The critical parameter in this method of τ_n determination is the values of G_A/G_V for the triton and neutron. This ratio for the triton, obtained using the quantity $(T_{1/2})_t$, was found to be $(G_A/G_V)_t = -1.2646 \pm 0.0035$. For the mixed superallowed $n \to p$ transition, the value of $(G_A/G_V)_n$ is determined from the measurement data for the coefficient which characterizes the asymmetry of β-electron escape relative to the spin of the decaying neutron. The results of four such experiments [10–13] have the weighted mean $\langle (G_A/G_V)_n \rangle_4 = -1.2637 \pm 0.0022$, which agrees well with the value of $(G_A/G_V)_t$, allowing the ratio G_A/G_V to be considered as a universal fundamental constant characterizing the β-processes. Assuming that the values of G_A/G_V for the triton and neutron are equal, we arrive at the following estimate of the neutron lifetime: $\tau_n = 891.7 \pm 3.9$ s. At the same time, it is pertinent to note that Abele et al. [14] obtained a value of $(G_A/G_V)_n = -1.274 \pm 0.003$ for the ratio between the axial-vector and vector coupling constants for the β-decay of the neutron. This value is significantly different from $(G_A/G_V)_t$. The inclusion of this result when determining the weighted mean ratio G_A/G_V for the neutron gives $\langle (G_A/G_V)_n \rangle_5 = -1.2670 \pm 0.0030$ [15]. The difference between $(G_A/G_V)_t$ and $\langle (G_A/G_V)_n \rangle_5$ may be testimony to a partial suppression of the axial-vector interaction in the presence of pion exchange in the triton. Under this assumption we obtain $\tau_n = 888.9$ s. Therefore, the summary result can be represented in the form $\tau_n = (890.3 \pm 3.9_{stat} \pm 1.4_{syst})$ s, where the third term defines the systematic error arising from the uncertainty as to the effect of strong interaction in the form of pion exchange on the weak interaction in the β-decay [16].

4. Conclusions

The main source of errors in the method of determining τ_n by way of measuring the decay exponent for an ensemble of ultracold neutrons is the free-neutron leakage from gravitational traps. The approach to τ_n determination proposed in our work is void of this source of systematic errors. Acquisition of trustworthy information on the lifetime of the free neutron is important both for theoretical and applied neutron physics. This permits us to develop methods for measuring the concentration of free neutrons in matter reliant on the detection of neutron decay products — that is, methods which do not necessitate a detailed knowledge of the neutron spectrum and the structure of neutron cross sections. The exact knowledge of the neutron decay period (like of the triton decay period) is also required in cosmology — this is demanded when calculating the parameters which characterize the transformation of matter in the universe: the n/p and $^3H/^3He$ ratios, as well as the cosmological constants depending on the substance density.

The concept of developing, on the basis of the effect of the chemical shift of the triton disintegration constant, a new technique for the diagnostics of the electronic states of hydrogen-bearing atomic-molecular systems by way of replacing the hydrogen atom with tritium holds promise in the area of molecular physics. The fact that hydrogen is present in many substances as the main component or an admixture makes it possible to introduce tritium into the composition of different structures, thus placing the electron probe directly in the atomic-molecular system under investigation. In doing this, one can count on successfully applying the tritium β-electron diagnostic technique to the solution of a number of physicochemical problems — from the problems of the shape of hybrid orbitals or the distribution of an unpaired electron in radicals to the problems of charge distribution between a sorbent and an adsorbent, the form of hydrocarbon chemisorption, and the physical nature of hydrogen bonds.

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Superconducting currents through a ferromagnet. Phase inversion in structures with Josephson π-junctions

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1. Introduction

The relationship between a superconducting current I_s and a phase difference φ in superconducting weak links (Josephson junctions) is described by a 2π-periodic function; in the simplest case of a tunnel barrier or a barrier of a dirty normal metal, one finds $I_s = I_c \sin\varphi$, where I_c is the Josephson-junction critical current. Recent experiments have shown that it is possible to realize Josephson structures (π-junctions) with a phase difference π in the ground state, i.e., with an anomalous current — phase relation and a dependence of the weak link energy on the phase difference, which are shifted by a half-period (Fig. 1):

$$I_s = -I_c \sin\varphi\,, \quad E = E_J(1 + \cos\varphi)\,. \tag{1}$$

Although the term 'π-junction' was introduced in Ref. [1] for superconducting tunnel junctions with magnetic impurities in the tunnel barrier, the superconducting weak links with a

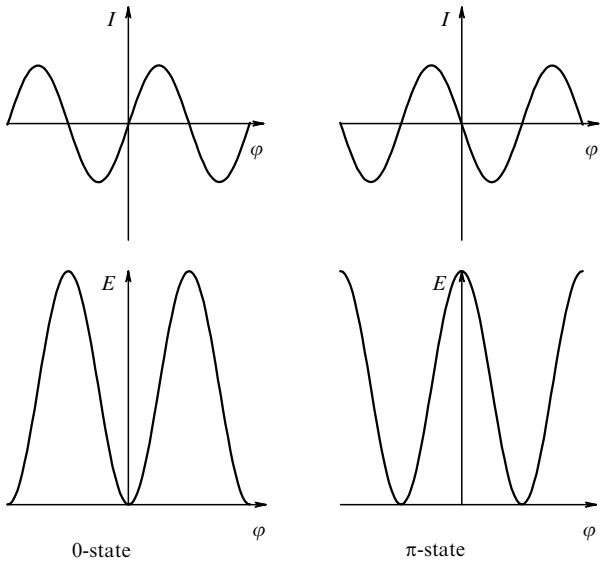

Figure 1. Current – phase relation and dependence of the weak link energy on the phase difference for the ordinary (0-) and π-junctions.

spontaneous shift in the superconducting phase difference were first realized for structures with other mechanisms of sign inversion of the superconducting order parameter [2, 3]. A brief review of experimental and theoretical works concerned with the investigation of Josephson structures that exhibit a spontaneous π-shift in the phase difference was published by one of the authors elsewhere [4], along with the first results on the experimental investigation of the Josephson thin-film superconductor – ferromagnet – superconductor (SFS junctions) sandwiches.

The problem of the coexistence of superconductivity and ferromagnetism has long been of basic interest. The antagonism between these two phenomena with different spin ordering is the cause of a strong superconductivity suppression in the region of S- and F-material contacts [5]. Attempts to produce Josephson SFS junctions were previously made by different scientific groups (see, for instance, the review [6]). However, the existent substantial nonuniformity of the ferromagnetic layers supposedly would not allow an unambiguous statement that the observed nonlinearities of characteristics arose from the flow of superconducting currents precisely through the ferromagnet. Our group proposed the use of weak ferromagnetic alloys to obtain Josephson junctions with high-uniformity of superconducting currents along the ferromagnetic interlayer, this uniformity being confirmed by the observation of perfect dependences of the critical current on the magnetic field applied along the junction plane [4]. The lack of superconducting shorts and appreciable nonuniformities in the thickness and composition of the ferromagnetic layer became possible due to a relatively large thickness of the F-layer (15 – 30 nm), which could be employed for ferromagnetic CuNi alloys with a low Curie temperature of 30 – 150 K. The most convincing corroboration of the existence of superconducting electron transport in the presence of an exchange field is the realization of SFS π-junctions [7, 8] and structures with spontaneous phase shifts on their basis [9]. In our report we briefly summarize the experimental data obtained for the Josephson $Nb - Cu_{1-x}Ni_x - Nb$ junctions with a different composition x of the F-layer and the structures on the basis of these junctions. Furthermore, we give a comparison of the results obtained for the SFS sandwiches and bilayer SF structures.

2. Proximity effect in an SF system

As in the case of a superconductor – normal metal (SN) interface, the superconducting pairs in an SF system are capable of penetrating the ferromagnetic F-layer some decay depth (which we denote by ξ_{F1}), to produce an induced superconducting order parameter. The order parameter length in the ferromagnet decreases as its exchange energy E_{ex} increases. The reason is that the exchange interaction is trying to align the electron spins in one direction, i.e., break the superconducting pairs made up of electrons with oppositely directed spins. When the Curie temperature T_{Curie} of the ferromagnet is much higher than the critical temperature T_c of the superconductor, the exchange interaction in a 'dirty' ferromagnet can be considered as the only pair-breaking factor. In this case, the decay length of the superconducting order parameter in the ferromagnet can be estimated by substituting the exchange energy E_{ex} for $k_B T$ in the conventional relation for the pair coherence length in a dirty normal metal:

$$\xi_{F1} \sim \left(\frac{\hbar D}{E_{ex}}\right)^{1/2}, \tag{2}$$

where D is the electron diffusion coefficient in the ferromagnet. Unlike the case of the proximity effect in an SN system, where the coherence length ξ_N defining the order parameter decay in the N-layer is a real value, the pair coherence length ξ_F in the ferromagnet is a complex quantity. This signifies that, apart from the decay determined by the characteristic length ξ_{F1}, the oscillations of the induced superconducting order parameter, related to the presence of the 'imaginary' coherence length ξ_{F2}, are bound to occur in the ferromagnet near the SF interface. The order parameter (the superconducting wave function) can be expressed in terms of these quantities in the following way:

$$\begin{aligned}\Psi_F(x) &= \Psi_{F0} \exp\left(-\frac{x}{\xi_F}\right) \\ &= \Psi_{F0} \exp\left(-\frac{x}{\xi_{F1}}\right) \exp\left(-\frac{\mathrm{i}x}{\xi_{F2}}\right).\end{aligned} \tag{3}$$

Here, Ψ_{F0} is the order parameter in the ferromagnet at the SF interface, and x is the coordinate in the direction perpendicular to the interface. The wavelength of order parameter oscillations equals $2\pi\xi_{F2}$. For a dirty ferromagnet with $E_{ex} \gg k_B T$, the magnitudes of ξ_{F1} and ξ_{F2} are equal and described by formula (2). Then, the complex coherence length can be written in the form

$$\xi_F = \left(\frac{\hbar D}{2\mathrm{i}E_{ex}}\right)^{1/2}. \tag{4}$$

For the first time, the induced sigh-reversal order parameter near the SF interface in a ferromagnet was obtained in the theoretical work of Buzdin et al. [10], where it was noted that this state is similar to the LOFF state (the Larkin – Ovchinnikov – Fulde – Ferrell state [11]) predicted for hypothetical ferromagnetic superconductors. The physical origin of spatial oscillations of the order parameter lies with the exchange splitting of electron subbands with different spin directions. The electron transport across the

SF interface is accompanied by the passage of a Cooper pair into the superconductor and the reflection of the hole-type excitation back into the ferromagnet (the Andreev reflection). The electron impinging on the interface changes not only its charge in the process, but its spin as well, i.e., it finds itself in the branch of the electron spectrum belonging to a different spin subband which is displaced along the momentum axis by an amount $Q = E_{ex}/v_F$ (v_F is the Fermi electron velocity in the ferromagnet) relative to the branch with the opposite spin [12]. As a result, in the ferromagnet there emerges an Andreev bound state with a nonzero momentum. In terms of the Cooper pairs penetrating the ferromagnet [13], this signifies that the paired electron with a spin aligned with the exchange field lowers its energy owing to the exchange interaction, which is compensated for by the increase in kinetic energy. On the contrary, the paired electron with the opposite momentum direction decreases its kinetic energy and momentum to compensate for the excess energy gained due to the exchange interaction. As a consequence, the pair as a whole shifts in the k-space by an amount $2Q$. The contribution of this pair to the order parameter is defined by an additional factor $\exp(\mathrm{i}2Qx/\hbar)$. For a dirty ferromagnet (3, 4), the oscillations of the order parameter are superimposed on its decay arising from pair breaking at impurities in the presence of an exchange field. Therefore, the induced 'sign-reversal' superconductivity in the ferromagnet near the SF interface, predicted in Refs [10, 14, 15], has proven to be an entirely realizable modification of the hypothetical LOFF state [11].

In the experiments discussed below, a CuNi alloy with a low Curie temperature and low exchange energies is used for the ferromagnetic layer of the SFS sandwiches. For relatively low exchange energies ($E_{ex} \geqslant k_B T$), comparable contributions to pair breaking are made by the thermal energy and the exchange field alike. The general expression for the complex coherence length in the dirty weak ferromagnet is of the form [7, 8]

$$\xi_F = \left(\frac{\hbar D}{2(\pi k_B T + \mathrm{i}E_{ex})}\right)^{1/2}. \tag{5}$$

From this expression we separate out the real and imaginary parts to obtain

$$\xi_{F1,2} = \sqrt{\frac{\hbar D}{((\pi k_B T)^2 + E_{ex}^2)^{1/2} \pm \pi k_B T}}. \tag{6}$$

This expression passes into expression (2) for $E_{ex} \gg k_B T$ and into the well-known expression for the coherence length in a normal metal at $E_{ex} = 0$. It is significant that, while the decay length ξ_{F1} increases with decreasing temperature (as for the SN junction), the wavelength $2\pi\xi_{F2}$ of order parameter oscillations shortens with decreasing T. The temperature dependence of ξ_{F2} makes it possible to observe the transition of the SFS junction to the π-state under changes in temperature.

3. Manifestation of spatial order parameter oscillations: transition of a Josephson SFS junction to the π-state, and nonmonotonic behavior of T_c in bilayer SF structures

The transition to the π-state manifests itself in an anomalous oscillatory dependence of the critical current of an SFS sandwich on the thickness d_F of the ferromagnetic layer. Since the order parameter (3) is sign-reversal, it would appear reasonable that the order parameter has opposite signs on the superconducting banks in the SFS junction with a ferromagnet thickness d_F ranging from about half the oscillation wavelength, $\lambda_{ex}/2 = \pi\xi_{F2}$, to about λ_{ex}. That is to say, the phase difference across the junction would be equal to π in the absence of an external field and current [which does not contradict the stationary Josephson equation (1)]. The transition to the π-state under variation of temperature and ferromagnetic layer thickness d_F was first observed in Ref. [7]. The reciprocal dependence of the critical current through the SFS junction on d_F in the transition region to the π-state (the $0-\pi$ transition) was measured in detail in Refs [16, 17] later. However, only the ferromagnetic layer thicknesses in the vicinity of the $0-\pi$ transition were investigated in these papers, and therefore there is no way of making a reliable comparison of the experimental results with theoretical inferences. Based on the solutions of the quasi-classical Usadel equations, Buzdin et al. [15] obtained the following expression for the critical current of the dirty SFS junction:

$$I_c = I_{c0}\, y\, \frac{|\sinh y \cos y + \cosh y \sin y|}{\sinh^2 y \cos^2 y + \cosh^2 y \sin^2 y}, \quad y = \frac{d_F}{\xi_F^*}, \tag{7}$$

where $\xi_F^* = \xi_{F1} = \xi_{F2}$ are defined by relation (2). This formula describes the nonmonotonic oscillating dependence of I_c on d_F when $E_{ex} \gg k_B T$.

Another well-known consequence of the occurrence of the sign-reversal induced order parameter near the SF interface in a ferromagnet is a nonmonotonic dependence of the critical temperature T_c of multilayer SF structures on the thickness of the F-layers [14, 18]. As shown in Refs [19–22], a minimum in the $T_c(d_F)$ dependence emerges both in multilayer and bilayer SF structures. This arises from the fact that the suppression of superconductivity in the S-layer depends nonmonotonically on the F-layer thickness. The strongest suppression of the order parameter and the minimum of $T_c(d_F)$ should be observed when the ferromagnet thickness is close to a quarter of the oscillation period of the order parameter λ_{ex} [22], i.e., when $d_F = (\pi/2)\xi_{F2}$. For a thickness $\lambda_{ex}/4$, the zero of the order parameter is near the SF interface because the boundary condition for its derivative, $\Psi_F'(d_F) = 0$, is responsible for the occurrence of an antinode of the order parameter at the free ferromagnet boundary. When the ferromagnet thickness is somewhat larger or smaller, the order parameter at the SF interface is nonzero, and therefore the ferromagnet suppresses the superconductor to a smaller degree.

4. Nonmonotonic behavior of the critical current of the Josephson SFS junction. Transitions to the π-state

We have conducted the experimental investigations of the Josephson characteristics of SFS junctions (see also Refs [4, 7, 8]) on thin-film $Nb - Cu_{1-x}Ni_x - Nb$ sandwiches. For the ferromagnetic interlayer, use was made of $Cu_{1-x}Ni_x$ alloys with x close to 0.5 and the Curie temperature $T_{Curie} = 30-150$ K. The weak ferromagnetism in the CuNi alloys, which takes place in this concentration range, was of significance primarily due to the necessity of obtaining continuous and uniform F-layers of thickness comparable to the pair decay length ξ_{F1}. In layers of classical ferromagnetic metals (Co, Fe, Ni), the pair decay length is close to 1 nm, and therefore thin-film Josephson SFS sandwiches are hard to prepare with the

employment of these metals. Employing ferromagnetic alloys with low Curie temperatures allowed us to increase the pair decay length by dozens of times. This permitted the supercurrents to flow through the F-layers ranging up to 20 – 30 nm in thickness, which could be prepared with a uniformity of 1 – 2 nm in thickness. Another important result of using ferromagnetic alloys with a low T_{Curie} is the attainment of the limit $E_{\text{ex}} \geqslant k_{\text{B}}T$, which enabled us to observe the transition of the Josephson SFS junction to the π-state upon lowering the temperature.

The inset to Fig. 3 shows the geometry of a thin-film $\text{Nb} - \text{Cu}_{1-x}\text{Ni}_x - \text{Nb}$ sandwich. The lower 110-nm thick niobium film electrode 100 μm in width was deposited by magnetron sputtering in a dc discharge with the subsequent photolithography and chemical etching. After the chemical etching of the niobium surface, high-frequency ion-plasma sputtering was employed to deposit the film of a copper – nickel alloy (use was made of targets of different compositions with x ranging from 0.52 to 0.57). Then, the procedure of lift-off photolithography was applied to form an insulation layer with a 'window' measuring 50 × 50 μm or 10 × 10 μm, which determined the area of the Josephson SFS junction. For the insulator, use was made of a 170-nm thick silicon monoxide (SiO) film produced by vacuum deposition. The structure fabrication was completed with the deposition of a 240-nm thick upper niobium electrode 80 μm in width after prior ion cleansing of the copper – nickel layer surface. The procedure of lift-off photolithography was applied when forming the upper electrode of the sample. The normal resistance R_{n} of the junctions was $10^{-4} - 10^{-5}\ \Omega$. As a result, the Josephson transport characteristics were measured by means of a superconducting picovoltmeter on the basis of an rf SQUID with a sensitivity better than 10^{-11} V. The $I_{\text{c}}(H)$ curves for as-fabricated or well-demagnetized samples were described by the well-known 'Fraunhofer relation' to a good approximation, which testified to a high uniformity in thickness and properties of the Josephson F-layer along the junction. In this case, the central peak of the Fraunhofer dependence was located at the zero of the magnetic field. The absence of the influence of macroscopic magnetic induction and domains in the ferromagnet is supposedly due to the good averaging of the small-scale domain magnetic structure of the F-layer in nonmagnetized samples, which underlay the high uniformity of superconducting current through the ferromagnet.

The main result of our work is a detailed investigation of the dependence of the critical current in SFS $\text{Nb} - \text{Cu}_{0.47}\text{Ni}_{0.53} - \text{Nb}$ sandwiches on the thickness in a wide range of values of d_{F}. In the $d_{\text{F}} = 12 - 26$ nm range, the critical current density variation amounted to five orders of magnitude. In this case, the behavior of the critical current was reversible in some thickness ranges, where it assumed the zero value. One can see two such negative peaks in the calculated (solid) curves plotted in Fig. 2, although the experimental points are not shown for ferromagnet thicknesses below 12 nm. The available experimental points furnish excellent evidence for the reverse transition from the π-state to the ordinary 0-state for a thickness $d_{\text{F},\pi 2} \simeq 2\pi\xi_{\text{F2}} = 22 - 23$ nm. The experimental data testifying to the existence of a minimum in the 10-nm region are also already at our disposal, but some technology-related irreproducibility does not permit us to present these data in our work. The $I_{\text{c}}(d_{\text{F}})$ dependence for small thicknesses, as well as the temperature $0 - \pi$ transition for junctions with $d_{\text{F}} = 10 -$

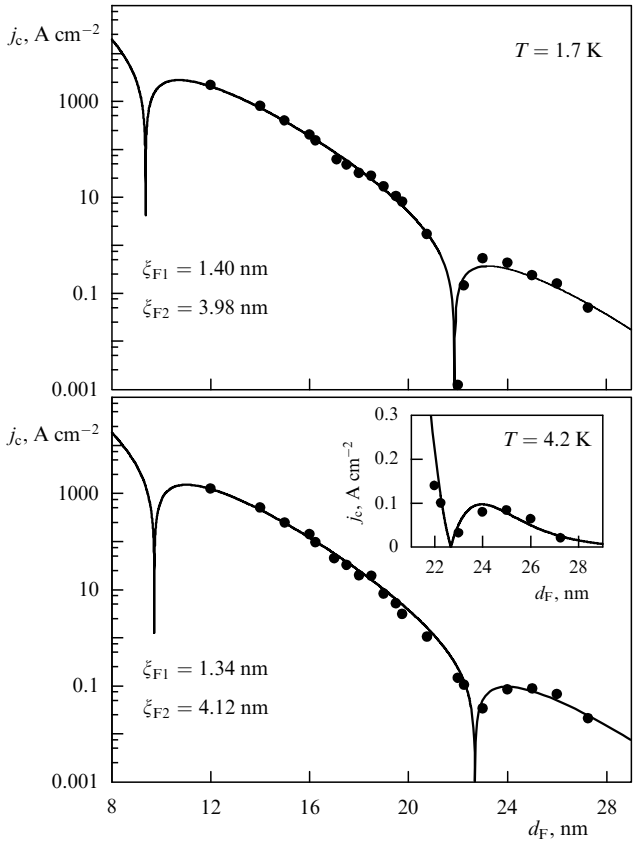

Figure 2. Critical current density of the $\text{Nb} - \text{Cu}_{0.47}\text{Ni}_{0.53} - \text{Nb}$ sandwiches vs. ferromagnetic layer thickness for temperatures of 1.7 K and 4.2 K. The $\pi - 0$ transition for $d_{\text{F}} \sim 22$ nm and $T = 1.7$ K also corresponds to the vanishing of critical current in the curve given in Fig. 3 (the middle panel). The inset to the lower figure shows a portion of the curve on a linear scale.

11 nm, will soon be published. Therefore, the 10 – 23-nm thickness range corresponds to the π-state, to which there formally correspond negative critical currents. When specifying the current through a sample in a real experiment, we actually measure the absolute values of I_{c}, and therefore the portion of the curve between the two narrow dips constitutes the formally negative branch of the I_{c} (d_{F}) dependence reflected to the positive part of the figure. The position of the $0 - \pi$ transitions in Fig. 2 allows us to estimate the value of ξ_{F2}, and the slope of the envelope the characteristic length ξ_{F1} of order parameter decay. It is easy to see that the magnitudes of ξ_{F1} and ξ_{F2} diverge greatly, with $d_{\text{F}} \gg \xi_{\text{F1}}$. To fit the experimental points to the theory (solid curves in the figures) in this limit, we replaced formula (7) with, generally speaking, a phenomenological expression (8) which makes use of different variables y of formula (7): the variable $y_1 = d_{\text{F}}/\xi_{\text{F1}}$ was employed as the argument in sinh and cosh, while the variable $y_2 = d_{\text{F}}/\xi_{\text{F2}}$ served as the argument of sin and cos:

$$j_{\text{c}} = j_{\text{c0}} \exp\left(-\frac{d_{\text{F}}}{\xi_{\text{F1}}}\right)\left|\cos\left(\frac{d_{\text{F}}}{\xi_{\text{F2}}}\right) + \sin\left(\frac{d_{\text{F}}}{\xi_{\text{F2}}}\right)\right|, d_{\text{F}} \gg \xi_{\text{F1}}\,. \tag{8}$$

In accordance with this relationship, the second zero of the critical current should occur for a thickness

$$d_{\text{F},\pi 2} = \frac{7}{4}\,\pi\xi_{\text{F2}} = \frac{7}{8}\,\lambda_{\text{ex}}\,.$$

From the fitting procedure we concluded that the values of ξ_{F1} and ξ_{F2} (see Fig. 2) differ by nearly a factor of three, which cannot be attributed only to the temperature contribution: referring to Fig. 2, this contribution changes the value of $\lambda_{ex} = 2\pi\xi_{F2}$ by less than 1 nm in the 1.7 – 4.2-K temperature range. In the derivation of formula (7), spin-orbit [13, 23] and spin-flip scatterings [17, 24] were disregarded. These processes should, like a temperature decrease, increase ξ_{F2} and decrease ξ_{F1}. Since copper and nickel possess moderate atomic numbers, we believe that the spin – orbit scattering effect can be neglected in comparison with spin-flip scattering. The latter may be quite significant due to the presence of nickel-enriched clusters in the CuNi alloy with a concentration close to 50% [25, 26], which produce substantial magnetism inhomogeneities in the F-layer. The presence of clusters in the CuNi films also accounts for the extended 'tails' in the temperature dependences of the magnetic moment and voltage for the anomalous Hall effect, which we employed to determine the Curie temperatures of the F-layers (see the inset to the middle panel in Fig. 3).

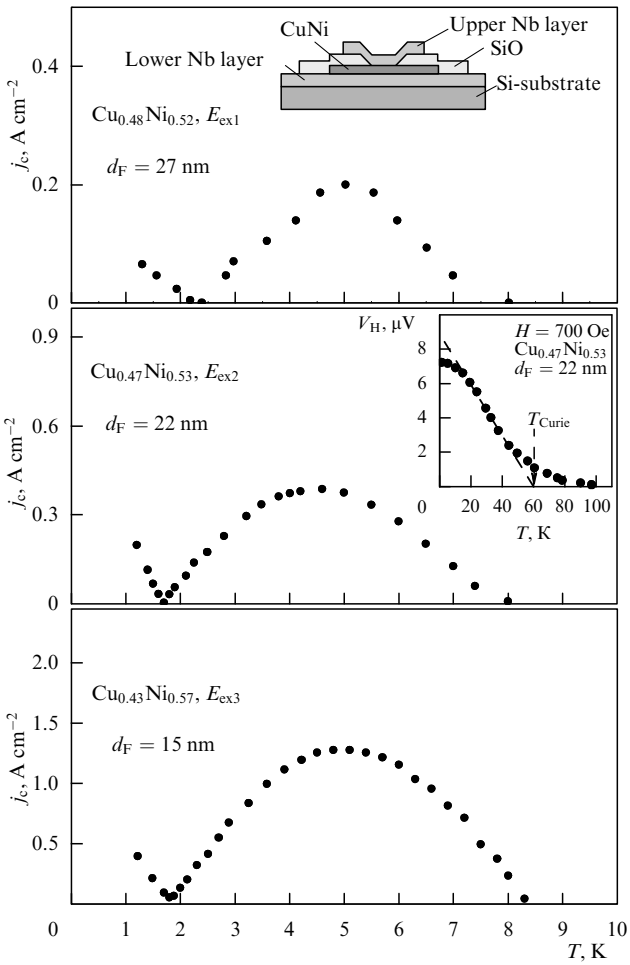

Figure 3. Anomalous temperature dependences of the critical current density of SFS sandwiches with a different content of Ni ($x = 0.52$, 0.53, and 0.57) in the $Cu_{1-x}Ni_x$ layer of Nb – $Cu_{1-x}Ni_x$ – Nb sandwiches with a thickness d_F close to the value corresponding to the reverse transition from the π- to the 0-state. The inset to the upper panel schematically diagrams the lateral section of the SFS sandwich. The inset to the middle panel exemplifies the determination of Curie temperature from the measurement of saturation magnetization with the aid of the anomalous Hall effect [16].

As mentioned above, the weak ferromagnetism of the CuNi alloy allows us to observe the temperature 0 – π transition. Some difference in the thicknesses $d_{F,\pi 2}$ of transitions at temperatures of 4.2 and 1.7 K in the two curves given in Fig. 2 is related to the temperature dependence $\xi_{F2}(T)$ [see expression (6)]. Figure 3 shows the experimentally established temperature dependences of the critical current densities $j_c(T)$ in SFS sandwiches with different concentrations of nickel ($x = 0.52$, 0.53, and 0.57) in the $Cu_{1-x}Ni_x$ layer for thicknesses d_F close to that corresponding to the reverse (π – 0) transition. The reciprocal temperature dependence is a direct consequence of the transition at a temperature of $T = T_{\pi 2}$. With decreasing temperature, the 'negative' branch corresponding to the π-state goes over to the positive domain on passing through the zero value of the critical current. In accordance with formula (4), the coherence length ξ_{F2} is inversely proportional to $\sqrt{E_{ex}}$, and therefore

$$d_{F,\pi 2} = \frac{7}{4}\,\pi\xi_{F2} \propto \sqrt{E_{ex}}\,.$$

Since we had no way of measuring E_{ex} directly and judged the F-layer magnetism only by the Curie temperature, we cannot perform a quantitative comparison of the resultant data with formulas (4) or (6). However, a qualitative agreement is evident: the higher the nickel content in the ferromagnetic layer, the shorter the spatial oscillation period of the order parameter in the F-layer, with the consequential decrease of ferromagnet thicknesses whereby it is possible to observe the temperature transition to the π-state in the SFS sandwich.

We have also been interested in comparing the dependence of the critical SFS-sandwich current on the F-layer thickness with the $T_c(d_F)$ dependence for SF bilayers [28]. The reason is as follows. Although the history of experimental investigations of the nonmonotonic behavior of T_c in multilayer SF structures [18, 27, 19, 21] is richer than that of the investigations of lateral transport in SFS sandwiches, for a long time they were considered to be insufficiently strong evidence of the existence of spatial oscillations of the super-

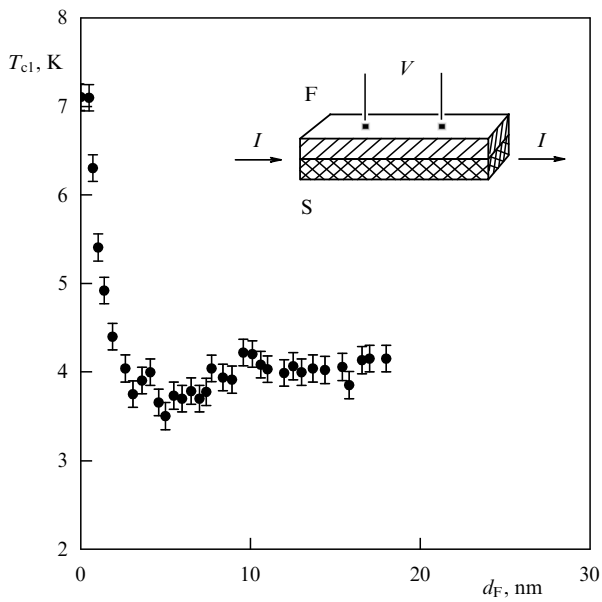

Figure 4. Critical temperature of the bilayer Nb – $Cu_{0.43}Ni_{0.57}$ structures against ferromagnetic layer thickness. Inset shows the geometry of the resistive experiment.

conducting order parameter in ferromagnets. Figure 4 displays the experiment geometry and the measurement data on the critical temperature dependence $T_{c1}(d_F)$ for the SF Nb–$Cu_{0.43}Ni_{0.57}$ bilayer. The fabrication technology of the bilayers employed in the experiment of Ref. [28], as well as the Nb- and CuNi-layer compositions, corresponded closely to the two lower layers of the $Nb - Cu_{0.43}Ni_{0.57} - Nb$ sandwich characterized by the results presented in the lower panel of Fig. 3. For a ferromagnetic layer, use was made of $Cu_{0.43}Ni_{0.57}$-alloy films with a Curie temperature T_{Curie} of about 150 K. The lower superconducting layer thickness in the bilayer was 11 nm, which was close to its coherence length. The critical bilayer temperature varied in the 3–7 K range, when the F-layer thickness was varied from 1 to 20 nm. It is easily seen that the critical temperature passes through a minimum for a thickness $d_F = 4-5$ nm, which should correspond to a quarter of the spatial oscillation period λ_{ex} as discussed above. On the other hand, the $d_{F,\pi 2} = 15$nm thickness, whereby the second temperature transition is observed in the SFS sandwich, should be equal to $(7/8)\lambda_{ex}$. Therefore, from both types of experiments there follows the same oscillation period of the order parameter in the $Cu_{0.43}Ni_{0.57}$ alloy, which is equal to 17 nm.

5. Phase-sensitive experiments. Direct observation of spontaneous phase shifts in structures with SFS π-junctions

Several experimental phase-sensitive methods for the direct observation of the transition to the π-state have been proposed and realized. The most direct way of detecting the phase difference shift by π in Josephson junctions is to investigate the dependences of the critical current on the magnetic field of superconducting interferometers with three junctions in the cell [9]. In these structures, when the junctions go over to the π-state, in the absence of current and an external field there emerges in each cell a superconducting phase incursion equal to an odd number of π. This is completely similar to the imposition of an external magnetic flux equal to half the magnetic flux quantum, $\Phi_0/2$, on the interferometer cell with junctions in the ordinary 0-state. It is easily comprehended that the temperature 0–π transition of the junctions in such a structure should manifest itself in a half-period shift of the dependence of the critical interferometer current on the applied magnetic flux, which was experimentally established [9, 8].

A signature of the π-state is also the emergence of spontaneous magnetic flux equal to half flux quantum, $\Phi_0/2$, in the superconducting ring with one π-junction. The existence of a phase π-shift in the junction generates the need for current flow around the ring to produce the magnetic flux $\Phi_0/2$ corresponding to the additional phase incursion π in the superconducting loop. Bulaevskiĭ et al. [1], who predicted the first π-junction, showed that the state with spontaneous flux can be realized in a one-junction interferometer only when $2\pi L I_c > \Phi_0$ (L is the inductance of the superconducting ring, and I_c is the critical current of the junction); otherwise, there is no way of producing the spontaneous flux $\Phi_0/2$ in the ring and the phase difference across the π-junction will be zero. However, even in the case when $2\pi L I_c < \Phi_0$, which corresponds to the nonhysteretic regime of the one-junction interferometer, the change of the current–phase relation from $I_s = I_c \sin\varphi$ to $I_s = -I_c \sin\varphi$ should result in the determinable half-period shift of the dependence of the flux Φ in the interferometer on the external flux Φ_e: the portion of the $\Phi(\Phi_e)$ curve near $\Phi_e = \Phi_0/2$, which corresponds to a phase difference π in the ordinary junction, will move to the origin upon the transition of this junction to the π-state and will correspond to the zero phase difference of the π-junction. The experiment outlined above was recently carried out in Ref. [29]. Use was made of the reciprocal dependence $I_c(T)$ of the $Nb - Cu_{0.47}Ni_{0.53} - Nb$ sandwich in the region of transition to the π-state, which is similar to the dependence given in Fig. 3. A nonhysteretic regime was realized in the immediate vicinity of $T_{\pi 2}$, and the transition to the π-state manifested itself in a half-period shift of the characteristics of a one-junction interferometer vs. the magnetic field. A further increase in the critical current in the π-state gave rise to spontaneous magnetic flux which built up to a value of $\Phi_0/2$.

6. Conclusions

Therefore, the peculiarities of the proximity effect and superconducting transport in the superconductor–ferromagnet–superconductor structures have been investigated in a series of experimental works carried out in 2001–2004. The coexistence of superconductivity and ferromagnetism was shown to directly manifest itself in the sigh-reversal spatial oscillations of the superconducting order parameter in the ferromagnet near the SF interfaces. In the Josephson SFS sandwiches, the change of sign in the order parameter may give rise to a spontaneous phase difference π across the sandwich plates, i.e., to a transition of the Josephson junctions to the π-state. Discovered in the above-outlined experiments were transitions to and out of the π-state, which show up in anomalous dependences of the critical current on the thickness and the temperature. Good accord was reached between the results of experiments on SFS sandwiches and bilayer SF structures. The minimum of the critical temperature of the SF bilayer was shown to correspond to a ferromagnet thickness equal to a quarter of the spatial oscillation period of the order parameter. Phase shifts and a spontaneous magnetic flux have been discovered in the interferometers with π-junctions.

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