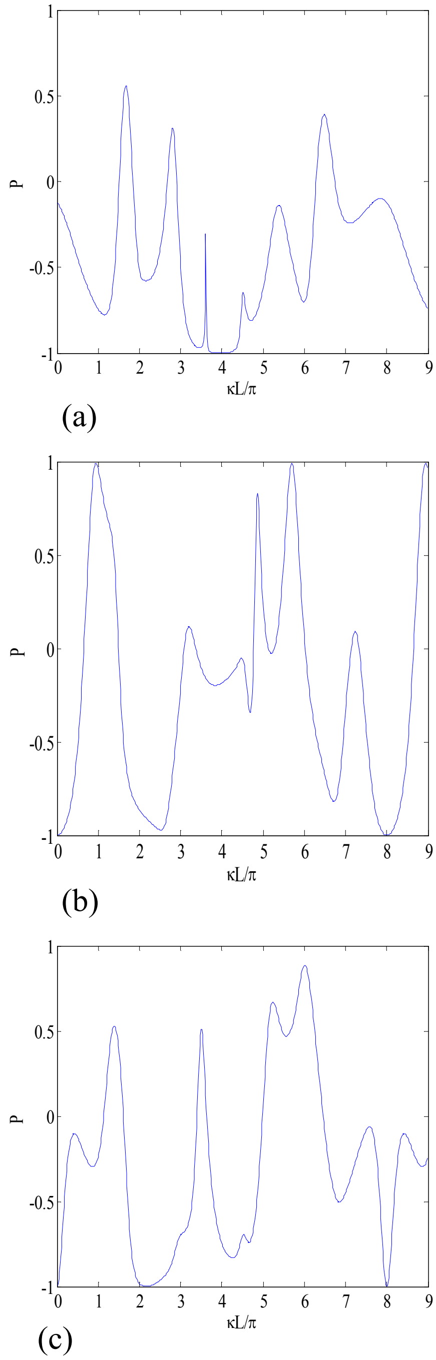

Fig. 2: Spin-polarization of electron as a function of the normalized wavelength $\kappa L/\pi$, for the coupling constant $J/\kappa = 2.5$ and different normalized magnetic flux (a) $\phi/\phi_\circ$ = 0, (b) $\phi/\phi_\circ$ = 0.6 and (c) $\phi/\phi_\circ$ = 0.8. It is obvious that P=1 will be achieved, at $\kappa L/\pi = 1$, only for the case that $\phi/\phi_\circ = 0.6$ [see Fig. 2. (b)].

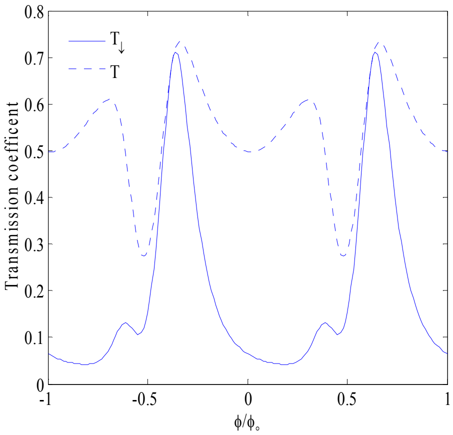

Fig. 4. The total transmission coefficient T and transmission coefficient of transmitted electron in down spin state $T_{\downarrow}$ as a function of normalized magnetic flux for coupling constant $J/\kappa = 2.5$ and normalized wavelength $\kappa L/\pi = 1$. It is observed that at $\phi/\phi_{\circ} = -0.4$ and 0.6, $T = T_{\downarrow} = 0.68$ and thus the efficiency of the spin polarizer is 68%.

4. Conclusion

In this paper, we have studied the spin properties of transmitted electron trough a quantum nano-ring with two magnetic impurities. We have shown that the system which consists of a quantum ring and two magnetic impurities can act as a spin-polarizer. We also have studied the efficiency of spin-polarizer and shown that it can be above 65%.

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