Phase-sensitive quantum effects in the Andreev conductance of an SNS system of metals with a macroscopic phase-breaking length

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(Submitted June 13, 2003)
Fiz. Nizk. Temp. **29**, 1311–1320 (December 2003)

A study is made of the dissipative component of the electron transport in a doubly connected Andreev S–N–S (indium–aluminum–indium) interferometer with elastic mean free paths l_{el} in the metals of around 100 μm and a macroscopic phase-breaking length L_φ that is two or more orders of magnitude larger than L_φ in disordered nanostructures, including two-dimensional ones. The studies are done under conditions not studied before in such interferometers: $\overline{m}<l_{\mathrm{el}}$ ($\overline{m}$ is the transverse size of the NS boundaries). At helium temperatures the samples are found to exhibit new phase-sensitive effects of a quantum-interference nature. Conductance oscillations with a period Φ_0/A (Φ_0 is the flux quantum and A is the aperture area of the interferometer) are observed in the non-domain (normal) state of the indium narrowing near the NS boundary. In the domain intermediate state of the narrowing, magneto-temperature resistive oscillations are observed, with a period $2\Phi_0/\xi^2_{H_c(T)}$ ($\xi_{H_c(T)}$ is the coherence length in a magnetic field close to critical). At sufficiently low temperatures ($T\approx 2$ K) the conductance of a macroscopic N region of the system has an oscillatory component of resonance shape which undergoes phase inversion relative to the phase of the nonresonance oscillations. An explanation for the effects is suggested in terms of the contribution to the Josephson current from coherent quasiparticles with energies of the order of the Thouless energy. The temperature behavior of the dissipative transport in a pure normal metal near an isolated NS point contact is investigated. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1630715]

1. INTRODUCTION

Our previous experiments[1–4] with SNS structures based on pure metals established that even at not very low helium temperatures the dependence of the normal conductivity of the structures on the coherent phase difference of the superconducting "banks" can be preserved at distances L between the NS boundaries several orders of magnitude larger than the size L of the normal spacer layers in disordered SNS nanostructures, where quantum interference effects in the dissipative transport were first observed and continue to be widely studied.[5–13] The typical scale L for such structures is of the order of 1 μm and is limited by the phase-breaking length L_φ, which for nanostructures is a quantity of the same order. In metals with an electron elastic mean free path $l_{\mathrm{el}} \sim 10^2$ μm the phase-breaking length is at least 10^3 times larger than in nanostructures with $l_{\mathrm{el}}\sim 0.01$ μm (in systems with a two-dimensional electron gas $l_{\mathrm{el}}\lesssim 1$ μm). The reason is apparently that at static defect densities leading to such values of l_{el} as in nanostructures, inelastic processes come into play in the scattering on these objects, limiting L_φ. At low defect densities in pure metals the contribution of such processes is unimportant. The macroscopic value of L_φ in pure metals allows one to increase the spatial region in which the long-range phase coherence (LPC) is investigated, expanding the interval of values $L/\xi_T>1$ from values of the order of 10^0 in nanostructures to 10^2 in systems with pure metals.

In addition, we note that the coherence length $\xi_T^d = \sqrt{\hbar D/k_B T}$ (D is the diffusion coefficient) in the "dirty" (diffusion) limit can be expressed in terms of the coherence length ξ_T^p in the "pure" limit $\xi_T^p \equiv \xi_T^{\mathrm{bal}} = \hbar v_F/k_B T$:

$$\xi_T^d = [(1/3) l_{\mathrm{el}} \xi_T^{\mathrm{bal}}]^{1/2}, \quad l_{\mathrm{el}} \ll \xi_T^{\mathrm{bal}}.$$

It follows that the temperature regions T^p and T^d which determine the values of L/ξ_T in the pure and dirty samples with distances between NS boundaries L^p and L^d, should be connected by the relation

$$\frac{(T^p)^2}{T^d} = 3\frac{\hbar v_F}{k_B l_{\mathrm{el}}^d}\left(\frac{L^d}{L^p}\right)^2\left[\frac{(L/\xi_T)^p}{(L/\xi_T)^d}\right]^2. \tag{1}$$

(We are presupposing that the phase-breaking length L_φ in each case is not less than L^p or L^d.) This means that the same values of the parameter $L/\xi_T = \sqrt{T/E_c}$ (E_c is the gap in the density of states),[14] characterizing the same behavior of the phase-coherent phenomena in the two limits, can be realized at very different temperatures—much higher for the pure systems. For example, in pure samples with $l_{\mathrm{el}} \gg 1$ μm this parameter at 2 K is of the same order of magnitude as in diffusional samples with $l_{\mathrm{el}}\sim 0.01$ μm at $T\lesssim 0.1$ K, for $L^p/L^d \sim 10$. (It will be shown below that the shift of the temperature regions of analogous behavior of the phase-coherent effects for 2DEG samples with $l_{\mathrm{el}}\sim 1$ μm (Ref. 11) and 3D samples with $l_{\mathrm{el}}\sim 0.01$ μm in the case $L^{3\mathrm{D}}/L^{2\mathrm{D}}\sim 1$ also corresponds to relation (1).)

Thus a manifestation of phase-coherent phenomena for $L/\xi_T>1$, which implies the existence of LPC under conditions of an exponentially small (in magnitude) proximity effect for the main group of electrons, which are excitations with energy $\varepsilon \sim T$, in ultrapure structures can be observed on macroscopic scales even at not very low helium temperatures; this effect may be of extremely topical interest for solving the problem of extracting quantum information from various quantum systems via macroscopic channels, for example.

Generally speaking, the first indications of a long-range (not purely exponential in the parameter L/ξ_T) influence of a superconductor on the conductivity of a normal metal bordering are directly contained already in the results of experiments on structures with an isolated NS boundary, where such an influence has been noted at distances from the boundary corresponding to values $L/\xi_T \sim 5-10$.[15,16] The interference effects subsequently observed in doubly connected SNS systems containing disordered metals (nanostructures) with small L_φ have also been studied until recently in a range of L/ξ_T not exceeding the values indicated above. However, experiment shows that the manifestation of phase-coherent phenomena in doubly connected SNS systems is not limited to this interval of values of the parameter L/ξ_T, and the presently available results on the behavior of phase-coherent phenomena in that interval (see Fig. 7) have been interpreted in different ways; it is therefore necessary to expand the study of these phenomena, especially under conditions of different L/ξ_T ratios unrealizable in disordered nanostructures.

In the present study we have investigated the temperature and phase-sensitive features in the behavior of the conductance of SNS systems formed by the contact of two pure metals with $l_{\mathrm{el}} \approx 100\ \mu$m, aluminum (in the normal state) and indium, in an interferometer geometry for $L/\xi_T \approx 10^2$ under the conditions $L, l_{\mathrm{el}} \gg \xi_T = \xi_T^p$. Under these conditions all three dimensions of the normal spacer layer of the SNS system are so much greater than the typical microscopic spatial parameters associated with the proximity effect that the contribution of a supercurrent due to the main group of carriers with energies $\varepsilon \sim T$ can be completely ruled out.

2. EXPERIMENTAL TECHNIQUE

Figure 1 shows a diagram of the overall layout and the equivalent circuit for the measurements (inset) of the investigated doubly connected system of two metals in contact, aluminum and indium. After the transition of the indium to the superconducting state, the system acquires an SNS configuration of the "Andreev interferometer with cavity" type. The area of the cavity between the aluminum girder (2×2 mm in cross section) and the indium strip, soldered at points a and b, was $A = ab \times h \approx 3\ \mathrm{mm} \times 15\ \mu$m.

Unlike the SNS system which we studied previously in Refs. 3 and 4, which used copper and had wide soldered NS contacts with a characteristic dimension $\overline{m}$ which could not increase the contact resistance R_{cont}, since $\overline{m} \gg l_{\mathrm{el}}$, in the present study the current regime was realized through contacts a and b with a significant distributed (Sharvin) resistance R_{Sh}, which usually arises for characteristic contact dimensions smaller than l_{el} (Ref. 17). Contacts of such a size were formed by spot welding the indium to the aluminum used in the present study. Here, as we have repeatedly confirmed in previous studies, the direct welding of ultrapure

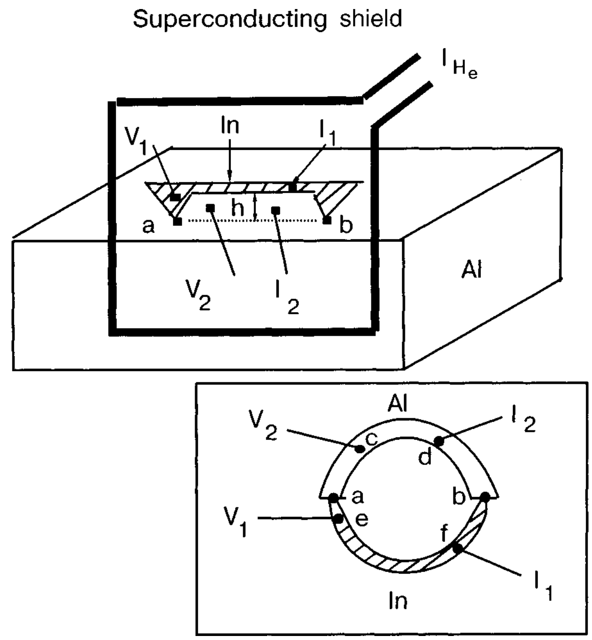

FIG. 1. Schematic illustration of the SNS interferometer and the equivalent circuit of the measurements (inset). The shaded region is the bulk part of the indium.

materials with ratios of the resistances at 300 and 4.2 K of $RRR \gtrsim 10^4$ ($l_{\mathrm{el}} \approx 100\ \mu$m) brings about a close to zero barrier height z in the contacts, which corresponds to a transmission coefficient $t = (1+z^2)^{-1} \approx 1$ (Ref. 18; $z \neq 0$ for technologies that do not partially or completely destroy the oxide layer or other kinds of contamination on the surface of the metals).

The characteristic dimensions of the contacts a and b (see Fig. 1) can be estimated by noting that for $l_{\mathrm{el}} > \overline{m}$ the total current through a contact of two metals in the normal state should be related to the contact area $\mathcal{A}_{\mathrm{cont}}$ by the expression[18]

$$I_{NN} = 2\nu(\varepsilon) e^2 v_F \mathcal{A}_{\mathrm{cont}} U_{\mathrm{Sh}} t \equiv U_{\mathrm{Sh}}/R_{\mathrm{Sh}}, \tag{2}$$

where $\nu(\varepsilon)$ is the density of states in one of the metals of the contact, and U_{Sh} is the voltage drop across the distributed resistance R_{Sh}. Choosing aluminum as the 3D part of the system, with a normal conductivity of $\sigma_N = (1/3) e^2 v_F \nu(\varepsilon) l_{\mathrm{el}}$, and taking into account that $I_{NN} = j^{\mathrm{Al}} A^{\mathrm{Al}} = j_{\mathrm{cont}} \mathcal{A}_{\mathrm{cont}}$ (j^{Al} and j_{cont} are the current density in the aluminum and in the contact, respectively), we obtain from (2) the area over which the two metals touch:

$$\mathcal{A}_{\mathrm{cont}} = (1/6)(l_{\mathrm{el}}^{\mathrm{Al}}/L^{\mathrm{Al}})(U^{\mathrm{Al}}/U_{\mathrm{Sh}}) A^{\mathrm{Al}}. \tag{3}$$

Here $A^{\mathrm{Al}} \approx 4\ \mathrm{mm}^2$ is the cross section of the aluminum girder, $L^{\mathrm{Al}} \approx 1.5$ mm is the length of the corresponding part of the Al between one of the contacts, e.g., a, and the measuring probe V_2 (ac in Fig. 1), with a potential difference across this part equal to $U^{\mathrm{Al}} = I_{NN} R^{\mathrm{Al}}$, where R^{Al} is the resistance of that part, measured independently in the case when the second contact is excluded. By measuring the voltage U across the probes V_1 and V_2 in this scheme, one can find the voltage drop across the distributed resistance as

$$U_{\mathrm{Sh}} = U - I_{NN}(R_{\mathrm{Al}} + R_{\mathrm{narr},N}^{\mathrm{In}}),$$

where $R^{In}_{\mathrm{narr},N}$ is the resistance of the indium narrowing in the normal state in the near-contact region (see the inset in Fig. 1). Measurements of the quantities necessary for evaluating $\mathcal{A}_{\mathrm{cont}}$ gave the following results: $R^{\mathrm{Al}} \approx 4 \times 10^{-10}\ \Omega$; $R_{\mathrm{Sh}} \approx 1.1 \times 10^{-8}\ \Omega$; $R^{\mathrm{In}}_{\mathrm{narr},N} \approx 1.7 \times 10^{-8}\ \Omega$. In accordance with (3) we find that the characteristic "spot" size $\overline{m}$ in contacts a and b could be around 25 μm, which corresponds to the inequality $l_{\mathrm{el}} > \overline{m}$ which gives rise to an additional distributed resistance of the residual type, which in our experiment exceeds the resistance of the N-metal segment ac of the system by two orders of magnitude.

After the contacts were formed, the indium narrowing at contact b was thinned (by drawing) so that the resistance of the interferometer branches dbf and daf (inset in Fig. 1) were in a relation $R_{dbf} \gg R_{daf}$ ($R_{dbf} = R^{\mathrm{In}}_{b,\mathrm{narr}} \sim 10^{-3}\ \Omega$). The measuring current was introduced to the system through normal probes, one of which, I_1, was mounted in the indium outside the narrowing region and the second, I_2, was in the aluminum. For resistances of contacts a and b obeying the above relation, practically all of the conduction current flowed along the loop I_1–indium narrowing–contact a–aluminum–I_2. The possibility of regulating a macroscopic phase difference is preserved.

The macroscopic phase difference in the interferometer was controlled by an external magnetic field H_e produced by a rectangular wire loop glued directly on the face of the aluminum girder and carrying a current I_{H_e}. The planes of the loop and interferometer cavity were parallel to each other, the cavity lying along the axial line of the loop, a position convenient for calculation of the value of the field produced in the cavity by the loop. For compensation of external fields the sample with the loop was placed in a closed superconducting shield. The normal (copper) probes V_1 and I_1 were soldered to the indium, and V_2 and I_2 were spot welded to the aluminum. The potential difference across the probes V_1 and V_2 was measured to an error of $(0.5-1) \times 10^{-12}$ V or better by a device utilizing a thermomagnetic superconducting modulator,[19] which made it possible, in particular, to study the effects down to 0.1% in the conductance of an N region of macroscopic dimensions. The error for the measurements of the working currents and temperature was 0.01–0.001%.

3. RESULTS AND DISCUSSION

3.1. $H_e = 0$. Temperature dependence

Figure 2 (curves *1* and *2*) shows the temperature dependence of the potential difference U, divided by the working current ($I \approx 0.5$ A) introduced to the system through probes I_1 and I_2 of the interferometer (Fig. 1) in the case $R^a_{\mathrm{cont}} \ll R^b_{\mathrm{cont}}$. At the transition through the critical temperature of the bulk part of the indium, $T^{\mathrm{In}}_c = 3.41$ K, where an NS boundary appears, a jumplike increase in the resistance of the part cae of the system is observed; this jump is like that which was first observed by the authors in 1988[15] and is a characteristic quantum effect accompanying the appearance of Andreev reflection.[20]

An analysis of the values given in the previous Section for the contributions to the resistance from individual elements of the system and curves *1* and *2* in Fig. 2 implies,

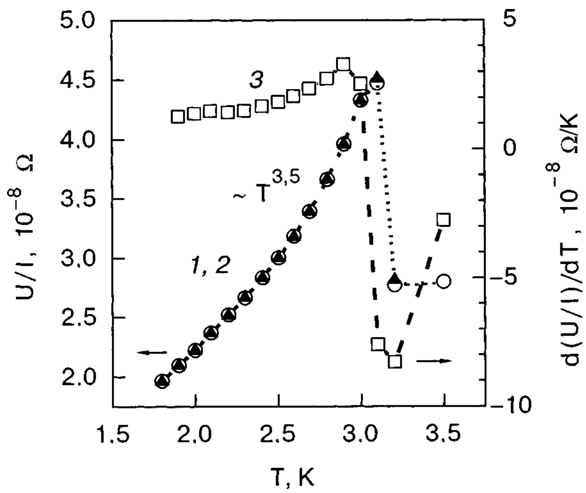

FIG. 2. Temperature dependence of the resistance of the indium narrowing at the contact a of the interferometer for $R^a_{\mathrm{cont}} \ll R^b_{\mathrm{cont}}$ (curves *1* and *2*) and its derivative (curve *3*). Curves *1* (○) and *2* (▲) are the measurements at the minimum ($H_e = 0$) and maximum ($H_e = 0.3$ mOe), respectively, of the resistive oscillations observed at 3.2 K. The jump on curves *1* and *2* corresponds to a twofold increase in the resistance of the indium narrowing when the NS boundaries appear (the values include the distributed resistance of the contact).

first, that the resistance jump near T^{In}_c and the subsequent change in the resistance of the system in the temperature interval down to ~ 1.8 K can only be due to the resistance of the indium narrowing (R_{Sh} is independent of temperature, and $R_{\mathrm{Al}} \ll R^{\mathrm{In}}_{\mathrm{narr},N}$). A comparison of the values of the resistance of the indium narrowing in the NN state ($\approx 1.7 \times 10^{-8}\ \Omega$ at $T = 3.5$ K) and for the NS configuration of the system ($\approx 3.4 \times 10^{-8}\ \Omega$ at $T = 3.2$ K) indicates a twofold increase in the resistance of the narrowing.

According to the microscopic theory,[21,22] such an increase in the normal resistance upon the onset of Andreev reflection, due to the twofold increase in the cross section for electron scattering on normal-metal impurities located within the coherence length ξ^p_T of the NS boundary (of the order of 10 μm for In at $T \approx 3$ K), can take place under the condition $L \sim \xi^p_T$, where L is the dimension of the metal layer reckoned from the boundary. A simple estimate of the dimensions of the narrowing with the use of the values $RRR_{\mathrm{In}} \approx 4 \times 10^4$, $\mathcal{A}_{\mathrm{cont}}$, and $R^{\mathrm{In}}_{\mathrm{narr}}$ shows that the size of the narrow boundary region of indium, L_{narr} (i.e., the distance from the "spot" to the place of the transition to the bulk part of the indium, where an NS boundary arises for $T < T^{\mathrm{In}}_c$) is of the order of 10 μm, i.e., comparable to ξ^p_T. Thus the conclusion of the theory that a twofold increase in resistance will occur upon the onset of Andreev reflection under the conditions $L_{NS} \sim \xi_T$ has apparently found its first direct confirmation. Previously the largest resistance increase that we had been able to observe did not exceed 60%.[23]

Curves *2–5* in Fig. 3 show the results of measurements of the conductance on the opposite side from contact a, on the normal aluminum side, as functions of the thickness of the normal layer adjacent to the NS boundary, i.e., on the distance L_{NS} between the normal probe N and the superconducting (S) point contact a. Measurements were made with the interferometer ring broken, permitting the use of a four-contact null method of measurement (see the inset in Fig.

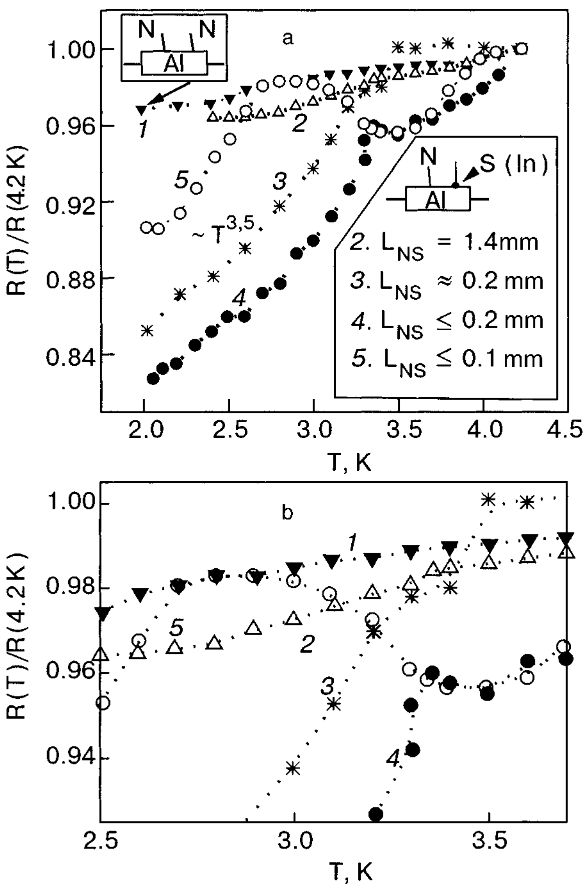

FIG. 3. Dependence of the rise of the resistance of aluminum near the boundary (in region ac, Fig. 1) on the distance between the N probe and the NS boundary; $H_e = 0$.

3a), which eliminated the contribution $R_{\mathrm{Sh}} + R_{\mathrm{narr}}^{\mathrm{In}}$ of the contact itself. Also shown for comparison in this figure is the temperature dependence of the resistance of the same aluminum (curve *1*) measured with the use of only normal probes that had been arc-welded on.

The curves in Fig. 3 (Figure 3a and 3b differ only in scale) demonstrate how the increase of the resistance of the near-contact layer in the aluminum upon the formation of an NS boundary evolves as with changing L_{NS}. It follows from a comparison of the curves in Figs. 2 and 3 that the change in resistance (an increase with decreasing temperature) upon the formation of an NS boundary, observed on both sides of the point contact a, is analogous to the effects observed in NS systems with pairs of different metals for an arbitrary area of the NS boundaries and for other positions of the probes.[2,23] The nature of the effect, as we have said, is due to the interference of coherent electrons appearing upon Andreev reflection, and its value under the conditions $L_\varphi \gg l_{\mathrm{el}} \gg \xi_T$ depends only on the ratios $\xi_T / L_{NS}, l_{\mathrm{el}}$ if $L_{NS} < L_\varphi$.

The results given in Fig. 3 again confirm that LPC can be maintained in a pure metal in the investigated temperature range over macroscopic distances, in our case at least 1.5 mm ($L/\xi_T \approx 10^2$), which, as before,[1–4,23] indicates that the phase-breaking length is of at least that scale.

It also follows from Figs. 2 and 3 that the temperature dependences of the resistance of both the indium and aluminum, measured on the two sides of the NS boundary a, in the low-temperature region of the jump and where $\xi_T < L_{NS}$ obey

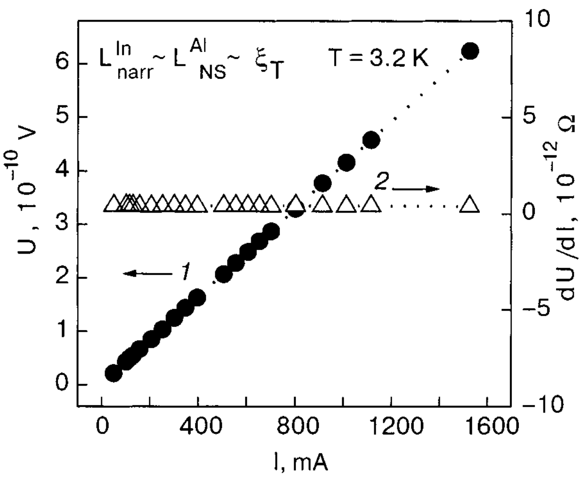

FIG. 4. Current–voltage characteristic for the smallest distance between the N probe and NS boundary (in the geometry $L_{NS} \leqslant 0.1\ \mu$m, corresponding to the distance L_{NS} for which curve *5* in Fig. 3 was measured) and its derivative. $T = 3.2$ K, $H_e = 0$.

the same power law ($\sim T^{3.5}$) and correspond to our previous result for aluminum, obtained in an NS system with a different method of measurement.[2] This fact provides additional confirmation of the role of the temperature dependence of the phase-breaking length in determining the temperature dependence of the conductance of a metal layer as a whole within the range $\xi_T < L_{NS} < L_\varphi$ under conditions of multiple Andreev reflection (see Ref. 2).

Figure 4 shows the current–voltage characteristic (curve *1*) measured at a temperature of 3.2 K and corresponding to case *5* in Fig. 3, and its derivative (curve *2*). It is seen that there are no nonlinear effects associated with the contact over a wide range of currents, including the measuring current 0.2–0.5 A.

3.2. $H_e \neq 0$

3.2.1. Nonresonance oscillations

In measurements of the potential difference U across probes V_1 and V_2 at a temperature of 3.2 K, depending on the magnetic field H_e of the wire loop, a component oscillatory in H_e with a period $(hc/2e)/A$ is observed, where A is the area in the gap h (see Fig. 1). The amplitude of the

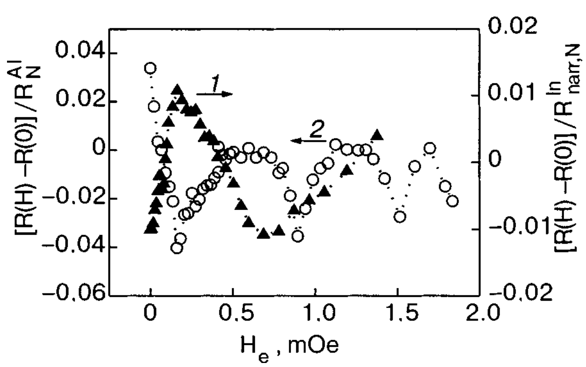

FIG. 5. Nonresonance oscillations of the phase-sensitive dissipative component of the resistance at $T = 3.2$ K in the indium narrowing (curve *1*) and the resonance oscillations of this component at $T = 2$ K in the aluminum (curve *2*) for an interferometer with $R_a \ll R_b$, as functions of the external magnetic field.

oscillatory component, shown by curve *1* of Fig. 5 in relative units, $U/I \propto (R_H - R_{H=0})/R_{H=0}$, has a value in absolute units $\Delta(U/I) = (R_{\max} - R_{\min}) \approx 4.5 \times 10^{-10}\ \Omega$, which corresponds to $\approx 2\%$ of the resistance of the indium narrowing, $R^{\mathrm{In}}_{\mathrm{narr},SN}$, with $R_{\min} \equiv R_{H=0}$. Figure 6 shows the temperature dependence of the difference $\Delta(U/I) = (R_{H=0.3\ \mathrm{mOe}} - R_{H=0})$, which, like the character of the temperature dependence of $d(U/I)/dT$ (curve *3* in Fig. 2), indicates that a domain intermediate state of the indium narrowing is realized on decreasing temperature no earlier than ≈ 3.1 K, as is indicated by the temperature position of the jumps on the corresponding curves. The same conclusion also follows from an independent analysis with the use of the size L_{narr}, which does not correspond to the condition for the onset of a domain structure with more than 1 domain in the presence of the self-magnetic field of the current (~ 10 Oe), since it is not comparable to the size of the domains for $T > 3.1$ K.[3] The transition of the narrowing to the domain intermediate state is evidenced by the appearance, at temperatures below 3 K, of magnetotemperature resistance oscillations with a period corresponding to the period of oscillations in the critical magnetic field, $\Delta_{H_c(T)} \sim hc/e\xi_H^2$, with $\xi_H \approx 2\sqrt{qR_L[H_c(T)]} \sim 1\ \mu$m for 3.0 K ($q$ is the screening radius of the impurity, and $R_L(H_c)$ is the Larmor radius).[1,3]

Let us compare the parameters of the oscillations observed at 3.2 K (curve *1* in Fig. 5) with the theory and the presently available results of other authors. The most characteristic results[7,11,13] on the temperature dependence of the relative amplitudes $|\Delta R/R_N|$ of the observed resistive oscillations are collected in Fig. 7, where they are plotted as functions of the parameter $T_{\mathrm{Th}}/T \equiv (\xi_T/L)^2$ with the values of the "Thouless temperatures" T_{Th} adopted by the authors. Also shown there is the theoretical curve $|\Delta R/R_N| = |R_{\max} - R_N|/R_N$, where $R_{\max}$ and R_N are the values of the resistances at the maximum and minimum of the oscillations, which were obtained in Ref. 24 by a numerical simulation

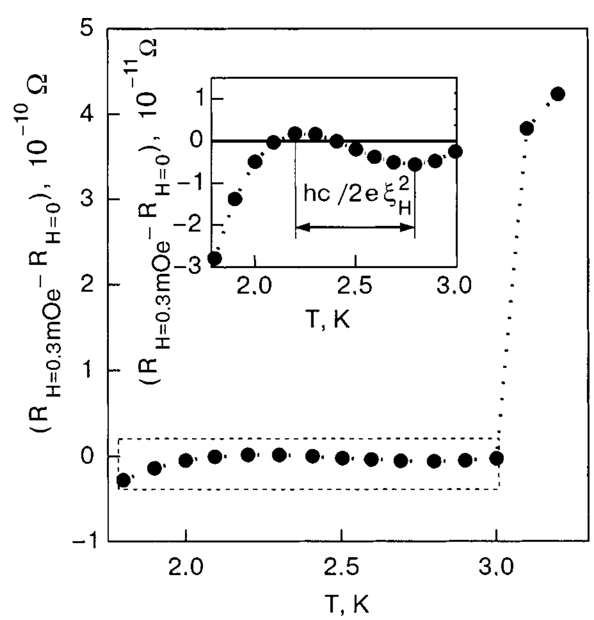

FIG. 6. Temperature dependence of the difference of the resistances for $H_e = 0.3$ mOe and $H_e = 0$ for an interferometer with $R_a \ll R_b$ (the inset shows the dependence on an expanded scale).

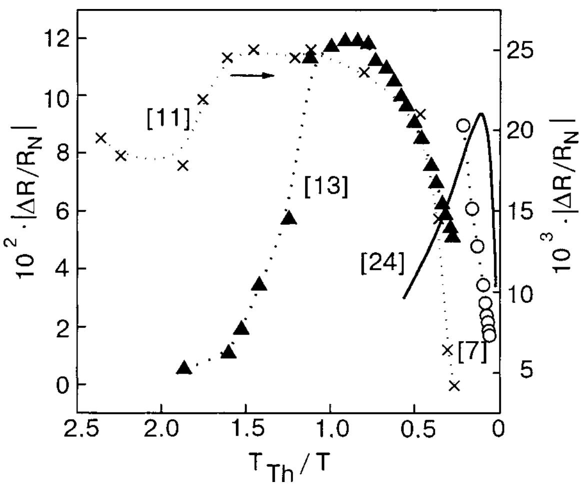

FIG. 7. Temperature dependence of the amplitude of the phase-sensitive nonresonance oscillations of the conductance from the experimental papers.[7,11,13] The solid curve is the theory.[24]

for $\varphi = \pi$ and $\varphi = 0$, respectively, with $T_{\mathrm{Th}} = D/\pi L^2$. The apparent disagreement of the experimental results on the parameter $T_{\mathrm{Th}}/T = (\xi_T/L)^2$ with the theory and with each other is eliminated practically completely if the gap that arises in the density of states upon localization by Andreev reflections of the coherent excitations in the normal space between the NS boundaries is everywhere taken equal to the energy criterion $T^* = D/2\pi L^2$ for the "dirty" limit from Ref. 25. Figure 8b shows the same results as in Fig. 7 but plotted with the "Thouless temperature" taken equal to the parameter T^* in the form indicated above, with L taken equal in all cases

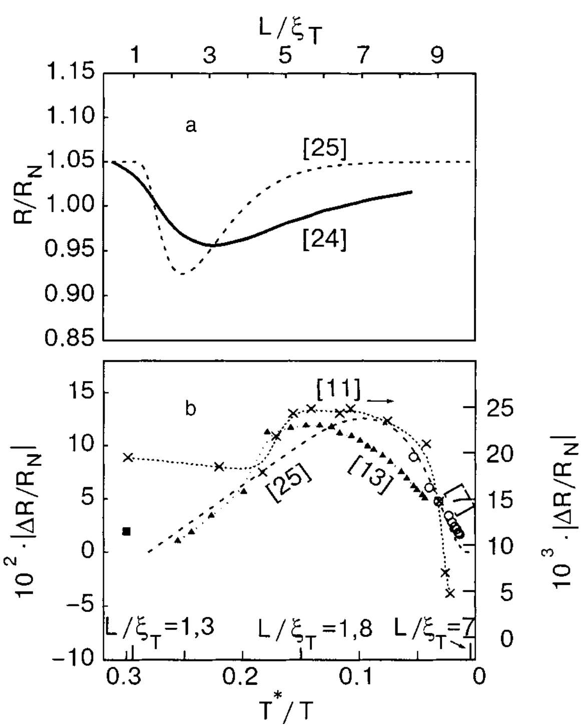

FIG. 8. Dependence of the resistance of an SNS system on the parameter L/ξ_T from Refs. 24 and 25 (a) and the temperature dependence of the amplitude of the nonresonance oscillations of the conductance from Refs. 7, 11, and 13 (see Fig. 7) after modification in accordance with the theory of Ref. 25 (b); ■—the amplitude of the nonresonance oscillations in our experiment.

to the distance between the superconducting "mirrors." It is seen that the set of experimental results thus modified forms a regular relation in the behavior of the amplitude of the oscillations with respect to the parameter T^*/T. As it turned out, this feature follows directly from the results of a theoretical analysis carried out back in 1968 by Aslamazov, Larkin, and Ovchinnikov.[25] Indeed, using the fact that the quasiparticle dissipative current ($\sim f(\cos\Delta\chi)$, where $\Delta\chi$ is the macroscopic phase difference) is the difference between the total current and the supercurrent,[26] we find on the basis of the analytical expressions for the nondissipative current ($\sim\sin\Delta\chi$) given in Ref. 25

$$\frac{R_{\Delta\chi=\pi/2}}{R_N}=\left[1-\frac{1}{\pi}\frac{L}{\xi_T}\exp\left(-\left(\frac{L}{\xi_T}+1\right)\right)\times\ln\left(\alpha\left(\frac{L}{\xi_T}\right)^{-2}\right)\right]^{-1}, \tag{4}$$

where $L/\xi_T\equiv(T/T^*)^{1/2}$ and α is a coefficient of the order of unity.

The curve corresponding to this expression for $\alpha=2$ is shown in Fig. 8a together with the curve for $R_{\Delta\chi=0}/R_N$ from Ref. 24. It is easy to see that both results predict the existence of LPC, i.e., nonexponential damping of the oscillatory dissipative component in the conductance of an SNS system for $L/\xi_T\gg 1$. The positions of the curves on the L/ξ_T scale do not coincide because of the difference of a factor of $\sqrt{2}$ between ξ_T in Refs. 24 and 25. The theoretical curve for the relative amplitude of the oscillations, $|\Delta R/R_N|$, corresponding to the curve from Ref. 25 in Fig. 8a, is shown by the dashed curve in Fig. 8b. It is seen that it describes completely the position on the temperature scale of all the experimental results presented in Fig. 7, confirming the conclusion about the relationship of the temperature intervals made on the basis of expression (1). (In processing the results of Ref. 11 we took into account that the size of the normal region in one of the directions is greater than l_{el} and does not satisfy the ballistic criterion ξ_T^p, and we were forced to make a substantial re-evaluation of the Thouless temperature.) The same curve also gives a correct quantitative estimate of the oscillation amplitude $|\Delta R/R_N|$ in the corresponding temperature intervals, except for the values given in Ref. 11, where the authors chose for R_N not the resistance of the region between the "mirrors," as required, but the resistance of the whole sample.

In contrast to the experimental results discussed,[7,11,13] the region of observation of which, as an analysis shows, most likely corresponds to the region of values $L/\xi_T>1$ ($T^*/T<0.3$), i.e., the "dirty" limit, the oscillations pertaining to the indium narrowing in the contact at 3.2 K, as was shown, are reasonably attributed to the quasiballistic oscillation regime, $L_{\mathrm{narr}}^{\mathrm{In}}/\xi_T\sim 1$. For this regime the characteristic temperature is $T^{\mathrm{bal}}=\hbar v_F/k_BL$. The position of the oscillation amplitude (the square data point in Fig. 8b) calculated with the use of this parameter for $L=L_{\mathrm{narr}}^{\mathrm{In}}$ is also in agreement with the theoretical curve from Fig. 8b.

3.2.2. Resonance oscillations

The oscillations shown by curve *2* in Fig. 5 are at first glance surprising from the standpoint of the dimensions of the system. These oscillations, which have a resonance shape, are observed at temperatures of ~ 2 K and differ from the oscillations measured at 3.2 K. Since at 2 K the resistance of the indium narrowing is already comparable in value to the resistance of the aluminum on the segment ac (see the inset in Fig. 1) and the phase of the resonance oscillations is shifted by π with respect to the phase of the nonresonance oscillations at 3.2 K, it can be assumed that the nature of the resonance oscillations is due to features of the phase-coherent interference in the aluminum. The period of these oscillations, like that of the oscillations observed at 3.2 K, is equal to $(hc/2e)/A$. (The above-mentioned phase inversion of the resistive oscillations has also been observed in other studies (e.g., Refs. 11 and 13) in a different geometry of the SNS interferometers (nanostructures) and with another method of measurement.)

First, as we emphasized before, in the system which we investigated the phase-breaking length is either much larger than the distance between electron injectors, as is the case in the indium narrowing in the domain state, or is of the order of that distance, as in the aluminum region (~ 1 mm); this is the first necessary condition for the manifestation of quasiparticle phase-coherent phenomena in the conductance of systems with a large distance between boundaries. The next fundamental argument, which was examined in detail in the theory of Ref. 27, is the restriction imposed on the possibility of establishing a coherent phase difference under these conditions. It concerns the dimensions of the injectors, which, playing the role of reservoirs, should, in particular, in the ballistic transport regime (like the regime in the indium narrowing) bring about a splitting of the electron beam at the place where the injectors are joined (at least, one of them). This is required for the creation of conditions of no return to the injector for a hole excitation after the first Andreev reflection, under which it is possible to form quasiclassical trajectories of low-energy electrons with energies $\varepsilon\leqslant E_c\sim\hbar v_F/L$ (or $\hbar D/2\pi L^2$); these trajectories connect the two superconducting "mirrors" and thereby establish the coherent phase difference between "mirrors." It has been shown that for this to take place in the regime indicated, the aperture of the injector–reservoir should not exceed the de Broglie wavelength λ_B (this circumstance was first pointed out in Ref. 28). It is not hard to understand that this restriction loses meaning if the role of at least one of the injectors is played by one of the superconducting "banks," since in that case splitting is not required for the formation of a trajectory connecting the two superconducting "banks." In our SNS system, where the current is introduced through one of the "mirrors" (Fig. 1), there is no restriction on the formation of a coherent phase difference, both for the indium narrowing, which is found in the ballistic regime, and for the aluminum region, which is in a regime that is close to diffusional.

Since the characteristic energy scale of the Andreev spectrum $\sim\hbar v_F/L$, one can assume that the oscillations observed at 2 K are due to the fine Andreev spectrum of low-energy electrons in the aluminum region, since the oscillations in the narrowing ($T=3.2$ K) do not have a resonance shape, nor do the conductance oscillations of the normal region (Cu) in the case of a large area of the "mirrors" when the current is not introduced through a "mirror."[4] If the observed oscillation amplitude is attributed to the resistance of the aluminum between the ''mirrors,'' then, as is seen in Fig. 5, the relative amplitude of the oscillations of resonance shape amounts to about 4%, which corresponds to the ratio $E_c(L^{\mathrm{Al}}_{acb})/T$ for the aluminum and not for the narrowing. According to the theory of Refs. 27 and 29, the appearance of oscillations of resonance shape can be expected because of degeneracy at the Fermi level of transverse modes with the energies of the Andreev levels

$$\varepsilon_n^{\pm}=\frac{\hbar v_F}{2L}[(2n+1)\pi\mp\Delta\chi]$$

($\Delta\chi$ is the macroscopic coherent phase difference between the ''mirrors''), when $\Delta\chi=(2n+1)\pi$ ($\varepsilon_n^{\pm}=0$). The degeneracy condition thus presupposes an inversion of the phase of the resonance oscillations with respect to the phase of the nonresonance oscillations, which corresponds to $\Delta\chi=2n\pi$. Such an inversion does take place for the oscillations of resonance shape which we observed.

CONCLUSIONS

The phase-coherent component of the dissipative electron transport in doubly connected hybrid systems with pure metals (In and Al) with elastic mean free paths of the order of 100 μm and a phase-breaking length of over 1 mm has been investigated at helium temperatures. The studies were done in the geometry of an Andreev SNS interferometer with In in the superconducting and Al in the normal state, with a characteristic size of the NS boundaries less than the mean free path and with the length of the normal region between boundaries comparable to the macroscopic phase-breaking length. In dissipative transport, when the current is introduced both through one of the NS boundaries and in an arrangement bypassing the boundaries, a number of phase-sensitive effects of a quantum interference nature are observed, which are indicative of the presence of a coherent component due to Andreev reflections. The effects pertaining to the different regions of the SNS system are separated.

Resistive oscillations with a period Φ_0/A (Φ_0 is the flux quantum, A is the aperture area of the interferometer) are observed, associated with the behavior of the electron transport in the indium narrowing at the boundary in the nondomain (normal) state of the narrowing. The appearance of the observed oscillations of a magnetotemperature character, with a period $2\Phi_0/\xi^2_{H_c(T)}$ ($\xi_{H_c(T)}$ is the coherence length in a magnetic field equal to the critical), are attributed to the domain intermediate state.

For $T\leqslant 2$ K we have observed resistive oscillations of a resonance shape which undergo phase inversion (a shift by π) with respect to the phase of the nonresonance oscillations; we attribute their appearance to the macroscopic normal region of the system (Al) and link to the degeneracy at the Fermi level of transverse modes of the Andreev spectrum of coherent quasi-particles with energies of the order of the Thouless energy.

We have studied the temperature behavior of the phase-coherent component of the transport in a pure metal near an isolated NS point contact.

The appearance of resonance phase-sensitive oscillations for a macroscopic distance L between boundaries in the normal region of the SNS system is attributed to the contribution of coherent excitations with the Thouless energy, for which the transport regime between the reservoir and the NS boundaries in the pure metal ($l_{\mathrm{el}}\gg\xi_T^{\mathrm{bal}}$) can be ballistic. Since under these conditions when an NS boundary is used as one of the electron injectors the appearance of phase coherence does not depend on L as long as $L\leqslant L_\varphi$, one can assume that the possibility of observation of phase-sensitive effects in the conductance of macroscopic SNS systems is restricted to such values of L for which the normal reflection becomes predominant at the NS boundaries. The latter will take place for $E_c/T<\sqrt{E_c/\varepsilon_F}$ (Ref. 27), which corresponds, for $L_\varphi\to\infty$ and $T\sim 2$ K, to $L>10$ cm—the limiting scale of interboundary distance for which the appearance of long-range phase coherence is possible at helium temperatures ($L/\xi_T^{\mathrm{bal}}\sim 10^4$).

The experimentally observed phase-sensitive quantum effects in the conductance of an SNS system of pure metals in the region of not very low helium temperatures with $L/\xi_T^{\mathrm{bal}}\sim 10^2$ find a completely reasonable explanation in the framework of the indicated scale of long-range phase coherence due to the contribution of low-energy coherent excitations with energies $E_c\ll T,\Delta$.

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Translated by Steve Torstveit