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Temperature-dependent transport characteristics of quasiballistic normal-metal–superconductor junctions

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We study the temperature effect on the zero-bias conductance and current fluctuations in a two-terminal heterostructure with a mesoscopic normal region connected to normal and superconducting reservoirs. For a quasiballistic regime, the shape of the conductance-voltage characteristic and its temperature behavior for an *s*-wave superconductor strongly depends on the transmission properties of the normal interlayer. On the contrary, in the low-frequency limit, the near-zero-voltage current noise power versus temperature is insensitive to the nature of the transition region but dramatically changes for different pairing states of the superconducting electrode. The relevant experiment could serve as a diagnostic tool to identify the symmetry of the superconducting order parameter in high-temperature superconductors.

Phase-coherent transport through a mesoscopic region between a normal (N) and a superconducting (S) reservoir has drawn great interest recently.[1] From the experimental point of view, it would be desirable to have some diagnostic measurements that could characterize the properties of the mesoscopic inhomogeneous interlayer, as well as those of the superconducting electrode. In this paper we discuss two possible tests of such kind: the temperature effect on the zero-bias differential conductance $G_0(T)=G(V=0,T)$, and the zero-frequency current noise power $S_I(\overline{V},T)$ versus T for a fixed voltage $\overline{V}$ near $V=0$. Dealing with these characteristics, we would like to avoid unnecessary complications that could arise for a junction driven out of equilibrium as a result of the distribution function changes,[2] or as a heating effect. Because the main contribution to the quantities to be studied comes from the energies near the Fermi level, we are able to perform the calculations along the lines of our non-self-consistent approach to the quasiballistic transport in an inhomogeneous superconducting heterostructure.[3]

The temperature behavior of $G_0(T)$ for a clean two-terminal normal-metal - *s*-wave superconductor contact was analyzed by Blonder, Tinkham, and Klapwijk[4] within a simple model where the scattering at the N-S interface was characterized by the dimensionless barrier strength $Z=\int H(x)dx/\hbar v_{Fx}$, where $H(x)$ is the repulsive potential of the delta-functional form, the x axis is perpendicular to the junction interface, and v_{Fx} is the corresponding Fermi-velocity component. The model[4] predicts significant changes of $G_0(T)$ for various barrier strengths: from a broad maximum around $T=0$ for a direct N-S contact (Z is nearly zero) to a minimum at zero temperature for a tunnel junction ($Z \gg 1$). According to Ref. 4, in an intermediate case ($Z\sim 1$) this minimum is accompanied with a local maximum near the critical temperature T_c. The same maximum was obtained in Ref. 5 in the diffusive regime limit when the relevant correlation energy $E_c=\hbar D/l^2$ (D is the diffusion constant) in a disordered normal conductor of the length l is much greater than the zero-temperature superconducting energy gap $\Delta_0=\Delta(T=0)$. Recently, it was shown[6] that when E_c is lower than Δ_0 and both sides of the N-S contact are weakly coupled a similar near-T_c peak occurs together with a low-temperature peak at k_BT comparable with E_c.[7,8]

In what follows, we will show that all these features are well reproduced and easily interpreted within the approach used in Ref. 3. In our model the multimode heterogeneous N-I-N'/S structure to be studied consists of a normal-metal injector (N), an insulating barrier (I) of a strength Z_L, a thin normal interlayer (N') where the interference effects take place, and a superconducting bulk with an N'/S interface characterized by the scattering parameter Z_R. To make the calculations closer to high-T_c superconductor experiments, we assume the distance l between two scattering planes to be significantly greater than the corresponding BCS coherence length $\xi_0=\hbar v_F/\pi\Delta_0$ (see Ref. 3). The temperature dependence of the two-terminal junction differential conductance $G_0(T)$ is given by[9]

$$G_0(T)=\frac{e^2}{2hk_BT}\int_{-\infty}^{\infty}d\varepsilon\sum_n G_n(\varepsilon)\cosh^{-2}(\varepsilon/2k_BT).$$

In the superconducting state a partial zero-temperature contribution of the n mode to the conductance spectrum is equal to[4] $G_n(\varepsilon)=1-|R_n^{ee}(\varepsilon)|^2+|R_n^{he}(\varepsilon)|^2$, where $R_n^{he}(\varepsilon)$ is the scattering amplitude for an electron in the n-th mode with an energy ε incident from left in the normal region and reflected back as a hole, $R_n^{ee}(\varepsilon)$ is the corresponding amplitude for its reflection as an electron. In the normal state only the latter processes occur and cause a weak energy dependence of the corresponding $G_n(\varepsilon)$. Using our previous results[3] for the

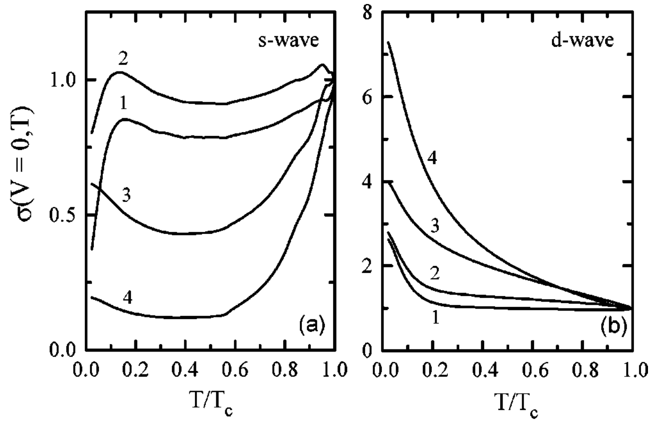

FIG. 1. Temperature dependence of the normalized zero-bias conductance for *N-I-N′/S* *s*-wave (a) and *N-I-N′/S* (110)-oriented $d_{x^2-y^2}$-wave structures (b): $l=10\xi_0$; $k_F=1$ Å^{-1}, and $Z_L=2.0$, $Z_R=0.5$ (curve 1); $Z_L=1.0$, $Z_R=0.5$ (curve 2); $Z_L=0.5$, $Z_R=1.0$ (curve 3); $Z_L=0.5$, $Z_R=2.0$ (curve 4).

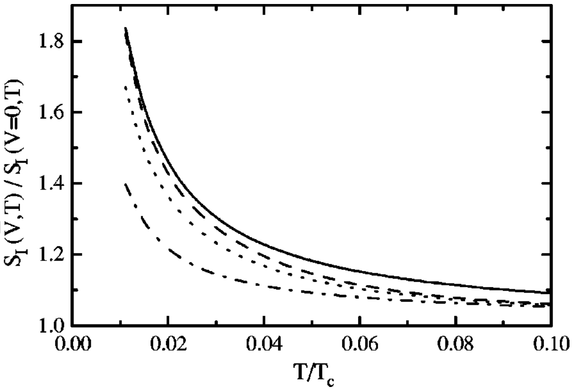

FIG. 2. Temperature dependence of the normalized current noise power for *N-I-N′/S* *s*-wave junctions at a fixed value $e\bar{V}=0.01k_BT_c$ and $k_F=1$ Å^{-1}: $l=0$, $Z_L=1.0$, $Z_R=0$ (solid line); $l=10\xi_0$, $Z_L=2.0$, $Z_R=0.5$ (dashed line); $l=10\xi_0$, $Z_L=1.0$, $Z_R=0.5$ (dotted line); $l=10\xi_0$, $Z_L=1.0$, $Z_R=1.0$ (dashed-dotted line).

amplitudes $R_n^{ee}(\varepsilon)$ and $R_n^{he}(\varepsilon)$ we can calculate the temperature-dependent $\sigma_0(T)$, the ratio of the junction conductances in superconducting and normal states, for different interrelations between the scattering parameters Z_L, Z_R, and the length l of the N' layer.

Although the temperature behavior of $\sigma_0(T)$ reproduces the main features of the conductance spectrum at $T=0$ the result is not as trivial as it could seem at first sight. For sufficiently large l the initial conductance curve has a set of peaks (bound states) and to get results comparable with experimental findings, it was necessary to take into account possible fluctuations of l (see Fig. 3 in Ref. 3). As it will be seen later, the temperature itself smears this fine structure but at the same time conserves the main character of the conductance spectrum. That is why it can be used as an indicator of the transition region state. The second important feature concerns temperatures near T_c when the energy gap is abruptly downfalling to zero and the relation between the gap and the correlation energy ($E_c=\hbar v_F/l$ in the quasiballistic case) changes. In our calculations we assume the BCS behavior of $\Delta(T)$ and the values $\Delta_0=25$ meV, $T_c=90$ K that are typical for high-temperature superconducting oxides.

In Fig. 1(a) we present $\sigma_0(T)$ for the *s*-wave superconducting pairing symmetry. If the scattering from the superconducting surface dominates over the barrier reflections ($Z_R>Z_L$) we get a zero-temperature peak (curves 3 and 4) as a result of the electron-hole symmetry.[9] For the inverse situation when $Z_R<Z_L$ we obtain a maximum (curves 1 and 2) at a finite temperature of the order of E_c/k_B. This maximum is a fingerprint of the main finite-energy bound state in the N' interlayer [see corresponding $G(V,T=0)$ curves in Ref. 3]. A small peak near T_c appears as an interplay between the conductance decrease caused by the Andreev-reflection suppression (the two-particle transport) and its increase determined by the quasiparticle tunneling. It takes place when both processes are of the same weight and thus reveals itself only for intermediate scattering parameters of the barrier and of the N'/S plane [curves 2 and 3 in Fig. 1(a)]. Experimentally, near-T_c local maxima were found for $\sigma_0(T)$ in Ag-Nb point contacts and junctions formed by Ag with the superconducting oxide Nd-Ce-Cu-O,[10] and recently in Al/n-GaAs structures at temperatures 20 mK lower than T_c.[11] Zero-temperature conductance peaks were observed for superconductor-semiconductor junctions[12] and a finite-temperature peak was detected in the experiments[13,14] with mesoscopic *N-S* structures.

Figure 1(b) demonstrates the results of simulations for a (110) oriented $d_{x^2-y^2}$-wave superconductor when the distinction between *s*- and *d*-wave symmetries is mostly pronounced.[15] In contrast to the *s*-wave data that are highly influenced by electron-scattering processes in the transition region, a prominent peak at $T=0$ appears for all parameters greatly increasing in the tunneling regime [curve 4 in Fig. 1(b)]. It is so because the appearance of the maximum at $V=0$ does not significantly depend on the contact properties as it is a result of the resonant transmission through mid-gap states formed at the *d*-wave superconductor surface.[15]

The mid-gap states manifest itself also in noise characteristics of an *N-S* junction. To study them, we refer to results of Anantram and Datta,[16] who obtained the general expression for the zero-frequency current fluctuations in an *N-S* contact along the lines of the Büttiker's approach[17] to purely normal mesoscopic systems. The case of low-voltage shot noise power at zero temperature was studied before by de Jong and Beenakker.[18] Finite-voltage shot noise at $T=0$ in two-terminal normal-metal–superconductor junctions was discussed in Ref. 19 for an *s*-wave superconductor and in Ref. 20 for the *d*-wave order parameter. In contrast to previous publications, in this paper we consider the case of finite temperatures in the low-bias limit when we get a superposition of thermal fluctuations and those caused by the stochastic quantum-mechanical passage of individual charges through the structure.

In the following we propose to characterize the noise in the system discussed with a ratio of the low-frequency limit of current fluctuation spectral density $S_I(\bar{V},T)$ ($\bar{V}$ is a fixed voltage much lower than Δ_0/e) to the pure thermal contribution $S(V=0,T)$. Limiting values of the spectral function $S_I(\bar{V},T)$ given by Eq. (38) from Ref. 16 are well known: the Johnson-Nyquist result[17] $S(V=0,T)=4k_BTG_0(T=0)$ for $k_BT\gg eV$ and the zero-temperature shot noise[18–20] for the

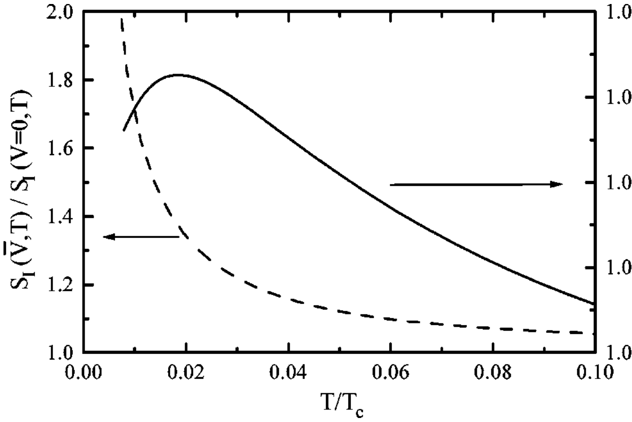

FIG. 3. Temperature dependence of the normalized current noise power for *N*-*I*-N'/*S* $d_{x^2-y^2}$-wave junctions at a fixed value $e\overline{V}=0.01k_BT_c$: $l=10\xi_0$, $k_F=1$ Å^{-1}, $Z_L=1.0$, and $Z_R=0.5$. Solid and dashed lines correspond to the (110) and (100) oriented *d*-wave superconductor surfaces, respectively.

inverse inequality. As it will be shown here, just the finite-temperature behavior can provide us with a valuable information about the nature of the order parameter symmetry in a superconducting electrode.

For an ideal tunnel *N*-*I*-*S* (s-wave) junction at low temperatures the shot noise power reaches the Poisson value $S_I^{(P)}=4eG_0(0)|V|$ and thus the normalized noise power is proportional to the ratio $e|V|/k_BT$ (the solid line in Fig. 2). It is an upper limit because the noise in a system with an N' interlayer of a finite thickness is always lower than $S_I^{(P)}$ as a consequence of the charge correlations during transferring this region (Fig. 2) that appear also as a resonance structure in the voltage dependence of the differential shot noise power calculated at $T=0$ in Ref. 19. At the same time we should note that the curves in Fig. 2 for an *s*-wave superconductor are not modified radically by changing parameters. This is not the case when we replace an *s*-wave electrode with a *d*-wave one (Fig. 3). Whereas for *s*-wave superconductors the normalized noise power increases with lowering the temperature, for the [110] oriented $d_{x^2-y^2}$-wave superconductor we obtain the radical suppression of the current fluctuations that reflects the resonant nature of the charge transport through mid-gap states (see also Ref. 20 for $T=0$). At the same time, as it follows from Fig. 3, for the [100] tunneling direction the noise power does not differ from that in an *s*-wave pairing state. Our numerical simulations show that fixed voltages $\overline{V}$ required to reveal the noise suppression are limited to $0.01k_BT_c/e$ and the temperature range where the effect is pronounced is about $0.01T_c$ (other parameters as the interbarrier distance *l*, or the interface scattering characteristics have no significant influence on the overall temperature behavior of the noise intensity). These values can be simply acquired in high-T_c superconducting junctions and thus we believe that such experiments should be good indicators of the superconducting order parameter symmetry. As far as we know, corresponding noise measurements in *N*-*S* heterocontacts are absent though nonequilibrium noise in *SNS* junctions has been actively studied in recent publications (see Ref. 21 and references therein for the experiment and Refs. 22 for the theory).

In summary, we have examined the temperature effect on conductance and current correlations of a heterogeneous *N*-*I*-N'/*S* system that can represent an artificial double-barrier structure, as well as a junction with a degraded superconducting surface like those with high-T_c cuprates. It is shown that parameters of an intermediate N' layer (its length and scattering amplitudes at the boundaries) govern the temperature behavior of the zero-bias conductance that can hence serve as an indicator of the *N*-*S* transition region properties. On the contrary, the noise intensity near $T=0$ is not influenced greatly by these parameters but is strongly determined by the nature of the superconducting pairing state. We have emphasized the principal difference between the *s*- and the $d_{x^2-y^2}$-wave superconductor noise characteristics. The noise power versus temperature measured at a small fixed voltage bias and normalized to the corresponding quantity at $V=0$ is proposed as a diagnostic tool to probe directly the symmetry of the superconducting pairing state, in particular, in high-T_c compounds. It is important that the total suppression of the noise intensity near $T=0$ that should prove the *d*-wave nature of the order parameter is independent of the presence or absence of the degraded layer as well as of its characteristics (of course, this conclusion is valid only for a specular scattering because the surface roughness at the N'/*S* interface will strongly diminish the effect as it was shown for the conductance spectrum in Ref. 23). The best way to prove the *d*-wave superconductivity with the noise measurements would be an experiment where the quasiparticle transport could be carried out in two directions of a high-T_c single crystal that exhibit clearly different temperature behavior (see Fig. 3). Such technique for contacts with supeconducting cuprates already exists[24] and can be directly applied to the relevant noise measurements.

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