Loss of interference in an Aharonov-Bohm ring

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Abstract : We study a simple model of dephasing of Aharonov-Bohm oscillations in the transmission of an electron across a mesoscopic ring. A magnetic impurity in one of the arms of the ring couples to the electron spin via an exchange interaction. This interaction leads to spin flip scattering and induces dephasing via entanglement. This is akin to the models evoked earlier to explain destruction of interference due to which-path information in double-slit experiments. Total transmission is found to be symmetric under flux reversal but not the spin polarization.

Keywords : Aharonov-Bohm oscillations, spin flip scattering, dephasing

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1. Introduction

The notion of intrinsic decoherence and dephasing of a particle interacting with its environment is being pursued actively in the area of mesoscopic physics. This is important from the basic point of view of understanding the emergence of classical behavior from the quantum dynamics. In this area, study of transmission of electrons across a mesoscopic Aharonov-Bohm ring occupies a prominent place from experimental as well as theoretical viewpoint[1–6]. Generally in these systems, such a transition can be observed as a function of temperature. At very low temperatures the inelastic scattering length is much larger than the sample dimensions and as a result the transport is completely phase coherent i.e., it is dominated by quantum interference effects. At very high temperatures the inelastic scattering length is much smaller than the sample dimensions which leads to Ohmic transport or classical behavior. This process is also referred to as dephasing owing to the loss of interference as a result of the randomization of the interfering particle's phase.

In a double slit setup, interference results from the lack of knowledge of (or indistinguishability of) the electron path. Thus a measurement of which path the electron has taken, wipes out the interference pattern. It is known that in a ring interferometer the electron affects the environment and changes its state differently in the two arms of the ring thereby affecting the interference. This amounts to a measurement of the path of the interfering particle by the environment resulting in loss of interference. Such interferometers are thus also termed as "which-path" detectors. In an alternate picture, the environment affects the electron phase differently in the two arms, thus randomizing their relative phase difference leading to dephasing. The two views were shown to be equivalent[7].

It is well known that the electron-environment entanglement can also lead to dephasing[8]. However, unlike other approaches, entanglement leads to dephasing in absence of any energy transfer[7]. Thus motivated we consider a simple model of dephasing in Aharonov-Bohm ring with a spin-half impurity (spin-flipper) in one arm. This example also serves to illustrate the effect of multiple reflections on "which-path" detection. We also show that the spin-polarization which is related to the spin conductance is asymmetric in flux reversal.

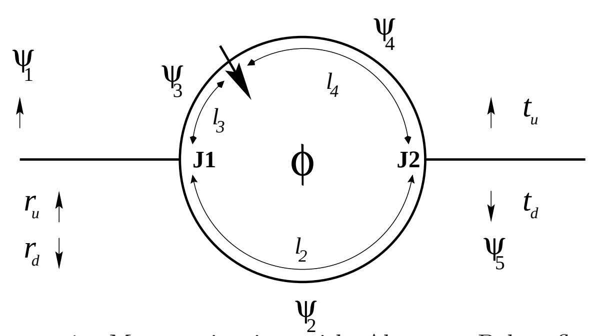

Figure 1. Mesoscopic ring with Aharonov-Bohm flux ϕ threading through the ring and a magnetic impurity in one arm of the ring.

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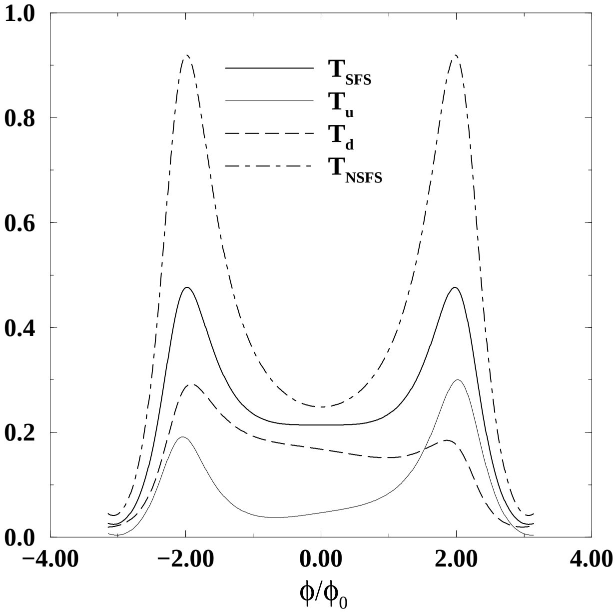

Figure 2. Plot of total transmission coefficient T_{NSFS} for NSFS, total transmission coefficient T_{SFS} for SFS, and spin-up transmission coefficient T_u and spin-down transmission coefficient T_d for the spin-flip scattering case. The interaction strength $G = 10.0$.

2. Model

Consider a spin-up electron incident from left onto the ring (see Fig. 1) in the presence of Aharonov-Bohm flux ϕ. The electron spin ($\vec{\sigma}$) is coupled to the spin of the flipper ($\vec{S}$) via an exchange interaction $-J\vec{\sigma}\cdot\vec{S}\delta(x-l_3)$. The vector potential along the ring circumference is $A = \phi/l$ where $l = l_2 + l_3 + l_4$ is the ring perimeter, l_2 being the length of the lower arm of the ring and $l_3(l_4)$ is the distance of the impurity from junction J1(J2) in the upper arm. The exchange interaction conserves the total spin angular momentum and its z-component. This leads to two kind of scattering processes depending upon the initial state of the impurity spin namely, spin flip scattering (SFS) when the initial state of impurity is down or no spin-flip scattering (NSFS) when it is up. It should be noted here that none of these two processes involve any exchange of energy and are perfectly elastic scattering events. In case of NSFS the problem at hand reduces to that of a simple potential scattering. However, the exchange interaction does lead to entanglement of the electron and impurity wavefunctions. By using the standard quantum waveguide theory[6,9] and applying continuity of wavefunctions and current conservation conditions at the impurity site and the junctions J1 and J2 we have calculated the probabilities of transmission of the electron as a spin-up electron ($T_u = |t_u|^2$) and spin-down electron ($T_d = |t_d|^2$). For details, we refer the reader to Ref. 10. The total transmission probability is simply the sum of the up and the down transmission probabilities i.e., $T = T_u + T_d$ and the spin-polarization is given by $\chi = (T_u - T_d)/T$. The lengthy analytical expressions restrict us to a graphical presentation of our results. In the following we have set $\hbar = 2m = 1$, $kl = 1$ and the value of the interaction strength $G = 2mJ/\hbar^2$ is given in dimensionless units. We have chosen $l_2/l = 0.5$, $l_3/l = 0.15$, $l_4/l = 0.35$ for the results presented below.

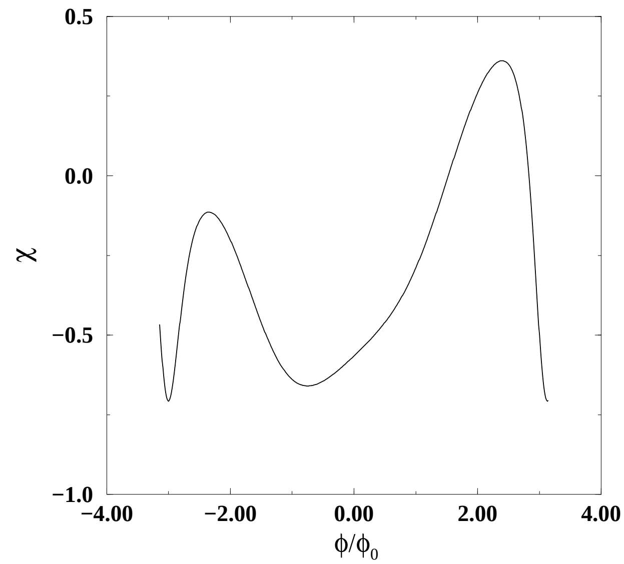

Figure 3. Spin polarization (χ) as a function of the flux ϕ for interaction strength $G = 10.0$.

3. Results and discussion

In figure 2 we show the plot of total transmission coefficient T_{NSFS} for no spin-flip scattering case (where incident electron spin is up $\sigma_z = 1/2$ and initial impurity spin is down $S_z = 1/2$) and total transmission T_{SFS}, spin-up transmission T_u, spin-down transmission T_d coefficients for the spin-flip scattering case (here incident electron spin is up $\sigma_z = 1/2$ and initial impurity spin is down $S_z = -1/2$) as a function of ϕ/ϕ_0, $\phi_0 = hc/e$ being the flux quantum. Perhaps the most easily recognizable feature of the figure is the symmetry of both T_{NSFS} and T_{SFS} under flux reversal and the $2\pi\phi_0$ flux periodicity of the AB oscillations. Such expected periodic oscillations in the transmittance have been observed experimentally[4]. However, individually the spin-up and spin-down transmission coefficients, although having the same $2\pi\phi_0$ flux periodicity, are not symmetric under flux reversal. The problem of transport in presence of spin-flip scattering, in spite of absence of any inelastic scattering reduces to the multichannel case. The symmetry properties noted above are consistent with reciprocity relations for transport in multichannel systems and are a consequence of the general symmetries of the Hamiltonian[12]. This asymmetry in the individual spin-up and spin-down components of transmission presents itself in the asymmetry observed in the spin-polarization χ as seen in Fig.

3. The spin-conductance in spin-polarized transport is related to the spin-polarization[11] and therefore is asymmetric under the flux reversal. The zero temperature total electrical conductance is a sum of total transmission coefficients for all the four possible initial conditions (σ_z,S_z)=($\pm1/2$,$\mp1/2$) and is symmetric under the flux reversal.

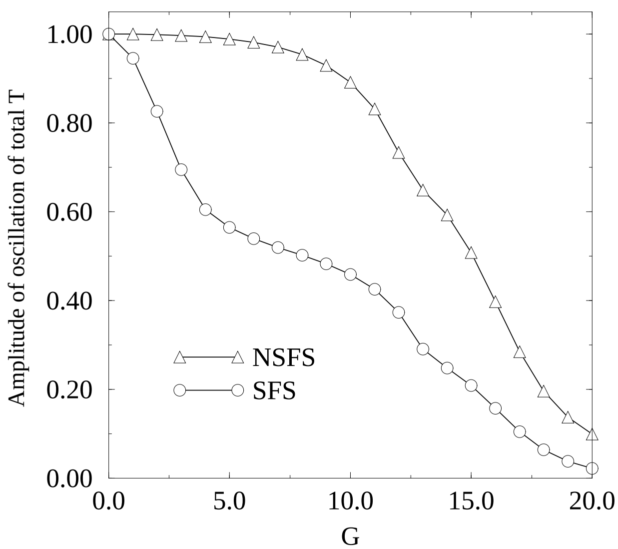

Figure 4. Variation of amplitude of oscillation of total transmission coefficient with the interaction strength G for the two cases of spin-flip scattering (SFS) and no spin-flip scattering (NSFS).

The second important feature which Fig. 2 exhibits and was mentioned above but not emphasized is that T_d also shows an interference pattern (AB oscillations with a flux periodicity of $2\pi\phi_0$) in the SFS case. This seems to contradict the naive expectation that a spin-flip would amount to path detection and therefore one should not, in principle, observe any interference pattern for spin-down component of transmission. Realizing that the above expectation rests on the belief that only two forward propagating partial waves, one in each arm of the ring, produce the interference pattern, helps to clarify the situation. In the present geometry there are infinitely many partial waves, owing their existence to the multiple reflections induced by the reflection and transmission at the junctions J1, J2 and impurity site, which superimpose to produce the interference pattern. To clarify the point further consider just one possible path that the electron could take out of the infinitely many. The incident spin-up electron moving in the upper arm of the ring gets spin-flipped and reflected at the impurity and finally traverses the lower arm. This partial wave will then interfere with the spin-flipped component transmitted across the impurity in the upper arm to give rise to an interference pattern for T_d. Thus the multiple reflections erase the "which-path" information. Naturally, then the question arises - will we still observe dephasing in such a situation. Figure 4 answers the question in the affirmative. The signature of dephasing is that the amplitude of AB oscillations of total transmission coefficient (or visibility factor) for the SFS case is always smaller than that for the NSFS case for all non-zero values of interaction strength G. For $G = 10.0$, by comparing the $T_{\rm SFS}$ with the $T_{\rm NSFS}$ reduction of amplitude can be seen explicitly from Fig. 2. The reduction in the amplitude of oscillations of the SFS case as compared to the NSFS case indicates dephasing. Thus we see that the spin-flipper acts as a dephasor.

4. Summary

In summary, we have studied the electron transmission across a AB-ring geometry with a spin half impurity in one arm of the ring using the quantum waveguide theory. The electron interacts with the impurity via an exchange interaction. The naive expectation of vanishing of interference pattern for the spin-down transmission due to which-path detection is to be modified in the light of the important role played by multiple reflections. The reduction in the amplitude of oscillations of the total transmission coefficient for SFS in comparison to that for NSFS, clearly brings out the feature of dephasing in this simple model. Moreover, it is important to note that the dephasing in this model is in the absence of any inelastic scattering. The study also reveals the asymmetric nature of the spin-polarized transport as against the symmetric two probe conductance. Our further studies[13] have shown that such a dephasor is not able to suppress the other well known quantum effect namely, the current magnification[3,6]. We believe that this effect will be suppressed only in the presence of inelastic scattering. Further work in regard to transport properties and additional resonances due to spin-flip is in progress.

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