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Transport currents and persistent currents in a mesoscopic loop connected with two reservoirs with two superconducting mirrors

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Abstract. We have studied the effect of the Andreev reflection on transport currents and persistent currents in a normal-metallic loop connected to two normal metals with two superconducting mirrors. It consists of two parts, one contributed by electrons and one by holes. The transport currents are periodic with a period equal to half a flux quantum, $\phi_0/2$, in addition to being periodic with a period equal to a single flux quantum, ϕ_0, in the threading magnetic flux when the strength of the barriers at the normal-metal–superconductor interfaces is finite. This result is consistent with earlier experiments. The persistent currents have a period equal to a flux quantum, ϕ_0, in any case. The absolute values of the hole parts have sharp peaks at the gap edge and decrease to zero as the barrier strength increases to infinity, but those of the electronic parts reach a minimum and a constant respectively for these two cases.

1. Introduction

Recently, there have been many experimental [1–7] and theoretical [8–18] studies of mesoscopic devices with superconducting regions. Most of them focused on normal-metal–superconductor (NS) junctions and they have helped to revive interest in this area. At low temperature, quasiparticles cannot tunnel into the superconductor from the metal. In this case, the transport properties of the system are determined by the tunnelling of electron pairs, which is known as Andreev reflection [35]. This reflection transforms an electron on the N side to a Cooper pair on the S side plus a hole reacting with the electron path on the N side (and vice versa for a hole-to-electron transformation). This process produces a phase shift proportional to the superconducting phase. The conductivity of a normal metal connected to two superconductors depends on the superconducting phase difference established between them. It has been found that the magnetoresistance for rings with two S boundaries which are not across the paths of the current flow is not just periodic with the period ϕ_0 but also periodic with the period $\phi_0/2$ (ϕ_0 is the magnetic flux quantum: $\phi_0 = h/2e$), and the amplitude of the Aharonov–Bohm [21] ϕ_0-oscillations is enhanced by a factor of more than 100 [2]. The magneto-oscillations in the conductance with period ϕ_0 have been observed in many experiments, but not those with period $\phi_0/2$ [2, 3, 7, 5]. The periodicity with the period ϕ_0 indicates that the conductance displays a component in the superconducting phase difference with period 2π. The oscillations with period $\phi_0/2$ indicate that the conductance has a component with period π. The enhancement cannot be

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interpreted to be due to the weak localization consisting in electron coherent backscattering along a closed diffusion path [3]. Courtois *et al* [7] studied the crossover between the low-temperature Josephson coupling and a phase-sensitive conductance enhancement at high temperature. This phase-sensitive contribution has a larger amplitude compared to the weak localization and a different origin. Dimoulas *et al* [5] also observed that the conductance is sensitive to the phase difference. In the diffusive transport regime, the theoretical results [9, 13] on the position and the amplitude of the conductance oscillations agree with experiments. Beenakker *et al* [18] predicted an order-G/G_0 (where G is the conductance of the junction and $G_0 = 2e^2/h$) enhancement of the coherent backscattering caused by a disordered metal being connected to a superconductor. This enhancement is greater than the weak-localization correction and provided ballistic point contacts. The ballistic transport regime has been analysed theoretically [14, 16] and giant conductance oscillations in mesoscopic Andreev interferometers have been predicted. In reference [14], the authors suggested that giant conductance peaks are produced when the $(2n + 1)\pi$ superconducting phase differences make $N_\perp$ Andreev levels in line with the Fermi energy, and they found that the amplitude of the giant oscillations is of the order of $N_\perp e^2/h \gg e^2/h$ ($N_\perp$ is the number of Andreev levels). Hence the results of reference [16] provide another mechanism by which a normal barrier at the NS interface or a broken crucial sum rule can produce giant conductance oscillations, leading to the conductance being at its minimum at zero phase difference and at its maximum at π phase difference. In this paper, we study the effect of quantum interference on the transport currents and persistent currents in a mesoscopic loop connected to two electronic reservoirs with two S mirrors by means of waveguide theory.

The persistent current can flow in a small metallic loop when it is threaded by a magnetic flux. This is a manifestation of pure quantum mechanical effects. The existence of persistent currents in an ordered one-dimensional ring threaded by a magnetic flux was predicted by Büttiker *et al* [19] in 1983 and proved by Lévy *et al* [20] in 1990. It is an obvious demonstration of the Aharonov–Bohm [21] effect. As the dimensions of a conductor are reduced, the magnitude of the quantum contributions to its transport properties becomes very sensitive to the size. When it is comparable to or less than the characteristic lengths: the phase-breaking length $L_\phi = (D\tau_\phi)^{1/2}$ and the coherence length $L_T = (hD/k_BT)^{1/2}$ (τ_ϕ is the sum of the scattering rates at which the phase of an electron is disrupted; D is the electron diffusion constant), the phase memory of the electron is maintained throughout such a conductor. L_ϕ and L_T are of the order of 0.1–2 μm in metallic thin film at liquid-helium temperature. Hence, it is possible to fabricate a mesoscopic structure by means of multilayer lithography with a submicrometre precision of the alignment. The systems used to research persistent currents have mainly been isolated closed loops. In 1985, Büttiker [22] studied the persistent currents in an open system which was a small normal-metal loop coupled to an electron reservoir, and were the first to investigate the effect of that reservoir on the persistent currents in the loop. Recently, persistent currents in mesoscopic rings have been studied by many physicists [22–34]. Theoretical studies have variously focused on the evolution patterns of persistent currents versus the number of channels M, the elastic mean free path L_e, the localization length ξ and the coherence length L_ϕ in quasi-one-dimensional single- and multi-channel metallic rings [22–30]. In experiment, Lévy *et al* [20] found that the persistent current of each loop equals $10^{-2}ev_F/L$ with a period of ϕ_0 (v_F is the Fermi velocity, L is the loop's circumference and ϕ_0 is the elementary magnetic flux quantum) when the system is working in the diffusion region, by observing the magnetization of one copper ring with 10^7 loops. Their results are consistent with theory. In 1993, Mailly *et al* [31] found that the persistent current is equal to ev_F/L in a semiconductor ring of

GaAs/Al$_x$Ga$_{1-x}$As when the system is in the ballistic region, which is consistent with the theoretical predictions.

The structure of our system is more like that of the samples reported on by Petrashov *et al* [2] in 1993. Both Al and Pb–Au alloys were used as the superconductors (their superconducting transition temperatures T_c are 1.3 K and 6.2 K respectively) and Ag as the ring and leads. The widths of the wires were 90–200 nm, the thickness 50 nm and the diameter 0.6–1.0 μm. At temperatures of 0.002–1.2 K, $L_\phi \approx$ 1–2 μm and $L_T = 0.1$–0.8 μm. Hence the phase memory of the electron was maintained throughout this structure. In other words, the coherence length of the electrons and holes, L_ϕ, extends over a distance of the order of the phase-breaking length L_T when the elastic mean free lengths $l_e, l_h \ll L_\phi, L_T$. In this case, electron wave packets which carry current in the metal are coherent superpositions of electron and hole wave functions. The superconducting phase difference is controlled by an external magnetic field according to $\Delta\theta = 2\pi\phi/\phi_0$, where ϕ is the magnetic field flux penetrating the ring area and ϕ_0 is the magnetic flux quantum. In recent work [12], we have studied the persistent currents in a normal-metallic loop connected to a normal metal and a superconductor. They consist of two parts, one contributed by electrons and one by holes. The Andreev reflection is a dominant contributing factor in their production. They are periodic with a period equal to the flux quantum ϕ_0 in the threading magnetic flux and periodic with the period π in the length of the lead linking the loop and the superconductor. They have sharp peaks at the gap edge. The hole parts decrease to zero when the barrier strength rises to infinity. Also, all of the reservoirs connected to the loop are independent, so there is no quantum interference. In this paper, the system that we choose to study has two NS junctions and the Andreev interference will have an effect on the persistent currents and the transport currents. The magnetic field not only produces the persistent currents, but also controls the superconducting phase difference. Because in this paper we are mainly studying whether the oscillation with period $\phi_0/2$ exists, it is assumed that the loop is one dimensional and that quasiparticles transport in a single channel. We do not consider impurities, disorder, weak localization and temperature. Hence the conductance enhancement does not occur because the prerequisite for it is not fulfilled in the system [9, 13, 18, 14, 16]. However, the period $\phi_0/2$ is independent of the number of channels [2].

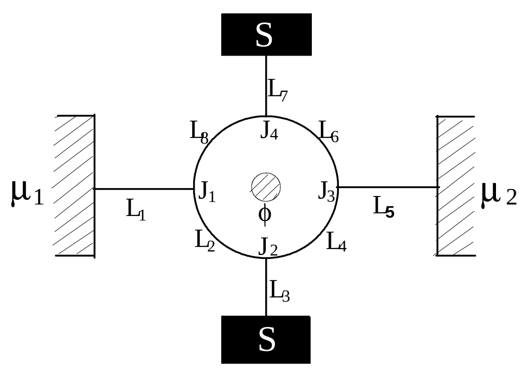

Figure 1. A one-dimensional normal-metallic loop connected to two normal metals with two superconducting mirrors. Two δ-function potentials with strength Z_0 exist at the two NS interfaces respectively. The structural parameters are chosen to be $L_3 = L_7 = 1$ and $L_2 = L_4 = L_6 = L_8 = 0.25$. The chemical potentials, μ_1 and μ_2, are chosen to be 1 for an equilibrium state and the gap Δ is chosen to be 0.01.

2. The theoretical method

Now we consider a one-dimensional metallic loop connected to two electronic reservoirs with two superconducting mirrors (see figure 1). The two reservoirs are normal metals with chemical potentials μ_1 and μ_2 respectively. There are two NS junctions where δ-function potentials with strength Z_0 exist. When μ_1 is greater than μ_2, a net current flows from the left N reservoir to the right N reservoir. In the presence of a transport current, a persistent current probably exists in the loop. We follow the method that we used in our recent work [12] to calculate the transport currents and the persistent currents. In the local coordinate system, the wave functions in the circuits L_1–L_8 shown in figure 1 can be written as

$$\begin{aligned}
\psi_1(x_1) &= \begin{pmatrix}1\\0\end{pmatrix} \mathrm{e}^{\mathrm{i}k^+x_1} + R_1^e \begin{pmatrix}1\\0\end{pmatrix} \mathrm{e}^{-\mathrm{i}k^+x_1} + R_1^h \begin{pmatrix}0\\1\end{pmatrix} \mathrm{e}^{\mathrm{i}k^-x_1} \\
\psi_i(x_i) &= A_i^e \begin{pmatrix}1\\0\end{pmatrix} \mathrm{e}^{\mathrm{i}k_1^+x_i} + B_i^e \begin{pmatrix}1\\0\end{pmatrix} \mathrm{e}^{-\mathrm{i}k_2^+x_i} + A_i^h \begin{pmatrix}0\\1\end{pmatrix} \mathrm{e}^{-\mathrm{i}k_1^-x_i} \\
&\quad + B_i^h \begin{pmatrix}0\\1\end{pmatrix} \mathrm{e}^{\mathrm{i}k_2^-x_i} \qquad (i = 2, 4, 6, 8) \\
\psi_i(x_i) &= T_i^e \begin{pmatrix}1\\0\end{pmatrix} \mathrm{e}^{\mathrm{i}k^+x_i} + T_i^e b^e \begin{pmatrix}1\\0\end{pmatrix} \mathrm{e}^{-\mathrm{i}k^+x_i} + T_i^e a^e \begin{pmatrix}0\\1\end{pmatrix} \mathrm{e}^{\mathrm{i}k^-x_i} + T_i^h \begin{pmatrix}0\\1\end{pmatrix} \mathrm{e}^{-\mathrm{i}k^-x_i} \\
&\quad + T_i^h b^h \begin{pmatrix}0\\1\end{pmatrix} \mathrm{e}^{\mathrm{i}k^-x_i} + T_i^h a^h \begin{pmatrix}1\\0\end{pmatrix} \mathrm{e}^{-\mathrm{i}k^+x_i} \qquad (i = 3, 7) \\
\psi_5(x_5) &= T_5^e \begin{pmatrix}1\\0\end{pmatrix} \mathrm{e}^{\mathrm{i}k^+x_5} + T_5^h \begin{pmatrix}0\\1\end{pmatrix} \mathrm{e}^{-\mathrm{i}k^-x_5}.
\end{aligned} \tag{1}$$

Here we use a two-component scheme to represent electrons and holes. The two elements are

$$\begin{pmatrix}1\\0\end{pmatrix} \qquad \text{and} \qquad \begin{pmatrix}0\\1\end{pmatrix}$$

which represent pure electrons and pure holes respectively. R_1^e and R_1^h are the reflection coefficients of electrons and holes which are reflected back to the left-hand reservoir. T_5^e and T_5^h are the transmission coefficients of electrons and holes which transmit to the right-hand reservoir. A_i^e, B_i^e, A_i^h and B_i^h ($i = 2, 4, 6$ and 8) are the amplitudes of all of the partial waves in the loop. T_i^e and T_i^h ($i = 3$ and 7) are the amplitudes of waves which transmit to the up and down leads connected to the loop and S. All of the coefficients are determined from the continuity of the wave functions and the conservation of the current density at the four junctions J_1, J_2, J_3 and J_4. k^+ and k^- are the wave vectors of the electrons and holes in the loop and leads, $\hbar k^\pm = \sqrt{2m(\mu_1 \pm E)}$ where m is the electronic mass and E is the kinetic energy of the incident electrons. $k_{1,2}^+$ and $k_{1,2}^-$ are the equivalent wave vectors when a magnetic flux penetrates the loop and destroys the time-reversal symmetry [36], $k_{1,2}^+ = k^+ \pm 2\pi\phi/L\phi_0$ and $k_{1,2}^- = k^- \mp 2\pi\phi/L\phi_0$. a^e and b^e are the reflection coefficients of holes and electrons for Andreev reflection when electrons are incident on the NS interface; a^h and b^h are those of electrons and holes when holes are incident on the NS interface. We calculate them using the method which Blonder *et al* [37] used to study Andreev reflection, using the expressions

$$a^e \approx \frac{4u_0v_0}{\Gamma} \tag{2}$$

$$b^e \approx -\frac{Z(Z+2\mathrm{i})(u_0^2 - v_0^2)}{\Gamma} \tag{3}$$

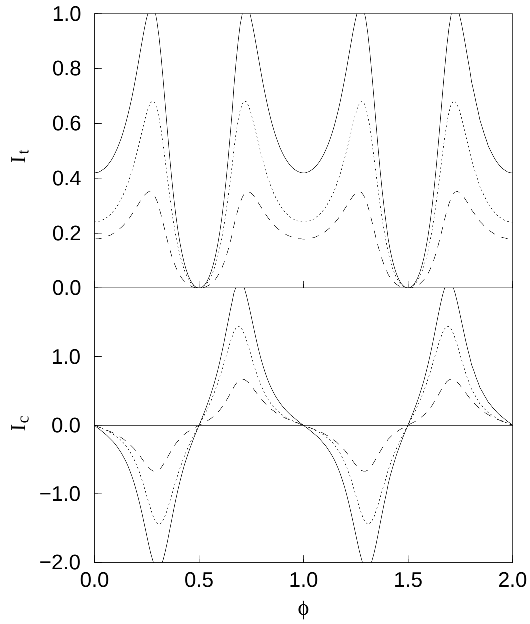

Figure 2. The transport current I_t and persistent current I_c as functions of the magnetic flux ϕ in units of ϕ_0 for $Z = 1$ and $E = 0.99\Delta$. The solid curves represent the transport current and the persistent current, the dotted curves represent their electronic parts and the dashed curves represent their hole parts (the same definitions hold for all of the figures below).

$$a^h \approx \frac{4u_0 v_0}{\Gamma} \tag{4}$$

$$b^h \approx -\frac{Z(Z-2\mathrm{i})(u_0^2 - v_0^2)}{\Gamma} \tag{5}$$

where

$$\Gamma \equiv 4u_0^2 + Z^2(u_0^2 - v_0^2) \tag{6}$$

and Z is the dimensionless barrier strength $Z = 2Z_0/\hbar v_F$ (v_F is the Fermi velocity). Also u_0 and v_0 are obtained by solving the Bogoliubov equations, $u_0^2 = 1 - v_0^2 = (1 - \sqrt{E^2 - \Delta^2}/E)/2$. Here Δ is the gap of S. Finally, we obtain a linear twenty-equation group and its numerical solutions. If the upper and lower arms of the structure are symmetric, the currents in them are equal when no magnetic field exists and circulating currents due to an imbalance are not produced. When a magnetic flux penetrates into the loop, the time-reversal symmetry is destroyed and persistent currents flow in the loop. At this time, the currents in the upper and lower arms are $I_{up} = I_0 - I_c$ and $I_{low} = I_0 + I_c$ respectively, where I_0 is the transport current from J_1 to J_3 in the two arms and I_c is the persistent current. It is easy to obtain $I_c = (I_{low} - I_{up})/2$. So the two parts of the persistent currents contributed by the electrons and holes are

$$I_c^e = \frac{e\hbar k^+}{8m} \sum_{i=2,4,6,8} (A_i^{e*} A_i^e - B_i^{e*} B_i^e) \tag{7}$$

and

$$I_c^h = -\frac{e\hbar k^-}{8m} \sum_{i=2,4,6,8} (A_i^{h*} A_i^h - B_i^{h*} B_i^h) \tag{8}$$

respectively. And the sum of the persistent currents is

$$I_c = I_c^e + I_c^h. \tag{9}$$

They have nonzero values only if the magnetic field exists. If the upper and lower arms are not symmetric, the persistent currents cannot be expressed by equations (7), (8) and (9) because these expressions indicate circulating currents due to the imbalance between the upper and lower arms. The two parts of the transport currents are

$$I_t^e = \frac{e\hbar k^+}{2m} T_5^{e*} T_5^e \tag{10}$$

and

$$I_t^h = \frac{e\hbar k^+}{2m} T_5^{h*} T_5^h \tag{11}$$

respectively. And the sum of the transport currents is

$$I_t = I_t^e + I_t^h. \tag{12}$$

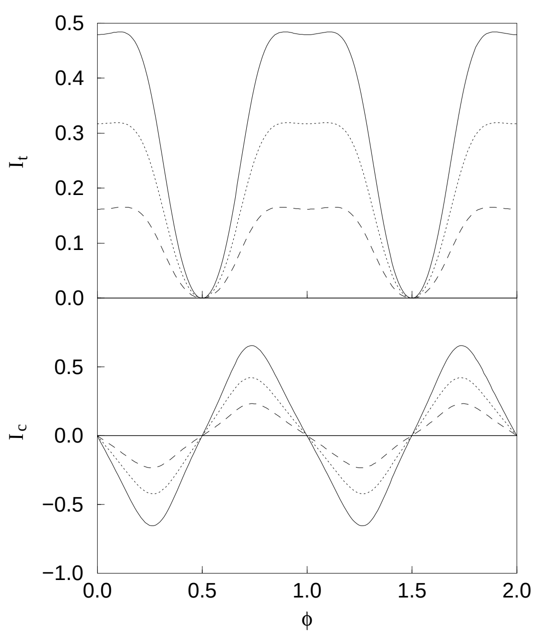

Figure 3. The transport current I_t and persistent current I_c versus the magnetic flux ϕ in units of ϕ_0 for $Z = 1$ and $E = 1.01\Delta$.

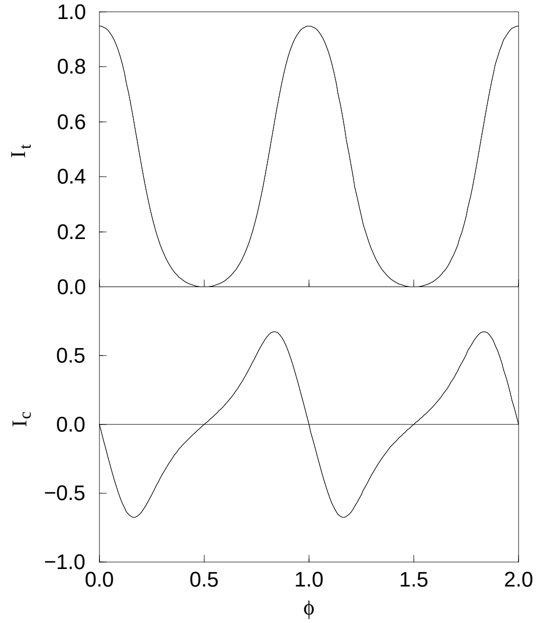

Figure 4. The transport current I_t and persistent current I_c versus the magnetic flux ϕ in units of ϕ_0 for $Z \to \infty$ and $E = 0.99\Delta$.

3. Results and discussion

In figures 2, 3 and 4, we plot the transport currents I_t and the persistent currents I_c as functions of the flux ϕ. We choose different incident energies $E = 0.99\Delta$ and 1.01Δ with the same barrier strength $Z = 1$ in figures 2 and 3. In figure 4, we choose the barrier strength $Z \to \infty$ and the incident energy $E = 0.99\Delta$. Oscillations with period $\phi_0/2$ of the transport currents are shown in addition to ϕ_0-oscillations in figures 2 and 3 but not in figure 4. The persistent currents in the loop each have the period ϕ in these three figures. From figures 2 and 3, we find that the transport currents I_t and the persistent currents I_c each consist of two parts for finite barrier strengths Z. One is contributed by electrons and the other is contributed by holes. The period $\phi_0/2$ and the hole currents totally originate from the Andreev reflection. Our results are consistent with those of reference [2] where the authors found a similarly drastic difference between the magnetoresistance of normal-metal (Ag) mesoscopic rings with superconducting boundaries (mirrors) and that of plain rings—the conductivity has periods $\phi_0/2$ and ϕ_0 in the former but only ϕ_0 in the latter. From figures 2 and 3, we find that the amplitude of the oscillations of period $\phi_0/2$ is very large when $E \to \Delta$ and nearly disappears when $E > \Delta$. The reason for this is that the Andreev reflection is strong when $E \to \Delta$ and depressed when $E > \Delta$. The Andreev reflection is completely depressed when $Z \to \infty$, so there is no period $\phi_0/2$ and no hole current in figure 4. We will discuss this in detail in the following paragraph.

We calculate the transport currents and the persistent currents versus the incident energy and the barrier strength (see figures 5 and 6). From figure 5, we find that they change quickly when E is close to Δ. The absolute values of the hole parts of the currents (not only of the transport currents but also of the persistent currents) have sharp peaks when $E \to \Delta$, but those of the electronic parts reach minima for that case. From figure 6, we see that the

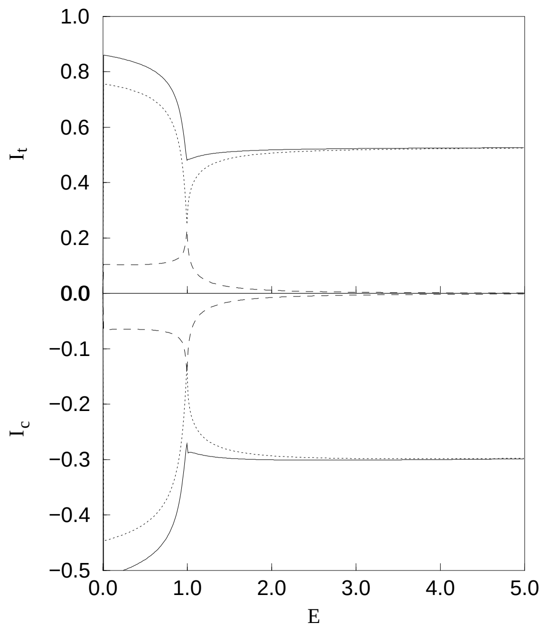

Figure 5. The transport current I_t and persistent current I_c as functions of the incident energy E in units of Δ for $Z = 1$ and $\phi = \phi_0/10$.

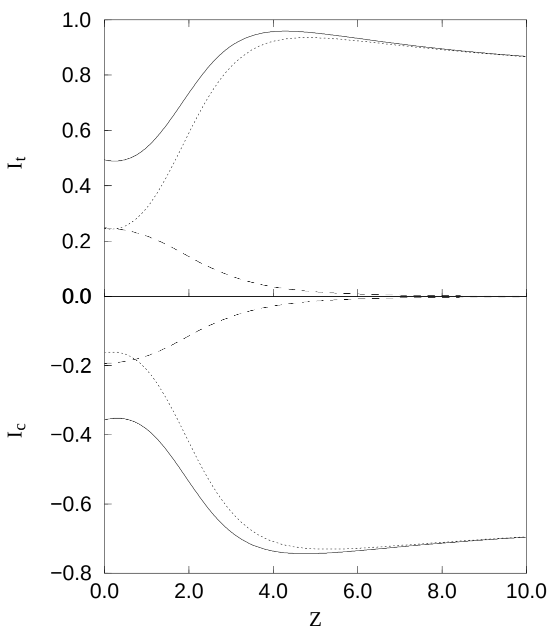

Figure 6. The transport current I_t and persistent current I_c versus the barrier strength Z for $\phi = \phi_0/8$ and $E = 0.99\Delta$.

hole parts of the currents decrease to zero but the electronic parts increase to a constant when $Z \to \infty$. The Andreev reflection is strongly dependent on the incident energy E and the barrier strength Z. The hole currents are produced by the Andreev reflection, so their values show the strength of the Andreev reflection. From formulae (2)–(5), we can obtain that $|a^e|^2 = |a^h|^2 = 1$ for $E < \Delta$ and $|a^e|^2 = |a^h|^2 = v_0^2/u_0^2$ for $E > \Delta$, and $|b^e|^2 = |b^h|^2 = 0$ for both cases without barriers ($Z = 0$); $|a^e|^2 = |a^h|^2 \approx \Delta^2/4Z^2(\Delta^2 - E^2)$ and $|b^e|^2 = |b^h|^2 \approx 1 - |a^e|^2$ for $E < \Delta$, and $|a^e|^2 = |a^h|^2 \approx u_0^2 v_0^2/Z^4(u_0^2 - v_0^2)^2$ and

$|b^e|^2 = |b^h|^2 \approx 1 - 1/Z^2(u_0^2 - v_0^2)$ for $E > \Delta$ with strong barriers ($Z^2(u_0^2 - v_0^2) \gg 1$) [37]. Therefore we can draw three conclusions. Firstly, the Andreev reflection is suddenly enhanced and the probability of pair tunnelling increases quickly when E is close to Δ. This can be obtained from formulae (2) and (4). The coefficients of the Andreev reflection, i.e., a^e and a^h, have sharp peaks at the gap edge for any finite barrier strength. More and more holes appear in the loop and leads as $E \to \Delta$ (see figure 5). When $E > \Delta$, the Andreev reflection begins to be depressed. So the amplitude of the oscillation with period $\phi_0/2$ becomes larger when E becomes close to the gap edge and nearly disappears when E goes beyond the gap edge (see figures 2 and 3). Secondly, when $Z \to \infty$, the reflection coefficient derived via the Andreev reflection, a^e, equals zero and the reflection coefficient of electrons, b^e, equals -1 according to formulae (2) and (3). So all electrons will be reflected back to the lead with an additional phase π when they are incident on the NS interface from the loop. So no hole arises and transports in the loop and leads in the whole process. Hence, the two superconducting mirrors seem to be two normal barriers with infinite strength and the Andreev reflection is completely depressed. Hence also, there is no oscillation of period $\phi_0/2$ of the transport current (see figure 4) and no hole current (either hole transport current or hole persistent current) flows in the system (see figures 4 and 6). Thirdly, the Andreev reflection appears most strongly when $Z = 0$. No electron (hole) will be reflected back to the leads when electrons (holes) are incident on the NS interface. Correspondingly, one hole (electron) will arise when one electron (hole) is incident on the NS interface for $E < \Delta$ because all particles tunnel to S in the form of Cooper pairs, not singles. For $E > \Delta$, although a few single particles can tunnel to S, the pair tunnelling is dominant. So the number of holes is considerable compared with that of electrons. The electrons and holes transport in circuits continuously and scatter at junctions repeatedly. The absolute values of the hole transport currents and the hole persistent currents reach their maxima at the point $Z = 0$ and decrease when Z rises, but those for the electrons exhibit opposite evolution patterns (see figure 6).

4. Conclusion

We have studied the transport currents and the persistent currents in a normal-metallic loop connected to two normal metals with two superconducting mirrors. They consist of two parts, one contributed by electrons and one by holes, and are strongly affected by the Andreev reflection. We found that an oscillation with a period of $\phi_0/2$ in addition to one with period ϕ_0 (ϕ_0 is the flux quantum) in the transport currents exists when the strength of the barriers at the NS interfaces is finite, but only oscillations with period ϕ_0 occur in the persistent currents. This finding is consistent with earlier experiments. The hole parts and the electronic parts of the transport currents and the persistent currents change differently as the incident energy and the barrier strength change. The absolute values of the hole parts have sharp peaks at the gap edge and decrease to zero as the barrier strength rises to infinity. But the absolute values of electronic parts are at their minima at the gap edge and increase to constants as the barrier strength rises to infinity. We extended the study on persistent currents to a system which has two coherent carriers, and our results are different from others which were derived for cases with no NS interface. The transport currents have been measured by experiments. We think that the persistent currents could also be investigated by experiments and that their two parts (electronic and hole) could be separated by recourse to their different properties. Our method is suitable for studying the persistent currents because we have used it to obtain the same results for transport currents as have been obtained in experiments. The Andreev reflection will always occur when the NS interface exists. Therefore, most of the conclusions on the effect of the Andreev reflection on the transport currents and the persistent currents reached in this paper can be extended to other systems that have NS interfaces.

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