Manifestation of coherent and spin-dependent effects in the conductance of ferromagnets adjoining a superconductor

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Electrotransport was investigated in the macroscopic ferromagnets (F) Fe and Ni in the presence of F/In interfaces with different area. The measurements were performed in two configurations—with a constant current flowing parallel and perpendicular to the interfaces. It was found that the transition of In into the superconducting (S) state is accompanied by an increase of the resistance of the ferromagnets. In the first configuration the increase concerned the change of the resistance of the region between the boundaries of the potential probes (superconducting "mirrors") and was of the order of the typical, weakly localized, contribution to the conductivity of ferromagnets from subgap singlet excitations, arising with Andreev reflection, for macroscopic distances between the "mirrors" at the coherence length characteristic for metals with a strong difference of the energy dispersion of the spin subbands. In the second configuration, where the conductivity of the F/S interface is also included in the measurements, the nonequilibrium resistive contribution of the latter, associated with the spin polarization of the region of the ferromagnet under the interface, was studied. The observed increase of the resistance corresponded to the theoretically predicted magnitude of the change occurring in the resistance of a single-domain region with spin-polarized electrons as a result of spin accumulation on the F/S interface under the conditions of limitations of Andreev reflections. The coefficients of current polarization and the coherence length in the exchange field were found for Fe and Ni from the experiemental data and the lower limit of the spin relaxation length was found for the samples investigated. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2720077]

I. INTRODUCTION

The possibility of coherent effects and the spin characteristics of the conduction electrons manifesting in transport phenomena in metals is now being widely studied theoretically and experimentally. Of keen interest are, for example, the special features of transport which are due to the influence of a superconductor (S) which is put into contact with a normal metal (N) and, especially, a ferromagnet (F). Specifically, a series of experimental results[1–3] has motivated the intriguing suggestion that magnets can exhibit a long-range proximity effect (LPE), which in the picture assumed presumes the existence of a nonzero order parameter $\Delta(x)$ at distances from the superconductor $x \gg \xi_{\mathrm{exch}}$ (ξ_{exch} is the coherence length in the exchange field of a magnet), which contradicts the theory of FS junctions, since $\xi_{\mathrm{exch}} \ll \xi_T \sim v_F/T$ (T and v_F are the temperature and the Fermi velocity, respectively; v_F/T is the ordinary scale of the proximity effect in the semiclassical theory of superconductivity[4]). However, the supposition indicated above was made on the basis of the results of experiments with diffusive mesoscopic heterosystems, which have their own specific features. Specifically, the F/S interfaces in such systems are not "Sharvin" interfaces, having a resistance comparable to that under the interface. The latter property results in the appearance of a shunting effect,[5] comparable to the transport effects under study. In addition, this feature introduces an uncertainty into the value of the transmission coefficient of an interface,[6] which also affects the magnitude and sign of the correction to the measured conductance.[7] Attempts have been made to explain the LPE by the manifestation of a triplet component of the order parameter,[8–10] but the contribution of triplet fluctuations can be substantial only if the conductance is close to the quantum conductance, which does correspond to the experiments indicated above.

It is appropriate to recall our first results,[11] which are presented in Fig. 1 for the system Cu/Sn and which demonstrate the dramatic influence of the shunting effect on the possible conclusions concerning the character of the effects in the conductance of metal–superconductor systems even in measurements performed with lower-resistance interfaces than in mesoscopic structures. Thus the curve 1, measured outside an interface, exhibits conductance behavior in accordance with the fundamental ideas of the semiclassical theory,[12,13] according to which because of "retroscattering" the cross section for elastic scattering by impurities in a metal increases at the coherence length of $e-h$ hybrids formed in the presence of Andreev reflection, i.e. *a decrease* of the conductivity of the metal and not an increase, as when the impurity scattering of Andreev holes is completely ignored in the case of a point-like ballistic junction,[14,15] occurs. The behavior of the resistance of a circuit which includes a non-Sharvin interface may not even reflect the behavior of the conductivity of the metal itself (curve 2; see also Ref. 2). But it is precisely this type of behavior that can be taken as a manifestation of a long-range proximity effect. In other words, several competing effects with different signs can appear together in the conductivity of heterosystems with a

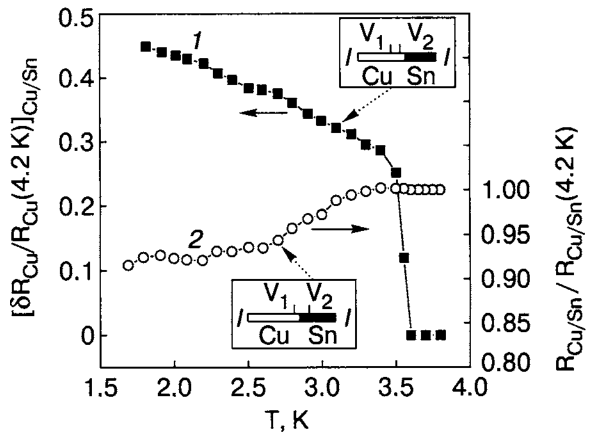

FIG. 1. Temperature dependences of the resistance of the system normal metal/superconductor (N/S) in the configuration for measurements outside the interface (curve 1) and with an interface (curve 2)[11].

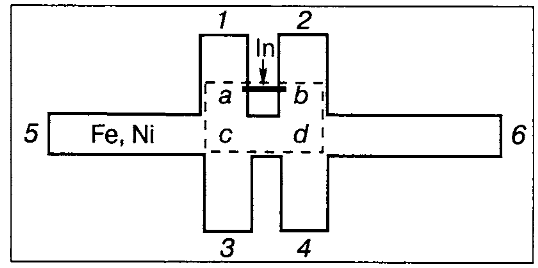

FIG. 2. Schematic diagram of the samples. The dashed line encloses the working region. The regimes of current flow parallel and perpendicular to F/In interfaces (at the locations a and b) were obtained by feeding current through the branches 1 and 2 in the absence of the indium jumper, shown in the figure, and through 5 and 6 in the presence of the jumper.

superconductor on switching to the N/S regime in a configuration encompassing an interface.

II. ARRANGEMENT OF THE EXPERIMENT

The present paper presents the results of experimental investigations of the transport properties of nonfilm cyrstalline ferromagnets Fe and Ni in the presence of F/In interfaces with different area, which were prepared by tinning the experimental metals with the tip of a soldering bit made of the same metal coated with a superconducting metal in the temperature where, according to published data, intermediate chemical compounds are not formed. Interfaces prepared by this method for samples with macroscopic thickness, making it possible to reduce the shunting effect at interfaces to a minimum, have repeatedly demonstrated high transmission and, therefore, reproducibility of their properties in different systems.[11] The objective of choosing metals with comparable densities of states in the spin subbands and electric and geometric interfacial parameters and a thickness of the experimental metal under interfaces which is large compared with the layer of superconductor on the interface was to reduce to a minimum the effects due to an increase of the conductivity of the system that could be construed as being a manifestation of the proximity effect.

The measurements were performed on samples cut out by the electric-spark method from bulk ferromagnetic materials with radically different purity and structure: polycrystalline Fe with "room/helium" resistance ratio $RRR \approx 3$ and single-crystal Ni with $RRR \approx 200$. The mean-free path l_{el} in Fe and Ni with the indicated RRR at liquid-helium temperatures is of the order of 0.01 μm (this value of l_{el} is most often encountered in nanostructures) and 1 μm, respectively. The geometry of the samples is shown (not in scale) in Fig. 2. The working frequency range of the samples, which contains F/S interfaces at the points a and b, is marked by a dashed line.

The effects in the conductivity of magnets were studied in two measurement configurations: with a constant current flowing parallel (insets a and b in Figs. 3 and 4) and perpendicular (inset a Fig. 6 and inset in Fig. 7) to the F/In interfaces. The latter configuration was implemented by an indium jumper between the F/In interfaces after the measurements in the first configuration (at the sites a and b in Fig. 2). The region $abdc$ acquired a closed "Andreev interferometer" geometry, making it possible to study the phase sensitivity of the effects at the same time (these results will published in the near future). In the first configuration both point (for Fe and Ni) and wide (for Ni) interfaces were used, and in the second configuration point interfaces were used for Fe and wide interfaces for Ni (the characteristic dimensions of both types of interfaces can be much greater than the mean-free path length). We term F/In interfaces "point" (p) or "wide" (w) when the ratio of their characteristic areas to the width of the conductor is of the order of 0.1 or 1, respectively. The point interfaces were prepared by fluxless "threading" into the experimental metal of fused indium on a sharpened tip (Fe) of the soldering iron with curvature diameter $\approx 50-100$ μm (ultrapure indium with $RRR \approx 4 \times 10^4$ was used in all cases). When the wide interface was subsequently prepared, the indium layer was deposited in a manner so that its bottom boundary approximately coincided with the position of the point interface. It is known that at the tinning temperature used ($<200\,^\circ$C) iron and nickel do not mix with indium. The intrinsic resistance of the

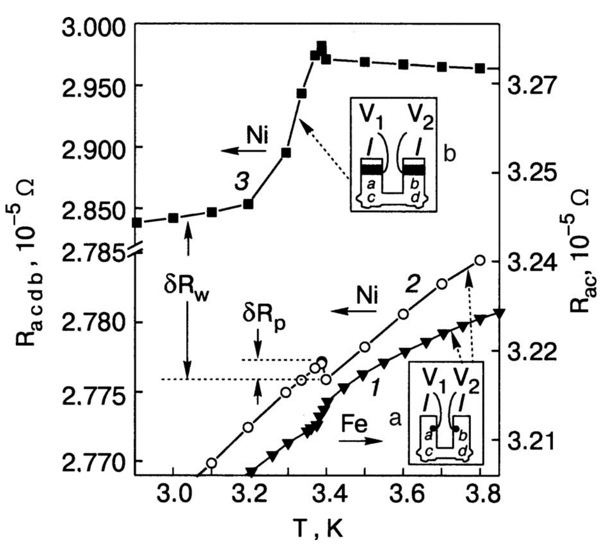

FIG. 3. Temperature dependences of the resistance of sections of Fe and Ni samples with point [inset (a)] for Fe (curve 1) Ni (curve 2) and wide [inset (b)] for Ni (curve 3) F/S interfaces as "superconducting mirrors" for $T < T_c^{\rm In}$.

prepared interfaces was many orders of magnitude lower than for interfaces prepared by nanotechnologies.

The dimensions of the components in the working region were as follows: for the Fe sample the width of the semiconductors of the magnet $W_{ac,bd}\approx 1.5$ mm, $W_{cd}\approx 0.5$ mm, and their lengths $L_{ac,bd}\approx 0.5$ mm and $L_{cd}\approx 0.3$ mm with thickness $t\approx 0.25$ mm; for the Ni sample: $W_{ac,bd}\approx 0.5$ mm, $W_{cd}\approx 0.7$ mm, and their lengths $L_{ac,bd}\approx 0.5$ mm and $L_{cd}\approx 0.4$ mm with thickness $t\approx 0.1$ mm. The measurement configuration in which the curves presented in the figures were obtained is shown in the insets in each figure. The resistances of the components of the circuit *acdb*, $R_{ac}(T)$, $R_{cd}(T)$, $R^{\mathrm{In}}(T)$, and $R_{acdb}(T)$,were measured independently without destroying the geometry of the interfaces and the current-flow configuration, using the taps 1–6 (Fig. 2) in different combinations with a closed or open In jumper.

The relative error in determining the resistance in our experiments was $\delta R/R\leq 10^{-4}$, which was attained by stabilizing the current 0.1–1 A in the external circuit and the temperature, and by using a voltmeter with resolution $\delta U\approx 10^{-11}$ V, based on a superconducting modulator, to measure potential differences.[16]

The current in the branch $ca-\mathrm{In}-bd$ was determined from the Kirchhoff relations:

$$I=I_{ca-\mathrm{In}-bd}(1+I_{cd}/I_{ca-\mathrm{In}-bd});$$

$$I_{cd}/I_{ca-\mathrm{In}-bd}=R_{ca-\mathrm{In}-bd}/R_{cd}:$$

$$I_{cabd}(T)=\left.\frac{IR_{cd}-U_{ab}^{\mathrm{In}}-2(U_{\mathrm{if}}+\delta U_{ac})}{R_{\Sigma}}\right|_{T},$$

$$R_{\Sigma}(T)=[R_{ac}+R_{bd}+R_{cd}]_{T};$$

$$[U_{\mathrm{if}}+\delta U_{ac}]_{T}=[U_{cb}-(U_{ab}^{\mathrm{In}}+U_{ac})]_{T}, \quad (1)$$

where R_{Σ} is the total resistance of the circuit *acdb* of the ferromagnet, U_{if} is the potential difference on one interface, U_{ab}^{In} is the voltage measured independently on the In jumper, and $\delta U_{ac}(T)$ is the possible addition to the voltage U_{ac} on the section *ac* of the ferromagnet, measured in a configuration which does not include the potential difference on the interface.

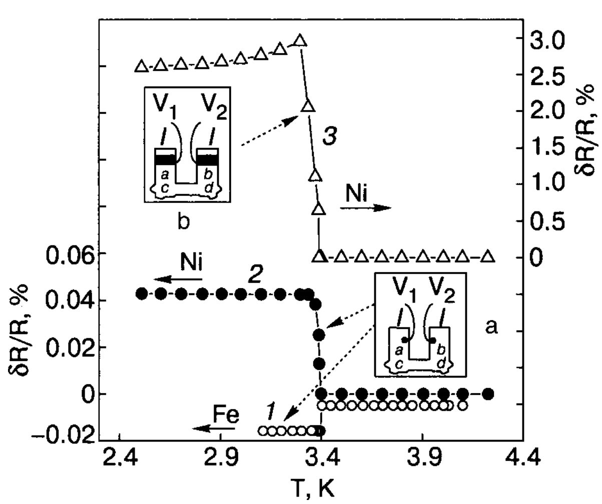

FIG. 4. *Coherent effect*. The same curves as in Fig. 3, in relative units. Curve 1 is shifted downword by $5\cdot 10^{-3}$%.

III. DISCUSSION

The main results are as follows: 1) the first observation of the interference contribution of long-wavelength Andreev excitations to the decrease of the conductivity of a ferromagnet (Ni) with the typical coherence length for ferromagnets; 2) observation of *an increase* of "the resistance of F/S interfaces" Fe/In and Ni/In, showing the limitations which are imposed on the Andreev reflection processes on a F/S interface (spin accumulation regime) by the polarization of the current in a ferromagnet.

A. Coherent effect

Figure 3 shows the results of measurements of the resistance $R(T)=U/I$ of the Fe and Ni sections with point (curves 1 and 2) and wide Ni (curve 3) F/S interfaces with current flow *parallel* to the interfaces (see inset), i.e. in the configuration where in the superconducting state of indium the interfaces, as part of the potential probes, play a passive role of "superconducting mirrors." Figure 4 also contains the same data in relative units $\delta R/R=R(T)-R_p(T=T_c^{\mathrm{In}})/R_p(T=T_c^{\mathrm{In}})$.

It is evident that for $T\leq T_c^{\mathrm{In}}$ (after Andreev reflection is actuated) the resistance of Ni increases abruptly by $\delta R_p\approx 1\times 10^{-8}\ \Omega$ (Fig. 3) in the case of two point contacts ($\delta R/R\approx 0.04\%$, Fig. 4) and by $\delta R_w\approx 7\times 10^{-7}\ \Omega$ (Fig. 3) in the case of two wide contacts ($\delta R/R\approx 3\%$, Fig. 4); the analogous effect in Fe with point contacts was not observed, but a negligible effect with the opposite sign and magnitude comparable to δR_p^{Ni} is observed.

We shall show that, just as in the case of a nonmagnetic metal (Fig. 1), the observed (because the shunting effect is small) decrease of the conductivity of nickel when the potential probes pass into the "superconducting mirrors" state corresponds to an increase of the efficiency of the elastic scattering by impurities in the metal adjoining the superconductor when Andreev reflection appears in it. Actually, the interference contribution of the scattering of a singlet pair of $e-h$ excitations by impurities in a layer of thickness of the order of the coherence length ξ, read from the N/S interface, measured at a distance L from the interface $\sim\exp(-L/\xi)$ and for $\xi\ll L$ can be written in the form[11–13]

$$\frac{\delta R}{R_L}=\frac{\xi}{L}\bar{r}, \quad (2)$$

where the coherence length ξ is the maximum distance at which $e-h$ excitations of a singlet pair are still capable of interacting with the same impurity (see Fig. 5); $\bar{r}$ is the effective probability of elastic scattering of excitations with Andreev scattering in the layer ξ as a whole. For a completely transparent interface it equals 1 irrespective of the number of such pairs — the probability of Andreev reflections, determined by the area of the N/S interface and the selection rules. Measurements of the voltages in the configurations including and not including interfaces showed that the voltages on the interfaces themselves are negligibly small in our systems, so that in our experiments $\bar{r}\approx 1$. Thus, the relation (2) indicates that it is in principle possible to observe a two-fold increase of the resistance of a layer with thickness

$L \sim \xi$ as compared with its resistance in the absence of Andreev reflection.

However, in the expression (2) the ratio of the magnitude of the effect δR to the resistance measured at an arbitrary distance from the boundary is viewed as a simple ratio of the corresponding spatial scales. It is hereby assumed that the specific conductivity σ_L is the only parameter for the entire conductor of length L, including the scale ξ. Actually, we find from Eq. (2) that the magnitude of the positive change of the resistance δR of the layer ξ as whole is

$$\delta R^{\xi} = \frac{\xi}{\sigma_{\xi} A_{\rm if}} \bar{r} \equiv \sum_{i=1}^{N_{\rm imp}} \delta R_i^{\xi}. \tag{3}$$

Here σ_{ξ} is the specific conductivity in the layer $\xi; A_{\rm if}$ area of the interface; $N_{\rm imp}$ is the number of Andreev channels (impurities) participating in the scattering; and, δR_i^{ξ} is the result $e-h$ scattering by a single impurity. It is evident that the expression (3) is the resistance of part of the conductor only for $\sigma_{\xi}=\sigma_L$. i.e. for $\xi > l_{\rm el}$. For ferromagnets $\xi \ll l_{\rm el}$ and $l_{\rm el}^{\rm L} \neq l_{\rm el}^{\xi}$. In this case, to compare δR from measurements on length L to the theory the value of R_L in the expression (2) must be renormalized.

In the semiclassical representation the coherence of an Andreev pair of excitations in a metal is considered to be destroyed if the displacement of their trajectories relative to one another reaches a magnitude of the order of their thickness, i.e., of the order of the de Broglie wavelength λ_B. The maximum possible distance ξ_m (collisionless coherence length) at which this could occur in a ferromagnet with rectilinear e and h trajectories (Fig. 5a) is

$$\xi_m \sim \frac{\lambda_B}{\varepsilon_{\rm exch}/\varepsilon_F} = \frac{\pi\hbar v_F}{\varepsilon_{\rm exch}}; \quad \varepsilon_{\rm eexch} = \mu_B H_{\rm exch} \sim T_{\rm exch} \tag{4}$$

(μ_B is the Bohr magneton, $H_{\rm exch}$ is the exchange field, and $T_{\rm exch}$ is the Curie temperature). However, taking account of the Larmor curvature of the e and h trajectories in the field $H_{\rm exch}$ together with the requirement that both types of excitations interact with the same impurity (see Fig. 5b) we shall find that the coherence length decreases to the value[17]

$$\xi^* = \sqrt{2qr} = \sqrt{2q\xi_m}, \tag{5}$$

where r is the Larmor radius in the field $H_{\rm exch}$ and q is the screening radius of the impurity $\sim \lambda_B$. Finally, for the values of the diffusion coefficient D for which $l_{\rm el} \ll \xi_m$, the coherence length could be additionally limited:

$$\xi_{\rm exch}^D \sim \sqrt{l_{\rm el}\xi^*}; \quad l_{\rm el} < \xi^* \tag{6}$$

(Fig. 5c), which would make it possible to return to the condition $\xi = \xi_{\rm exch}^D$ and use the expression (2) without renormalization. (This case does not occur in our samples.) Thus Fig. 5 gives a qualitative idea of the existence of scales on which the dissipative contribution of Andreev hybrids as a result of scattering by impurities with the characteristic dimensions of the interfaces $y,z \gg l_{\rm el}(N_{\rm imp} \gg 1)$ can appear.

For Fe with $T_{\rm exch} \approx 10^3$ K and Ni with $T_{\rm exch} \approx 600$ K we have $\xi^* \approx 0.001$ μm. Hence it follows that in our experiment with $l_{\rm el} \approx 0.01$ μm (Fe) and $l_{\rm el} \approx 1$ μm (Ni) the limiting case $l_{\rm el} \gg \xi^*$ and $l_{\rm el}^{\rm L} \neq l_{\rm el}^{\xi}$ is realized. It is evident in Fig. 5b that for $y,z \gg l_{\rm el} \gg \xi^*$ in the normal state of the interface the length $l_{\rm el}^{\xi}$ in the layer ξ^* corresponds to the shortest distance between the impurity and the interface, i.e. $l_{\rm el}^{\xi} \equiv \xi^* (\sigma_L \neq \sigma_{\xi^*})$. (We note that for an equally probable distribution of the impurities the probability of finding an impurity at any distance from the interface in a finite volume with at least one dimension greater than $l_{\rm el}$ is 1.)Renormalizing the expression (2) with ξ^* replacing ξ gives an expression for estimating the coherent effect we are studying in ferromagnetics from measurements on the length L:

$$\frac{\delta R^{\xi^*}}{R_L} = \frac{\xi^*}{L}\frac{l_{\rm el}}{l_{\rm el}^{\xi^*}}\bar{r} \approx \frac{l_{\rm el}}{L}\bar{r};$$

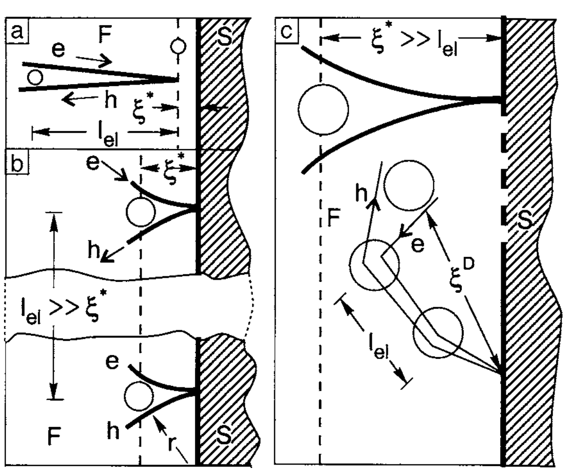

FIG. 5. Scattering of Andreev $e-h$ hybrids and their coherence length ξ^* in a normal ferromagnetic metal with characteristic F/S interfacial dimensions greater than $l_{\rm el}$: $\xi^* \ll l_{\rm el}$ (a, b); $\xi^* \gg l_{\rm el}$ (c). See text for details.

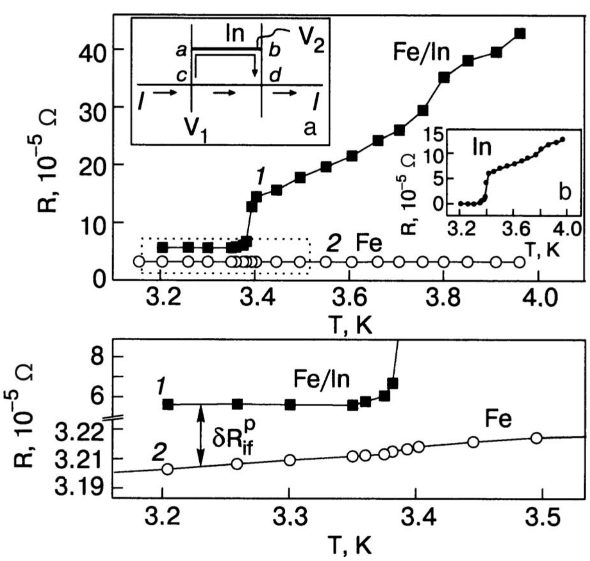

FIG. 6. Temperature dependences of the resistances in the system Fe–In with point F/In interfaces, measured in a configuration with a current normal to the interfaces (inset a). Top panel: 1—$R(T)=U_{cb}/I_{cabd}(T)$; 2—$R_{ac}(T)$; inset b —jumper resistance $R^{\rm In}(T)$. Bottom panel: part of the curves 1 and 2 on an enlarged scale; $\delta R_{\rm if}^p$— increase of the resistance of a point “interface” (spin-polarization region of a ferromagnet near the junction) below $T_c^{\rm In}$.

$$\delta R^{\xi^*} = \frac{\xi^*}{\sigma_{\xi^*} A_{\text{if}}} \bar{r} \equiv \sum_{i=1}^{N_{\text{imp}}} \delta R_i^{\xi^*}. \quad (7)$$

Here σ_{ξ^*} is the specific conductivity in the layer ξ^*; $\delta R_i^{\xi^*}$ is the result of $e-h$ scattering by one impurity. Thus the expression (7) can serve as an observability criterion for the coherent effect in ferromagnets with different degrees of purity. For a point Fe/In interface with $l_{\text{el}}^{\text{Fe}} \approx 0.01\ \mu$m the interference increase of the resistance of a segment of Fe with the length studied should be $\approx 10^{-9}\ \Omega$ and could not be observed with the current $I_{acdb} \leq 0.1$ A, at which the measurement was performed, against the background due to the shunting effect (see curves 1 in Figs. 3 and 4). At the same time, for a point Ni/In interface with a comparable area (with a shunting effect of the same order of magnitude) δR^{ξ^*} should be an order of magnitude larger, which agrees with the observed increase of the resistance of nickel with $l_{\text{el}}^{\text{Ni}} \approx 1\ \mu$m (curves 2).

Comparing the effects in Ni for interfaces with different areas also shows that the observed effects pertain precisely to the type of coherent effect studied. Since the number of Andreev channels is proportional to the area of a N/S interface, for measurements on samples differing only by the interface area A_{if} we should have $\delta R_w^{\xi^*} / \delta R_p^{\xi^*} = N_{\text{imp}}^w / N_{\text{imp}}^p \sim A_w / A_p$ (the indices p and w refer to point and wide interfaces, respectively). Comparing the jumps in the curves 2 and 3 (Figs. 3 and 4) gives the ratio $\delta R_w / \delta R_p = 70$, which corresponds reasonably to the ratio $A_w / A_p = 25-100$.

In summary, the magnitude and special features of the observed effects are undoubtedly directly related with the above-discussed coherent effect, thereby proving that, in principle, it can manifest in ferromagnets and be observed with *an appropriate instrumental resolution*. Although this is somewhat surprising, it remains, as proved above, within the bounds of our ideas about the scale of the coherence length of Andreev excitations in metals, which determines the dissipation and therefore cannot be regarded as a manifestation of the proximity effect in ferromagnets.

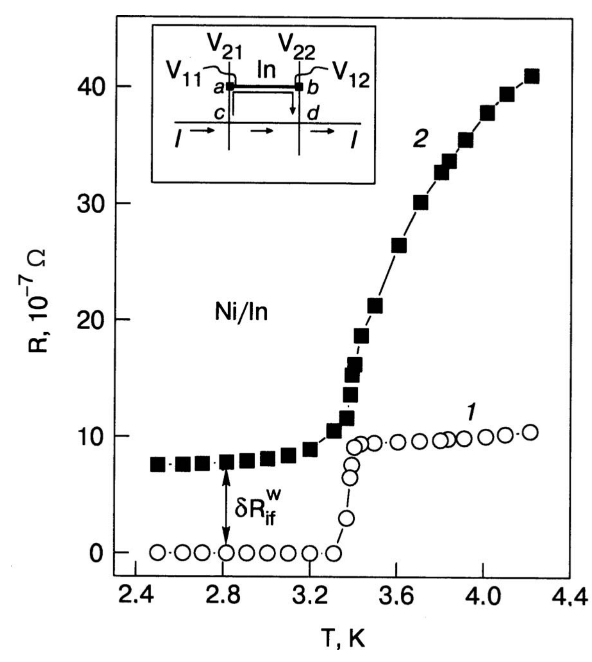

FIG. 7. Temperature dependences of the resistances in the system Ni-In with wide F/In interfaces, measured in a configuration with current normal to the interfaces (see inset): 1—jumper resistance $R^{\text{In}}(T)$; 2—$R^{\text{In}}(T) + R_{\text{if}}^w(T)$; δR_{if}^w—increase of the resistance of a wide "interface" (spin-polarization region of a ferromagnet near the junction) below T_c^{In}.

B. Spin accumulation effect

The macroscopic thickness of ferromagnets under interfaces made it possible to investigate the contribution of F/S interfaces under the conditions realizable for current flow perpendicular to the interfaces in the branch of a sample with an indium jumper with current fed through the contacts 5 and 6 (Fig. 2). Figure 6 (curve 1) shows for a system consisting of Fe with point interfaces the temperature behavior of the difference of the potentials V_1 and V_2 at the ends of the section *cab* of the indicated branch (see inset *a*), $U_{cb}(T) = |V_1 - V_2|(T)$, normalized to the current in this branch. Just as in the case with a nonmagnetic metal (Fig. 1, curve 2), the temperature dependence of the resistance $U_{cb}/I_{cabd}(T)$, including the resistance of the entire region of the interface, in itself does not give an idea about the possible changes in the resistive behavior of the ferromagnet itself under the interface with a transition of the state of the interface from F/N to F/S. To make a judgment about such changes the functions $R_{ac}^{\text{Fe}}(T) \equiv [U_{ac}/I_{cabd}]_T$ (curve 2) and $R^{\text{In}}(T)$ of the indium jumper must be calculated (in inset *b*). The result of subtracting R_{if}^p, referring to the region of the ferromagnet under the interface, is shown in the bottom panel. It is evident that it is monotonically greater than the contribution of the shunting to the system of interest with a point interfacial geometry (see curve 1, Fig.3) and the possible magnitude of the coherent effect, estimated in the preceding paragraph, and therefore is of different origin.

Similarly, the behavior of R_{if}^w was studied in a Ni sample with wide interfaces but in a somewhat different arrangement of the measurements which makes it unnecessary to take account of the resistance of the ferromagnet outside the regions under the interfaces. The temperature dependences of the differences of the potentials on both sides of the interfaces were measured (see inset in Fig. 7): $U_{ab}^1(T) = |V_{11} - V_{12}|(T)$ and $U_{ab}^2(T) = |V_{21} - V_{22}|(T)$. Figure 7 shows the corresponding functions $R(T)$ (curves 1 and 2), obtained by normalizing the indicated potential differences to the current in the branch *cabd* [see Eq. (1)]. The difference of the curves 1 and 2 measured in this manner serves as a measure of the resistance R_{if}^w of the regions of the ferromagnet that adjoin the superconducting "mirror."

Figure 8 presents in relative units the temperature behavior R_{if}^p for point Fe/In interfaces (curve 1) and R_{if}^w for wide Ni/In interfaces (curve 2) as $\delta R_{\text{if}} / R_{\text{if}} = [R_{\text{if}}(T) - R_{\text{if}}(T_c^{\text{In}})] / R_{\text{if}}(T_c^{\text{In}})$. The form of the curves shows that with the transition of the interfaces from the F/N state to the F/S state the resistance of the interfaces abruptly *increases* but compared with the increase due to the previously examined coherent effect it increases by an incomparably larger amount. It is also evident that irrespective of the interfacial geometry the behavior of the function $R_{\text{if}}(T)$ is qualitatively similar in both systems. The value of $R_{\text{if}}(T_c^{\text{In}})$ is the lowest resistance of the interface that is attained when the current is displaced to the edge of the interface by the Meissner effect. The magnitudes of the positive jumps with respect to this

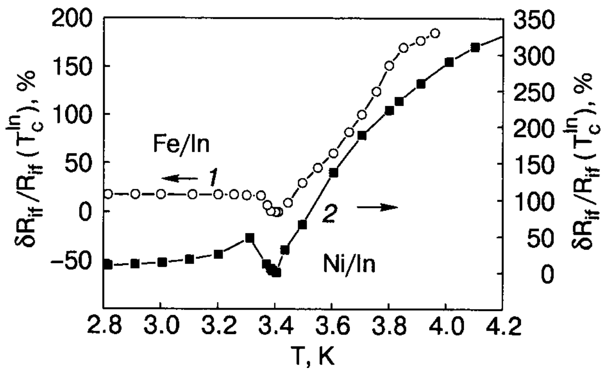

FIG. 8. *Spin accumulation effect*. Relative temperature dependences of the resistive contribution of spin-polarized regions of Fe and Ni near the interfaces with small (Fe/In) and large (Ni/In) area.

resistance, $\delta R_{\rm if}/R_{\rm if}(T_c^{\rm In}) \equiv \delta R_{F/S}/R_{F/N}$, are about 20% for Fe (curve 1) and about 40% for Ni (curve 2).

The values obtained are more than an order of magnitude greater than the contribution to the increase in the resistance of ferromagnets which is related with the coherent interaction of the Andreev excitations with impurities (as shown below, because of the incomparableness of the spatial scales in which they are manifested). This makes it possible to view the indicated results as being a direct manifestation of the mismatch of the spin states in the ferromagnet and superconductor, resulting in the accumulation of spin on the F/S interfaces, which decreases the conductivity of the system as a whole. We suppose that such a decrease is equivalent to a decrease of the conductivity of a certain region of the ferromagnet under the interface, if the exchange spin splitting in the ferromagnetic sample extends over a scale not too small compared to the size of this region. In other words, the manifestation of the effect in itself already indicates that the dimensions of the region of the ferromagnet which make the effect observable are comparable to the spin relaxation length. Therefore the effect which we observed should reflect a resistive contribution from the regions of ferromagnets of precisely such a scale. The presence of such nonequilibrium regions and the possibility of observing their resistive contributions using a four-contact measurement scheme are due to the "non-point-like nature" of the potential probes (finiteness of their transverse dimensions). In addition, the data show that the dimensions of such regions near Fe/S and Ni/S interfaces are comparable in our experiments. Indeed, the value of $\delta R_{\rm Ni/S}/R_{\rm Ni/N}$ corresponding according to the configuration to the contribution from *only* the nonequilibrium regions (inset in Fig. 7) and the value of $\delta R_{\rm Fe/S/}/R_{\rm Fe/N}$ obtained from a configuration which includes a ferromagnetic conductor of length obviously *greater* than the spin-relaxation length (as in the inset *a* in Fig. 6) are actually of the same order of magnitude. In addition, according to the spin-accumulation theory,[5,18,19] the expected magnitude of the change of the resistance of the F/S interface in this case is of the order of

$$\delta R_{F/S} = \frac{\lambda_s}{\sigma A}\frac{P^2}{1-P^2};$$

$$P = (\sigma_\uparrow - \sigma_\downarrow)/\sigma; \quad \sigma = \sigma_\uparrow + \sigma_\downarrow. \tag{8}$$

(Here λ_s is the spin relaxation length; P is the coefficient of spin polarization of the conductivity; $\sigma, \sigma_\uparrow, \sigma_\downarrow$, and A are the total and spin-dependent conductivities and the cross section of the ferromagnetic conductor, respectively.) Using this expression, substituting the data for the geometric parameters of the samples, and assuming $P^{\rm Fe} \sim P^{\rm Ni}$, we obtain $\lambda_s({\rm Fe/S})/\lambda_s^*({\rm Ni/S}) \approx 2$. This is additional confirmation of the comparability of the scales of the spin-flip length λ_s for Fe/S and λ_s^* for Ni/S, indicating that the size of the non-equilibrium region determining the magnitude of the observed effects for Fe/S and Ni/S interfaces is no greater than (and in Fe equal to) the spin relaxation length in each metal. In this case, according to Eq. (8) the length of the conductors with whose normal resistance the values of $\delta R_{F/S}$ must be compared should be set equal to precisely the value of λ_s for Fe/S and λ_s^* for Ni/S.Hence follows an estimate of the coefficients of spin polarization of the conductivity for each metal

$$P = \sqrt{(\delta R_{F/S}/R_{F/N})/[1 + (\delta R_{F/S}/R_{F/N})]}. \tag{9}$$

Using our data we obtain $P^{\rm Fe} \approx 45\%$ for Fe and $P^{\rm Ni} \approx 50\%$ for Ni, which is essentially the same as the values obtained from other sources.[20] If A in the expression (8) is taken to be the area of the conductor of the order of the area of the current entrance into the jumper, i.e. of the order of the product of the length of the contour of the interface by the width of the Meissner layer, then a rough estimate of the spin relaxation lengths in the metals investigated in accordance with the assumption of single-domain magnetization of the samples will give the values $\lambda_s^{\rm Fe} \sim 900$ Å and $\lambda_s^{\rm Ni} > 500$ Å. Comparing these values with the coherence length in ferromagnets $\xi^* \approx 10$ Å we see that although the coherent effect leads to an almost 100% increase of the resistance, the latter refers to a layer whose thickness is two orders of magnitude less than that of the layer responsible for the appearance of the spin accumulation effect and therefore does not mask the latter effect.

C. Shunting effect

Our experiments showed that one source of inadequate information about the physics of the processes in film ferromagnetic samples with measurement configurations encompassing interfaces could be the planar geometry of the latter. In this case the superconductor, being part of the potential probe, covers an appreciable area δA of the sample, whose thickness is comparable to that of the superconductor. This should lead to a strong shunting effect — an apparent increase in the conductivity of the metal under study. If the layer between the superconductor and the film in the interface-sandwich (for example, the appreciable "non-Sharvin" values of the resistance of the barriers on film mesoscopic interfaces attest to the presence of such a layer) is comparatively thin, the unavoidable drop, due to the shunting, of the resistance of the system should be of the order of $\delta R/R \approx \delta A/A$, which is, in fact, observed.[2,3] The shunting effect can also appear in experiments with such interfaces, even if they are far from the main current channel (the typical configuration for measurements of "nonlocal" resistance[21]). The reality of such a situation follows directly from the picture of the distribution of the potential in branches whose dimensions in mesoscopic samples are comparable to those of the main current channels. As is well-known, this distribution satisfies the Laplace equation (see, for example, Ref. 22), whose solution for the current on a N/S interface in a branch of length L with the same width and thickness as in the main current-carrying circuit will be an expression of the form[23]

$$j(x) \approx j(x_0)\left(\frac{\sqrt{\pi}}{4}\right)\left(\frac{x}{x_0}\right)\exp\left[-\frac{x-x_0}{x_0}\right],$$

where x_0 is the start of the branching measured from the current injector, $x_0 \leq x \leq L$. In samples of mesoscopic size this contribution is quite large because of the small values of x. As a s result, in heterostructures with a superconductor at a transition to a N/S (specifically, to F/S) regime several competing mechanisms can appear at the same time, complicating, generally speaking, the identification of the effects of interest. One such effect increases the measured potential difference on the scale of the $e-h$ coherence length in the nonsuperconducting part of the system, and another effect decreases this difference because of shunting (behavior which is similar to that observed in Ref. 21). Finally, for F/S systems there is one other mechanism that increases the resistance of the system. It is due to the mismatch at the F/S interface of the spin-polarized current in the magnet and the singlet current of Cooper pairs in the superconductor (spin accumulation effect[18,19]).

Comparing the results of our experiment for point (Figs. 3, 4, and 6) and wide (Figs. 3, 4, and 7) contacts clearly shows the scale of the shunting effect associated with the shunting of part of the current into the superconducting probe on the cover. For small elastic mean-free path lengths (just as in nanostructures) it is capable, specifically, of predominating over the coherent effect (curve 1, Fig. 3). The contribution of the shunting could have been determined with adequate accuracy only if we used two-layer interfaces with transmittance close to 1. In the three-layer sandwich geomtery (in planar nanostructures), where, as a rule, the resistance of the intermediate layer is less than the resistance of a normal metal but greater than that of a layer of superconductor, the shunting effect, apparently, can predominate over any effects in the conductivity of the metal which is itself being studied. Consequently, we investigated metal samples of macroscopic thickness with a layer of superconductor on the interfaces with incomparably smaller thickness. As follows, for example, from the form of the curve 3 in Fig. 3, for such a geometry the shunting effect, though it does appear, is comparable to the effect of the interference decrease of the conductivity of the experimental metal near the superconducting transition, exceeding the latter by more than factor of 2. Only in a dirty ferromagnet can it completely suppress the manifestation of a coherent effect in a point F/S interfacial geomtery (curves 1, Figs. 3 and 4).

IV. CONCLUSIONS

Coherent and spin-dependent effects in the conductance of macroscopic heterosystems magnet (Fe, Ni)-superconductor (In) were investigated. The first proof of the possibility of observing with adequate resolution the characteristic coherent effect in the conductivity of sufficiently pure ferromagnets was given for the example of nickel. The effect consists of an interference decrease of the conductivity on the scale of the very small coherence length of Andreev $e-h$ hybrids. It was shown that this length does not exceed the coherence length estimated using the semiclassical theory for ferromagnetic metals with a high exchange energy. This makes untenable the suggestion that a long-range proximity effect can exist in ferromagnets under ordinary conditions (for the typical purity of metals), presupposing the presence of coherent correlations for excitations with energy $\varepsilon \sim T$ and opposite spins at distances *typical* for nonmagnetic metals.

Additional proof was obtained for spin accumulation on F/S interfaces. Such accumulation is due to the special features of Andreev reflection under the conditions of spin polarization of the current in a ferromagnet. (Experiments on the submicron-size system Ni/Al lead to a similar conclusion.[24])

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