PHYSICAL REVIEW B **66**, 075312 (2002)

Spin-fluctuation-induced dephasing in a mesoscopic ring

Kicheon Kang,[1] Sam Young Cho,[2] and Kyoung Wan Park[1]
[1]*Basic Research Laboratory, Electronics and Telecommunications Research Institute, Taejon 305-350, Korea*
[2]*Department of Physics, University of Queensland, Brisbane 4072, Australia*
(Received 8 April 2002; published 5 August 2002)

We investigate the persistent current in a hybrid Aharonov-Bohm ring–quantum-dot system coupled to a reservoir which provides spin fluctuations. It is shown that the spin exchange interaction between the quantum dot and the reservoir induces dephasing in the absence of direct charge transfer. We demonstrate an anomalous nature of this spin-fluctuation-induced dephasing which tends to *enhance* the persistent current. We explain our result in terms of the separation of the spin and the charge degrees of freedom. The nature of the spin-fluctuation-induced dephasing is analyzed in detail.

DOI: 10.1103/PhysRevB.66.075312 PACS number(s): 73.23.Ra, 72.15.Qm, 73.23.Hk

Persistent current (PC) in a mesoscopic Aharonov-Bohm (AB) ring is an ideal probe of the quantum coherence of electron motion in the equilibrium state.[1] Usually the PC is likely to be suppressed by various dephasing processes. The role of intrinsic dephasing at low temperature has not been well understood until now.[2] An alternative viewpoint to this is to introduce an artificial dephasor, in order to study the effect of decoherence in a controlled manner.[3] A conceptually simple but instructive example for that purpose is an AB ring attached to an electron reservoir which exchanges charges with the ring.[4] In the reservoir electrons are scattered inelastically and there is no phase coherence between electrons absorbed and those emitted by the reservoir. Therefore charge transfer between the ring and reservoir diminishes the coherence and thus the AB oscillation. On the other hand, the effect of spin exchange interactions on the PC has been attracting growing interest in recent years.[5–11] It has been proposed that the spin fluctuation affects the PC in a drastically different manner compared to the case of charge fluctuation.[6–8,12] Experimentally, the role of coherent spin fluctuation has been investigated by transport measurements using an AB interferometer setup.[15,16]

In this paper, we address the effect of dephasing induced by spin fluctuations. For this purpose we consider the geometry schematically drawn in Fig. 1, where the spin fluctuation between the ring and reservoir is mediated via antiferromagnetic exchange interactions with the quantum dot (QD), while direct charge transfer is prohibited by the Coulomb blockade. We find a counterintuitive result that the dephasing tends to *enhance* the PC rather than to reduce it in this geometry. We argue that this enhancement can be regarded as a signature of the separation of the spin and charge degrees of freedom. Our geometry can be realized in the experiment, for, e.g., by using a two-dimensional electrons gas (2DEG) system combined with nanofabrication. Actually, a persistent current setup containing an external reservoir (without quantum dot) was realized in some previous experiments.[17,18]

Our model is described by the Hamiltonian

$$H=H_0+H_R+T, \tag{1}$$

where H_0, H_R, and T stand for the hybrid dot-ring system, reservoir, and tunneling between the QD and reservoir, respectively. H_0 is decomposed into the three parts as

$$H_0=H_{QD}+H_{ring}+H_{t'}, \tag{2}$$

where H_{QD}, H_{ring}, and $H_{t'}$ correspond to the Hamiltonians describing the quantum dot, the AB ring, and the dot-ring hybridization, respectively:

$$H_{QD}=\sum_{\sigma} \varepsilon_d d_{\sigma}^{\dagger} d_{\sigma}+U n_{\uparrow} n_{\downarrow}, \tag{3a}$$

$$H_{ring}=-t\sum_{j=1}^{N}\sum_{\sigma} (e^{i\varphi/N} c_{j\sigma}^{\dagger} c_{j+1\sigma}+\text{H.c.}), \tag{3b}$$

$$H_{t'}=-t'\sum_{\sigma} (d_{\sigma}^{\dagger} c_{0\sigma}+c_{0\sigma}^{\dagger} d_{\sigma}). \tag{3c}$$

Here, we describe the ring by using a tight-binding Hamiltonian with N lattice sites, and the QD by a single Anderson impurity. The single-particle energy and on-site Coulomb repulsion in the QD are represented by ε_d and U, respectively. The phase φ in Eq. (3b) comes from the AB flux and is defined by $\varphi=2\pi\Phi/\Phi_0$, where Φ and Φ_0 are the external flux and the flux quantum $(=hc/e)$, respectively. Note that Eq. (3b) can be diagonalized and the corresponding eigenvalues are given by $-2t\cos[(1/N)(2\pi m-\varphi)]$ (m being an integer number). The reservoir is modeled by a Fermi sea of electrons with single-particle energies $\{E_k\}$:

$$H_R=\sum_{k\sigma} E_k a_{k\sigma}^{\dagger} a_{k\sigma}. \tag{4}$$

Finally, the coupling between the QD and reservoir is given by a tunneling Hamiltonian

$$T=\sum_{k\sigma} \tau_k (a_{k\sigma}^{\dagger} d_{\sigma}+\text{H.c.}). \tag{5}$$

The hopping strengths of the reservoir-dot and ring-dot systems are represented by Γ_R and Γ', respectively. Γ_R, assumed to be constant at the energy interval of $-D<\varepsilon<D$, is defined as

$$\Gamma_R=\pi\rho_R(\varepsilon)|\tau(\varepsilon)|^2, \tag{6}$$

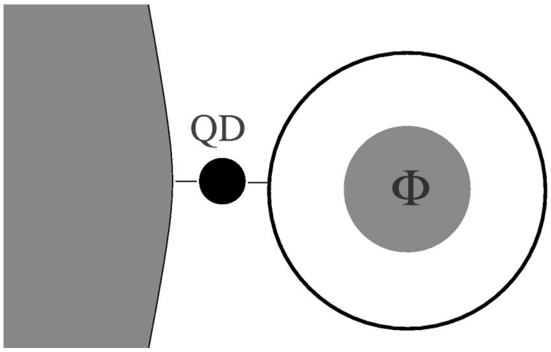

FIG. 1. Schematic diagram of the hybrid quantum-dot–AB-ring structure coupled to a reservoir.

where ρ_R and τ represent the density of states in the reservoir and the tunneling amplitude between the reservoir and QD. For the half-filled case (where the Fermi energy is set to be zero) in the continuum limit, Γ' can be simply written as[12]

$$\Gamma' = \frac{t'^2}{2t}, \tag{7}$$

and the level discreteness at the Fermi energy is given by

$$\delta = \frac{2\pi t}{N}. \tag{8}$$

Our study is restricted to the simplest half-filled case, which does not affect the result and conclusion we will draw.

To rule out the effect of charge fluctuation, we consider the parameter limit of $-\varepsilon_d, \varepsilon_d + U \gg \Gamma' + \Gamma_R$. In the absence of the reservoir, the Bethe ansatz result[7] shows that the PC is not affected by the QD in the Kondo limit with $\delta/T_K \to 0$, where T_K stands for the Kondo energy scale. For a finite value of δ/T_K, the coupling of the ring to the QD linearly reduces the PC as a function of δ/T_K for small δ/T_K and induces a crossover from the continuum Kondo limit ($\delta/T_K \ll 1$) to an effectively decoupled ring-dot system ($\delta/T_K \gg 1$).[8]

To calculate the PC in the presence of the reservoir, we adopt the leading order $1/N_s$ expansion with N_s being the magnetic degeneracy. This approach was shown to describe well the essence of the Kondo correlation preserving the Fermi liquid properties.[13] In addition, for the ring-dot system without reservoir, this approximation reproduces the rigorous Bethe ansatz result for $\delta/T_K \to 0$.[8]

Here it should be noted that there has been some disagreement concerning the behavior of the PC of ring-dot system in the $\delta/T_K \to 0$ limit. Some authors[9] obtained a contradictory result to ours and the Bethe ansatz one, based on a renormalization group (RG) argument combined with the assumption that the PC can be obtained as if it were a transport current. A slave-boson mean-field treatment gives a similar result.[10] The details of the disagreement are well summarized in Refs. 19–21. In a recent Comment[20] the authors doubt the Bethe ansatz result of Ref. 7 based on their RG result. But the authors of the Reply[21] point out that the assumption made in a RG result (that the PC can be calculated if it were the transport current) would not be valid in an interacting system. (At best its validity was never proved.) In their debates, they conclude that large-scale simulations are required for further clarification. However, there is a numerical result based on cluster diagonalization[11] which supports the $1/N_s$ and Bethe ansatz results. Though the discrepancy has not been completely settled yet, our treatment is strongly supported by rigorous treatments (Bethe ansatz, numerical simulation).

We consider the infinite-U limit since the consideration of finite U and double occupancy in the QD does not provide any modification to the renormalized physical quantities.[14] Then the problem is reduced to solving the self-consistent equation

$$E'_G = \frac{\Gamma'}{\pi}\delta \sum_{m\sigma} \frac{f(\varepsilon_m)}{E'_G + \varepsilon_m - \varepsilon_d} + \sum_{k\sigma} \frac{f(E_k)|\tau_k|^2}{E'_G + E_k - \varepsilon_d}, \tag{9}$$

where $f(\varepsilon)$ is the Fermi distribution function and $E'_G \equiv E_G - E_\Omega$, where E_Ω is the energy of the ground state without tunneling. E_G corresponds to the ground-state energy of the coupled system at zero temperature.

At zero temperature the second term of Eq. (9) can be calculated analytically and the latter is rewritten as

$$E'_G = 2\frac{\Gamma'}{\pi}\delta \sum_{\varepsilon_m<0} \frac{1}{E'_G + \varepsilon_m - \varepsilon_d} + \frac{2\Gamma_R}{\pi} \ln \frac{\varepsilon_d - E'_G}{D}. \tag{10}$$

The PC is defined in terms of the phase sensitivity of the ground-state energy as

$$I(\varphi) = -\frac{e}{\hbar}\frac{\partial E_G}{\partial \varphi}. \tag{11}$$

Combining Eq. (11) with Eq. (10), the PC can be expressed as the sum of two terms I_{ring} and I_{int} originating from the ideal ring and interactions, respectively:

$$I(\varphi) = I_{ring}(\varphi) + I_{int}(\varphi), \tag{12a}$$

$$I_{ring}(\varphi) = 2\sum_{\varepsilon_m<0} I_m(\varphi), \tag{12b}$$

$$I_{int}(\varphi) = -2\frac{\Gamma'}{\pi}\delta \mathcal{Z} \sum_{\varepsilon_m<0} \frac{1}{E'_G + \varepsilon_m - \varepsilon_d} I_m(\varphi), \tag{12c}$$

where

$$I_m(\varphi) = -\frac{e}{\hbar}\frac{\partial \varepsilon_m}{\partial \varphi} \tag{12d}$$

is the contribution to the PC from the bare ring energy level ε_m and

$$\mathcal{Z} = \left(1 + 2\frac{\Gamma'}{\pi}\delta \sum_{\varepsilon_m<0} \frac{1}{(E'_G + \varepsilon_m - \varepsilon_d)^2} + \frac{2\Gamma_R}{\pi}\frac{1}{\varepsilon_d - E'_G}\right)^{-1} \tag{12e}$$

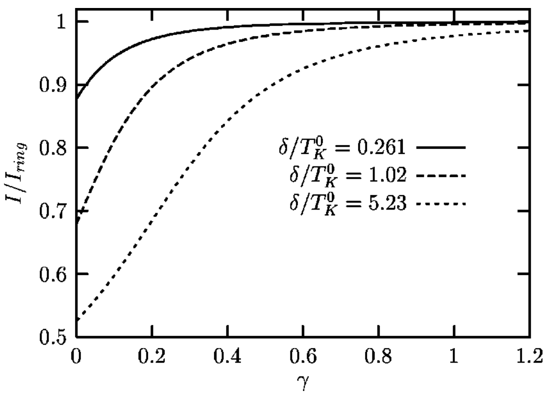

FIG. 2. Persistent current as a function of the renormalized coupling strength of the reservoir to the QD (γ) for $\Gamma'=0.125t$, $\varepsilon_d=-0.7t$, and $\varphi=0.1\pi$ with several values of δ/T_K^0.

corresponds to the renormalization constant for the ground state. Note the negative sign on the right-hand side of Eq. (12c) which leads to a reduction of the PC for finite values of δ/T_K.

Figure 2 displays the effect of the coupling to the reservoir on the PC. The PC is plotted as a function of the dimensionless coupling strength γ defined by

$$\gamma \equiv \Gamma_R/\Gamma'. \tag{13}$$

Note that the PC is a universal function of γ, φ, and δ/T_K^0, which does not depend on the parameter detail chosen here. T_K^0 in the figure denotes the Kondo energy scale in the absence of a coupling to the reservoir ($\Gamma_R=0$) for $\delta\to 0$ (while T_K stands for the counterpart including the reservoir). First, one should recall that for $\Gamma_R=0$ the PC is reduced to I_{ring} in the continuum limit ($\delta \ll T_K^0$) and is suppressed for finite values of δ/T_K^0.[8] It will be natural to believe that the reservoir would reduce the AB oscillation since it is expected to play the same role as a charge reservoir which induces decoherence. However, the result is *opposite* to this simple expectation. Coupling to the reservoir *enhances* the PC as shown for several values of δ/T_K^0. As γ increases, the PC is enhanced and eventually it saturates to I_{ring} for sufficiently large γ.

This anomalous result is interpreted as follows. Instead of reducing the PC, coupling to the reservoir suppresses I_{int} only, the contribution originating from the spin exchange interactions. This causes a net increase of the PC because the direction I_{int} is opposite to I_{ring}. (This point was addressed in Ref. 8 for a system without a reservoir.) This is a unique signature that the spin and the charge degrees of freedom are decoupled. That is, the reservoir degrades the coherence of the spin degree of freedom (I_{int}) only, while it does not affect the charge one (I_{ring}).

To be more precise, the influence of the reservoir on the system can be classified into two factors. (i) Increase of the Kondo binding energy: As the coupling turns on, the effective spin exchange interactions between the electrons in the QD and the conduction electrons increase. This results in the enhancement of the binding energy (or reducing the size of the Kondo screening cloud). (ii) Decoherence of electrons: The Kondo scattering provides effective charge flow between

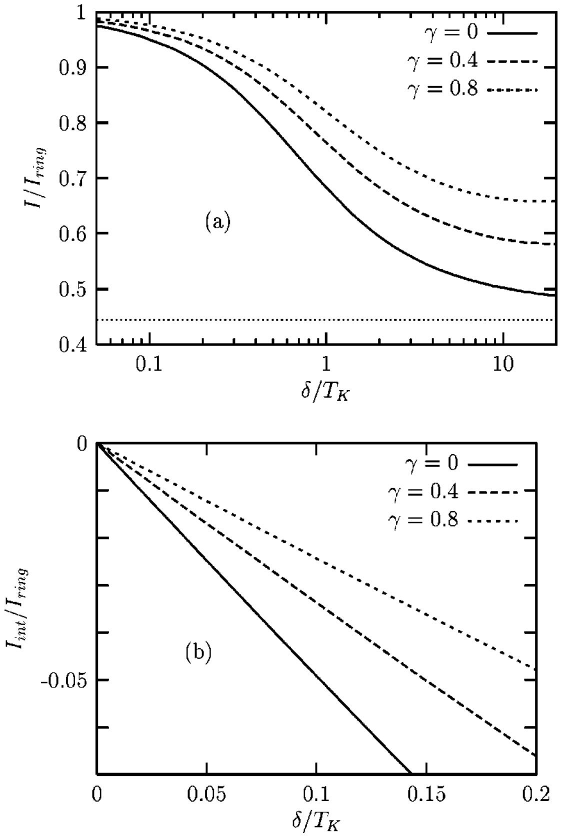

FIG. 3. (a) Persistent current as a function of the renormalized level spacing (δ/T_K) for three different values of γ. Other parameters are given the same as those in Fig. 2. The dotted line indicates the PC of the ideal ring with one electron subtracted. (For $\varphi=0.1\pi$, it corresponds to $\frac{4}{9}I_{ring}$.) (b) Interaction contribution to the persistent current for the same parameters.

the ring and reservoir. Since the electrons in the reservoir are scattered inelastically, no phase coherence exists between the electrons absorbed and those emitted by the reservoir. This feature has never been addressed before in the Kondo limit.

Both effects [(i) and (ii)] are present in the result of Fig. 2. The effect of enhanced Kondo binding energy is not a unique feature of our geometry. That is, the energy scale is modified by changing other parameters as well, and it can be well understood in terms of the renormalized energy scale T_K. In order to extract the dephasing effect, we show the PC as a function of δ/T_K for three different values of γ in Fig. 3(a). Effect (i) is already included in the renormalized parameter δ/T_K with γ-dependent T_K. The PC displays a crossover at $\delta/T_K\sim 1$ from the Kondo limit ($\delta/T_K\ll 1$) to the effectively decoupled limit ($\delta/T_K \gg 1$), regardless of the coupling to the reservoir. For large δ/T_K the PC saturates to a value which corresponds to that of an ideal ring with one electron subtracted from the present system (denoted by the dotted line). This demonstrates the effective decoupling of the ring from the rest of the system.

Here we point out that the PC increases as γ increases even after subtracting the effect of rescaled Kondo energy, as shown in Fig. 3(a). This demonstrates the anomalous nature of the Kondo-assisted dephasing that enhances AB oscilla-

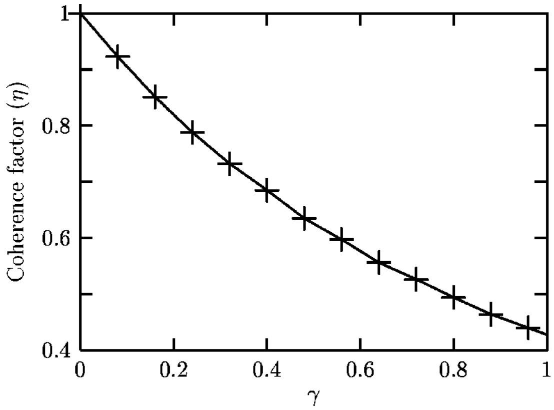

FIG. 4. Coherence factor [defined in Eq. (14)] as a function of γ.

tions. That is, the dephasing influences only the interaction part of the current, I_{int}, through the spin-fluctuation channel, which results in a net increase of the PC. This property is analyzed in more detail in Fig. 3(b). For small δ/T_K, I_{int}/I_{ring} shows γ-dependent linear behavior as $I_{int}/I_{ring} = -c(\gamma)\delta/T_K$, where $c(\gamma)>0$. One can see that the slope $c(\gamma)$ decreases as γ increases. The reduction of the slope as a function of γ is the result of dephasing through spin exchange interactions.

To complete our discussion it is instructive define the coherence factor η associated with the spin-fluctuation-induced dephasing by the ratio

$$\eta \equiv \frac{c(\gamma)}{c(0)}. \tag{14}$$

The coherence factor (Fig. 4) decreases monotonically as γ increases. This is a manifestation of decoherence mediated by the spin fluctuations. This behavior is quite universal, independent of any parameter detail.

In conclusion, we have investigated the effect of reservoir coupled to a composite AB-ring–QD system on the PC. In the Coulomb blockade limit, spin fluctuations induce decoherence of the system in an anomalous way. The persistent current circulating the ring is enhanced due to dephasing in the Kondo limit. We have argued that this enhancement is closely related to the separation of spin from the charge degree of freedom.

This work has been supported by the National Research Laboratory program of the Korean Ministry of Science and Technology and also by the Korean Ministry of Information and Communication.

[1] M. Büttiker, Y. Imry, and R. Landauer, Phys. Lett. **96A**, 365 (1983); Y. Imry, *Introduction to Mesoscopic Physics* (Oxford University Press, Oxford, 1997).

[2] See, e.g., P. Mohanty, E.M.Q. Jariwala, and R.A. Webb, Phys. Rev. Lett. **78**, 3366 (1997), and related references.

[3] E. Buks *et al.*, Nature (London) **391**, 871 (1998); D. Sprinzak *et al.*, Phys. Rev. Lett. **84**, 5820 (2000).

[4] M. Büttikker, Phys. Rev. B **32**, 1846 (1985).

[5] V. Ferrari, G. Chiappe, E.V. Anda, and M.A. Davidovich, Phys. Rev. Lett. **82**, 5088 (1999).

[6] K. Kang and S.-C. Shin, Phys. Rev. Lett. **85**, 5619 (2000); J. Korean Phys. Soc. **37**, 145 (2000).

[7] H.-P. Eckle, H. Johannesson, and C.A. Stafford, Phys. Rev. Lett. **87**, 016602 (2001).

[8] S.Y. Cho, K. Kang, C.K. Kim, and C.-M. Ryu, Phys. Rev. B **64**, 033314 (2001).

[9] I. Affleck and P. Simon, Phys. Rev. Lett. **86**, 2854 (2001); P. Simon and I. Affleck, Phys. Rev. B **64**, 085308 (2001).

[10] H. Hu, G.-M. Zhang, and L. Yu, Phys. Rev. Lett. **86**, 5558 (2001).

[11] E.V. Anda, C. Busser, G. Chiappe, and M.A. Davidovich, Phys. Rev. B **66**, 035307 (2002).

[12] K. Kang, S.Y. Cho, and J.-J. Kim, Phys. Rev. B **65**, 153303 (2002).

[13] For a review, see. e.g., A. C. Hewson, *The Kondo Problem to Heavy Fermions* (Cambridge University Press, Cambridge, England, 1993).

[14] See, e.g., K. Kang and B.I. Min, Phys. Rev. B **54**, 1645 (1996).

[15] W.G. van der Wiel, S. De Franceschi, T. Fujisawa, J.M. Elzerman, S. Tarucha, and L.P. Kouwenhoven, Science **289**, 2105 (2000).

[16] Y. Ji, M. Heiblum, D. Sprinzak, D. Mahalu, and H. Shtrikman, Science **290**, 779 (2000); Y. Ji, M. Heiblum, and H. Shtrikman, Phys. Rev. Lett. **88**, 076601 (2002).

[17] D. Maily, C. Chapelier, and A. Benoit, Phys. Rev. Lett. **70**, 2020 (1993).

[18] W. Rabaud, L. Saminadayar, D. Maily, K. Hasselbach, A. Benoit, and B. Etienne, Phys. Rev. Lett. **86**, 3124 (2001).

[19] K. Kang and S.Y. Cho, Phys. Rev. Lett. **87**, 179705 (2001).

[20] I. Affleck and P. Simon, Phys. Rev. Lett. **88**, 139701 (2002).

[21] H.-P. Eckle, H. Johannesson, and C.A. Stafford, Phys. Rev. Lett. **88**, 139702 (2002).